Observation of
Top quark pair production in association with a Higgs boson
using the Compact Muon Solenoid

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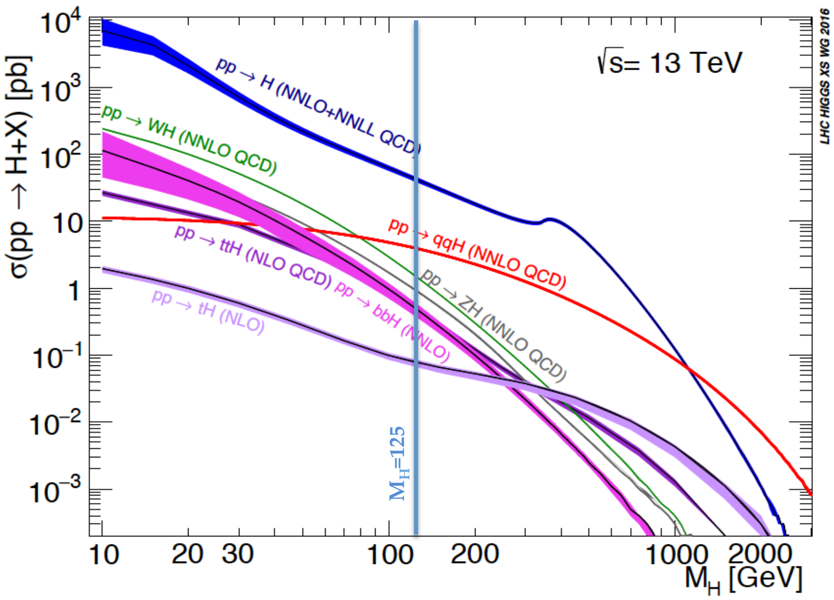
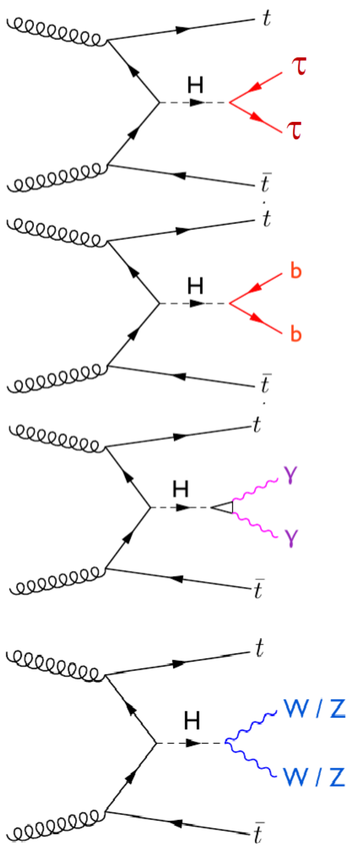
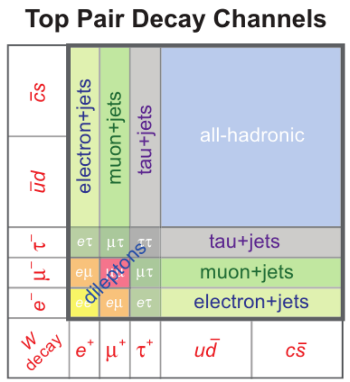
top quarks + Higgs: production



- H → ttbar not kinematically possible at m_H=125 GeV so associated production main mode
- Associated ttbar+Higgs production has ~0.5 pb cross section and dwarfed by ttbar background
- All ttbar decay channels and many decays of Higgs considered



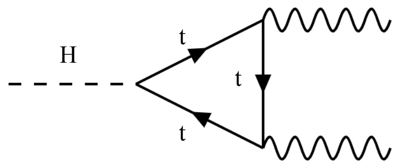


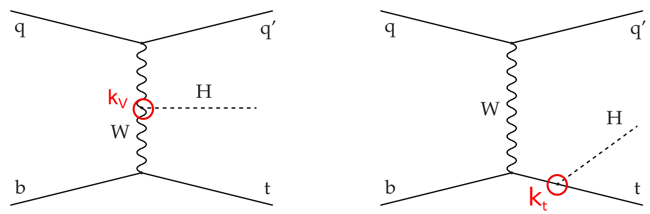
√s	7 TeV	8 TeV	13 TeV
σ (ttH (125))	90 fb	130 fb	510 fb
σ (tt+jets)	177000 fb	253000 fb	830000 fb
Ratio	5.0E–4	5.1E–4	6.1E–4

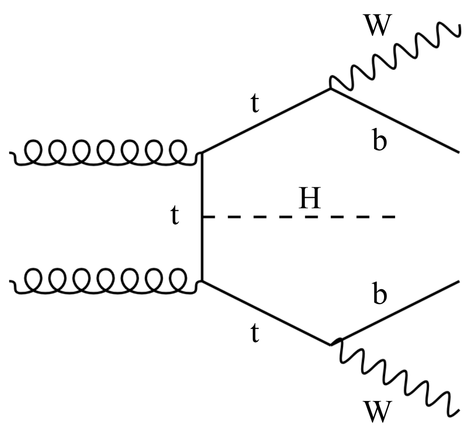
The Top-Higgs coupling

- Vital step in probing SM nature of the Scalar boson
- Top quark has strongest SM coupling (y_t ~1)
- Direct and indirect measurement of y_t possible
  - Direct: ttH production
  - Direct: tH production (inc. access to sign)
  - Indirect: top loops dominate gluon fusion and γγ decay channel

H → γγ:

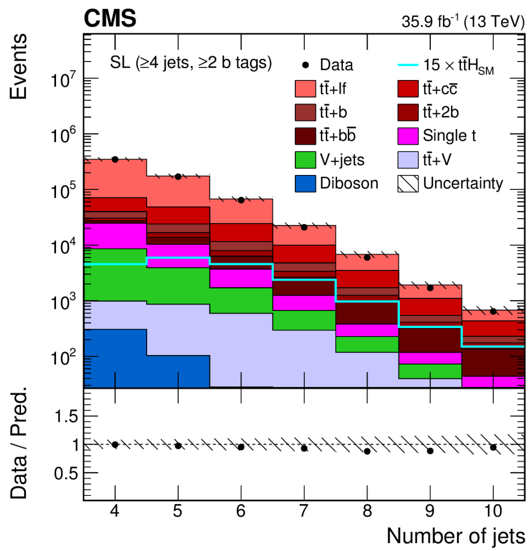


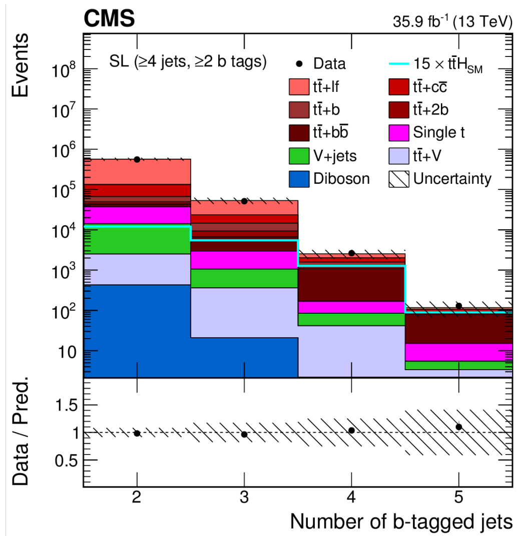




Decay modes: ttbarH (H → bb)

- Largest Higgs boson branching ratio
- Access to coupling both 3rd generation quarks
- Huge combinatorics
- Poor Higgs mass resolution
- Background comes with large theory uncertainties





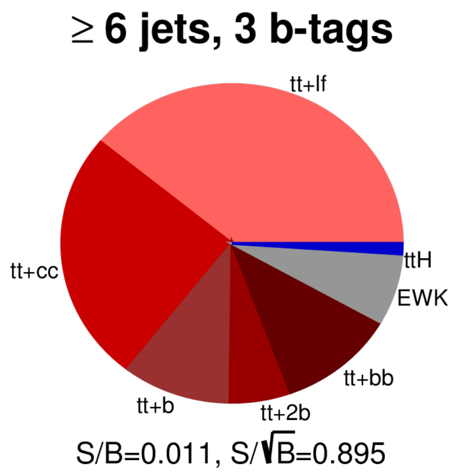
Channels:

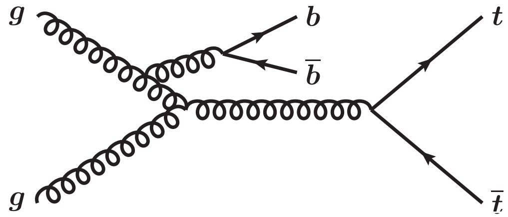
Leptonic tt: higher purity

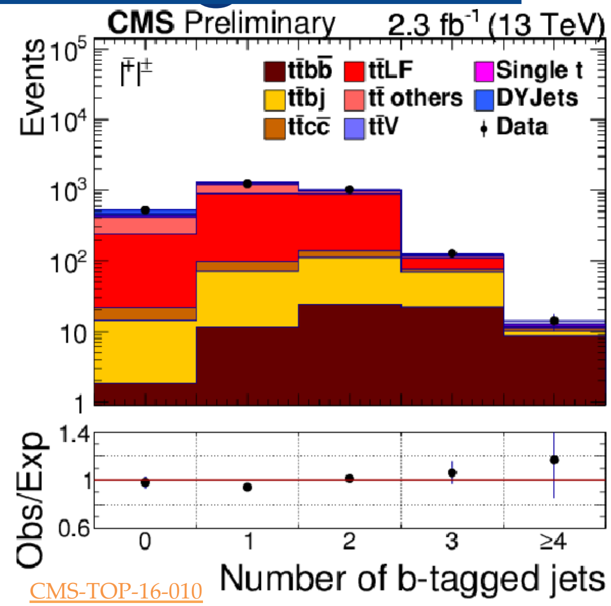
Fully hadronic tt: higher rate

arXiv:1804.03682, submitted to JHEP

ttbarH (H → bb): tt+bb background







- Modeling of tt+jets process:
  - Powheg+Pythia8, normalised to NNLO
  - Consider tt+X backgrounds separately: tt+b, tt+bb, tt+2b(in 1 jet), tt+cc, tt+light flavour
  - Rate uncertainty is large (50%), independent per process, and among the leading uncertainties
  - Main irriducible background, also measured in preliminary result TOP-16-010
  - Additional `theory' uncertainty sources: parton shower model, hadronisation model, PDFs, ISR/FSR

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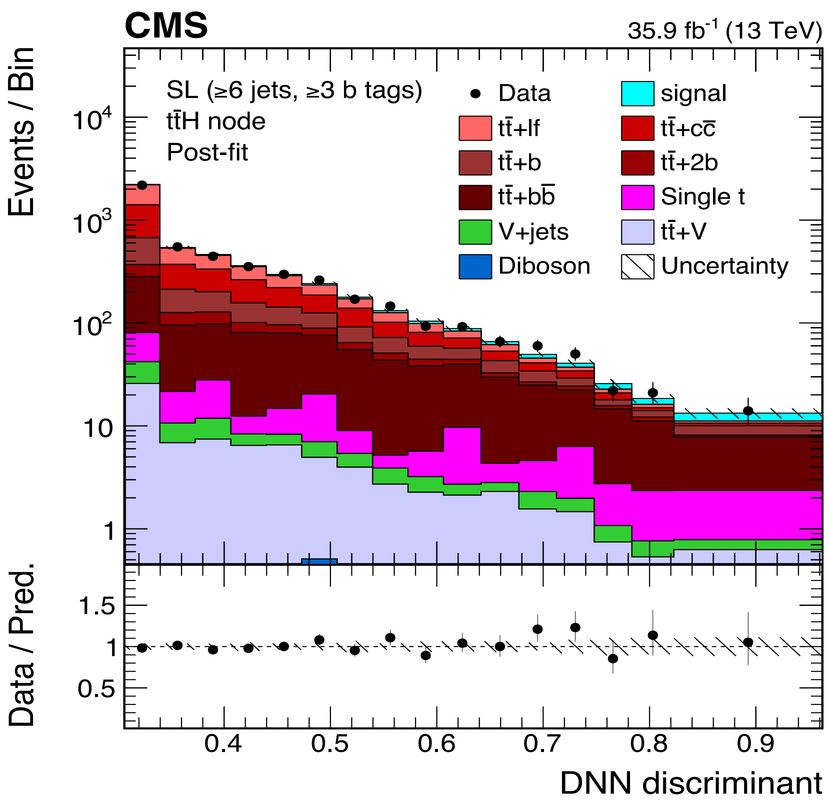
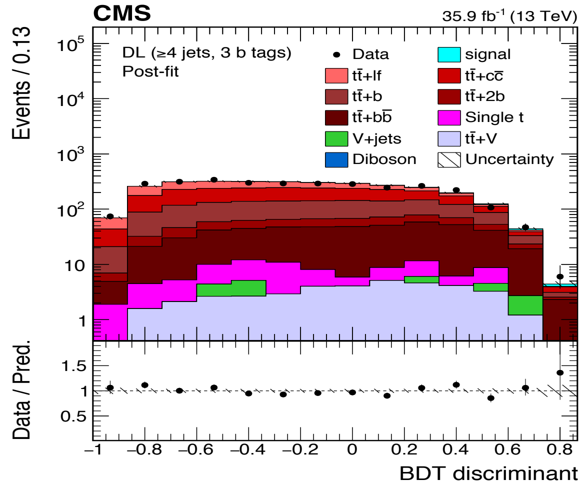
arXiv:1804.03682, submitted to JHEP

ttH (H → bb): leptonic distributions

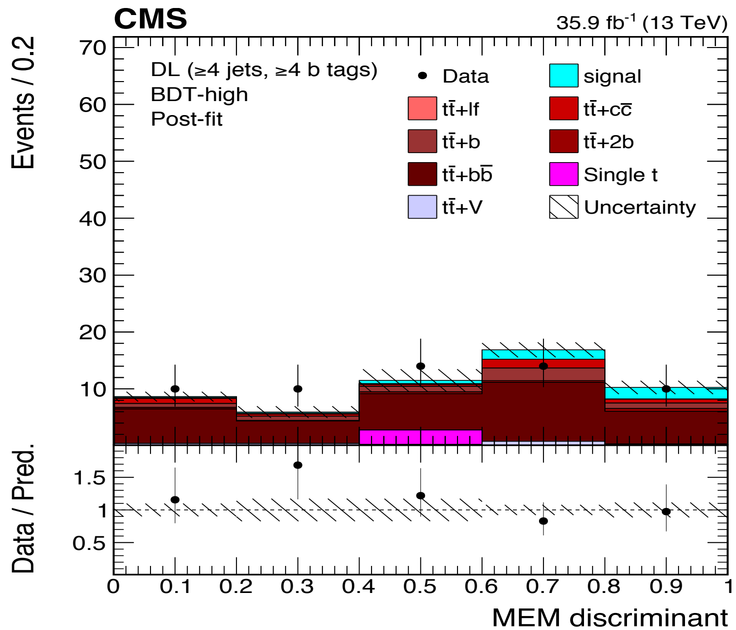




Dilepton channel: events categorised by **number of jets**, number of **b-tagged jets**

BDT separates signal

Highest sensitive category (4+j4+b): **Matrix Element Method** provides further separation



Single lepton channel:

Deep neural network per jet category: classifies and categorises each of the 5 tt+jets backgrounds

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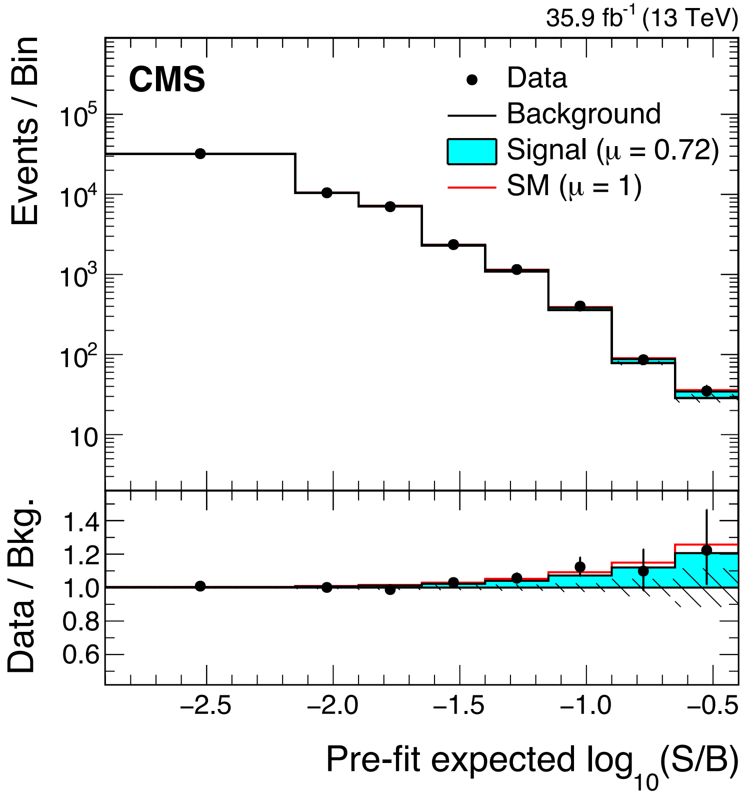
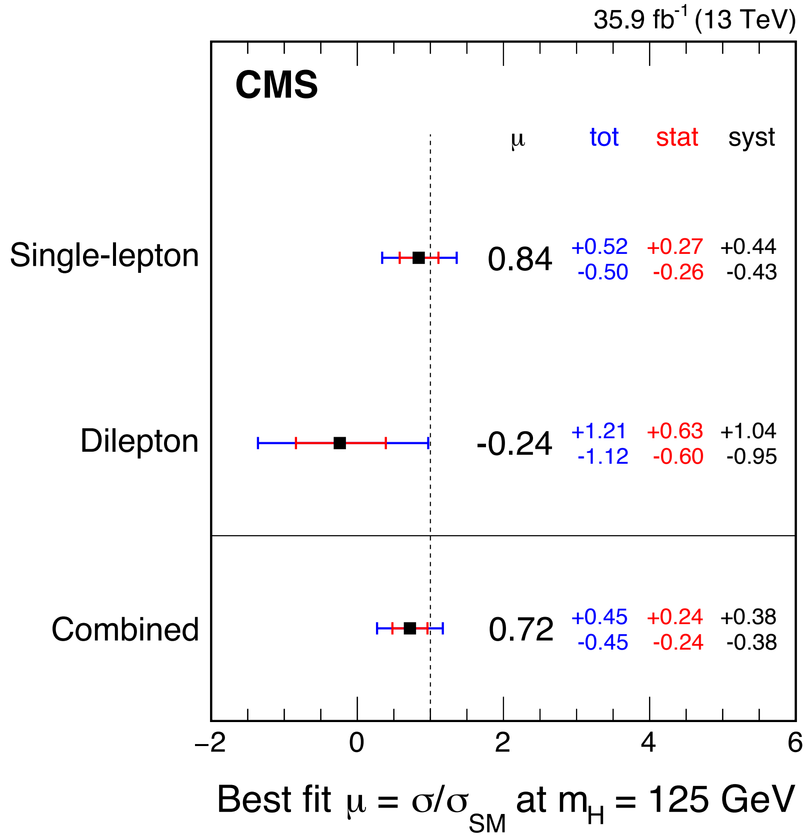
Single- and multilepton: Results

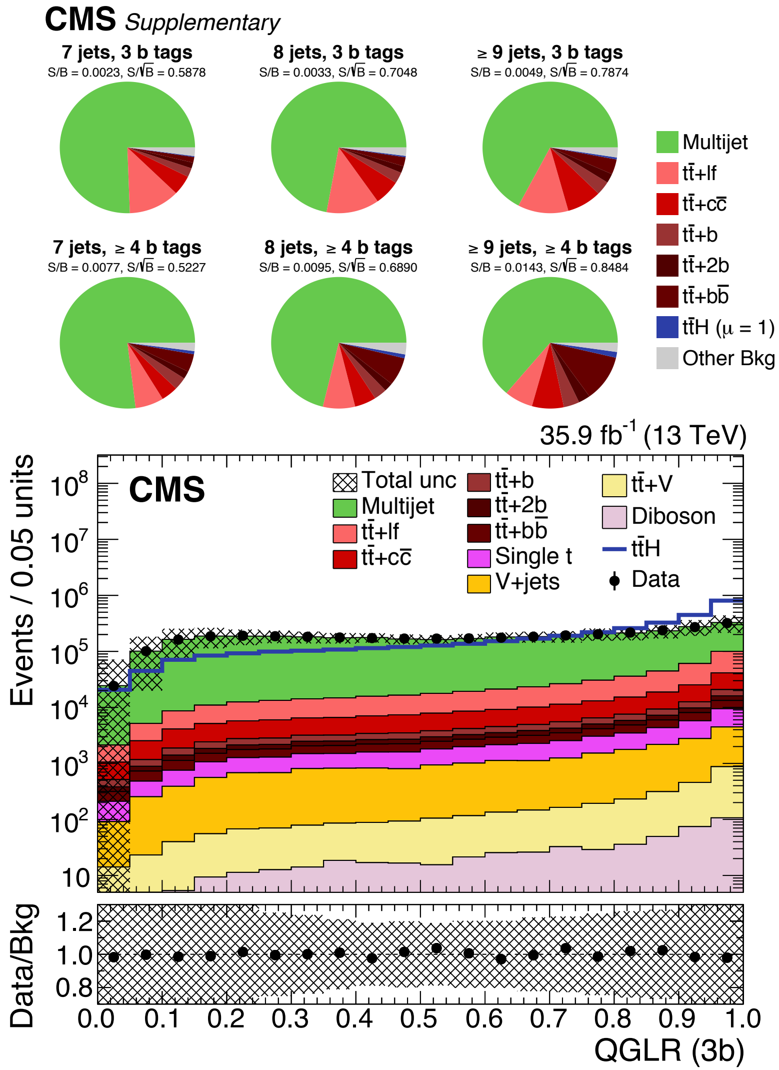




Best-fit $\mu = 0.72^{+0.45}_{-0.45}$, at 1.6 (2.2) σ obs. (exp.) significance

All hadronic final state

- At least 7 jets
- At least 3 b-tagged jets
- No leptons, HT>500 GeV
- QCD multijet production shapes and rate determined from data control regions
- Use Matrix Element Method
  - discriminate between QCD multijet, ttbar+HF and ttH



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arXiv:1803.06986, submitted to JHEP

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- At least 7 jets
- At least 3 b-tagged jets
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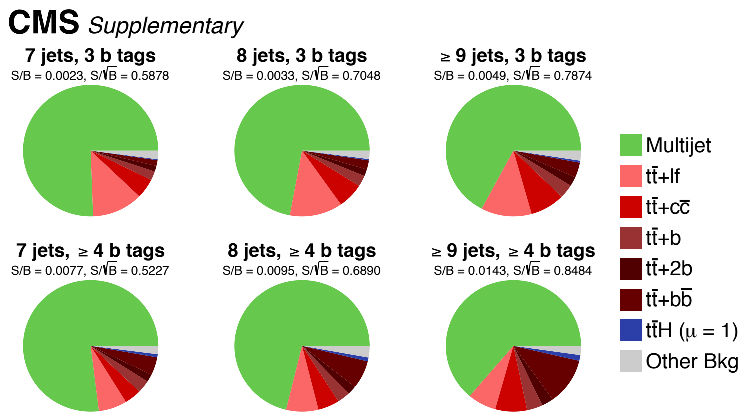

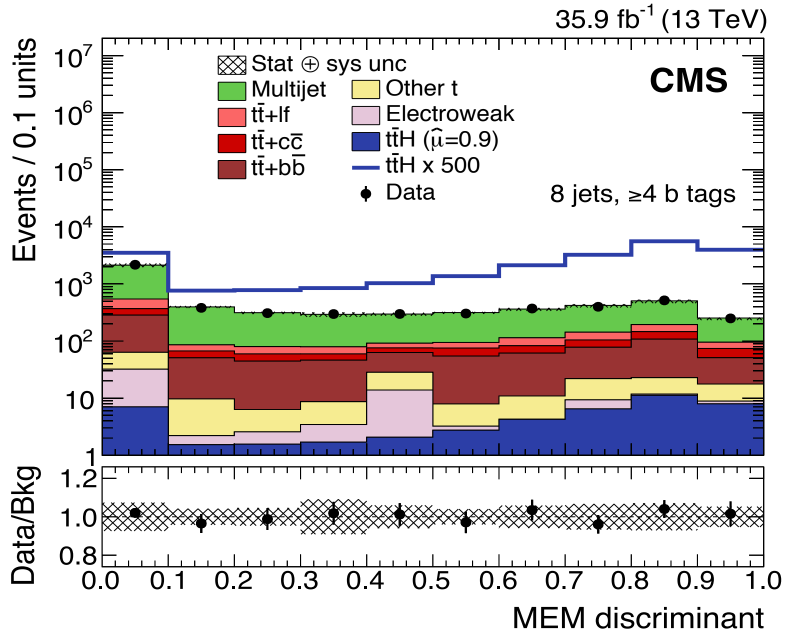

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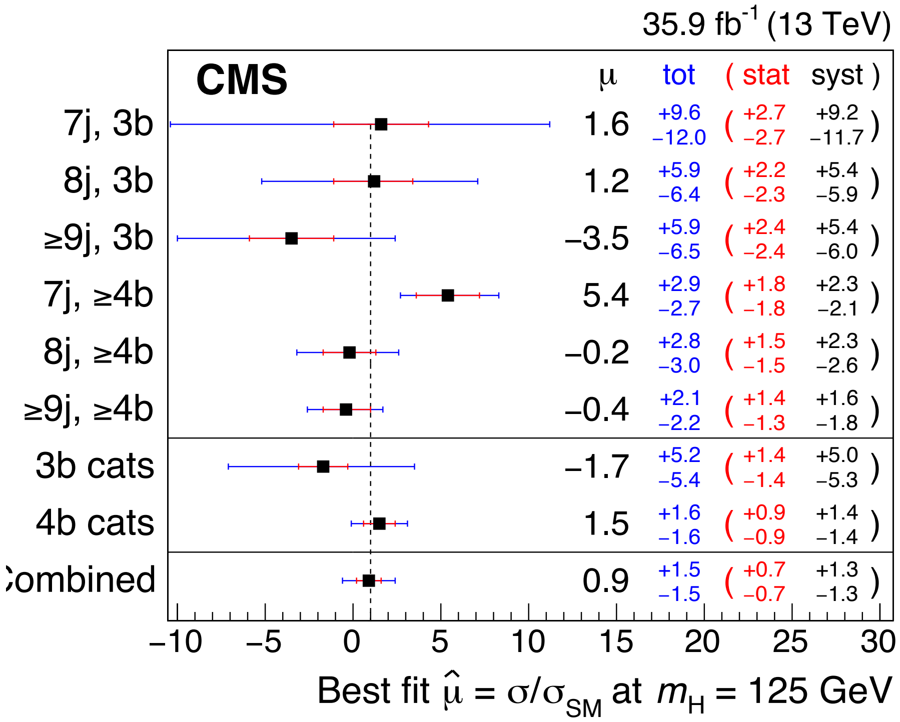
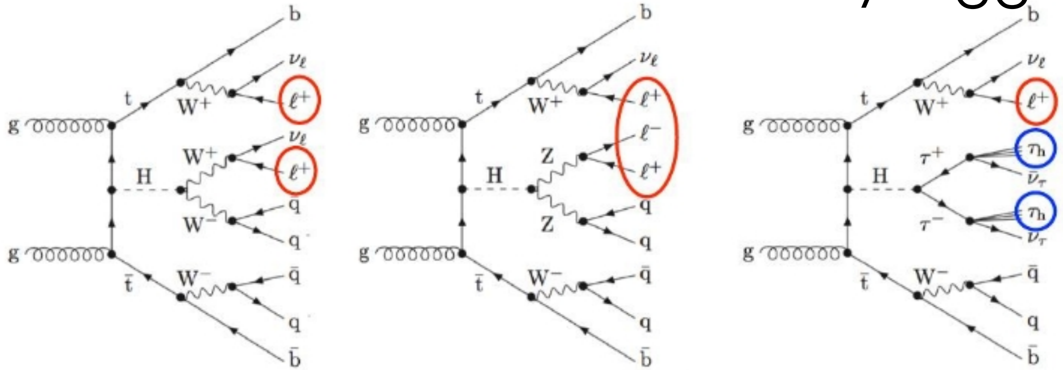


Best-fit $\mu = 0.9^{+1.5}_{-1.5}$

Multileptons

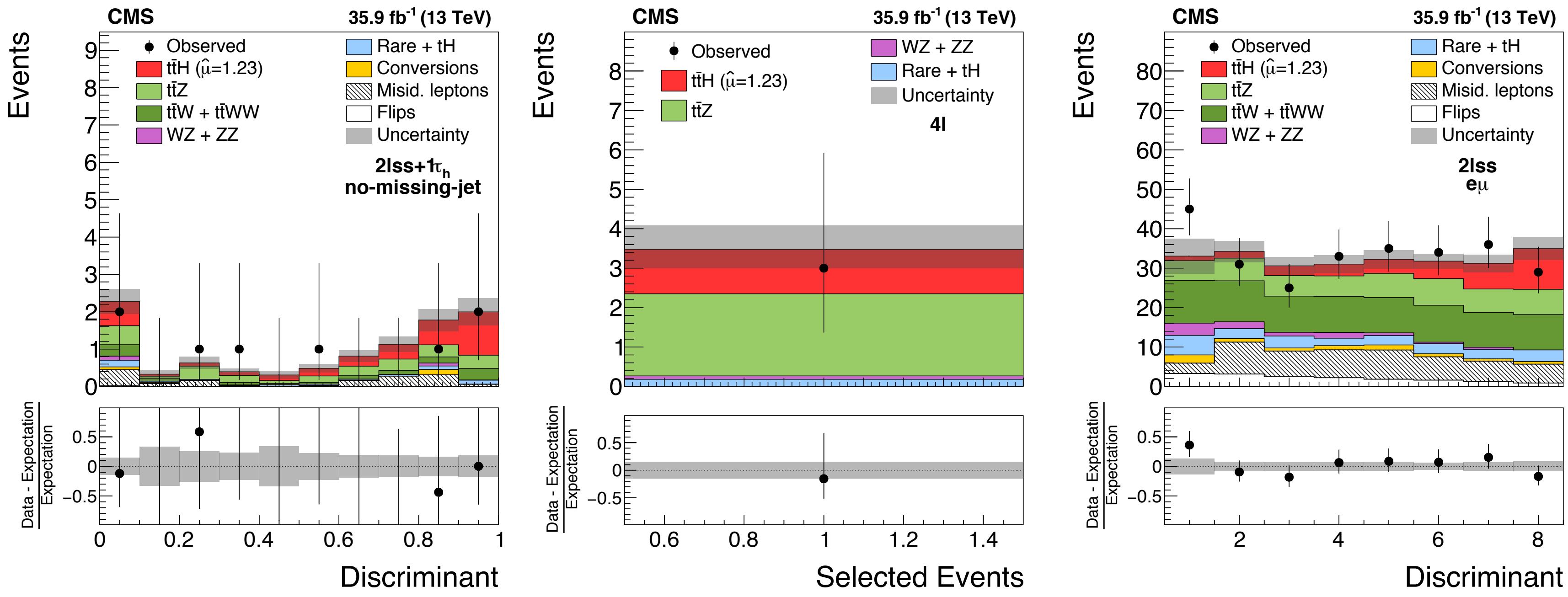
- Many possible final states when decay Higgs to WW, ZZ, $\tau\tau$



- Categorise on number of e,μ (=`leptons') and number of hadronic taus
  - 1 lepton + 2τ_h, 2 same-sign leptons + 0/1τ_h, 3 leptons + 0/1τ_h, 4 leptons
  - Also require jets and b-tagged jets consistent with final states
  - Backgrounds: tt+Z/W, dibosons (from simulation and control regions)
- Discriminate signal from background using MEM and BDT

ttH multilepton: analysis

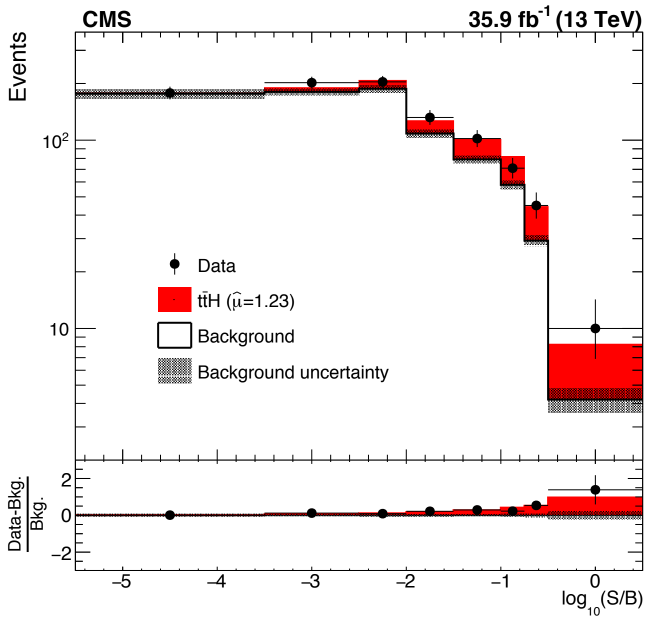
- Categorising events in lepton flavour and b-jet multiplicity
- Using combination of simple yield, BDT and MEM depending on final state

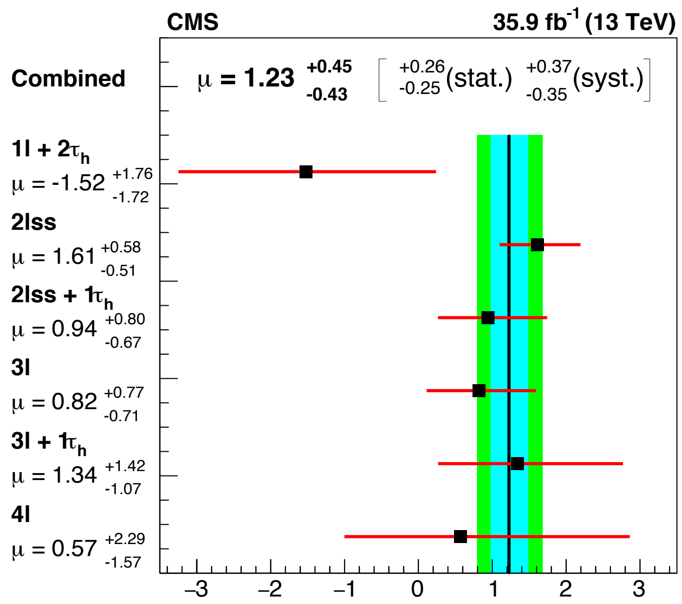


arXiv:1803.05485, submitted to JHEP

ttH multilepton: analysis

- Categorising events in lepton flavour and b-jet multiplicity
- Using combination of simple yield, BDT and MEM depending on final state

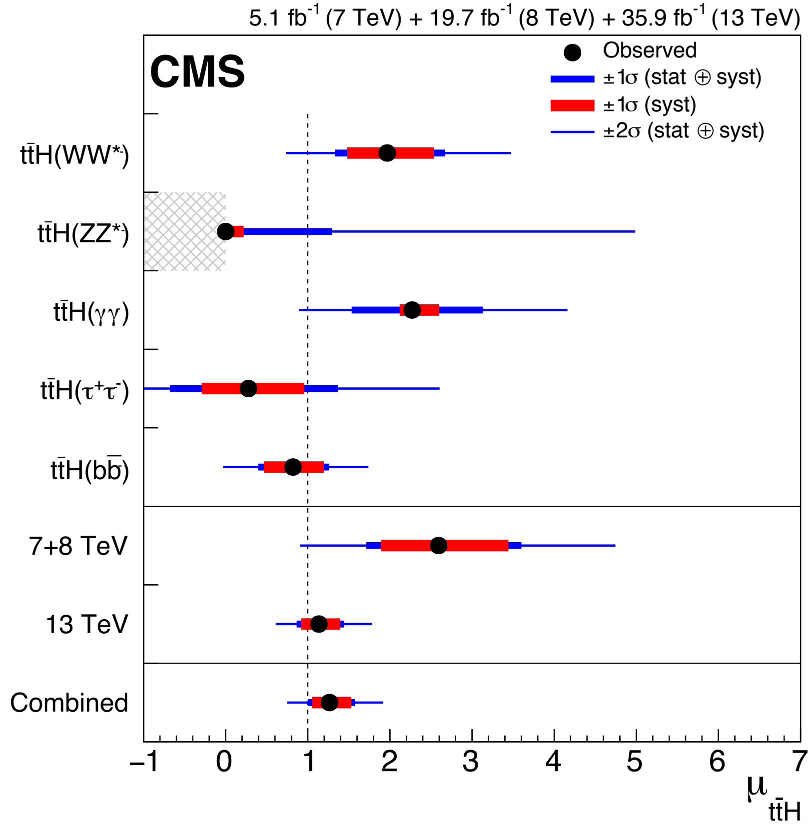




Best-fit $\mu = 1.23^{+0.45}_{-0.43}$, at 3.2 (2.8) σ obs. (exp.) significance

Combination: first observation of ttH

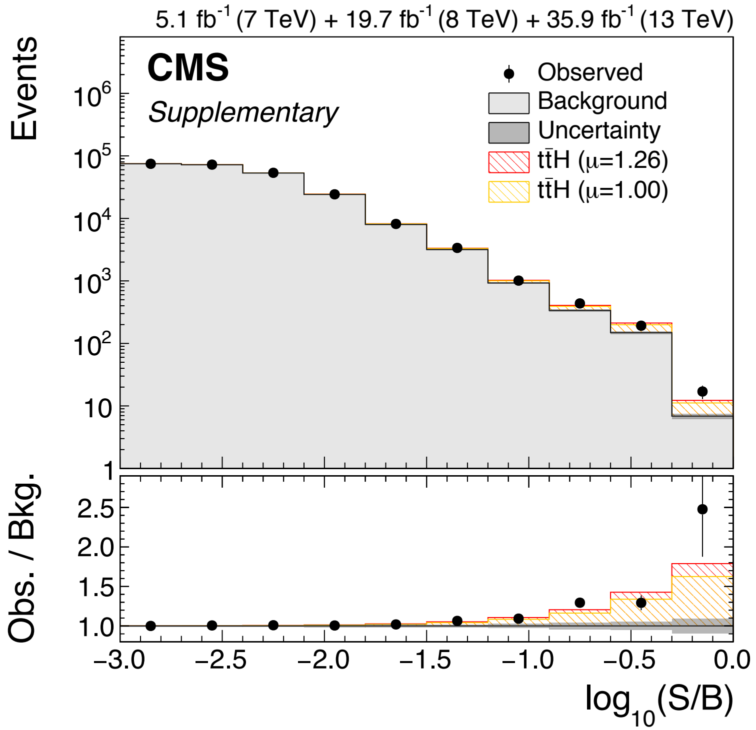
- Includes:
  - All ttH analyses using 2016 data including what I showed earlier
  - All ttH analyses using 2011 and 2012 datasets (up to 5.1 fb^{-1}, 19.7 fb^{-1})
  - 2016 H → γγ analysis has ttH categories, which are also included

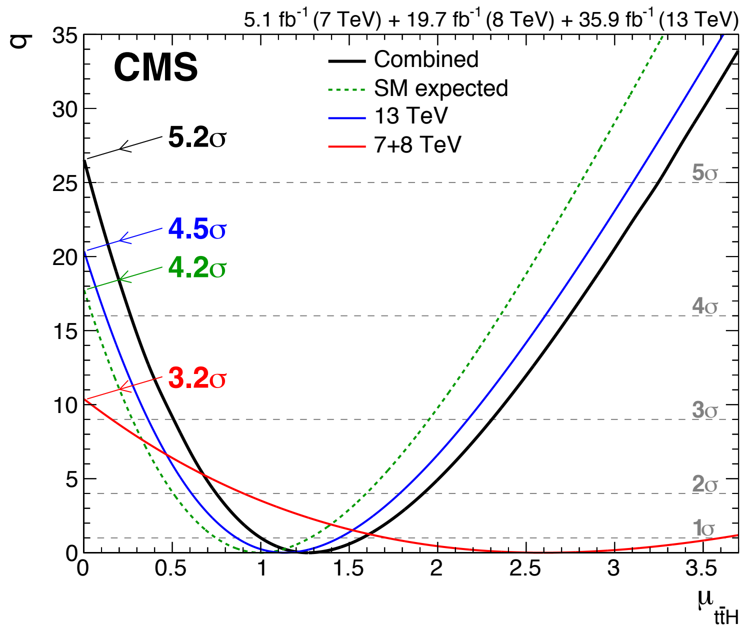


- Correlations Run 1 vs Run 2:
  - Theory uncertainties (signal, some background) are correlated when appropriate
  - Experimental uncertainties mostly uncorrelated

Combination: first observation of ttH

- Observed significance is 5.2σ (4.2σ expected) with respect to no-ttH hypothesis
- **First observation of ttH production!**





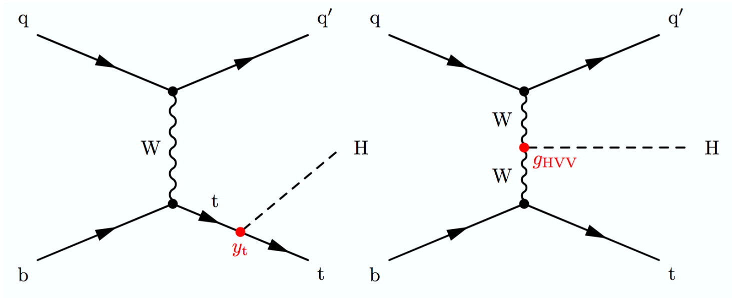
$$\mu_{t\bar{t}H} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16}(\text{stat})^{+0.17}_{-0.15}(\text{expt})^{+0.14}_{-0.13}(\text{Th. bkg})^{+0.15}_{-0.07}(\text{Th. sig})$$

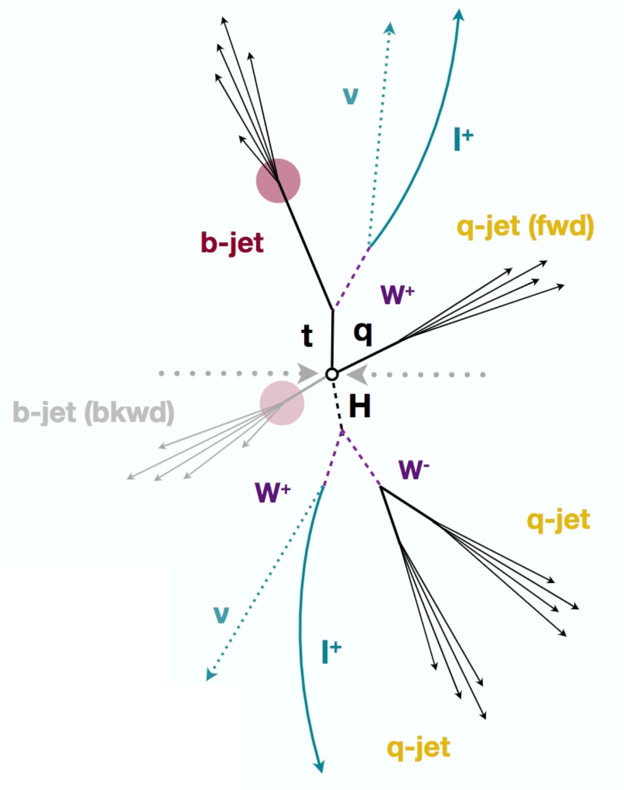
tH production: new preliminary results

- Single top plus Higgs is sensitive to amplitude, relative sign and phase Y_t (and g_{HVV})
- Destructive interference in SM – but BSM could enhance this!

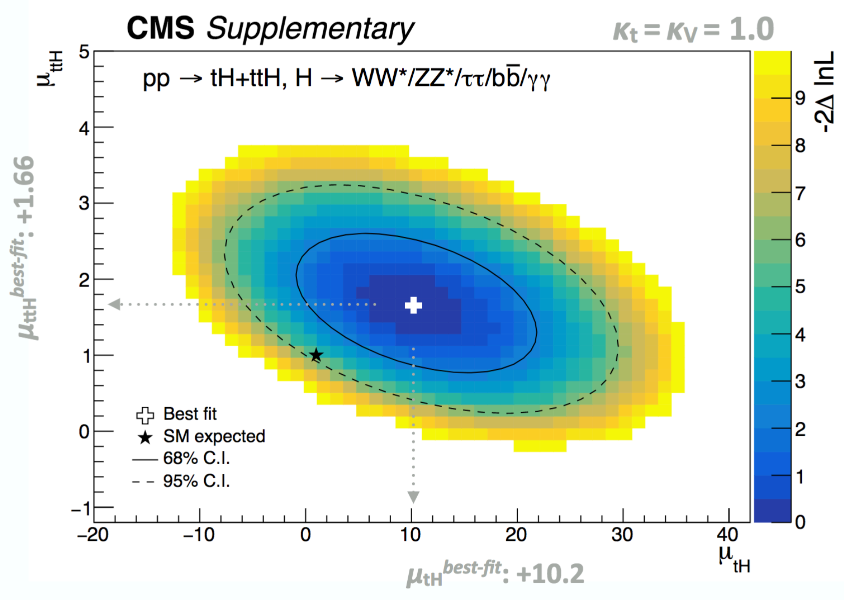
Experimental signature: back-to-back top-Higgs with light forward jet again **using machine learning to discriminate signal from background**

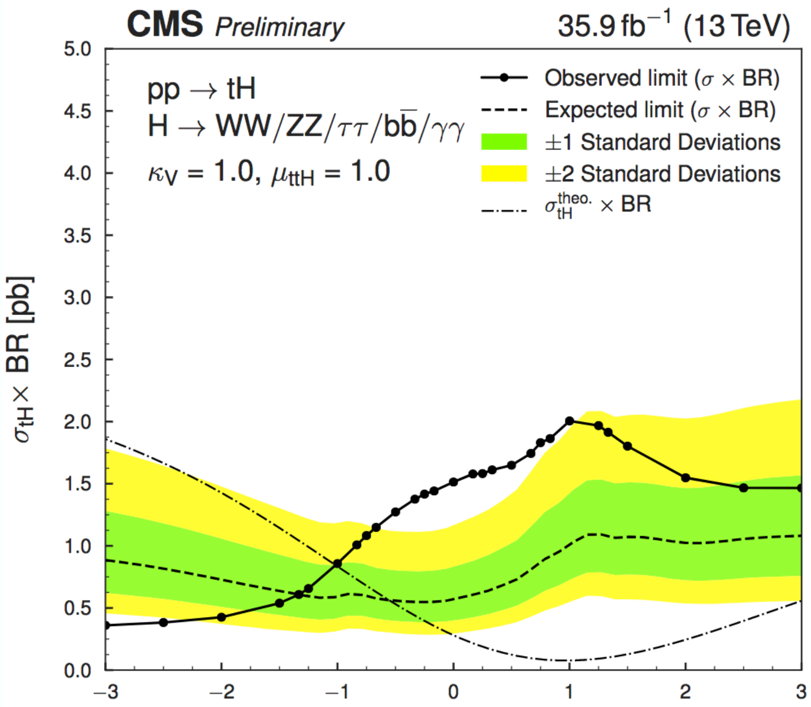
- CMS has preliminary results based on 2016 dataset (36 fb^{-1}) combining 3 decay channels: **HIG-18-009** using an extension of subset ttH analyses:
  - Multileptons (H → WW/ZZ/ττ)
  - Leptonic top + b jets (H → bb)
  - Leptonic top + diphotons (H → γγ)





Correlation ttH vs tH: fitting coupling





- Observed $\mu_{tH} < 26.5$ ($\sigma \times BR < 2.03$ pb)
- Expected $\mu_{tH} < 13.6$ ($\sigma \times BR < 1.04$ pb)

Note: Limits on signal strength tH are assuming SM couplings ttH

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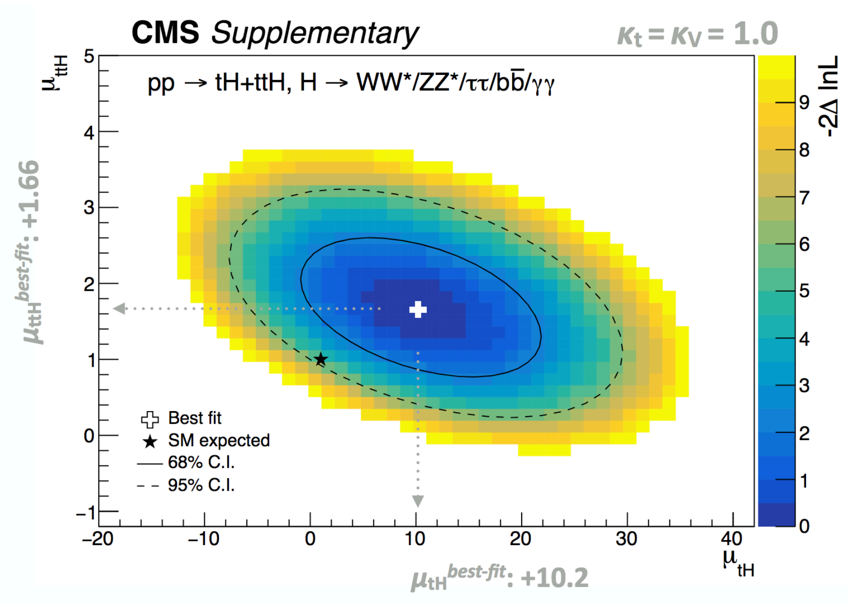
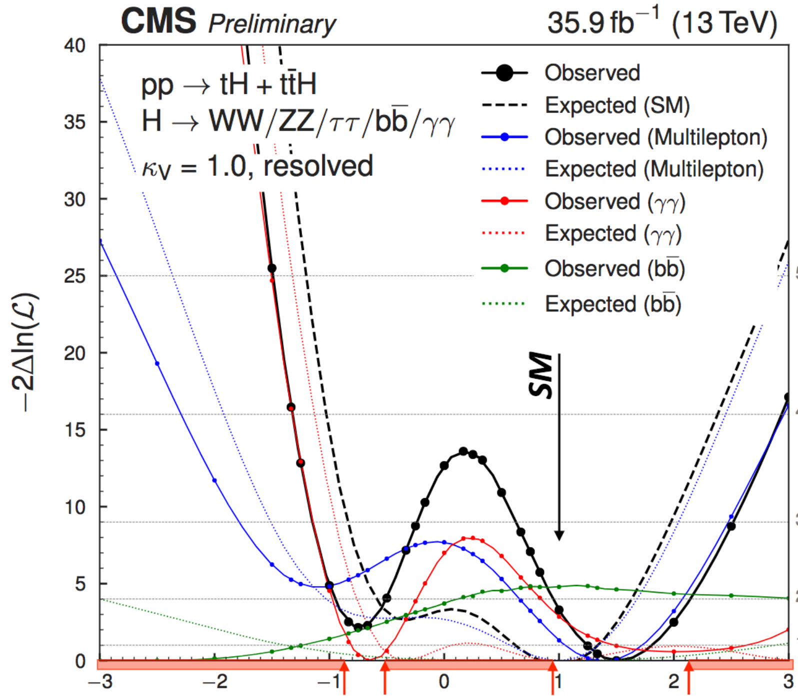
Correlation ttH vs tH: fitting coupling





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Note: Limits on signal strength tH are assuming SM couplings ttH

Summary and outlook

- Higgs physics has now moved from search and discovery phase into precision measurement era
- CMS has performed a combination of all published ttH results and observed ttH production

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

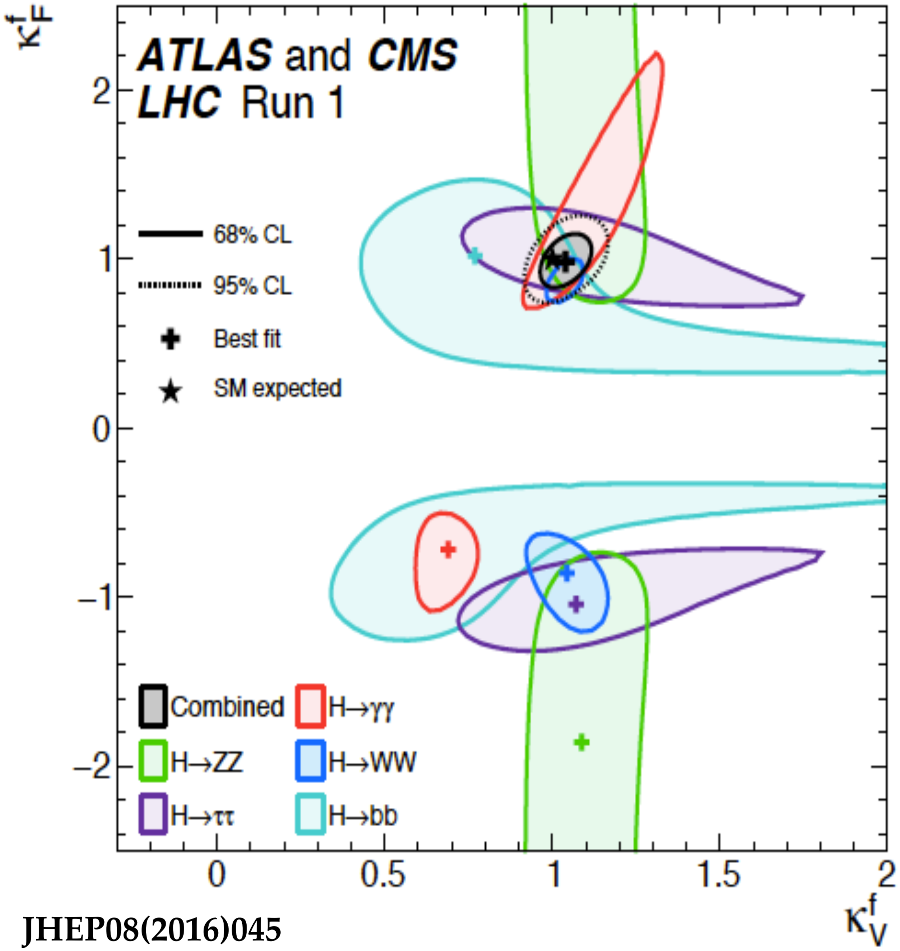
- Measurement of the top-Higgs coupling is among the primary goals of the LHC physics program
- Edging closer to tH production with (non significant still) preference to positive coupling
- Future plans: differential cross sections, many EFTs / top partners / exotic 4th gen / 2HDM / etc look like SM top-Higgs...until you look in the tails

Backup

The Top-Higgs coupling

- Vital step in probing SM nature of the Scalar boson
- Top quark has strongest SM coupling ($y_t \sim 1$)
- Direct and indirect measurement of y_t possible
  - Direct: ttH production
  - Direct: tH production (inc. access to sign)
  - Indirect: top loops dominate gluon fusion and γγ decay channel

SM = (1.0,1.0)



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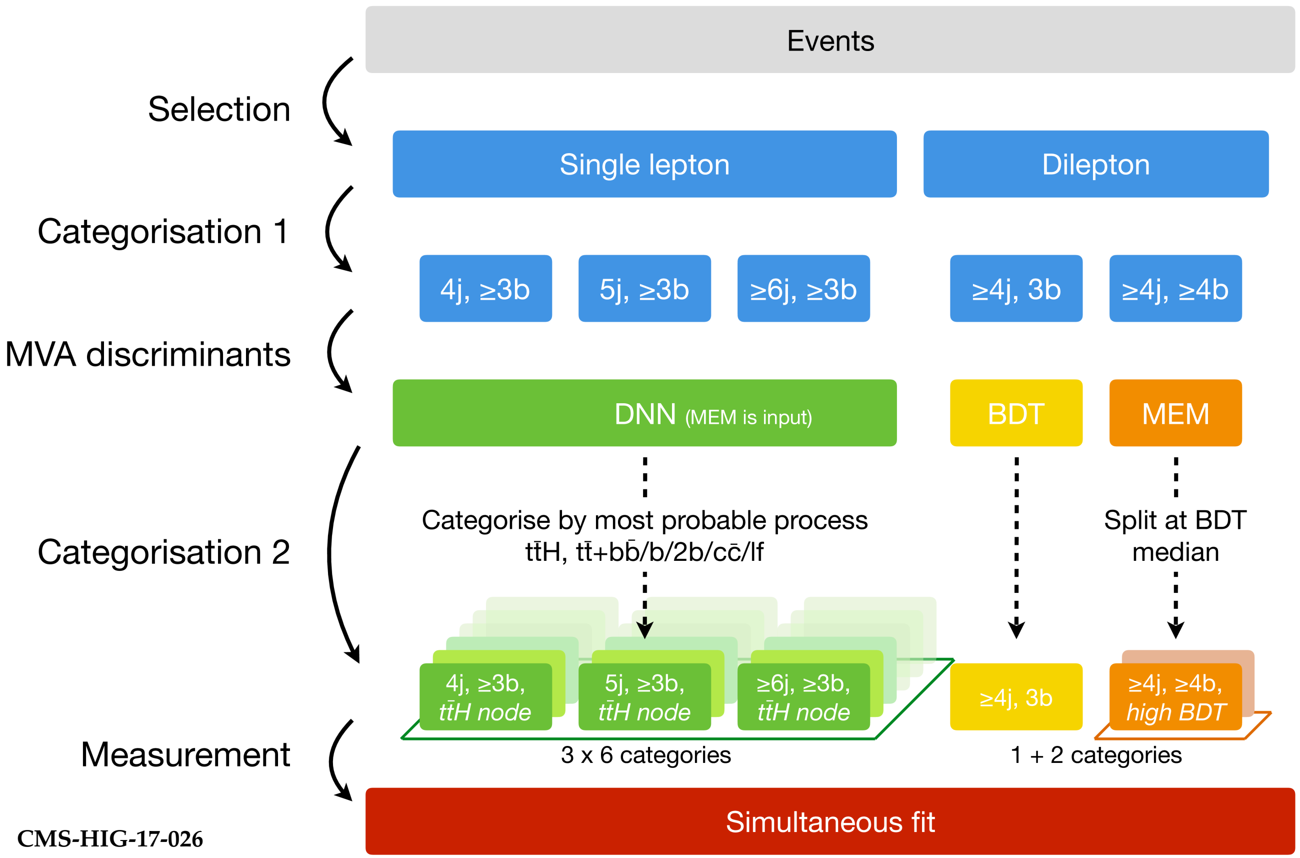
Signal extraction ttH with H → bb



- Overwhelming background means advanced analysis like MEM & machine learning techniques are optimal
- After optimization (full comparison :
  - in single lepton Deep Neural Network is best, in multi-lepton channel matrix element method combined with boosted decision tree

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h-t yields

Multilepton

Process	$\ell\ell\ell$	$\mu\mu$	$e\mu$
$t\bar{t}W^{\pm}$	22.50 ± 0.35	68.03 ± 0.61	97.00 ± 0.71
$t\bar{t}Z/t\bar{t}\gamma$	32.80 ± 1.79	25.89 ± 1.12	64.82 ± 2.42
WZ	8.22 ± 0.86	15.07 ± 1.19	26.25 ± 1.57
ZZ	1.62 ± 0.33	1.16 ± 0.29	2.86 ± 0.45
$W^{\pm}W^{\pm}qq$	–	3.96 ± 0.52	6.99 ± 0.69
$W^{\pm}W^{\pm}$(DPS)	–	2.48 ± 0.42	4.17 ± 0.54
VVV	0.42 ± 0.16	2.99 ± 0.34	4.85 ± 0.43
tttt	1.84 ± 0.44	2.32 ± 0.45	4.06 ± 0.57
tZq	3.92 ± 1.48	5.77 ± 2.24	10.73 ± 3.03
tZW	1.70 ± 0.12	2.13 ± 0.13	3.91 ± 0.18
γ conversions	7.43 ± 1.94	–	23.81 ± 6.04
Non-prompt	25.61 ± 1.26	80.94 ± 2.02	135.34 ± 2.83
Charge flips	–	–	58.20 ± 0.30
Total Background	106.05 ± 3.45	210.74 ± 3.61	443.30 ± 8.01
$t\bar{t}H$	18.29 ± 0.41	24.18 ± 0.48	35.21 ± 0.58
tHq (SM)	0.52 ± 0.02	1.43 ± 0.04	1.92 ± 0.04
tHW (SM)	0.62 ± 0.03	0.71 ± 0.03	1.11 ± 0.04
Total SM	125.48 ± 3.47	237.06 ± 3.64	481.54 ± 8.03
tHq ($\kappa_V = 1 = -\kappa_t$)	7.48 ± 0.14	18.48 ± 0.22	27.41 ± 0.27
tHW ($\kappa_V = 1 = -\kappa_t$)	7.38 ± 0.16	7.72 ± 0.17	11.23 ± 0.20
Data	**127**	**280**	**525**

lepton + bb

Process	3 tags	4 tags	Dilepton
$t\bar{t}$ + LF	24127 ± 5812	320 ± 181	5248 ± 998
$t\bar{t} + c\bar{c}$	8521 ± 4869	339 ± 256	2084 ± 1204
$t\bar{t} + b\bar{b}$	4115 ± 2265	777 ± 429	745 ± 436
$t\bar{t}$ + b	3946 ± 2116	183 ± 113	766 ± 427
$t\bar{t}$ + 2b	2299 ± 1148	138 ± 88	401 ± 228
Single top	1979 ± 353	78.4 ± 25.8	285 ± 37
$t\bar{t}Z$	202 ± 30	32.0 ± 6.6	54.8 ± 7.3
Z +jets	–	–	69.0 ± 31.5
$t\bar{t}W^{\pm}$	90.3 ± 22.8	4.2 ± 2.8	31.4 ± 5.9
tZq	28.3 ± 5.7	2.9 ± 2.3	–
Total Background	45308 ± 8279	1875 ± 551	9684 ± 1695
$t\bar{t}H$	268 ± 31	62.0 ± 9.9	48.9 ± 5.9
tHq (SM)	11.1 ± 3.3	1.3 ± 0.3	0.31 ± 0.08
tHW (SM)	7.6 ± 1.1	1.1 ± 0.3	1.4 ± 0.2
Total SM	45723 ± 8279	1941 ± 551	9735 ± 1695
tHq ($\kappa_V = 1 = -\kappa_t$)	160 ± 38	19.1 ± 5.2	3.9 ± 1.0
tHW ($\kappa_V = 1 = -\kappa_t$)	91.9 ± 11.9	13.7 ± 2.3	17.6 ± 2.2
Data	**44311**	**2035**	**9065**

tH bb postfit classifiers

bb Postfit Classifiers