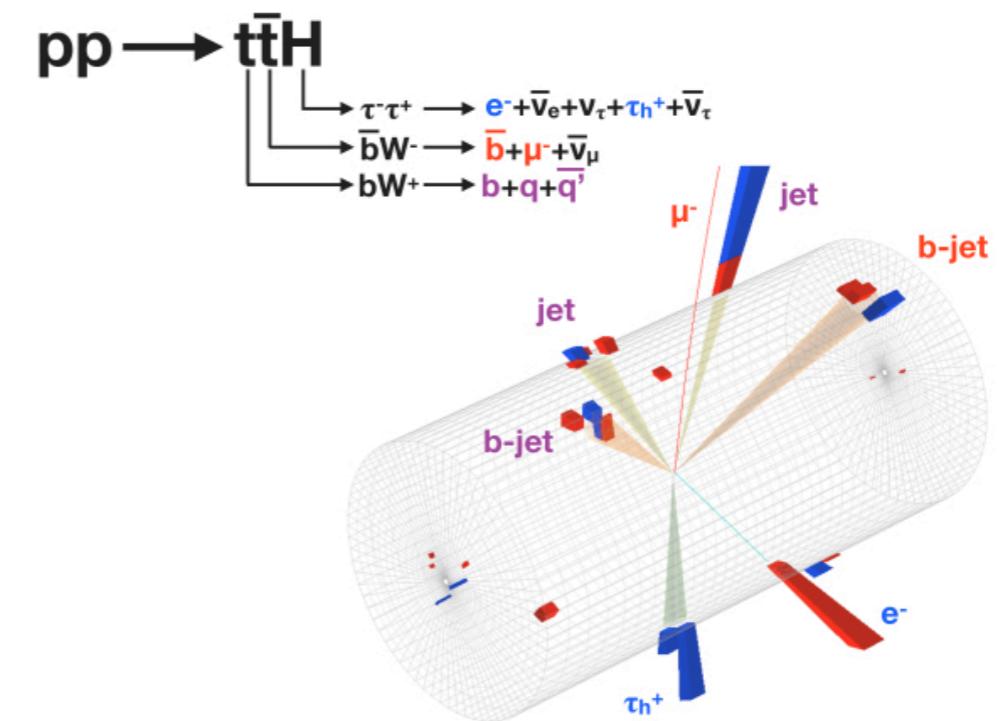
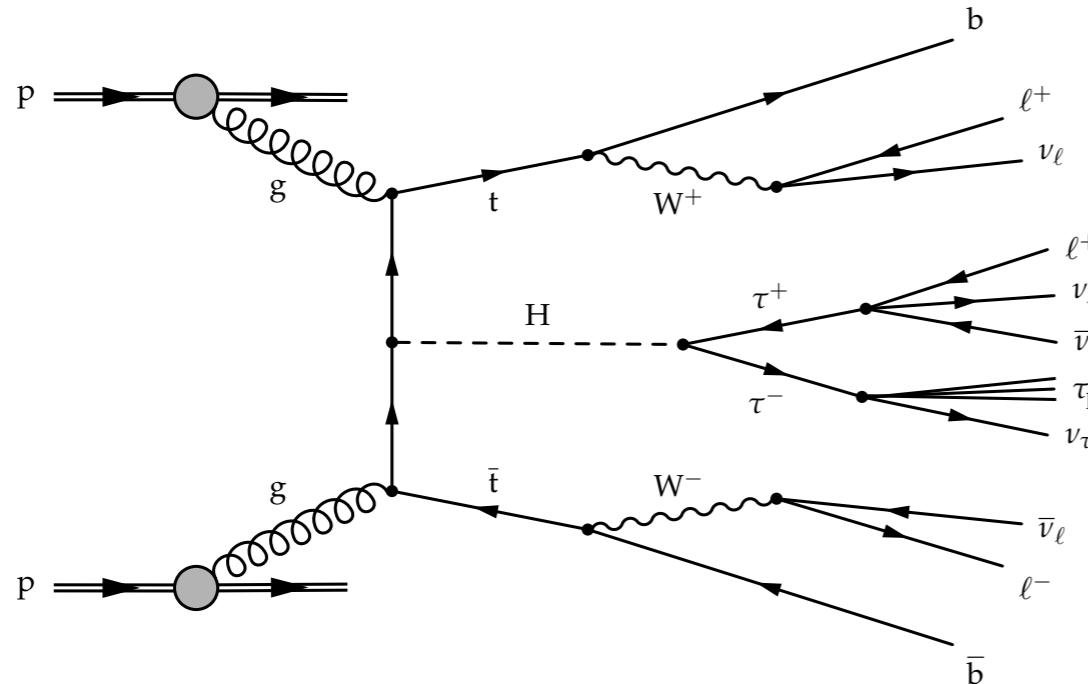


# Measurements of ttH at CMS

Joosep Pata (Caltech)  
for the CMS Collaboration

February 15, 2019

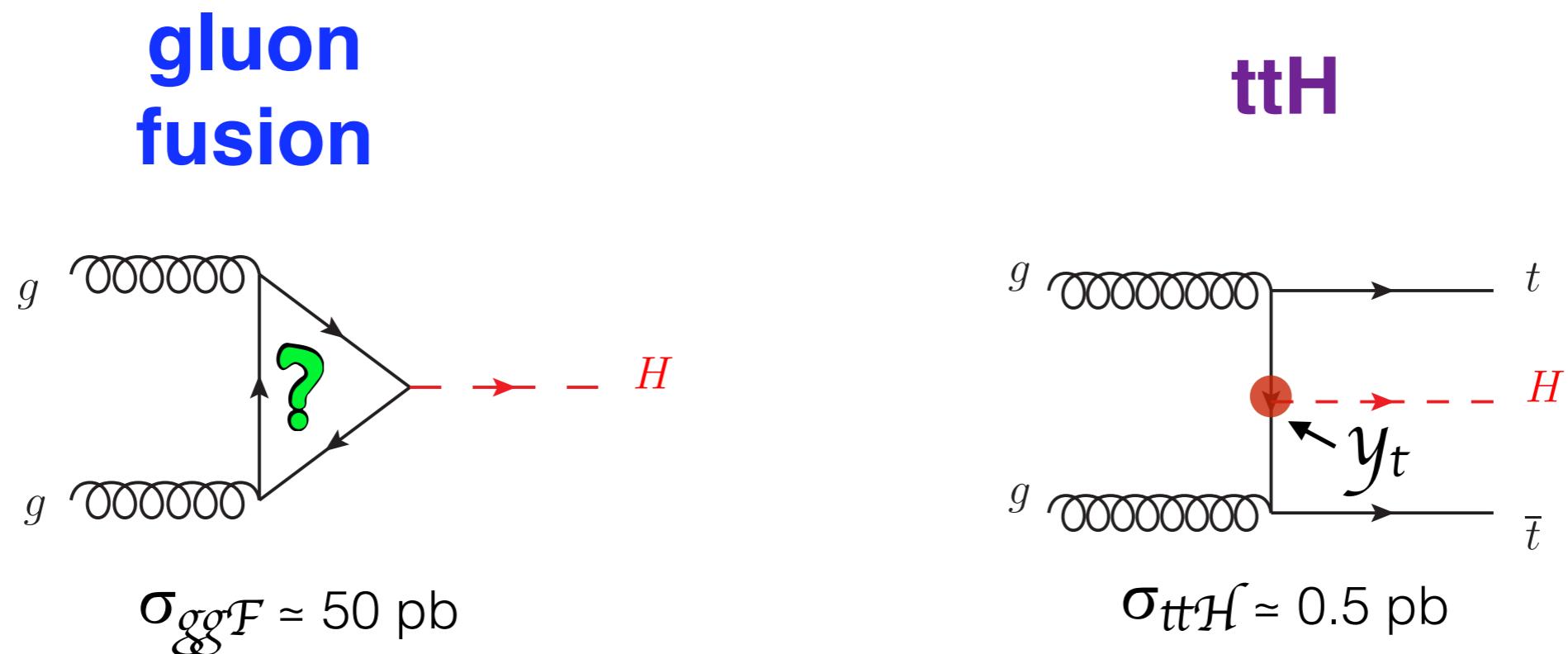
Lake Louise Winter Institute 2019





# ttH in a nutshell

Does the Higgs boson interact with fermions?

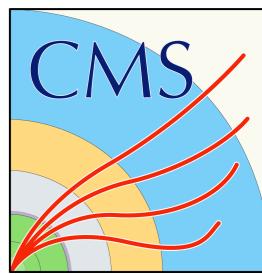


Can we observe it directly?

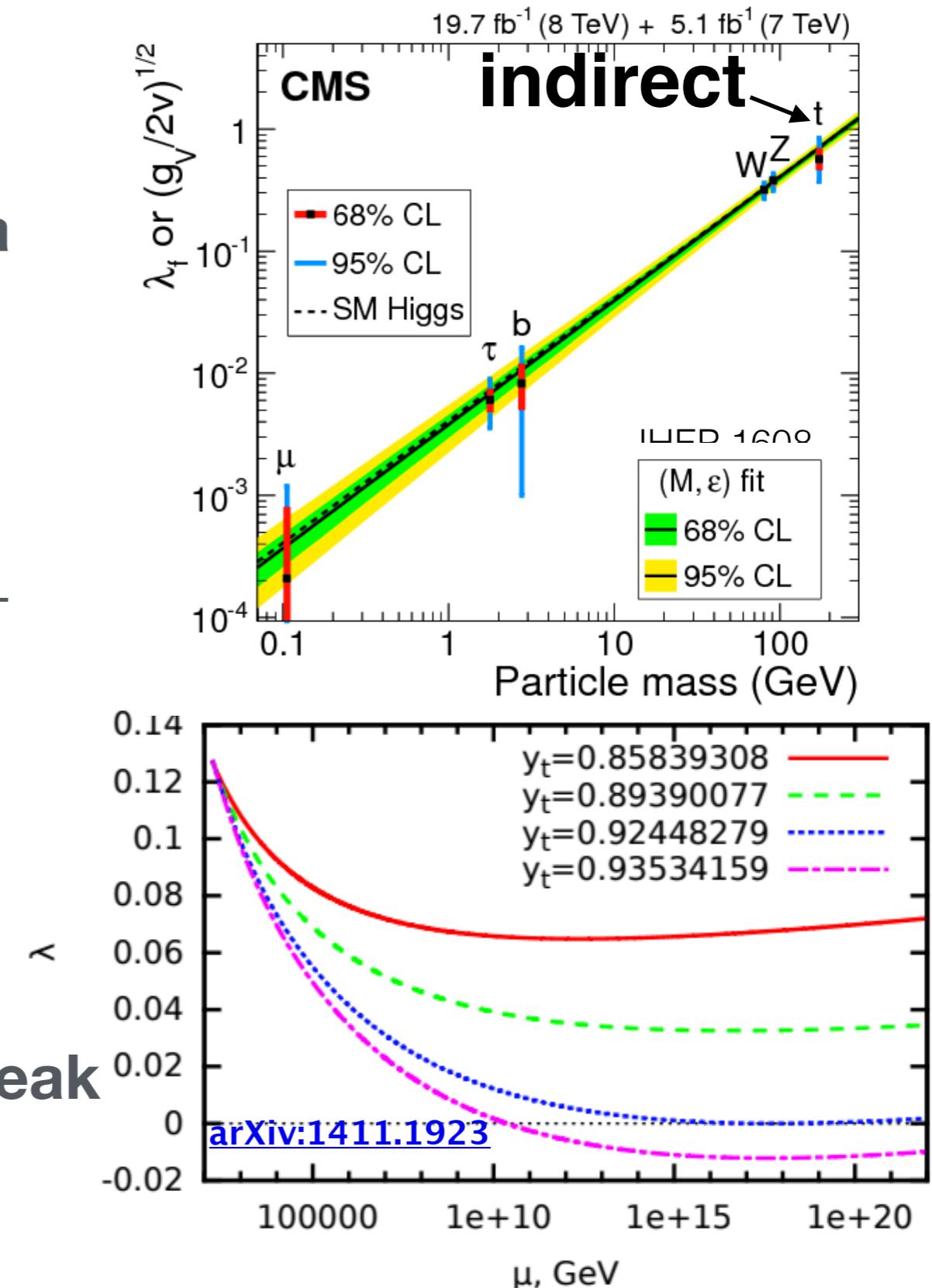
**Direct probe of top-Higgs Yukawa coupling:**  $\sigma_{ttH} \propto y_t^2$



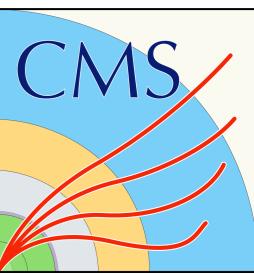
# Why study ttH?



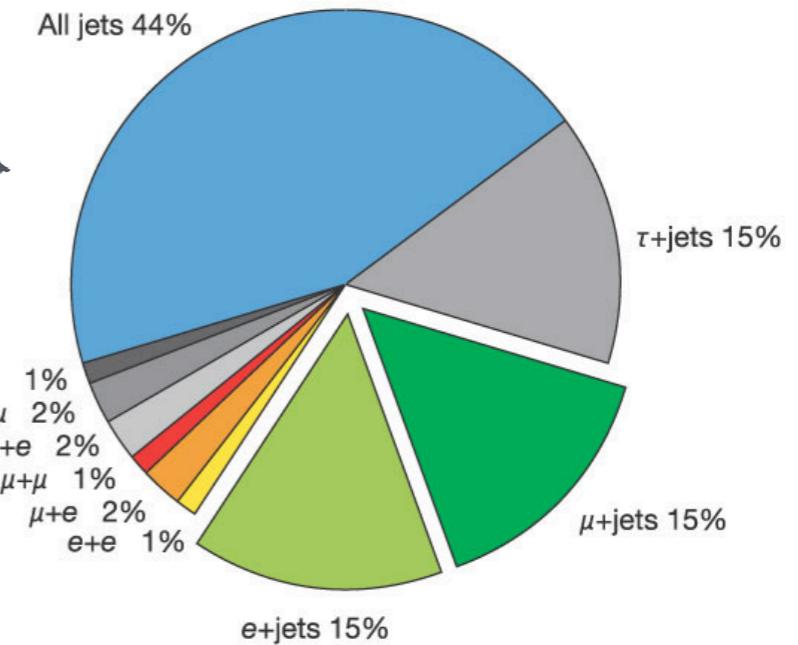
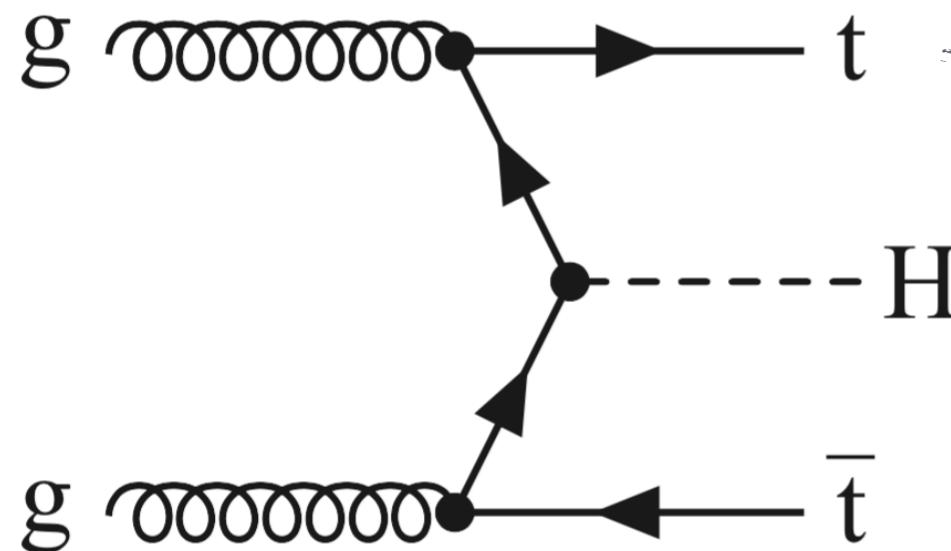
- **Test of SM:** top quark Yukawa coupling uniquely predicted to be  $y_t \sim 1$ , test Higgs mechanism **at a natural scale** by measuring  $\sigma_{ttH}$
- **Probe new physics:** precise value of  $y_t$  determines the energy-evolution of the Higgs self-coupling and the stability of the EWK vacuum: sensitive to the scale of new physics



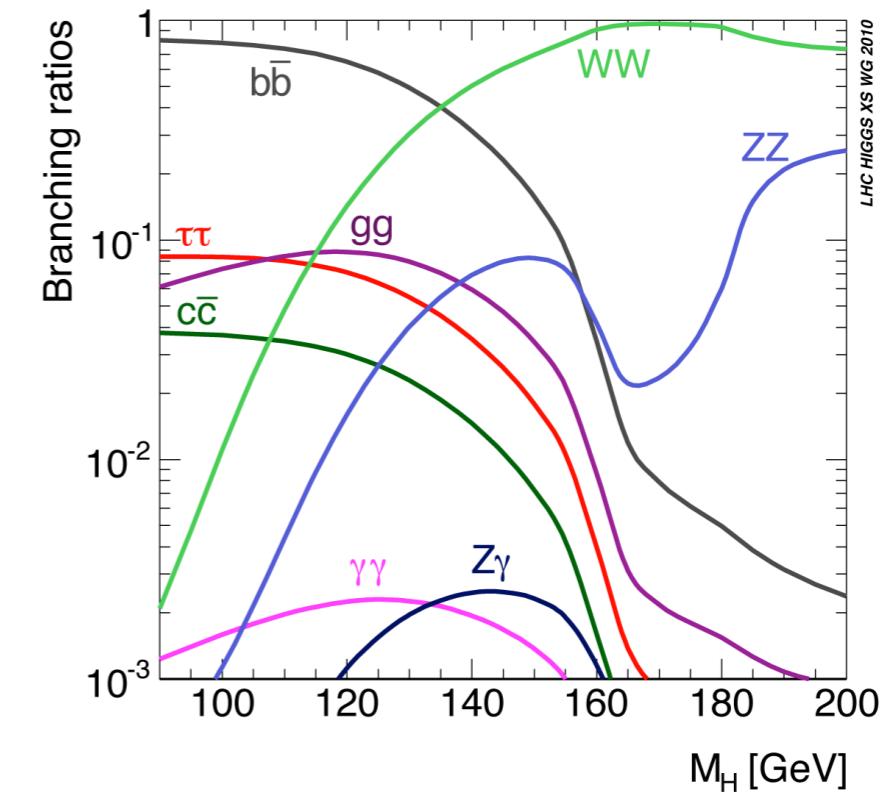
What is the nature of the electroweak symmetry breaking for fermions?



# Analysis channels



- **H(bb) hadronic tops:** highest rate, multi-jet background, [JHEP 06 \(2018\) 101](#)
- **H(bb) lepton+jets & dileptons:** high-rate, challenging tt+heavy flavour backgrounds, [1804.03682 \(JHEP\)](#)
- **H(WW, ZZ, \tau\tau):** clean, tt+W/Z backgrounds & misid, [JHEP 08 \(2018\) 066](#)
- **H(\gamma\gamma) with ttH tag:** cleanest, low-rate bump-hunt, [JHEP 11 \(2018\) 185, CMS-PAS-HIG-18-018](#)
- **Run1 + 2016 combination:** 5 $\sigma$  observation, [Phys. Rev. Lett. 120 \(2018\) 231801](#)

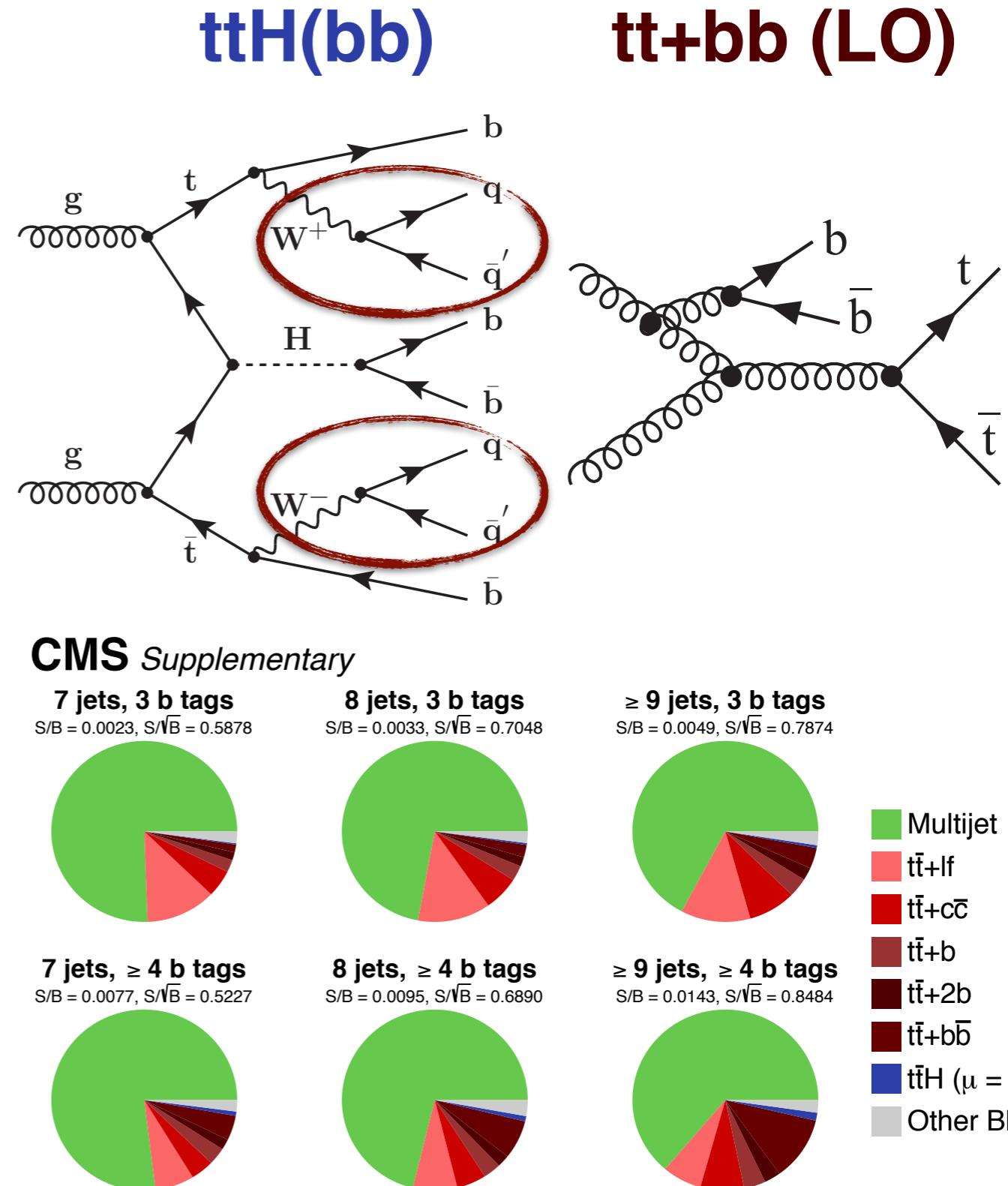




# ttH(bb) all-hadronic



- Highest branching ratio, high QCD multi-jet and tt+bb backgrounds
- Trigger on hadronic activity ( $H_T$ ) and b-tagging
- Reject gluon radiation activity based on quark-gluon likelihood (QGL) discriminator on jets
- Data-driven background model based on QGL and b-tagging control region

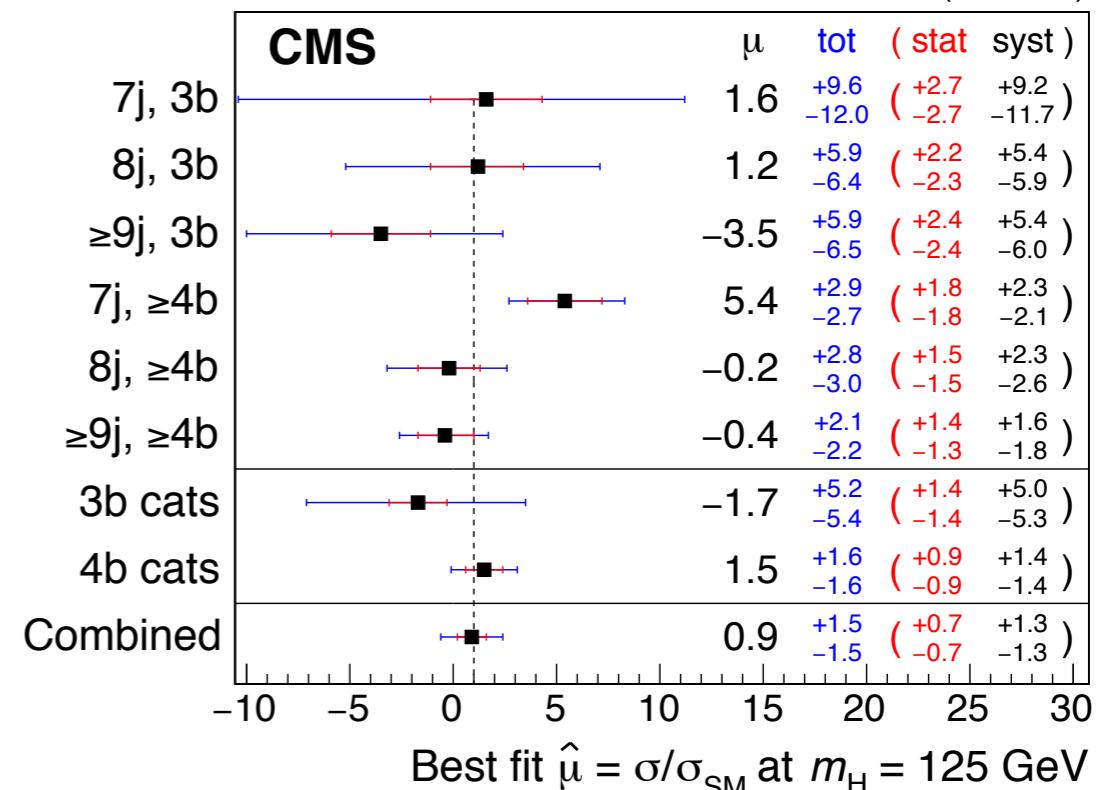
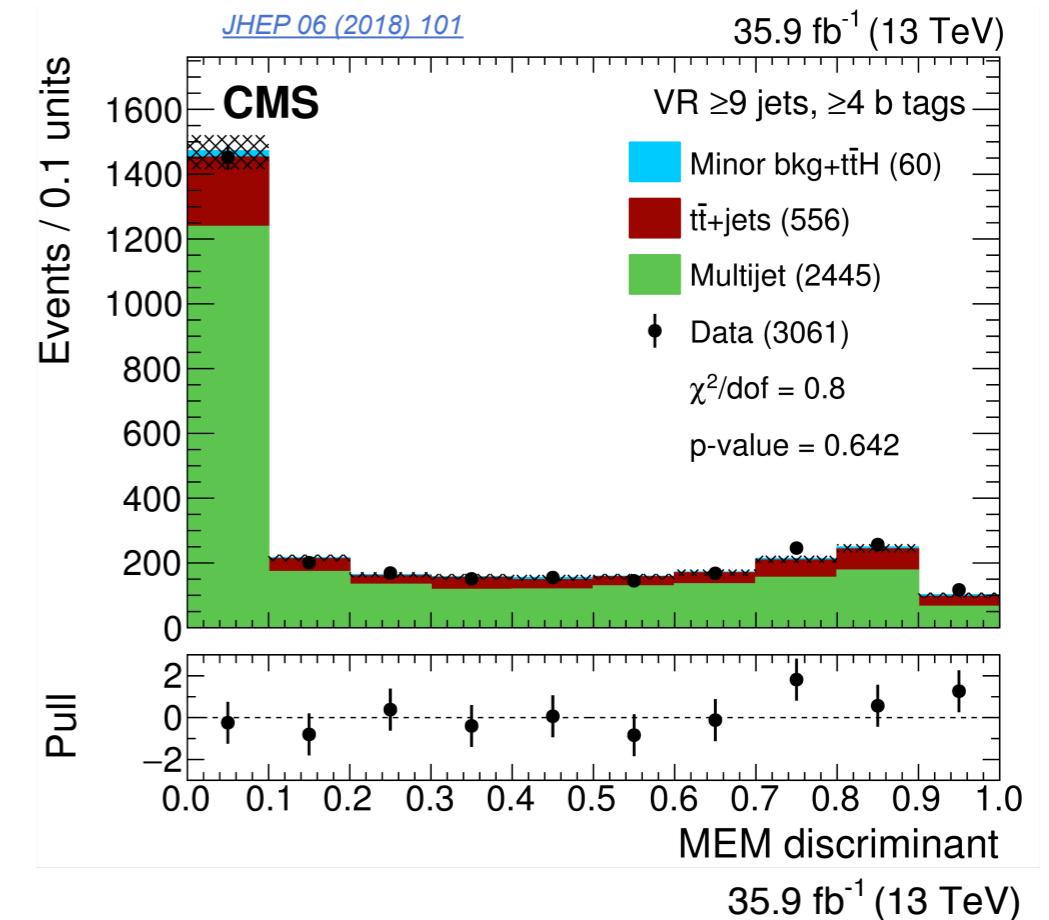




# ttH(bb) all-hadronic

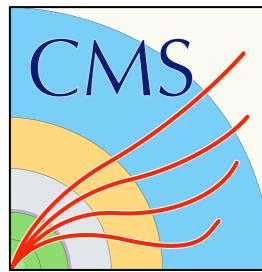


- Final state fully reconstructed, but multivariate methods needed to distinguish ttH(bb) from irreducible tt+bb
- Signal vs background probability from matrix element method (MEM): leading-order amplitude  $\otimes$  transfer functions
- Determine signal yield by combined template fit in six jet-btag categories
- $\hat{\mu} = \sigma/\sigma_{SM} = 0.9 \pm 0.7 \text{ (stat.)} \pm 1.3 \text{ (syst.)}$  with  $35.9 \text{ fb}^{-1}$  of data

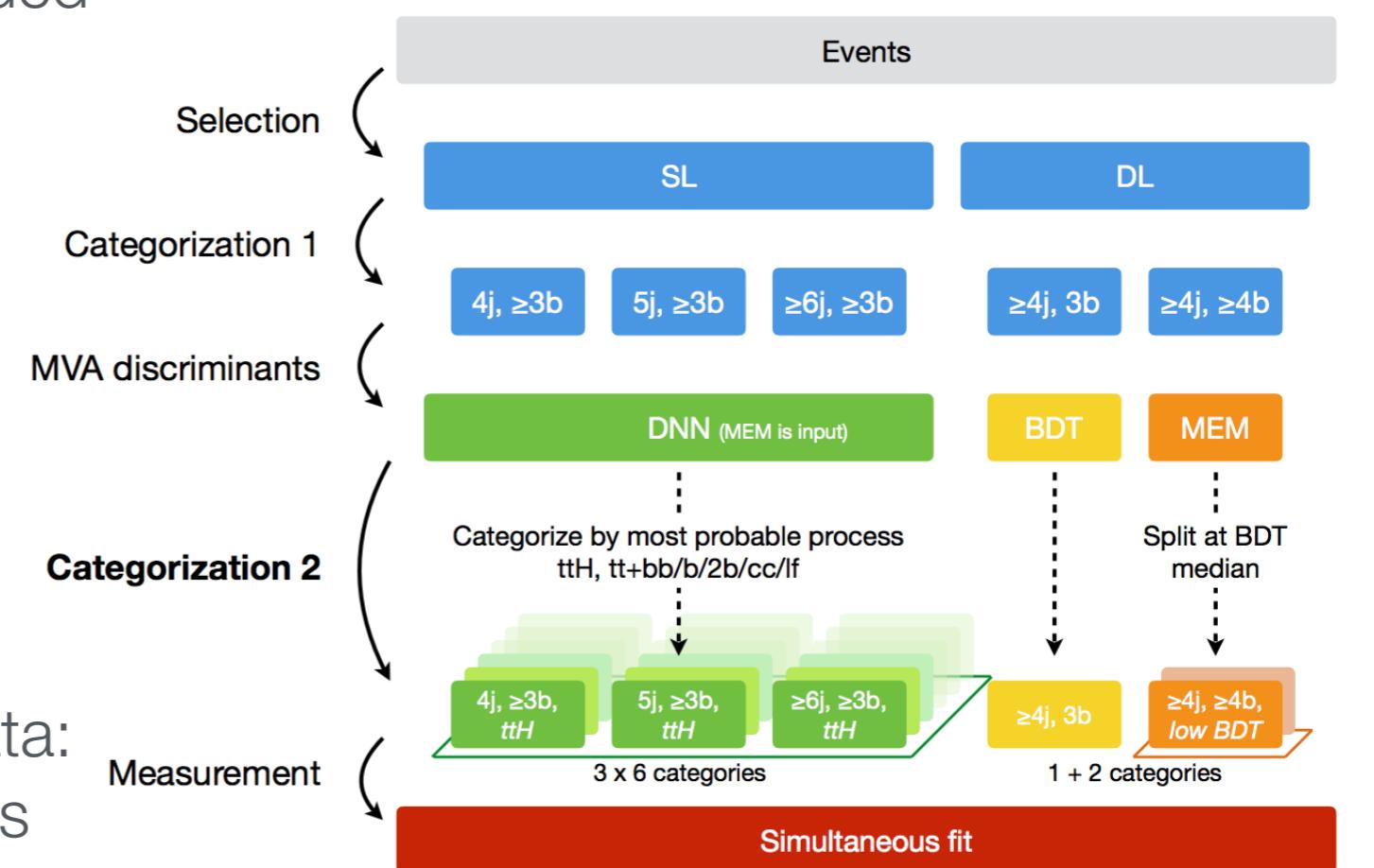
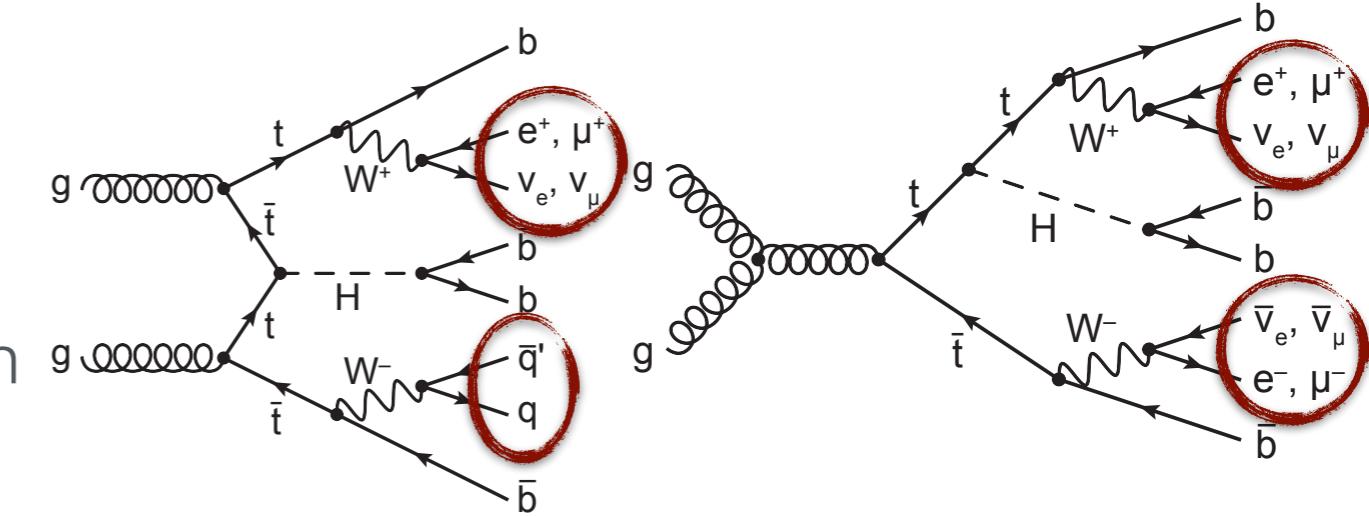




# ttH(bb) leptonic

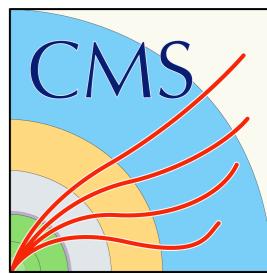


- High branching ratio, trigger on isolated, high-pT electrons or muons from W decay
- Main background from QCD production of top quark + b quark pairs: NLO description of tt+heavy flavour needed
- Mass resolution on b quark jets not sufficient to identify H peak: **use multivariate & machine learning methods**
- Construct jet-process categories enriched in signal and background subcomponents, constrain from data: DNN with multiple output likelihoods

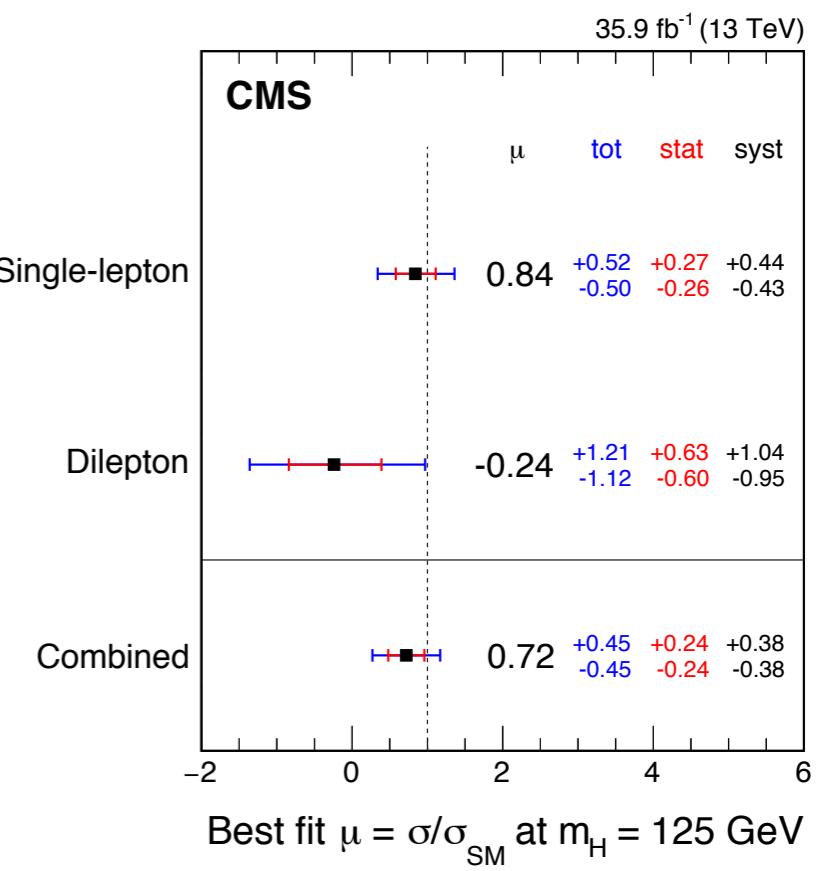
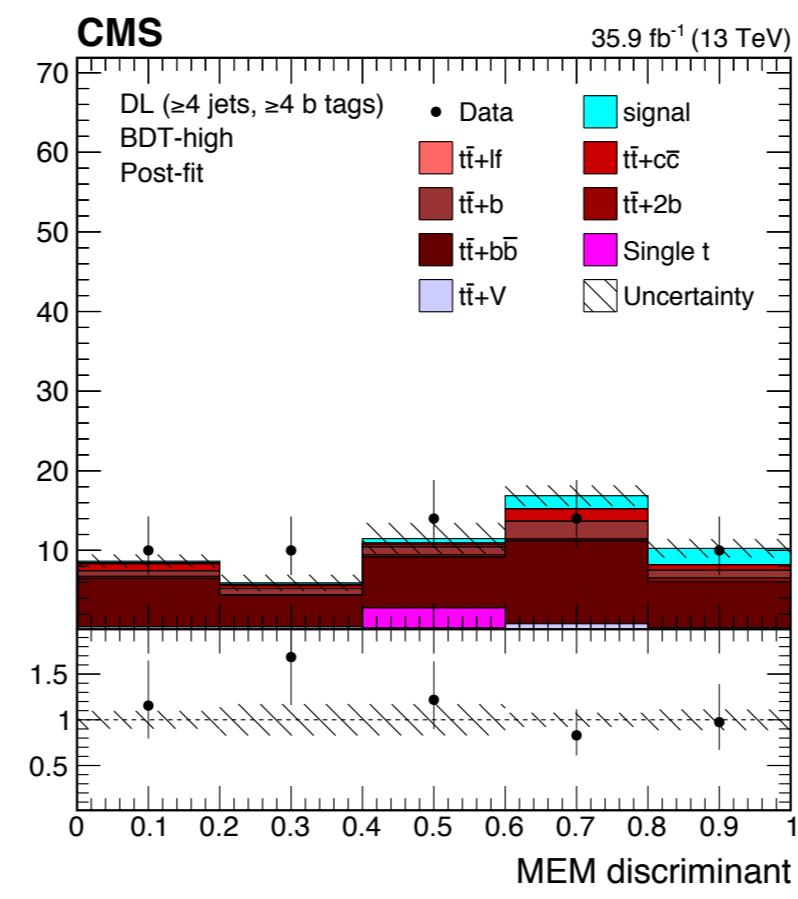
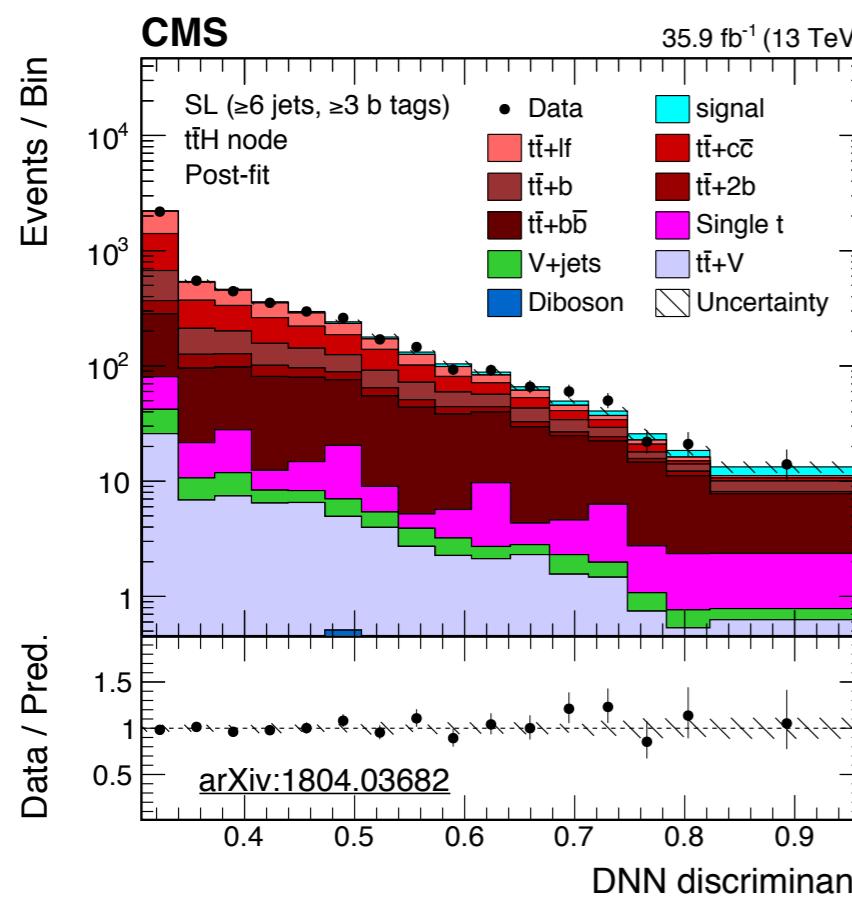




# ttH(bb) leptonic

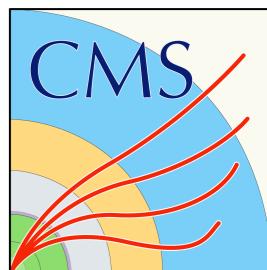


- Combined template fit on discriminators in jet-process categories
- $\hat{\mu} = 0.72 \pm 0.24 \text{ (stat.)} \pm 0.38 \text{ (syst.)}$  with  $35.9 \text{ fb}^{-1}$  of data
- Analysis is systematically dominated: uncertainties on theory modelling tt+hf & detailed b-tagging efficiencies

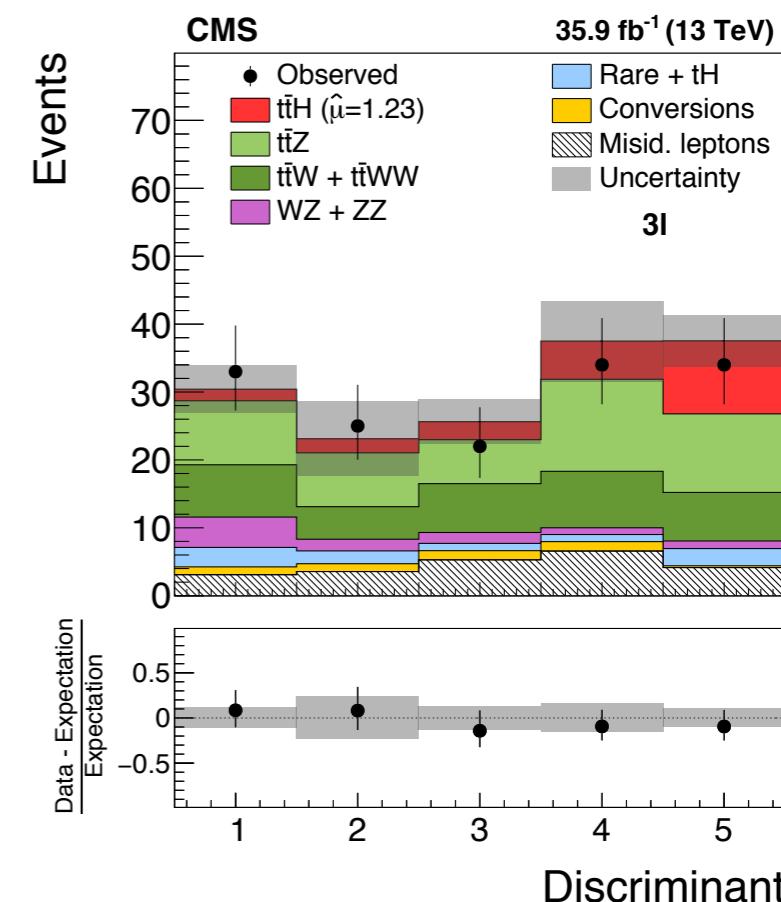
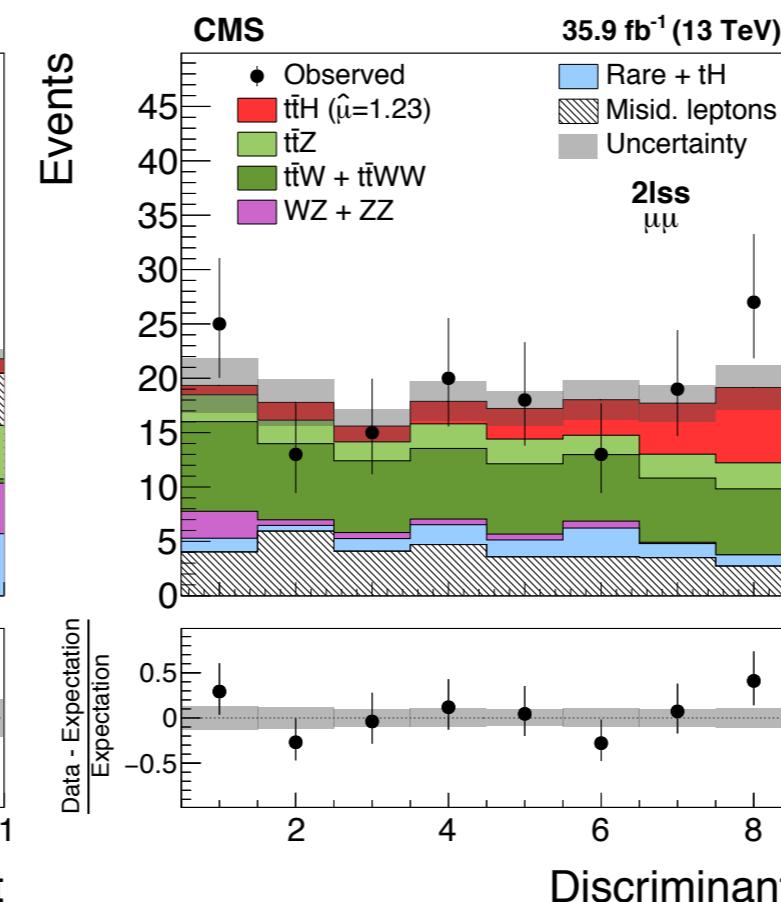
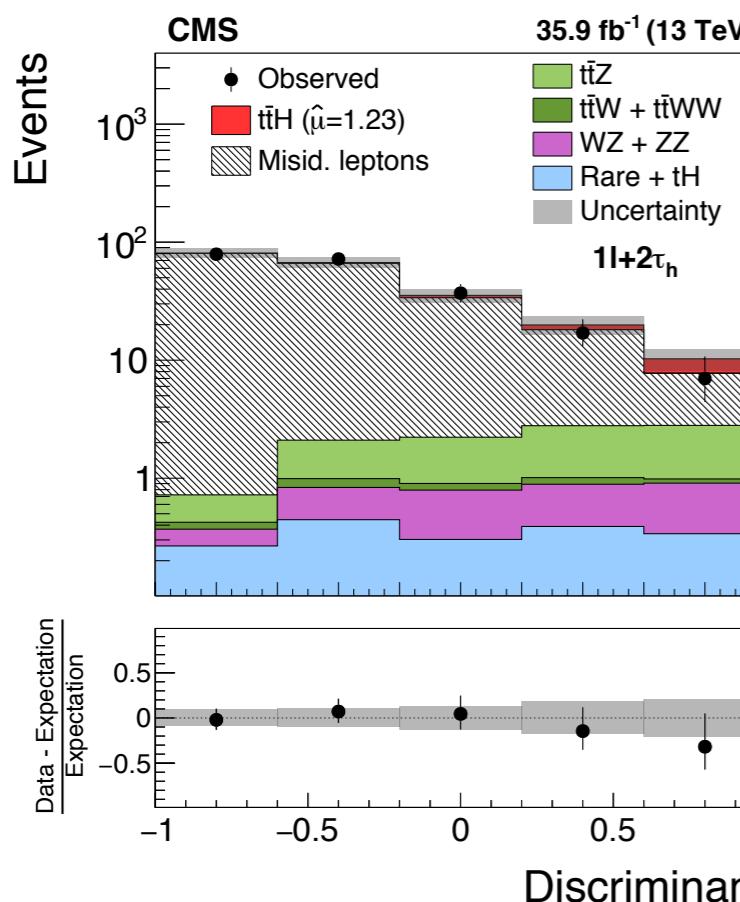
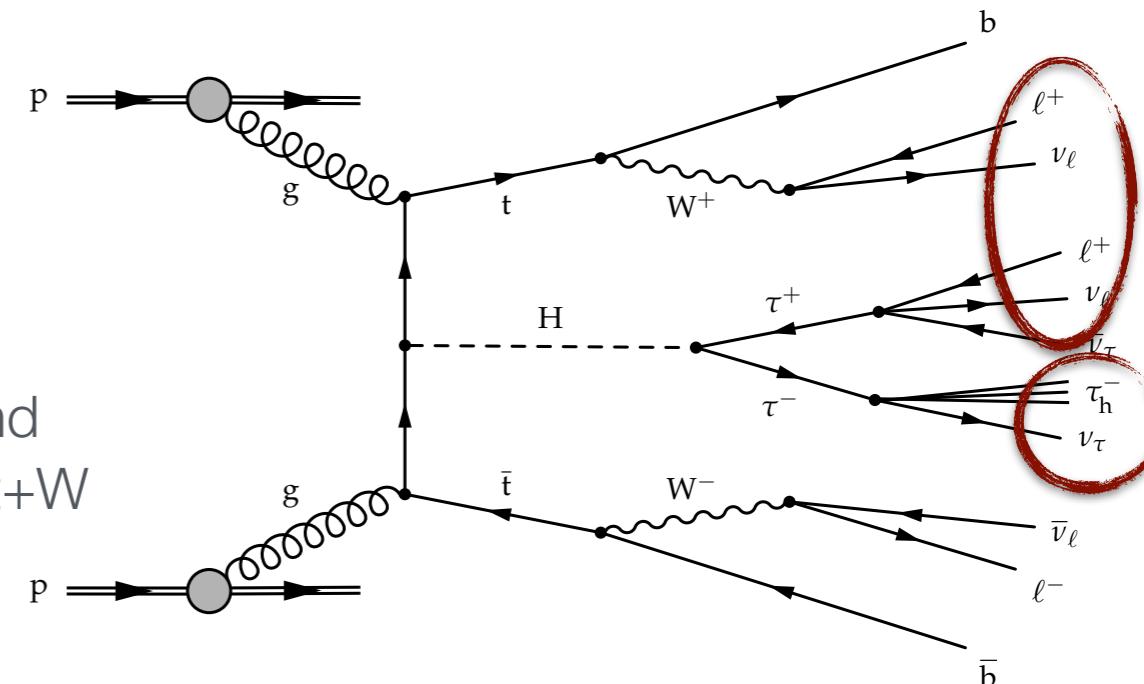




# ttH multilepton



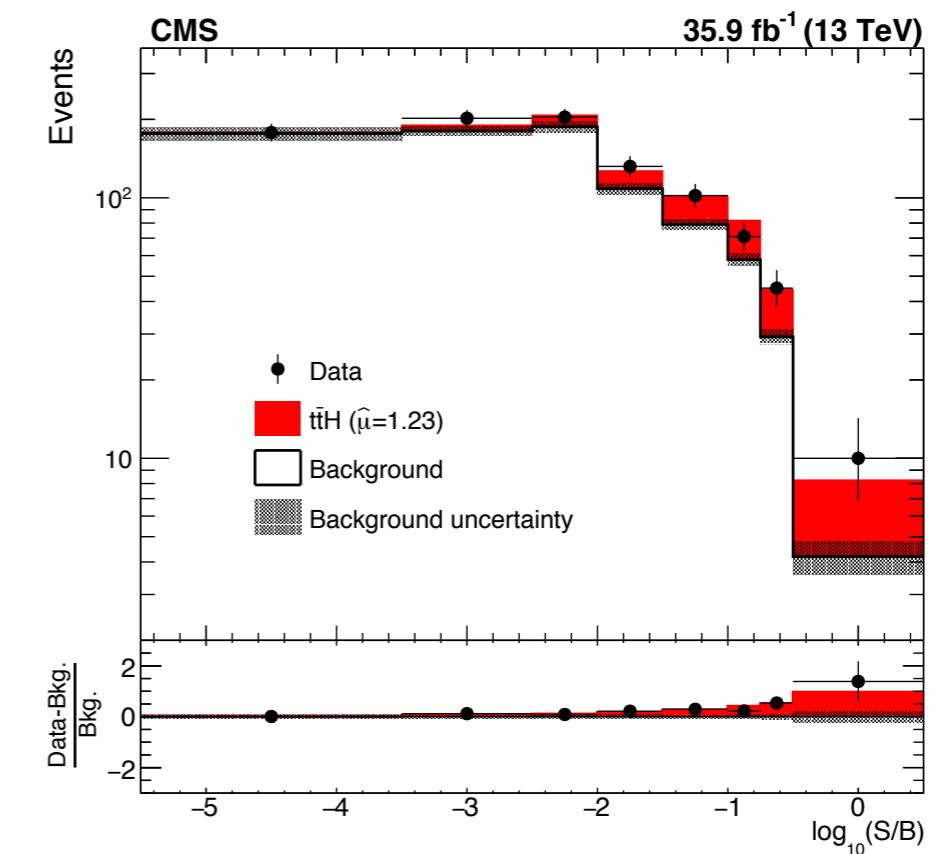
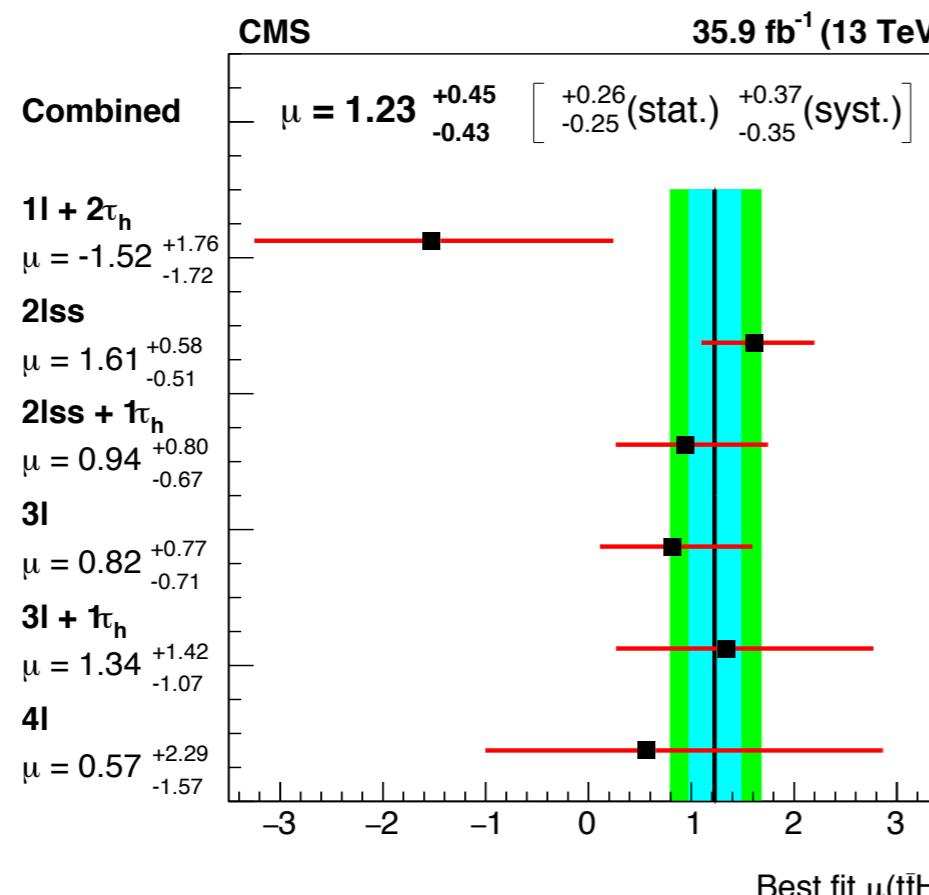
- Covers the decay modes  $H \rightarrow WW, ZZ$  and  $\tau\tau$
- Main backgrounds from lepton misidentification and electroweak production of  $t\bar{t} + W/Z$
- Split events into categories based on multiplicity, flavor and charge of leptons: 2-lepton same sign enriched in  $t\bar{t}+H$ ,  $t\bar{t}+W$
- Multivariate discriminants used to select ttH

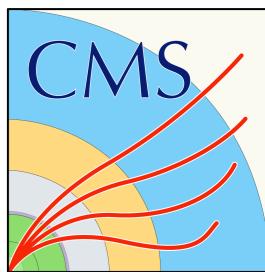




# ttH multilepton

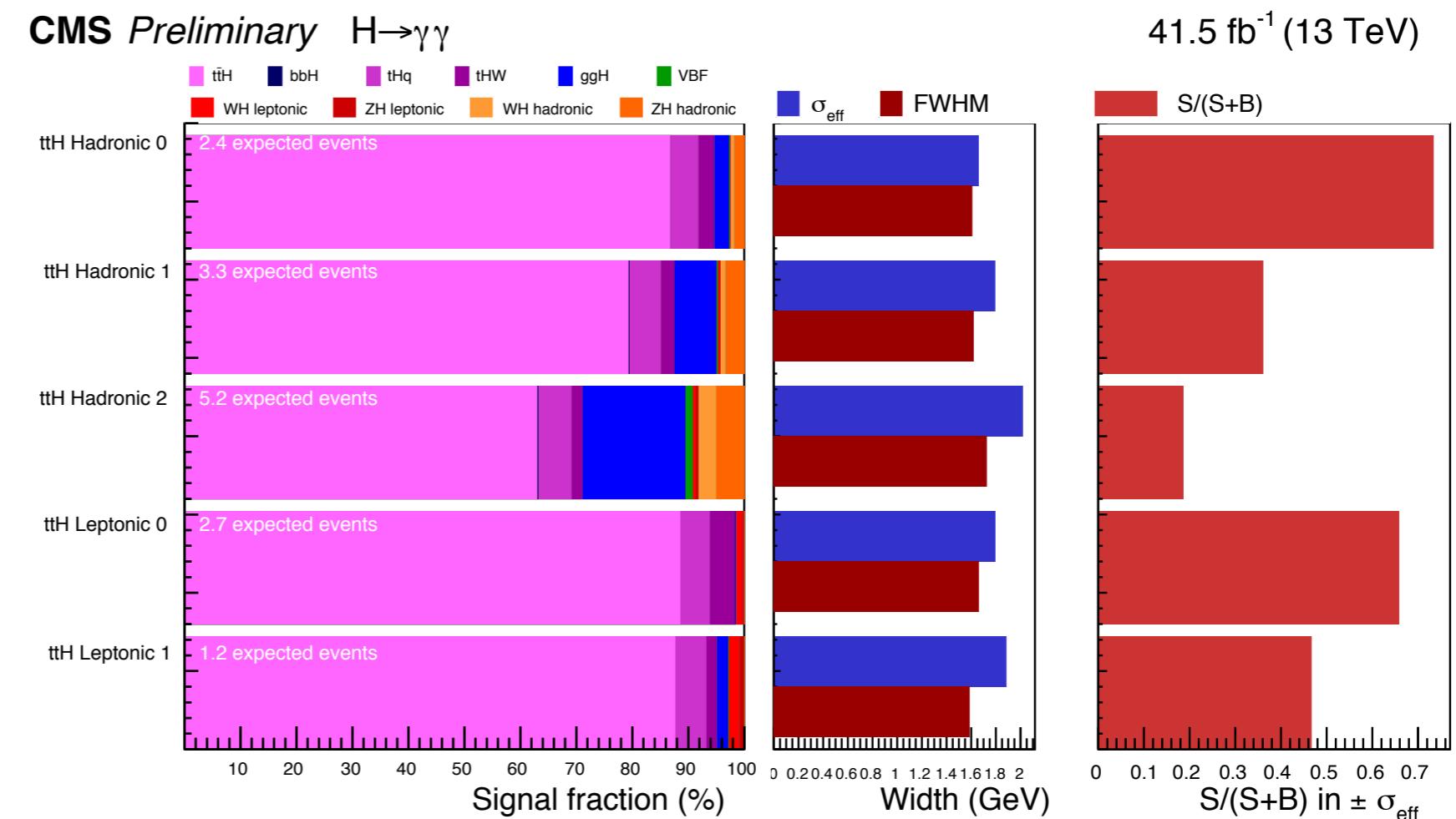
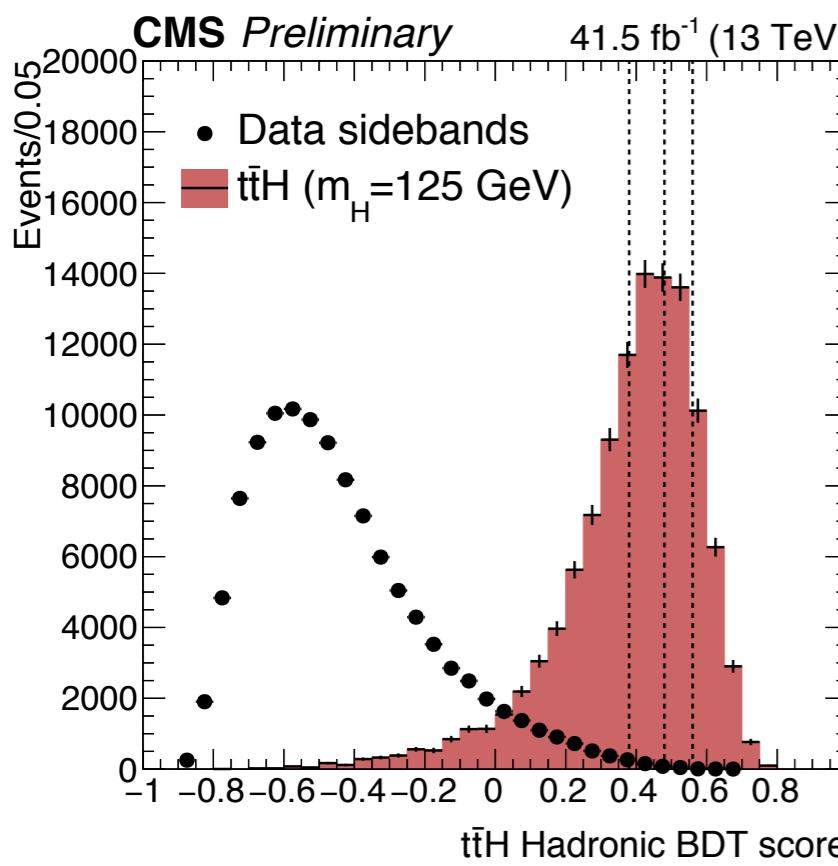
- Final signal strength determined in combined template fit
- **JHEP 08 (2018) 066:**  $\hat{\mu} = 1.23 \pm 0.26 \text{ (stat.)} \pm 0.37 \text{ (syst.)}$  with  $35.9 \text{ fb}^{-1}$  of 2016 data, observed (expected) significance of  $3.2\sigma$  ( $2.8\sigma$ )
- **CMS-PAS-HIG-18-019:** reloaded with 2017 data ( $41.5 \text{ fb}^{-1}$ ), observed (expected) significance  $3.2\sigma$  ( $4.0\sigma$ )





# Diphoton ttH tag

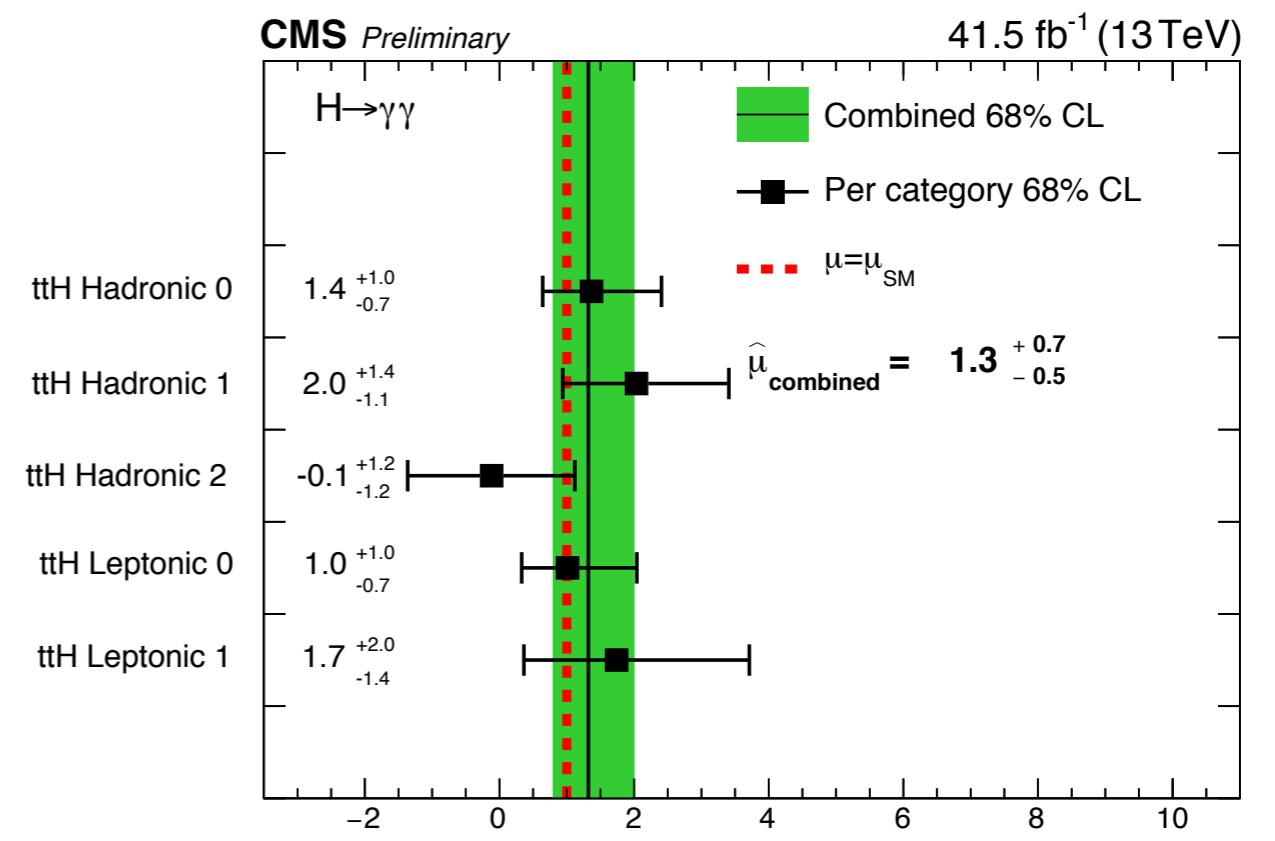
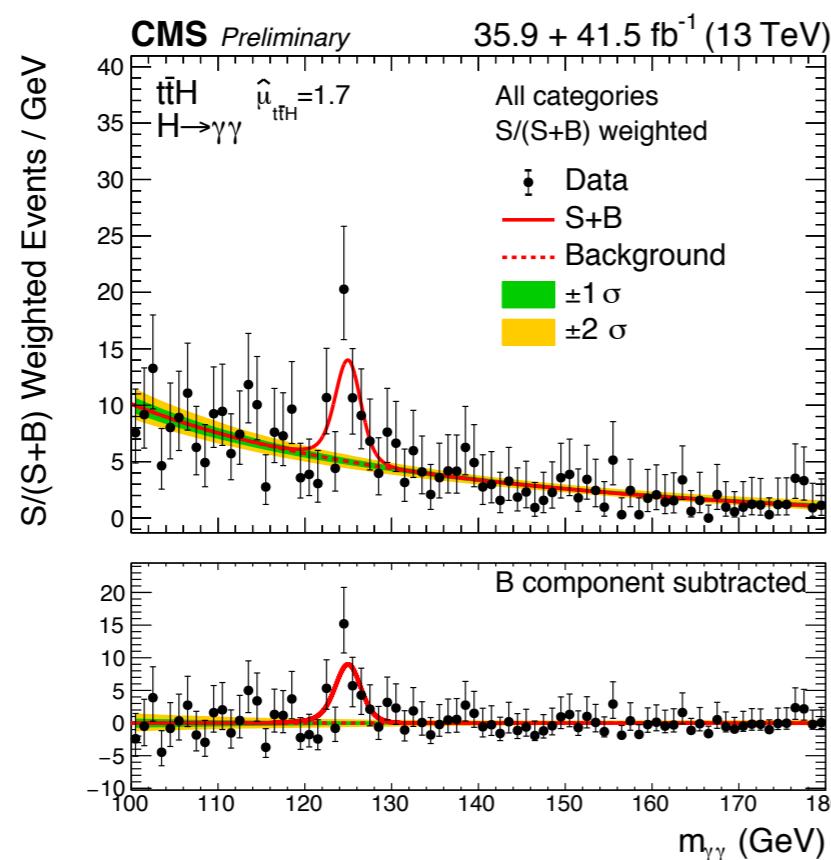
- Very small branching ratio but clean signature: mass peak
- Tag top pair decay products: hadronic and leptonic, ttH or background enriched (BDT)
- **JHEP 11 (2018) 185**: 2016 data ( $35.9 \text{ fb}^{-1}$ ), Higgs properties
- **CMS-PAS-HIG-18-018**: 2017 data ( $41.5 \text{ fb}^{-1}$ ) + 2016 combination





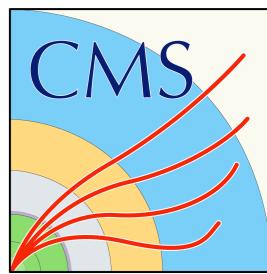
# Diphoton ttH tag

- Signal extracted in a simultaneous parametric fit of diphoton invariant mass, background modelled by a family of candidate functions
- Major uncertainties from QCD scale (9%), PDFs (5%) as well as from photon ID (6%) and b-tagging (5%)
- Statistically dominated:  $\hat{\mu} = 1.3 \pm 0.6 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \text{ (2016)}$

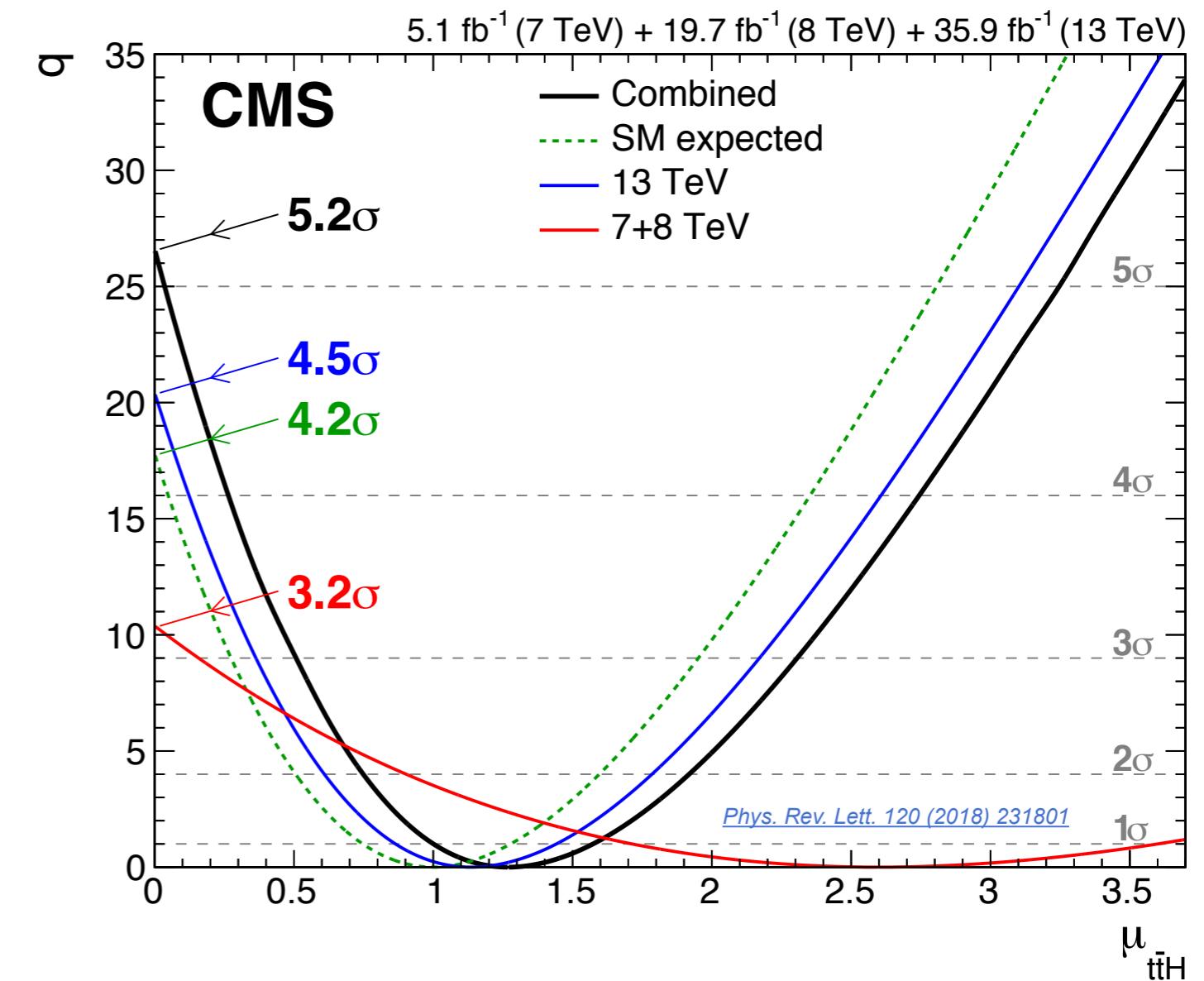
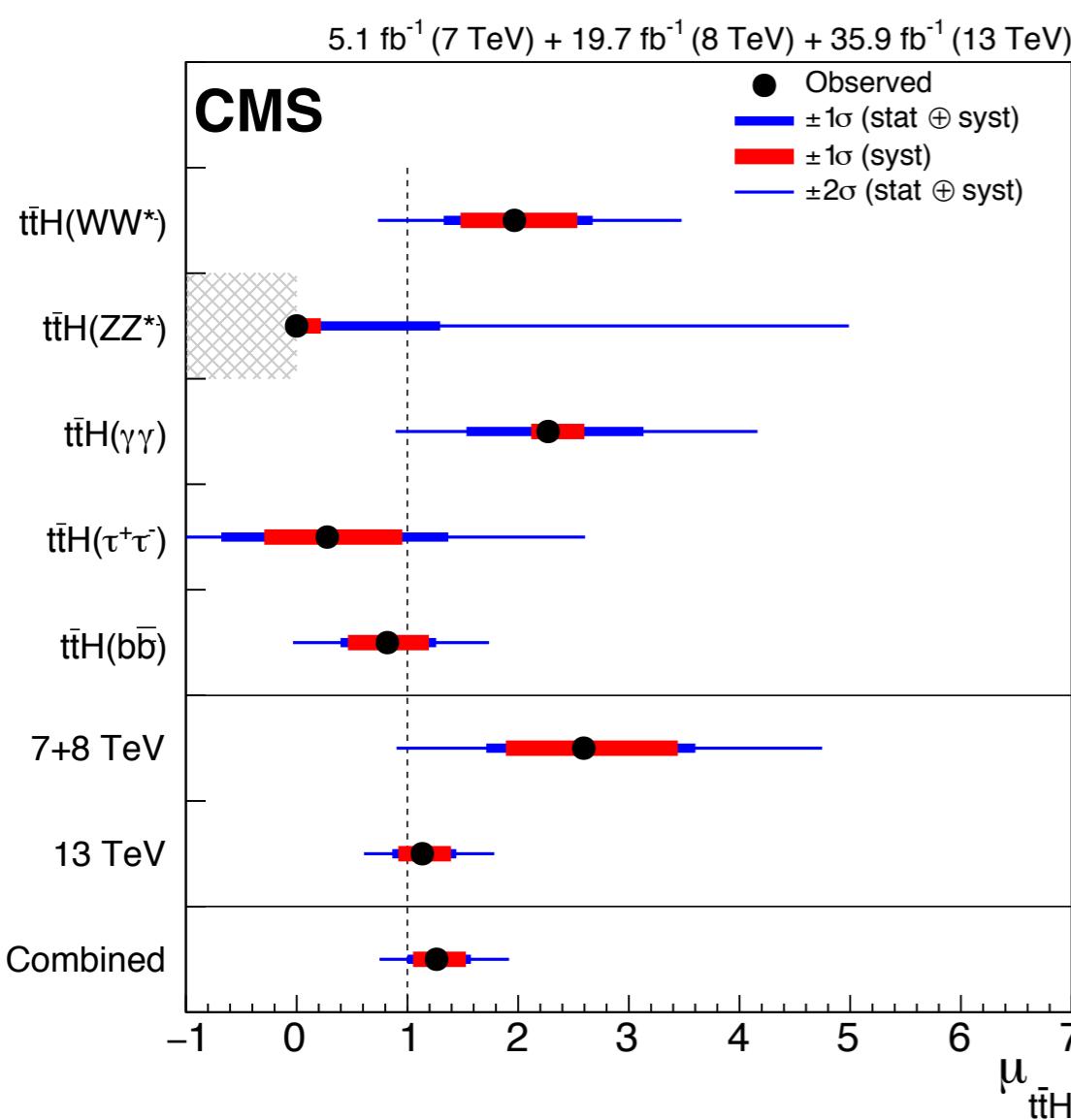




# Observation



	total	stat.	exp.	theory (bkg)	theory (sig)
$\mu_{t\bar{t}H}$	$1.26^{+0.31}_{-0.26}$	$+0.16$ $-0.16$	$+0.17$ $-0.15$	$+0.14$ $-0.13$	$+0.15$ $-0.07$





# Future

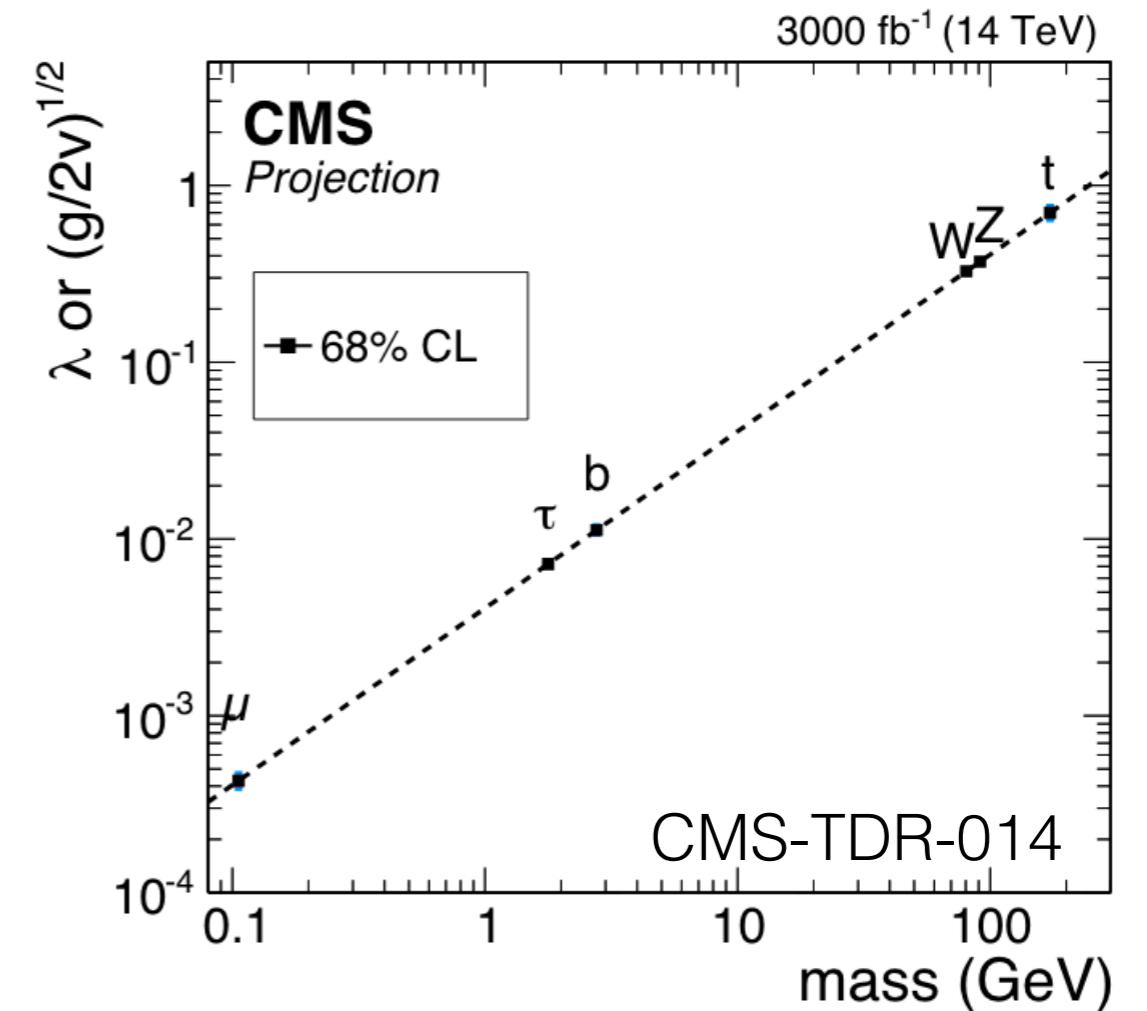
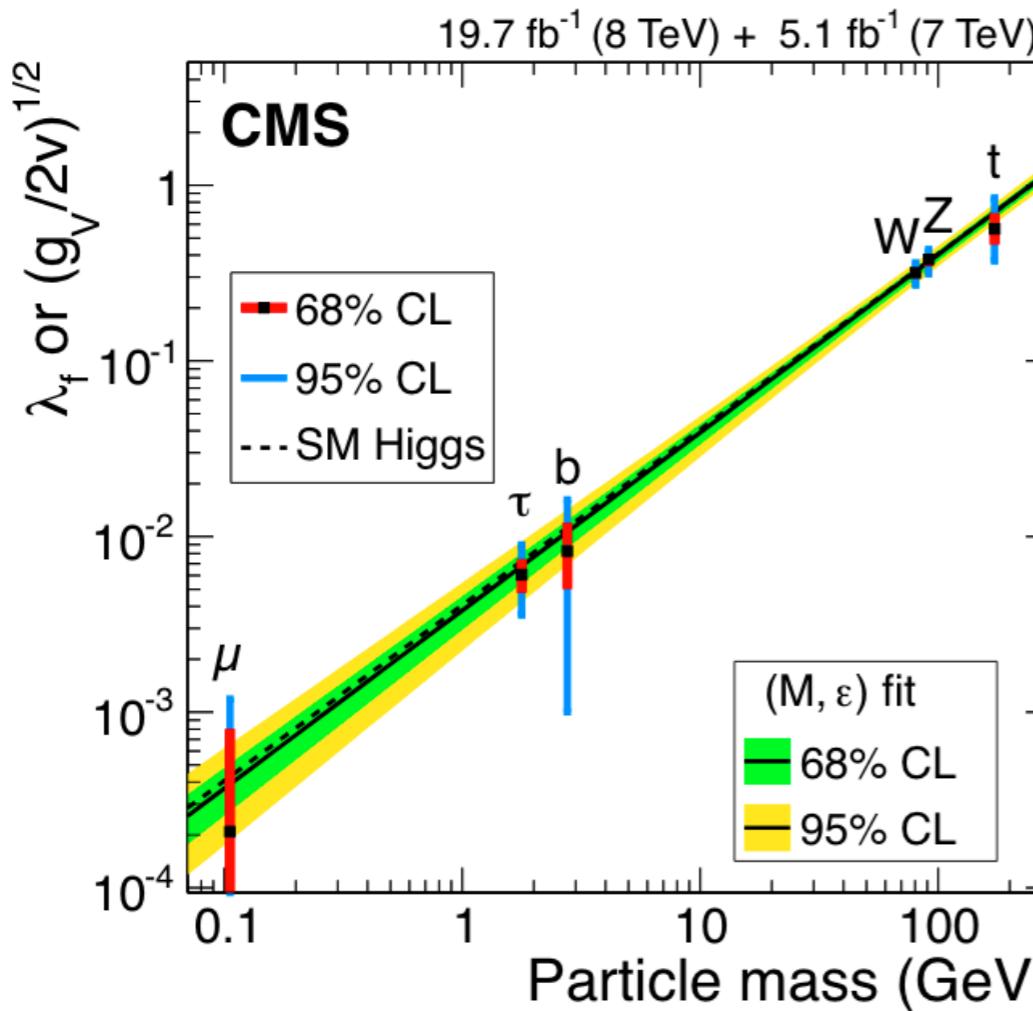
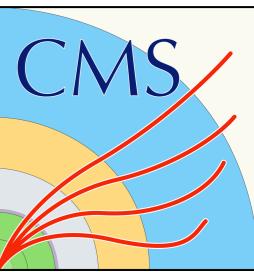
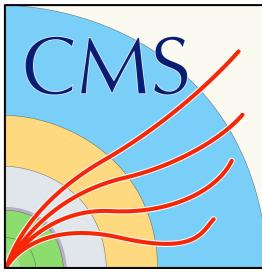
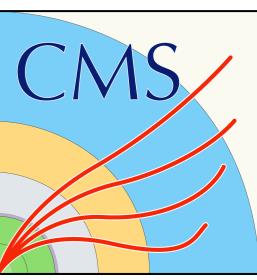


Figure 1.2: Higgs couplings to fermions (Yukawa coupling,  $\lambda_f$ ) and bosons (parametrized as  $(g_V/2v)^{1/2}$ , where  $v$  is the SM Higgs boson vacuum expectation value) as measured using Run 1 data (left), and projection for the uncertainties, assuming standard model couplings, for an integrated luminosity of  $3000 \text{ fb}^{-1}$  (right), both as a function of the particle's mass.

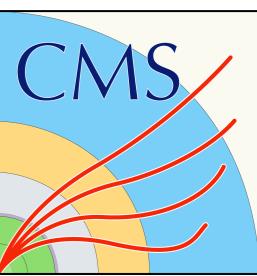


# Summary

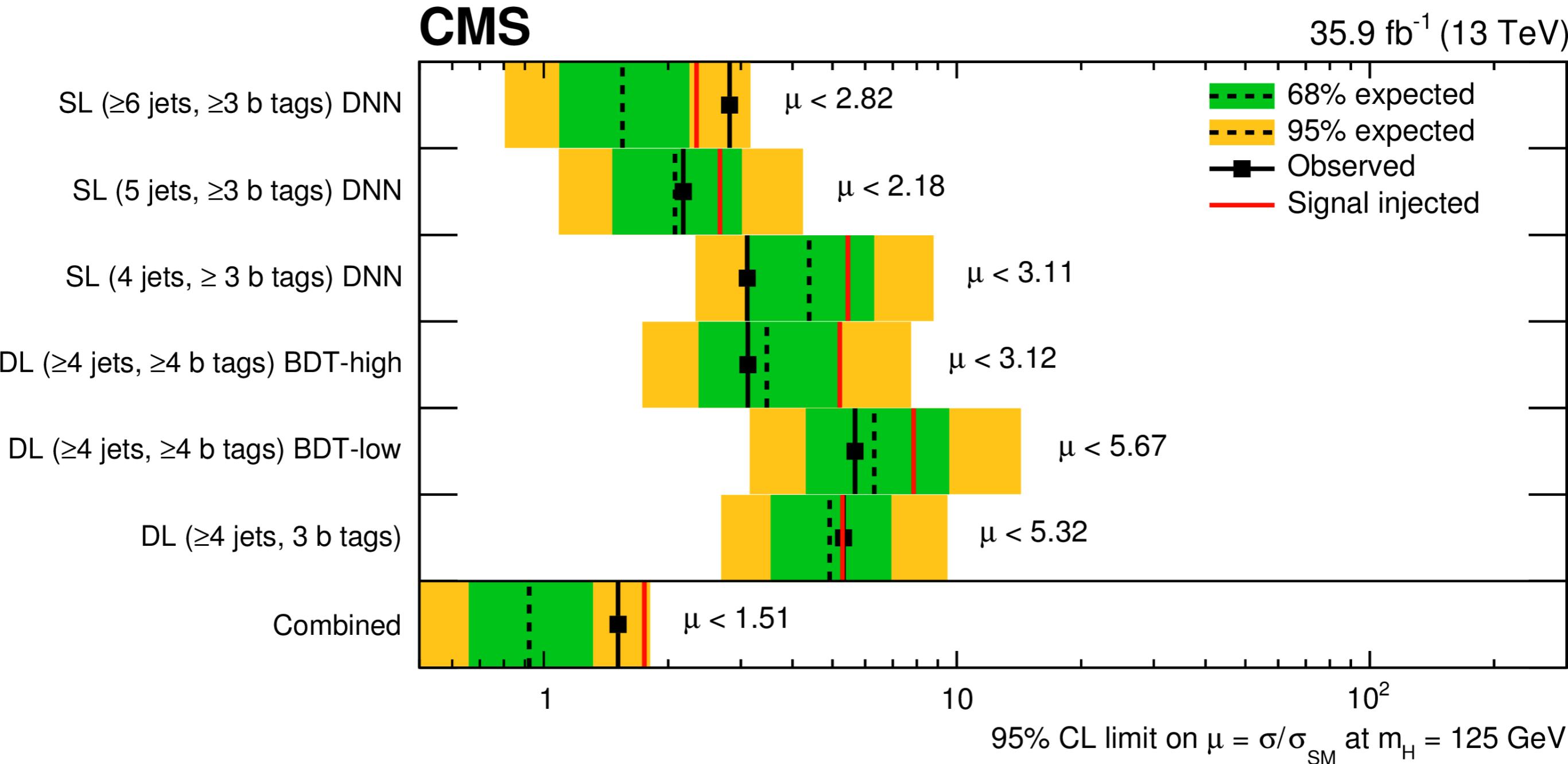
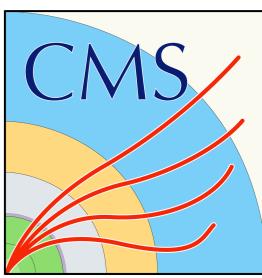
- All major decay modes of ttH covered at CMS, use full arsenal of detector and analysis methods
- Complex backgrounds and small signals require NLO predictions, multivariate analyses and combined template fits
- ttH observed at CMS at  $5.2\sigma$  significance using 7+8+13 (2016) TeV data: **the top quark couples to the Higgs, consistent with SM**
- Reloads with 2017+2018 ( $>3x$  statistics) data are underway
- Ultimate goal: ~10% precision measurement of top quark cross-section & Yukawa coupling in HL-LHC

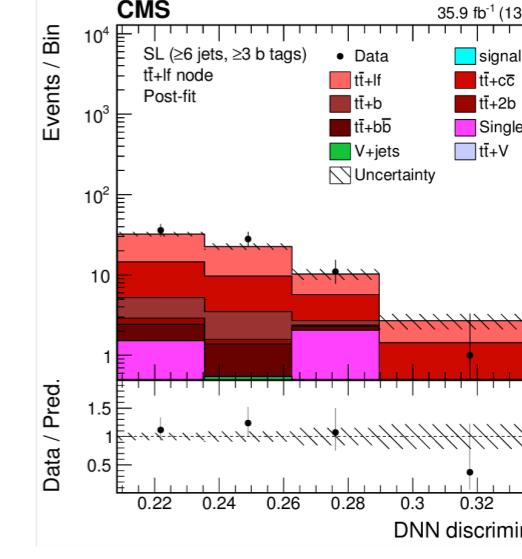
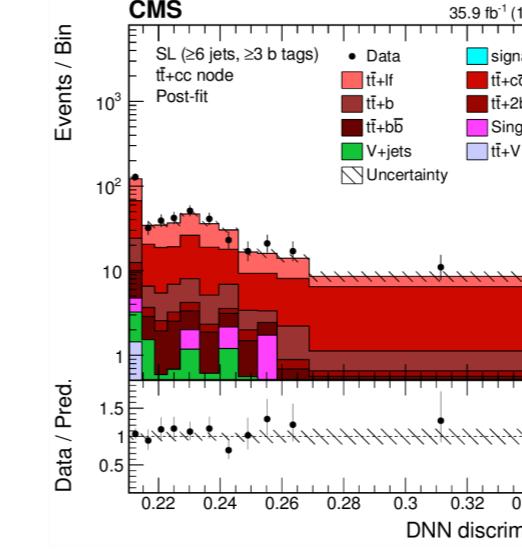
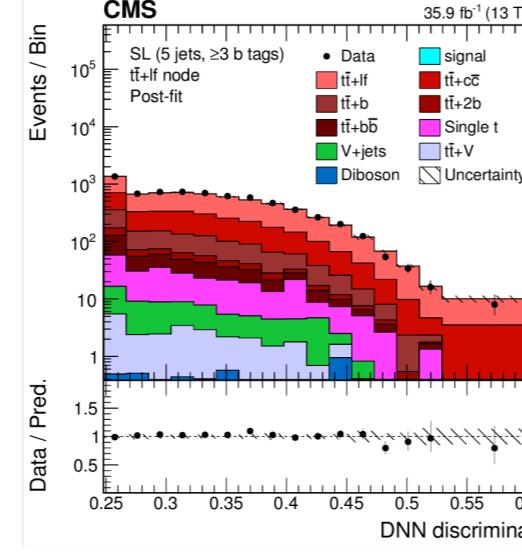
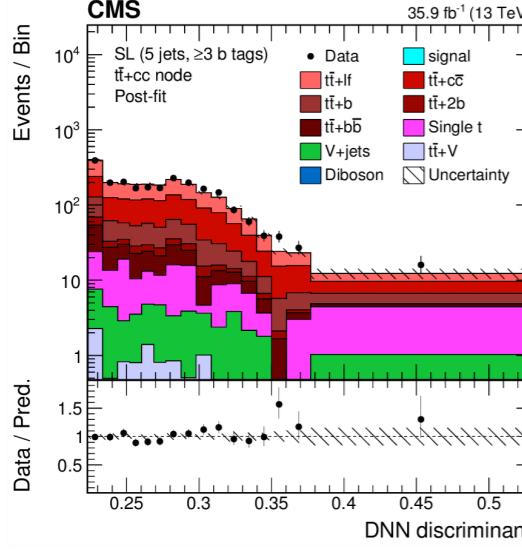
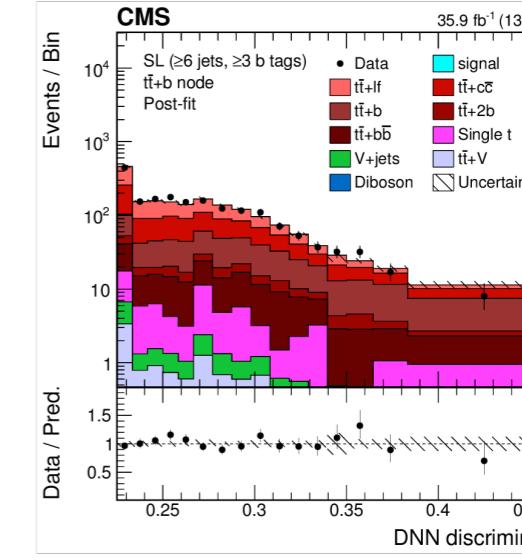
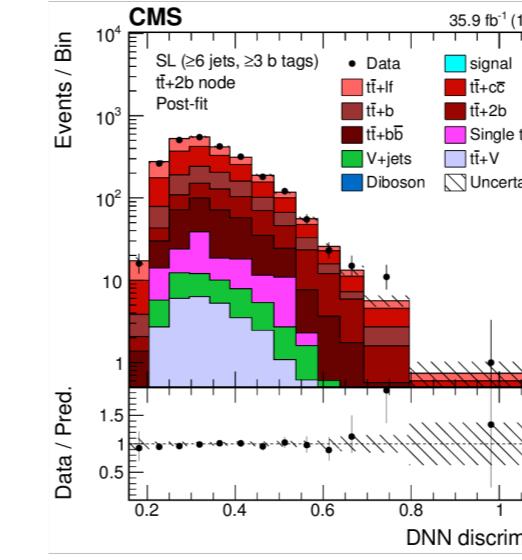
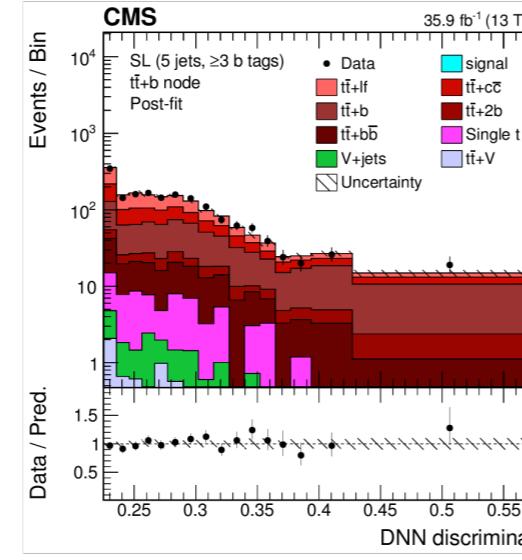
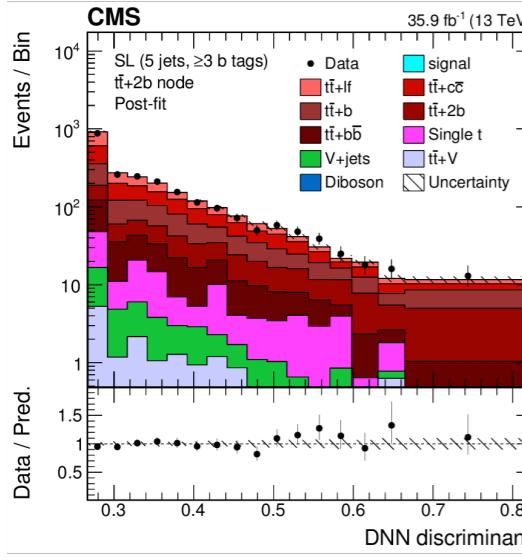
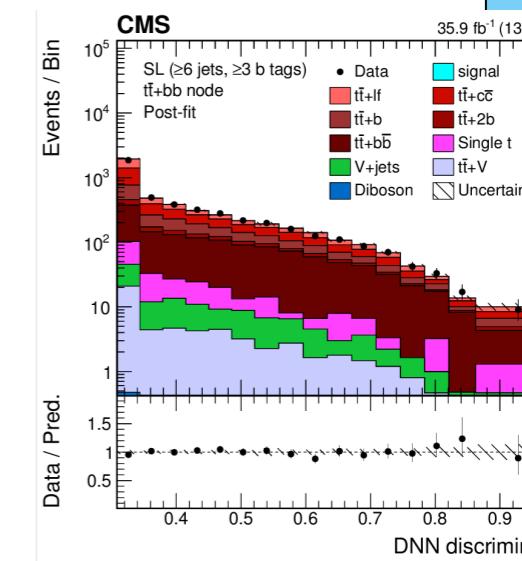
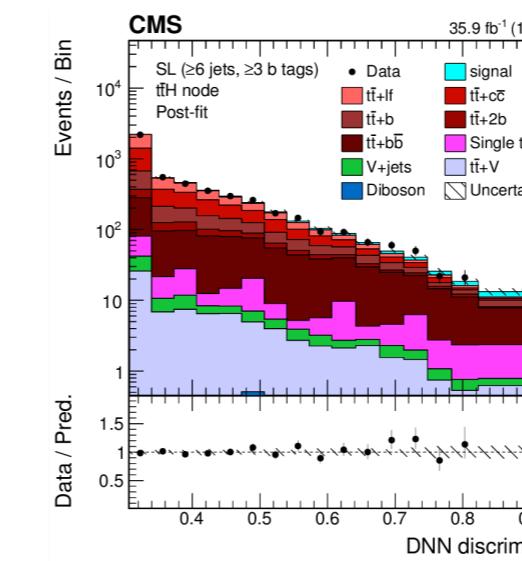
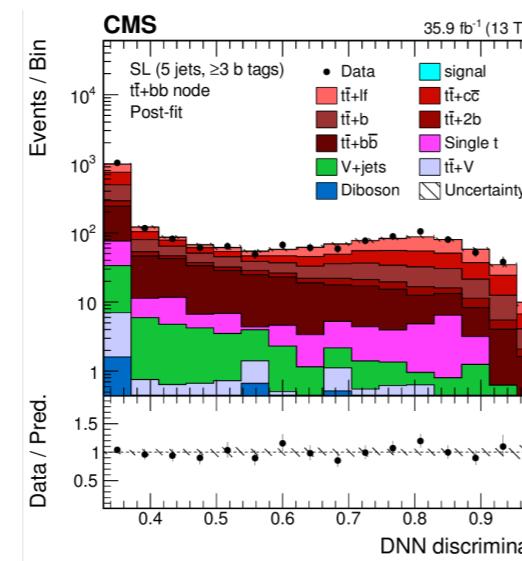
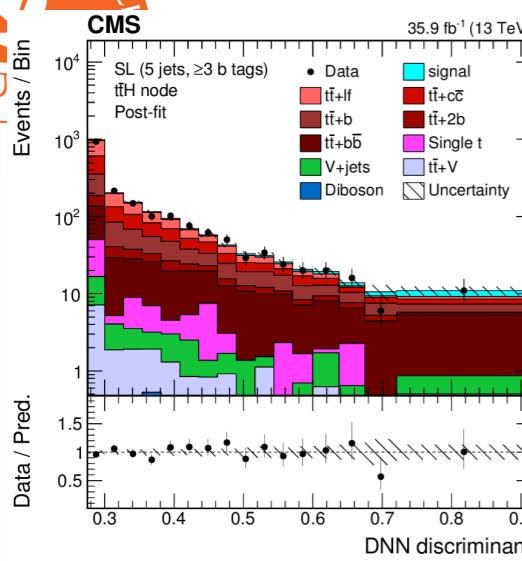
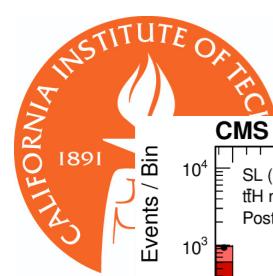


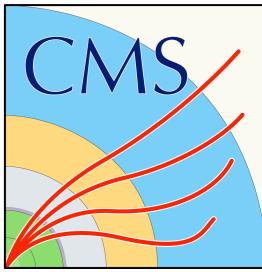
# Bonus slides



# **ttH(bb) leptonic**



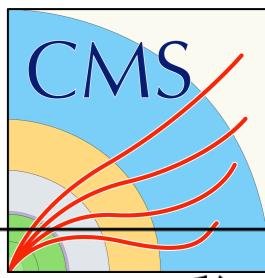




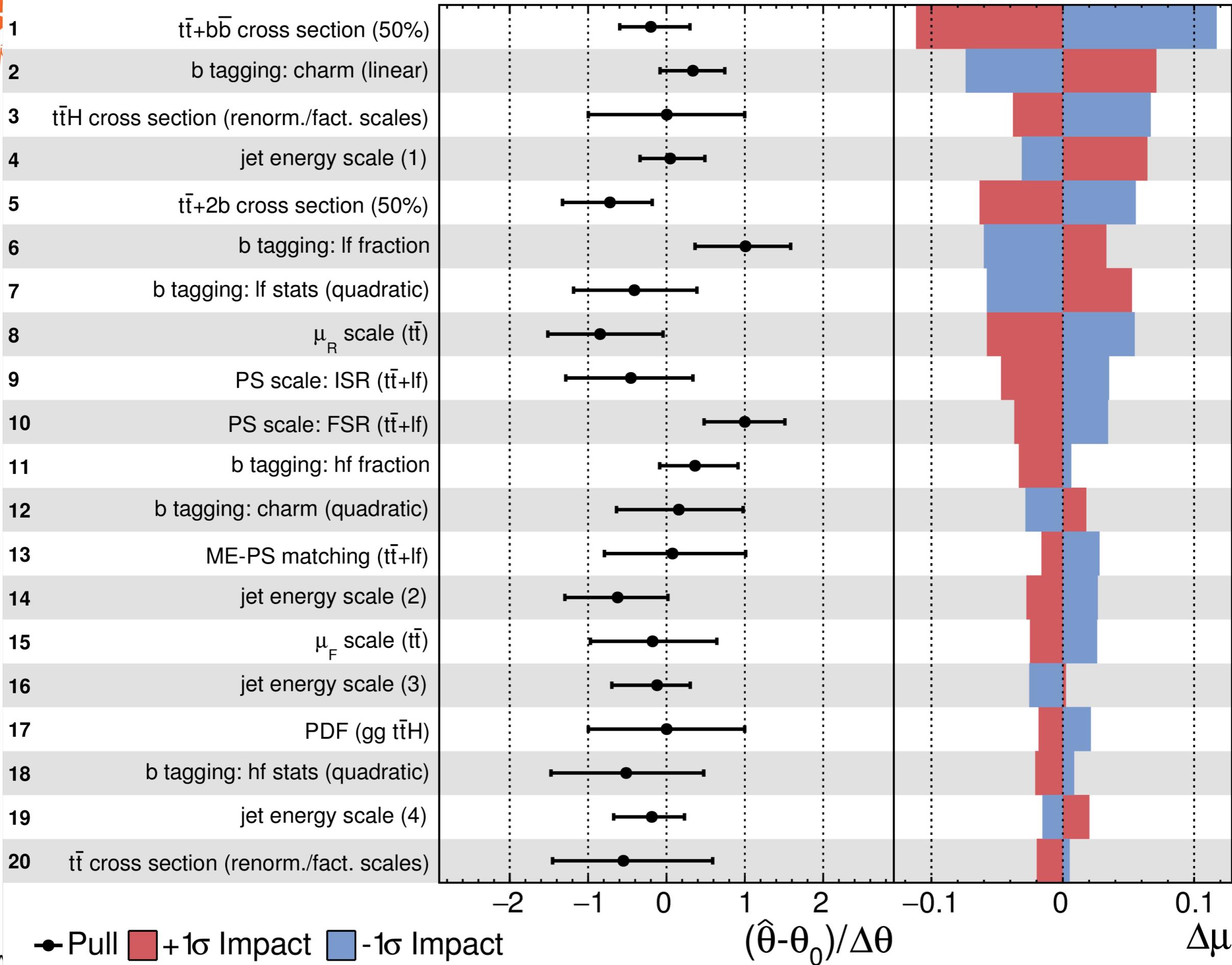
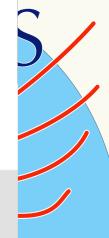
Process	SL channel	DL channel
$t\bar{t}+lf$	$463\ 658 \pm 174$	$241\ 032 \pm 99$
$t\bar{t}+c\bar{c}$	$76\ 012 \pm 70$	$24\ 550 \pm 32$
$t\bar{t}+b$	$22\ 416 \pm 38$	$5\ 979 \pm 16$
$t\bar{t}+2b$	$9\ 052 \pm 24$	$1\ 785 \pm 9$
$t\bar{t}+b\bar{b}$	$10\ 897 \pm 27$	$1\ 840 \pm 9$
Single t	$25\ 215 \pm 166$	$12\ 206 \pm 125$
V+jets	$12\ 309 \pm 58$	$5\ 684 \pm 209$
$t\bar{t}+V$	$2\ 457 \pm 12$	$2\ 570 \pm 23$
Diboson	$449 \pm 14$	$430 \pm 15$
Total bkg.	$622\ 466 \pm 263$	$296\ 077 \pm 266$
$t\bar{t}H$	$1\ 232 \pm 2$	$314.0 \pm 0.9$
Data	$610\ 556$	$283\ 942$

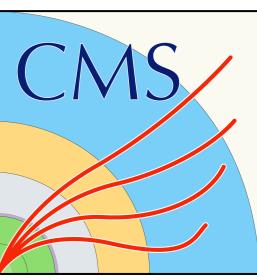


Process	pre-fit (post-fit) yields						
	t <bar>t&gt;H node</bar>	t <bar>t&gt;+bb node</bar>	t <bar>t&gt;+2b node</bar>	t <bar>t&gt;+b node</bar>	t <bar>t&gt;+c<bar>c node</bar></bar>	t <bar>t&gt;+lf node</bar>	
t <bar>t&gt;+lf</bar>	1982 (1381)	1280 (897)	852 (595)	916 (661)	243 (172)	50 (36)	
t <bar>t&gt;+cc</bar>	1150 (1415)	998 (1230)	636 (805)	444 (567)	115 (147)	16 (19)	
t <bar>t&gt;+b</bar>	549 (705)	575 (746)	314 (409)	253 (338)	28 (35)	4 (5)	
t <bar>t&gt;+2b</bar>	306 (233)	282 (215)	372 (293)	78 (62)	10 (8)	1 (0.8)	
t <bar>t&gt;+bb</bar>	834 (769)	1156 (1082)	299 (266)	145 (129)	17 (15)	3 (2)	
Single t	110 (116)	146 (145)	92 (82)	53 (53)	4 (4)	3 (3)	
V+jets	38 (37)	78 (76)	34 (30)	10 (9)	7 (6)	0.6 (0.6)	
t <bar>t&gt;+V</bar>	80 (75)	58 (54)	31 (28)	11 (11)	4 (4)	0.4 (0.4)	
Diboson	0.9 (0.9)	0.5 (0.5)	0.4 (0.4)	0.4 (0.4)	— (—)	— (—)	
Total bkg.	5049 (4733)	4575 (4447)	2629 (2509)	1911 (1831)	429 (392)	77 (67)	
± tot unc.	±1216 (±186)	±1156 (±142)	±603 (±80)	±422 (±65)	±107 (±14)	±18 (±3)	
t <bar>t&gt;H</bar>	142 (108)	53 (40)	24 (18)	10 (7)	2.1 (1.5)	0.30 (0.23)	
± tot unc.	±19 (±15)	±8 (±6)	±3 (±2)	±1 (±1)	±0.2 (±0.2)	±0.03 (±0.03)	
Data	4822	4400	2484	1852	422	76	

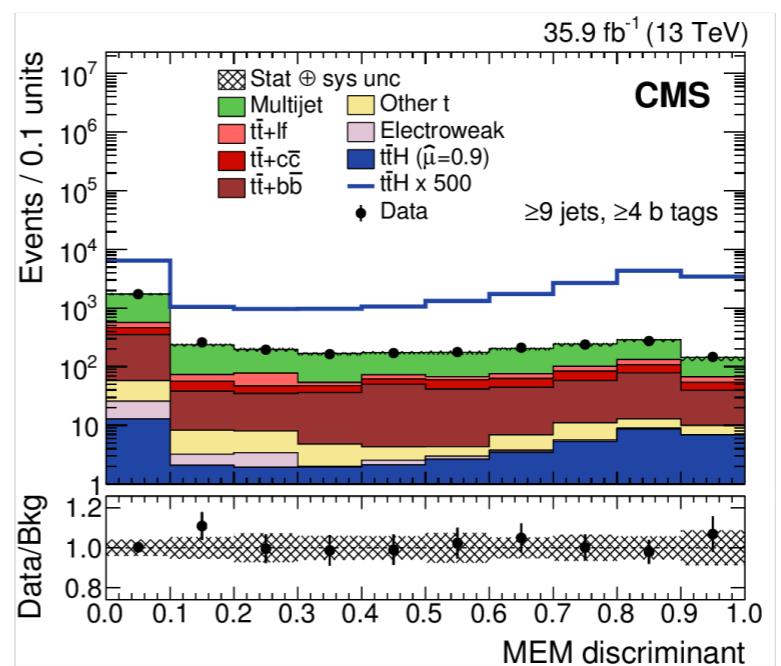
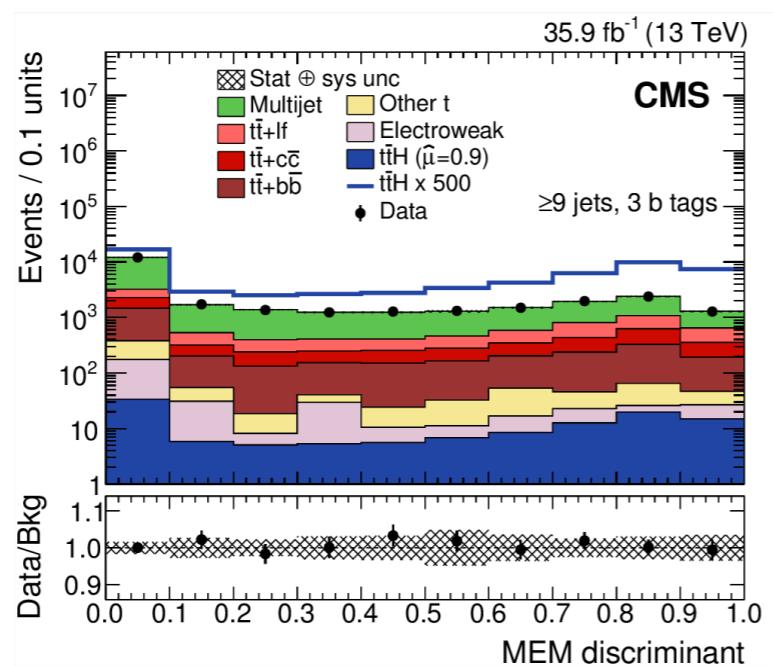
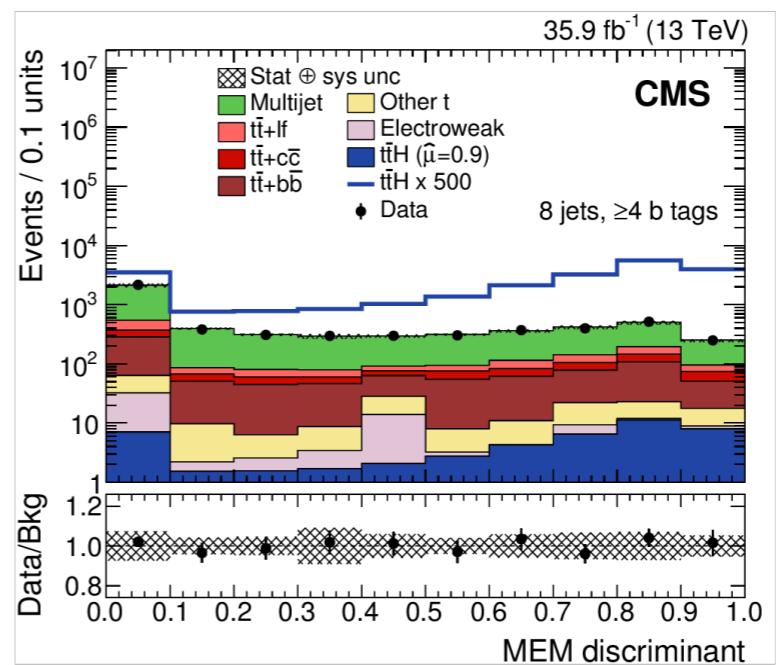
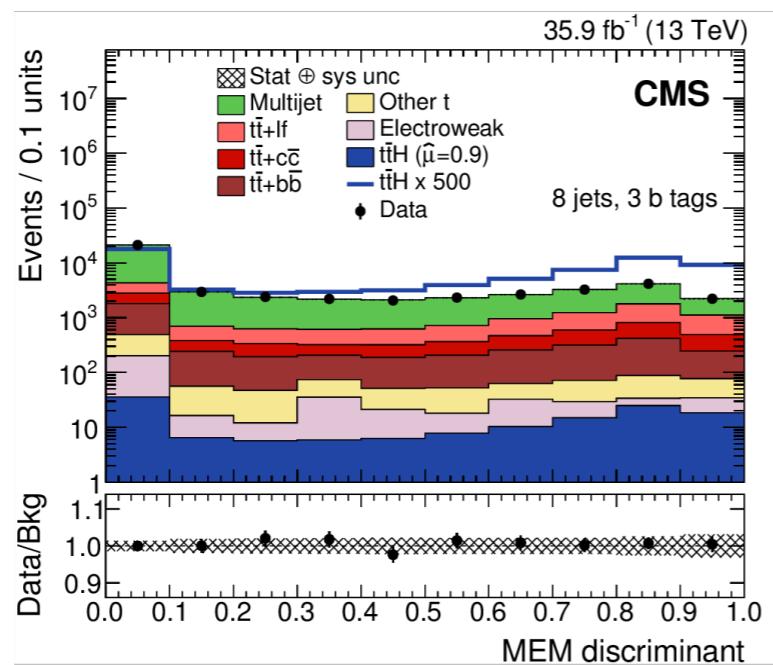
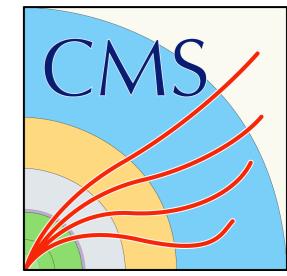
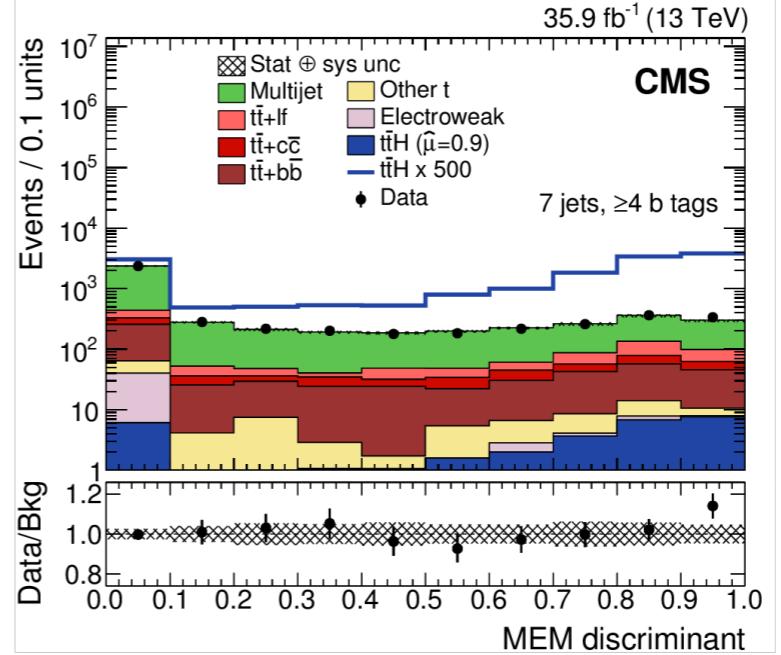
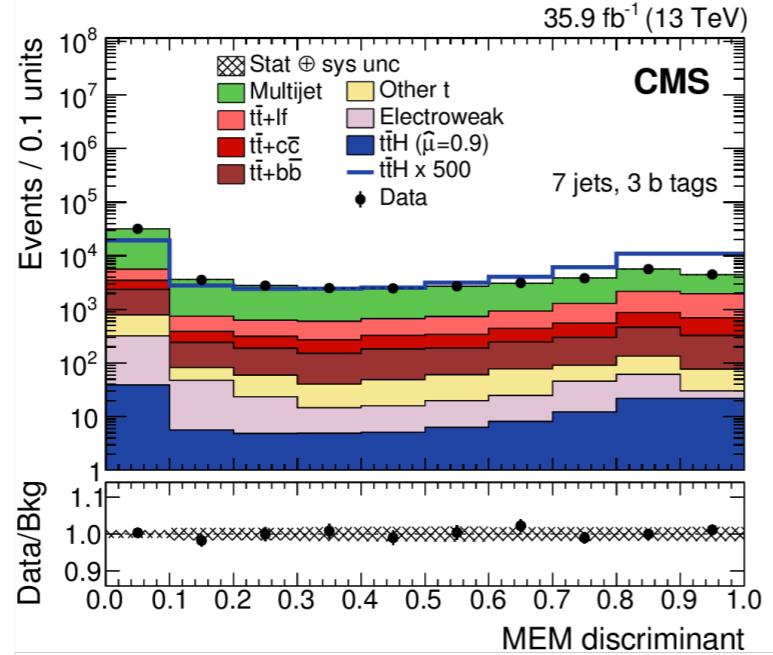


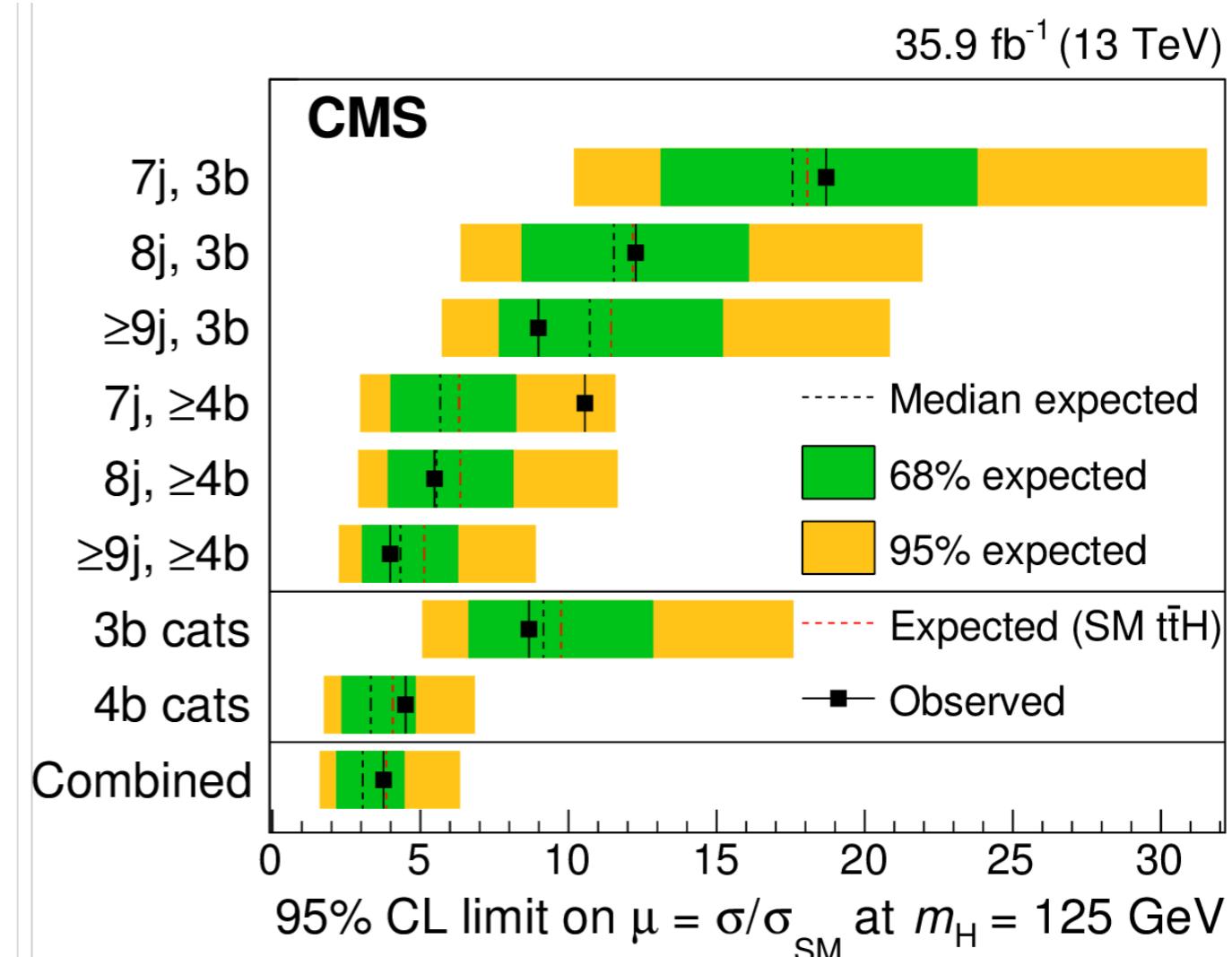
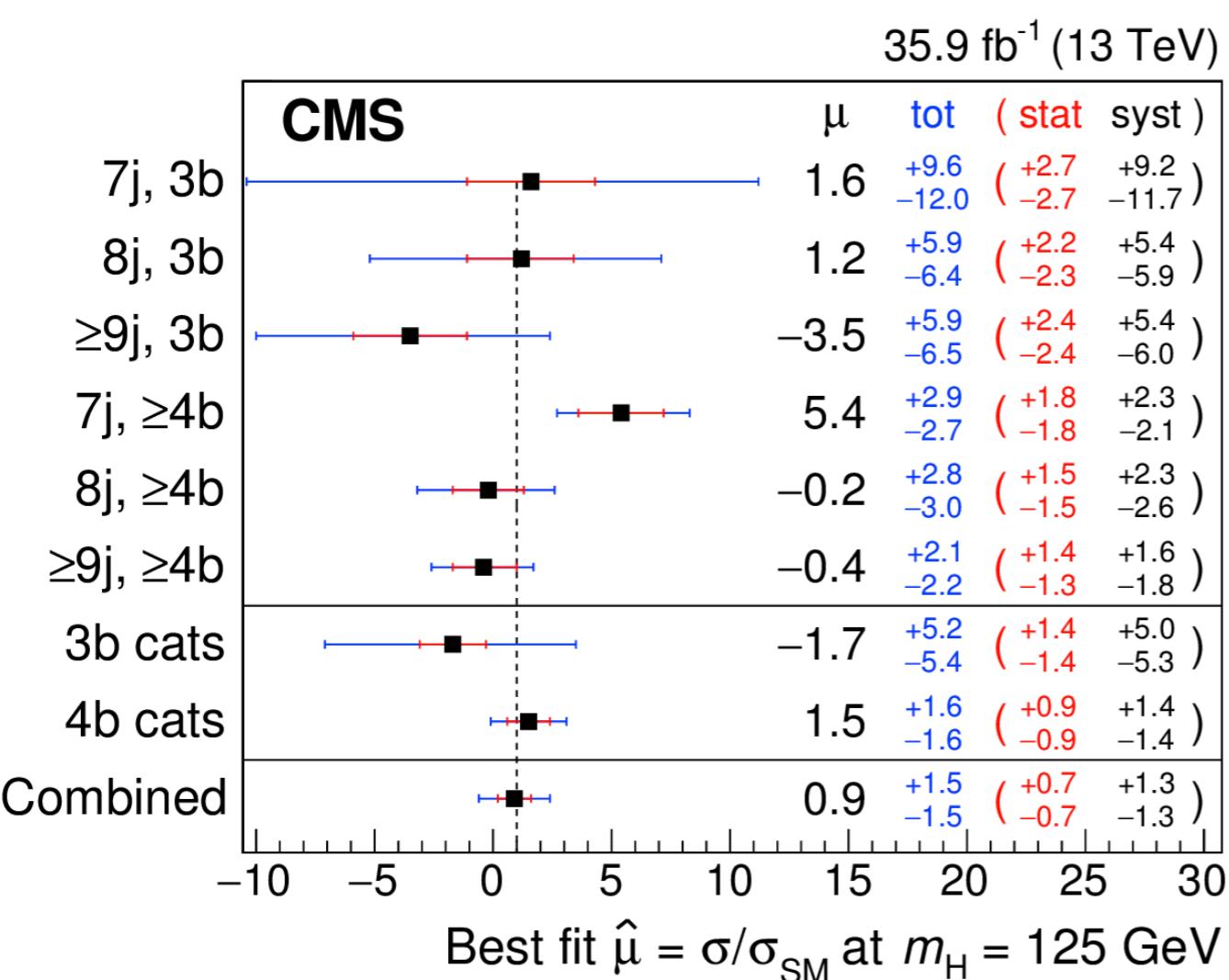
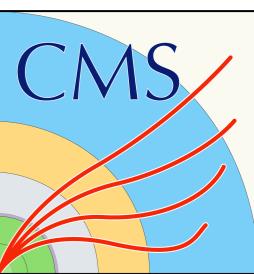
Uncertainty source	$\pm \Delta\mu$ (observed)	$\pm \Delta\mu$ (expected)
Total experimental	+0.15 / -0.16	+0.19 / -0.17
b tagging	+0.11 / -0.14	+0.12 / -0.11
jet energy scale and resolution	+0.06 / -0.07	+0.13 / -0.11
Total theory	+0.28 / -0.29	+0.32 / -0.29
t̄t+hf cross section and parton shower	+0.24 / -0.28	+0.28 / -0.28
Size of the simulated samples	+0.14 / -0.15	+0.16 / -0.16
Total systematic	+0.38 / -0.38	+0.45 / -0.42
Statistical	+0.24 / -0.24	+0.27 / -0.27
Total	+0.45 / -0.45	+0.53 / -0.49

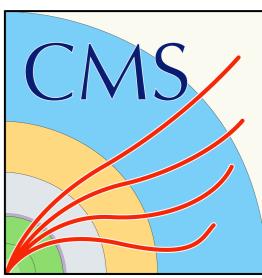




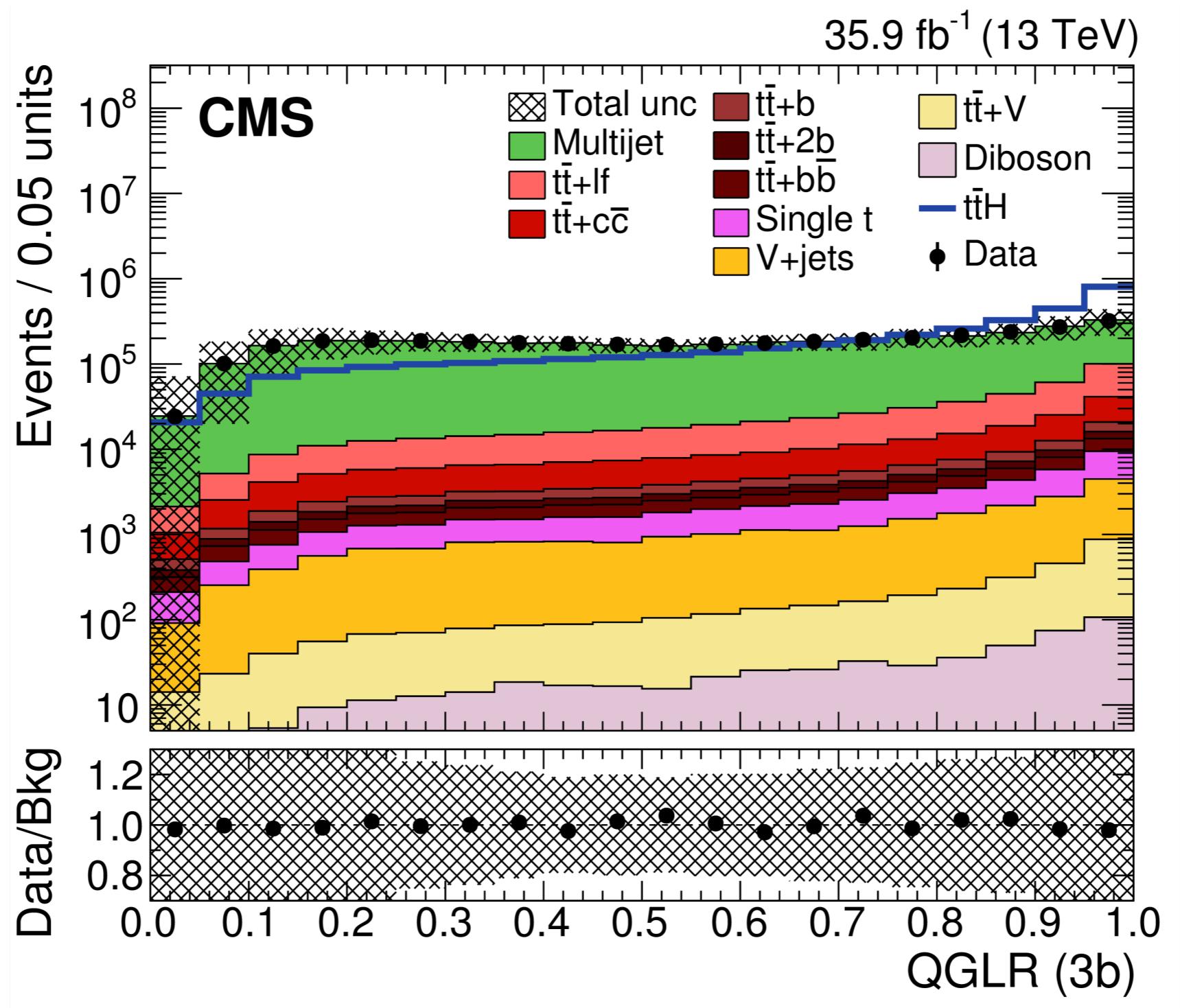
# ttH(bb) hadronic



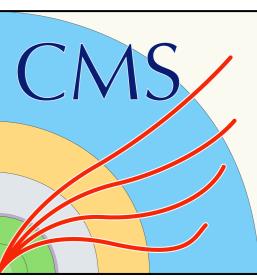




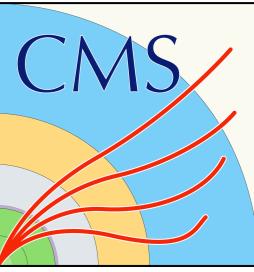
Process	7j, 3b	8j, 3b	$\geq 9j, 3b$	7j, $\geq 4b$	8j, $\geq 4b$	$\geq 9j, \geq 4b$
Multijet	$8\,560 \pm 820$	$5\,510 \pm 590$	$3\,120 \pm 400$	$608 \pm 61$	$748 \pm 74$	$376 \pm 57$
$t\bar{t}+lf$	$3\,300 \pm 470$	$2\,220 \pm 330$	$1\,110 \pm 170$	$121 \pm 34$	$107 \pm 31$	$54 \pm 21$
$t\bar{t}+c\bar{c}$	$1\,050 \pm 410$	$920 \pm 370$	$660 \pm 260$	$53 \pm 27$	$88 \pm 39$	$70 \pm 30$
$t\bar{t}+b$	$380 \pm 160$	$330 \pm 140$	$240 \pm 110$	$44 \pm 27$	$51 \pm 25$	$33 \pm 17$
$t\bar{t}+2b$	$208 \pm 94$	$167 \pm 79$	$128 \pm 59$	$21 \pm 12$	$36 \pm 22$	$15 \pm 8$
$t\bar{t}+b\bar{b}$	$192 \pm 64$	$249 \pm 84$	$228 \pm 80$	$46 \pm 18$	$88 \pm 30$	$95 \pm 33$
Single t	$130 \pm 32$	$100 \pm 32$	$50 \pm 15$	$8 \pm 5$	$24 \pm 23$	$5 \pm 4$
V+jets	$79 \pm 48$	$39 \pm 20$	$28 \pm 21$	$1 \pm 2$	$4 \pm 5$	$0 \pm 1$
$t\bar{t}+V$	$34 \pm 6$	$39 \pm 8$	$32 \pm 8$	$5 \pm 3$	$8 \pm 3$	$7 \pm 3$
Diboson	$1 \pm 1$	$0.24 \pm 0.23$	$0.00 \pm 0.00$	$0.33 \pm 0.29$	$0.00 \pm 0.00$	$0.13 \pm 0.23$
Total bkg	$13\,930 \pm 260$	$9\,580 \pm 250$	$5\,610 \pm 170$	$910 \pm 50$	$1\,154 \pm 76$	$656 \pm 44$
$t\bar{t}H (\hat{\mu} = 0.9)$	$56 \pm 83$	$58 \pm 89$	$47 \pm 71$	$18 \pm 27$	$26 \pm 38$	$21 \pm 31$
Data	13 937	9 620	5 640	958	1 162	660
S/B ( $\mu = 1$ )	0.005	0.007	0.009	0.023	0.025	0.036



The hatched bands reflect the total statistical and systematic uncertainties in the background prediction, prior to the fit to data, which are dominated by the systematic uncertainties in the simulated multijet background



# ttH multilepton

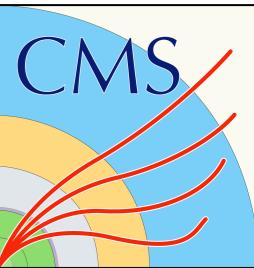


Selection	$2\ell\text{ss}$	$2\ell\text{ss} + 1\tau_h$
Targeted $t\bar{t}H$ decay	$t \rightarrow b\ell\nu, t \rightarrow bqq,$ $H \rightarrow WW \rightarrow \ell\nu qq$	$t \rightarrow b\ell\nu, t \rightarrow bqq,$ $H \rightarrow \tau\tau \rightarrow \ell\tau_h + \nu's$
Trigger	Single- and double-lepton triggers	
Lepton $p_T$	$p_T > 25 / 15 \text{ GeV}$	$p_T > 25 / 15 (\text{e}) \text{ or } 10 \text{ GeV } (\mu)$
$\tau_h p_T$	—	$p_T > 20 \text{ GeV}$
Charge requirements	2 same-sign leptons and charge quality requirements	2 same-sign leptons and charge quality requirements $\sum_{\ell, \tau_h} q = \pm 1$
Jet multiplicity	$\geq 4$ jets	$\geq 3$ jets
b tagging requirements	$\geq 1$ tight b-tagged jet or $\geq 2$ loose b-tagged jets	
Missing transverse momentum	$L_D > 30 \text{ GeV}$	$L_D > 30 \text{ GeV}^*$
Dilepton mass	$m_{\ell\ell} > 12 \text{ GeV}$ and $ m_{ee} - m_Z  > 10 \text{ GeV}^*$	
Selection	$3\ell$	$3\ell + 1\tau_h$
Targeted $t\bar{t}H$ decays	$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu,$ $H \rightarrow WW \rightarrow \ell\nu qq$ $t \rightarrow b\ell\nu, t \rightarrow bqq,$ $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ $t \rightarrow b\ell\nu, t \rightarrow bqq,$ $H \rightarrow ZZ \rightarrow \ell\ell qq \text{ or } \ell\ell\nu\nu$	$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu,$ $H \rightarrow \tau\tau \rightarrow \ell\tau_h + \nu's$
Trigger	Single-, double- and triple-lepton triggers	
Lepton $p_T$	$p_T > 25 / 15 / 15 \text{ GeV}$	$p_T > 20 / 10 / 10 \text{ GeV}$
$\tau_h p_T$	—	$p_T > 20 \text{ GeV}$
Charge requirements	$\sum_{\ell} q = \pm 1$	$\sum_{\ell, \tau_h} q = 0$
Jet multiplicity	$\geq 2$ jets	
b tagging requirements	$\geq 1$ tight b-tagged jet or $\geq 2$ loose b-tagged jets	
Missing transverse momentum	No requirement if $N_j \geq 4$ $L_D > 45 \text{ GeV}^+$ $L_D > 30 \text{ GeV}$ otherwise	
Dilepton mass	$m_{\ell\ell} > 12 \text{ GeV}$ and $ m_{\ell\ell} - m_Z  > 10 \text{ GeV}^{\ddagger}$	

\* Applied only if both leptons are electrons.

† If the event contains a SFOS lepton pair and  $N_j \leq 3$ .

‡ Applied to all SFOS lepton pairs.

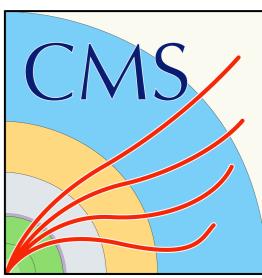


Selection	$1\ell + 2\tau_h$	$4\ell$
Targeted $t\bar{t}H$ decays	$t \rightarrow b\ell\nu, t \rightarrow bqq,$ $H \rightarrow \tau\tau \rightarrow \tau_h\tau_h + \nu'\nu$	$t \rightarrow b\ell\nu, t \rightarrow b\ell\nu,$ $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ $t \rightarrow b\ell\nu, t \rightarrow b\ell\nu,$ $H \rightarrow ZZ \rightarrow \ell\ell qq \text{ or } \ell\ell\nu\nu$
Trigger	Single-lepton and lepton+ $\tau_h$ triggers	Single-, double- and triple-lepton triggers
Lepton $p_T$	$p_T > 25$ (e) or $20$ GeV ( $\mu$ )	$p_T > 25 / 15 / 15 / 10$ GeV
$\tau_h p_T$	$p_T > 30 / 20$ GeV	—
Charge requirements	$\sum_{\tau_h} q = 0$ and $\sum_{\ell, \tau_h} q = \pm 1$	$\sum_{\ell} q = 0$
Jet multiplicity	$\geq 3$ jets	$\geq 2$ jets
b tagging requirements	$\geq 1$ tight b-tagged jet or $\geq 2$ loose b-tagged jets	
Missing transverse momentum	—	No requirement if $N_j \geq 4$ $L_D > 45$ GeV <sup>†</sup> $L_D > 30$ GeV otherwise
Dilepton mass	$m_{\ell\ell} > 12$ GeV	$m_{\ell\ell} > 12$ GeV
Four-lepton mass	—	and $ m_{\ell\ell} - m_Z  > 10$ GeV <sup>‡</sup> $m_{4\ell} > 140$ GeV <sup>§</sup>

<sup>†</sup> If the event contains a SFOS lepton pair and  $N_j \leq 3$ .

<sup>‡</sup> Applied to all SFOS lepton pairs.

<sup>§</sup> Applied only if the event contains 2 SFOS lepton pairs.



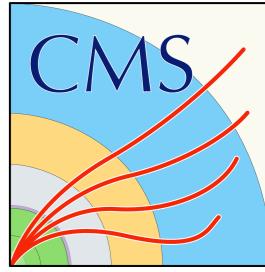
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, $\mu$ selection efficiency	2–4	11
$\tau_h$ selection efficiency	5	4.5
b tagging efficiency	2–15 [? ]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [? ]	5
$\tau_h$ energy calibration	3	1
Theoretical sources	$\approx$ 10	12
Integrated luminosity	2.5	5

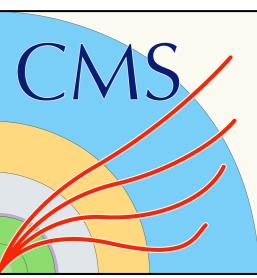


Process	$1\ell + 2\tau_h$	$2\ell ss$	$2\ell ss + 1\tau_h$
t̄H	$5.8 \pm 1.9$	$53.8 \pm 17.0$	$9.4 \pm 2.8$
t̄Z/ $\gamma^*$	$6.3 \pm 1.1$	$80.9 \pm 10.4$	$9.2 \pm 1.2$
t̄W + t̄WW	$0.5 \pm 0.1$	$150.0 \pm 16.9$	$9.1 \pm 1.0$
WZ + ZZ	$2.1 \pm 1.6$	$16.5 \pm 13.1$	$3.9 \pm 3.0$
tH	$0.4 \pm 0.1$	$2.7 \pm 0.2$	$0.5 \pm 0.04$
Conversions	$< 0.02$	$12.1 \pm 5.8$	$1.4 \pm 0.5$
Sign flip	—	$27.5 \pm 8.0$	$0.5 \pm 0.1$
Misidentified leptons	$195.7 \pm 13.6$	$94.2 \pm 21.2$	$8.6 \pm 2.1$
Rare backgrounds	$1.4 \pm 0.7$	$39.0 \pm 21.2$	$3.1 \pm 1.5$
Total expected background	$206.3 \pm 14.0$	$423.0 \pm 38.0$	$36.1 \pm 4.2$
Observed	212	507	49

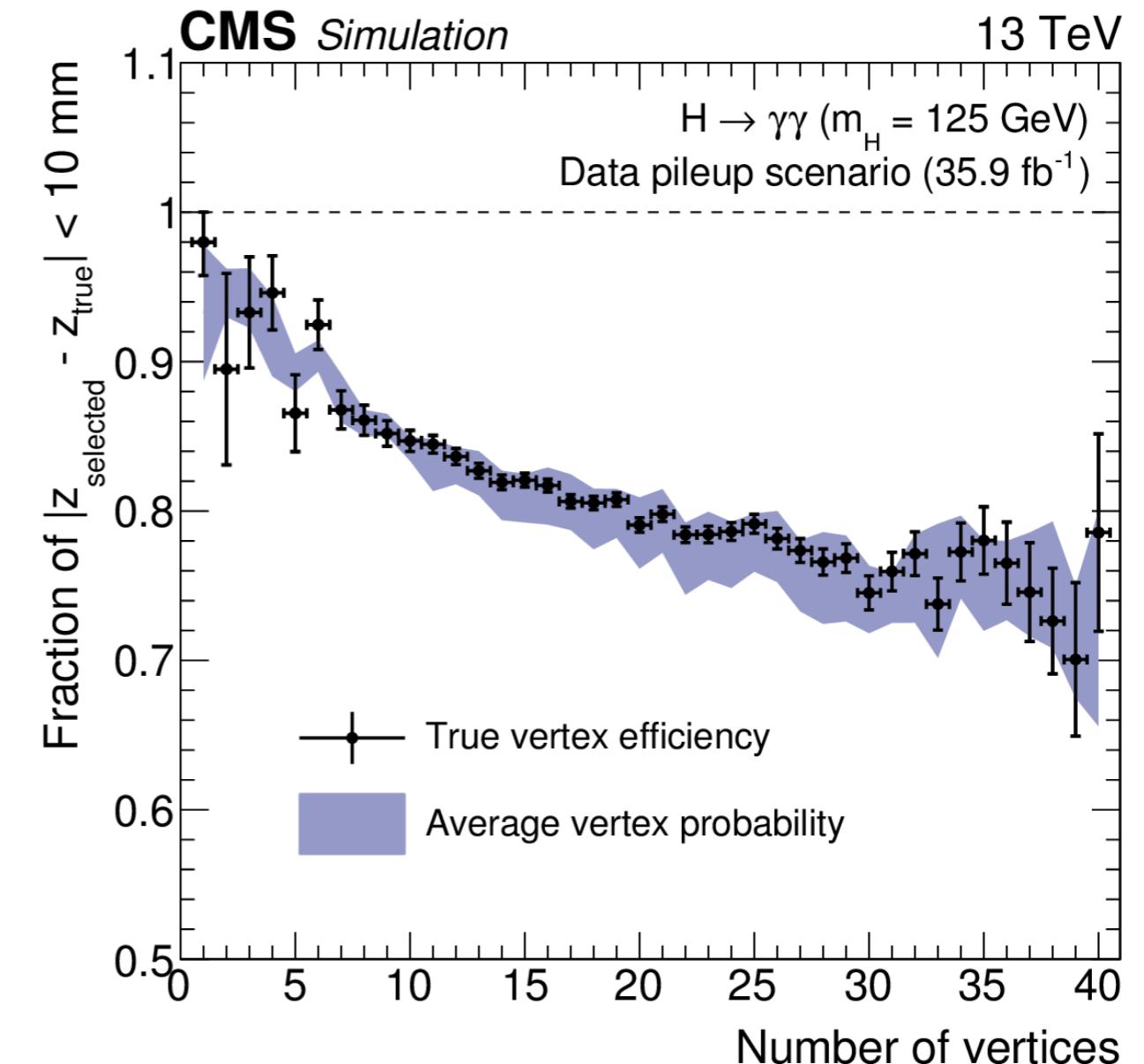
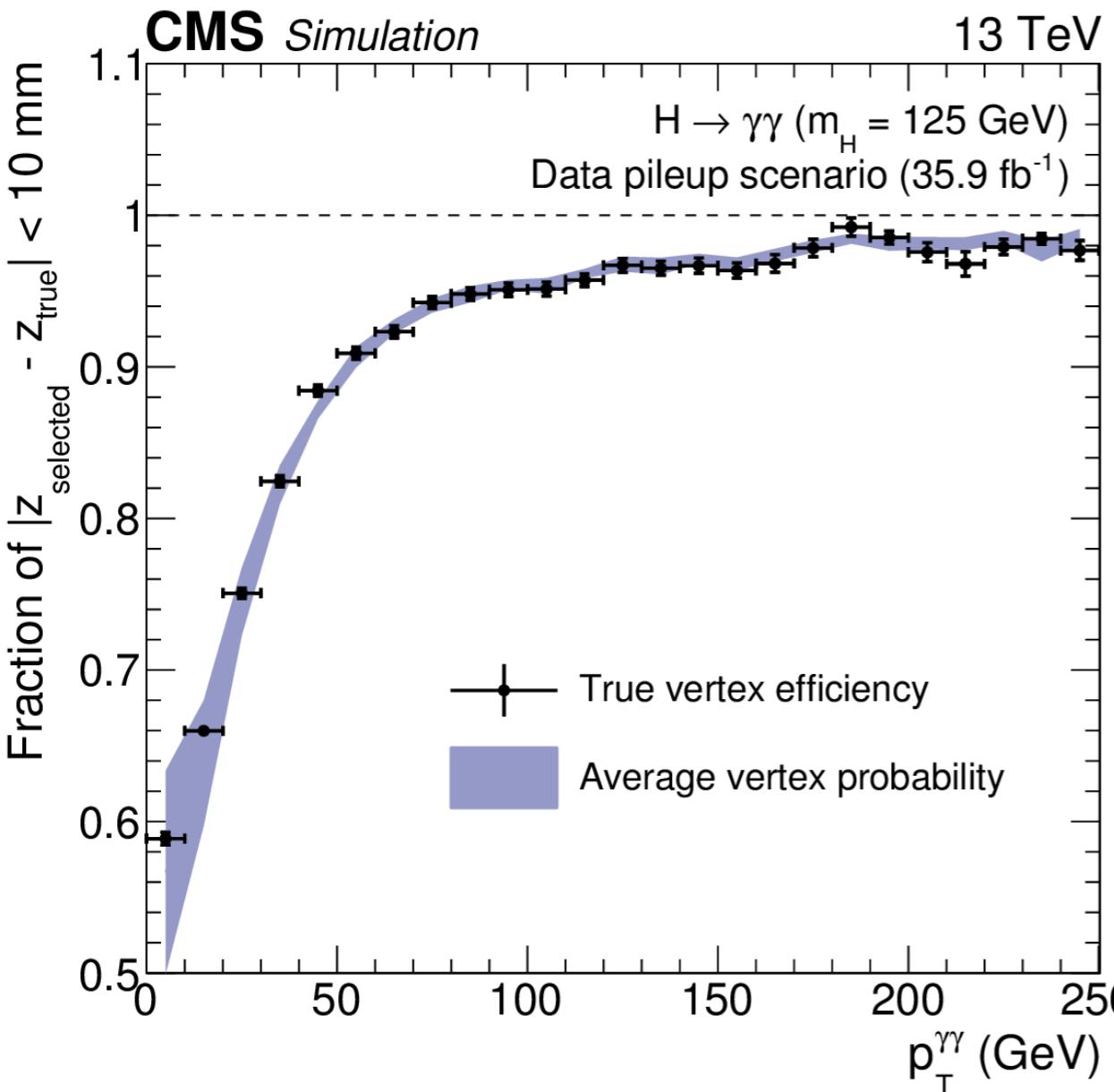
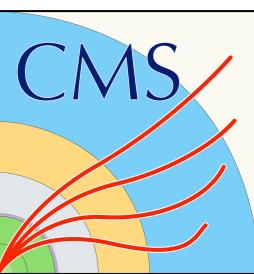
  

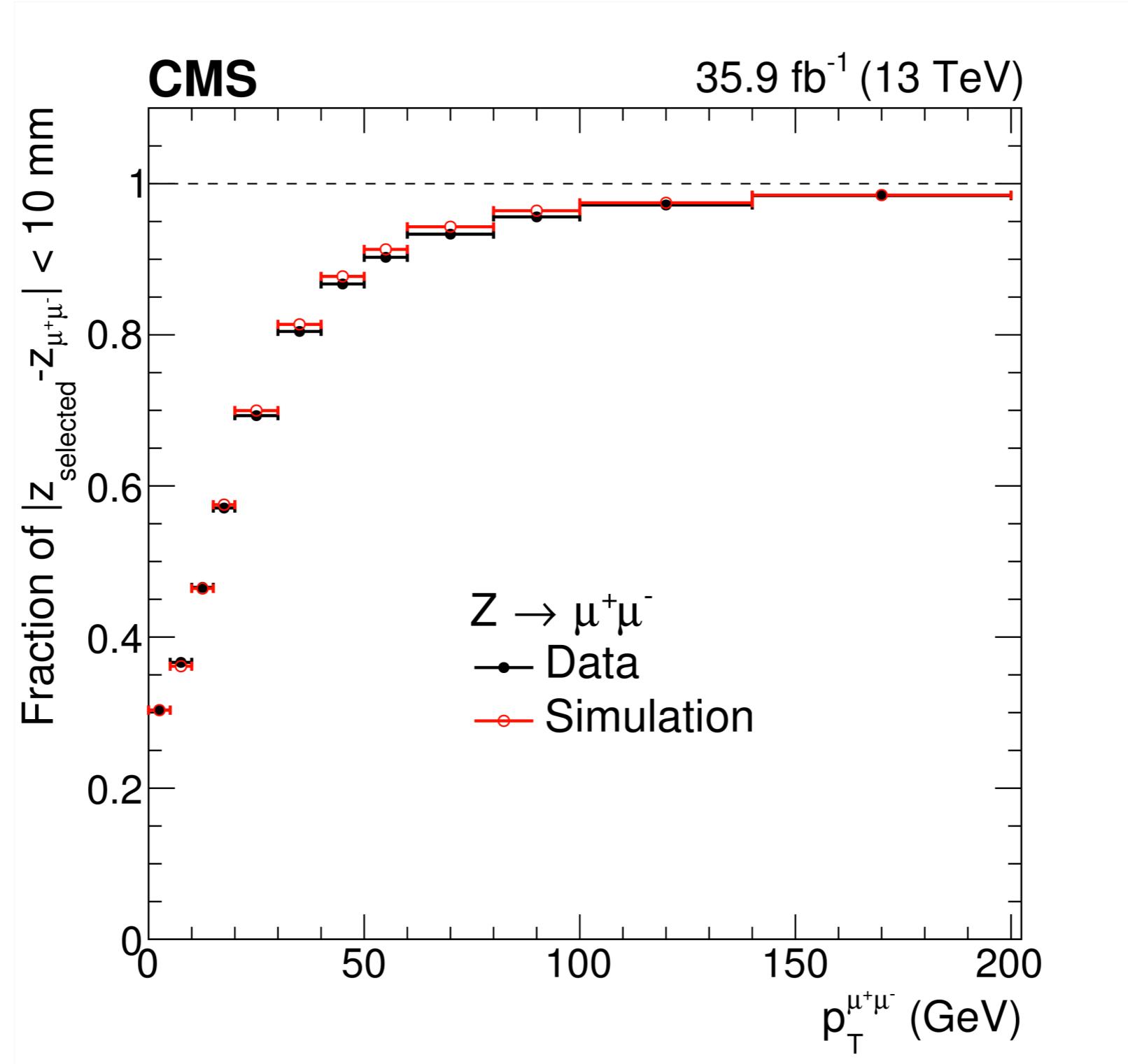
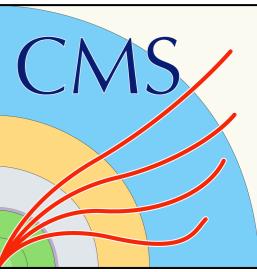
Process	$3\ell$	$3\ell + 1\tau_h$	$4\ell$
t̄H	$18.5 \pm 6.0$	$2.1 \pm 0.7$	$0.9 \pm 0.3$
t̄Z/ $\gamma^*$	$49.0 \pm 6.9$	$3.4 \pm 0.5$	$2.1 \pm 0.4$
t̄W + t̄WW	$35.2 \pm 4.2$	$0.4 \pm 0.04$	$< 2 \times 10^{-3}$
WZ + ZZ	$9.9 \pm 2.4$	$0.3 \pm 0.05$	$0.1 \pm 0.1$
tH	$1.2 \pm 0.2$	$0.1 \pm 0.01$	$< 4 \times 10^{-4}$
Conversions	$5.3 \pm 2.9$	$< 0.02$	$< 0.02$
Misidentified leptons	$22.7 \pm 6.7$	$0.9 \pm 0.2$	$< 0.04$
Rare backgrounds	$8.2 \pm 13.8$	$0.2 \pm 0.1$	$0.1 \pm 0.2$
Total expected background	$131.4 \pm 18.2$	$5.3 \pm 0.5$	$2.4 \pm 0.4$
Observed	148	7	3

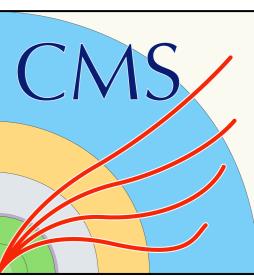




# Diphoton, ttH tag

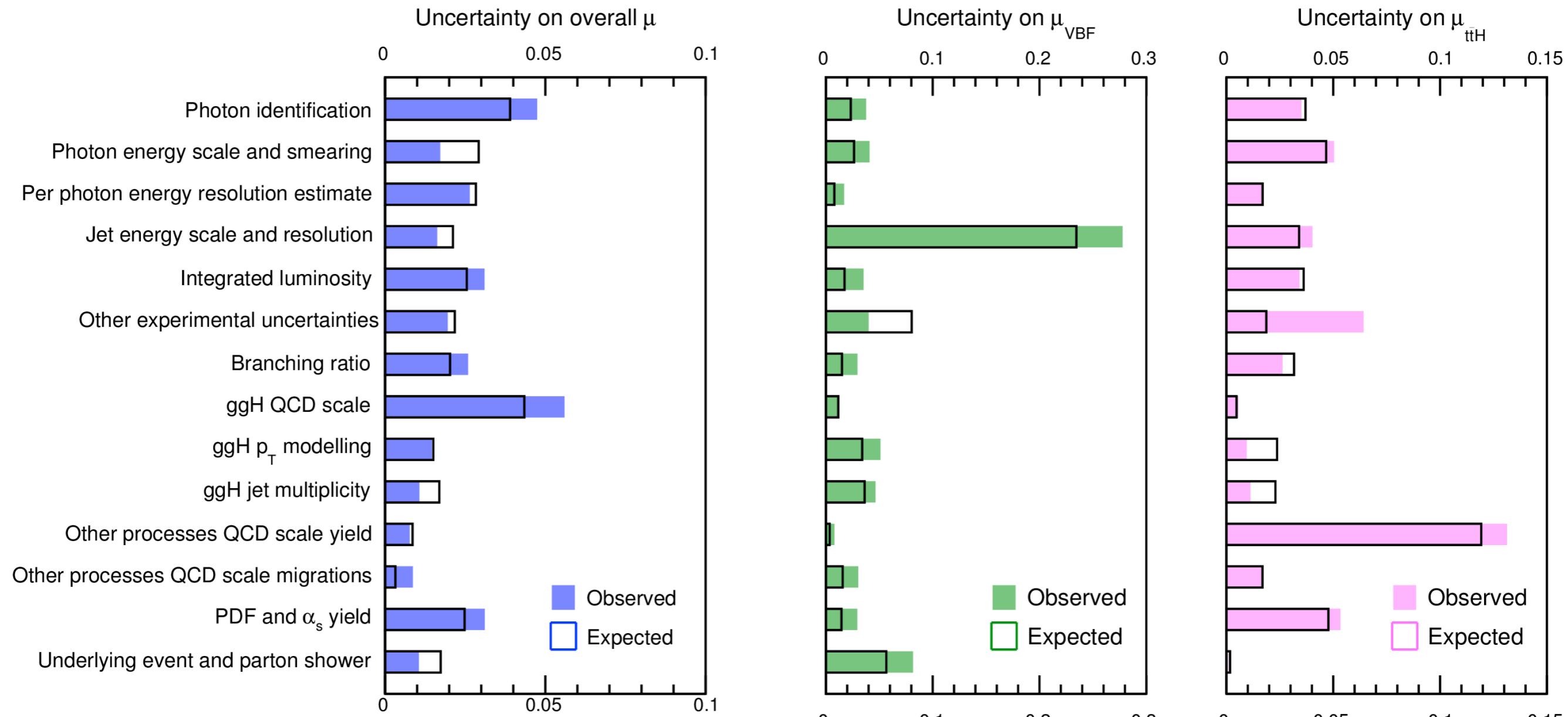


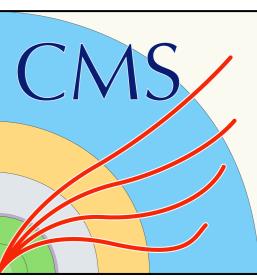




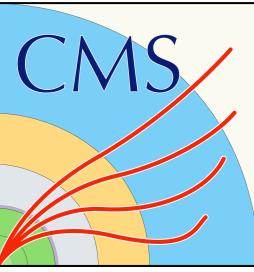
CMS  $H \rightarrow \gamma\gamma$

35.9  $\text{fb}^{-1}$  (13 TeV)

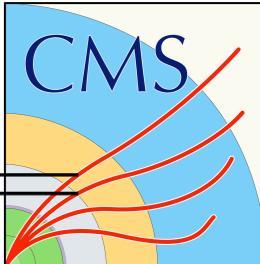




# ttH combination



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



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. $\tau_h$ ) 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 $\tau_h$ 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