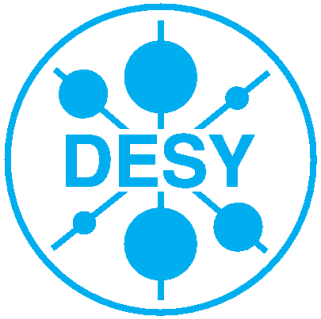
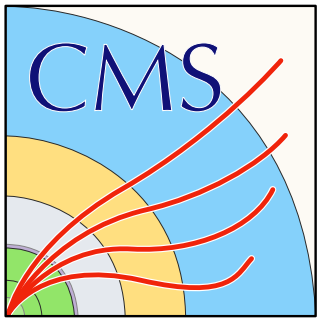




Measurements of the Yukawa couplings of the Higgs boson at CMS

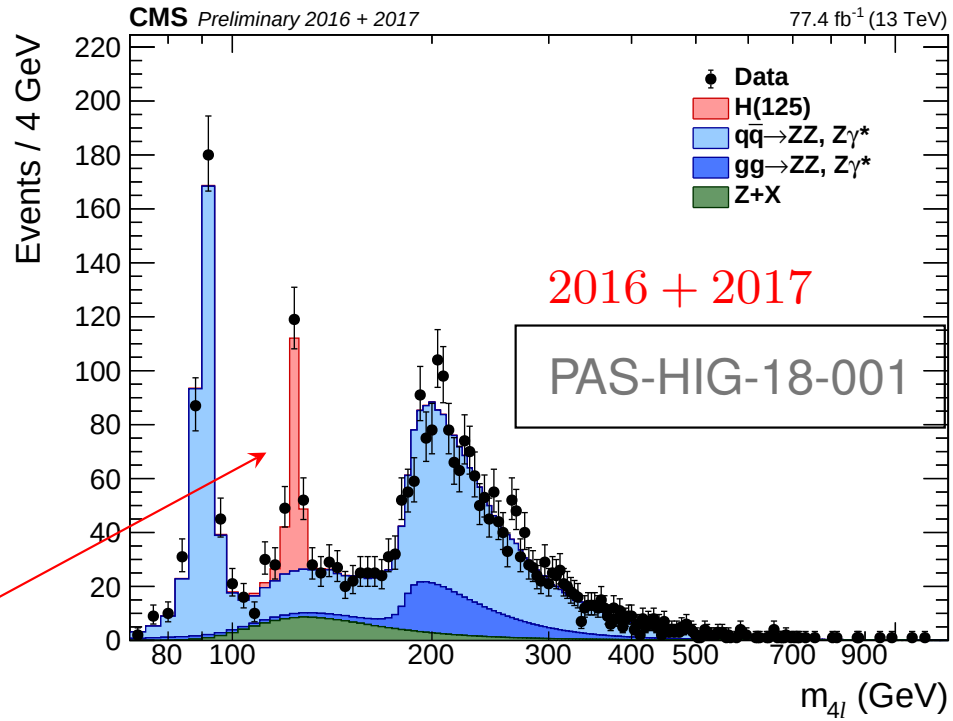
Marino Missiroli (DESY),

on behalf of the CMS Collaboration

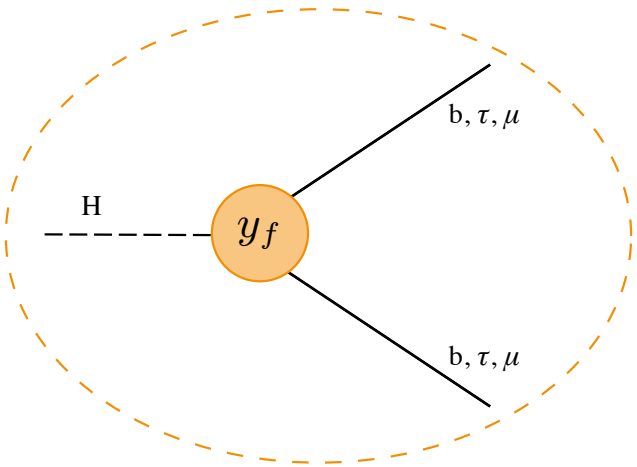
30th Rencontres de Blois, 3-8 June 2018

The SM Higgs boson

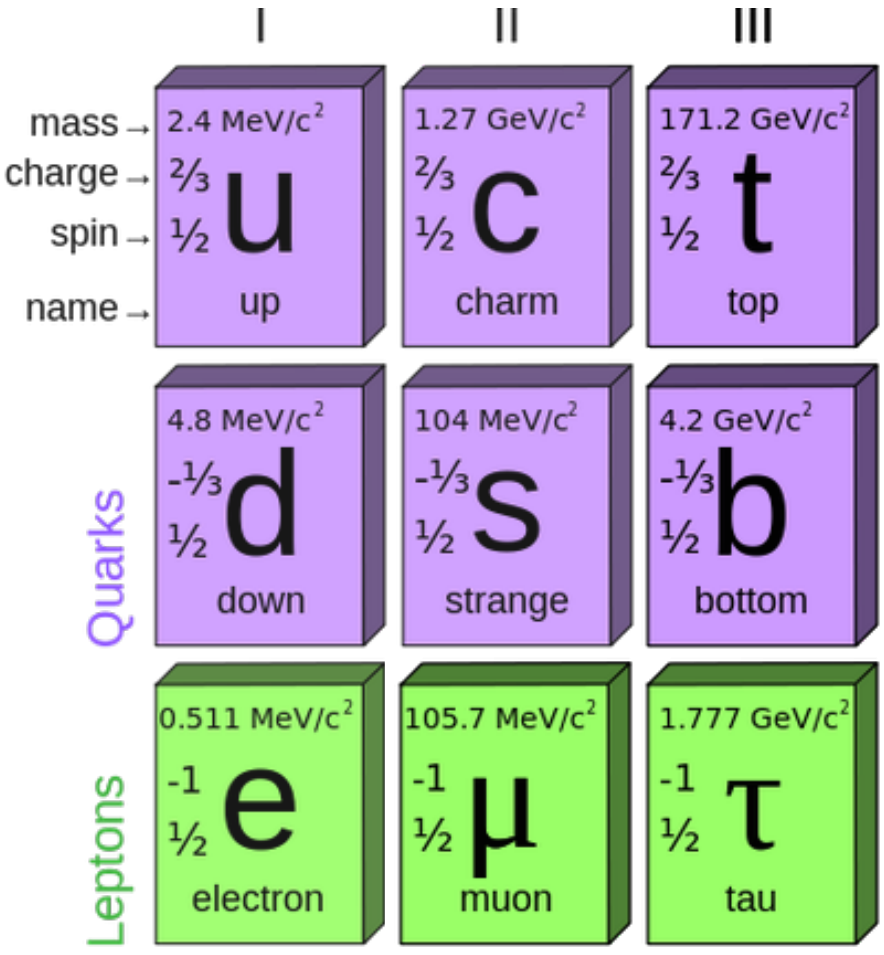
- *The* milestone of LHC Run-1
  - discovery of a new boson with $m \sim 125\ \mathrm{GeV}$ by ATLAS and CMS
- first discovered in bosonic decay modes: $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$
- thus far consistent with SM Higgs



- key to the SM Higgs: coupling to fermions
  - $Hf\bar{f}$ Yukawa interaction leads to fermion masses
  - y_f coupling strength proportional to m_f



Higgs couplings to fermions



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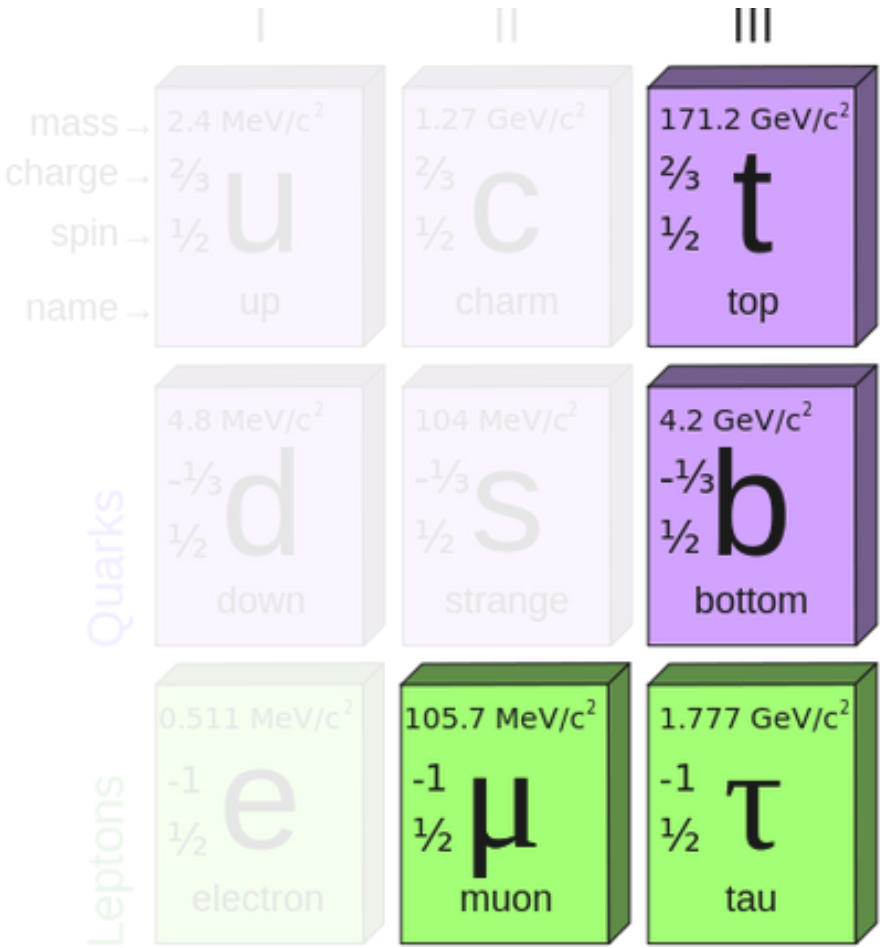
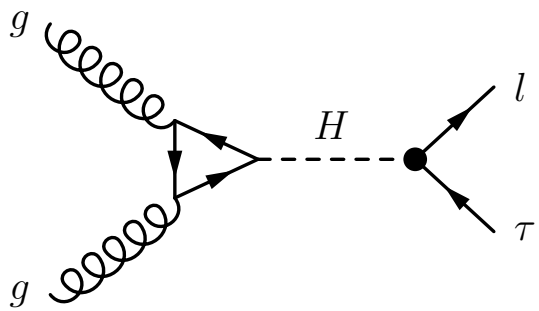


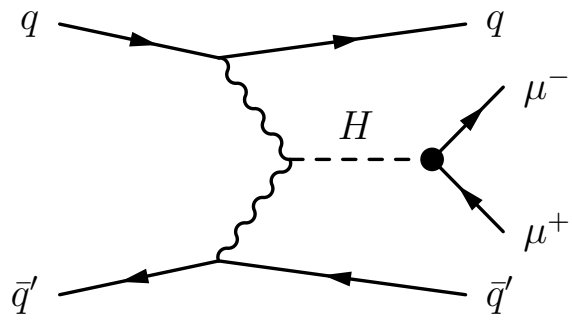
- Focus on couplings within reach at the LHC:
  - Higgs decays to $\mu\mu$, $\tau\tau$, $b\bar{b}$
  - $t\bar{t}H$ production to directly probe Higgs-top coupling

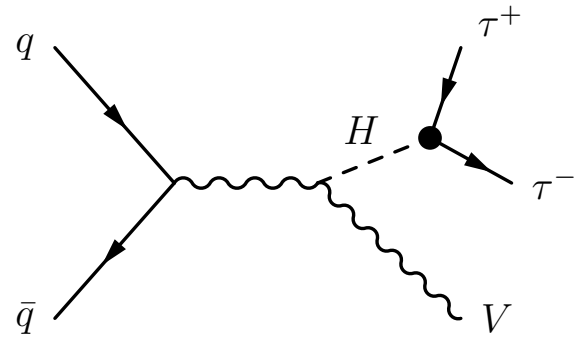
$$\mu = \sigma/\sigma_{\text{SM}}$$

- Reminder: CMS results from Run-1

$H \to \mu\mu$	$\mu_{95\%\ \text{CL}} < 7.4$ obs
$H \to \tau\tau$	evidence (3.2σ obs)
$H \to b\bar{b}$	excess of 2.1σ (obs)
$t\bar{t}H$	$\mu_{\text{fit}} = 2.8 \pm 1.0$ (3.4σ)







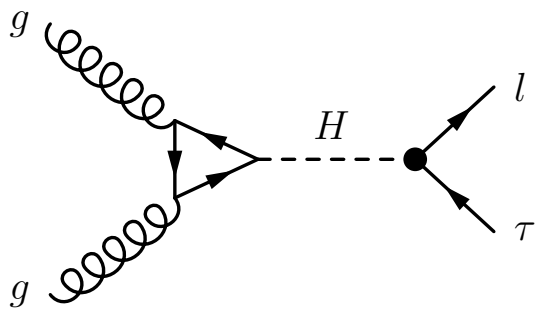
Higgs couplings to leptons

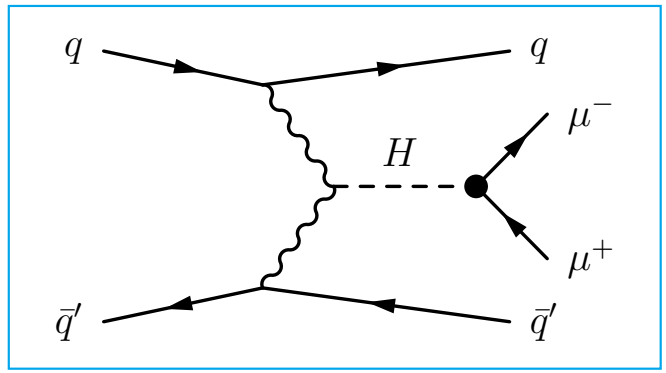
HIG-17-001 search for lepton-flavor violating $H \to \ell\tau$ decays

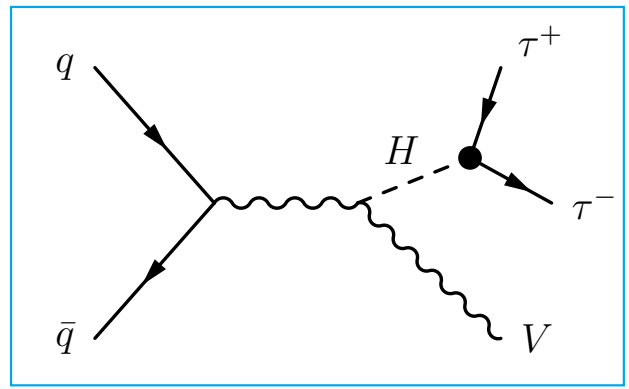
PAS-HIG-17-019 search for $H \to \mu\mu$

HIG-16-043 observation of $H \to \tau\tau$

PAS-HIG-18-007 NEW search for $VH(\to \tau\tau)$ with leptonic V decays







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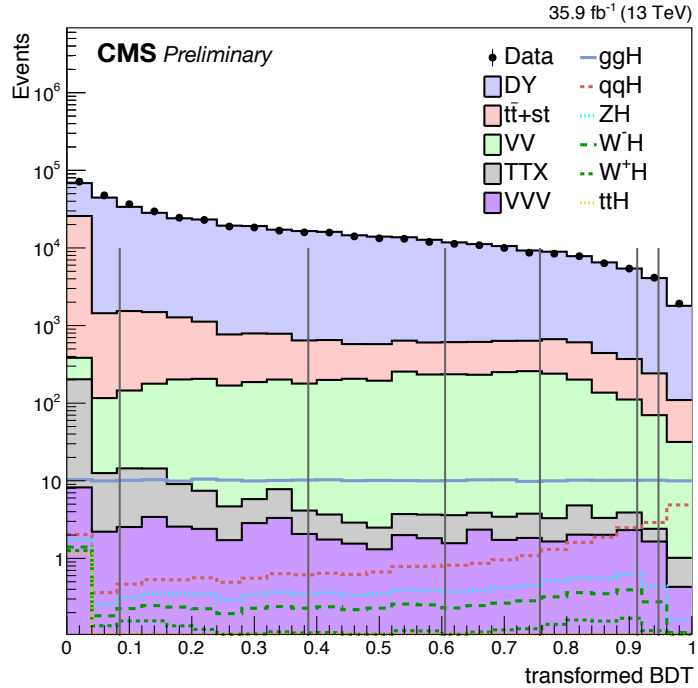
Search for $H \to \mu\mu$ decays

PAS-HIG-17-019

- very rare process $\sigma_{\text{SM}}(H \to \mu\mu) \sim 10$ fb, but clean exp. signature:

  $\mu^{\pm}\mu^{\mp}$ (+ 2 jets, for VBF)

- 15 SR categories defined by BDT discrim.
- signal and bkg modeled with analytical functions and fit to $m_{\mu\mu}$ spectra

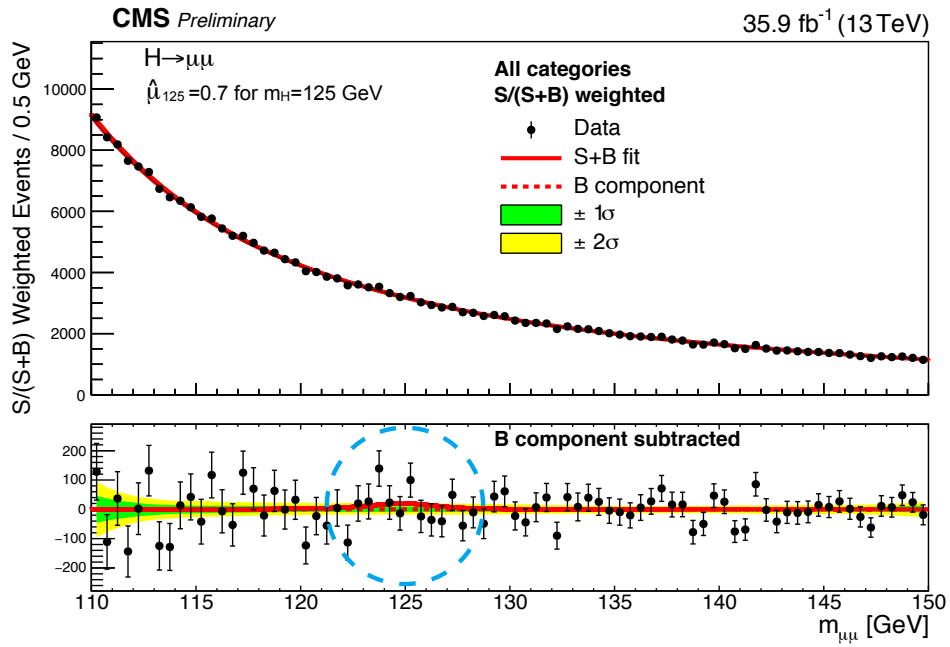


no significant excess observed, but sensitivity approaching SM prediction

Obs. (Exp.) significance: 0.98σ (1.09σ)

95% CL upper limit on $\mu = \sigma/\sigma_{\text{SM}}$:

$\mu < 2.64\,(1.89)$ obs (exp)

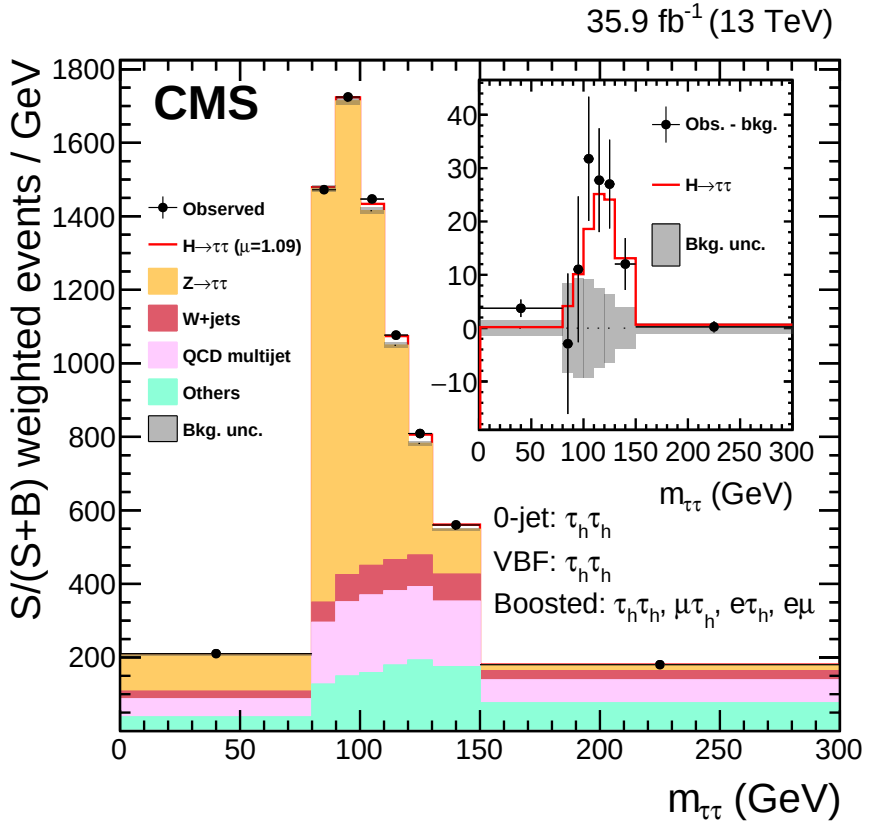


Observation of $H \to \tau\tau$ decays

HIG-16-043, Phys. Lett. B 779 (2018) 283

- $\tau\tau$ channels: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$
- 3 categories: 0-jet, VBF, boosted
- bkgs data-driven (QCD multi-jet), or from MC+CR-corrections ($Z \to \tau\tau$)
- combined fit to $m_{\tau\tau}$ (or m_{vis})
  - VBF (boosted): 2D fit in m_{jj} ($p_T^{\tau\tau}$) bins
- excess of events in data around 125 GeV

best-fit $\mu = 1.09^{+0.27}_{-0.26}$ (Run 2)



Obs (Exp) $H \to \tau\tau$ significance

Run-2	4.9σ (4.7σ)

Observation of $H \to \tau\tau$ decays

HIG-16-043, Phys. Lett. B 779 (2018) 283

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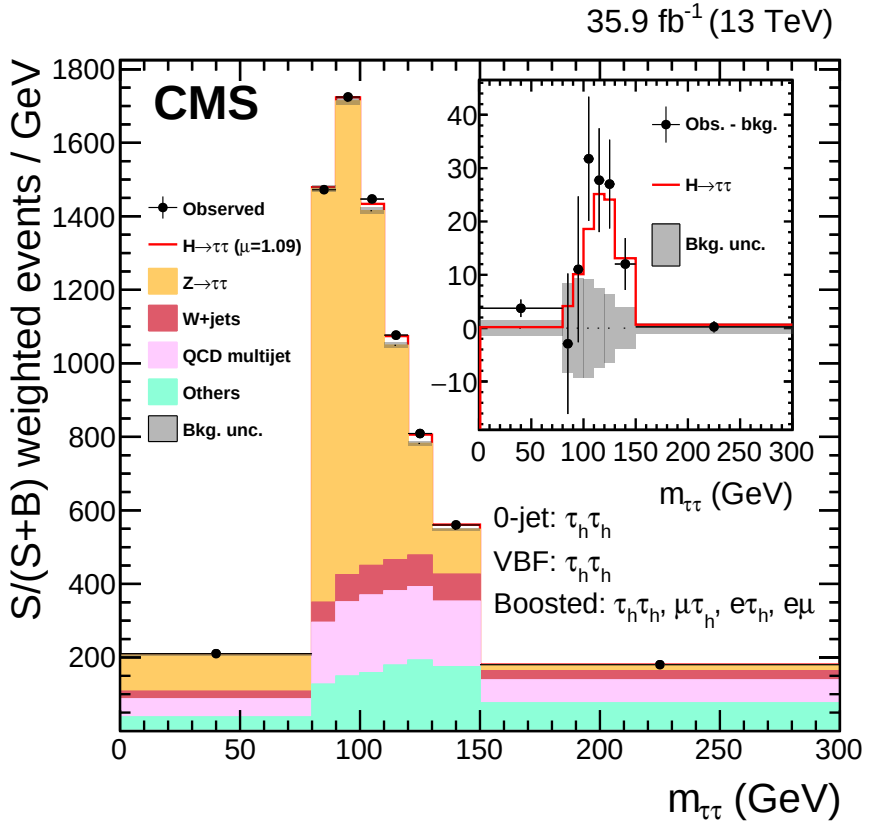
  - VBF (boosted): 2D fit in m_{jj} ($p_T^{\tau\tau}$) bins
- excess of events in data around 125 GeV

best-fit $\mu = 0.98^{+0.18}_{-0.18}$ (Run 1+2)

$\Longrightarrow$ Observation of $H \to \tau\tau$



Obs (Exp) $H \to \tau\tau$ significance

Run-2	4.9σ (4.7σ)
Run-1 + Run-2	5.9σ (5.9σ)

NEW Search for $VH(\to \tau\tau)$ with $V \to \ell\nu,\ \ell\ell$

PAS-HIG-18-007

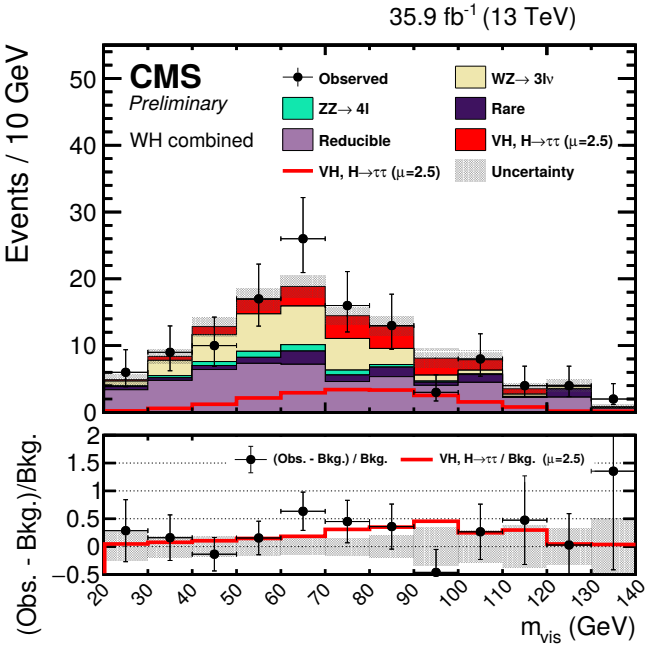
WH channels: $e^{\pm}\mu^{\pm}\tau_h,\ \mu^{\pm}\mu^{\pm}\tau_h,\ e\tau_h\tau_h,\ \mu\tau_h\tau_h$

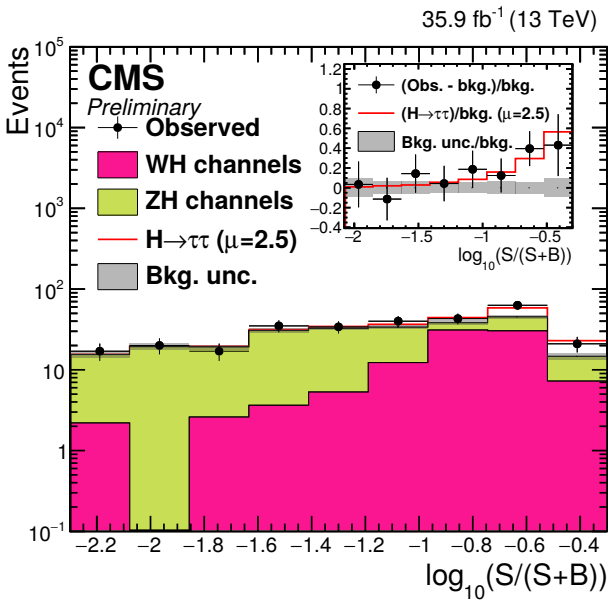
ZH channels: $(ee, \mu\mu) \times (e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h)$

- SM backgrounds:
  - irreducible WZ, ZZ bkgs from simulation
  - jet $\to e, \mu, \tau_h$ fake-rate ($t\bar{t}$, DY) data-driven
- combined fit to $m_{\tau\tau}$ (ZH) and m_{vis} (WH)
  - main syst: lepton eff., reducible bkgs

Obs. (Exp.) significance: 2.3σ (1.0σ)

Best-fit $\mu = 2.54^{+1.35}_{-1.26}$ (Run-2, VH)





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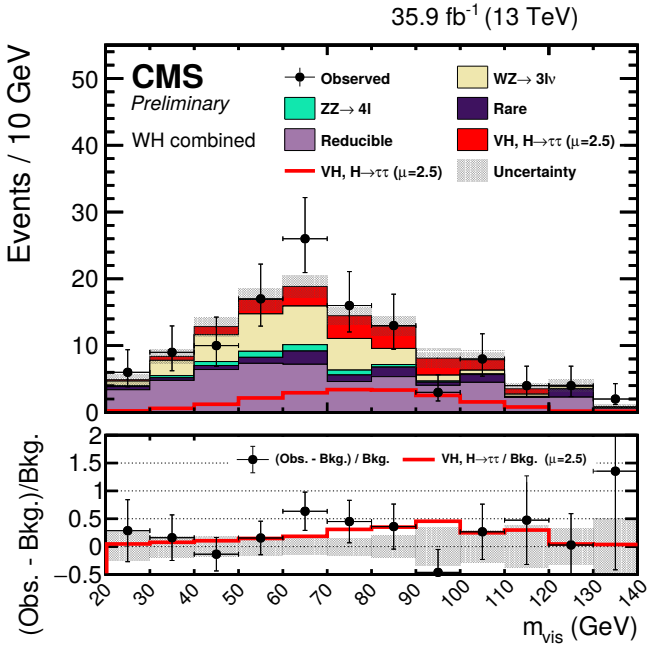
WH channels: $e^{\pm}\mu^{\pm}\tau_h,\ \mu^{\pm}\mu^{\pm}\tau_h,\ e\tau_h\tau_h,\ \mu\tau_h\tau_h$

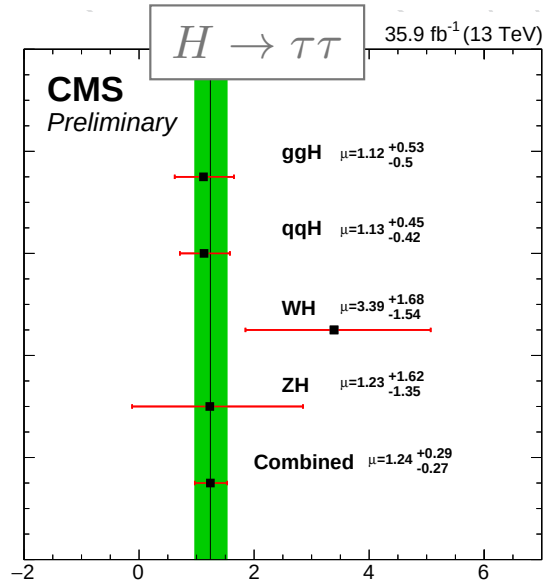
ZH channels: $(ee, \mu\mu) \times (e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h)$

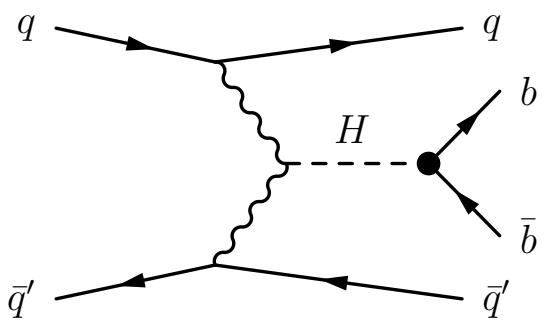
- SM backgrounds:
  - irreducible WZ, ZZ bkgs from simulation
  - jet $\to e, \mu, \tau_h$ fake-rate ($t\bar{t}$, DY) data-driven
- combined fit to $m_{\tau\tau}$ (ZH) and m_{vis} (WH)
  - main syst: lepton eff., reducible bkgs

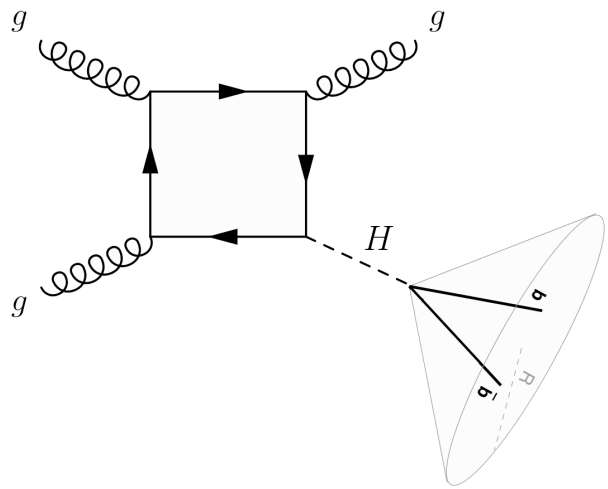
➤ combined with Run-2 $H \to \tau\tau$:

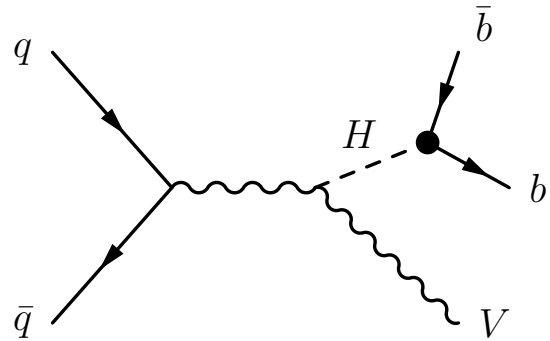
Best-fit $\mu = 1.24^{+0.29}_{-0.27}$ (Run-2, ggF+VBF+VH)









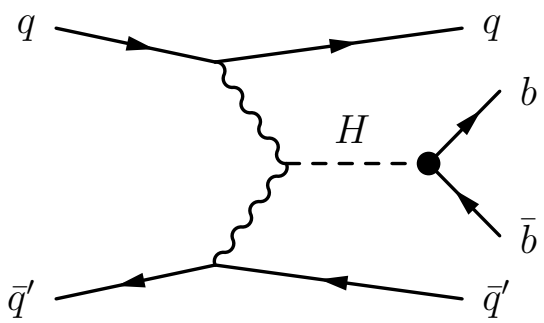


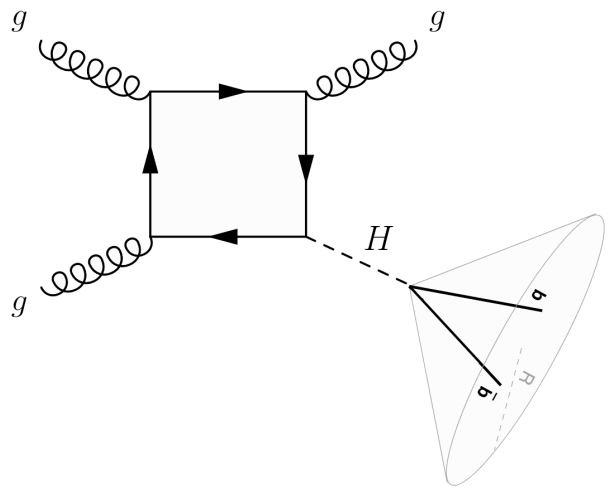
Higgs coupling to the bottom quark

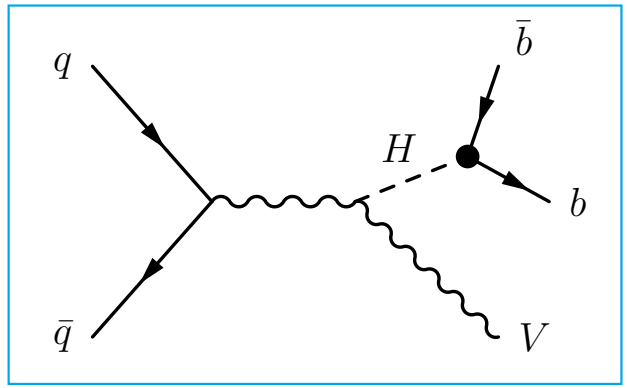
PAS-HIG-16-003 search for $H \to b\bar{b}$ in VBF production

HIG-17-010 search for boosted $gg \to H \to b\bar{b}$

HIG-16-044 evidence of $VH(\to b\bar{b})$







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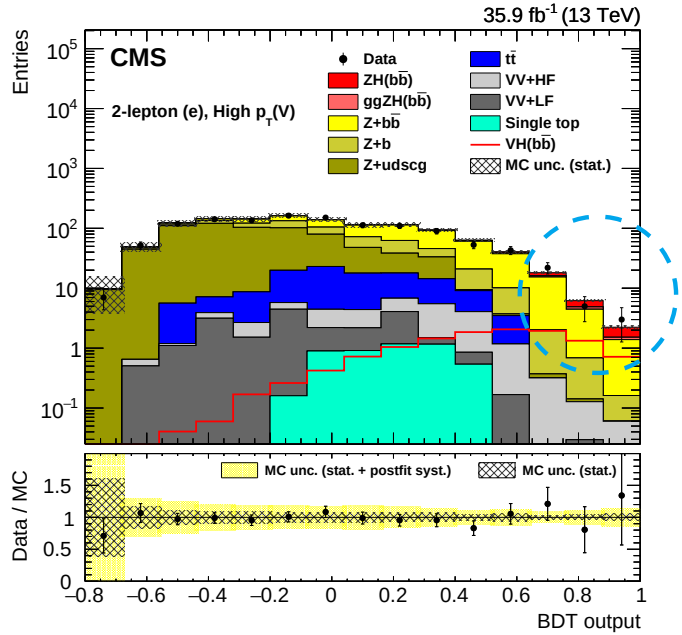
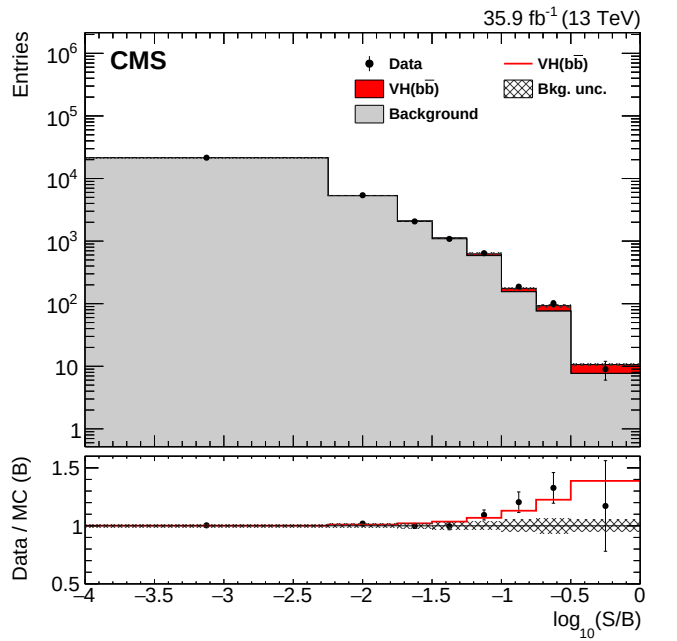
Evidence of $VH(\to b\bar{b})$ production

HIG-16-044, Phys. Lett. B 780 (2018) 501

- $H(b\bar{b})$ in association with W, Z boson
  - leptonic V decays: 0ℓ ($\nu\nu$), 1ℓ ($\ell\nu$), 2ℓ ($\ell\ell$)
  - main bkgs: V + light-f, V + heavy-f, $t\bar{t}$
  - high-$p_T(V)$ cut to suppress bkgs
- combined fit to BDT discriminators in SRs + dedicated CRs for DY and $t\bar{t}$
  - bkgs from MC with free-floating norm.
  - main syst: V + lf/hf norm., MC modeling

Data used	Significance expected	Significance observed	Signal strength observed
Run 1	2.5	2.1	$0.89^{+0.44}_{-0.42}$
Run 2	2.8	3.3	$1.19^{+0.40}_{-0.38}$
Combined	3.8	3.8	$1.06^{+0.31}_{-0.29}$





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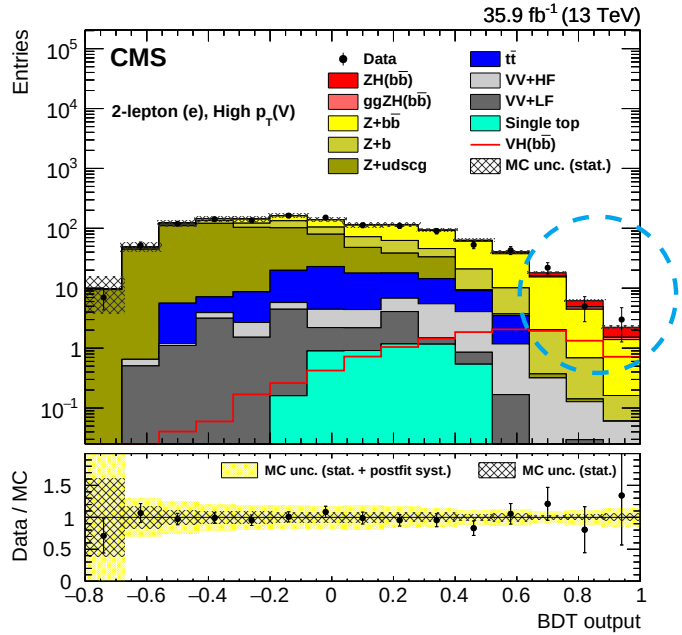

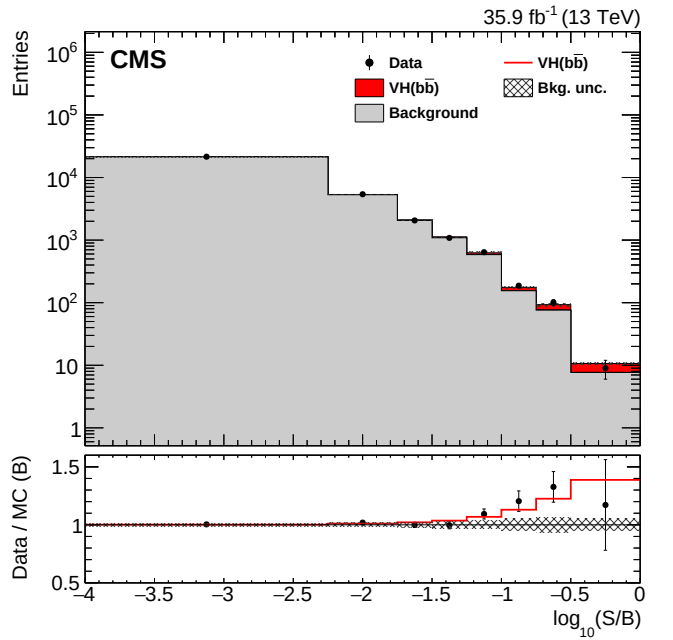

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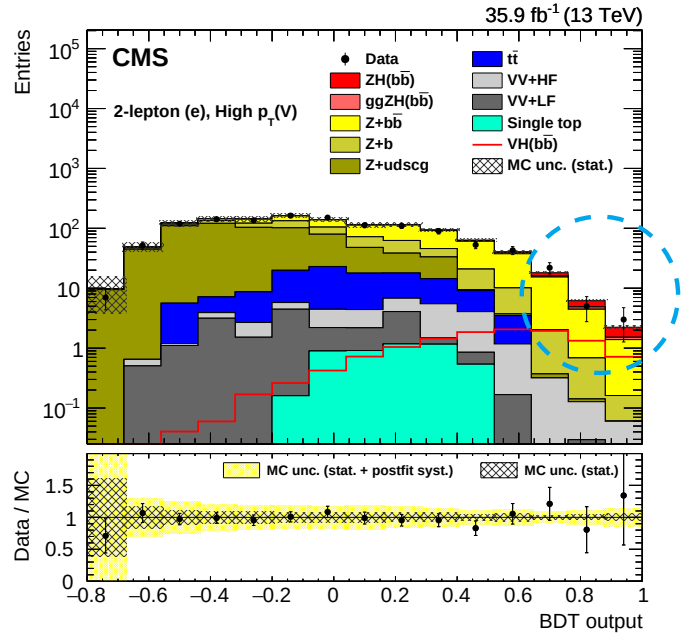
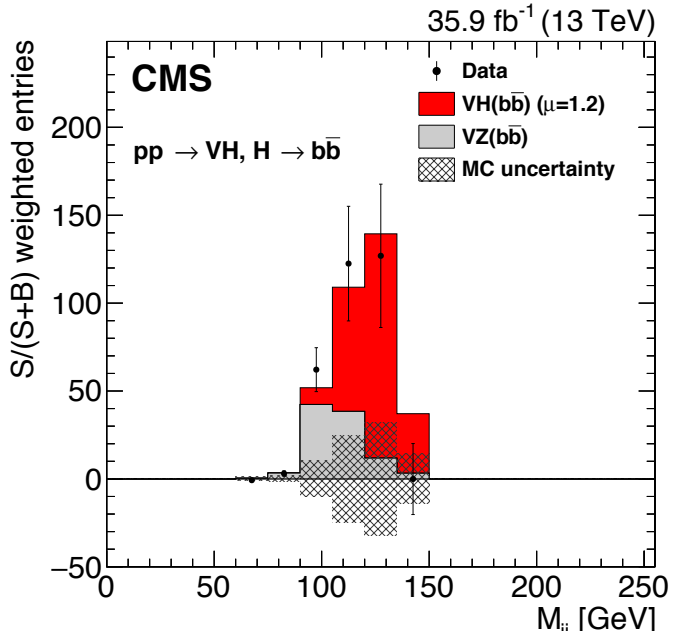
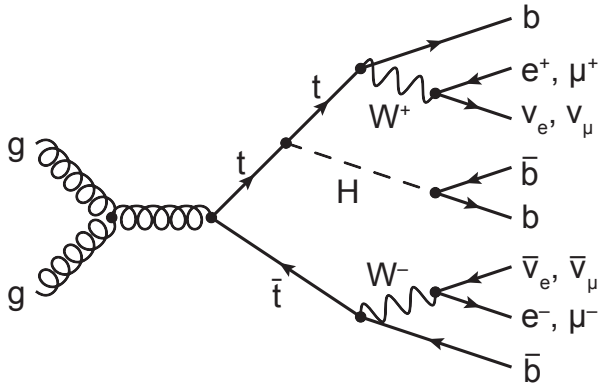
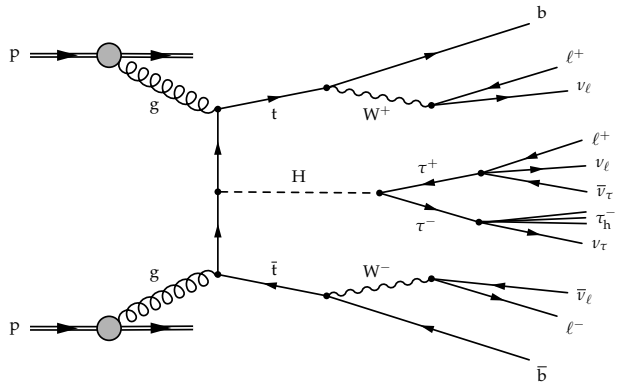
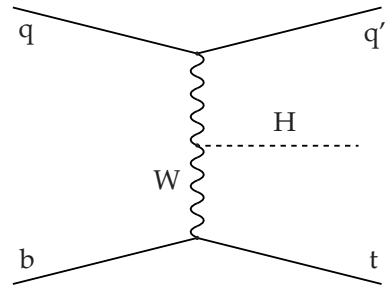










Higgs coupling to the top quark

PAS-HIG-17-005 search for tH in multilepton final states

PAS-HIG-17-016 NEW search for tH with $H \to b\bar{b}$

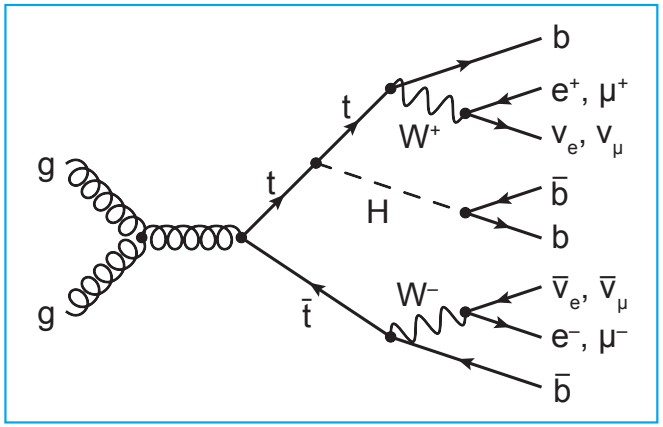
HIG-17-018 evidence of $t\bar{t}H$ in multilepton final states

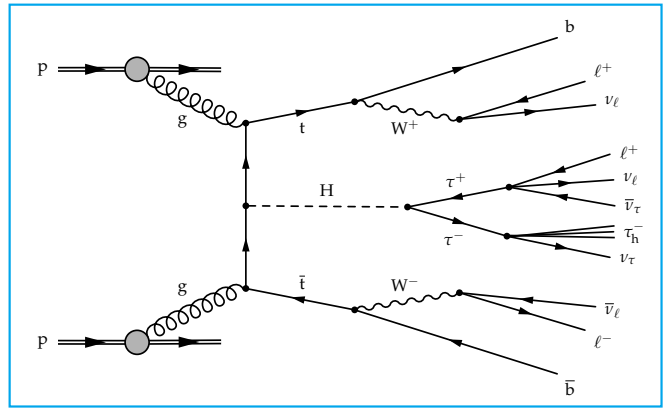
HIG-17-026 search for $t\bar{t}H(\to b\bar{b})$ with leptonic top decays

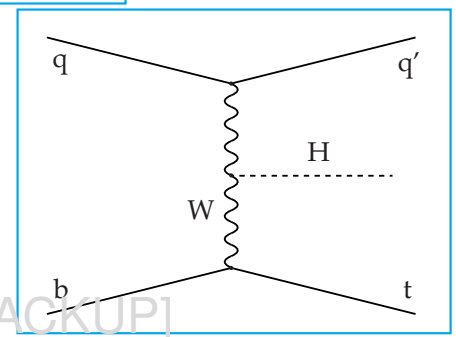
HIG-17-022 search for $t\bar{t}H(\to b\bar{b})$ in all-jet final states

HIG-17-035 combination of $t\bar{t}H$ searches at CMS

see talk by D. Salerno







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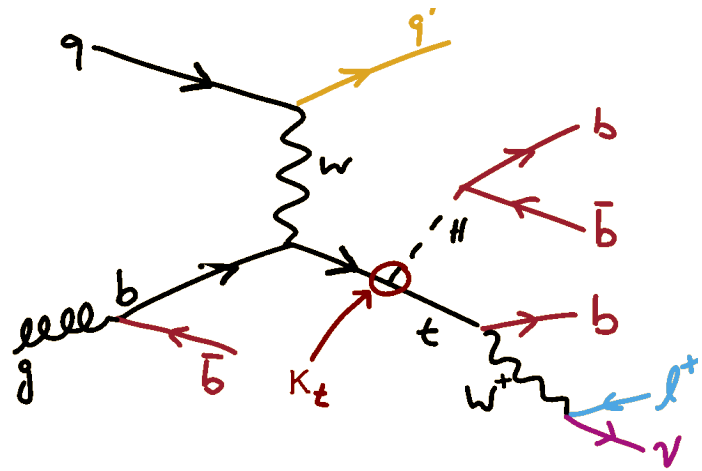
HIG-17-035 combination of $t\bar{t}H$ searches at CMS

see talk by D. Salerno

NEW Search for tHq and tHW with $H \to b\bar{b}$

PAS-HIG-17-016



- tH sensitive to sign of top-Higgs coupling

  1ℓ + MET + $\geqslant 3$ b-jets + 1 forward-jet

- BDT for jet-parton assignment under tHq, tHW and $t\bar{t}$ hypotheses

- BDTs as final discriminators:

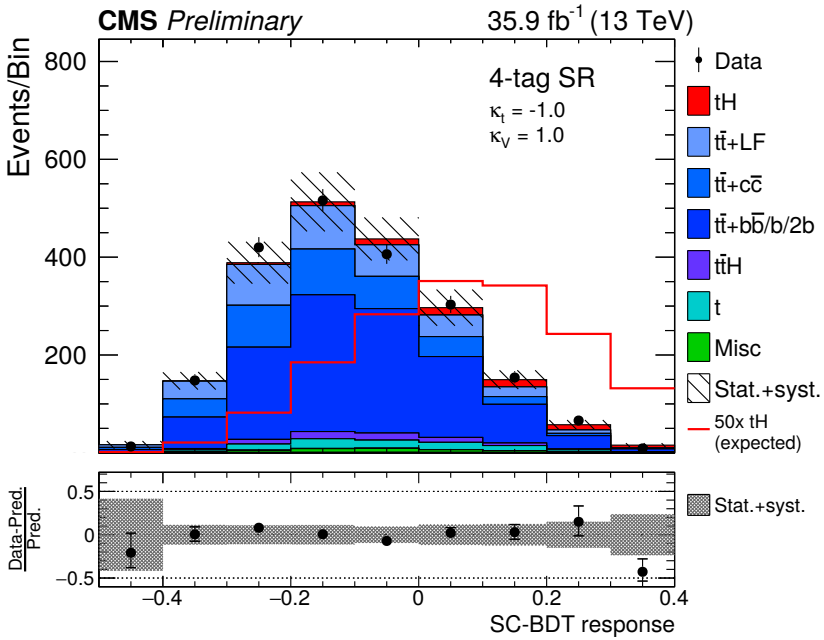
  3b and **4b** SRs tH vs. $t\bar{t}$

  2ℓ category $t\bar{t}+$ light vs. $t\bar{t}+$ hf

- main sys: $t\bar{t}+$ hf modeling, b-tagging eff.

- limits on $\mu_{tH(+t\bar{t}H)}$ as func. of κ_t and κ_V

tH-only $[\kappa_t = +1]$	$\mu_{95\%} < 89.5\,(41.4)$ obs. (exp.)
tH-only $[\kappa_t = -1]$	$\mu_{95\%} < 5.83\,(2.94)$ obs. (exp.)



Search for $t\bar{t}H(\to b\bar{b})$ with leptonic top decays

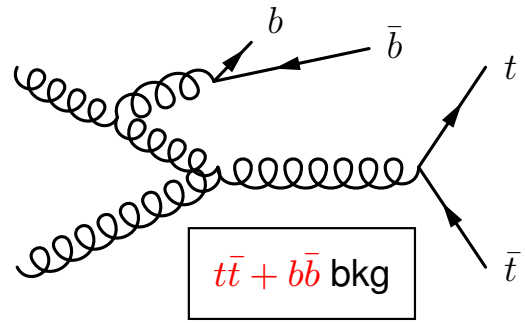
HIG-17-026, submitted to JHEP

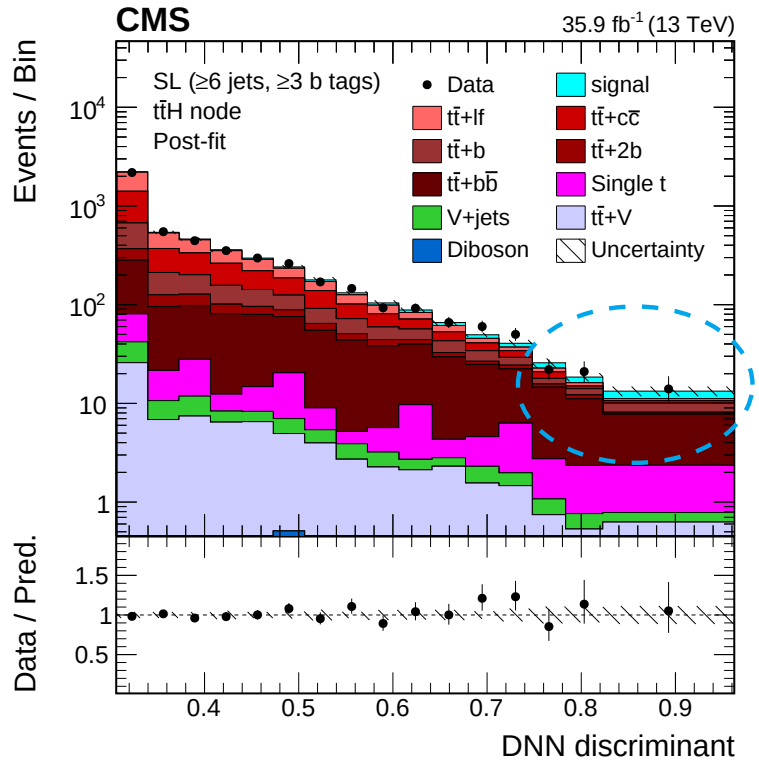
- $(1\ell$ or $\ell^{\pm}\ell^{\mp}) + \geq 4$ jets and ≥ 3 b-jets
- dominant bkg: $t\bar{t}$ (+ heavy flavor: $c\bar{c}$, b, $b\bar{b}$)
  - bkgs from simulation with large prior unc.
- jet combinatorics hinders $H \to b\bar{b}$ reco

  $\Longrightarrow$ MVA methods for final discriminant

  ℓ + jets: multi-class Deep Neural Network

  dilepton: (BDT, MEM) 2D dist.
- main sys: $t\bar{t}$ + hf modeling, b-tagging eff.





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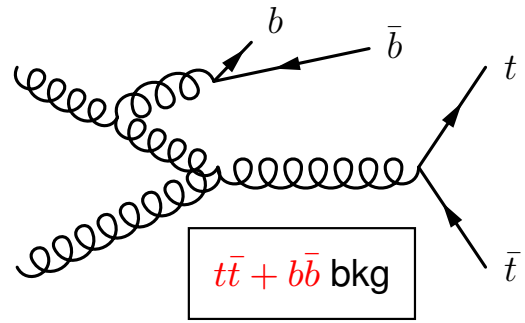

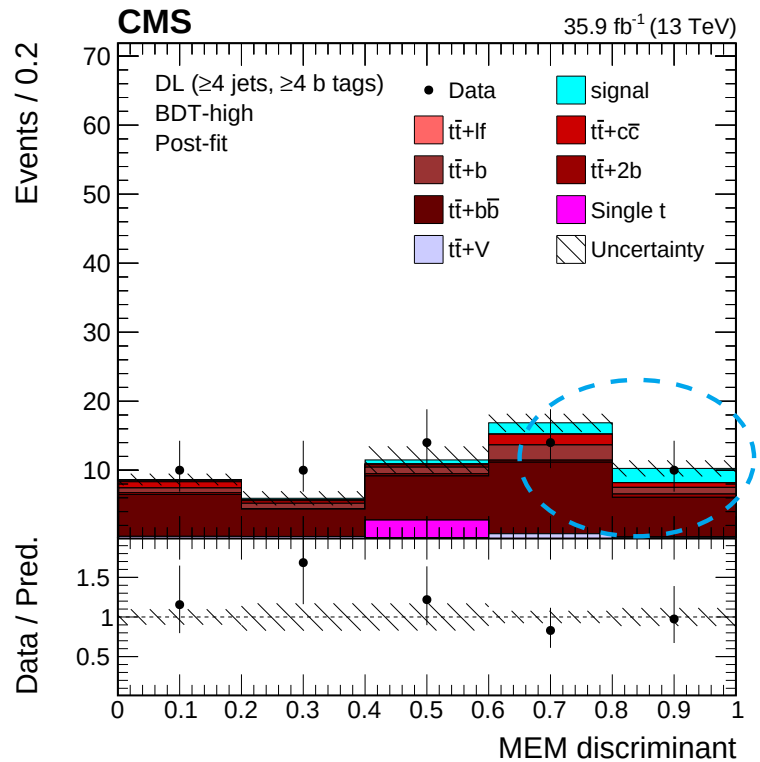

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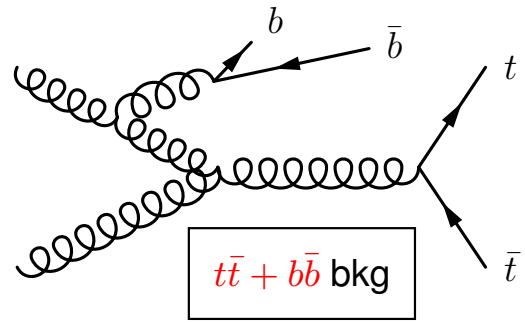
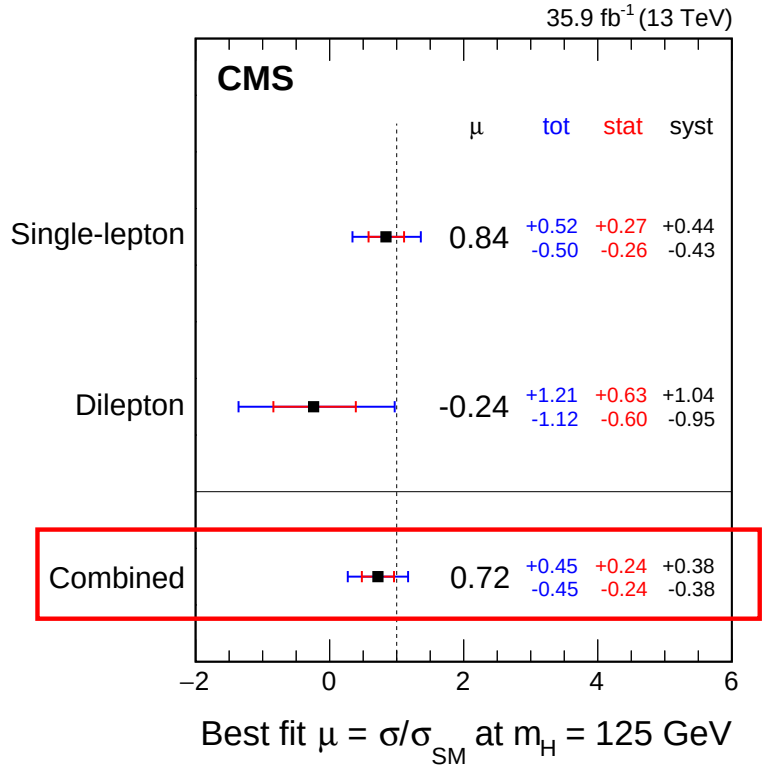
Obs. (Exp.) significance: 1.6σ (2.2σ)





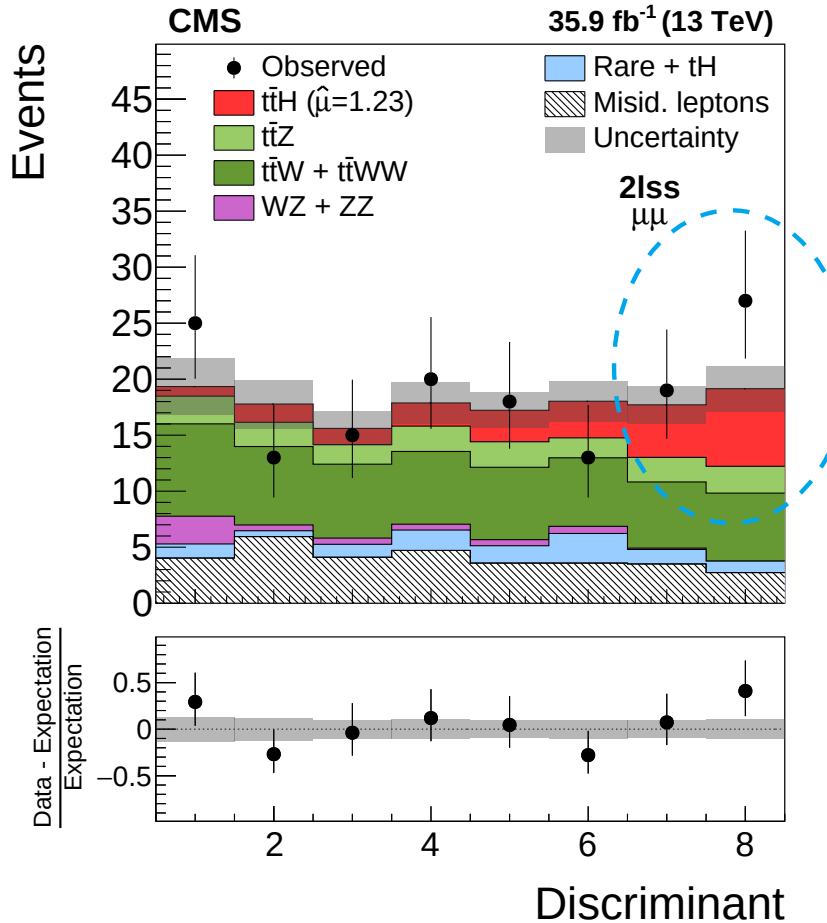
Evidence of $t\bar{t}H$ in multilepton final states

HIG-17-018, submitted to JHEP

- targets H decays to WW^*, ZZ^*, $\tau\tau$

$1\ell{+}2\tau_{\mathrm{h}}$	2ℓ SS $(+\tau_{\mathrm{h}})$	$3\ell(+\tau_{\mathrm{h}})$	4ℓ

- extensive use of MVA techniques:
  - lepton-ID, final discriminants (BDT, MEM)
- bkgs: $t\bar{t}V$, VV (MC+CR), fake-ℓ (data-dr.)
- main systematics: lepton ε, fake-ℓ bkg



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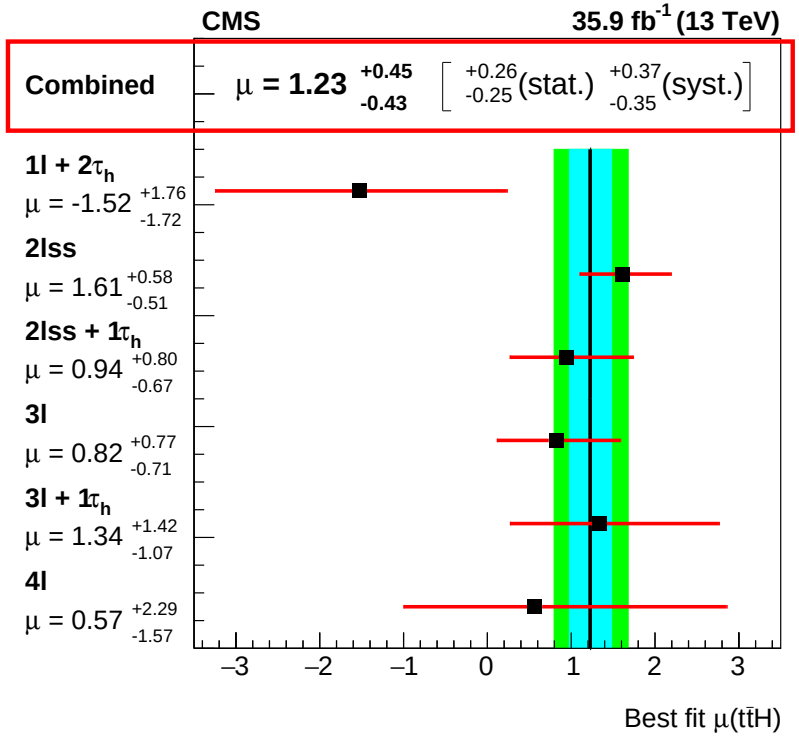
Obs. (Exp.) significance: 3.2σ (2.8σ)

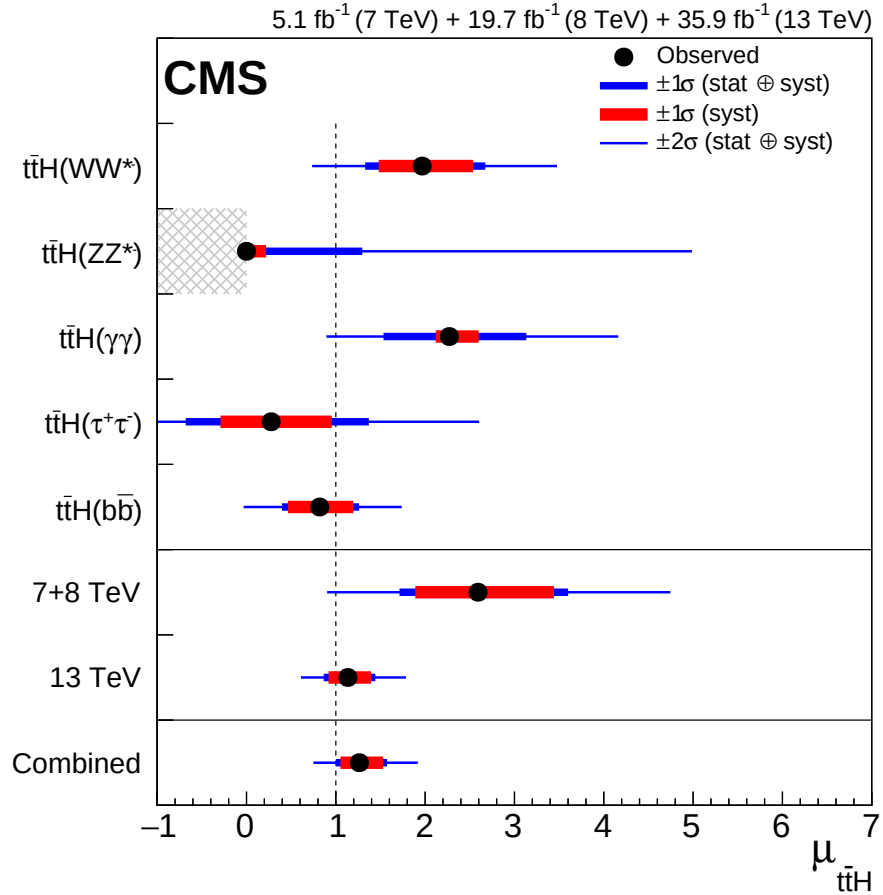
$\Longrightarrow$ Evidence of $t\bar{t}H \rightarrow$ multilepton



First LHC $t\bar{t}H$ observation

HIG-17-035, accepted by PRL

- CMS combination of all $t\bar{t}H$ searches in Run-1 and Run-2
  - multilepton and $b\bar{b}$: $\Delta\mu^{\text{syst}} > \Delta\mu^{\text{stat}}$
  - $\gamma\gamma$ and ZZ^*: limited by stats



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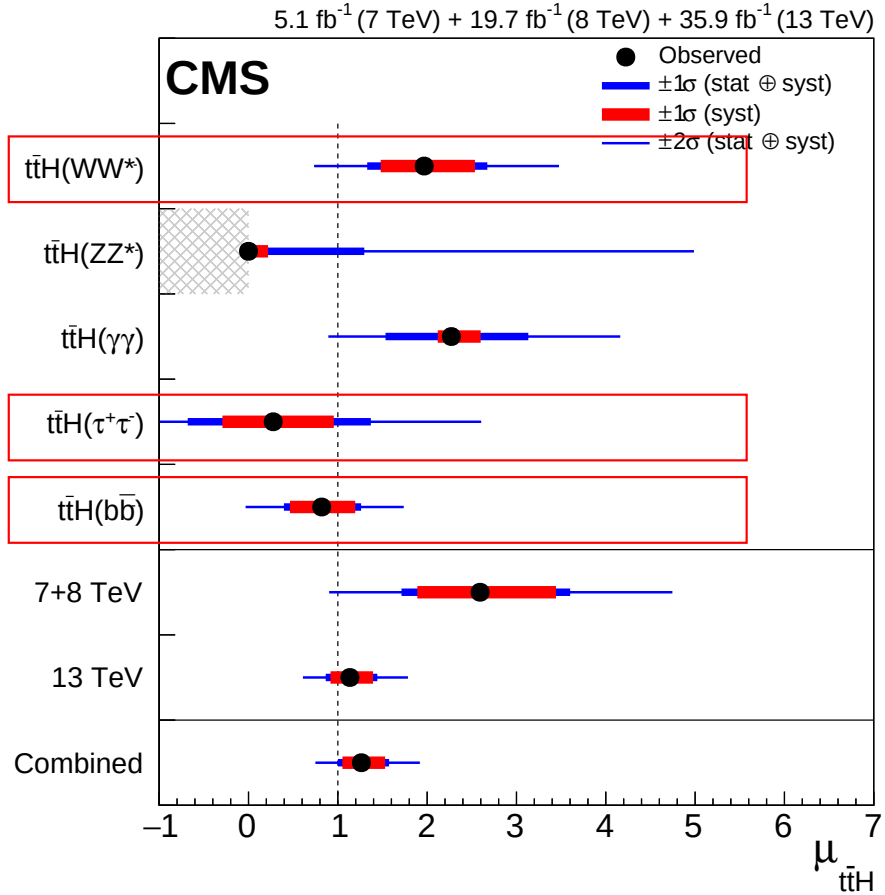

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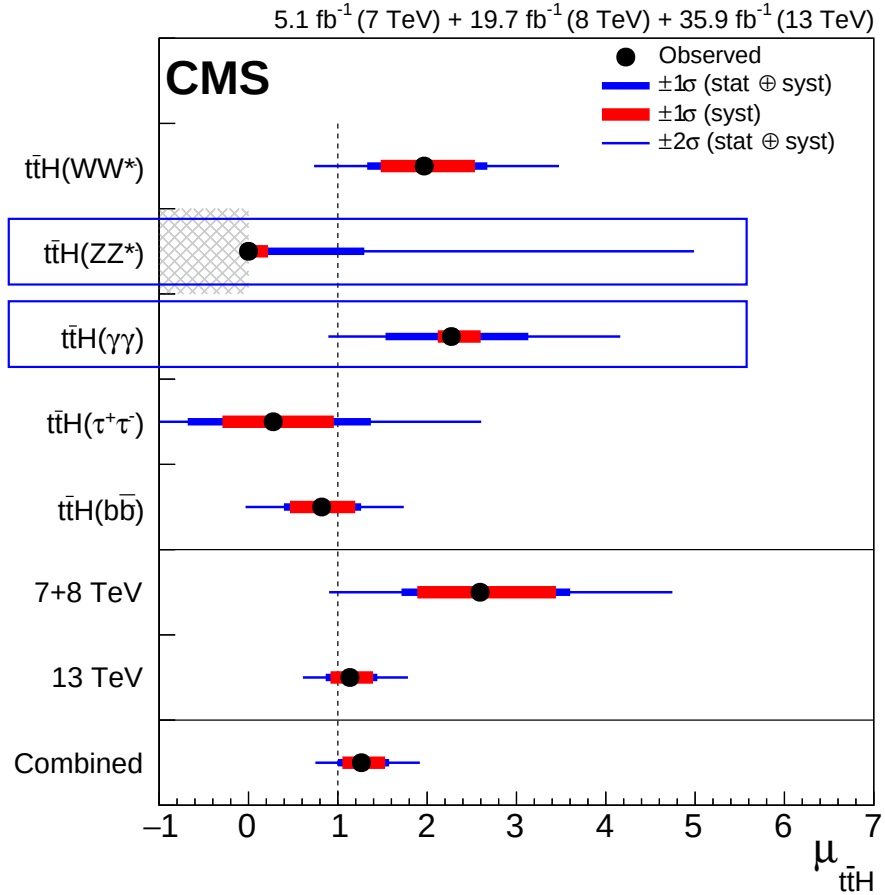

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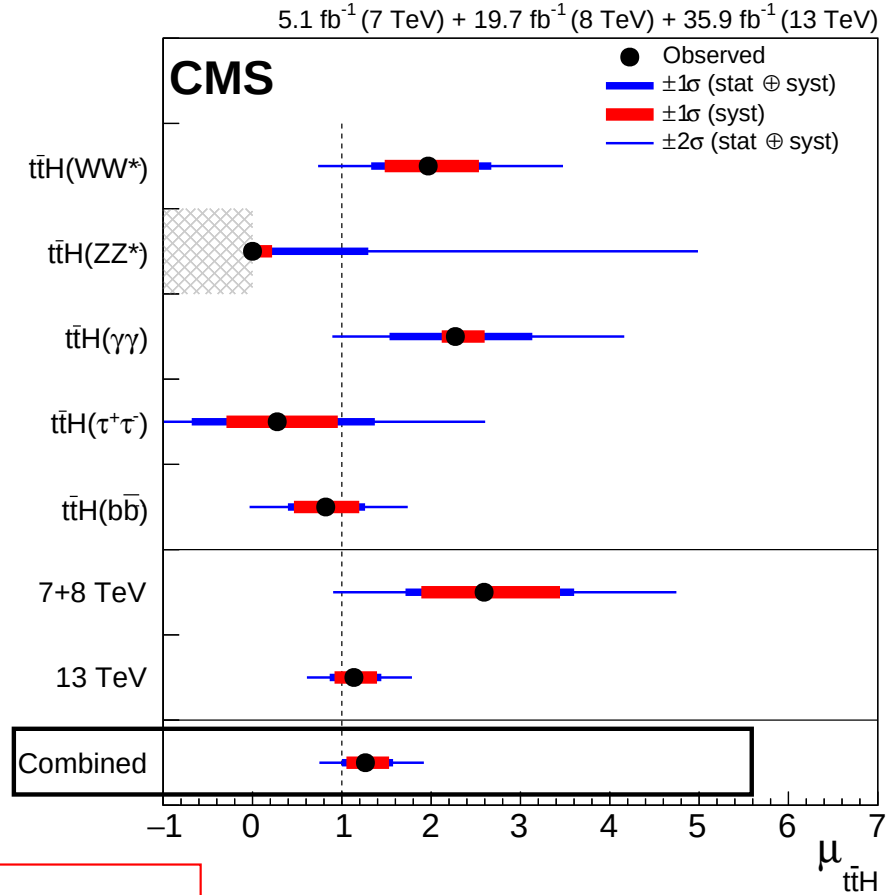
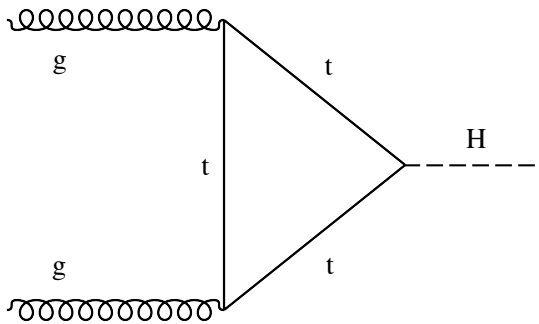
Parameter	Best fit	Uncertainty Stat	Expt	Thbgd	Thsig
$\mu_{\text{t}\bar{\text{t}}\text{H}}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.15}_{-0.15}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.15}_{-0.07}$ $\left(^{+0.11}_{-0.05}\right)$

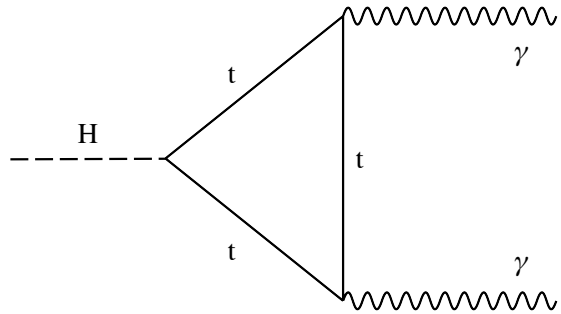
Obs. (Exp.) significance: 5.2σ (4.2σ)

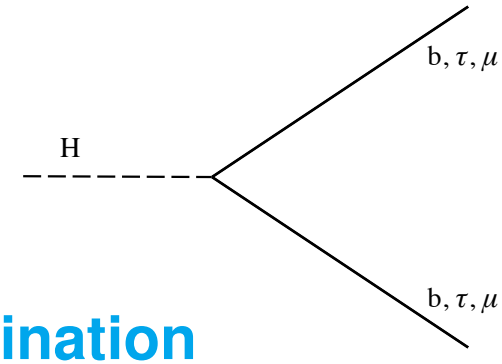


- observation of $t\bar{t}H$ production
- $\mu_{t\bar{t}H}$ in agreement with SM

$\Delta\mu_{t\bar{t}H} \sim 23\%$







A look at Yukawa couplings in Higgs combination

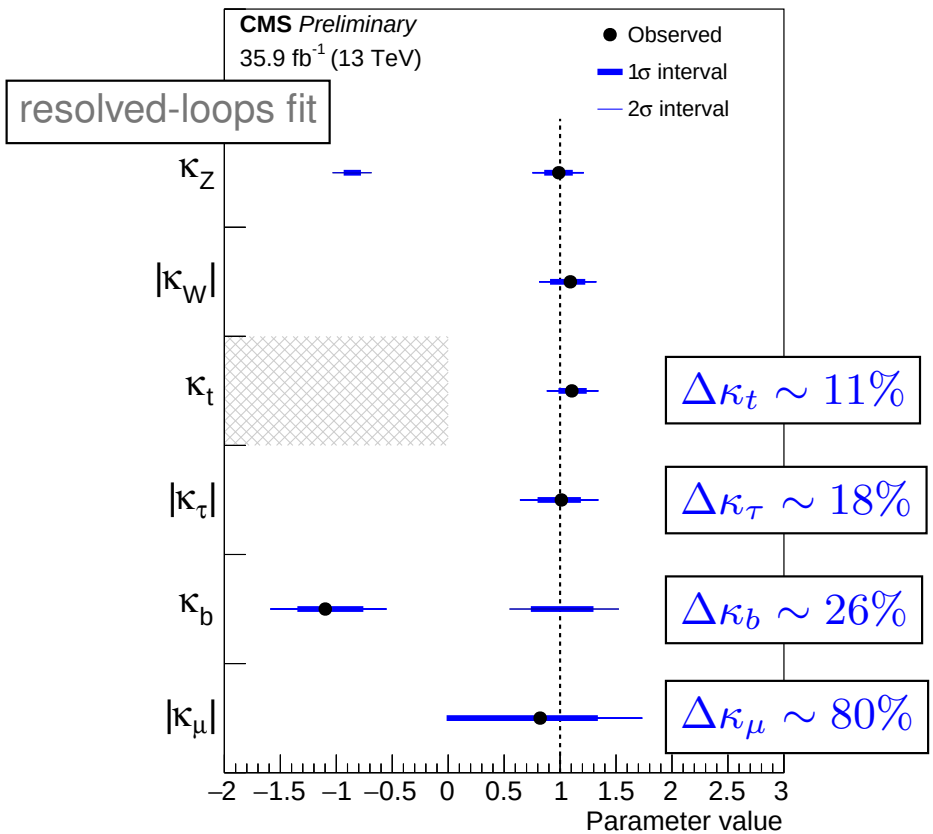
PAS-HIG-17-031 Combined measurements of Higgs boson couplings in pp collisions at $\sqrt{s} = 13$ TeV

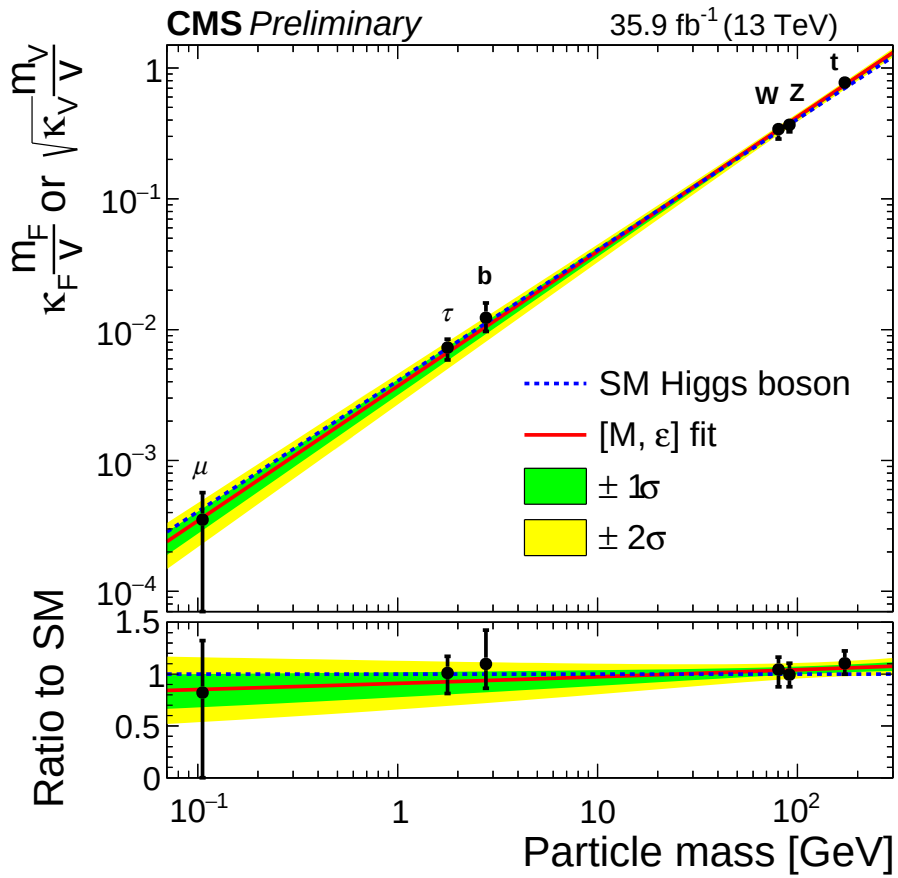
see talk by T. Strebler

Yukawa couplings in combined Higgs analyses

PAS-HIG-17-031

- combined measurements of Higgs boson couplings with Run-2 data
- showing only fit assuming SM expr. for ggF and $H(\gamma\gamma)$ loops
- focus on Higgs-fermion couplings



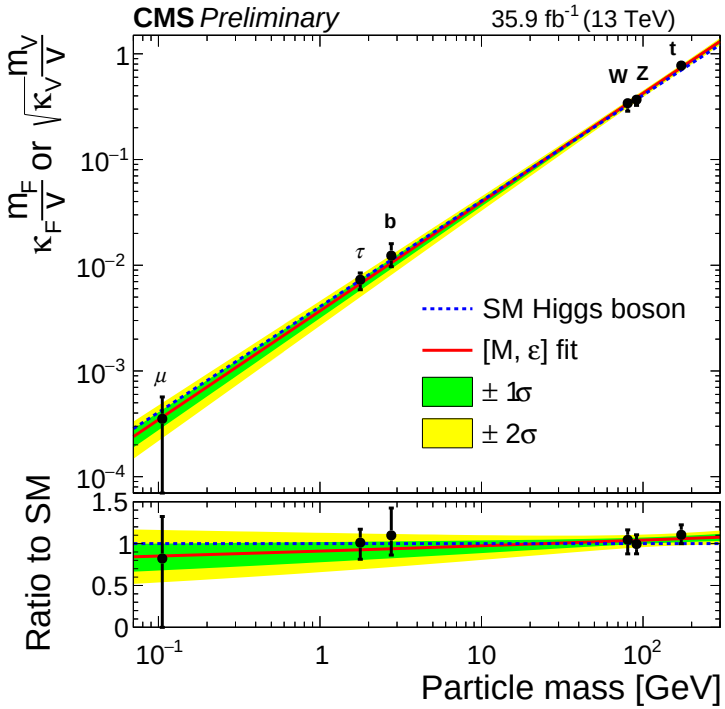


Summary

- measurements of Higgs Yukawa couplings crucial test of the SM

- wide range of results produced by CMS:
  - best upper limit on $\sigma(H \to \mu\mu)$
  - observation of $H \to \tau\tau$
  - evidence of $VH(\to b\bar{b})$
  - observation of $t\bar{t}H$ production

- no significant deviations from SM



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- already looking at **2017** data (e.g. HIG-18-001) and **2018** data-taking underway
- new and updated results to be expected in the months ahead

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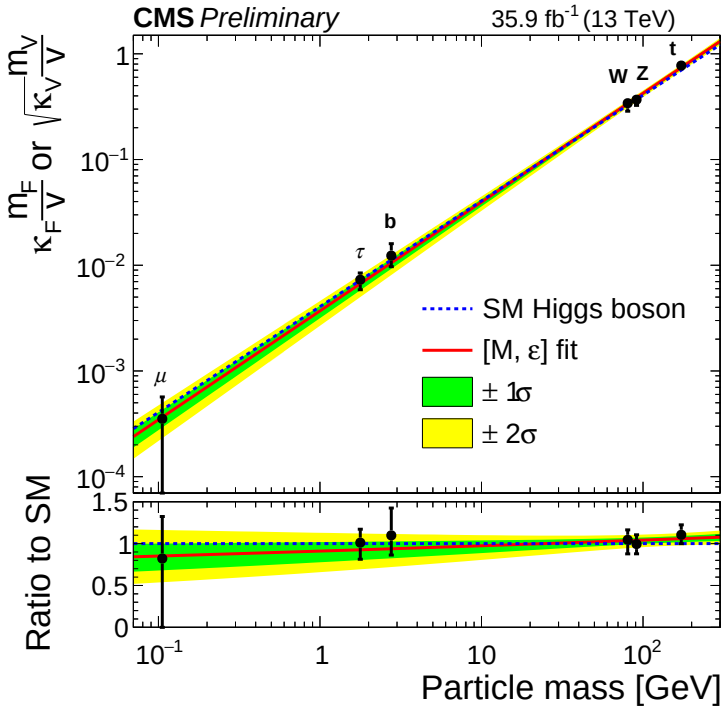

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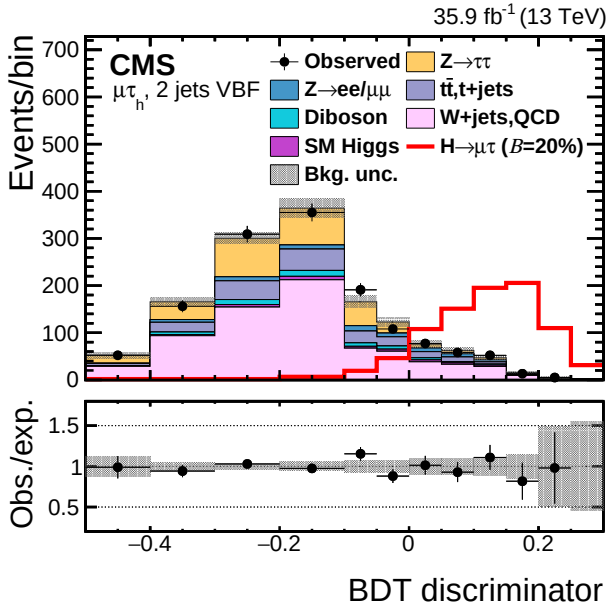
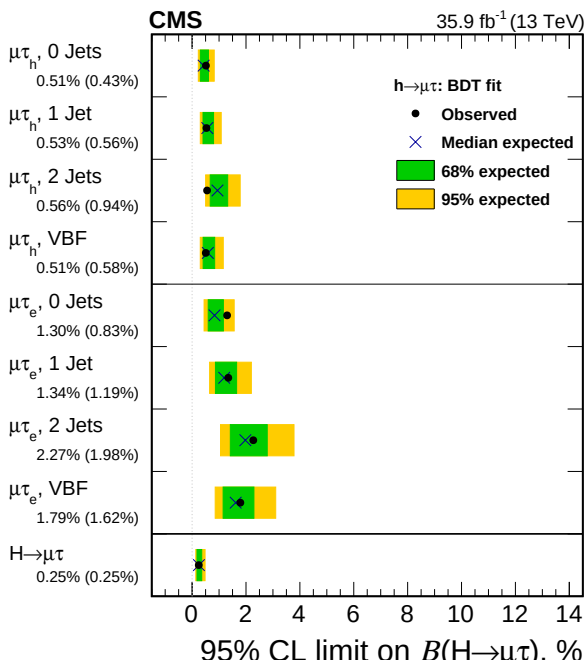
BACKUP

Search for lepton-flavor violating $H \to \ell\tau$ decays

HIG-17-001, accepted by JHEP

- off-diagonal Yukawa couplings
  expected to be zero in SM
- 4 channels: $e\tau_\mu$, $e\tau_\mathrm{h}$, $\mu\tau_e$, $\mu\tau_\mathrm{h}$
- DY from MC, W and multi-jet data-driven
- BDT discriminant for final fit to data
  - sensitivity limited by systematics
- no significant excess observed
- Obs (Exp) 95% CL limit on $\mathrm{BR}_{\ell\tau}$:
  - $\mathrm{BR}(H \to \mu\tau) < 0.25\%\,(0.25\%)$
  - $\mathrm{BR}(H \to e\tau) < 0.61\%\,(0.37\%)$



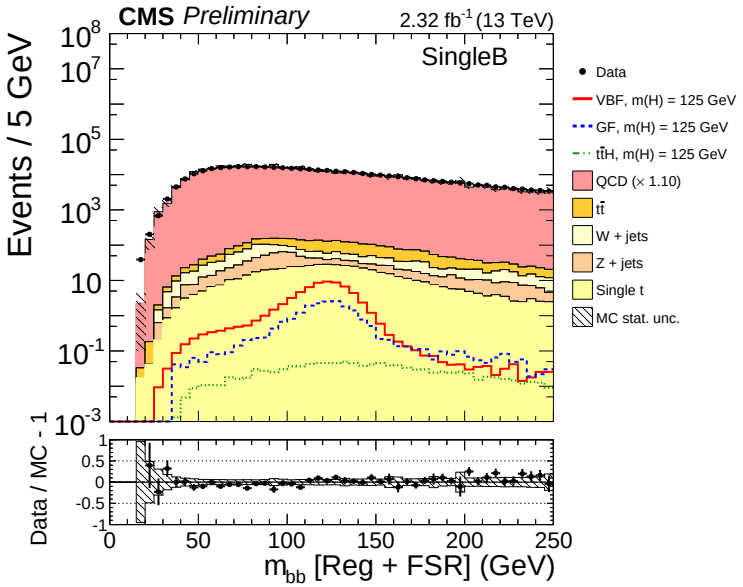


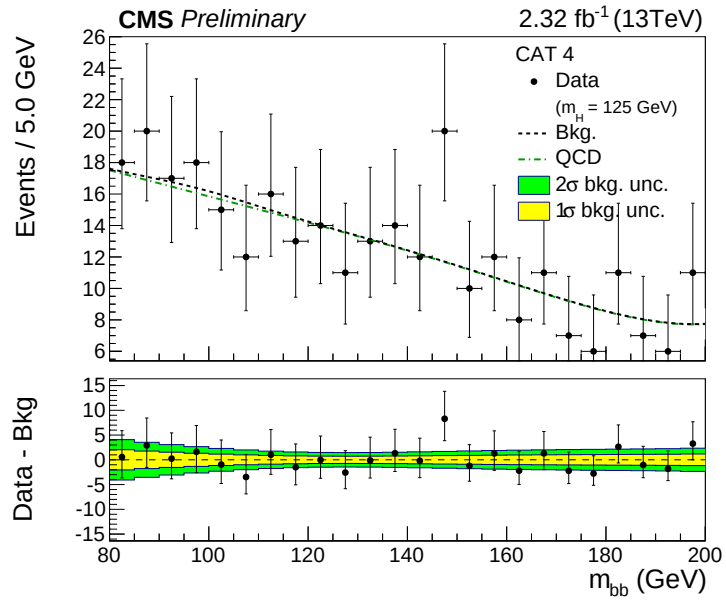
Search for $H \to b\bar{b}$ in VBF production

PAS-HIG-16-003

- events with $\geqslant 4$ jets and $\geqslant 1$ b-jet
- dedicated triggers requiring b-jet(s) and dijet with large $\Delta\eta_{jj}$ and m_{jj}
- b-energy regr. to improve $m_{b\bar{b}}$ resolution
- unbinned fit to $m_{b\bar{b}}$ in 7 SR categories
- sensitivity limited by stats (only $2.3\ \mathrm{fb}^{-1}$)
  - main sys. unc. from QCD bkg modeling
- combined with Run-1 search:

Obs. (Exp.) upper limit: $\mu_{95\%} < 3.4\,(2.3)$

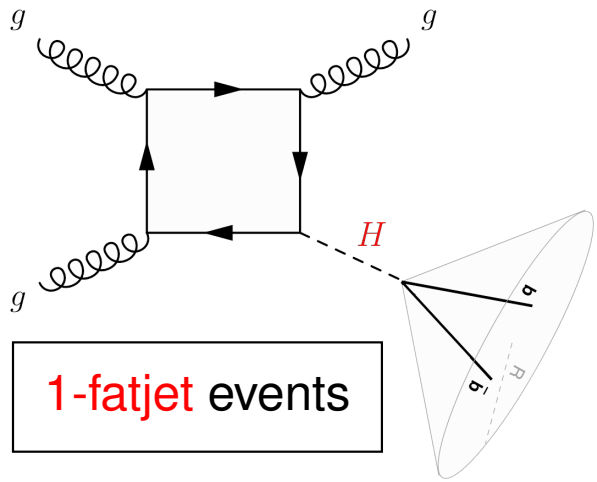




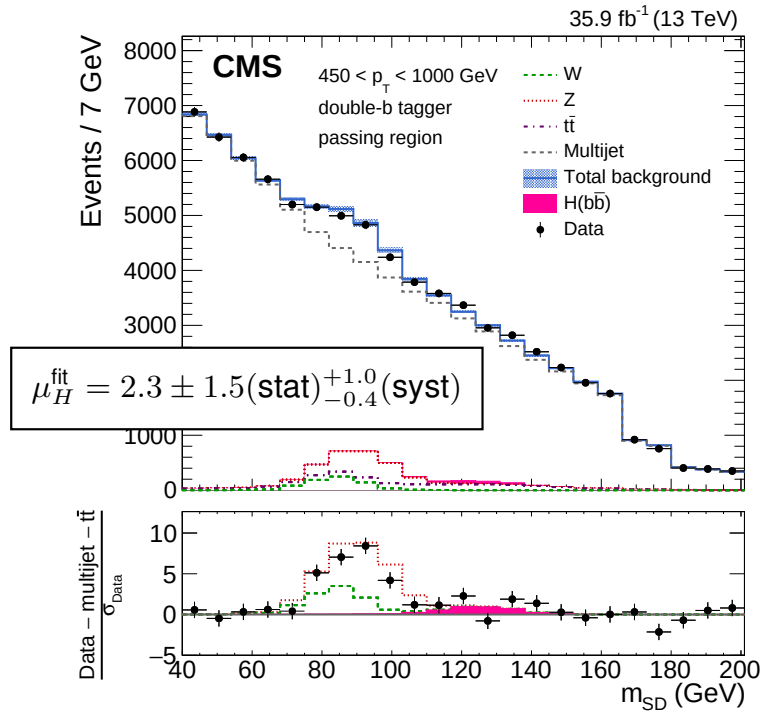
Search for boosted $gg \to H \to b\bar{b}$ production

HIG-17-010, Phys. Rev. Lett. 120 (2018) 071802

- boosted $H(b\bar{b})$ recoiling against ISR jet
- inclusive search for $H \to b\bar{b}$
  made possible at the LHC using
  b-tagging and jet substructure techniques
- search in fatjet mass (6 p_T categories)
  - data-driven method for QCD multi-jet bkg
  - $W/Z \to q\bar{q}$ to constrain jet-related sys



1-fatjet events



Obs. (Exp.) upper limit: $\mu_{95\%} < 5.8\,(3.3)$

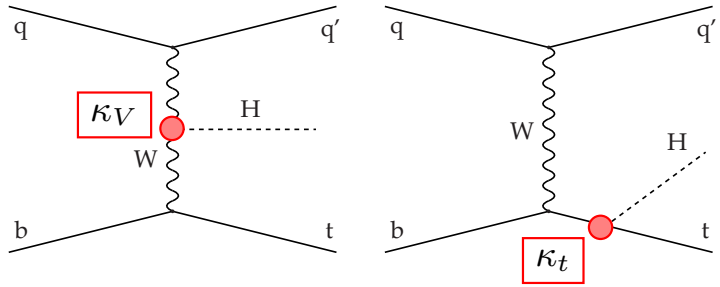
$H(b\bar{b})$ significance: obs. 1.5σ (exp. 0.7σ)

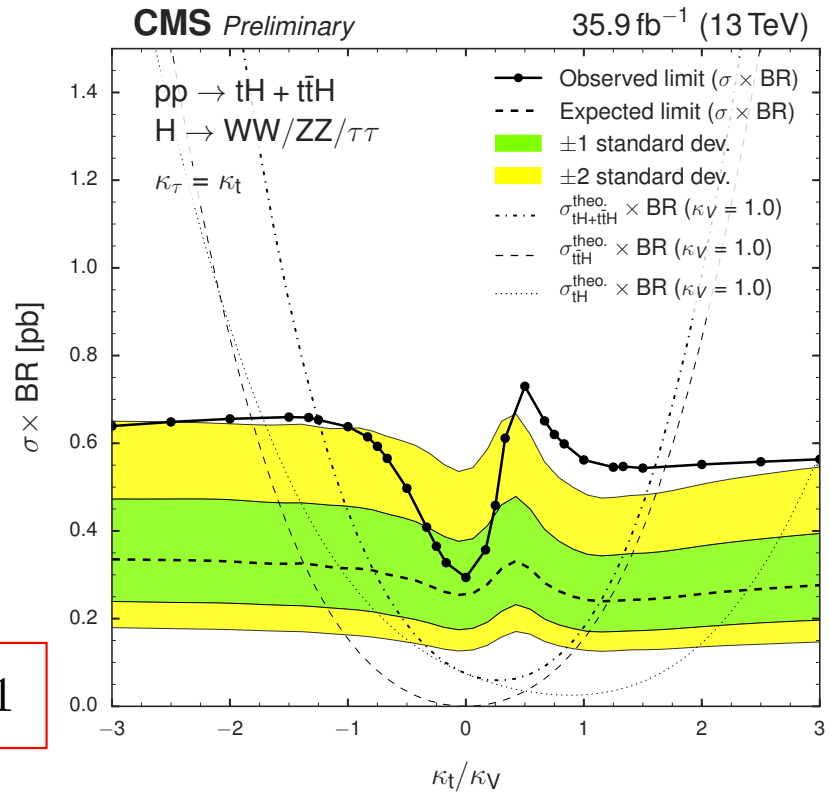
Search for tHq in multilepton final states

PAS-HIG-17-005

- tH sensitive to sign of top-Higgs coupling
- (SS 2ℓ or 3ℓ) + 1 b-jet + 1 forward-jet
- methods similar to $t\bar{t}H$ multilepton
  - lepton ID, bkg modeling, MVA discrim.
- sensitivity limited by systematics
  - lepton eff., bkg normalizations
- limits on $\mu_{tH+t\bar{t}H}$ as func. of κ_t and κ_V

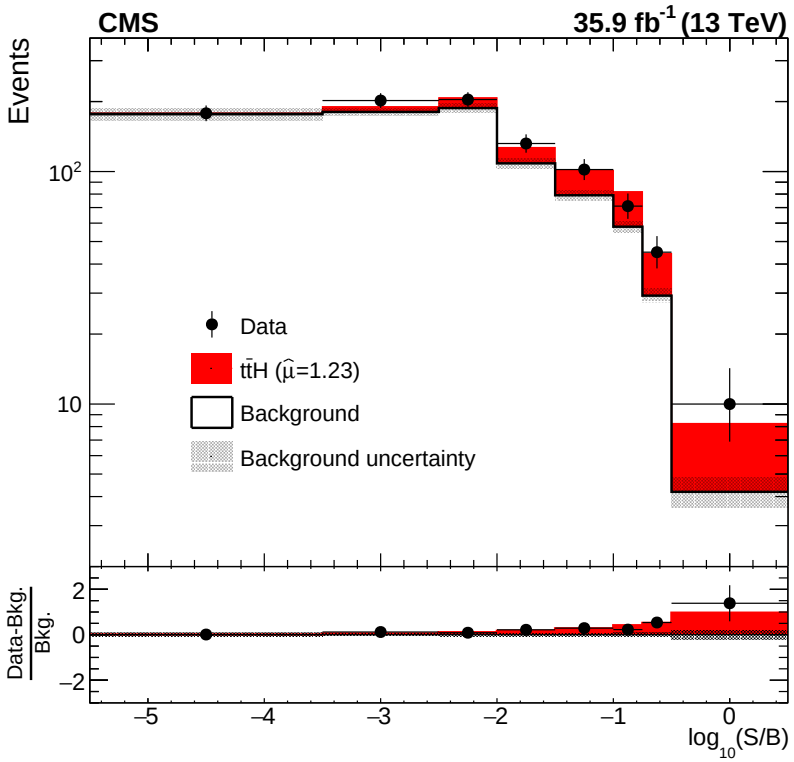
$-1.25 > \kappa_t > 1.6$ excluded at 95% CL for $\kappa_V = 1$

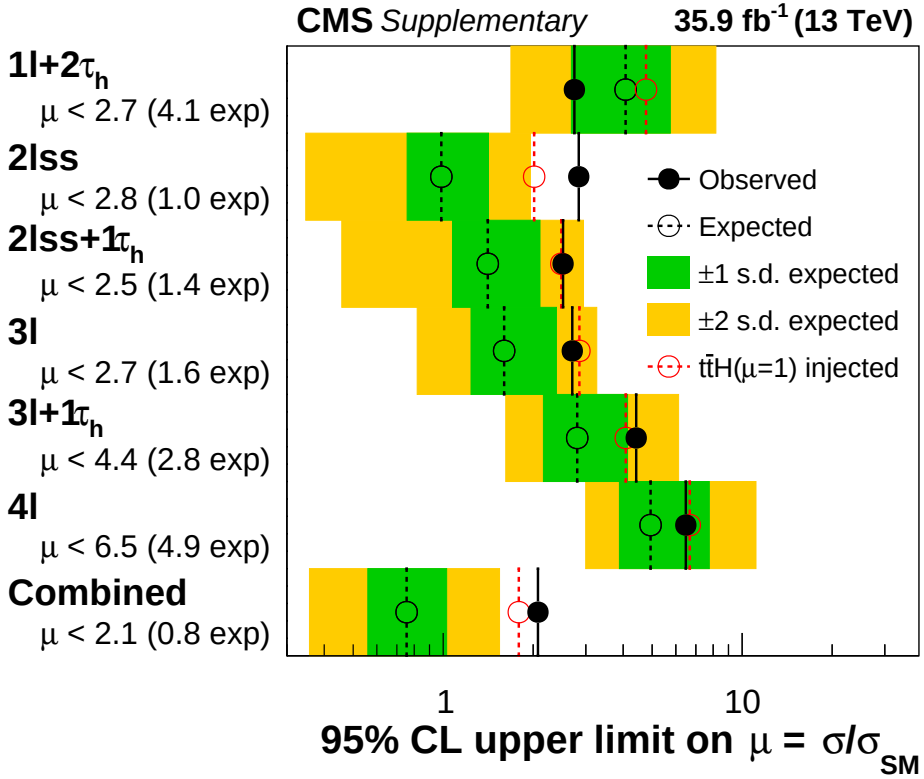




Evidence of $t\bar{t}H$ in multilepton final states

HIG-17-018, submitted to JHEP



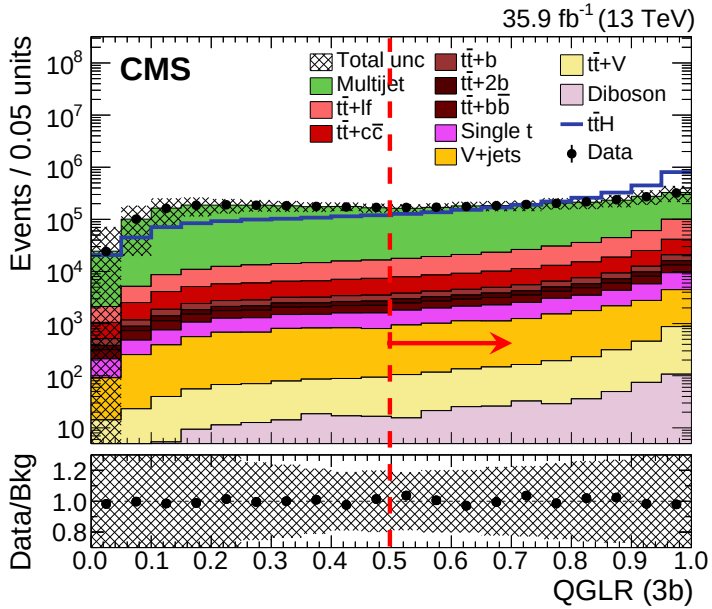


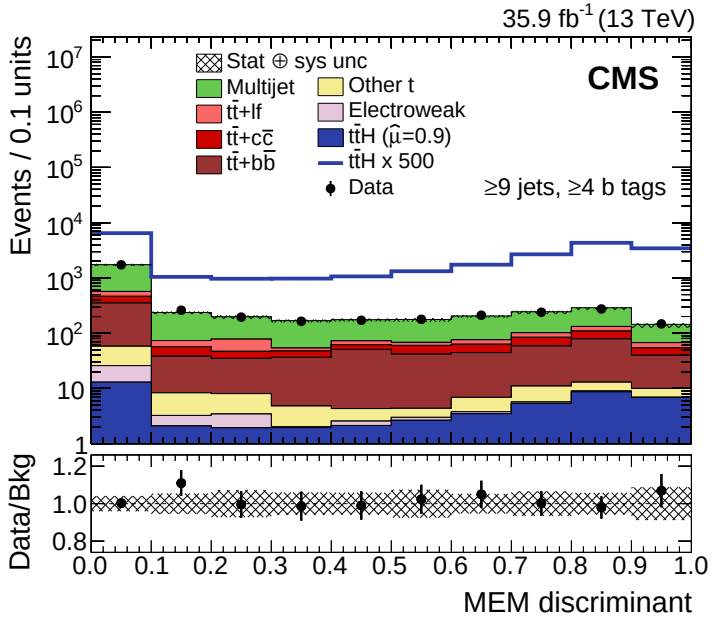
Search for $t\bar{t}H(\to b\bar{b})$ in fully-hadronic decays

HIG-17-022, submitted to JHEP

- events with $\geqslant 7$ jets and $\geqslant 3$ b-jets
  - highest $t\bar{t}H$ BR, but huge QCD multijet bkg
- quark-gluon jet tagger to reduce bkg
- data-driven QCD bkg using 2b CR
- fit to Matrix Element discriminant designed to separate $t\bar{t}H$ and $t\bar{t}+b\bar{b}$
  - 6 categ based on # of jets and b-jets
- sensitivity limited by systematics
  - QCD shape modeling, b-tagging

Obs. (Exp.) upper limit: $\mu_{95\%} < 3.8\,(3.1)$

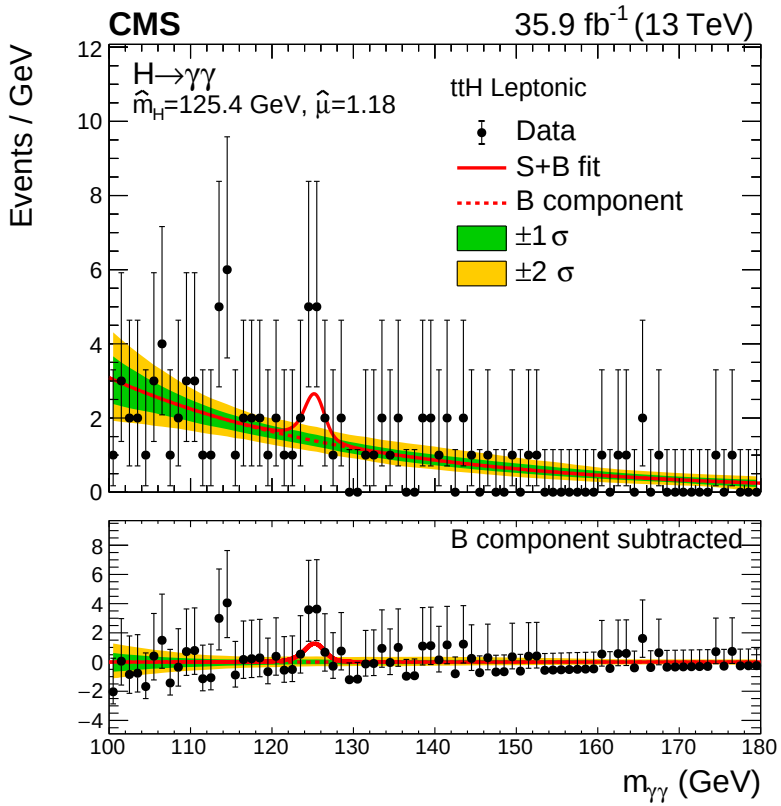


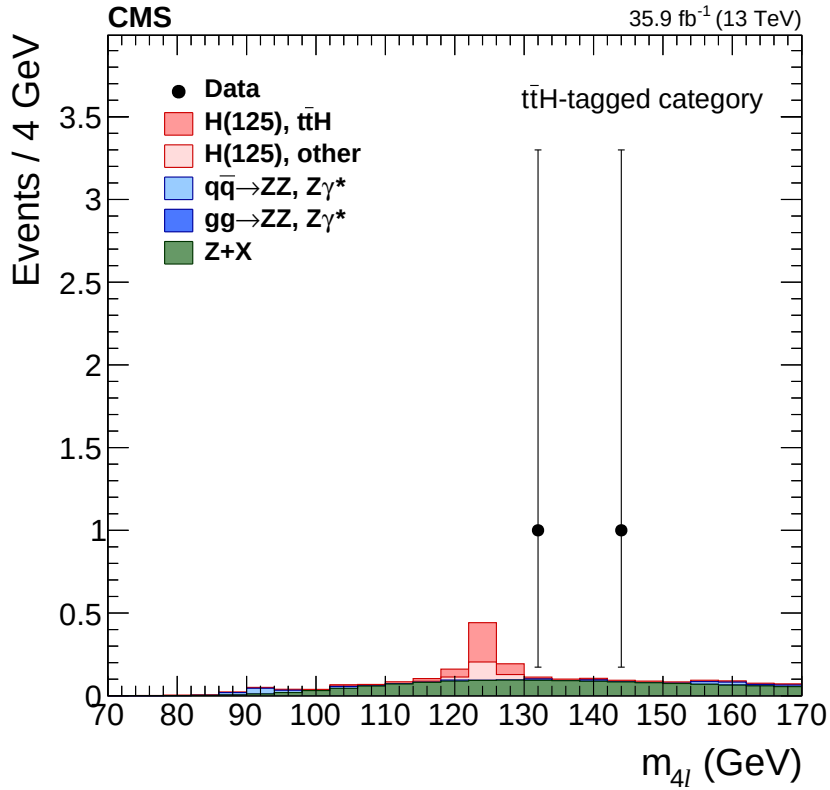


$t\bar{t}H(\to \gamma\gamma)$ and $t\bar{t}H(\to ZZ^* \to 4\ell)$ channels

HIG-16-040, HIG-16-041

- $t\bar{t}H$ categories in inclusive $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ analyses
- both channels statistically limited





Combination of $t\bar{t}H$ searches

HIG-17-035, accepted by PRL

uncertainties on $\mu_{t\bar{t}H}$

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

best-fit $\mu_{t\bar{t}H}$

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