ttH and tH production at the LHC

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on behalf of the ATLAS and CMS collaborations

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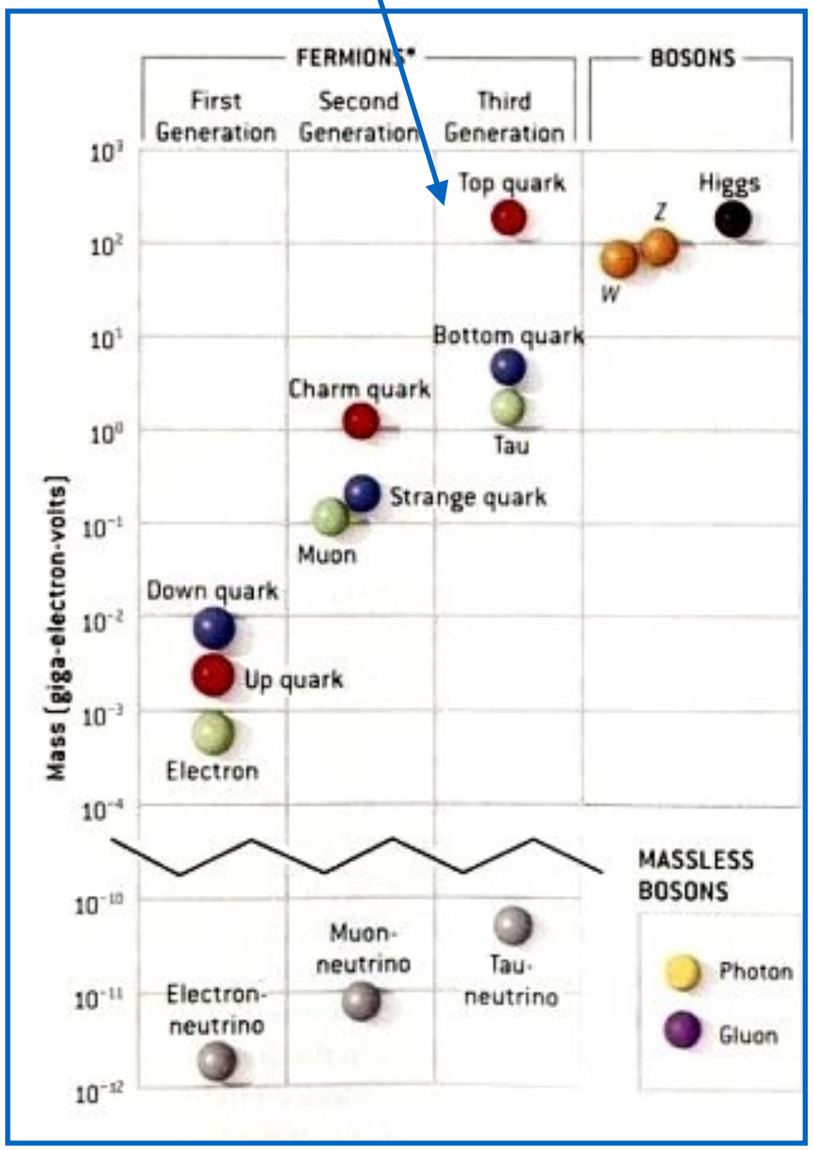
Introduction & Motivation

- After discovery of the Higgs boson by the CMS and ATLAS new focus is to measure Higgs properties
- Higgs coupling to the top quark is a key property to measure
  - Large m_t implies large top-Higgs coupling Y_t
  - Strongest known coupling - $Y_t \sim 1$ - may give insight into the scale of new physics
  - Important for understanding EW symmetry breaking
  - Allows testing theories beyond the Standard Model

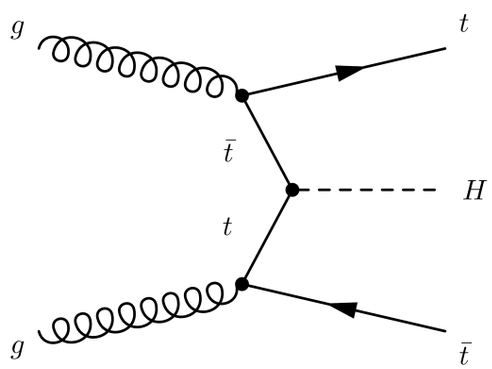
$$Y_f = \sqrt{2} m_f v$$

top quark - heaviest fundamental particle known

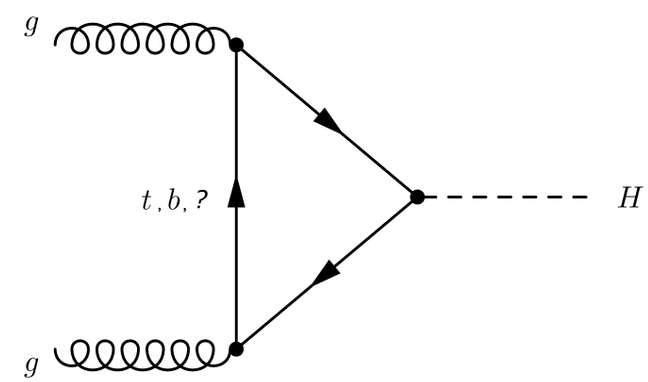


ttH and tH production

- **ttH**: Higgs production in association with ttbar gives $|Y_t|$



ttH: Higgs from tops only

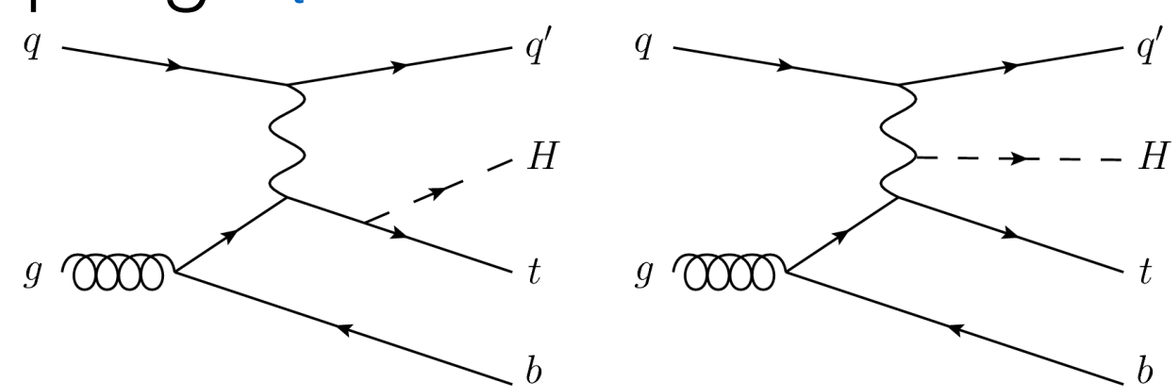


H: Higgs from tops, bottoms, new physics

  - SM: σ_{SM} = 129 fb^{-1}

- **tH**: Higgs production in association with single top probes relative sign of the top-Higgs coupling Y_t

  - SM: very small σ_{SM} = 18 fb^{-1}
  - BSM: $\kappa_t = Y_t/Y_t^{SM}$ =-1, σ_{SM} = 234 fb^{-1}



Analyses covered

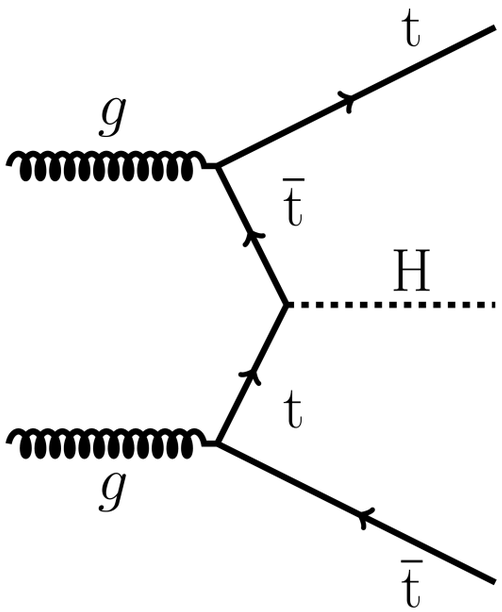
<table>
<tr><th>Analyses - Run I</th><th>ATLAS</th><th colspan="2">CMS</th></tr>
<tr><td>ttH (H→γγ)</td><td>Phys Lett B 740 (2015) 222</td><td></td><td rowspan="3">JHEP 09 (2014) 087, ttH(H→hadrons)</td></tr>
<tr><td>ttH (H→bb)</td><td>EPJC 75 (2015) 349</td><td>EPJC 75 (2015) 251 - MEM</td></tr>
<tr><td>ttH (H→WW, $\tau\tau$, ZZ)</td><td>Phys Lett B 749 (2015) 519</td><td></td></tr>
<tr><td>tH (H→γγ)</td><td>Phys Lett B 740 (2015) 222</td><td colspan="2" rowspan="3">arXiv:1509.08159
Submitted to JHEP</td></tr>
<tr><td>tH (H→bb)</td><td></td></tr>
<tr><td>tH (H→WW, $\tau\tau$, ZZ)</td><td></td></tr>
</table>

ttH combination

- *ATLAS* - CERN-PH-EP-2015-125 (submitted EPJC) - *effectively includes tH*
- *CMS* - EPJC 75 (2015) 212
- *ATLAS+CMS* - ATLAS-CONF-2015-044

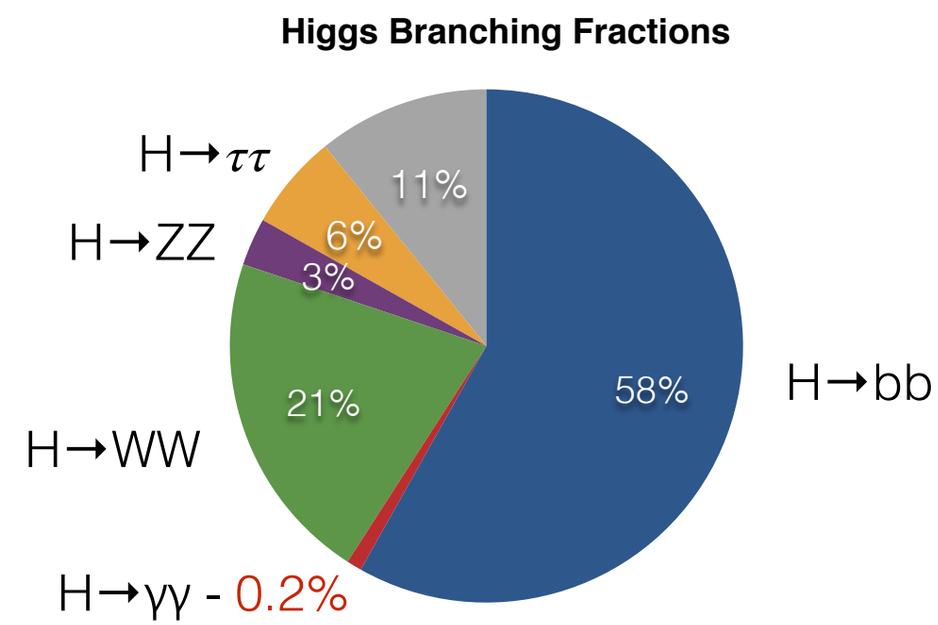
ttH

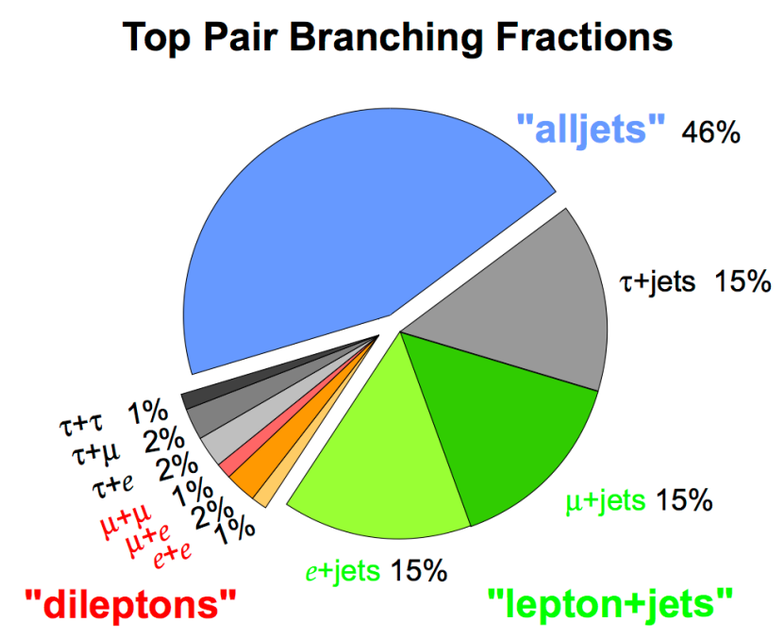
- 3 Analyses
  - ttH (H→γγ)
  - ttH (H→bb)
  - ttH (H→WW,$\tau\tau$, ZZ)



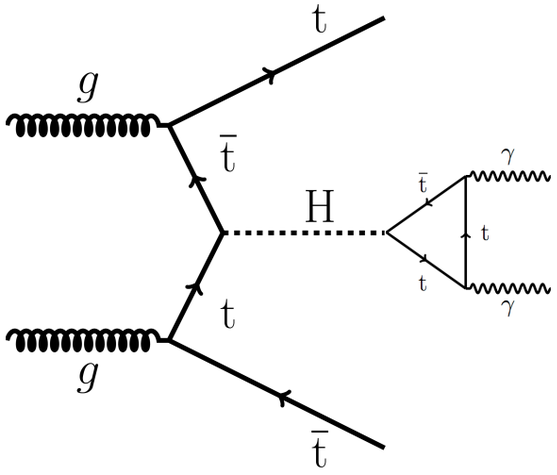
Higgs and Top Decay Modes

- ttH results in complex final states
- Higgs decay modes
  - ttH(bb) - highest branching fraction, abundant tt background
  - ttH(WW,$\tau\tau$, ZZ) - second highest branching fraction, good signal purity
  - ttH(γγ) - low branching fraction, clean mass peak
- tt decay modes
  - single lepton - tt → 2bqq'lν
  - dilepton - tt → 2blνlν
  - all jets - tt → 2bqq'q''q'''





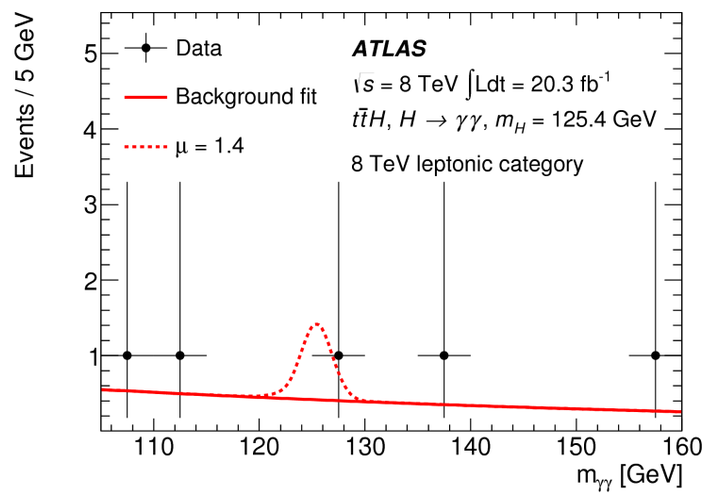
ttH (H→γγ), Strategy

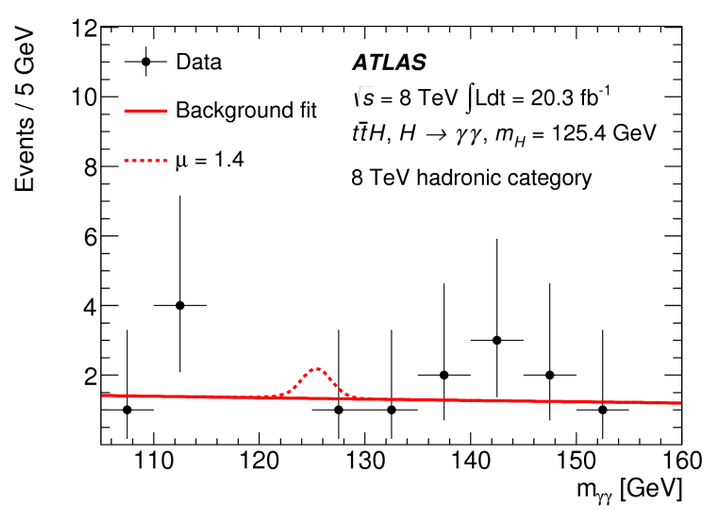


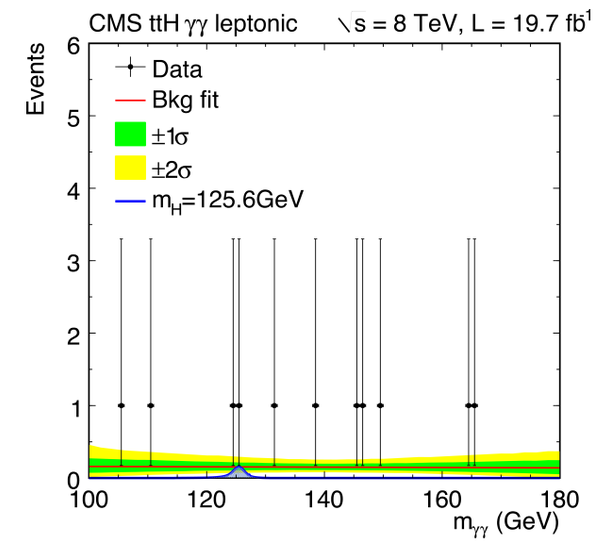
- Two signal regions according to top pair decay
  - Leptonic mode - single lepton and dilepton
    - Lepton and b-tag requirements to suppress non-ttH
  - Hadronic mode - top decayed hadronically
    - high number of jets and b-tag requirements to suppress non-ttH
- ATLAS event selections - loose to allow high selection efficiency for tH
  - CMS has a dedicated tH (H→γγ) search
- Strategy - background shape is taken from data $m_{\gamma\gamma}$ sidebands, ttH (H→γγ) is fitted on top of it in the signal region
- Signal strength $\mu = \sigma/\sigma_{SM}$ is extracted from $m_{\gamma\gamma}$ fit and results are interpreted in cross section limit

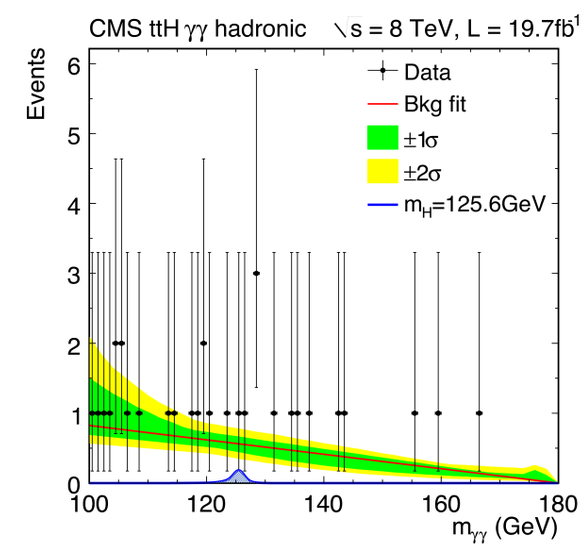
ttH (H→γγ), Results I

- About 1 signal event expected
- $m_{\gamma\gamma}$ spectra for the candidate events





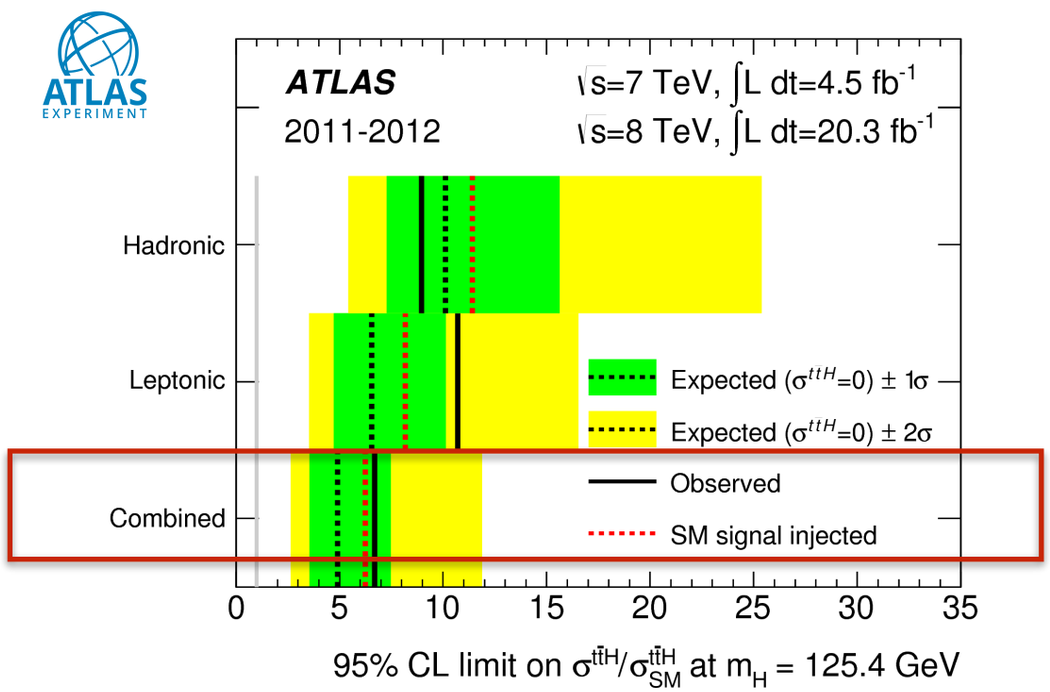


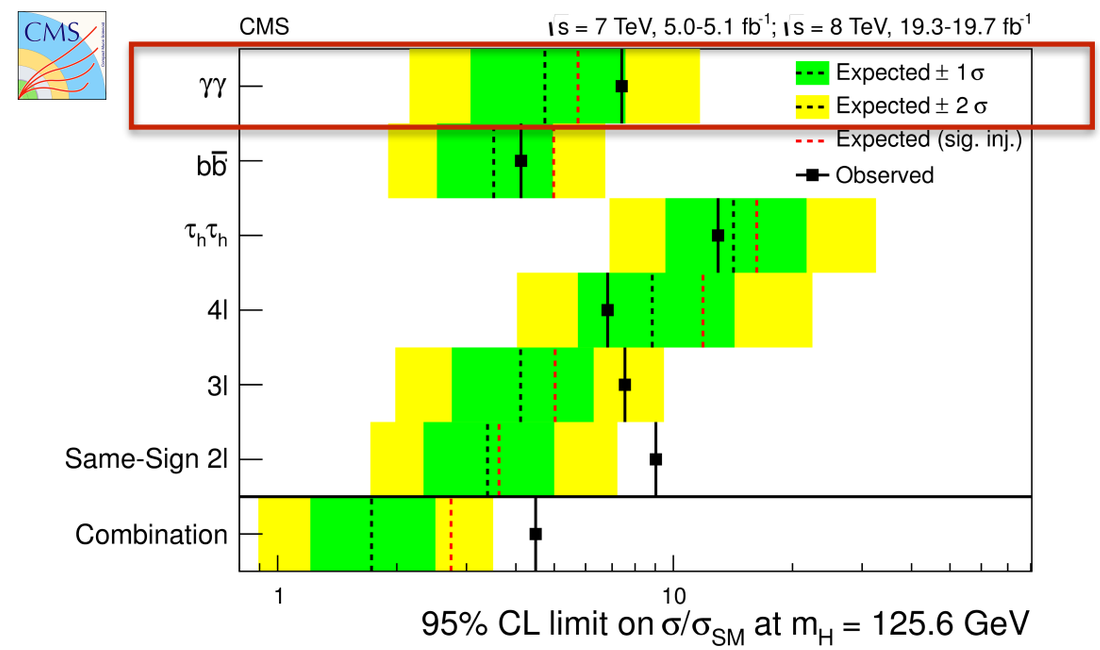


- Best-fit - $\mu_{ttH} = 1.3^{+2.6}_{-1.7}$ ATLAS , $\mu_{ttH} = 2.7^{+2.6}_{-1.8}$ CMS

ttH (H→γγ), Results II

- 95% CL exclusion upper limits on σ/σ_{SM} are set for ttH production times BR(H→γγ)
  - ATLAS: 6.7 obs (4.9 exp), CMS: 7.4 obs (4.7 exp)

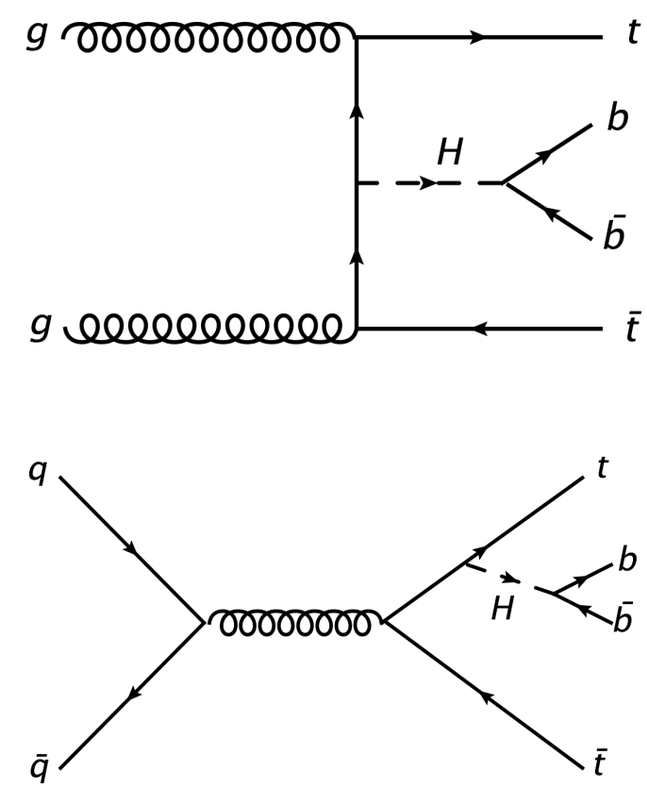




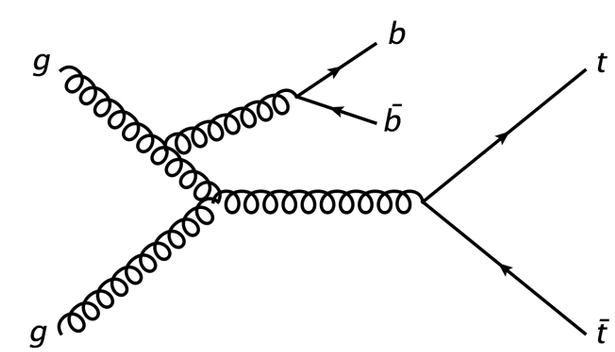
- Results are consistent with SM expectations

ttH (H→bb), Strategy

- Highest Higgs branching fraction, but abundant major background tt+jets and tt+bb results in small signal purity
- Split in categories by number of objects: leps, jets, b-jets, …
- Separate signal from background MVA (BDT, NN) trained in each category separately, Matrix Element Method (MEM)
- Fit all the categories simultaneously
- Obtain results as signal strength and cross-section limits
- Low S/B regions are used to constrain backgrounds and reduce systematics



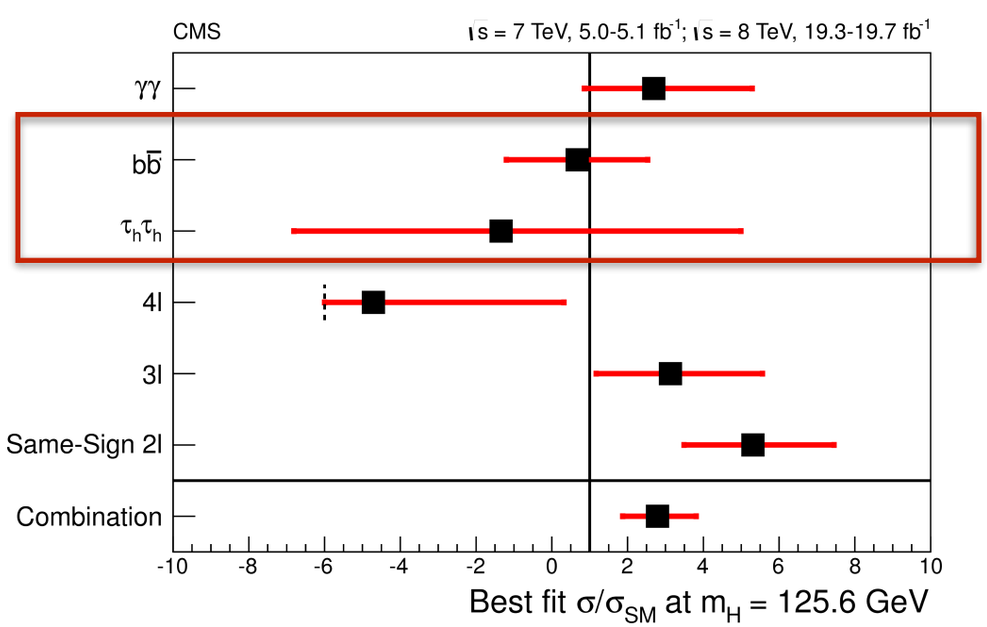
Signal production modes

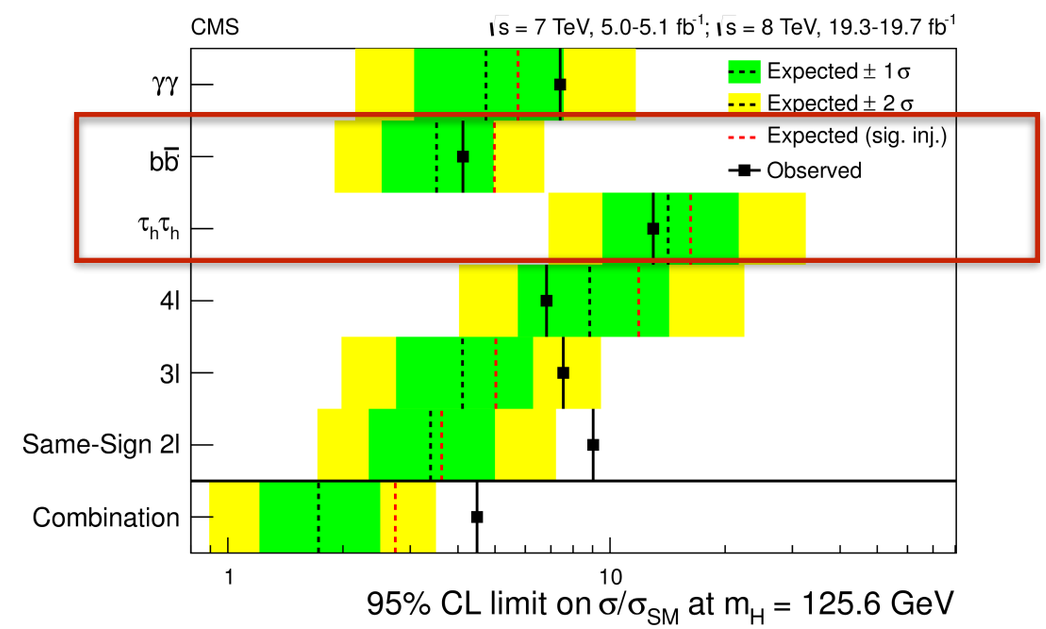


Dominant background

ttH (H→hadrons), BDT

- Three channels analyzed - single lepton, dilepton, $\tau_h\tau_h$
  - Categorized by N_{jets} and $N_{b\text{-}jets}$
- tt+jets background (MadGraph) subsampled in tt+lf, tt+b, tt+bb, tt+cc
    - different systematics in rates and shapes
- Boosted Decision Tree used to extract signal
  - different variables used for training in each category
  - tiered BDT approach: first ttH from tt+bb, then ttH from tt+jets
- Results:
  - $\mu_{ttH(bb)}$= 0.7±1.9, limits - 4.1 obs (3.5 exp)
  - $\mu_{ttH(\tau_h\tau_h)}$= $-1.3^{+6.3}_{-5.5}$, limits - 13.0 obs (14.2 exp)





ttH (H→bb), MEM

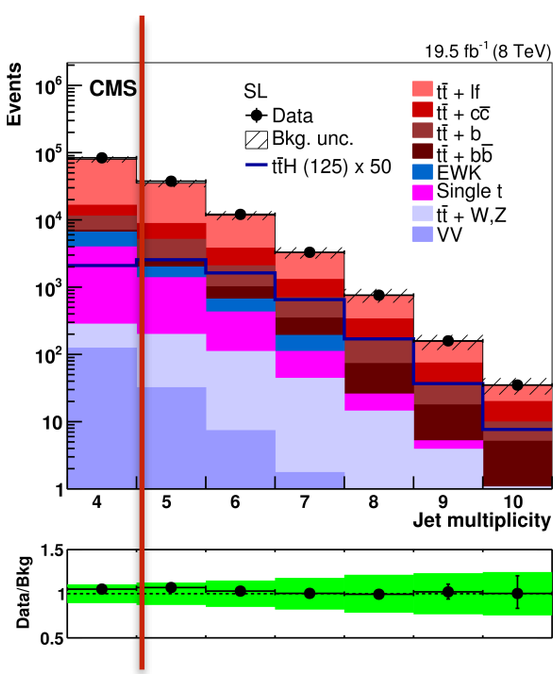
- Classified into single lepton (SL), dilepton (DL) events
  - Categorized by N_{jets} - ≥ 5 jets (SL), ≥ 4 jets (DL) to enhance sensitivity
- To further increase S/B, construct likelihood ratio

$$\mathcal{F}(\boldsymbol{\xi}) = \frac{f(\boldsymbol{\xi}|\mathrm{t\bar{t}+hf})}{f(\boldsymbol{\xi}|\mathrm{t\bar{t}+hf}) + f(\boldsymbol{\xi}|\mathrm{t\bar{t}+lf})}.$$

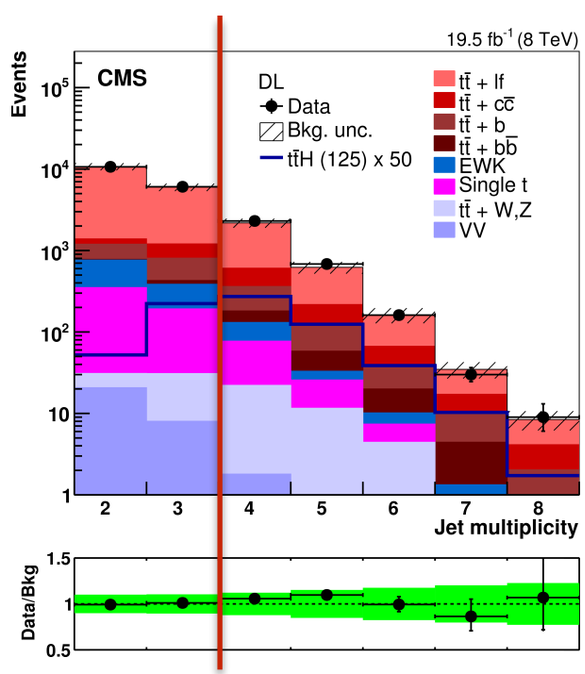
$\boldsymbol{\xi}$ - b-tag values of all jets

$f(\boldsymbol{\xi}|\mathrm{t\bar{t}+hf})$ - likelihood under tt+hf hypothesis

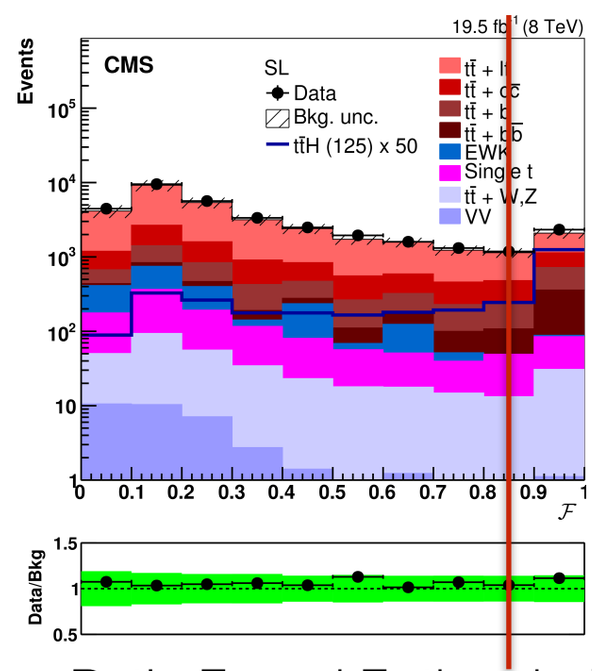
$f(\boldsymbol{\xi}|\mathrm{t\bar{t}+lf})$ - likelihood under tt+lf hypothesis



SL: ≥ 5 jets



DL: ≥ 4 jets



Ratio F_L and F_H threshold

$F_L \in [0.85 - 0.97]$

$0 < F_L < F_H < 1$

$[F_L , F_H]$:
tt+lf control region

$[F_H , 1]$
tt+hf control region

Retain events > F_L

ttH (H→bb), MEM

- To aid MEM pdf evaluation, events are further split in orthogonal reconstruction categories
  - Single lepton
    - Cat-1: all jets and b-jets reconstructed, W_{jj} mass - ok
    - Cat-2: all b-jets, all jets except one quark + gluon jet, W_{jj} mass - fails
    - Cat-3: exactly 5 jets reconstructed, W_{jj} mass - fails
  - Dilepton
    - all quarks are properly reconstructed as jets
- Two event discriminants are defined

$w(\mathbf{y}|\mathcal{H})$ - calculated ME PDF weight for each event under ttH and tt+bb hypotheses

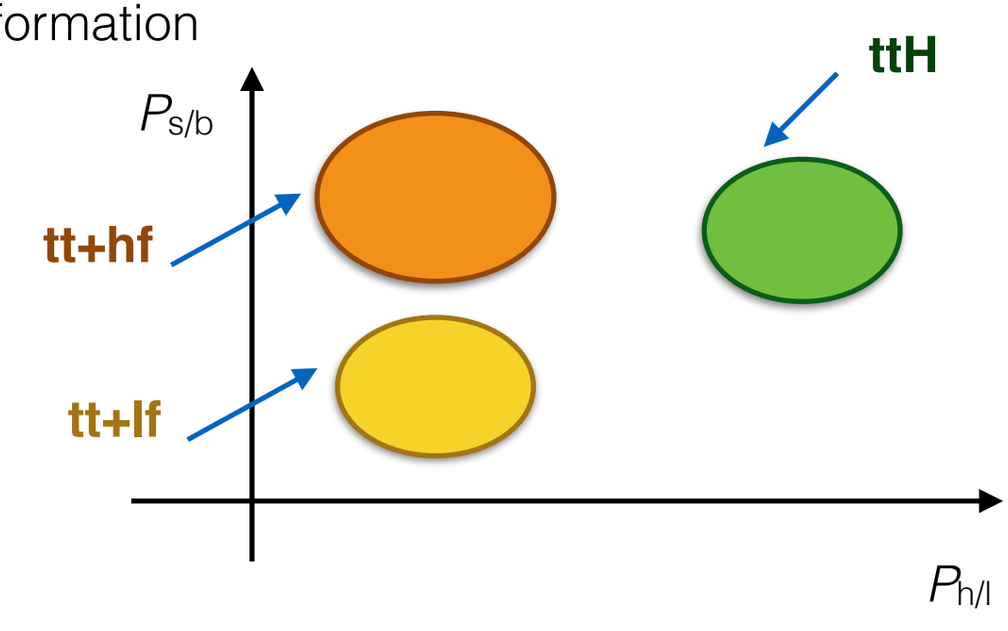
$$P_{s/b} = \frac{w(\mathbf{y}|t\bar{t}H)}{w(\mathbf{y}|t\bar{t}H) + k_{s/b}\, w(\mathbf{y}|t\bar{t} + b\bar{b})}$$

contains kinematics and dynamics information

$$P_{h/l} = \frac{f(\boldsymbol{\xi}|t\bar{t} + hf)}{f(\boldsymbol{\xi}|t\bar{t} + hf) + k_{h/l}\, f(\boldsymbol{\xi}|t\bar{t} + lf)}$$

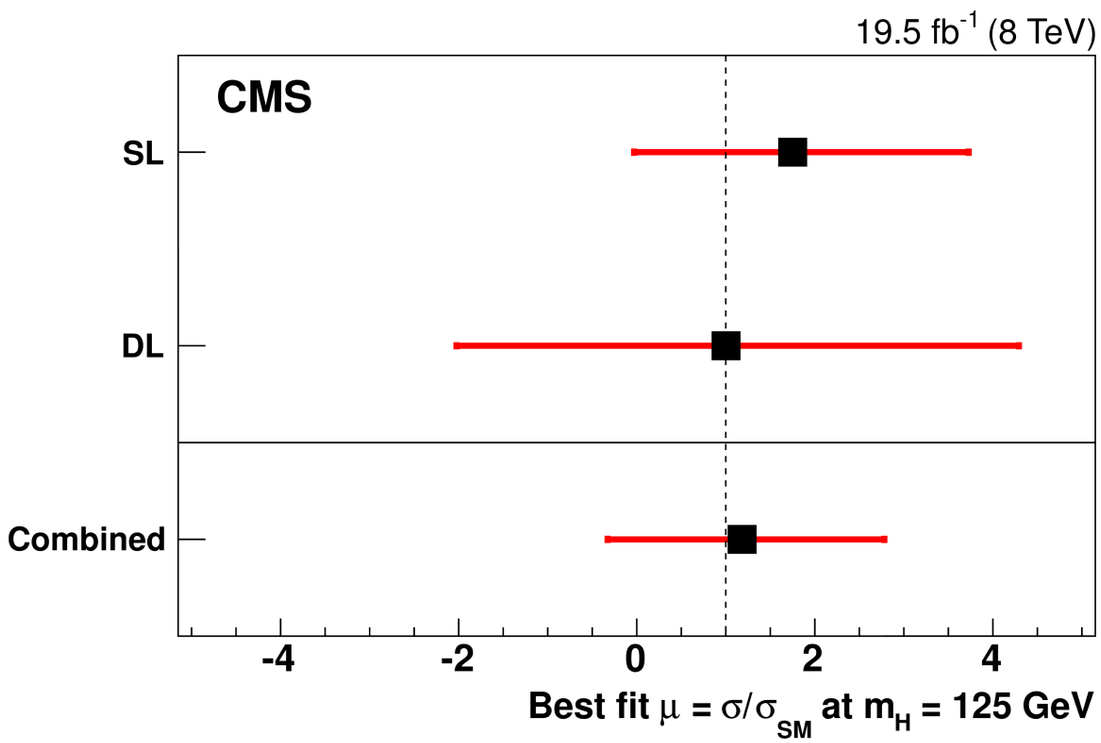
contains b-tagging information

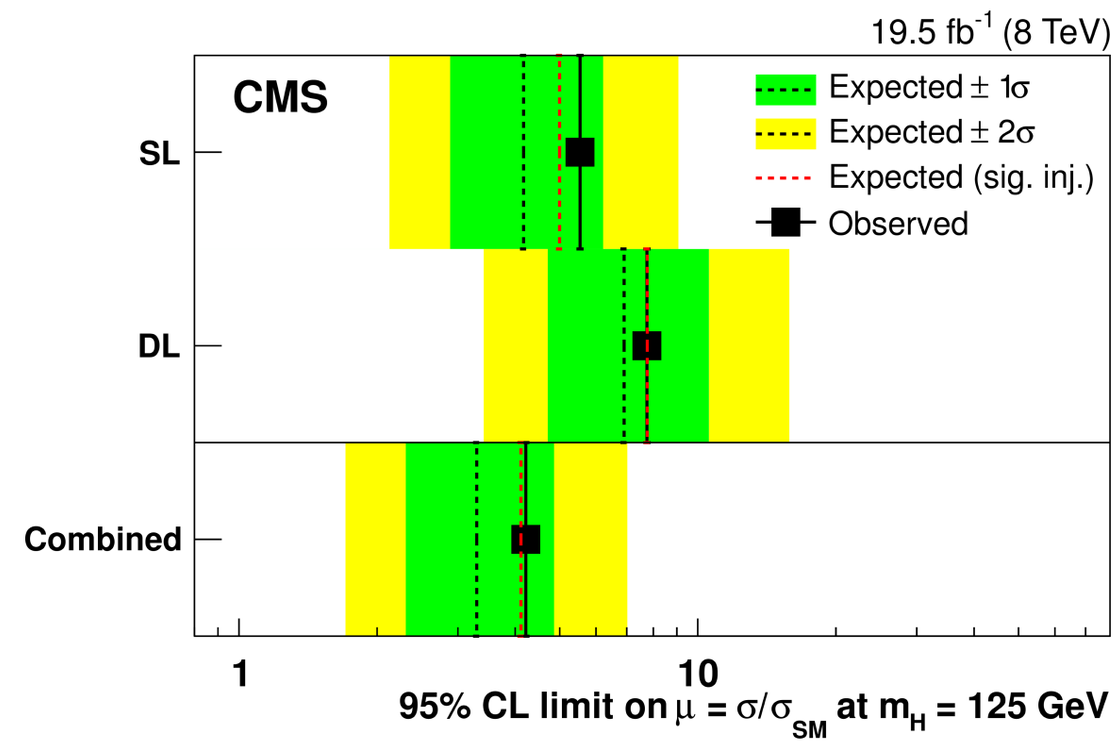
- Joint distribution of the ($P_{s/b}$, $P_{h/l}$) discriminants is used in a two-dimensional maximum likelihood fit to search for signal events



ttH (H→bb), MEM

- Simultaneous fit to the discriminant is performed in 8 regions and exclusion upper limits are set @ 95% CL

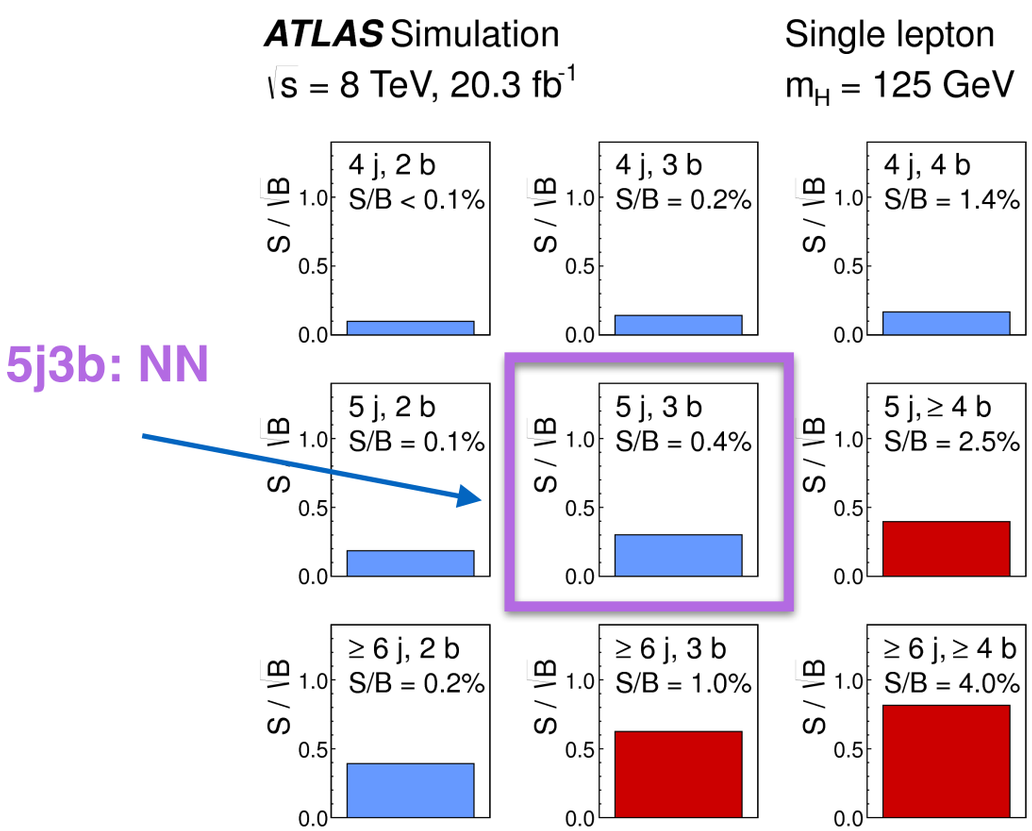


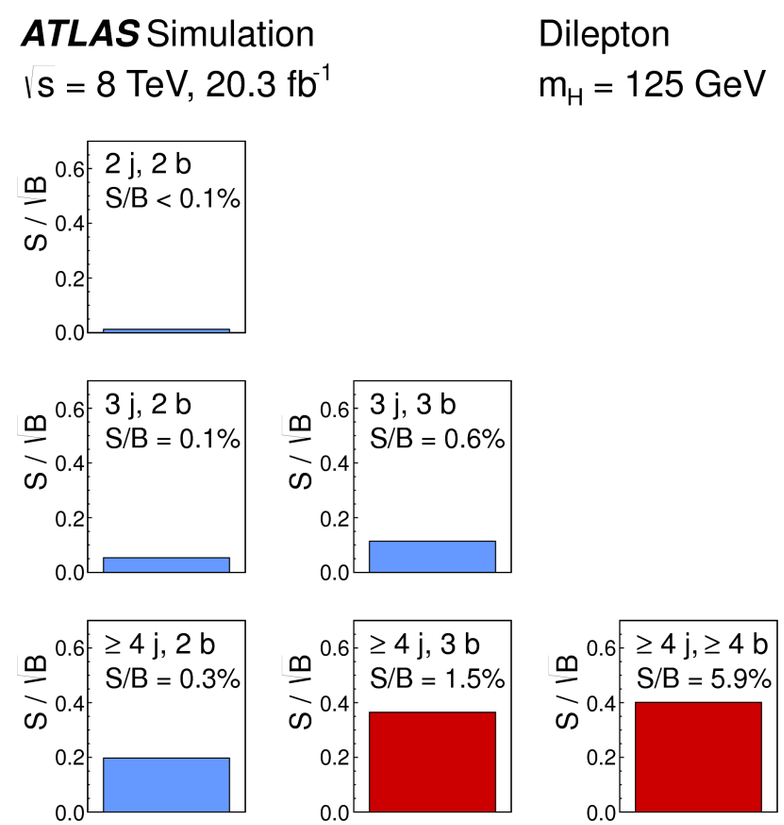


- Combined results
  - Best-fit value - $\mu_{ttH} = 1.2^{+1.6}_{-1.5}$, Limits - 4.2 obs (3.3 exp)
- Consistent with SM expectations within uncertainty

ttH (H→bb), MEM+NN

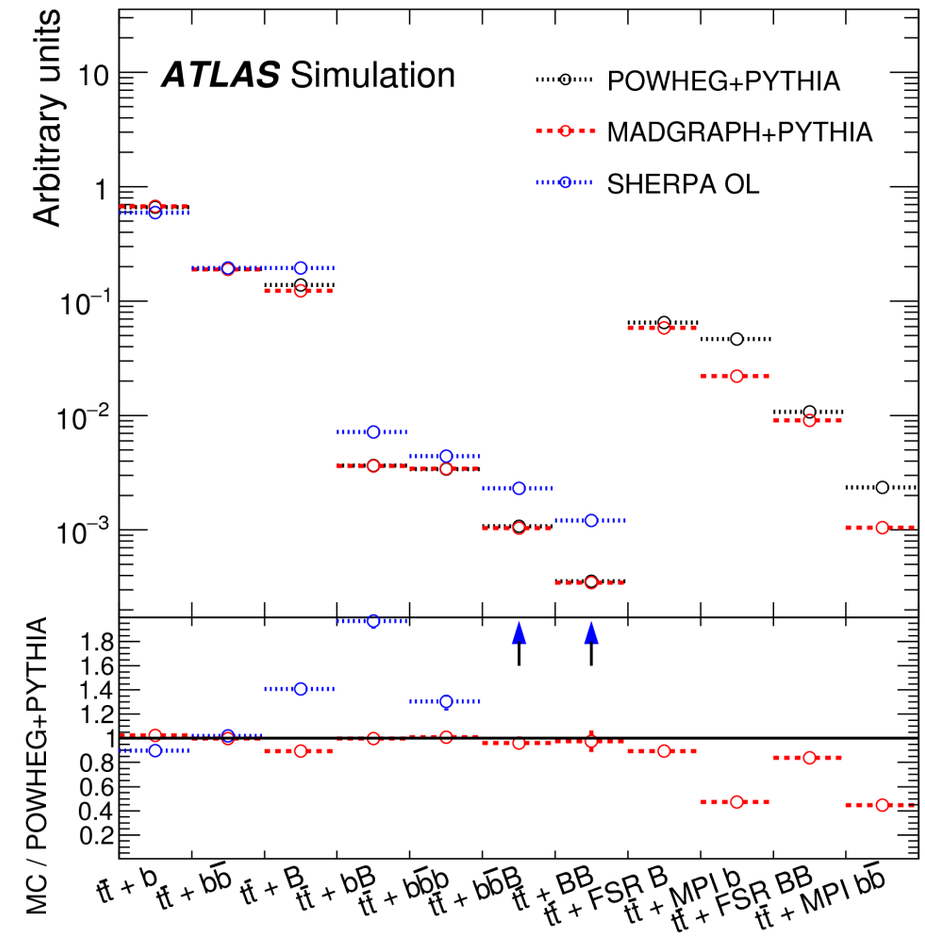
- SL and DL channels - signal and background regions by S/B ratio
  - S/B > 1% & S/√B > 0.3 - signal, rest is background
- Perform profile likelihood fit in signal and control regions simultaneously
  - Use NN variable as input in signal regions
  - Use H_t variable (sum(pt) of leps and jets) in background regions
  - Exception: 5j3b - use NN for tt+HF / tt+LF separation





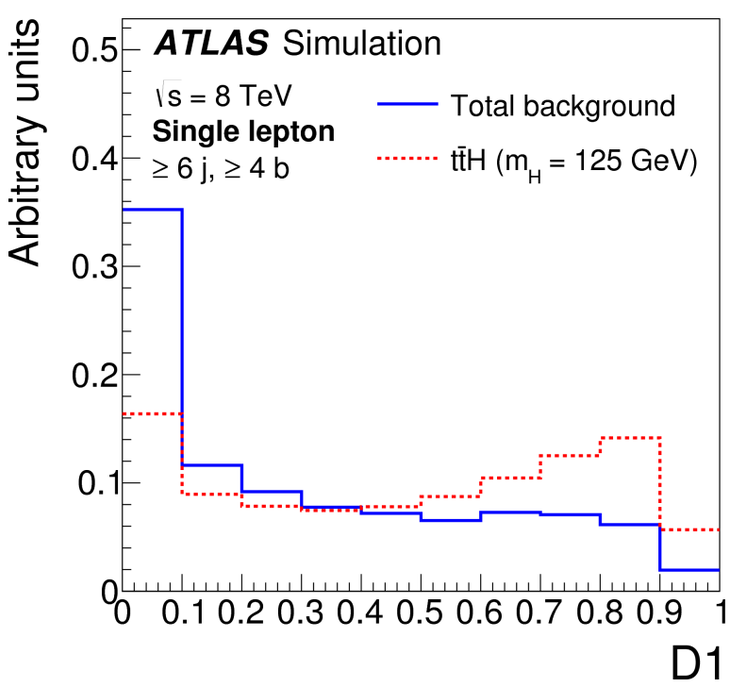
ttH (H→bb), MEM+NN

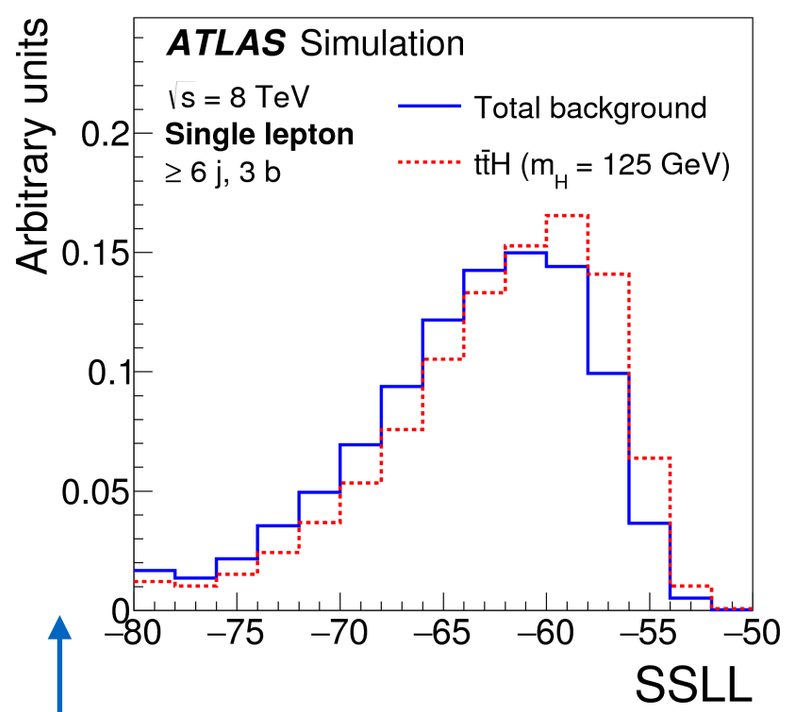
- tt+jets - largest background
  - Powheg+Pythia, normalized to NNLO, models via parton showering
  - *tt+bb at tree level with MadGraph+Pythia, models tt +* up to 3 partons including *c* and *b-quarks*
- Recently Sherpa+OpenLoops - tt+jets (NLO) with massive b-quarks
- Finer categorization of tt+HF - for generator comparison and systematics
  - tt+bb - 2 jets match 2 b-quark
  - tt+b - 1 jet match 1 b-quark
  - tt+B - 1 jet match bb pair (unresolved gluon splitting)
- tt+bb events are reweighted from Powheg+ Pythia to reproduce the NLO tt+bb prediction from SherpaOL



ttH (H→bb), MEM+NN

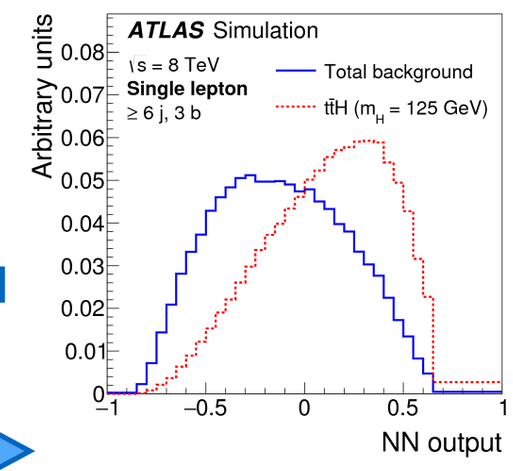
- NN input is an optimized choice of variables for each category - shape and object pair variables
  - Single lepton includes also MEM variables in ≥6j3b and ≥6j4b
    - D1 - the Neyman–Pearson likelihood ratio - separates ttH signal from tt+bb background
    - SSLL - the logarithm of the summed signal likelihood

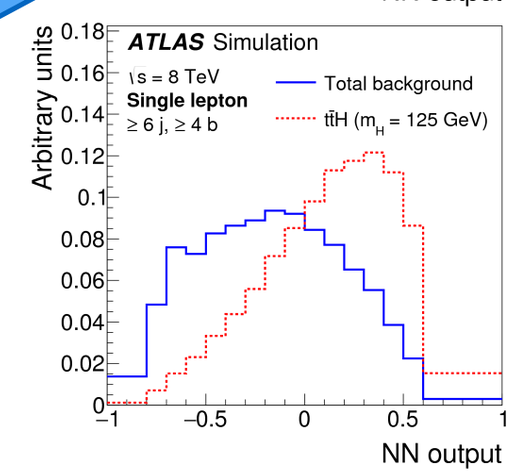




+ additional input variables

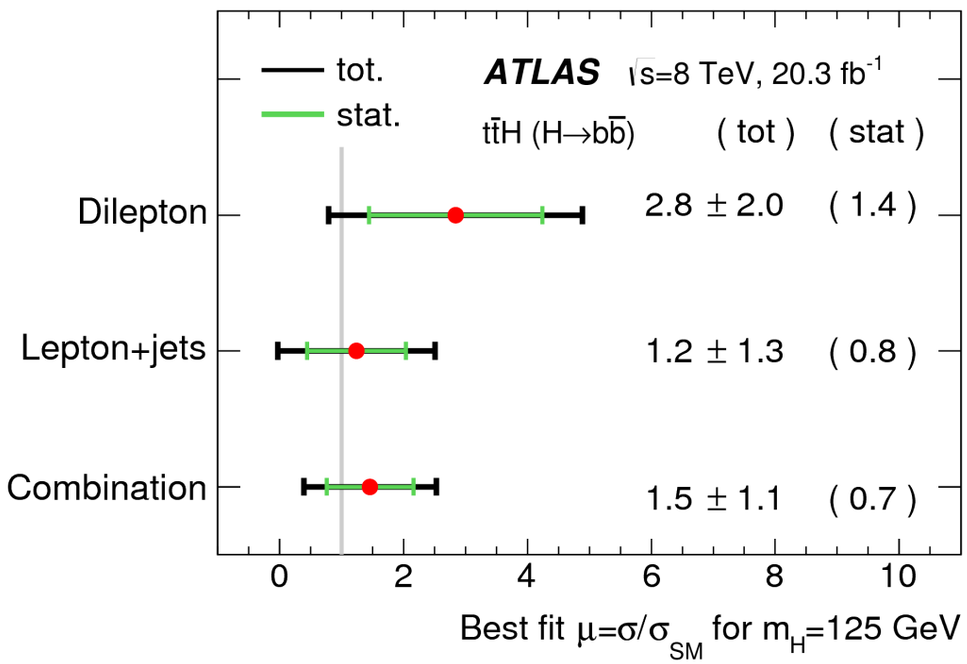
train/test NN

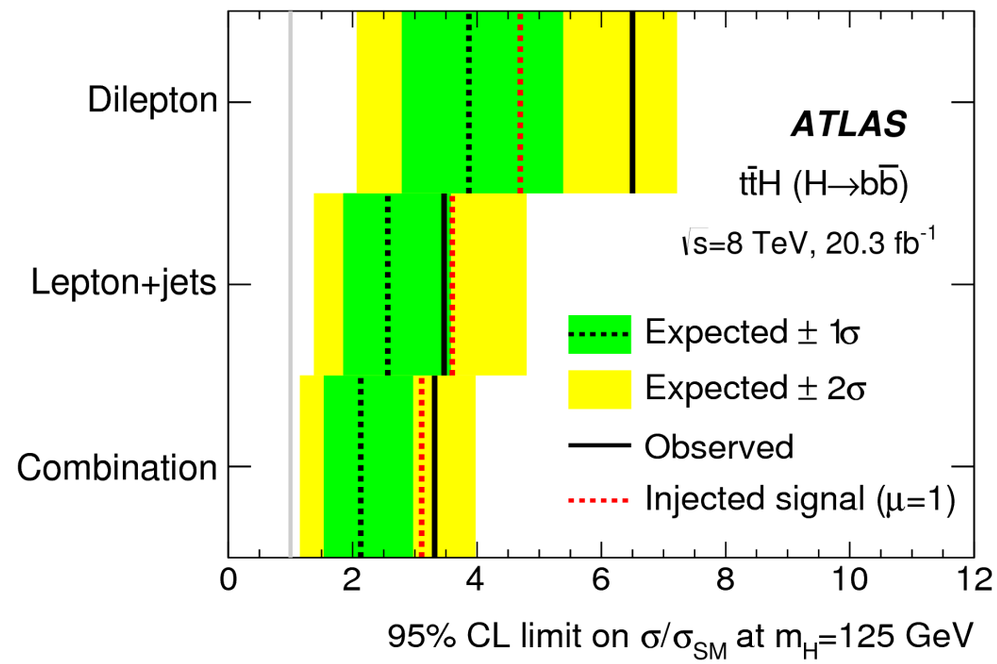




ttH (H→bb), MEM+NN

- Simultaneous fit to the discriminant is performed in 15 regions and exclusion upper limits are set @ 95% CL



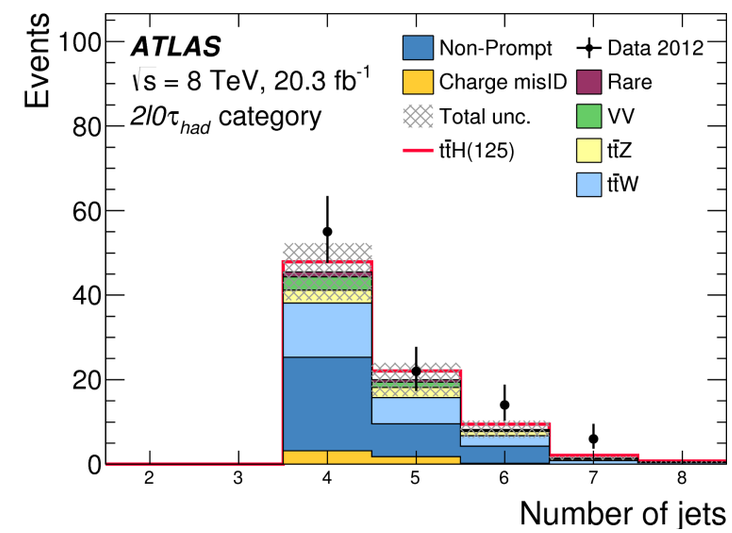


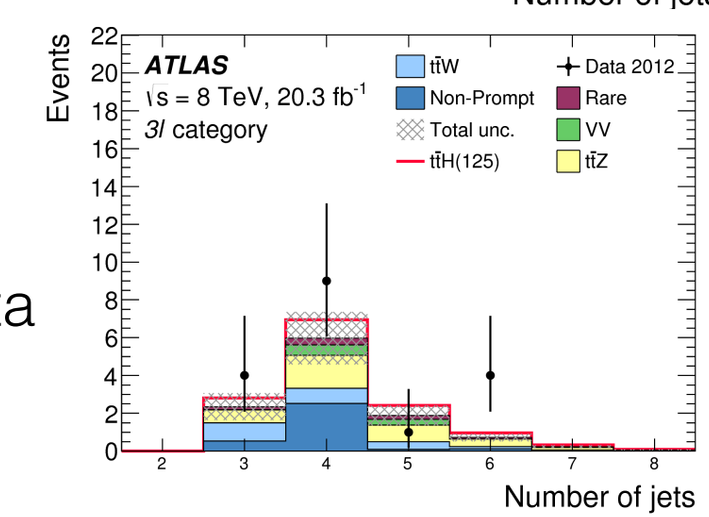
- Combined results
  - Best-fit value - μ_{ttH}= 1.5±1.1, Limits - 3.4 obs (2.2 exp)
- No significant excess
- Consistent with SM expectation within uncertainty

ttH (H→WW, $\tau\tau$, ZZ)

- Analysis is split in N_ℓ and $N\tau_h$
  - Categorized by N_{jets} and $N_{b\text{-}jets}$ to define signal and control regions
    - $2\ell SS+0\tau_h$
      - SR: =4j,≥1b, >4j,≥1b ⊗ ee, eμ , μμ
    - $2\ell SS+1\tau_h$
      - SR: ≥4j,≥1b
    - 3ℓ
      - SR: ≥4j, ≥1b or ≥3j,2b
    - 4ℓ
      - SR: ≥2j, ≥1b + *Z*-enriched and *Z*-depleted
    - $1\ell+2\tau_h$
      - SR: ≥3j, ≥1b

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{had}$	4%	93%	0%	3%

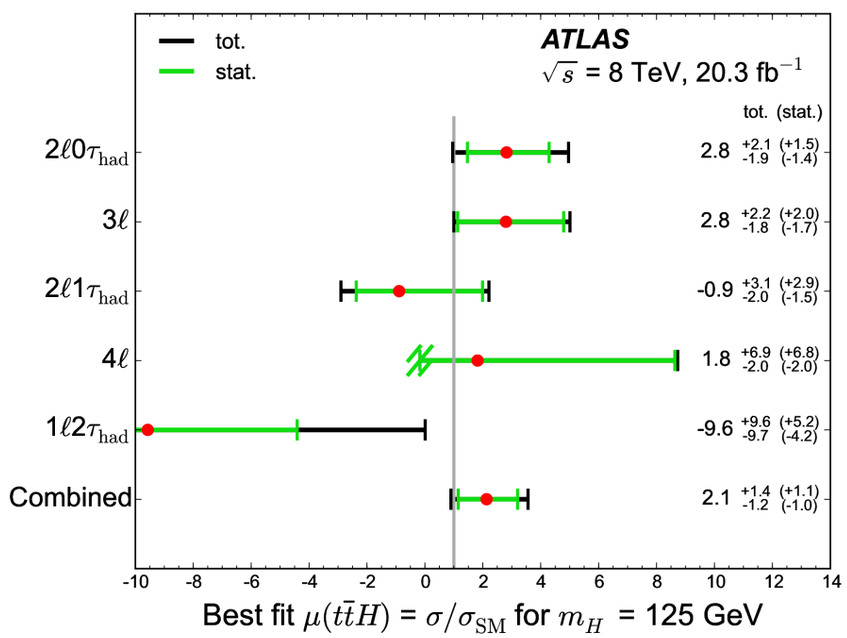


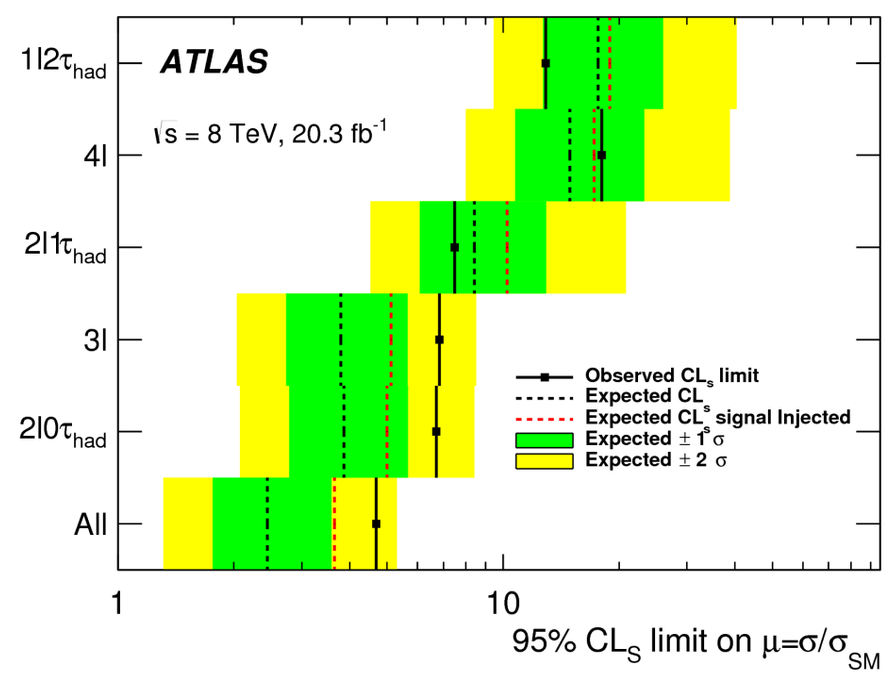


- Dominant backgrounds
  - irreducible - ttW, ttZ, diboson from MC
  - reducible - charge mis-id, non-prompts leps - from data
- Cut-and-count analysis - estimate yield in signal region

ttH (H→WW, $\tau\tau$, ZZ)

- Simultaneous maximum likelihood fit of the SR yields to the data is performed in 11 regions





- Combined results
  - Best-fit value - $\mu_{ttH} = 2.1^{+1.4}_{-1.2}$, Limits - 4.7 obs (2.4 exp)
- Observed (expected) p-value of the no-signal hypothesis corresponds to 1.8σ (0.9σ)
- Result is consistent with the Standard Model expectation

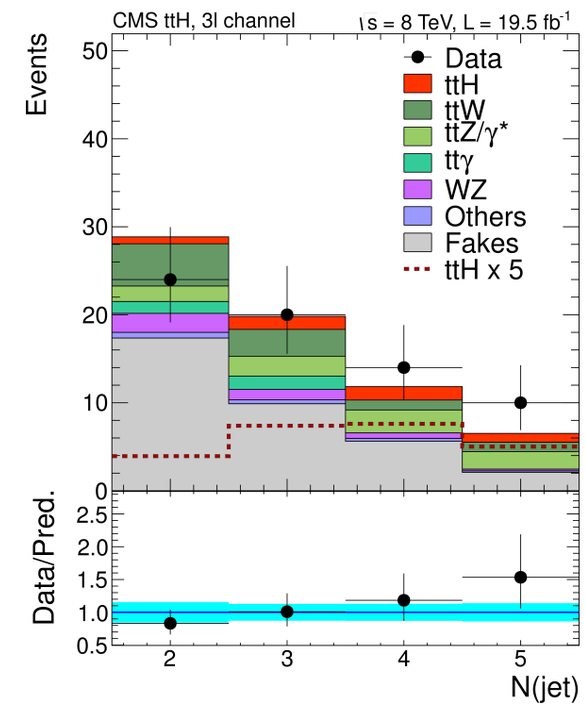
ttH (H→WW, $\tau\tau$, ZZ)

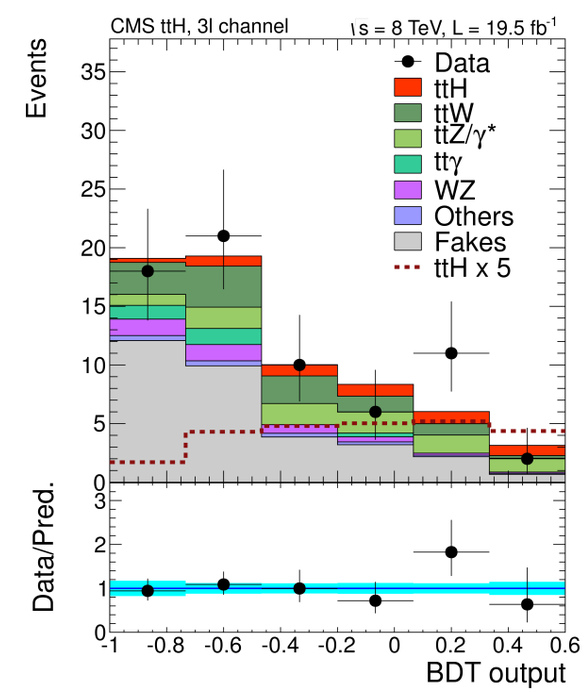
- Events are classified in N_ℓ
  - Categorized by N_{jets} and $N_{b\text{-}jets}$ to define SR and CR

- 2ℓSS
  - SR: ≥4j, ≥1b_{tight} or ≥2b_{loose} ; tight lep MVA disc + L_D cut
- 3ℓ
  - SR:
    - ≥2j, ≥2b_{loose} or ≥2b_{tight}; tight lep MVA disc + L_D cut
    - ≥4j, ≥2b_{loose} or ≥2b_{tight}; tight lep MVA disc
- 4ℓ
  - SR: ≥2j, ≥2b_{loose} or ≥2b_{tight}; loose lep MVA disc

$$L_{\mathrm{D}} = 0.60 E_{\mathrm{T}}^{\mathrm{miss}} + 0.40 H_{\mathrm{T}}^{\mathrm{miss}},$$

sensitive to Z+jets bkg

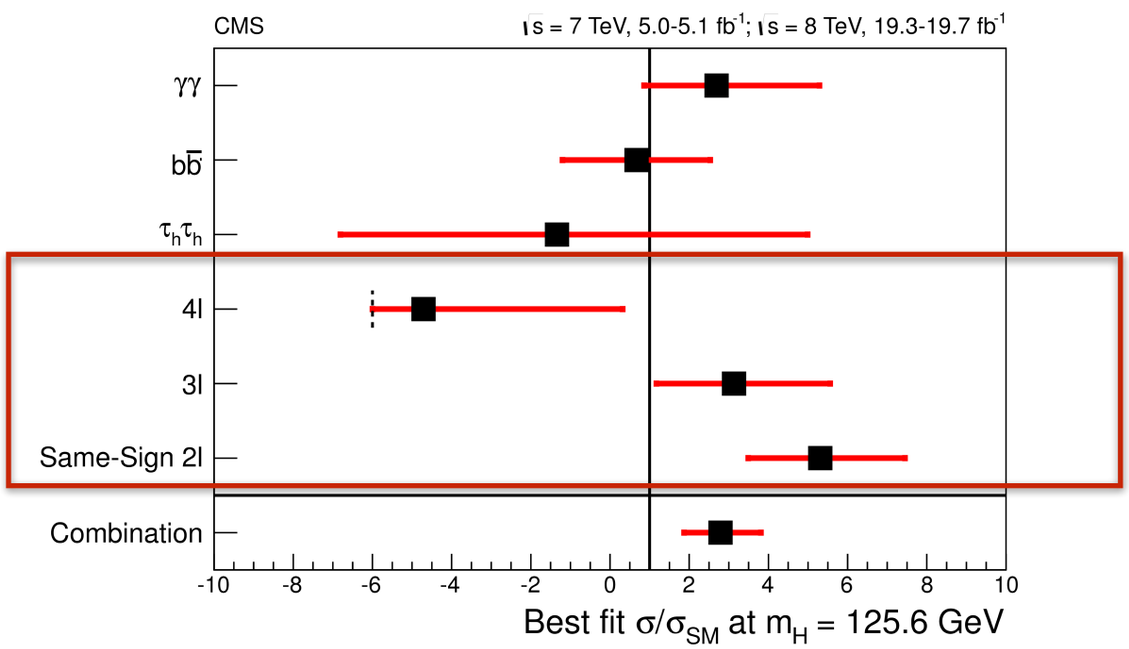


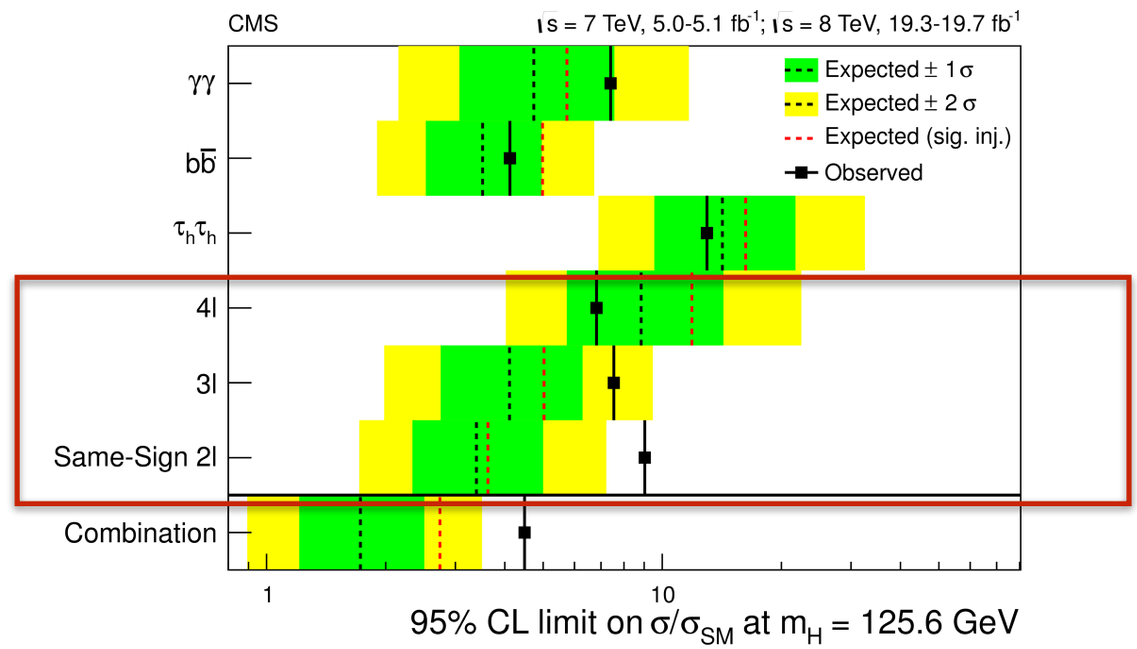


- 2ℓSS & 3ℓ employ BDT to separate ttH and tt+jets
  - Trained on six variables - kinematic, shape, obj pair
- 4ℓ uses N_{jets} variable as discriminating variable

ttH (H→WW, $\tau\tau$, ZZ)

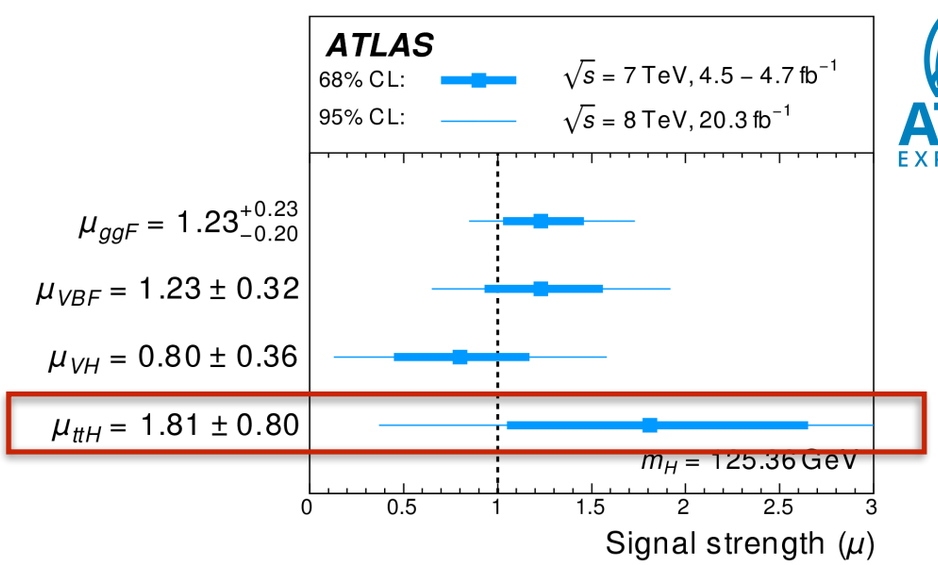
- Simultaneous fit to the discriminant is performed in 11 regions and exclusion upper limits are set @ 95% CL

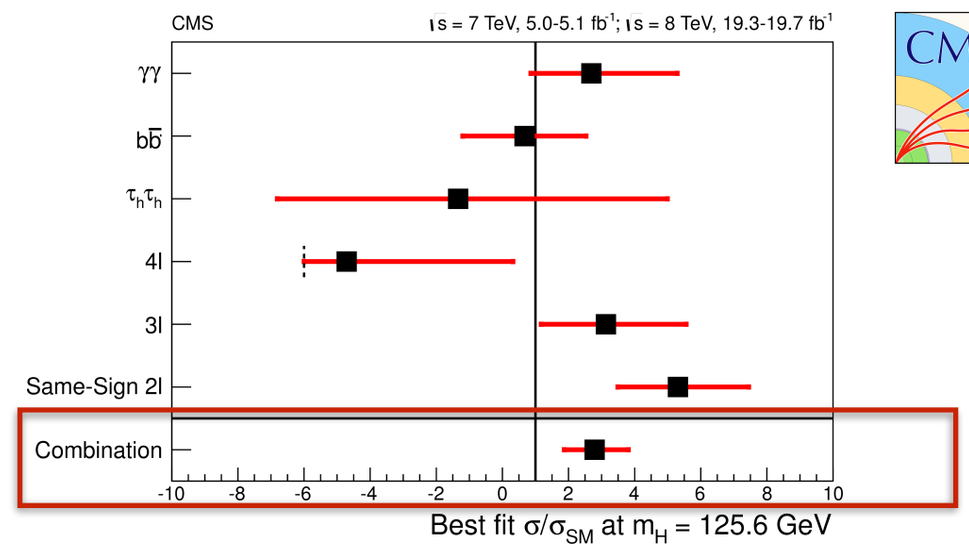




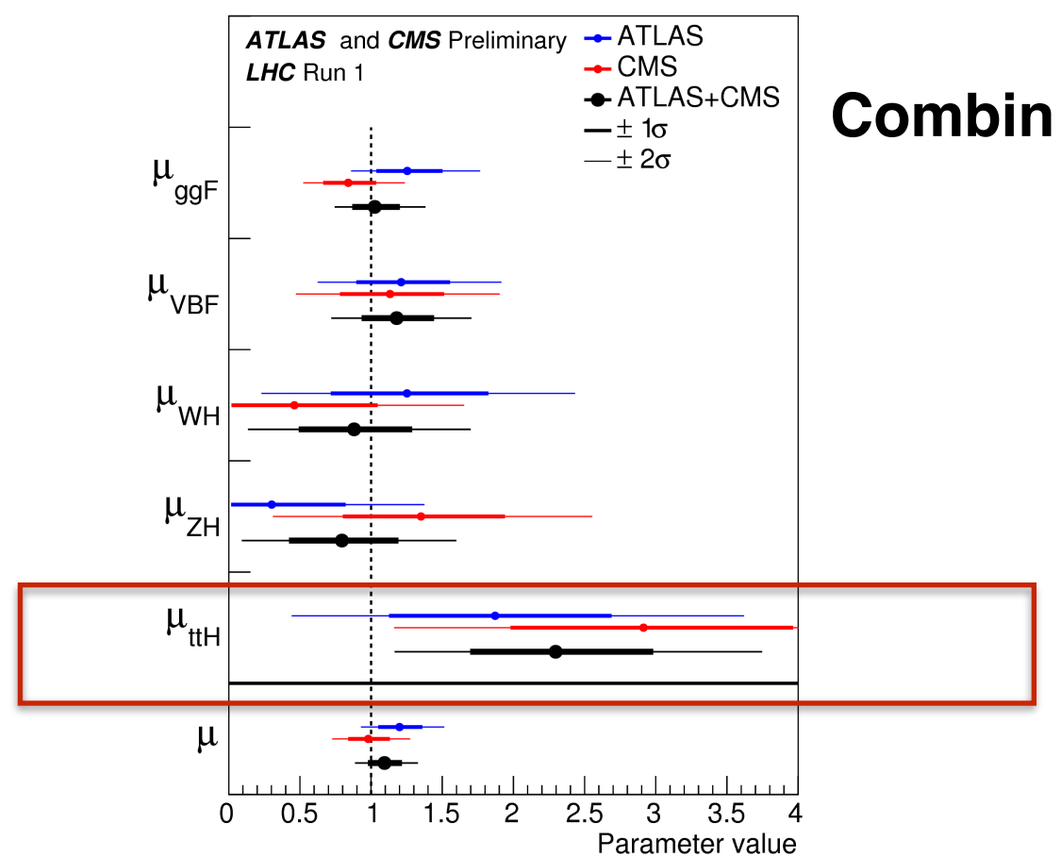
- Combined results
  - 2ℓ: $\mu_{ttH} = 5.3^{+2.1}_{-1.8}$, Limits - 9.0 obs (3.4 exp)
  - 3ℓ: $\mu_{ttH} = 3.1^{+2.4}_{-2.0}$, Limits - 7.5 obs (4.1 exp)
  - 4ℓ: $\mu_{ttH} = -4.7^{+5.0}_{-1.3}$, Limits - 6.8 obs (8.8 exp)
- Results are consistent with SM expectation

ttH combination





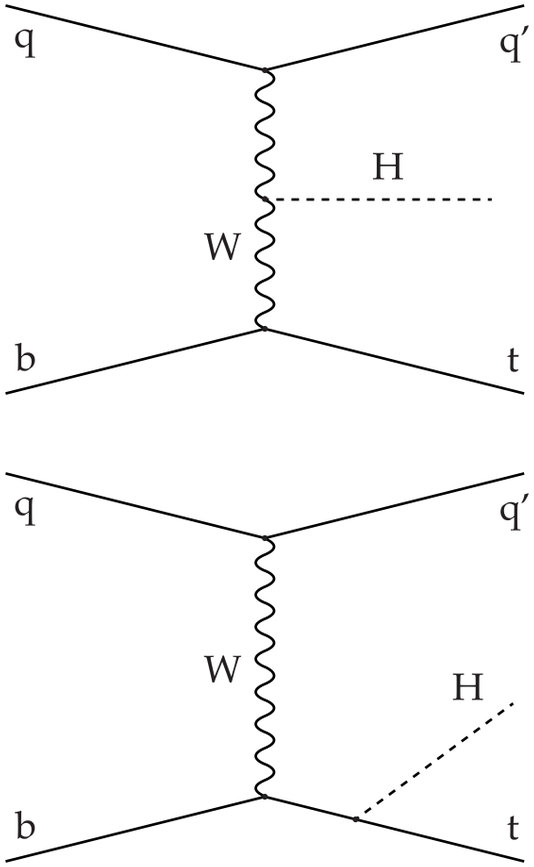
- Best fit signal strength
  - $\mu_{ttH} = 1.9^{+0.8}_{-0.7}$ - *ATLAS*
  - $\mu_{ttH} = 2.9^{+1.0}_{-0.9}$ - *CMS*
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ - *Combined*
    - significance - 4.4σ obs (2.0σ exp)
- Combined upper limits on σ/σ_{SM}
  - 3.2 obs (1.4 exp) - ATLAS
  - 4.5 obs (1.7 exp) - CMS



Combined μ_{ttH}

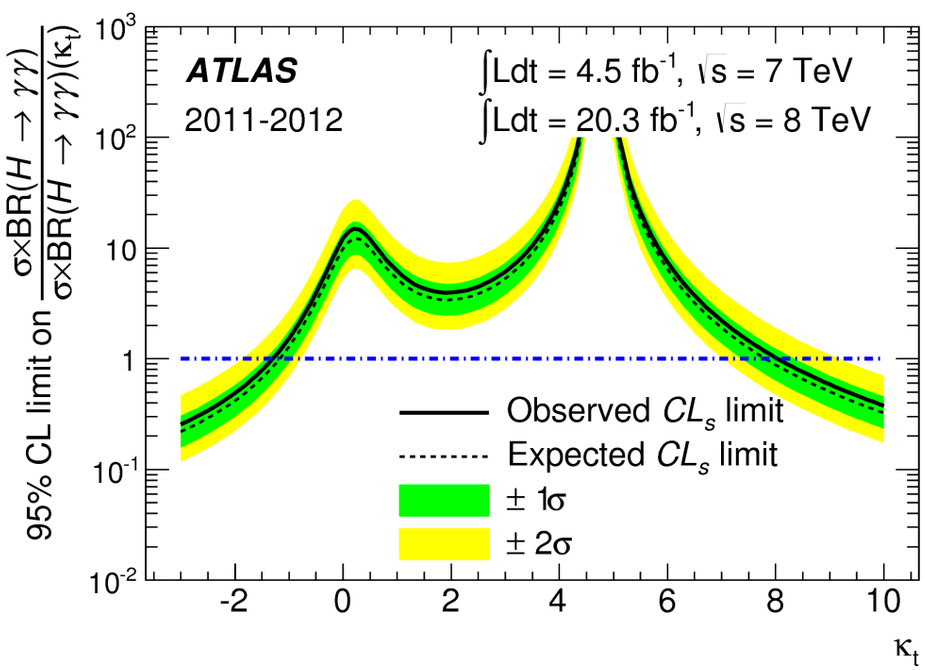
tHq

- 4 Analyses
  - tHq (H→γγ)
  - tHq (H→bb)
  - tHq (H→WW)
  - tHq (H→$\tau\tau$)

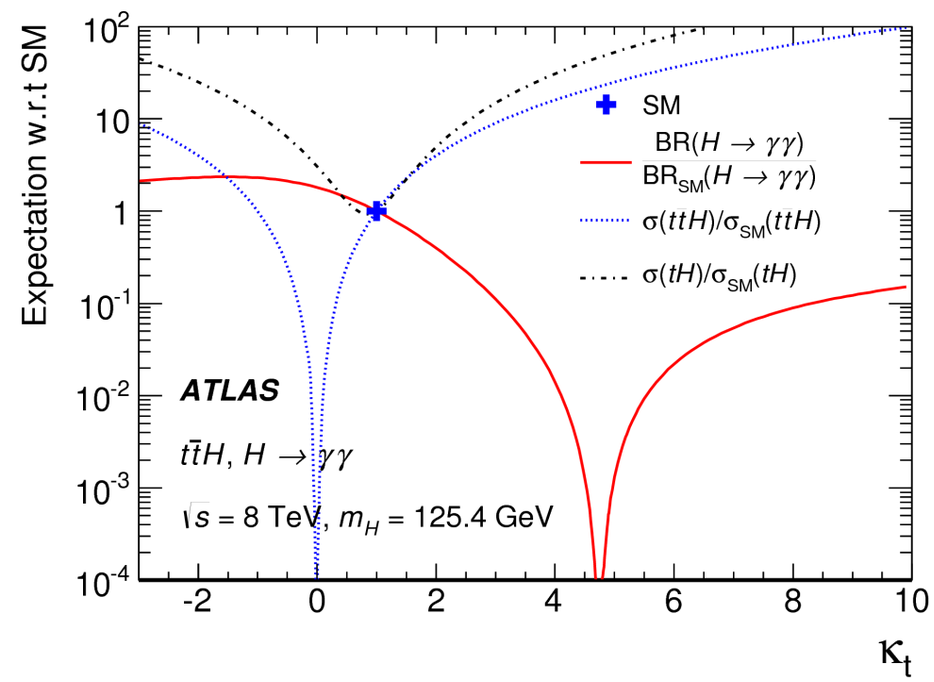


ttH (H→γγ), Interpretation

- Results can be interpreted in terms of limits on strength of top-Yukawa coupling, κ_t
  - At 95% CL: $-1.3 < \kappa_t < 8.0$,



Observed and expected 95% CL upper limits on production σ as function of κ_t



Production σ/σ$_{SM}$ for ttH and tH as function of κ_t
Also shows BR(H→γγ)/BR(H→γγ)$_{SM}$ as function of κ_t

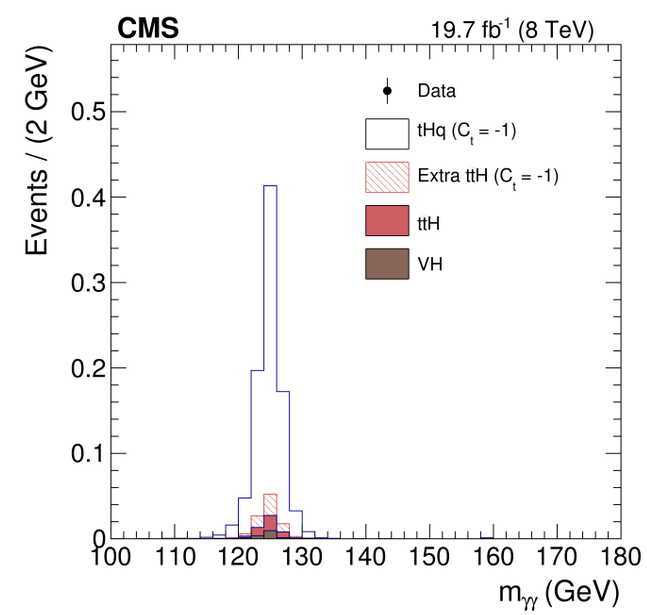
tHq (H→γγ)

- Very small branching ratio
- Single lepton (e/μ) final state
  - SR: ≥1j, ≥1b
- Major backgrounds
  - resonant - VH, ttH from MC
  - non-resonant - *γγ*+jets, *γ*+jets, tt*γγ*, t*γγ* from $m_{\gamma\gamma}$ sidebands
- A Bayes classifier - L(x) - is used to separate tH from ttH
  - 6 input variables, with <10% linear correlation
- No events pass selections

$$L(x) = \frac{L_S(x)}{L_S(x) + L_B(x)}$$

where $L^i(x) = \prod_j p^i_j(x^j)$

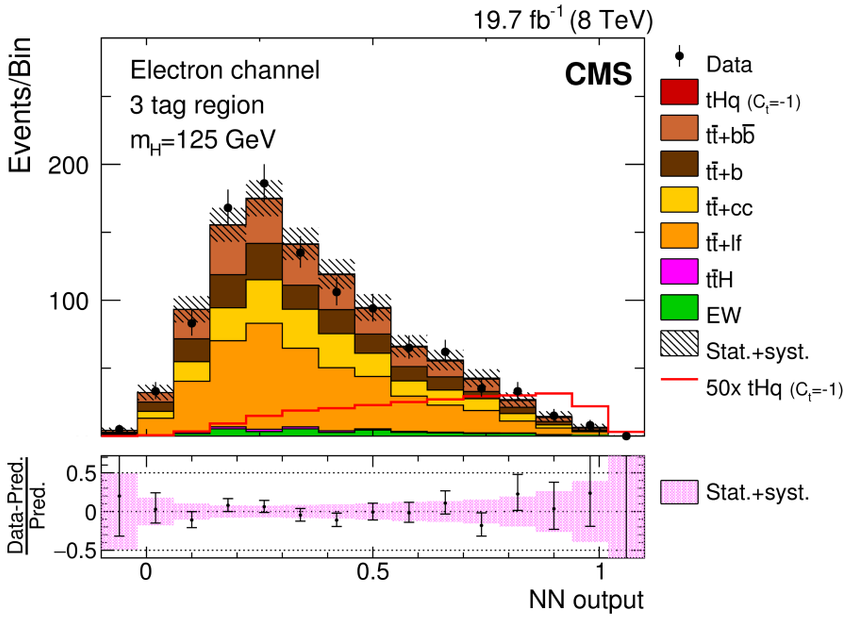
p_j - pdf , x_j - j-th observable

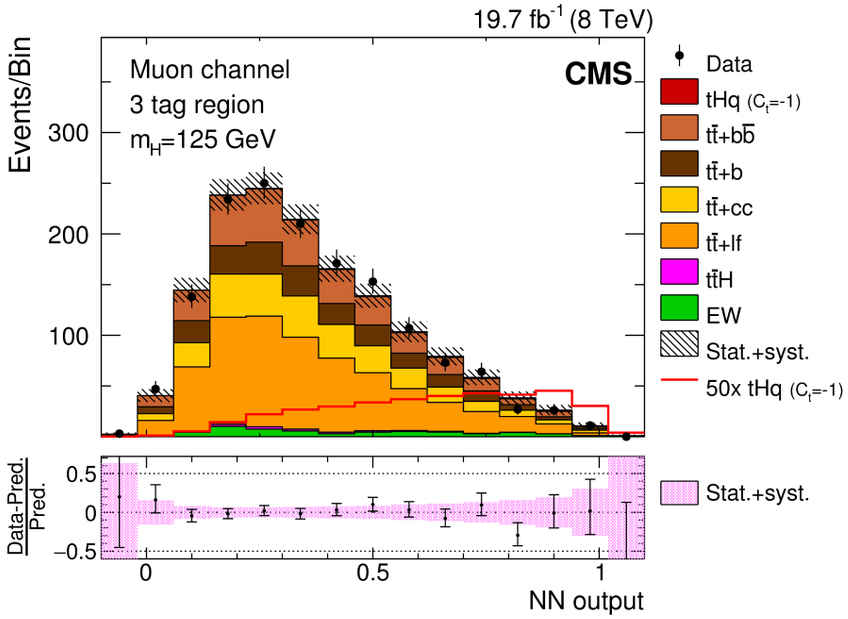


Process	Events
tHq ($C_t = -1$)	0.67
$t\bar{t}H$	$0.03 + 0.05^{\dagger}$
VH	$0.01 + 0.01^{\dagger}$
Other H	0
Data	0

tHq (H→bb)

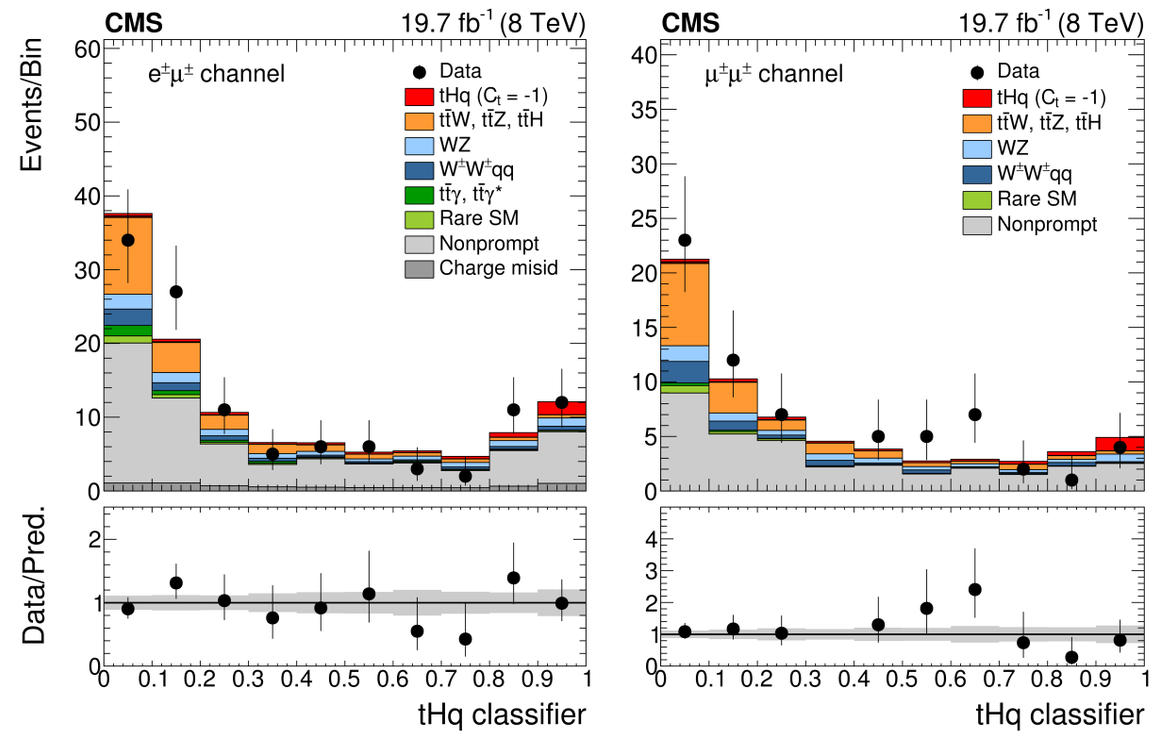
- Single lepton final state (tHq → 3bqlv) - categorized by lepton flavor (e/μ), N_{jets} and $N_{b\text{-}jets}$
  - SR: ≥ 4j, ≥3b
  - SR: ≥ 5j, ≥4b
- **tt** (tt → 2b2qlv) is dominant background
- Two NN are trained to match reconstructed jets and the final-state objects
  - under tH hypothesis
  - under tt hypothesis
  - select combination w/ highest NN score
- NN for final separation tH and tt
  - two sets of observables under tH and tt hypotheses + lep charge
- Perform simultaneous fit to the discriminant in all 4 channels

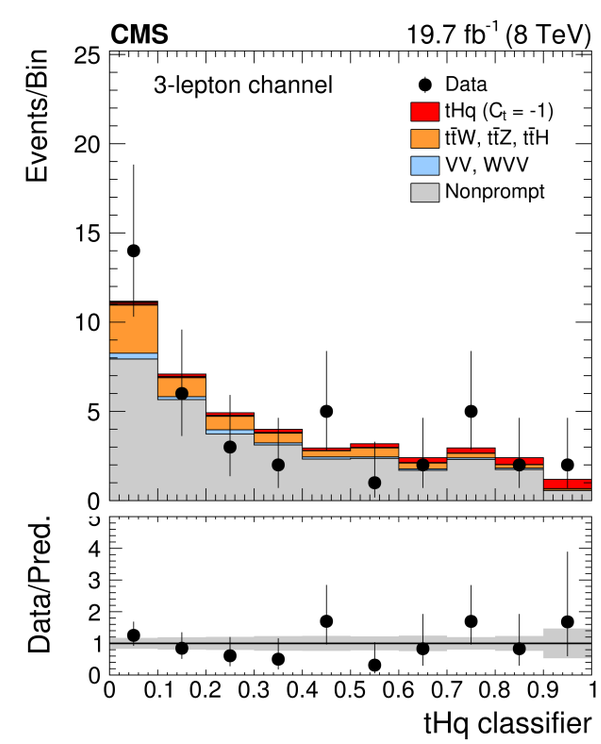




tHq (H→WW)

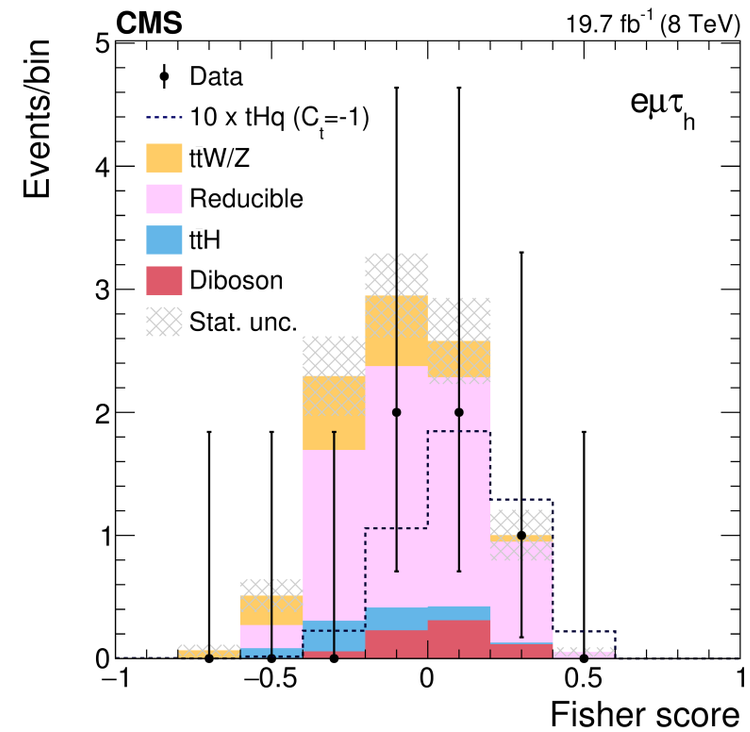
- Events are classified in N_ℓ
  - Categorized by N_{jets} and $N_{b\text{-}jets}$ to define SR and CR
- 2ℓSS - eμ + μμ
  - SR: =1j, =$1b_{loose}$
- 3ℓ
  - SR: =1j, =$1b_{medium}$
- Signal is extracted with MVA classifier similar to tH (H→γγ)
- Simultaneous maximum likelihood fit is performed in all 3 regions

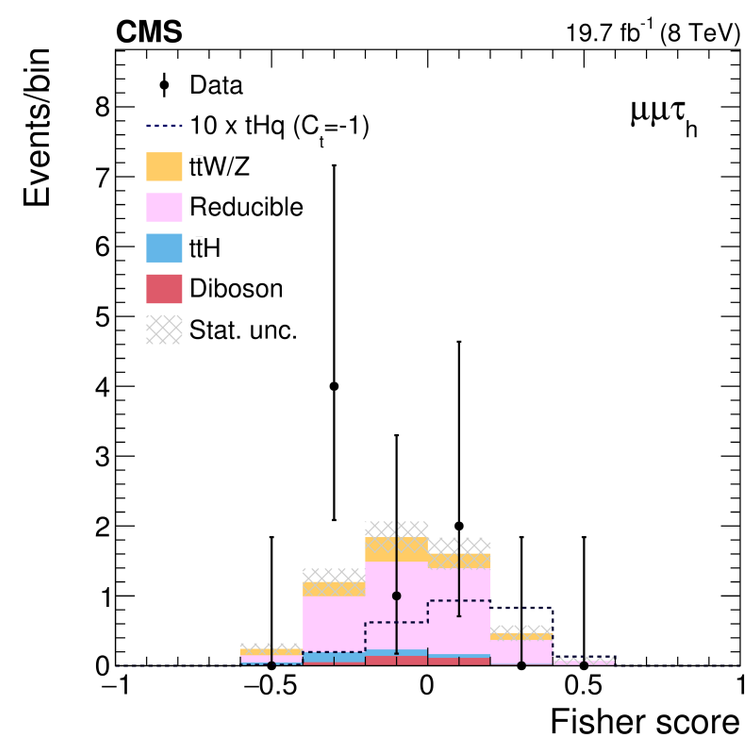




tHq (H→$\tau_\ell\tau_h$)

- Events classification - two channels
  - 2ℓSS+1τ_h (eμτ_h + μμτ_h)
    - leps are required tight lep MVA discriminant
    - τ_h - opposite charge to e and/or μ; id + iso req
    - ≥1j, ≥1b_{medium}
- Dominant backgrounds
  - irreducible - WZ, ZZ, ttH, and tt + W/Z
  - reducible - non-prompts estimated from data
- Fisher discriminant from TMVA used for signal extraction
  - trained on 10 variables
- Simultaneous maximum likelihood fit of the Fisher discriminant distributions in 2 channels



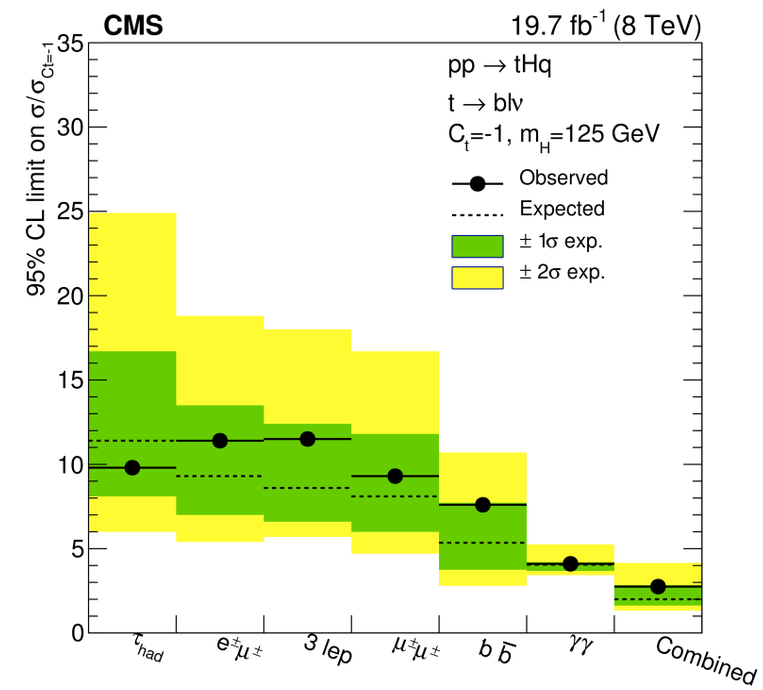


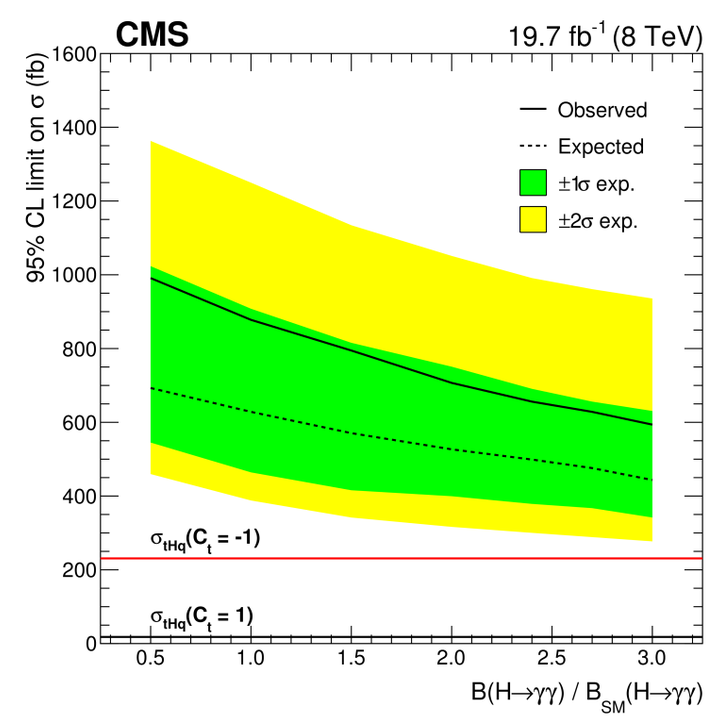
tH, Results

- Simultaneous fit to the discriminants is performed to estimate signal strength and exclusion upper limits set on $\sigma(C_t = -1)$ @ 95 CL

tHq channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{C_t=-1}$		
	Observed	Expected		
		Median	68% CL range	95% CL range
$\gamma\gamma$	4.1	4.1	[3.7, 4.2]	[3.4, 5.3]
$b\bar{b}$	7.6	5.4	[3.8, 7.7]	[2.8, 10.7]
Multilepton	6.7	5.0	[3.6, 7.1]	[2.9, 10.3]
$\tau\tau$	9.8	11.4	[8.1, 16.7]	[6.0, 24.9]
Combined	2.8	2.0	[1.6, 2.8]	[1.2, 4.1]

The observed and expected 95% CL upper limits on μ





- μ_{tH}= 2.8 - *Combined*
- No evidence of new physics

Summary

Summary

- ttH and tH searches have been performed in all main Higgs decay modes at LHC - ATLAS & CMS - 7 and 8 TeV
  - $\mu_{ttH} = 2.3^{+0.7}_{-0.6}$ - *LHC combination*
  - $\mu_{tH} = 2.8$ - *CMS; ATLAS included in ttH search*
- *Most of the searches are statistically limited*

Plans

- Run-II cross-section at 13 TeV - $4x\sigma_{ttH}$, $4x\sigma_{tH}$,, $3.3x\sigma_{tt}$
- Ongoing work to optimize analyses for Run-II data
- *Sensitivity is quickly rising*

Back-up

ttH (H→bb), MEM+NN

- Two channels analyzed - SL and DL
  - Categorized by N_{jets} and $N_{b\text{-}jets}$
  - Major background - tt+jets, tt+bb (Powheg+Pythia)