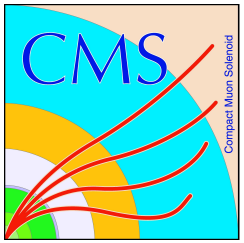
Rare SM processes: $t\bar{t}H$, tH

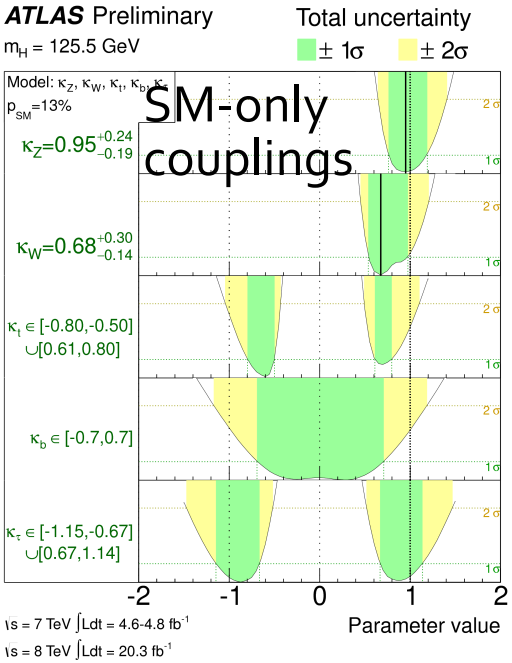
Peter Onyisi, for the ATLAS and CMS collaborations

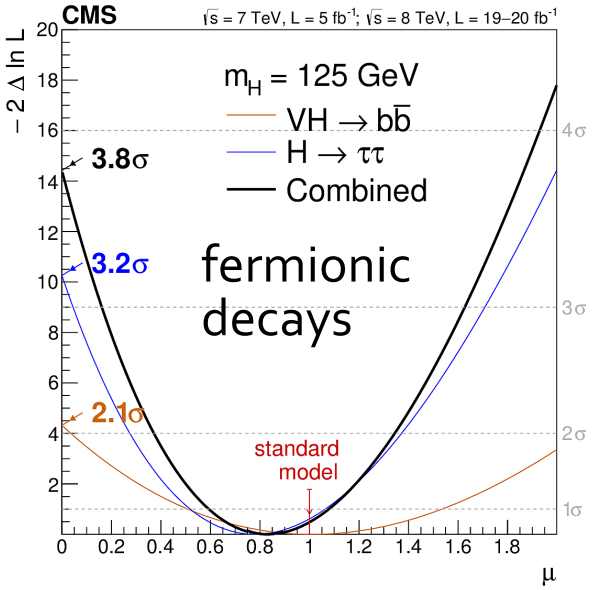
BSM Higgs@LPC Workshop, 4 Nov 2014

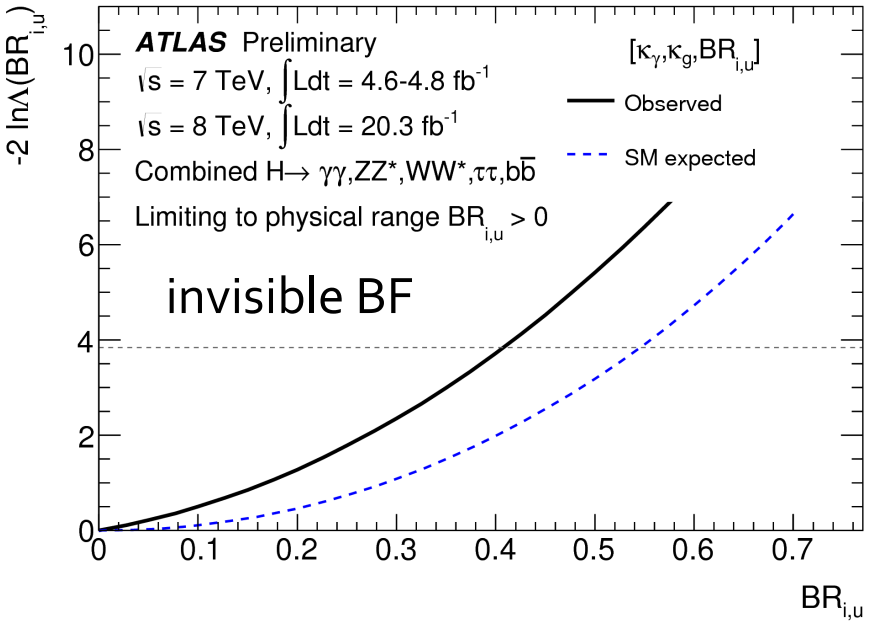


The Story of a New Particle

- A new particle observed at ~ 125 GeV.
  - No radical departure from SM Higgs boson, but errors still large: (model-dependent!) constraints on couplings of order ~ 15%
  - Does it couple to the SM particles as it should? Does it couple to anything else?

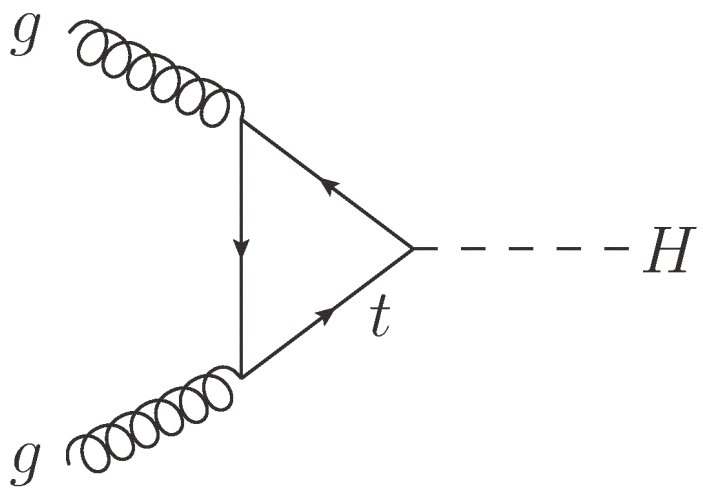






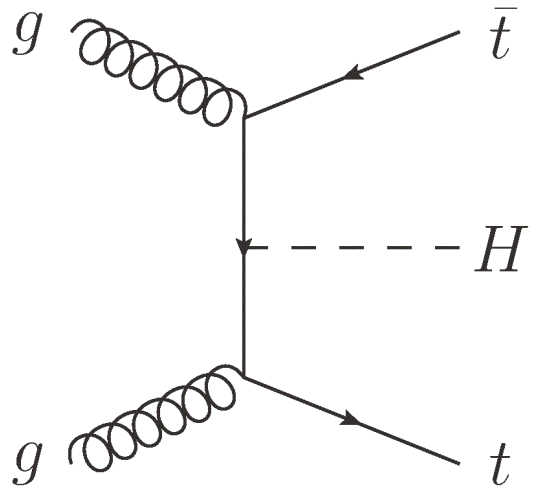
How to measure the Top-Higgs Coupling

- Highest rate way: gg ⟶ H through top loop
- Effects of top are not distinguishable from new physics in gg ⟶ H
- A tree-level measurement is possible: pp ⟶ $t\bar{t}H$



@ 8 TeV: 19 pb
@ 13 TeV: 44 pb

NNLL+NNLO QCD
+ NLO EW



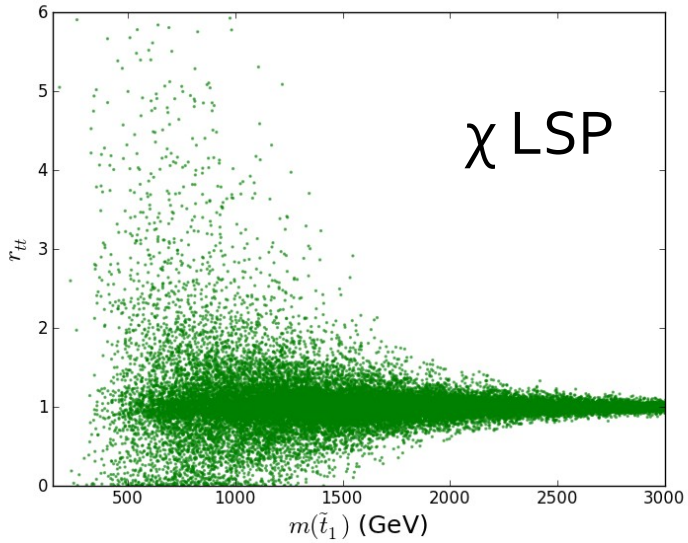
130 fb
510 fb

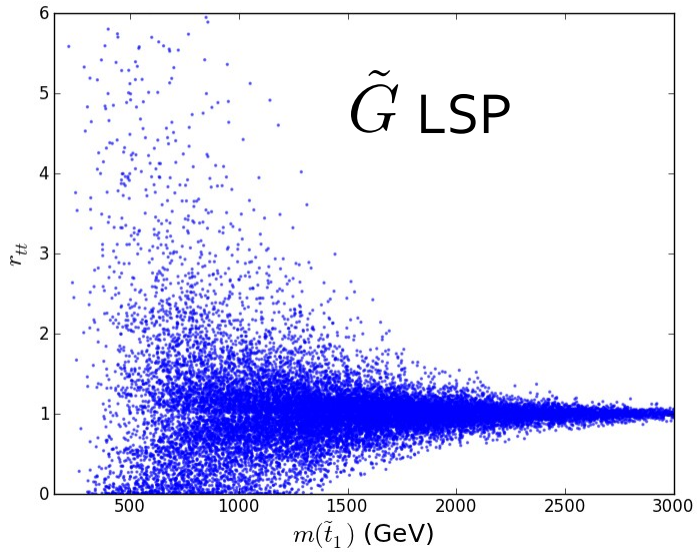
NLO QCD

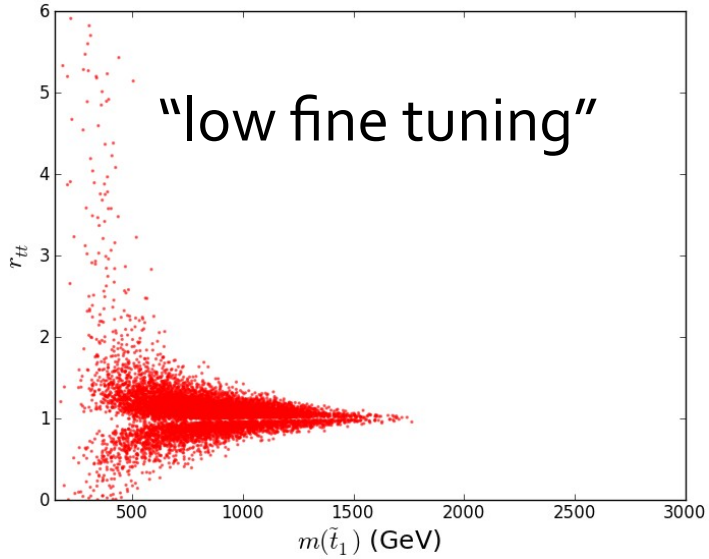
$t\bar{t}H$ in MSSM

- Scans of "phenomenological MSSM" models surviving experimental constraints: $t\bar{t}H$ rate potentially strongly modified

  Cahill-Rowley, Hewett, Ismail, Rizzo
  arxiv:1308.0297



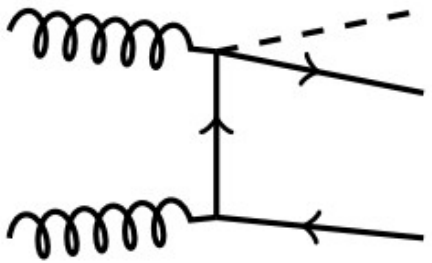




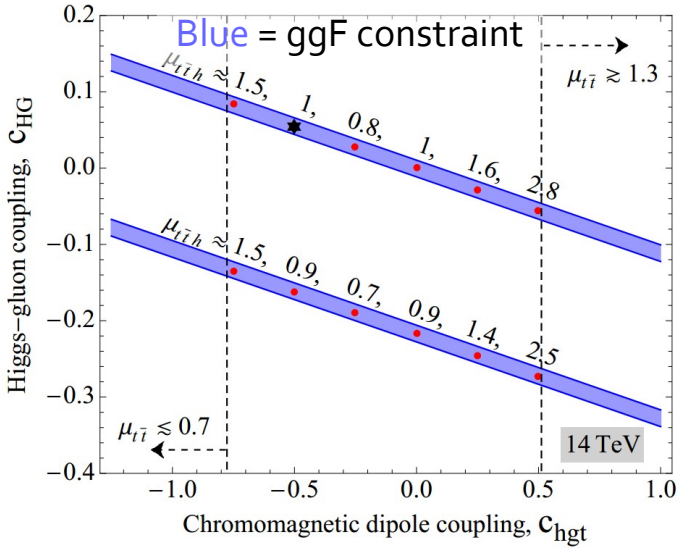
$t\bar{t}H$ + EFT

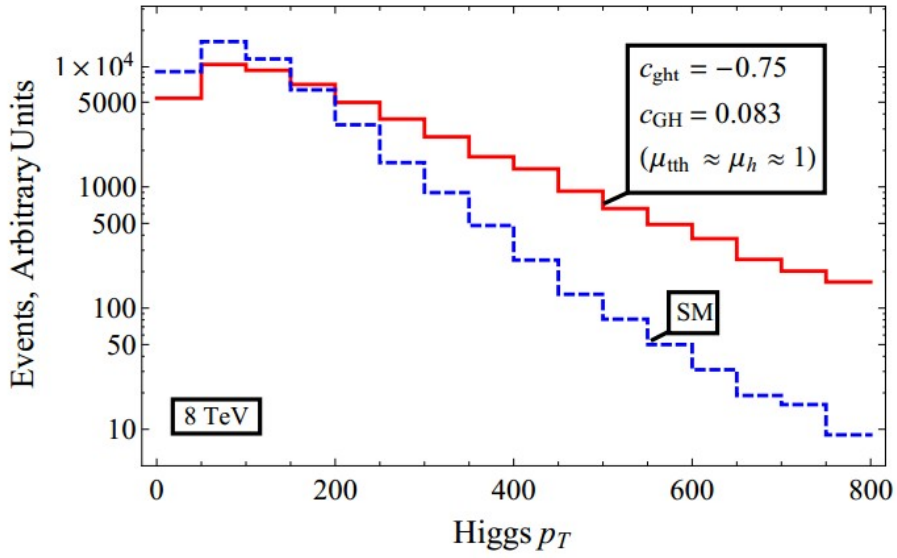
- Higher dimensional operators can affect $t\bar{t}H$ rates
  - top-fermion operators typically badly constrained by EW precision measurements
- Potential to change kinematics of $t\bar{t}H$ production – e.g. chromomagnetic dipole operator

$$\mathcal{O}_{hgt} = \frac{c_{hgt}}{\Lambda^2}(\bar{Q}_L H)\sigma^{\mu\nu}T^a t_R G^a_{\mu\nu}$$



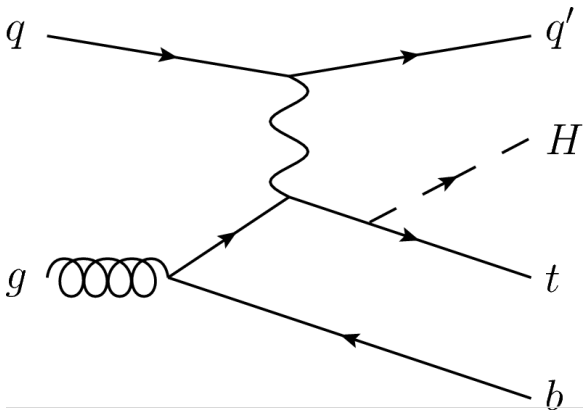
Bramante, Delgado, Martin
arxiv:1402.5985

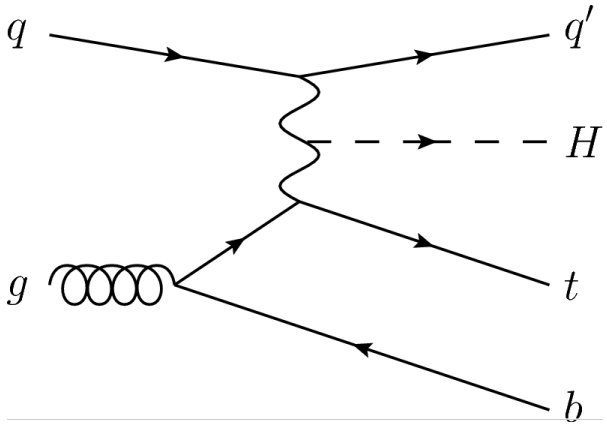


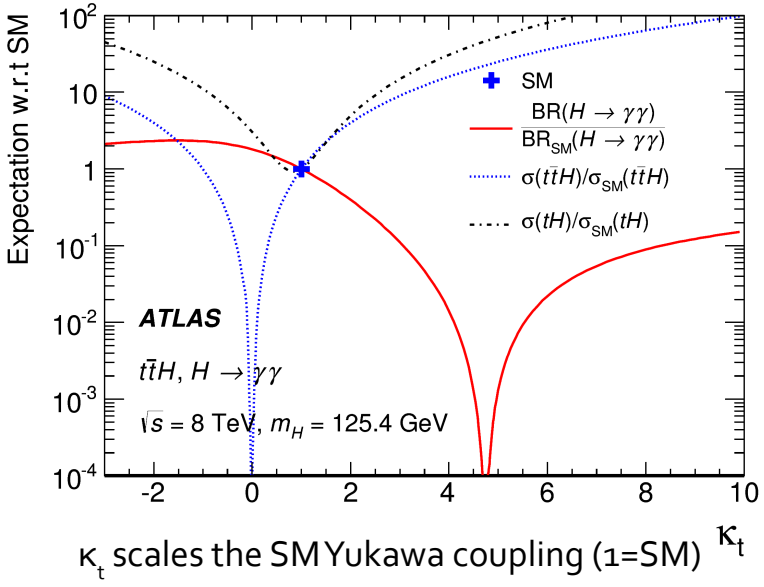


tH

- SM has destructive interference between H emission from top and from W: if relative sign of top coupling flips, have large constructive interference
- Can resolve sign ambiguity between fermionic and bosonic Higgs couplings
  - interesting interplay with Br(H → γγ), which also depends on HWW/Htt̄ interference





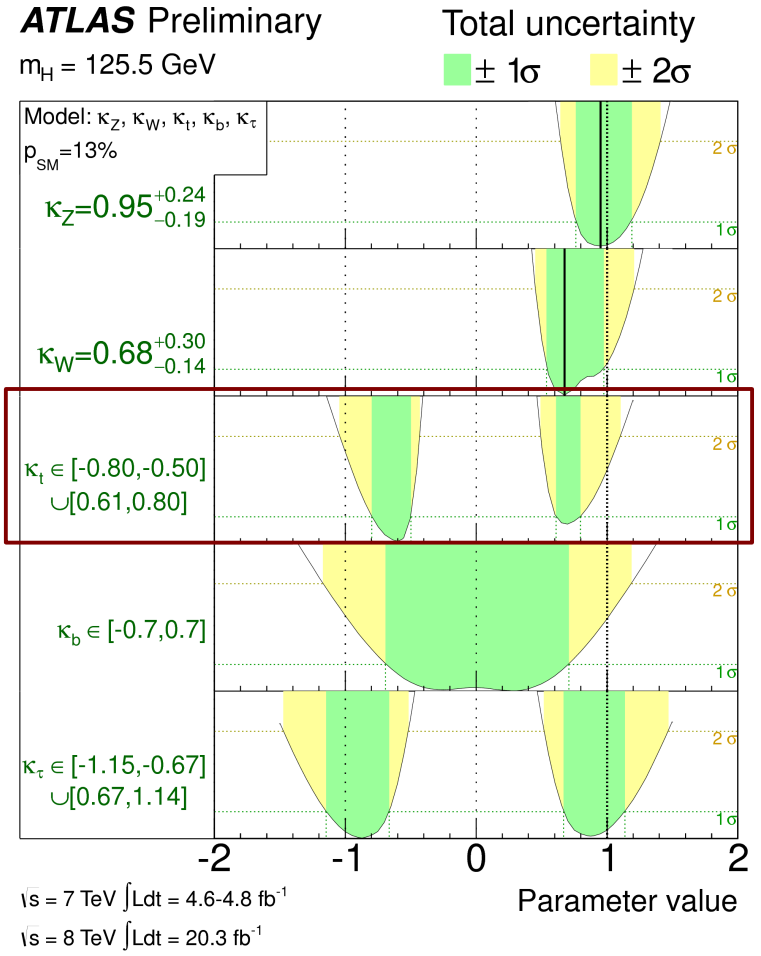


Constraints on Higgs Couplings

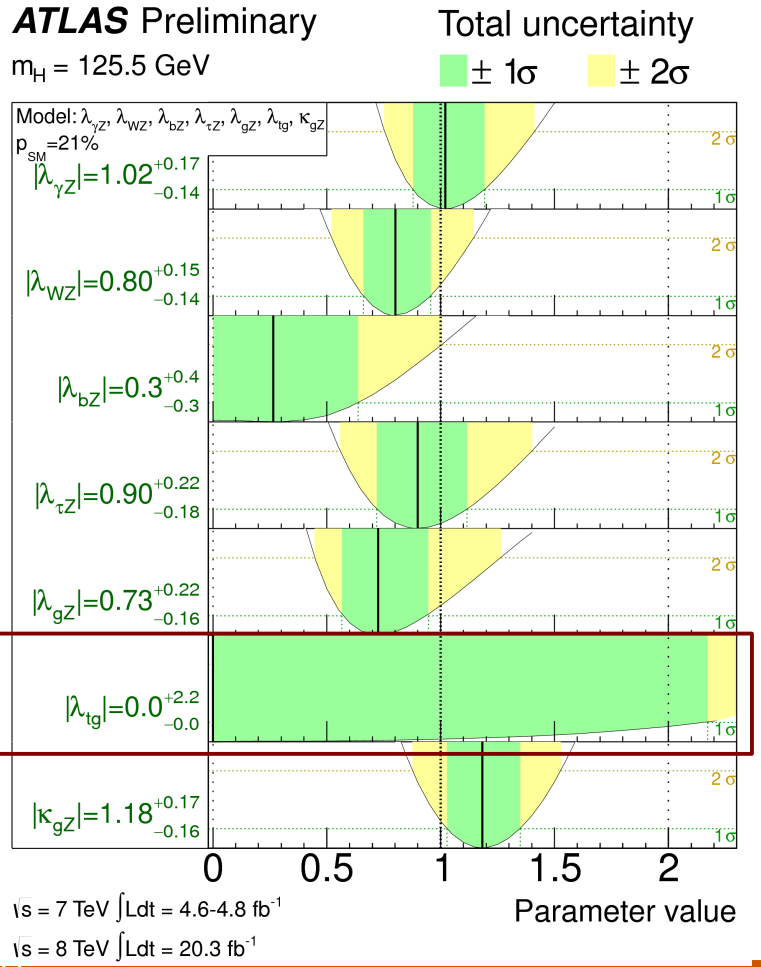
- Without $t\bar{t}H$, unable to simultaneously constrain top coupling and new physics in ggF loop

ATLAS-CONF-2014-009

SM particles only



Allowing new particles in loops



$t\bar{t}H$ Signatures

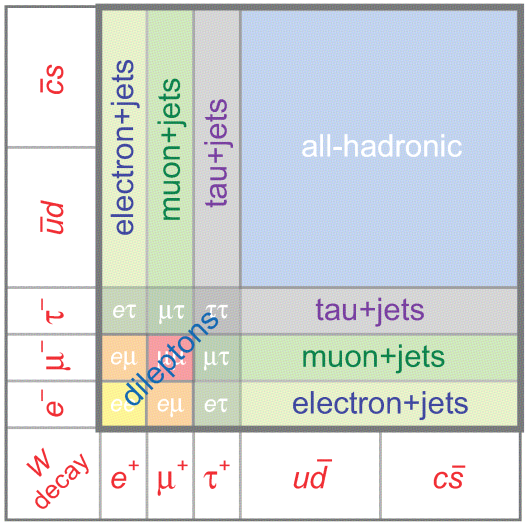
- Generic signature is top pair + a Higgs decay
  - $H \to \gamma\gamma$ has a narrow bump
  - $H \to b\bar{b}$ has a large rate
  - $H \to WW$, $H \to \tau\tau$ produce multilepton events
  - $H \to ZZ \to 4\ell$ has too low a rate

Results to show

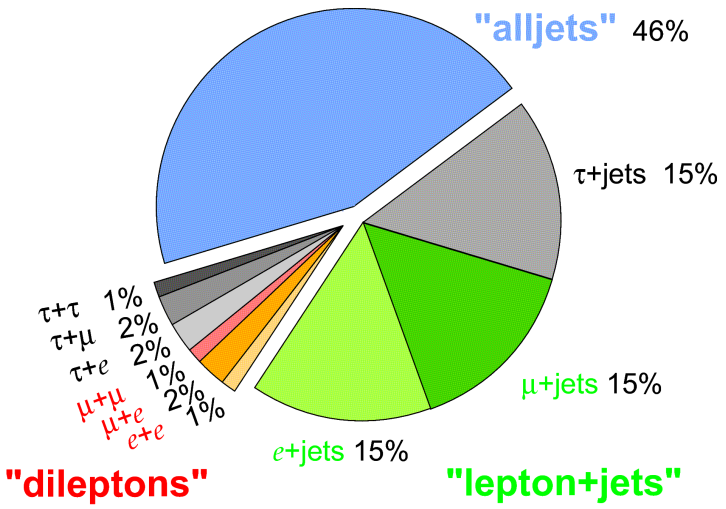
CMS results from *JHEP 09 (2014) 087* unless otherwise noted

- Top quark pair can be dileptonic, semileptonic ("lepton+jets"), or all hadronic
  - dileptonic with e and μ ~ 4% of $t\bar{t}$ decays
  - all hadronic must be separated from pure QCD multijet events

Top Pair Decay Channels



Top Pair Branching Fractions



$t\bar{t}H$, $H \rightarrow \gamma\gamma$

- Main challenge is to reduce contamination from other Higgs production modes
  - A bump at 125 GeV is a Higgs: but is it $t\bar{t}H$?
- Split by top pair decays:
  - lepton + jets: lepton and b-tag requirement enough to remove all other major Higgs production mechanisms
  - all hadronic: contaminated by gluon-gluon fusion. Require high #jets to improve purity of observed signal

CMS: JHEP 09 (2014) 087
ATLAS: arxiv:1409.3122

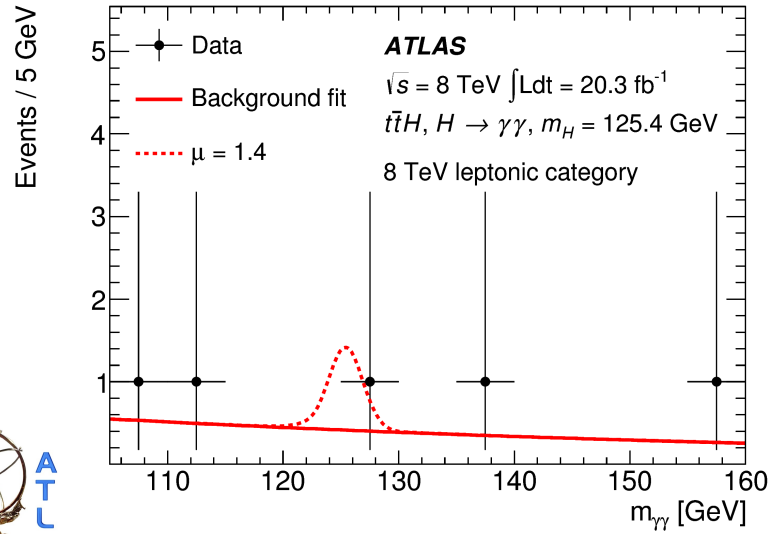
leptonic

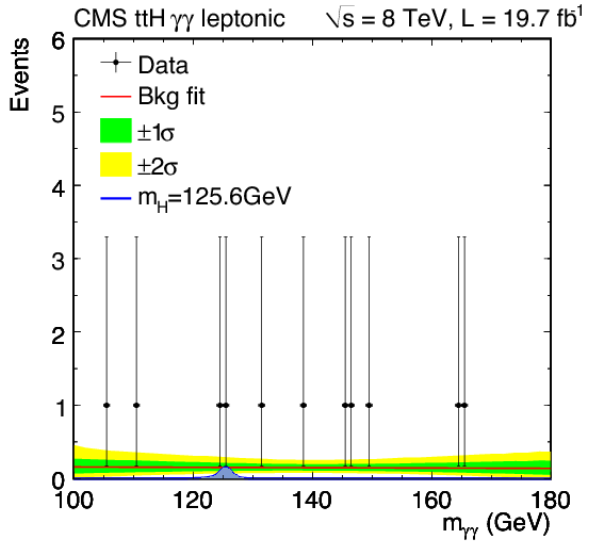
	CMS	ATLAS
leptons	≥1 lep : 20 GeV	≥1 lep: 15 GeV (e) or 10 GeV (μ)
jets	≥ 2j @ 25 GeV, ≥ 1 b @ 70%	≥ 1j @ 25 GeV, ≥ 1b @ 80%

hadronic

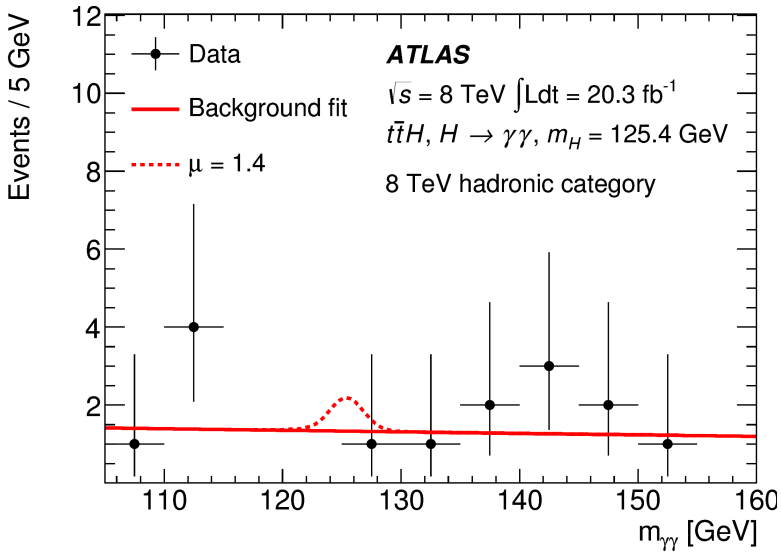
	CMS	ATLAS
leptons	0 lep : 20 GeV	0 lep: 15 GeV (e) or 10 GeV (μ)
jets	≥ 4j @ 25 GeV, ≥ 1 b @ 70%	≥ 6j @ 25 GeV, ≥ 2b @ 80% OR ≥ 5j @30 GeV, ≥ 2b @ 70% OR ≥ 6j @30 GeV, ≥ 1b @ 60%

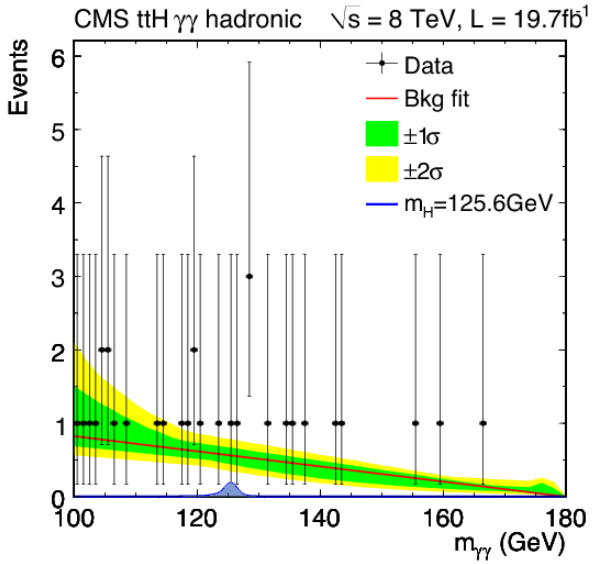
H → γγ





O(1) H → γγ event expected in both analyses





95% limits (obs, exp) x σ(SM)

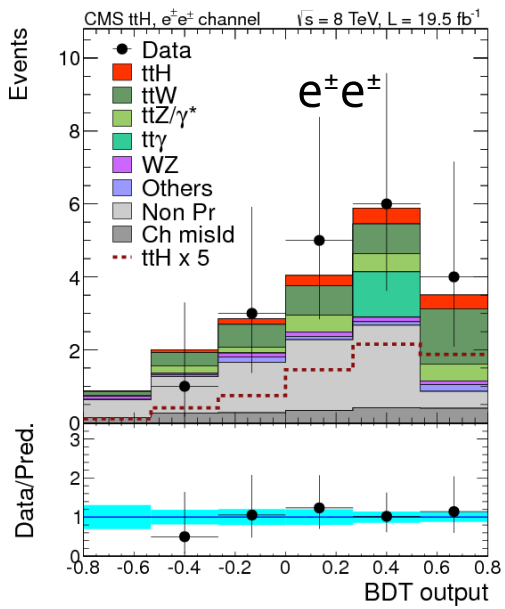
ATLAS	CMS
6.7 (4.9)	7.4 (4.7)

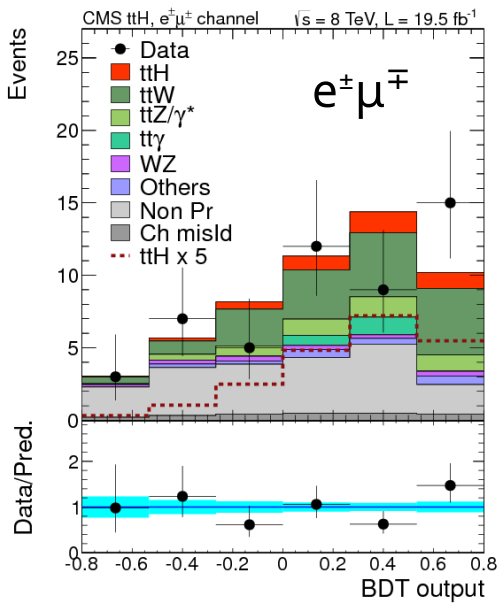
Multileptonic $t\bar{t}H$

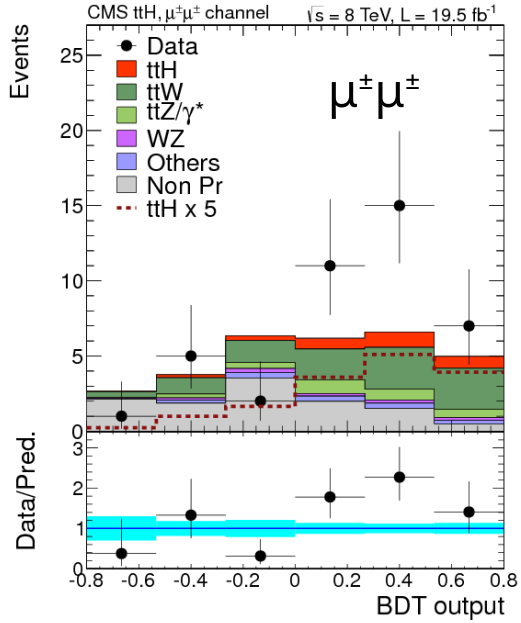
- Target $H \rightarrow WW, \tau\tau, ZZ$ decays
- Use signatures not available in $t\bar{t}$ decay: 2 same sign leptons, 3 leptons, 4 leptons
  - main backgrounds are $t\bar{t}$ with fake leptons, $t\bar{t}W$, $t\bar{t}Z$
  - 2 and 3l use event BDT, 4l fits in # jets
- 2l: both leptons ≥ 20 GeV; ≥ 4 jets; ≥ 1 b-jet
- 3l: leptons ≥ (20, 10, 7[e]/5[μ]) GeV; ≥ 2 jets; ≥ 1 b-jet
- 4l: leptons ≥ (20, 10, 7/5, 7/5) GeV; ≥ 2 jets; ≥ 1 b-jet

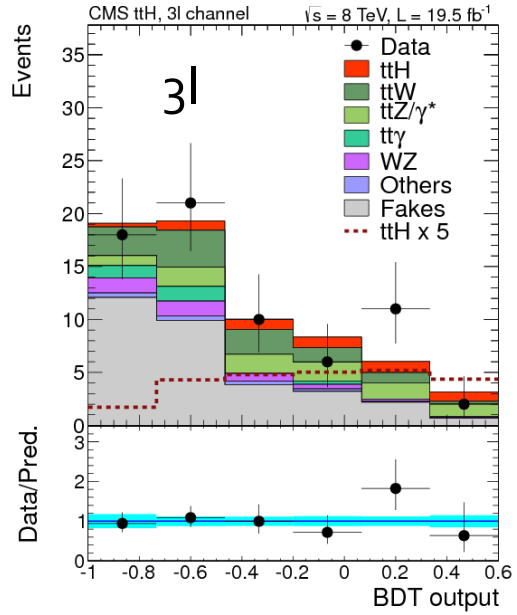
JHEP 09 (2014) 087

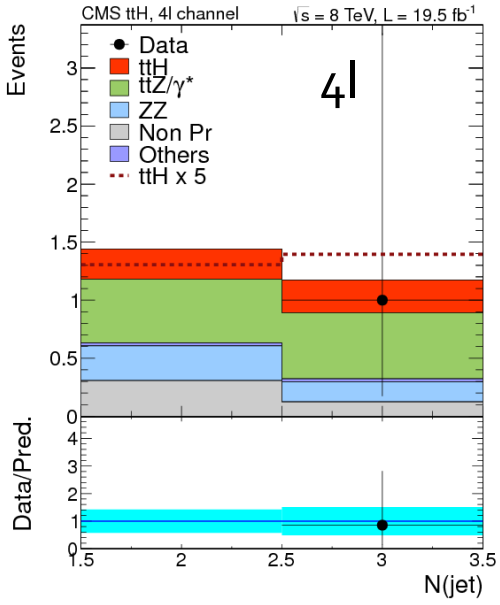
Multilepton Channels











95% limit obs (exp) xσ(SM)

2l SS	9.0 (3.4)
3l	7.5 (4.1)
4l	6.8 (8.8)

- 2l SS is expected to be single most sensitive $t\bar{t}H$ channel
- Excess in $\mu^{\pm}\mu^{\pm}$ pulls entire $t\bar{t}H$ combination
- Investigations show no apparent problems with dimuon events

Many control plots: CMS-PAS-HIG-13-020

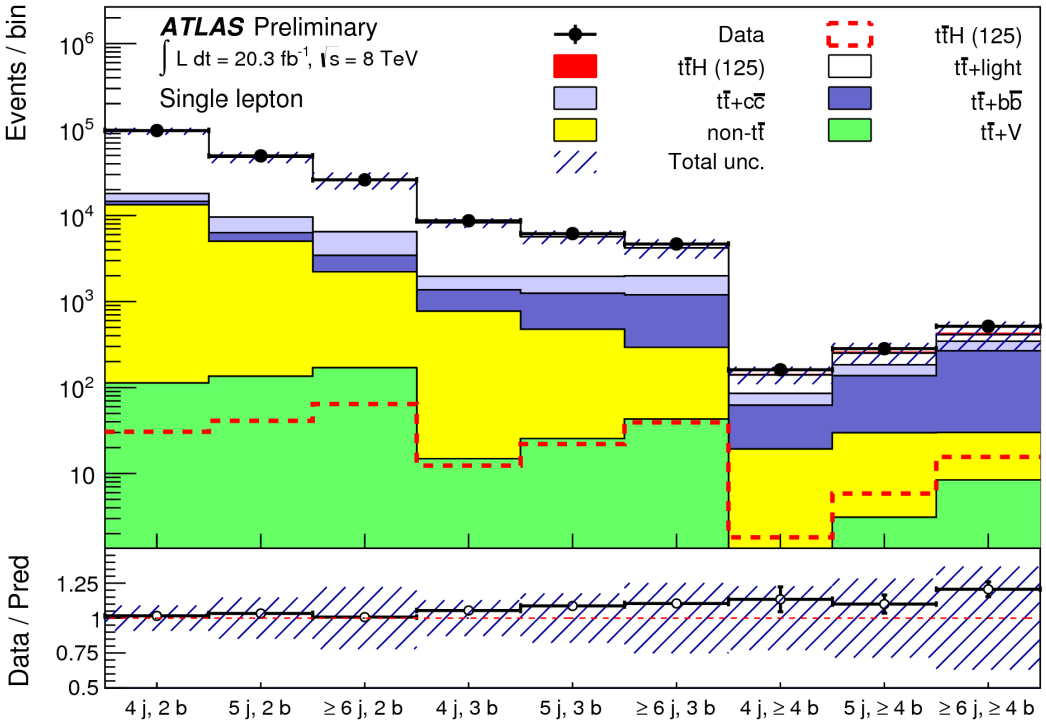
H → bb/hadrons

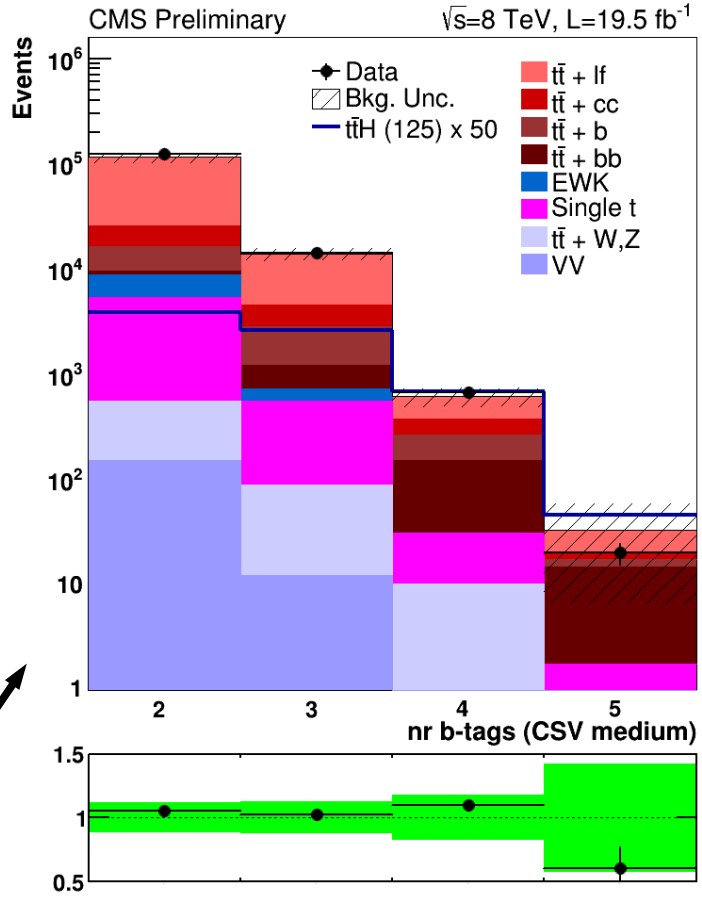
- Analyses primarily target H → bb: large rate
  - lepton+jets, dileptonic top decays reported so far
- Dominant background is QCD $t\bar{t}$+$b\bar{b}$, not under full theoretical control yet
  - background modeling needs the right degrees of freedom, especially when using complex MVAs
  - Different simulations for ATLAS (Powheg+Pythia 6) and CMS (Madgraph+Pythia 6)
- Construct MVAs in various bins of jet and b-jet multiplicity, simultaneously fit regions
  - constrain nuisance parameters
- CMS also does a search for H → $\tau_h\tau_h$ (lower b-jet multiplicity)

CMS: JHEP 09 (2014) 087
ATLAS: ATLAS-CONF-2014-011

Pre-fit Distributions

- Good quality MC
- Best S/B in ≥ 6j, ≥ 4b (l+jets) and ≥ 4j, ≥ 4b (dilepton)





l+jets

H → bb analysis bins

l+jets

	2b	3b	≥ 4b
4j			
5j			
≥ 6j			

dilepton

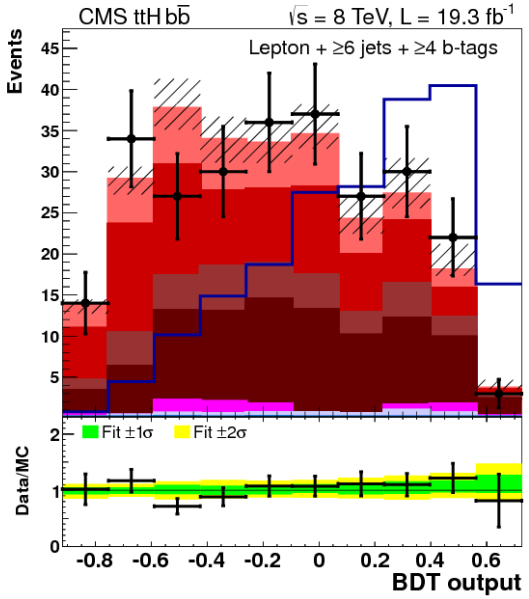
	2 b	3b	≥ 4b
2j			
3j			
≥ 4j			

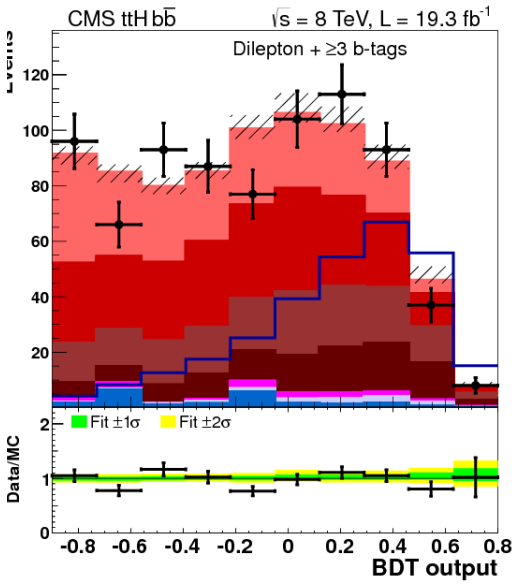
	2b	3b	≥ 4b
4j			
5j			
≥ 6j			

	2 b	3b	≥ 4b
2j			
3j			
≥ 4j			

CMS analysis has higher p_T thresholds for jets than the ATLAS one

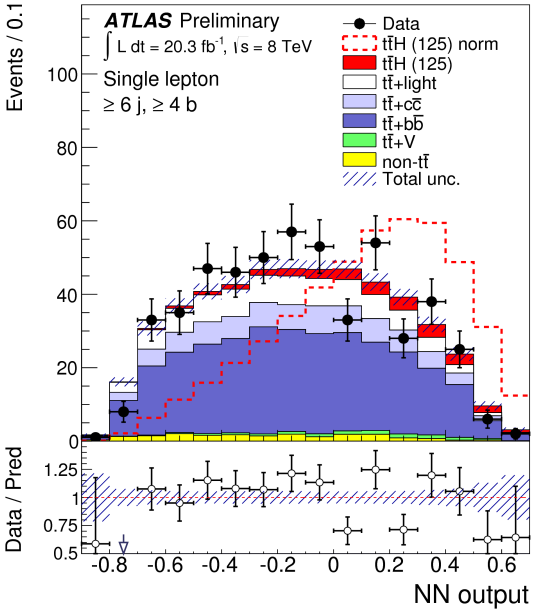
H → bb Results

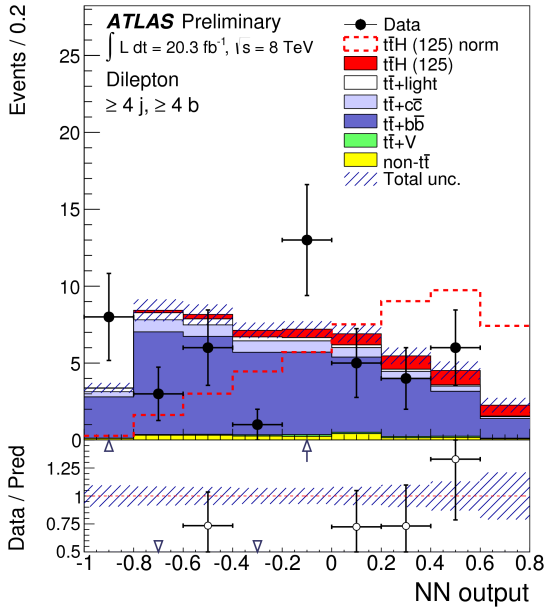


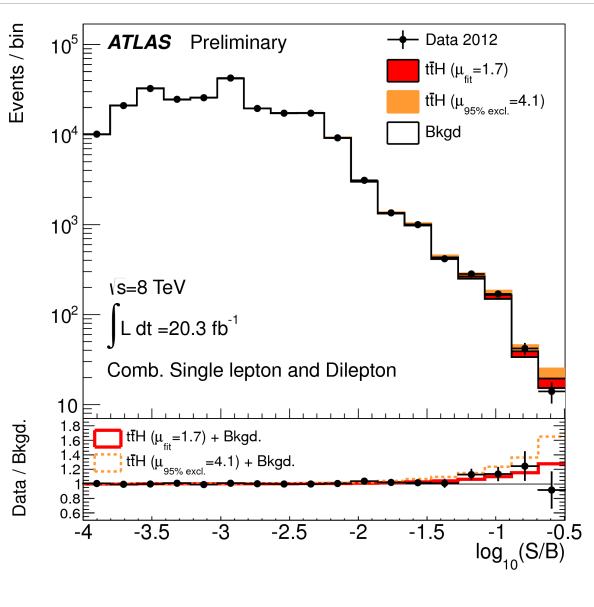


95% limits: observed (expected) x σ(SM)

	ATLAS	CMS
combined	4.1 (2.6)	4.1 (3.5)

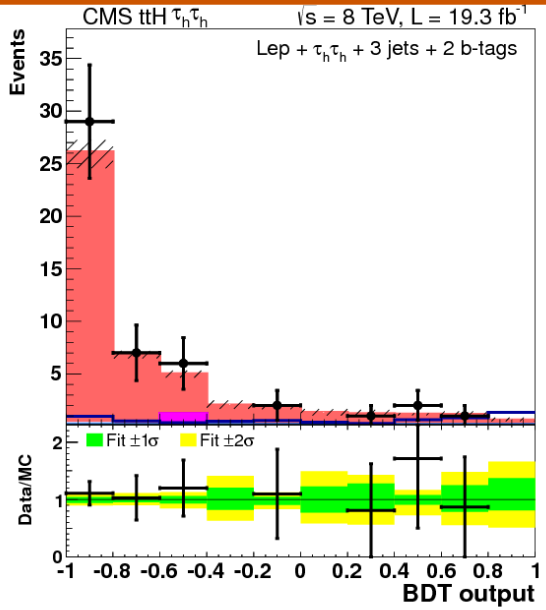


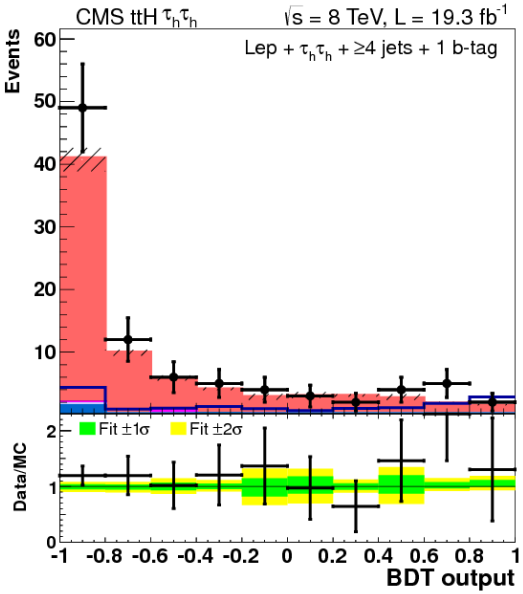


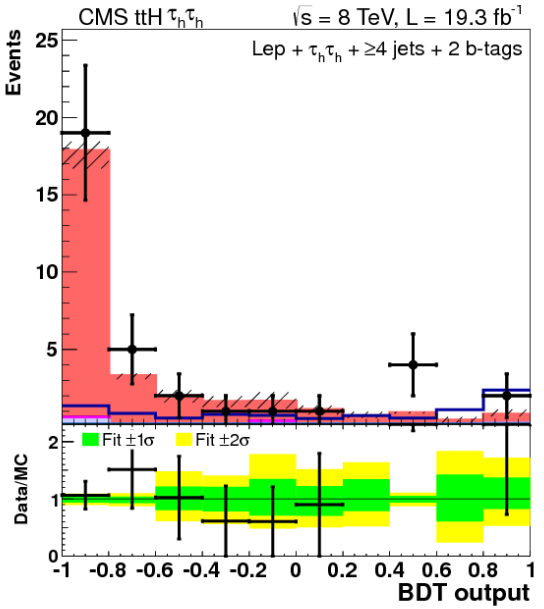


$H \rightarrow \tau_h \tau_h$

- Done with l+jets tt decay
- ~2.1 total signal events expected
- Show high sensitivity channels here
- 95% limit: 13.0 obs (14.2 exp) x σ(SM)



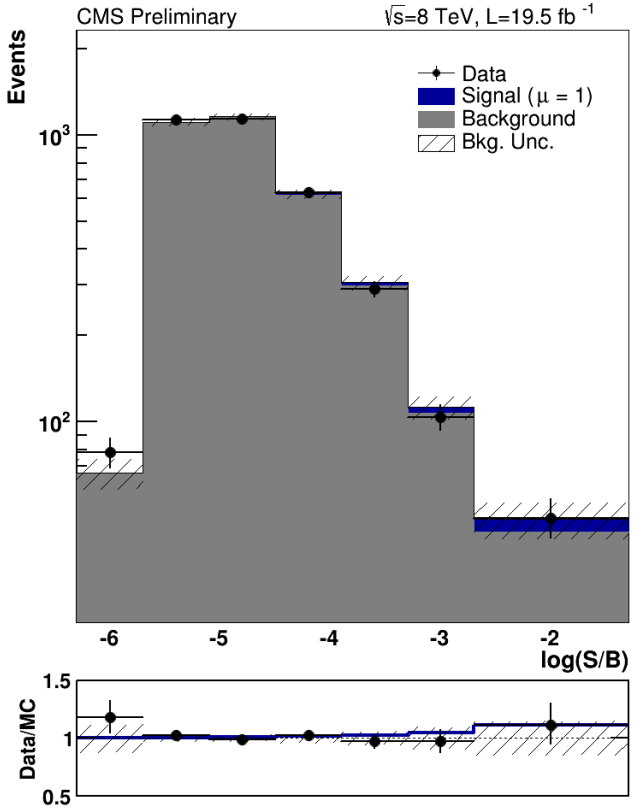


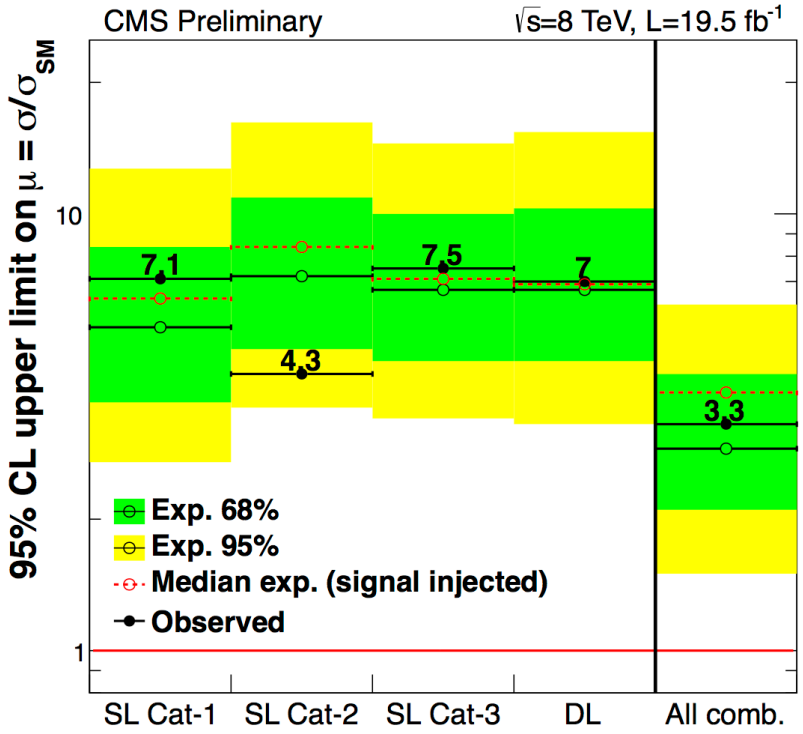


H → bb Matrix Element

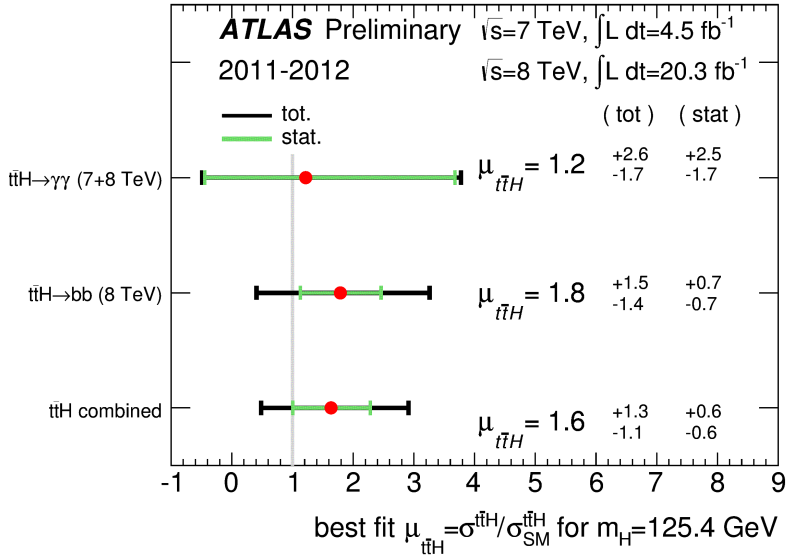
- Another approach to discriminating $t\bar{t}H$ from $t\bar{t}bb$: matrix element method
- Tighter limit than BDT analysis

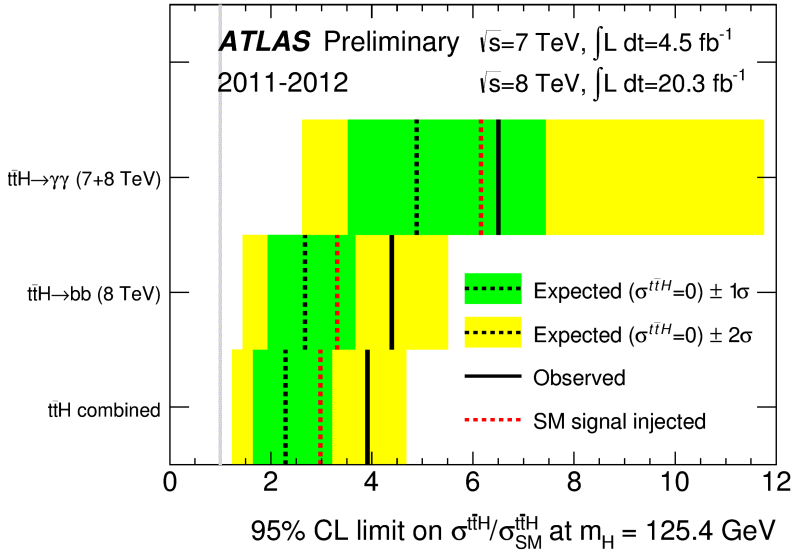
CMS-PAS-HIG-14-010

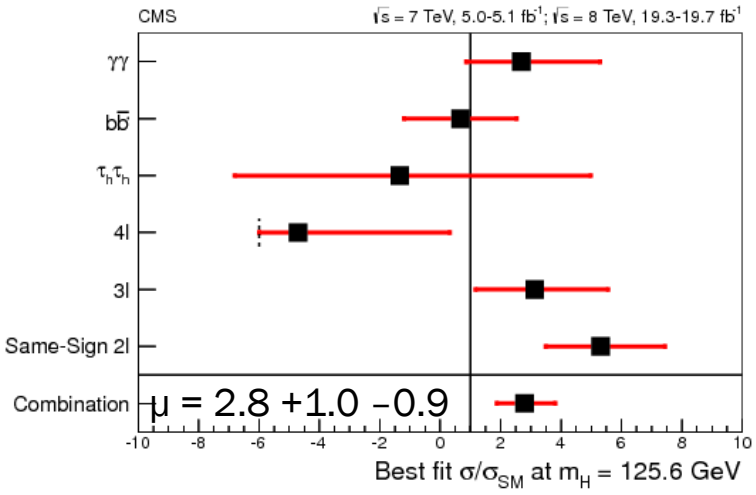


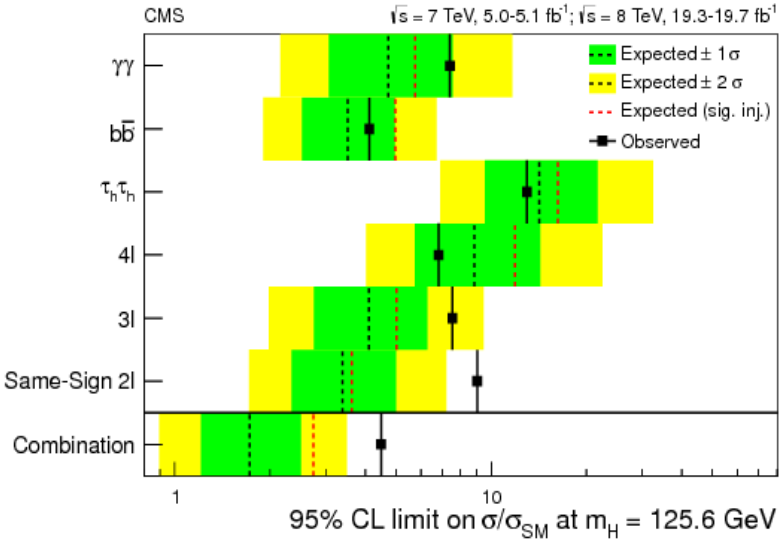


$t\bar{t}H$ Combination/Summary





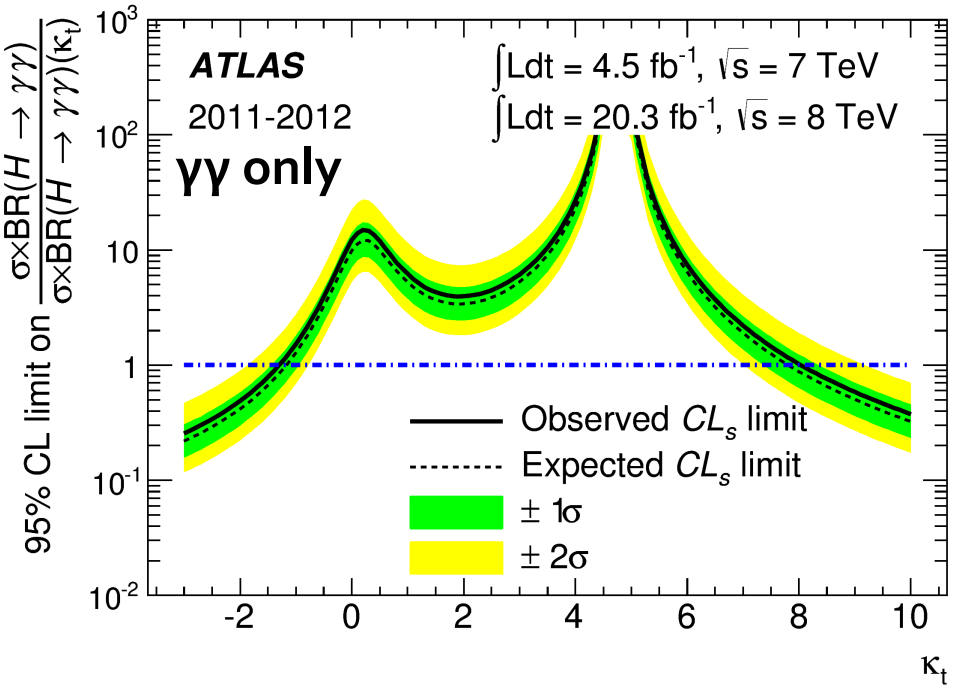


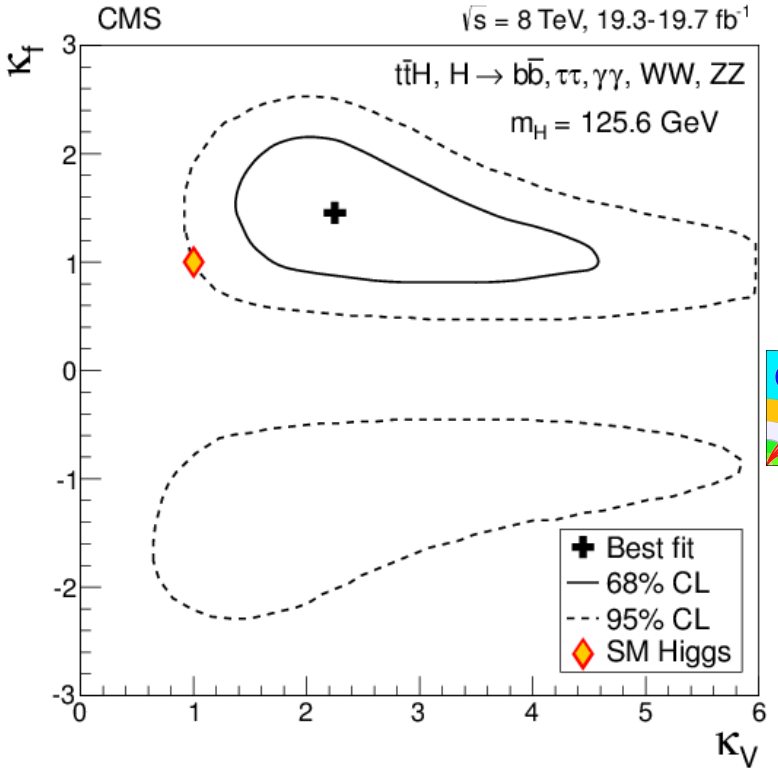


CMS errors already at ~ SM expectation

$t\bar{t}H$ Couplings Interpretation

- $t\bar{t}H$ can access many couplings simultaneously
  - can do κ_f vs κ_v scan
- Sign flip of top Yukawa coupling disfavored



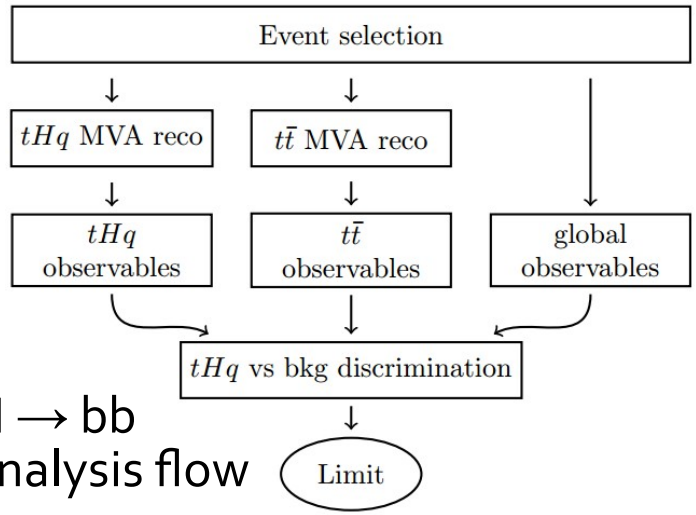


How to look for tH?

- Fewer jets than $t\bar{t}H$
- Typically a forward jet (for same reason as in VBF)
- CMS analyses:
  - diphoton: 1 lepton, 1 b-jet, hardest additional jet has $|\eta| > 1$. Likelihood used for $t\bar{t}H$ rejection *CMS-PAS-HIG-14-001*
  - $H \rightarrow bb$: 1 lepton; categories ≥4j, ≥3b / ≥5j, ≥4b. Reconstruction under signal, bkg hypotheses via NN, then signal classification *CMS-PAS-HIG-14-015*

95% CL limits
x $\sigma(\kappa_t = -1)$

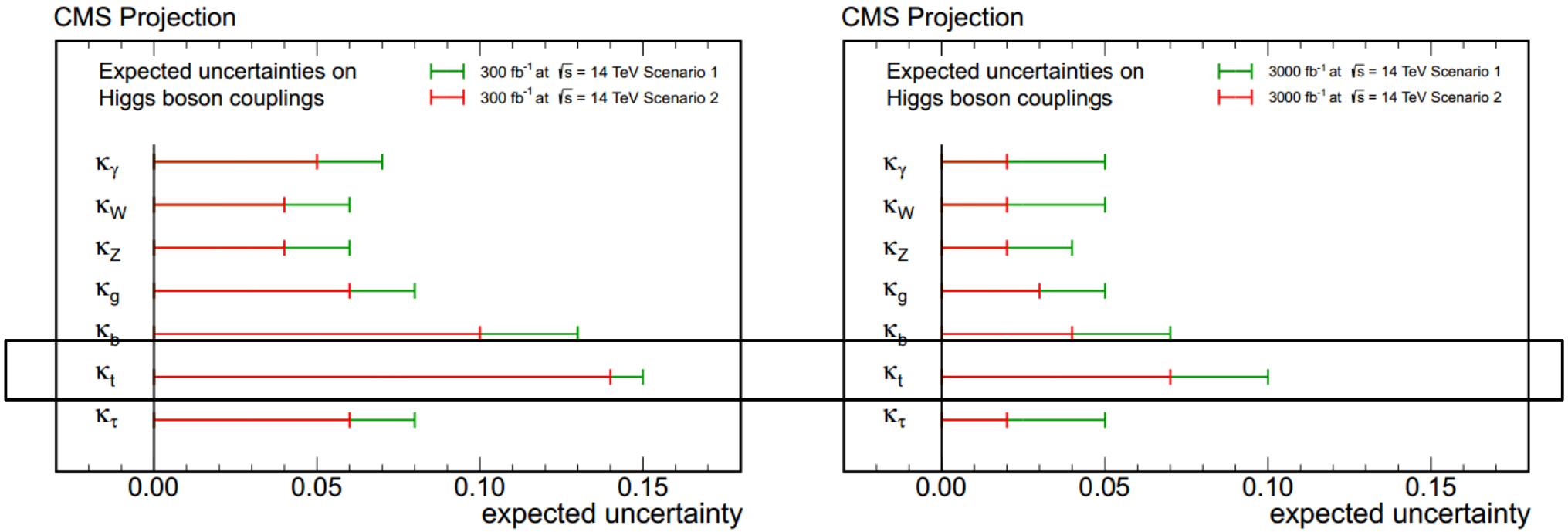
	$H \rightarrow \gamma\gamma$	$H \rightarrow bb$
Expected	4.1	5.1
Observed	4.1	7.6



$H \rightarrow bb$ analysis flow

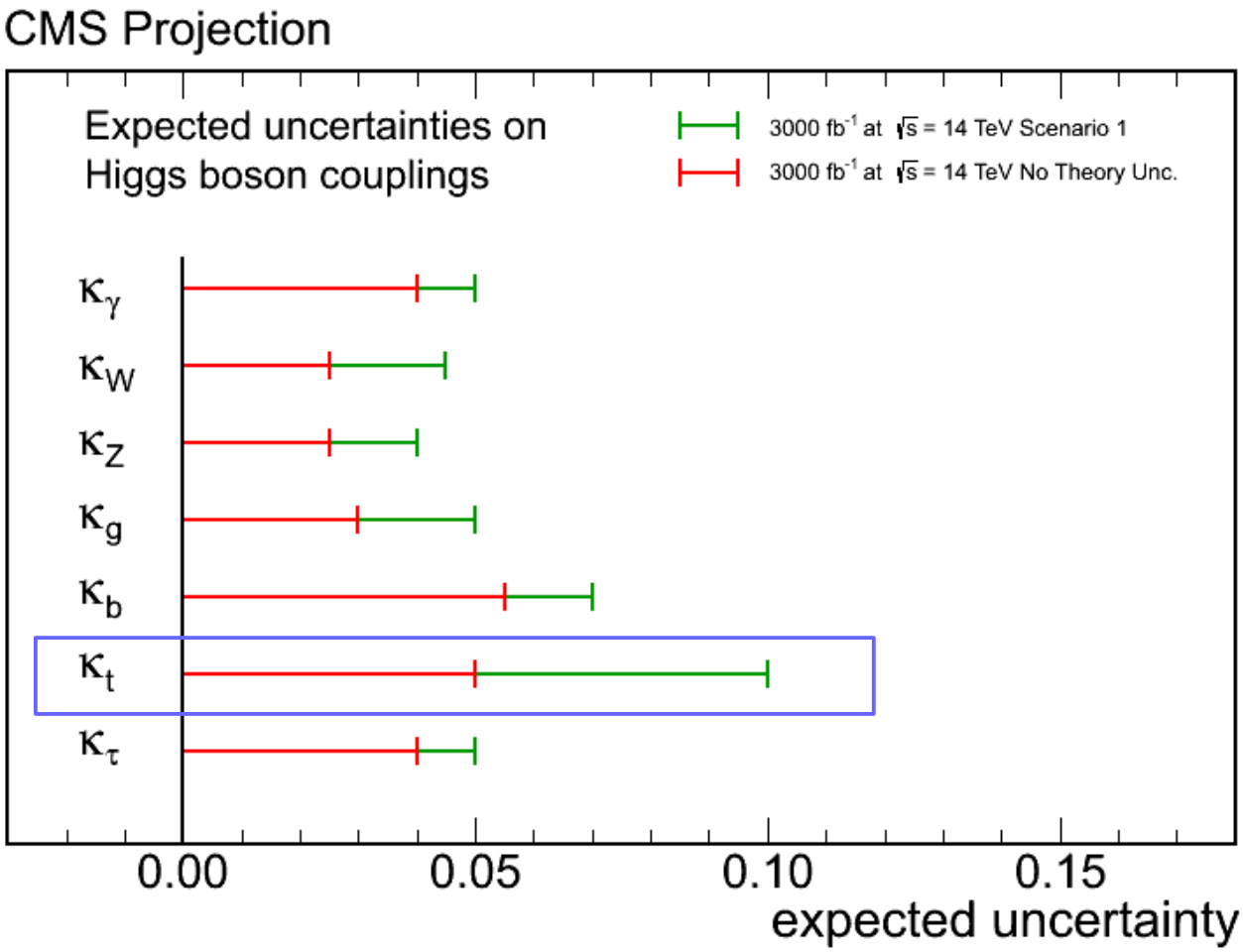
Looking Forward

- Projections from Snowmass white paper
- Conservative … only has $t\bar{t}H(bb)$ channel



arXiv:1307.7135

Theory Impact



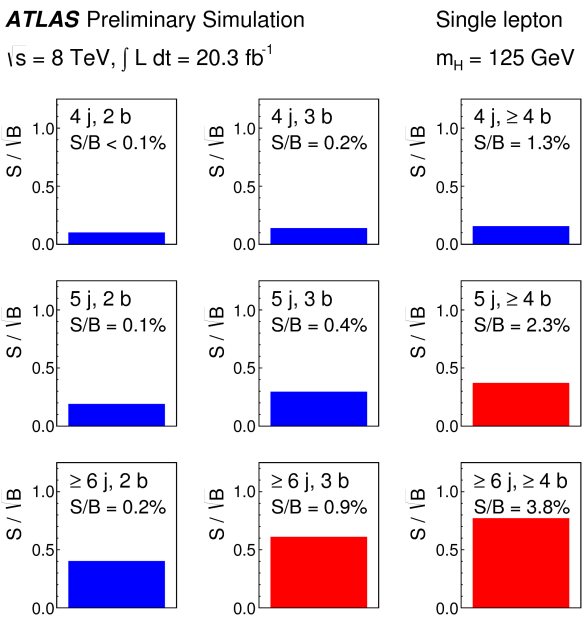
Generically, find $t\bar{t}H$ theory systematics dominate HL-LHC precision
Scale, PDF uncertainties on signal rate comparable, ~ 9% each

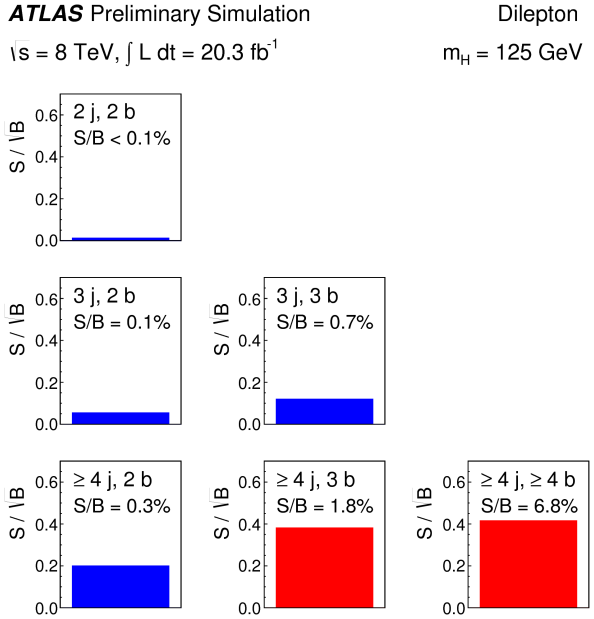
Conclusion

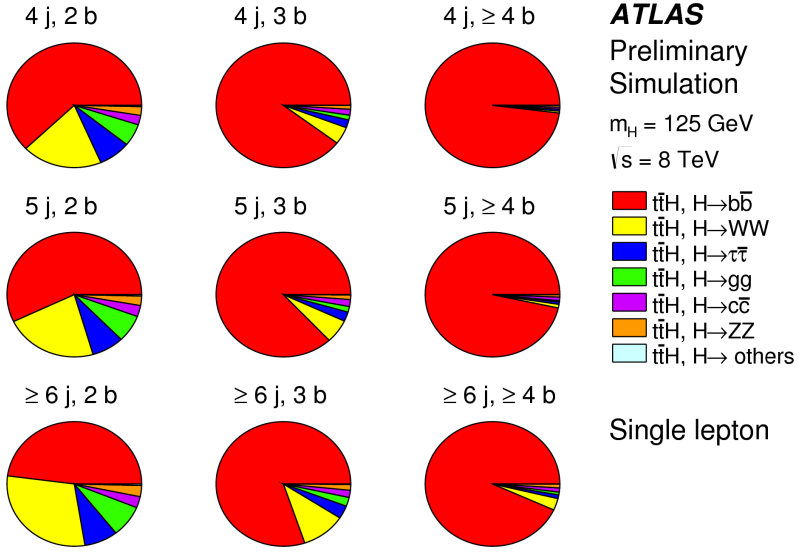
- $t\bar{t}H$ is a key channel to constrain the top Yukawa coupling independent of new physics in gluon-Higgs coupling & search for new physics from higher dimensional operators
  - tH is interesting due to sensitivity to $Ht\bar{t}$/HWW interference
- Multiple channels are available to search for the signal
  - each has interesting wrinkles, different systematics
  - discovery will be from combination, not from a single channel
- Prospects for observation of SM rate in Run 2 are very bright
  - for HL-LHC theory uncertainties become a problem

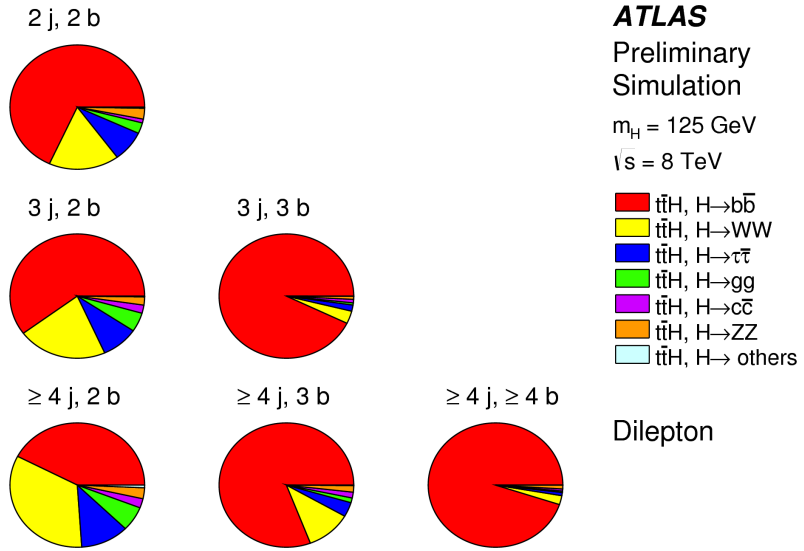
Extra

bb Categories



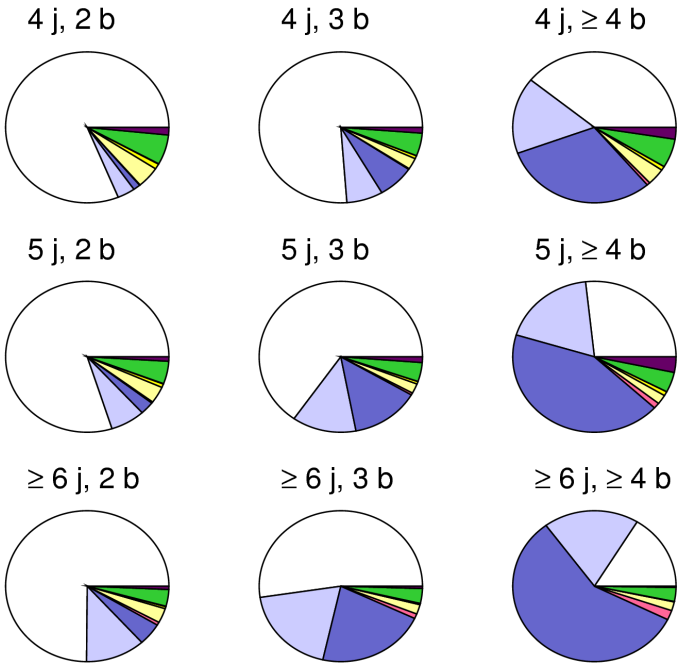


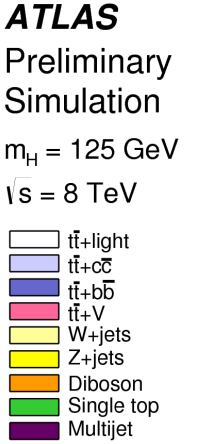




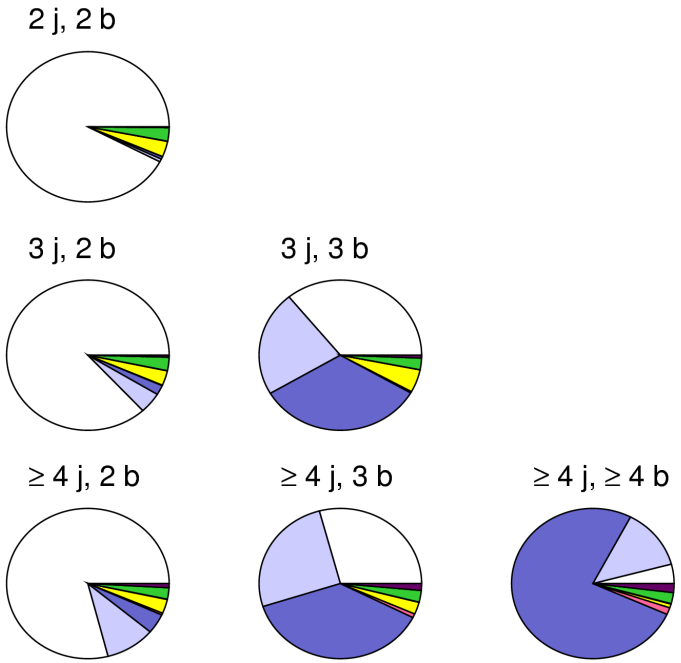
bb Backgrounds

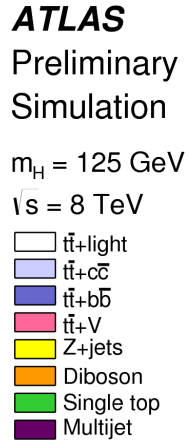
- dominated by tt + heavy flavor jets in all signal-rich regions





Single lepton

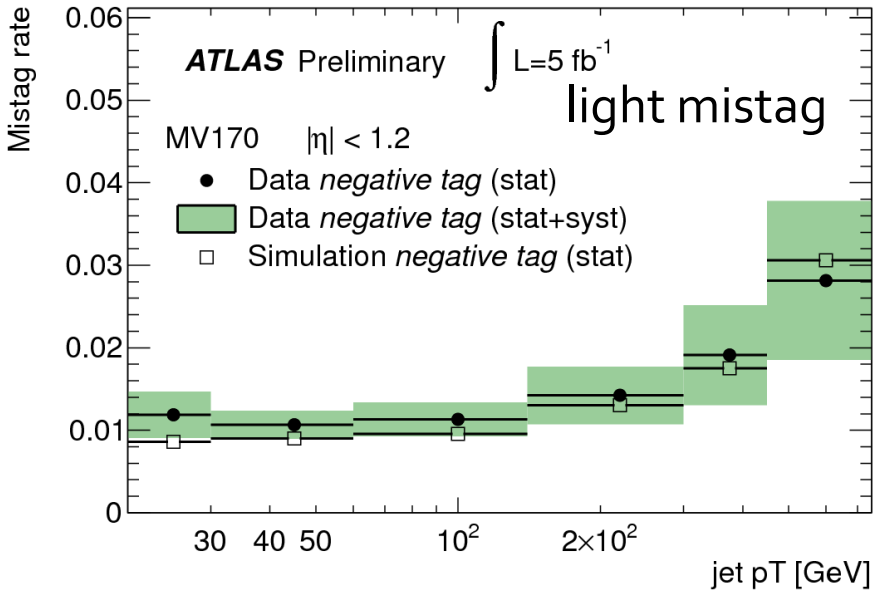


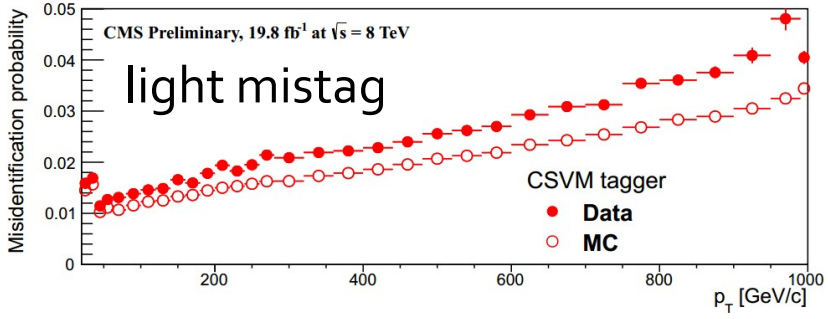


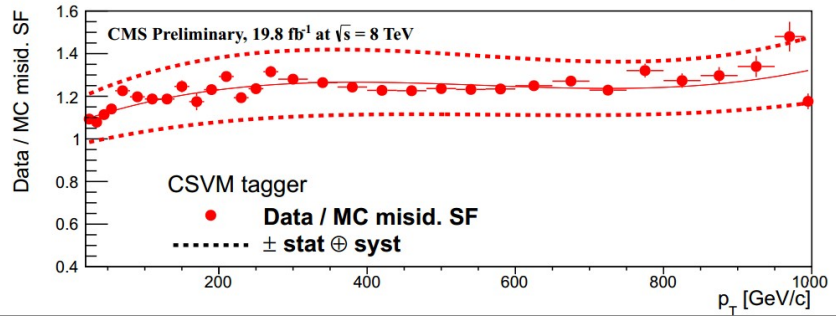
Dilepton

B-tagging

- Both experiments use multivariate taggers combining impact parameter + secondary vertex info







CMS μμ excess

- Many diagnostic plots at public TWiki

Cut-based muon selection

Looser muons excluding 2 tight

== 3 jets (not ≥4)