Searches for the SM Higgs Boson in Association with Top Quarks at LHC

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on behalf of the ATLAS and CMS Collaborations
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Top Quarks and Higgs Bosons

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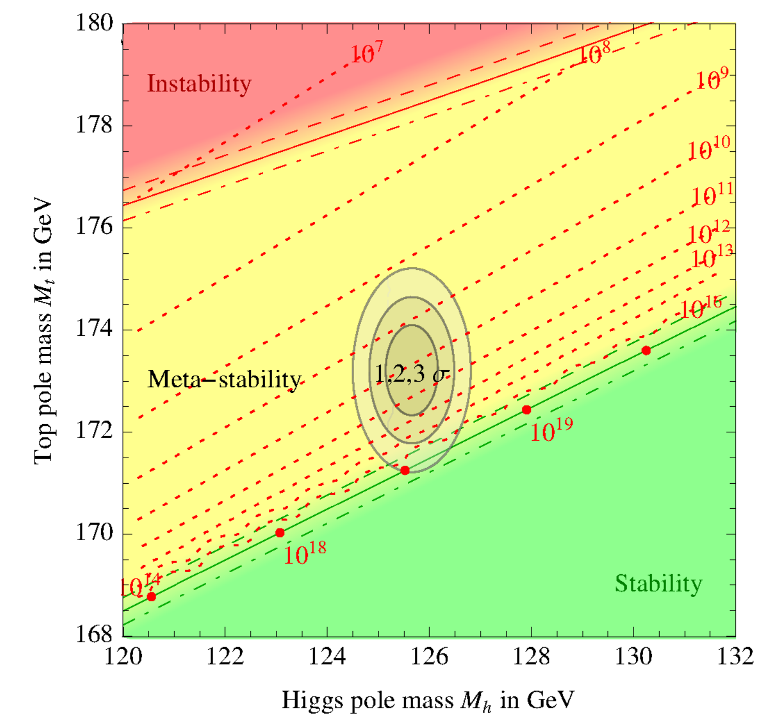
- No deviations from SM, but large uncertainties on Higgs couplings
- Top-Yukawa coupling ($y_t \simeq 1$) is a key parameter of the SM, crucial for the stability of the EW vacuum and to get hints on NP scale
- Searches for events with Higgs boson(s) and top quarks are important for probing extended EWSB scenarios
- Significant boost in sensitivity for these searches from higher energy in Run-II



JHEP 1208 (2012) 098

A couple of catchy titles from literature:

Why should we care about the top quark Yukawa coupling?[1]

Fedor Bezrukov[1,2,3,*] and Mikhail Shaposhnikov[4,†]

"… at the *present moment* the *only quantity* which can help us to get an idea about the scale of new physics is the top Yukawa coupling y_t."

arXiv:1411.1923

The Hunt for the Rest of the Higgs Bosons

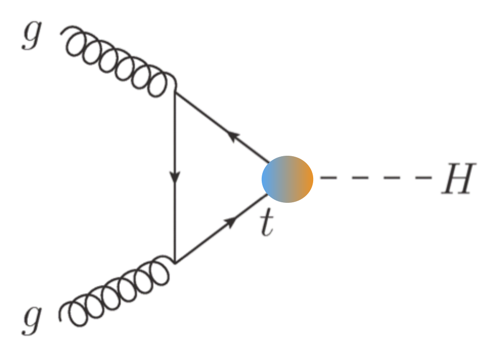
Nathaniel Craig,[a] Francesco D'Eramo,[b,c] Patrick Draper,[a] Scott Thomas,[d] and Hao Zhang[a]

"… three LHC searches that are critical components of a comprehensive program to investigate extended electroweak symmetry breaking sectors: production of a heavy scalar or pseudoscalar with decay to tt; bb and tt associated production of a heavy scalar or pseudoscalar with decay to invisible final states; and tb associated production of a charged Higgs with decay to tb"

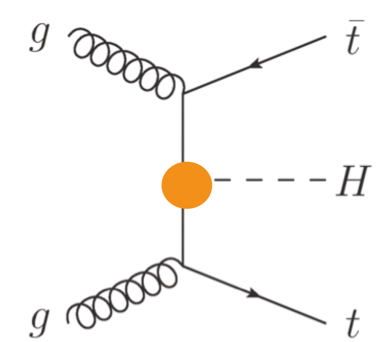
arXiv:1504.04630

SM ttH and tH Productions

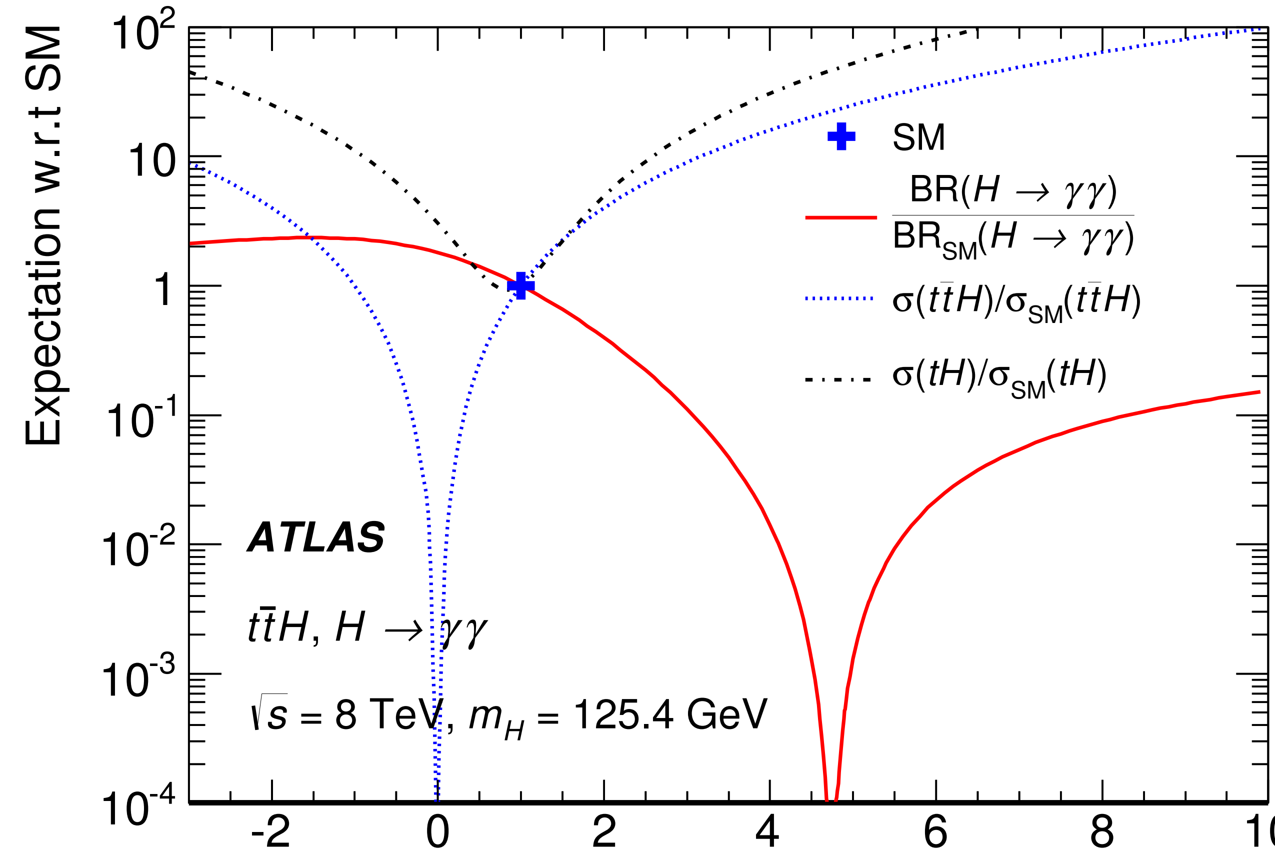
- **ttH** production
  - two orders of magnitude smaller than ggF cross section
  - allows direct measurement of y_t
  - without ttH, unable to simultaneously constrain top-Yukawa and NP in ggF loop
- **tH** production gives sensitivity to sign of y_t
  - suppressed in SM (much smaller than ttH) due to destructive interference between top and W diagrams
  - In BSM models with negative y_t, increase in tH production rate and interplay with BR(H→$\gamma\gamma$)
  - presence of forward jet like in VBF



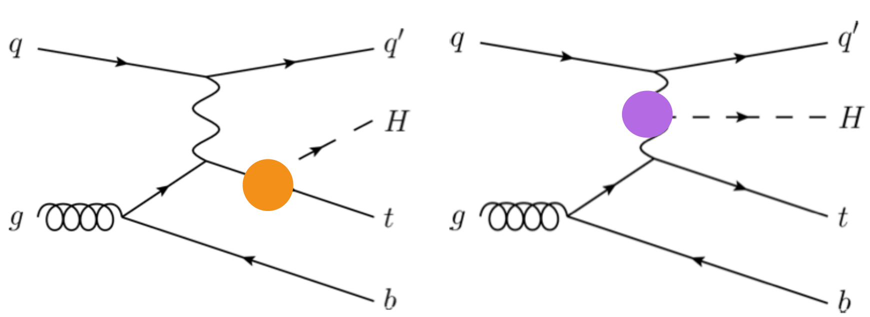
t,b,NP



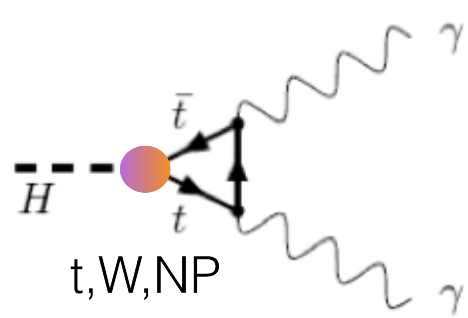
only top



Phys Lett B 740 (2015) 222



Destructive Interference!



ttH@LHC: Production and Final States

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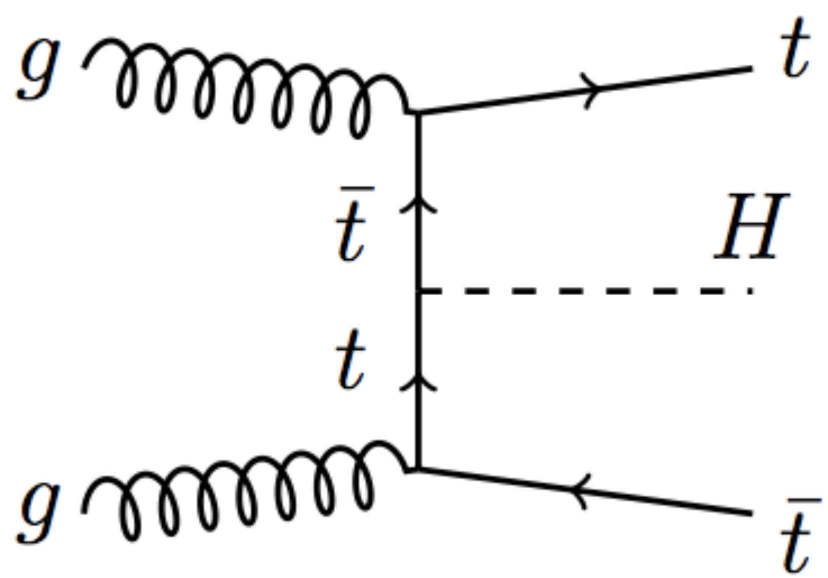
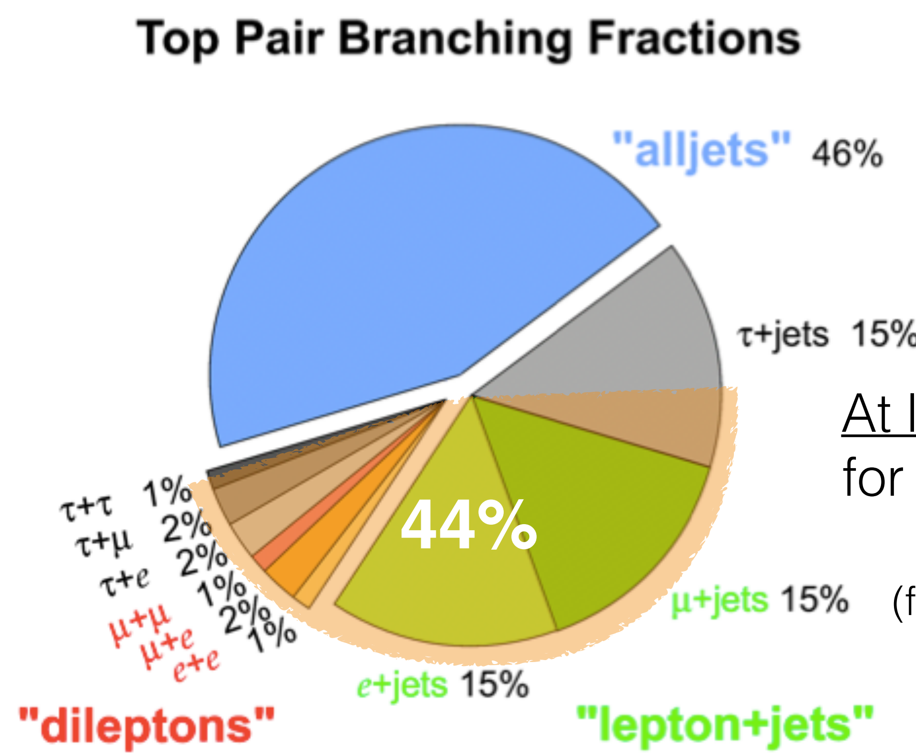
- Complex final state, all experimental signatures involved: mu, el, photon, tau, bjet, jet, E_T^{miss}



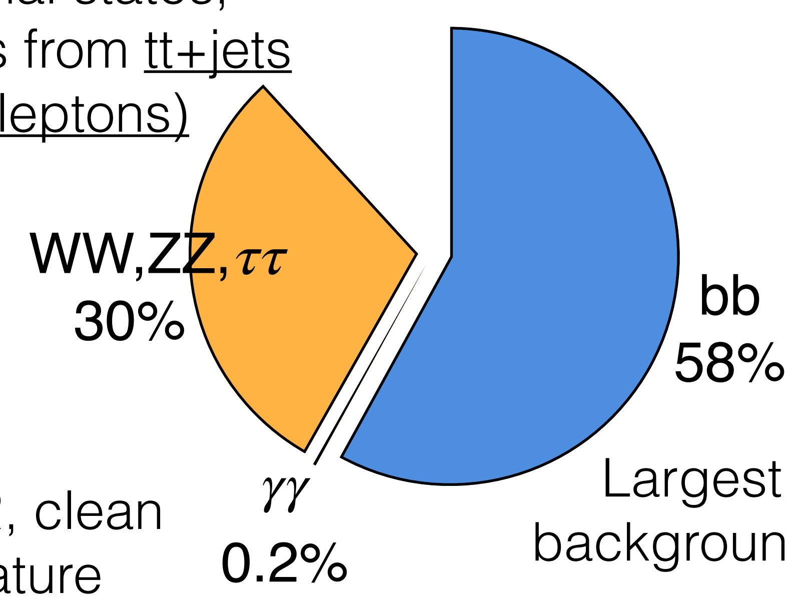
√s [TeV]	8	13	13/8
σ(ttH) [fb]	130	510	x4



At least one lepton required for triggering and to reduce hadronic background
(full hadronic only with $H \rightarrow \gamma\gamma$ to maximise acceptance)

Higgs Boson Decays

leptonic final states, backgrounds from tt+jets (w/ fake leptons)



Tiny BR, clean signature

Largest BR, large background from tt+HF

Run-I Searches

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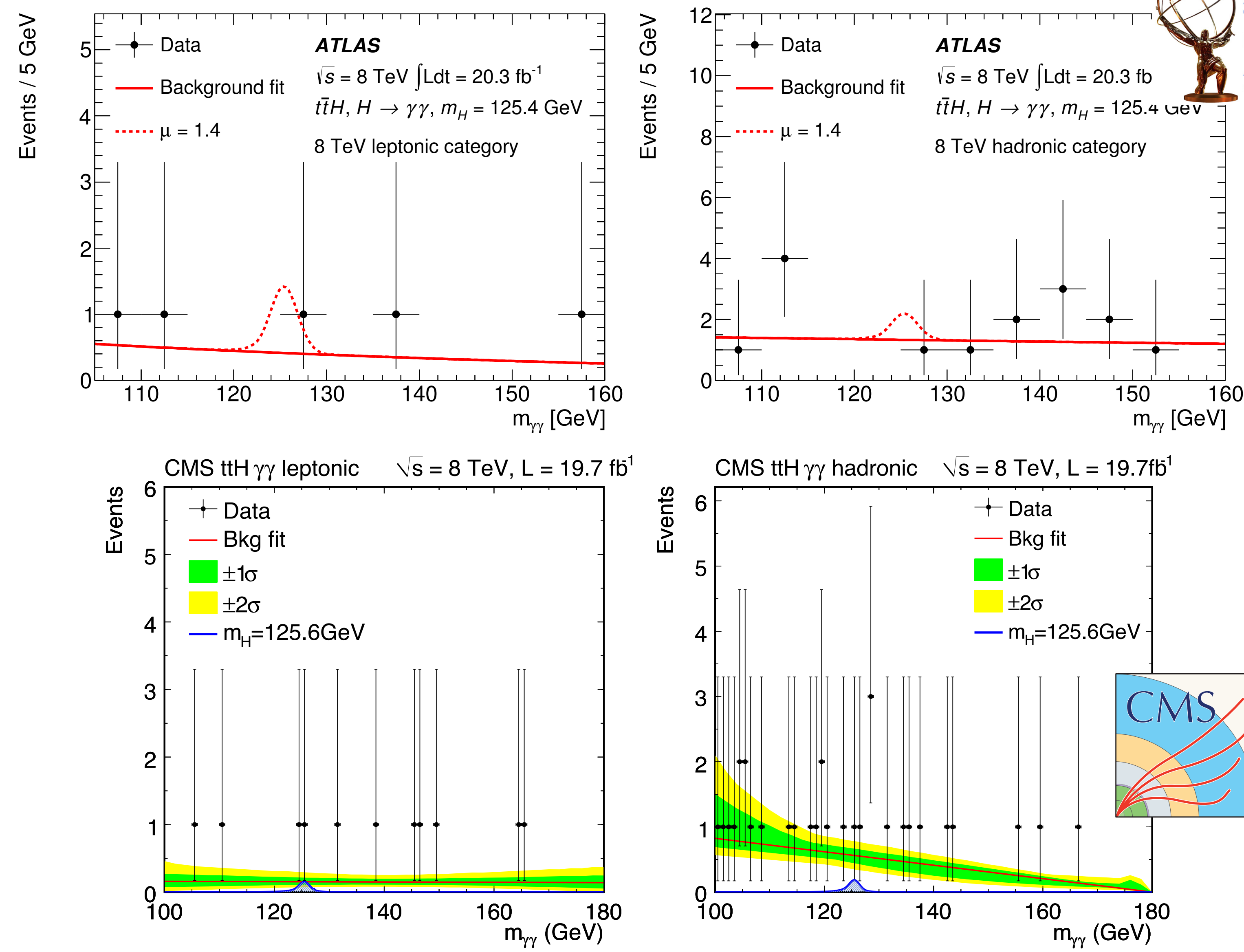
		H→$\gamma\gamma$	H→bb	H→WW,$\tau\tau$	H→ZZ
ttH	ATLAS	Phys Lett B 740 (2015) 222 (7+8TeV)	arXiv:1503.05066 (submitted to EPJC) with MEM (8TeV)	CONF-2015-006 (8TeV)	
	CMS	JHEP09 (2014) 087 (7+8TeV)	arXiv:1502.02485 (submitted to EPJC) with MEM (8TeV) JHEP09 (2014) 087 (w/o MEM)	JHEP09 (2014) 087 (7+8TeV)	
tH	ATLAS	Phys Lett B 740 (2015) 222 (7+8TeV)			
	CMS	HIG-14-001 (8TeV)	HIG-14-015 (8TeV)	HIG-14-026 (8TeV)	
Comb.	ATLAS	CONF-2015-007 (7+8TeV)			
	CMS	JHEP09 (2014) 087 (ttH only, bb w/o MEM, 7+8TeV), arXiv:1412.8662 (submitted to EPJC, bb w/o MEM, 7+8TeV)			

ttH+tH, H→$\gamma\gamma$

- O(1) signal events expected
- Non-ttH Higgs production modes suppressed by:
  - Leptonic top-pair decay: lepton and b-tag requirements
  - Hadronic top-pair decay: high #jets and b-tag requirements
- Non-resonant background from $m_{\gamma\gamma}$ sidebands
- ttH Results:
  - CMS $\mu=2.7^{+2.6}_{-1.8}$
  - ATLAS $\mu=1.3^{+2.5}_{-1.7}$(stat)$^{+0.8}_{-0.4}$(syst)
- tH Results:
  - ATLAS result included in ttH search (tH as background for ttH)
  - CMS dedicated search for tHq, no events observed, 95%CL upper limit at:

$$4.1 \times \sigma^{Yt=-1}_{tHq} \times BR(H\rightarrow\gamma\gamma)$$



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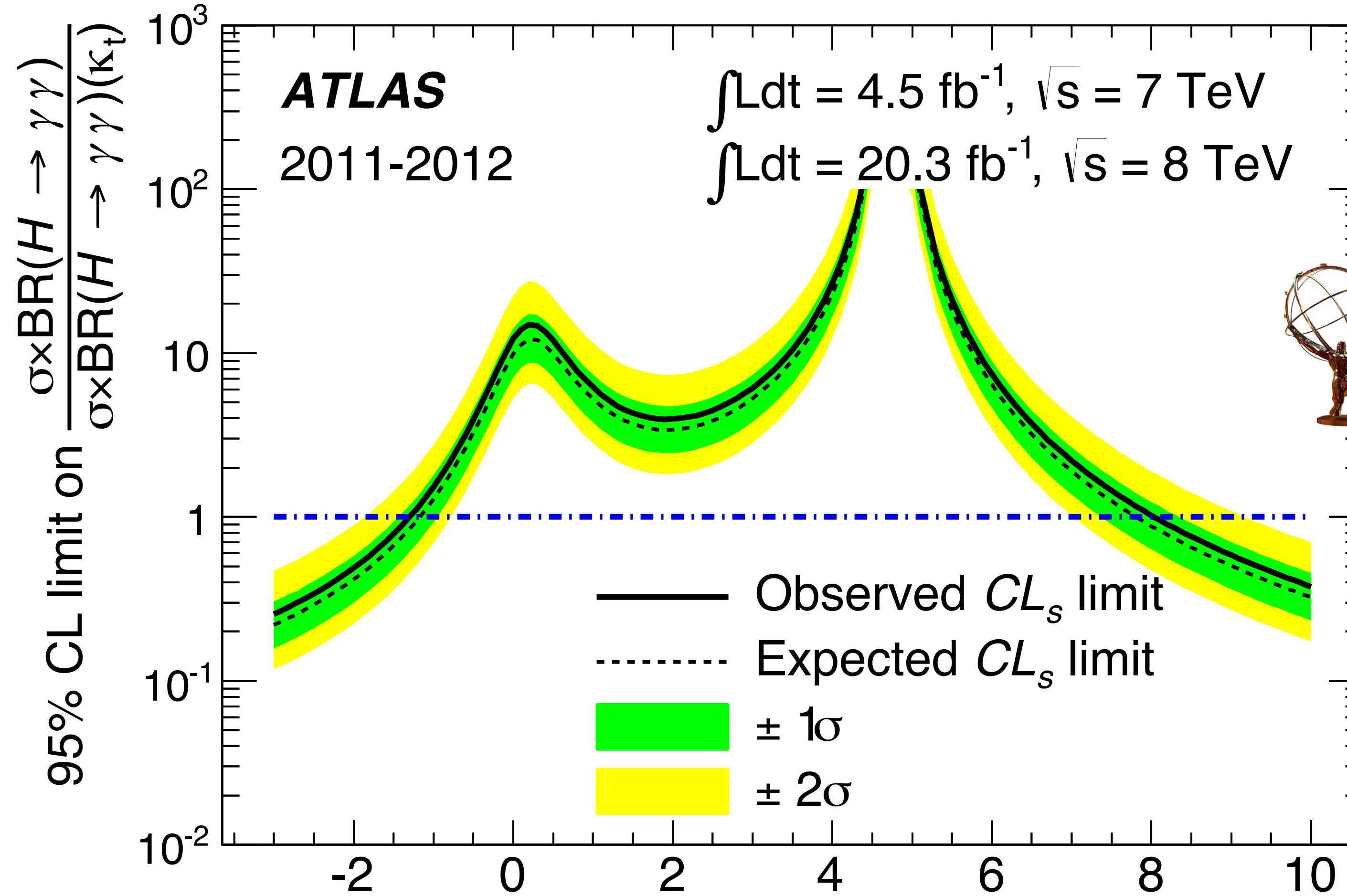
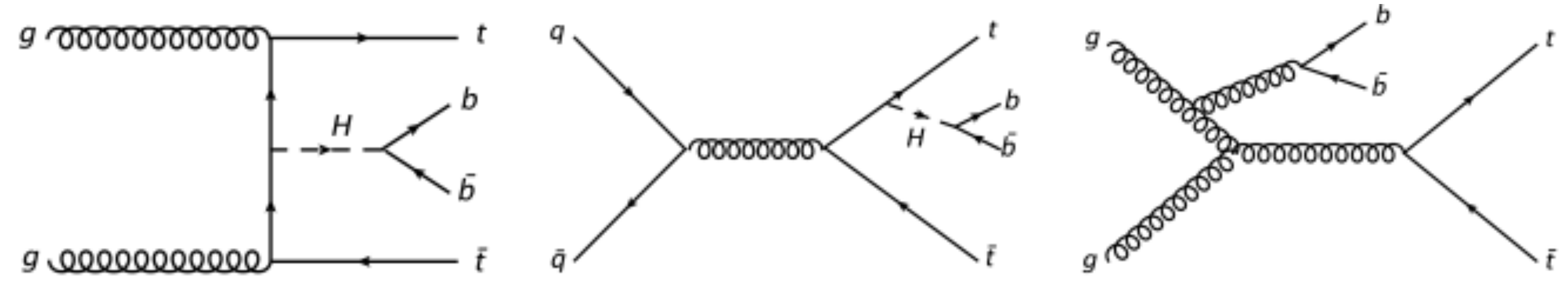
$$4.1 \mathrm{X} \sigma^{Yt=-1}_{tHq} \mathrm{X} BR(H\rightarrow\gamma\gamma)$$



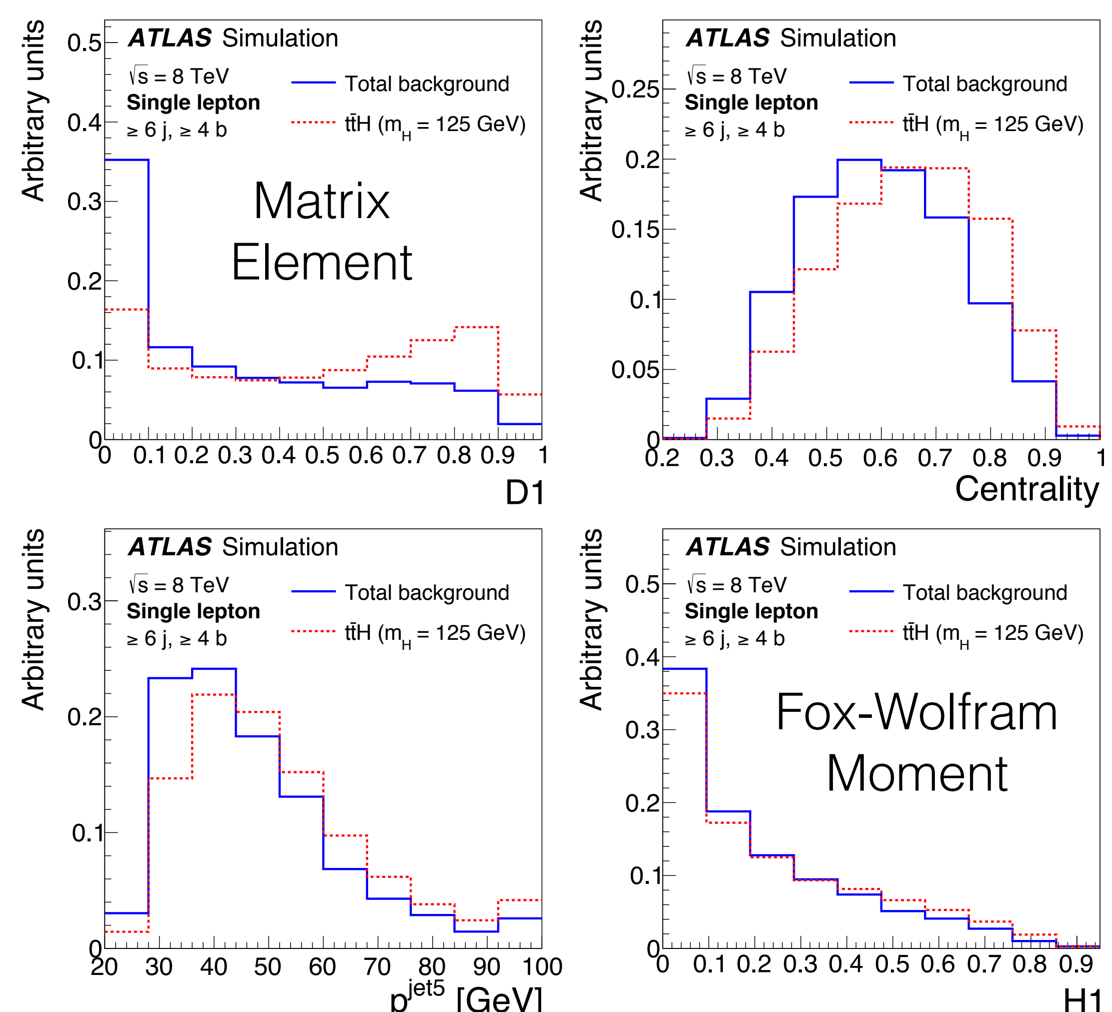
k_t in [-1.3,+8.0] @95%CL

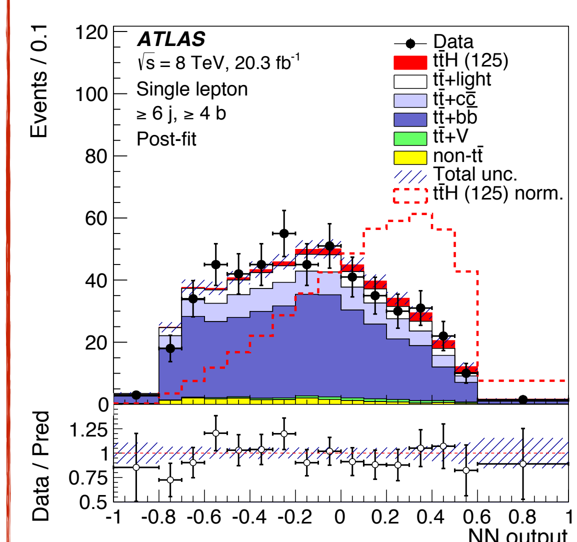
ttH, H→bb

- Largest Higgs decay fraction, at least one lepton from top-pair decay
- Complex final state and background composition, small signal purity
- MVA methods to discriminate signal first from tt+jets and then also from tt+bb continuum, e.g. NN and Matrix Element Method (MEM)
- tt+bb dominant irreducible background with large theoretical uncertainties (up to 50% of cross section)
- Background-dominated regions used to reduce systematic uncertainties

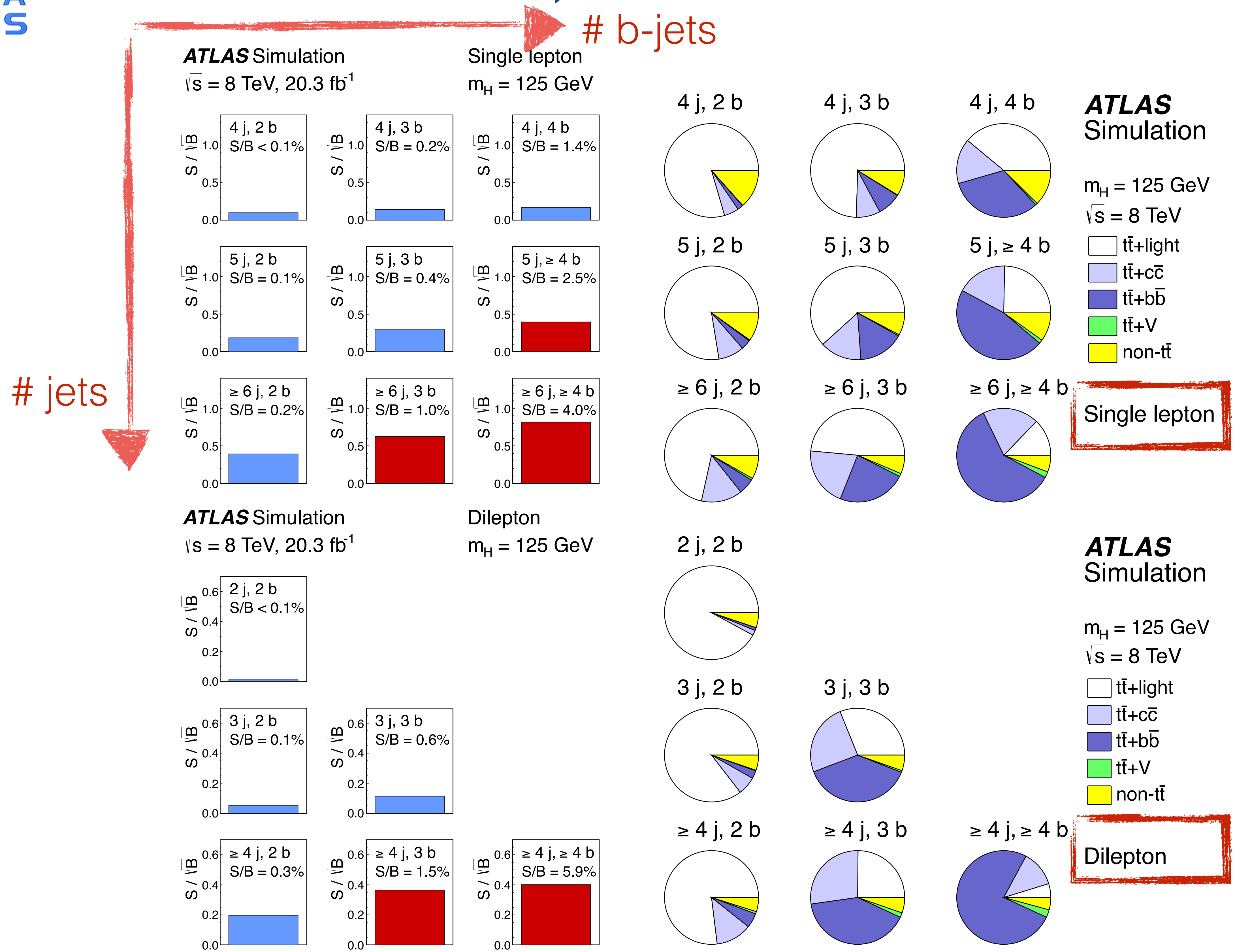


4 top-ranked inputs for the NN in ≥6j,≥4b cat.

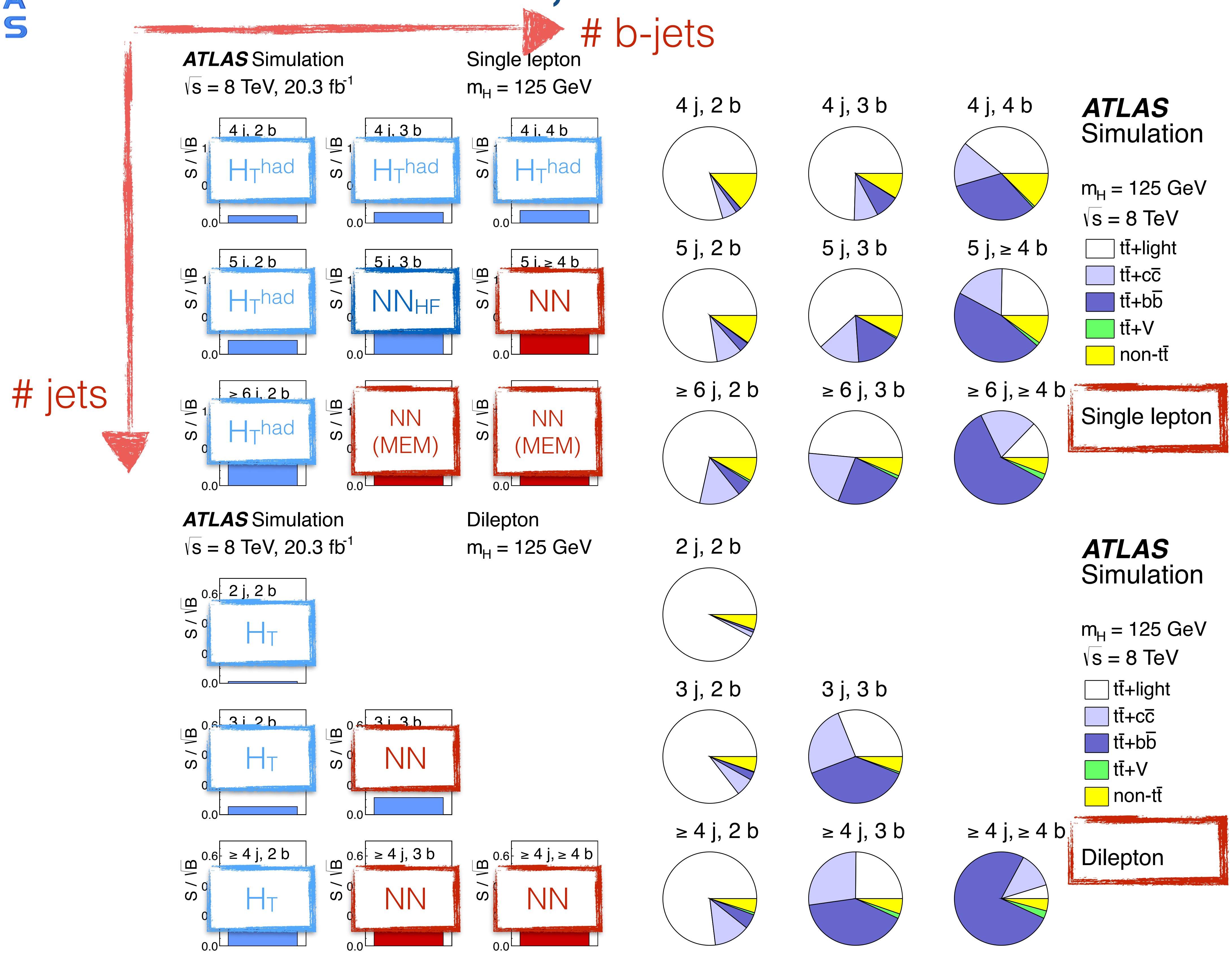




ttH, H→bb

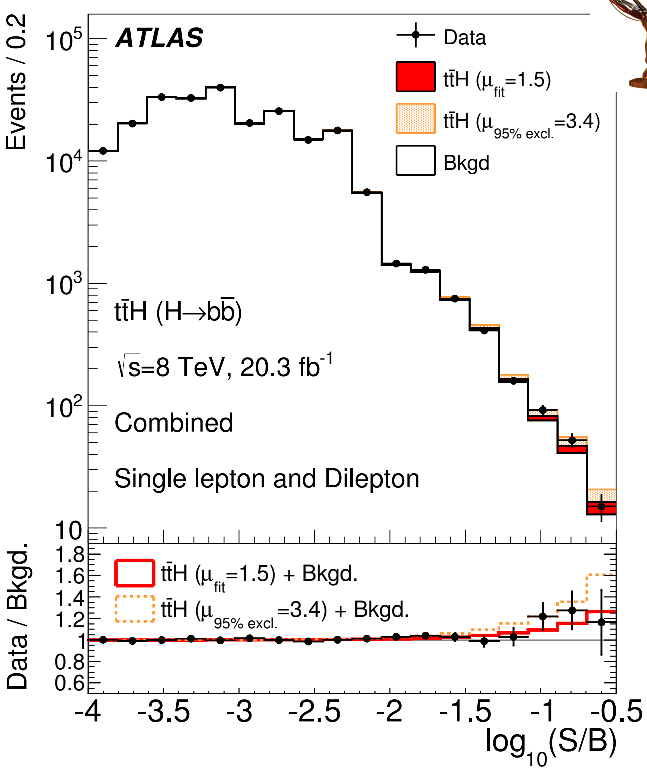

b-jets
jets
ATLAS Simulation
√s = 8 TeV, 20.3 fb-1
Single lepton
mH = 125 GeV
4 j, 2 b S/B < 0.1%
4 j, 3 b S/B = 0.2%
4 j, 4 b S/B = 1.4%
5 j, 2 b S/B = 0.1%
5 j, 3 b S/B = 0.4%
5 j, ≥ 4 b S/B = 2.5%
≥ 6 j, 2 b S/B = 0.2%
≥ 6 j, 3 b S/B = 1.0%
≥ 6 j, ≥ 4 b S/B = 4.0%
ATLAS Simulation
√s = 8 TeV, 20.3 fb-1
Dilepton
mH = 125 GeV
2 j, 2 b S/B < 0.1%
3 j, 2 b S/B = 0.1%
3 j, 3 b S/B = 0.6%
≥ 4 j, 2 b S/B = 0.3%
≥ 4 j, 3 b S/B = 1.5%
≥ 4 j, ≥ 4 b S/B = 5.9%
S / √B
4 j, 2 b
4 j, 3 b
4 j, 4 b
5 j, 2 b
5 j, 3 b
5 j, ≥ 4 b
≥ 6 j, 2 b
≥ 6 j, 3 b
≥ 6 j, ≥ 4 b
ATLAS Simulation
mH = 125 GeV
√s = 8 TeV
tt̄+light
tt̄+cc̄
tt̄+bb̄
tt̄+V
non-tt̄
Single lepton
2 j, 2 b
3 j, 2 b
3 j, 3 b
≥ 4 j, 2 b
≥ 4 j, 3 b
≥ 4 j, ≥ 4 b
Dilepton

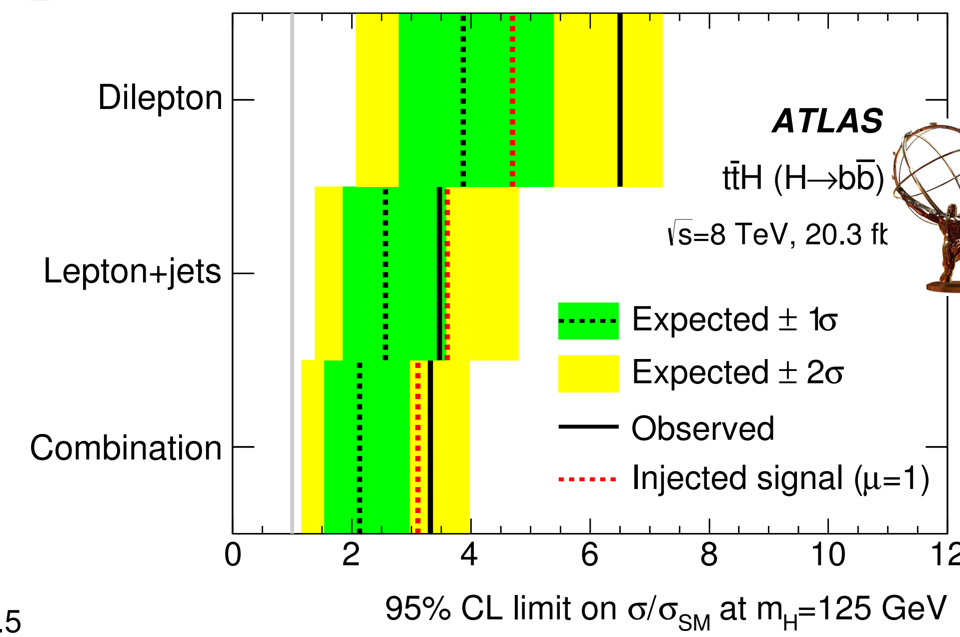
ttH, H→bb

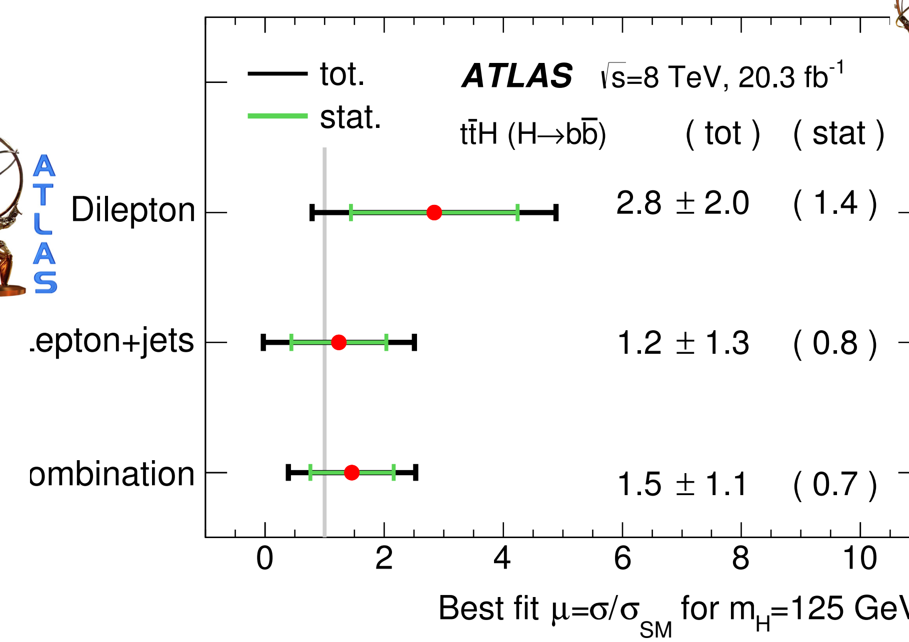


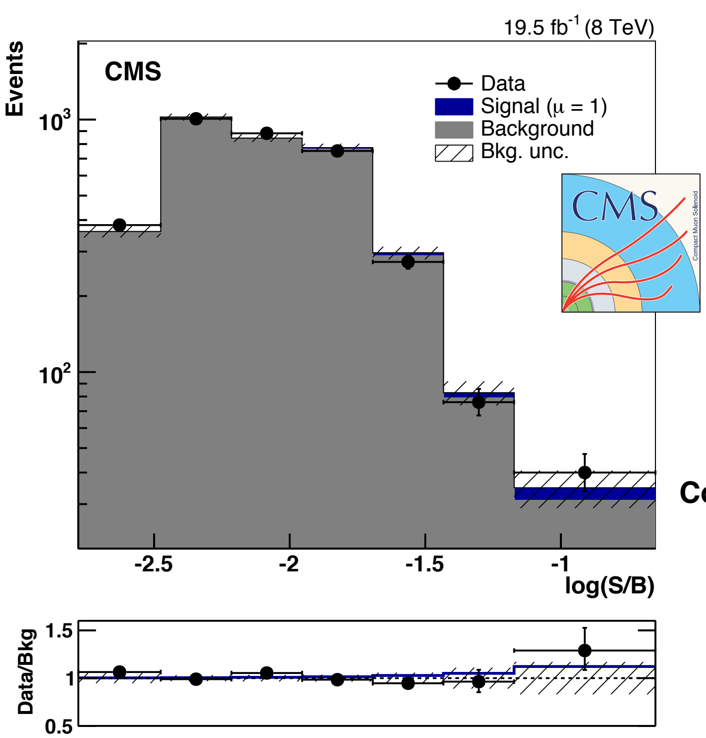
b-jets
jets
ATLAS Simulation
√s = 8 TeV, 20.3 fb-1
Single lepton
mH = 125 GeV
4 j, 2 b
4 j, 3 b
4 j, 4 b
5 j, 2 b
5 j, 3 b
5 j, ≥ 4 b
≥ 6 j, 2 b
≥ 6 j, 3 b
≥ 6 j, ≥ 4 b
S / √B
HThad
NNHF
NN
NN (MEM)
ATLAS Simulation
√s = 8 TeV, 20.3 fb-1
Dilepton
mH = 125 GeV
2 j, 2 b
3 j, 2 b
3 j, 3 b
≥ 4 j, 2 b
≥ 4 j, 3 b
≥ 4 j, ≥ 4 b
HT
NN
ATLAS Simulation
mH = 125 GeV
√s = 8 TeV
tt̄+light
tt̄+cc̄
tt̄+bb̄
tt̄+V
non-tt̄
Single lepton
ATLAS Simulation
mH = 125 GeV
√s = 8 TeV
tt̄+light
tt̄+cc̄
tt̄+bb̄
tt̄+V
non-tt̄
Dilepton

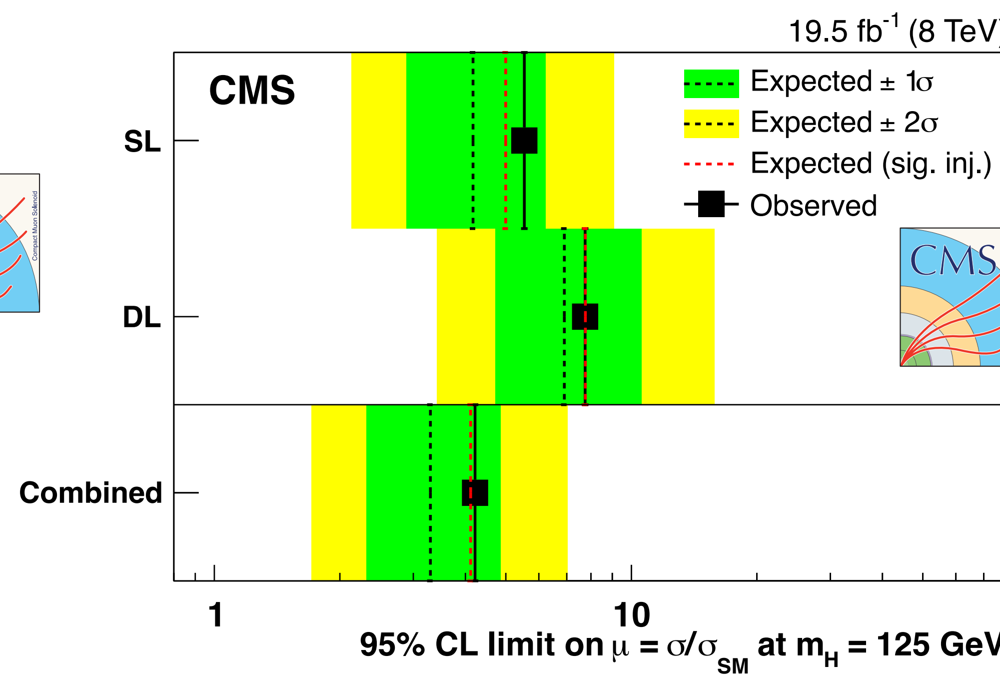
ttH, H→bb

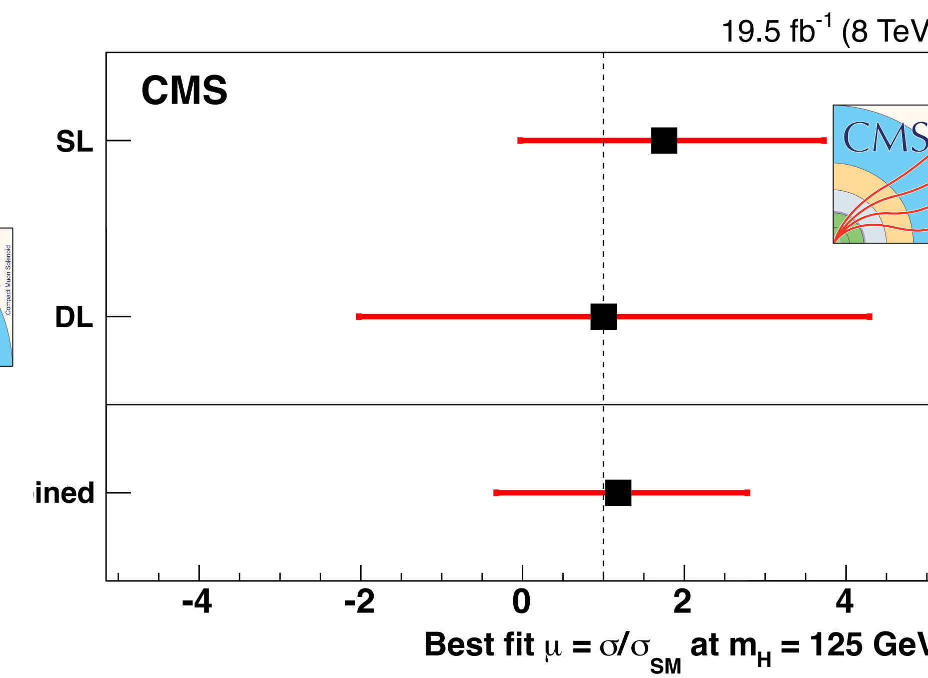

ATLAS
Data
$t\bar{t}H$ (μ_{fit}=1.5)
$t\bar{t}H$ ($\mu_{95\% excl.}$=3.4)
Bkgd
$t\bar{t}H$ ($H\to b\bar{b}$)
$\sqrt{s}$=8 TeV, 20.3 fb^{-1}
Combined
Single lepton and Dilepton
$t\bar{t}H$ (μ_{fit}=1.5) + Bkgd.
$t\bar{t}H$ ($\mu_{95\% excl.}$=3.4) + Bkgd.
Events / 0.2
Data / Bkgd.
$\log_{10}$(S/B)


Dilepton
Lepton+jets
Combination
ATLAS
$t\bar{t}H$ ($H\to b\bar{b}$)
$\sqrt{s}$=8 TeV, 20.3 fb
Expected ± 1σ
Expected ± 2σ
Observed
Injected signal (μ=1)
95% CL limit on σ/σ_{SM} at m_H=125 GeV

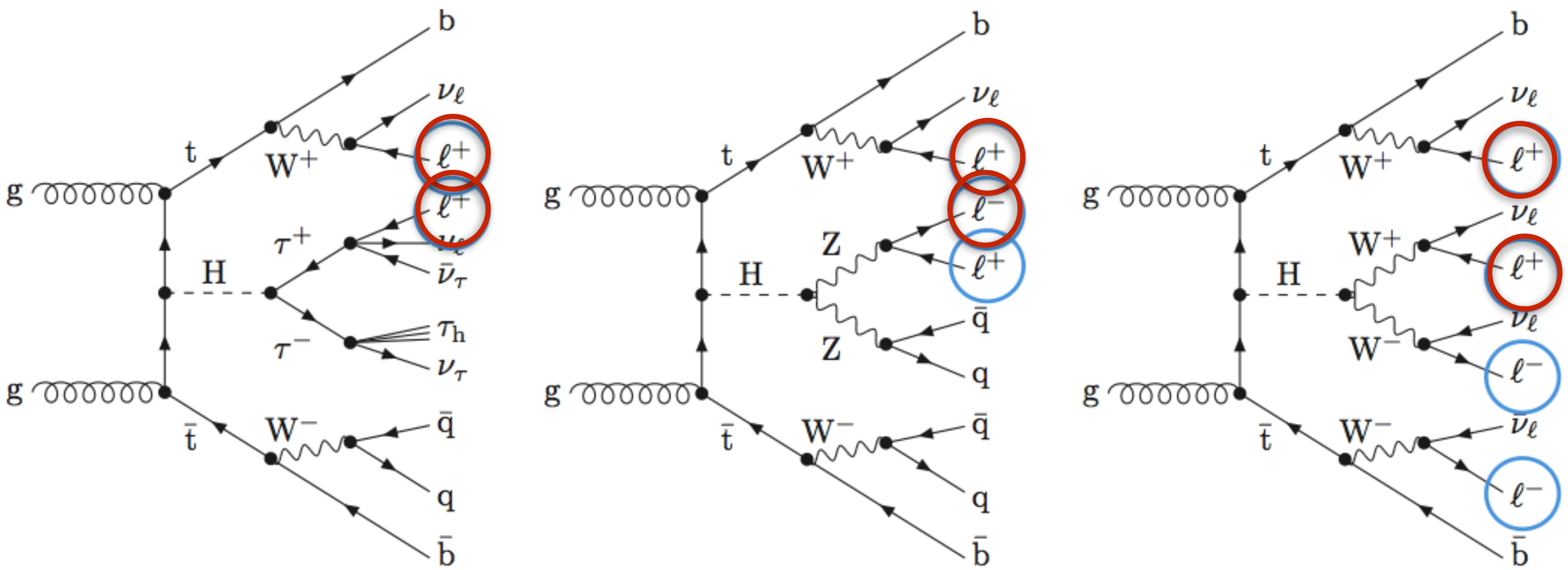

tot.
stat.
ATLAS $\sqrt{s}$=8 TeV, 20.3 fb^{-1}
$t\bar{t}H$ ($H\to b\bar{b}$) (tot) (stat)
Dilepton 2.8 ± 2.0 (1.4)
Lepton+jets 1.2 ± 1.3 (0.8)
Combination 1.5 ± 1.1 (0.7)
Best fit $\mu=\sigma/\sigma_{SM}$ for m_H=125 GeV


CMS
19.5 fb^{-1} (8 TeV)
Data
Signal (μ = 1)
Background
Bkg. unc.
Events
Data/Bkg
log(S/B)


CMS
19.5 fb^{-1} (8 TeV)
SL
DL
Combined
Expected ± 1σ
Expected ± 2σ
Expected (sig. inj.)
Observed
95% CL limit on $\mu = \sigma/\sigma_{SM}$ at m_H = 125 GeV


CMS
19.5 fb^{-1} (8 TeV)
SL
DL
Best fit $\mu = \sigma/\sigma_{SM}$ at m_H = 125 GeV

ttH, H → leptons



Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other
$2\ell0\tau_{had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell1\tau_{had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell2\tau_{had}$	4%	93%	0%	3%

- H→WW*,ZZ*,$\tau\tau$→leptons: final states with e, μ, jets, b-tagged jets, E_T^{miss} and τ-jets
- all hadronic top-pair decay not targeted
- 2 same-signed leptons to reject top pair events

Category	Signature	Trigger	Signature
H → Leptons H → WW H → $\tau\tau$ H → ZZ	Same-Sign Dilepton ($t\bar{t}H \to \ell^\pm\nu\ell^\pm[\nu]jjj[j]bb$)	Dilepton	2 e/μ, $p_T > 20$ GeV $\geq$4 jets + $\geq$1 b-tags, $p_T > 25$ GeV
	3 Lepton ($t\bar{t}H \to \ell\nu\ell[\nu]\ell[\nu]j[j]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 1 e(μ), $p_T > 7(5)$ GeV $\geq$2 jets + $\geq$1 b-tags, $p_T > 25$ GeV
	4 Lepton ($t\bar{t}H \to \ell\nu\ell\nu\ell[\nu]\ell[\nu]bb$)	Dilepton, Trielectron	1 e/μ, $p_T > 20$ GeV 1 e/μ, $p_T > 10$ GeV 2 e(μ), $p_T > 7(5)$ GeV $\geq$2 jets + $\geq$1 b-tags, $p_T > 25$ GeV

Dominant Backgrounds
Non-prompt and charge-flip from ttbar, ttV
Non-prompt from ttbar, ttV, WZ
ttV, ZZ

ttH, H → leptons

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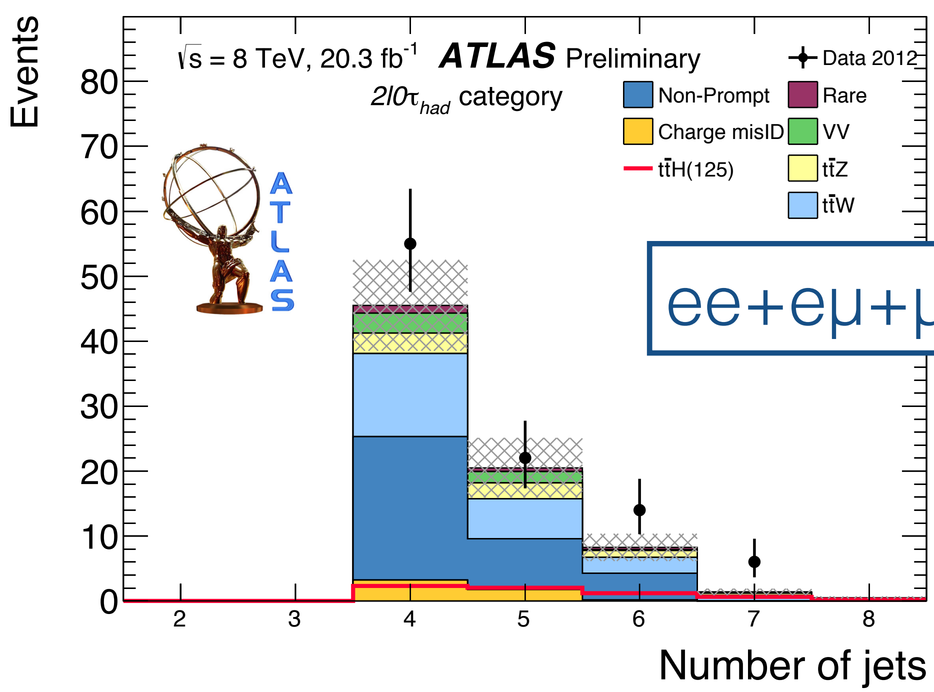
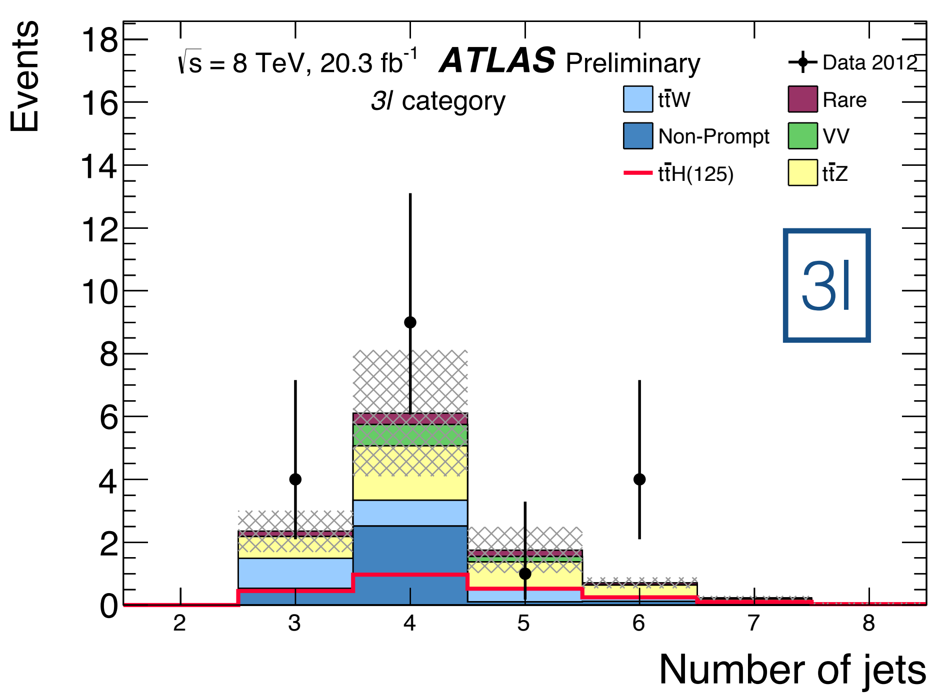
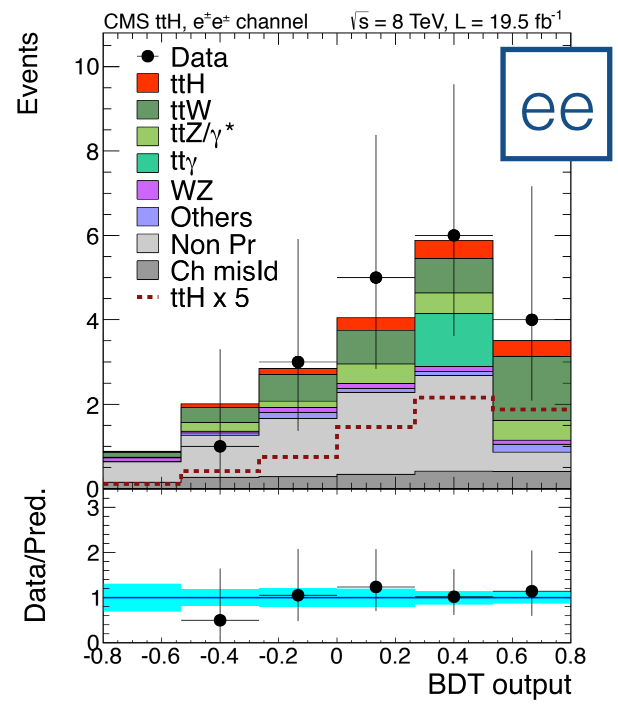
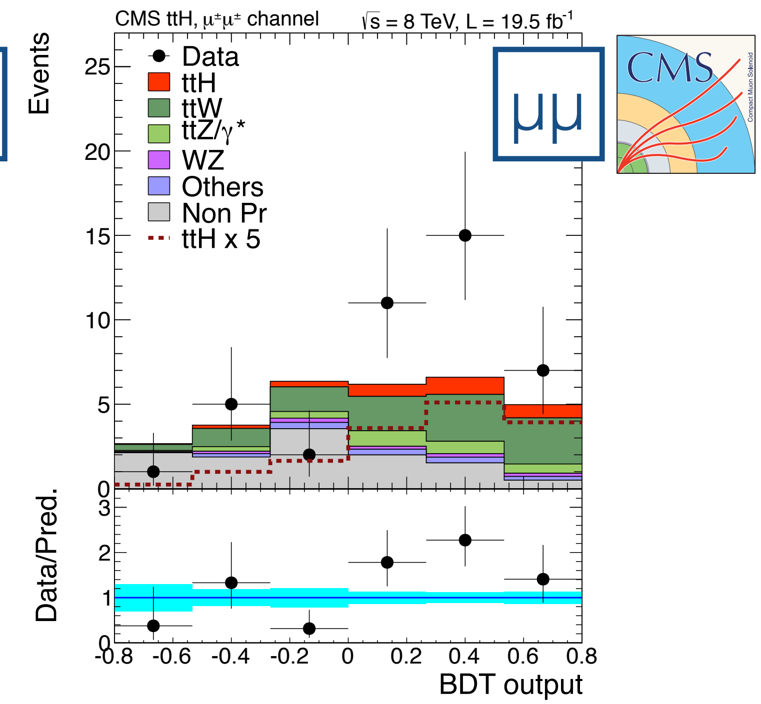
- ATLAS: cut&count in regions with high jet multiplicity

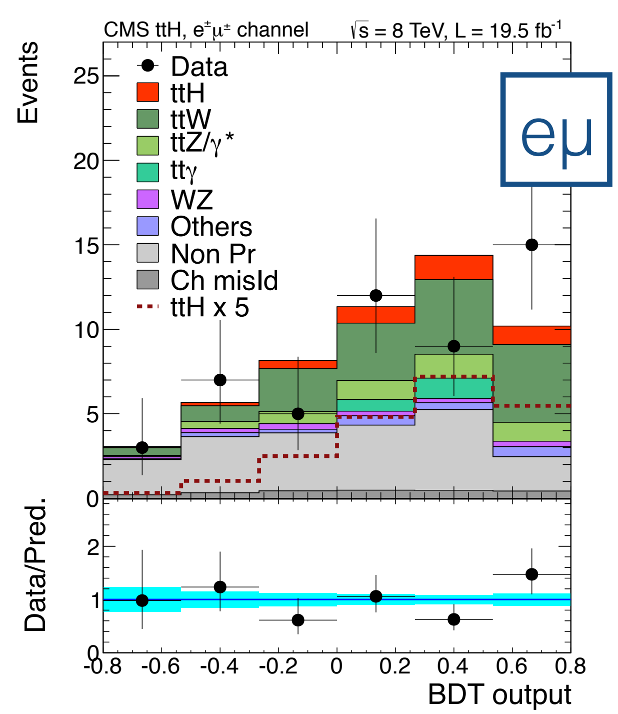


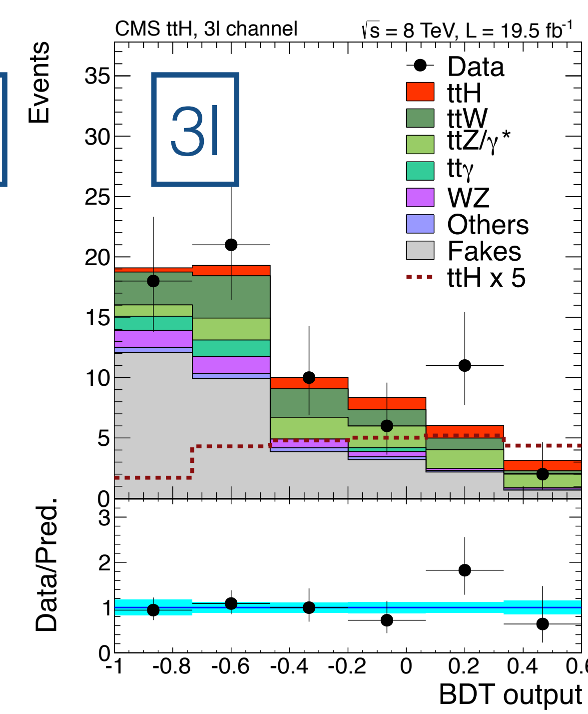


- CMS: fit to #jet and BDT score



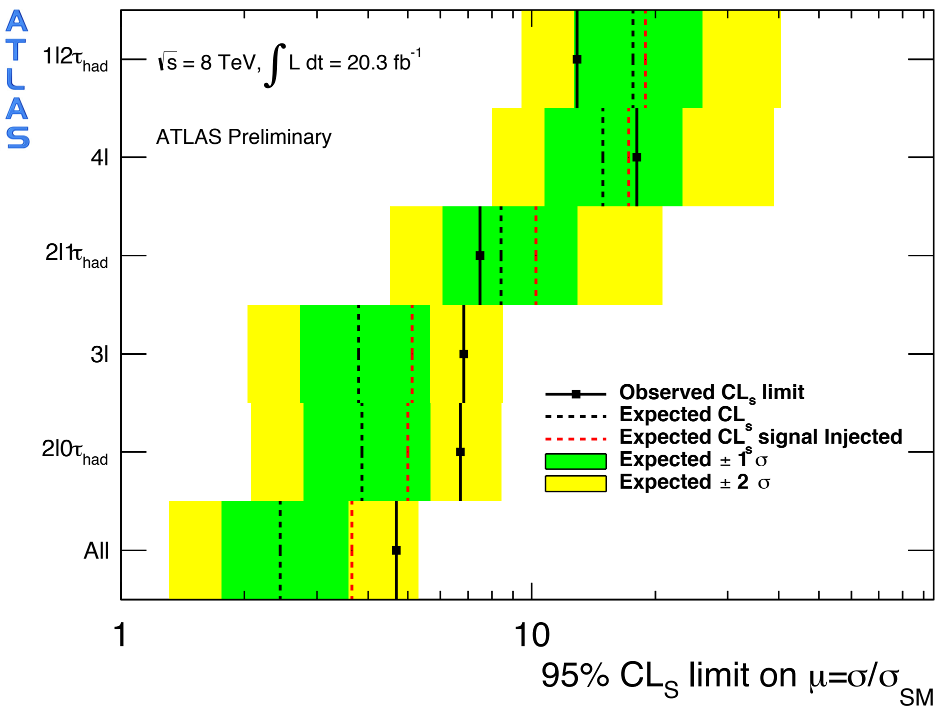


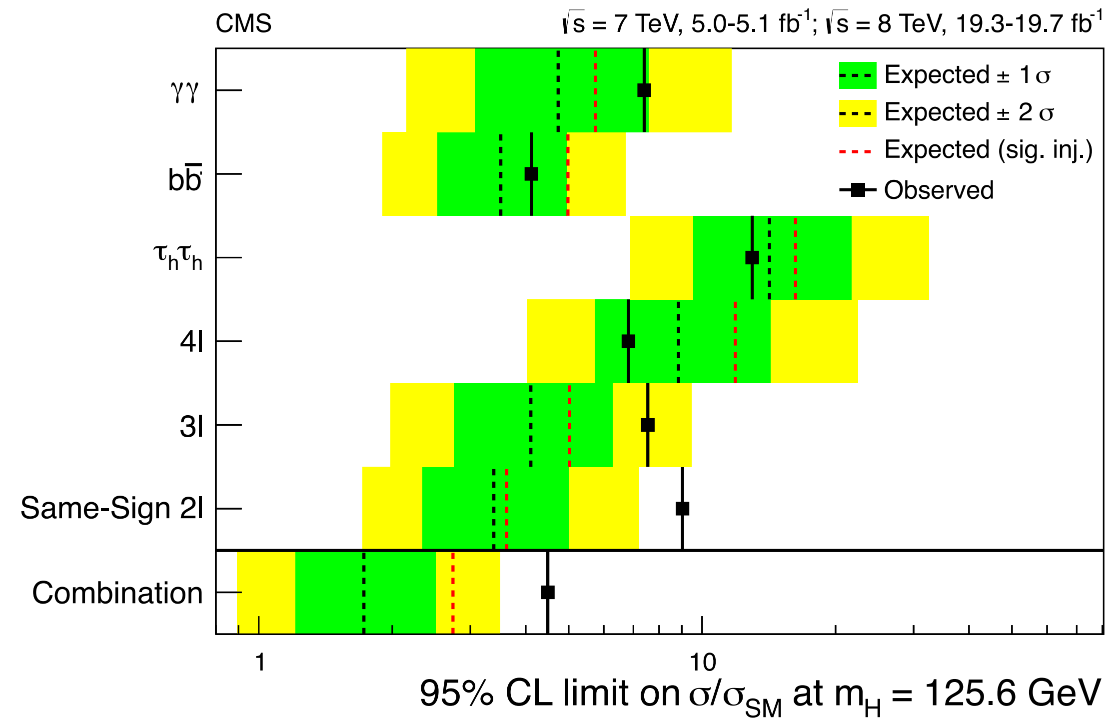




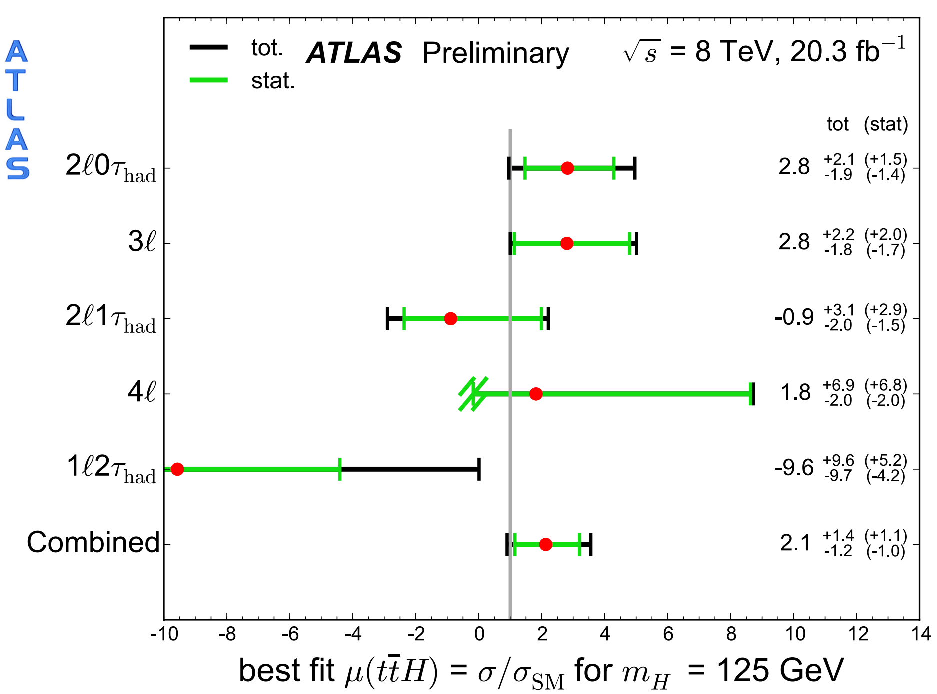
Hig13020TWiki for more plots

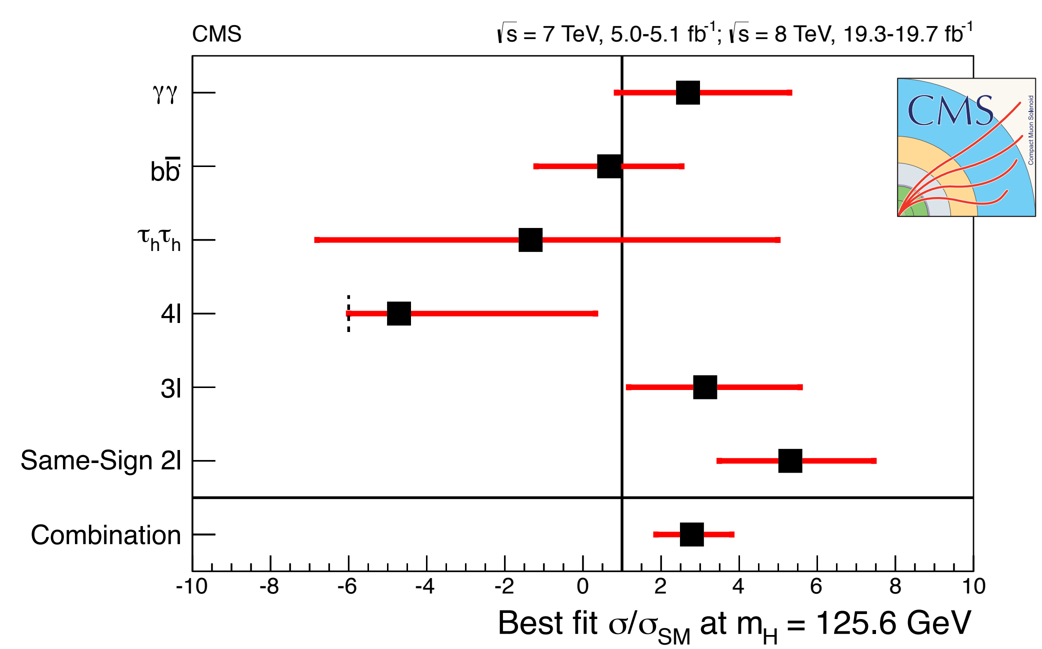
ttH, H → leptons





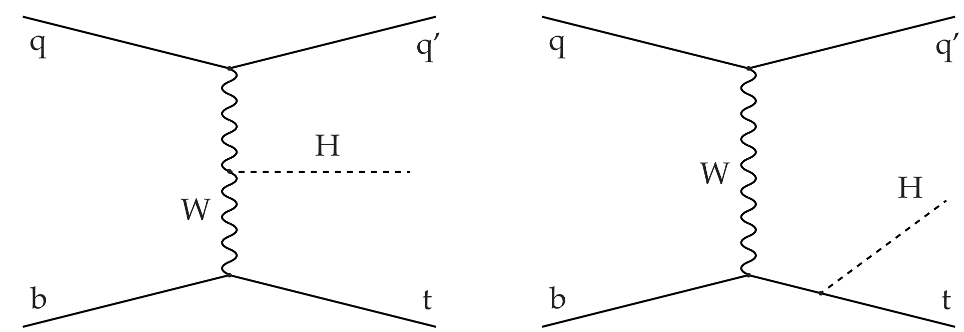
- 2l SS: single most sensitive category at ~3.5xσ_{SM} (exp), excess observed in both experiments

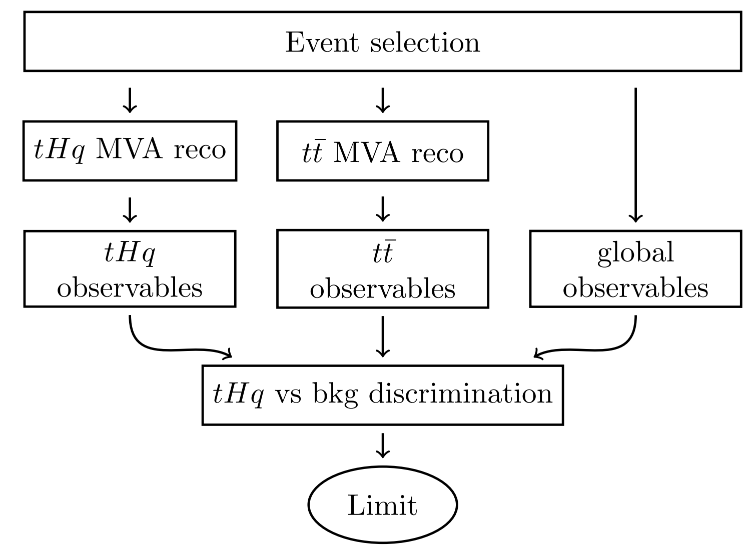




tH Searches

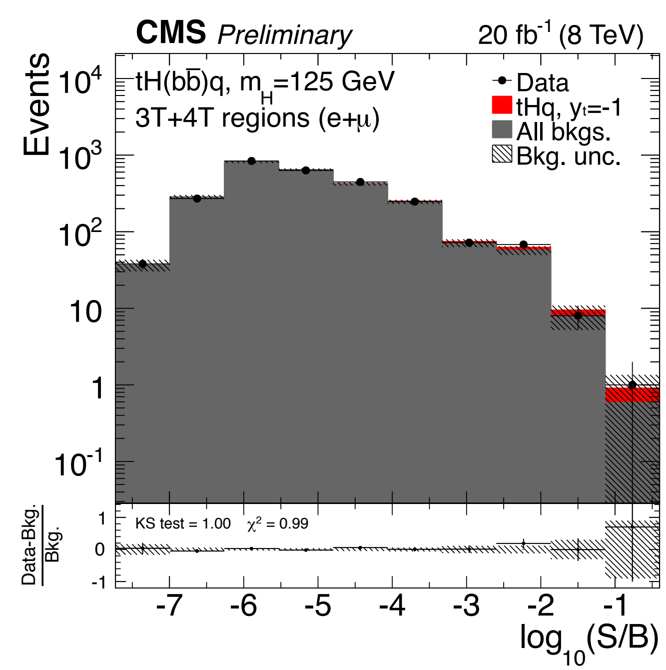
- If $y_t=-1 \rightarrow \sigma_{tHq}^{Yt=-1} = 13x\sigma_{tHq}^{SM}$
- CMS: dedicated searches for $H \rightarrow \gamma\gamma$, $H \rightarrow bb$ and $H \rightarrow WW,\tau\tau$ decays
- Forward jet, like in VBF production
- MVA analyses to discriminate signal from top-pair background
- Upper limit on $\sigma_{tHq}^{Yt=-1}$ @95%CL:

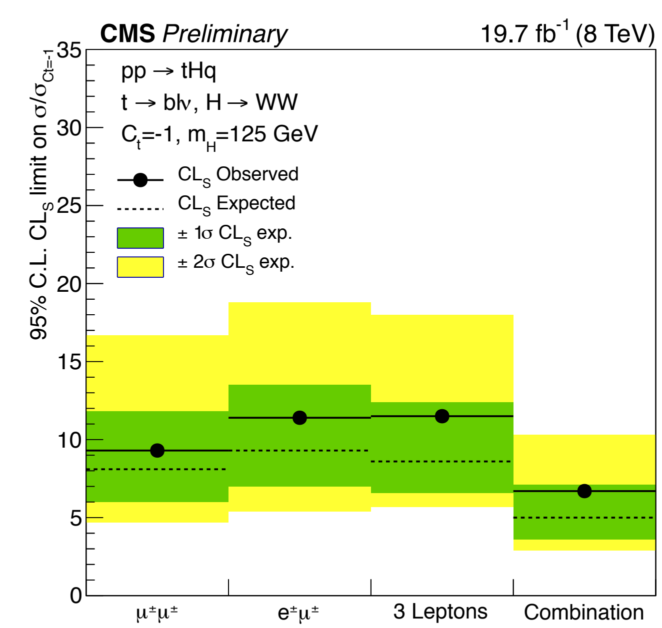




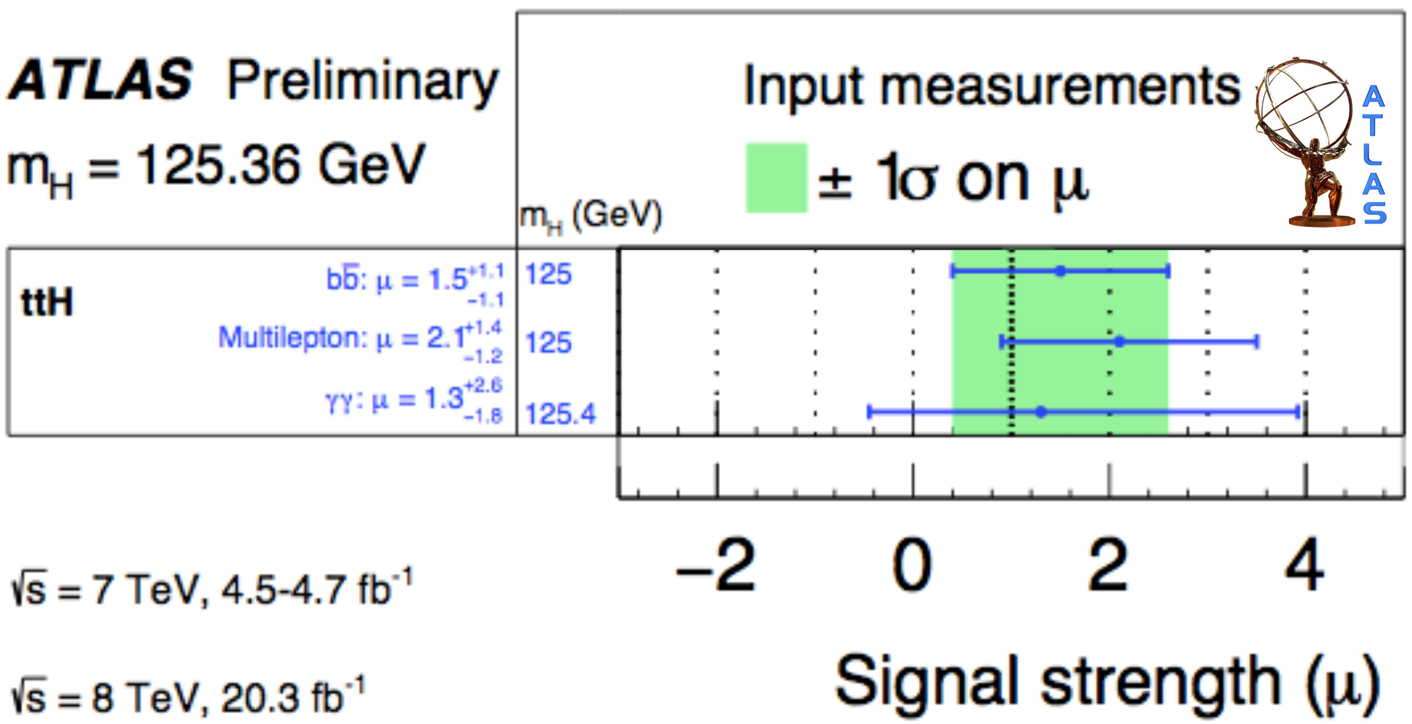
H→bb analysis flow

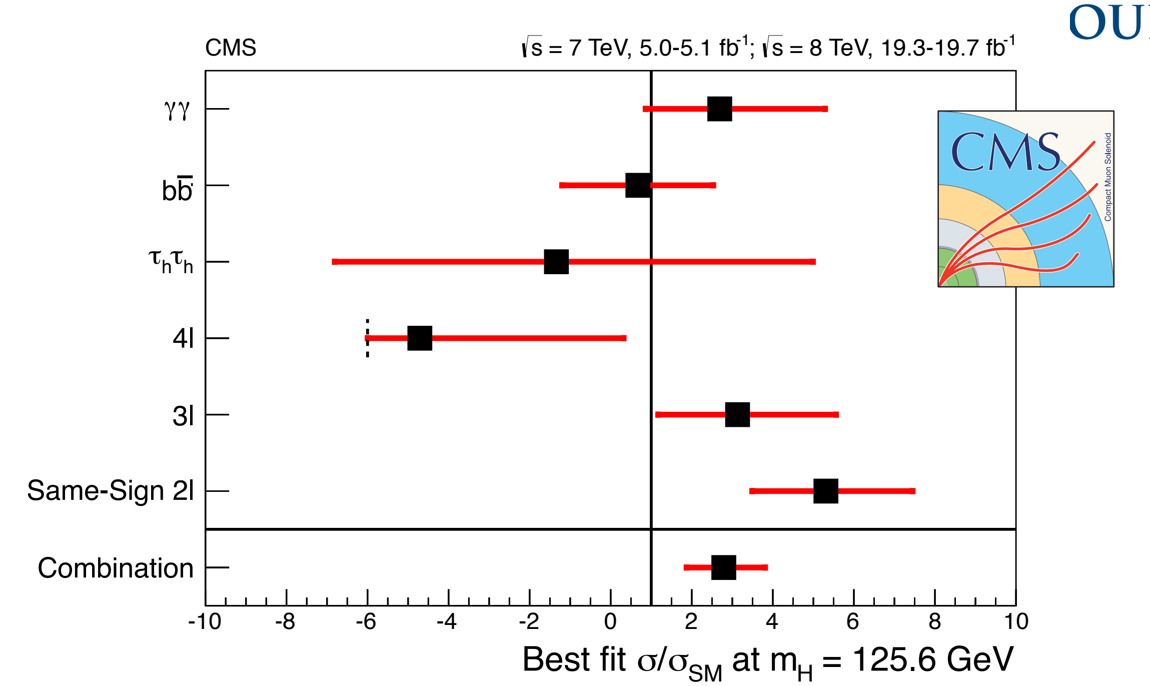
H Decay	$\gamma\gamma$	bb	$WW,\tau\tau$
Obs	4.1	7.6	6.7
Exp	4.1	5.2	5.0



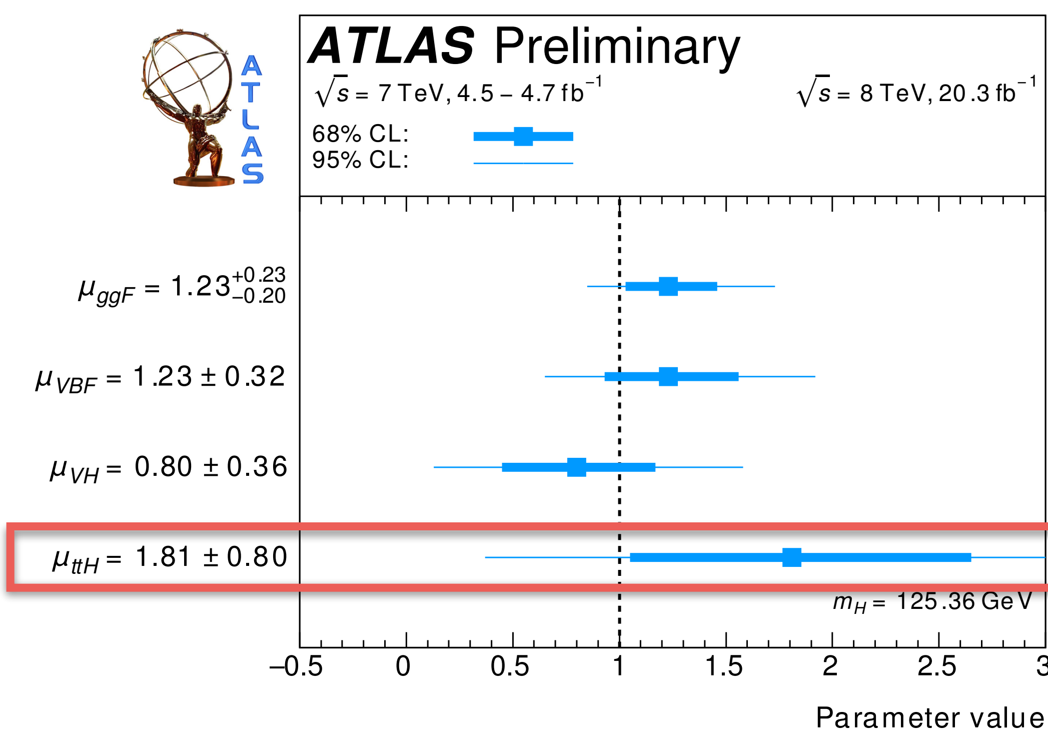


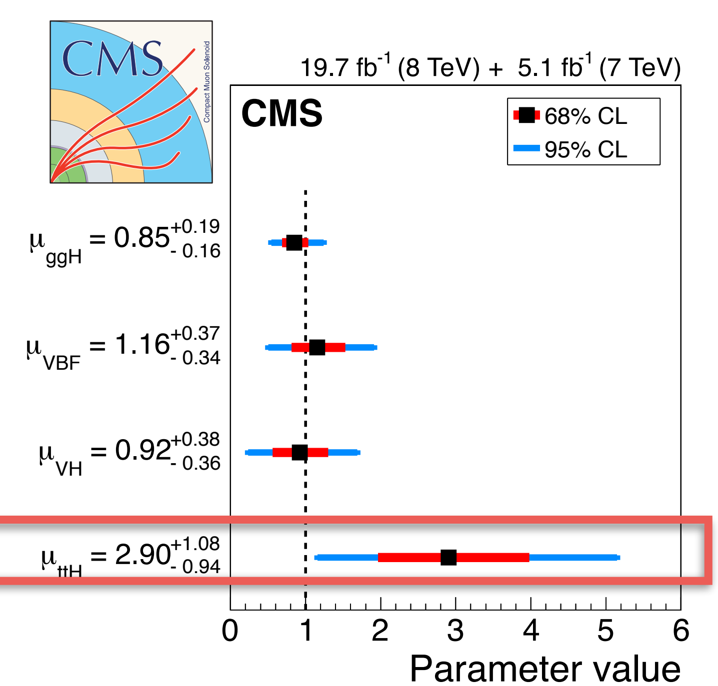
ttH Signal Strength





Combined result compatible with SM at 2.0σ level

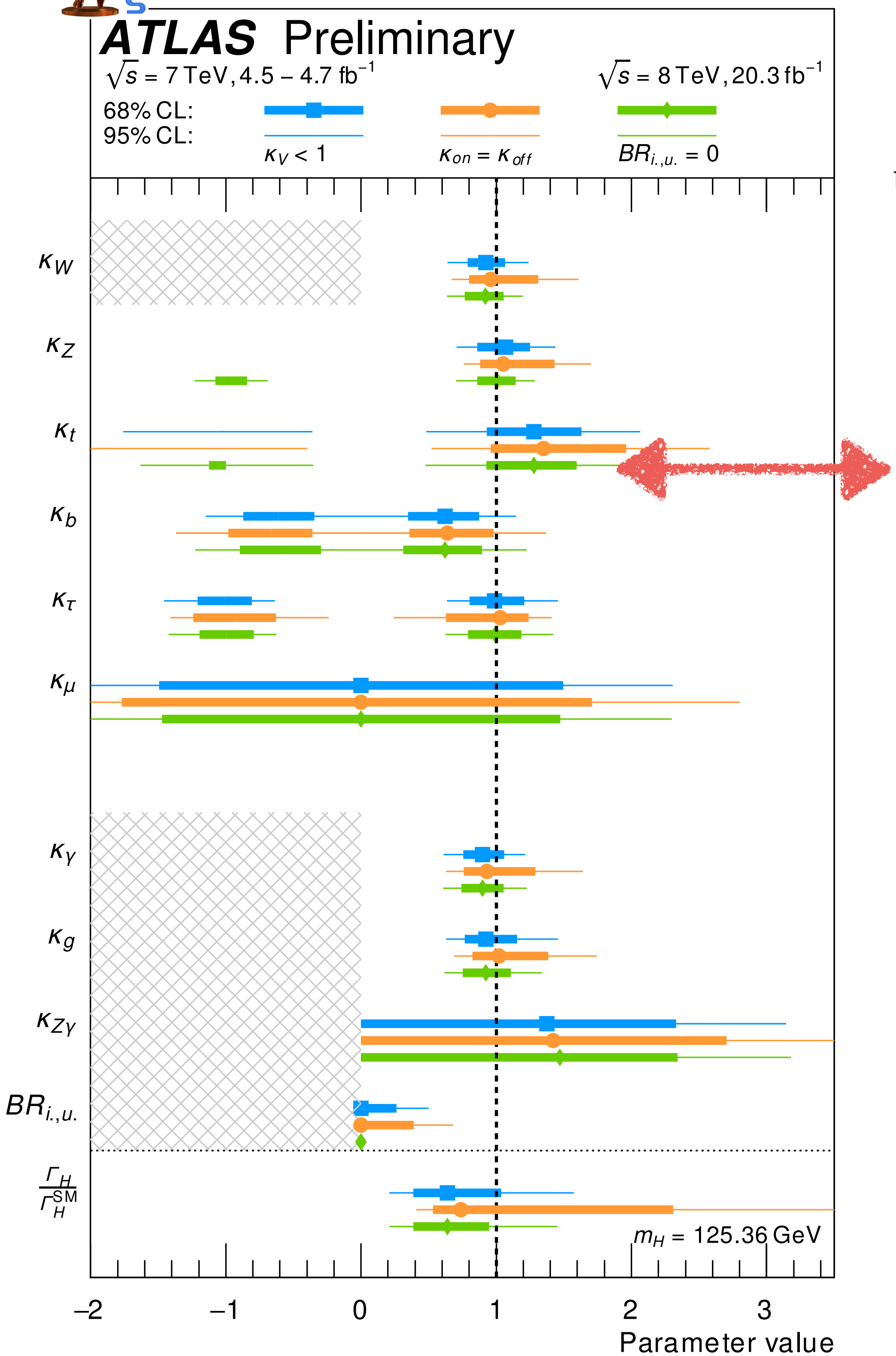


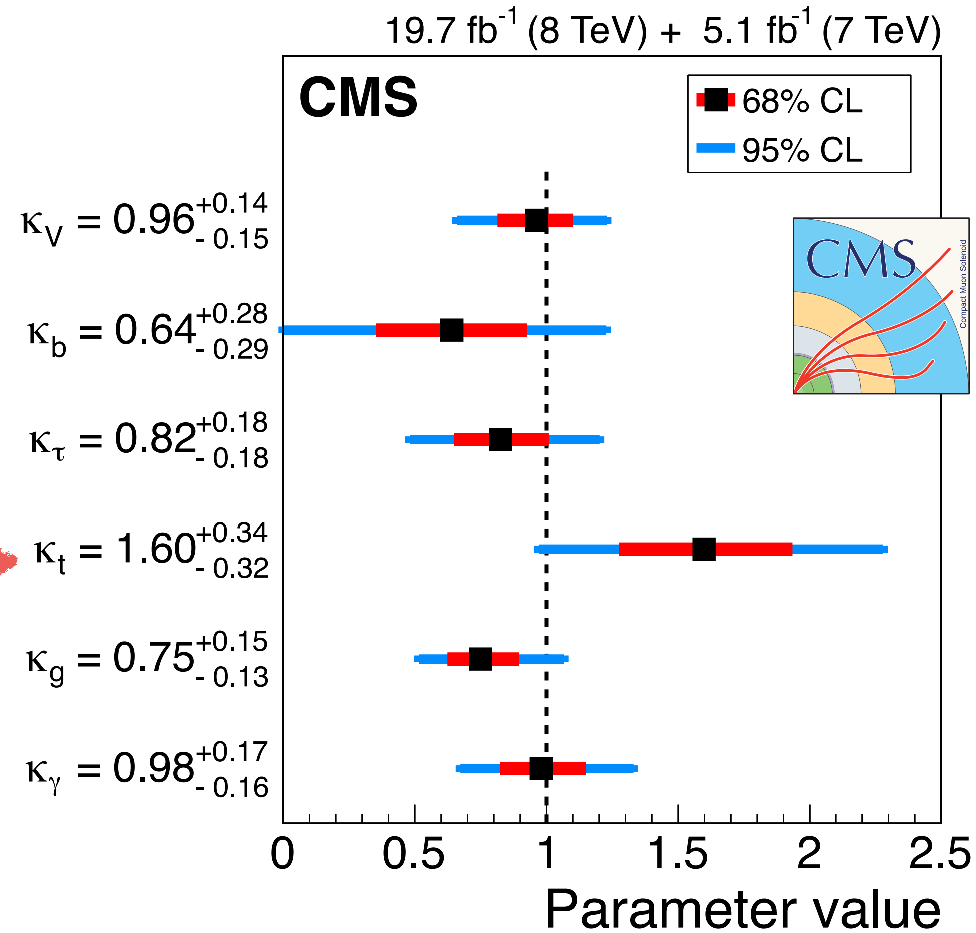


- Full Higgs combination, Higgs decay fractions set to SM values
- ATLAS:
  - μ_{ttH}<3.2(obs), 1.4(exp)
  - $R_{ttH/ggF}$>0 at 2.4σ
- CMS:
  - μ_{ttH}<3.5(obs),1.2(exp)
  - Pull to SM +2.2σ

*Here and following, CMS ttH→bb w/o MEM from JHEP09 (2014) 087, tH not included

Fit to Higgs Coupling





- Higgs production and decay parametrised at LO with independent strength modifiers to Higgs coupling to SM particles $k_i = y_i / y_i^{SM}$ ($k_W > 0$)
- Independent effective couplings for Higgs loops (ggH, H→$\gamma\gamma$,Zγ) allowing for BMS contributions. No Higgs invisible decays, only SM particles
- Best fit fot k_t in both experiments higher than SM, but still compatible in 2σ

Fit to Higgs Coupling

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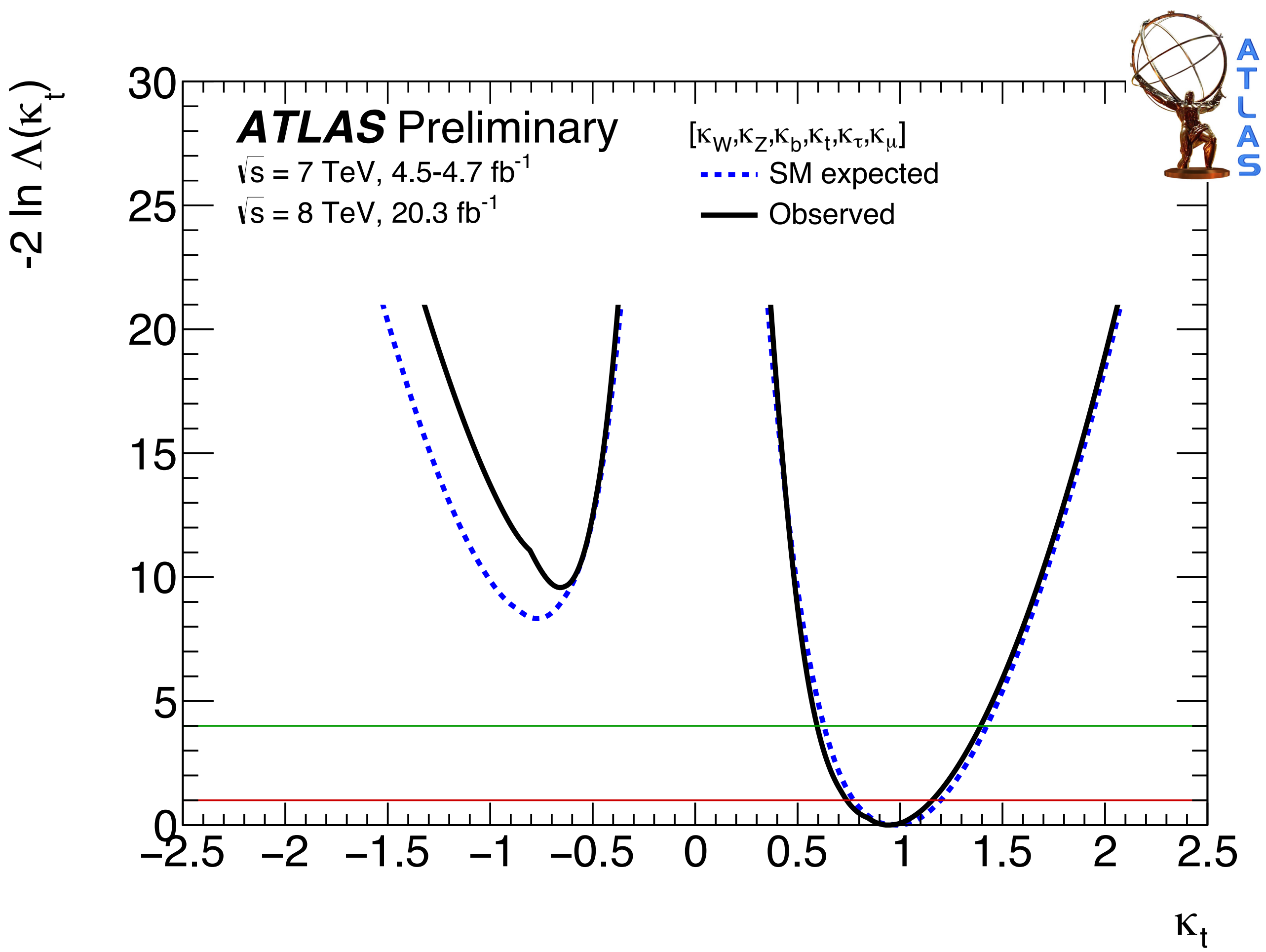
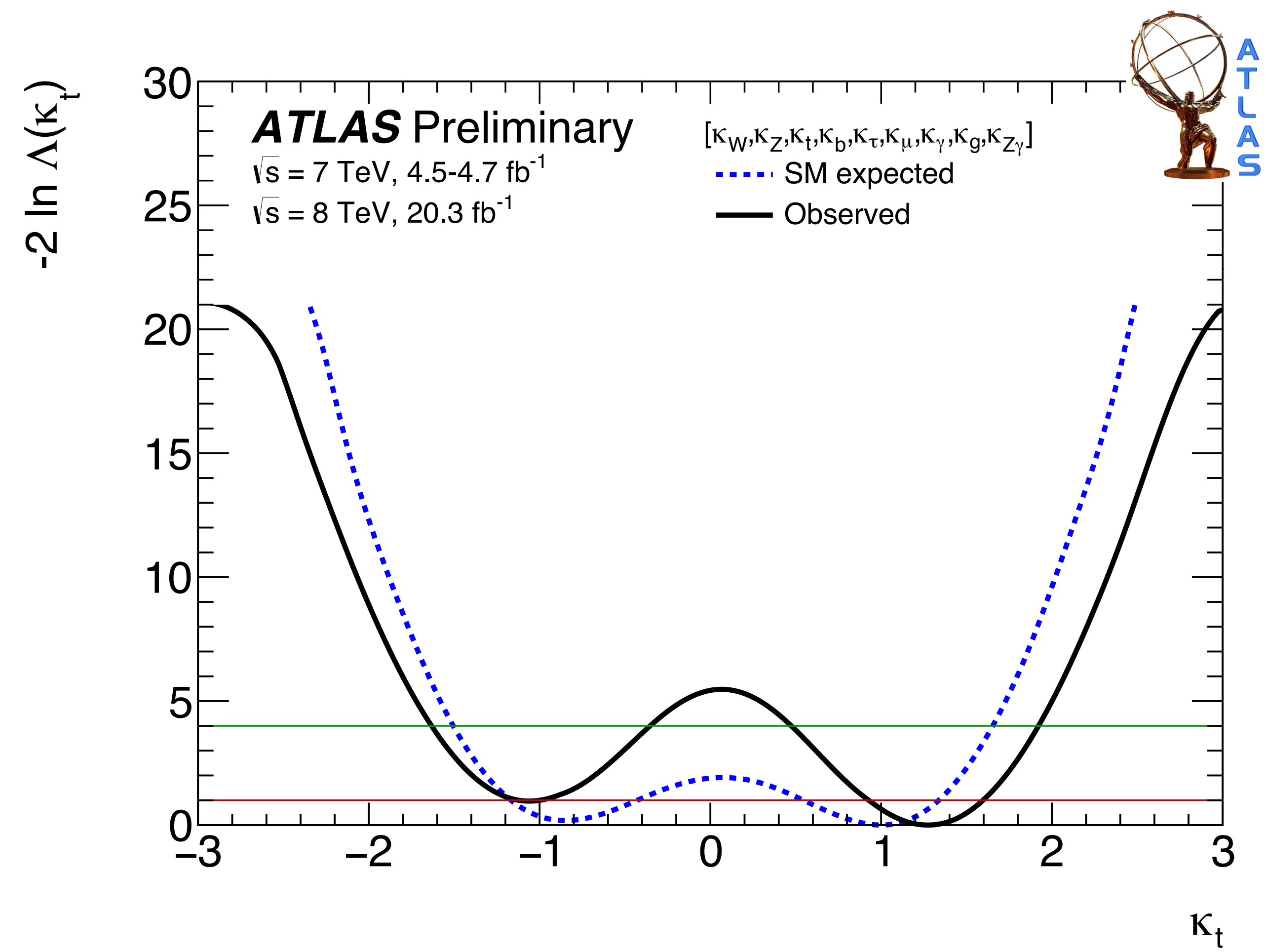
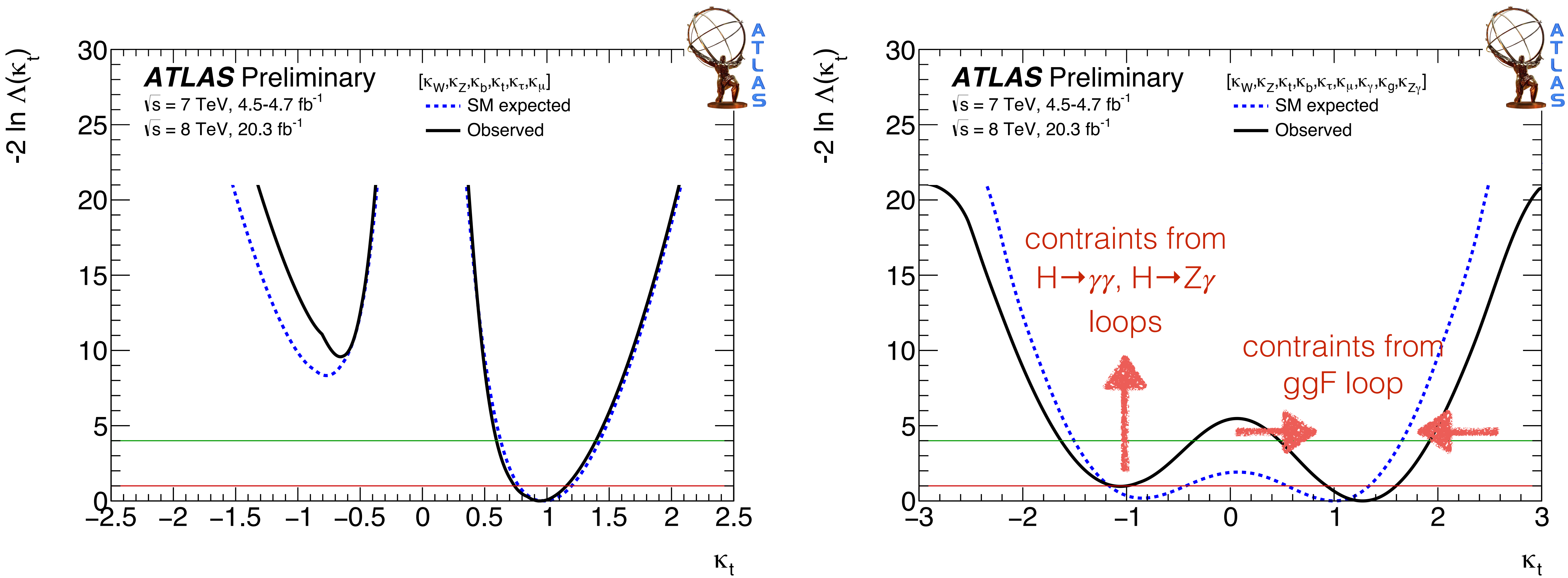




- <u>Only SM particles (no BSM in loop, nor invisible decay)</u>
- Sensitivity to top-W relative sign mostly from tH, $H\to\gamma\gamma$, $H\to Z\gamma$
- k_t<0 ruled out at more than 3σ

- <u>No assumptions on particles in loops nor on Higgs total width</u>
- **Sensitivity to top-W relative sign only from tree-level interference of the tH background of the ttH channel**
- k_t<0 disfavoured at 1.0σ

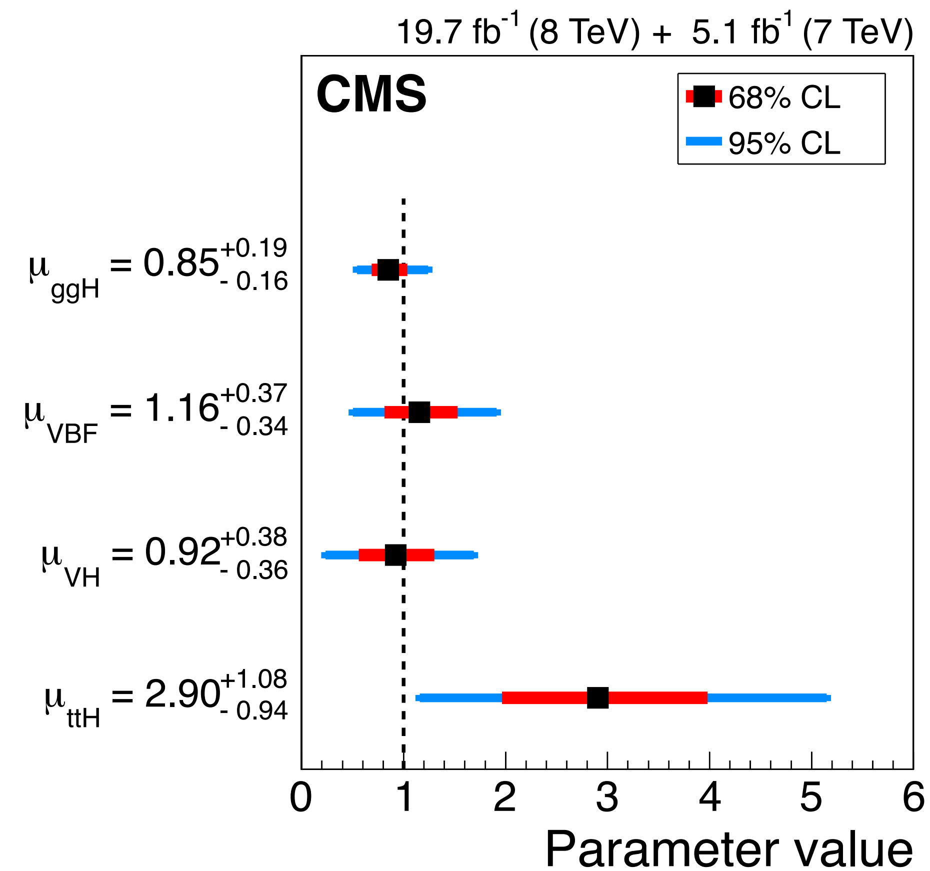
Fit to Higgs Coupling

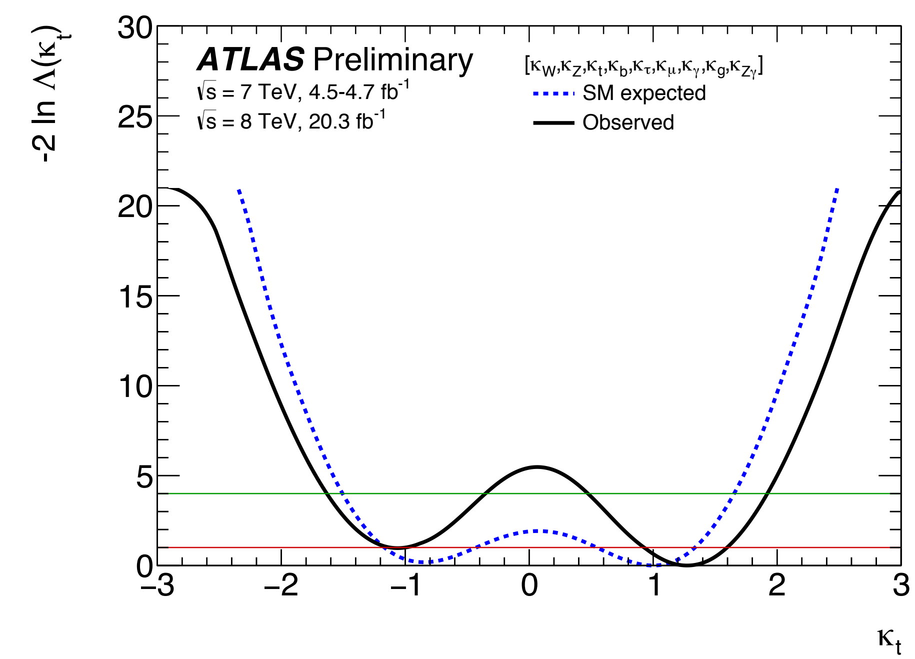


- Observations of ttH (and tH) signals will greatly improve the sensitivity to NP in Higgs production and decay loops!

Summary

- Searches for Higgs boson in association with top(s) allow direct measurement of magnitude and sign of top Yukawa coupling, a key parameter of EWSB in SM
- Run-I:
  - sensitivity of Run-I searches below $2\times\sigma_{ttH}^{SM}$
  - observed excess in multi-lepton final states in both experiments, but within 2σ from SM expectation
  - combined signal strength: $\mu_{ttH}=1.81\pm0.80$ (ATLAS) and $\mu_{ttH}=2.9^{+1.08}_{-0.94}$ (CMS)
  - negative top Yukawa disfavoured at 1σ without assumptions on BSM contributions in Higgs loops and decay
- Run-II
  - ttH cross section 4 times bigger at 13TeV
  - Run-I results will be quickly exceeded
  - better precision for top Yukawa will boost sensitivity to resolve new physics in Higgs loops





Additional Material

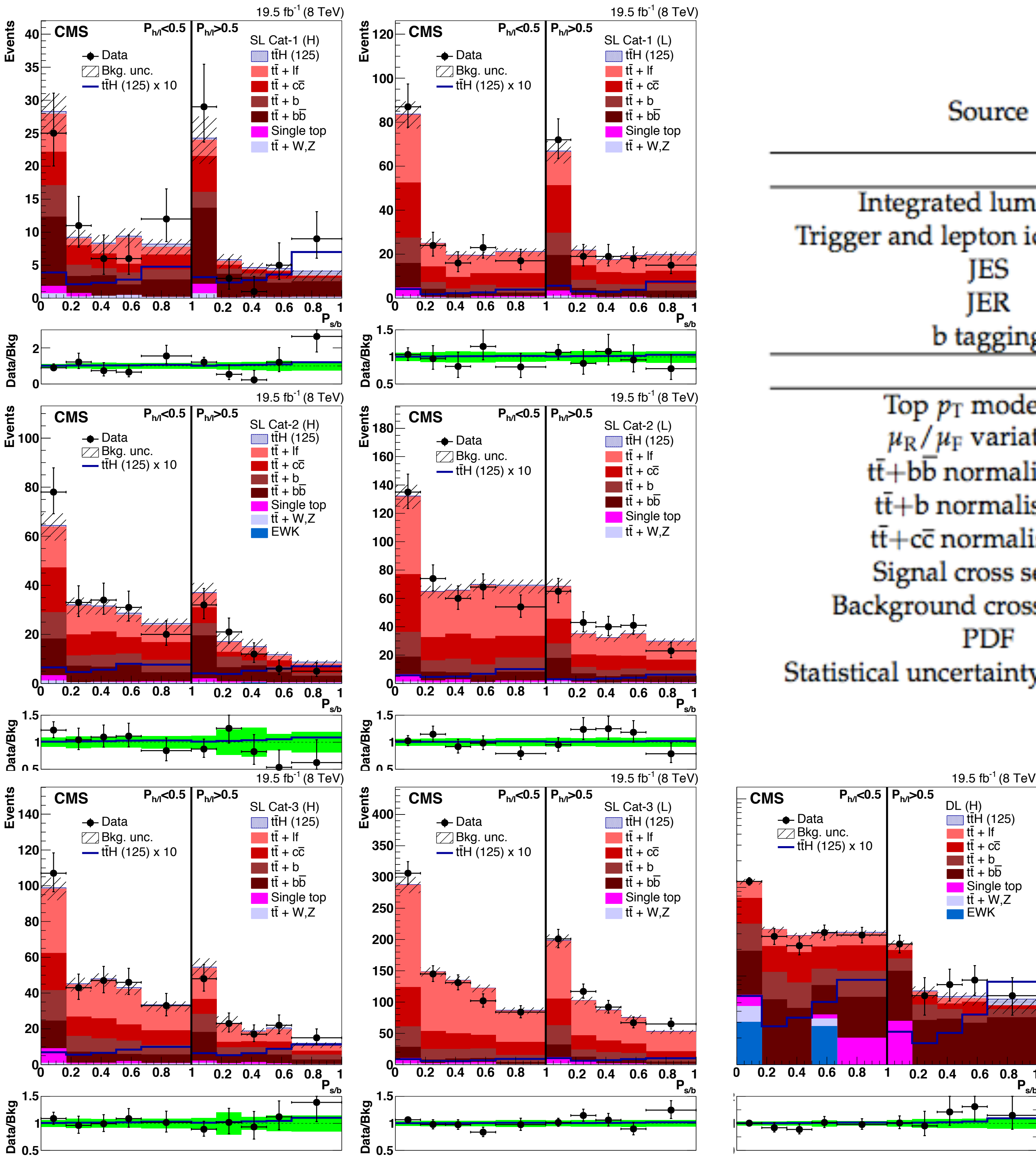
$t\bar{t}H$, H → leptons

	ee	eμ	μμ	3ℓ	4ℓ
$t\bar{t}$H, H → WW	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}$H, H → ZZ	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}$H, H → ττ	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}$W	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}$WW	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1

Table 2: Expected and observed yields in each channel. Uncertainties shown are the quadrature sum of systematic uncertainties and Monte Carlo simulation statistical uncertainties. "Non-prompt" includes the misidentified τ_{had} background to the $1\ell 2\tau_{had}$ category. Rare processes (tZ, $t\bar{t}WW$, triboson production, $t\bar{t}t\bar{t}$, tH) are not shown as a separate column but are included in the total expected background estimate.

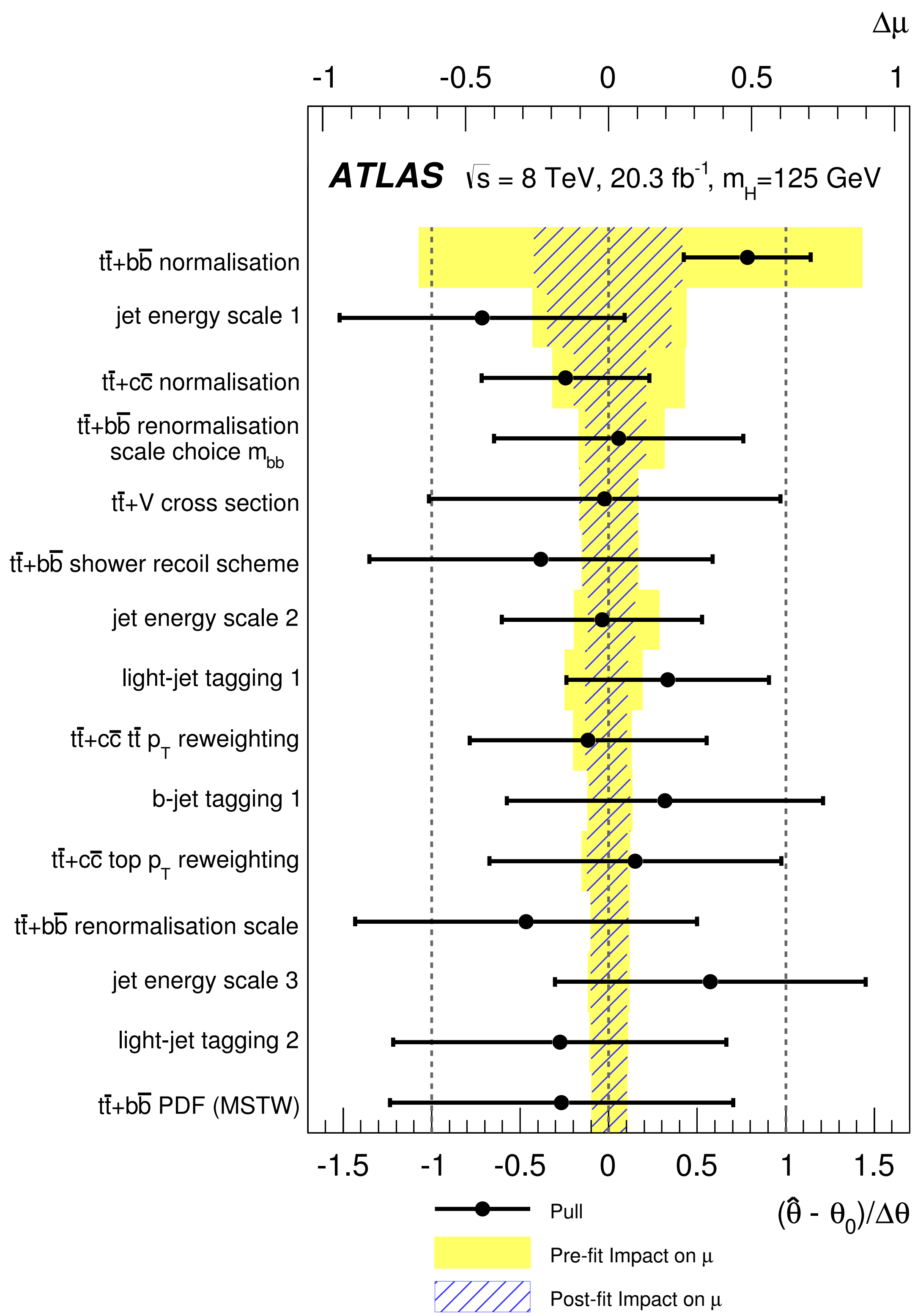
Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected Bkg.	$t\bar{t}H$ ($\mu = 1$)	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.32	0.47 ± 0.42	6.5 ± 2.0	0.73 ± 0.11	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.4	2.1 ± 0.7	0.38 ± 0.32	15 ± 4	2.13 ± 0.31	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 1.1	0.95 ± 0.31	0.69 ± 0.63	8.6 ± 2.5	1.41 ± 0.21	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.25	0.74 ± 0.58	9.1 ± 2.3	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 0.9	1.5 ± 0.2	1.9 ± 1.2	24.0 ± 4.5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.26	0.53 ± 0.30	12.7 ± 3.0	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.9	3.9 ± 0.9	0.86 ± 0.59	11.4 ± 3.1	2.34 ± 0.32	18
$2\ell 1\tau_{had}$	–	$0.4^{+0.6}_{-0.4}$	0.38 ± 0.15	0.37 ± 0.09	0.12 ± 0.15	1.4 ± 0.6	0.47 ± 0.02	1
$1\ell 2\tau_{had}$	–	15 ± 5	0.17 ± 0.07	0.37 ± 0.10	0.41 ± 0.42	16 ± 6	0.68 ± 0.07	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.13	0.05 ± 0.02	0.55 ± 0.17	0.17 ± 0.01	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.03 ± 0.00	0

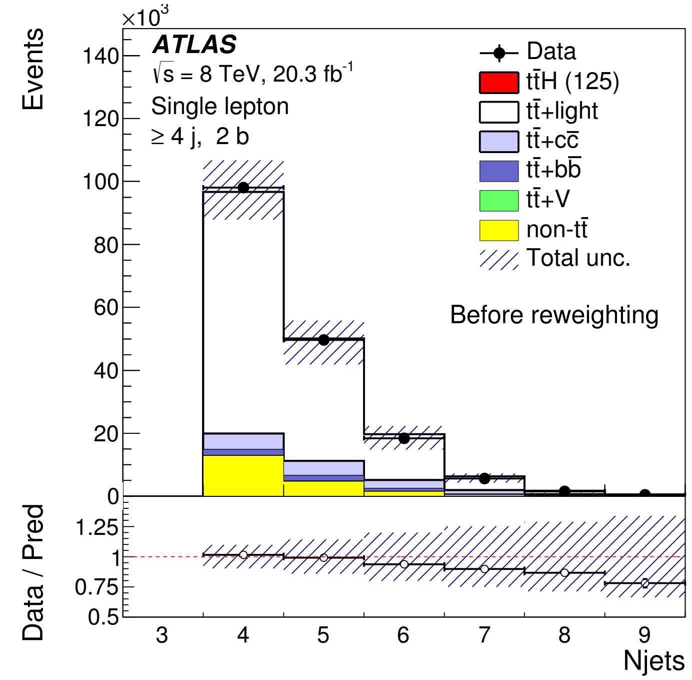
ttH, H→bb with MEM

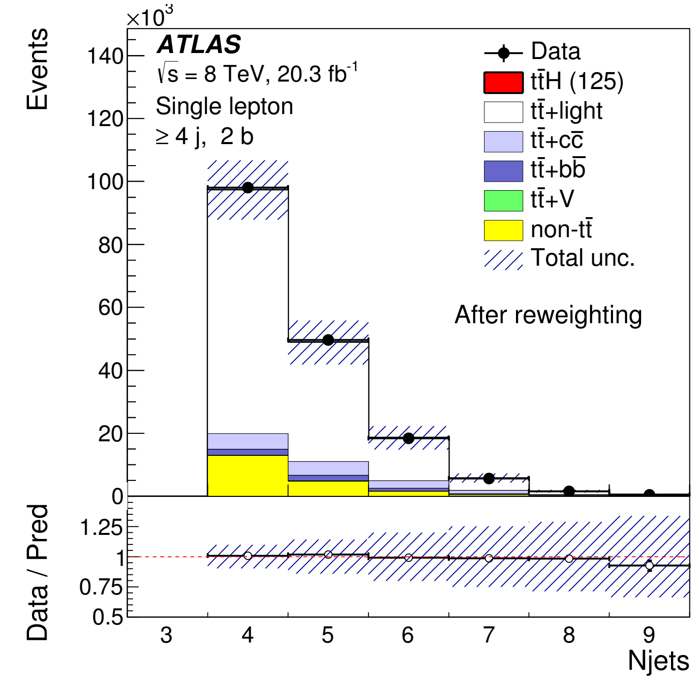


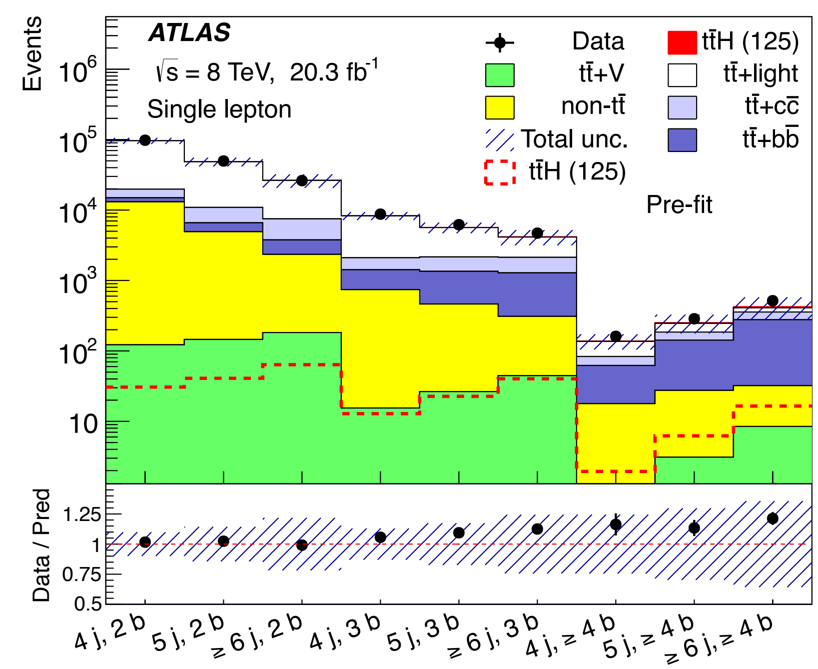
Source	Rate uncertainty	Shape	Process		
			$t\bar{t}H$	$t\bar{t}$+jets	Others
Experimental uncertainties					
Integrated luminosity	2.6%	No	✓	✓	✓
Trigger and lepton identification	2–4%	No	✓	✓	✓
JES	4–13%	Yes	✓	✓	✓
JER	0.5–2%	Yes	✓	✓	✓
b tagging	2–17%	Yes	✓	✓	✓
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R / μ_F variations	2–25%	Yes		✓	
$t\bar{t}+b\bar{b}$ normalisation	50%	No		✓	
$t\bar{t}$+b normalisation	50%	No		✓	
$t\bar{t}+c\bar{c}$ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

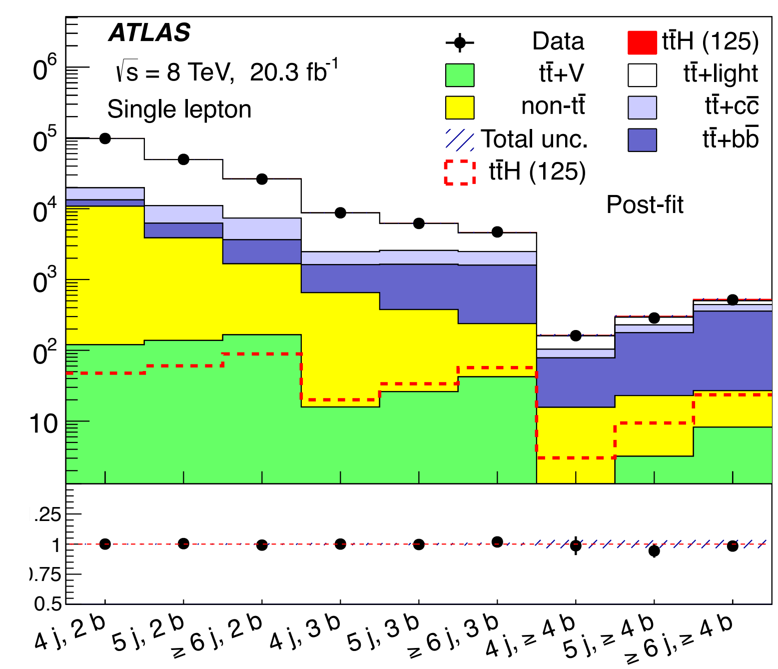
ttH, H→bb with MEM











Systematics

ATLAS $H \to \gamma\gamma$

	$t\bar{t}H$ [%] had.	$t\bar{t}H$ [%] lep.	$tHqb$ [%] had.	$tHqb$ [%] lep.	WtH [%] had.	WtH [%] lep.	ggF [%] had.	WH [%] lep.
Luminosity	±2.8							
Photons	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5	±5.6	±5.5
Leptons	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.6	< 0.1	±0.7
Jets and E_T^{miss}	±7.4	±0.7	±16	±1.9	±11	±2.1	±29	±10
Bkg. modeling	0.24 evt.	0.16 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10, −13		+7, −6		+14, −12		+11, −11	+5.5, −5.4
MC modeling	±11	±3.3	±12	±4.4	±12	±4.6	±130	±100

ATLAS Multileptons

Source	$\Delta\mu$	
$2\ell 0\tau_{had}$ non-prompt muon transfer factor	+0.38	−0.35
$t\bar{t}W$ acceptance	+0.26	−0.21
$t\bar{t}H$ inclusive cross section	+0.28	−0.15
Jet energy scale	+0.24	−0.18
$2\ell 0\tau_{had}$ non-prompt electron transfer factor	+0.26	−0.16
$t\bar{t}H$ acceptance	+0.22	−0.15
$t\bar{t}Z$ inclusive cross section	+0.19	−0.17
$t\bar{t}W$ inclusive cross section	+0.18	−0.15
Muon isolation efficiency	+0.19	−0.14
Luminosity	+0.18	−0.14

ATLAS $H \to bb$ (MEM)

≥ 4 j, ≥ 4 b

	Pre-fit $t\bar{t}H$ (125)	Pre-fit $t\bar{t}$ + light	Pre-fit $t\bar{t}+c\bar{c}$	Pre-fit $t\bar{t}+b\bar{b}$	Post-fit $t\bar{t}H$ (125)	Post-fit $t\bar{t}$ + light	Post-fit $t\bar{t}+c\bar{c}$	Post-fit $t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±2.5	±2.5	±2.5	±2.5	±1.8	±1.8	±1.8	±1.8
Jet energy scale	±4.5	±12	±9.4	±7.0	±2.0	±5.5	±4.5	±3.3
Jet efficiencies	–	±5.9	±1.6	±0.9	–	±2.6	±0.7	±0.4
Jet energy resolution	±0.1	±4.5	±1.1	–	±0.1	±2.3	±0.6	–
b-tagging efficiency	±10	±5.5	±5.4	±11	±5.6	±3.1	±3.0	±5.8
c-tagging efficiency	±0.5	–	±12	±0.6	±0.3	–	±10	±0.3
l-tagging efficiency	±0.7	±34	±7.0	±1.6	±0.4	±21	±4.2	±0.9
High p_T tagging efficiency	–	–	±0.6	–	–	–	±0.3	–
$t\bar{t}$: p_T reweighting	–	±5.8	±6.2	–	–	±5.0	±5.4	–
$t\bar{t}$: parton shower	–	±14	±18	±14	–	±4.8	±11	±8.1
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$+HF: modelling	–	±11	±16	±12	–	±3.8	±10	±10
Theoretical cross sections	–	±6.3	±6.3	±6.2	–	±4.1	±4.1	±4.1
$t\bar{t}H$ modelling	±1.9	–	–	–	±1.8	–	–	–
Total	±12	±40	±59	±55	±6.7	±22	±22	±13

CMS $H \to \gamma\gamma$, leptons, bb

Source	Rate uncertainty Signal	Rate uncertainty Backgrounds	Shape
Experimental			
Integrated luminosity	2.2–2.6%	2.2–2.6%	No
Jet energy scale	0.0–8.4%	0.1–11.5%	Yes
CSV b-tagging	0.9–21.7%	3.0–29.0%	Yes
Lepton reco. and ID	0.3–14.0%	1.4–14.0%	No
Lepton misidentification rate (H → leptons)	—	35.1–45.7%	Yes
Tau reco. and ID (H → hadrons)	11.3–14.3%	24.1–28.8%	Yes
Photon reco. and ID (H → photons)	1.6–3.2%	—	Yes
MC statistics	—	0.2–7.0%	Yes
Theoretical			
NLO scales and PDF	9.7–14.8%	3.4–14.7%	No
MC modeling	2.3–5.1%	0.9–16.8%	Yes
Top quark p_T	—	1.4–6.9%	Yes
Additional hf uncertainty (H → hadrons)	—	50%	No
H contamination (H → photons)	36.7–41.2%		No
WZ (ZZ) uncertainty (H → leptons)	—	22% (19%)	No

CMS $H \to bb$ (MEM)

Source	Rate uncertainty	Shape	Process tt̄H	Process tt̄+jets	Process Others
Experimental uncertainties					
Integrated luminosity	2.6%	No	✓	✓	✓
Trigger and lepton identification	2–4%	No	✓	✓	✓
JES	4–13%	Yes	✓	✓	✓
JER	0.5–2%	Yes	✓	✓	✓
b tagging	2–17%	Yes	✓	✓	✓
Theoretical uncertainties					
Top p_T modelling	3–8%	Yes		✓	
μ_R/μ_F variations	2–25%	Yes		✓	
tt̄+bb̄ normalisation	50%	No		✓	
tt̄+b normalisation	50%	No		✓	
tt̄+cc̄ normalisation	50%	No		✓	
Signal cross section	7%	No	✓		
Background cross sections	2–20%	No		✓	✓
PDF	3–9%	No	✓	✓	✓
Statistical uncertainty (bin-by-bin)	4–30%	Yes	✓	✓	✓

ATLAS Higgs Combination Inputs

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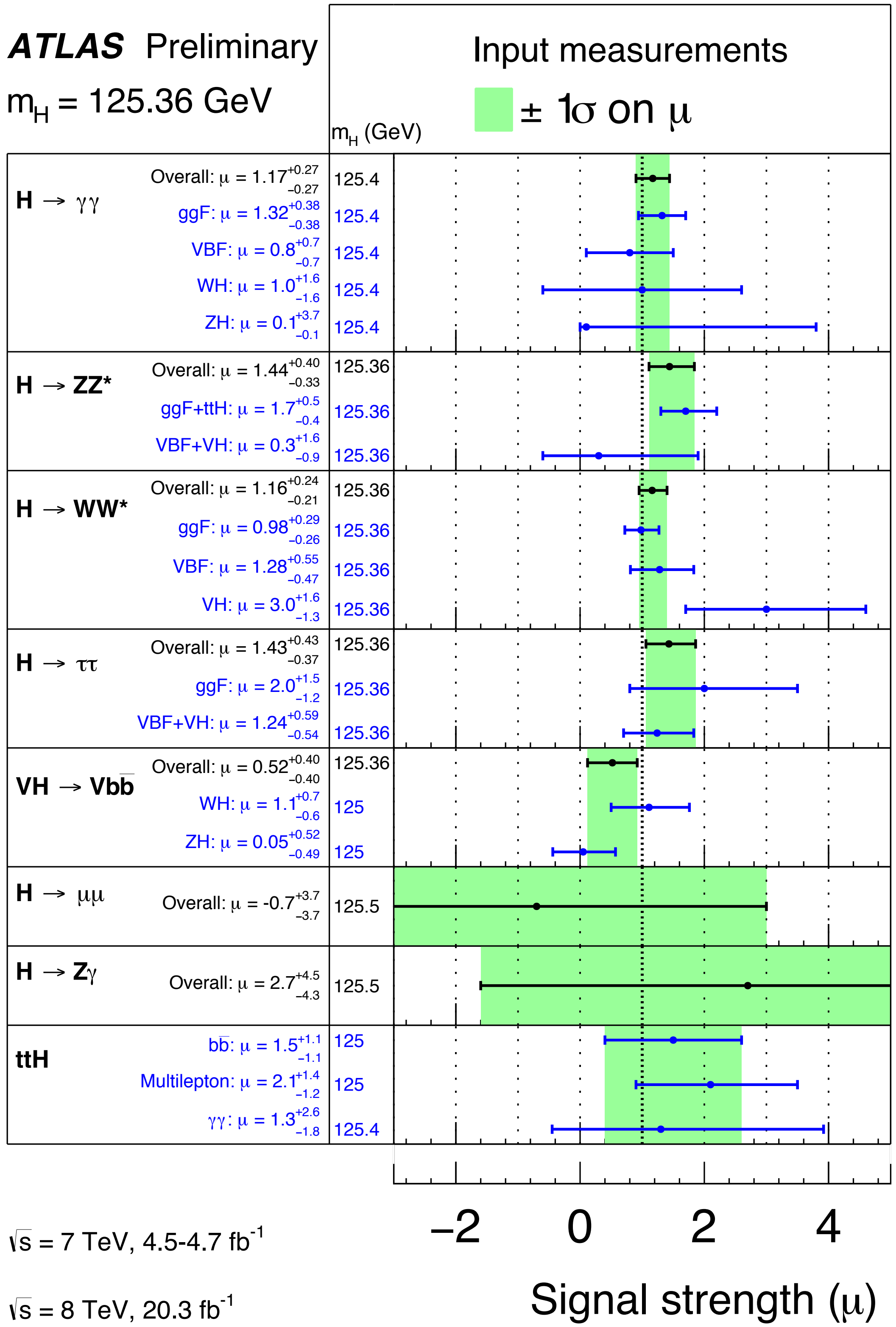
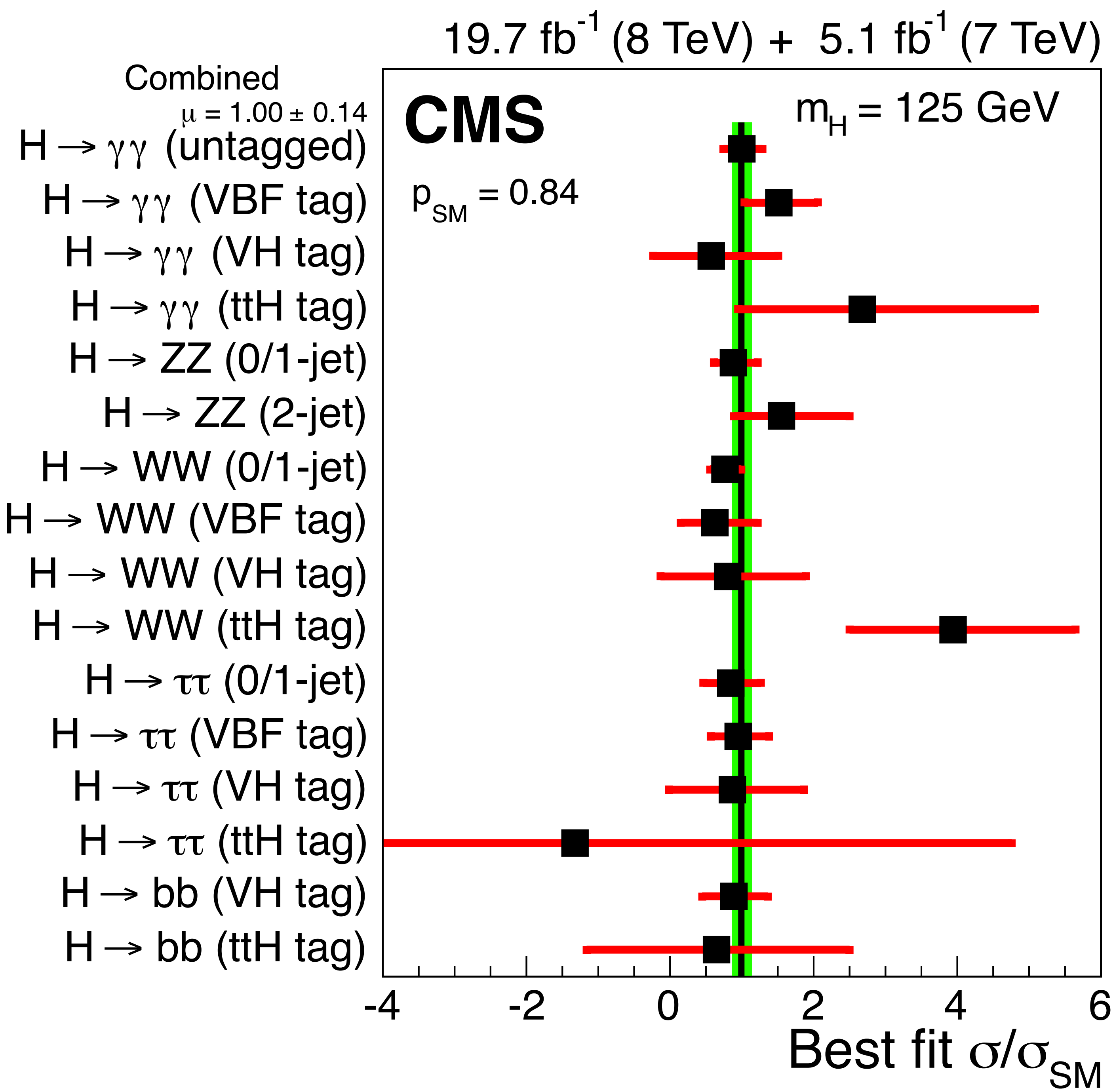


Analysis / Categorisation or final states	Signal Strength	Signal Significance [σ]	$\int \mathcal{L}dt$ (fb^{-1}) 7 TeV	$\int \mathcal{L}dt$ (fb^{-1}) 8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories			✓	✓
$H \to ZZ^* \to 4\ell$ [13]	$1.44^{+0.40}_{-0.33}$	8.1 (6.2)	4.5	20.3
VBF			✓	✓
VH: hadronic, leptonic			✓	✓
ggF			✓	✓
$H \to WW^*$ [14,15]	$1.16^{+0.24}_{-0.21}$	6.5 (5.9)	4.5	20.3
ggF: (0-jet, 1-jet) $\otimes$ ($ee+\mu\mu$, $e\mu$)			✓	✓
ggF: $\geq$ 2-jet and $e\mu$				✓
VBF: $\geq$ 2-jet $\otimes$ ($ee+\mu\mu$, $e\mu$)			✓	✓
VH: opposite-charge dilepton, three-lepton, four-lepton			✓	✓
VH: same-charge dilepton				✓
$H \to \tau\tau$ [17]	$1.43^{+0.43}_{-0.37}$	4.5 (3.4)	4.5	20.3
Boosted: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
VBF: $\tau_{lep}\tau_{lep}, \tau_{lep}\tau_{had}, \tau_{had}\tau_{had}$			✓	✓
$VH \to Vb\bar{b}$ [18]	0.52 ± 0.40	1.4 (2.6)	4.7	20.3
0ℓ ($ZH \to \nu\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V >$ and $<$ 120 GeV			✓	✓
1ℓ ($WH \to \ell\nu bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V >$ and $<$ 120 GeV			✓	✓
2ℓ ($ZH \to \ell\ell bb$): $N_{jet} = 2, 3$, $N_{btag} = 1, 2$, $p_T^V >$ and $<$ 120 GeV			✓	✓
	95% CL limit			
$H \to Z\gamma$ [19]	$\mu < 11$ (9)		4.5	20.3
10 categories based on $\Delta\eta_{Z\gamma}$ and p_{Tt}			✓	✓
$H \to \mu\mu$ [20]	$\mu < 7.0$ (7.2)		4.5	20.3
VBF and 6 other categories based on η_μ and $p_T^{\mu\mu}$			✓	✓
ttH production [21,22,23]			4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton	$\mu < 3.4$ (2.2)			✓
ttH →multileptons: categories on lepton multiplicity	$\mu < 4.7$ (2.4)			✓
$H \to \gamma\gamma$: leptonic, hadronic	$\mu < 6.7$ (4.9)		✓	✓
Off-shell H^* production [24]	$\mu < 5.1 - 8.6$ ($6.7 - 11.0$)			20.3
$H^* \to ZZ \to 4\ell$				✓
$H^* \to ZZ \to 2\ell 2\nu$				✓
$H^* \to WW \to e\nu\mu\nu$				✓

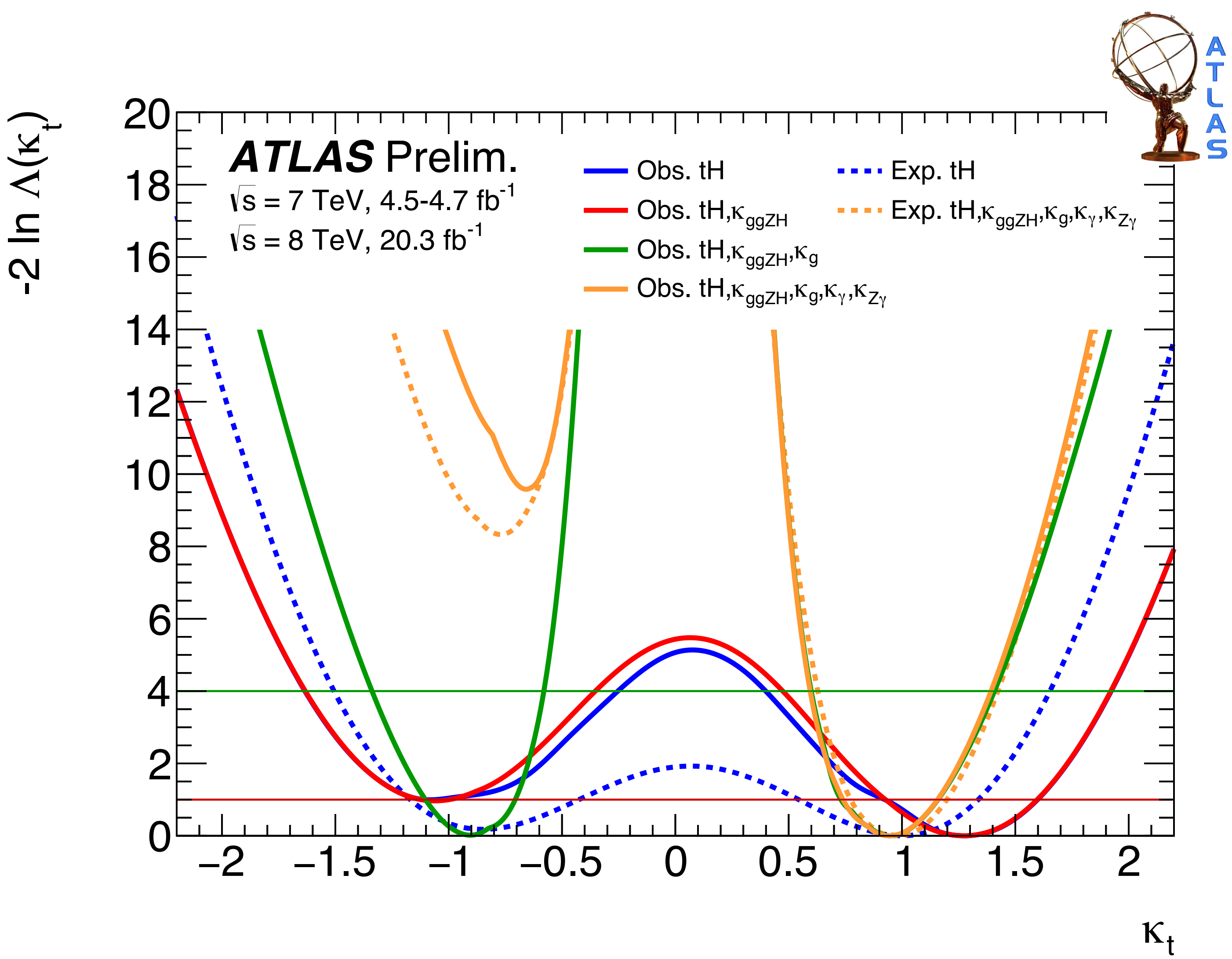
CMS Higgs Combination Inputs



Decay tag and production tag		Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) No. of categories 7 TeV	8 TeV
$H \to \gamma\gamma$ [18], Section 2.1				5.1	19.7
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic ttH	≈95% ttH	1.1%	1†	1
	Multijet ttH	>90% ttH	1.1%		1
$H \to ZZ \to 4\ell$ [16], Section 2.2				5.1	19.7
4μ, $2e2\mu/2\mu 2e$, $4e$	Untagged	≈90% ggH	1.3, 1.8, 2.2%‡	3	3
	2-jet	42% (VBF + VH)		3	3
$H \to WW \to \ell\nu\ell\nu$ [22], Section 2.3				4.9	19.4
$ee + \mu\mu$, $e\mu$	0-jet	96–98% ggH	16%‡	2	2
	1-jet	82–84% ggH	17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
$3\ell 3\nu$ (WH)	SF-SS, SF-OS	≈100% WH, up to 20% ττ		2	2
$\ell\ell + \ell'\nu jj$ (ZH)	eee, eeμ, μμμ, μμe	≈100% ZH		4	4
$H \to \tau\tau$ [23], Section 2.4				4.9	19.7
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	—	2
	2-jet VBF	80% VBF	11%	—	1
$e\mu$	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ (ZH)	$LL' = \tau_h\tau_h, \ell\tau_h, e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ ($e\mu$)		8	8
$\ell + \tau_h\tau_h$ (WH)		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ (WH)		ZH/WH ≈ 5%, 9–11% WW		2	4
VH production with $H \to bb$ [21], Section 2.5				5.1	18.9
W($\ell\nu$)H(bb)	p_T(V) bins	≈100% VH, 96–98% WH	≈10%	4	6
W($\tau_h\nu$)H(bb)	—	93% WH		—	1
Z($\ell\ell$)H(bb)	p_T(V) bins	≈100% ZH		4	4
Z($\nu\nu$)H(bb)	p_T(V) bins	≈100% VH, 62–76% ZH		2	3
ttH production with H → hadrons or H → leptons [29], Section 2.6				5.0	≤19.6
$H \to bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% ττ		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% ττ, 13–22% WW, 5–13% bb		—	6
2ℓ SS	≥ 2 jets, ≥ 1 b jet	WW/ττ ≈ 3		—	6
3ℓ		WW/ττ ≈ 3		—	2
4ℓ		WW : ττ : ZZ ≈ 3 : 2 : 1		—	1
H → invisible [28], Section 2.7				4.9	≤19.7
H(inv)	2-jet VBF	≈94% VBF, ≈6% ggH		—	1
ZH → Z(ee, μμ)H(inv)	0-jet	≈100% ZH		2	2
	1-jet			2	2
$H \to \mu\mu$ [30], Section 2.8				5.0	19.7
$\mu\mu$	Untagged	88–99% ggH	1.3–2.4%	12	12
	2-jet VBF	≈80% VBF	1.9%	1	1
	2-jet boosted	≈50% ggH, ≈50% VBF	1.8%	1	1
	2-jet other	≈68% ggH, ≈17% VH, ≈15% VBF	1.9%	1	1

† Events fulfilling the requirements of either selection are combined into one category.
‡ Values for analyses dedicated to the measurement of the mass that do not use the same categories and/or observables.
* Composition in the regions for which the ratio of signal and background $s/(s+b) > 0.05$.

Fit to Absolute Higgs Coupling



- Red: No assumptions on particles in loops and Higgs total width. Sensitivity to k_t sign from tH and ttH cross sections
- Blue: as Red, but with ggZH loop resolved in SM content. No improvement
- Green: as Blue, but with ggF loop resolved in SM content. Improvement in precision of k_t, but no gain in sensitivity to sign (also reduction in observed magnitude of k_t to more SM-compatible level)
- Orange: As Green, but resolving $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loops. Great improvement in sensitivity to k_t sign from W-t interference, no improvement in precision of k_t magnitude