Search for Higgs bosons produced in association with top quarks - ATLAS detector at the LHC

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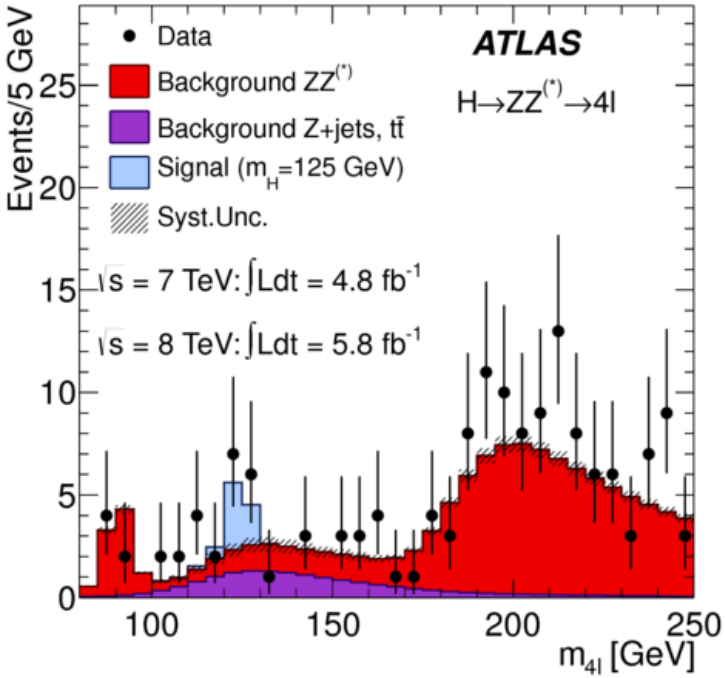
Fermilab Wine & Cheese, July 10, 2015

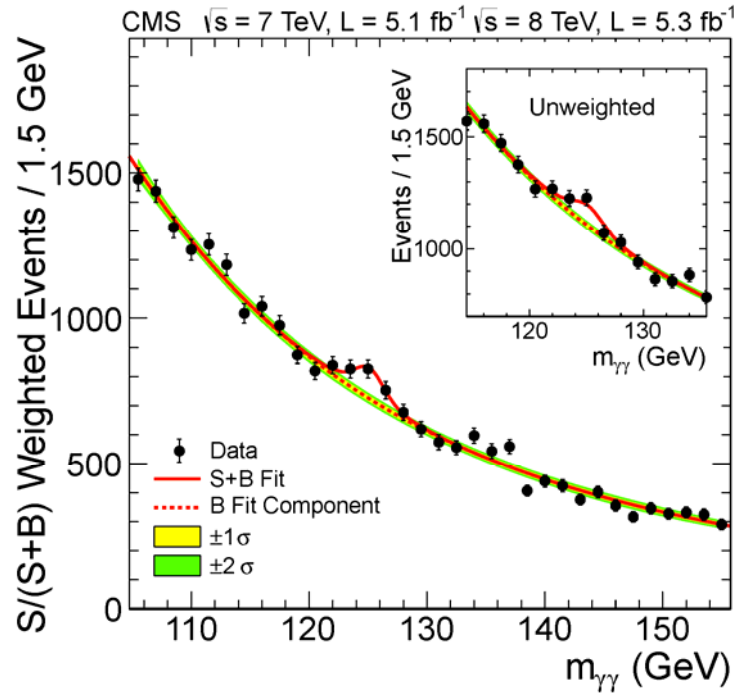
Outline

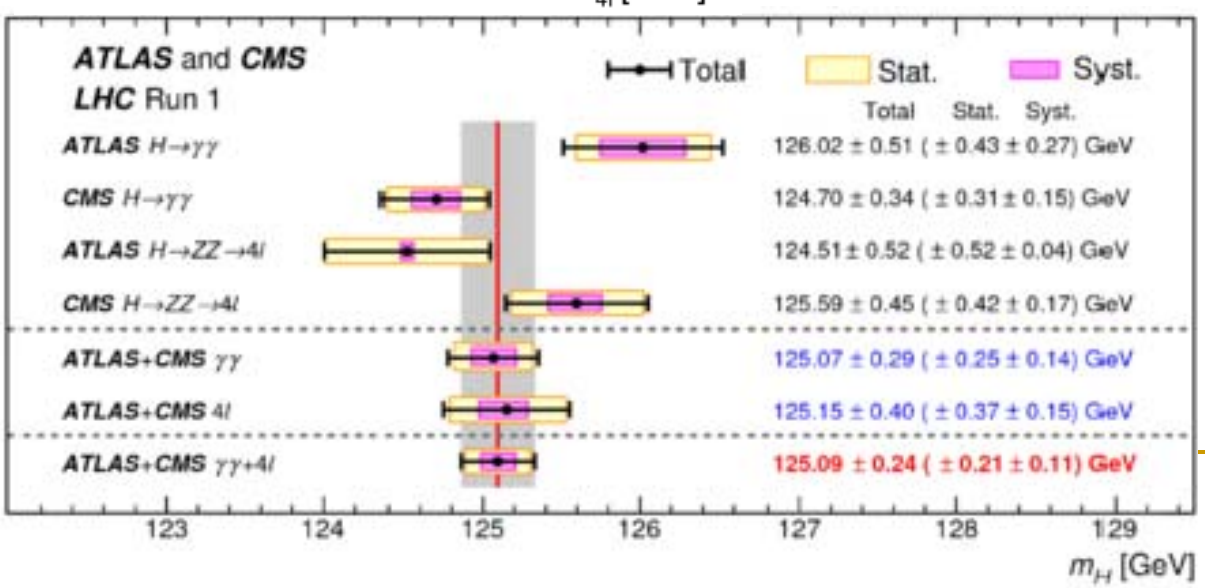
- Current status of Higgs measurements
- Why the search for Higgs produced in association with top quarks (aka ttH)?
- Various ttH analyses at ATLAS
  - $H \rightarrow bb$ (single and dilepton events)
  - $H \rightarrow$ Multileptons (> 2 leptons)
  - $H \rightarrow \gamma\gamma$
  - Top Yukawa coupling strength
- Summary and Outlook

From discovery onward

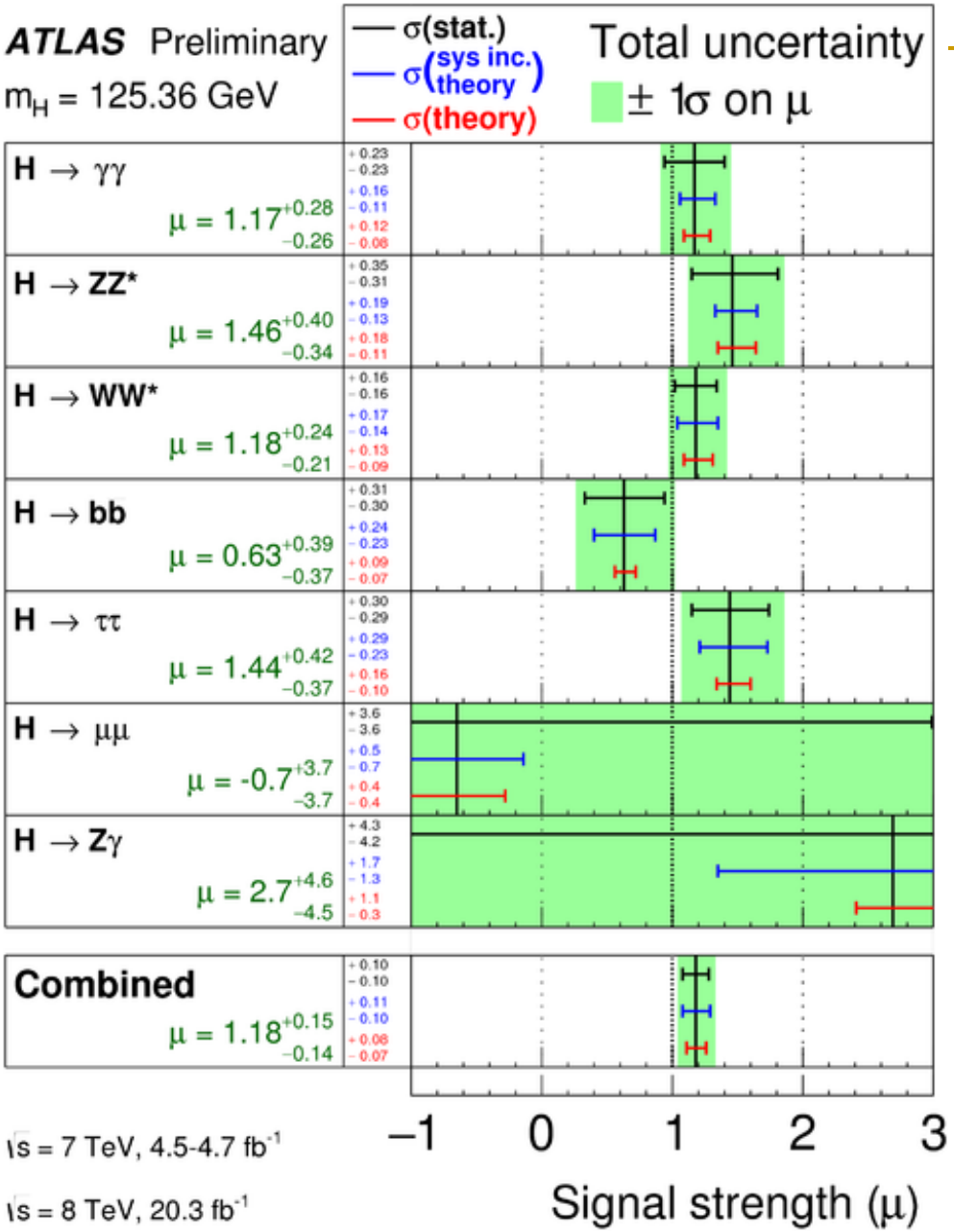


From 2012 discovery papers





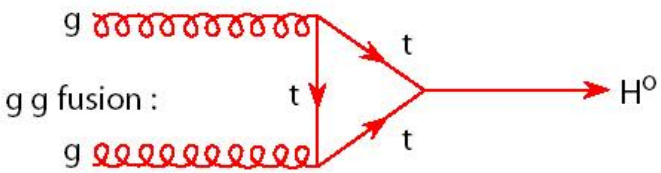
Alternative models of spin-parity are excluded at the >99% CL, in favour of 0^+ (SM)



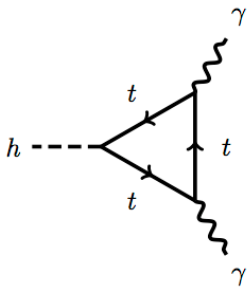
μ: signal strength relative to SM

$1.18 \pm 0.10 \pm 0.07^{+0.08}_{-0.07}$

Why search for ttH?



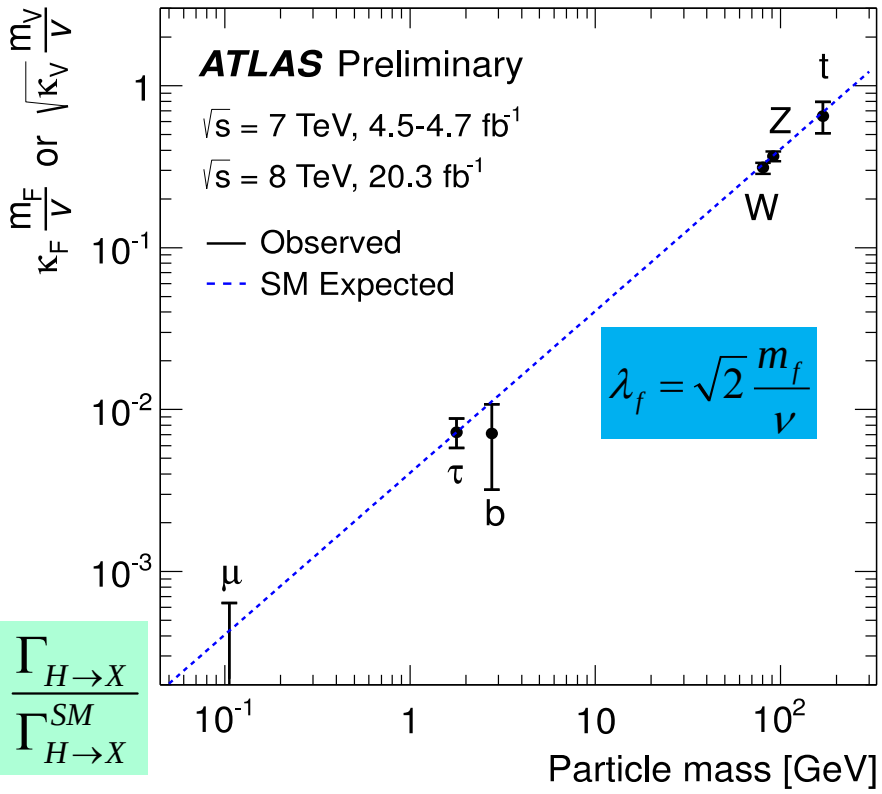
- We have indirect evidence for ttH
  - Largest production is via gluon+gluon fusion - proceeds mainly through top loop (b-loop is small)
  - Higgs → $\gamma\gamma$ proceeds through W & top loops



  - Since these are loops, BSM particles could also contribute. Current precision not enough to discriminate

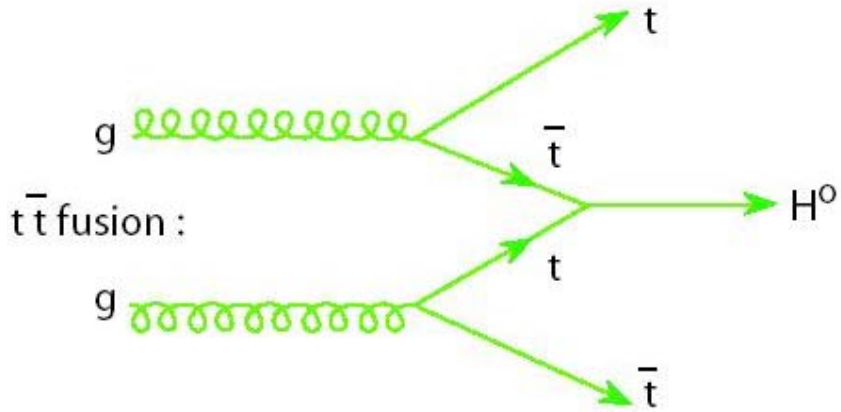
ttH

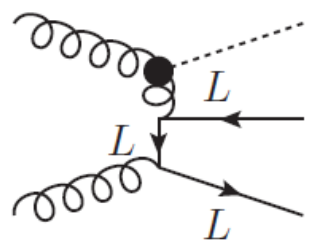
- Observation of ttH production process gives measure of top quark Yukawa coupling
  - Coupling is $\mathcal{O}(1)$ - may play special role in EWSB



$$\lambda_f = \sqrt{2}\frac{m_f}{v}$$

$$\kappa_X^2 = \frac{\Gamma_{H\to X}}{\Gamma_{H\to X}^{SM}}$$

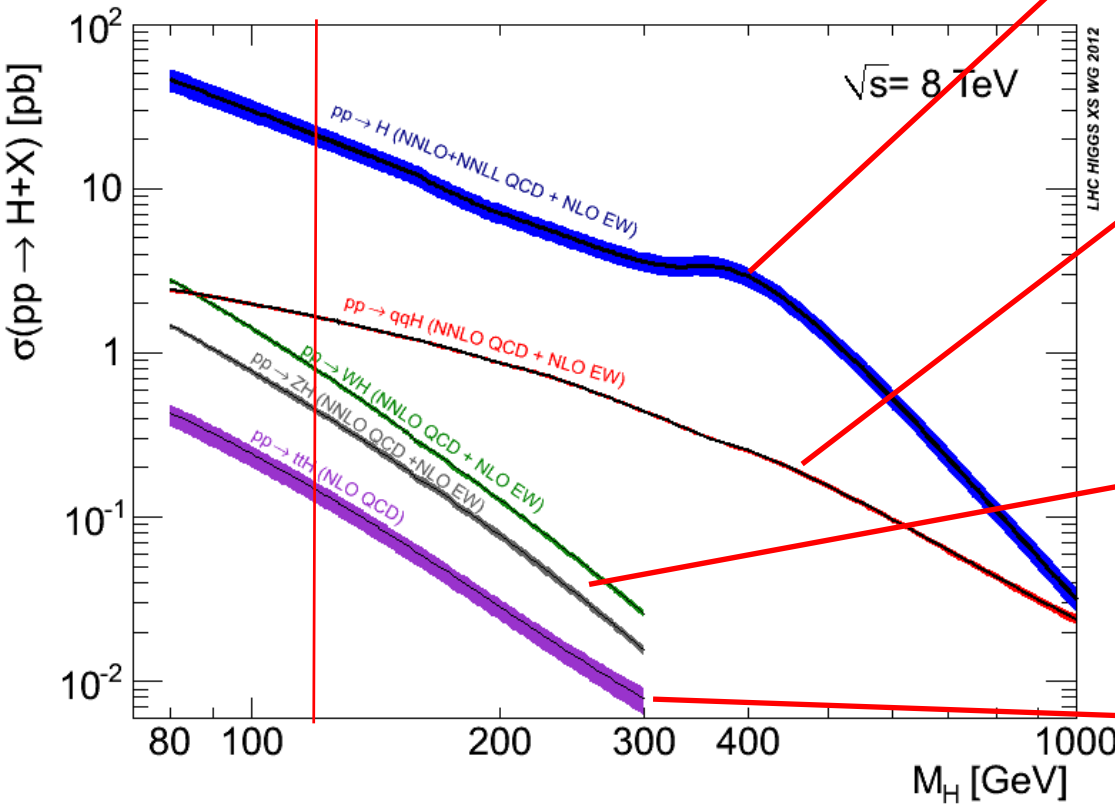




Small contribution from ggF

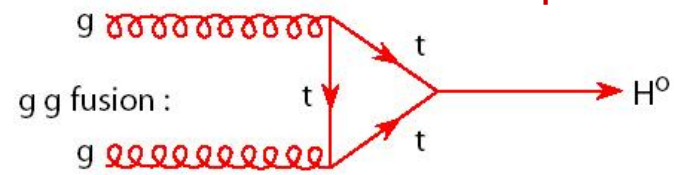
Higgs Production mechanisms

(single top processes discussed later)

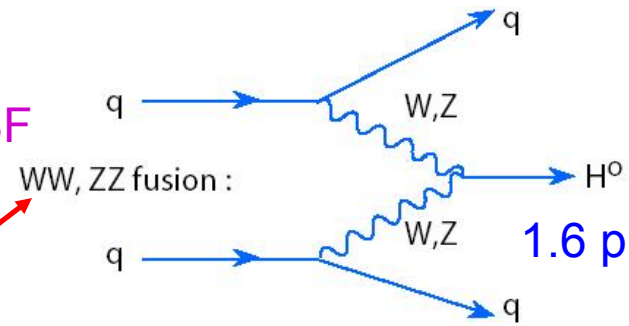


ggF

19.3pb



VBF



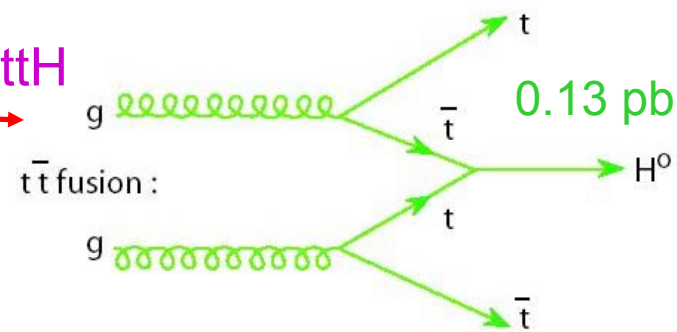
1.6 pb

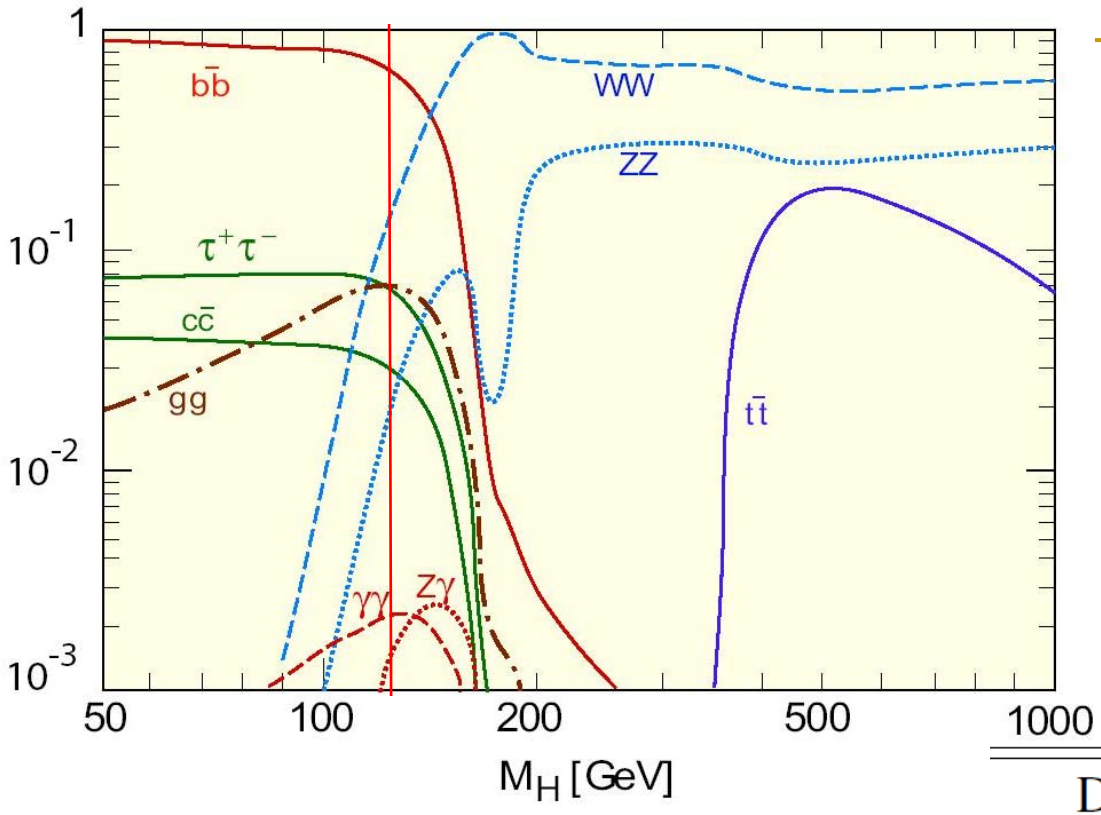
VH

0.7/0.4 pb

ttH

0.13 pb



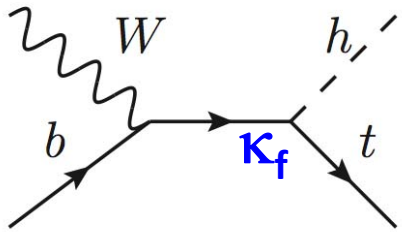


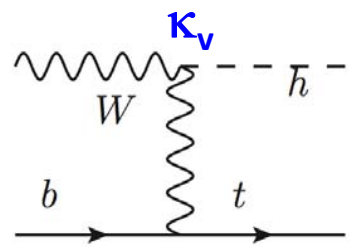
M_H = 125.36 GeV

Higgs branching fractions:

Decay channel	Branching ratio (%)
$H \to b\bar{b}$	57.1 ± 1.9
$H \to WW^*$	22.0 ± 0.9
$H \to gg$	8.53 ± 0.85
$H \to \tau\tau$	6.26 ± 0.35
$H \to c\bar{c}$	2.88 ± 0.35
$H \to ZZ^*$	2.73 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.157 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

σ(ttH) goes as κ_t^2 - To get information on sign, need a process that is proportional to κ_t , e.g., one where there is interference at LO - single top processes – ttH analyses can be made sensitive to tH processes





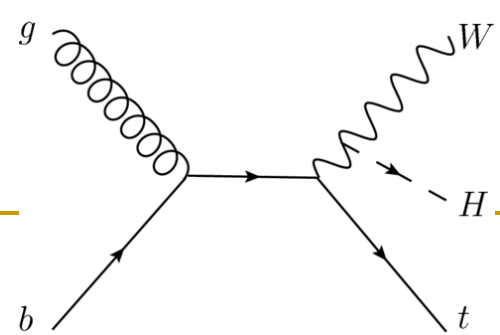
$K_i = 1 \Rightarrow$ SM

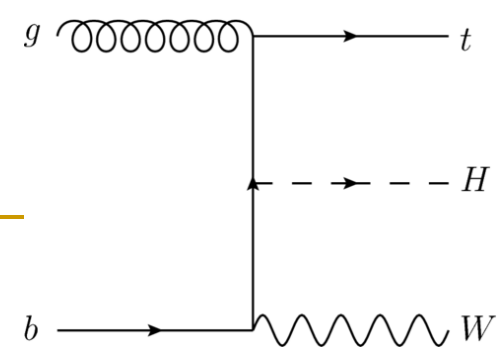
Large (destructive) interference between them, e.g.,

$$\sigma(qb \rightarrow tHq') \sim 3.4\kappa_f^2 + 3.56\kappa_v^2 - 5.96\kappa_f\kappa_v$$

If relative sign of the two **κ** factors is -1, cross-section will be larger than SM

Similarly for **σ(gb → WtH)**

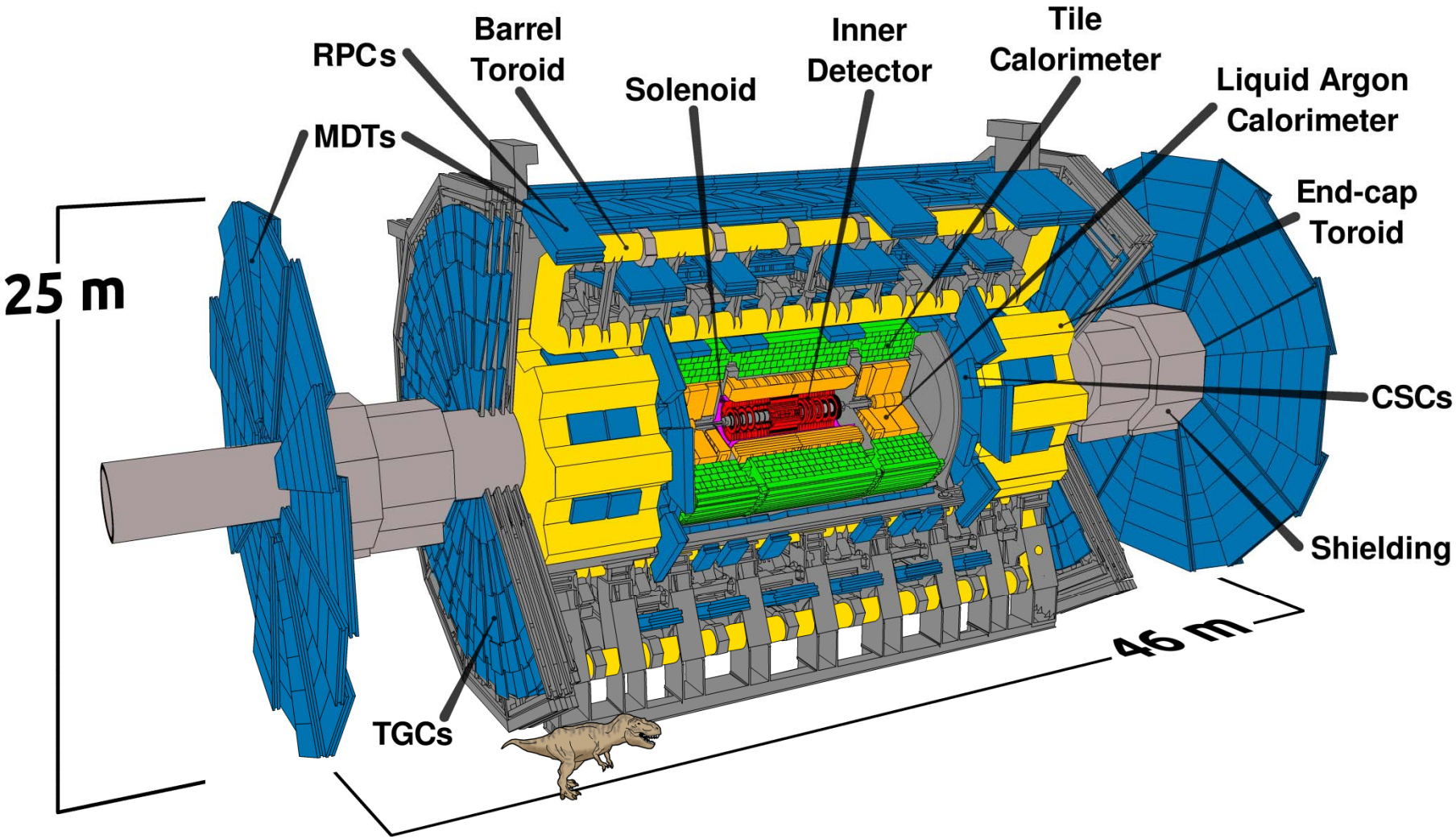




Effect of non-SM couplings on tH processes

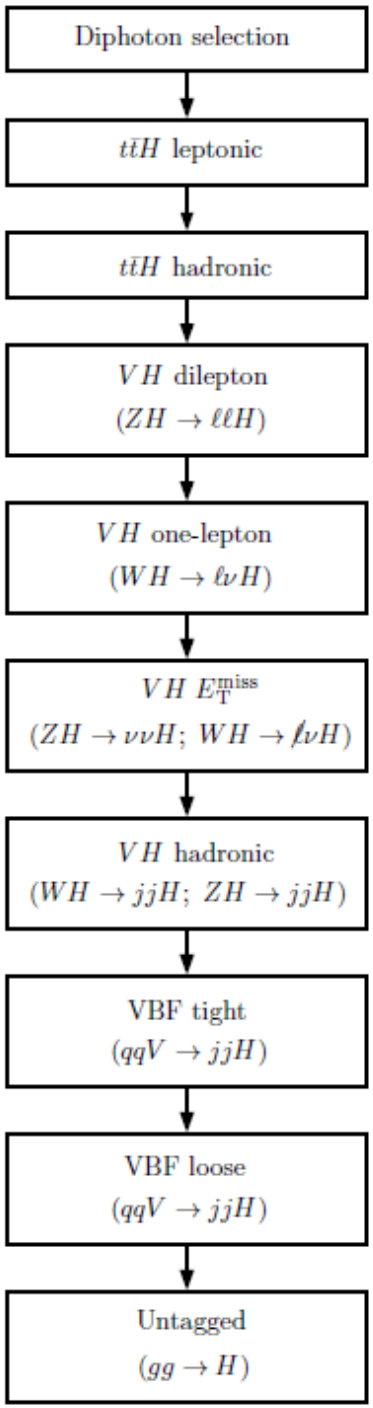
Process	σ [pb] at 7 TeV	σ [pb] at 8 TeV
$t\bar{t}H$	$0.086^{+0.008}_{-0.011}$	$0.129^{+0.012}_{-0.016}$
$tHqb, \kappa_t = +1$	$0.0111^{+0.0009}_{-0.0008}$	$0.0172^{+0.0012}_{-0.0011}$
$tHqb, \kappa_t = 0$	$0.040^{+0.003}_{-0.003}$	$0.059^{+0.004}_{-0.004}$
$tHqb, \kappa_t = -1$	$0.129^{+0.010}_{-0.009}$	$0.197^{+0.014}_{-0.013}$
$WtH, \kappa_t = +1$	$0.0029^{+0.0007}_{-0.0006}$	$0.0047^{+0.0010}_{-0.0009}$
$WtH, \kappa_t = 0$	$0.0043^{+0.0011}_{-0.0008}$	$0.0073^{+0.0017}_{-0.0013}$
$WtH, \kappa_t = -1$	$0.016^{+0.004}_{-0.003}$	$0.027^{+0.006}_{-0.005}$
ggF	15.1 ± 1.6	19.3 ± 2.0
VBF	1.22 ± 0.03	1.58 ± 0.04
WH	0.579 ± 0.016	0.705 ± 0.018
ZH	0.335 ± 0.013	0.415 ± 0.017

ATLAS:


RPCs
Barrel Toroid
Solenoid
Inner Detector
Tile Calorimeter
Liquid Argon Calorimeter
MDTs
End-cap Toroid
25 m
CSCs
Shielding
46 m
TGCs

Object Selection

- Analyses uses information from entire detector:
  - Electrons – tracker and calorimeter
  - Muons – tracker, muon system, calorimeter
  - Taus – calorimeter, tracker, muon system
  - Photons – tracker and calorimeter
  - Jets – calorimeter (and some tracker for cleanup cuts)
    - b-jet tagging: tracker
  - Neutrinos – Missing transverse momentum (Calo+Mu)
- Event selection and cut values chosen to provide sensitivity to various production processes



Sample case for (inclusive) Higgs → γγ analysis

Depending on pt of photons, # b-jets, # of leptons, Etmiss… events are categorized as coming from various production processes

TABLE II. Signal efficiencies ϵ, which include geometrical and kinematic acceptances, and expected signal event fractions f per production mode in each event category for $\sqrt{s} = 7$ TeV and $m_H = 125.4$ GeV. The second-to-last row shows the total efficiency per production process summed over the categories and the overall average efficiency in the far right column. The total number of selected signal events expected in each category N_S is reported in the last column while the total number of selected events expected from each production mode is given in the last row.

	ggF		VBF		WH		ZH		$t\bar{t}H$		$b\bar{b}H$		$tHbj$		tHW		
Category	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	N_S
Central - low p_{Tt}	15.5	92.2	8.5	4.1	7.2	1.6	7.9	1.0	3.4	0.1	15.5	1.0	-	-	-	-	26.0
Central - high p_{Tt}	1.0	71.8	2.7	16.4	2.1	6.1	2.3	3.7	2.9	1.2	1.0	0.7	-	-	-	-	2.1
Forward - low p_{Tt}	23.3	91.5	13.2	4.2	13.5	2.0	14.3	1.2	4.3	0.1	23.3	0.9	-	-	-	-	39.5
Forward - high p_{Tt}	1.3	70.6	4.0	16.7	3.5	6.9	3.6	4.1	2.9	0.9	1.3	0.7	-	-	-	-	3.0
VBF loose	0.4	38.6	7.9	60.0	0.2	0.6	0.2	0.3	0.2	0.1	0.4	0.4	-	-	-	-	1.7
VBF tight	0.1	18.1	6.3	81.5	< 0.1	0.1	< 0.1	0.1	0.1	< 0.1	0.1	0.2	-	-	-	-	1.0
VH hadronic	0.2	43.5	0.1	3.3	3.2	31.8	3.4	19.8	0.9	1.3	0.2	0.4	-	-	-	-	0.6
VH E_T^{miss}	< 0.1	8.7	0.1	3.7	1.7	35.7	3.6	44.8	2.3	7.1	< 0.1	0.1	-	-	-	-	0.3
VH one-lepton	< 0.1	0.7	< 0.1	0.2	5.0	91.4	0.6	5.9	0.7	1.8	< 0.1	< 0.1	-	-	-	-	0.3
VH dilepton	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1.3	99.3	< 0.1	0.6	< 0.1	< 0.1	-	-	-	-	0.1
$t\bar{t}H$ hadronic	< 0.1	10.5	< 0.1	1.3	< 0.1	1.3	< 0.1	1.4	6.1	81.0	< 0.1	0.1	1.5	2.6	4.3	1.9	0.1
$t\bar{t}H$ leptonic	< 0.1	0.6	< 0.1	0.1	0.3	14.9	0.1	4.0	8.[illegible]	72.6	< 0.1	< 0.1	4.8	5.3	8.7	2.5	0.1
Total efficiency (%)	41.8	-	42.9	-	36.7	-	37.3	-	32.2	-	41.8	-	-	-	-	-	41.6%
Events	64.8		5.4		2.2		1.3		0.3		0.7		< 0.1		< 0.1		74.5

Efficiency and purity of various categories (for 7 TeV)

Analysis Overview

In these analyses, the top quarks decay to all-hadronic, 1-lepton+jets or 2-lepton+jets final states

Higgs decays add more particles (photons/jets/leptons) to the final state

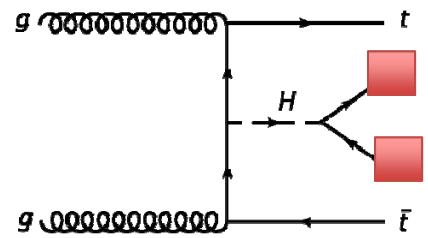
$t\bar{t}H \rightarrow b\bar{b}$

ATLAS-HIGG-2013-27
Accepted by EPJC

$\mathcal{L} = 20$ fb^{-1} (8 TeV)

Highest branching fraction

But important ttbar+heavy/light flavour background



$t\bar{t}H \rightarrow multileptons$

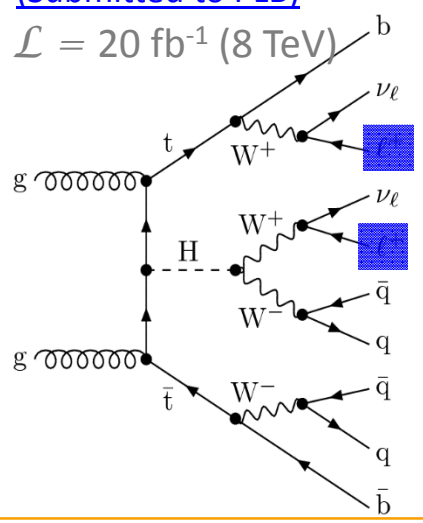
(WW/ττ/ZZ)

ATLAS-HIGG-2013-26
(Submitted to PLB)

$\mathcal{L} = 20$ fb^{-1} (8 TeV)

Good signal purity and branching ratio

Low statistics



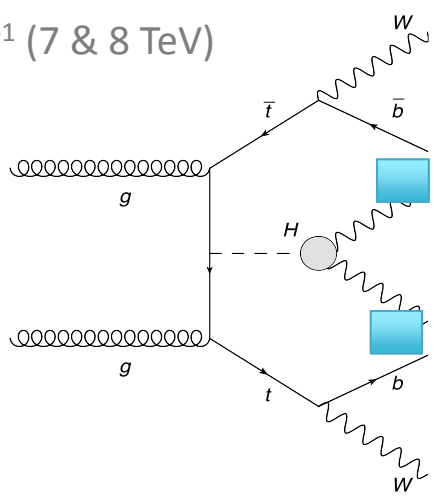
$t\bar{t}H \rightarrow \gamma\gamma$

Physics Letters B 740 (2015) 222-242

$\mathcal{L} = 25$ fb^{-1} (7 & 8 TeV)

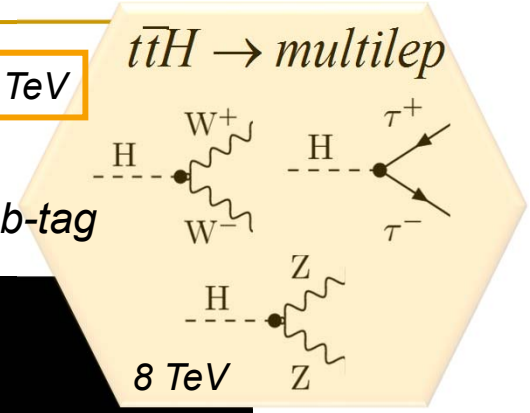
Best mass peak resolution

High signal purity
Low statistics
BR(H→γγ)~0.2%

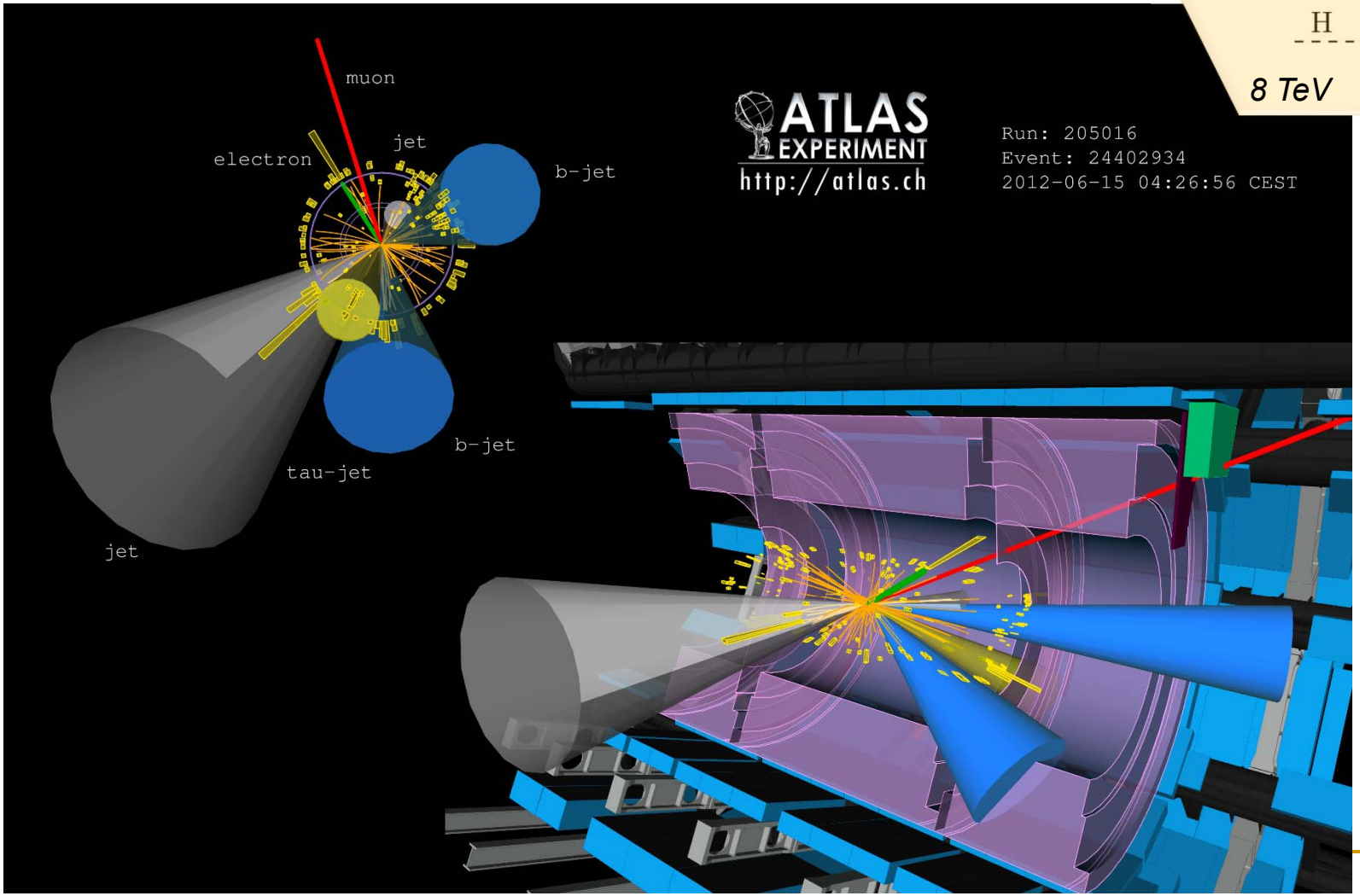


$2\ell ss+1\tau^{had}$ event display

8 TeV

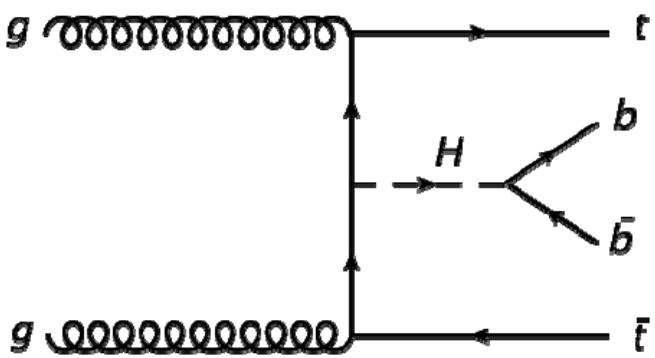


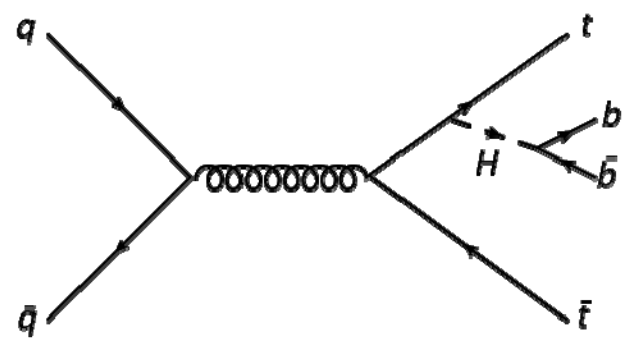
In final state: 1 electron, 1 muon, 1 hadronic tau and 4 jets of which 2 b-tag

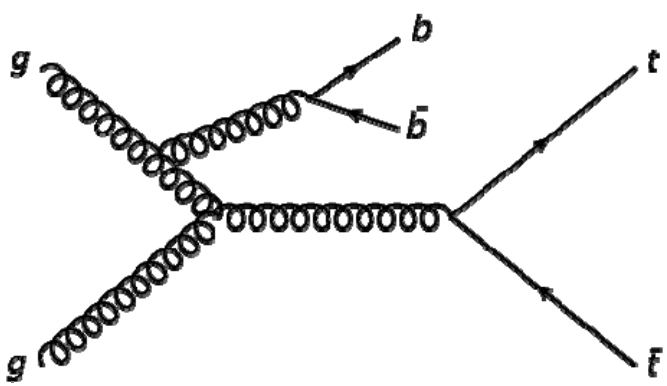


H → bb

σ(ttH) at 8 TeV ~ 0.13 pb







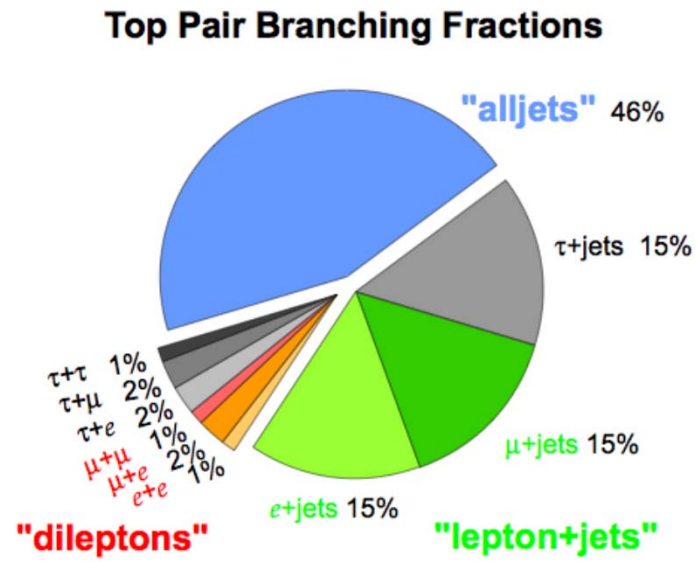
σ(ttbb) at 8 TeV ~ $\mathcal{O}$(12) pb

Irreducible background

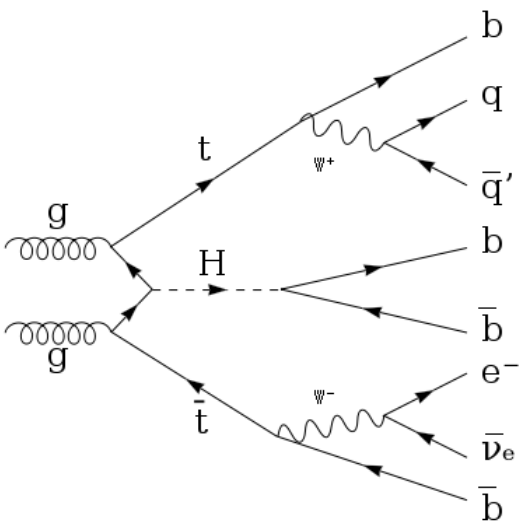
Complex analysis - needs detailed modelling of various background sources

Gluon can also go into light jets or ccbar

Analysis strategy



- Divide according to top decay:
  - Single lepton+jets: one top (W) decays semi-leptonically



6 jets (4 of which are b-jets) + one lepton

Lepton means e or mu (can be from tau decay)

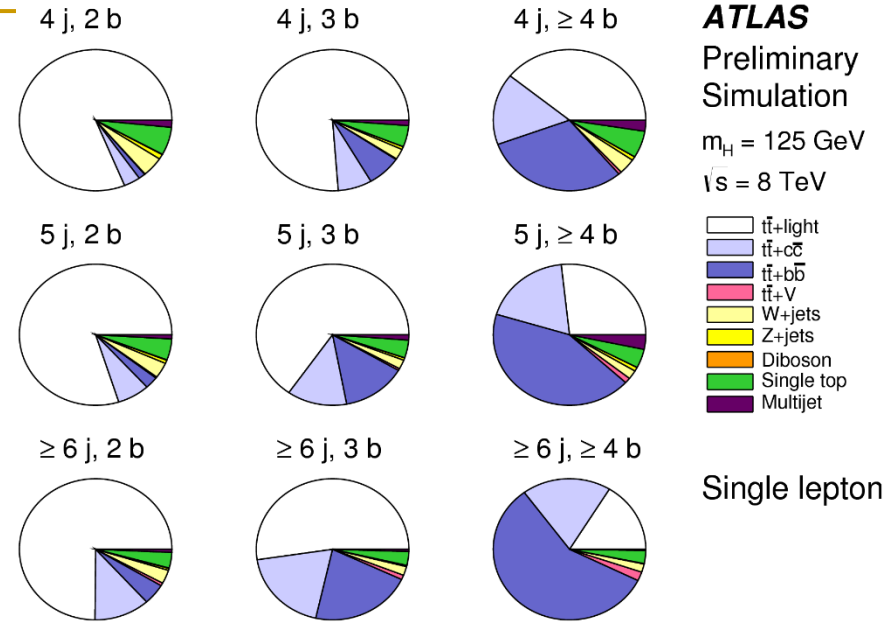
4 jets (all bjets) + 2 leptons

  - Dilepton+jets: both tops (W) decay semi-leptonically

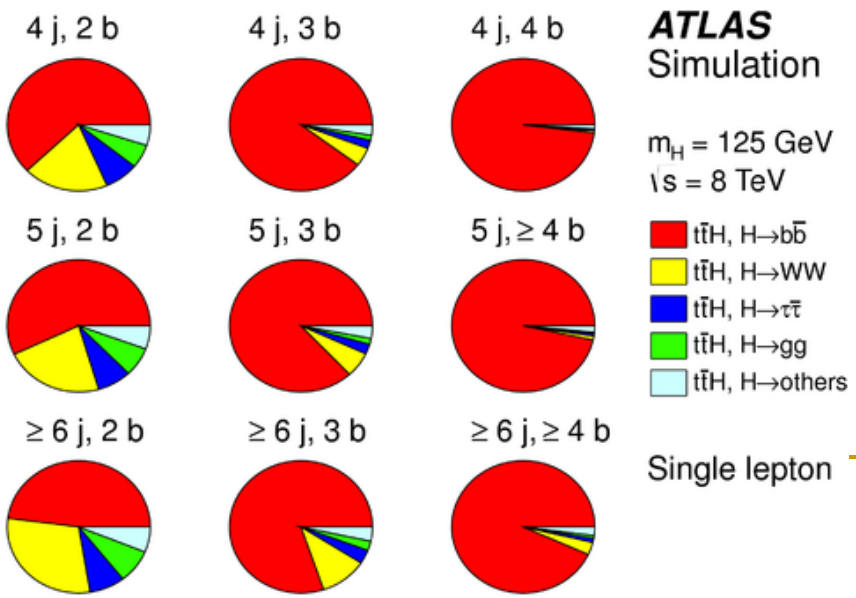
Single Lepton

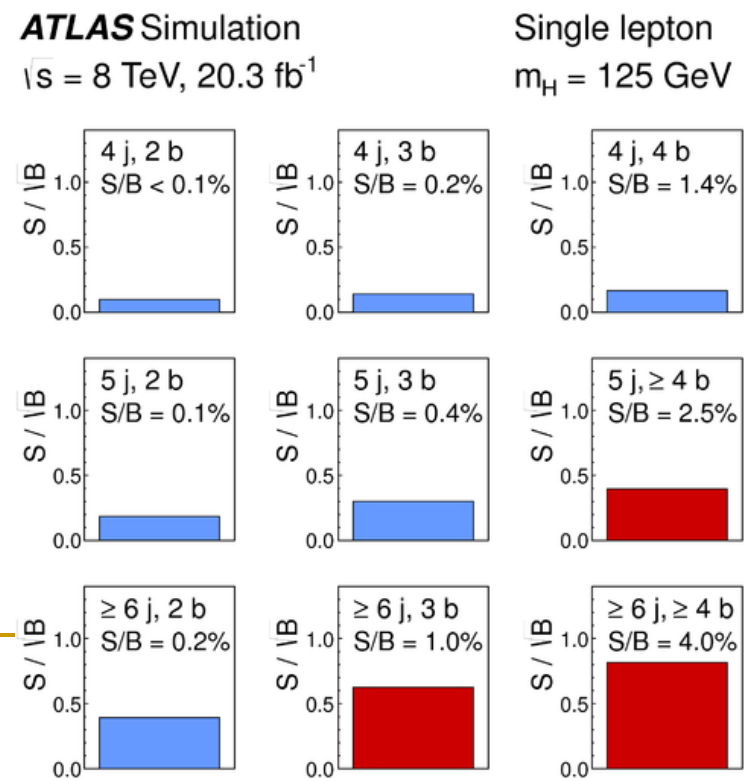
Both single and dilepton analyses categorize events in bins of Njets/Nbtags

Various backgrounds – ttbar most important



Analysis allows for all Higgs decays, but H to bb is dominant





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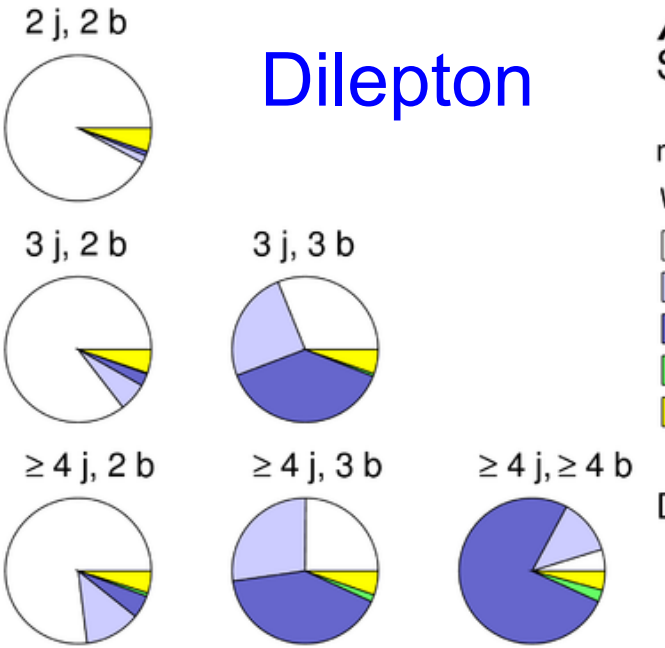
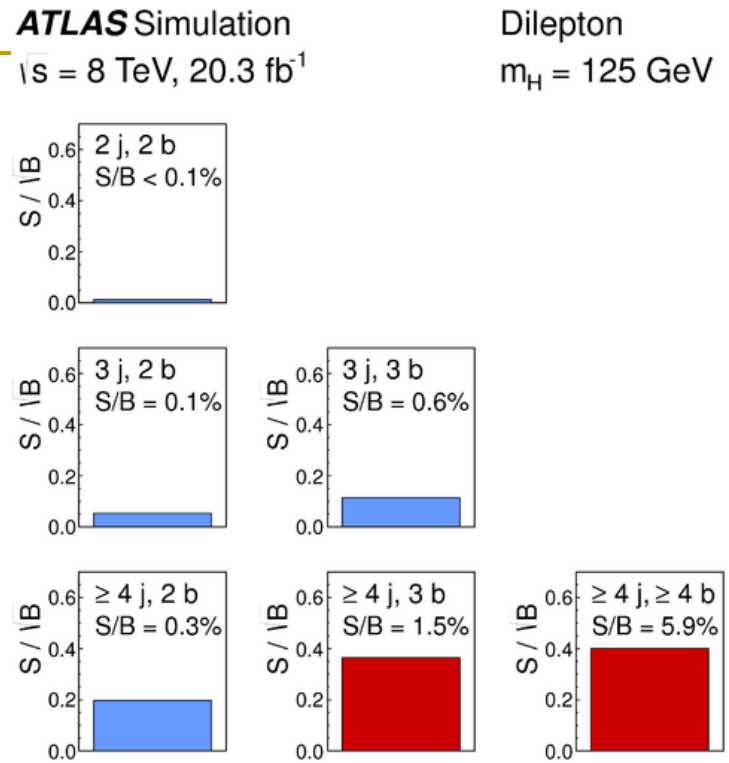
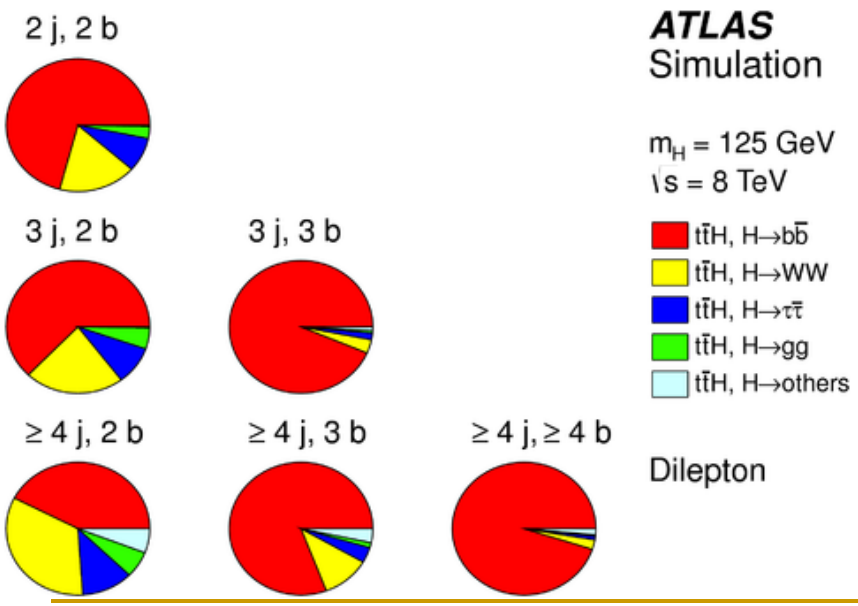
Dilepton

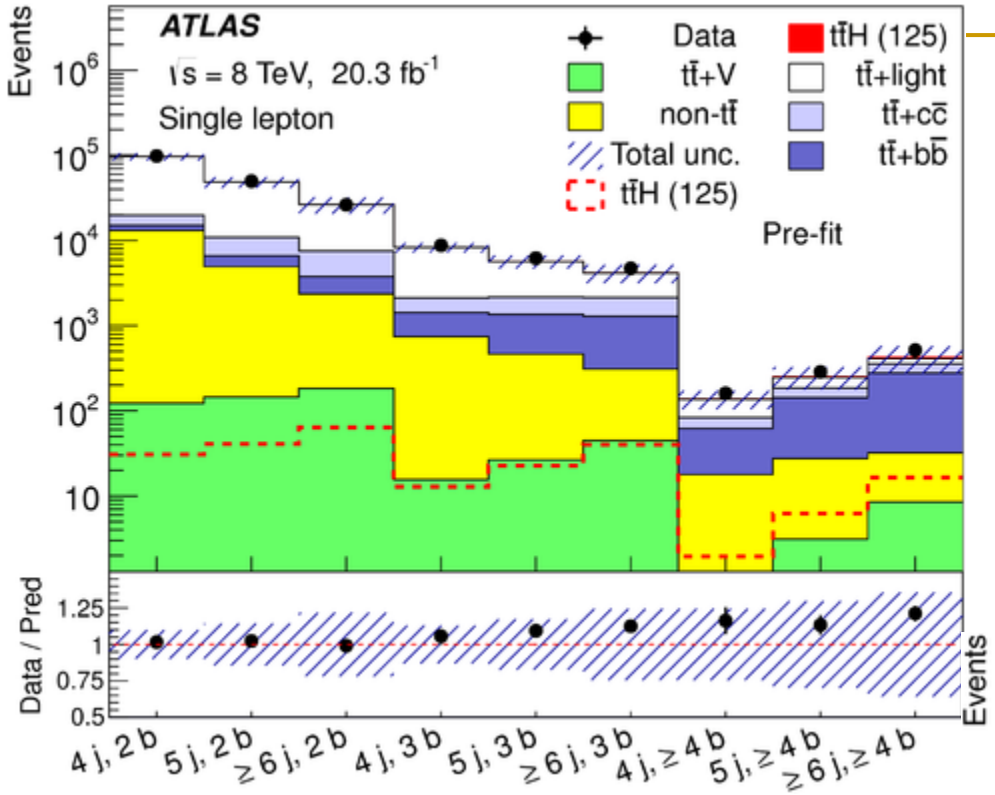






Many control regions – Constrain backgrounds with Profile likelihood fit

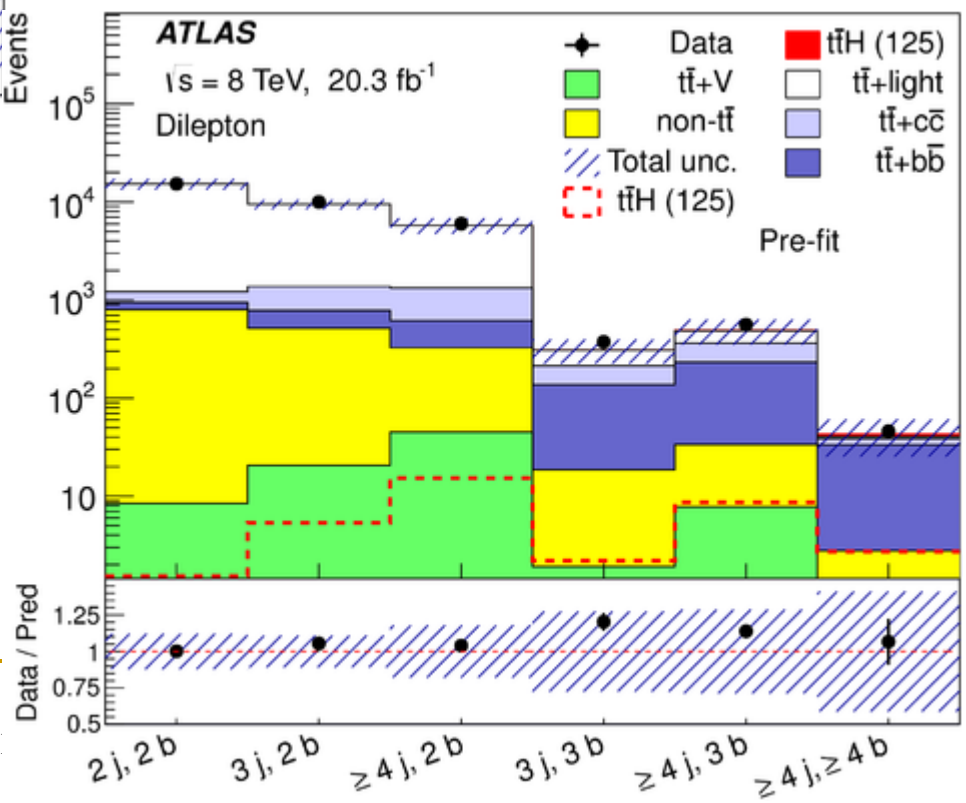
Use NN to discriminate between S/B in signal-rich regions



Overwhelming background

Single lepton

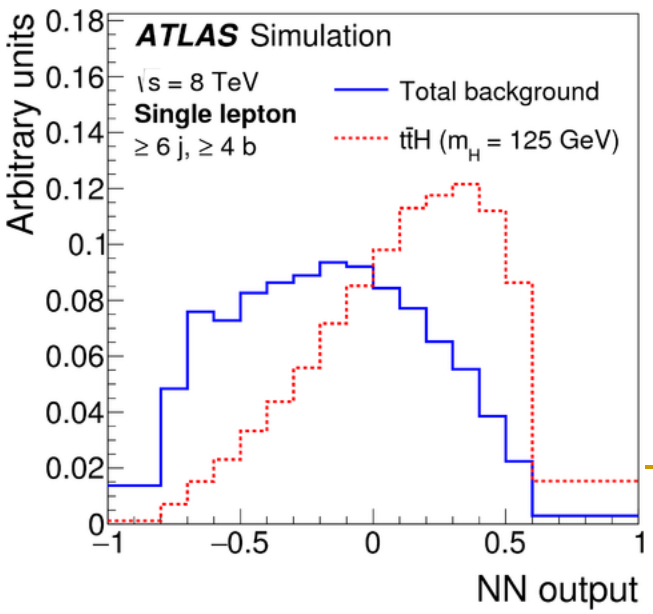
Dilepton

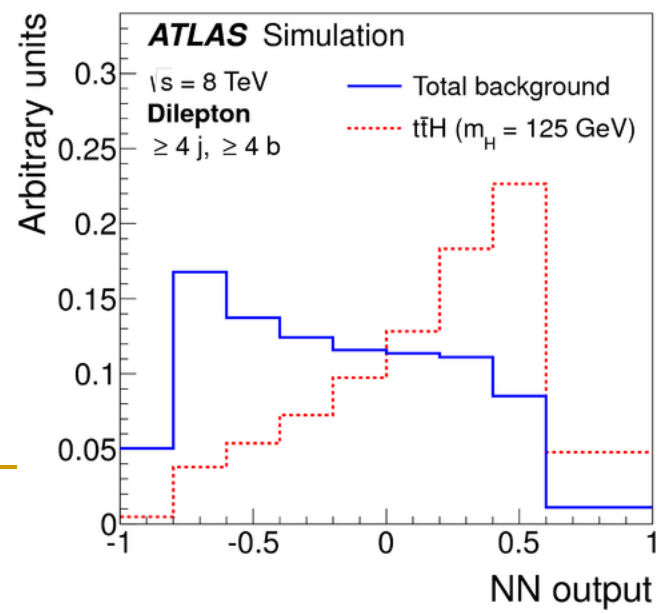


Pre-fit yields in various regions

Neural nets

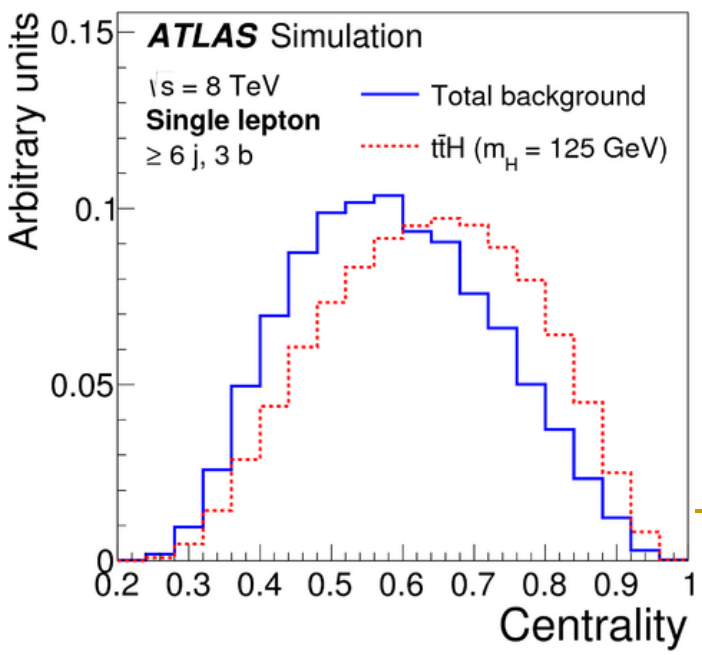
- Use NN to discriminate between signal and background in signal-rich regions
  - Based on kinematic, event shape variables, etc.
  - Single lepton final state also uses discriminants from Matrix Element method in NN
- Use kinematic variable, $H_T^{(had)}$ in other regions

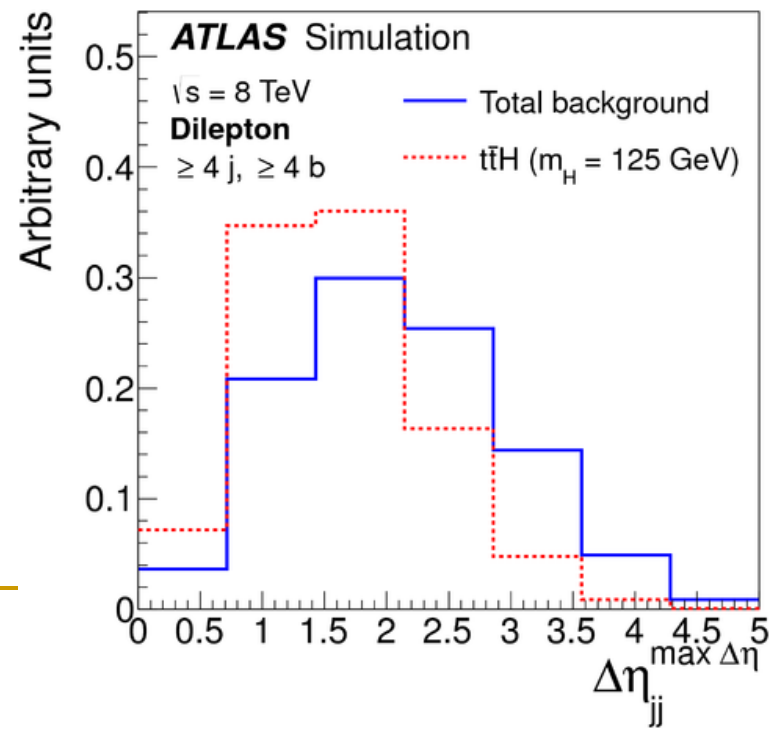




Kinematic Neural Net

- NN separately optimized for each signal rich region, 1, 2 lepton
- NNs built from:
  - Event shape variables (e.g., centrality)
  - Object pair properties (e.g., $\Delta\eta_{jj}$ max)
  - Object kinematics (e.g., p_T)
  - Event Kinematics (e.g., H_T)





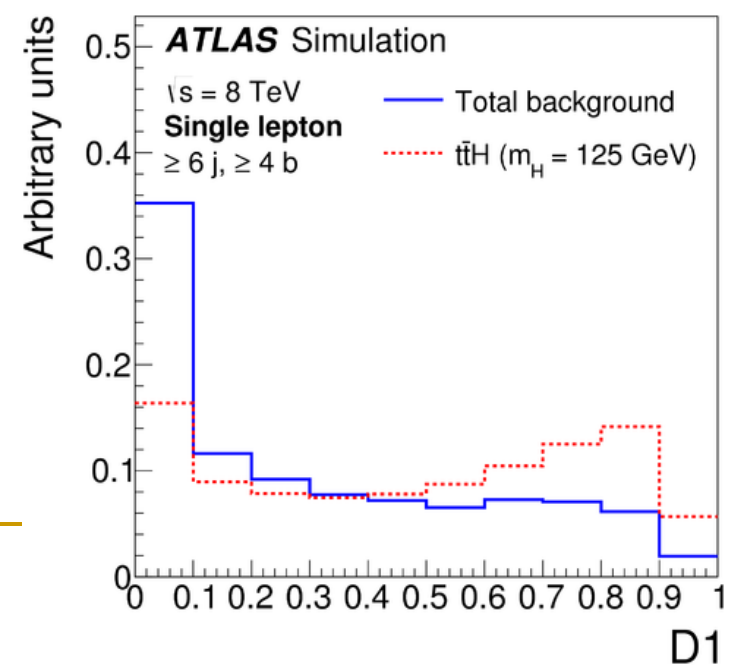
Matrix Element Method for 1-lepton

- Links theoretical calculations and observed quantities & makes the most complete use of the kinematic information of a given event
  - First used by CDF/D0 for top mass, single top
  - Now by CMS/ATLAS to separate ttH from ttbb

$$D1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + \alpha \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}}$$

is the best output of MEM

& used in NN (for 6/3 and 6/4)



Many sources of systematic uncertainties

Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency	SN	1
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: p_{T} reweighting	SN	9
$t\bar{t}$ modelling: parton shower	SN	3
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}$+$c\bar{c}$: p_{T} reweighting	SN	2
$t\bar{t}$+$c\bar{c}$: generator	SN	4
$t\bar{t}$+$b\bar{b}$: NLO Shape	SN	8
W+jets normalisation	N	3
W p_{T} reweighting	SN	1
Z+jets normalisation	N	3
Z p_{T} reweighting	SN	1
Lepton misID normalisation	N	3
Lepton misID shape	S	3
Single top cross section	N	1
Single top model	SN	1
Diboson+jets normalisation	N	3
$t\bar{t}+V$ cross section	N	1
$t\bar{t}+V$ model	SN	1

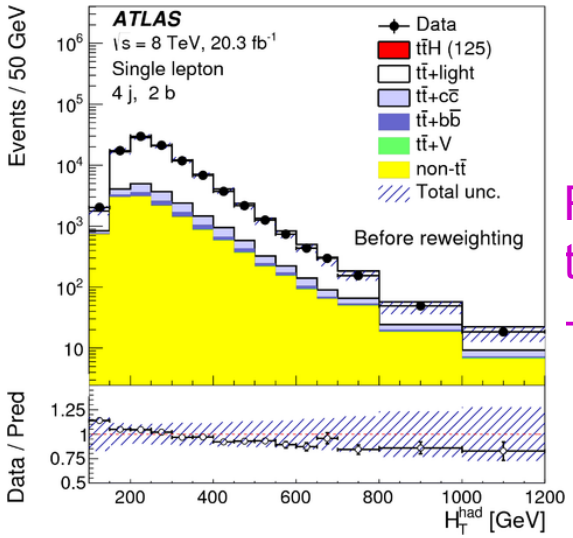
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1

Each source of syst. uncert. is represented by a nuisance parameter, e.g.,

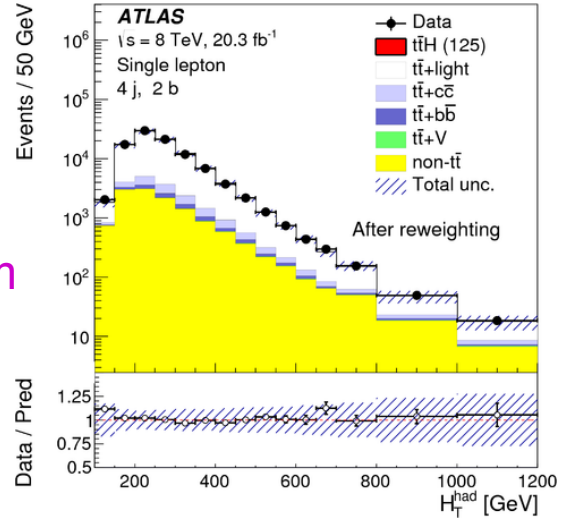
Jet energy scale has 22 uncorrelated sources, which can have different pT and η dependence – largest arises from the η dependence of the JES calibration in the end-cap regions of the CALO

Syst. uncerts. are generally prescribed by various combined performance groups

ttbar background studied in great detail



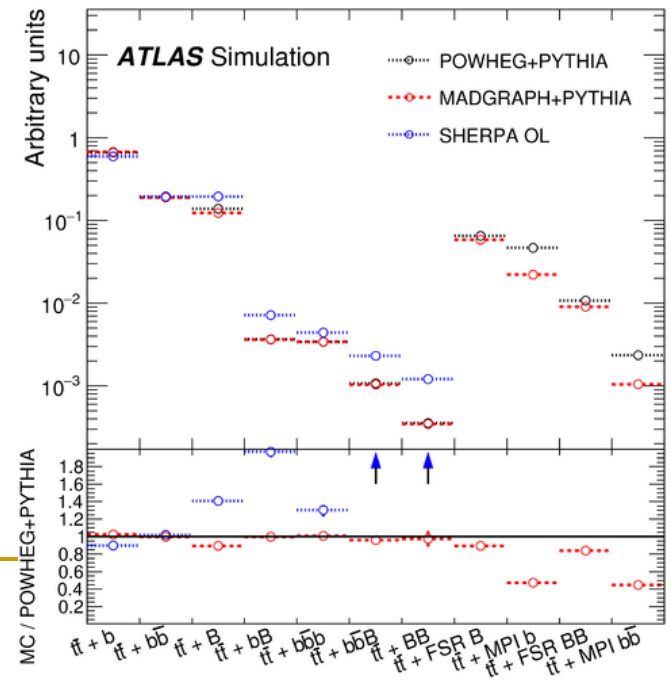
Reweight MC
t & tt spectrum
- 7 TeV data



For tt+light & tt+cc

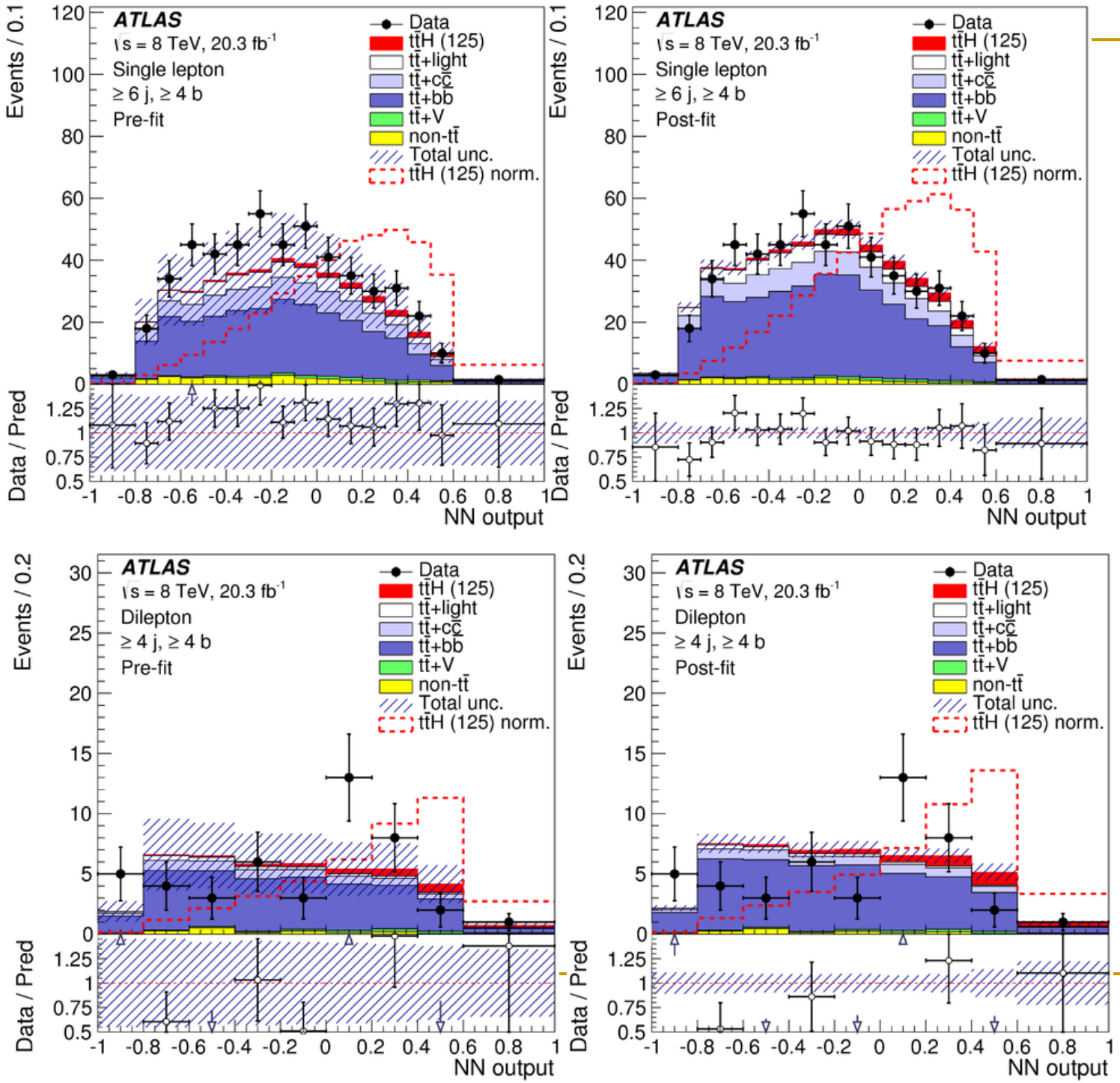
Split ttbb into various categories, e.g., only one particle jet is matched to b-quark from top, both are matched, both b-quarks are merged into one jet, etc.

Compare various generators (LO, PS, NLO) – reweight MC to SHERPA OpenLoops



Profile Likelihood Fit

- Technique used when fitting models with many unknown parameters:
  - μ: Signal strength
  - θ: Nuisance parameters (for systematic uncert.)
- Uses "machinery" of RooFit
- Fit all Njet/Nbtag regions simultaneously - PLF allows for improved measure of syst. uncert., e.g.,
  - Initial σ(ttbb) taken from theory and error on it is assumed to be ± 50%. Actual values are determined from the fit



Samples of pre- & post-fit distributions

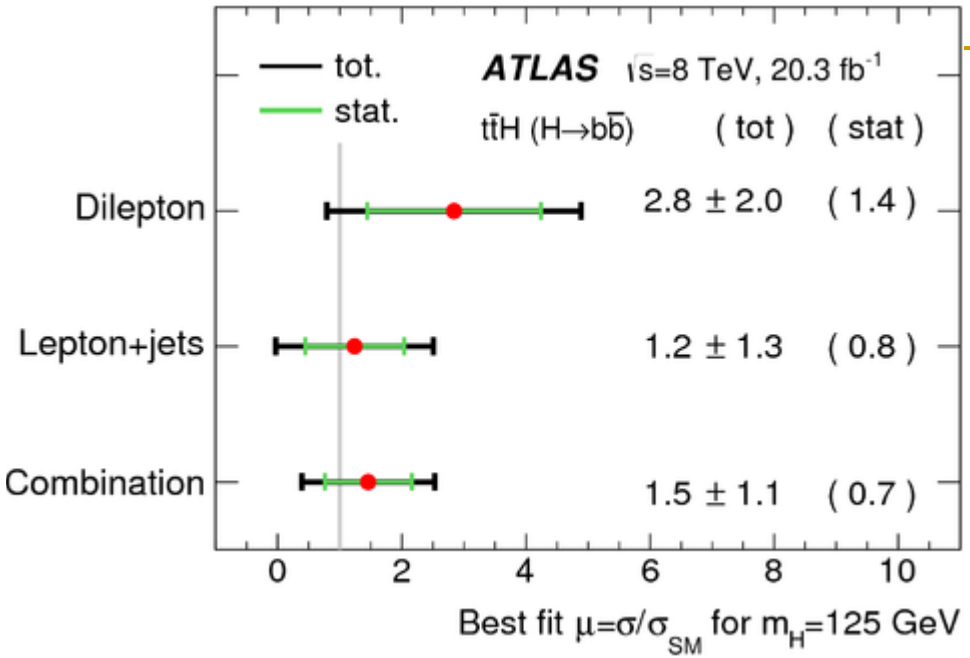
Pre-fit yields in dilepton bins

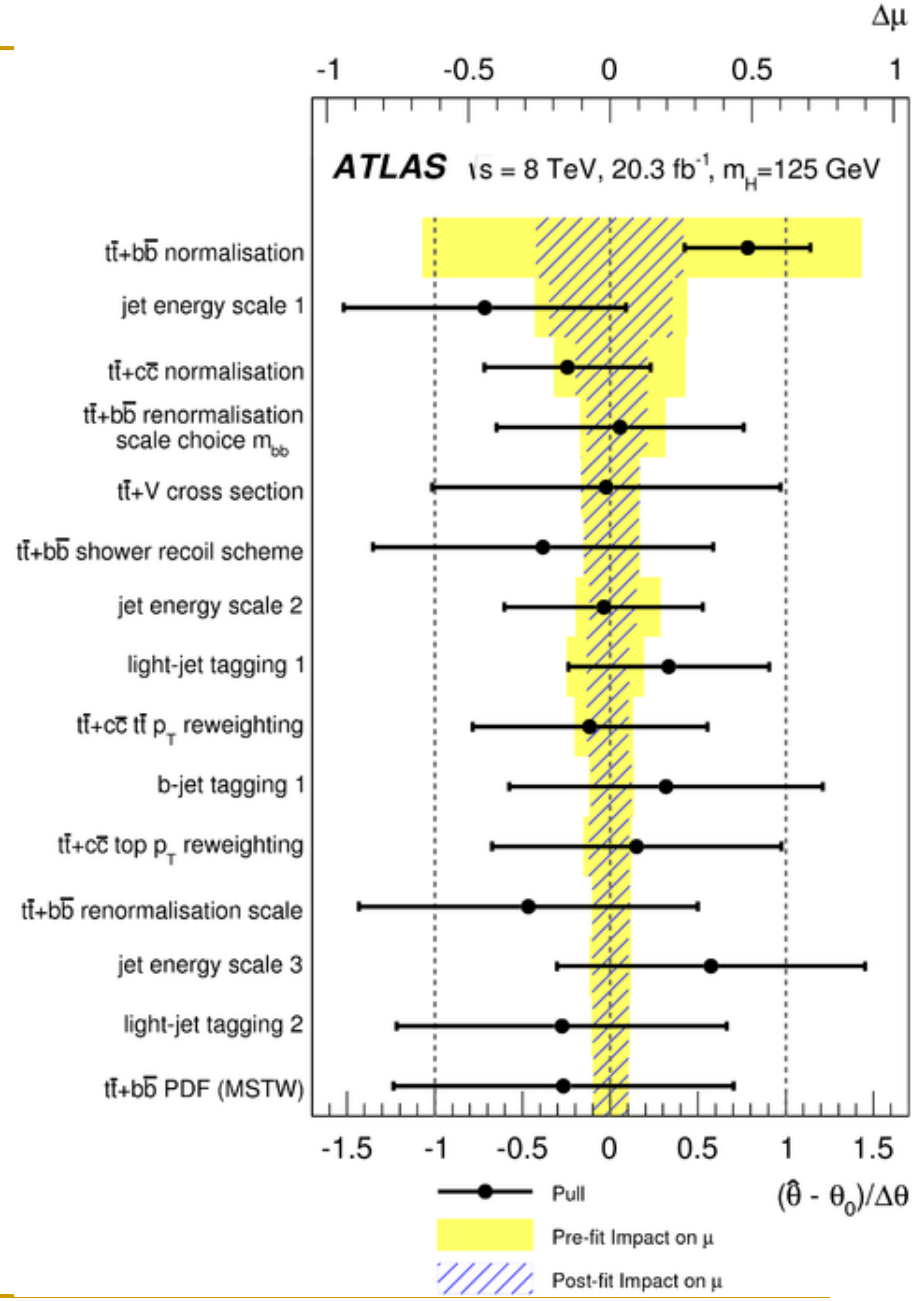
	≥ 4 j, 2 b	≥ 4 j, 3 b	≥ 4 j, ≥ 4 b
$t\bar{t}H$ (125)	15 ± 1	8.6 ± 0.6	2.7 ± 0.3
$t\bar{t}$+ light	4400 ± 810	120 ± 31	1.9 ± 0.8
$t\bar{t} + c\bar{c}$	710 ± 380	130 ± 74	5.0 ± 3.0
$t\bar{t} + b\bar{b}$	290 ± 150	200 ± 100	31 ± 17
Z+jets	100 ± 39	10 ± 4	0.6 ± 0.2
Single top	140 ± 55	11 ± 5	0.8 ± 0.2
Diboson	4.0 ± 1.3	0.4 ± 0.1	$\leq 0.1 \pm 0.1$
$t\bar{t} + V$	45 ± 14	7.8 ± 2.4	1.1 ± 0.4
Lepton misID	38 ± 19	4.3 ± 2.2	0.4 ± 0.2
Total	5800 ± 1000	490 ± 140	43 ± 18
Data	6006	561	46

Post-fit yields in dilepton bins

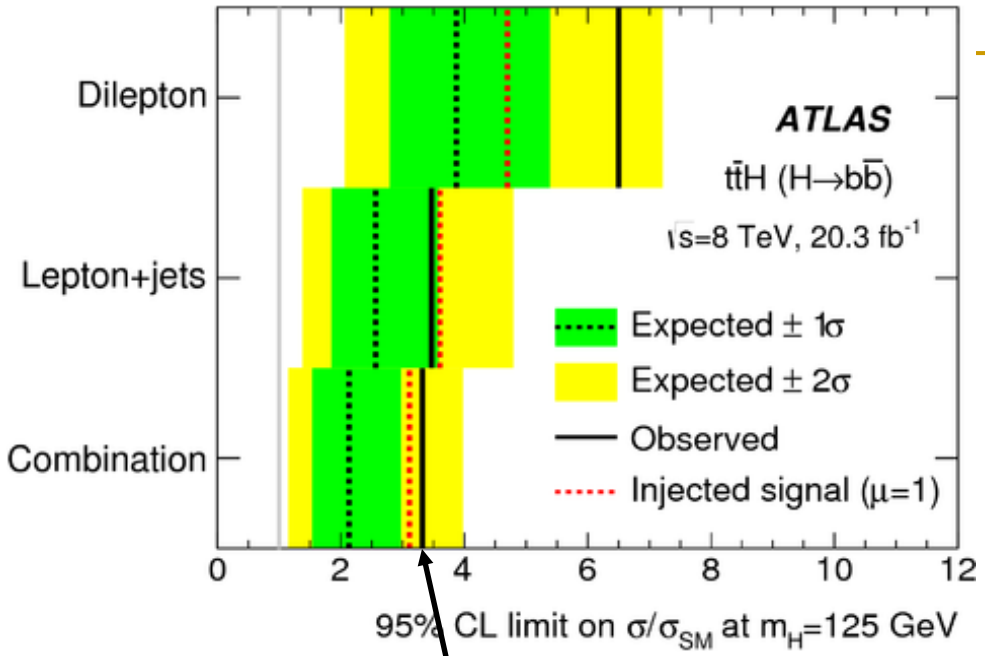
	≥ 4 j, 2 b	≥ 4 j, 3 b	≥ 4 j, ≥ 4 b
$t\bar{t}H$ (125)	22 ± 16	11 ± 8	3.1 ± 2.3
$t\bar{t}$+ light	4500 ± 150	100 ± 12	1.4 ± 0.3
$t\bar{t} + c\bar{c}$	740 ± 170	140 ± 30	4.8 ± 1.1
$t\bar{t} + b\bar{b}$	370 ± 59	230 ± 31	30 ± 4
Z+jets	100 ± 33	9.5 ± 3.1	0.4 ± 0.2
Single top	140 ± 23	11 ± 2	0.6 ± 0.1
Diboson	4.2 ± 1.3	0.3 ± 0.1	$\leq 0.1 \pm 0.1$
$t\bar{t} + V$	43 ± 13	7.0 ± 2.1	0.9 ± 0.3
Lepton misID	34 ± 18	3.5 ± 1.8	0.2 ± 0.1
Total	5900 ± 65	520 ± 18	42 ± 4
Data	6006	561	46

Notice the difference in background estimates and their uncertainties


tot.
stat.
ATLAS √s=8 TeV, 20.3 fb-1
tt̄H (H→bb̄) (tot) (stat)
Dilepton 2.8 ± 2.0 (1.4)
Lepton+jets 1.2 ± 1.3 (0.8)
Combination 1.5 ± 1.1 (0.7)
0 2 4 6 8 10
Best fit μ=σ/σSM for mH=125 GeV


Δμ
-1 -0.5 0 0.5 1
ATLAS √s = 8 TeV, 20.3 fb-1, mH=125 GeV
tt̄+bb̄ normalisation
jet energy scale 1
tt̄+cc̄ normalisation
tt̄+bb̄ renormalisation scale choice mbb
tt̄+V cross section
tt̄+bb̄ shower recoil scheme
jet energy scale 2
light-jet tagging 1
tt̄+cc̄ tt̄ pT reweighting
b-jet tagging 1
tt̄+cc̄ top pT reweighting
tt̄+bb̄ renormalisation scale
jet energy scale 3
light-jet tagging 2
tt̄+bb̄ PDF (MSTW)
-1.5 -1 -0.5 0 0.5 1 1.5
(θ̂ - θ0)/Δθ
Pull
Pre-fit Impact on μ
Post-fit Impact on μ

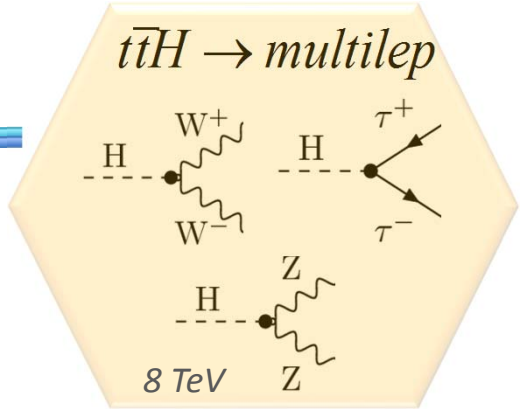
Results



Assuming μ=0

95% CL upper limit	Observed	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median ($\mu = 1$)
Single lepton	3.6	1.4	1.9	2.6	3.7	4.9	3.6
Dilepton	6.7	2.2	3.0	4.1	5.8	7.7	4.7
Combination	3.4	1.2	1.6	2.2	3.0	4.1	3.1

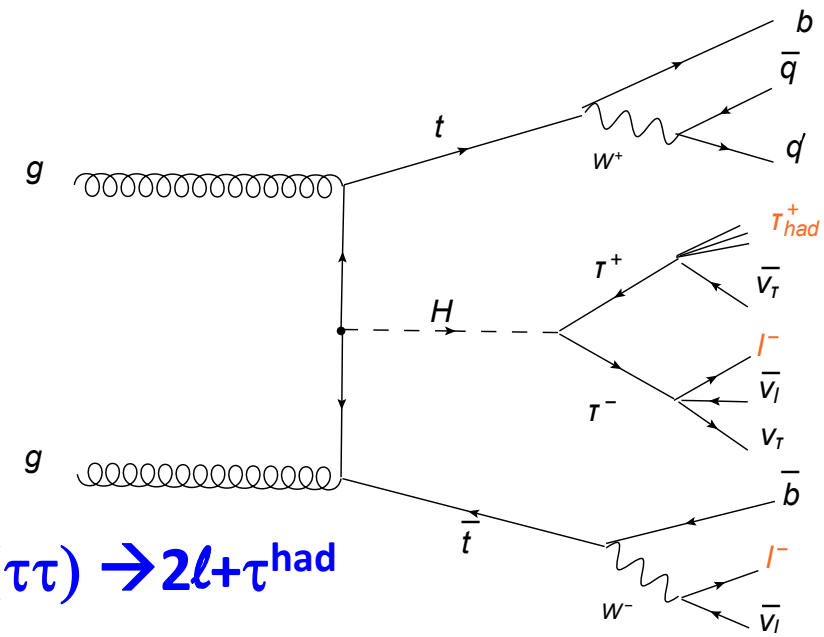
ttH→ multileptons



- Targets Higgs → WW*, ττ and ZZ* decays

- Requiring many leptons (and (b-)jets) makes contamination from other processes (ggF, VBF, VH) negligible

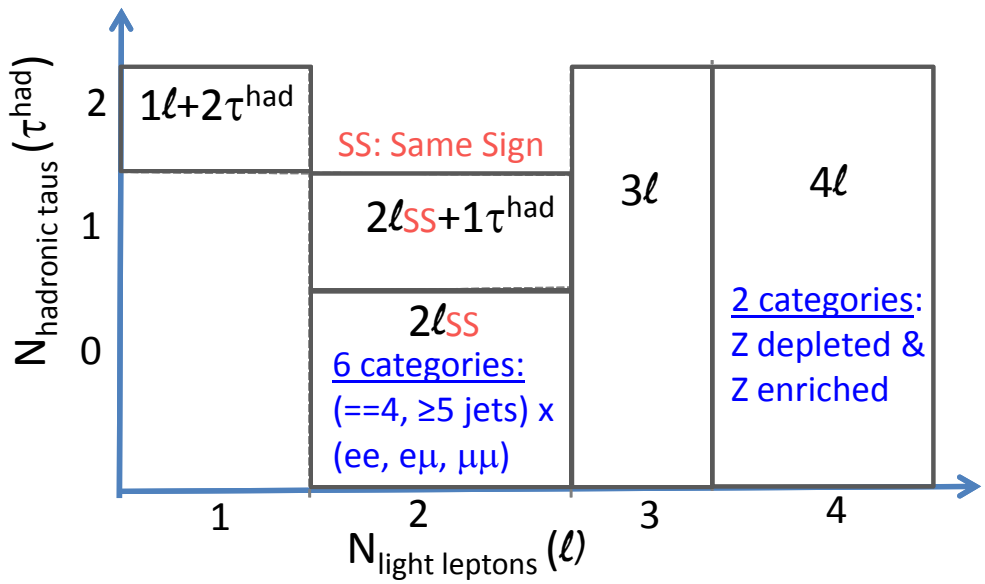
- Reject ttbar background with:
  - same sign di-leptons
  - $N_{lep} \geq 3$



ttH(ττ) →2ℓ+τ^{had}

ttH→ multileptons

- 5 channels in e/μ and hadronic tau multiplicity



Selection criteria for each category tuned to maximize sensitivity for various final states, e.g. cuts on # jets, m(OS lepton pairs), # b-tags, etc…

- Sensitivity to WW*, ττ and ZZ* decays

	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%

bb, μμ

Main background sources:

ttV (V= W/Z) – Irreducible
(tZ – subleading)
Diboson + jets – Irreducible

Non-prompt leptons
Charge mis-id

Control regions to get handle on backgrounds

Example of event selection

- **2(SS)ℓ + 0τ^{had}**
  - Exactly 2 same-sign e/μ and **0τ^{had}**
  - To remove non-prompt background, tight pT cuts on lep. (25 & 20 GeV), and tight isolation
  - To reduce lower mult. tt+jets and ttW, ≥ 4 jets
  - To reduce dibosons/W+jets, ≥ 1 btag
  - Separate into ee, μμ, eμ each with 4 or ≥ 5 jets

- Similarly for other final states

Expected and observed yields in various channels

Search channels have been expanded to show individual sub-channels

Background from rare processes (tZ, tttt, tH, VVV, ttWW) are in expect. bkg. column

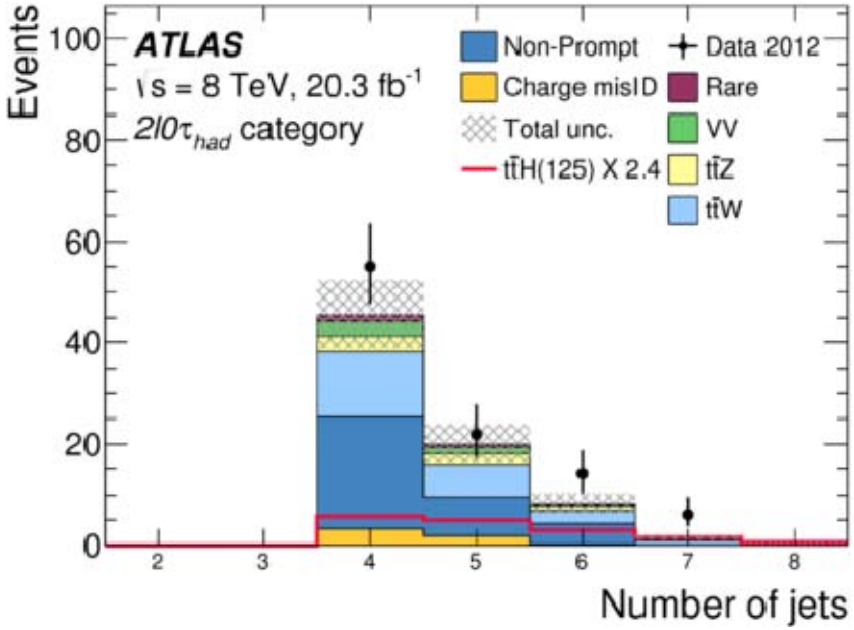
S/B in 4 and ≥ 5 jets: 0.05/0.14

If one category, S/B is 0.09

Expected signal in 2(SS)lep+0τ_{had} ~ 6.6

Expected bkgd ~ 75.9±7.8 Obsvd = 98

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

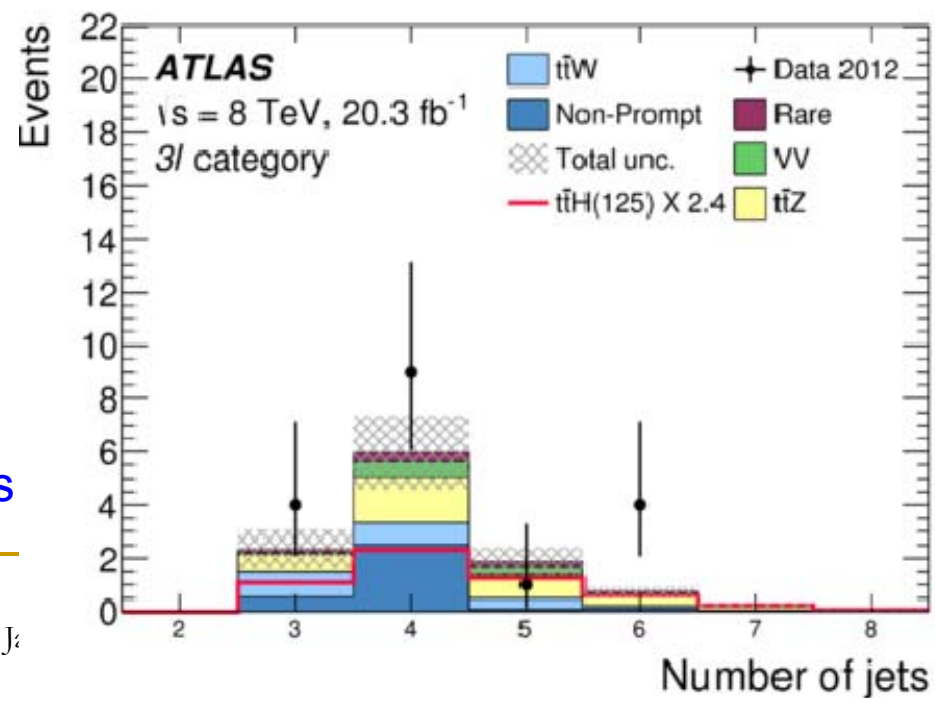


2(SS)leptons+0τ_{had}

All six categories (for display purposes)
In fit they are treated separately

Discriminant in Profile Likelihood Fit: # jets

3 leptons



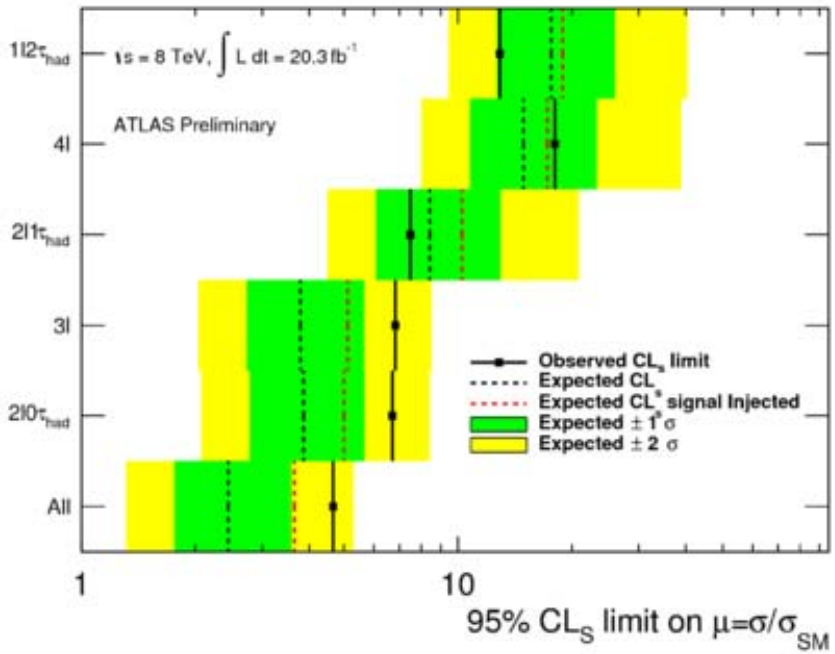
Systematic Uncertainties

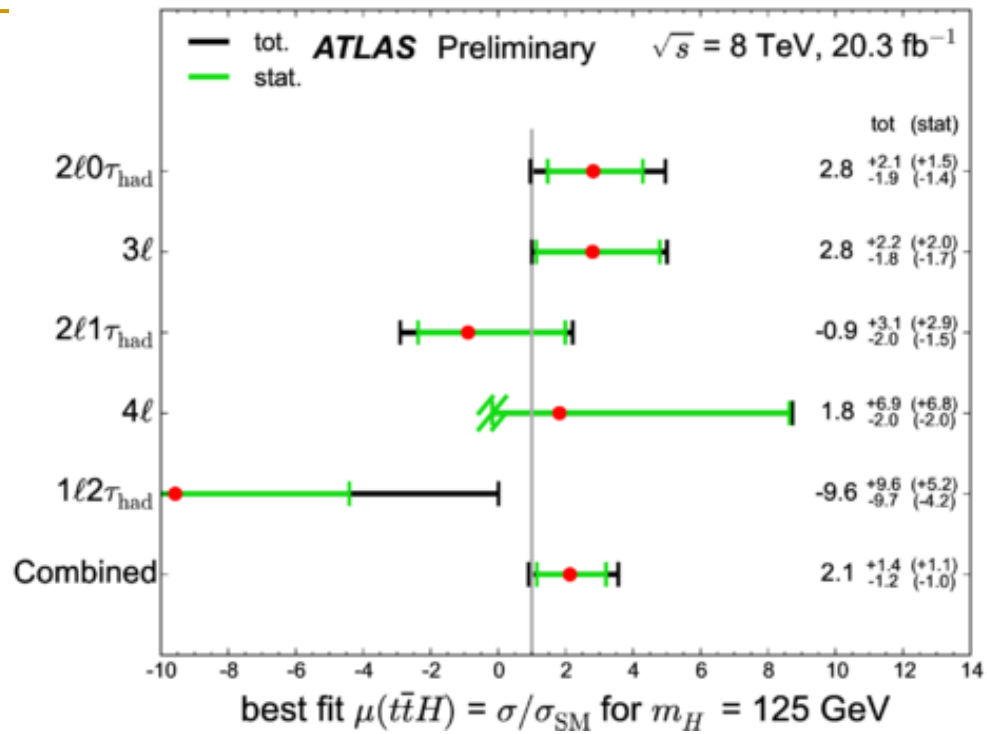
Table 3: Leading sources of systematic uncertainty and their impact on the measured value of μ.

Source	$\Delta\mu$	
$2\ell 0\tau_{\text{had}}$ 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
$2\ell 0\tau_{\text{had}}$ 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

Non-prompt transfer factors estimate backgrounds in signal regions based on control regions

Results



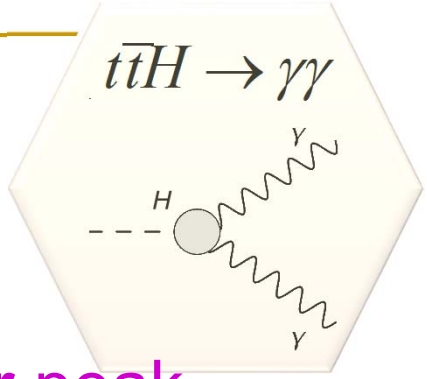


Combined result < 4.7

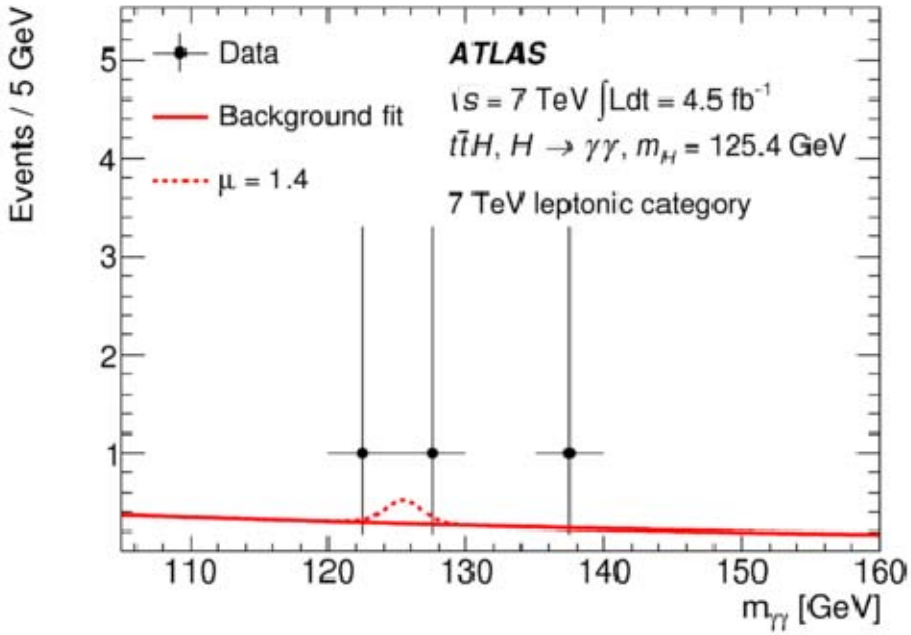
Table 4: Observed and expected 95% CL limits, derived using the CL_s method, on the strength parameter $\mu = \sigma_{t\bar{t}H,\mathrm{obs}}/\sigma_{t\bar{t}H,\mathrm{SM}}$. The last column shows the median expected limit in the presence of a $t\bar{t}H$ signal of Standard Model strength.

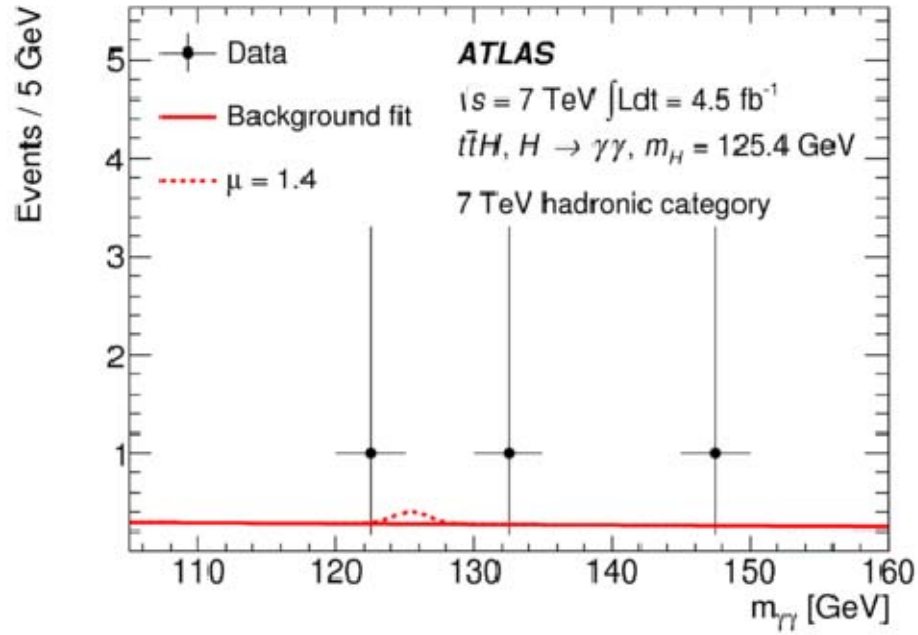
		Expected Limit					
Channel	Observed Limit	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median ($\mu = 1$)
$2\ell 0\tau_{\mathrm{had}}$	6.7	2.1	2.8	3.9	5.7	8.4	5.0
3ℓ	6.8	2.0	2.7	3.8	5.7	8.5	5.1
$2\ell 1\tau_{\mathrm{had}}$	7.5	4.5	6.1	8.4	13	21	10
4ℓ	18	8.0	11	15	23	39	17
$1\ell 2\tau_{\mathrm{had}}$	13	10	13	18	26	40	19
Combined	4.7	1.3	1.8	2.4	3.6	5.3	3.7

Higgs → γγ

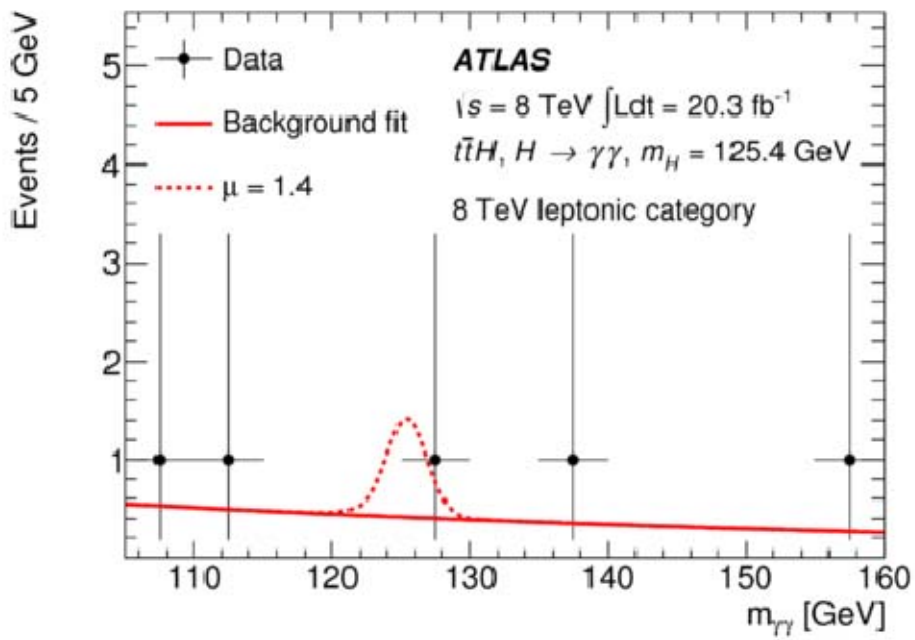


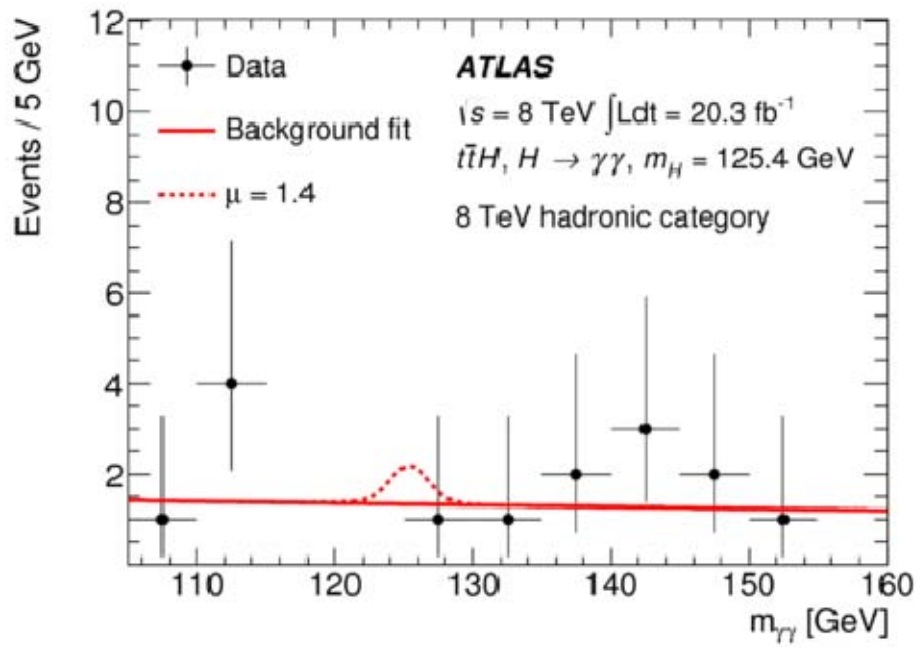
- Analysis strategy:
  - Fit sideband (in Mγγ) for background under peak
  - Background shape validated in control regions
- Classify events depending on ttbar decay:
  - Semi-leptonic + dileptonic (decay of top pair)
  - Cuts for the leptonic states are loose enough to retain high efficiency for tH final state, e.g.,
    - ≥ 1 lepton, ≥ 1 b-jet
    - Etmiss > 20 GeV (to reduce non-top bkgd., for 1 b-jet events)
  - All-hadronic (decay of top pair)
    - – cuts optimized to reduce ggF bkgd





# of observed events in signal region (120-130 GeV) = 5





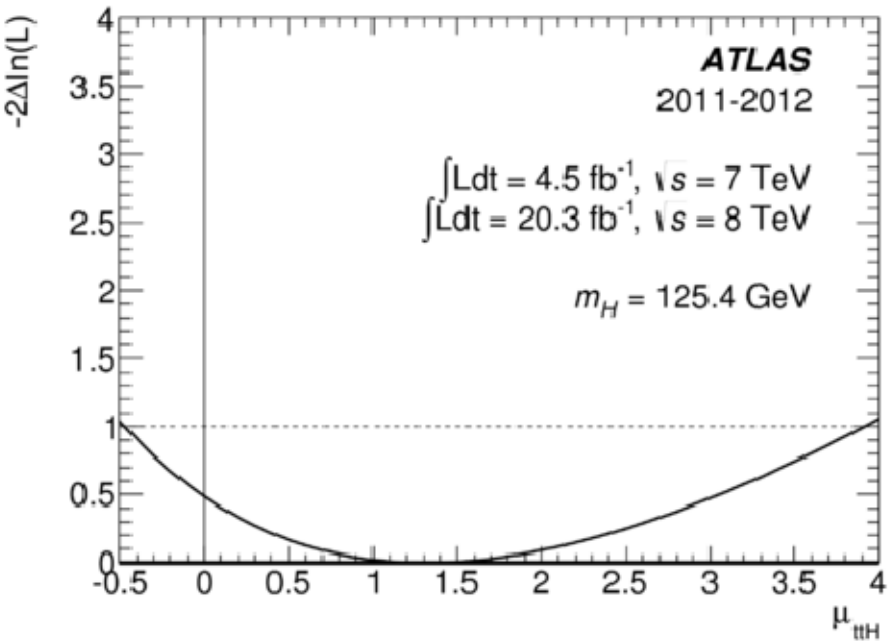
Expected number of events
for M_H = 125.4 GeV
after event selection – **Total = 1.3**

Background integral in
signal region (120-130)
determined from S+B
unbinned fit to the
range 105-160 GeV
Total = $4.6^{+1.3}_{-0.9}$

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9%	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

Expected percentage of various production sources contributing to signal

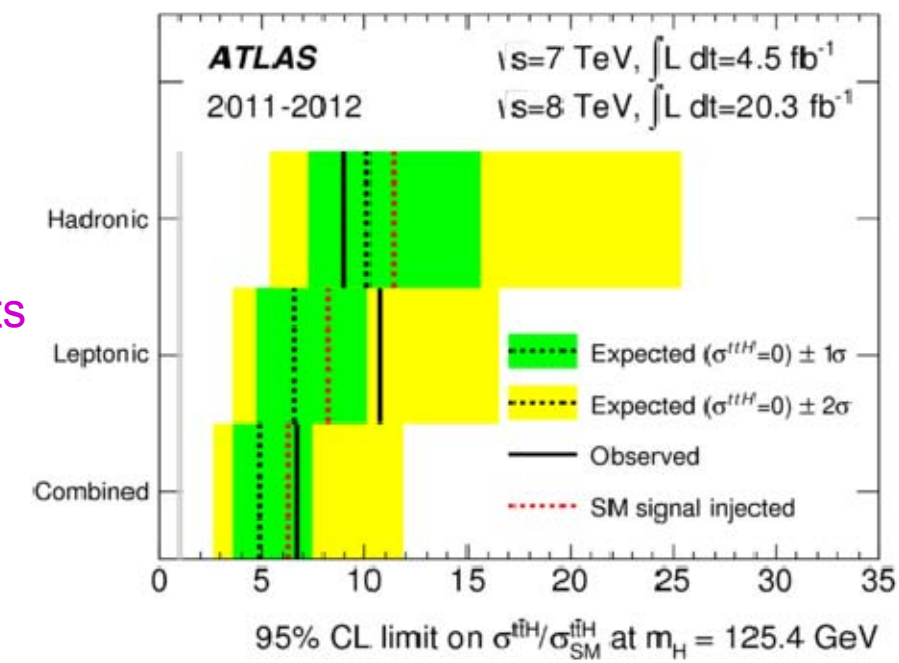
Results



Negative log-likelihood scan for the $\sigma(t\bar{t}H) \times BR(H \rightarrow \gamma\gamma)$ relative to SM value, at m_H = 125.4 GeV, where all other Higgs boson prod. σ, including tH prod., are set to their respective SM expectations:

$1.3^{+2.5}_{-1.7}{}^{+0.8}_{-0.4}$ (stat + syst.)

If all are allowed to float,
$1.4^{+2.1}_{-1.4}{}^{+0.6}_{-0.3}$ (stat + syst.)



Observed and expected 95% CL upper limits on $\sigma(t\bar{t}H) \times BR(H \rightarrow \gamma\gamma)$ (relative to SM)

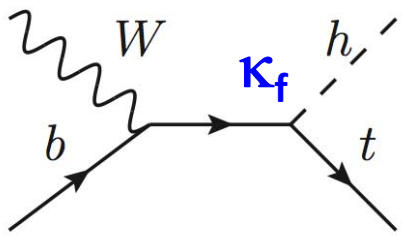
Combined result < 6.7

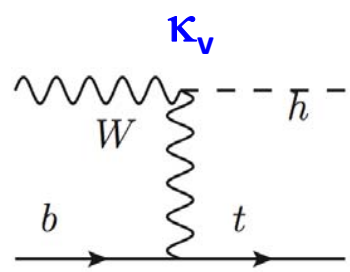
Limits on $\sigma(t\bar{t}H) \times BR(H \rightarrow \gamma\gamma)$ – all other processes assumed to have SM values

Expected limit evaluated for $\mu(ttH) = 0$

	Observed limit	Expected limit	$+2\sigma$	$+1\sigma$	-1σ	-2σ
Combined (with systematics)	6.7	4.9	11.9	7.5	3.5	2.6
Combined (statistics only)		4.7	10.5	7.0	3.4	2.5
Leptonic (with systematics)	10.7	6.6	16.5	10.1	4.7	3.5
Leptonic (statistics only)		6.4	15.1	9.6	4.6	3.4
Hadronic (with systematics)	9.0	10.1	25.4	15.6	7.3	5.4
Hadronic (statistics only)		9.5	21.4	14.1	6.8	5.1

With looser selections, ttH analyses can be made sensitive to single top processes, hence to sign of k_t





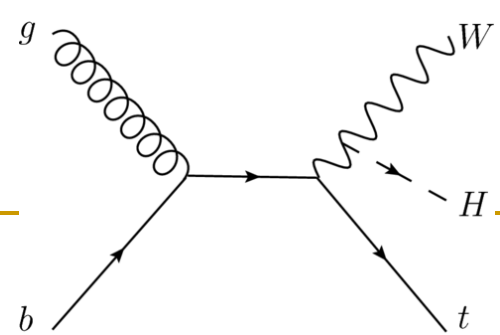
$K_i = 1 \Rightarrow$ SM

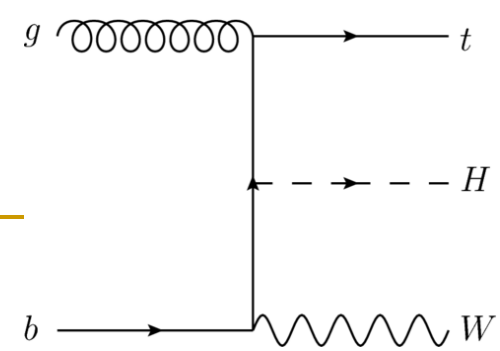
Large (destructive) interference between them, e.g.,

$\sigma(qb \rightarrow tHq') \sim 3.4\kappa_f^2 + 3.56\kappa_v^2 - 5.96\kappa_f\kappa_v$

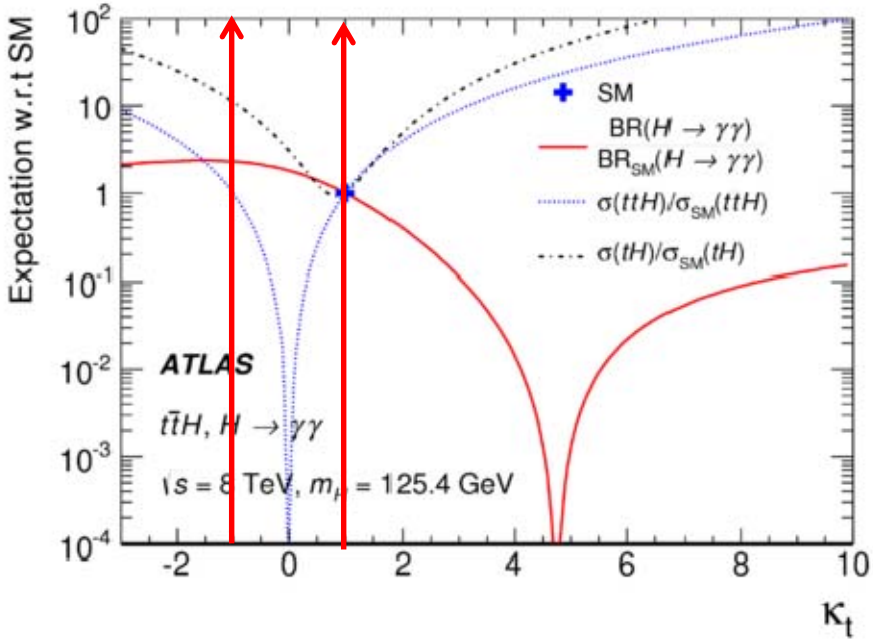
If relative sign of the two **κ** factors is -1, cross-section will be larger than SM

Similarly for $\sigma(gb \rightarrow WtH)$

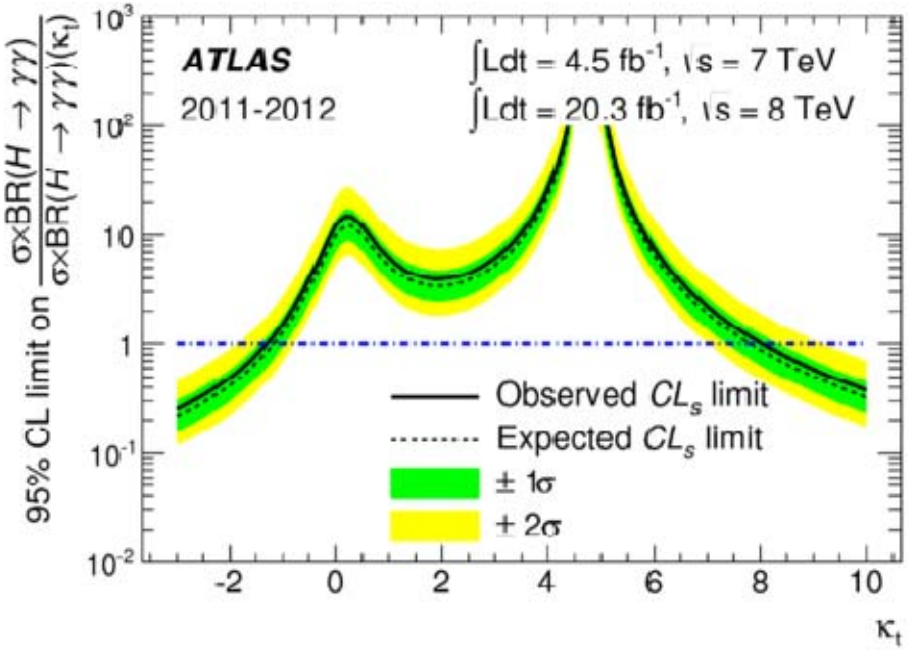




Information on K_t (= Y_t (meas)/Y_t(SM))



From γγ results

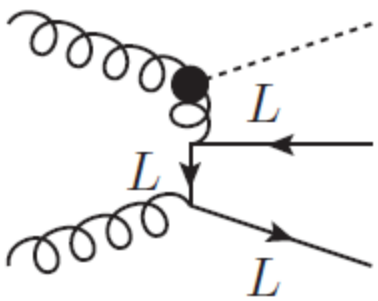


Observed (expected) lower and upper limits on κ_t at 95% CL are

−1.3 and +8.0 (−1.2 and+7.8)

Combining all Higgs results

- Currently only upper limits on ttH - to extract information on K_t requires inputs from all Higgs processes
  - Caveat: ttH final state has a small contribution (~10%) from ggF, so this would need to be done even where there is a signal
  - Cuts for various analyses are set to isolate different production processes
  - Many different ways to do these fits
    - Depends on what assumptions and what models are being tested

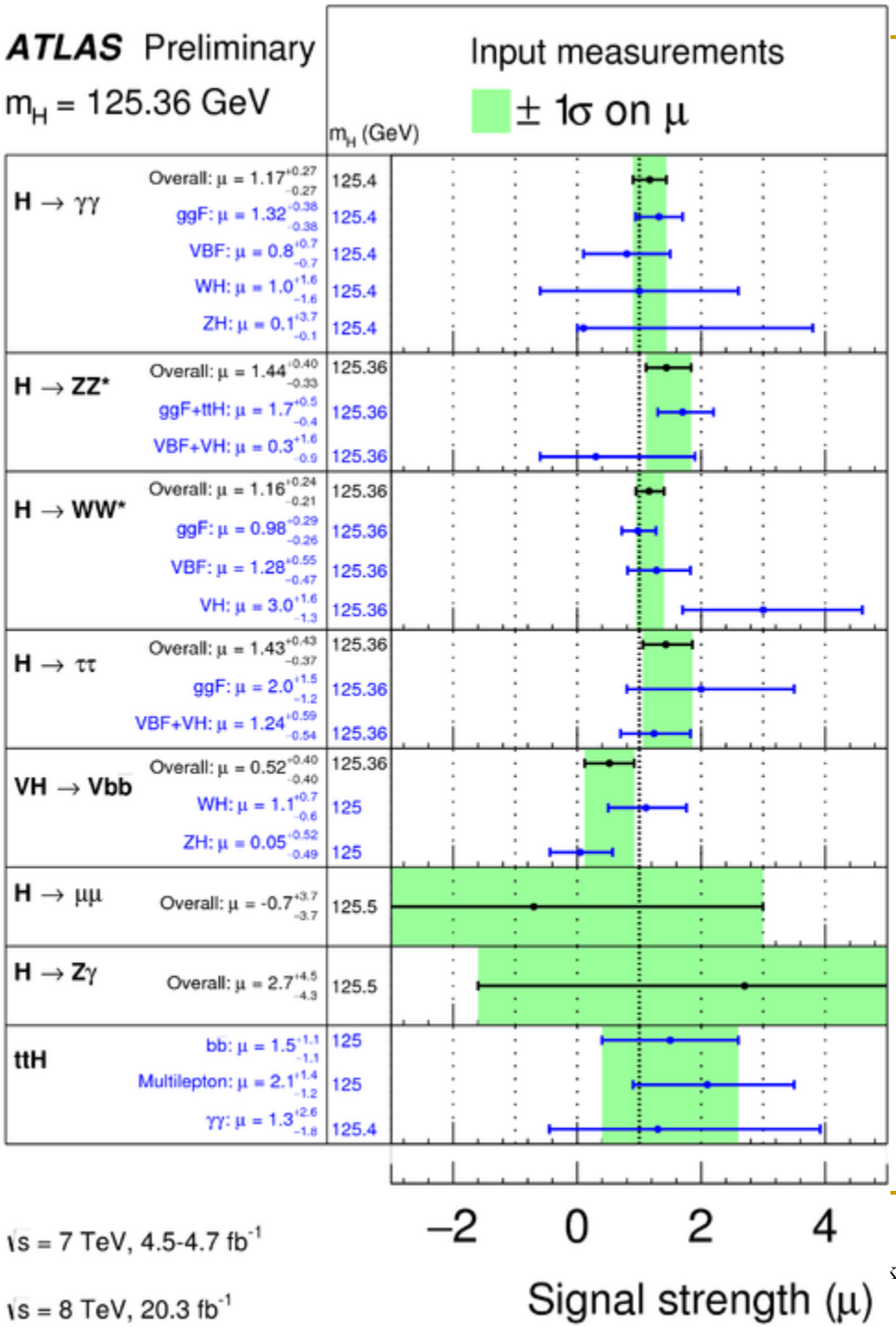


Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
$t\bar{t}H$: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} 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 $p_T^{\mu\mu}$			✓	✓
$t\bar{t}H$ production [21–23]			4.5	20.3
$H \to b\bar{b}$: single-lepton, dilepton		$\mu < 3.4$ (2.2)		✓
$t\bar{t}H \to$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
$H^* \to ZZ \to 4\ell$				✓
$H^* \to ZZ \to 2\ell 2\nu$				✓
$H^* \to WW \to e\nu\mu\nu$				✓

Cuts for various analyses are set to isolate different production processes

Production	Loops	Interference	Expression in terms of fundamental coupling strengths
$\sigma(\mathrm{ggF})$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	$W-t$	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

$\kappa_i = 1$ means SM value of coupling

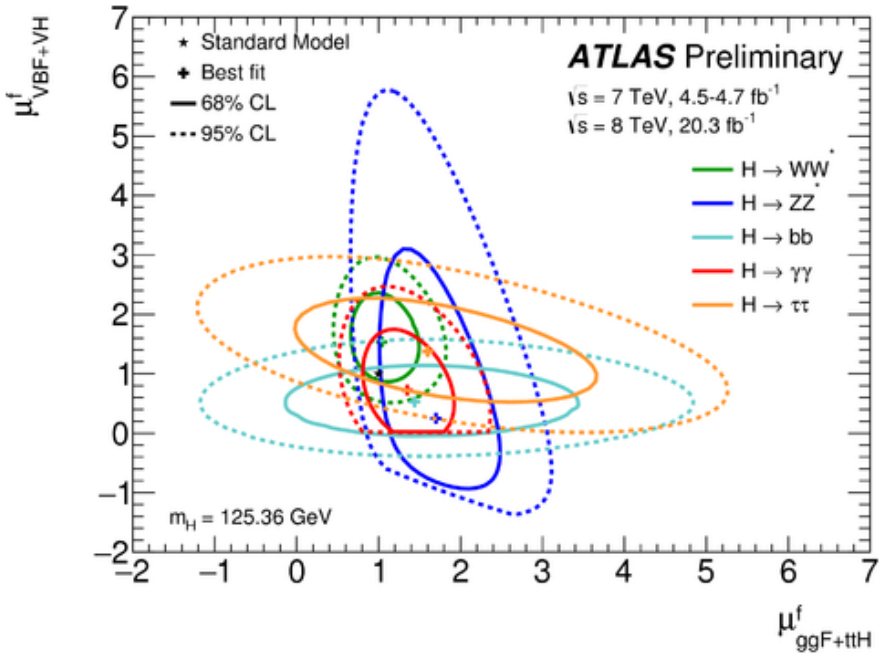


Summary of signal-strength measurements from individual analyses. Higgs boson mass column indicates the m_H value at which the result is quoted.

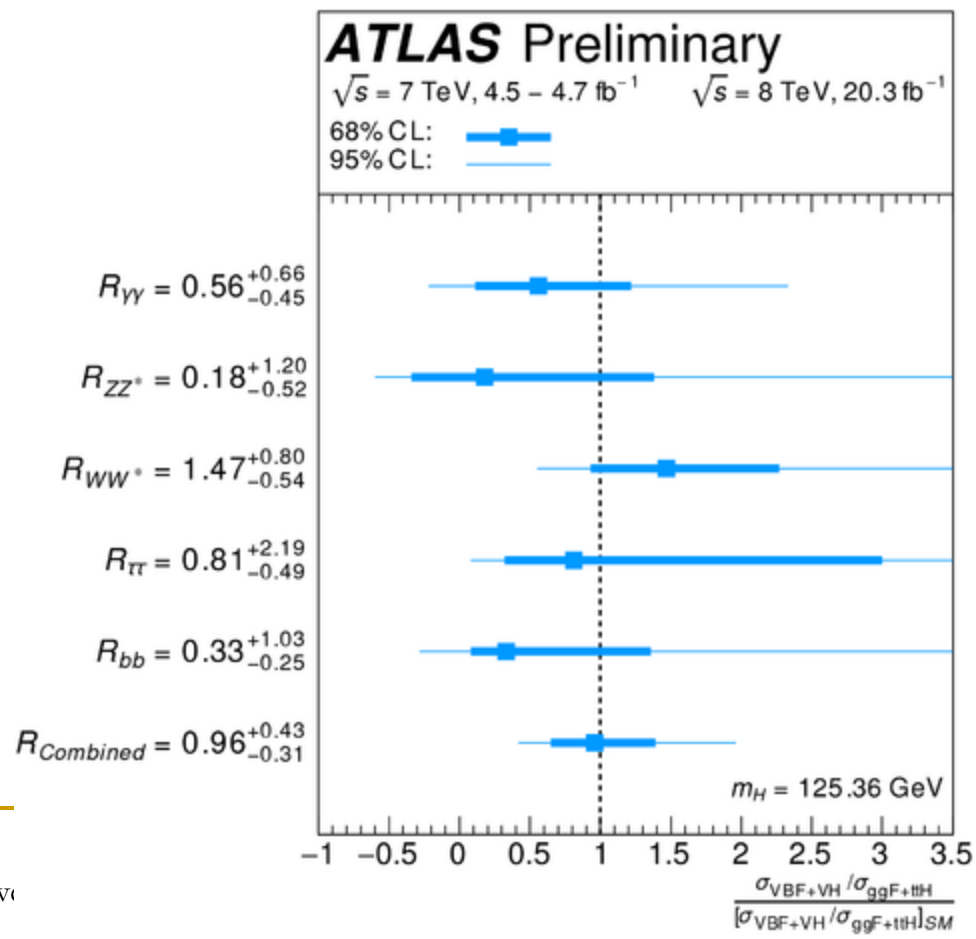
The overall signal strength of each analysis (black) is the combined result of the measurements for different production processes (blue).

These assume SM values for various production processes & decays

Potential deviations from the SM can be tested with two signal-strength parameters, $\mu^f_{ggF+ttH} \equiv (\mu^f_{ggF} = \mu^f_{ttH})$ and $\mu^f_{VBF+VH} \equiv (\mu^f_{VBF} = \mu^f_{VH})$ for each decay f

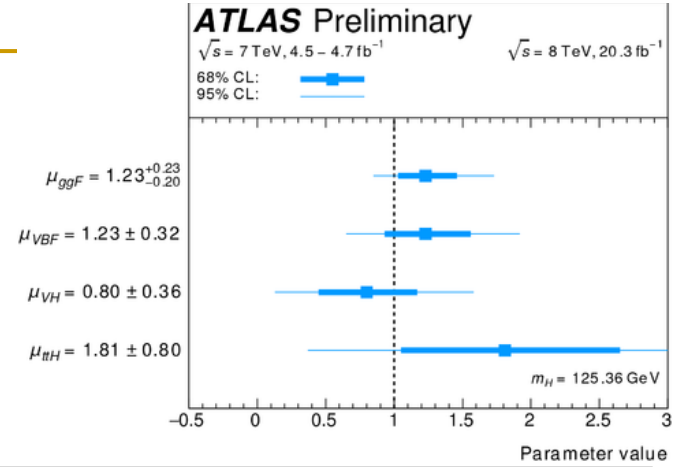


SM value is within 68% contour for most



R is the ratio of these two production parameters measured separately for each decay mode.

Extracting information on individual production processes assuming SM values for decay channels



Production process	Signal strength μ at m_H = 125.36 GeV			
	$\sqrt{s}$ = 8 TeV		Combined $\sqrt{s}$ = 7 and 8 TeV	
ggF	$1.23^{+0.25}_{-0.21}$	$\begin{bmatrix} +0.16 & +0.10 & +0.16 \\ -0.16 & -0.08 & -0.11 \end{bmatrix}$	$1.23^{+0.23}_{-0.20}$	$\begin{bmatrix} +0.14 & +0.09 & +0.16 \\ -0.14 & -0.08 & -0.12 \end{bmatrix}$
VBF	$1.55^{+0.39}_{-0.35}$	$\begin{bmatrix} +0.32 & +0.17 & +0.13 \\ -0.31 & -0.13 & -0.11 \end{bmatrix}$	1.23 ± 0.32	$\begin{bmatrix} +0.28 & +0.13 & +0.11 \\ -0.27 & -0.12 & -0.09 \end{bmatrix}$
VH	0.93 ± 0.39	$\begin{bmatrix} +0.37 & +0.20 & +0.12 \\ -0.33 & -0.18 & -0.06 \end{bmatrix}$	0.80 ± 0.36	$\begin{bmatrix} +0.31 & +0.17 & +0.10 \\ -0.30 & -0.17 & -0.05 \end{bmatrix}$
ttH	1.62 ± 0.78	$\begin{bmatrix} +0.51 & +0.58 & +0.28 \\ -0.50 & -0.54 & -0.10 \end{bmatrix}$	1.81 ± 0.80	$\begin{bmatrix} +0.52 & +0.58 & +0.31 \\ -0.50 & -0.55 & -0.12 \end{bmatrix}$

Thus, a 95% upper limit on its signal strengths is also derived. Combining the results from various analyses with sensitivity to ttH production, the observed and expected limits are $\mu_{ttH} < 3.2$ and 1.4, respectively.

Extraction of K_t (as well as other couplings) depends on what assumptions are being made and what models are being tested:

- Is width of Higgs fixed to SM value or allowed to float?
- Are non-SM particles allowed to be in the loops? …

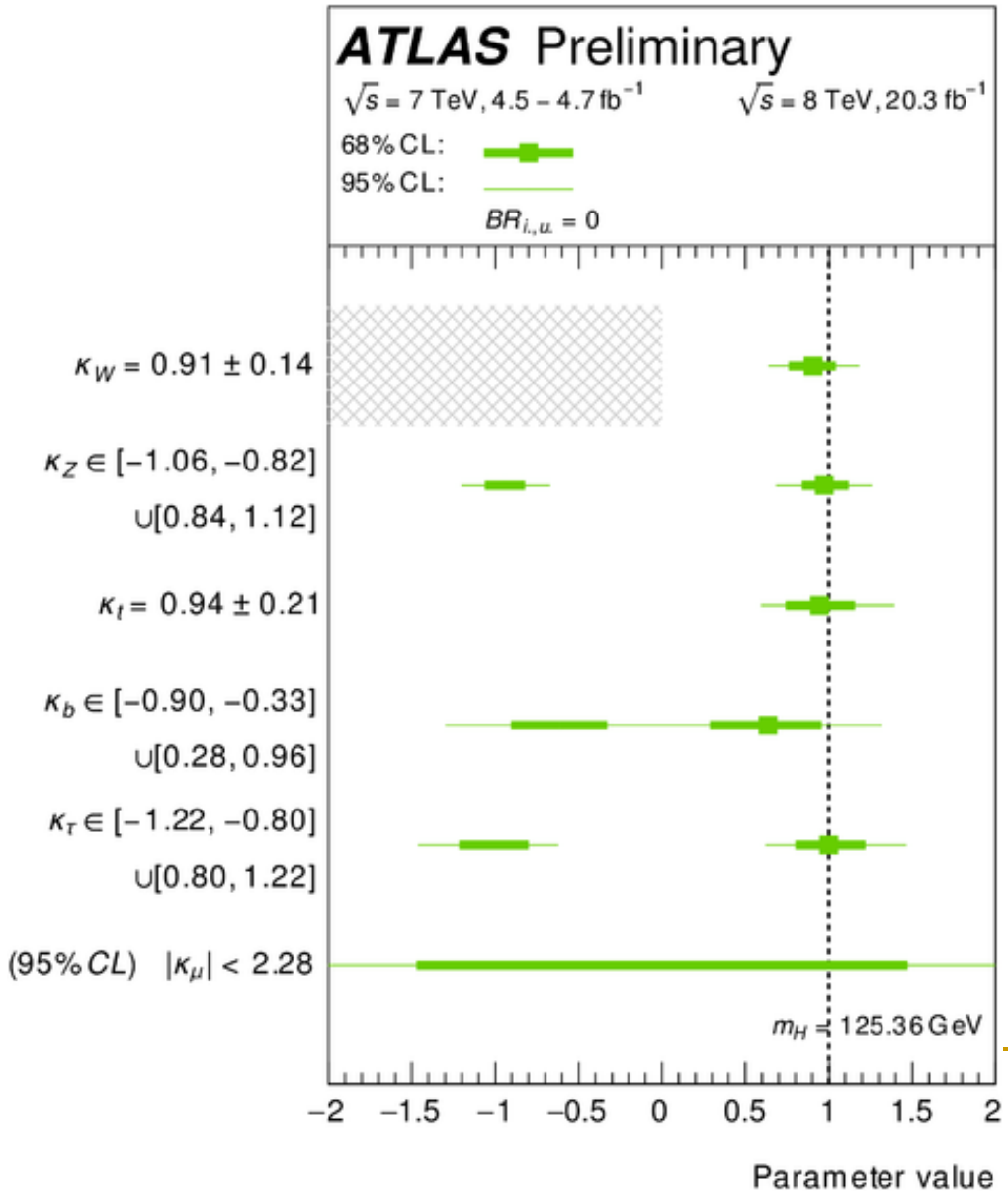
- Comparing couplings to up-type fermions vs. down-type fermions
- Probing quark-lepton symmetry

- Generic Models – treat each coupling strength independently:

  - Only SM particles in loops, no invisible/undetected Higgs decays
  - Allowing deviations in vertex loop couplings, and invisible/undetected decays (when allowing the latter, total width is constrained)
  - Allowing deviations in vertex loop couplings, no assumptions on total width

Will show one result (Generic Model 1)

Generic Model 1



Due to the interference terms, fit is sensitive to relative sign between W & t couplings (via tH, H→γγ, H → Zγ)

and relative sign between Z and t couplings (via gg → ZH), providing indirect sensitivity to the relative sign between the W - and Z-coupling.

Also, model has some sensitivity to the relative sign between the top- and bottom-coupling (gg → H)

Conclusions

- Run-I ATLAS results on production of Higgs boson in association with top quarks:
  - ttH→γγ: $\mu < 6.7$ obs (4.9 exp); $\mu = 1.3^{+2.5}_{-1.7}(\text{stat.})^{+0.8}_{-0.4}(\text{syst.})$
  - ttH→bb: $\mu < 3.4$ obs (2.2 exp); $\mu = 1.5 \pm 1.1$
  - ttH→leptons: $\mu < 4.7$ obs (2.4 exp); $\mu = 2.1^{+1.4}_{-1.2}$

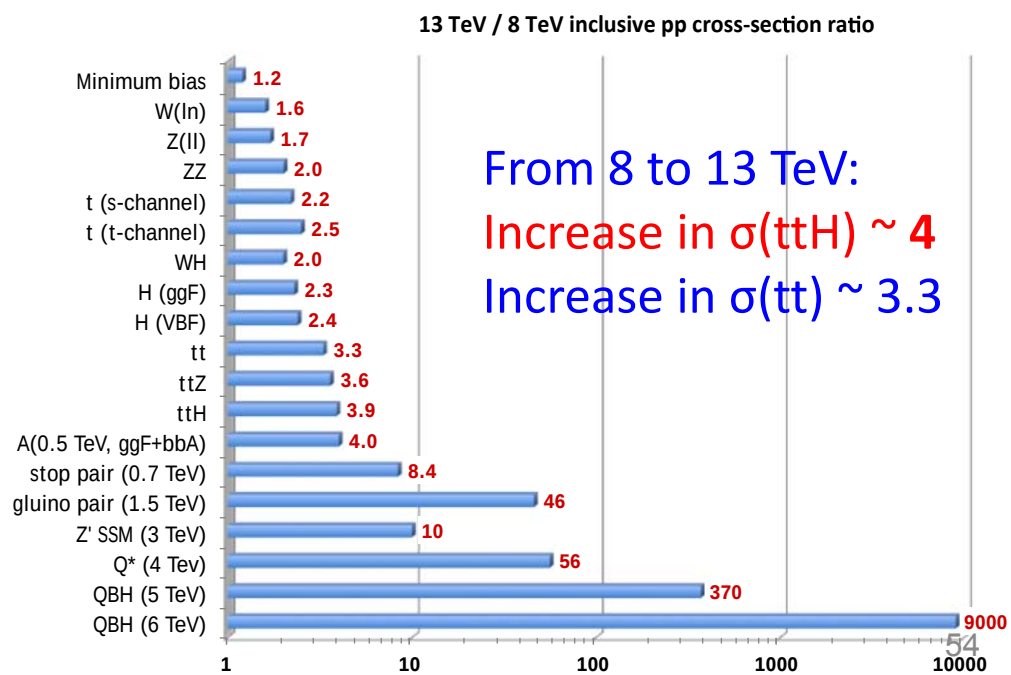
All consistent with Standard Model

Combined fitted result for ttH production: **μ=1.81±0.80**

CMS (μ=2.8±1.0) & ATLAS combination for EPS

- All Run-1 results statistically limited

→ **ttH very promising in Run II**



From 8 to 13 TeV:
Increase in σ(ttH) ~ **4**
Increase in σ(tt) ~ 3.3

From Marine Kuna's talk