Search for Higgs bosons produced in association with top quarks -

ATLAS detector at the LHC

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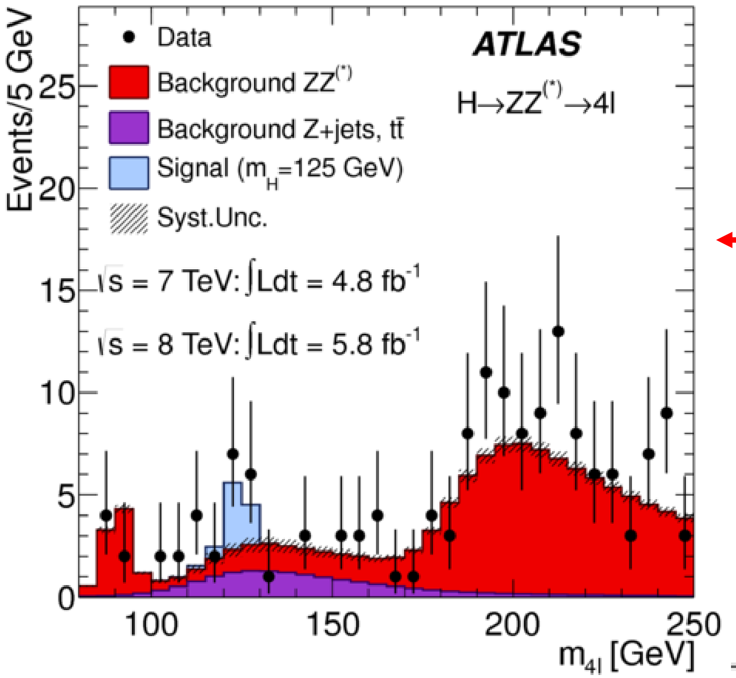
Outline

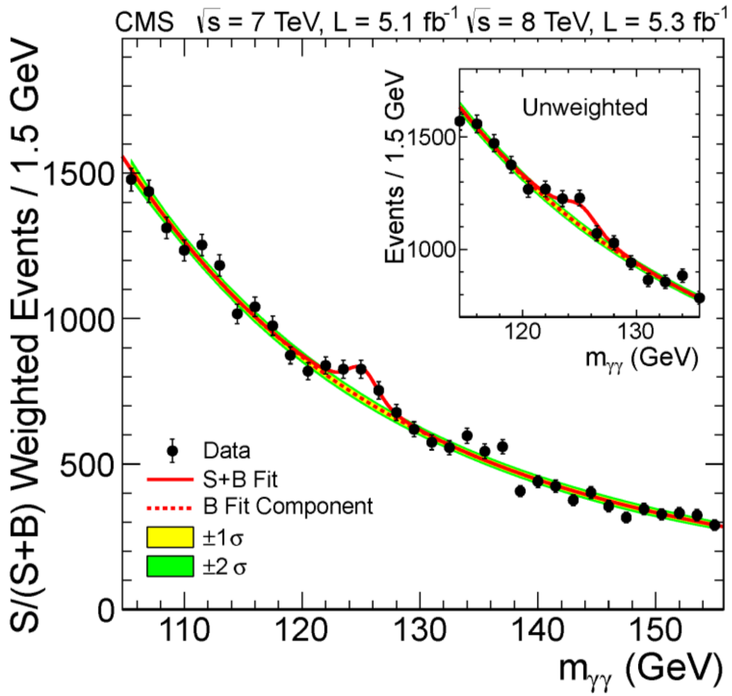
- Current status of Higgs measurements
- Why the search for Higgs produced in association with top quarks (aka ttH)?
- Various ttH analyses at ATLAS
  - H → bb (single and dilepton events)
  - H → Multileptons (> 2 leptons)
  - H → $\gamma\gamma$
  - Top Yukawa coupling strength
- Summary and Outlook

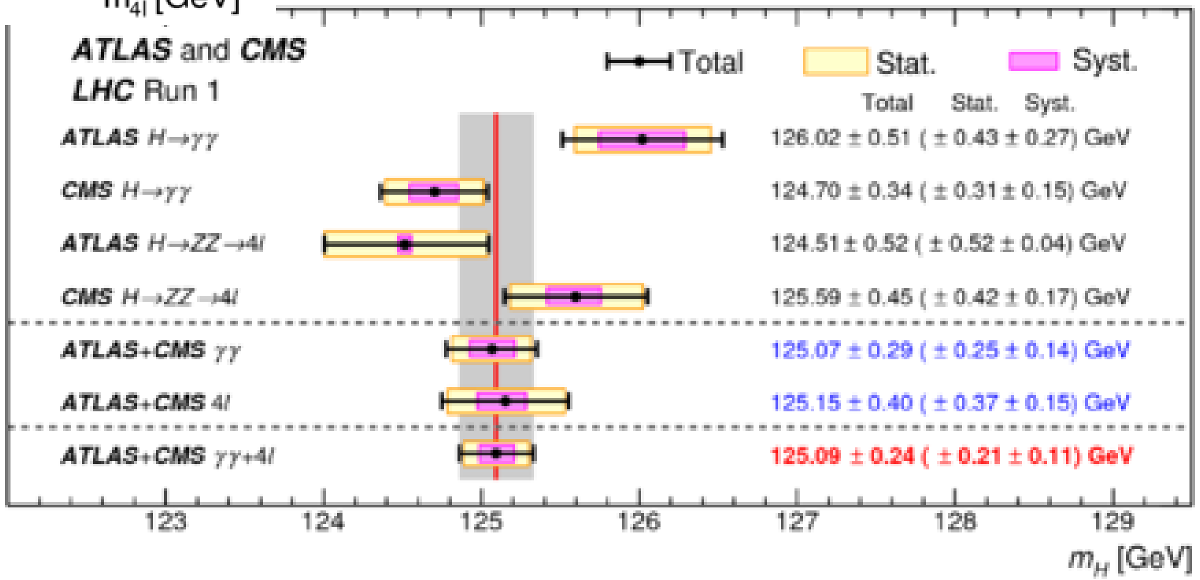
From discovery onward



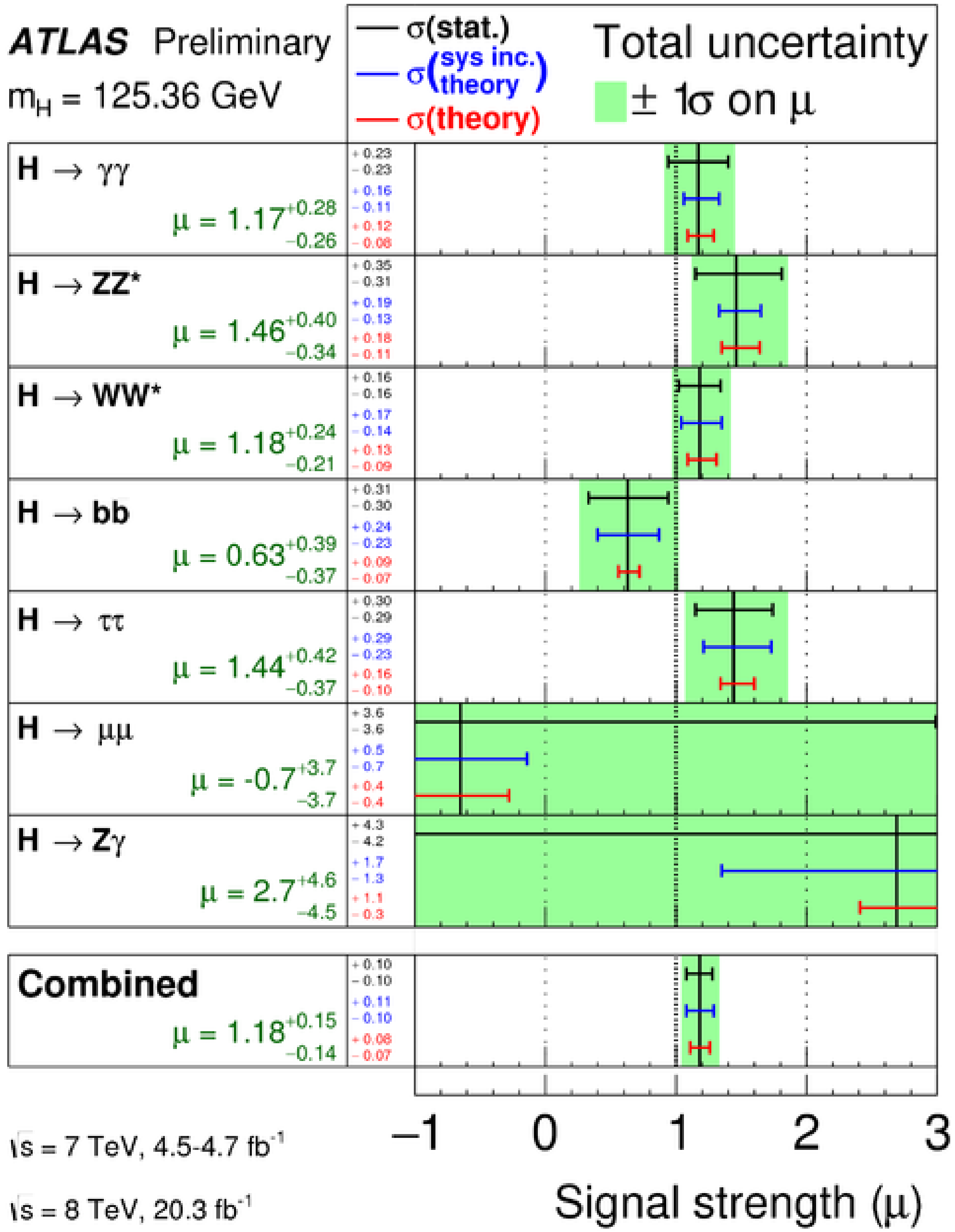
From 2012 discovery papers

Present





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



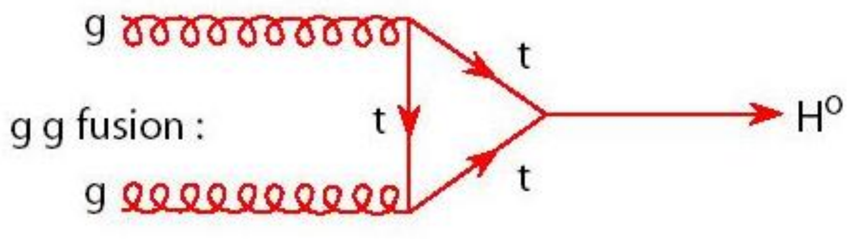
μ: signal strength relative to SM

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}} .$$

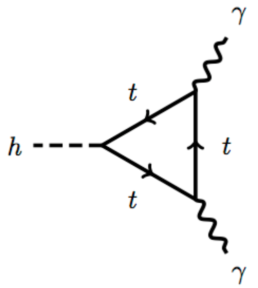
$1.18 \pm 0.10 \pm 0.07^{+0.08}_{-0.07}$

Focus has now shifted to proving that this particle is indeed the "one we had been waiting for"

Why search for ttH?



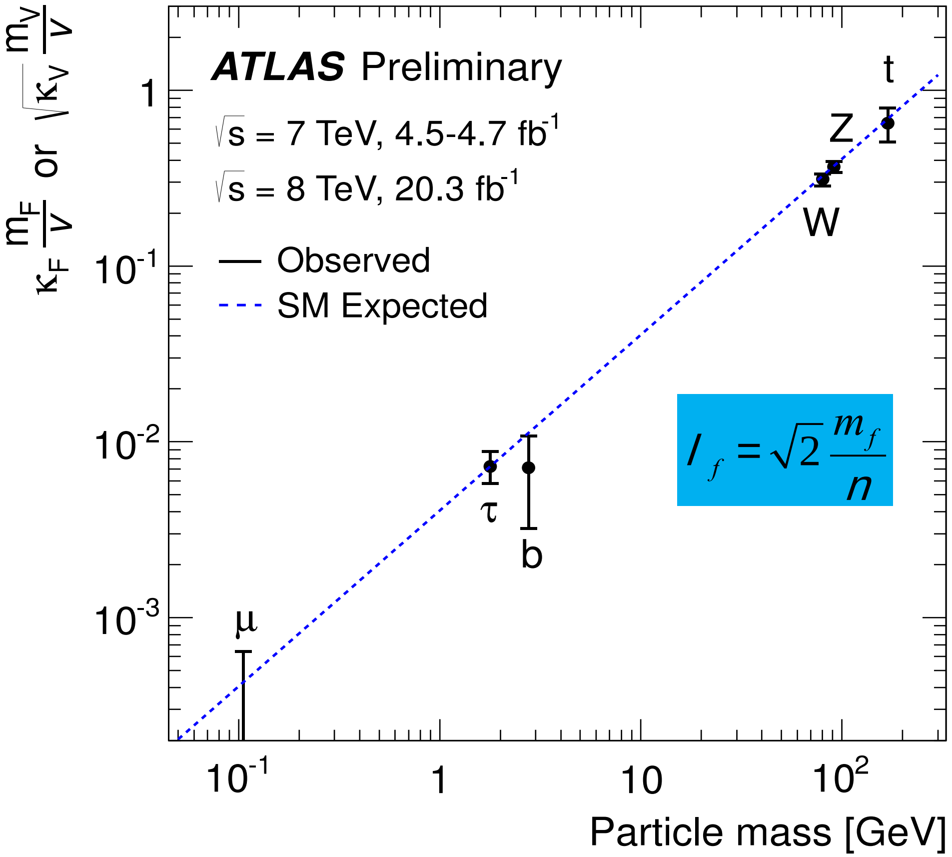
- We have indirect evidence for ttH
  - Largest production is via gluon+gluon fusion - proceeds mainly through top loop (b-loop is small)
  - Higgs → γγ proceeds through W & top loops

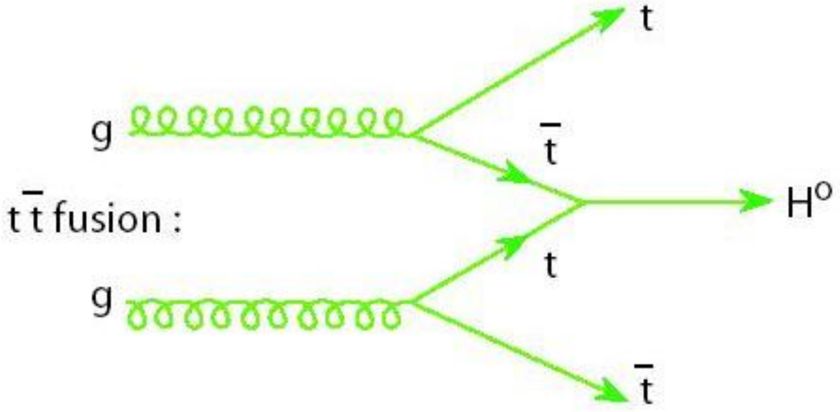


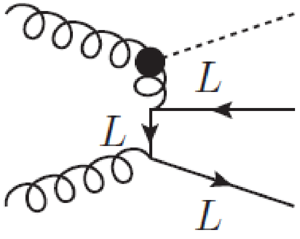
  - Since these are loops, BSM particles could also contribute. Current precision not enough to discriminate
  - Higgs too light to decay to a pair of top quarks

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

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



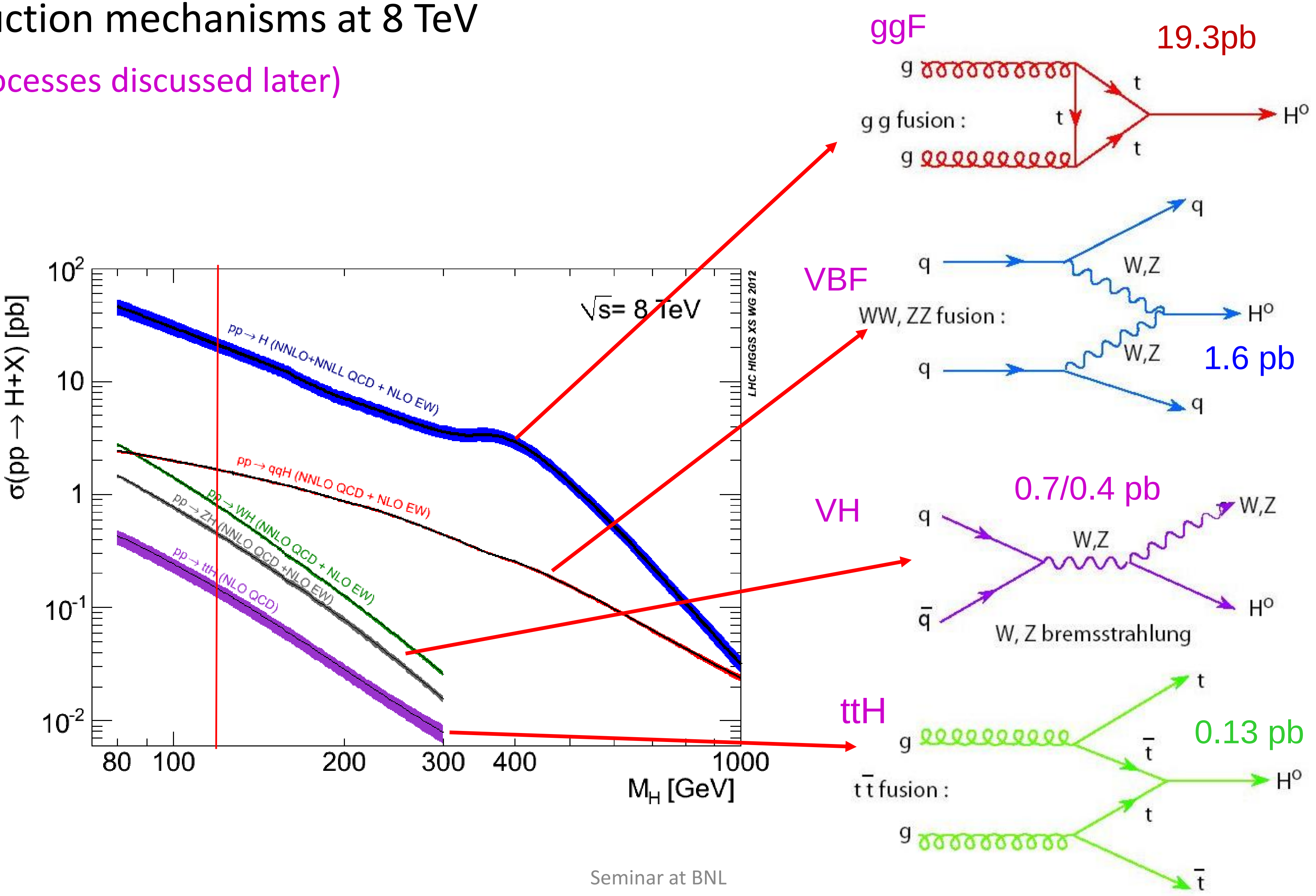


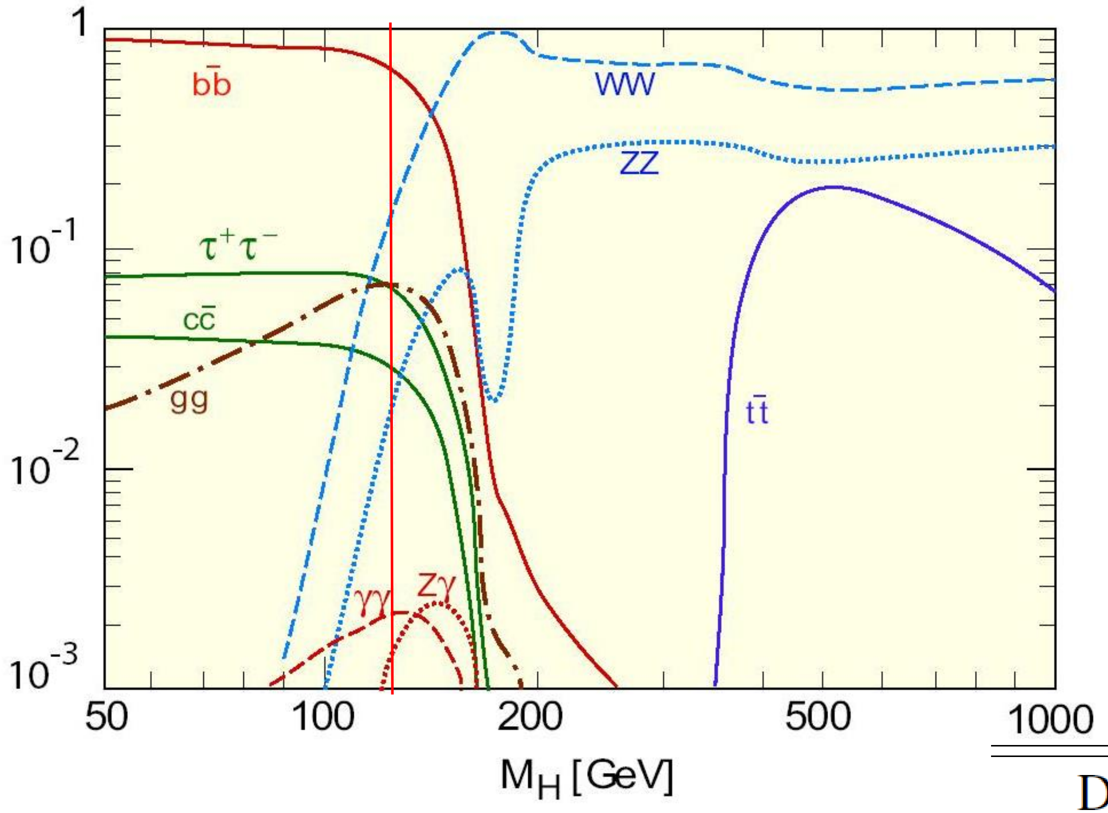


Small contribution from ggF

Higgs Production mechanisms at 8 TeV

(single top processes discussed later)



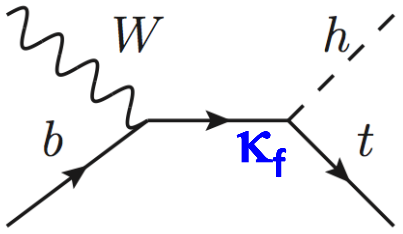


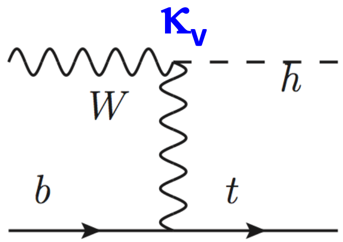
Higgs branching fractions in the SM:

M_H = 125.36 GeV

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





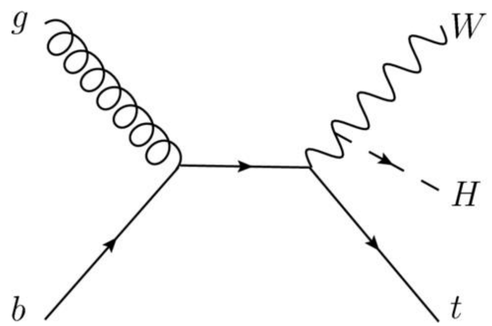
$K_i = 1 \Rightarrow$ SM

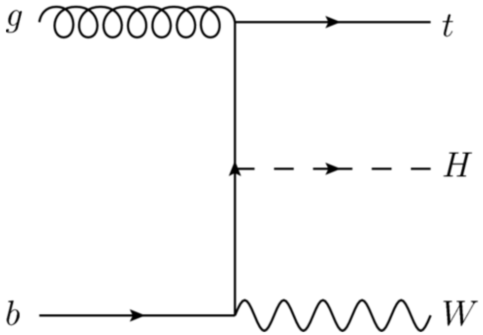
Large (destructive) interference between them, e.g.,

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

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

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





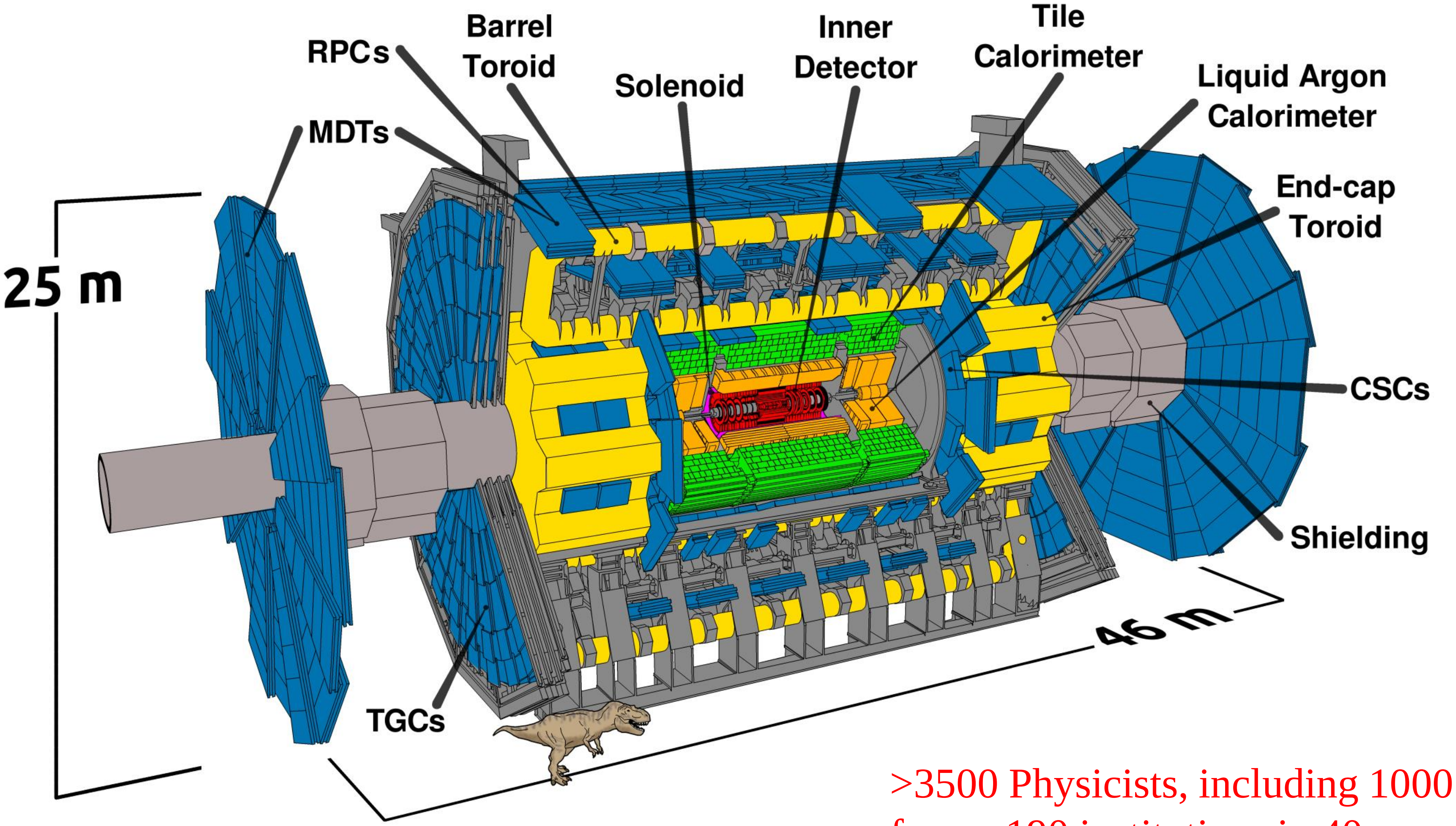
Effect of non-SM couplings on tH processes

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

SM

BSM

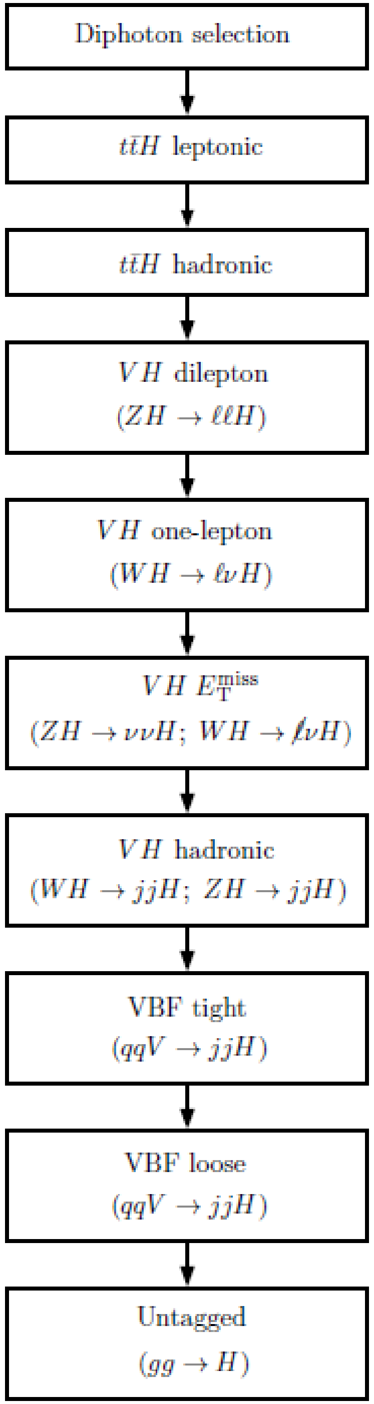
ATLAS:



>3500 Physicists, including 1000 Ph.D. students from ~190 institutions in 40 countries

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.

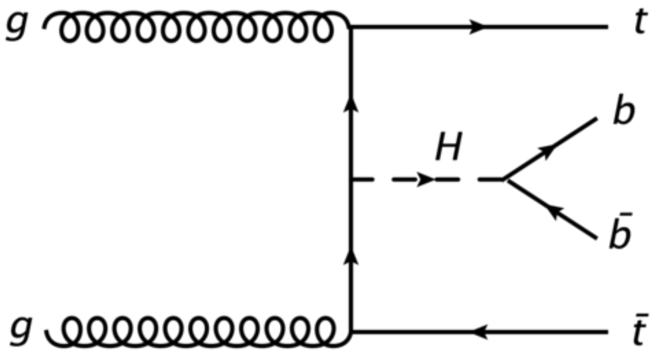
	ggF		VBF		WH		ZH		ttH		$b\bar{b}H$		$tHbj$		tHW		
Category	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	ϵ(%)	f(%)	N_S
Central - low p_{Tt}	15.5	92.2	8.5	4.1	7.2	1.6	7.9	1.0	3.4	0.1	15.5	1.0	-	-	-	-	26.0
Central - high p_{Tt}	1.0	71.8	2.7	16.4	2.1	6.1	2.3	3.7	2.9	1.2	1.0	0.7	-	-	-	-	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	8.5	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

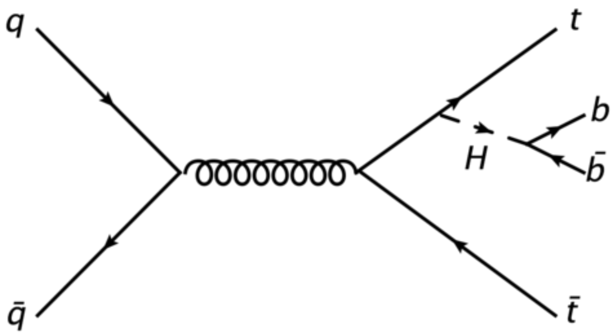
Efficiency and purity of various categories (for 7 TeV)

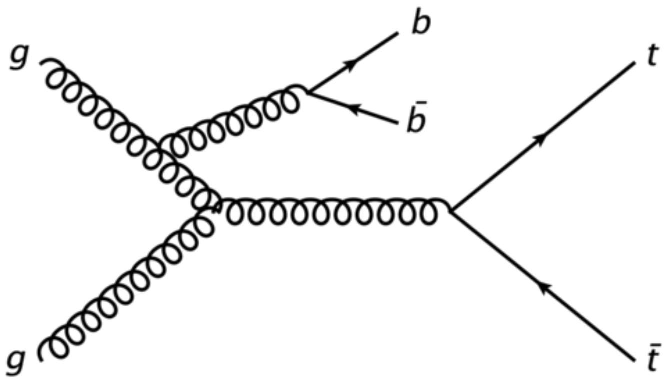
H → bb

EPJC 75, 349 (2015), arXiv:1503.05066

σ(ttH) at 8 TeV ~ 0.13 pb





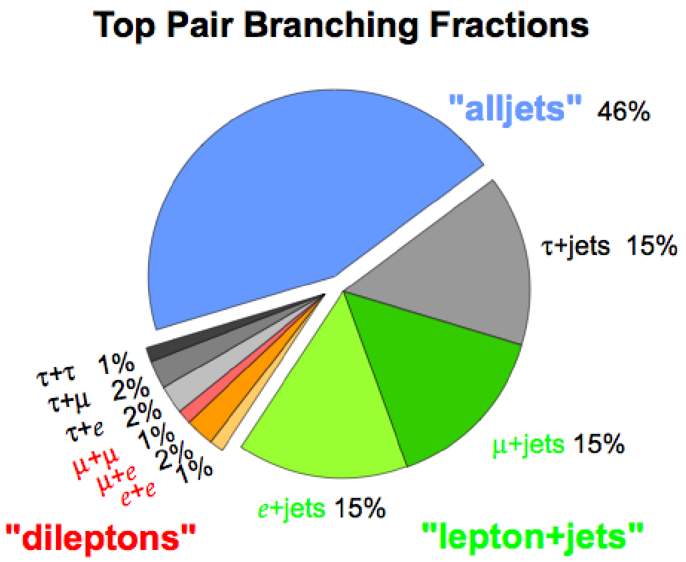


σ(ttbb) at 8 TeV ~ $\mathcal{O}$(12) pb - Irreducible background

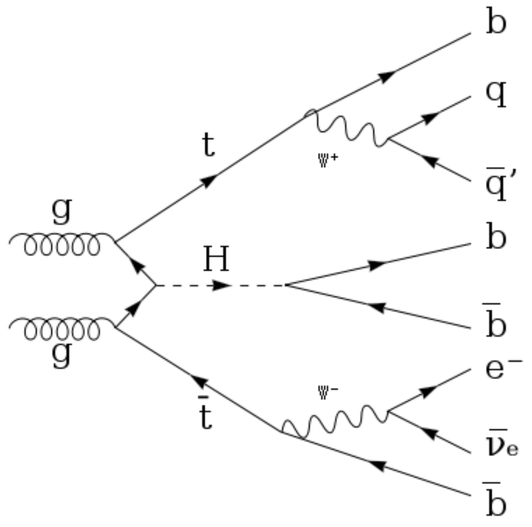
Complex analysis - needs detailed modelling of various background sources

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)

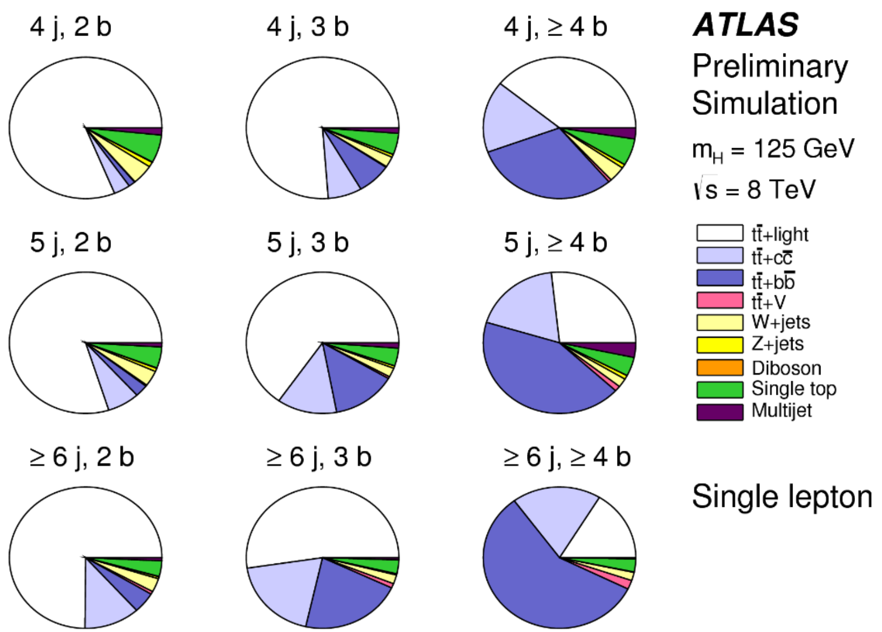
- Dilepton+jets: both tops (W) decay semi-leptonically (Albany group + Jahred + Quake)

4 jets (all bjets) + 2 leptons

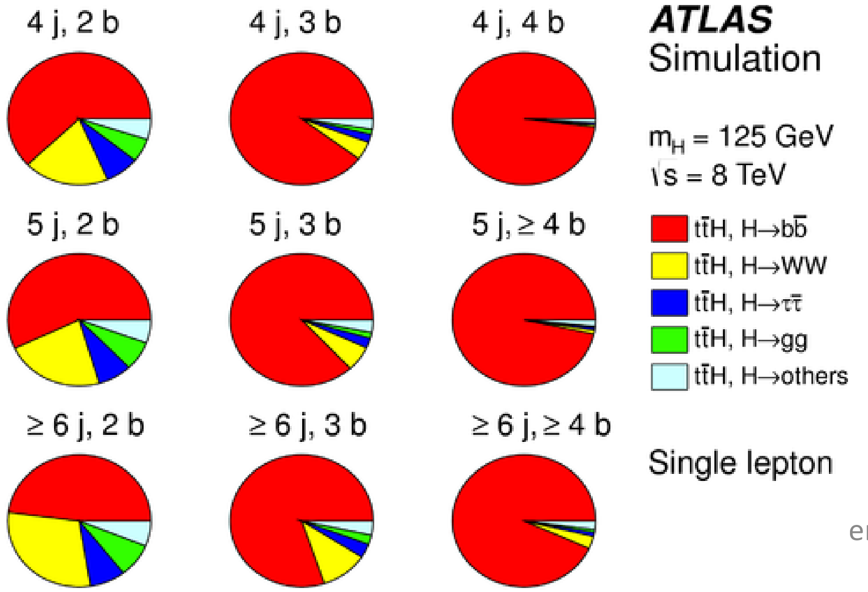
Single Lepton

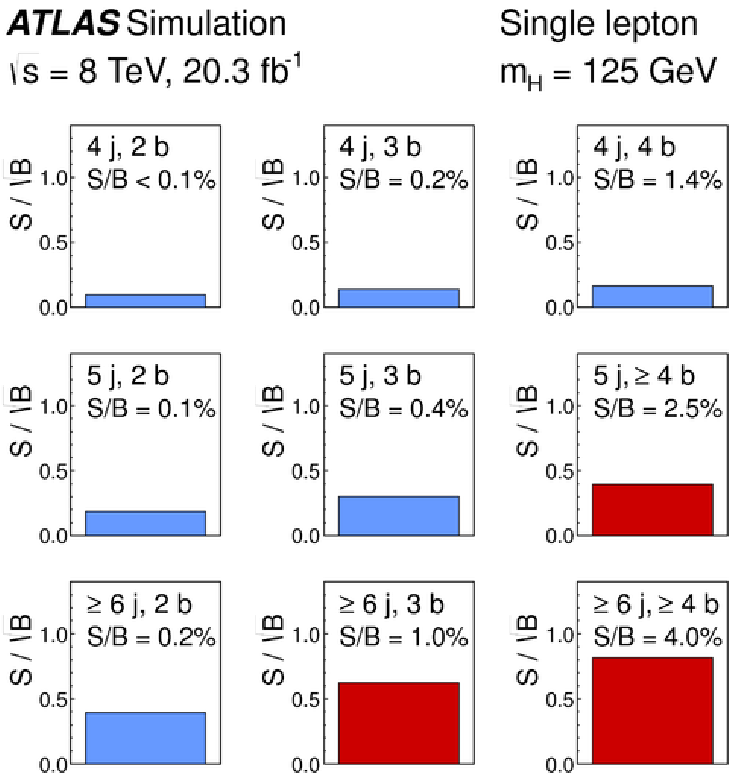
To maximize sensitivity:
both single and dilepton analyses
categorize events in bins of Njets/Nbtags

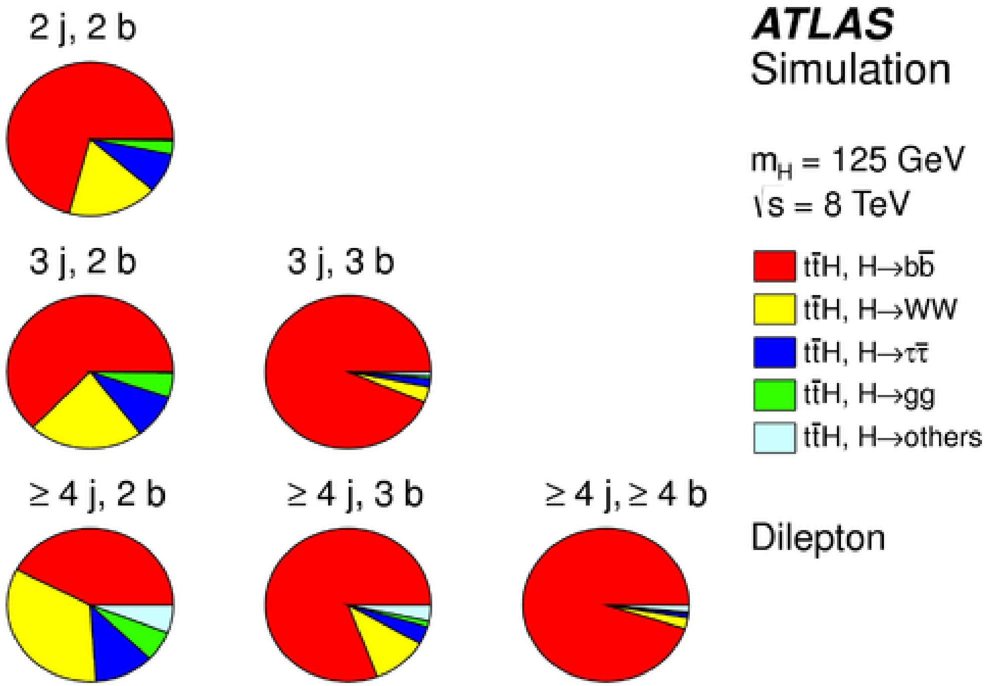
Various backgrounds – ttbar most important



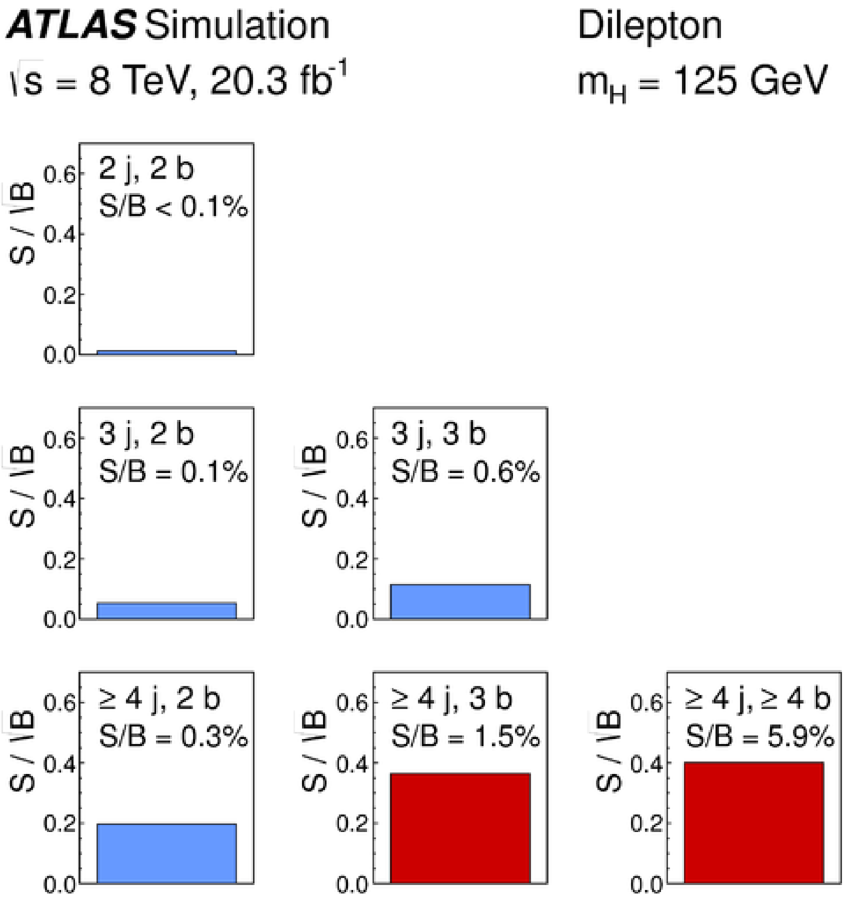
Analysis allows for all Higgs decays,
but H to bb is dominant

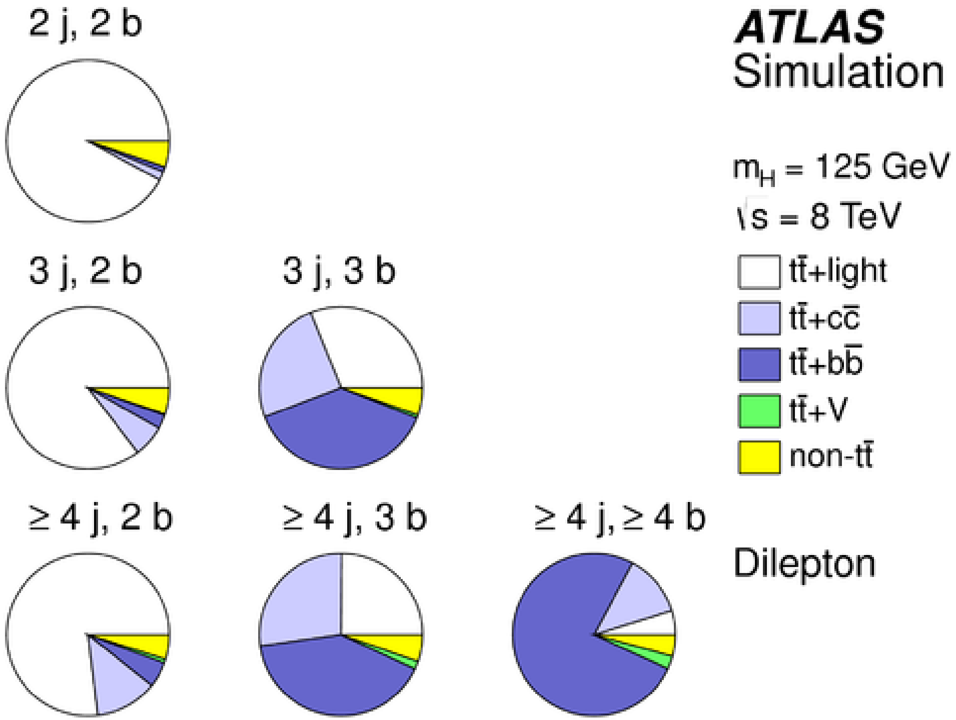






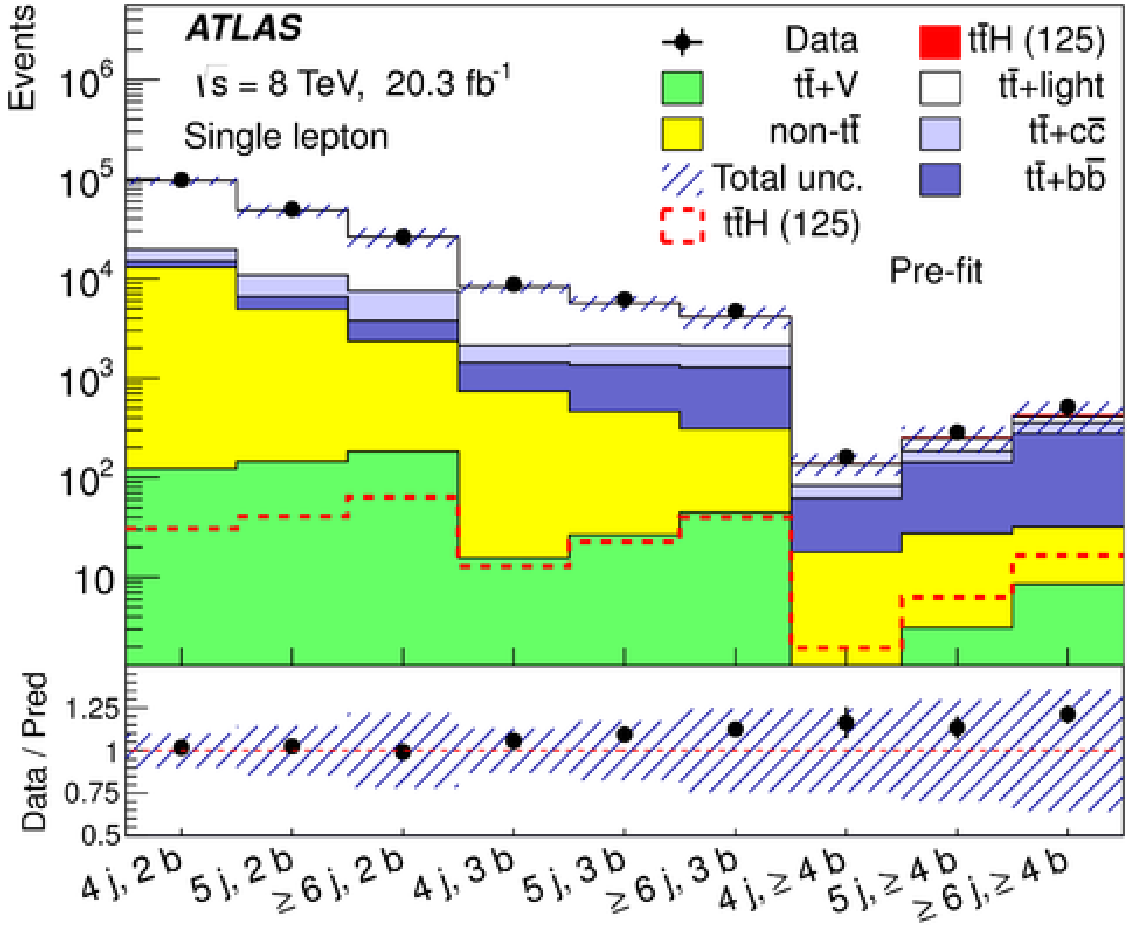
Dilepton





Many control regions –
Constrain backgrounds with Profile likelihood fit

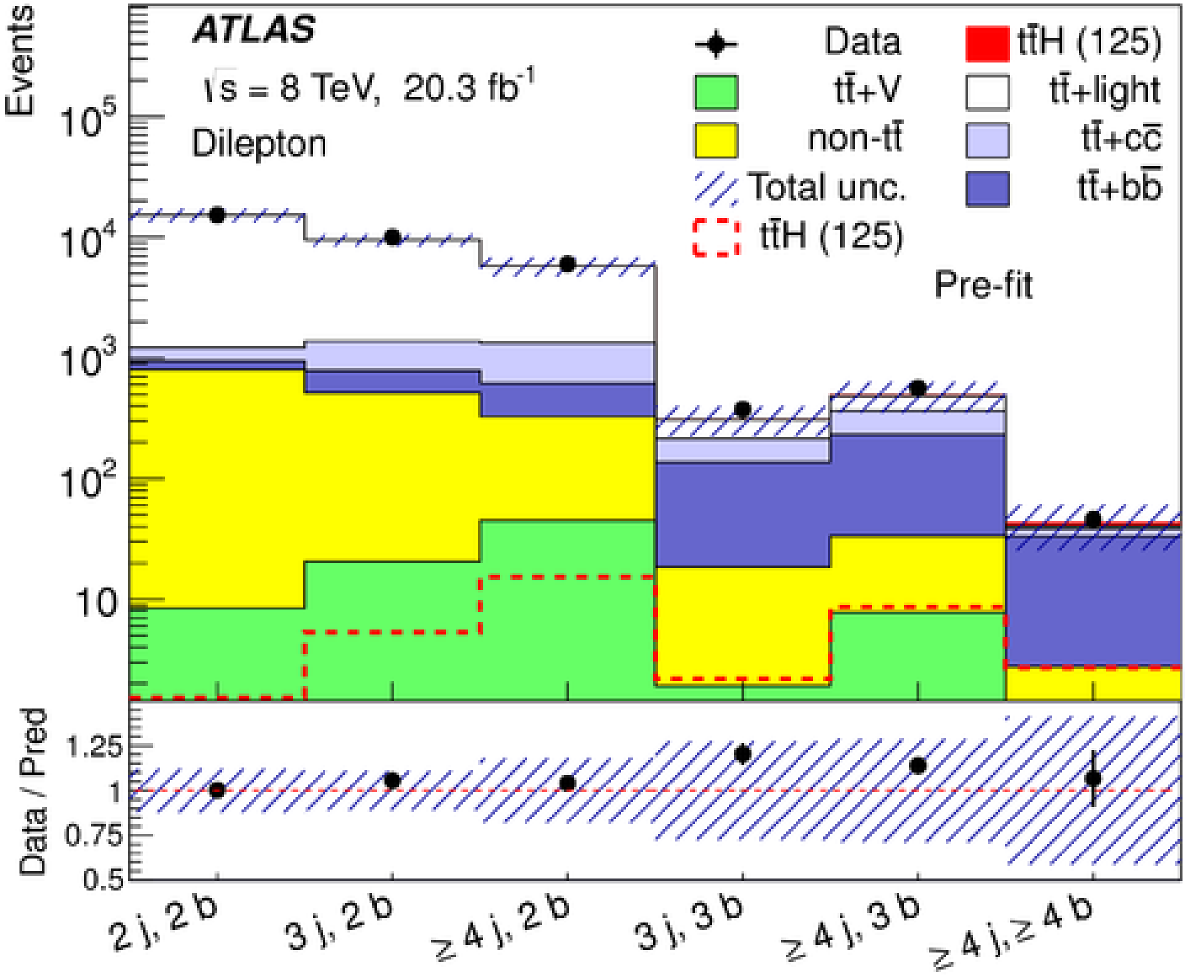
Use NN to discriminate between S/B in signal-rich regions



Single lepton

Overwhelming background

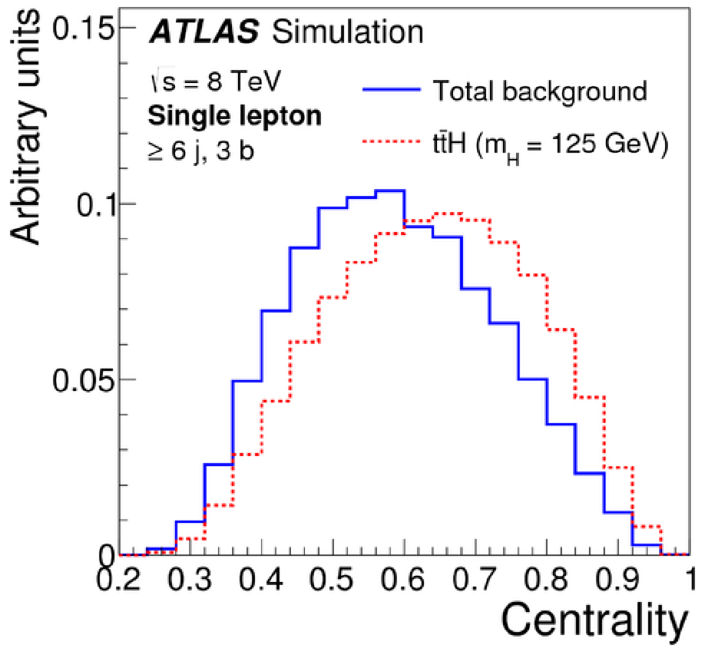
Dilepton

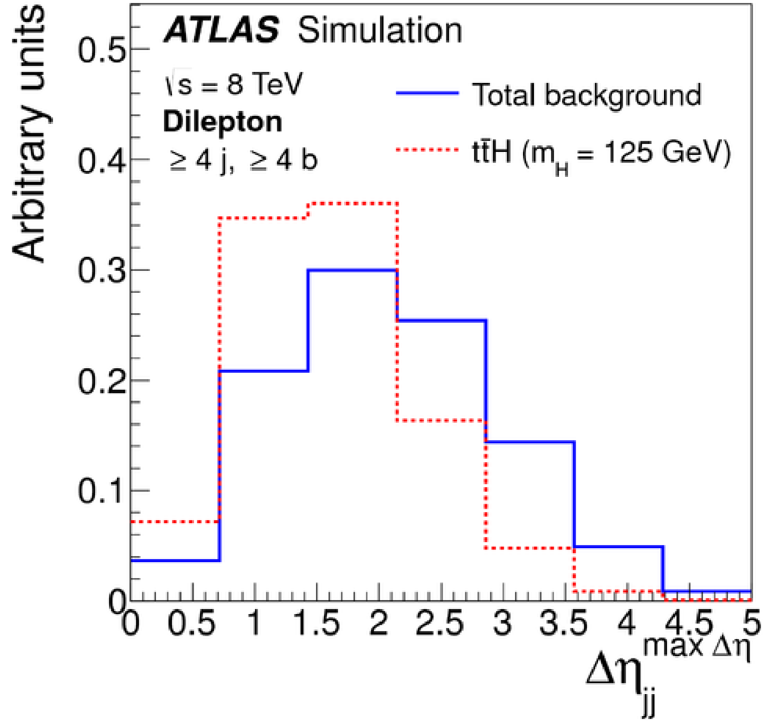


Pre-fit yields in various regions

Neural Nets – discriminate between S and B

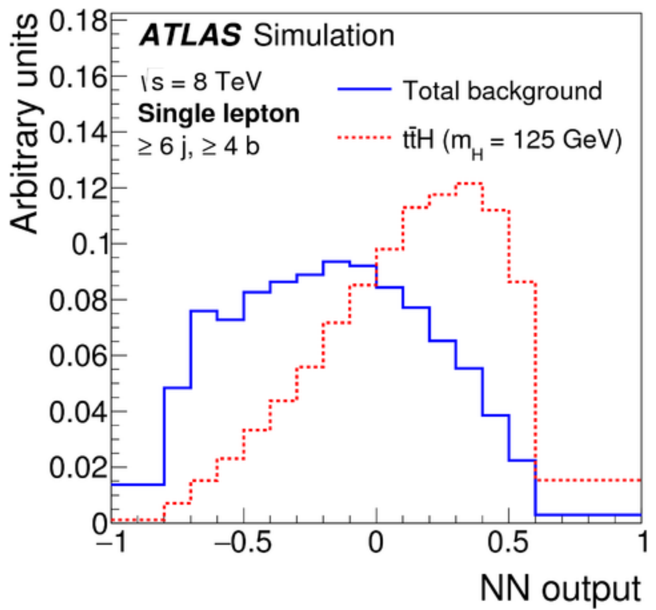
- NN separately optimized for each signal rich region, 1, 2 lepton
- NNs built from:
  - Event shape variables (e.g., centrality)
  - Object pair properties (e.g., $\Delta\eta_{jj}$ max)
  - Object kinematics (e.g., p_T)
  - Event Kinematics (e.g., H_T)

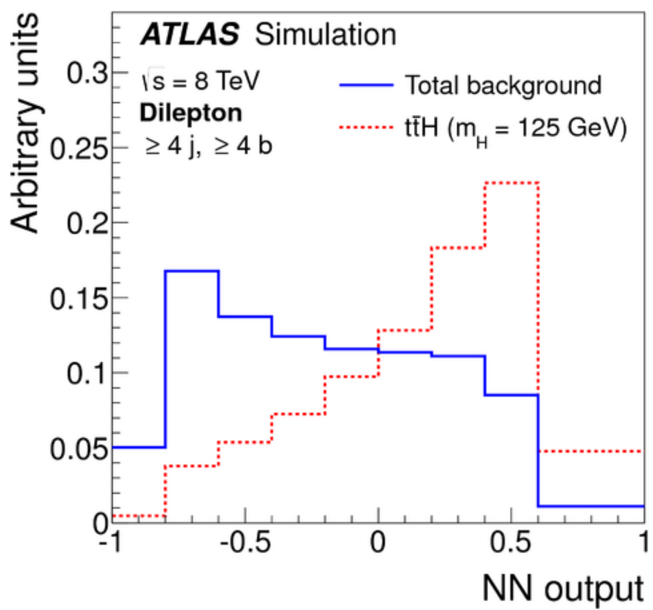




Neural nets

- Use NN to discriminate between signal and background in signal-rich regions – separately optimized
  - 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



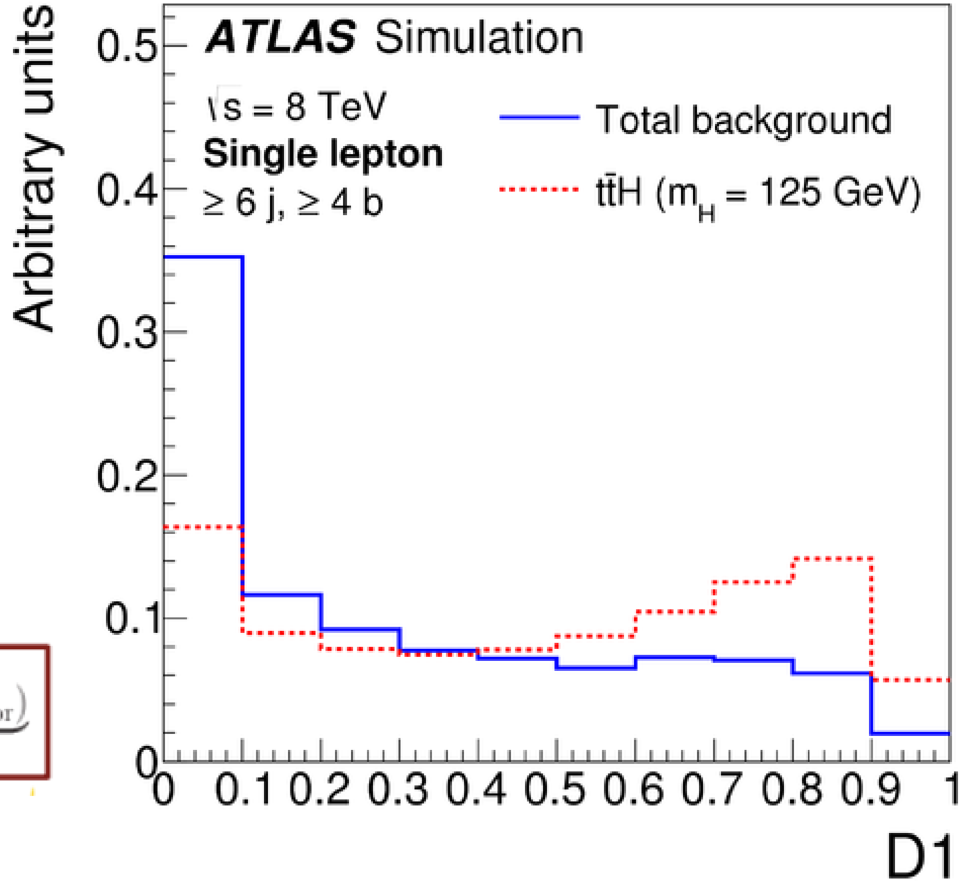


Matrix Element Method for 1-lepton

- 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, 6/4)



- Testing LO ME for $t\bar{t}+bb$ and $t\bar{t}H$ hypothesis:

$$\underbrace{P_{t\bar{t}H}\left(\vec{x}_{\text{Detector}}, m_H\right)}_{\text{probability}} = \underbrace{\frac{1}{\sigma_{t\bar{t}H}\left(m_H\right)}}_{\text{normalization}} \int \underbrace{\mathrm{d}p_{g1}\mathrm{d}p_{g2} f\left(p_{g1}\right) f\left(p_{g2}\right)}_{\text{parton density function}} \underbrace{\mathrm{d}\sigma_{t\bar{t}H}\left(\tilde{x}_{\text{Parton}}, m_H\right)}_{\text{differential cross section}} \underbrace{W\left(\vec{x}_{\text{Parton}}, \vec{x}_{\text{Detector}}\right)}_{\text{transfer functions}}$$

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

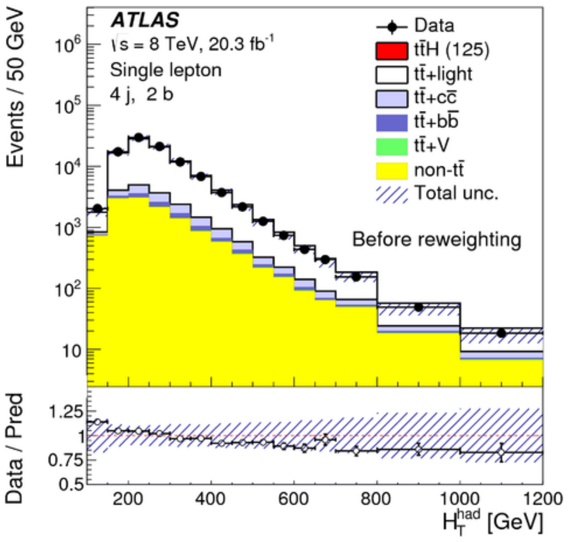
Each source of syst. uncert. represented by nuisance parameter:

Jet energy scale has 22 uncorrelated sources, with different pT, η dependence:

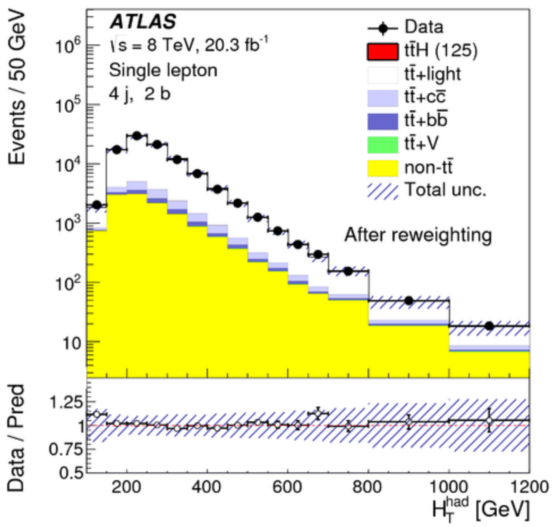
Largest arises from the η dependence of the JES calibration in the end-cap regions of the CALO, corrections for quark vs. gluon jets, b- vs. light-jets…

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

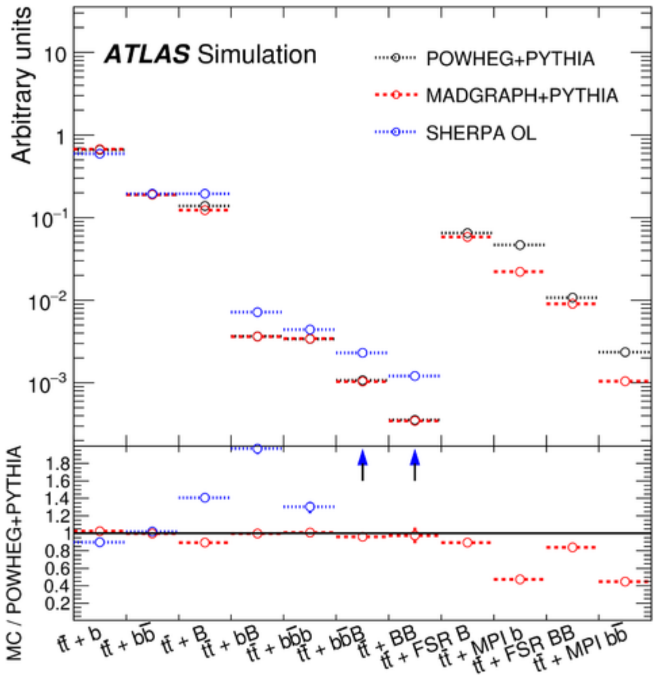
ttbar background studied in great detail



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.

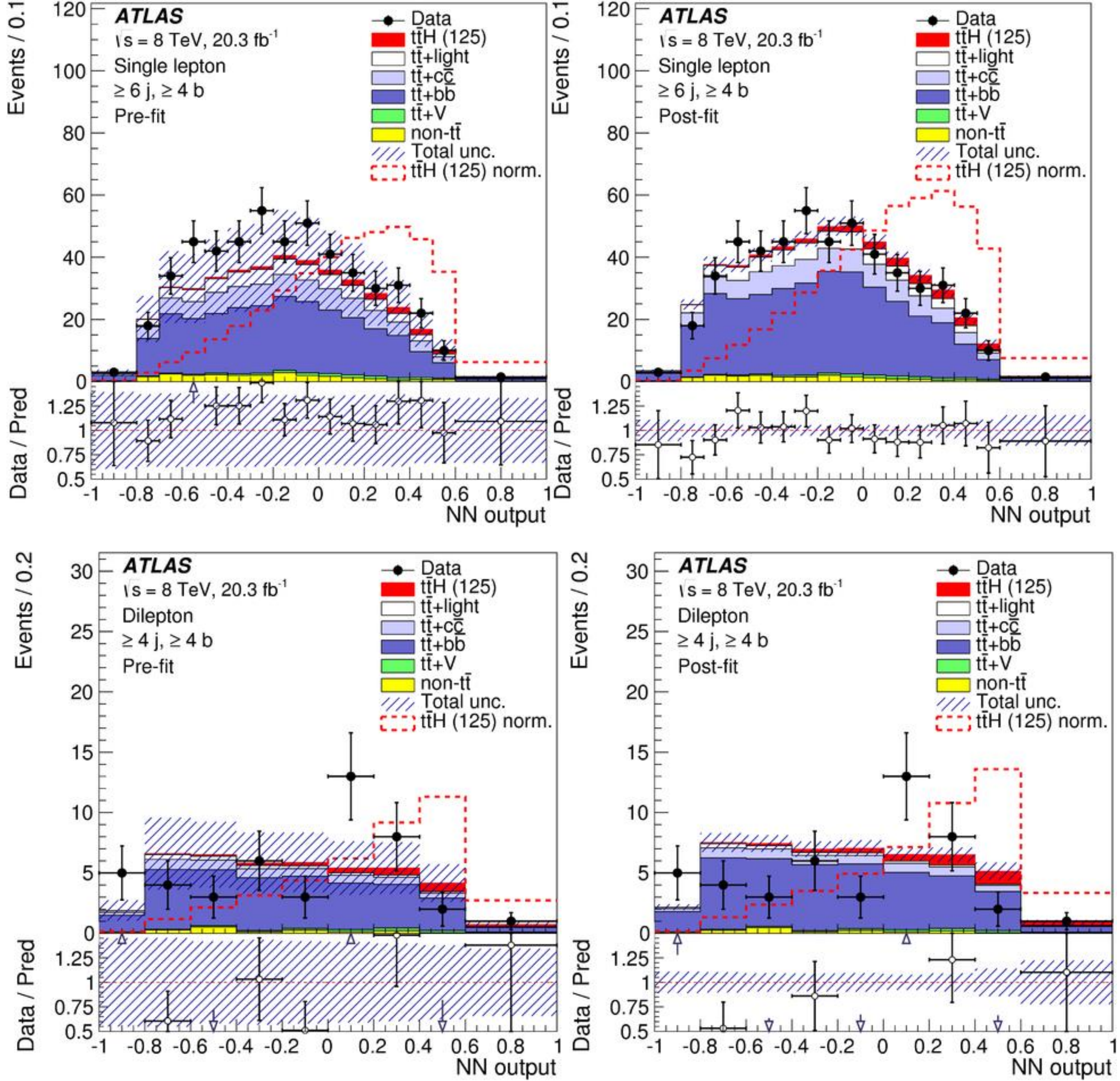
Compare various generators (LO, PS, NLO) – reweight nominal MC to SHERPA OpenLoops

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

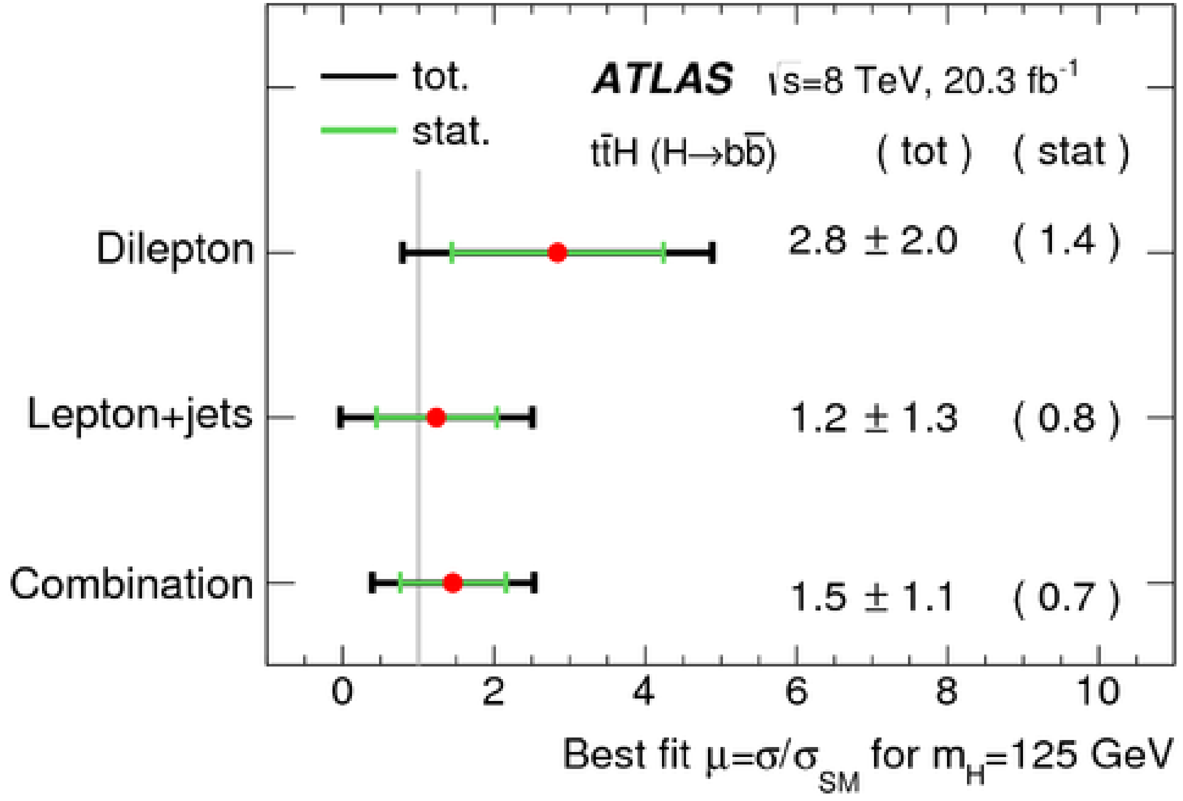
Pre-fit yields in dilepton bins

	≥ 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

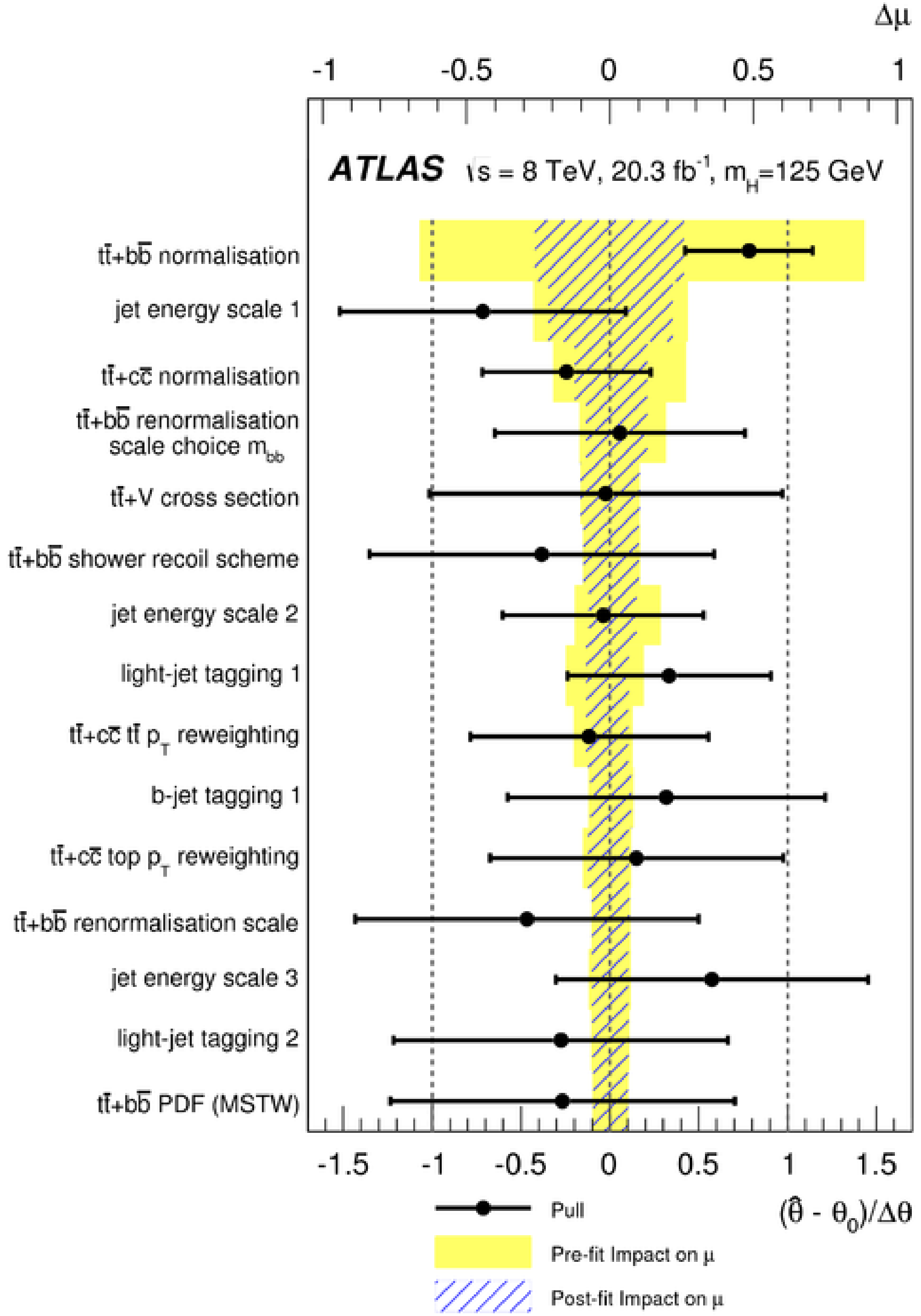
	≥ 4 j, 2 b	≥ 4 j, 3 b	≥ 4 j, ≥ 4 b
$t\bar{t}H$ (125)	22 ± 16	11 ± 8	3.1 ± 2.3
$t\bar{t}+$ light	4500 ± 150	100 ± 12	1.4 ± 0.3
$t\bar{t} + c\bar{c}$	740 ± 170	140 ± 30	4.8 ± 1.1
$t\bar{t} + b\bar{b}$	370 ± 59	230 ± 31	30 ± 4
Z+jets	100 ± 33	9.5 ± 3.1	0.4 ± 0.2
Single top	140 ± 23	11 ± 2	0.6 ± 0.1
Diboson	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

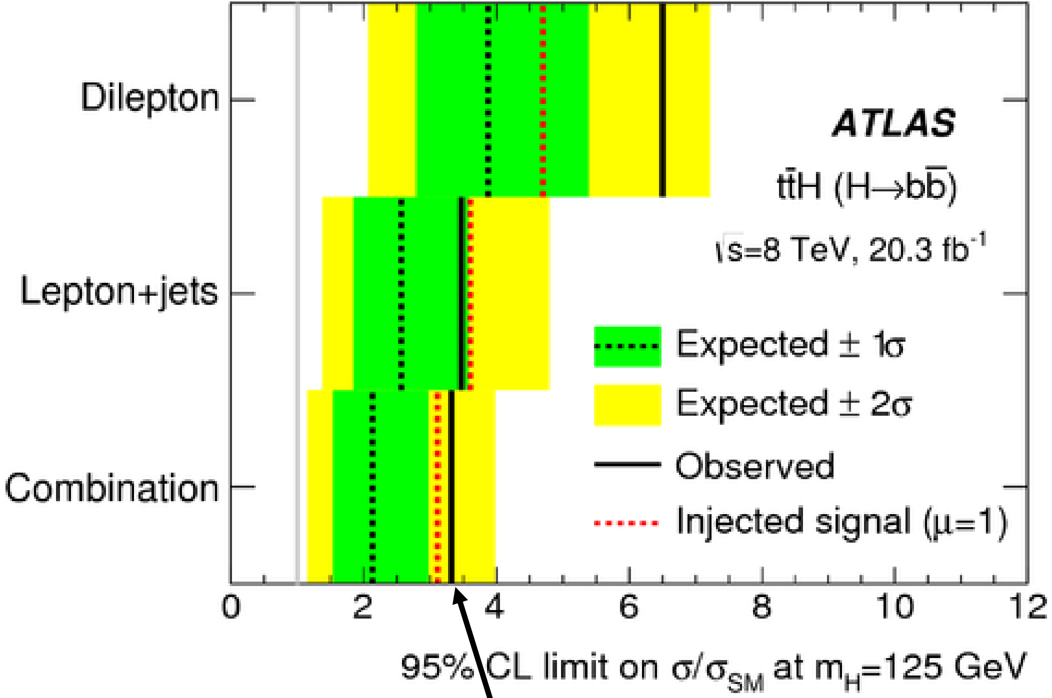


tot.
stat.
ATLAS √s=8 TeV, 20.3 fb⁻¹
tt̄H (H→bb̄) (tot) (stat)
Dilepton
2.8 ± 2.0 (1.4)
Lepton+jets
1.2 ± 1.3 (0.8)
Combination
1.5 ± 1.1 (0.7)
0 2 4 6 8 10
Best fit μ=σ/σ_SM for m_H=125 GeV

Results



Δμ
-1 -0.5 0 0.5 1
ATLAS √s = 8 TeV, 20.3 fb⁻¹, m_H=125 GeV
tt̄+bb̄ normalisation
jet energy scale 1
tt̄+cc̄ normalisation
tt̄+bb̄ renormalisation scale choice m_bb
tt̄+V cross section
tt̄+bb̄ shower recoil scheme
jet energy scale 2
light-jet tagging 1
tt̄+cc̄ tt̄ p_T reweighting
b-jet tagging 1
tt̄+cc̄ top p_T 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

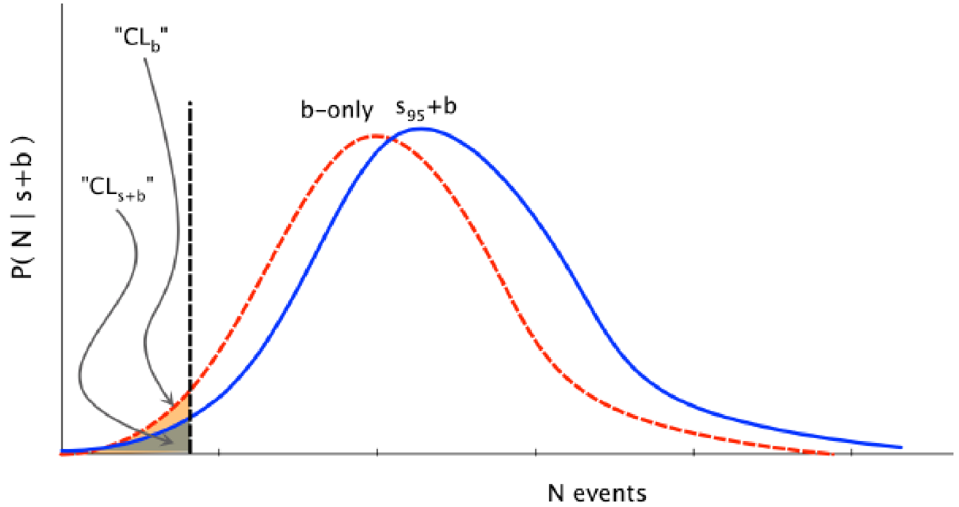


Assuming μ=0

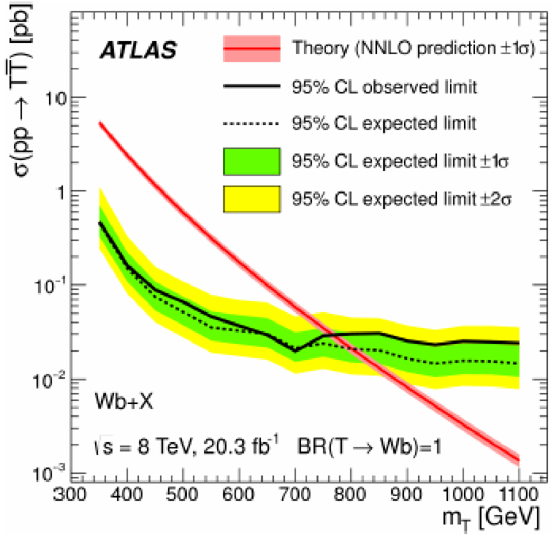
95% CL upper limit	Observed	-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median ($\mu = 1$)
Single lepton	3.6	1.4	1.9	2.6	3.7	4.9	3.6
Dilepton	6.7	2.2	3.0	4.1	5.8	7.7	4.7
Combination	3.4	1.2	1.6	2.2	3.0	4.1	3.1

Limit Setting

- Brief word on Limit Setting at LHC
- When looking for a tiny signal on top of background, worry to exclude signal due to a downward fluctuation



K. Cranmer: Statistics Lecture at HCP



- Using CL_{s+b}, one would expect to exclude the signal 5 % of the time

$$CL_s = CL_{s+b}/CL_b$$

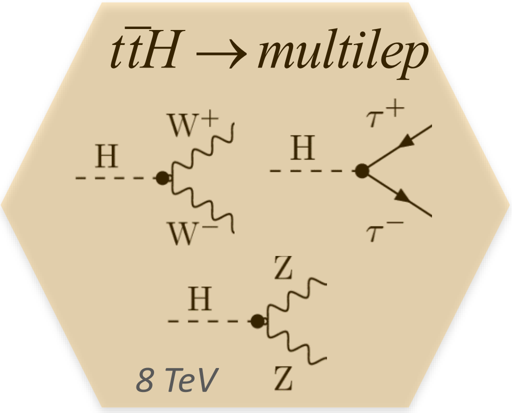
test signal hypothesis:

only exclude if $CL_s < 5$ %

- As a result, we use CL_s to test a signal hypothesis (*not a probability*).
- A downward fluctuation in s+b will not exclude signal since CL_b with also be small
- ***Over-conservative***

ttH→ multileptons

PLB 749, 519 (2015) – arxiv:1506.05988

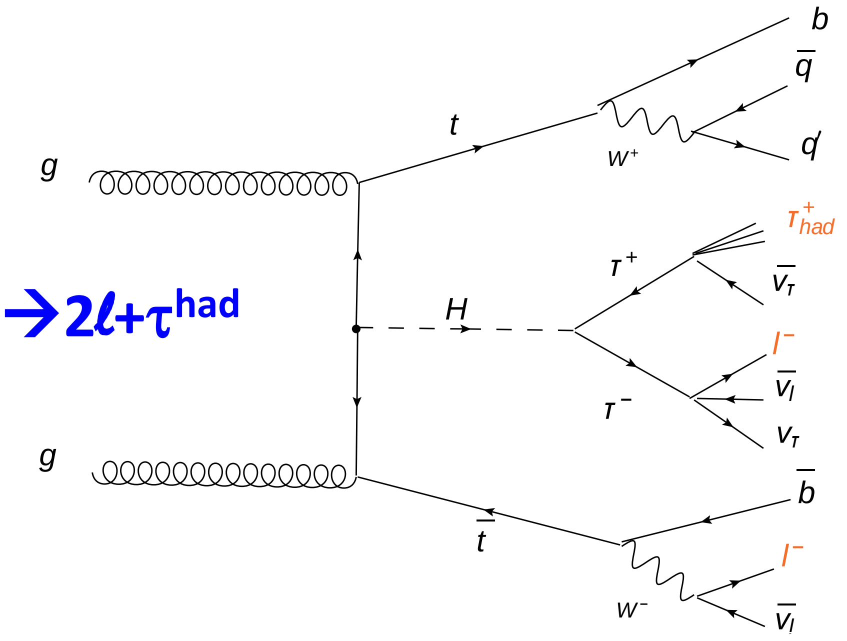


- Targets Higgs → WW*, ττ and ZZ* decays

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

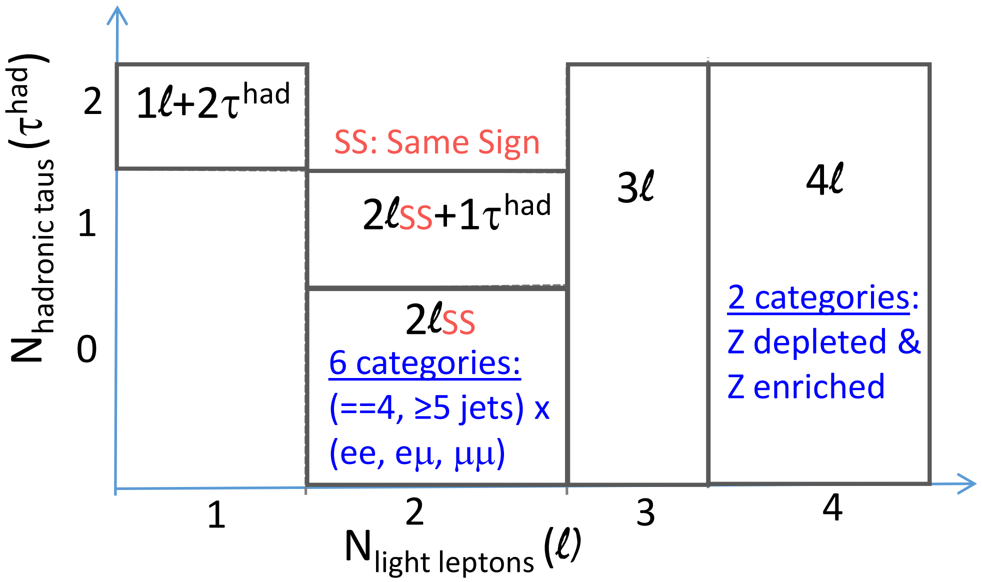
- Reject ttbar background with:
  - same sign di-leptons and/or $N_{lep} \geq 3$

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 bkgds

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

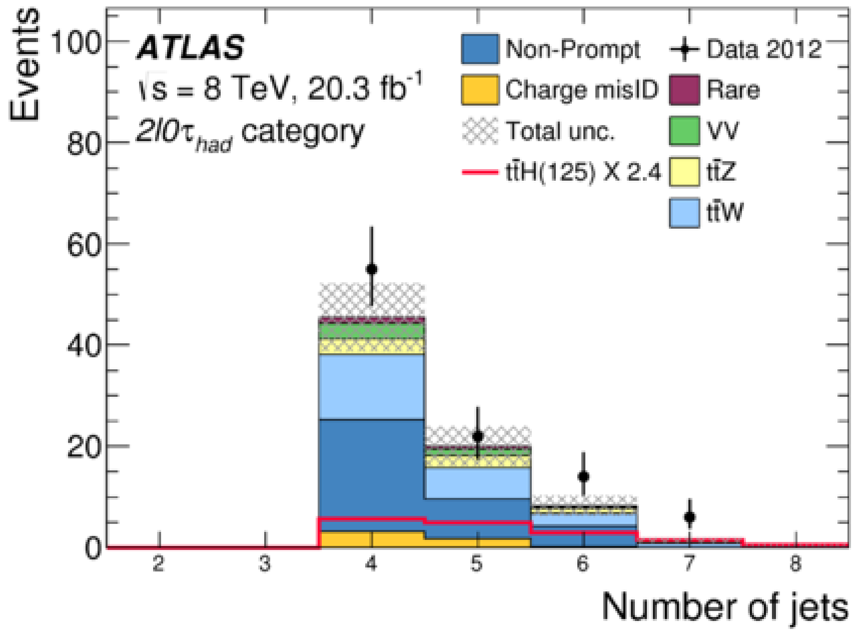
Search channels have been expanded to show individual sub-channels

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

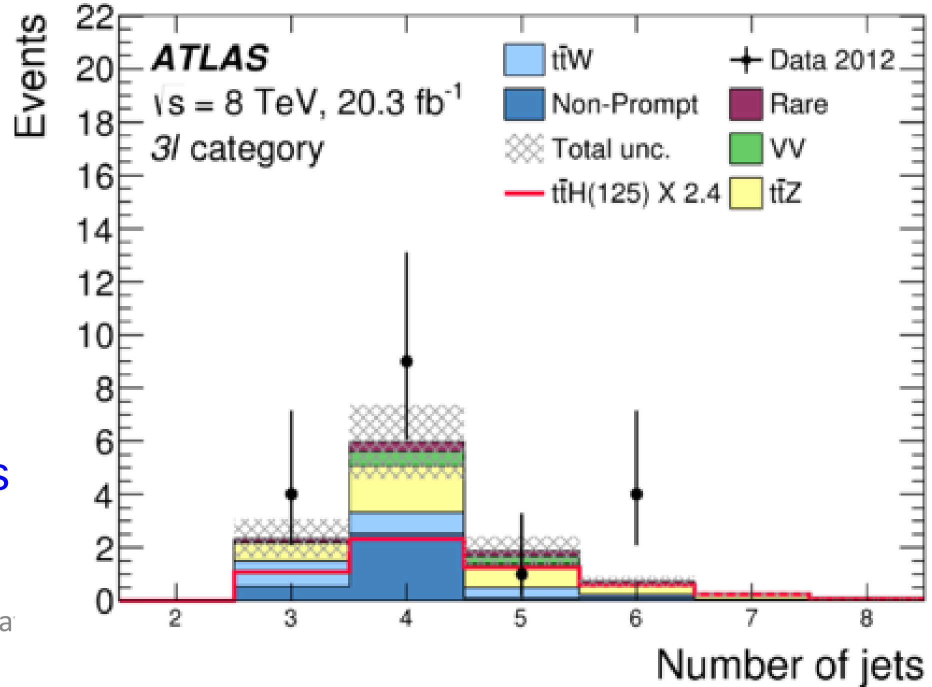


2(SS)leptons+0τ_{had}

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

Discriminant in Profile Likelihood Fit: # jets

3 leptons



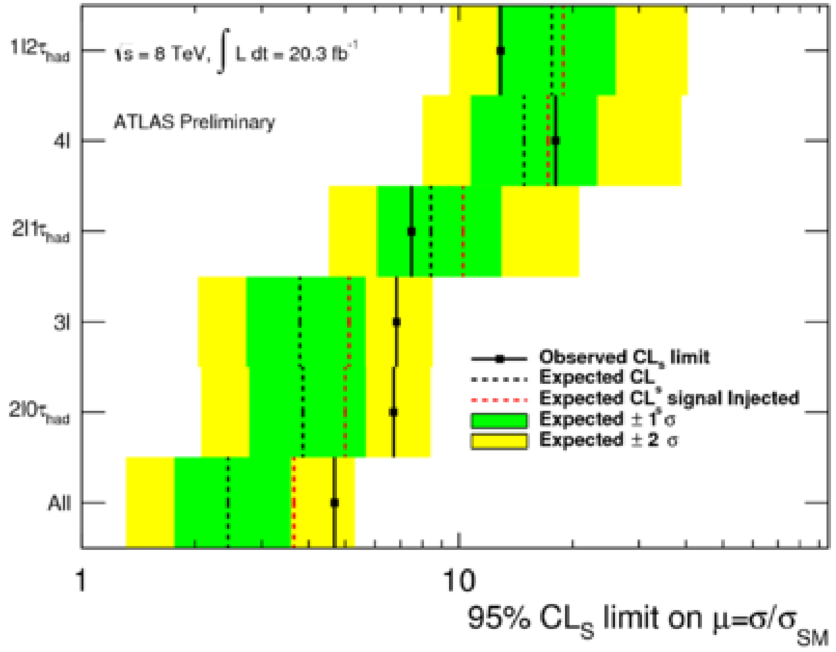
Systematic Uncertainties

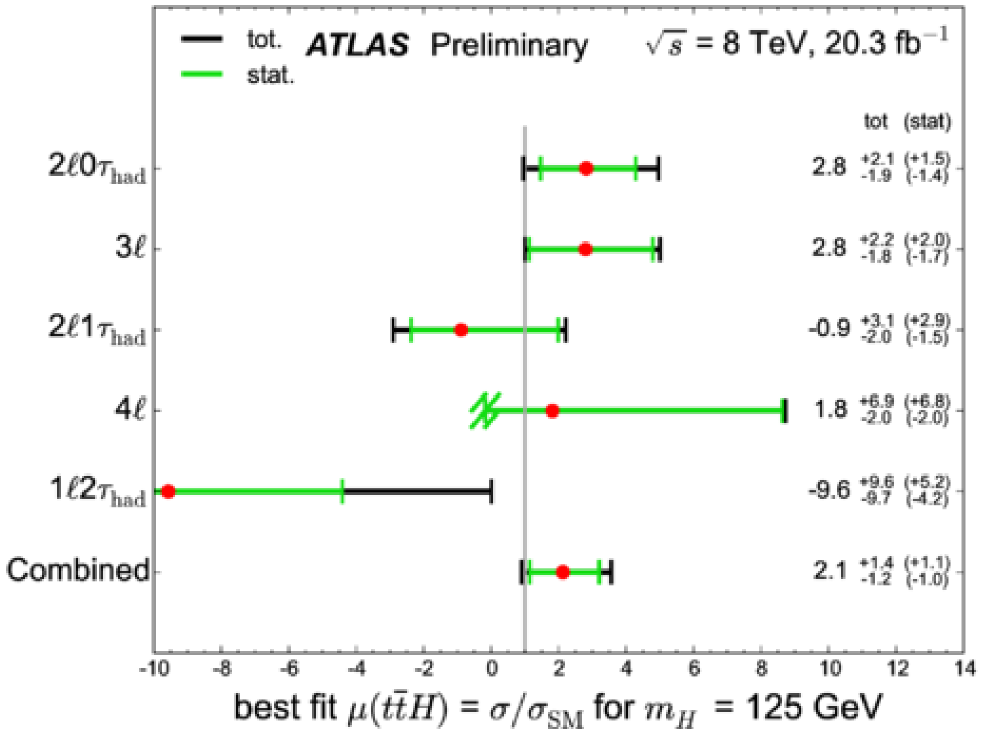
Table 3: Leading sources of systematic uncertainty and their impact on the measured value of μ.

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





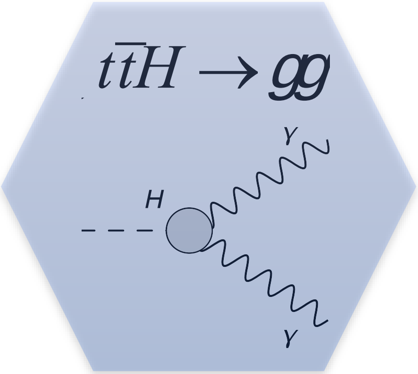
Combined result < 4.7

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.

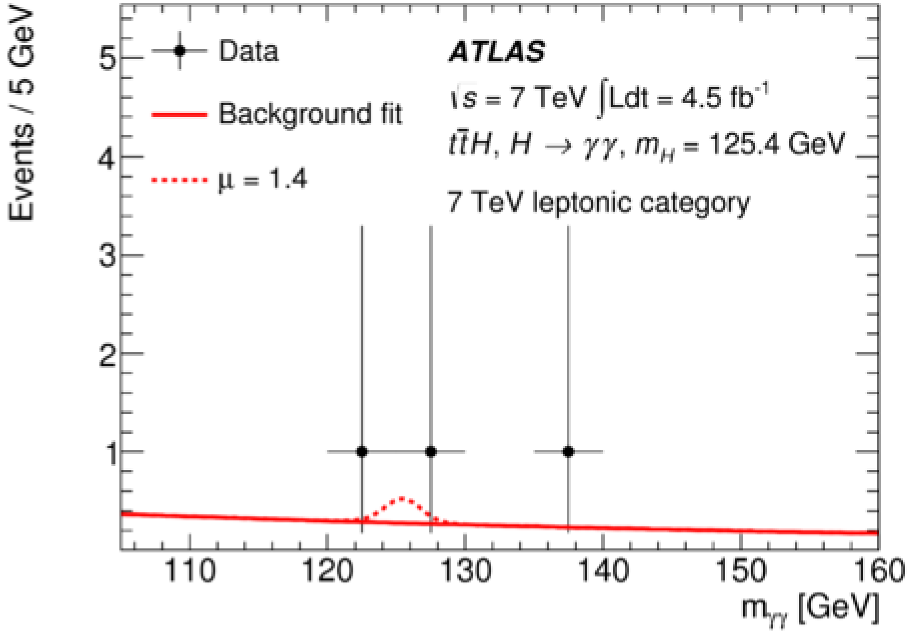
Channel	Observed Limit	Expected Limit					
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$	Median ($\mu = 1$)
$2\ell 0\tau_{\mathrm{had}}$	6.7	2.1	2.8	3.9	5.7	8.4	5.0
3ℓ	6.8	2.0	2.7	3.8	5.7	8.5	5.1
$2\ell 1\tau_{\mathrm{had}}$	7.5	4.5	6.1	8.4	13	21	10
4ℓ	18	8.0	11	15	23	39	17
$1\ell 2\tau_{\mathrm{had}}$	13	10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

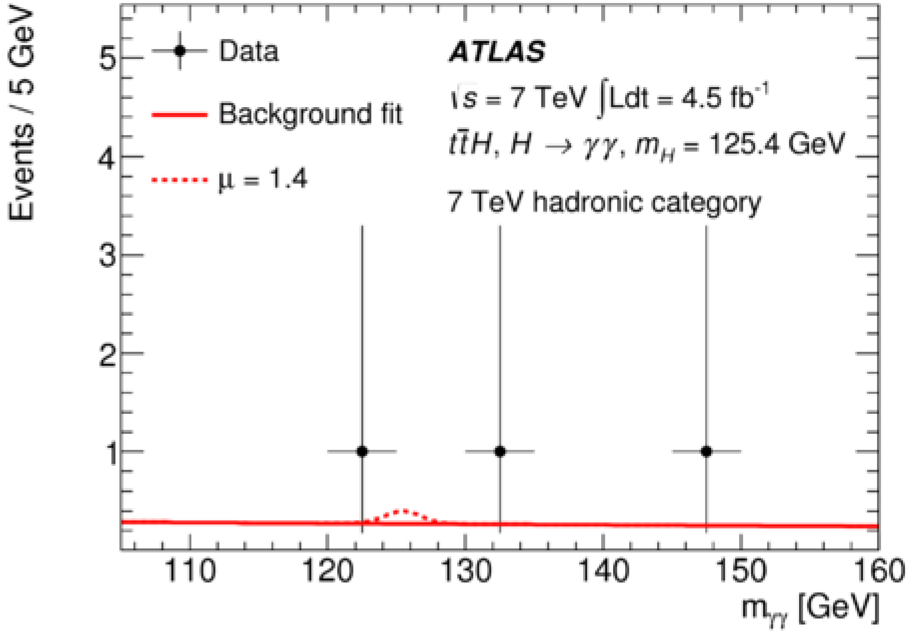
Higgs → γγ

PLB 740, 222 (2015) – [arXiv:1409.3122]

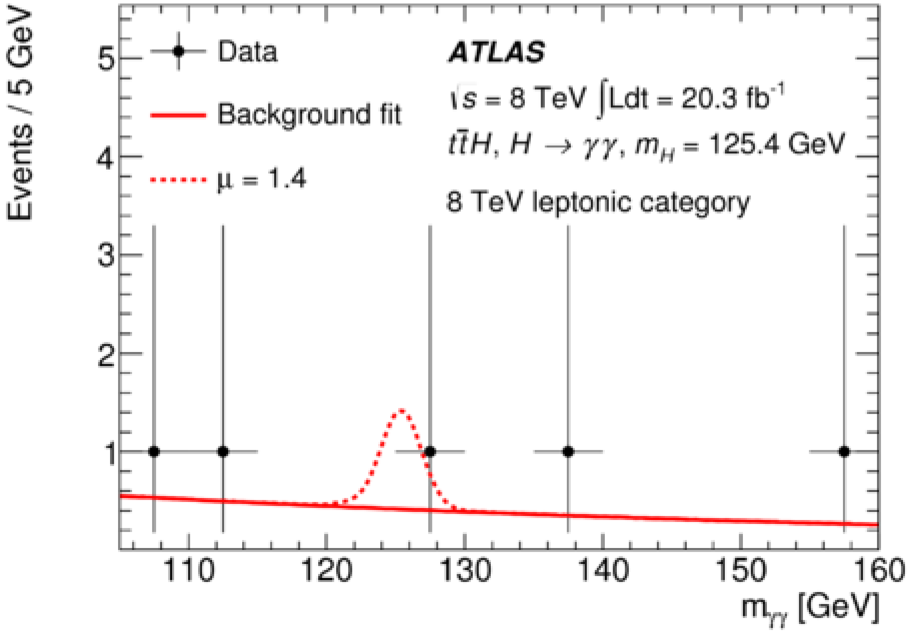


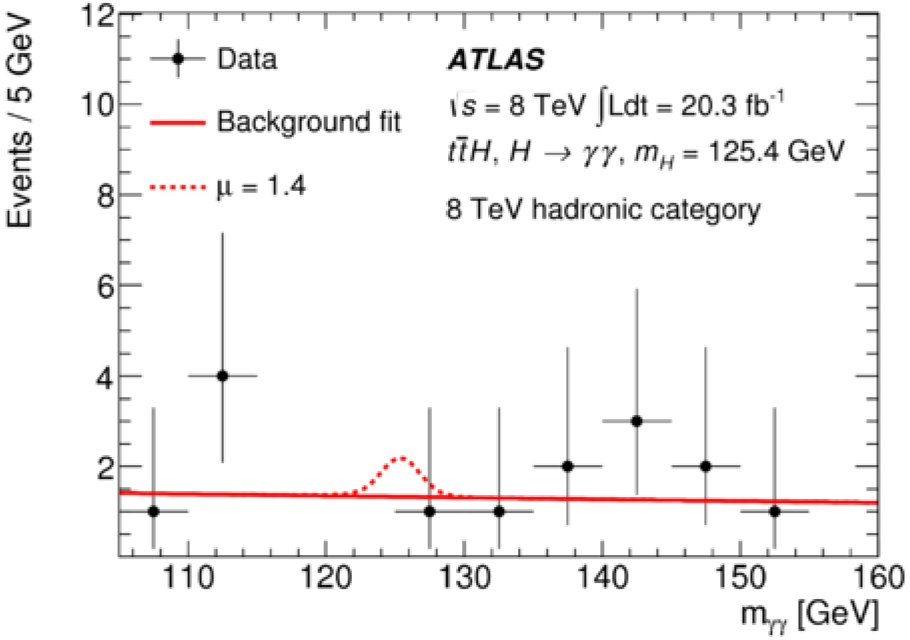
- Analysis strategy:
  - Fit sideband (in Mγγ) for background under peak
  - Background shape validated in control regions
- Classify events depending on ttbar decay:
  - Semi-leptonic + dileptonic (decay of top pair)
  - Cuts for the leptonic states are loose enough to retain high efficiency for tH final state:
    - ≥ 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





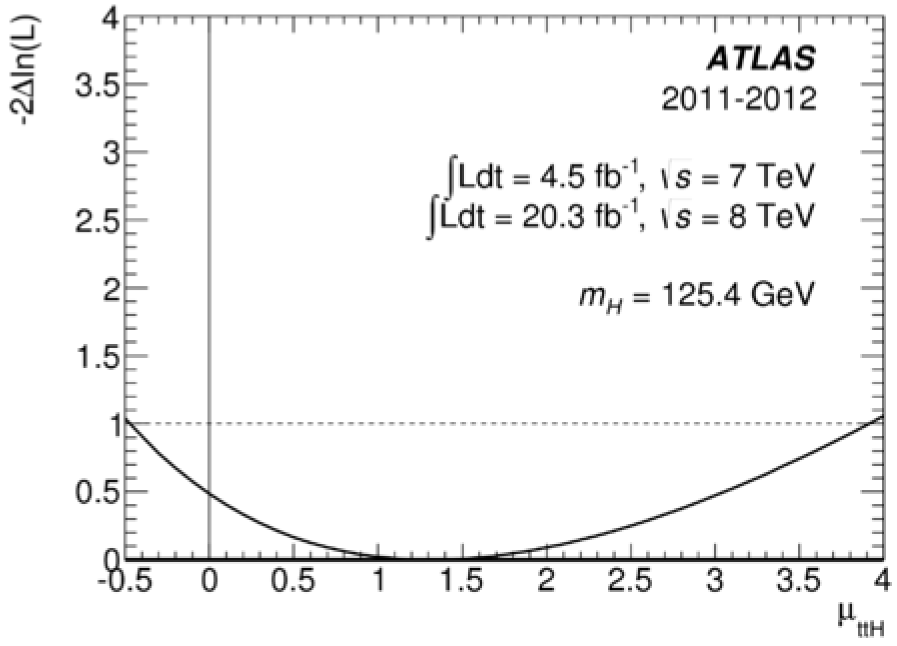
Expected number of events
for M_H = 125.4 GeV
after event selection – **Total = 1.3**

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



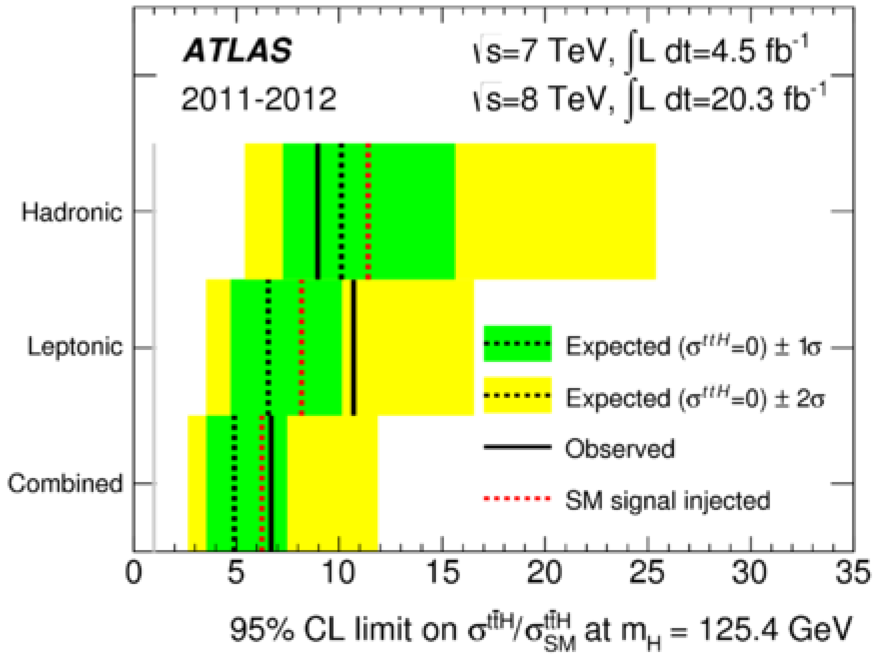
Negative log-likelihood scan for the $\sigma(t\bar{t}H)\times BR(H \to \gamma\gamma)$ relative to SM value, at m_H = 125.4 GeV, where all other Higgs boson prod. σ, including tH prod., are set to their respective SM expectations:

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

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

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

Combined result < 6.7

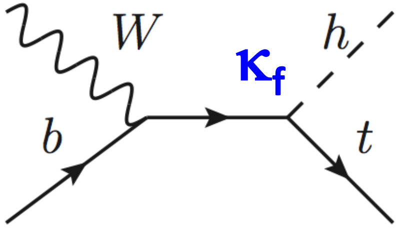


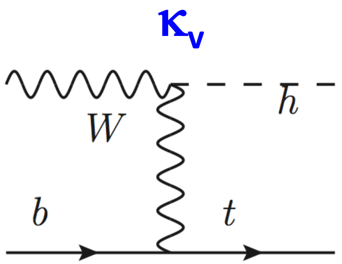
Limits on $\sigma(t\bar{t}H) \times BR(H \to \gamma\gamma)$ – all other processes assumed to have SM values

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





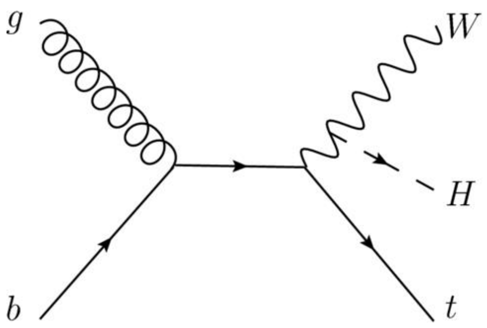
$K_i = 1 \Rightarrow$ SM

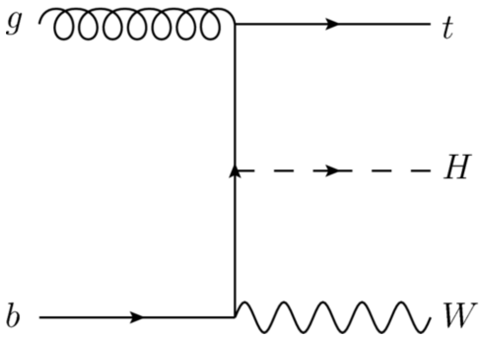
Large (destructive) interference between them, e.g.,

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

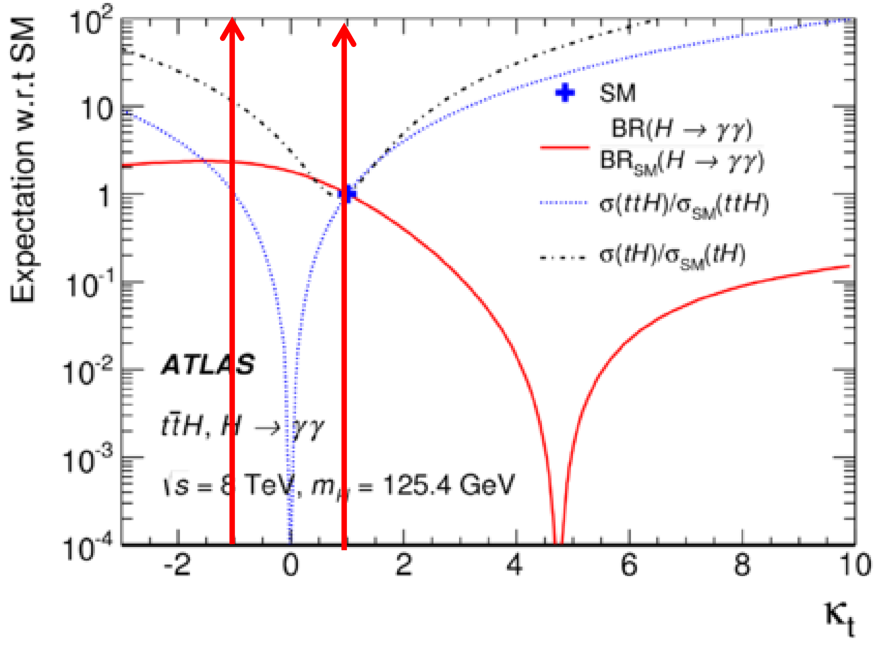
If relative sign of the two **κ** factors is -1, cross-section will be larger than SM

Similarly for **$\sigma(gb \to WtH)$**

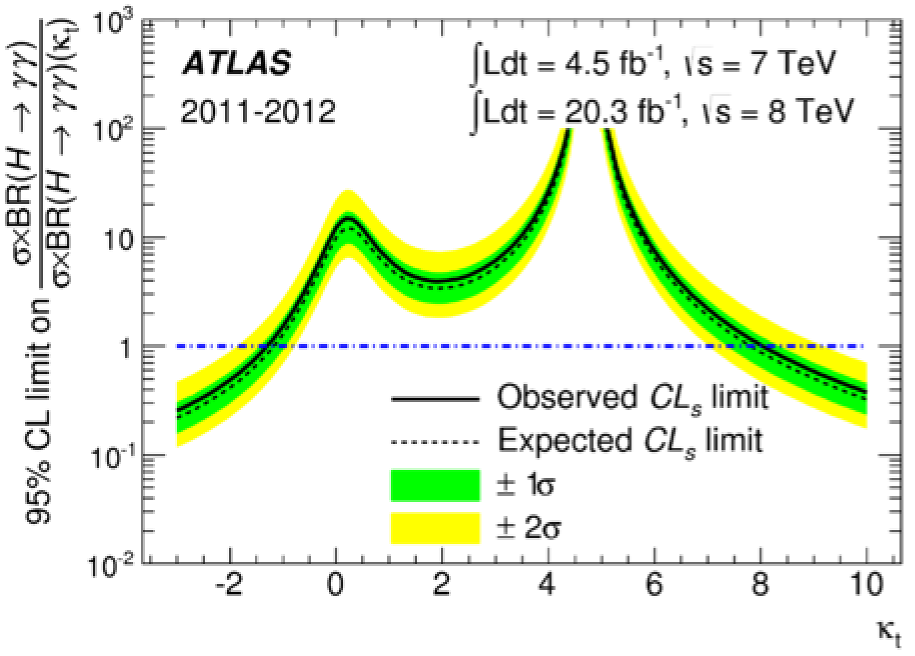




Information on K_t (= Y_t (meas)/Y_t(SM))



From $\gamma\gamma$ results



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

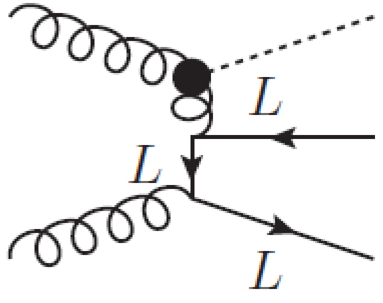
−1.3 and +8.0 (−1.2 and+7.8)

Combining all Higgs results

- For discussion, I will use ATLAS only results (arXiv:1507.04548)
  - Preliminary ATLAS/CMS combination (ATLAS-CONF-2015-044) - mention at end

- 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 proces
    - Earlier I showed you the strategy for Higgs → γγ
  - Many different ways to do these fits
    - Depends on what assumptions and what models are being tested



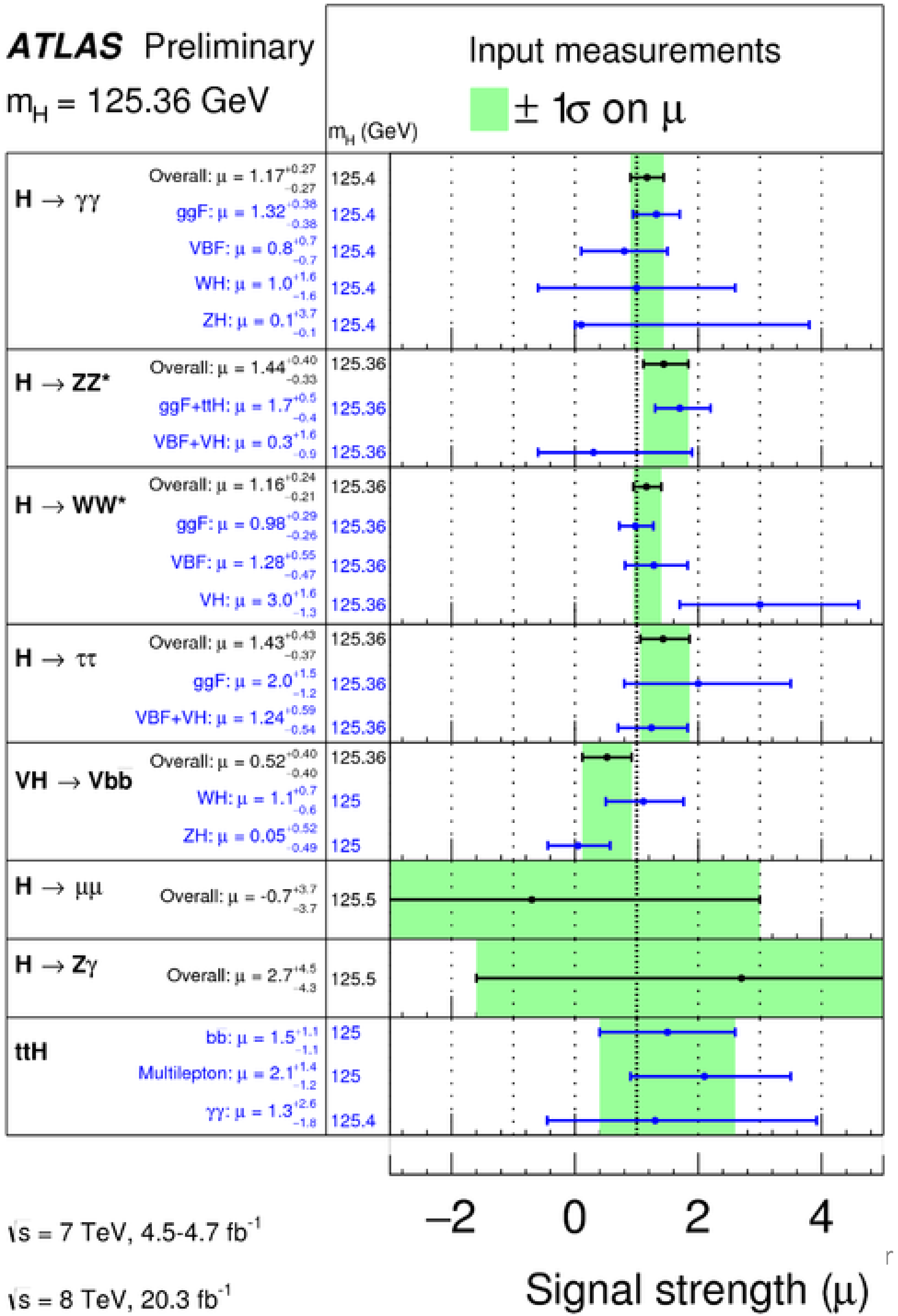
Analysis	Signal		$\int \mathcal{L}dt$ (fb^{-1})	
Categorisation or final states	Strength	Significance [σ]	7 TeV	8 TeV
$H \to \gamma\gamma$ [12]	1.17 ± 0.27	5.2 (4.6)	4.5	20.3
ttH: leptonic, hadronic			✓	✓
VH: one-lepton, dilepton, E_T^{miss}, hadronic			✓	✓
VBF: tight, loose			✓	✓
ggF: 4 p_{Tt} categories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



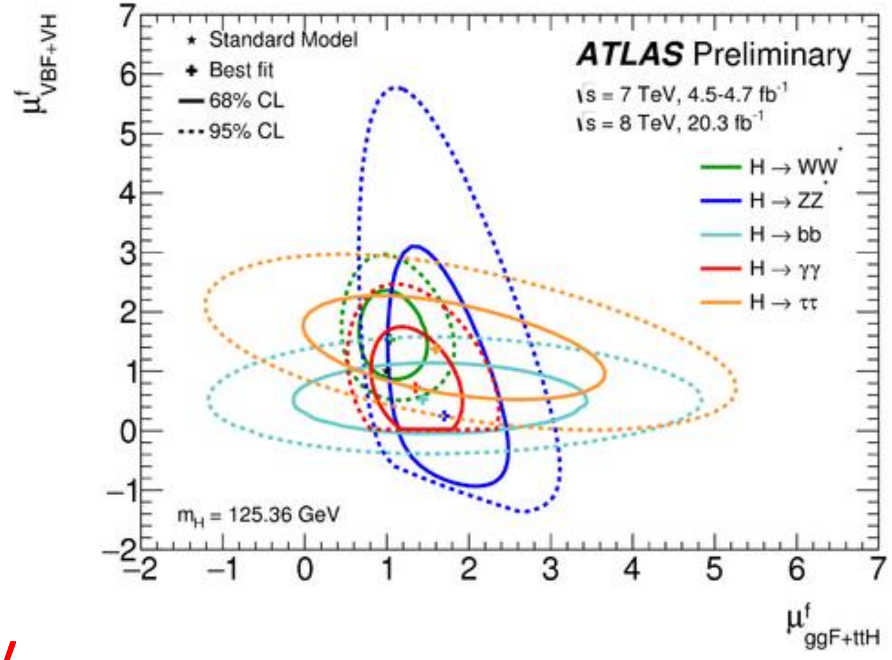
Summary of signal-strength measurements from individual analyses. Higgs boson mass column indicates the m_H value at which the result is quoted.

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

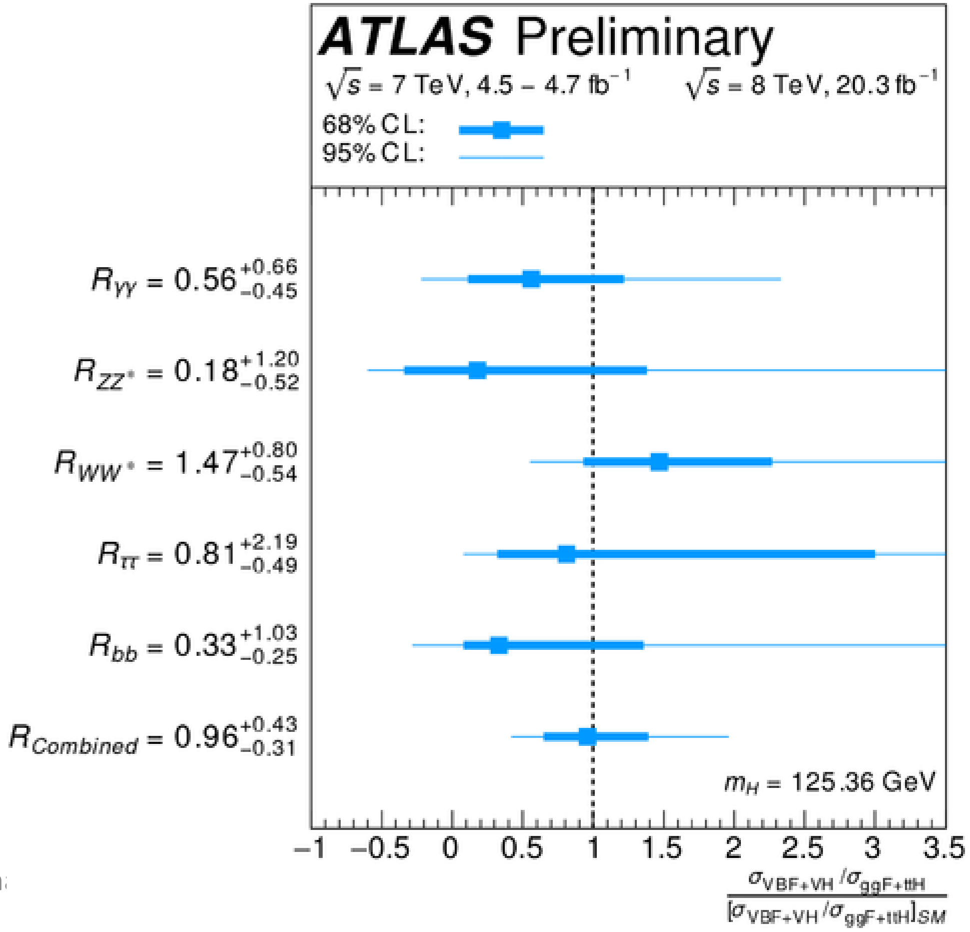
ATLAS only

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

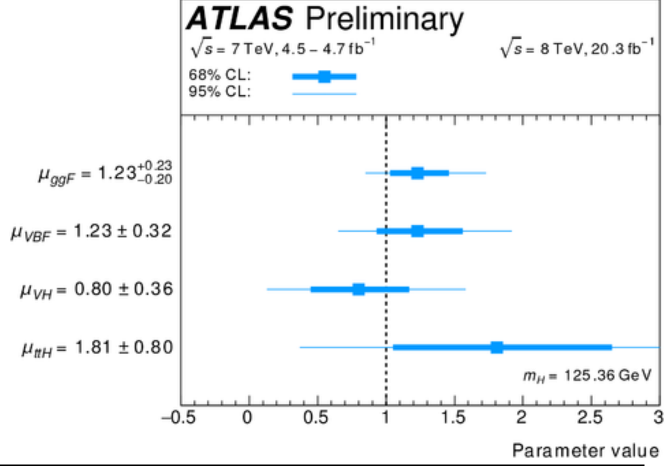
ATLAS only



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

ATLAS only

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 μ_{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

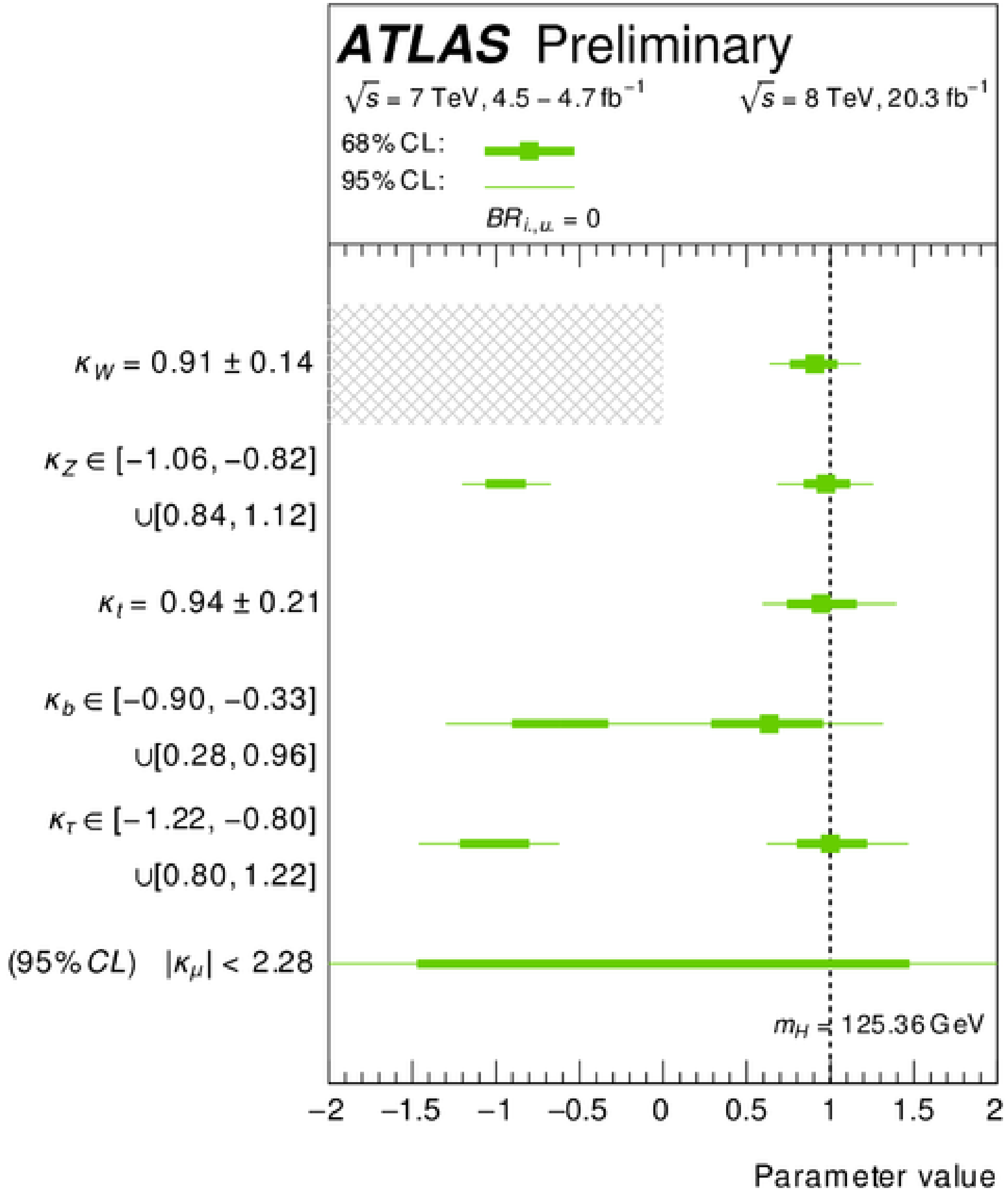
Will show one result (Generic Model 1)

Generic Model 1

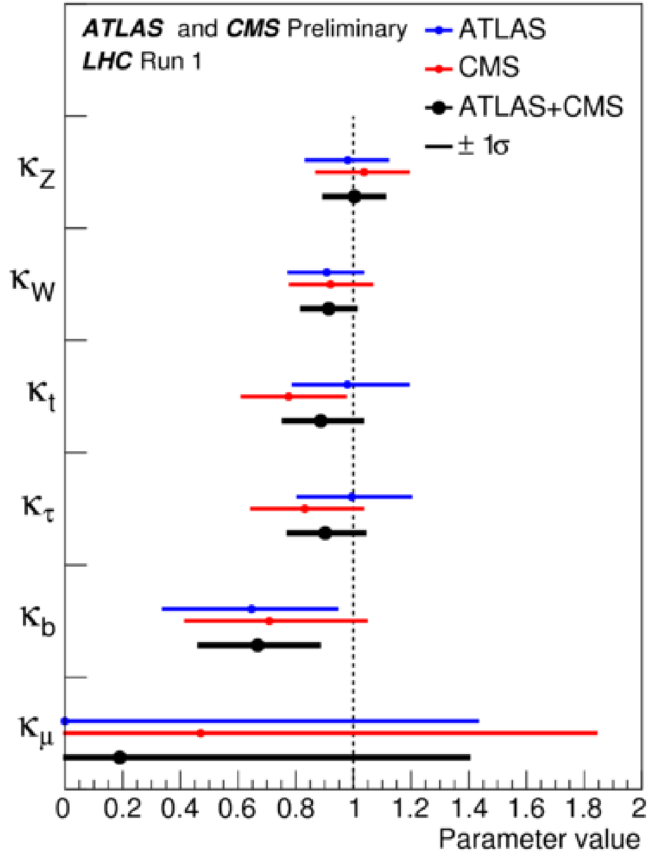
Due to the interference terms, fit is sensitive to relative sign between W & t couplings (via tH, H→γγ, H → Zγ)

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

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



ATLAS+CMS
Assuming BR_{BSM}=0,
and $\kappa_j \geq 0$



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); $\mu = 2.1^{+1.4}_{-1.2}$

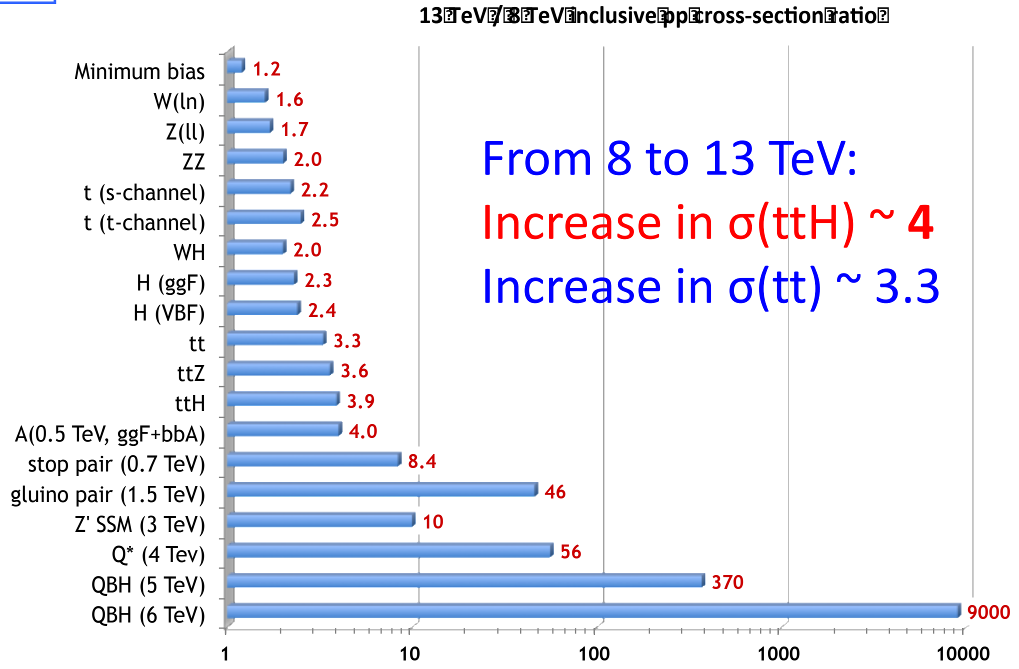
All consistent with Standard Model

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

CMS (μ=2.8±1.0)

➢ 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

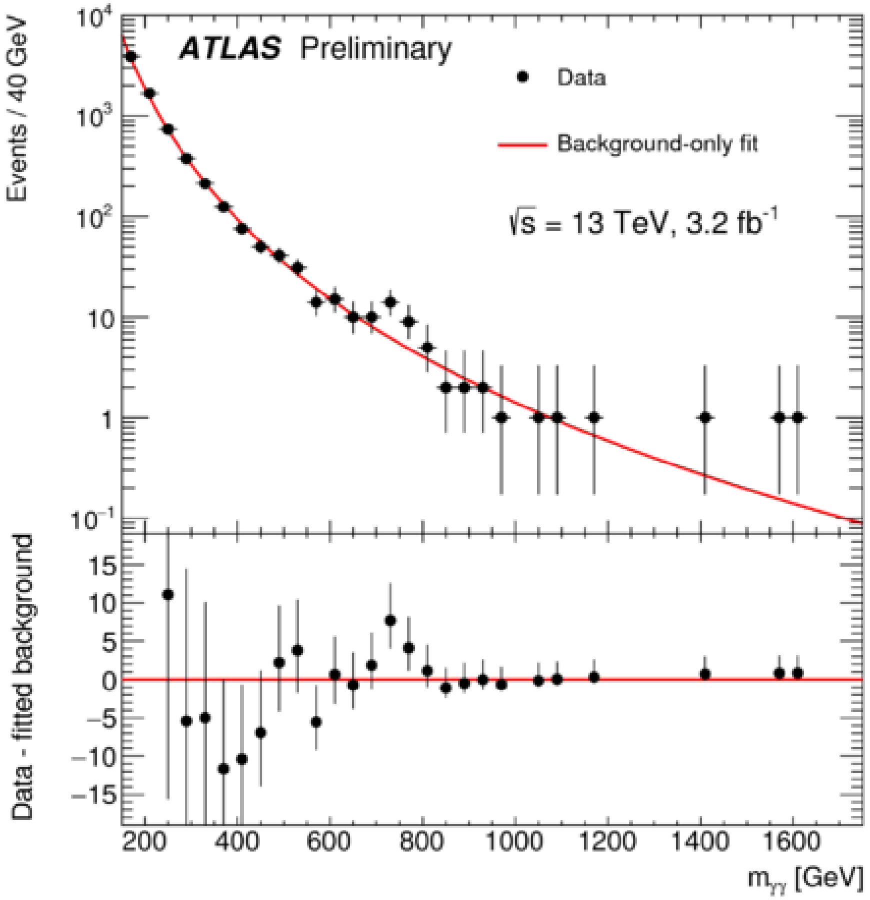
Sen

Channel	References for individual publications		Signal strength [μ]		Signal significance [σ]	
			from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[51]	[52]	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.24}_{-0.22}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[53]	[54]	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			$\left(^{+0.33}_{-0.27}\right)$	$\left(^{+0.31}_{-0.26}\right)$	(5.5)	(6.8)
$H \to WW$	[55,56]	[57]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[58]	[59]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[38]	[39]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[60]	[61]	-0.7 ± 3.6	0.8 ± 3.5		
			(± 3.6)	(± 3.5)		
ttH production	[28,62,63]	[65]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.72}_{-0.66}\right)$	$\left(^{+0.88}_{-0.80}\right)$	(1.6)	(1.3)

Backup

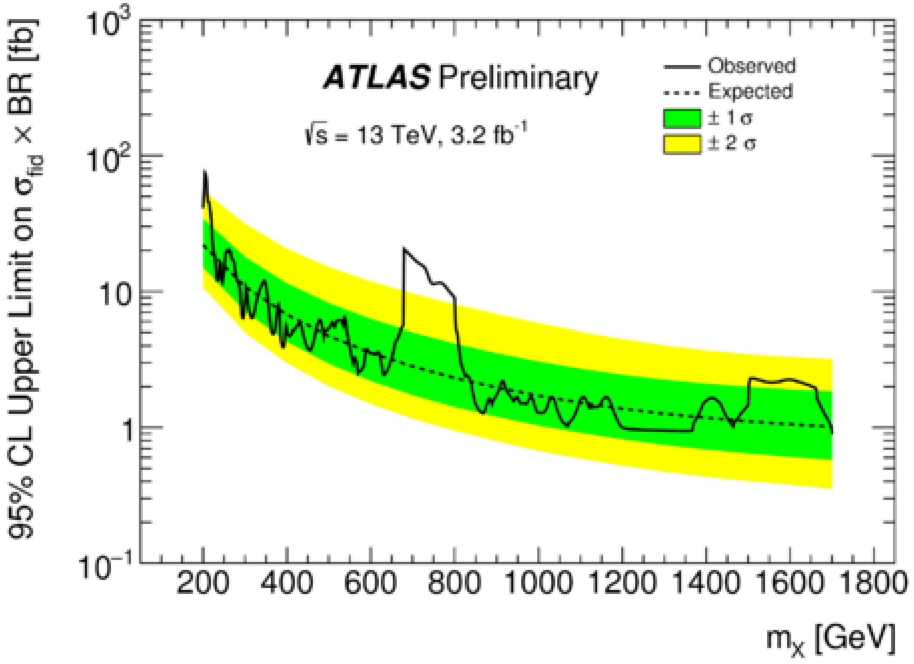
γγ resonances

ATLAS-CONF-2015-081

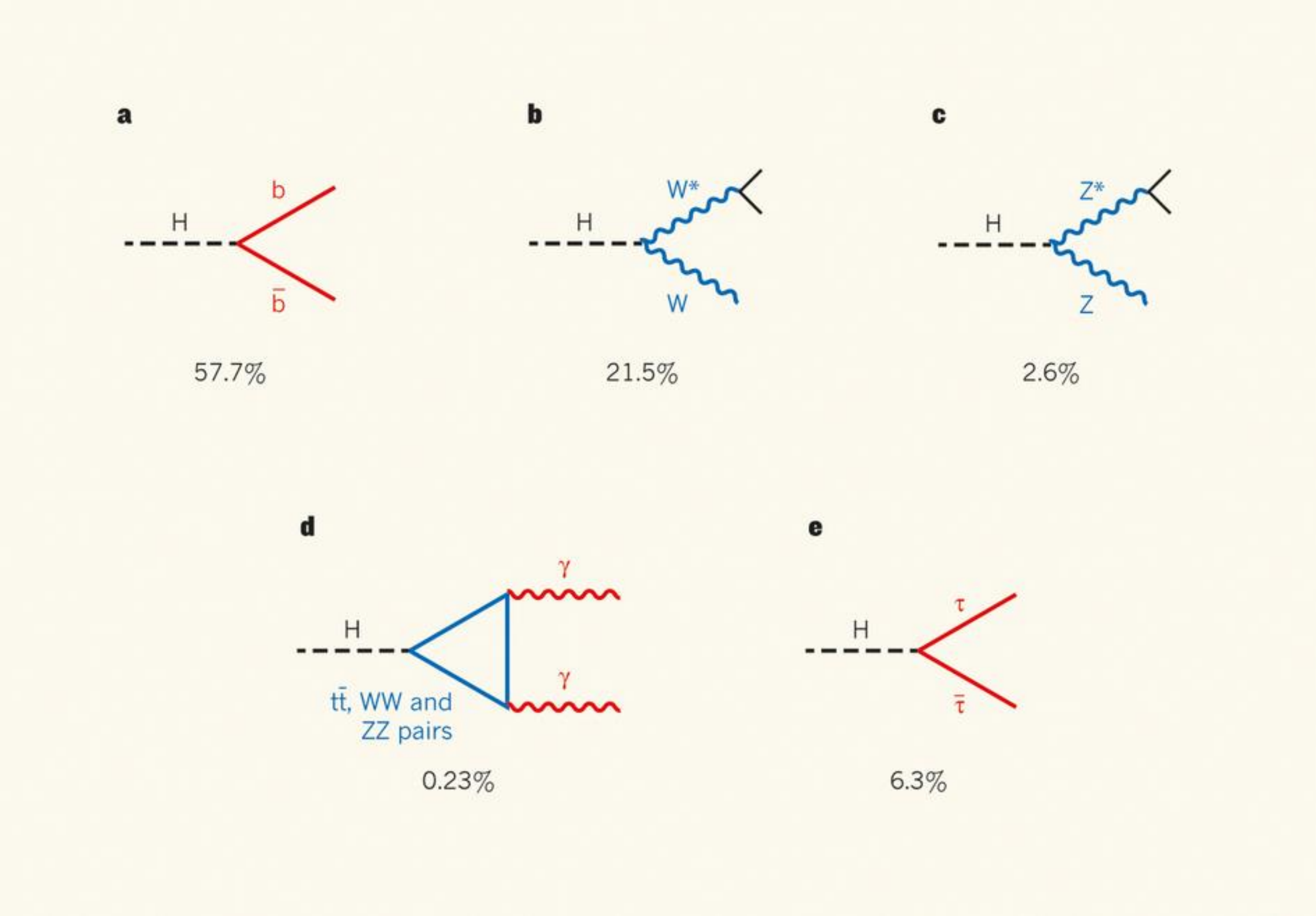


Search optimized for high mass γγ pairs

Both narrow & large width scalars studied

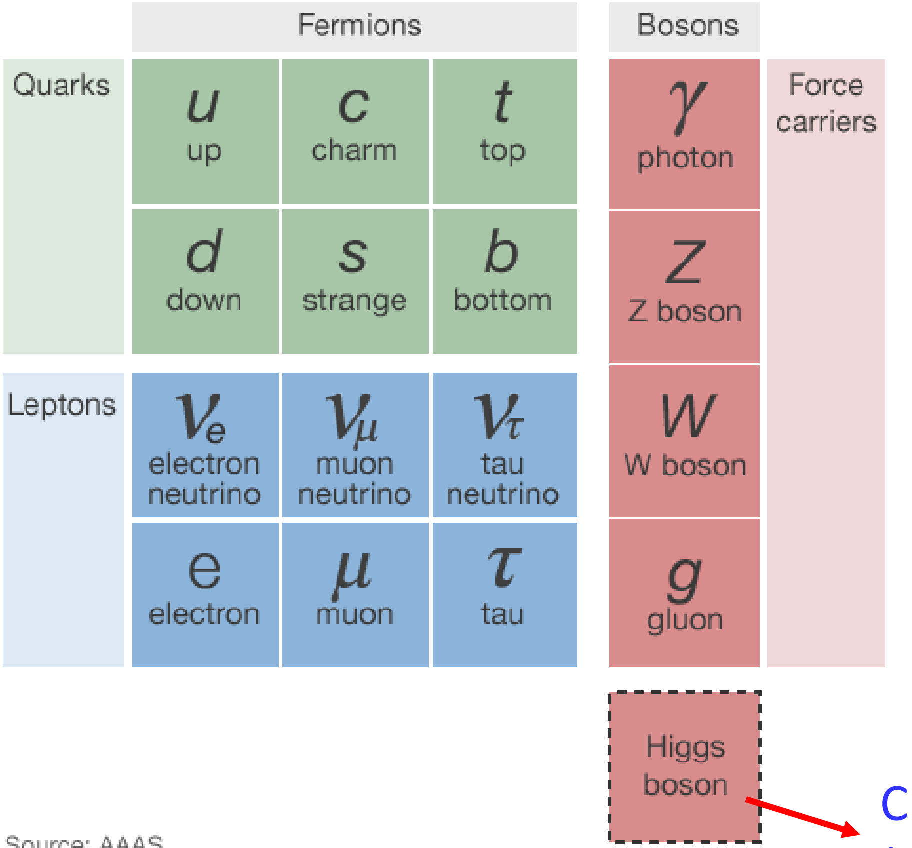


2.0σ (global) excess ~ 750 GeV
Smaller excess at 1.6 TeV



M_H (125)

Higgs boson



Source: AAAS

The new periodic table

Crucial for the Standard Model – gives mass to all particles
(there were/are(?) alternative theories that do not need the Higgs boson)

Variable	Definition	NN rank			
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b	5j, 3b
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_{T} divided by sum of the E for all jets and the lepton	2	2	1	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	p_{T} of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	4	3	2	-
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs	5	6	5	-
SSLL	Logarithm of the summed signal likelihoods (Eq. (2))	6	4	-	-
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	8	8	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	9	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$\mathrm{Aplan}_{\mathrm{b-jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor[92] built with only b-tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_{\mathrm{T}} \geq 40GeV$	-	1	3	-
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}	-	-	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_{T}	-	-	-	1
$p_{\mathrm{T,uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Scalar sum of the p_{T} of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}	-	-	-	7

H(bb)
Single L

H(bb) - dileptons

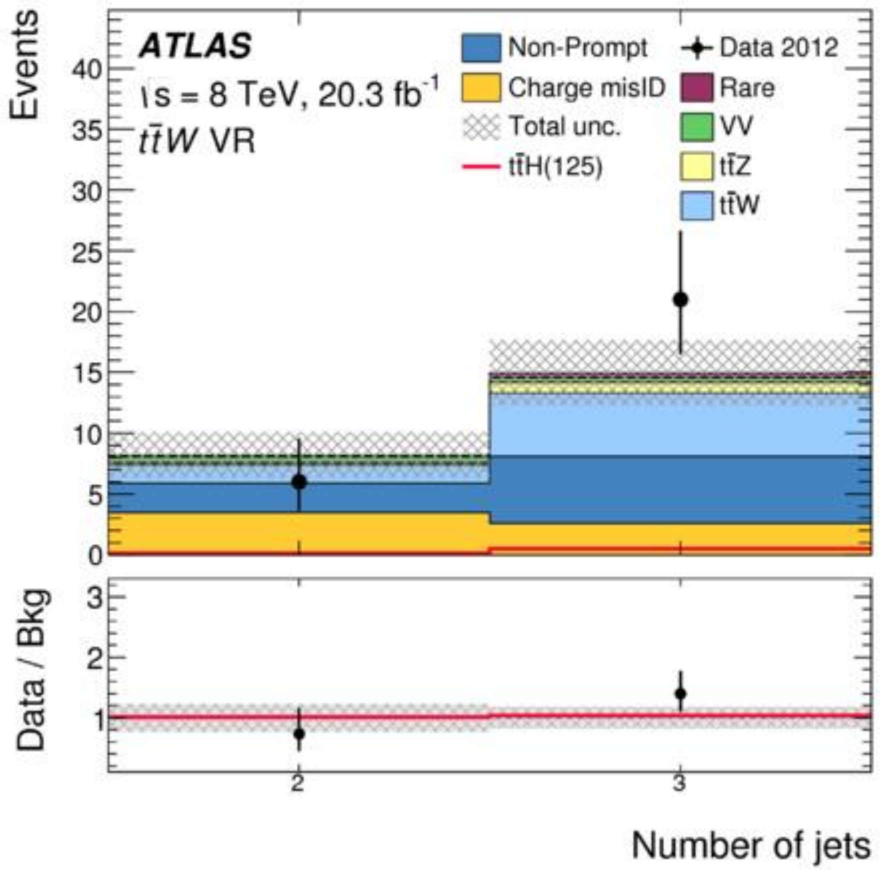
Variable	Definition	NN rank		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
$\Delta\eta_{jj}^{max\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event	1	1	1
$m_{bb}^{min\ \Delta R}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	2	8	-
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system	3	-	-
$\Delta R_{hl}^{min\ \Delta R}$	ΔR between the Higgs candidate and the closest lepton	4	5	-
N_{30}^{Higgs}	Number of Higgs candidates within 30 GeV of the Higgs mass of 125 GeV	5	2	5
$\Delta R_{bb}^{max\ p_T}$	ΔR between the two b-tagged jets with the largest vector sum p_T	6	4	8
Aplan_{jet}	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	7	7	-
$m_{jj}^{min\ m}$	Minimum dijet mass between any two jets	8	3	2
$\Delta R_{hl}^{max\ \Delta R}$	ΔR between the Higgs candidate and the furthest lepton	9	-	-
$m_{jj}^{closest}$	Dijet mass between any two jets closest to the Higgs mass of 125 GeV	10	-	10
H_T	Scalar sum of jet p_T and lepton p_T values	-	6	3
$\Delta R_{bb}^{max\ m}$	ΔR between the two b-tagged jets with the largest invariant mass	-	9	-
$\Delta R_{lj}^{min\ \Delta R}$	Minimum ΔR between any lepton and jet	-	10	-
Centrality	Sum of the p_T divided by sum of the E for all jets and both leptons	-	-	7
$m_{jj}^{max\ p_T}$	Mass of the combination of any two jets with the largest vector sum p_T	-	-	9
$H4$	Fifth Fox–Wolfram moment computed using all jets and both leptons	-	-	4
p_T^{jet3}	p_T of the third leading jet	-	-	6

Yields in CMS and ATLAS

Publicly available numbers for ttH shown at the Collider Cross Talk

Semi-Lep	4 jets / 4 b-tags			5 jets / 4 b-tags			6 jets / 4 b-tags		
	CMS	ATLAS	Diff. (%)	CMS	ATLAS	Diff. (%)	CMS	ATLAS	Diff. (%)
ttH	1.8	1.8	0	5.2	5.8	-10	8.3	16	-48
tt+light	74	55	35	79	67	18	71	67	6
tt+cc	19	23	-17	32	47	-32	52	80	-35
tt+bb	34.1	43	-21	67	110	-39	111	240	-54

Di-Lep	≥ 3 jets / ≥ 3 b-tags			3 jets / 3 b-tags	4 jets / 3 b-tags	4 jets / 4 b-tags
	CMS	ATLAS	Diff. (%)	ATLAS	ATLAS	ATLAS
ttH	11.2	12.8	-13	2	8.3	2.5
tt+light	289	244.6	18.2	105	138	1.6
tt+cc	147	195	-25	70	120	5
tt+bb	229	309	-26	100	180	29



Higgs to multi-leptons:

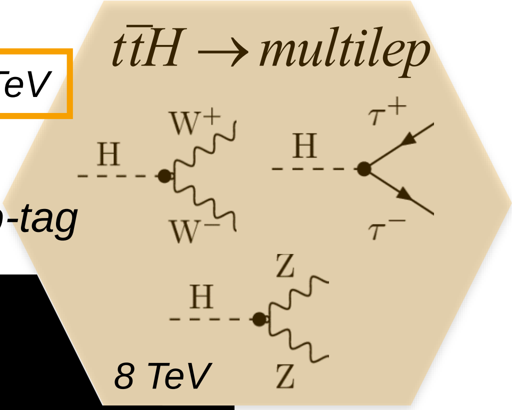
Control region to get handle on ttW:

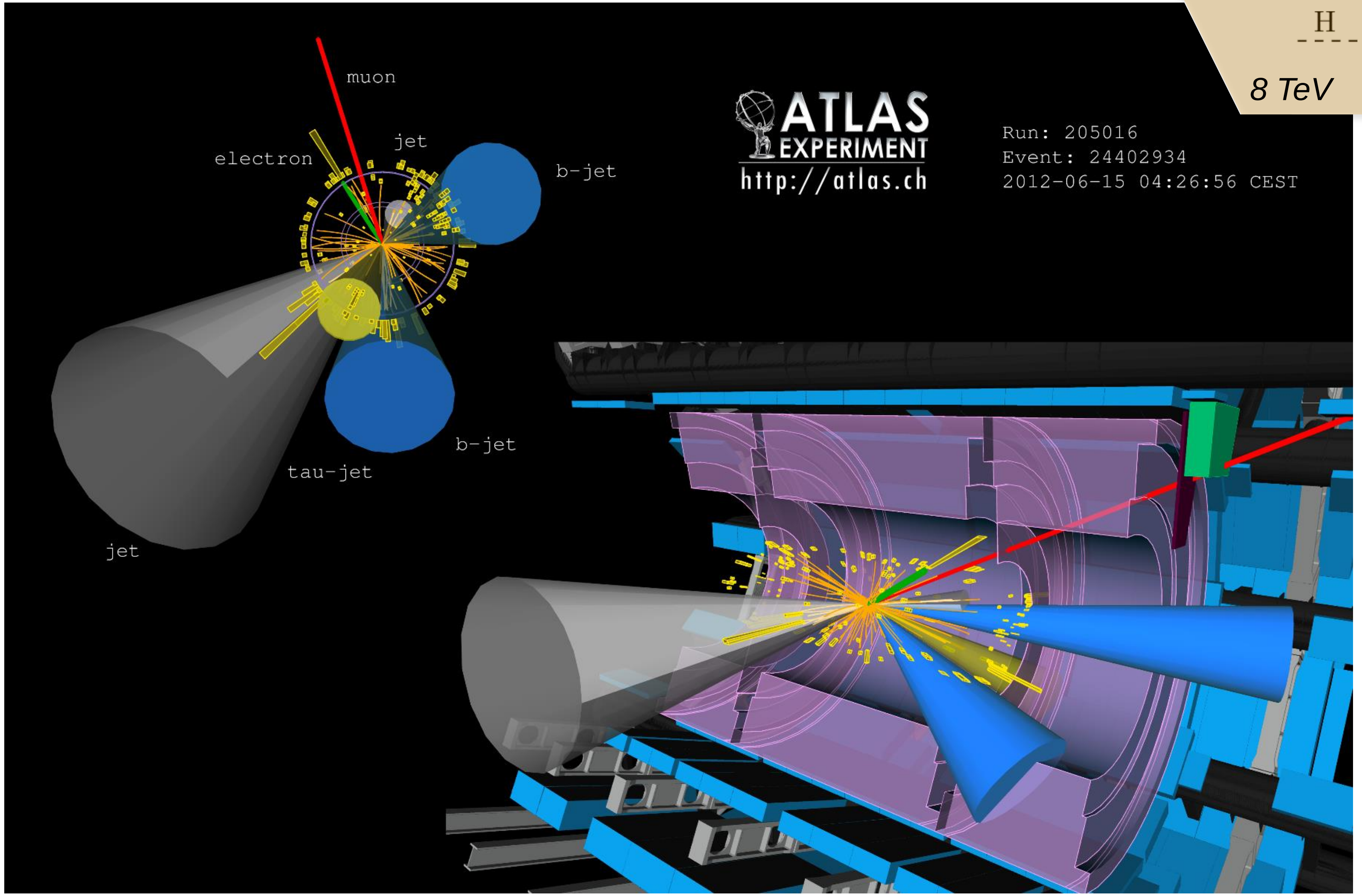
Validation region defined with 2lep+0tau selection except with >=2 b-tagged jets and either two or three jets, where the tt¯W purity is ≈ 30%, and are found to be consistent within uncertainties.

$2\ell_{SS}+1\tau^{had}$ event display

8 TeV

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

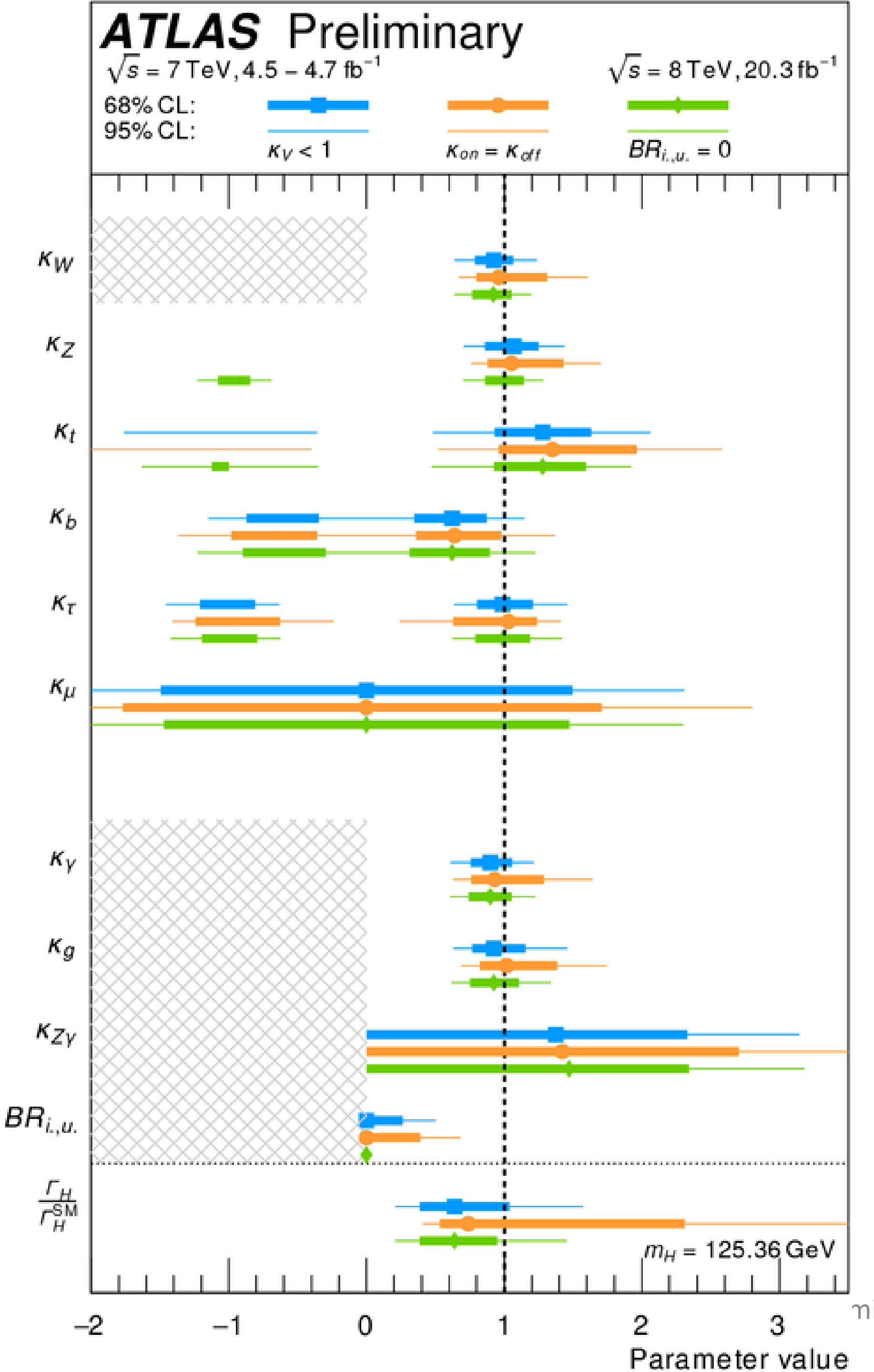




jets. For the 8 TeV dataset three sets of requirements are defined, out of which at least one must be satisfied for an event to be considered:

1. At least six jets, out of which at least two must be b-tagged using the 80% WP.
2. At least five jets with an increased p_{T} threshold of 30 GeV, out of which at least two must be b-tagged using the 70% WP.
3. At least six jets with an increased p_{T} threshold of 30 GeV, out of which at least one must be b-tagged using the 60% WP.

These requirements were optimized to suppress in particular the contribution from ggF Higgs boson production with $H \to \gamma\gamma$ to the hadronic category, while retaining good sensitivity to $t\bar{t}H$ production. For the 7 TeV dataset only events with at least six jets, at least two of which are b-tagged with the 85% WP, are considered.



Results of fits for the generic model 2:

The results indicated by full box are obtained for a benchmark model with effective coupling strengths for loop processes allowing non-SM contributions, and a floating $BR_{inv.,undet.}$ allowing non-SM contributions to the total decay width.

Need to understand the three constraints

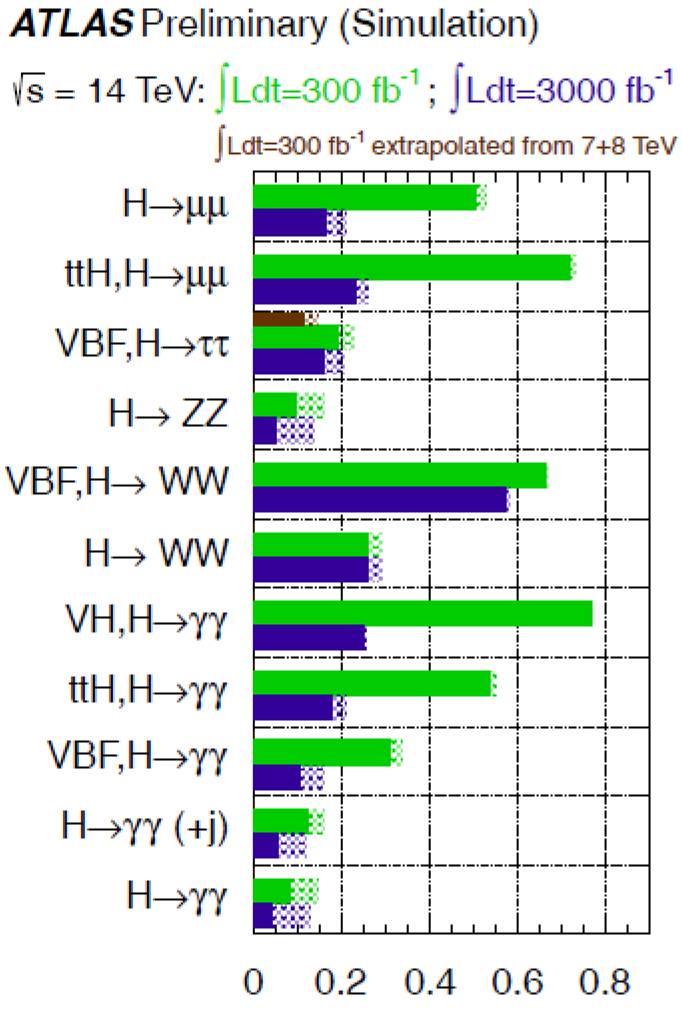
Systematic Uncertainties (for H->gamma/gamma)

	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	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 $E_{\mathrm{T}}^{\mathrm{miss}}$	±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

Summary of systematic uncertainties on final yield of events for 8 TeV data from tt¯H, tHqb and WtH production after applying leptonic and hadronic selection requirements.

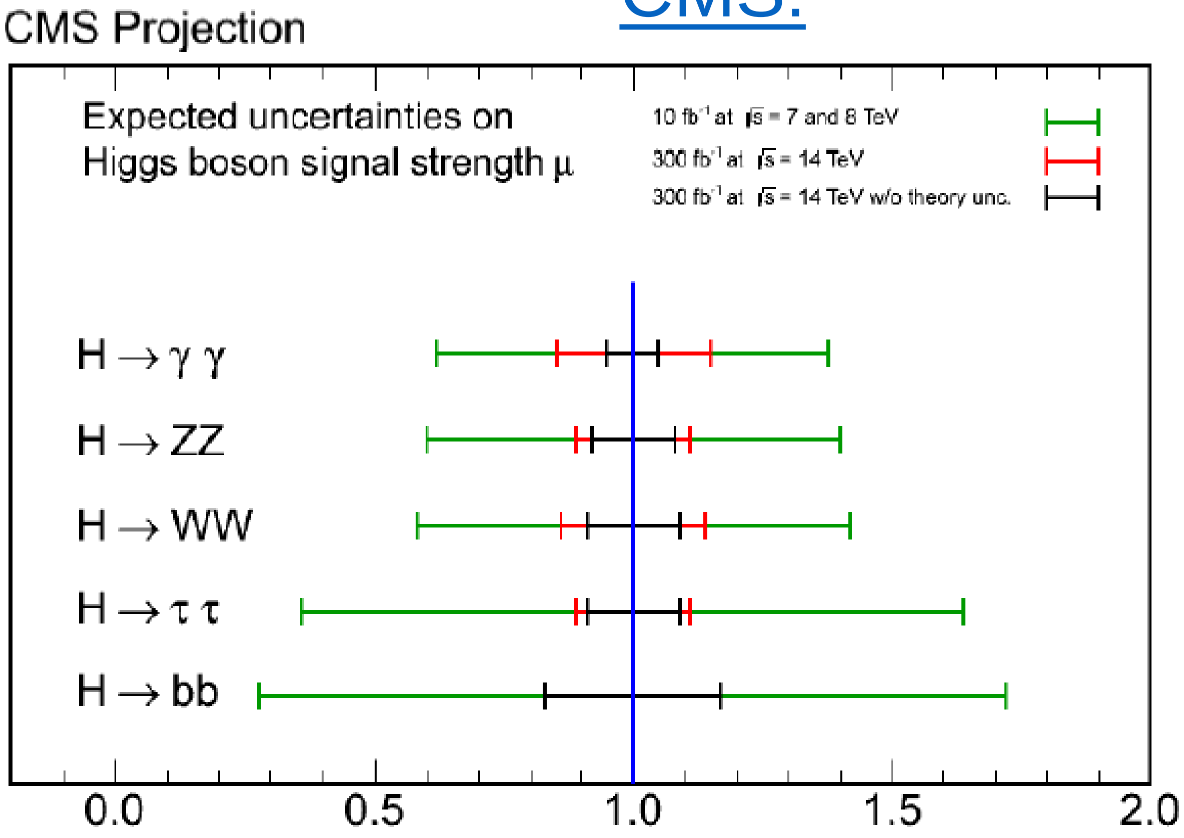
Uncertainties also shown for other Higgs boson production processes that do not include the associated production of top quarks and have significant contributions - These are WH production in the leptonic category and ggF production in the hadronic category. For both tH production processes, the maximum uncertainty observed for all values of κt generated (+1, 0, −1) is reported.

Projections:
European Strategy – '12

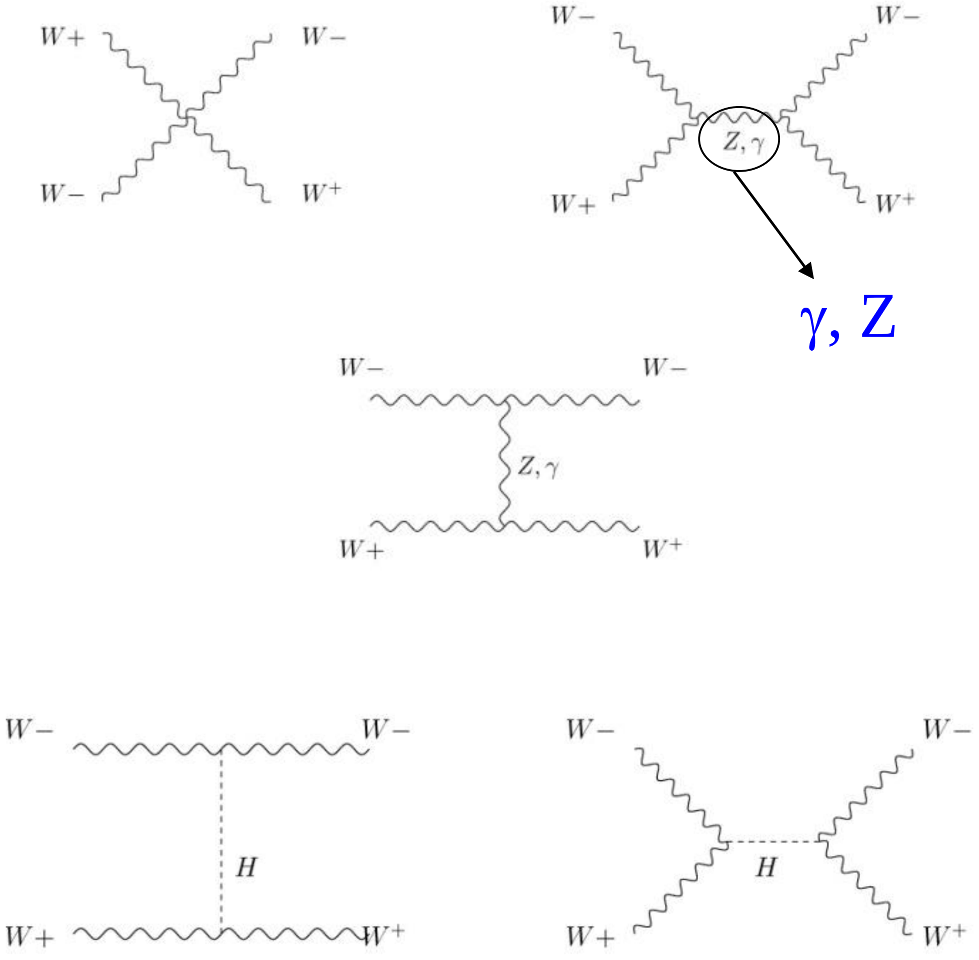


ATLAS

CMS:



Restores Unitarity



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_W

This cancellation requires M_H < 800 GeV

SM Higgs has just the right couplings so amplitudes don't grow with energy