Searches for associated Top quark and Higgs boson production at the ATLAS Experiment

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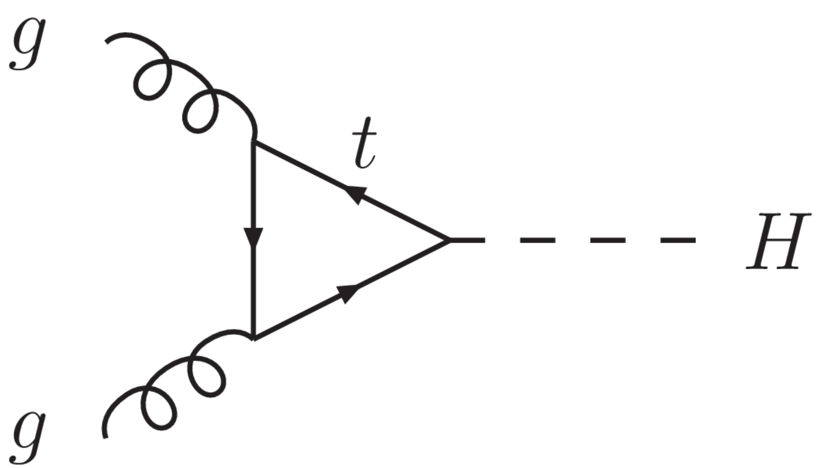
ATLAS EXPERIMENT

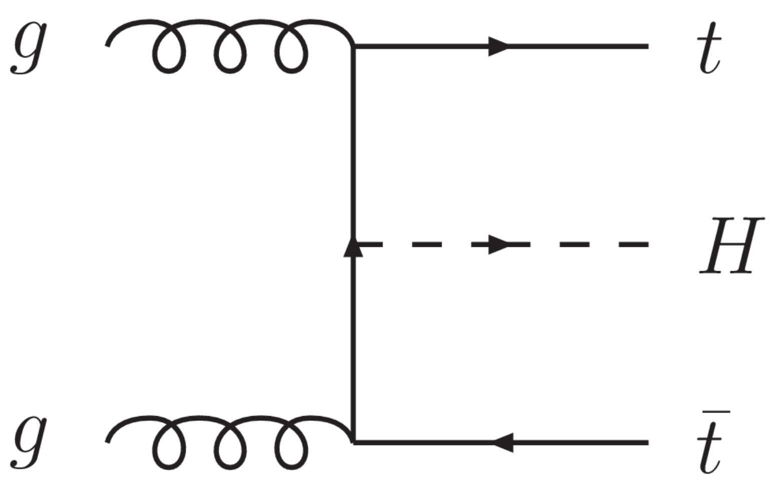
Fermion Couplings

- Want to check whether fermion mass generation mechanism is that of SM (coupling to single Higgs field)
  - a priori gauge boson masses are a *different* problem
- SM Higgs couples ∝ to fermion mass, decay rate ∝ mass^2
  - only decays into the heaviest fermions are observable
- 2HDM can change ratio of leptons/quarks, up/down-type fermions, or overall fermion rate compared to SM for lightest neutral CP-even Higgs
- Assuming generation independence … want to constrain
  - H ⟶ leptons: H ⟶ ττ
  - H ⟶ down-type fermions: H ⟶ bb, H ⟶ ττ
  - H ⟶ up-type fermions: pp ⟶ ttH, pp ⟶ H (gluon-gluon fusion)

How to measure the Top Coupling?

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



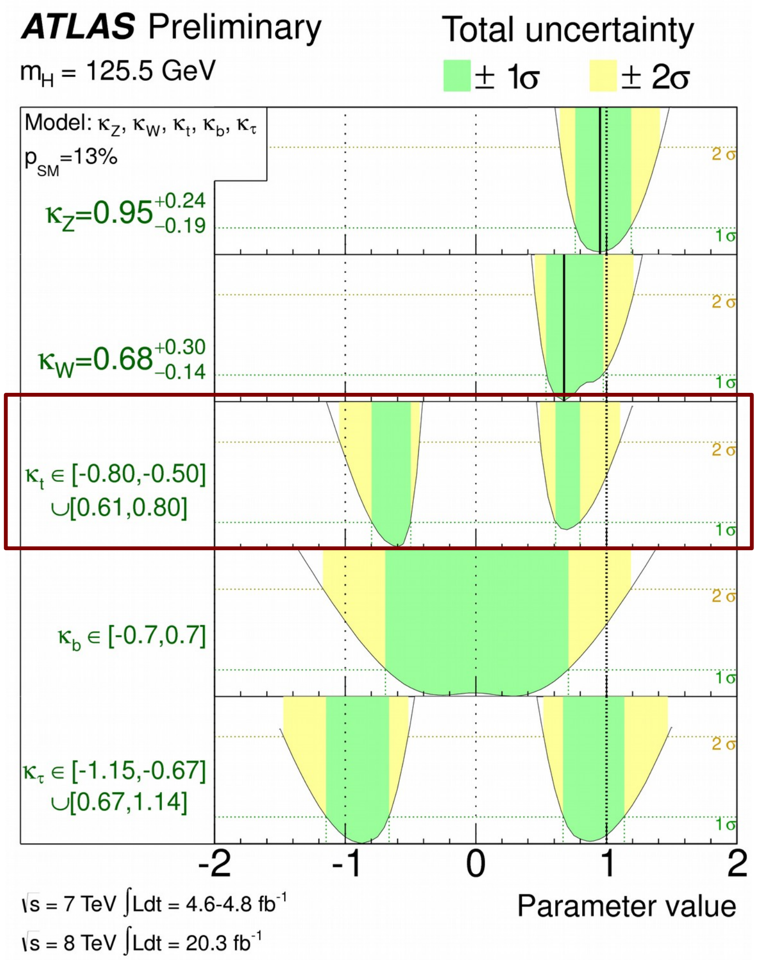


Constraints on Higgs Couplings

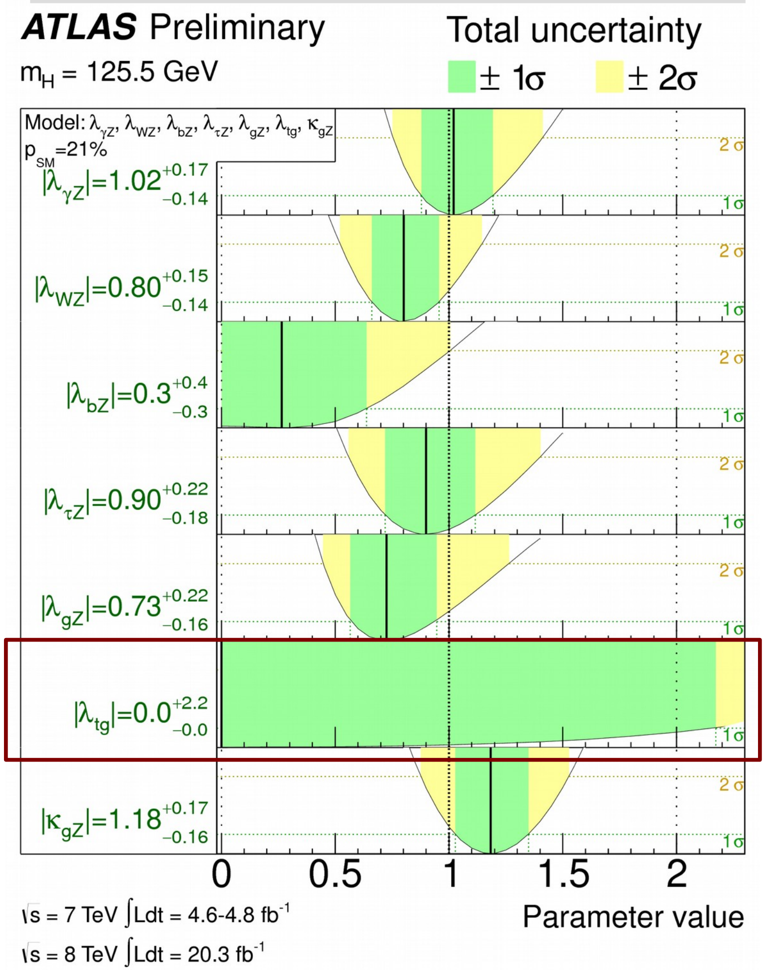
- Without ttH, unable to simultaneously constrain top coupling and new physics in ggF loop

ATLAS-CONF-2014-009
outdated – for illustration…

SM particles only



Allowing new particles in loops



ttH + EFT

- Explicit example of degeneracy between dim-6 operators affecting pp → H and pp → ttH

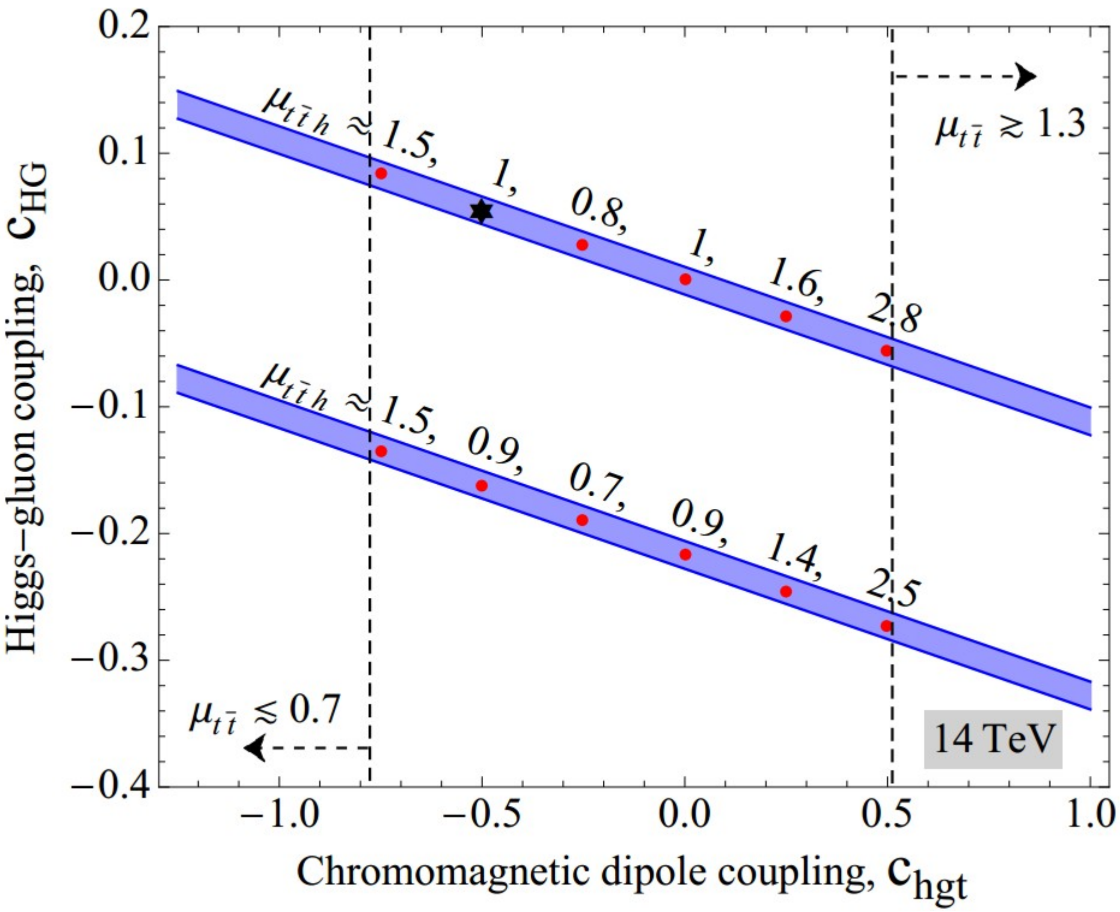
Higgs-gluon coupling:

$$\mathcal{O}_{HG} = \frac{c_{HG}}{2\Lambda^2}(H^\dagger H)G_a^{\mu\nu}G^a_{\mu\nu}$$

Top chromomagnetic dipole:

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

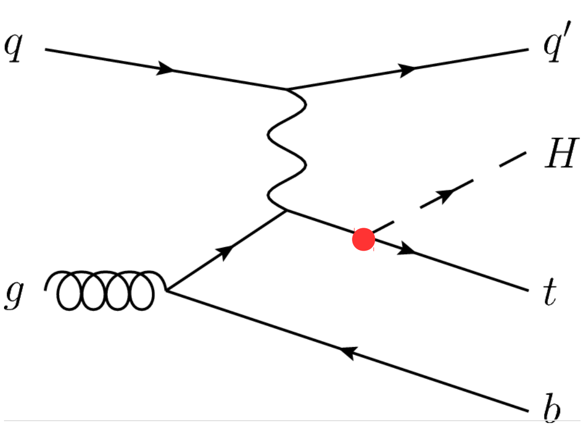
Blue band shows constraint from ggF

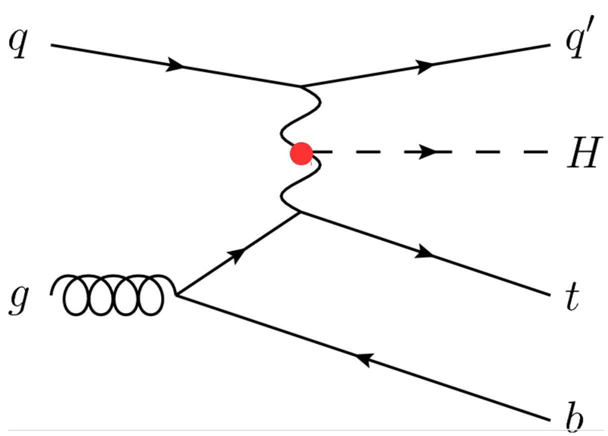


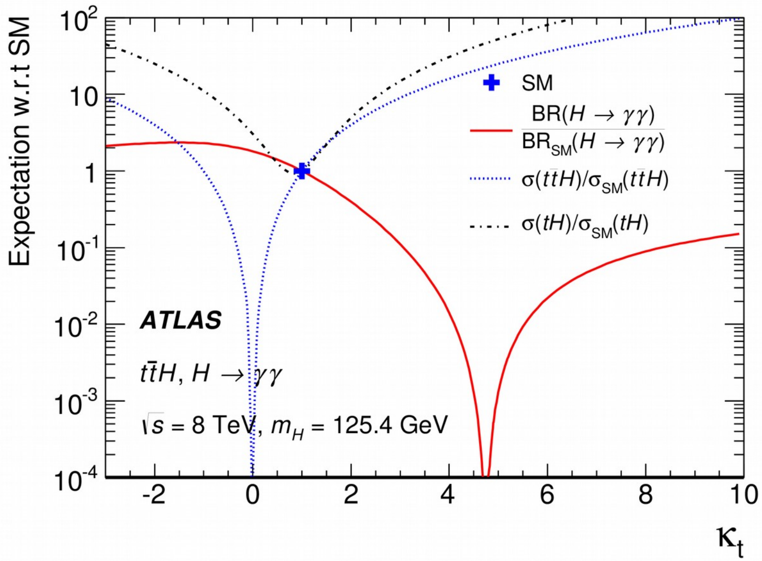
Bramante, Delgado,Martin PRD 89, 093006 (2014)

tH

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

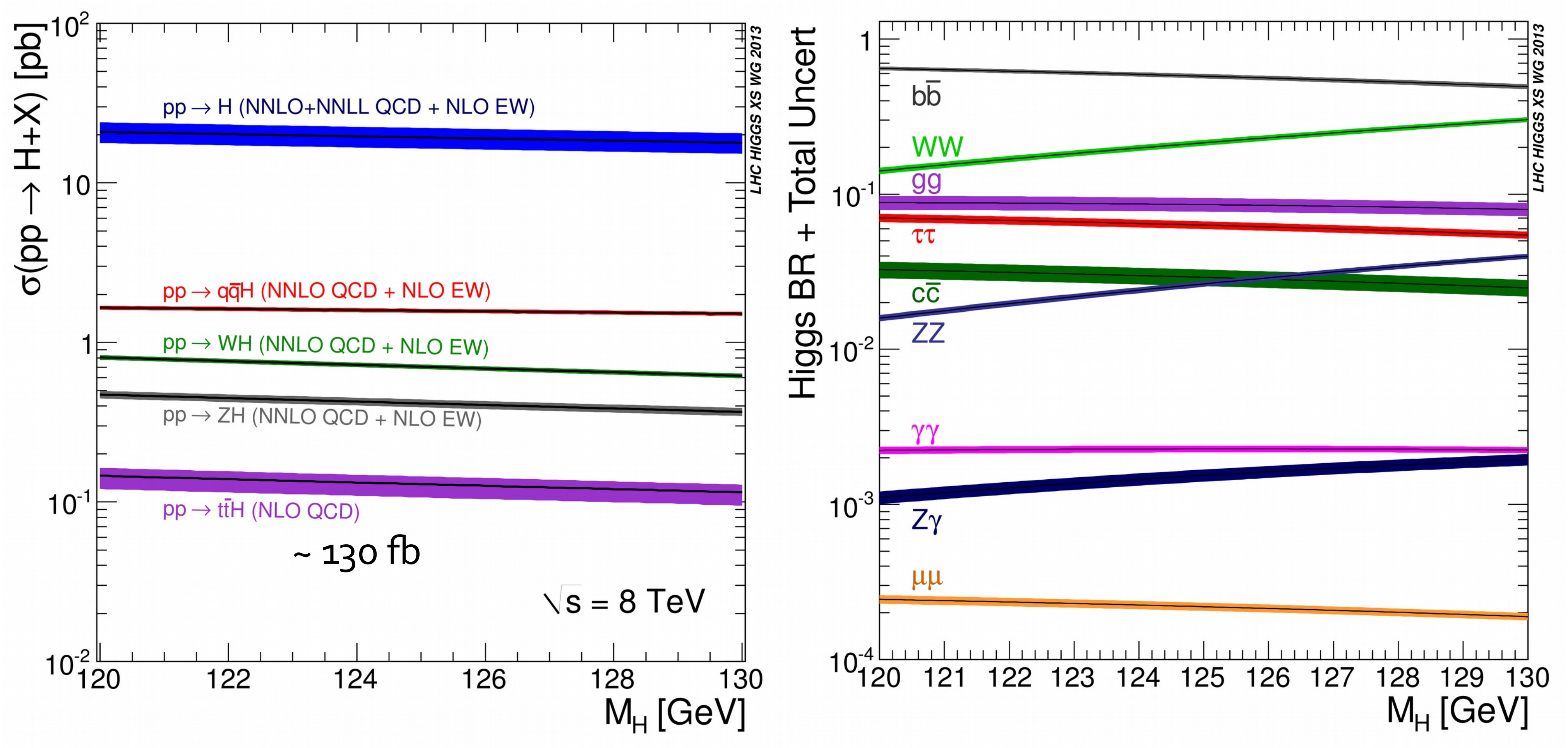






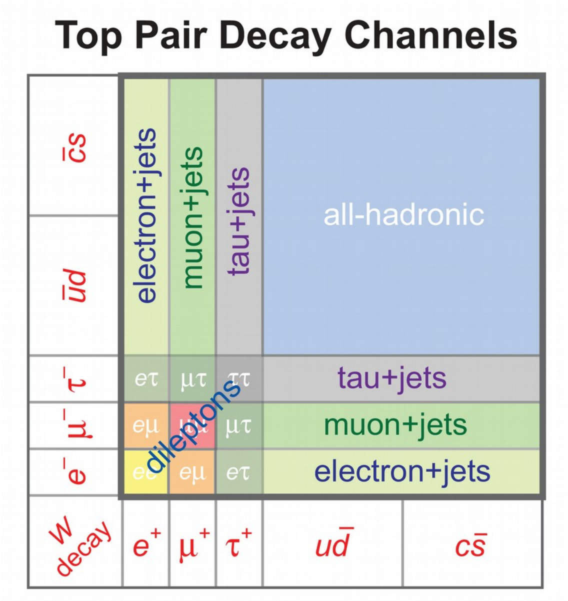
Process xsec

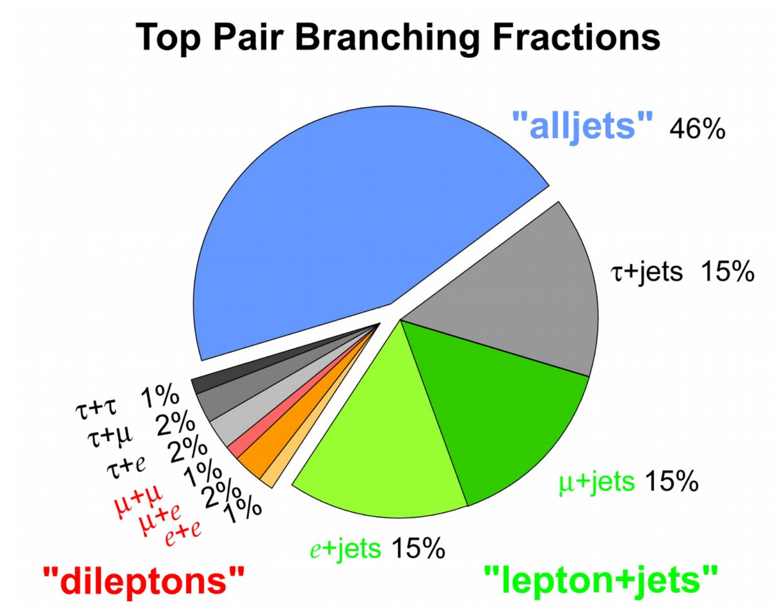
- Rarest "major" production process – but distinct signature



Finding ttH

- Signature is top pair decay + Higgs decay
- Top quarks decay ~ 100% via t → W b
  - W decays 68% of the time to quarks, ~ 11% to each of e, μ, τ
- Top quark pair can be dileptonic, semileptonic ("lepton+jets"), or all hadronic
  - dileptonic with e and μ ~ 4% of $t\bar{t}$ decays
  - all hadronic must be separated from pure QCD multijet events





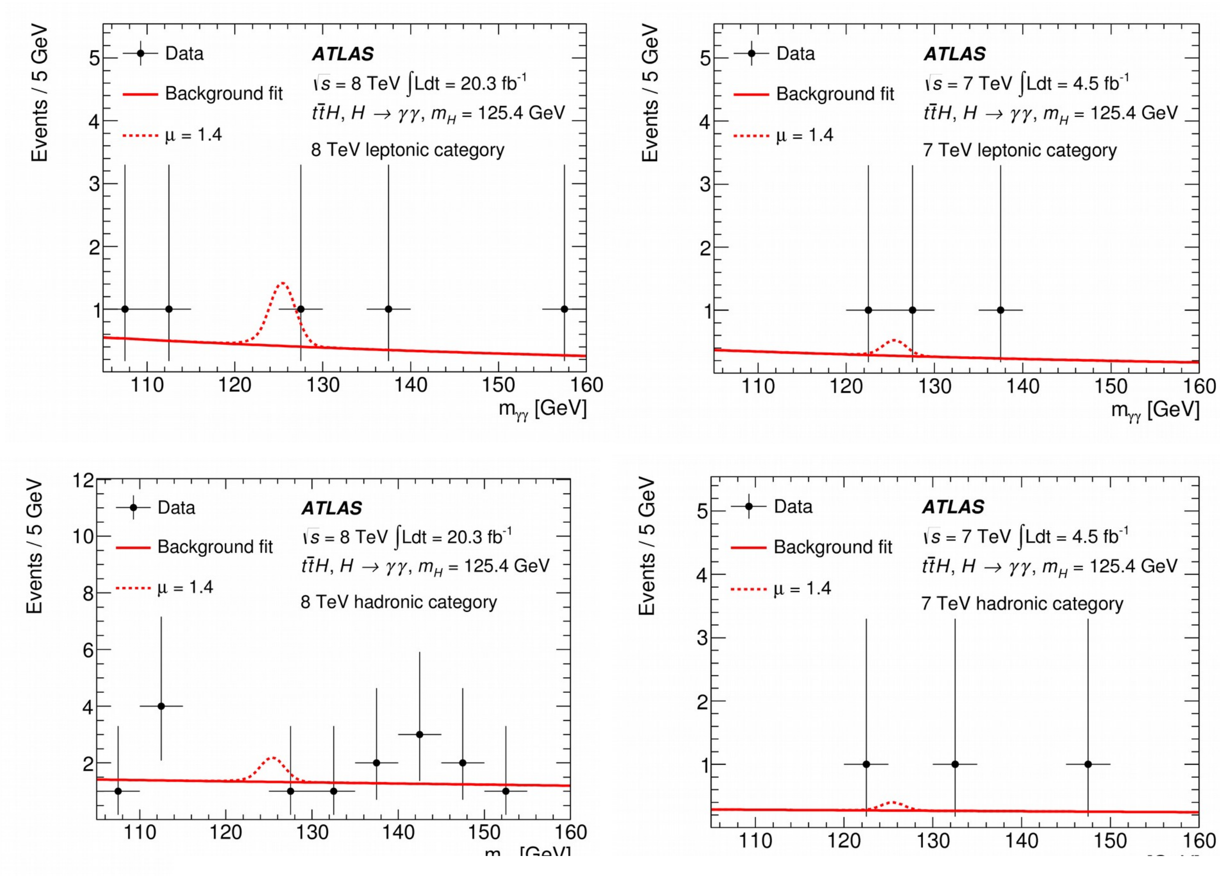
Diphotons

- Diphoton requirement makes channel so clean that main challenge is to reduce contamination from other Higgs production modes
  - A bump at 125 GeV is a Higgs: but is it ttH?
- Split by top pair decays:
  - lepton + jets: lepton and b-tag requirement enough to remove all other major Higgs production mechanisms
  - all hadronic: contaminated by gluon-gluon fusion. Strict cuts applied to improve purity of observed signal

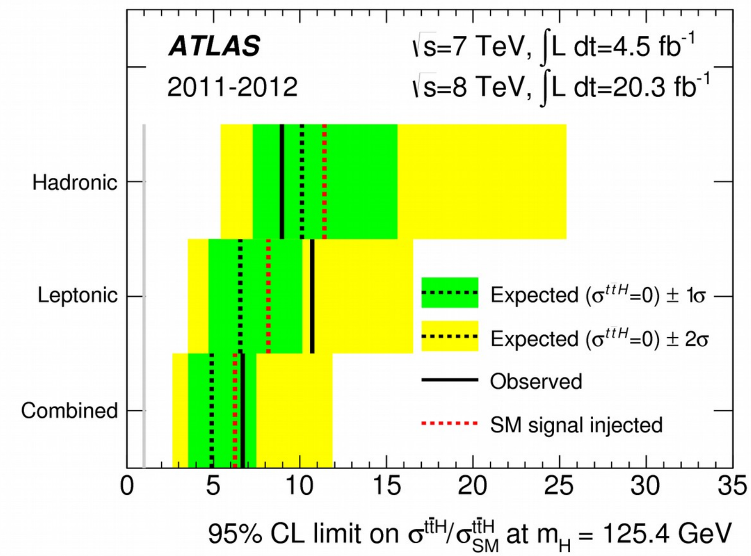
PLB 740 222 (2015)

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	$2.7^{+0.9}_{-0.7}$

Diphoton Results



PLB 740 222 (2015)



Set $\mu_{\text{non-ttH}} = 1$

(μ = scaling of observed rate in acceptance)

	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)	6.3	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)	10.2	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)	8.5	9.5	21.4	14.1	6.8	5.1

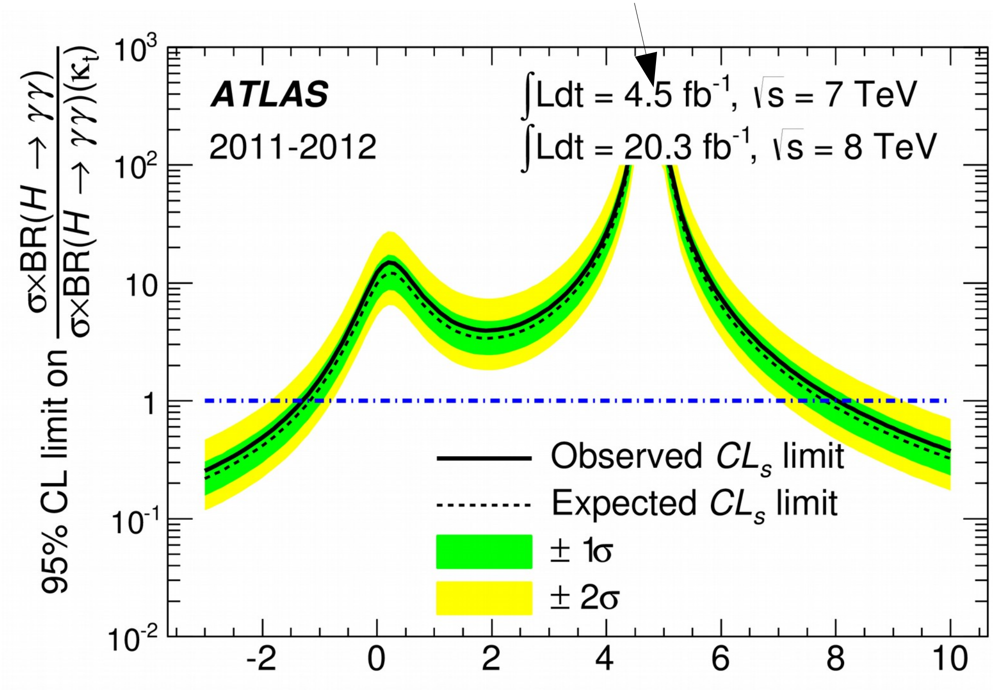
tH, H → γγ

- Scan κ_t and compare yields to observation
- Rule out $\kappa_t < -1.3$ and $\kappa_t > 8.0$ at 95% CL

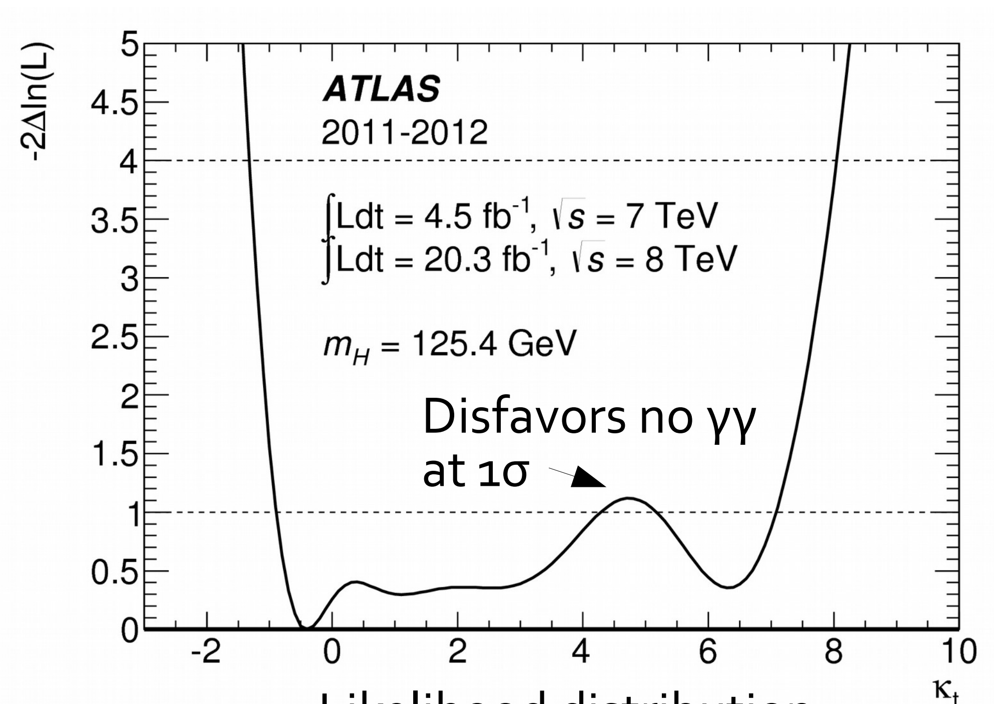
κ_X = scaling factor for X-H coupling

PLB 740 222 (2015)

B(H → γγ) = 0



"One-sided limit" - null hypothesis is zero signal



Likelihood distribution

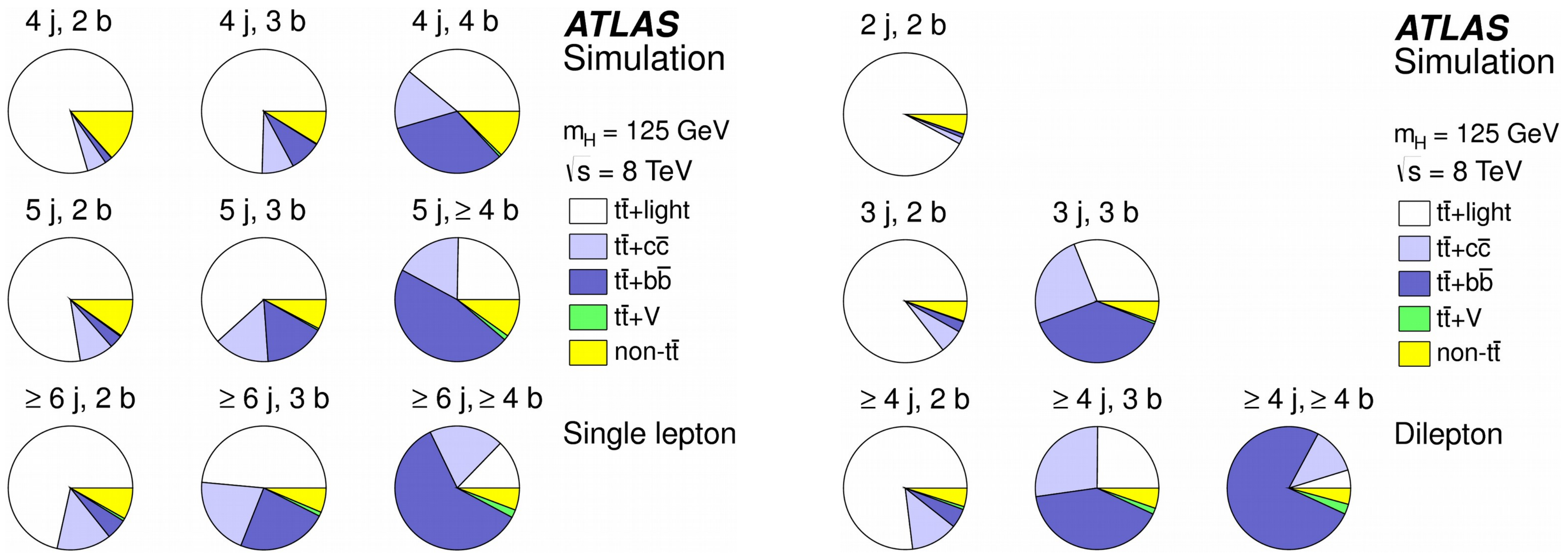
$H \longrightarrow bb$

- $H \rightarrow bb$ is 58% of the SM Higgs width @ 125 GeV
  - Mass resolution is much worse than for γγ
  - Background (tt + heavy flavor jets) tricky to model
- Strategy: sort events by number of jets and b-tags, then in each channel classify events with a neural network
  - use background-rich channels to constrain background and detector systematics
- For now use only lepton+jets and dilepton channels

EPJC 75 349 (2015)

Backgrounds

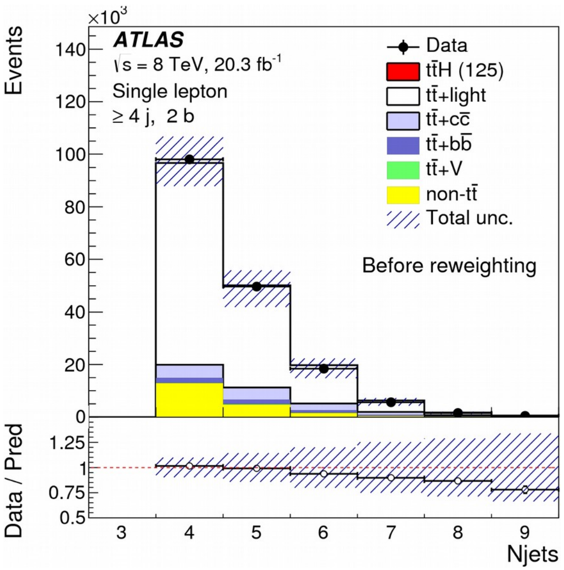
- dominated by tt + heavy flavor jets in all signal-rich regions

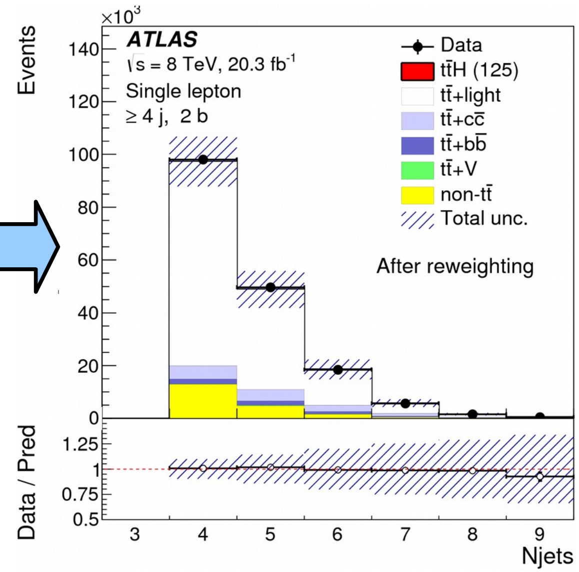


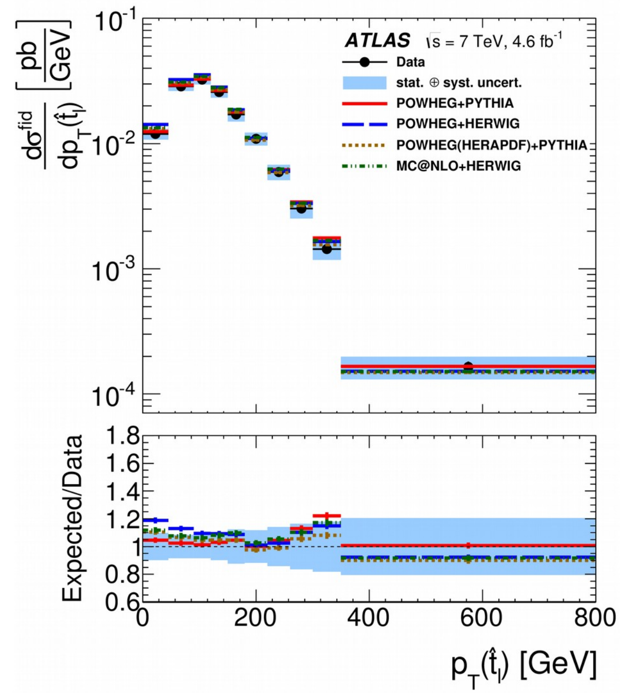
Top Reweighting

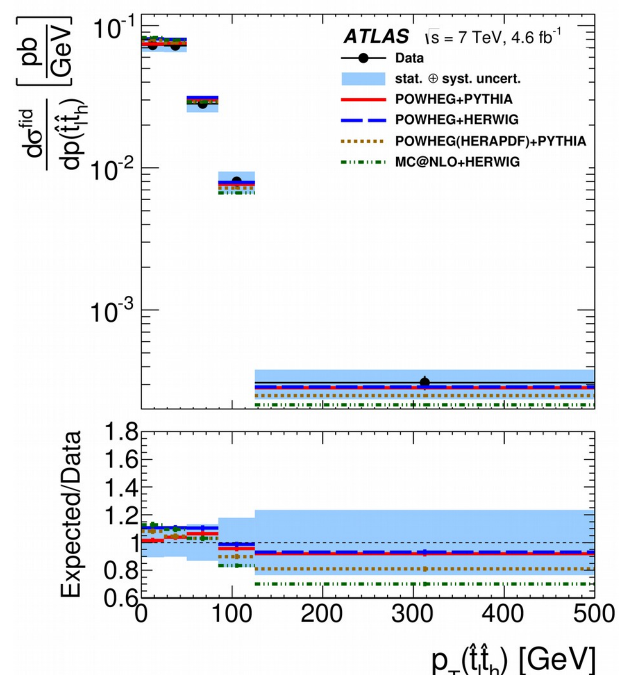
- To improve agreement of MC and data, **reweight** the $t\bar{t}$ pair p_T and the top quark p_T with scalings derived from 7 TeV data
  - Powheg+Pythia spectra generally too hard
  - tt p_T improves # jets recoiling against top pair system; top p_T fixes energy of top decay products
  - tt+light, tt+cc events only; tt+bb handled differently

top kinematics:
arxiv:1502.05923, accepted by JHEP





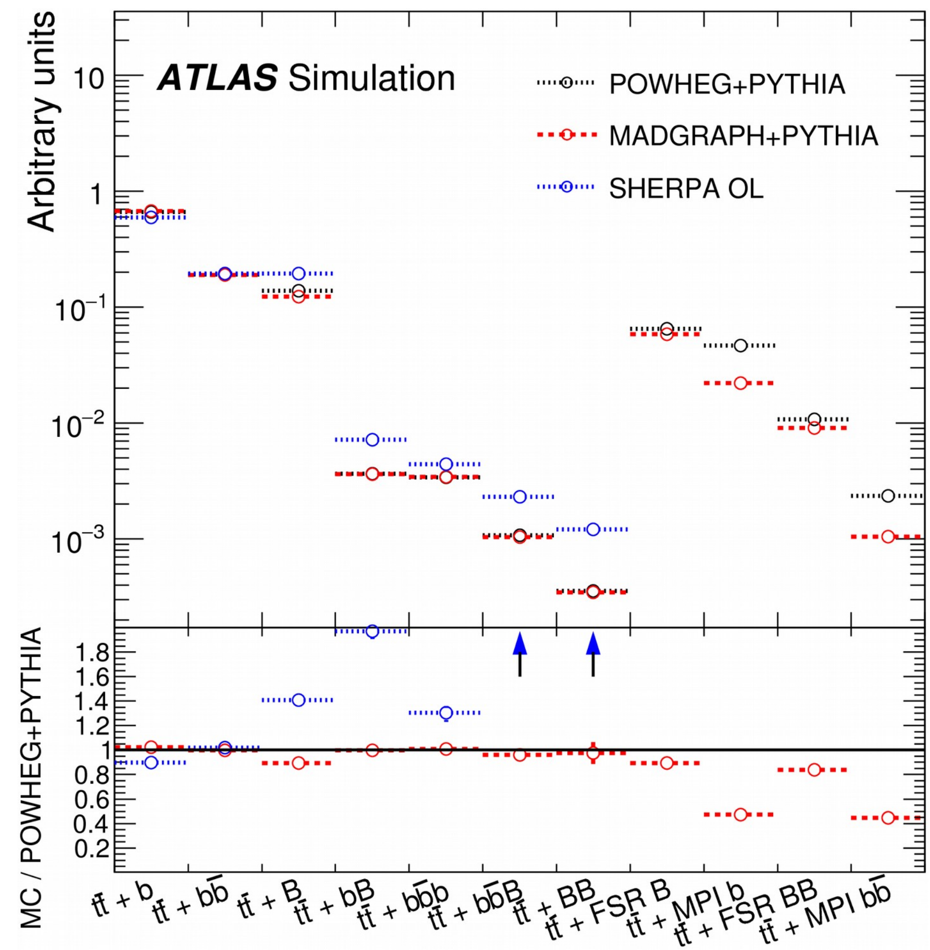




tt+bb Reweighting

b = b-matched jet in acceptance
B = bb-matched jet in acceptance

- Powheg+Pythia tt+bb reweighted to shower-matched NLO calculation of Sherpa+OpenLoops
  - particular attention paid to separation of b quarks
- Provides theoretically-motivated systematics (Sherpa scale, PDF, shower variations)



NN construction

- Variables that are well modeled in background-dominated channels are used to construct neural network discriminants (with NeuroBayes)
  - even in signal-rich channels, checked modeling after applying anti-NN cut ("partial unblinding")
- lepton+jets 6-jet channels also have matrix element discriminant

lepton + jets

	2b	3b	4b
4j	H_T^{had}	H_T^{had}	H_T^{had}
5j	H_T^{had}	NN †	NN
6j	H_T^{had}	NN[ME]	NN[ME]

† trained for tt+HF vs tt+LF

dilepton

	2b	3b	4b
2j	H_T		
3j	H_T	NN	
4j	H_T	NN	NN

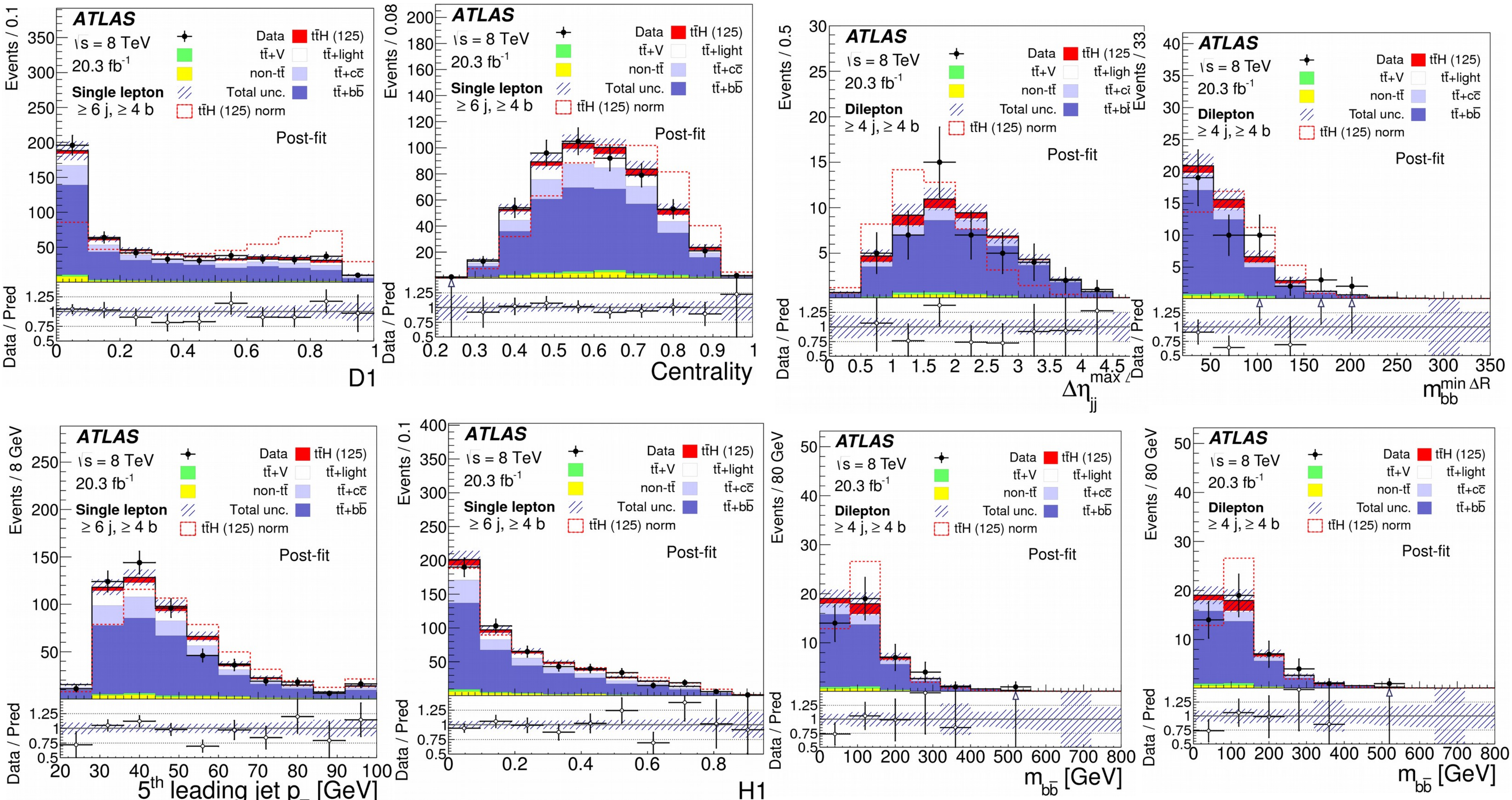
Variable Modeling

- Four highest ranked variables shown

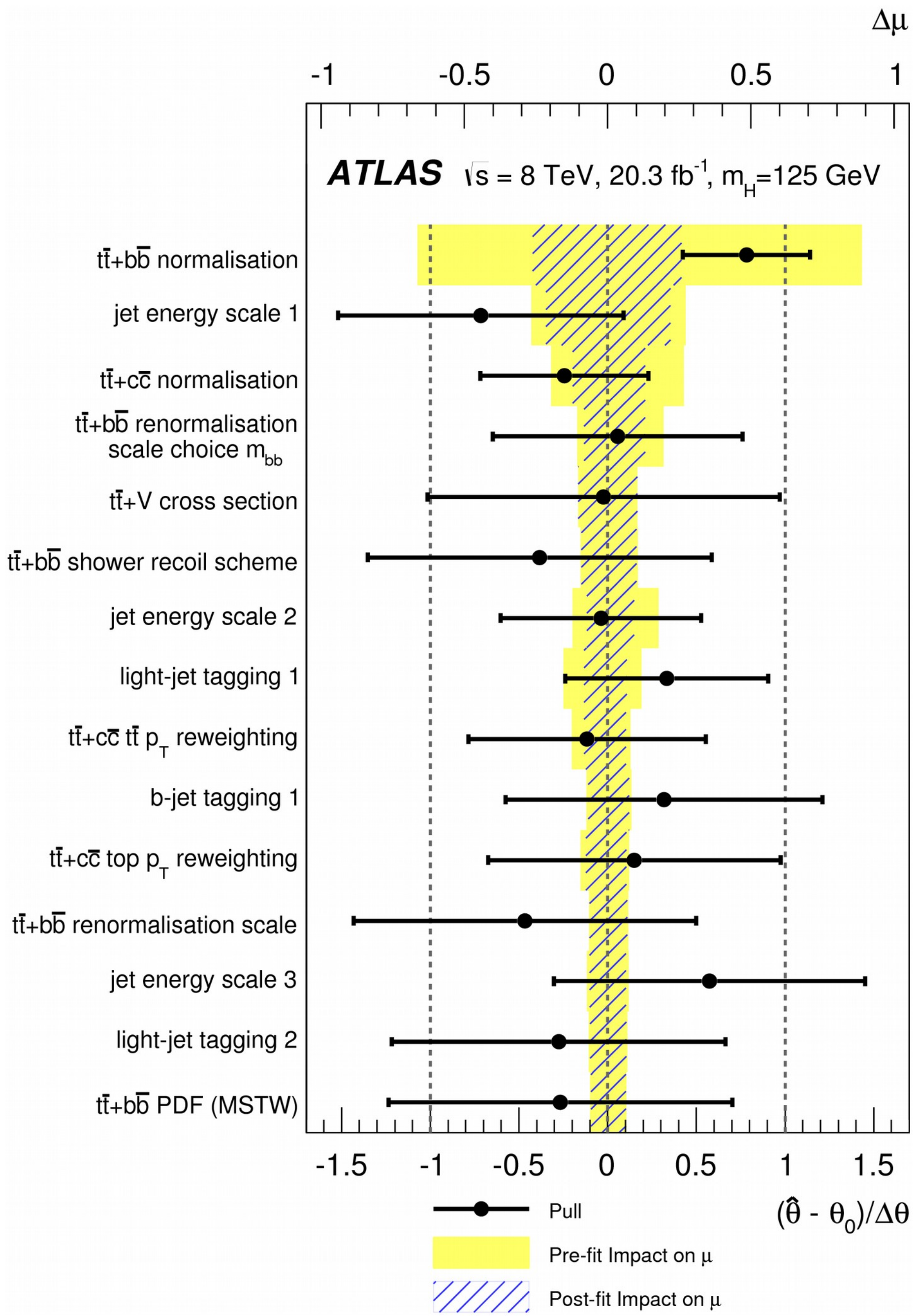
$$D1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + 0.23 \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}}$$

l+jets ≥6j ≥4b

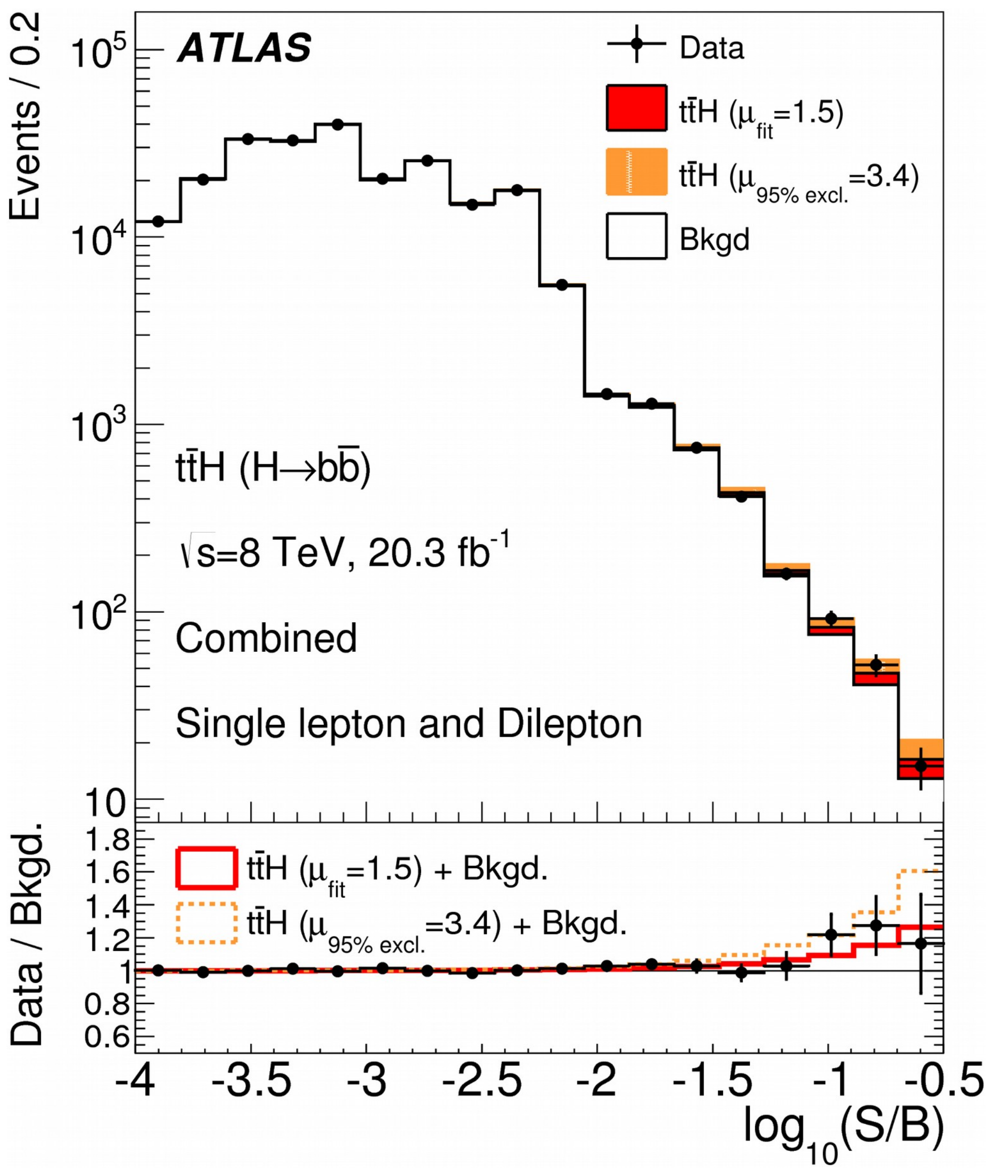
dilepton ≥4j ≥4b



Fit Results



ATLAS √s = 8 TeV, 20.3 fb⁻¹, m_H=125 GeV
Δμ
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)
(θ̂ - θ₀)/Δθ
Pull
Pre-fit Impact on μ
Post-fit Impact on μ

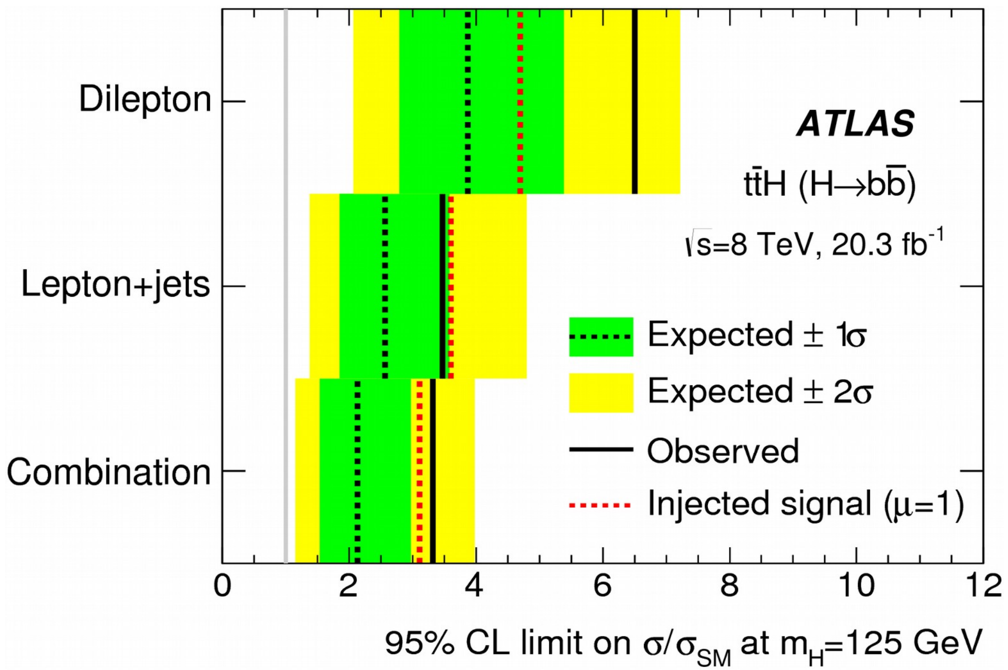


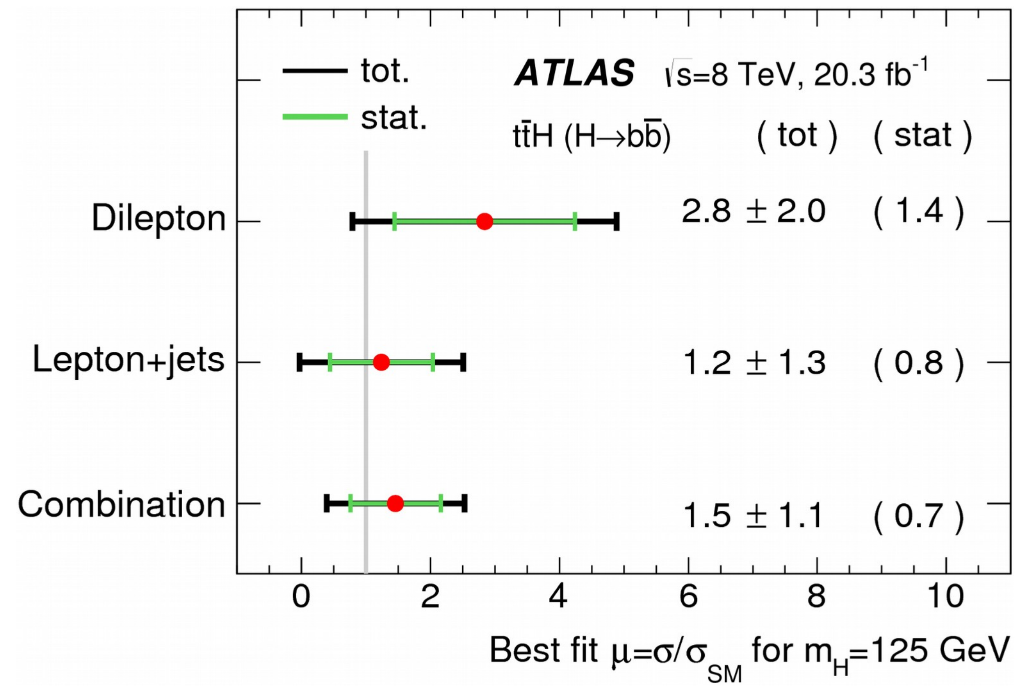
ATLAS
Data
tt̄H (μ_fit=1.5)
tt̄H (μ_95% excl.=3.4)
Bkgd
tt̄H (H→bb̄)
√s=8 TeV, 20.3 fb⁻¹
Combined
Single lepton and Dilepton
Events / 0.2
Data / Bkgd.
tt̄H (μ_fit=1.5) + Bkgd.
tt̄H (μ_95% excl.=3.4) + Bkgd.
log₁₀(S/B)

Results

- Combined obs (exp) limit 3.4 (2.2) x SM
  - median limit with SM signal = 3.1 x SM
- Best fit rate (1.5 ± 1.1) x SM
- Many systematics (e.g. tt+HF normalization) will be reduced with more data

EPJC 75 349 (2015)





ttH, H → WW/ττ

- Complex topology: WWWWbb or ττWWbb
  - rich set of final states with high multiplicities
  - backgrounds mostly tt + EWK, not tt + QCD
- Take advantage of final states not reachable from tt production
  - ≥ 3 leptons, or 2 same sign leptons
- H → ττ worth exploiting
  - σ(ttZ) and σ(ttH) similar: no overwhelming Z bkg to H → ττ

	Higgs boson decay mode			
	WW*	ττ	ZZ*	other
2ℓ same sign 0τ	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
2ℓ same sign 1τ	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
1ℓ 2τ	4%	93%	0%	3%

arxiv:1506.05988, acc. by PLB

ttH multilepton decays

Signal

Higgs decay	*tt decay*: ℓνℓν bb	ℓνjj bb
$H \rightarrow WW \rightarrow \ell\nu\ell\nu$	4ℓ	3ℓ
$H \rightarrow WW \rightarrow \ell\nu jj$	3ℓ	2ℓ0τ
$H \rightarrow \tau_l \tau_l$	(4ℓ)	3ℓ
$H \rightarrow \tau_l \tau_h$	3ℓ	2ℓ1τ
$H \rightarrow \tau_h \tau_h$	---	1l2τ

all-hadronic top not targeted

only accept same sign ℓ

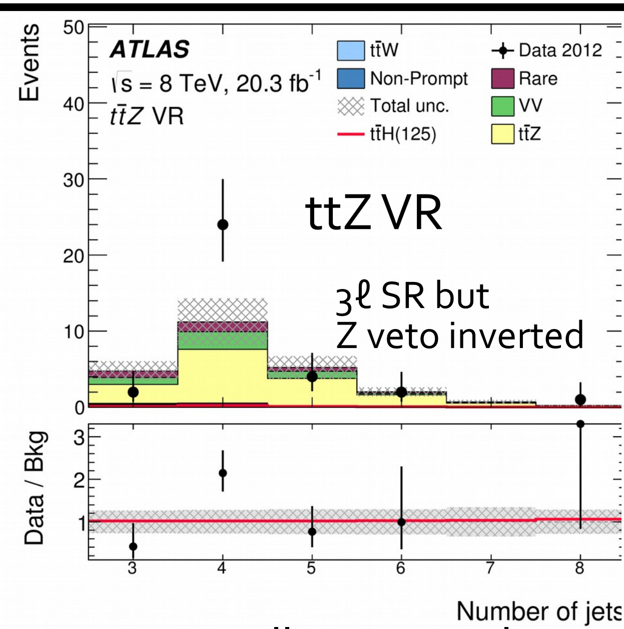
+ require ≥1 b-jet,
high (≥2-5) jet multiplicity

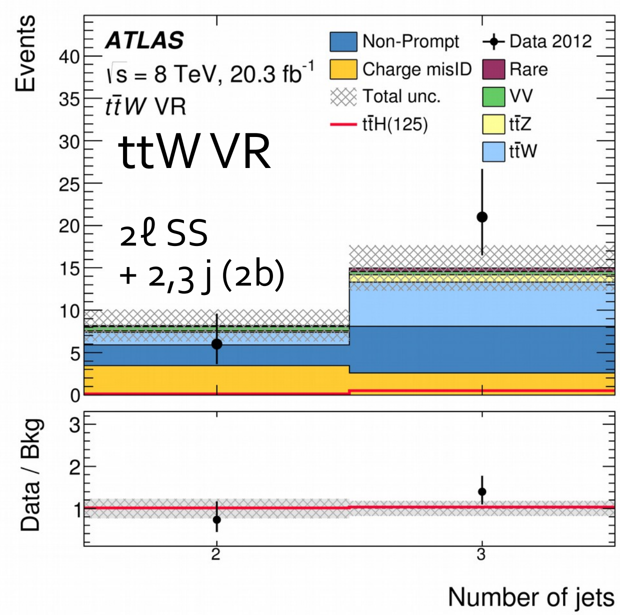
$H \rightarrow ZZ$ not very important due to low BF and Z vetoes

Backgrounds

Main bkg: non-prompt leptons, ttZ, ttW, diboson + jets, fake τ

- non-prompt lepton bkg estimated from extrapolation in isolation, ID variables, p_T
- other backgrounds estimated from Monte Carlo, checked in various validation regions

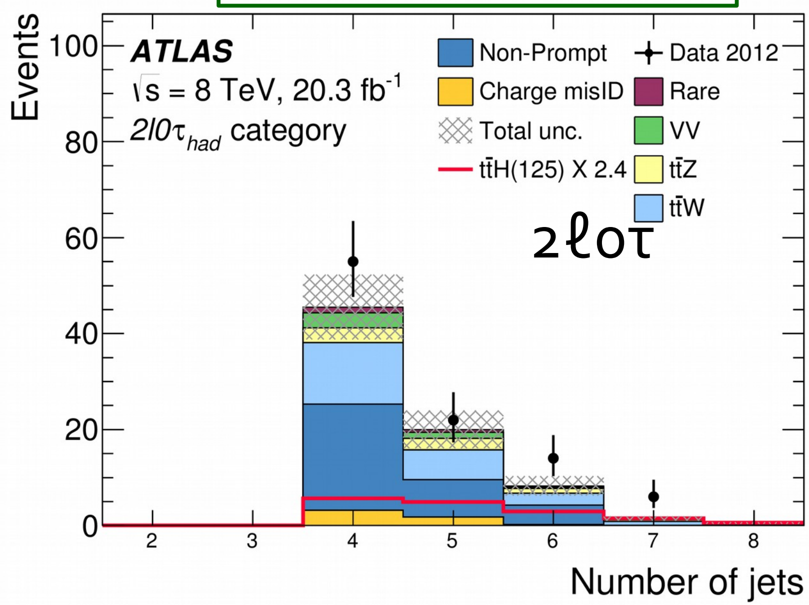




inv mass, smallest ΔR OS lepton pair

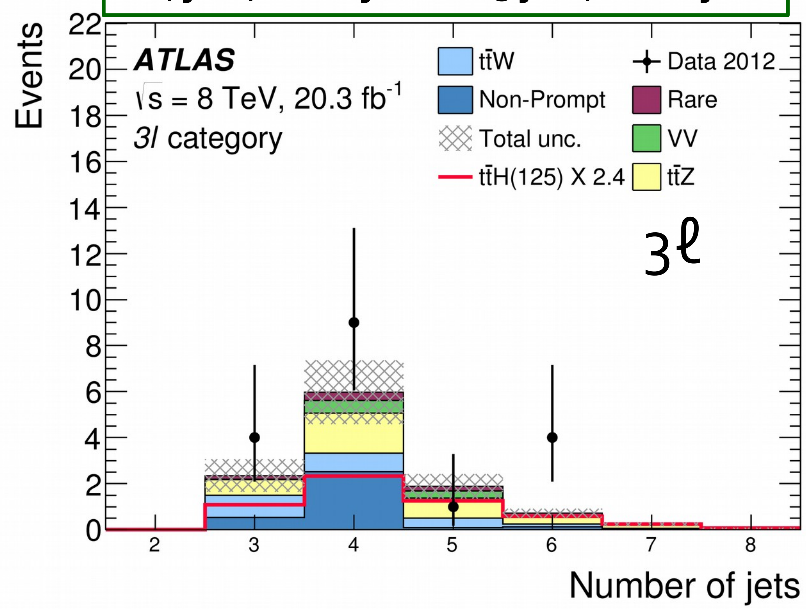
ttH, H → WW/ττ

2 same sign leptons, no tau
≥ 4 jets, ≥ 1 b-jet



Total bkg	77 ± 13
SM H(125)	6.6 ± 1.4
Observed	98

3 leptons
≥ 4 jets, ≥ 1 b-jet or = 3 jets, ≥ 2 b-jets



Total bkg	11.4 ± 3.1
SM H(125)	2.34 ± 0.32
Observed	18

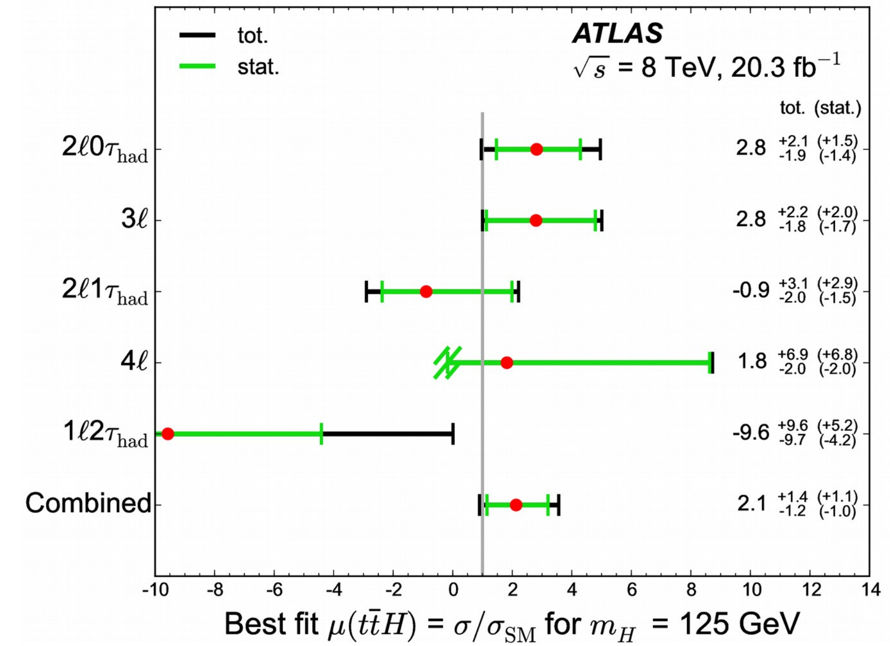
	2ℓ 1τ	4ℓ	1ℓ 2τ
Total bkg	1.4 ± 0.6	0.55 ± 0.17	16 ± 6
SM H(125)	0.47 ± 0.02	0.20 ± 0.01	0.68 ± 0.07
Observed	1	1	10

Combined multilepton channels:

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

$$\mu < 4.7 \text{ obs } (2.4 \text{ exp}) \text{ @ } 95\% \text{ CL}$$

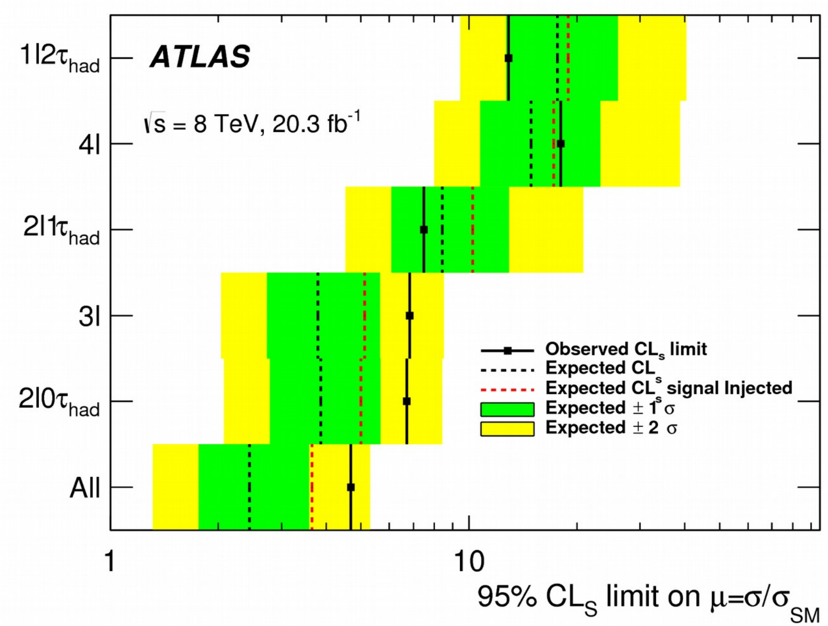
Consistent with SM



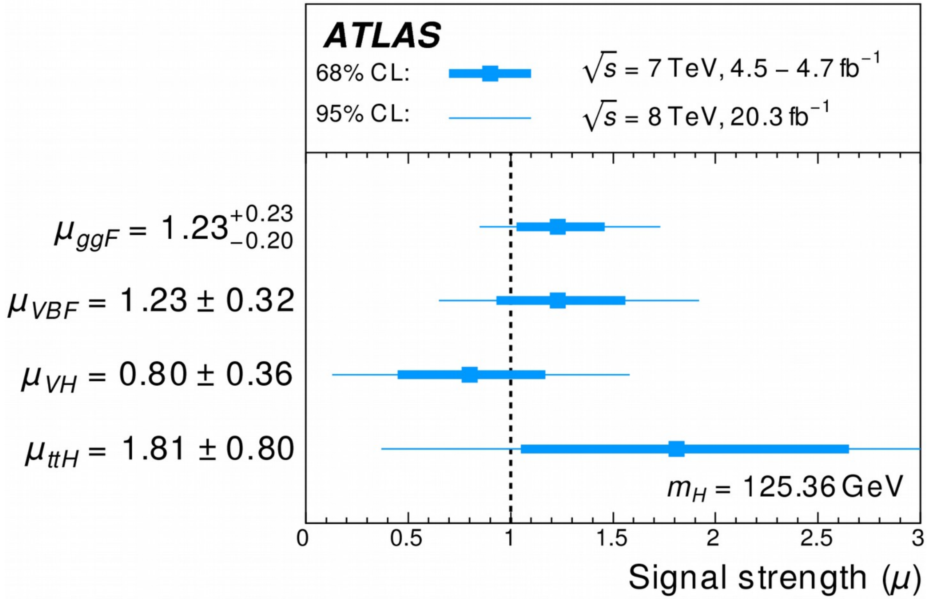
Leading systematics:

non-prompt lepton rate in 2ℓ0τ
acceptance for ttW+jets
cross sections for ttW, ttZ

arxiv:1506.05988, acc. by PLB



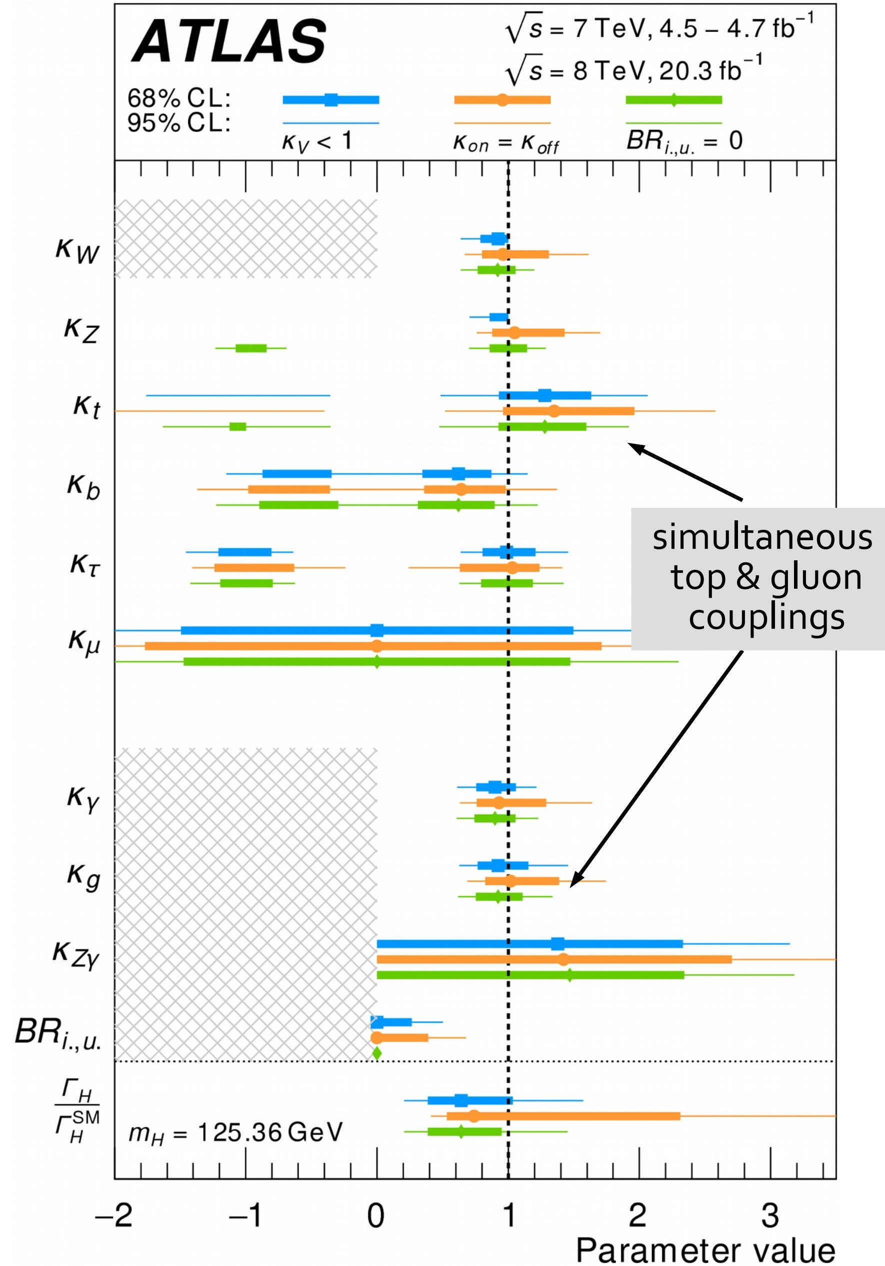
Combination, Couplings



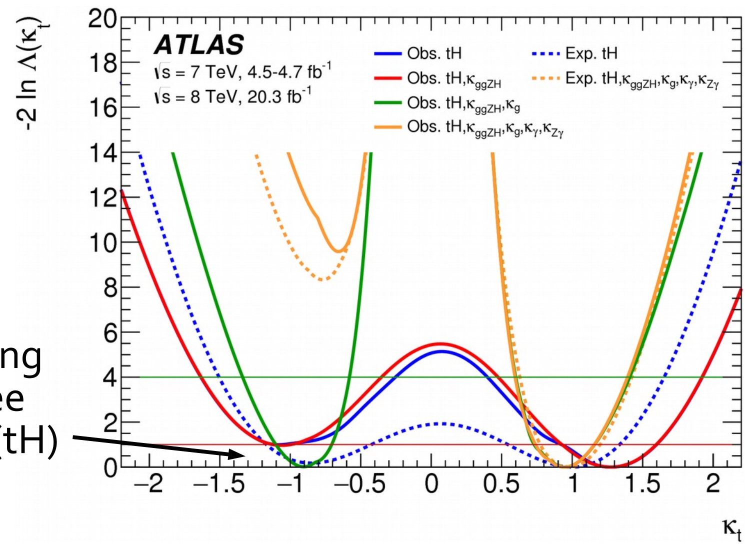
$\mu_{ttH} < 3.2$ (1.4 exp) @ 95% CL

Signal significance: 2.4σ (1.5σ exp)

Start to constrain top coupling independent of gluon, photon loops



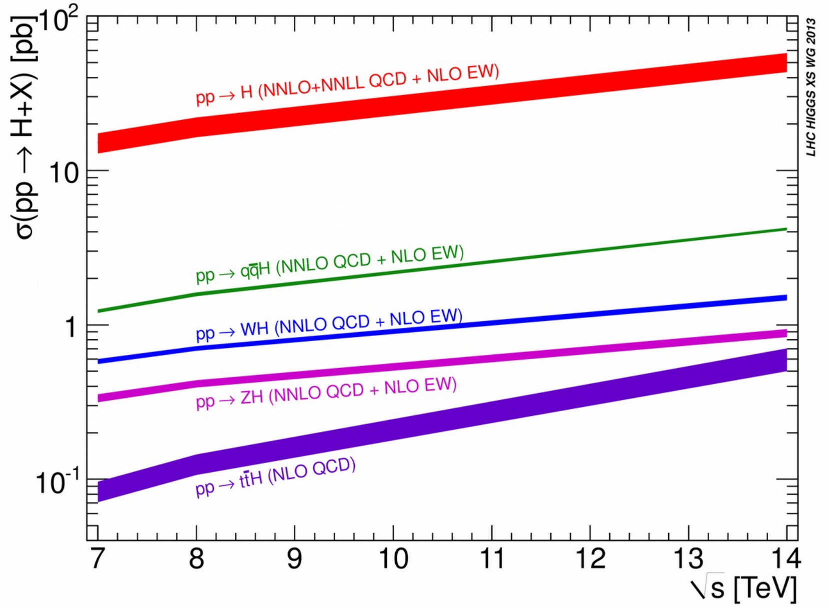
arxiv:1507.04548
sub. to EPJC

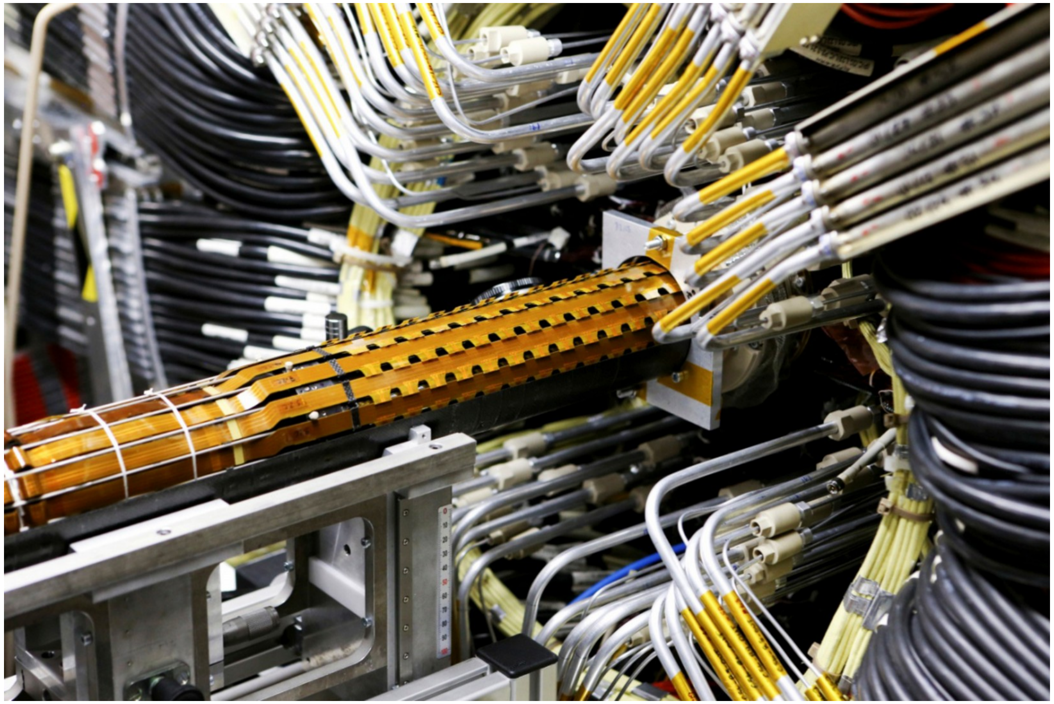


Sign flip for top coupling disfavored at 1σ by tree measurements alone (tH)

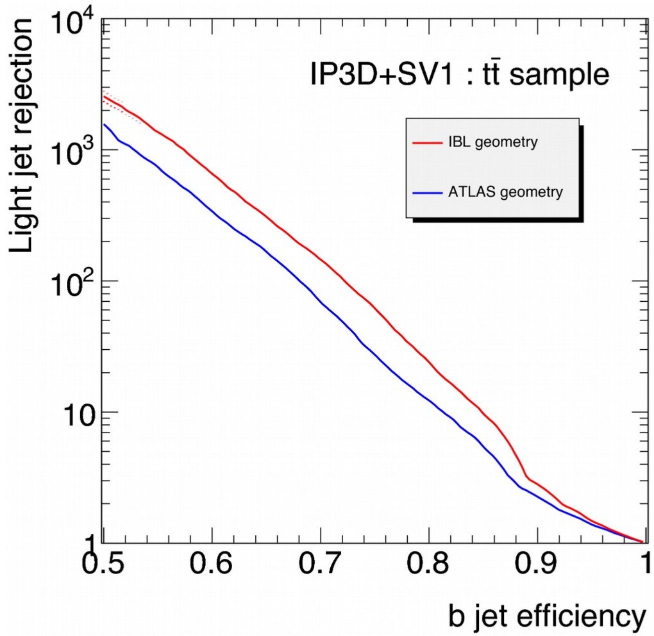
Run 2

- Each fb^{-1} worth more @ 13 TeV
  - σ(ttH) up a factor ~ 4, S/B is better
- New innermost pixel layer ("IBL"), b-tagging improvements give better expected mistag rate





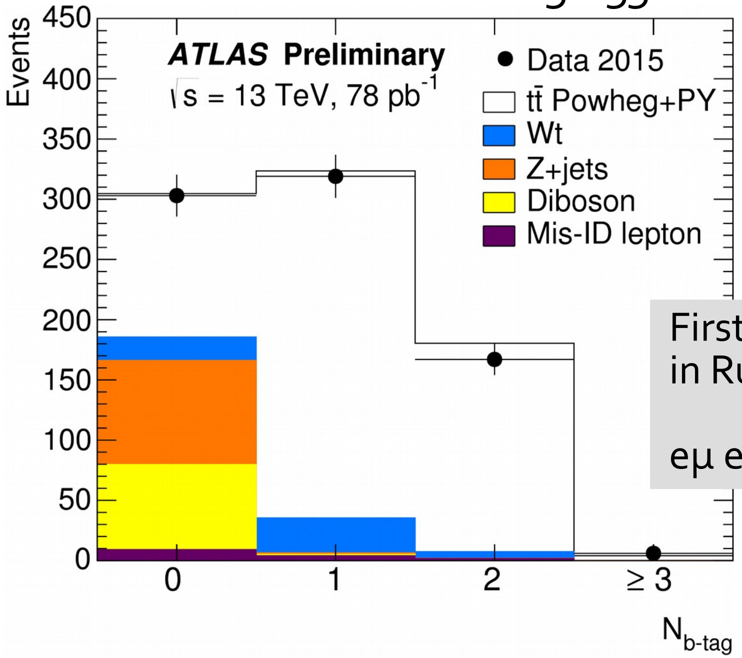
ATLAS-TDR-19



Summary

- ttH is a key channel to measure the top Yukawa coupling and constrain new physics
- Multiple channels are available to search for the signal
  - discovery will be from combination, not from a single channel
- Core Run 1 analyses done, look forward to increased statistics of Run 2!

ATLAS-CONF-2015-033

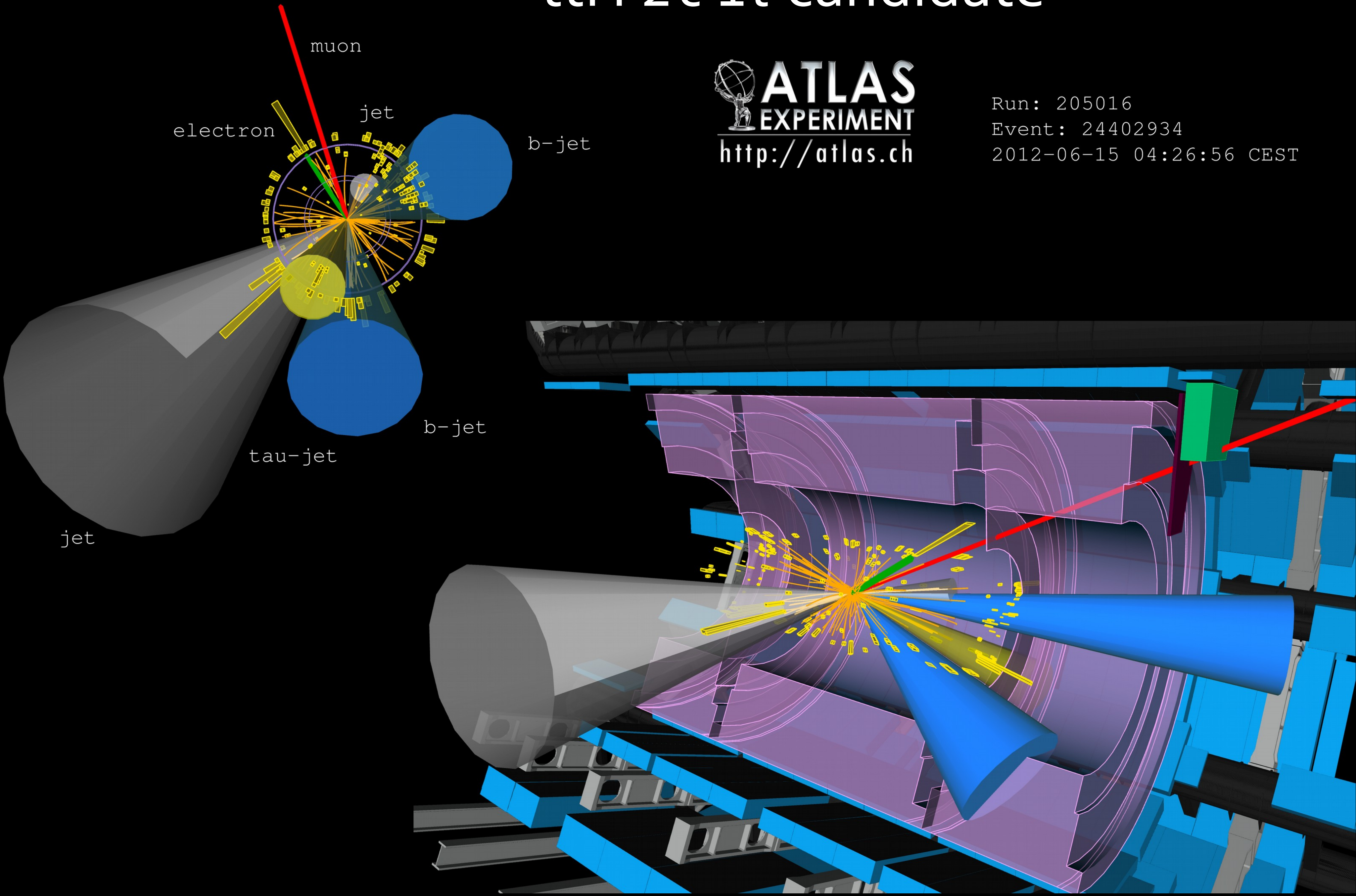


First dilepton $t\bar{t}$ in Run 2

eμ events

ttH observation is likely in Run 2: needs combination of channels

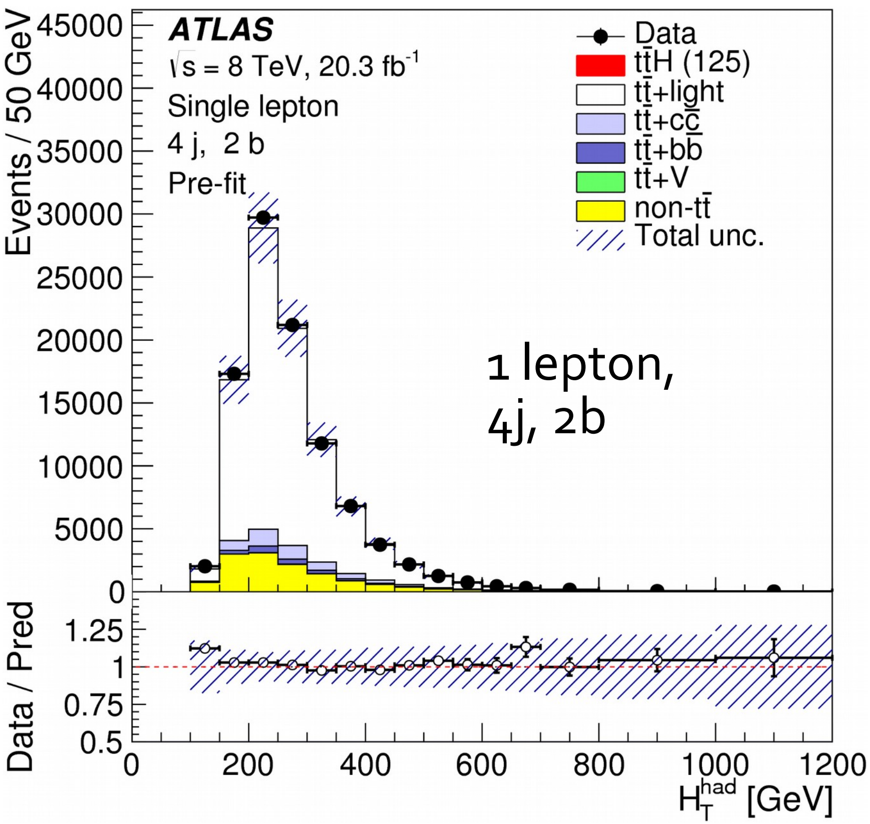
ttH 2ℓ 1τ candidate



Extra

How to look for ttH?

- Generic signature is top pair + a Higgs decay
  - H ⟶ γγ has a narrow bump
  - H ⟶ bb has a large rate
  - H ⟶ WW, H ⟶ ττ produce multilepton events
  - H ⟶ ZZ ⟶ 4ℓ has too low a rate
- Top pairs have a characteristic signatures of leptons, jets, and b-tagged jets

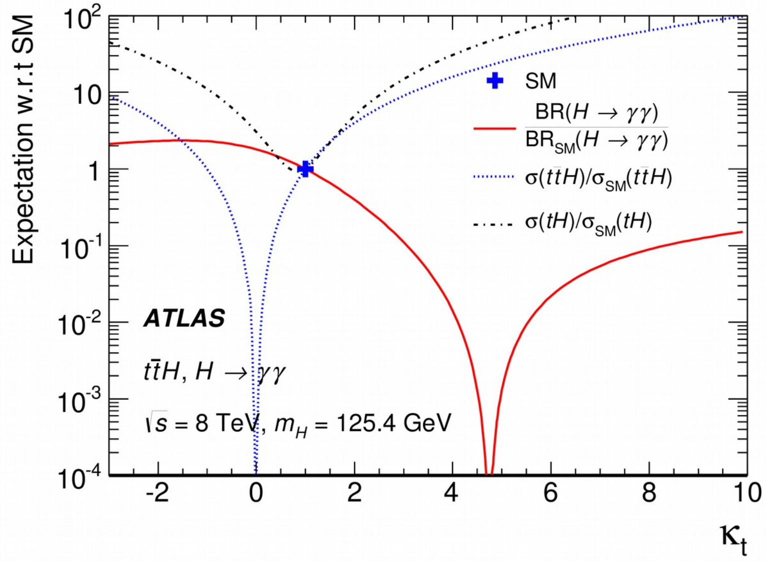


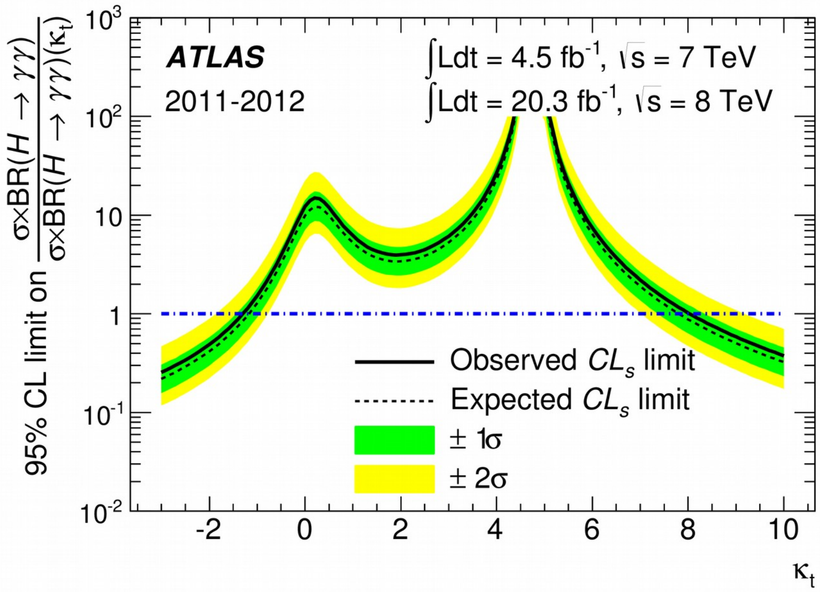
[8 TeV] Diphoton Selection

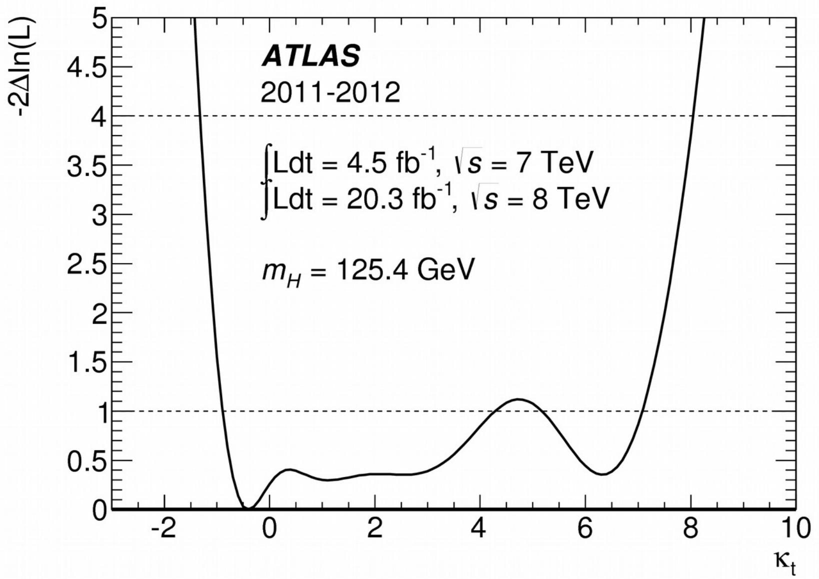
- trigger: diphoton, p_T > (35, 25) GeV
- photons: leading (subleading) p_T > 0.35 (0.25) x $m_{\gamma\gamma}$; require == 2 photons
- leptons: e p_T > 15 GeV; μ p_T > 10 GeV
- leptonic channel: ≥1 lepton, M(eγ) not in [84, 94] GeV, ≥ 1j @ 25 GeV, ≥ 1b @ 80% WP, ETmiss > 20 GeV if only one b-jet
- hadronic channel: no leptons
  - ≥ 6j @ 25 GeV, ≥ 2b @ 80% OR
  - ≥ 5j @30 GeV, ≥ 2b @ 70% OR
  - ≥ 6j @30 GeV, ≥ 1b @ 60%

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	$2.7^{+0.9}_{-0.7}$

Diphoton Coupling Interpretation

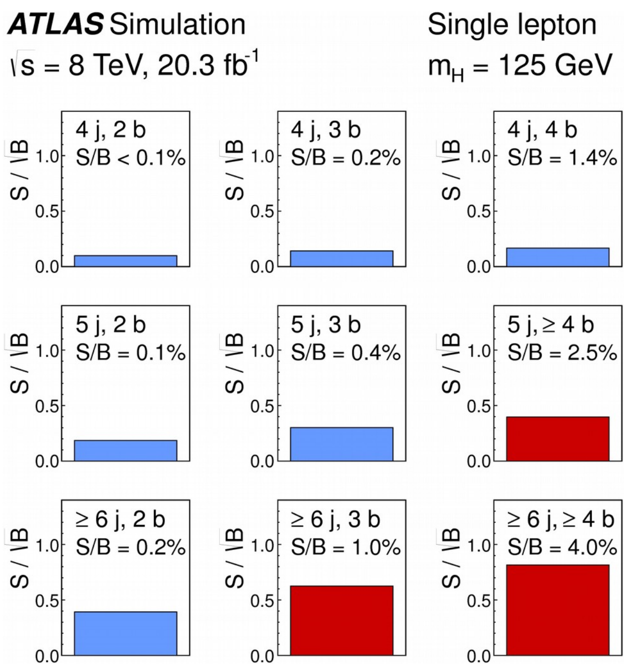


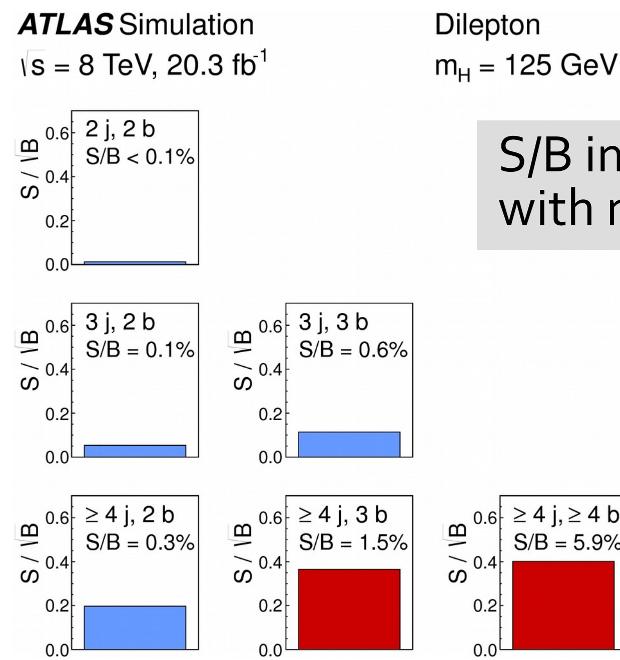




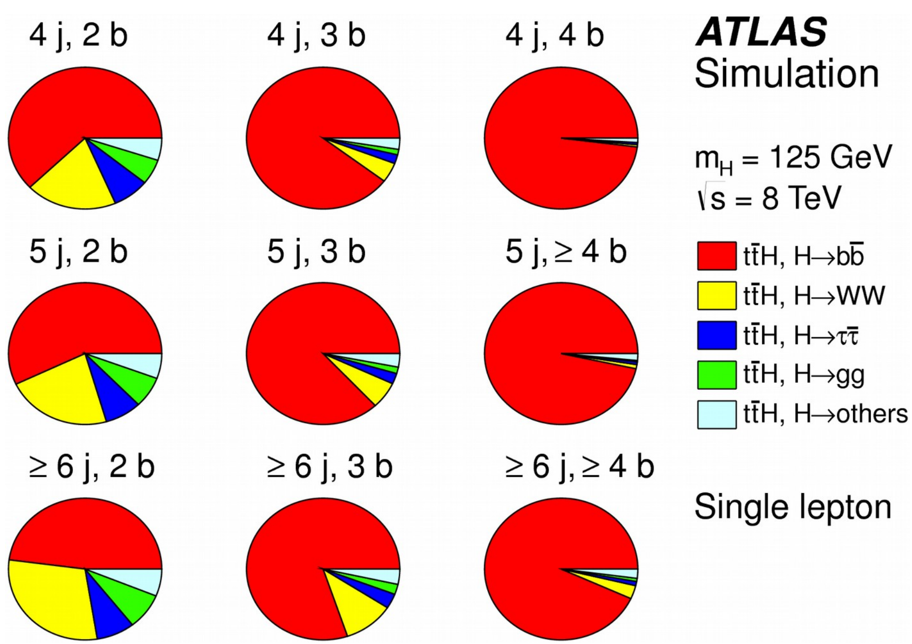
κ_t scales the SM Yukawa coupling (1=SM)

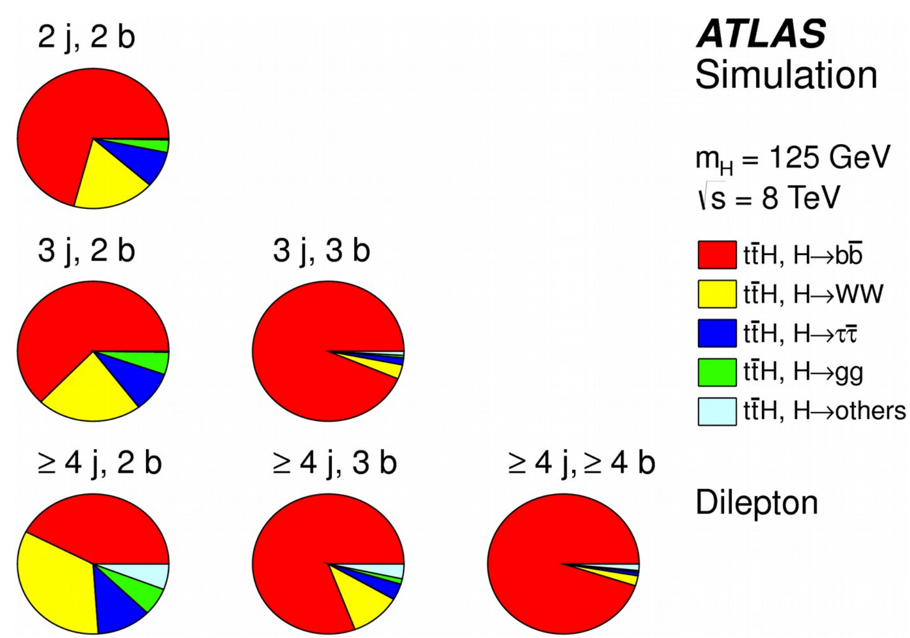
Categories





S/B improved with neural net





Event Selection

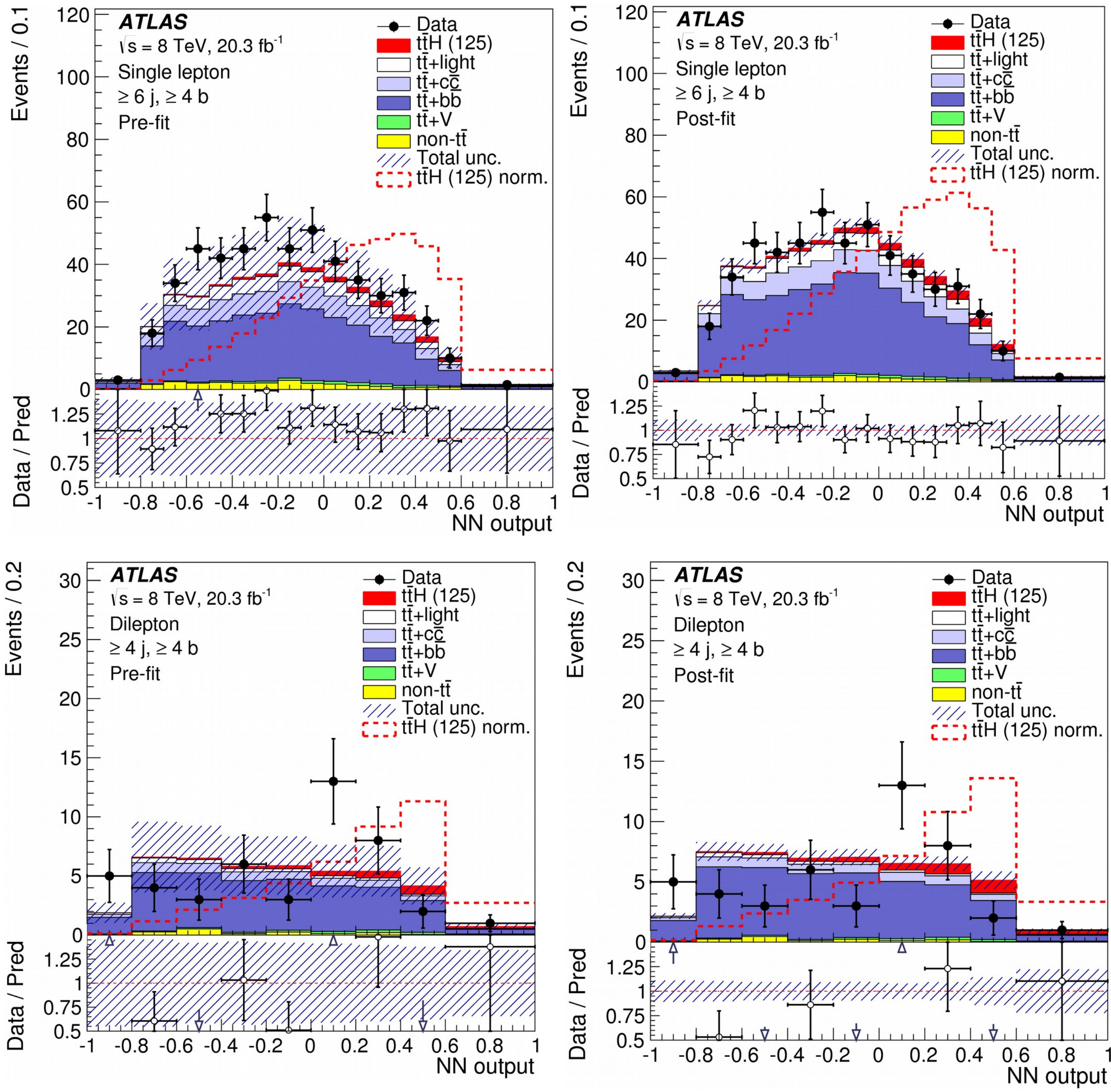
- trigger: single lepton triggers (e or μ); full efficiency @ 25 GeV
- leptons: leading $p_T > 25$ GeV, subleading $p_T > 15$ GeV (dilepton channel)
  - 1, 2-lep channels have no overlap
  - dilepton: Mll > 15 GeV, veto events with Mll = $M_Z \pm 8$ GeV for same flavor; $H_T > 130$ GeV for eμ
- jets: anti-k_T 0.4, $p_T > 25$ GeV, $|\eta| < 2.5$
- b tagging: 70% efficiency working point

Top Pair Modeling

- Simulations of top quarks + extra jets are still not super-sophisticated
  - Leading order matched simulations (MadGraph/Sherpa) can certainly do a consistent job
  - NLO generation for extra heavy flavor just becoming available, not yet possible to do *full* (light+heavy quark) matched NLO with mass effects
- The vast majority of tt+bb in the relevant kinematic regions comes from parton shower, even in LO matched simulations
  - guessing the kinematic regions where ME and PS are important (which you need to do for Alpgen matching) is a **bad idea**
- We find best agreement in control regions with Powheg+Pythia (NLO) – this is our baseline

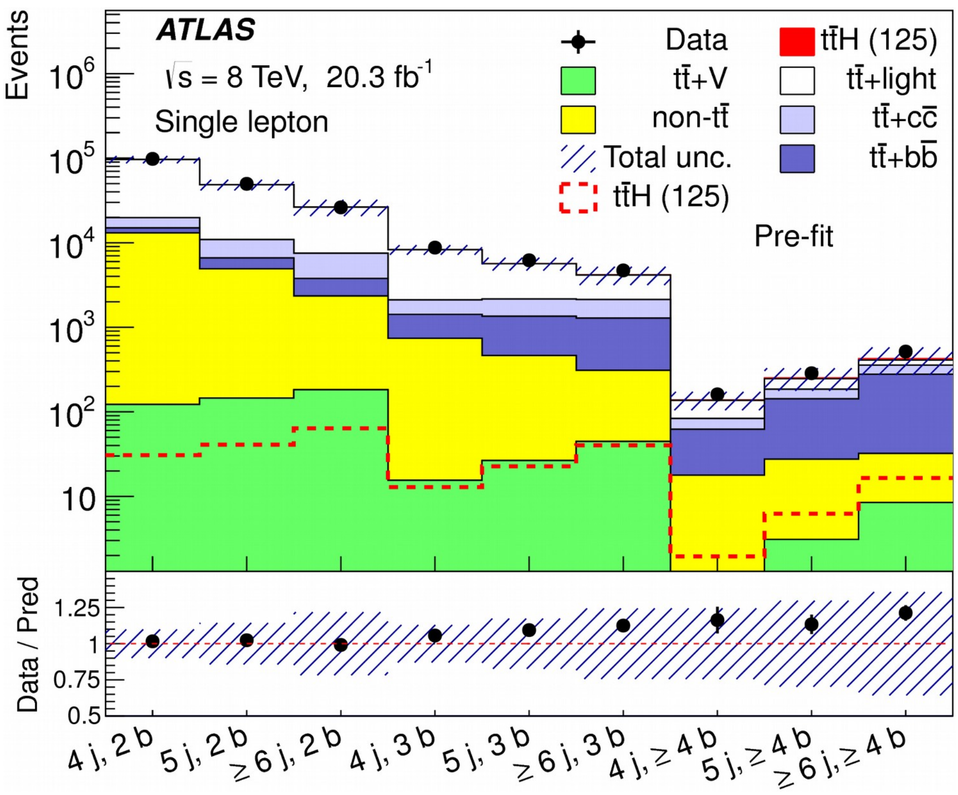
Fit effect on Signal-Rich Regions

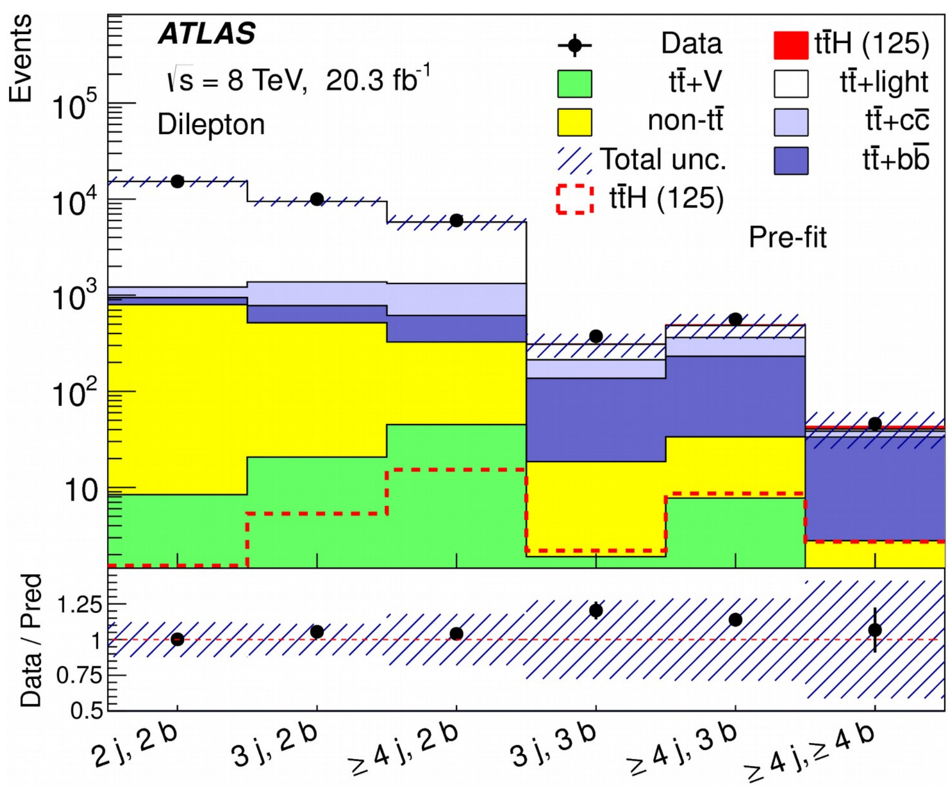
Profile fit collapses systematics – large correlations



Pre-Fit Yields

- Most tt+light in l+jets 3b comes from W → cs tags
  - no analog in 2l



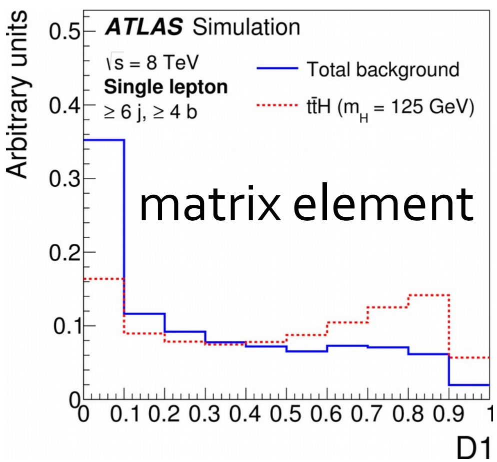


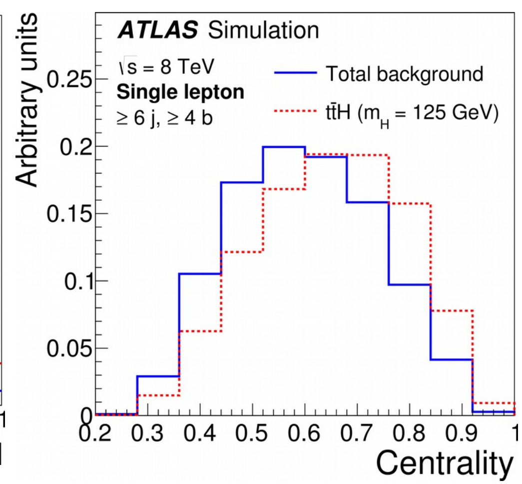
NN Variable Separation

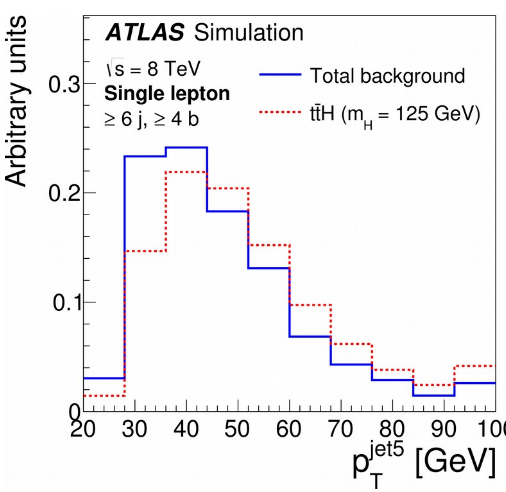
- Four highest ranked variables shown

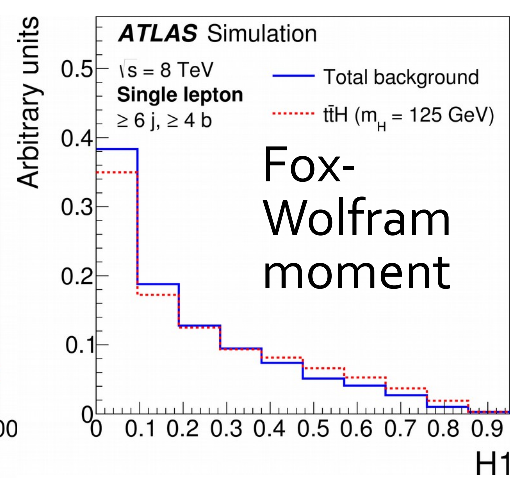
$$D1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + 0.23 \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}}$$

l+jets ≥6j ≥4b

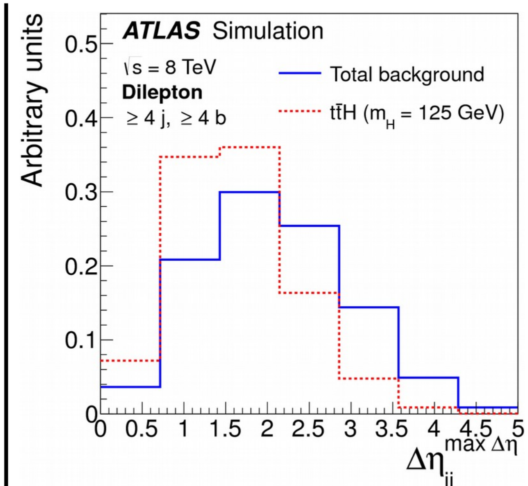


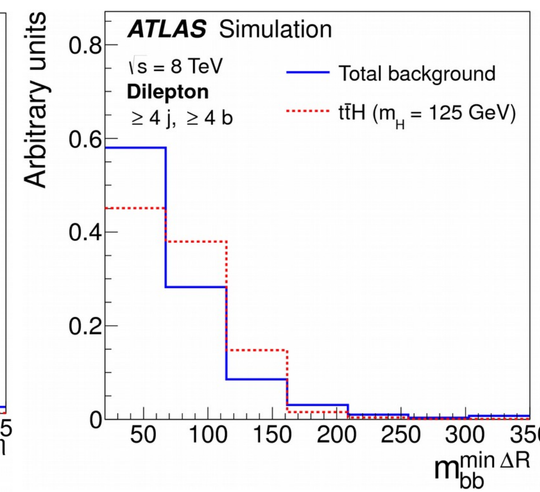


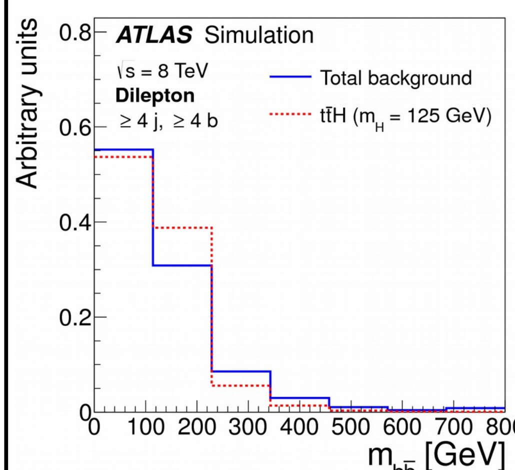


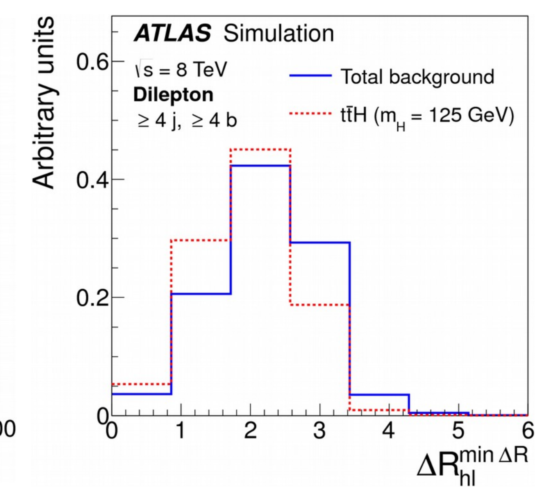


dilepton ≥4j ≥4b









The Fit

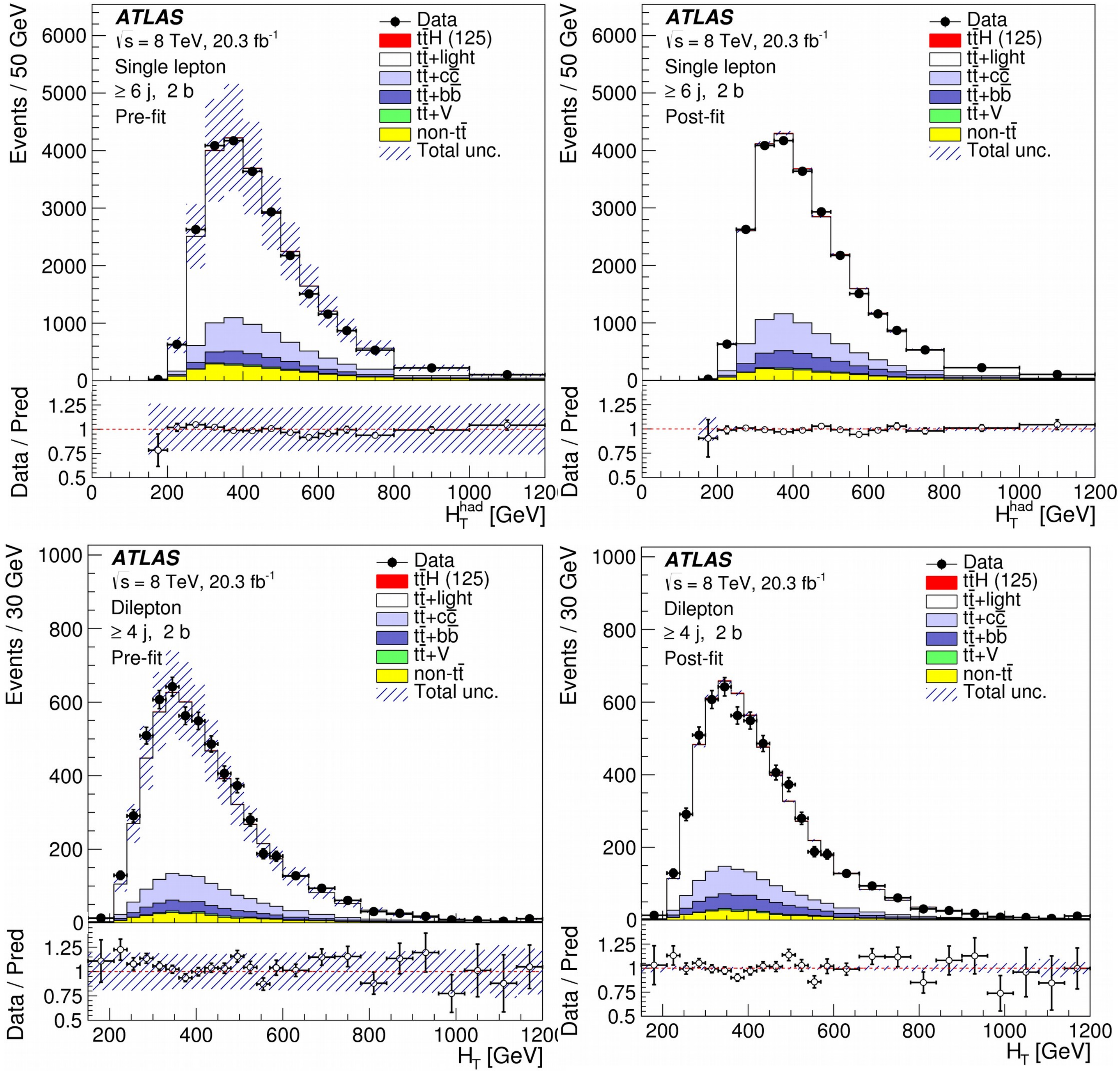
- Systematic uncertainties are "profiled" in the fit: we provide an initial constraint and allow data to update the values & errors
  - in particular this constrains background systematics using bkg-rich regions, and allows in situ charm tagging measurement
- All control and signal regions for lepton + jets and dileptons fit simultaneously
  - of course we can cross check between the channels; excellent agreement seen on central value of systematic nuisance parameters

bb Systematics

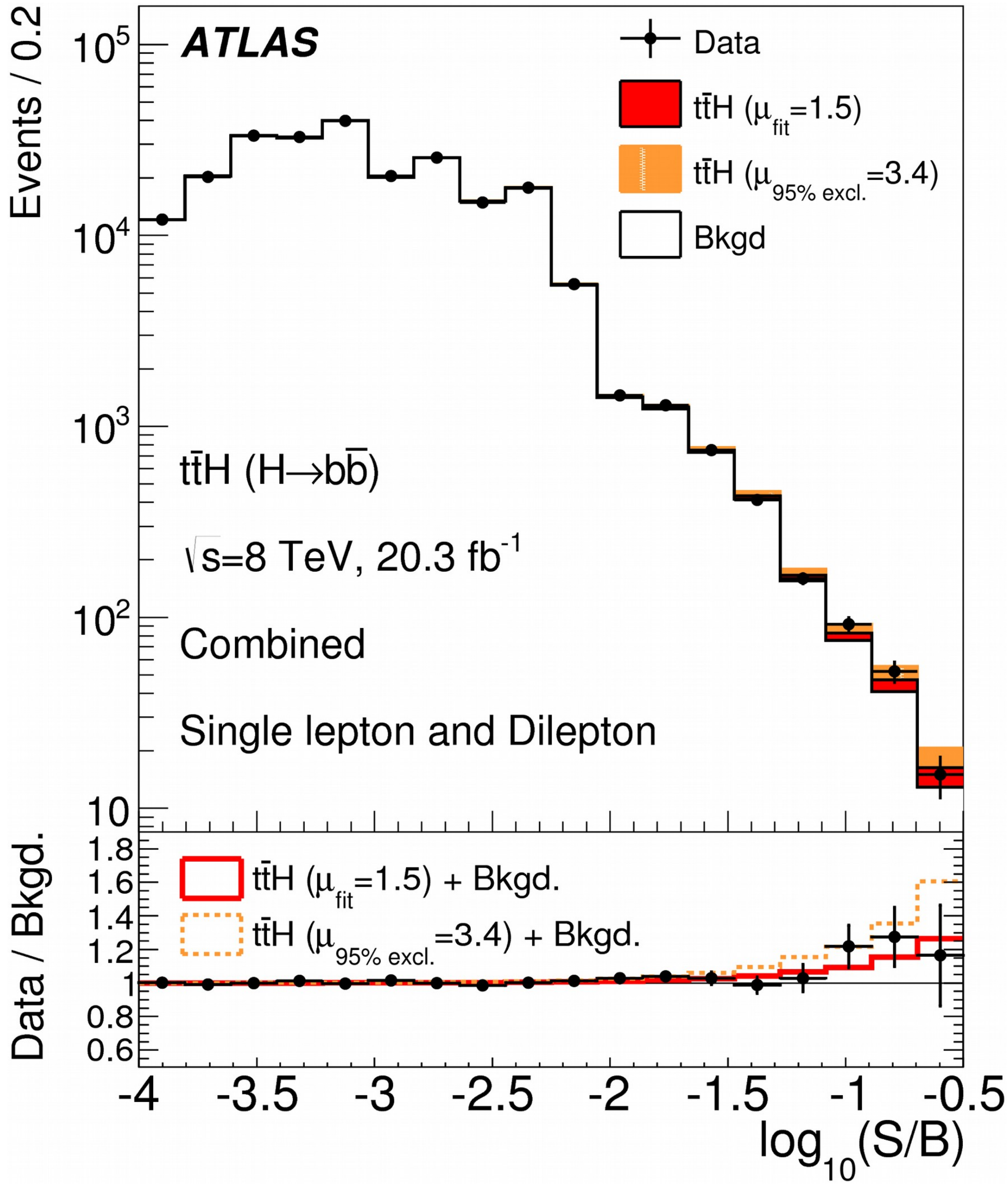
Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency	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

Largest effects come from tt+HF normalization, the tt reweighting, and b-tagging

Fit effect in Background-Rich Regions

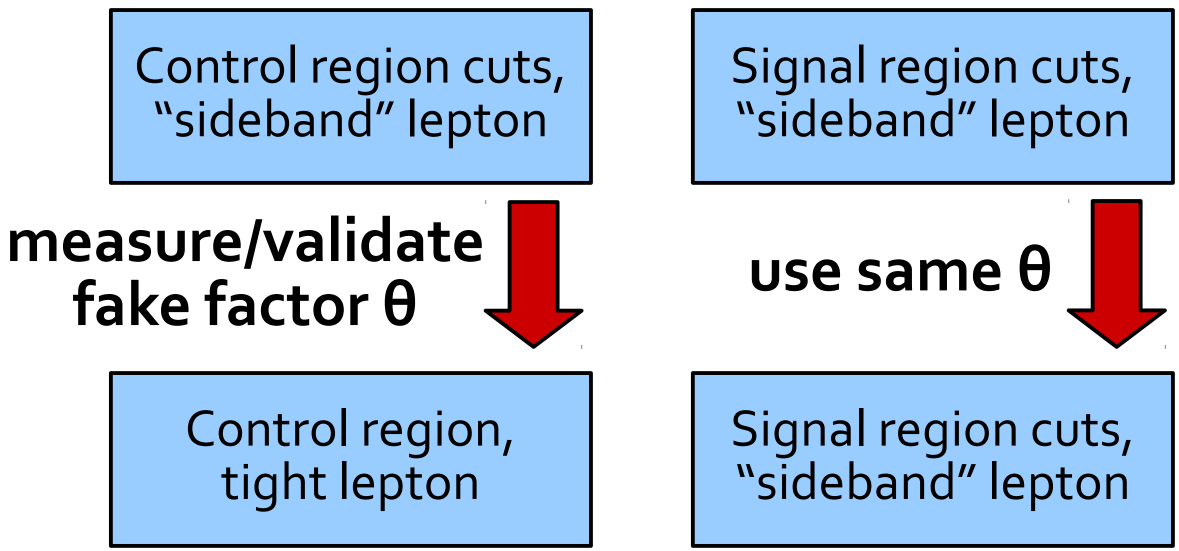


S/B Visualization



Fake Lepton Backgrounds

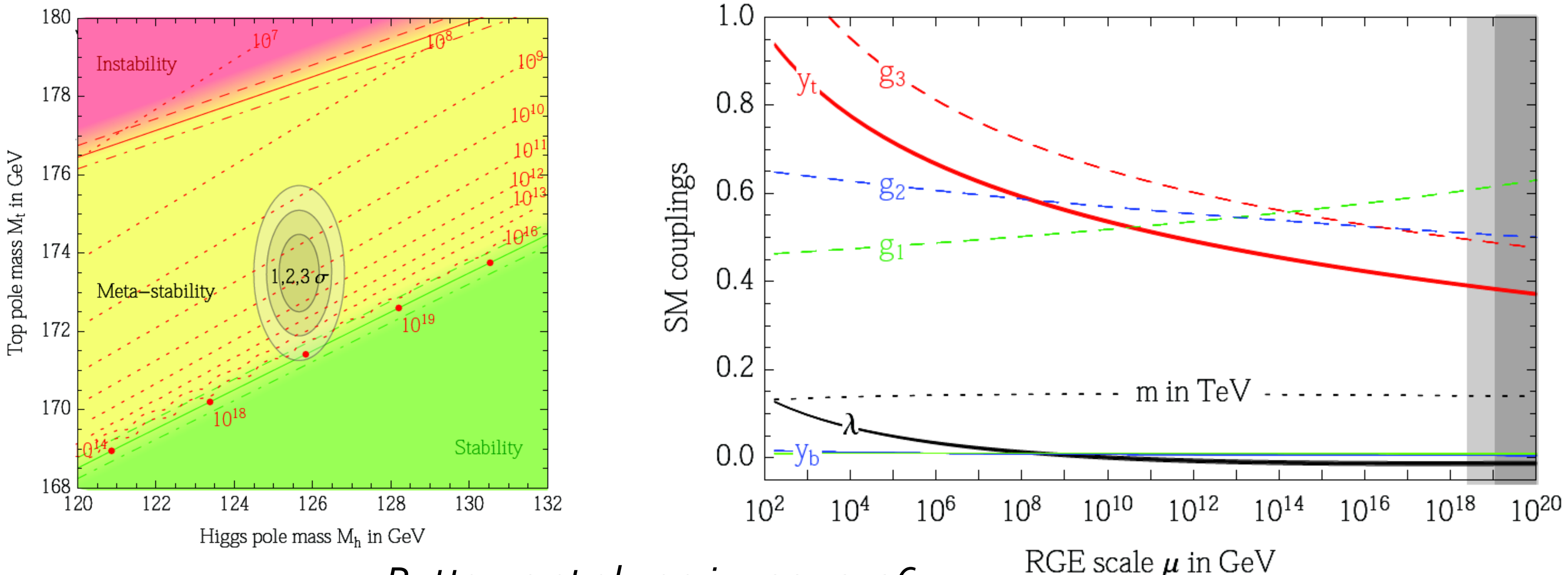
- Slightly different techniques in each channel.
  - 2ℓ0τ, 3ℓ, 2ℓ1τ: variants on "fake factor" methods
  - 4ℓ: limit from MC
  - 1ℓ2τ: predict fake τ bkg from MC (well modeled with looser event cuts)



e.g. 2ℓ0τ: control region cuts: lower # jets than SR
sideband leptons: non-isolated electrons, low-p_T muons

Vacuum Metastability

- Another reason to care about the top Yukawa: SM vacuum apparently metastable given m_H and m_t (aka, y_t). If actual y_t is different from SM, this issue has a different resolution



Buttazzo et al., arxiv:1307.3536