ttH + other near term Higgs measurements

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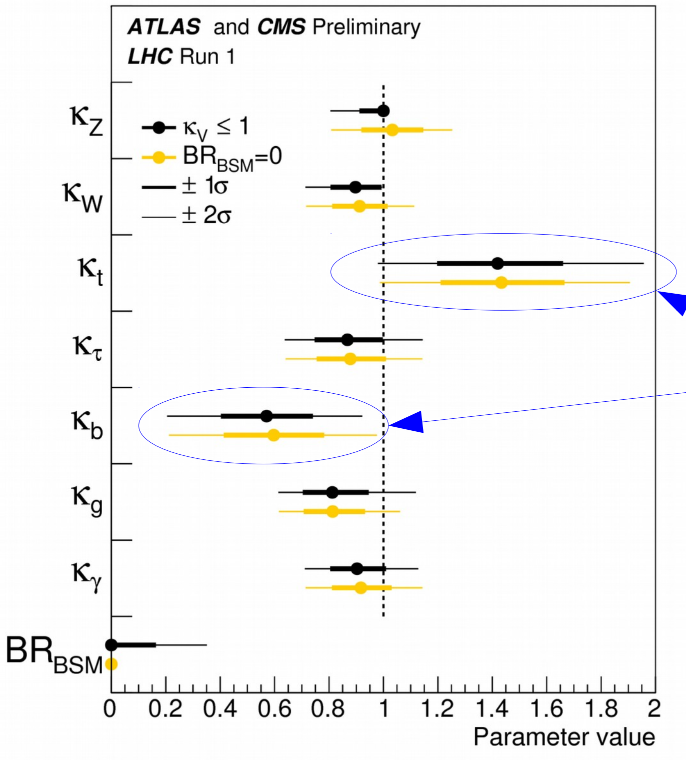
Intro

- Fermion couplings
  - with special attention to ttH …
- Differential σ
- Alternate presentations of data

Of course, there are many more measurements coming!

Details shown will be from ATLAS - expts typically have very similar solutions to problems



The 2σ anomalies in the combined ATLAS+CMS fit are in the fermion couplings…

(leaving gluon coupling free)

ATLAS+CMS combo:
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

SM Matrix

	ggF	VBF	VH	ttH
γγ	✓	✓	✓	✓
ZZ	✓	✓	✓	✓
WW	✓	✓	✓	✓
ττ	✓	✓	✓	✓
bb		✓	✓	✓

- Measurements/searches in all reasonable channels
- Production mode searches also probe decays
  - e.g. $H \longrightarrow bb$ constrant from ttH, $H \longrightarrow bb$ search

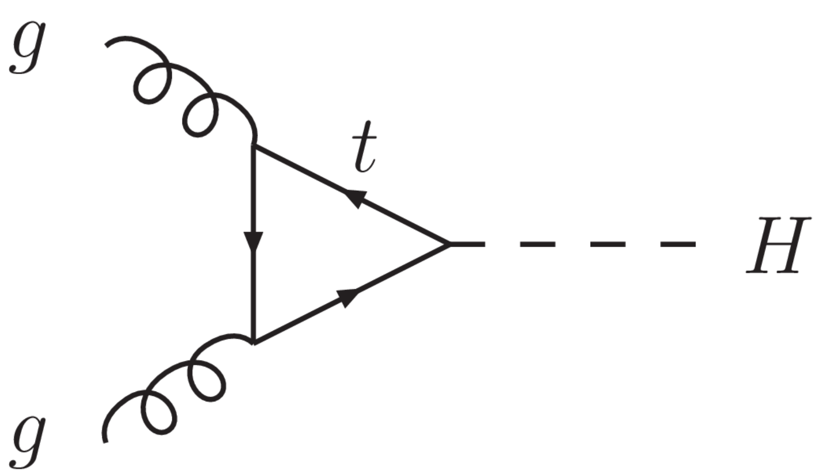
A Note on Projections

- We tend to brute-force "early" measurements using dirtier signatures (high stats, but large systematics)
- Currently subleading channels may dominate sensitivity in the future – but "future" may be > 300 fb^{-1}
  - and, honestly, we learn how to do existing analyses better with time
- Comments about projected sensitivity only "official" if explicitly noted

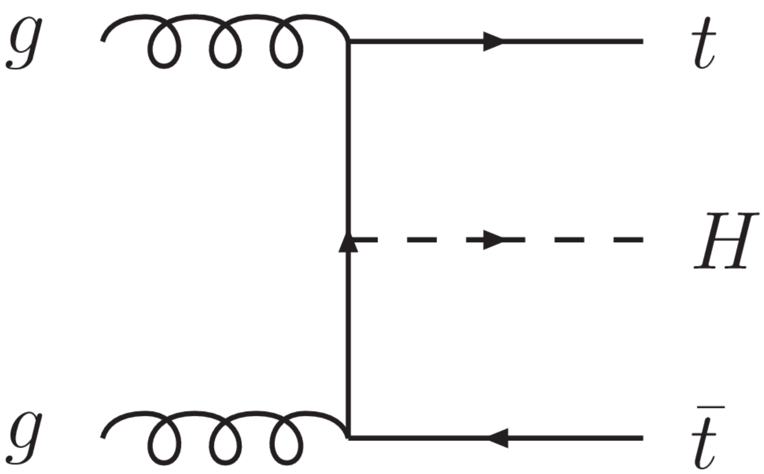
It's tough to make predictions, especially about the future

How to measure the Top-Higgs Coupling?

- Highest rate way: gg ⟶ H through top loop
- However, with just rate measurement, effects of top are not distinguishable from new physics in gg ⟶ H or qq ⟶ H
- Tree-level measurement: pp ⟶ $t\bar{t}$H
  - sensitive to NP in different ways



19 pb @ 8 TeV
44 pb @ 13 TeV



130 fb @ 8 TeV
510 fb @ 13 TeV

ttH + EFT

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

Higgs-gluon coupling:

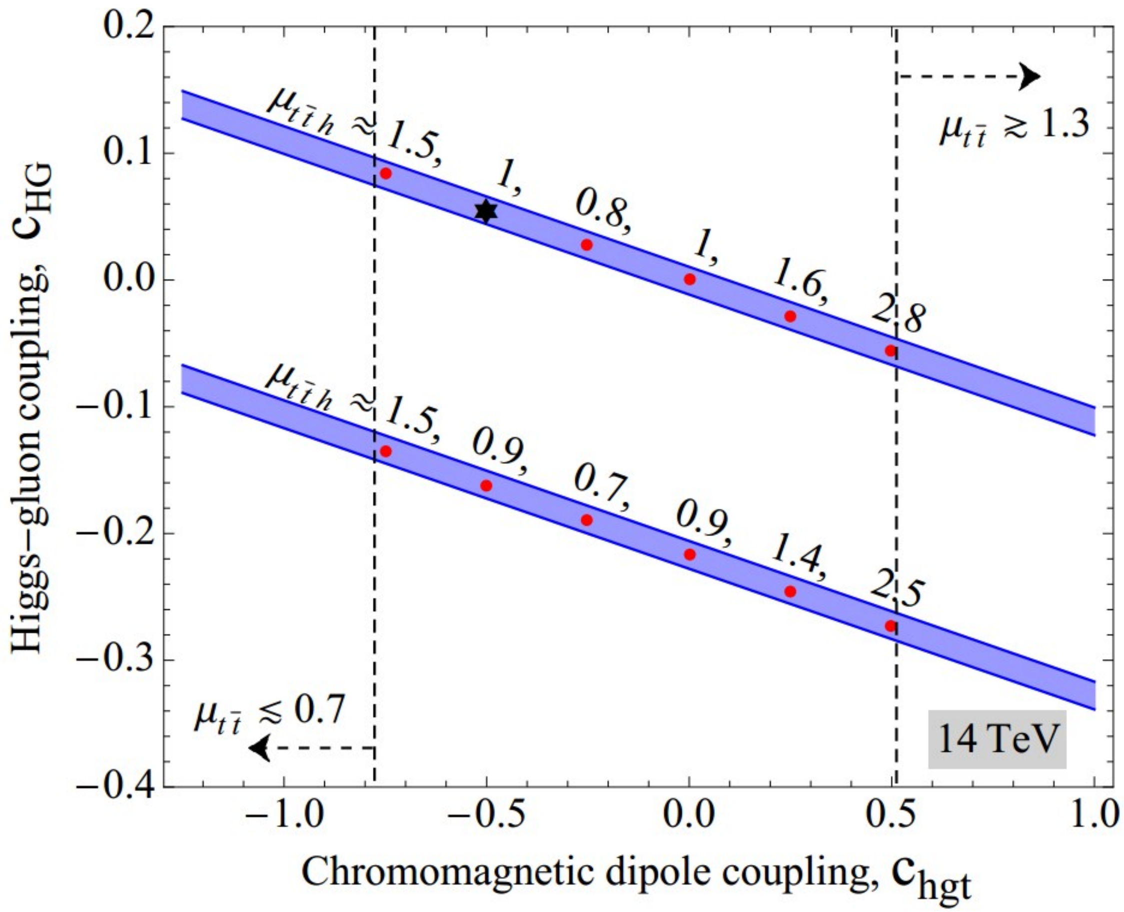
$$\mathcal{O}_{HG} = \frac{c_{HG}}{2\Lambda^2}(H^\dagger H)G_a^{\mu\nu}G^a_{\mu\nu}$$

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

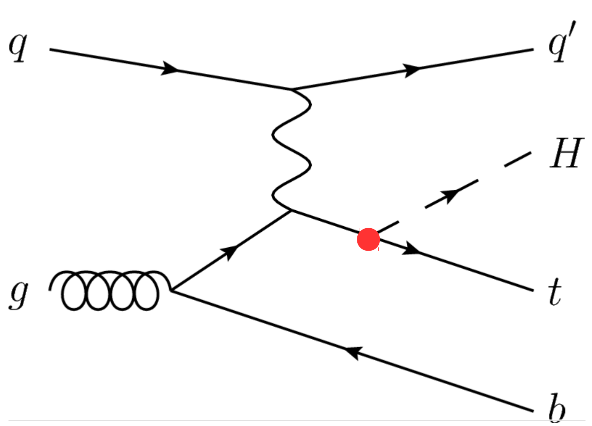
Also illustrates interplay with precision top measurements

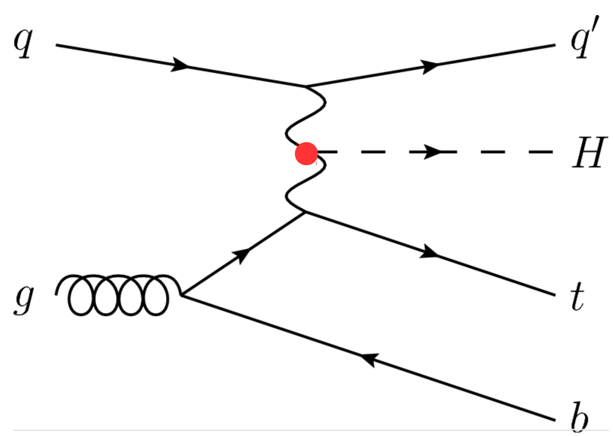


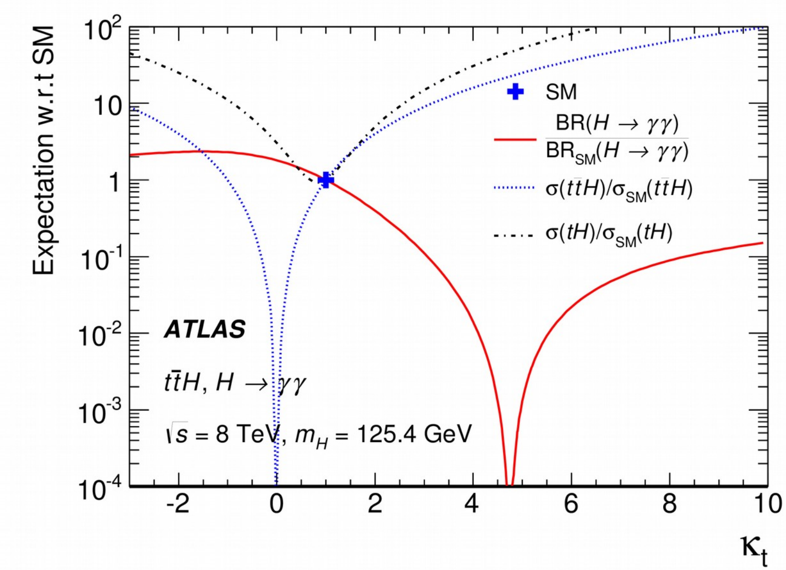
Bramante, Delgado, Martin PRD 89, 093006 (2014)

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/Ht$\bar{t}$ interference

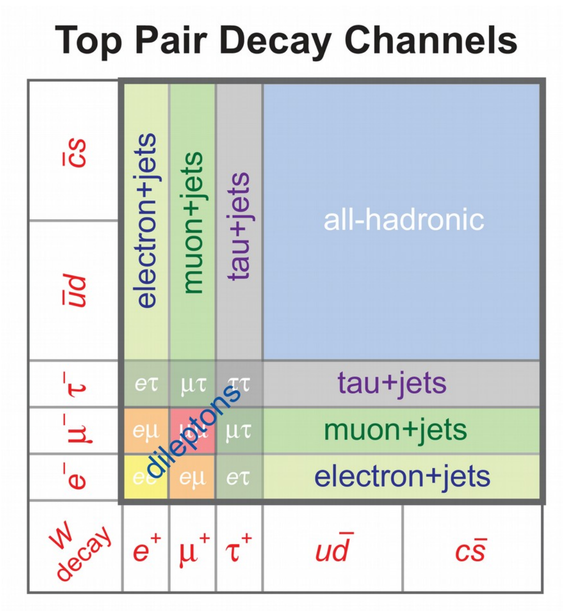


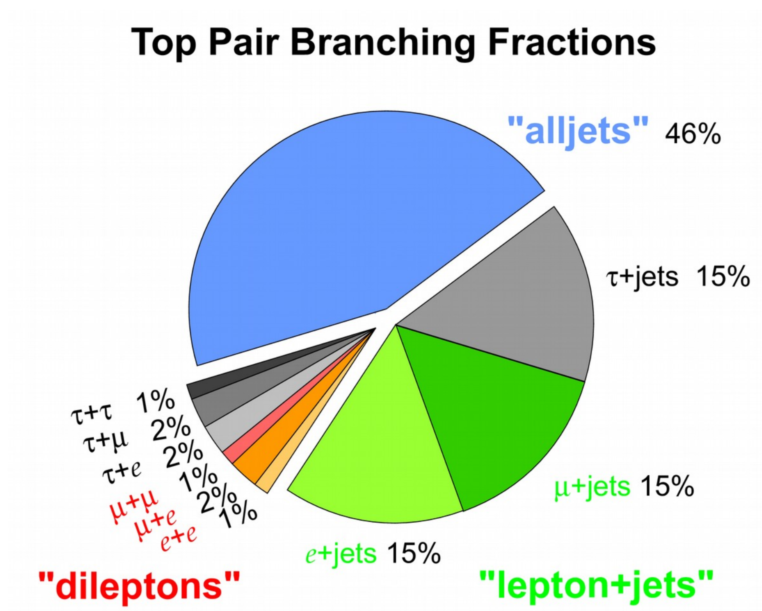




Finding ttH

- Signature is top pair decay + Higgs decay
- Top quarks decay ~ 100% via $t \rightarrow W\,b$
  - 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? Contamination of 15-30% of other production
- Indirectly sensitive to tH (leptonic selection can be very loose)
  - Can imagine an additional "tH" category to improve sensitivity

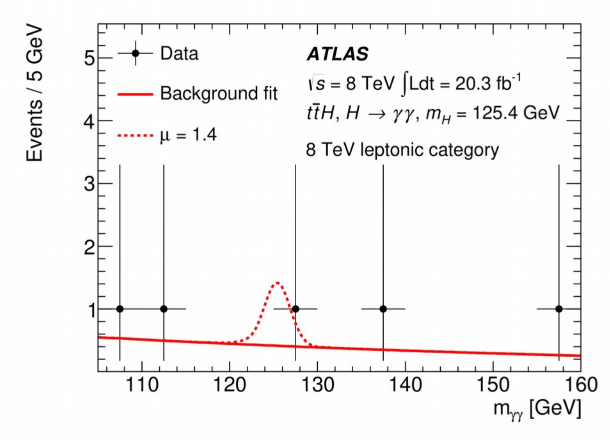
ATLAS ttH, H → γγ purity

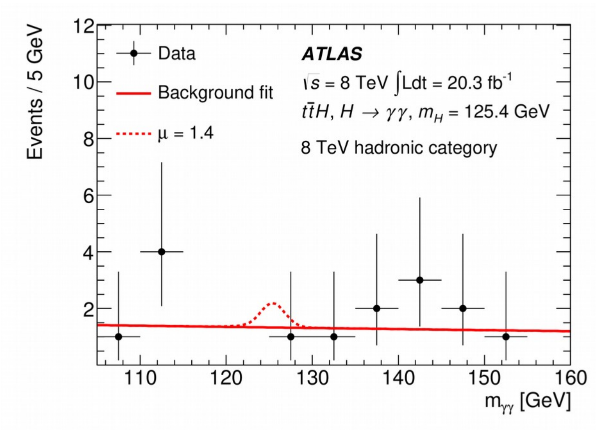
PLB 740 222 (2015)

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

SM tH production

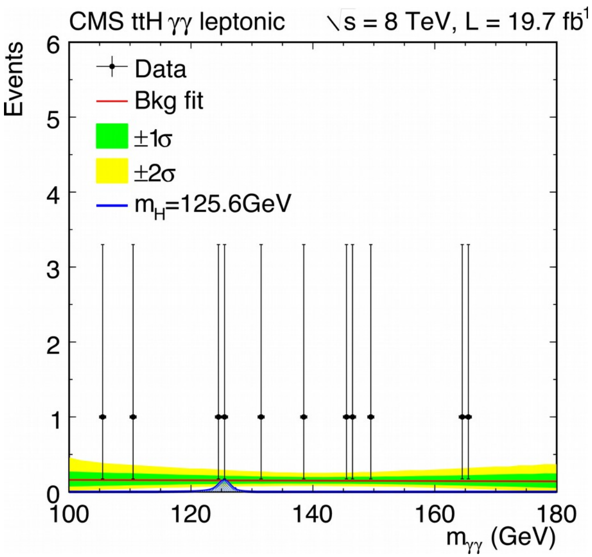
Diphoton Results

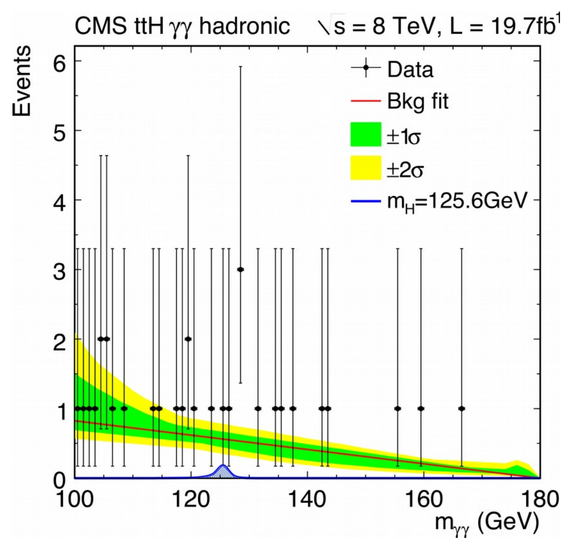




PLB 740 222 (2015)

$\mu < 6.7$ (4.9 exp) @95%





JHEP 09(2014) 087

$\mu < 7.4$ (4.7 exp) @95%

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

(μ = scaling of observed rate in acceptance)

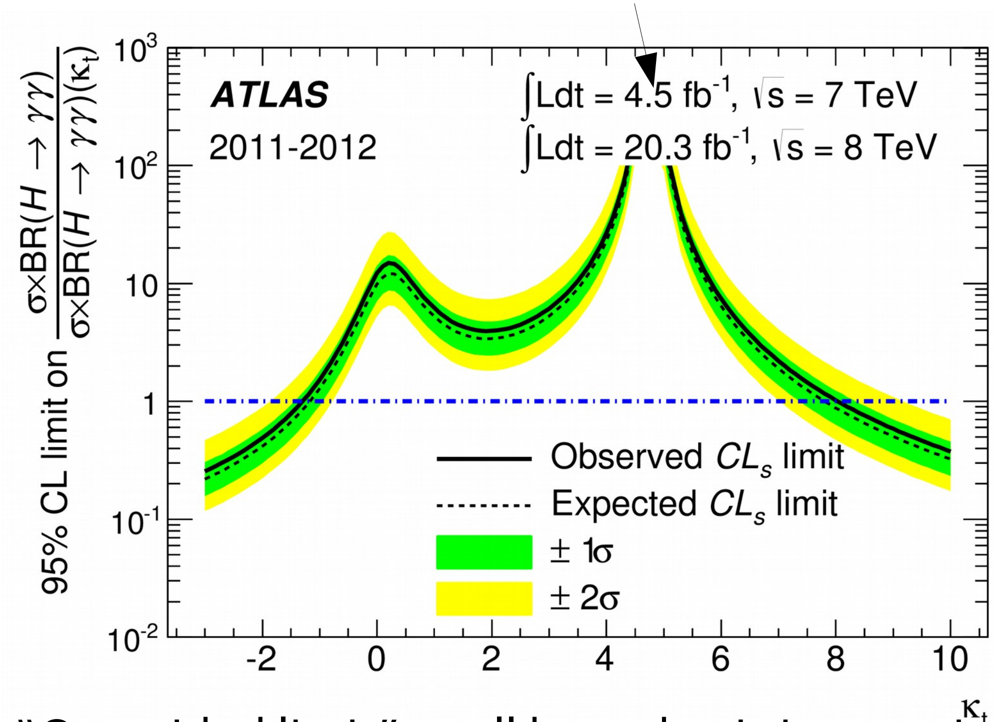
tH, H → γγ

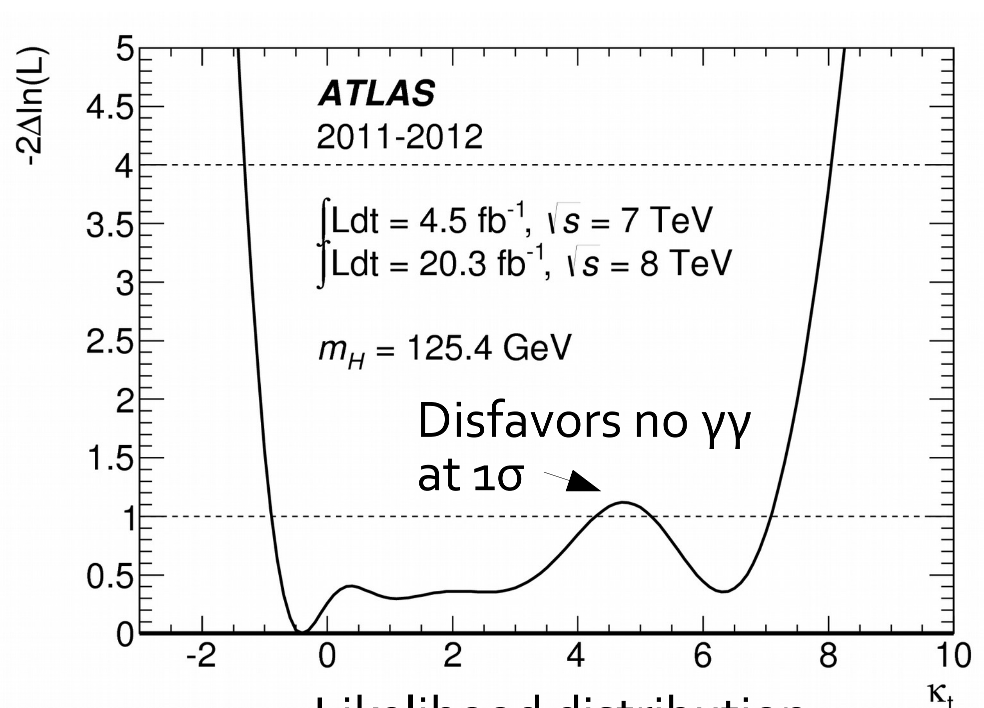
- Additional interpretation of ATLAS ttH[γγ] search
- Scan κ_t: rule out $\kappa_t < -1.3$ and $\kappa_t > 8.0$ at 95% CL

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

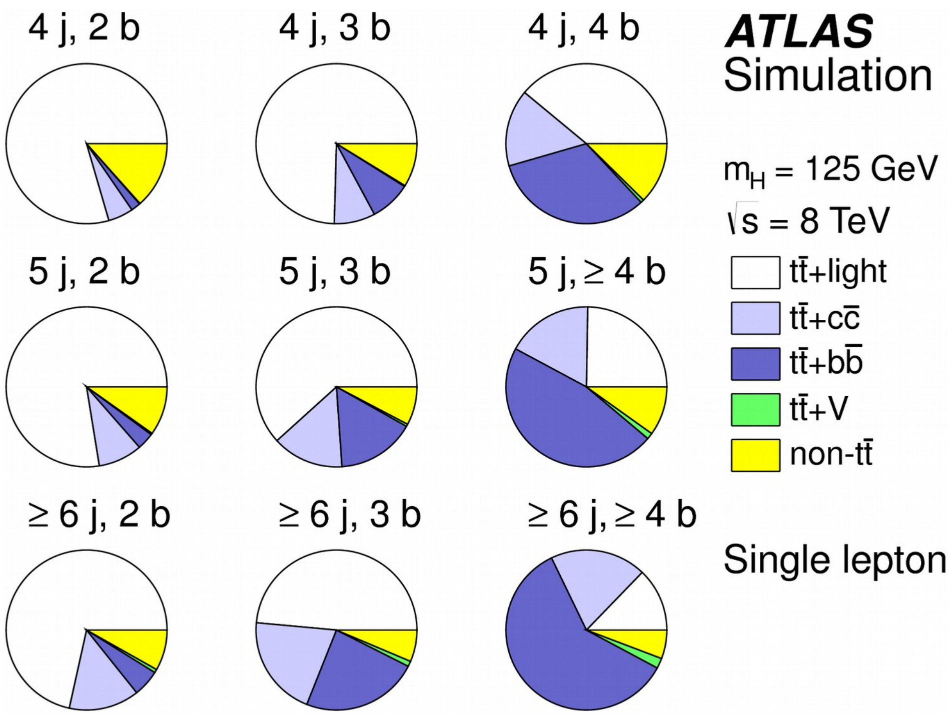
$H \to bb$

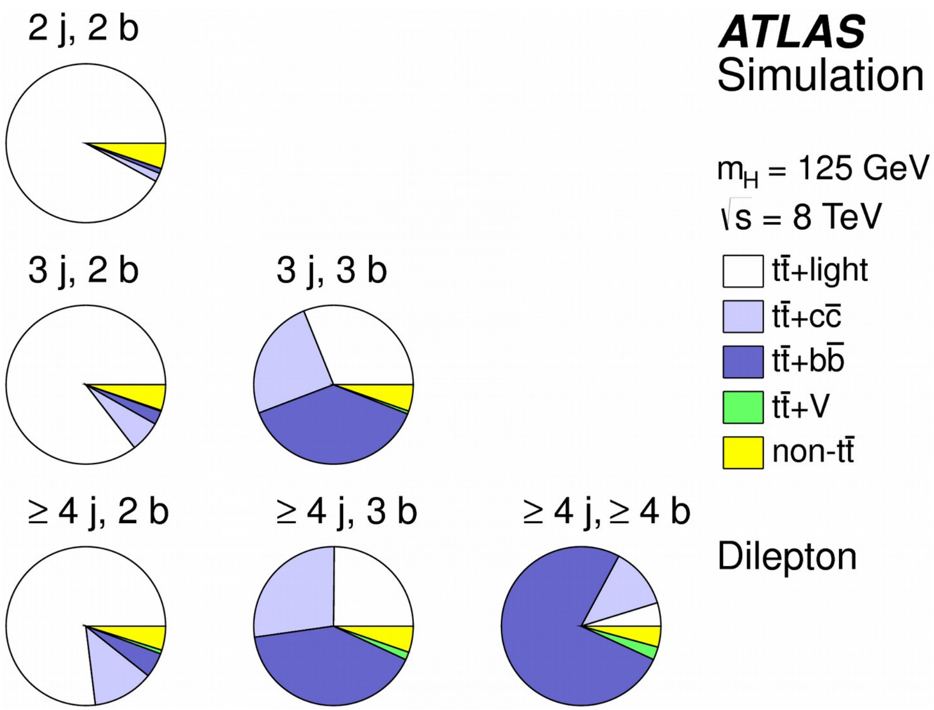
- $H \to bb$ is 58% of the SM Higgs width @ 125 GeV
  - Mass resolution is much worse than for γγ
  - Background (tt + heavy flavor jets) tricky to model
- Strategy: sort events by number of jets and b-tags, then in each channel classify events
  - if you're feeling sophisticated, use a neural network or matrix element methods
  - use background-rich channels to constrain background and detector systematics
  - sensitivity depends somewhat on where you place your jet p_T cut
- Only lepton+jets and dilepton channels shown by experiments so far

ATLAS: *EPJC 75 349 (2015)*
CMS: *JHEP 09(2014) 087*
CMS matrix element: *EPJC 75 251 (2015)*

Backgrounds

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





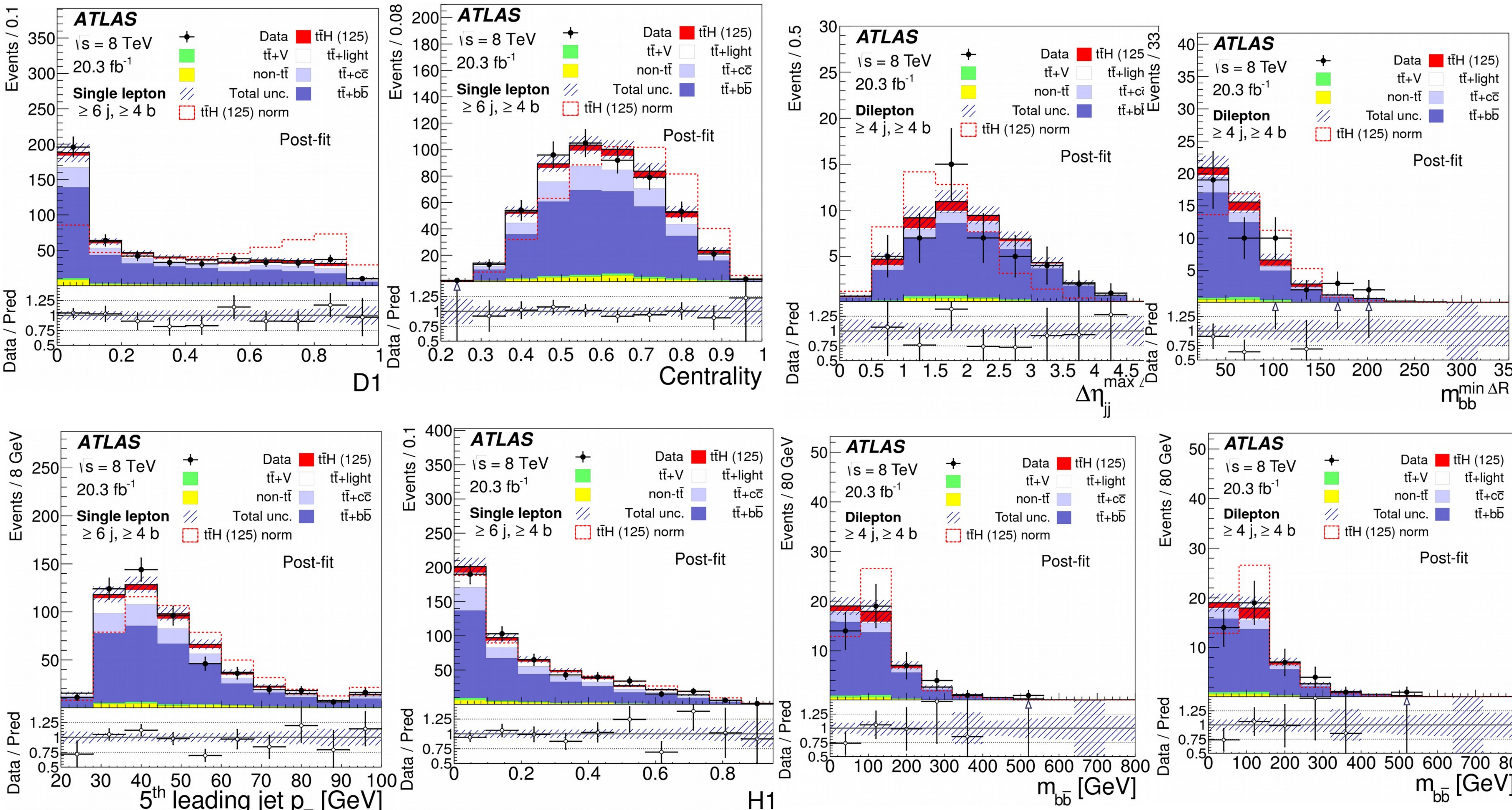
Variable Modeling

- Four highest ranked variables shown

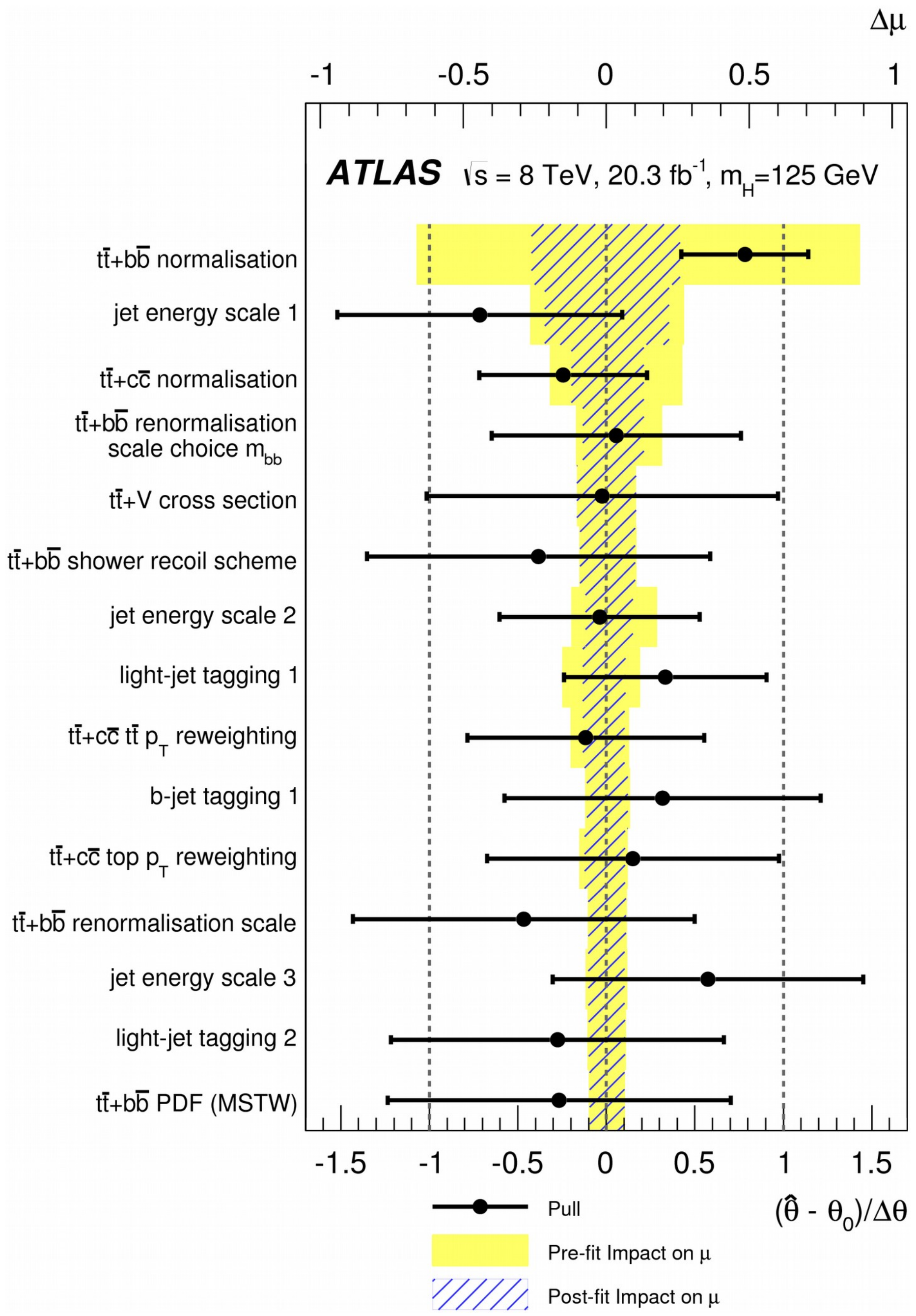
$$D1 = \frac{\mathcal{L}_{t\bar{t}H}}{\mathcal{L}_{t\bar{t}H} + 0.23 \cdot \mathcal{L}_{t\bar{t}+b\bar{b}}}$$

l+jets ≥6j ≥4b

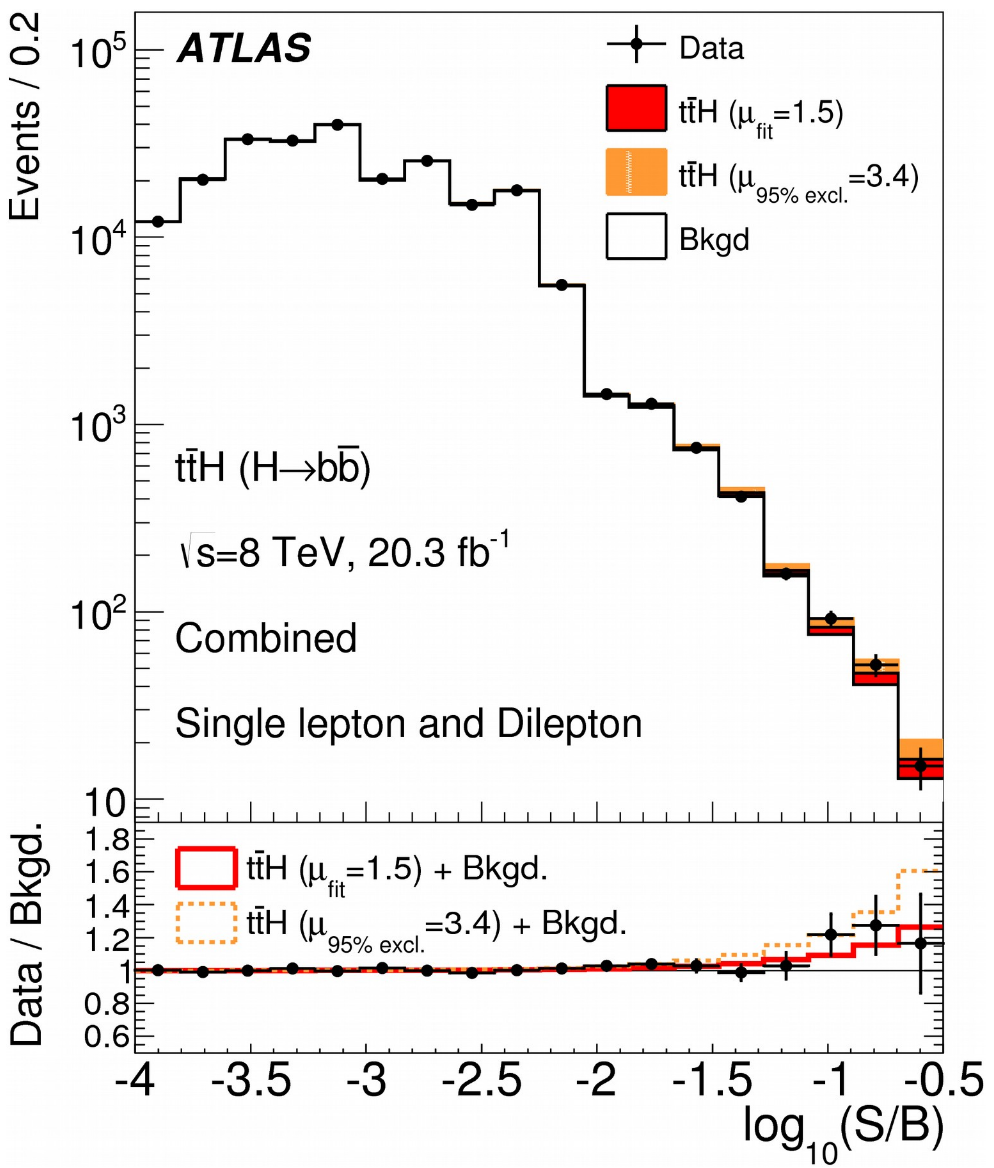
dilepton ≥4j ≥4b



Fit Results



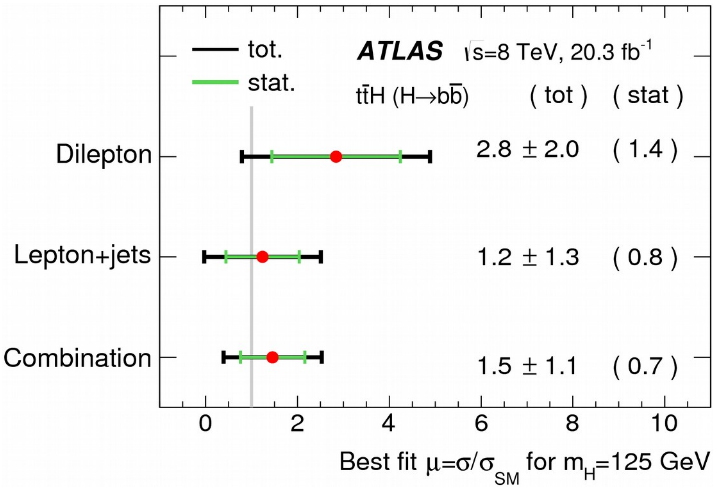
ATLAS √s = 8 TeV, 20.3 fb-1, mH=125 GeV
Δμ
tt̄+bb̄ normalisation
jet energy scale 1
tt̄+cc̄ normalisation
tt̄+bb̄ renormalisation scale choice mbb
tt̄+V cross section
tt̄+bb̄ shower recoil scheme
jet energy scale 2
light-jet tagging 1
tt̄+cc̄ tt̄ pT reweighting
b-jet tagging 1
tt̄+cc̄ top pT reweighting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



ATLAS
Data
tt̄H (μfit=1.5)
tt̄H (μ95% 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 (μfit=1.5) + Bkgd.
tt̄H (μ95% excl.=3.4) + Bkgd.
log10(S/B)

Results

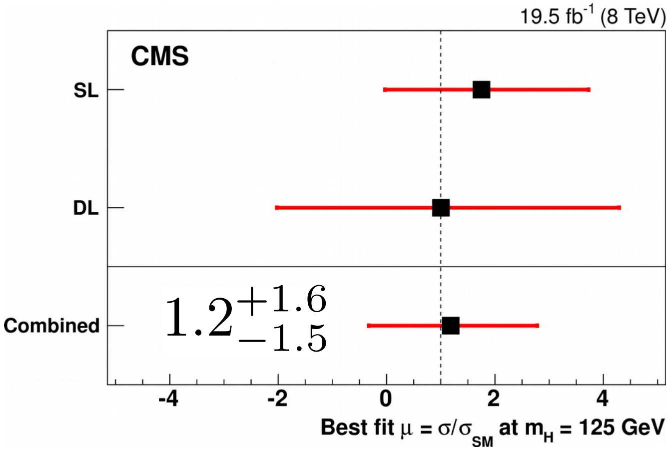
ATLAS

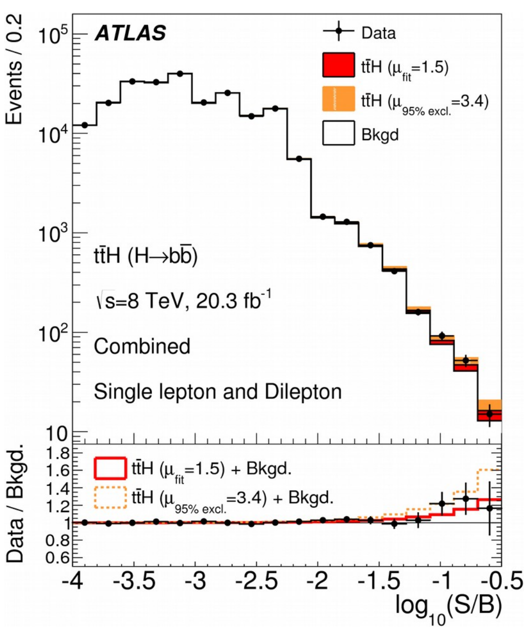


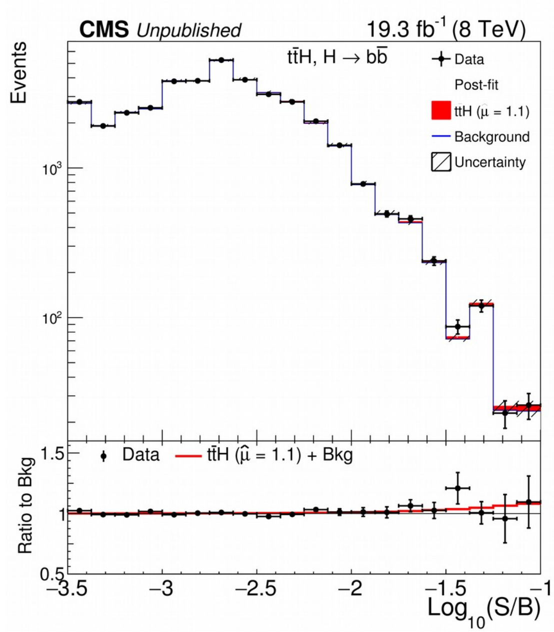
CMS nominal

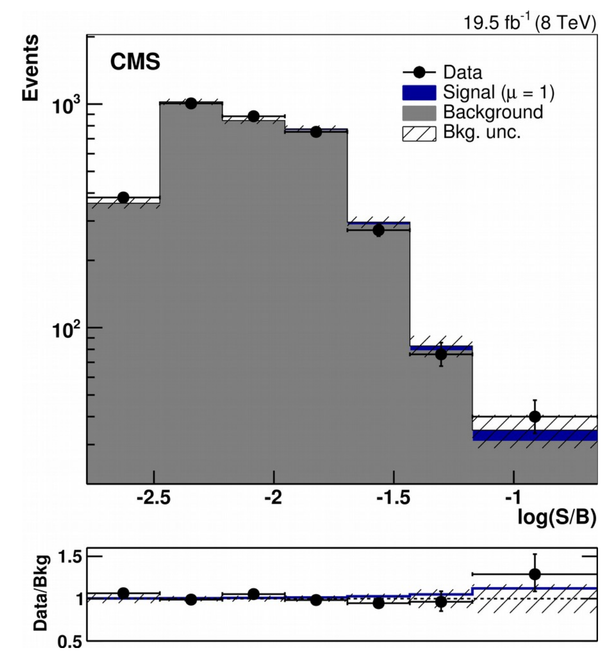
$$0.7 \pm 1.9$$

CMS matrix element









EPJC 75 349 (2015)

JHEP 05(2013) 145

EPJC 75 251 (2015)

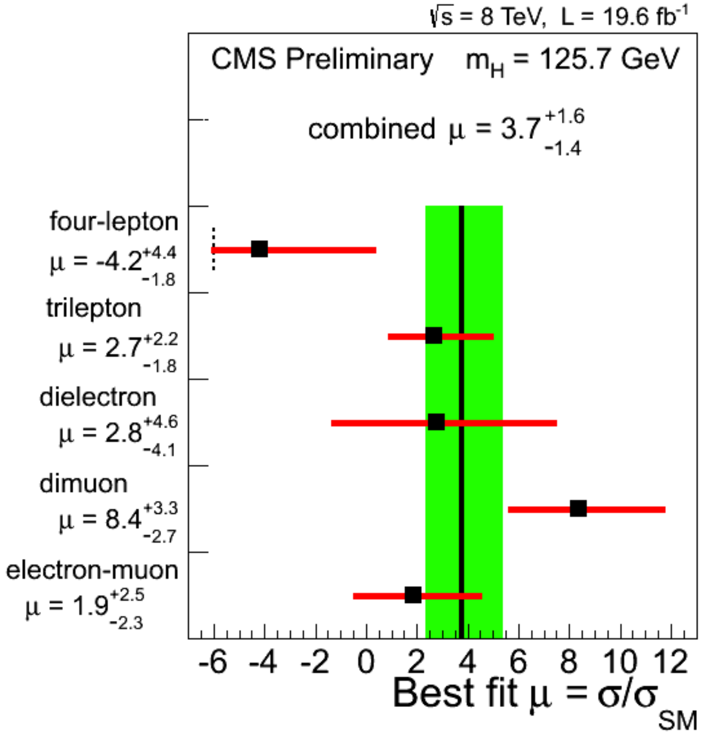
ttH, H → WW/ττ

- 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

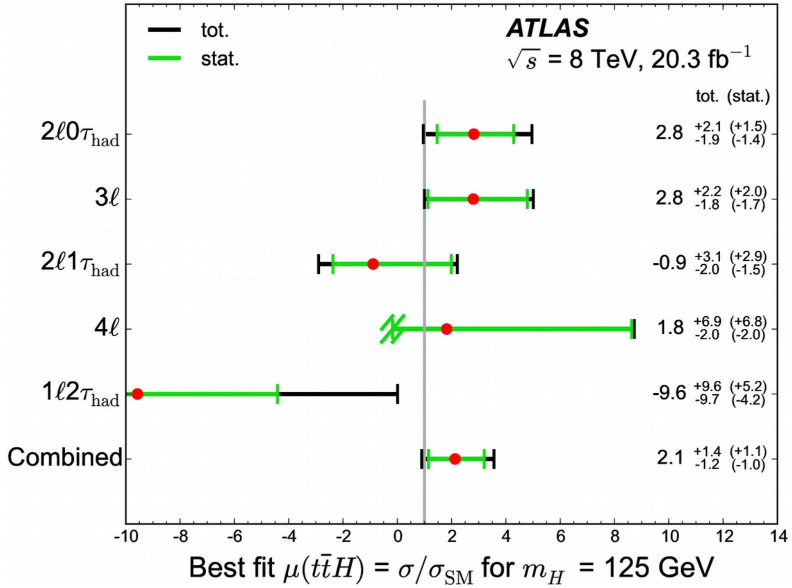
ATLAS	Higgs boson decay mode			
	WW*	ττ	ZZ*	other
2ℓ same sign 0τ	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
2ℓ same sign 1τ	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
1ℓ 2τ	4%	93%	0%	3%

ATLAS: *PLB 749 519 (2015)*
CMS: *JHEP 09(2014) 087*
+ *CMS-PAS-HIG-2013-020*

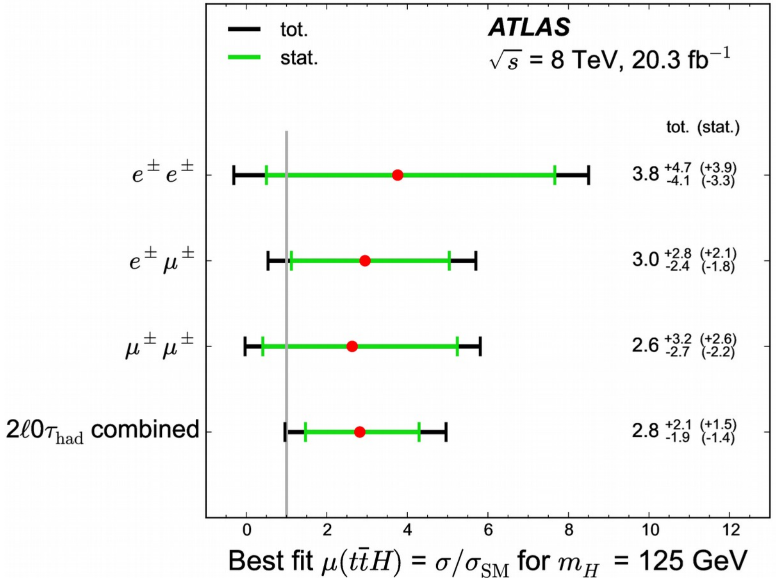
ttH, H → WW/ττ



CMS: CMS-PAS-HIG-2013-020



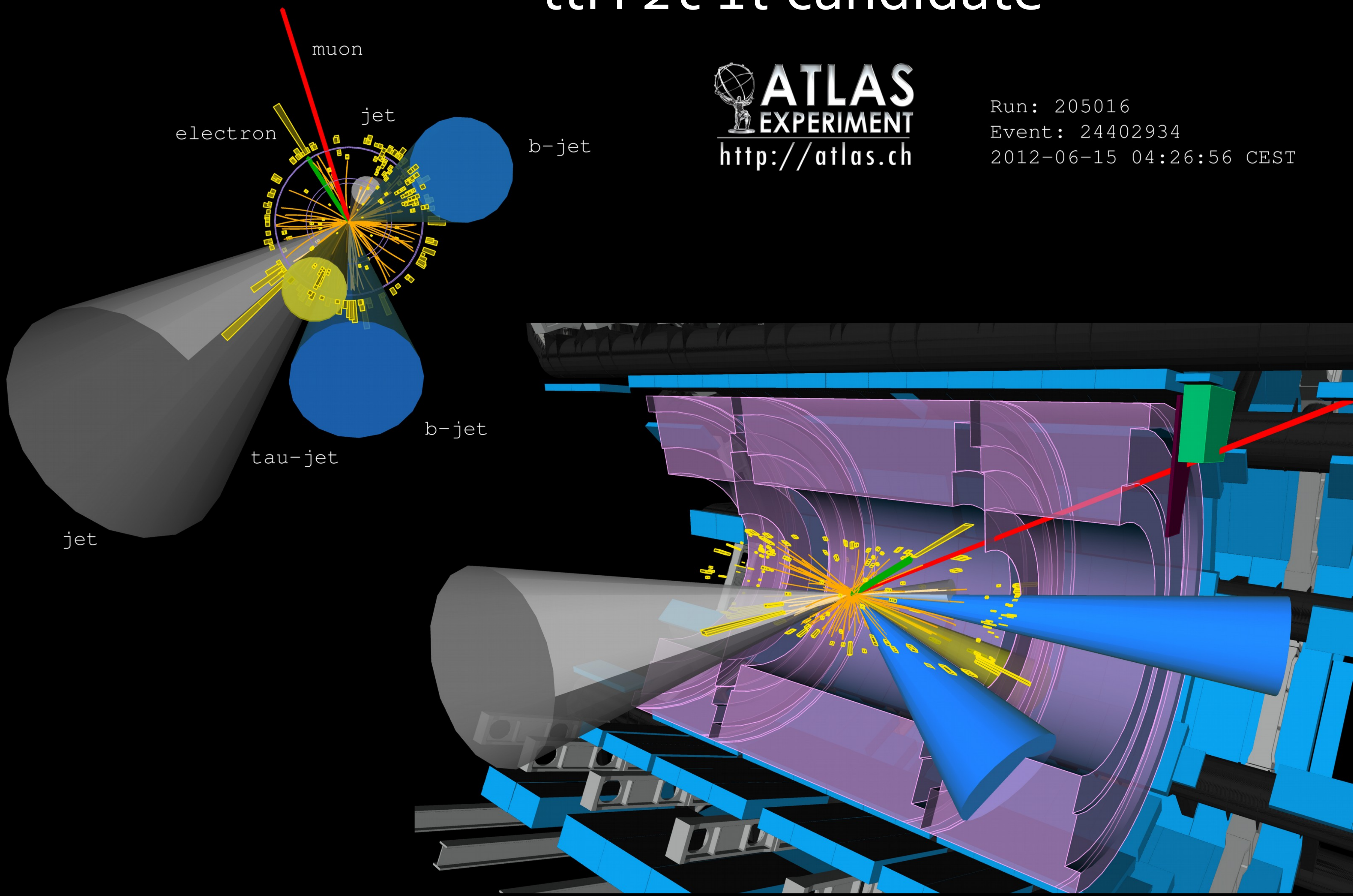
ATLAS: PLB 749 519 (2015)



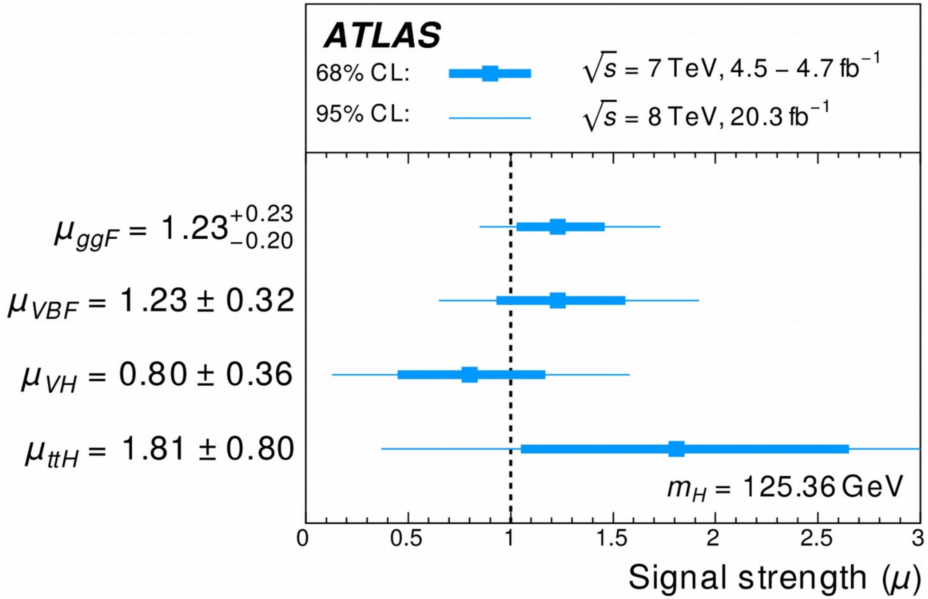
Nothing apparently wrong with CMS μμ

ATLAS does not see dimuon excess; combined results very compatible

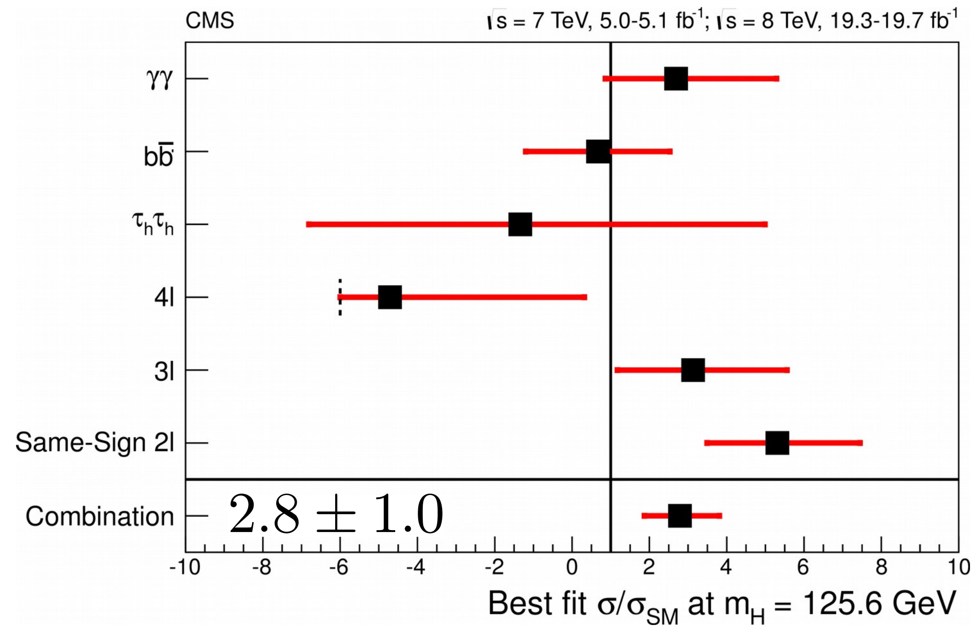
ttH 2ℓ 1τ candidate



Combination



Signal significance: 2.4σ (1.5σ exp)



Signal significance: 3.4σ (1.2σ exp)

Full ATLAS combo:
PLB 749 519 (2015)

CMS ttH combo:
JHEP 09(2014) 087

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Production process	ATLAS+CMS	ATLAS	CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

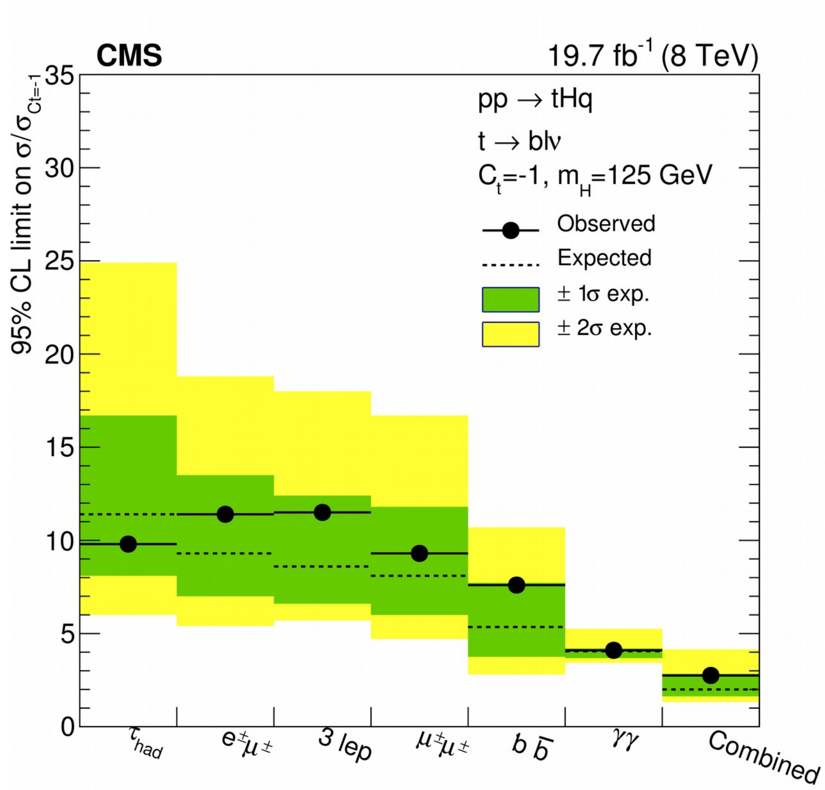
SM ttH sensitivity is on the way!

ATLAS+CMS combo:
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

Dedicated tH searches

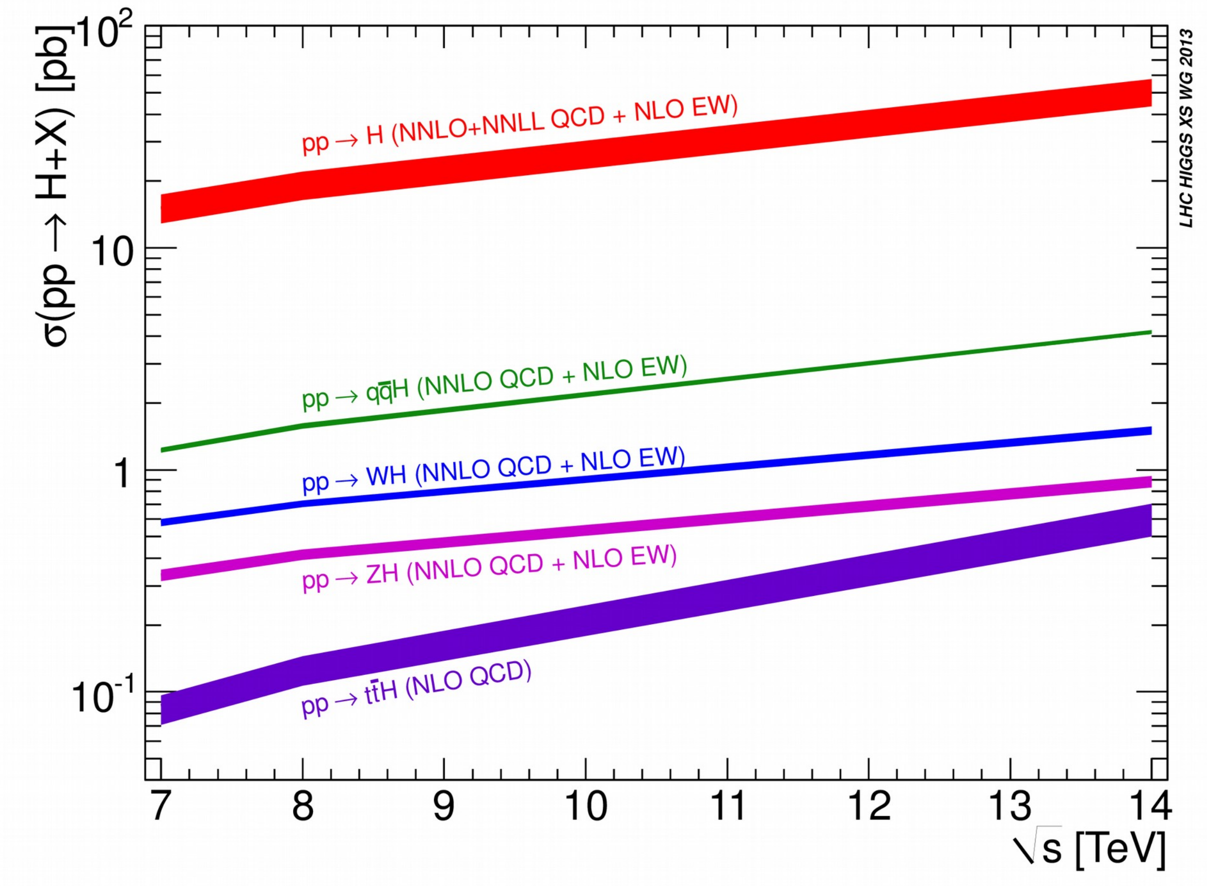
- CMS has done dedicated tH searches (vetoing ttH) in γγ, bb, WW, ττ
  - dominated by diphoton
- Results quoted relative to reversed top Yukawa coupling (maximal constructive interference – x10 SM)
- Combined μ < 2.8x non-SM (2.0 exp)

Combination:
1509.08159, sub to JHEP



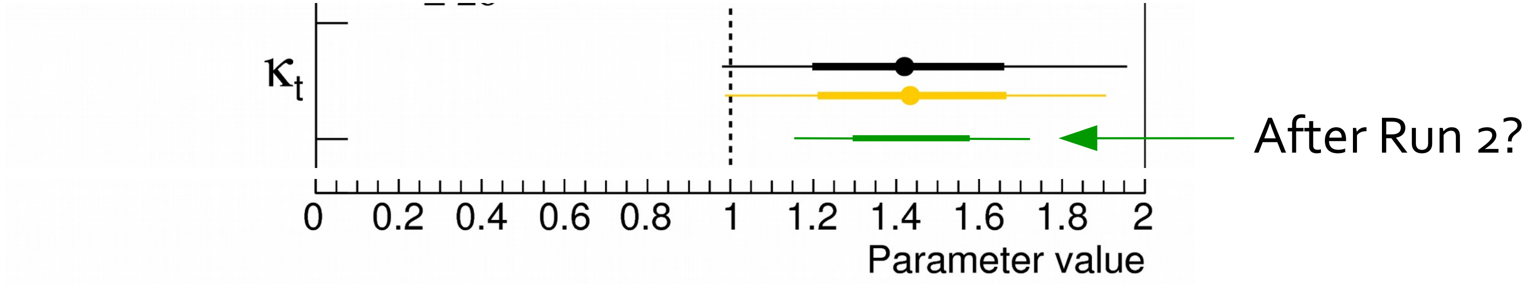
Run 2 for ttH

- Each fb^{-1} worth more @ 13 TeV
  - σ(ttH) up a factor ~ 4
  - however, expect more pileup, and tt+X production has more jet activity: reoptimization work needs to be done



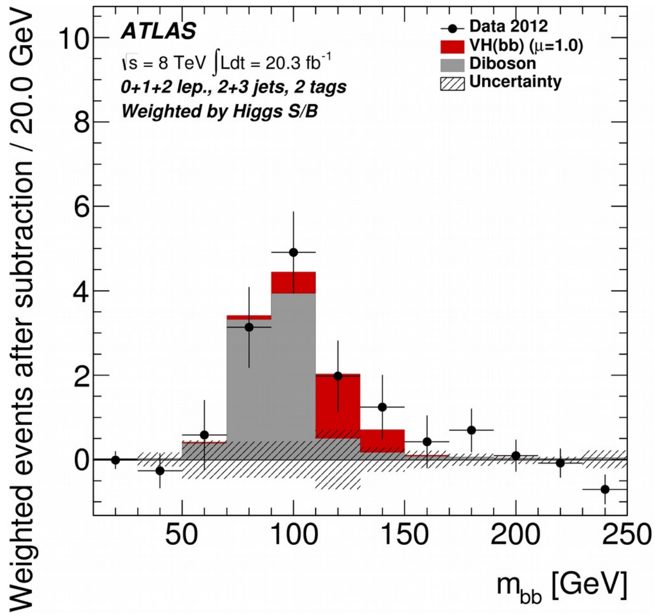
ttH Projections

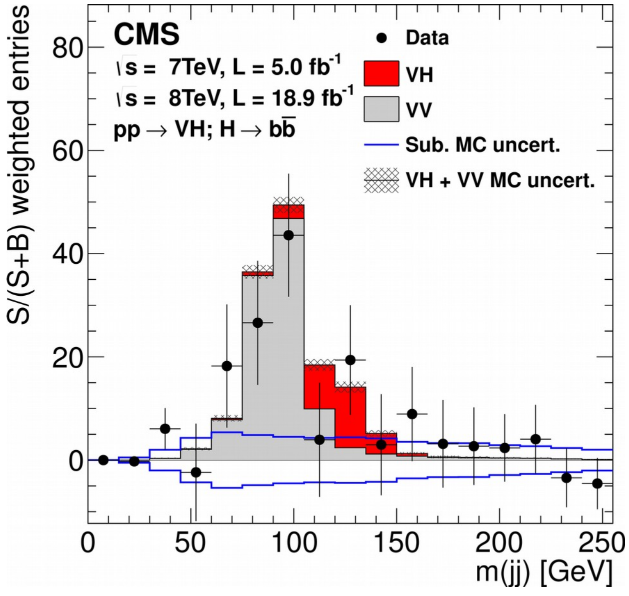
- ttH has advantage of having many decay modes with quite different systematics
  - e.g. with more data $H \rightarrow \gamma\gamma$, $(ttH) \rightarrow 4\ell bb$ becomes very relevant
- Personal opinion: a good chance of 5σ sensitivity for SM signal *per experiment* with full Run 2 dataset
  - combination of channels necessary
  - ≈ ±10% on coupling
  - theory systematics become relevant
- tH analyses will also progress



VH, H ⟶ bb

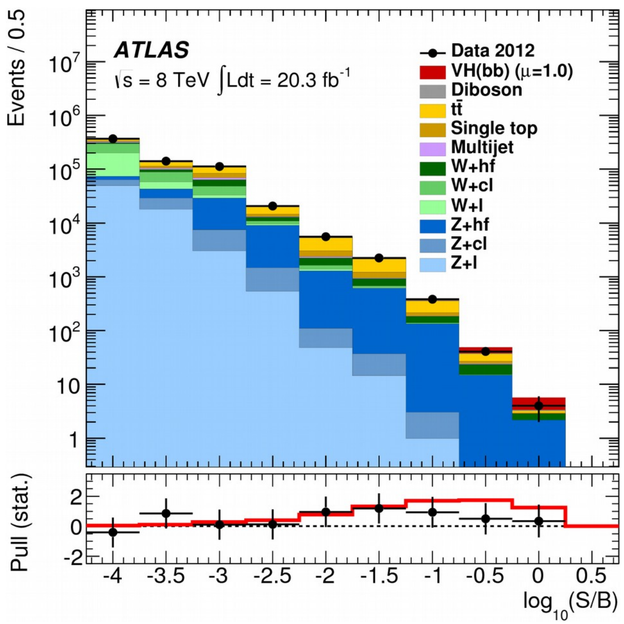
- Use Z ⟶ ℓℓ, W ⟶ ℓν, Z ⟶ νν decays (2/1/0 leptons)
  - enhance S/B by looking separately at high $p_T(V)$ categories
  - combine b-tagging info with kinematics in MVA
- Sensitive to $t\bar{t}$, W/Z + heavy flavor jet modeling
- Validate with (W/Z)Z, Z ⟶ bb search

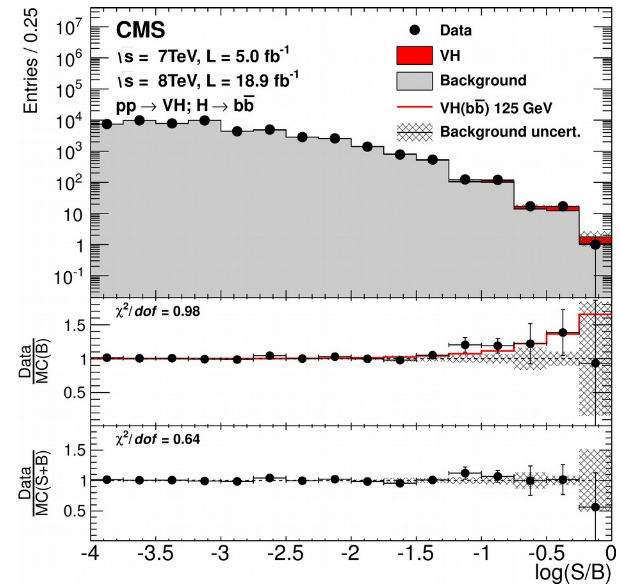


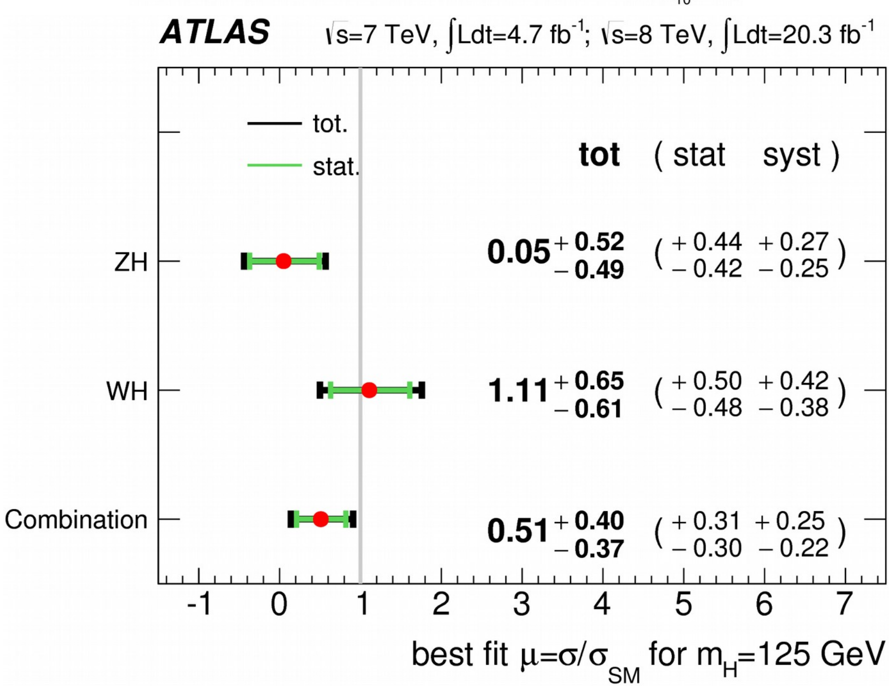


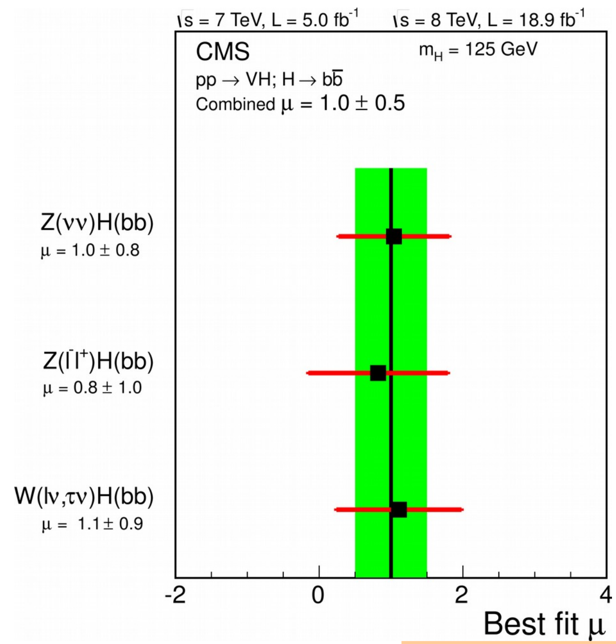
ATLAS: *JHEP 01(2015) 069*
CMS: *PRD 89 012003 (2014)*
CMS Update: *EPJC 75 212 (2015)*

VH, H → bb results









qq → ZH only

With gg → ZH, combined μ = 0.9 ± 0.4

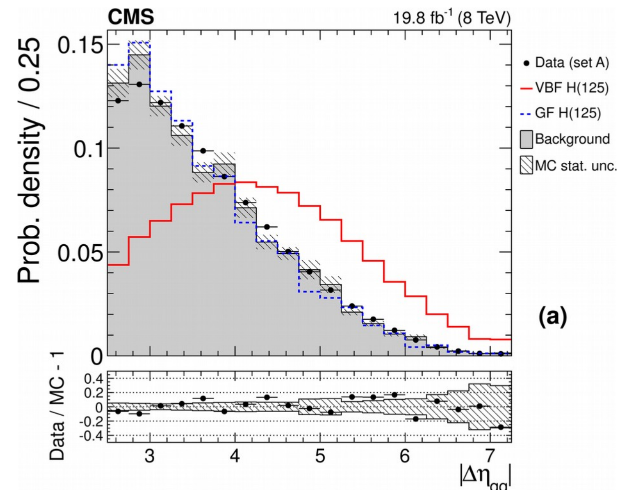
ATLAS: *JHEP 01(2015) 069*

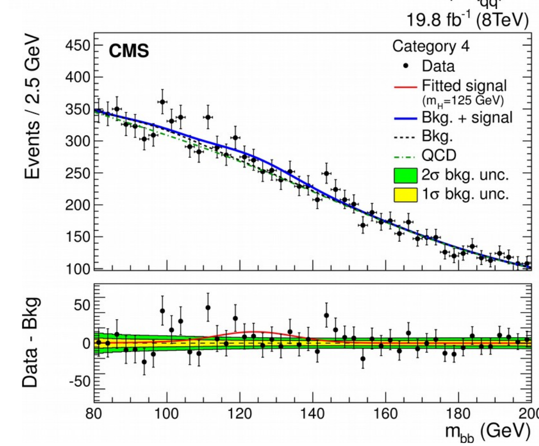
CMS: *PRD 89 012003 (2014)*
CMS Update: *EPJC 75 212 (2015)*

VBF H → bb

- Topology: light quark jets with large rapidity gap, little activity in between except for H → bb candidate
- all-hadronic final state: trigger is an issue
  - pick out VBF-like topologies in trigger
- BDT to choose most likely b-jets; additional variables to
  - separate q from g jets
  - reject QCD multijet production
- Fit m_{bb}

CMS: *PRD 92, 032008 (2015)*





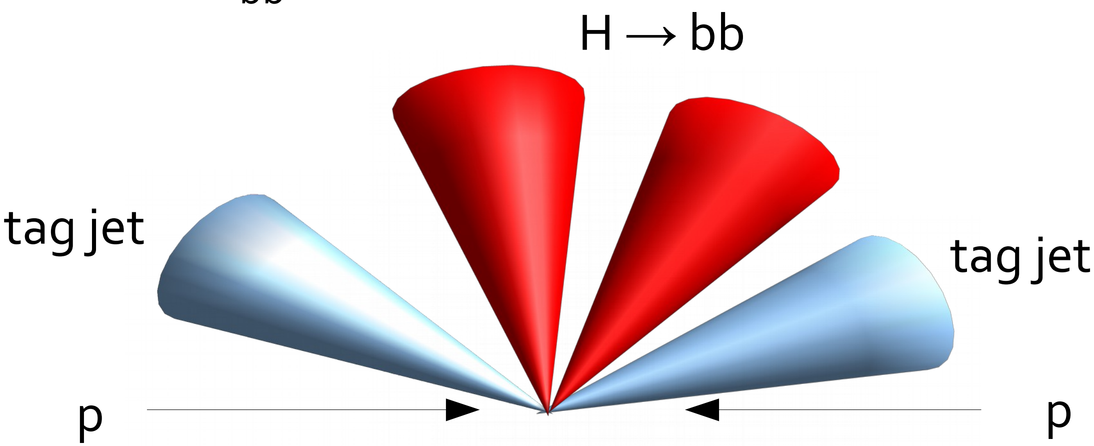
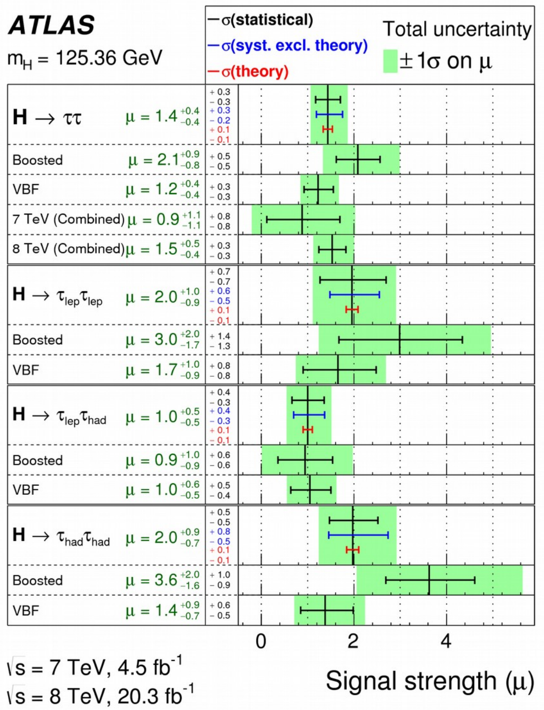


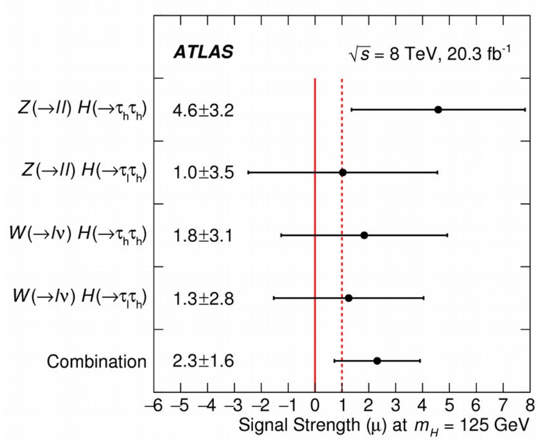
TABLE V. Observed and expected 95% CL limits, best fit values on the signal strength parameter $\mu = \sigma/\sigma_{SM}$ and signal significances for $m_H = 125$ GeV, for each $H \to b\bar{b}$ channel and their combination.

$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

$H \to \tau\tau$

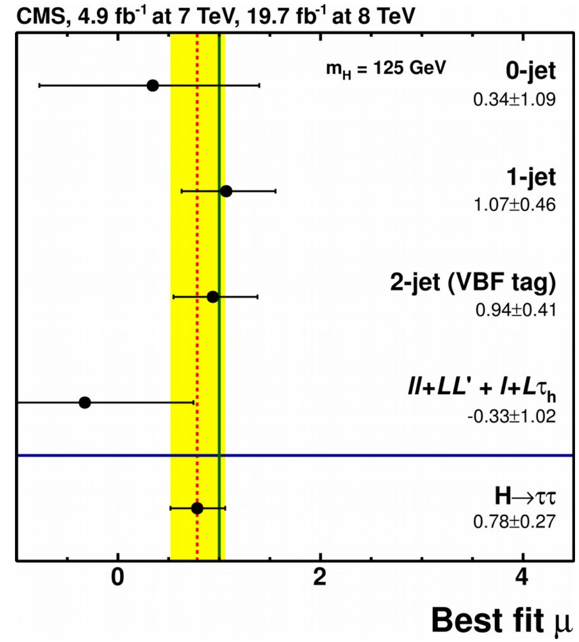
JHEP 04(2015) 117

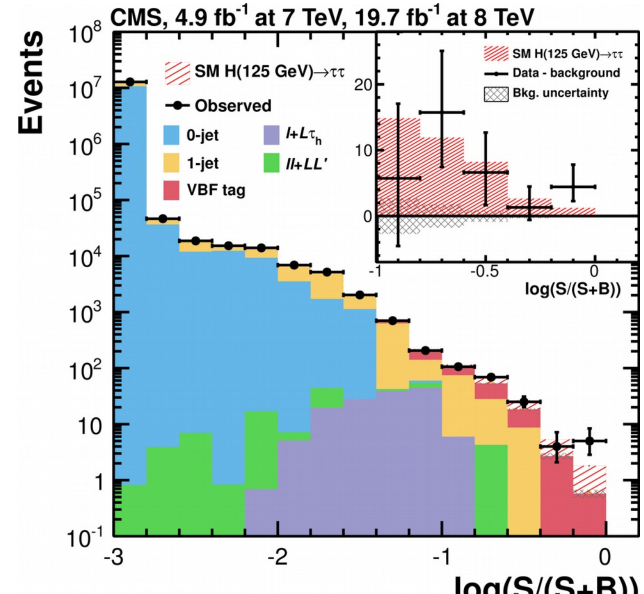




1511.08352 (sub to PRD)

JHEP 05(2014) 104



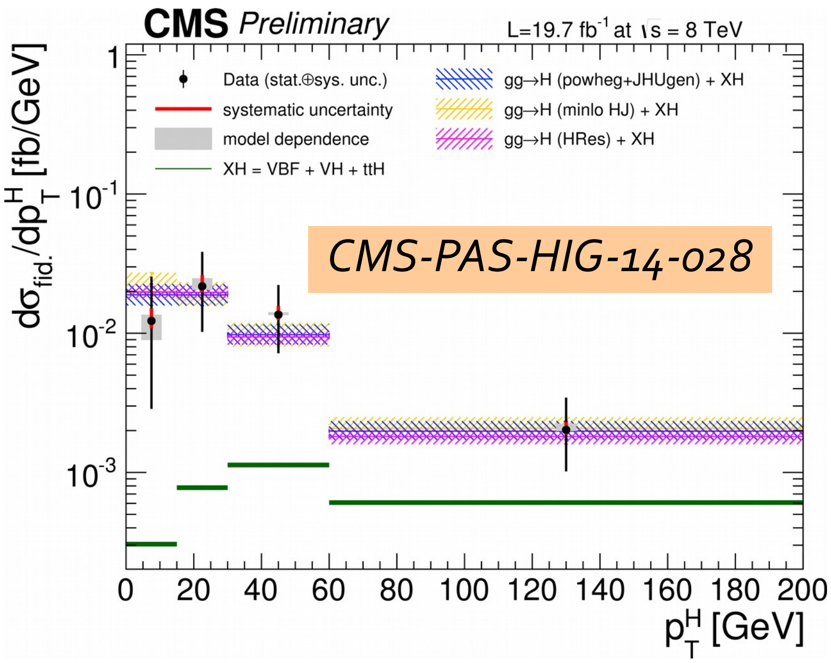


Significance
ATLAS 4.5σ obs (3.4σ exp)
CMS 3.8σ obs (3.9σ exp)

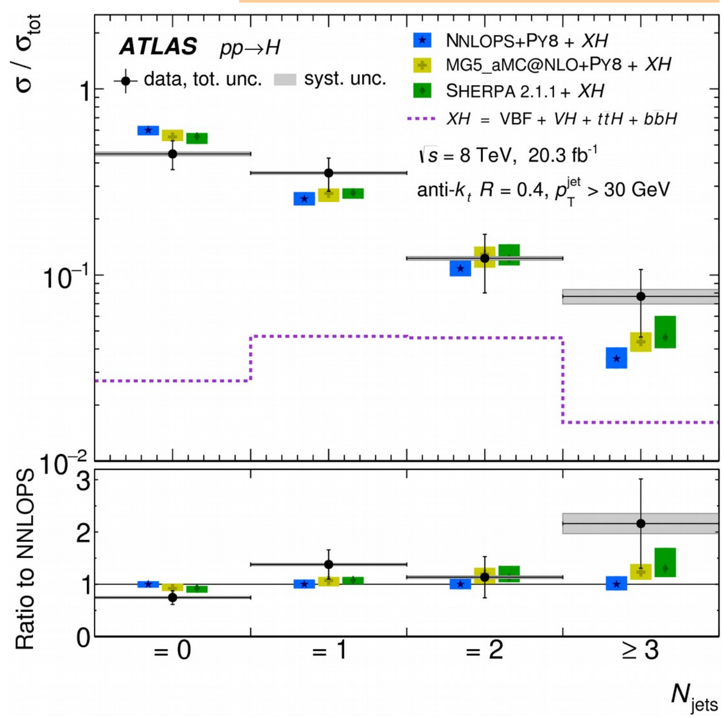
Differential cross sections

- High-resolution modes H → γγ, H → 4ℓ allow us to extract differential distributions in Higgs kinematic properties
  - e.g. look for deviations from SM at high p_T, #jets, …
- Will benefit enormously from more statistics

ATLAS γγ: *JHEP 09(2014) 112*
ATLAS 4ℓ: *PLB 738 234 (2014)*
ATLAS combo: *PRL 115 091801 (2015)*
CMS γγ: *1508.07819 (sub to EPJC)*
CMS 4ℓ: *CMS-PAS-HIG-14-028*



PRL 115 091801 (2015)



EFT probe

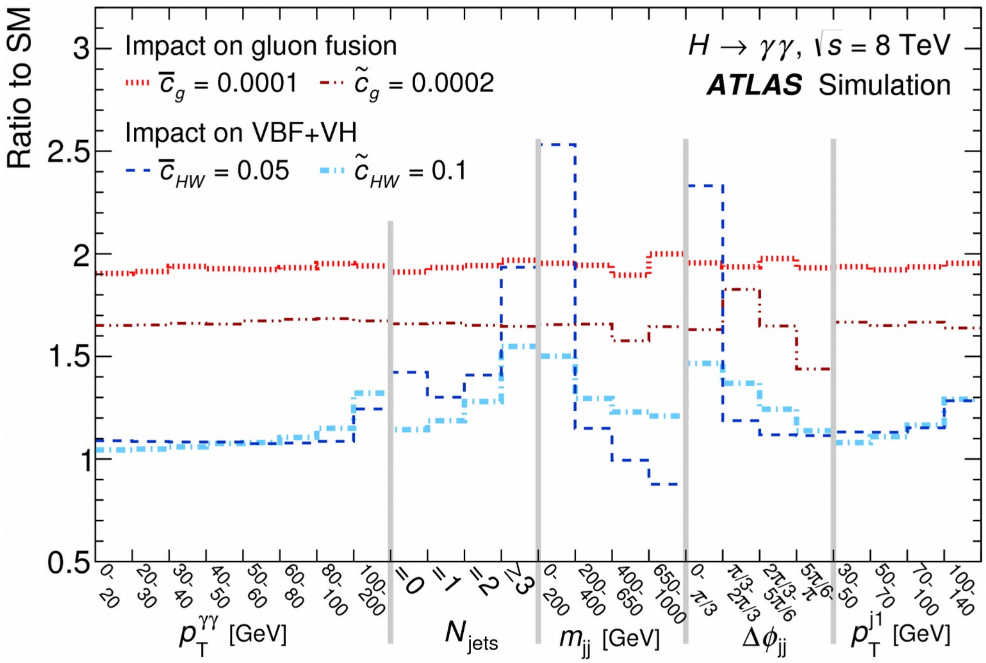
- Effective field theory analysis: fit H → γγ differential distribution allowing for dimension six operators
  - sensitive to Hgg interaction through ggF, to HVV via VBF+VH production

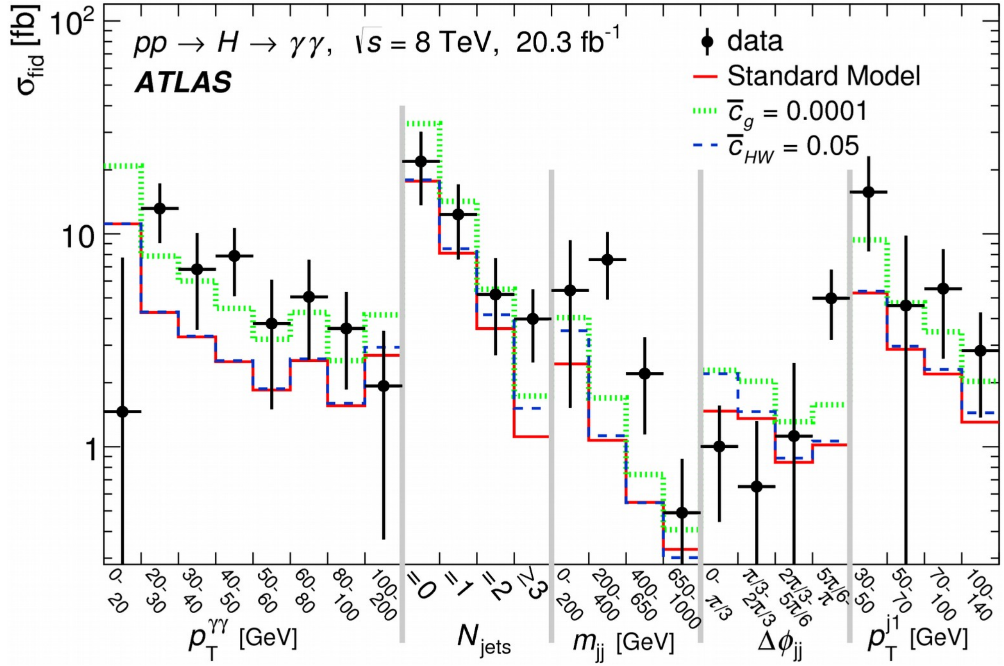
1508.02507, sub to PLB

Hγγ Hgg HWW/HZZ/HZγ

$$\mathcal{L}_{\rm eff} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} \quad \text{CP-even}$$
$$+ \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}, \quad \text{CP-odd}$$

Coefficient	95% $1-CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$





“Simplified” Cross Sections

- Measurements typically reported as a ratio μ to SM (including theory errors)
  - Hard to recompute if theory changes
  - Potentially tie together very different phase space regions
  - Hard to understand how effects of NP may affect μ in any given measurement
- Simplified cross section concept:
  - Split each production mode into kinematic bins (aligned to experimental sensitivity), e.g. ggF 0j, 1j, 2j VBF-like, …
  - Determine coefficients of contributions of each kinematic bin to an observation channel
  - SM acts as kinematic template, but only within each region: more transparent what the observation sees
- Done within context of LHC Higgs XS Working Group

Simplified xsec

Definition of Simplified Cross Sections.

Current μ fits:

$$\sigma_1^{\mathrm{meas}} = A_1^{ggH} \times \underbrace{\mu_{ggH} \times \sigma_{ggH}^{\mathrm{SM}}}_{} + A_1^{\mathrm{VBF}} \times \underbrace{\mu_{\mathrm{VBF}} \times \sigma_{\mathrm{VBF}}^{\mathrm{SM}}}_{}$$
$$= A_1^{ggH} \times \sigma_{ggH} + A_1^{\mathrm{VBF}} \times \sigma_{\mathrm{VBF}}$$

$$\sigma_2^{\mathrm{meas}} = A_2^{ggH} \times \underbrace{\mu_{ggH} \times \sigma_{ggH}^{\mathrm{SM}}}_{} + A_2^{\mathrm{VBF}} \times \underbrace{\mu_{\mathrm{VBF}} \times \sigma_{\mathrm{VBF}}^{\mathrm{SM}}}_{}$$
$$= A_2^{ggH} \times \sigma_{ggH} + A_2^{\mathrm{VBF}} \times \sigma_{\mathrm{VBF}}$$

- Fit for σ_{ggH}, σ_{VBF}
  - In the SM: Correspond to total ggH and VBF production cross sections
- A_i^{ggH}, A_i^{VBF} are acceptances for SM processes $\longrightarrow$ theory-dependent
  - Split each production cross section into several kinematic bins/slices a, b, ...

$$\sigma_1^{\mathrm{meas}} = A_1^{ggH\,a} \times \sigma_{ggH\,a} + A_1^{ggH\,b} \times \sigma_{ggH\,b} + A_2^{\mathrm{VBF\,c}} \sigma_{\mathrm{VBF\,c}} + \cdots$$
$$\sigma_2^{\mathrm{meas}} = \ldots$$

  - A_i^j only depend on SM kinematics *inside* a given bin
  - If this becomes a problem, split the bin

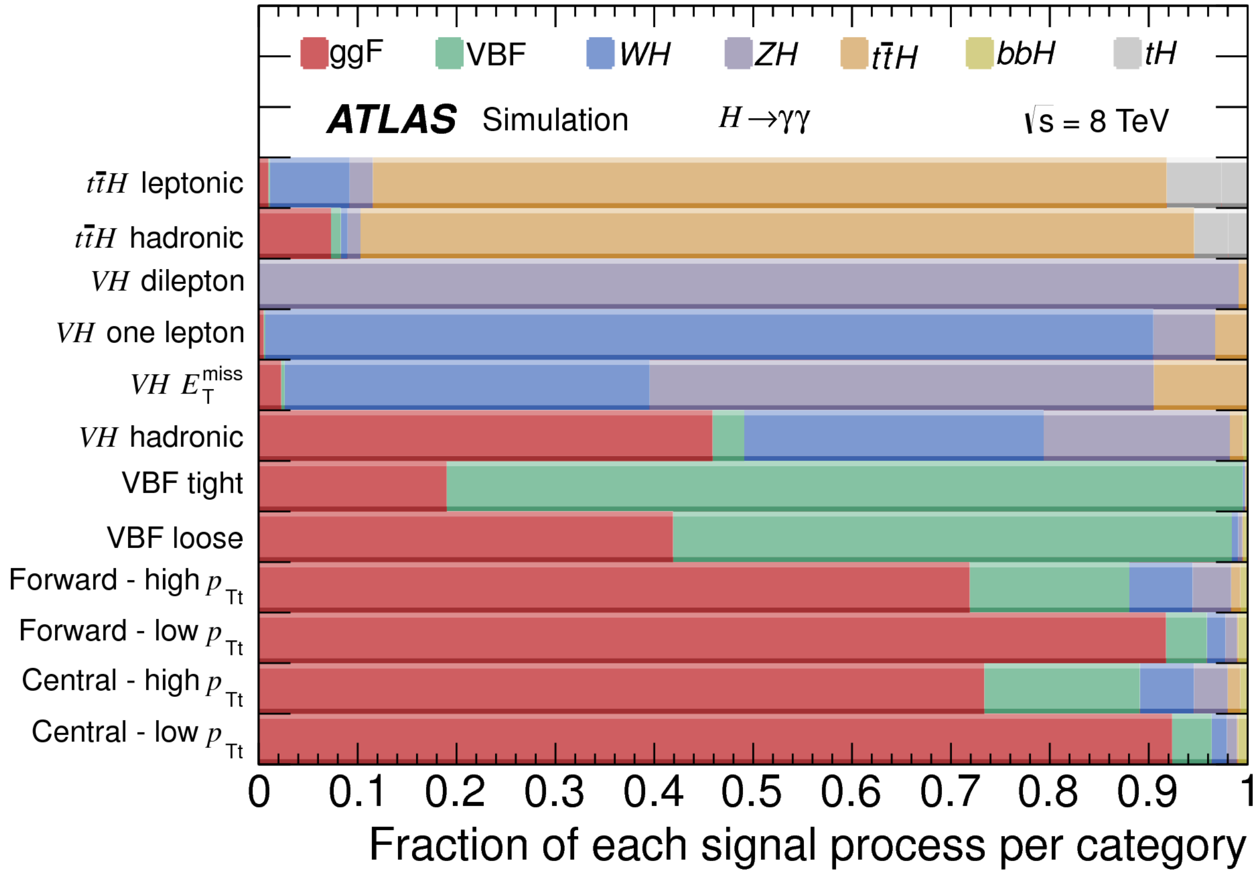
$\Rightarrow$ SM processes act as kinematic templates

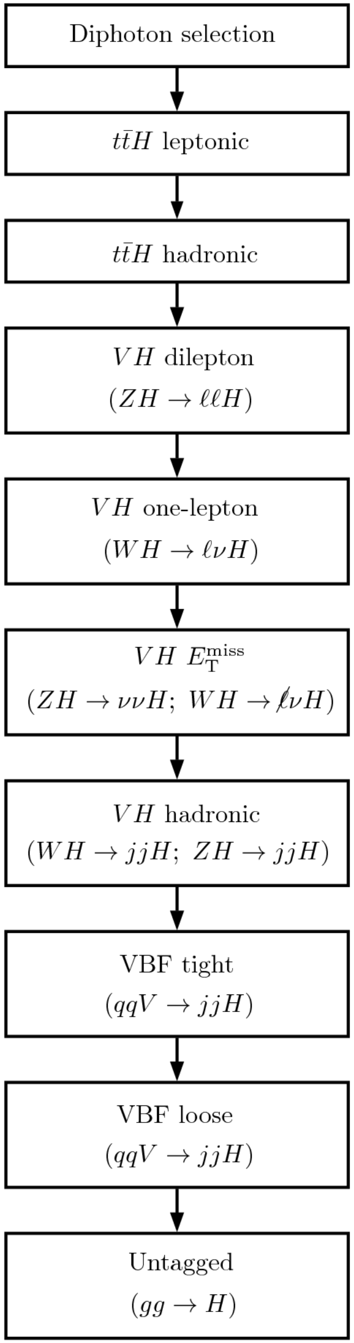
Frank Tackmann (DESY) | Simplified Cross Section Framework | 2015-06-24 | 5 / 18

F. Tackmann

On the way there …

- ATLAS H → γγ: multiple categories, varying sensitivity to different production modes
- In future, imagine publishing acceptance matrix and measured cross sections in each category





PRD 90, 112015 (2014)

Conclusion

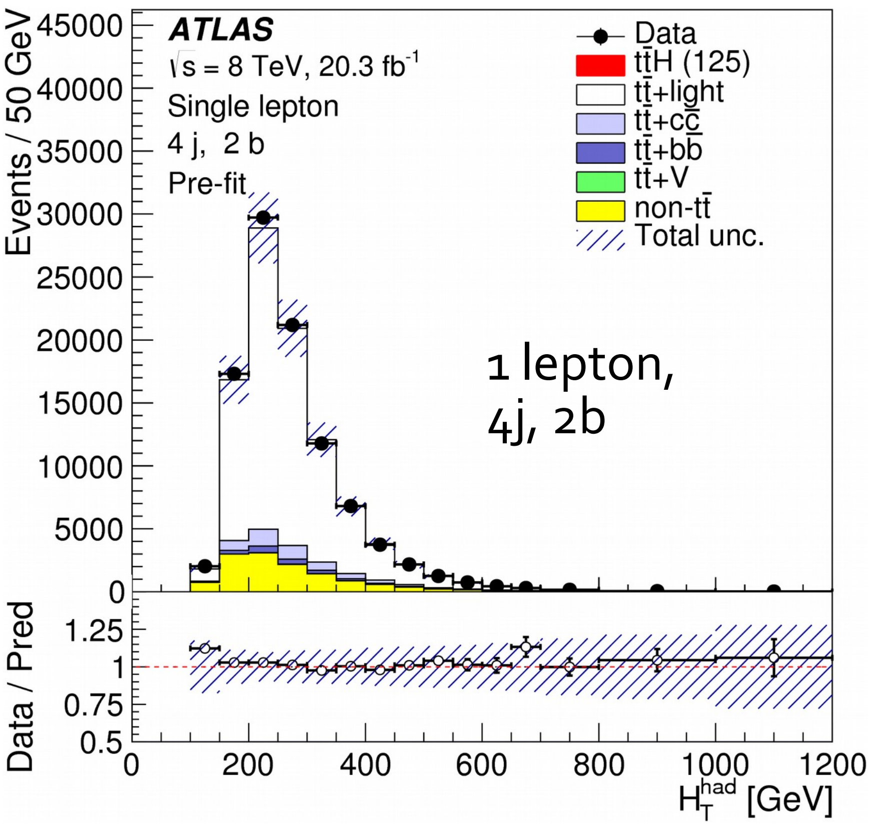
- Near-term future is bright for fermion couplings
  - generally have high S/B rare modes that will gain importance with more data
- ttH has large cross section gain
  - also, technically "evidence" already after Run 1
- Additional data will allow finer binning of other processes and enable more sophisticated probes of new physics

Run 2: exciting for Higgs physics

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

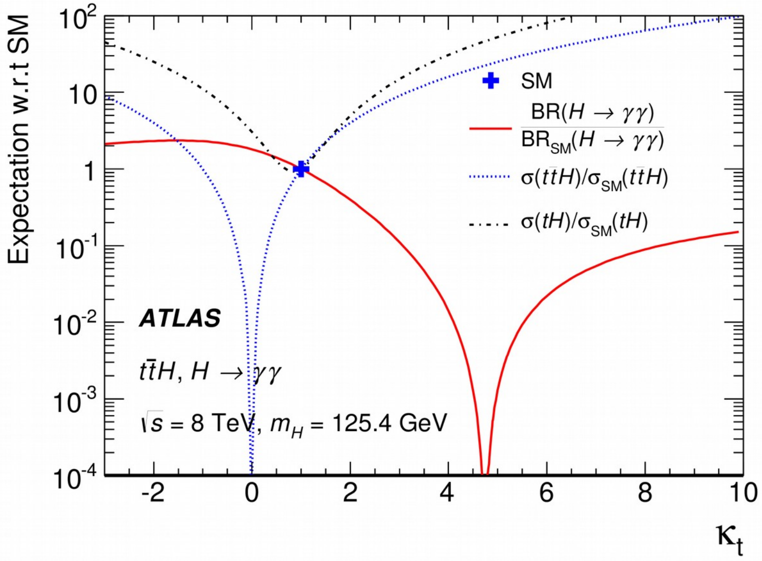


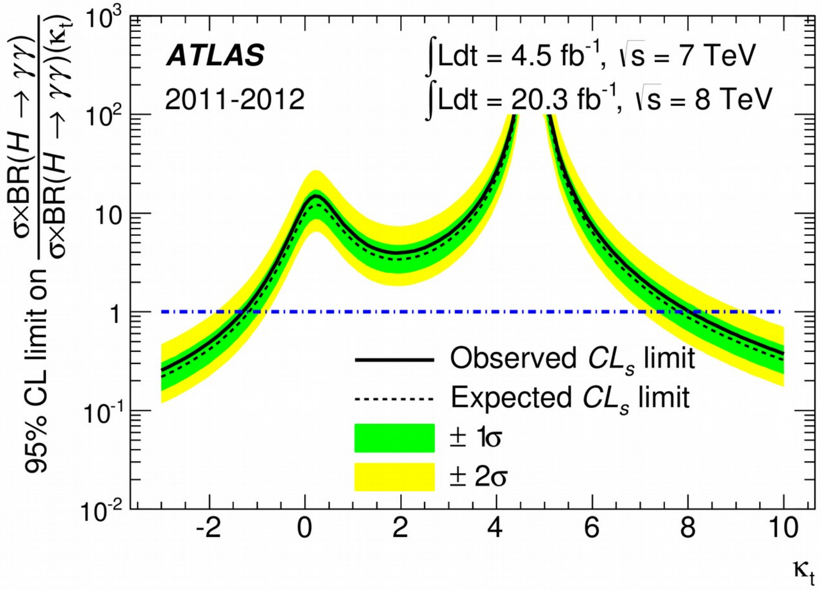
[8 TeV] Diphoton Selection

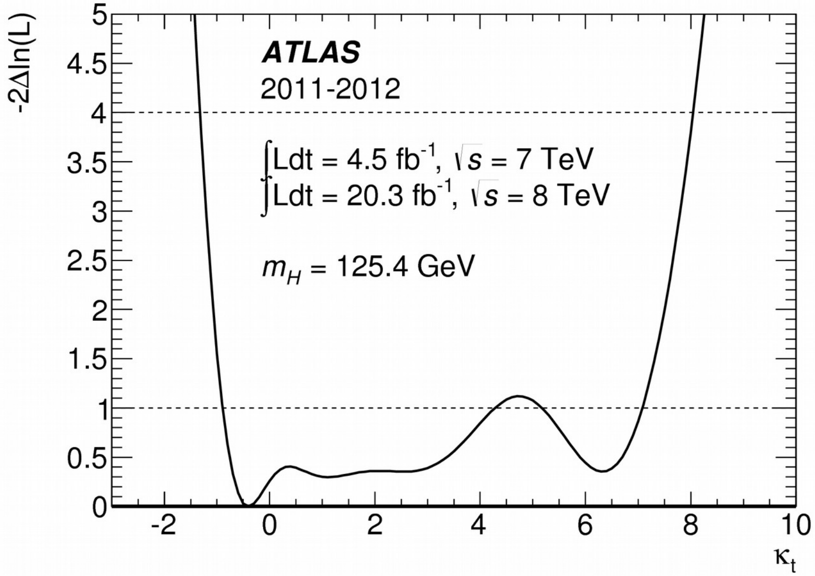
- trigger: diphoton, p_T > (35, 25) GeV
- photons: leading (subleading) p_T > 0.35 (0.25) x $m_{\gamma\gamma}$; require == 2 photons
- leptons: e p_T > 15 GeV; μ p_T > 10 GeV
- leptonic channel: ≥1 lepton, M(eγ) not in [84, 94] GeV, ≥ 1j @ 25 GeV, ≥ 1b @ 80% WP, ETmiss > 20 GeV if only one b-jet
- hadronic 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

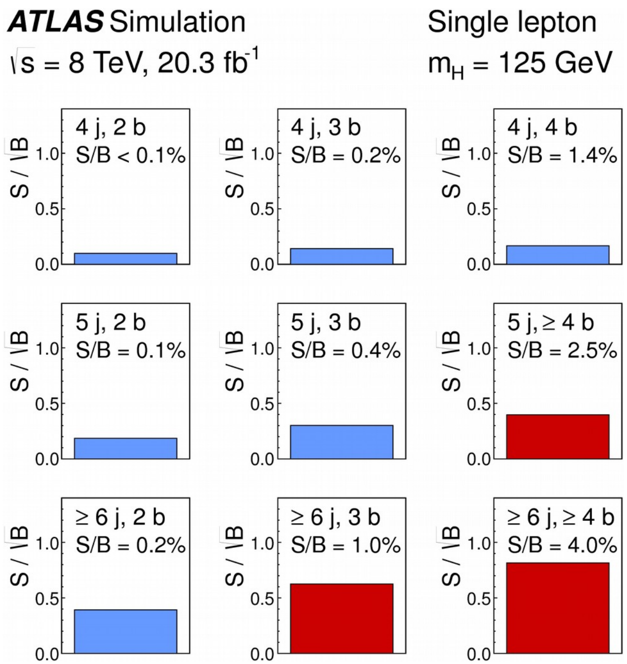


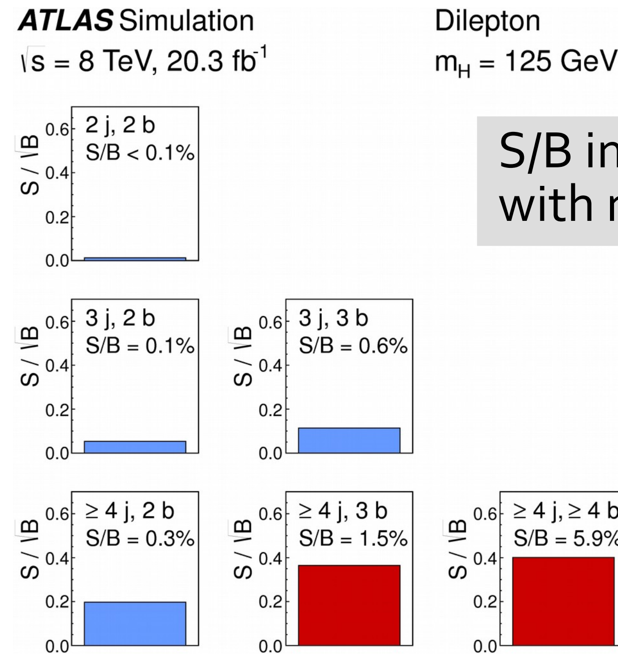




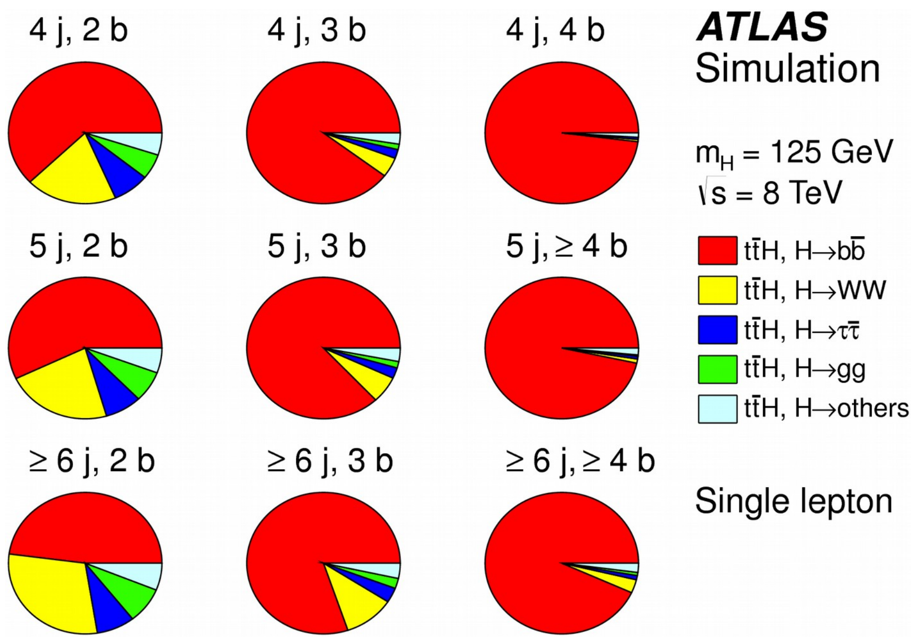
κ_t scales the SM Yukawa coupling (1=SM)

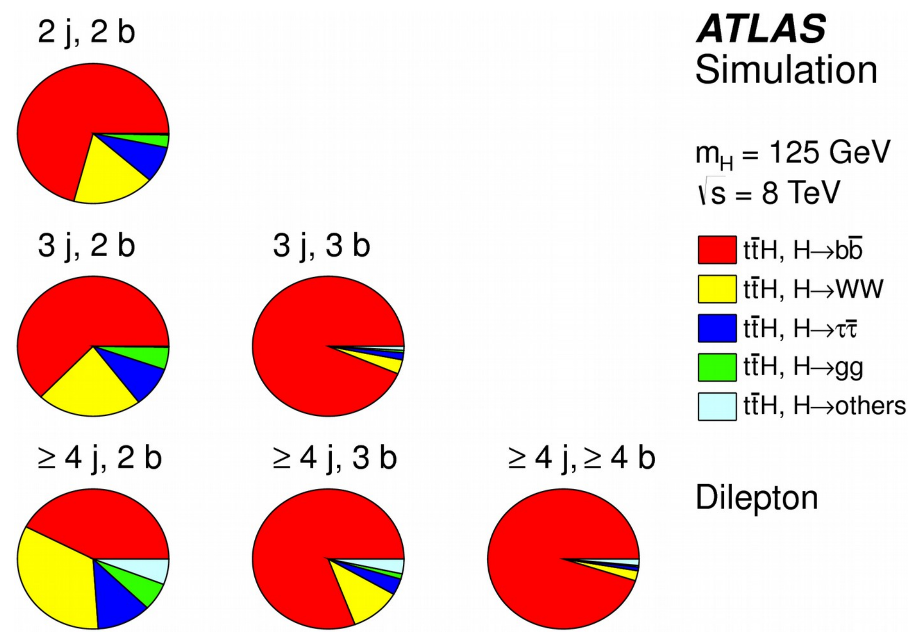
Categories





S/B improved with neural net





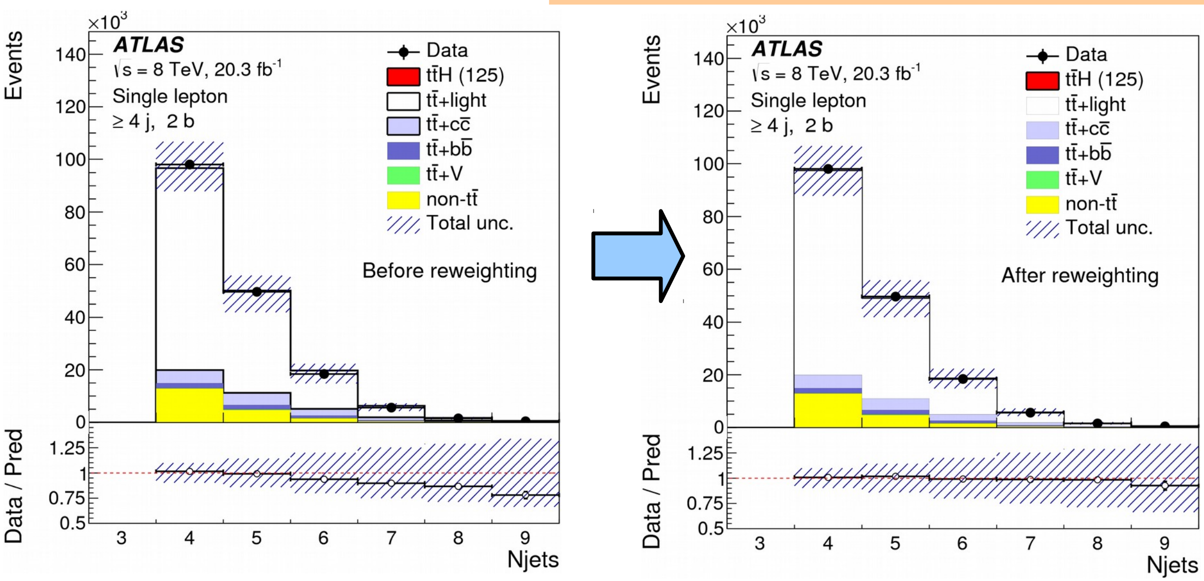
Event Selection

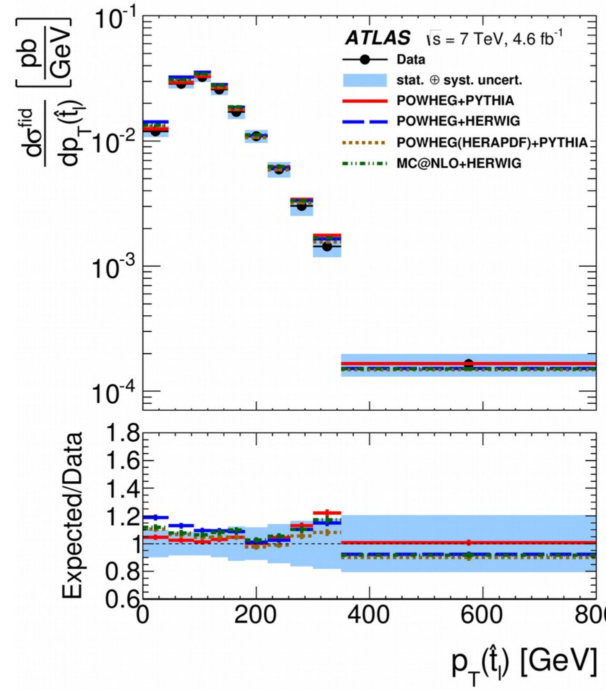
- trigger: single lepton triggers (e or μ); full efficiency @ 25 GeV
- leptons: leading p_T > 25 GeV, subleading p_T > 15 GeV (dilepton channel)
  - 1, 2-lep channels have no overlap
  - dilepton: Mll > 15 GeV, veto events with Mll = $M_Z \pm 8$ GeV for same flavor; H_T > 130 GeV for eμ
- jets: anti-k_T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

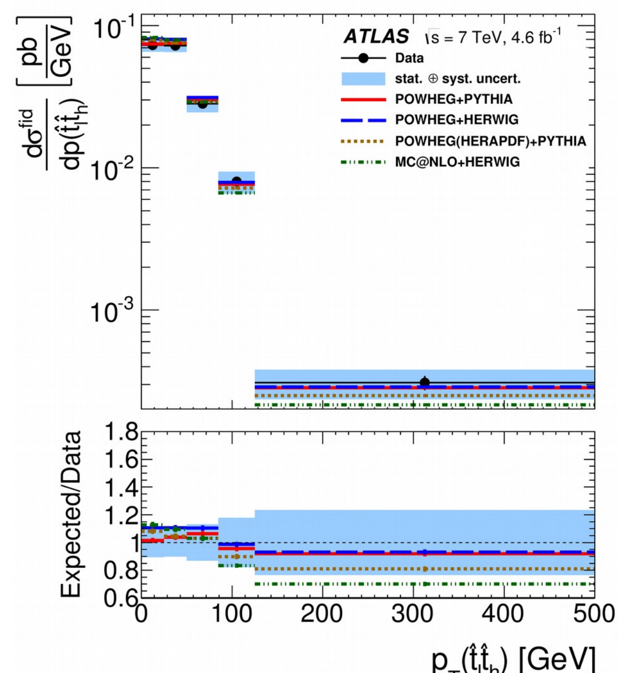
Top Reweighting

- 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

ATLAS *top kinematics: arxiv:1502.05923, accepted by JHEP*





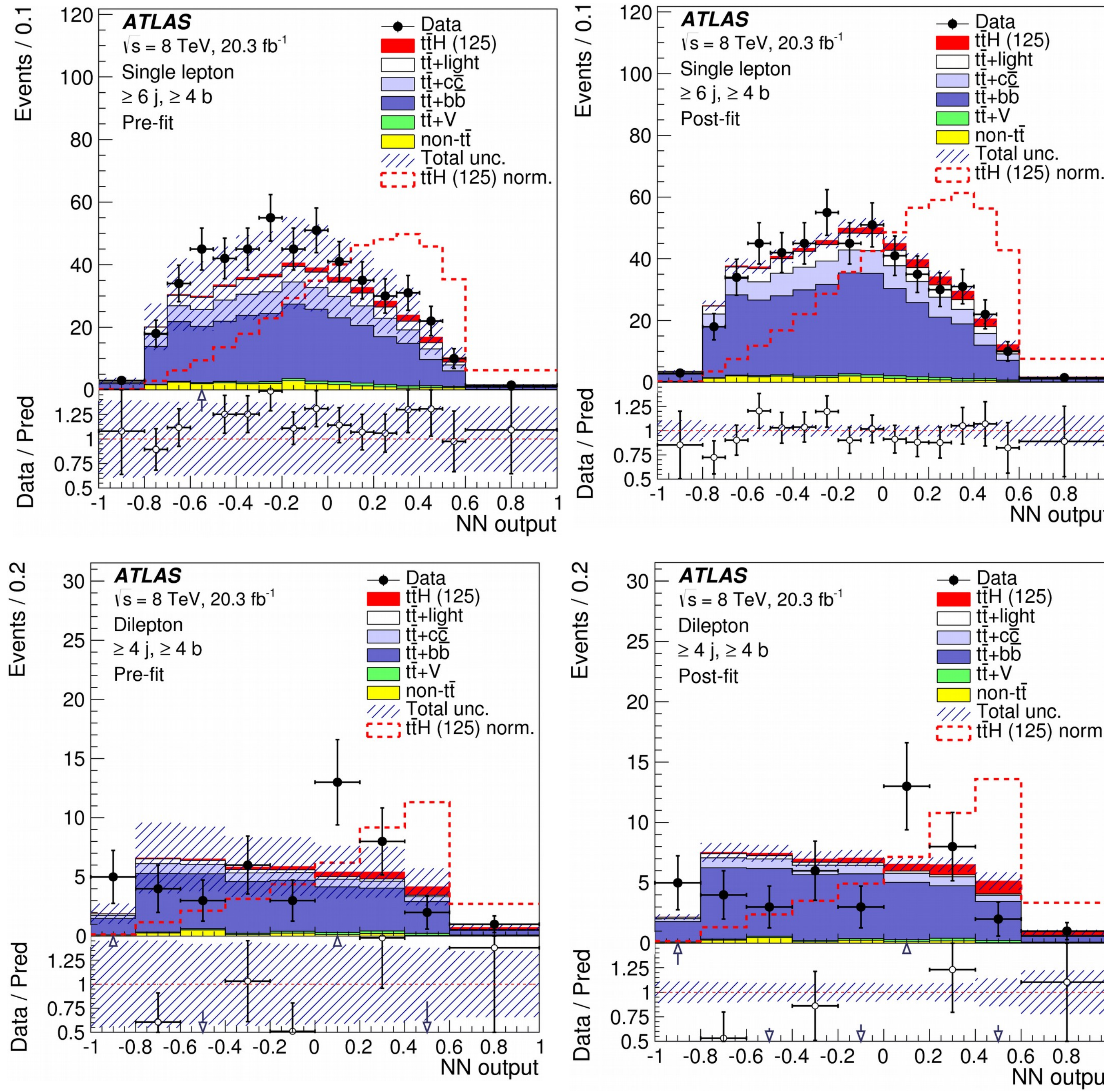


Top Pair Modeling

- 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

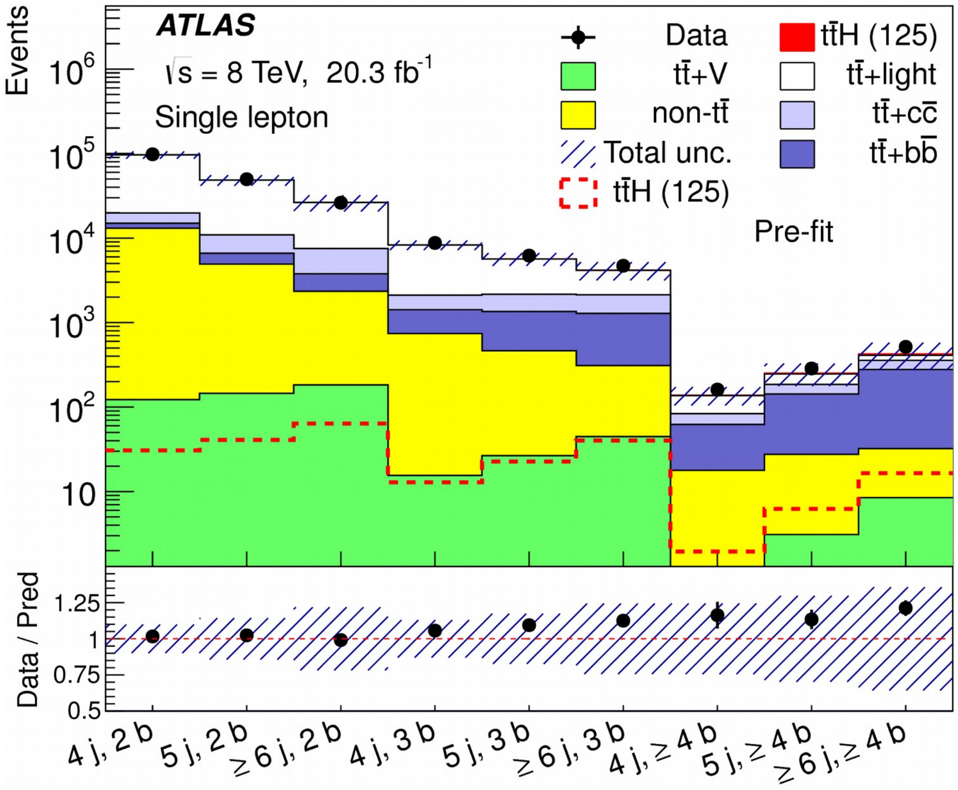
Fit effect on Signal-Rich Regions

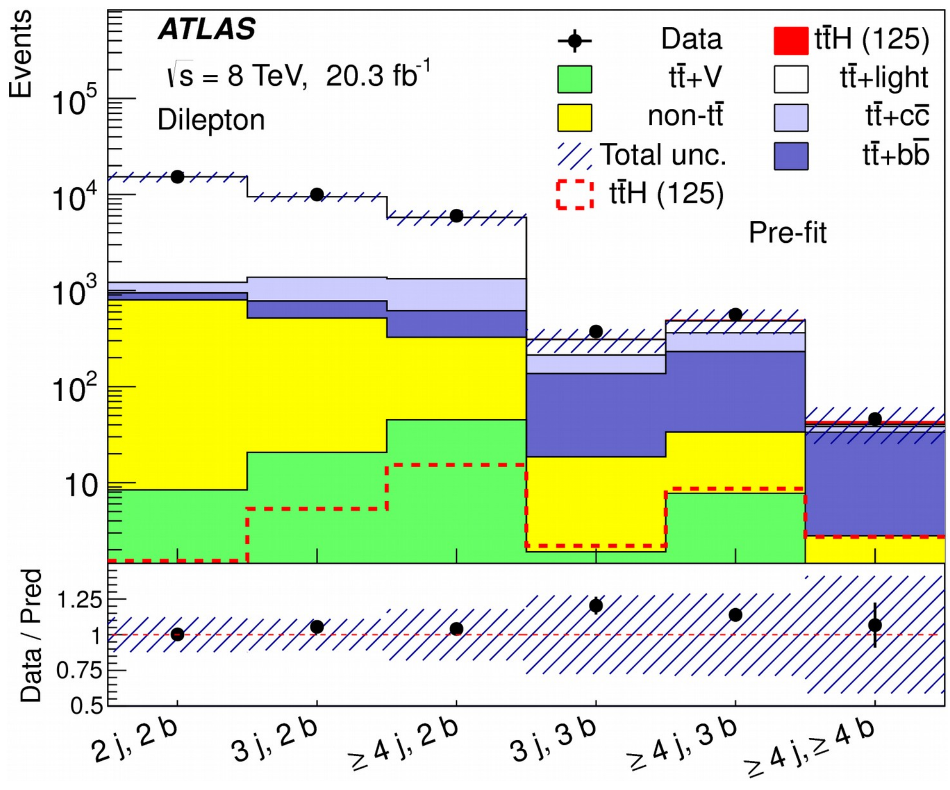
Profile fit collapses systematics – large correlations



Pre-Fit Yields

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





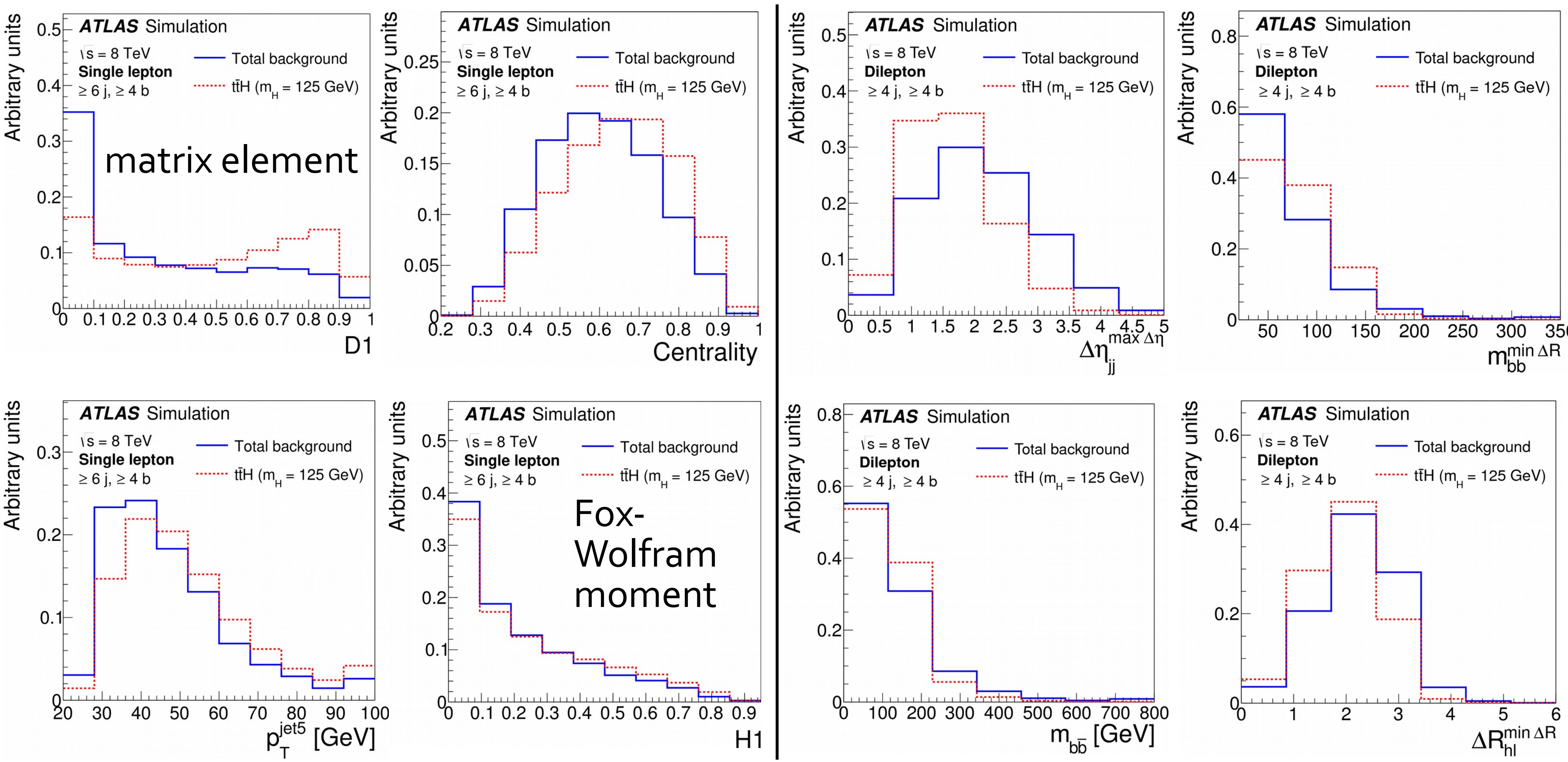
NN Variable Separation

- 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

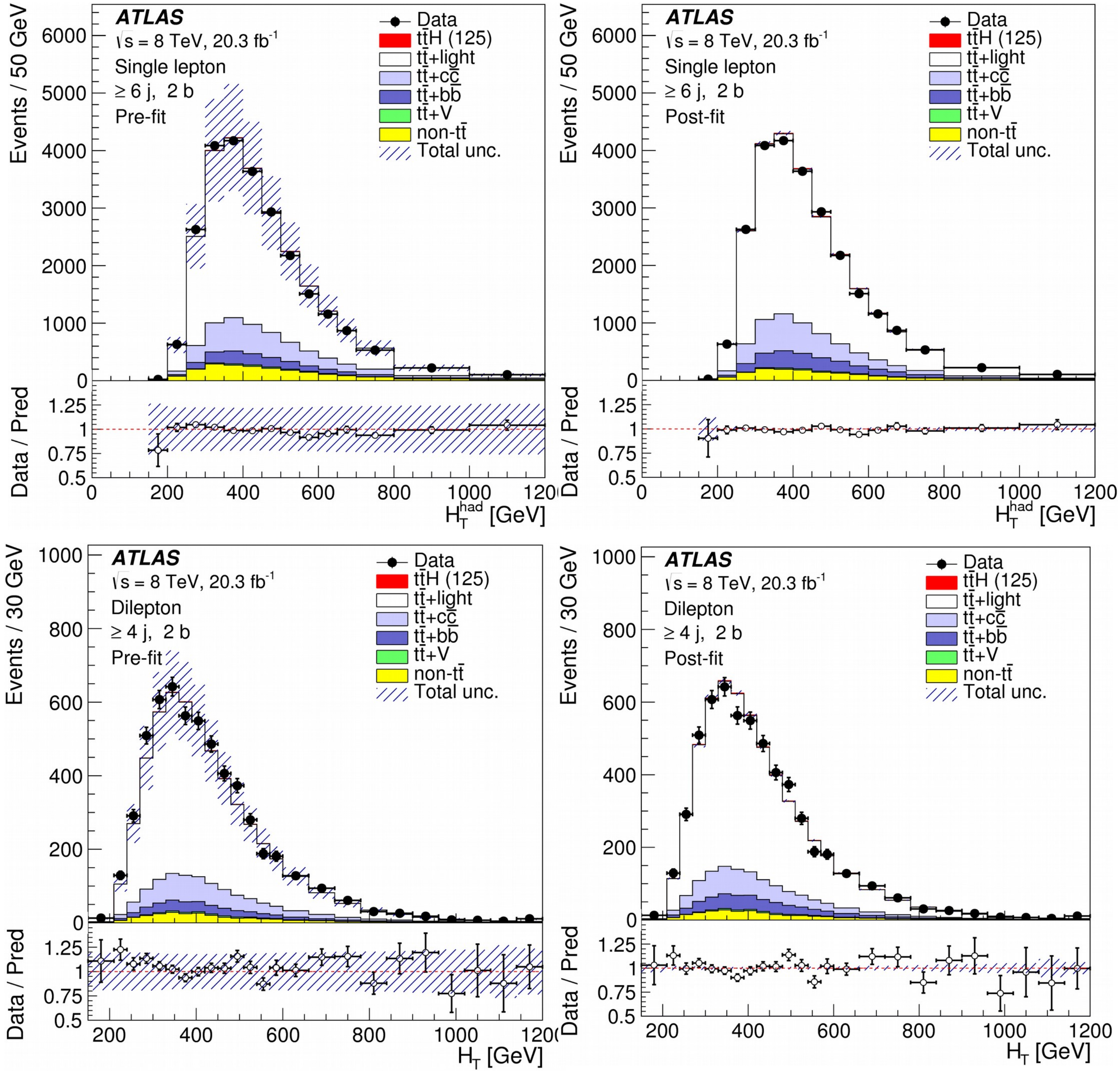
- Systematic uncertainties are "profiled" in the fit: we provide an initial constraint and allow data to update the values & errors
  - in particular this constrains background systematics using bkg-rich regions, and allows in situ charm tagging measurement
- All control and signal regions for lepton + 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

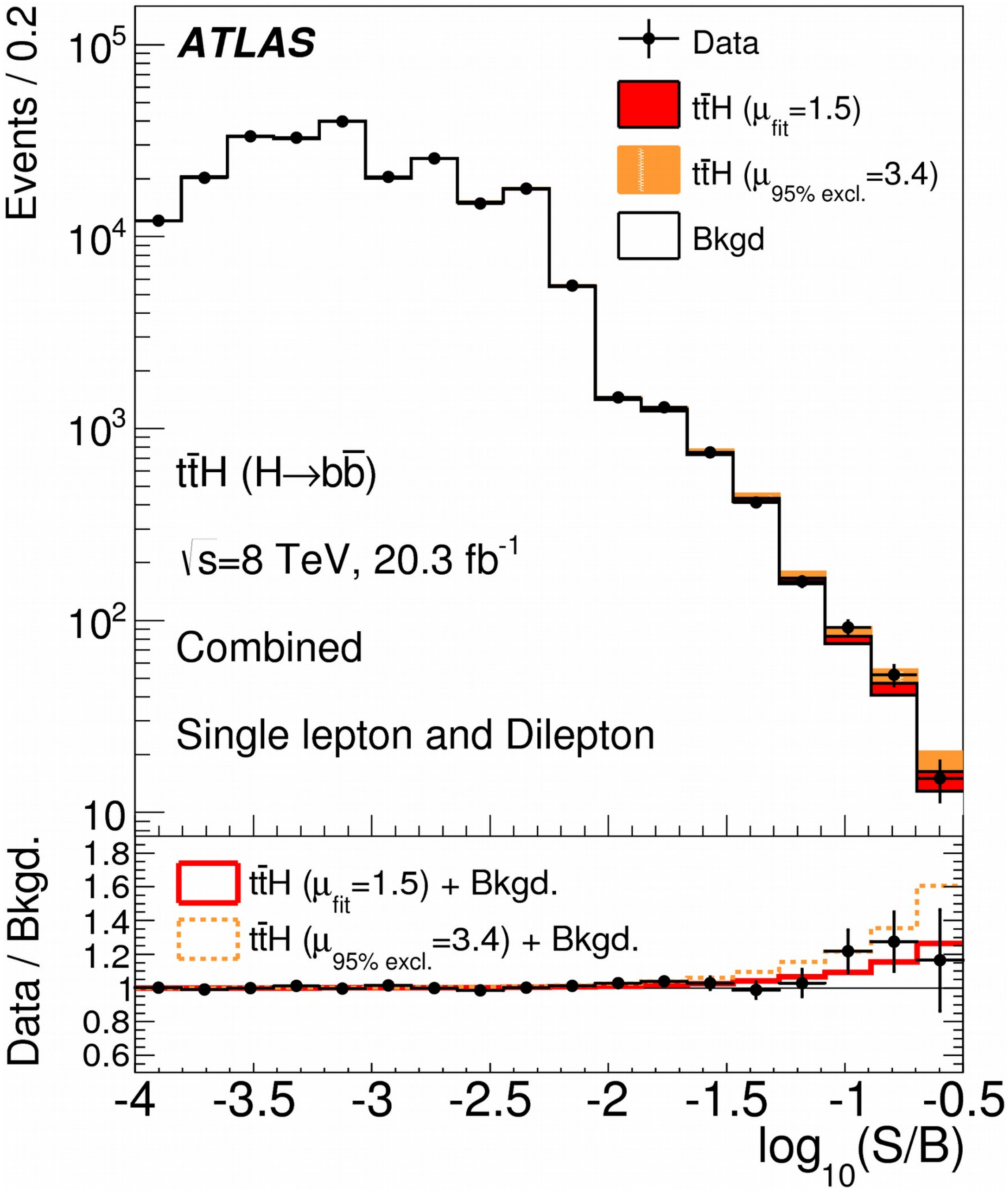
Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency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

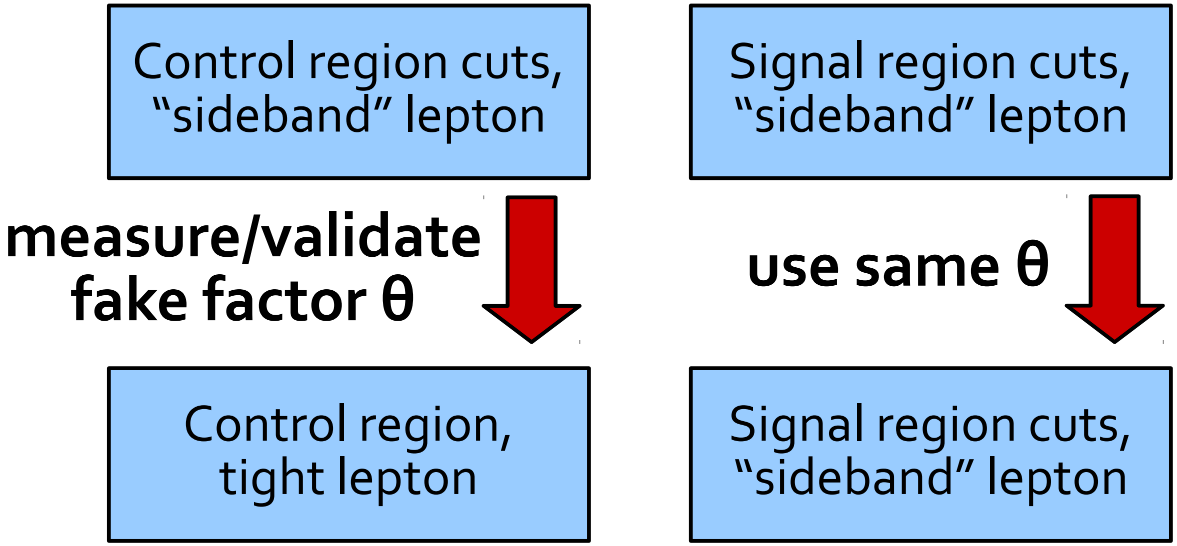


S/B Visualization



Fake Lepton Backgrounds

- Slightly different techniques in each channel.
  - $2\ell 0\tau$, 3ℓ, $2\ell 1\tau$: variants on “fake factor” methods
  - 4ℓ: limit from MC
  - $1\ell 2\tau$: predict fake τ bkg from MC (well modeled with looser event cuts)



e.g. $2\ell 0\tau$: control region cuts: lower # jets than SR
sideband leptons: non-isolated electrons, low-p_T muons

ttH multilepton decays

Signal

tt decay

Higgs decay	ℓνℓν bb	ℓνjj bb
H → WW → ℓνℓν	4ℓ	3ℓ
H → WW → ℓνjj	3ℓ	2ℓ0τ
H → $\tau_l \tau_l$	(4ℓ)	3ℓ
H → $\tau_l \tau_h$	3ℓ	2ℓ1τ
H → $\tau_h \tau_h$	---	1l2τ

all-hadronic top not targeted

only accept same sign ℓ (2ℓ0τ)

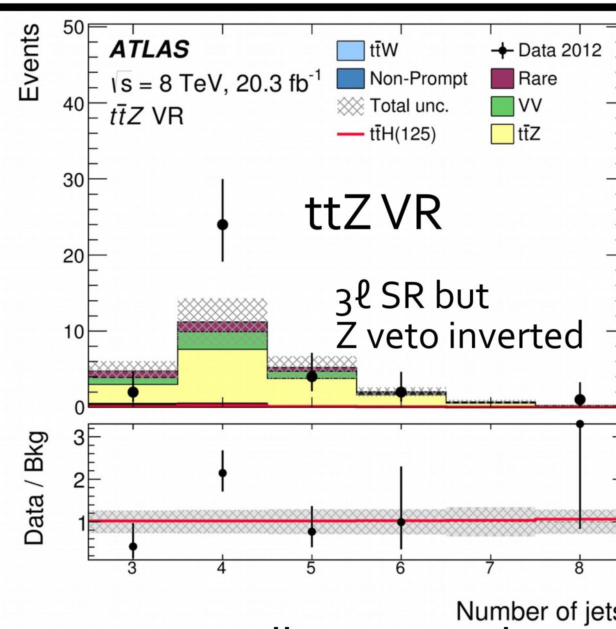
+ require ≥1 b-jet, high (≥2-5) jet multiplicity

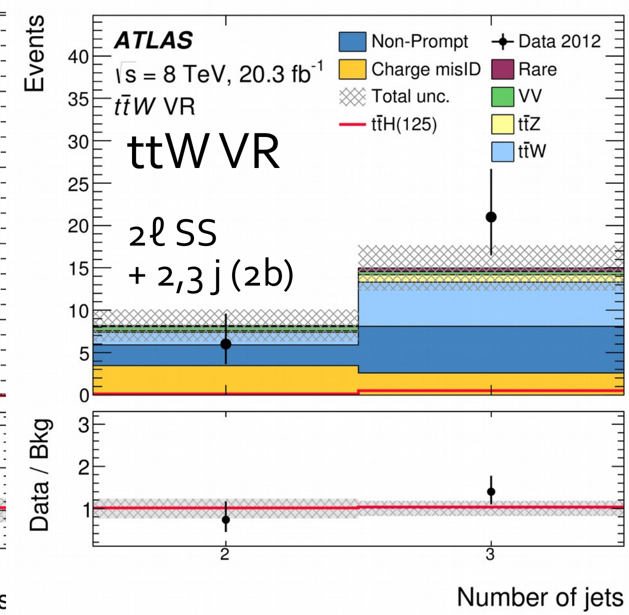
H → ZZ not very important due to low BF and Z vetoes

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

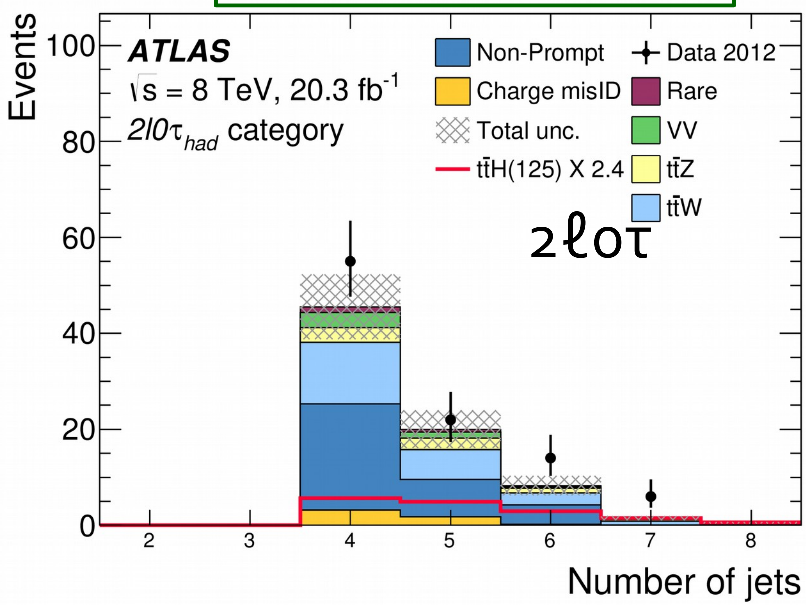




inv mass, smallest ΔR OS lepton pair

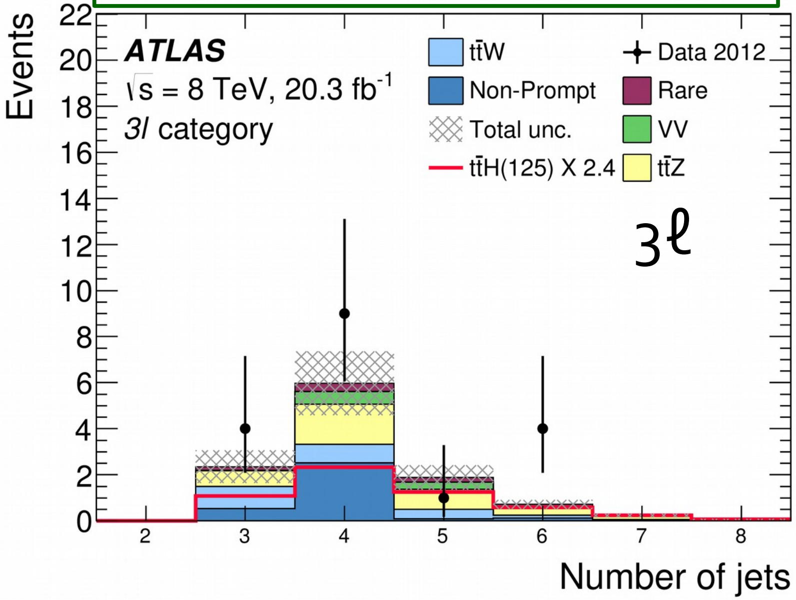
ttH, H → WW/ττ

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



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

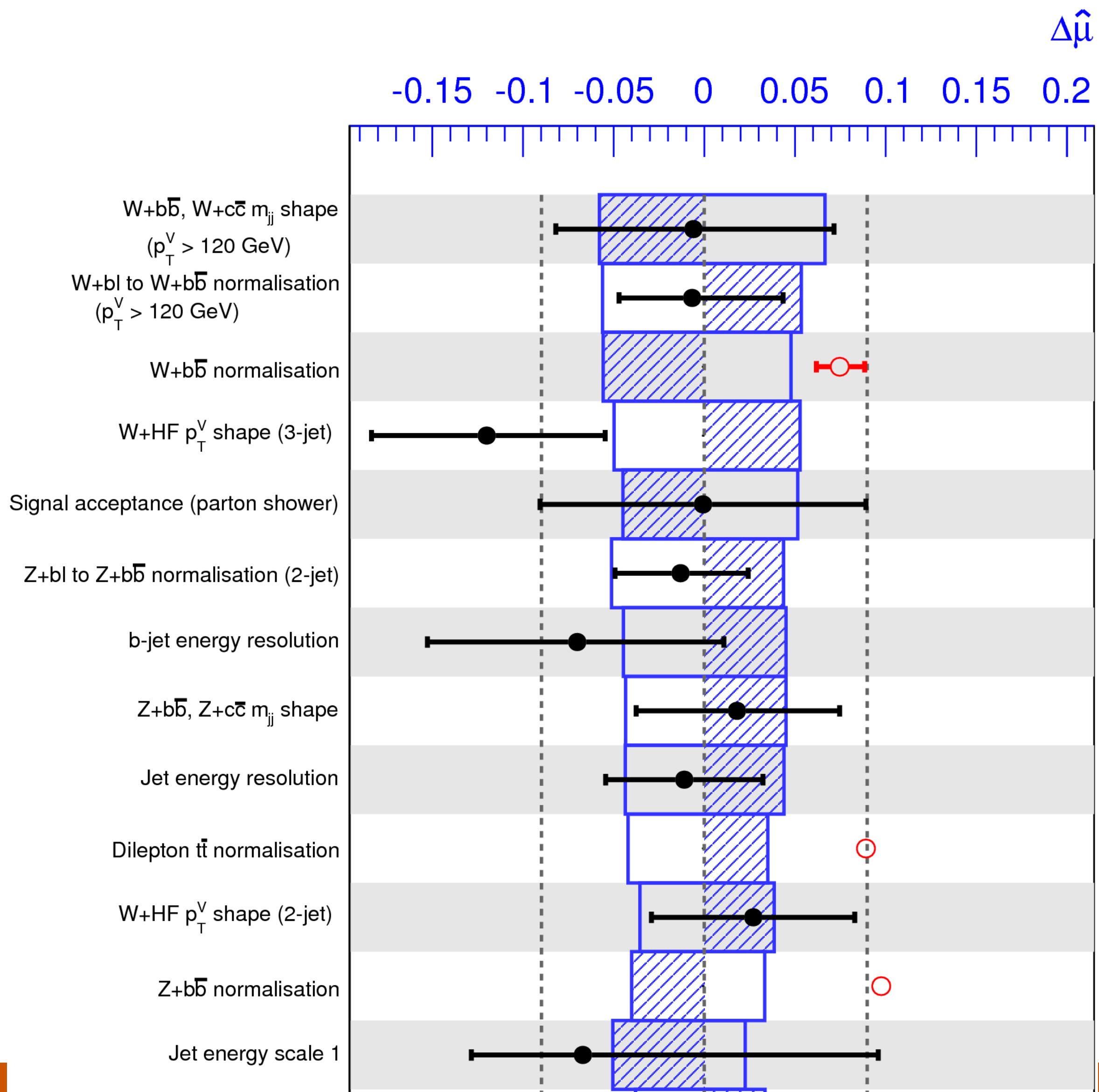
3 leptons
≥ 4 jets, ≥ 1 b-jet or = 3 jets, ≥ 2 b-jets



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

VH, H → bb systematics



VH, H → bb breakdowns