Measurement of Higgs couplings to fermions in the ATLAS experiment

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for the ATLAS Collaboration

Contents:

- $H \to \tau^+\tau^-$ (1501.04943, subm. to JHEP)
- $H \to \mu^+\mu^-$ (1406.7663, PL B738 (2014) 68)
- $H \to b\bar{b}$ (1409.6212, JHEP01 (2015) 69)
- $t\bar{t}(H \to \gamma\gamma)$ (1409.3122, PL B740 (2014) 222)

Not discussing $t\bar{t}H \to b\bar{b}$: discussed in detail by J. Montejo
Interpretation in terms of coupling constants: A. Armbruster

XXIX Rencontres de Physique, 1-7 March 2015

Radboud Universiteit Nijmegen

HIGGS BOSON "PARTY"-SICLE

PEACH SCHNAPPS

VODKA

BOURBON SOAKED CHERRY

GELATIN

BLOOD ORANGE ITALIAN SODA

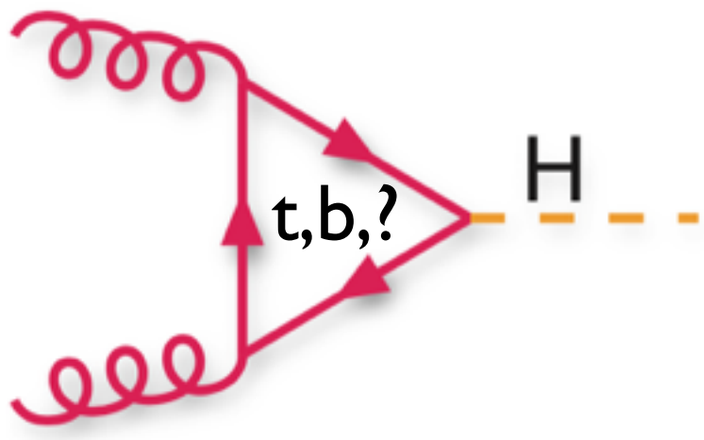
HIGGS BOSON aka "The GOD PARTICLE"

is a hypothetical massive scalar elementary particle predicted to exist by Standard Model of particle physics, ~~only particle that has yet to be observed.~~

Motivation

BEH discovery essentially involved bosons only (even if in part through couplings to fermions) ➠ opportune to focus on fermions now!

- extra particles in loop?
- non-SM couplings?



Type-2 2HDM:

SM particle type	h coupling	H coupling	A coupling
up-type quarks	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\cot\beta$
down-type quarks, $\ell^{\pm}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\cos\beta}$	$\tan\beta$
W, Z bosons	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0

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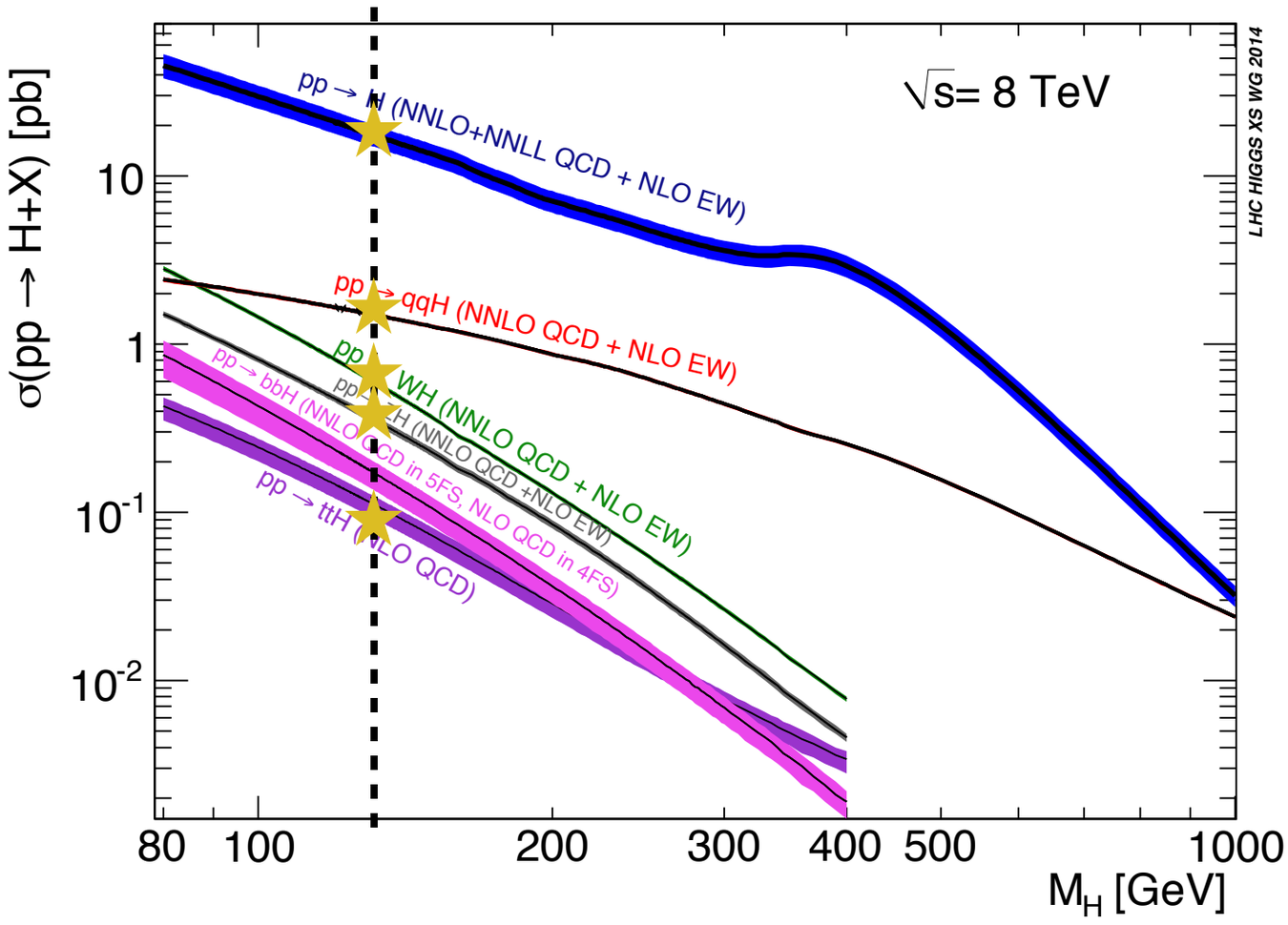
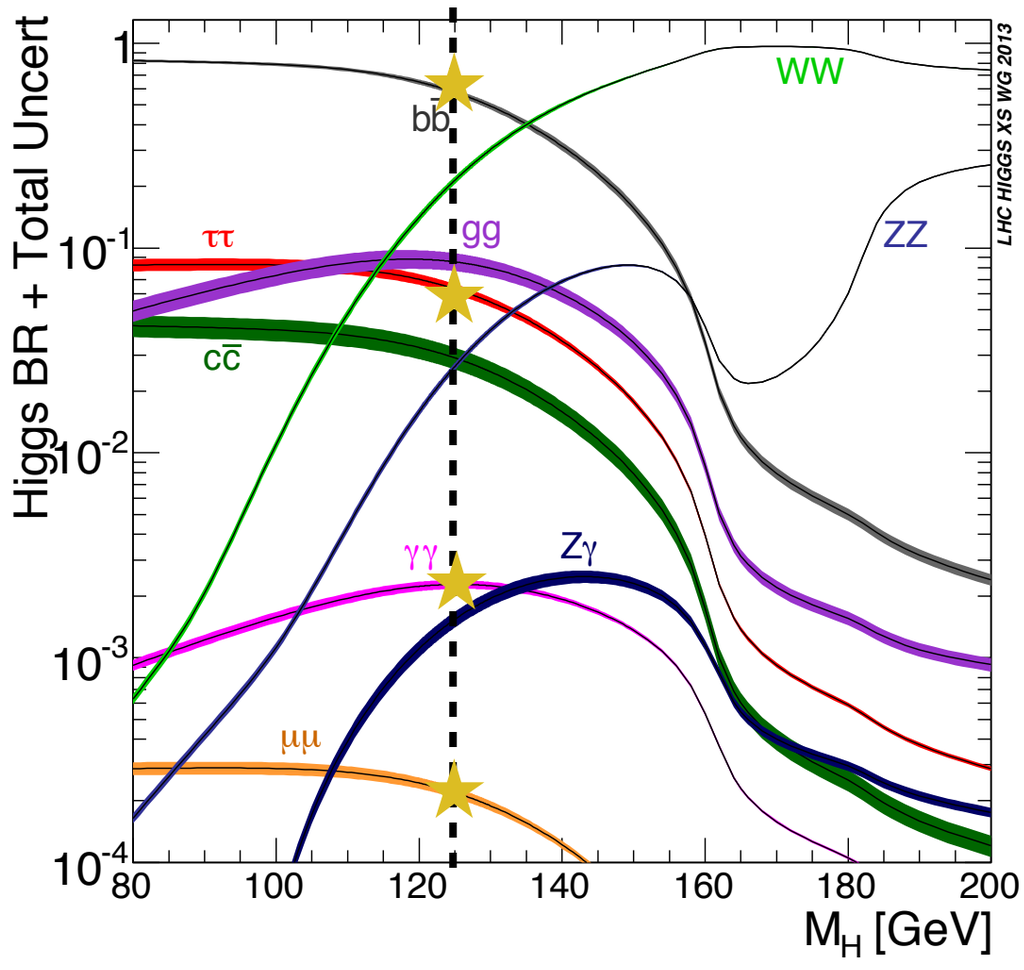
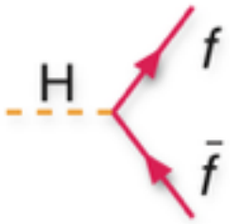




Challenging analyses

- most sensitive ($H \to \tau^+\tau^-, b\bar{b}$) use all the available sophistication (MVA)
- analyses use full Run-1 dataset; will show essentially no 2011 results

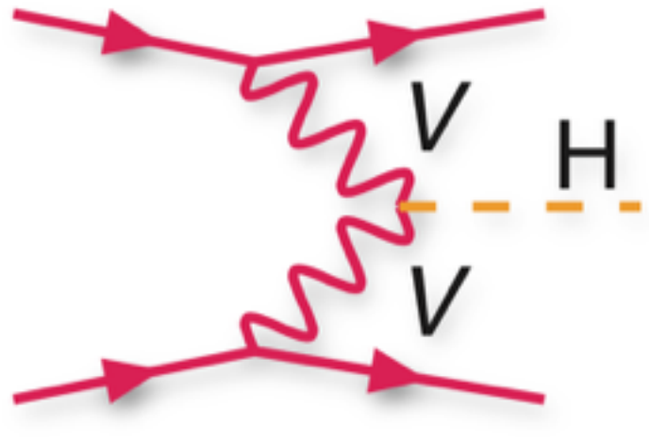


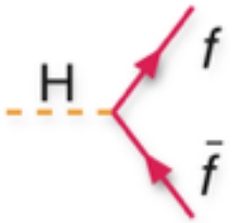
$H \rightarrow \tau^+\tau^-$

High production cross section & decent branching fraction… but many τ decay modes involving ν present significant complications

Strategy: after preselection, optimise separately in

- $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$ decay modes
- VBF, boosted ggF ($p_T(H) > 100$ GeV) production modes





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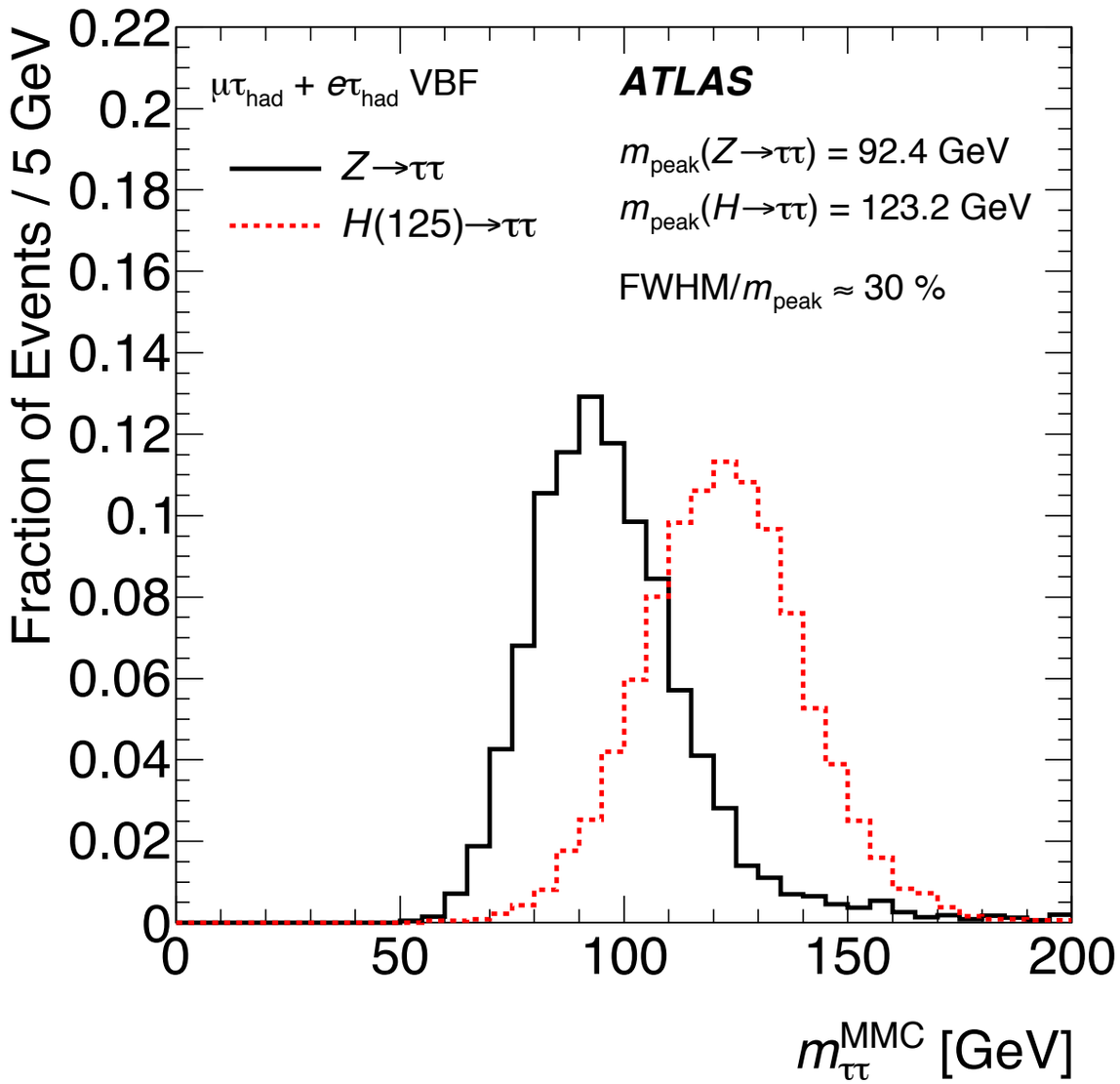
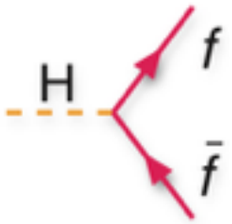
Tools:

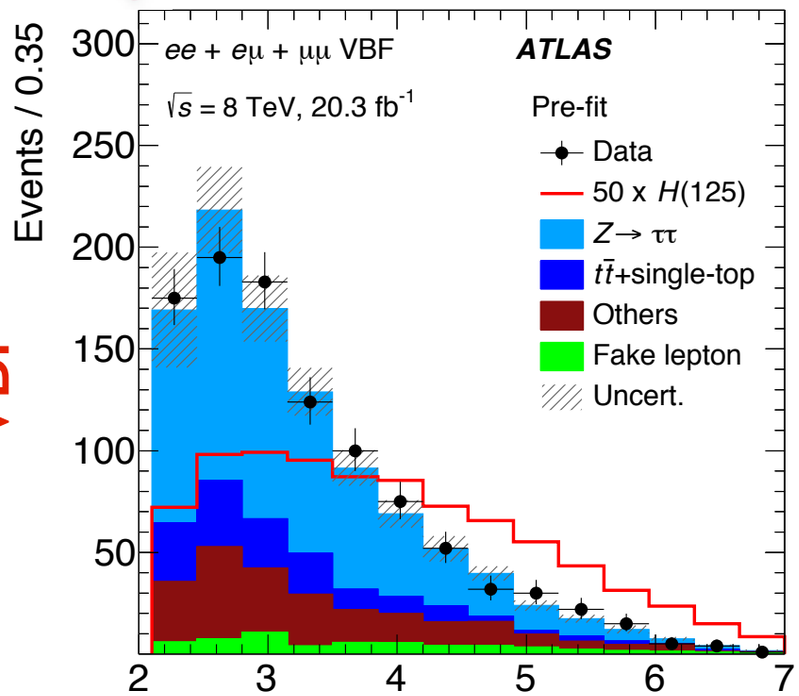
- Missing Mass Calculator: under-constrained system improving $m_{\tau\tau}$ measurement
- "embedding": in data $Z/\gamma^* \rightarrow \mu^+\mu^-$ events ($m_{\mu\mu} > 40$ GeV), replace μ with simulated τ
- BDT analyses in all 6 categories
  - exploiting VBF/boosted event kinematics

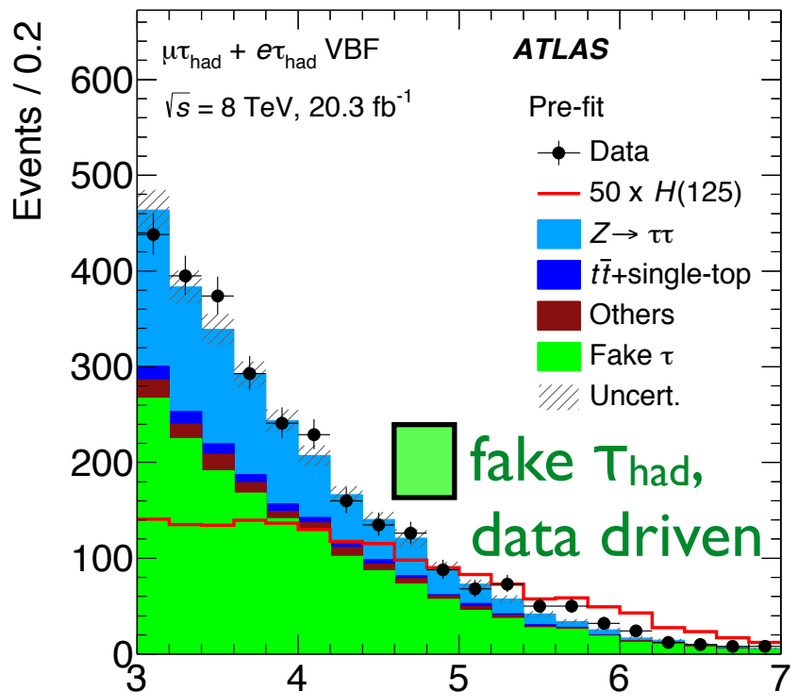


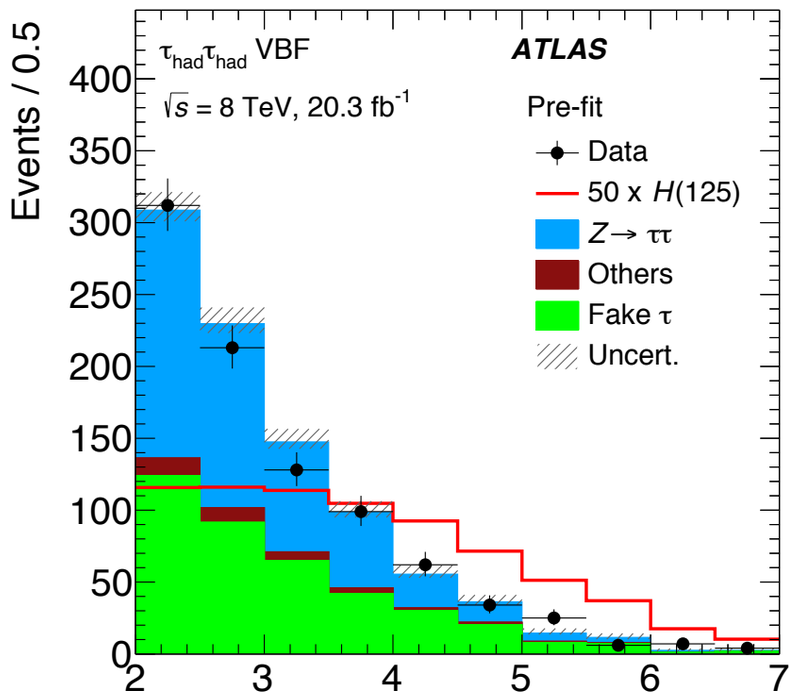


H → τ⁺τ⁻ (2)

VBF





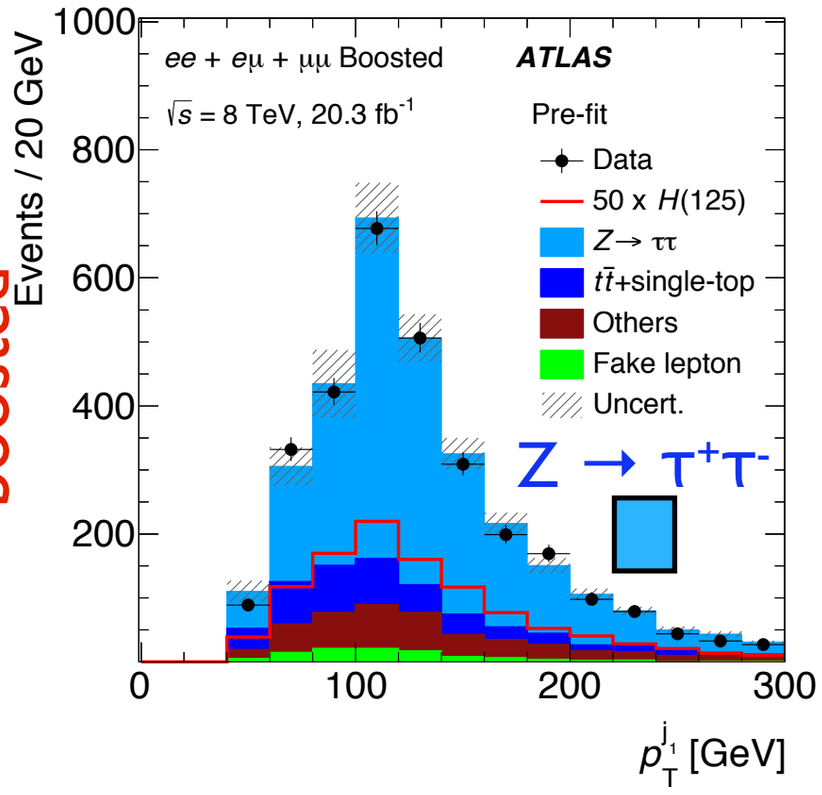


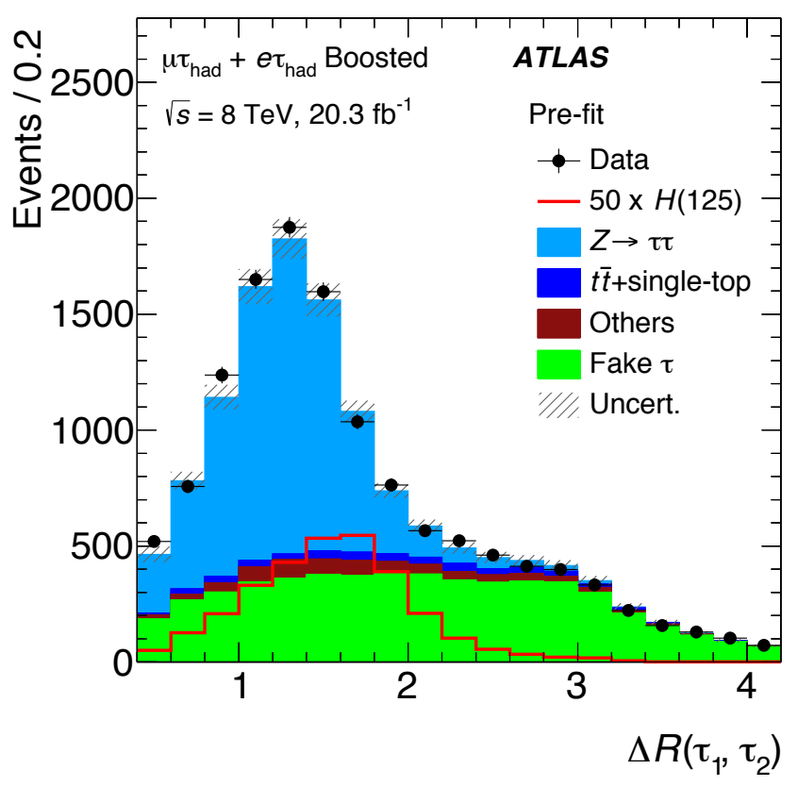
Tlep Tlep Δη(j1, j2)

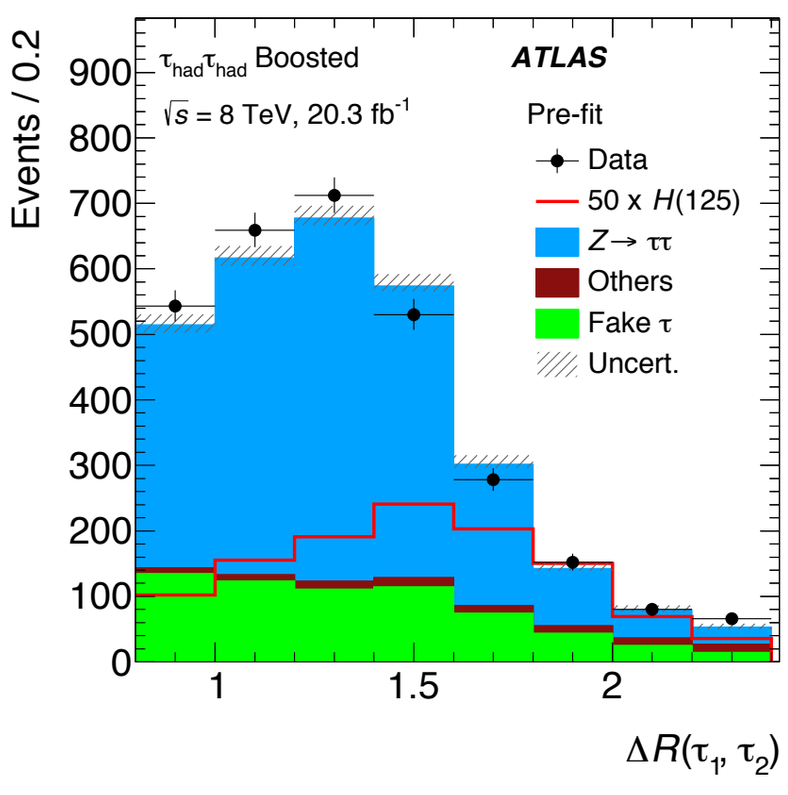
Tlep Thad Δη(j1, j2)

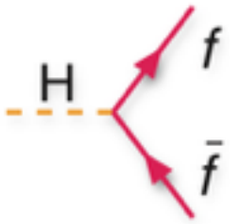
Thad Thad Δη(j1, j2)

boosted









$H \rightarrow \tau^+\tau^-$ (3)

Results extracted using profile likelihood ratio fits

$$\lambda(\mu) = L\left(\mu, \hat{\hat{\vec{\theta}}}(\mu)\right) / L\left(\hat{\mu}, \hat{\vec{\theta}}\right)$$

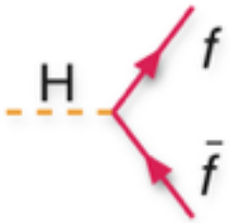
global maximum of L

assumed signal strength

best-fit nuisance parameters for given μ

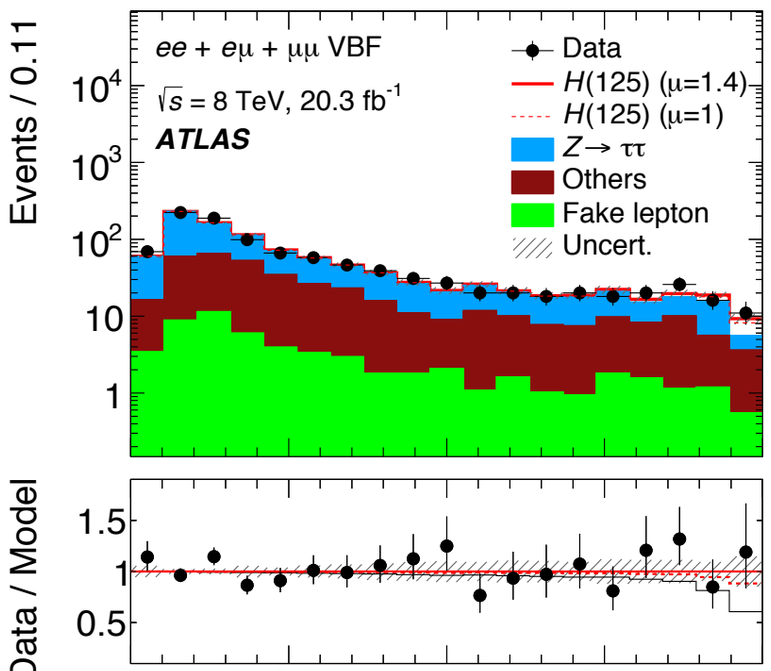
Dominant uncertainties:

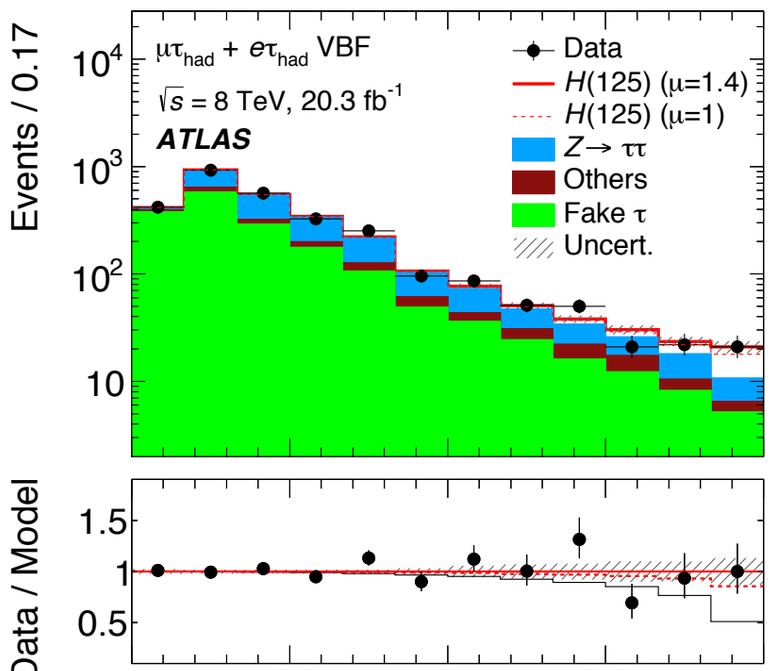
- jet energy scale & resolution (≲ 10%, mostly signal)
- τ_{had} identification (≲ 7%, signal + bg)
- higher-order QCD corrections (~ 10% VBF signal, ~20% boosted ggF signal)

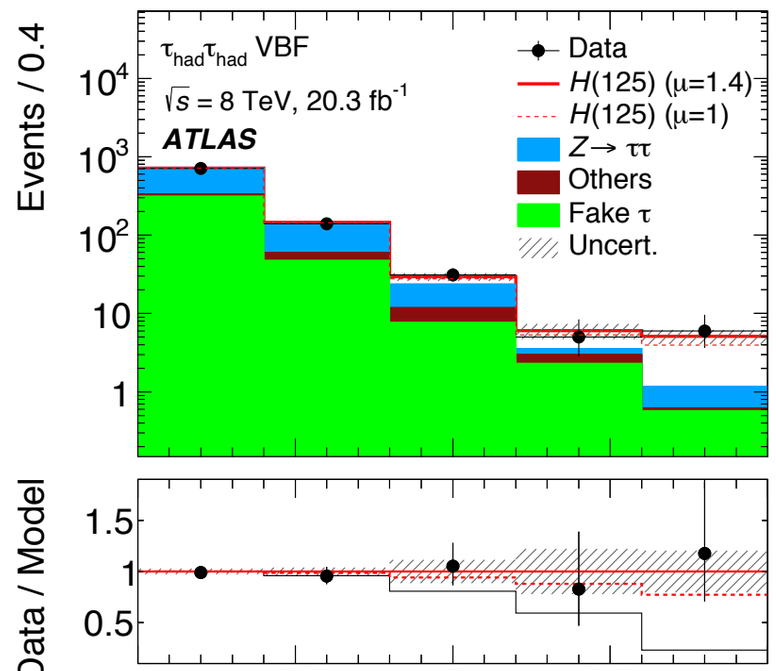


H → τ⁺τ⁻ (4)

VBF





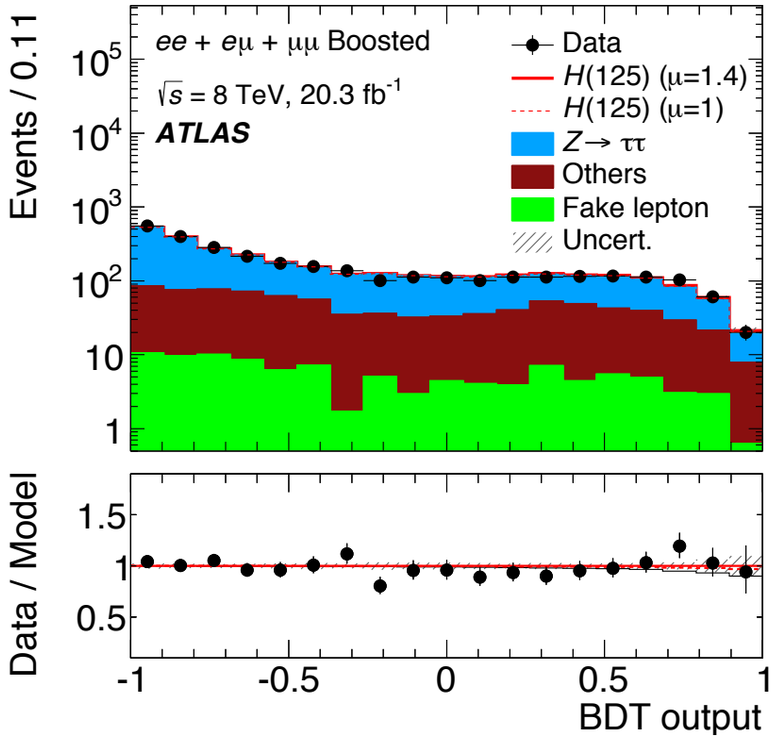


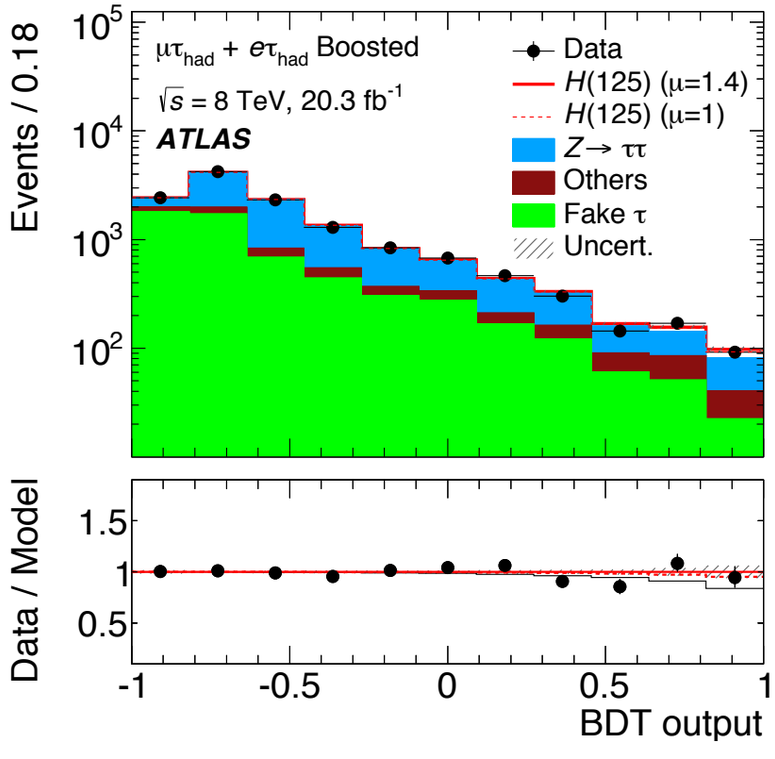
$\tau_{lep}\tau_{lep}$ BDT output

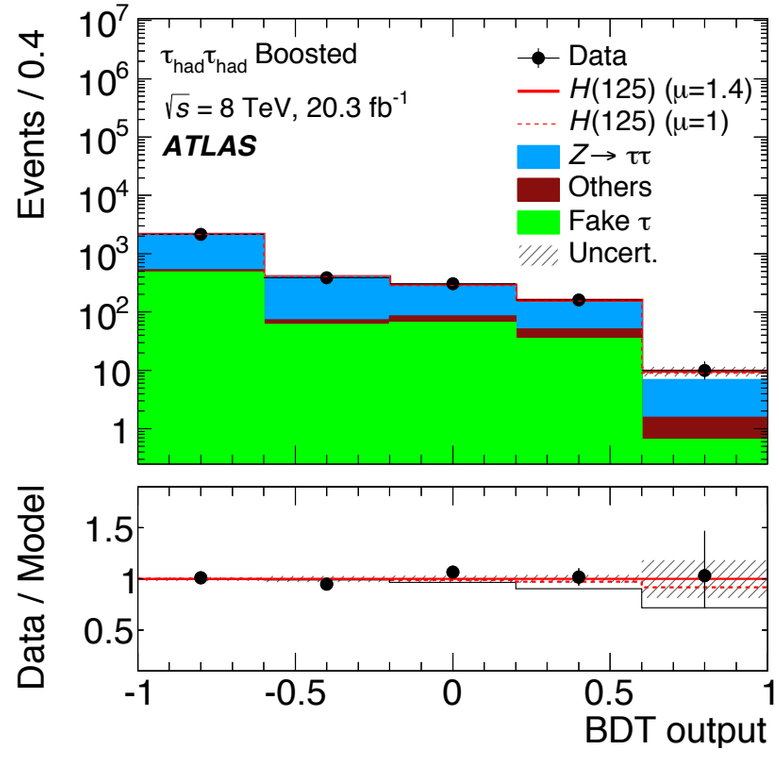
$\tau_{lep}\tau_{had}$ BDT output

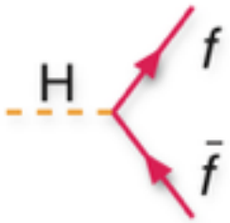
$\tau_{had}\tau_{had}$ BDT output

boosted









$H \to \tau^+\tau^-$ (5)

Results:

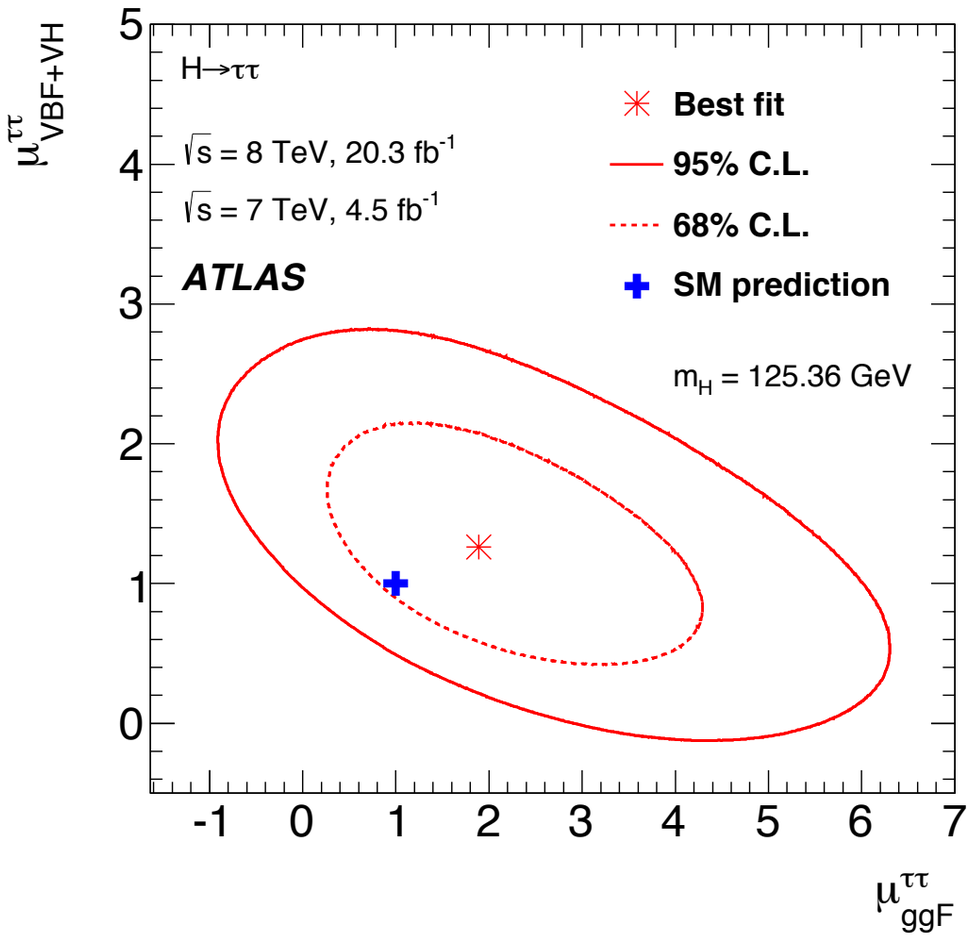
- grand combination:

$$\mu = 1.43^{+0.27}_{-0.26}(\text{stat.})^{+0.32}_{-0.25}(\text{syst.}) \pm 0.09(\text{theory})$$

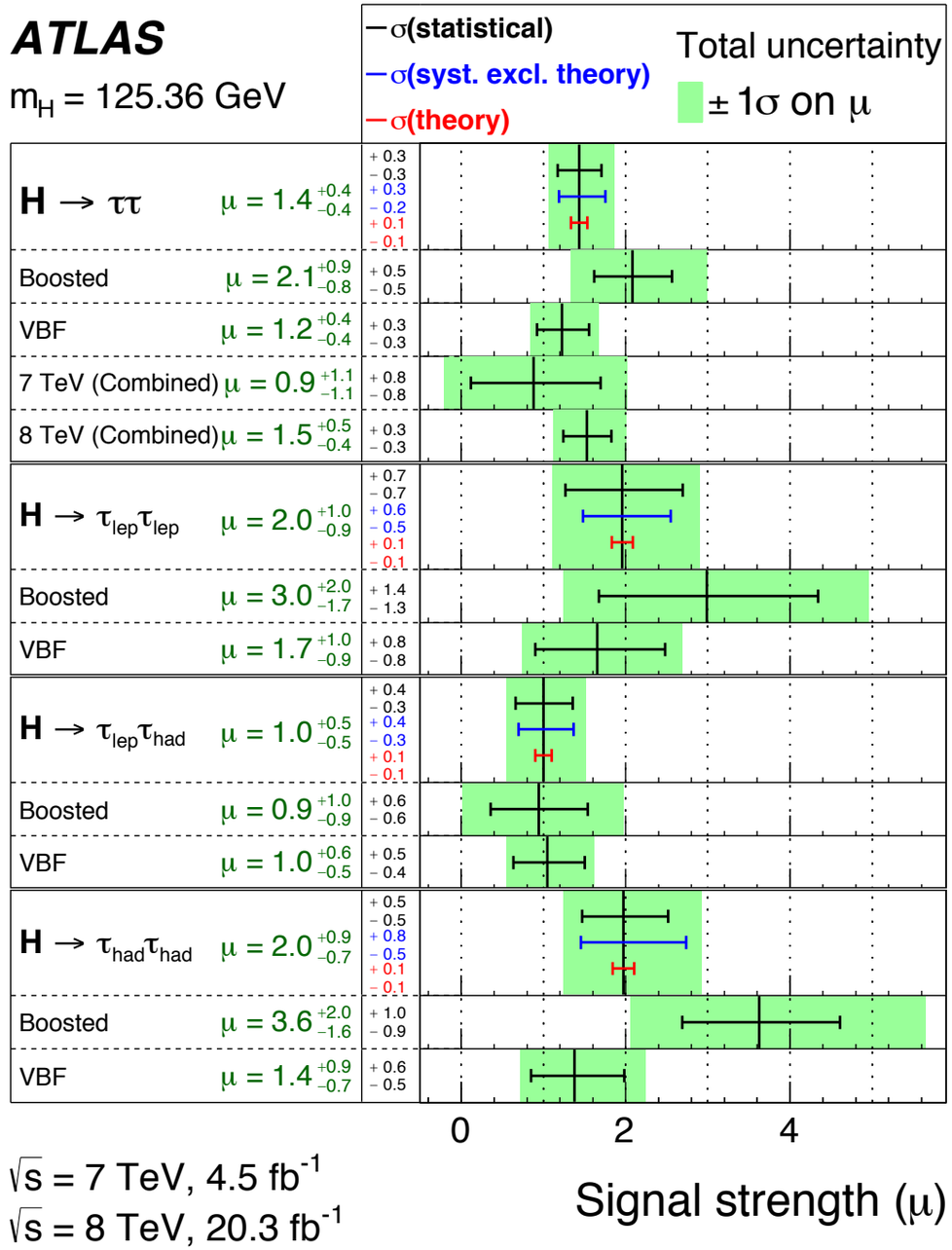
- separate VBF / ggF signal strengths:

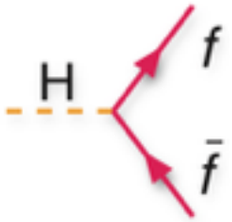
$$\mu_{ggF} = 2.0 \pm 0.8(\text{stat.})^{+1.2}_{-0.8}(\text{syst.}) \pm 0.3(\text{theory})$$

$$\mu_{\text{VBF}+VH} = 1.24^{+0.49}_{-0.45}(\text{stat.})^{+0.31}_{-0.29}(\text{syst.}) \pm 0.08(\text{theory})$$



- observed discovery significance: 4.5σ (expected: 3.4σ)

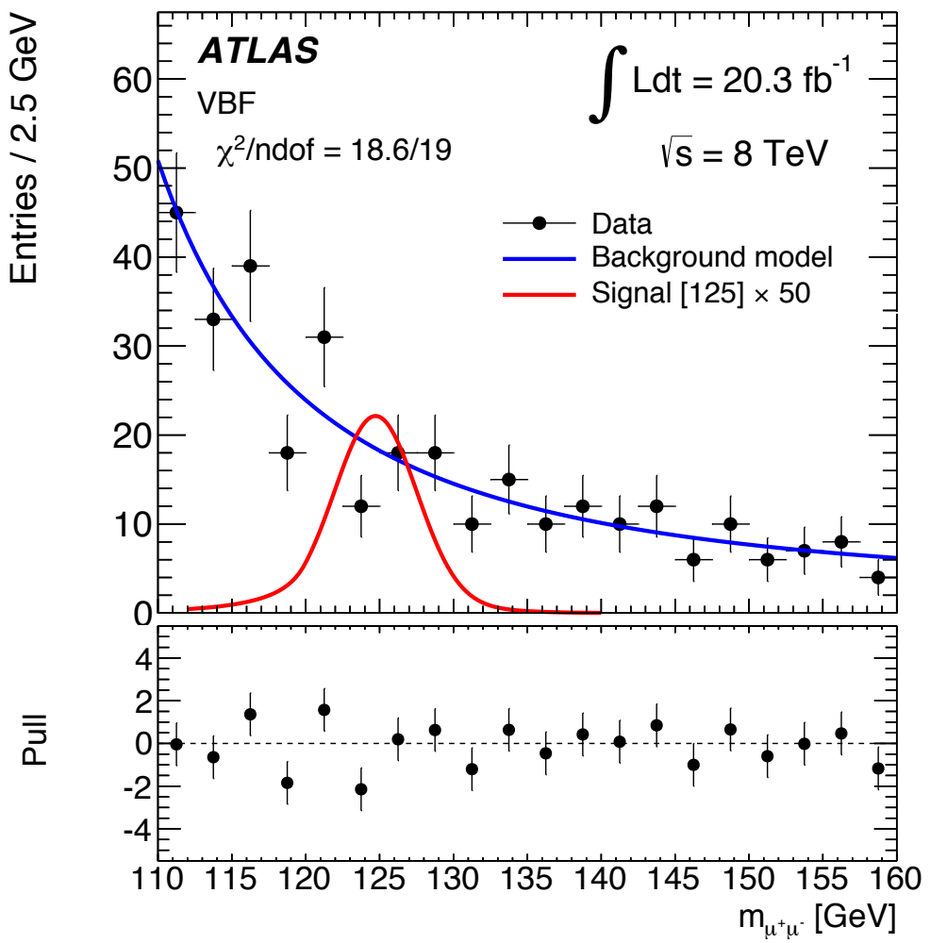


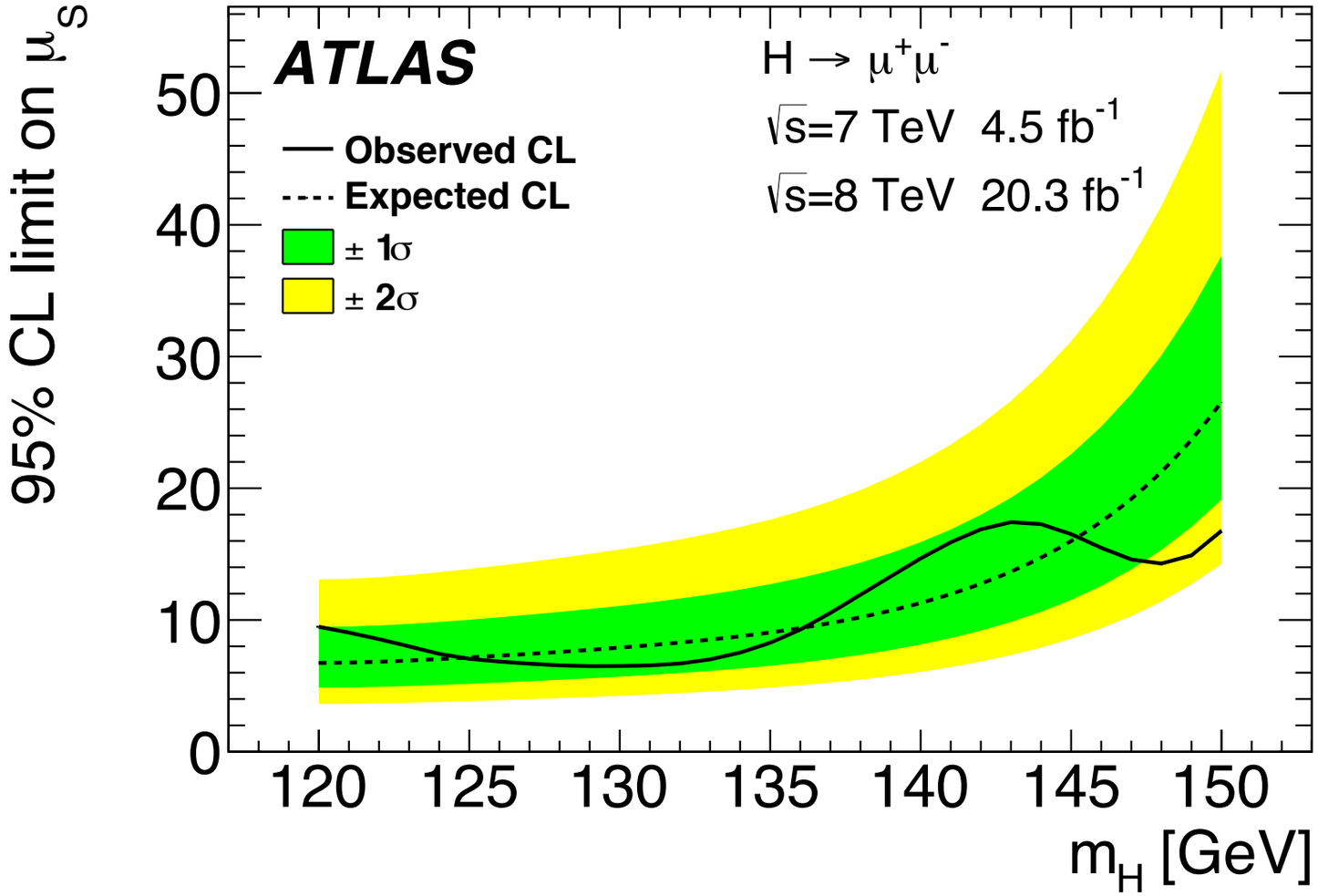


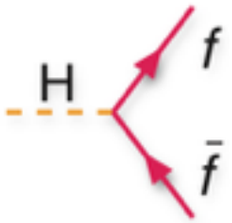
$H \rightarrow \mu^+\mu^-$

"Simple" analysis but made difficult by low branching fraction and overwhelming $Z/\gamma^* \rightarrow \mu^+\mu^-$ background

- categories similar to $H \rightarrow \tau^+\tau^-$: VBF / 3 separate $p_T(H)$ bins
- result: observed $\mu < 7.0$ (95% CL) (expected: $\mu < 7.2$)







$H \to b\bar{b}$

Due to QCD $b\bar{b}$ background, little hope to observe in ggF production; use W/Z associated production.
"Simple" topology but separate analyses in many categories!

- leptonic W/Z decays: $Z \to \nu\nu$, $W \to l\nu$, $Z \to ll$ (l = e, μ)
- events with 2 or 3 jets (with $|\eta| < 2.5$, $p_T > 20$ GeV)
- 2 $p_T(V)$ regions (120 GeV boundary)
  - 0-lepton: $p_T(Z) > 100$ GeV (trigger)

2-lepton channel: kinematic fit to improve mass resolution

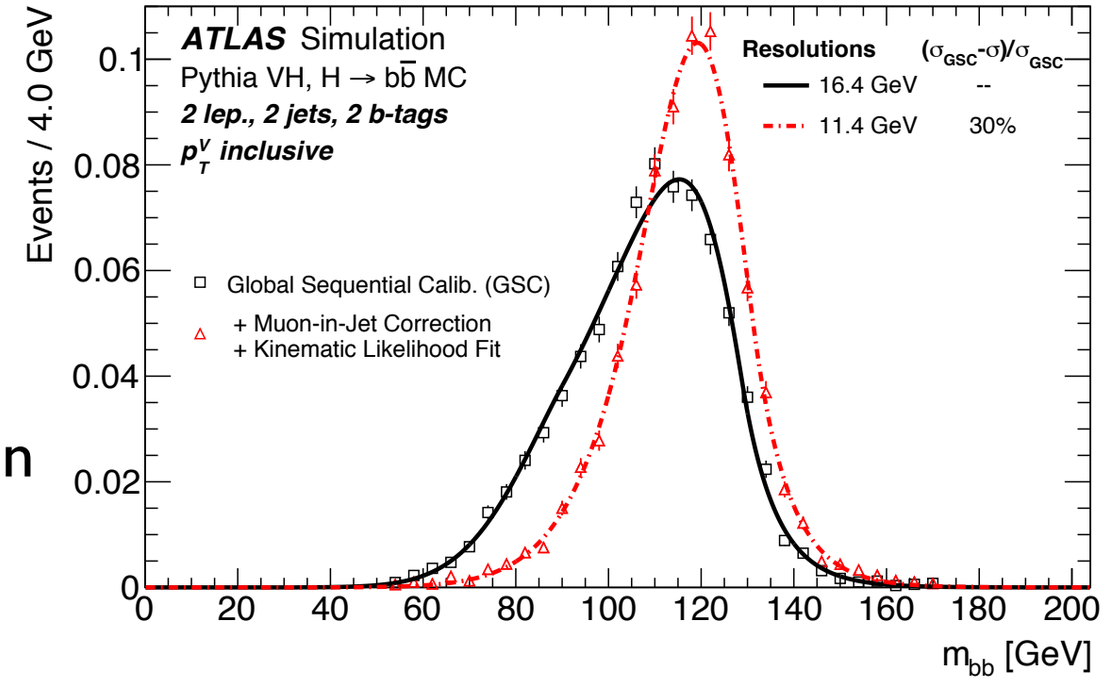
- 0, 1-lepton channels: dedicated b-jet correction

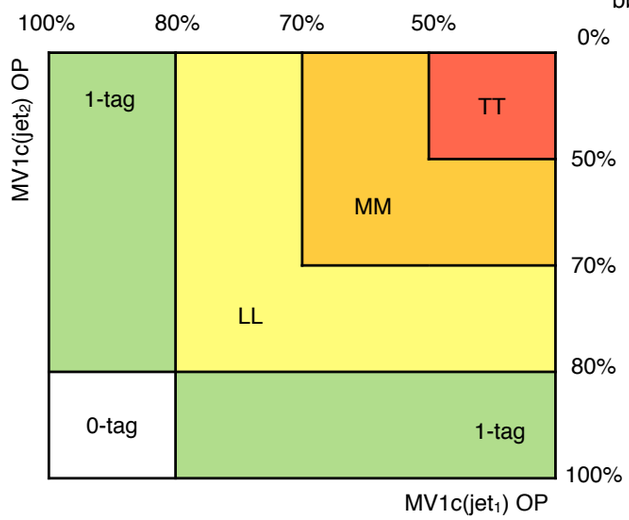
0-lepton channel: improve multijet rejection using both calorimeter & track based $E_T(miss)$

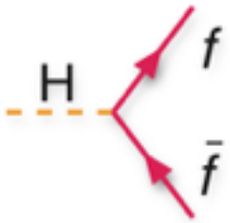
- consistency check: $\Delta\varphi(\mathbf{p}_T(miss), \mathbf{E}_T(miss)) < \pi/2$

Analysis binned in discriminant output of b-jet tagger with improved c-jet rejection (after loose b-jet requirement):

- Loose (80%), Medium (70%), Tight (50%)

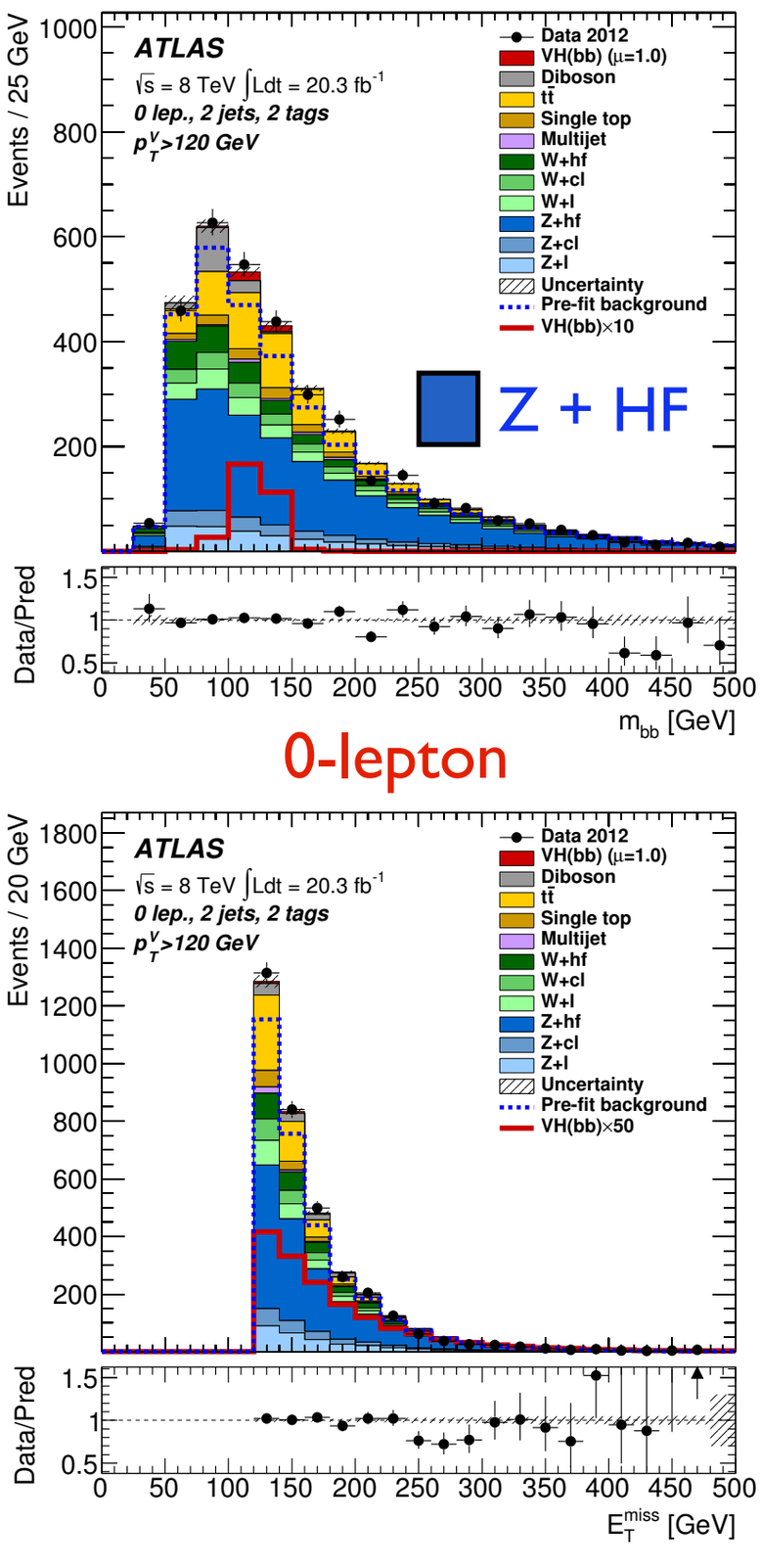


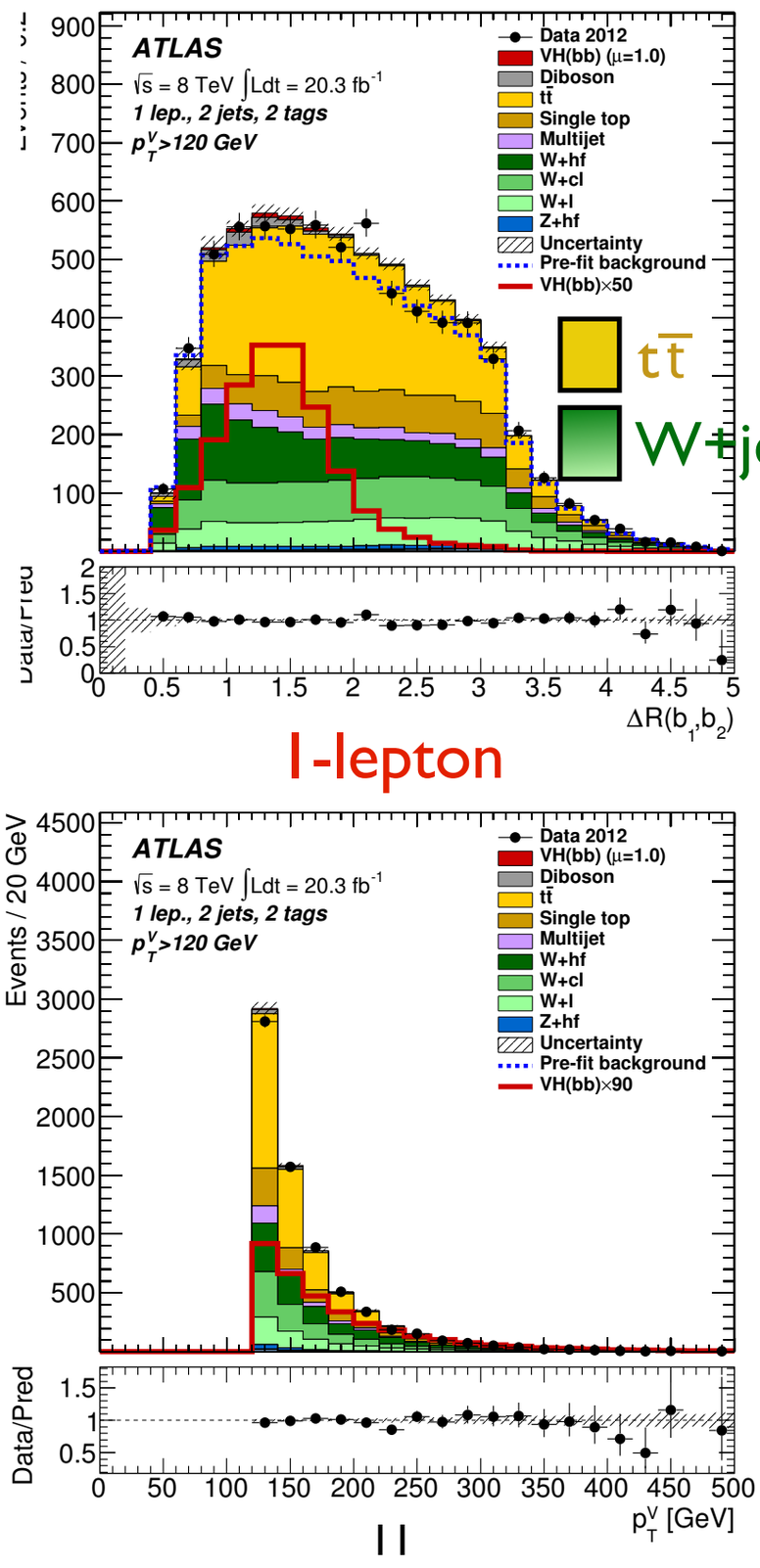


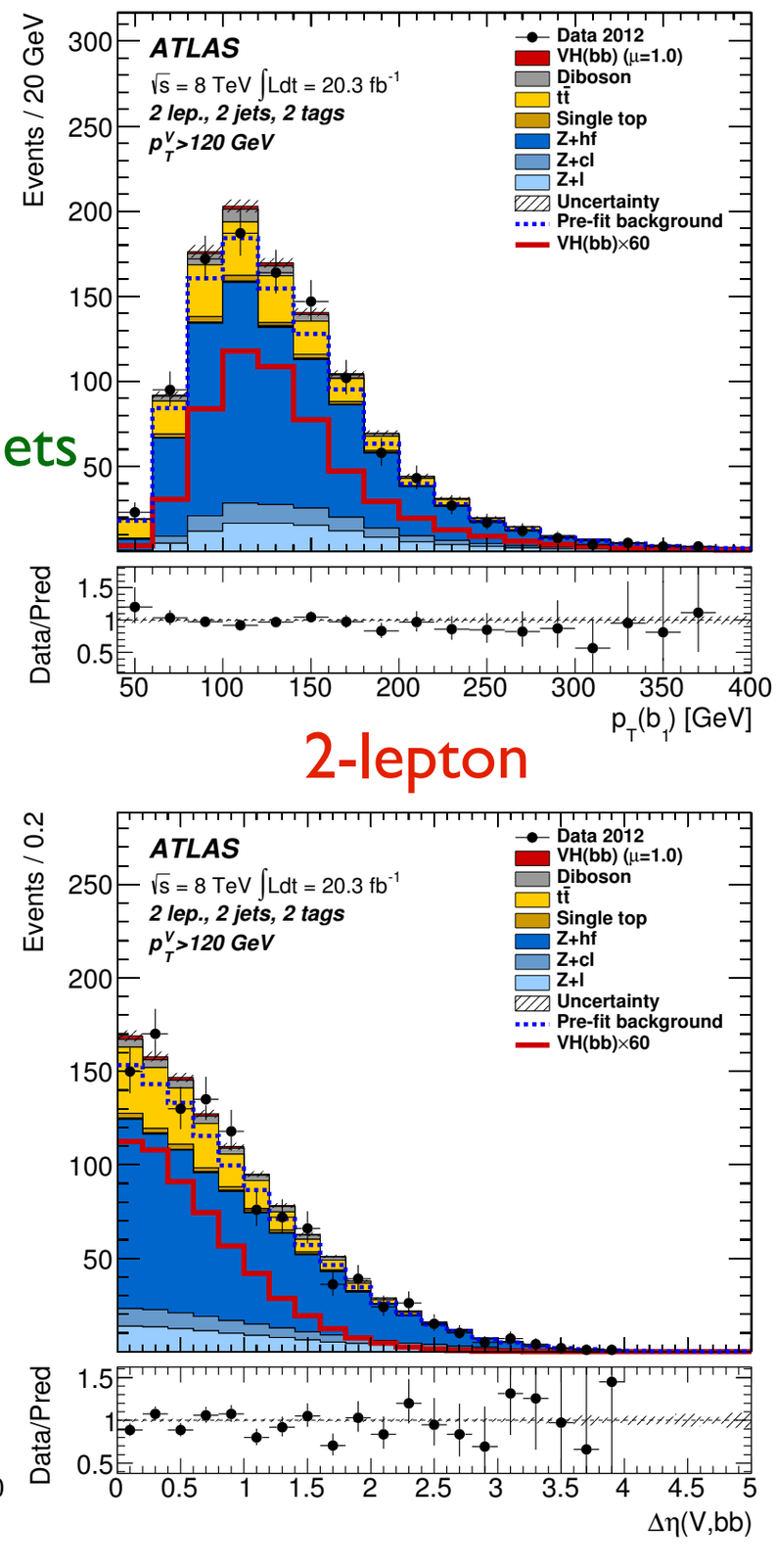


H → bb̄ (2)

BDT input variables



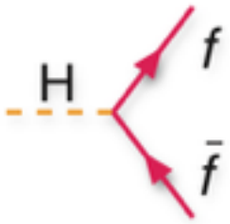




0-lepton

1-lepton

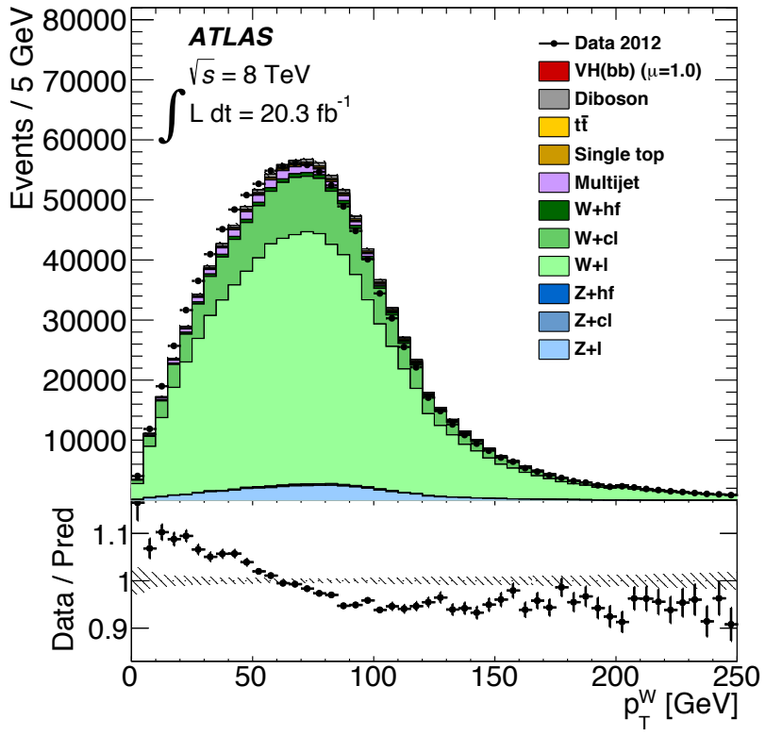
2-lepton

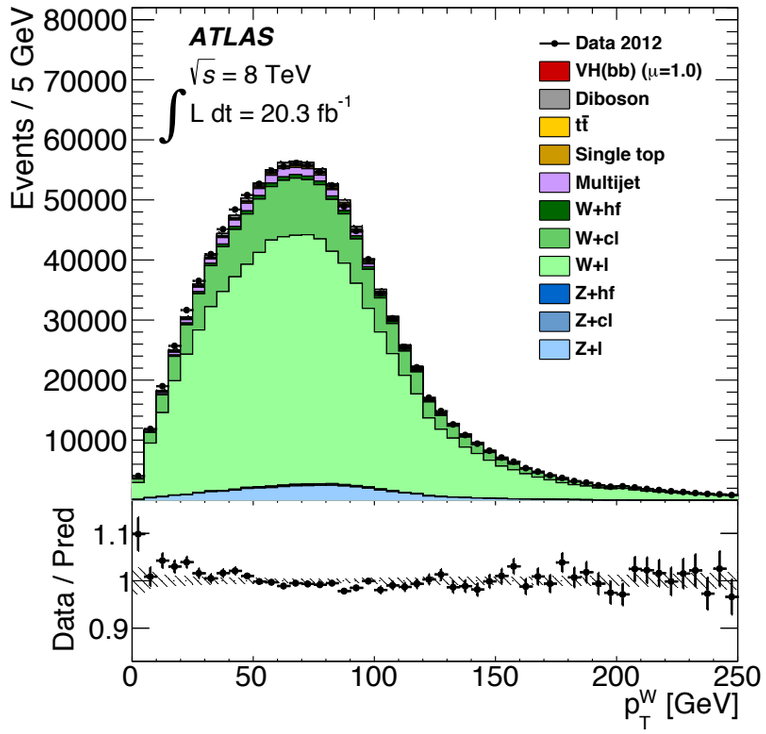


H → bb̄ (3)

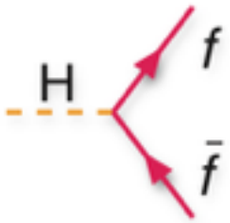
Extensive background modelling required (only small multijet background estimated using data driven methods)

- SHERPA modelling of $p_T(W)$ distribution improved by reweighting $\Delta\varphi(j_1, j_2)$
  - applied to W+l, W+cl



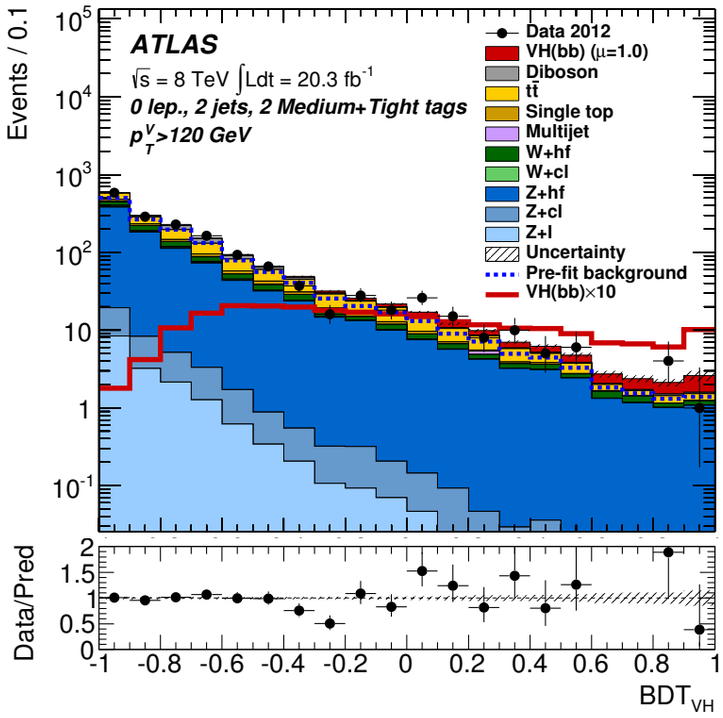


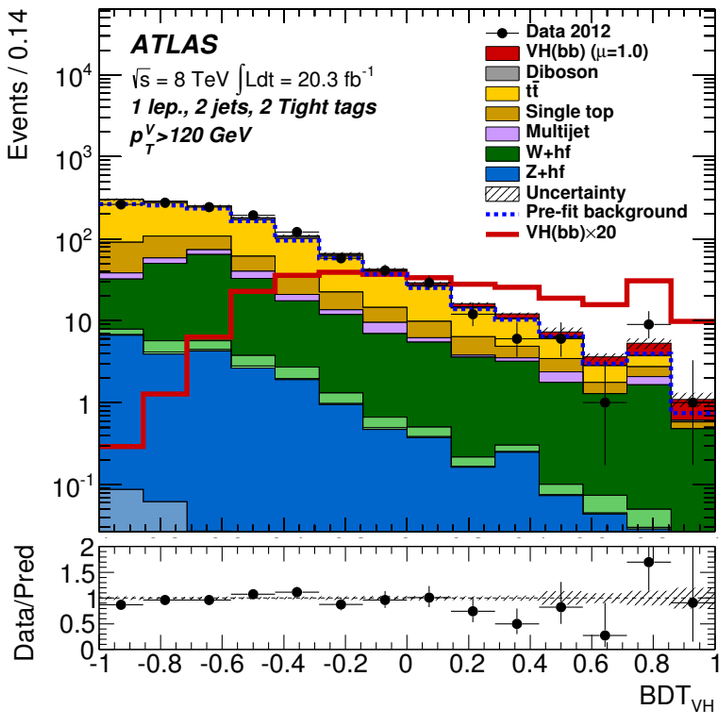
- similar reweighting carried out for (SHERPA) Z+jets background
  - $\Delta\varphi(j_1, j_2)$ reweighted for Z+l; directly $p_T(Z)$ for Z+b, Z+c
- $p_T(t)$ spectrum in $t\bar{t}$ reweighted to bring it in agreement with measurement

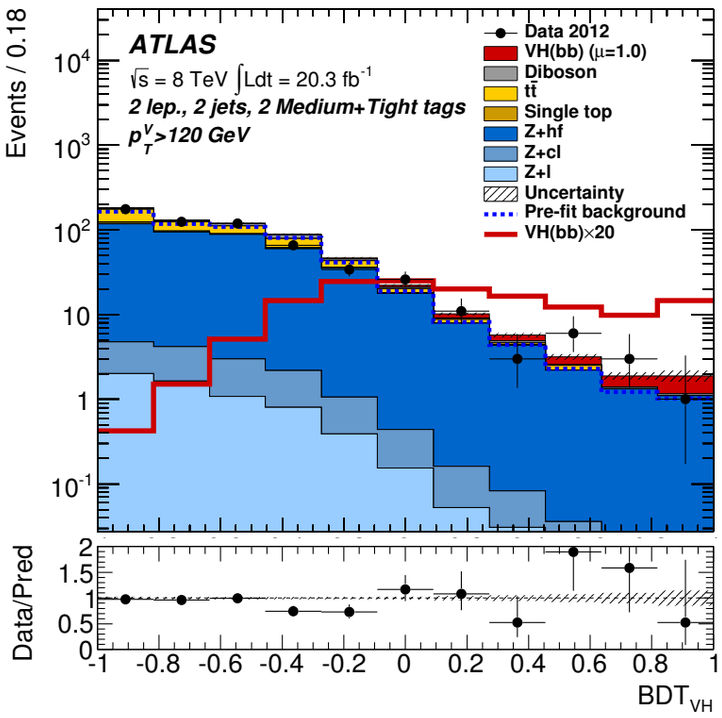


$H \to b\bar{b}$ (4)

BDT output distributions in most discriminating 0-, 1-, 2-lepton regions

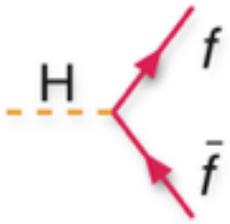






Systematic uncertainties obtained mostly from generator comparisons (bg), theory (signal). Dominant contributions and impact on signal strength estimate:

- W+HF m_{jj} shape (0.06), W+bl/$b\bar{b}$ ratio, W+$b\bar{b}$ normalisation, W+HF $p_T(V)$ shape (0.05), Z+bl/$b\bar{b}$ ratio, b-jet energy resolution (0.04)
- signal: effect μ_F, μ_R scale variations on acceptance (0.04)



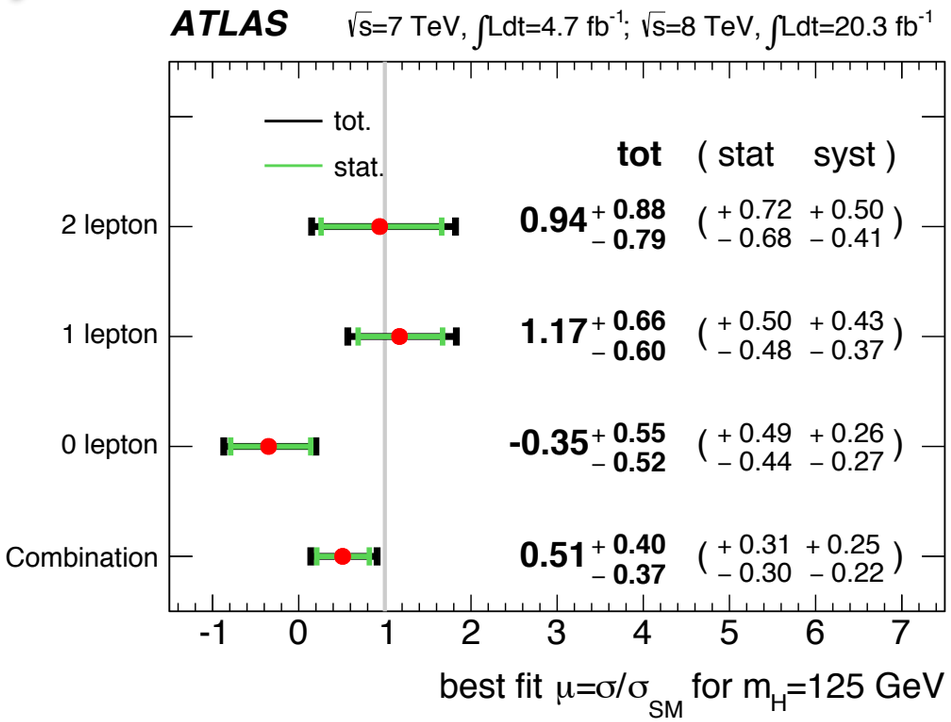
H → bb̄ (5)

Profile likelihood fit (as in H → τ⁺τ⁻ analysis):

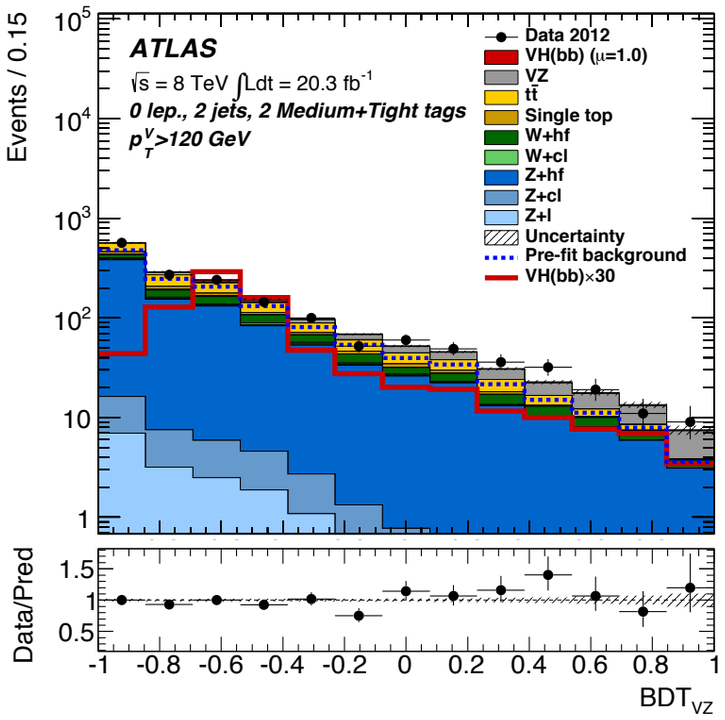
$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{syst.})$$

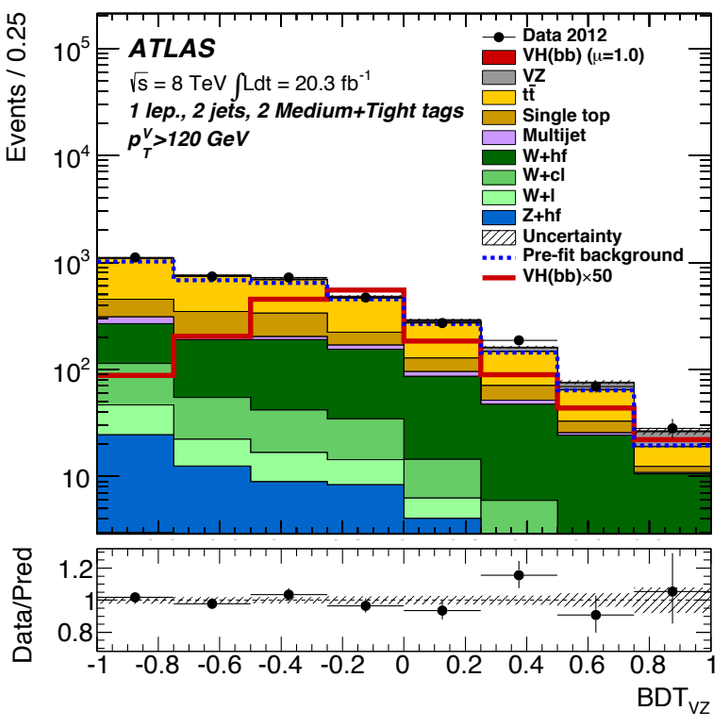
- significance: 1.4σ (expected: 2.6σ)
- μ < 1.2 at 95% CL (expected: 0.8)

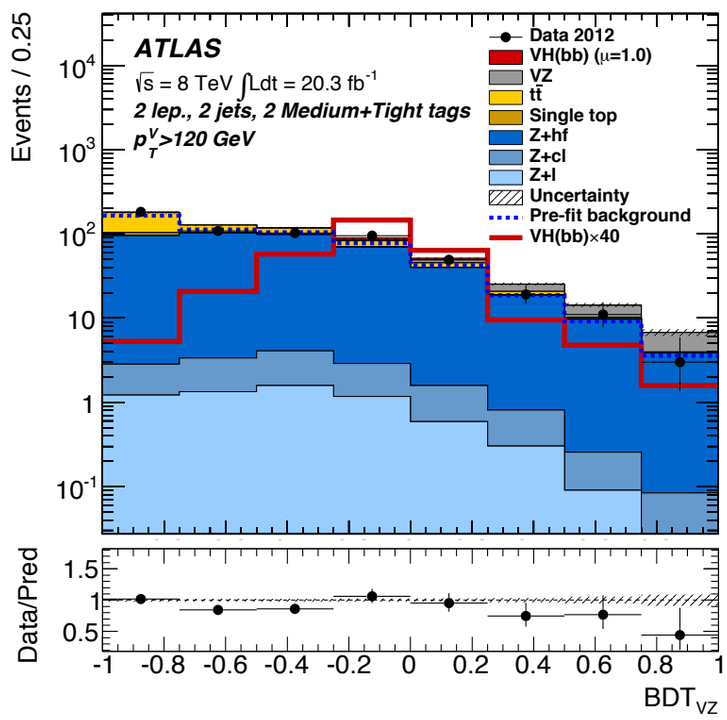
Cross-check analysis done searching for W/Z+Z→bb events

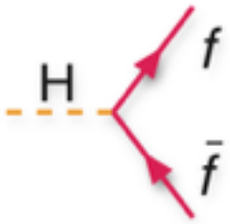


- 5 times larger cross section; softer $p_T(Z)$ spectrum









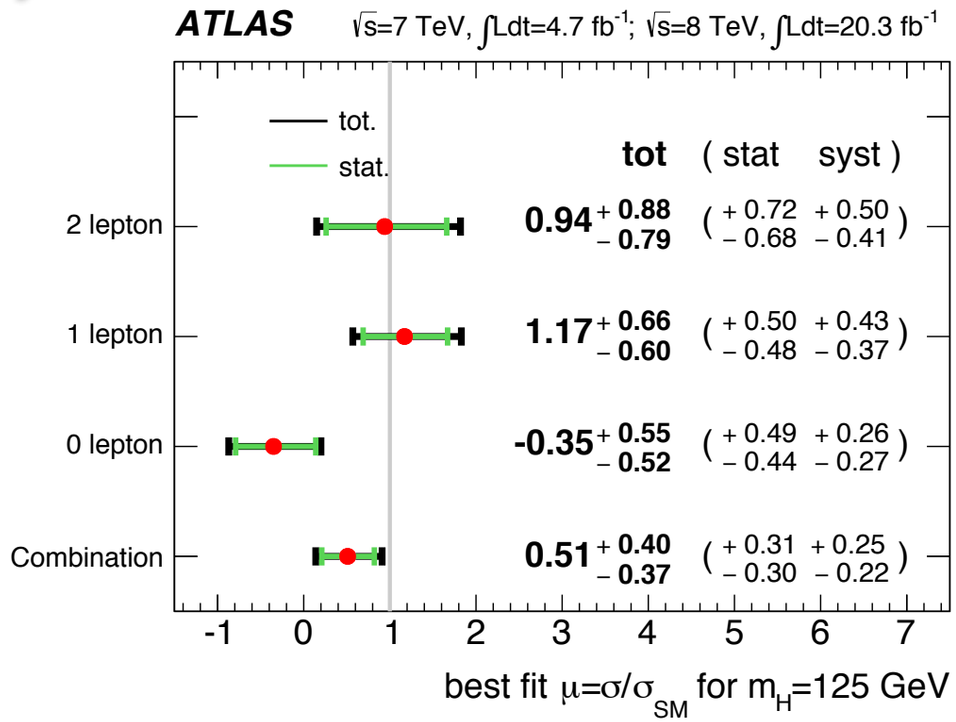
H → bb̄ (5)

Profile likelihood fit (as in H → τ⁺τ⁻ analysis):

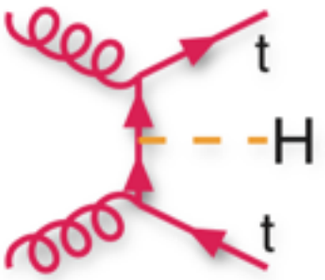
$$\mu = 0.51^{+0.31}_{-0.30}(\text{stat.})^{+0.25}_{-0.22}(\text{syst.})$$

- significance: 1.4σ (expected: 2.6σ)
- μ < 1.2 at 95% CL (expected: 0.8)

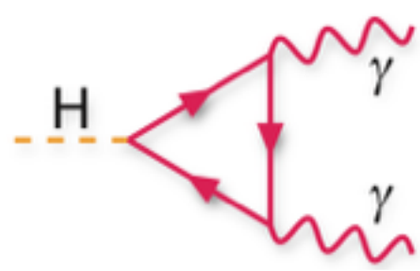
Cross-check analysis done searching for W/Z+Z→bb events



- 5 times larger cross section; softer $p_T(Z)$ spectrum
- separately trained BDTs (SM W/Z+H "background")
- results:
  - μ_{VZ} = 0.74 ± 0.09 (stat.) ± 0.14 (syst.)
  - simultaneous fit of μ, μ_{VZ} does not affect the measured μ (correlation between systematics only 35%)

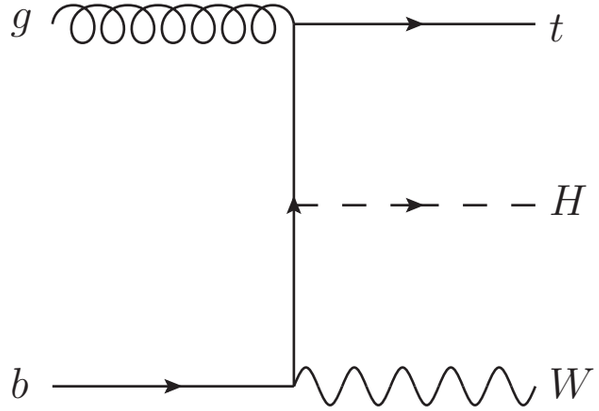


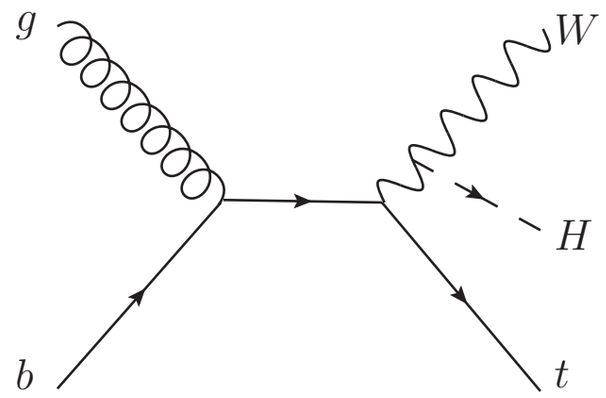
$t\bar{t}H$



Process provides tree level access to Htt coupling

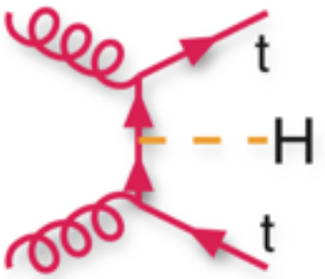
- $H \rightarrow \gamma\gamma$ decay mode: tiny branching fraction ($2.3 \cdot 10^{-3}$), but very low background which can be estimated from $m_{\gamma\gamma}$ sidebands (except contributions from other $H \rightarrow \gamma\gamma$ decays)
- selection kept inclusive to allow tHqb and tHW contributions
  ➠ sensitivity to relative sign of Htt and HWW couplings, due to destructive interference in tHW final state



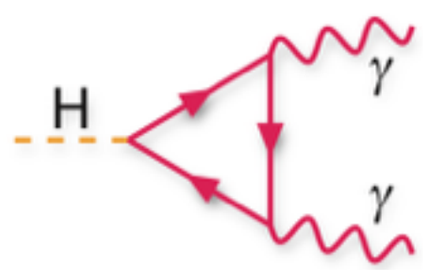


- similar interference for tHqb production
- parametrise Htt coupling using additional factor κ_t

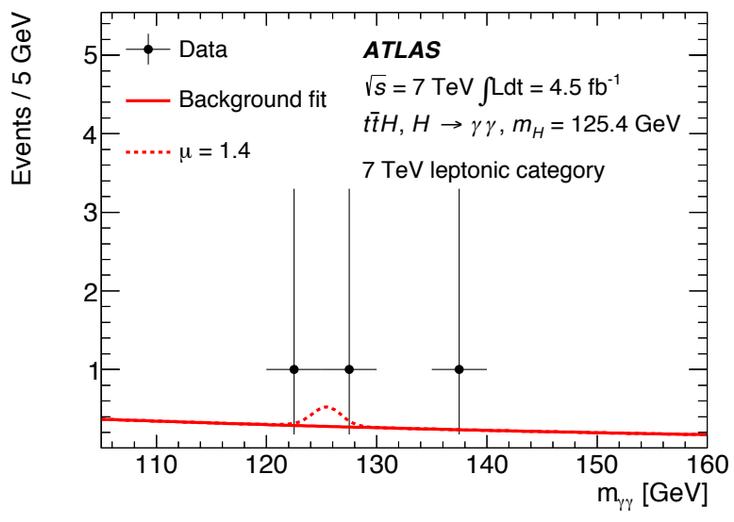
- loose $t\bar{t}$ selection for both l+jets ("leptonic") and hadronic final states
  - but tight photon selection

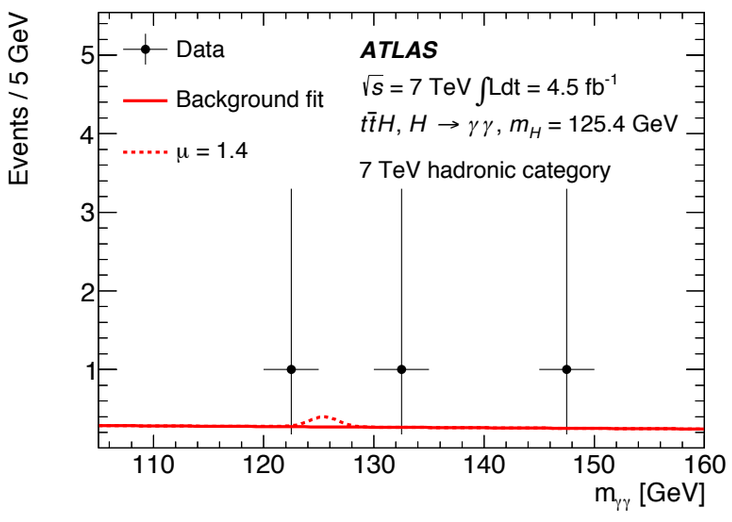


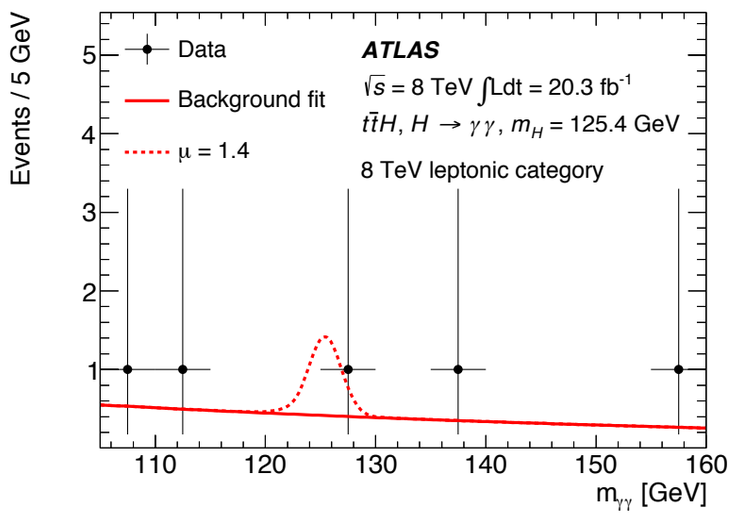
$t\bar{t}H$ (2)



Results obtained from unbinned fit to $m_{\gamma\gamma}$ spectrum assuming signal + exponential background

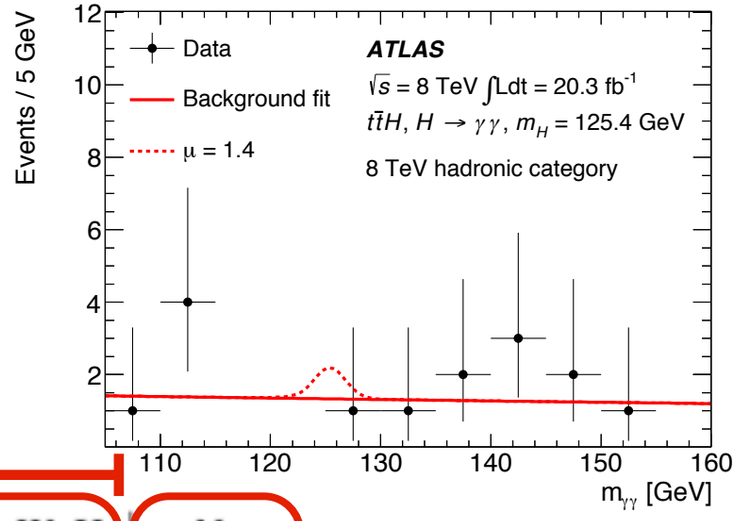




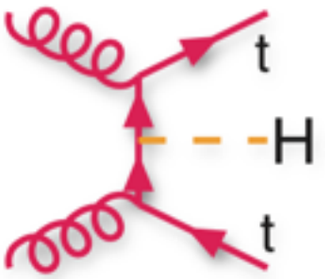


Expected composition in 120—130 GeV range:

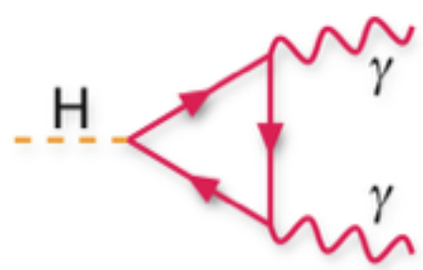
- background from fit
- signal composition dominated by processes involving Htt coupling



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



$t\bar{t}H$ (3)



Results:

- best-fit signal strength:

$$\mu = 1.4^{+2.3}_{-1.4}(\text{stat.})^{+0.6}_{-0.3}(\text{syst.})$$

  - not far less precise than result obtained using $t\bar{t}H \rightarrow b\bar{b}$ (1.5 ± 1.1)

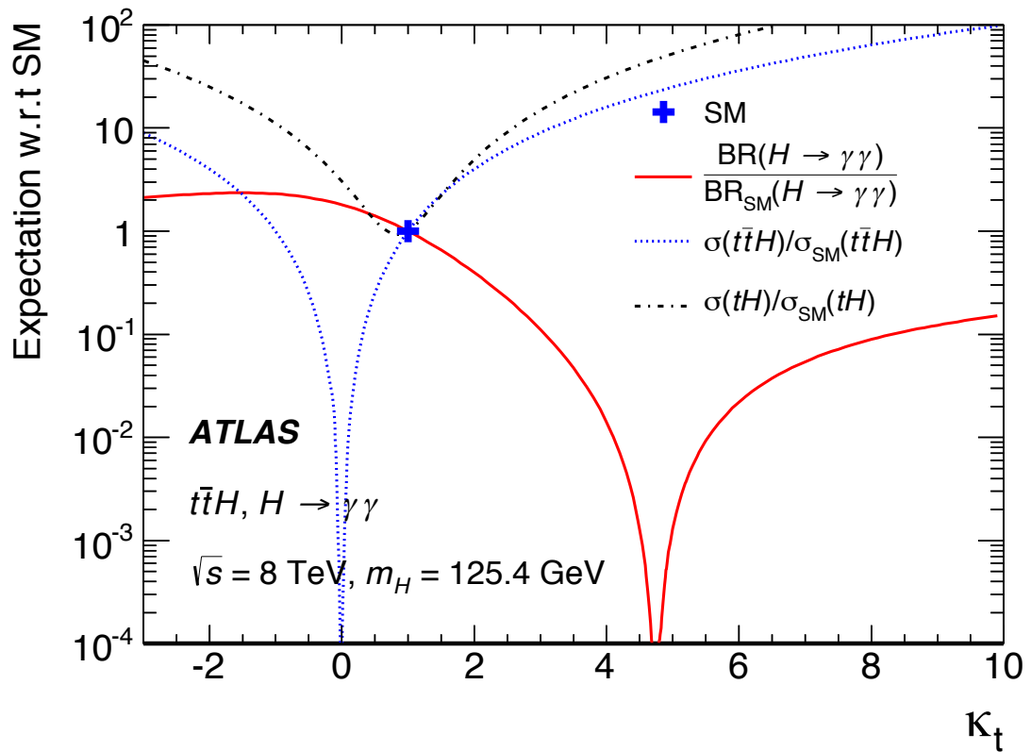
- fixing other $H \rightarrow \gamma\gamma$ contributions to SM:

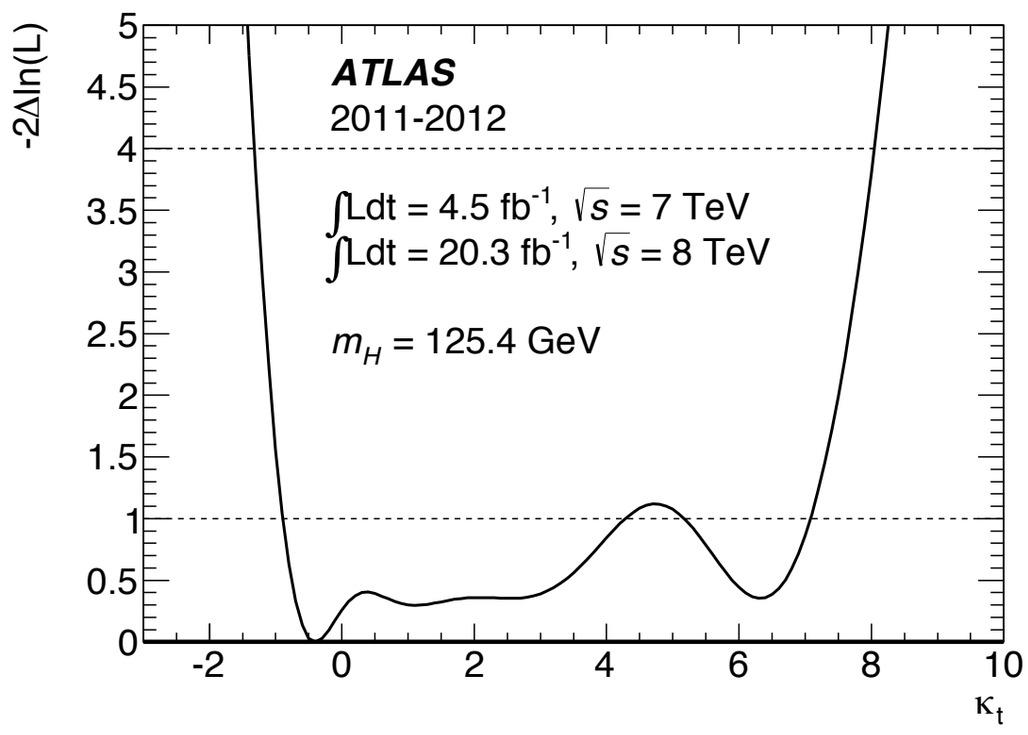
$$\mu_{t\bar{t}H} = 1.3^{+2.5}_{-1.7}(\text{stat.})^{+0.8}_{-0.4}(\text{syst.})$$

  - $\mu_{ttH} < 6.7$ at 95% CL

Interpretation of μ_{ttH} in terms of κ_t:

- also interference with W boson loop in $H \rightarrow \gamma\gamma$
- significant constraints imposed especially on negative values:
  $-1.3 < \kappa_t < 8.0$ at 95% CL



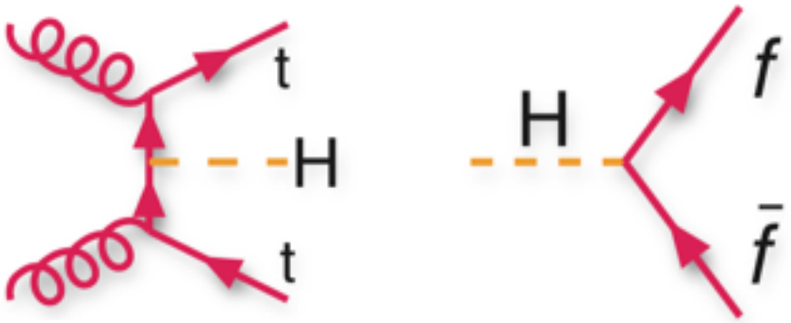


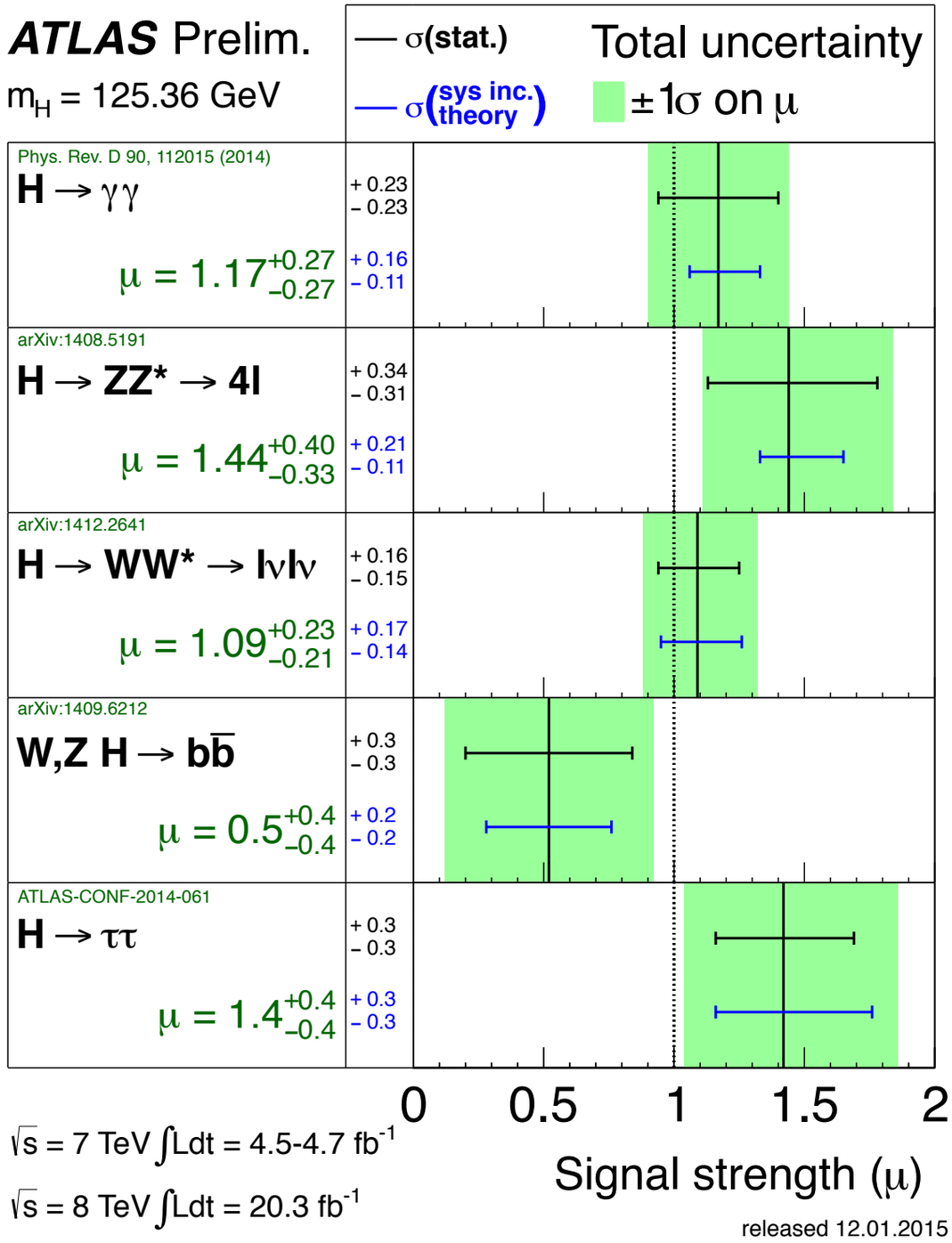
Conclusion & outlook

After the BEH boson's discovery, tremendous progress has been made in constraining its couplings to fermions

No significant deviations from SM predictions observed yet… but the search continues!

- systematic uncertainties becoming important in many analyses
- but higher statistics promised for Run 2 will definitely help to improve precision





(incomplete) list of channels