What we have learned about the Higgs boson coupling to fermions

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on behalf of the ATLAS and CMS Collaborations

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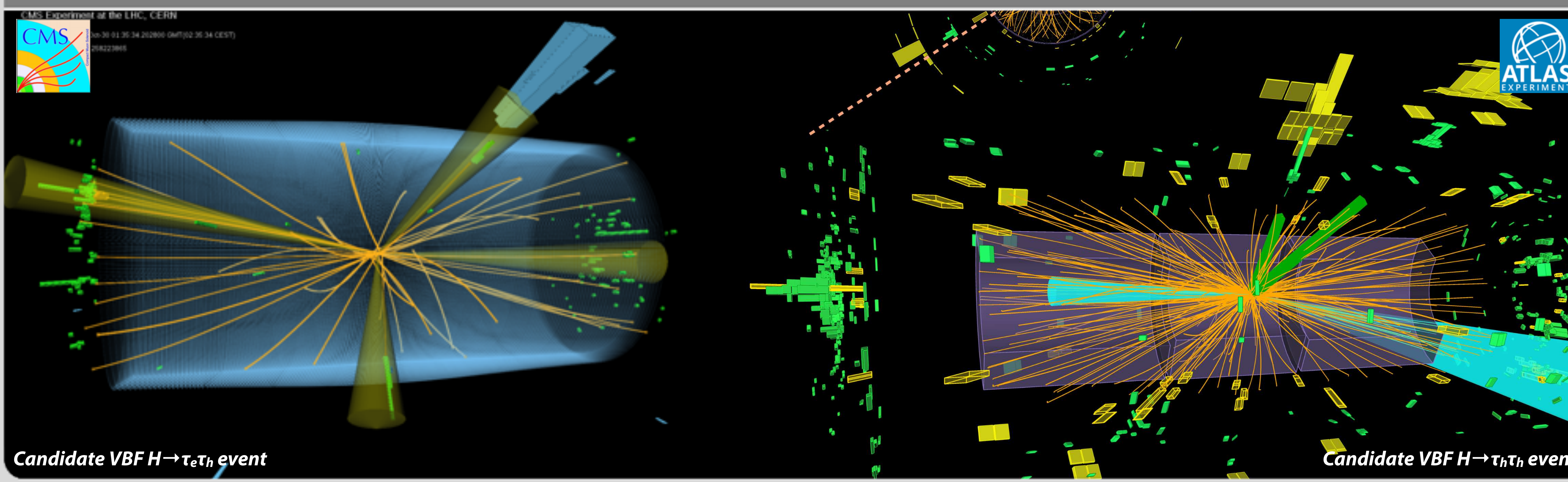
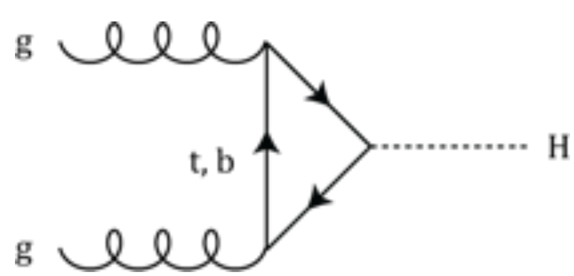
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS DEPARTMENT

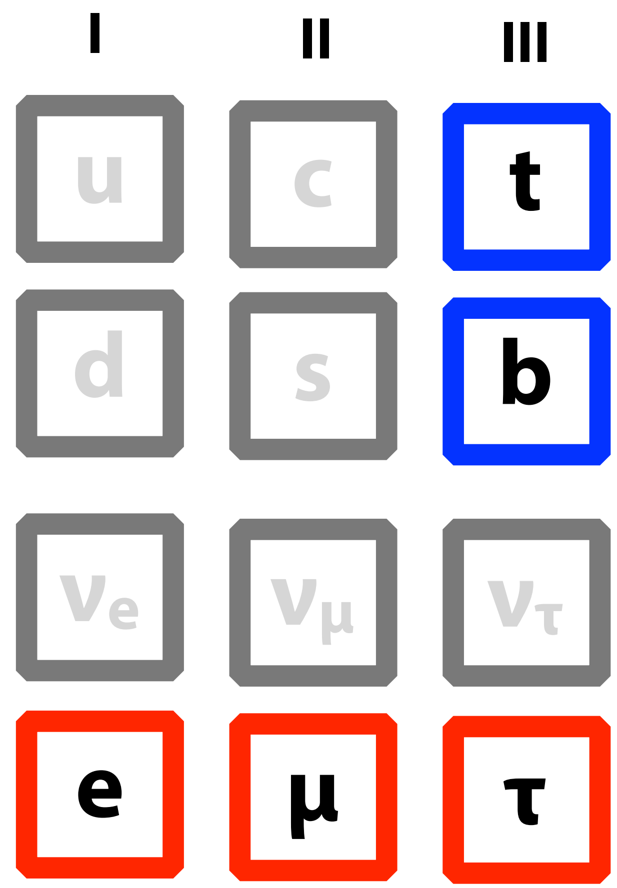


Outline

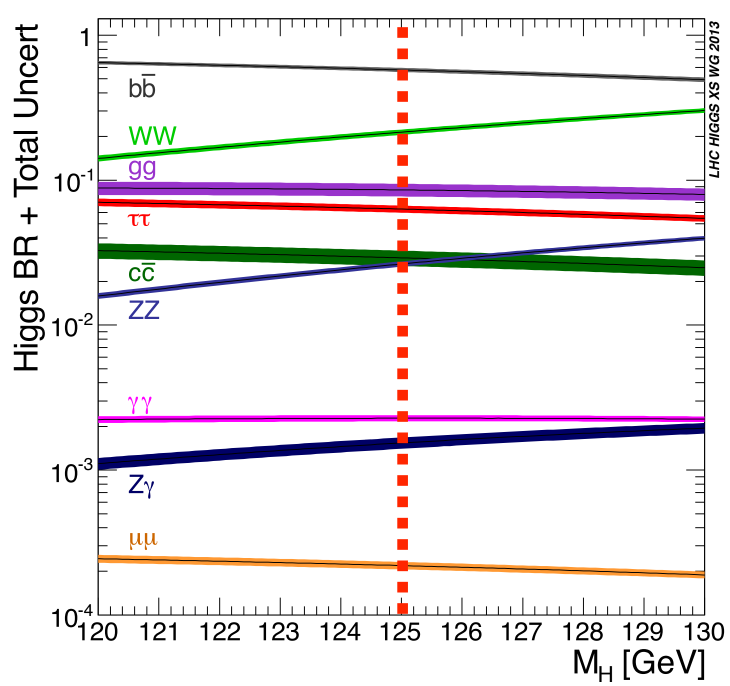
- Review what we have learned about the Higgs coupling to fermions since the discovery three years ago

- **July 2012** discovery driven by bosonic decay channels**:**
    - $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$
    - Indirect evidence of fermion coupling from loop contributions





- Fortunately at $m_H = 125$ GeV many opportunities to study fermion couplings directly at the LHC
    - **Leptons**: $H\to\tau\tau$, $H\to\mu\mu$
    - **Quarks**: $H\to bb$, $t\bar{t}H$ and tH production

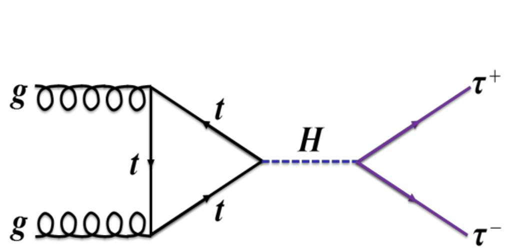


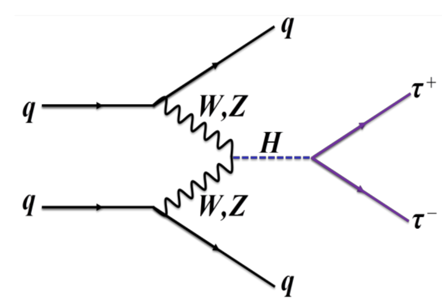
H→ττ

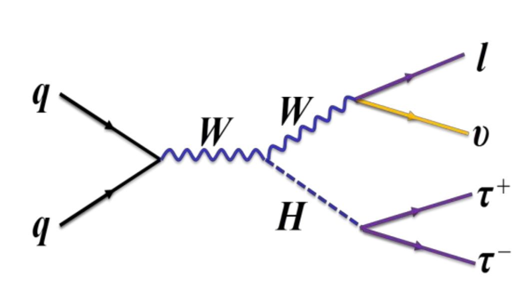
τ μ e b t

ATLAS JHEP 04 (2015) 117
CMS JHEP 05 (2014) 104

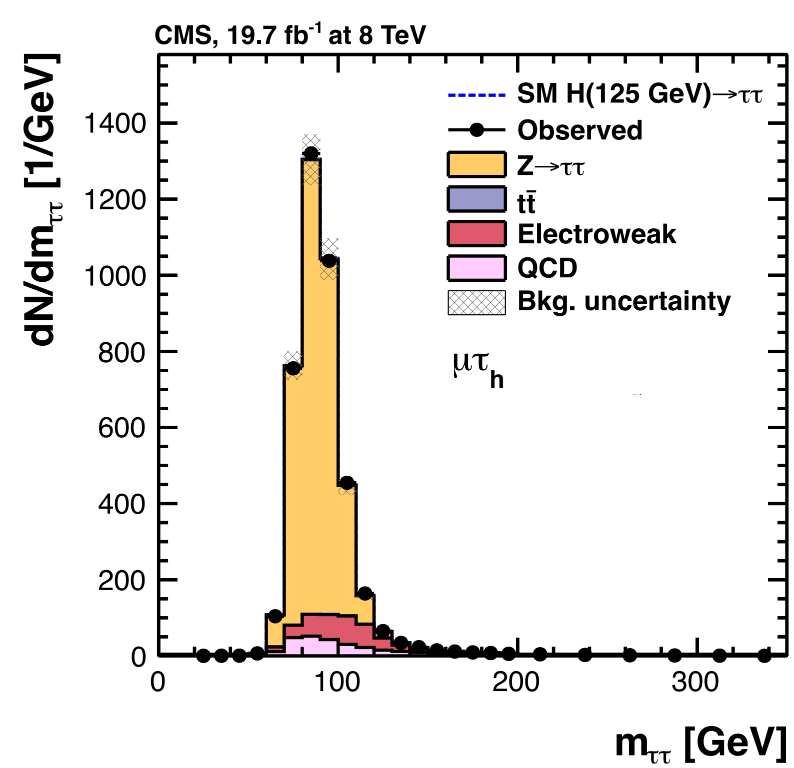
- Branching fraction @ 125 GeV: **~6.3%**
- Consider **all ττ final states:** $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, eμ, μμ, ee
- Target **production modes**:
  - ggH, VBF, VH, ttH





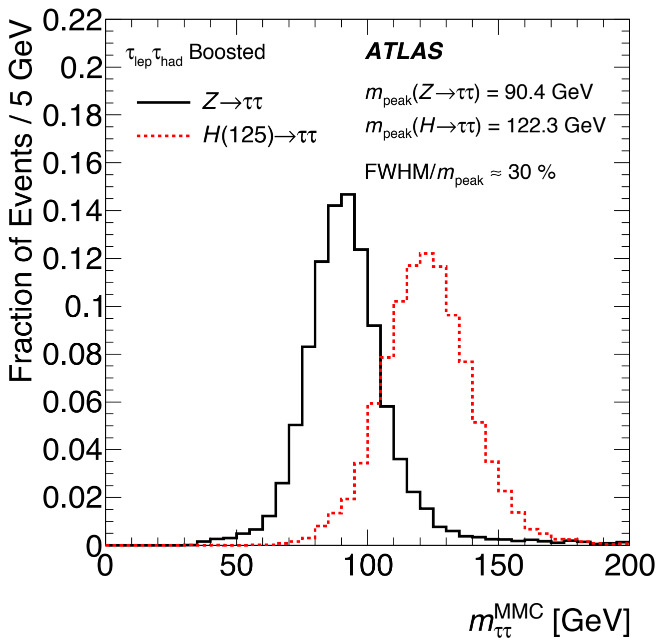


- Main backgrounds: **Irreducible Z→ττ**, **Reducible W+jets**, **QCD multi-jet**
  - Need good τ ID performance & di-τ mass estimation
- Exploit event categorisation and multivariate methods to increase sensitivity

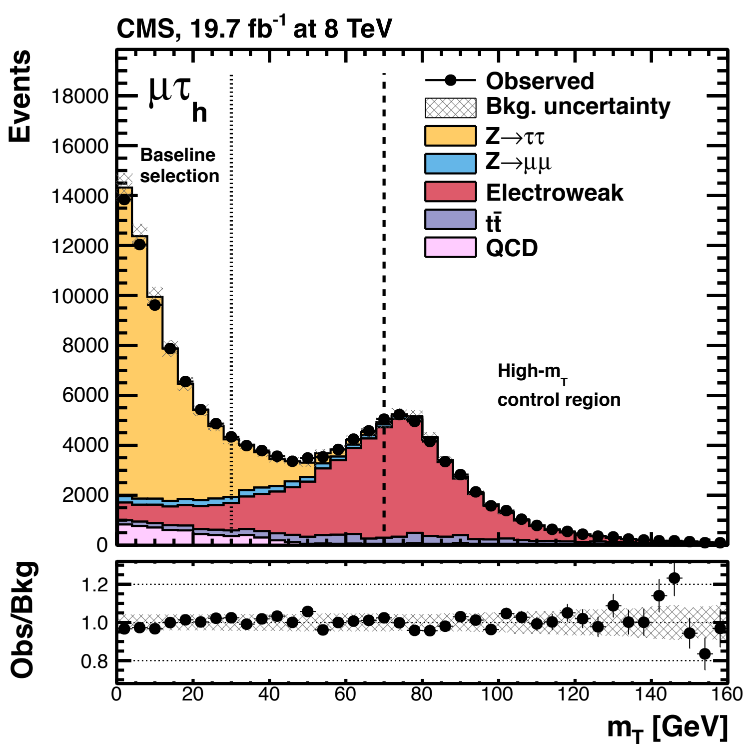


Analysis Techniques

τ μ e b t

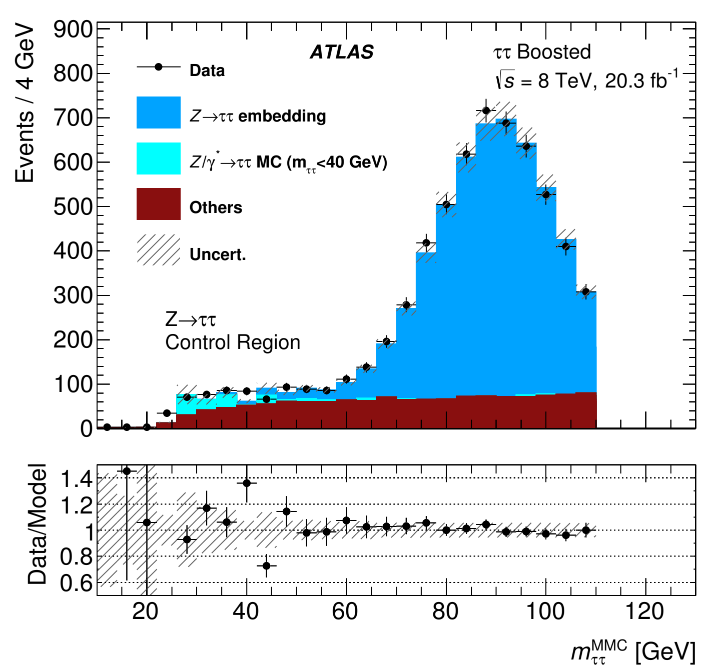


- **Need to distinguish Z→ττ and H→ττ mass peak**
  - Likelihood method to estimate full $m_{\tau\tau}$
  - Better separation and mass resolution **15-30%**



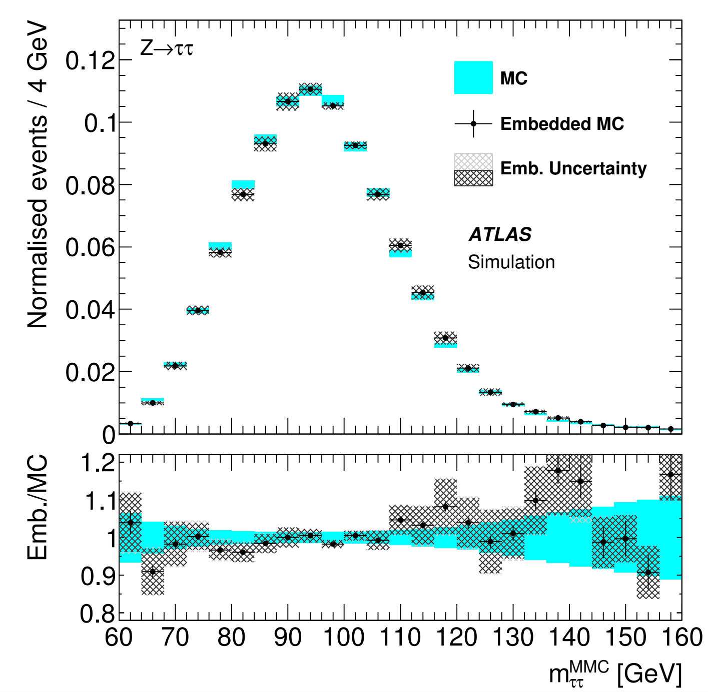
W + jets control region

- **Data-driven background estimates where possible**
- Control regions to predict and normalise backgrounds
  - E.g. high m_T(lep, E_T^{miss}) for **W+jets**
- "Embedding" of **Z→μμ data events** to model **Z→ττ bkg.**



Embedding validation
← In data
In Simulation →

ATLAS arXiv:1506.05623

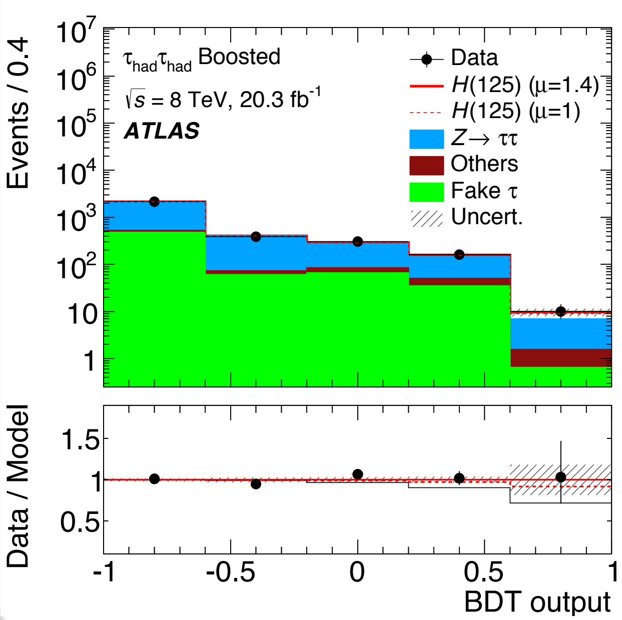


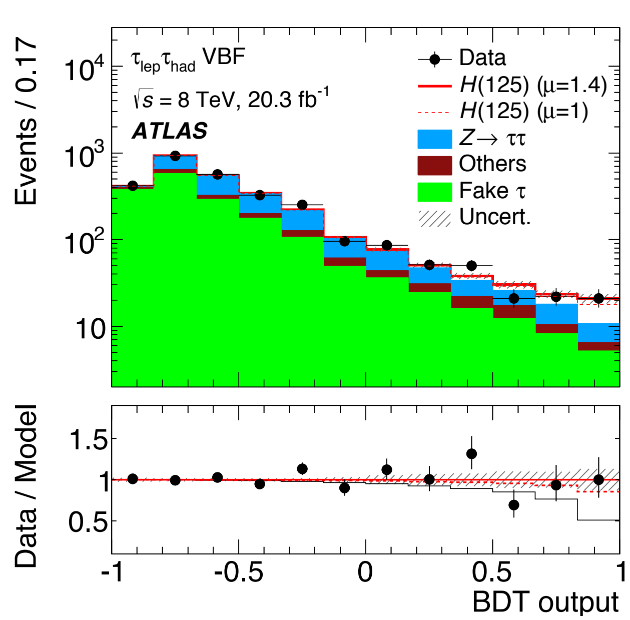
Signal Extraction

τ μ e b t

ATLAS

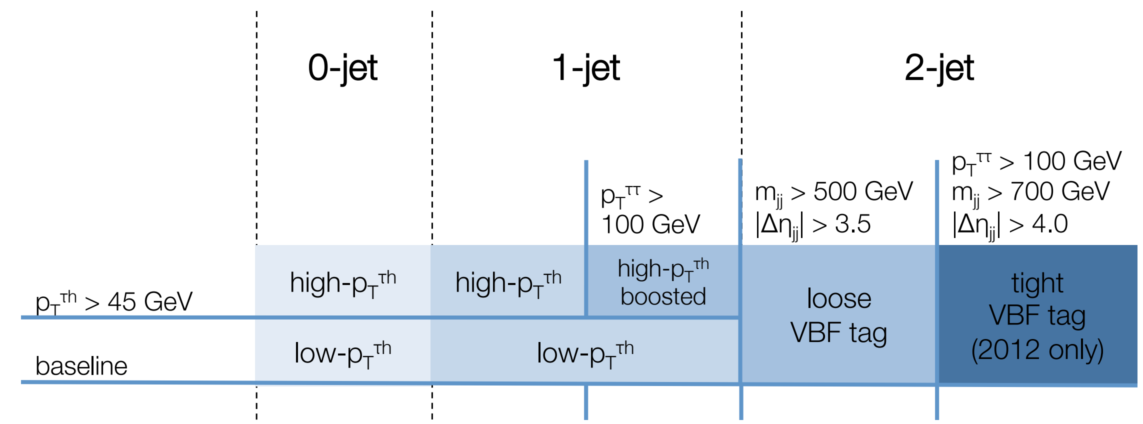
- Loose pre-selection splits events into **Boosted** and **VBF** categories
- BDT discriminator: $m_{\tau\tau}$, **event kinematics**, ($P_T^{1,2}$, m_T), **topological variables** (centrality, $\Delta\varphi^{1,2}$), **VBF properties** (m_{jj}, $\Delta\eta_{jj}$) + others
- Fit control regions simultaneously to constrain backgrounds



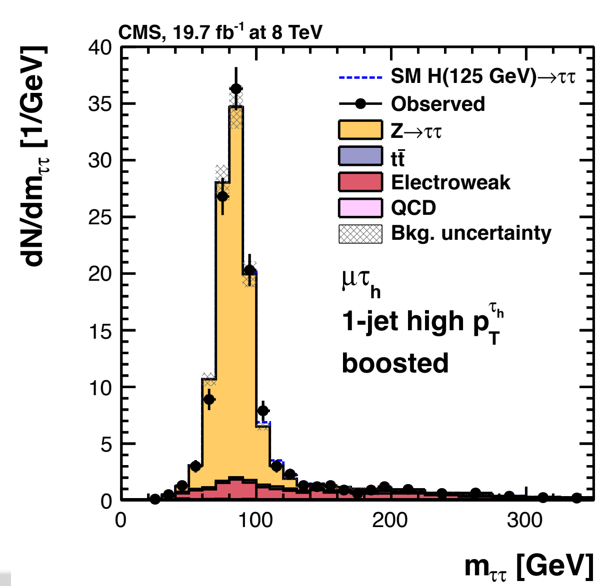


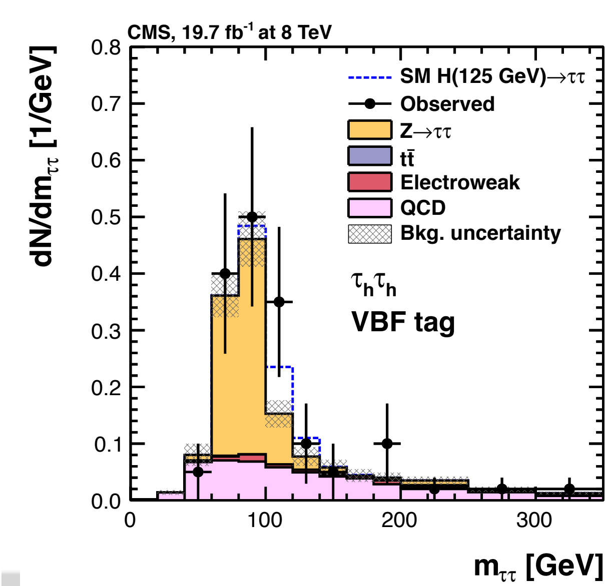
CMS

- Split events into categories to improve sensitivity + dedicated WH, ZH selections



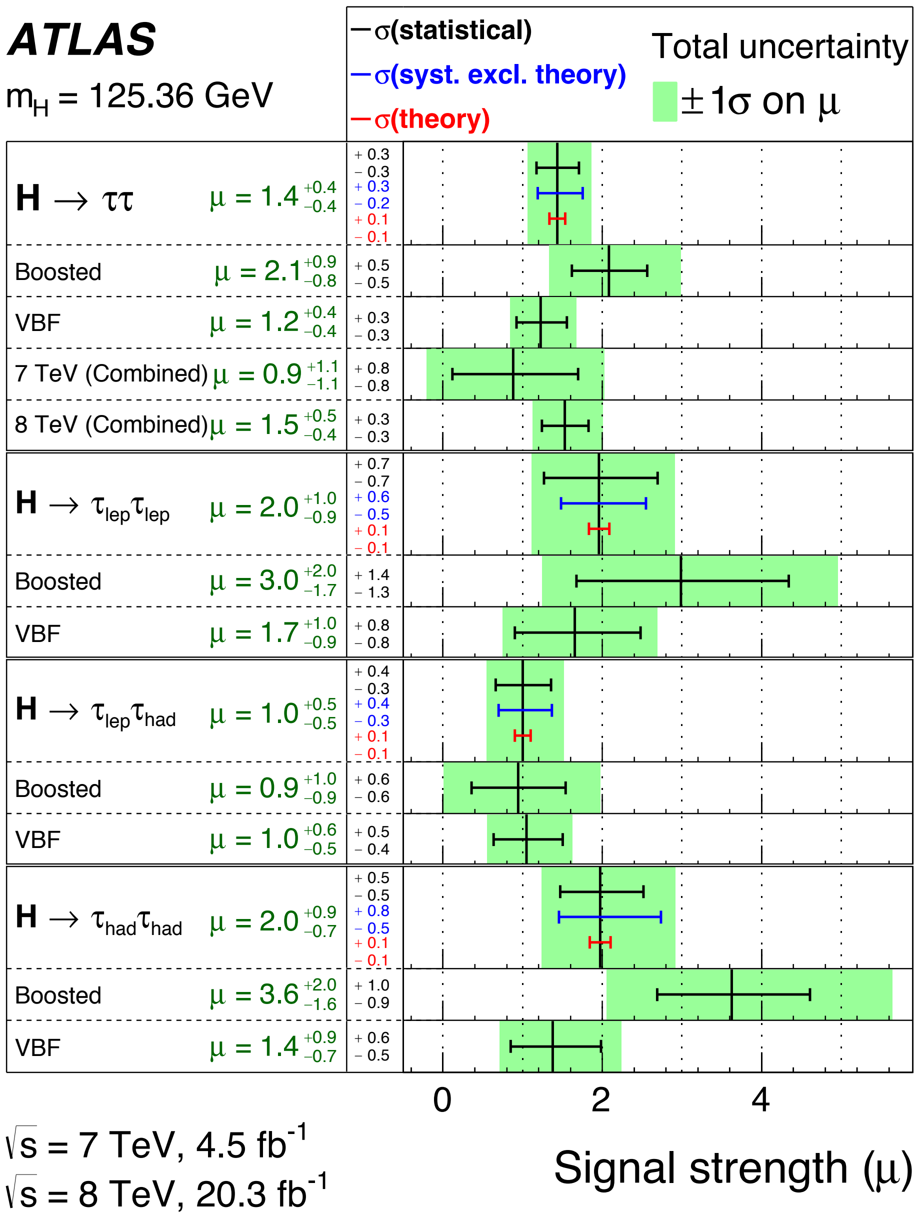
- Discriminator: **di-tau invariant mass**
- Low S/B 0-jet categories constrain uncertainties in 1-jet and VBF categories

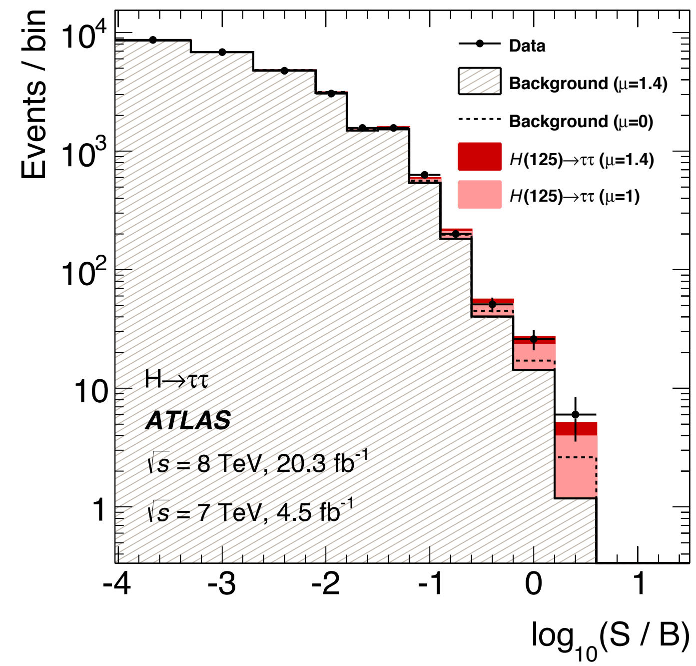


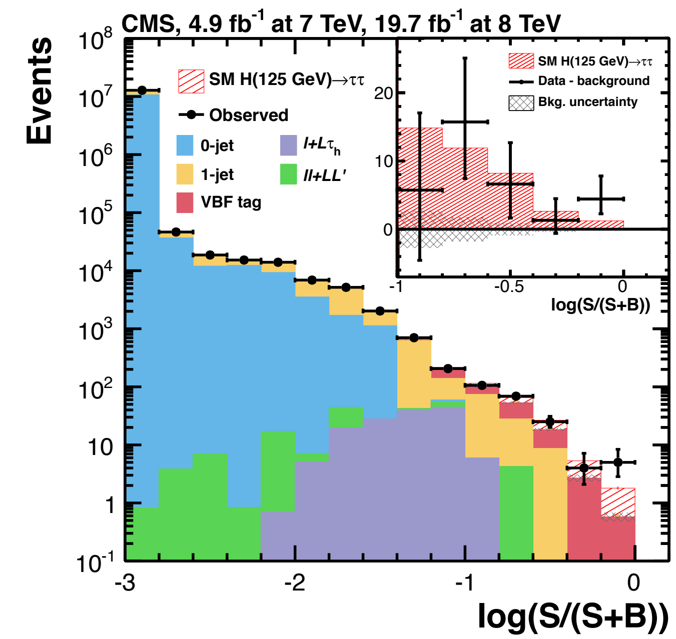


Results

τ μ e b t

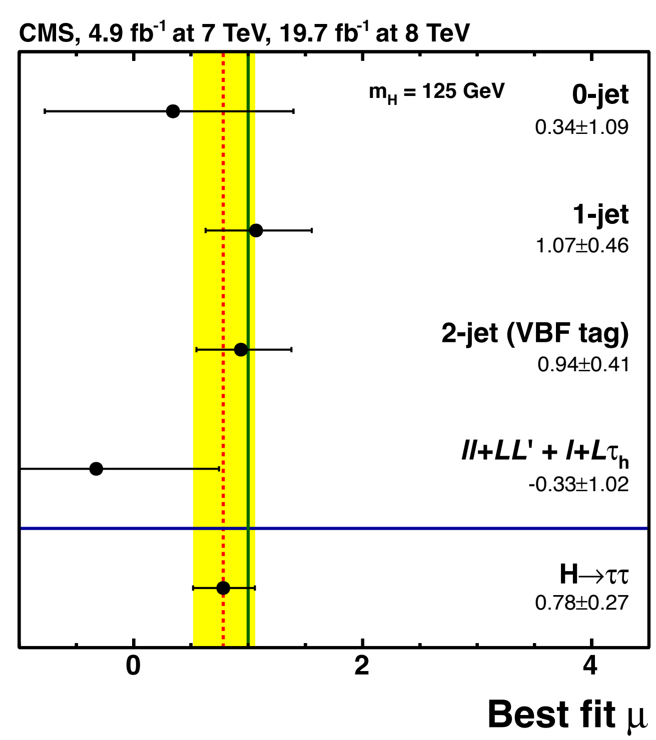


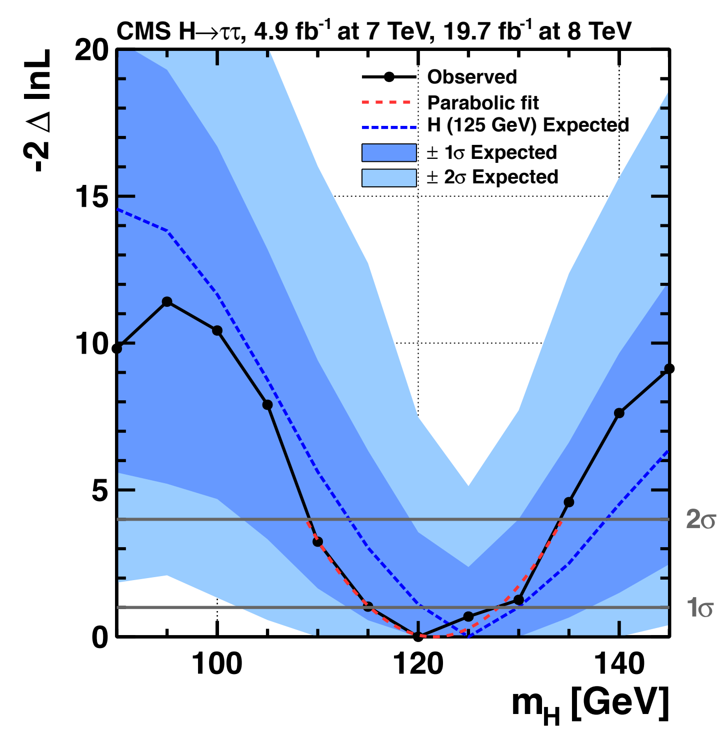




4.5σ (3.4σ exp) @ 125.36 GeV

3.2σ (3.7σ exp) @ 125 GeV





- **ATLAS:** $\hat{\mu} = 1.43^{+0.43}_{-0.37}$ @ 125.36 GeV
- **CMS:** $\hat{\mu} = 0.78 \pm 0.27$ @ 125.0 GeV

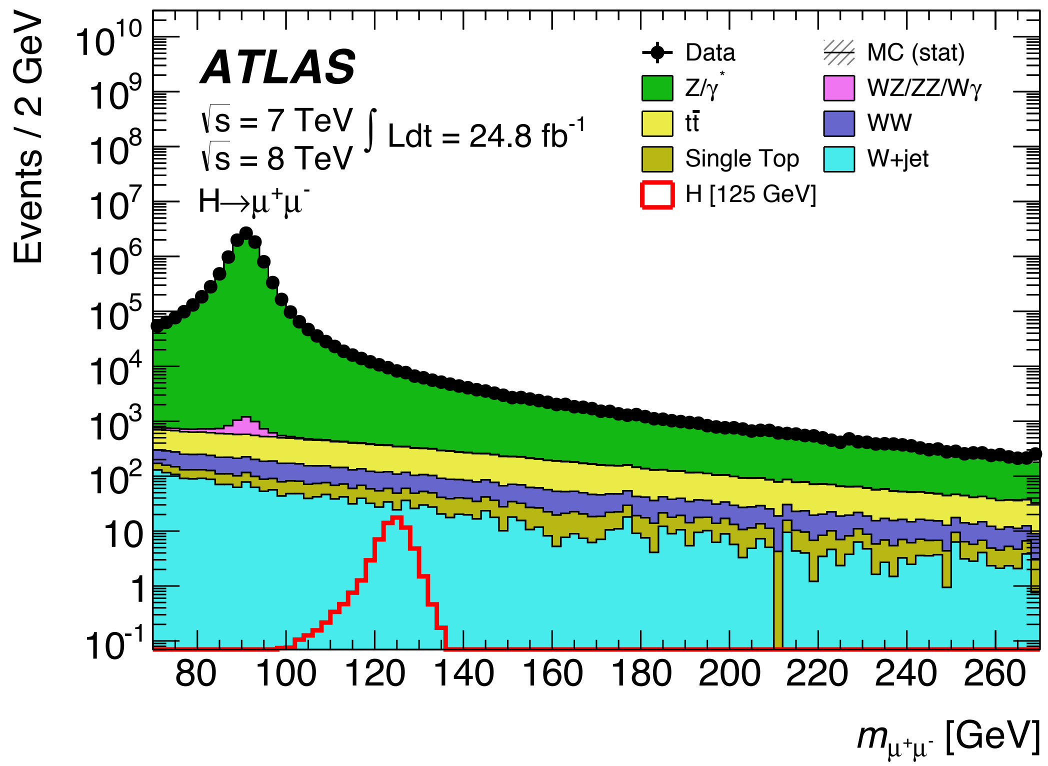
$m_H = 122 \pm 7$ GeV

H→μμ / ee

τ μ e b t

ATLAS PLB 738 (2014) 68-86
CMS PLB 744 (2015) 184

- Branching ratio @ 125 GeV:
  - **H→μμ**: 2.2 x 10^{-4}
    - Observable at > 5σ with HL-LHC (need > 300 fb^{-1})
  - **H→ee**: ~ 5 x 10^{-9}



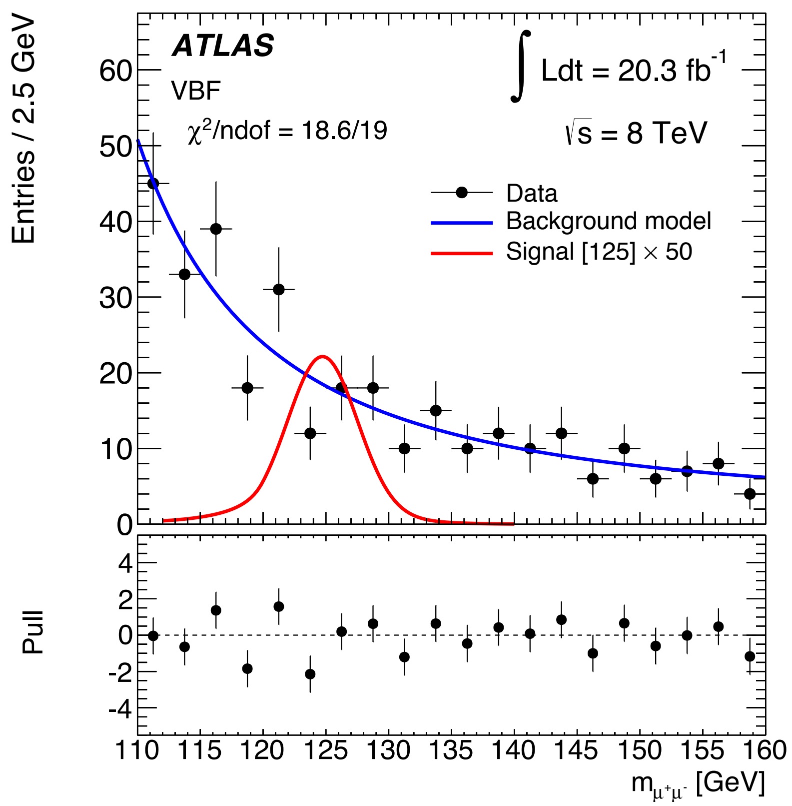
- With Run I data test if Higgs⇔lepton coupling is flavour-universal or proportional to mass

- Look for a narrow signal peak on top of the dominant **Drell-Yan background**

- **Strategy:**
  - Categorise events to **target ggH and VBF production** modes as well as leptons in the **best-measured detector regions**

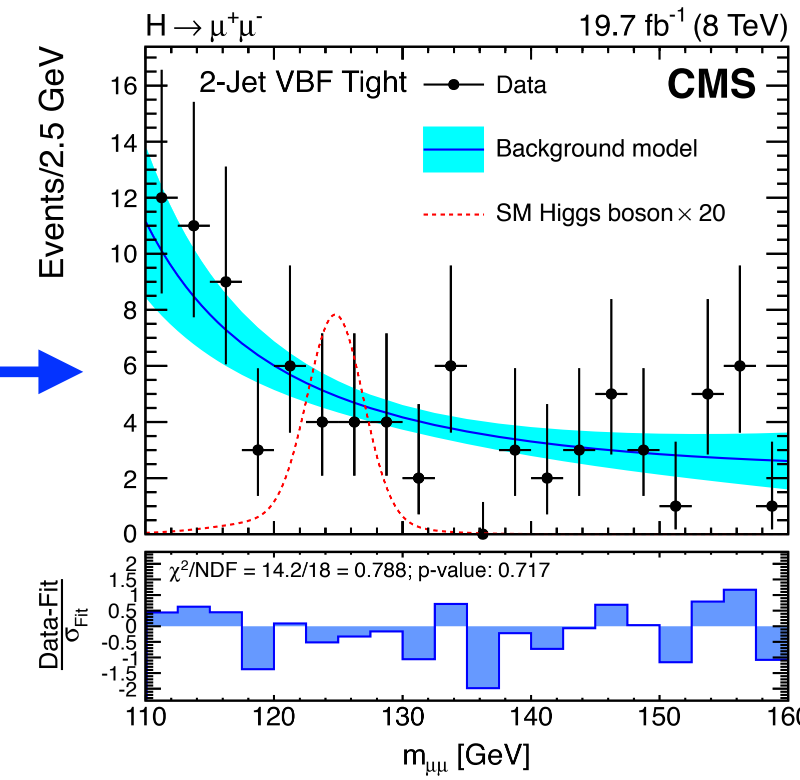
Signal Extraction

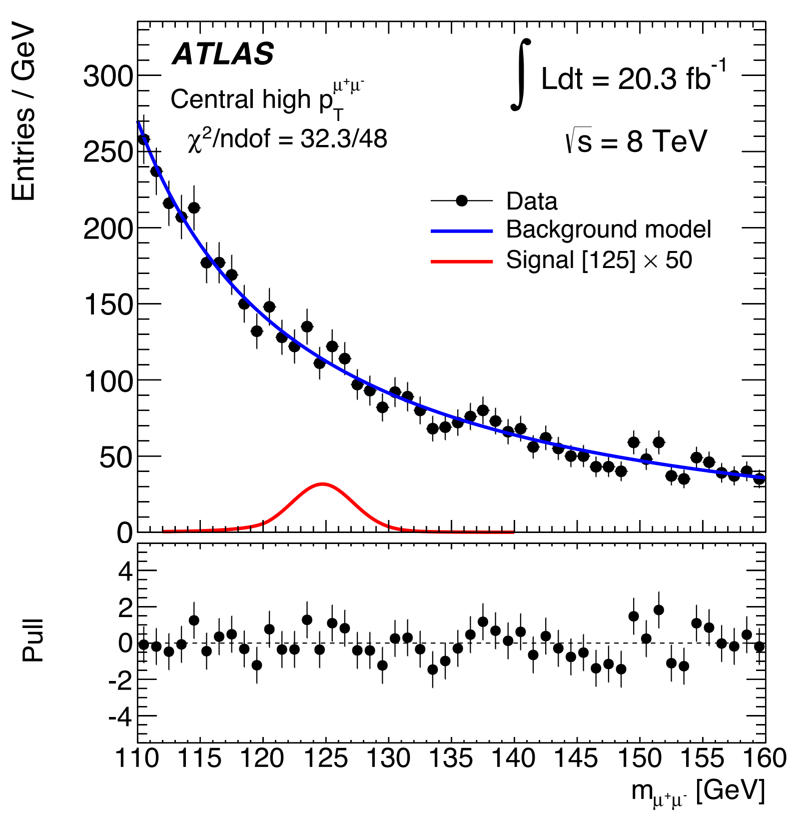
τ μ e b t



VBF Categories

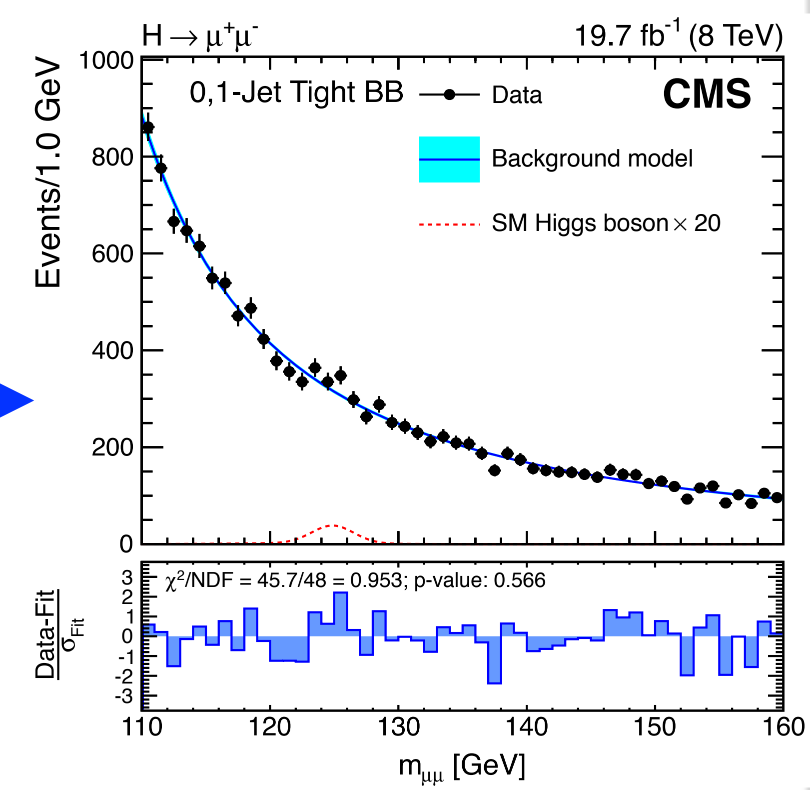
- high m_{jj} and $\Delta\eta_{jj}$ requirements to increase signal purity





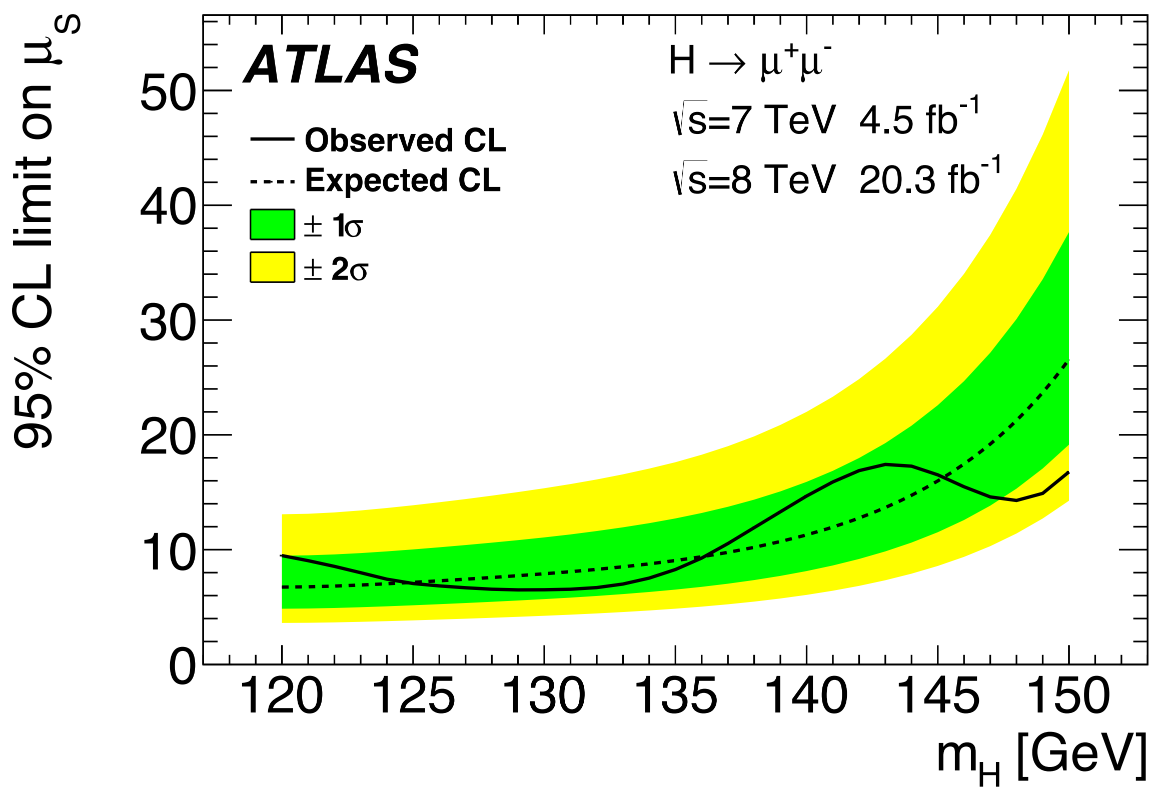
ggH Categories

- Categorise on $\mathbf{p_T^{\mu\mu}}$ (higher in signal) and **central vs. non-central** leptons (better mass resolution)

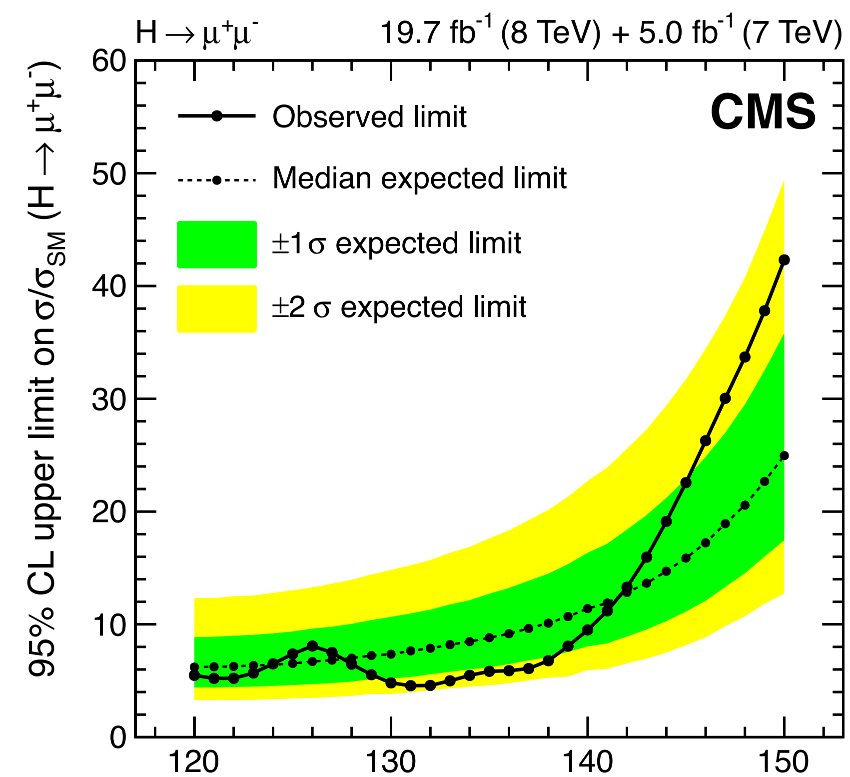


Results

τ μ e b t



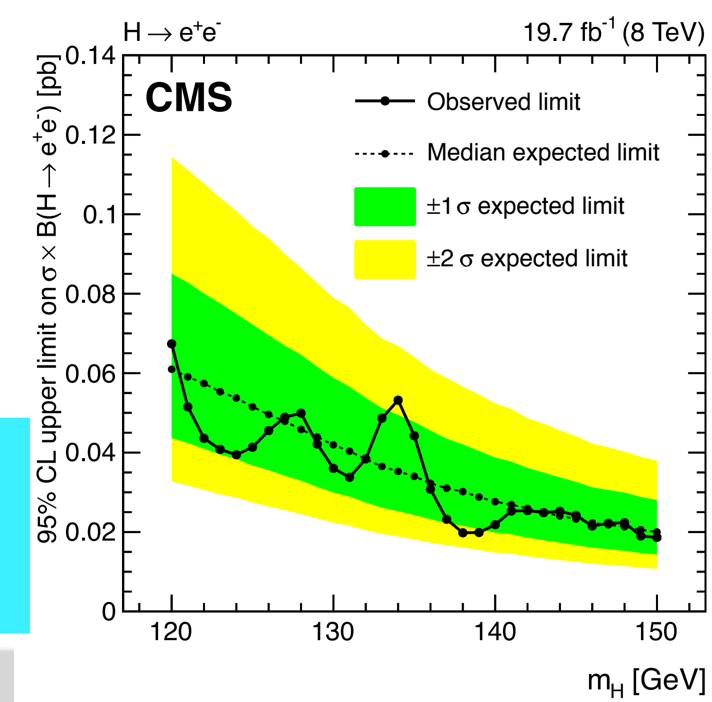
μ < 7.0 (7.2) obs (exp) 95% CL @ 125.5 GeV



μ < 7.4 (6.5) obs (exp) 95% CL
(B < 0.0016) @ 125 GeV

- No excess over-background only expectation
- Limits on the H→μμ and H→ee branching fraction imply **lepton coupling is non-universal** **(i.e. unlike Z→l+l-)**

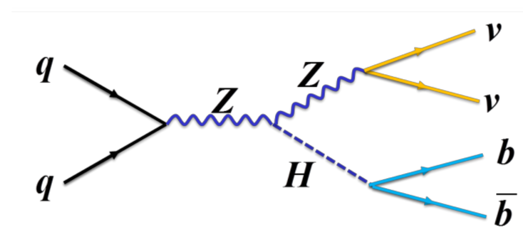
H→ee σxBR: < 0.041 pb
(B < 0.0019 @ 125 GeV



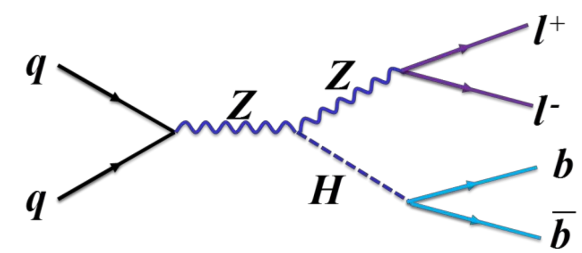
H→bb

ATLAS JHEP 01 (2015) 069
CMS PRD 89, 012003 (2014)

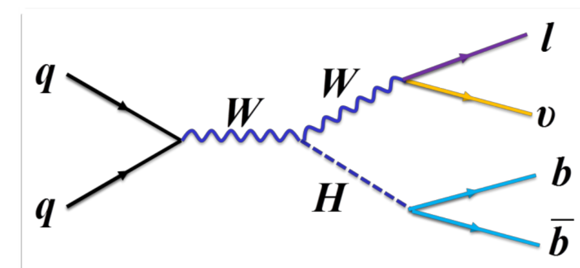
- Branching fraction @ 125 GeV: **~58%**
- Overwhelming multi-jet background to ggH production: focus on associated W/Z production
- Decay channels:



Z(νν) H

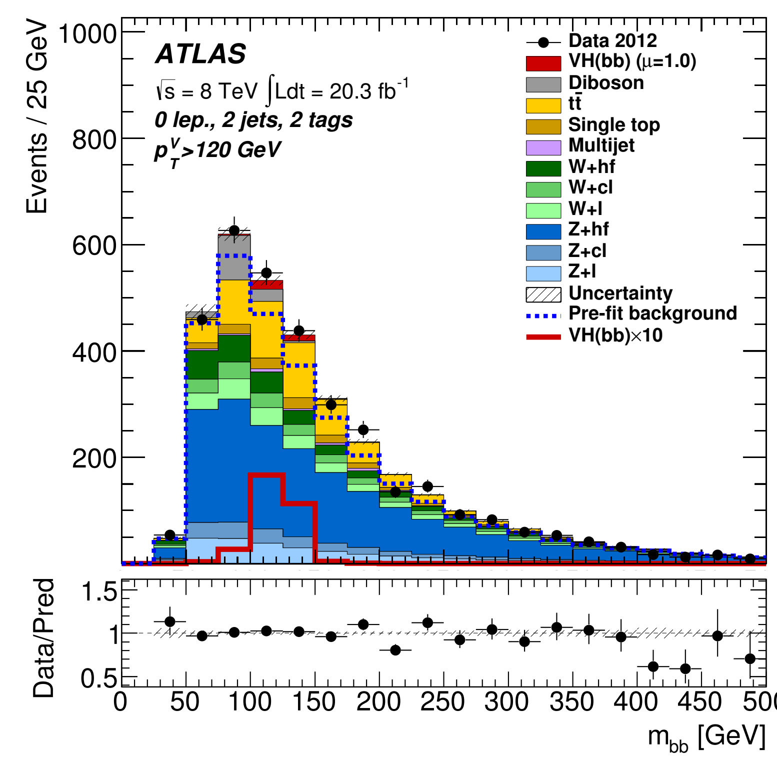


Z(ee/μμ) H



W(e/μ/τ_h) H

- Backgrounds from **W/Z + HF**, **$t\bar{t}$**, **W/Z + LF**, **diboson**

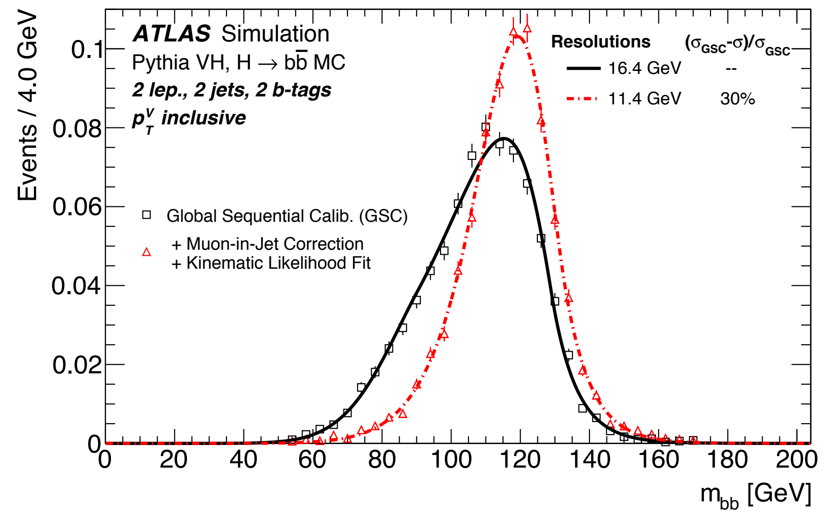


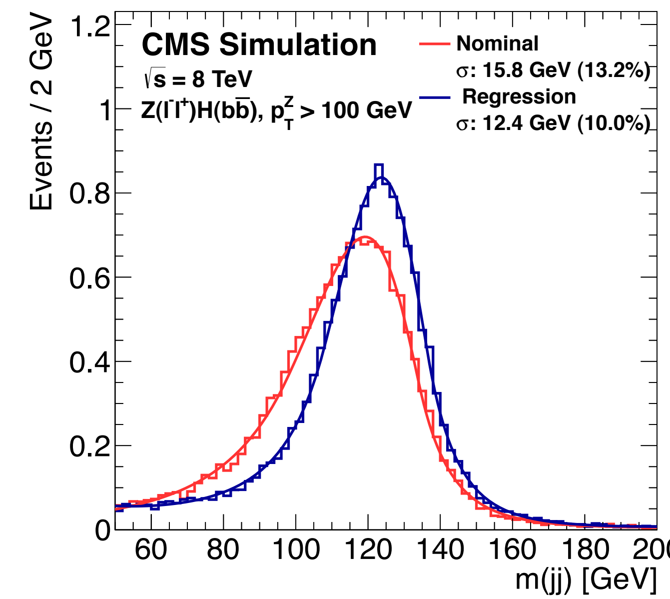
- **Strategy:**
  - b-tagging of jets to identify candidate H→bb decay
  - Exploit V-H recoil with $p_T(V)$ categorisation
  - Reconstruct m_{bb} and combine with other variables in a multivariate discriminator

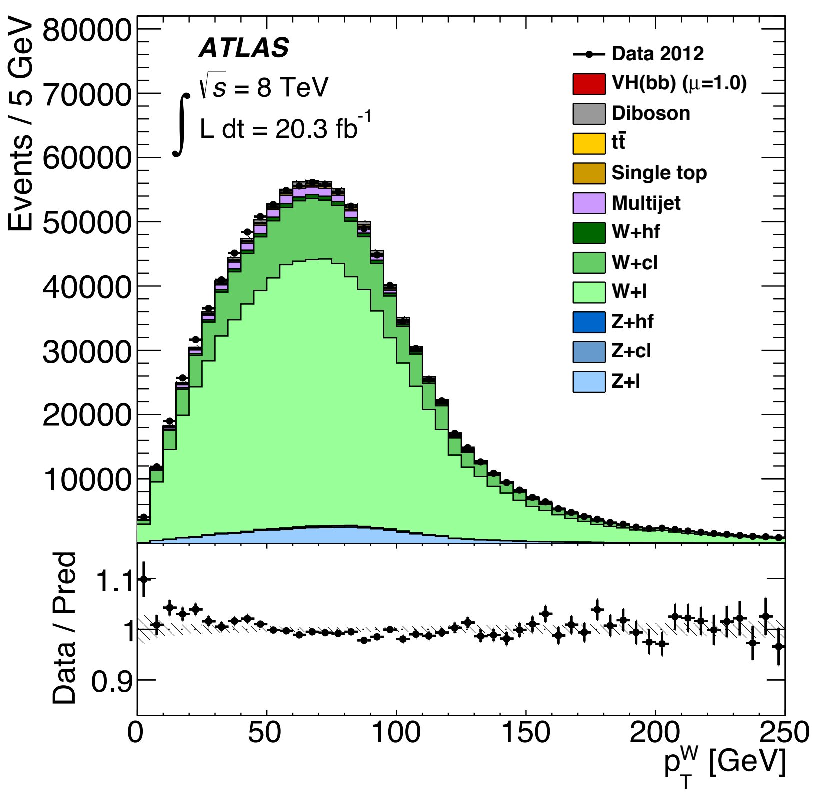
Analysis Techniques

τ μ e **b** t

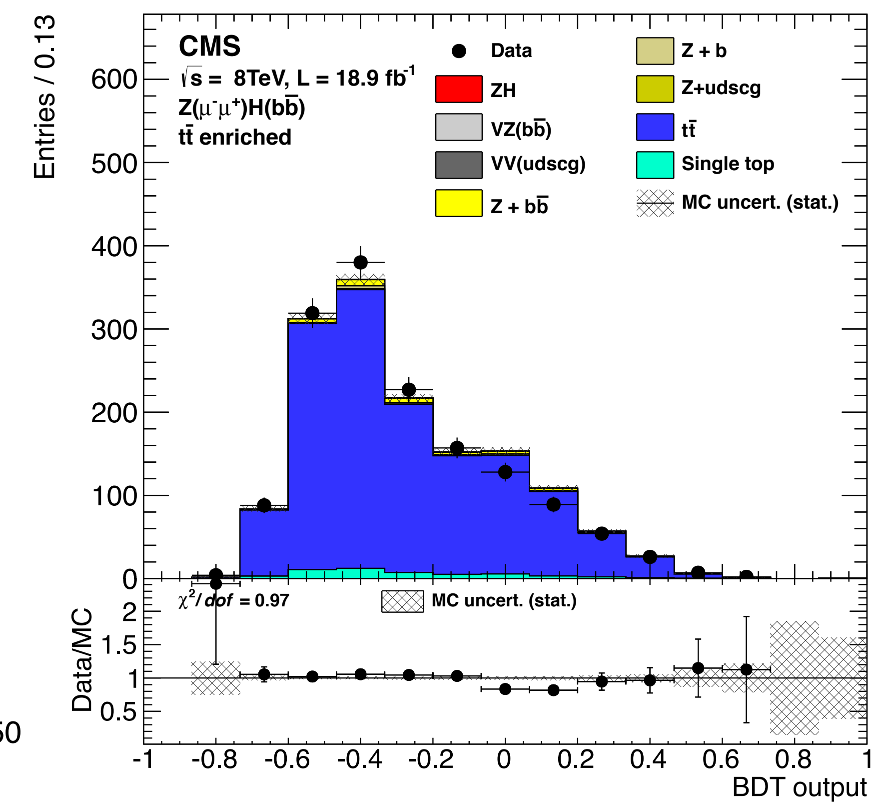
- b-jet energy corrections
  - **CMS:** multivariate regression
  - **ATLAS:** response correction & likelihood fit
- m_{jj} resolution improves 15-30%







W+jets enriched



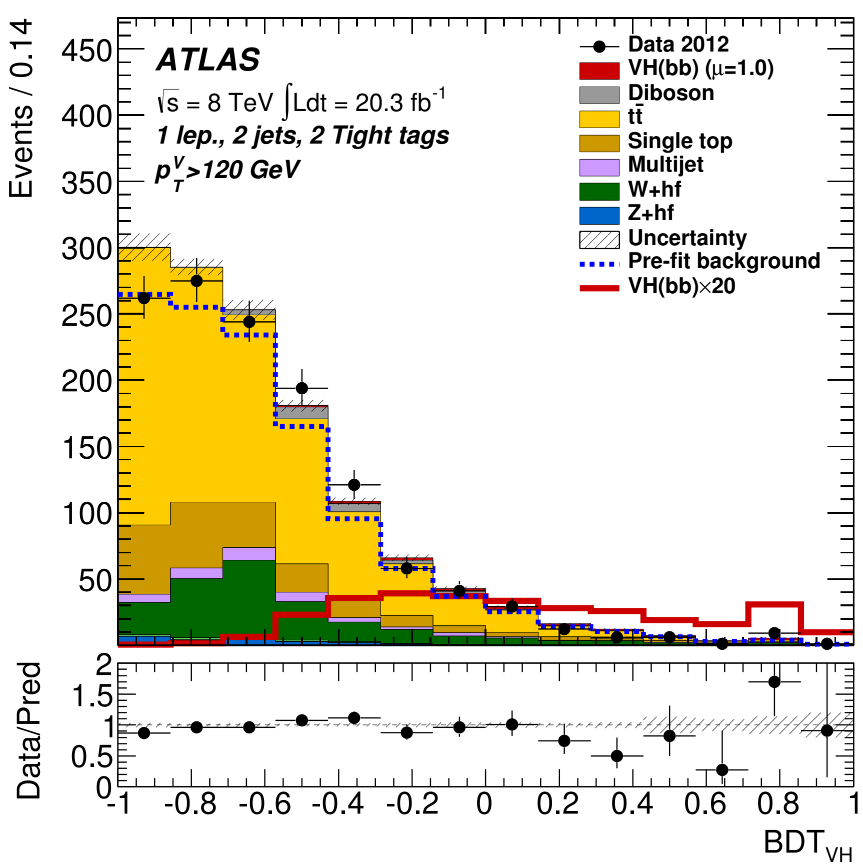
tt̄ enriched

- Calibration of backgrounds in control regions
- Constrains shape and normalisation in signal-region fits

Signal Extraction

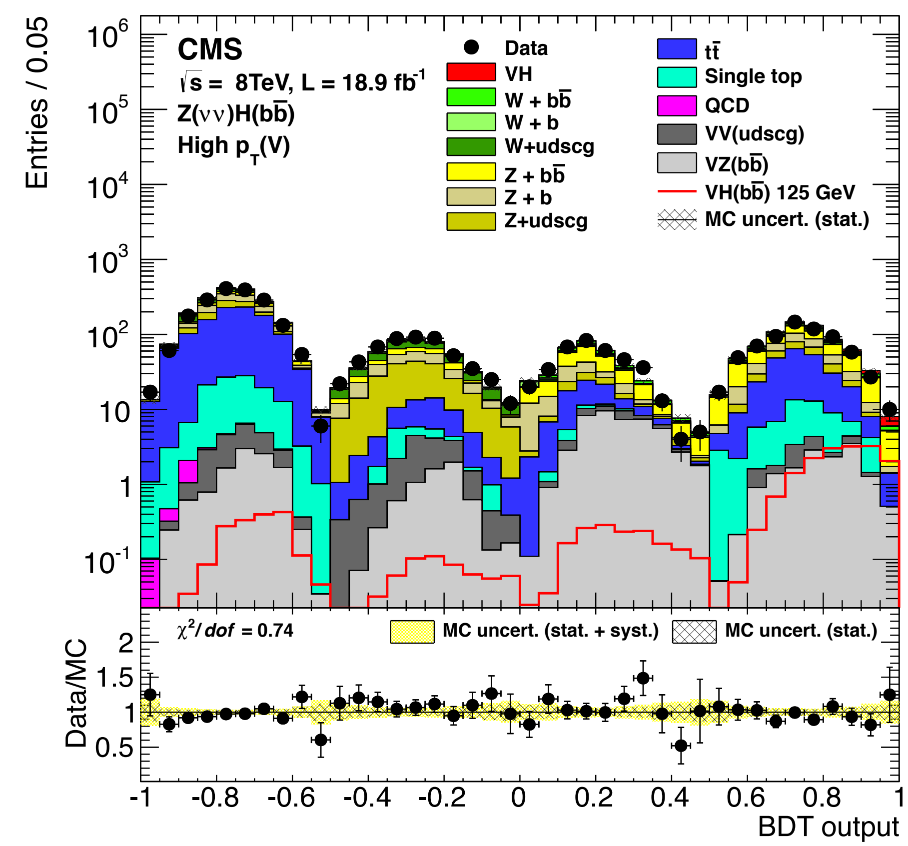
ATLAS

- Categorise events on $p_T(V)$, number of jets, b-tagging criteria
- Fit BDT distribution in most sensitive categories
- Input variables cover di-jet kinematics & event topology



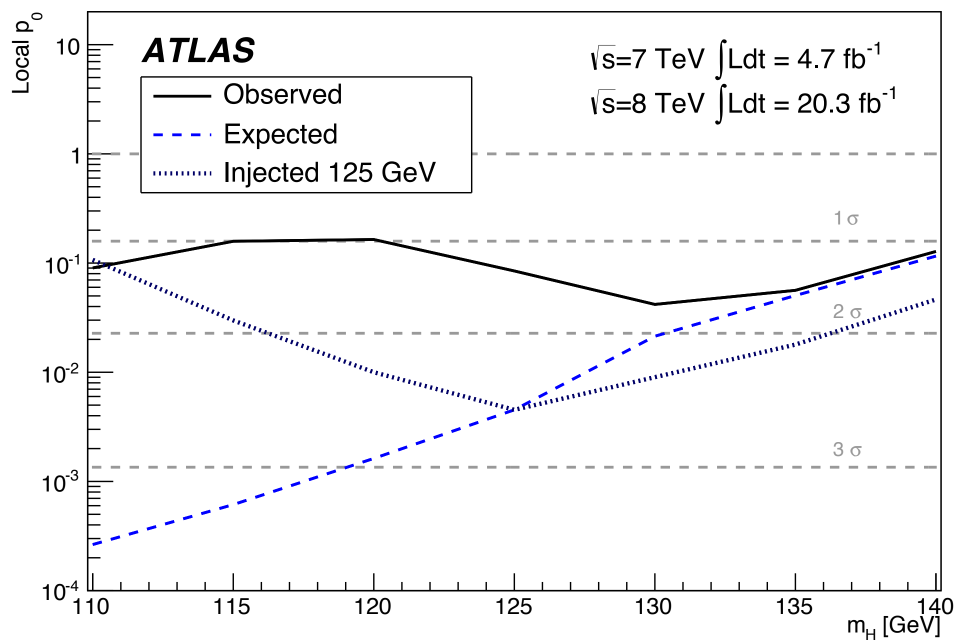
CMS

- Categorise events on $p_T(V)$
- Fit "cascade" of BDT outputs designed to constrain specific backgrounds
- Input variables include b-tagging discriminators, di-jet kinematics & event topology

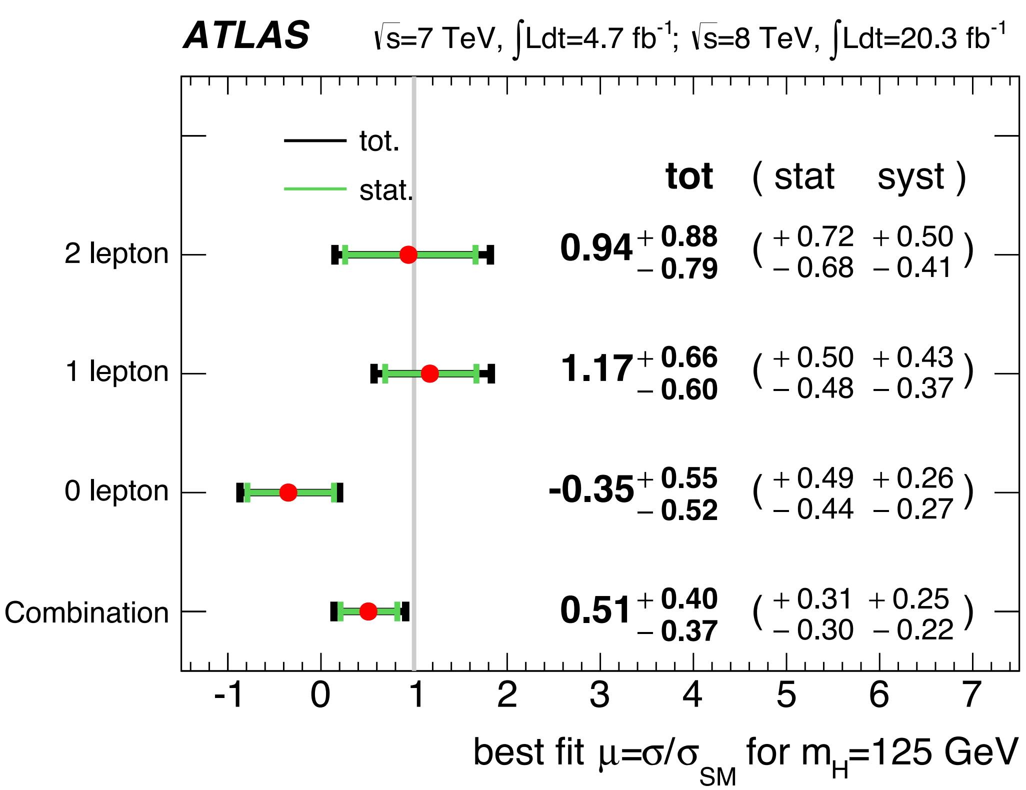


Results

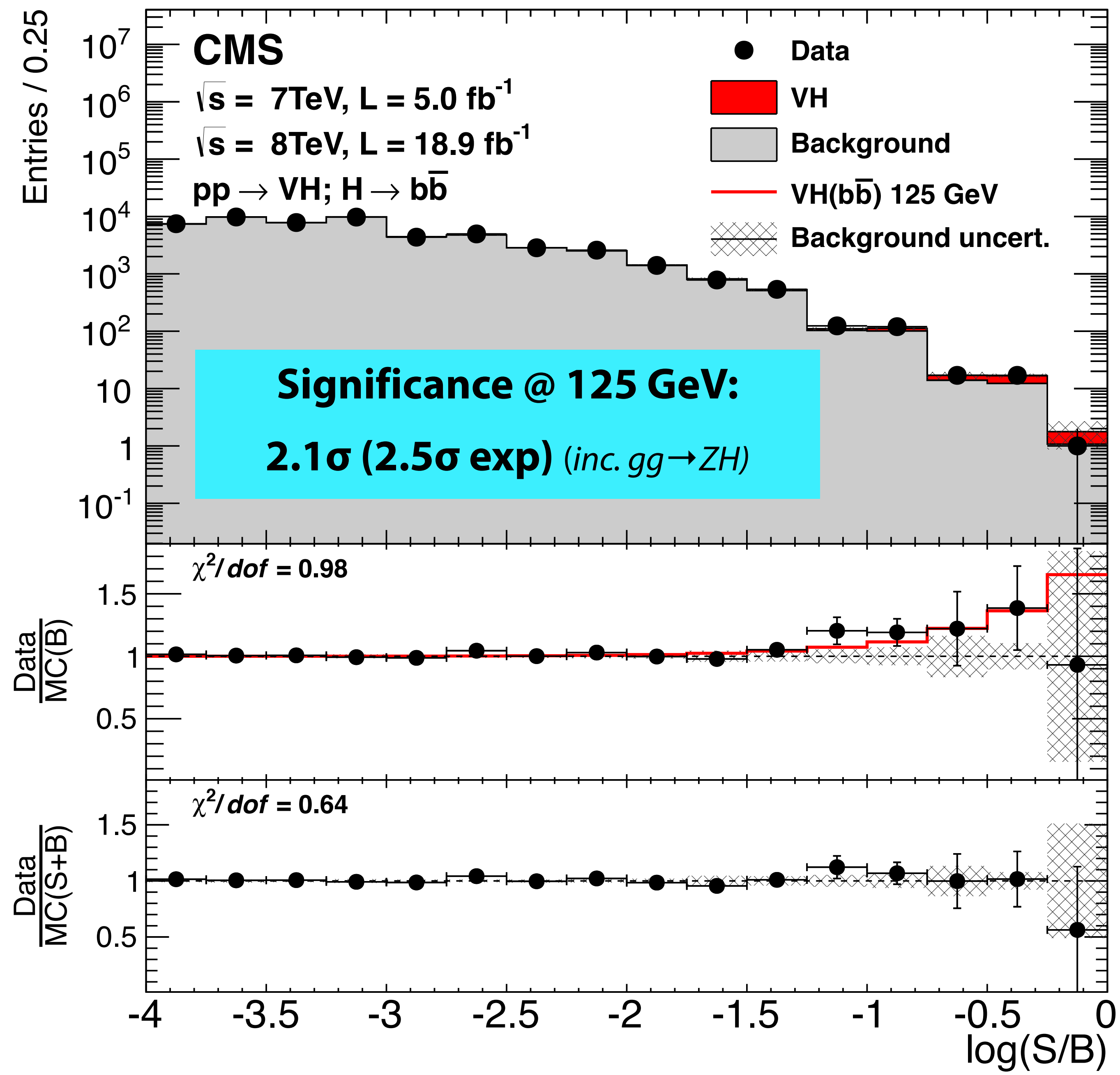
τ μ e **b** t



Significance @ 125 GeV: 1.4σ (2.6σ exp)



$\hat{\mu} = 0.51^{+0.40}_{-0.37}$ @ 125 GeV



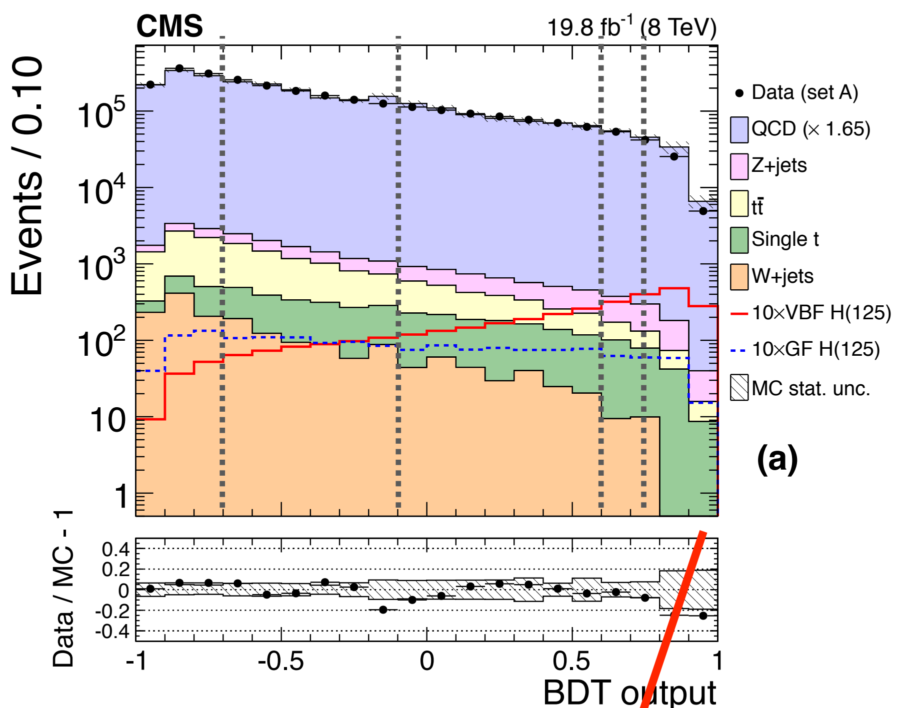
Significance @ 125 GeV:
2.1σ (2.5σ exp) *(inc. gg→ZH)*

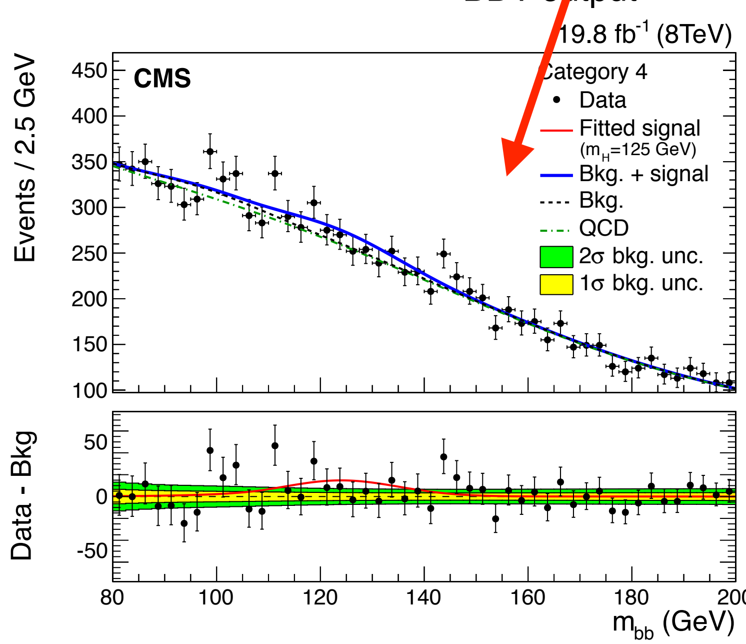
$\hat{\mu} = 0.89^{+0.47}_{-0.44}$ @ 125 GeV *(inc. gg→ZH)*

VBF H→bb

CMS arXiv:1506.01010

τ μ e **b** t

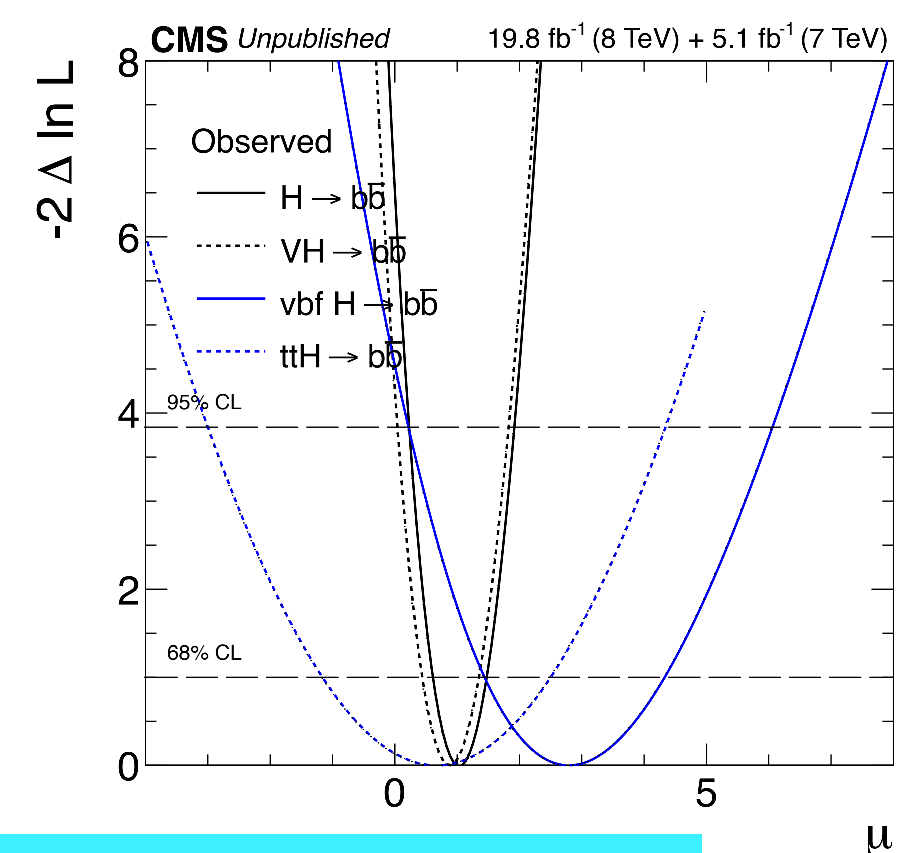




$\hat{\mu} = 2.8^{+1.6}_{-1.4}$ @ 125 GeV

- 4 jet final state with background dominated by QCD multi-jet production
- BDT discriminator to separate signal:
  - VBF topology
  - b-tagging information
  - quark/gluon discriminating variables
- Fit m_{bb} distribution in bins of BDT score

- Combination of VH, VBF and ttH H→bb searches
- Significance of 2.6σ (2.7 exp) @ 125 GeV



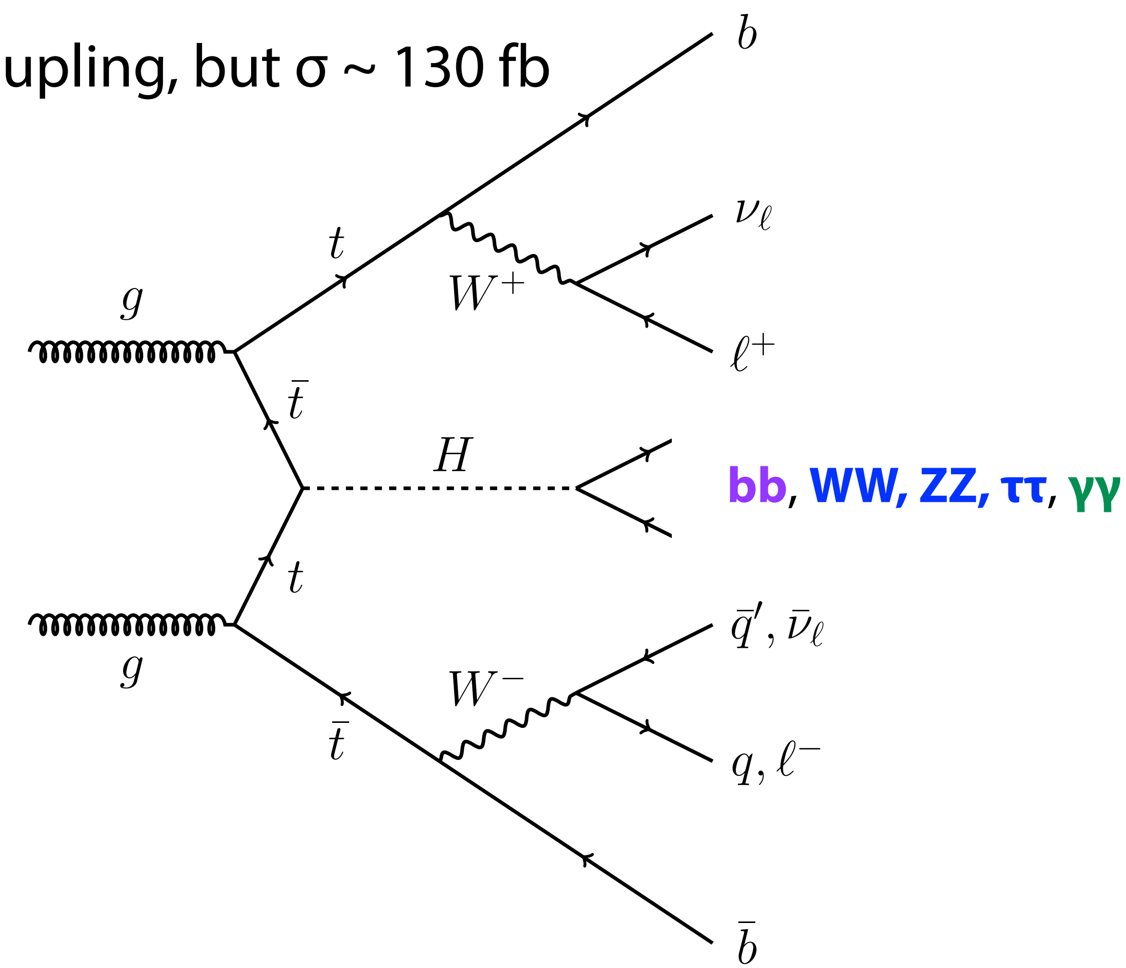
$\hat{\mu} = 1.0 \pm 0.4$ @ 125 GeV

ttH

τ μ e b **t**

- Want to measure top-quark Yukawa coupling: **y_t ~ O(1) in the SM**

- Indirect evidence from ggH production and H→γγ decay via loop contribution
  - But possibly modified by BSM contributions
  - ttH production is the best handle for tree-level coupling, but σ ~ 130 fb



- **Strategy**:
  - Target as many combinations of the tt̄ final state (0,1 or 2 leptons) and Higgs decay as possible
  - Analyses for **bb**, **leptons** and **γγ** Higgs decay
  - Exploit **high jet** and **b-jet multiplicity**
  - Extract signal using MVA or matrix element methods

CMS	**ATLAS**
JHEP 09 (2014) 087 (*comb*) EPJ C 75 (2015) (*bb ME*)	arXiv:1506.05988 (*leptons*) arXiv:1503.05066 (*bb*) PLB 740 (2015) 222-242 (*γγ*)

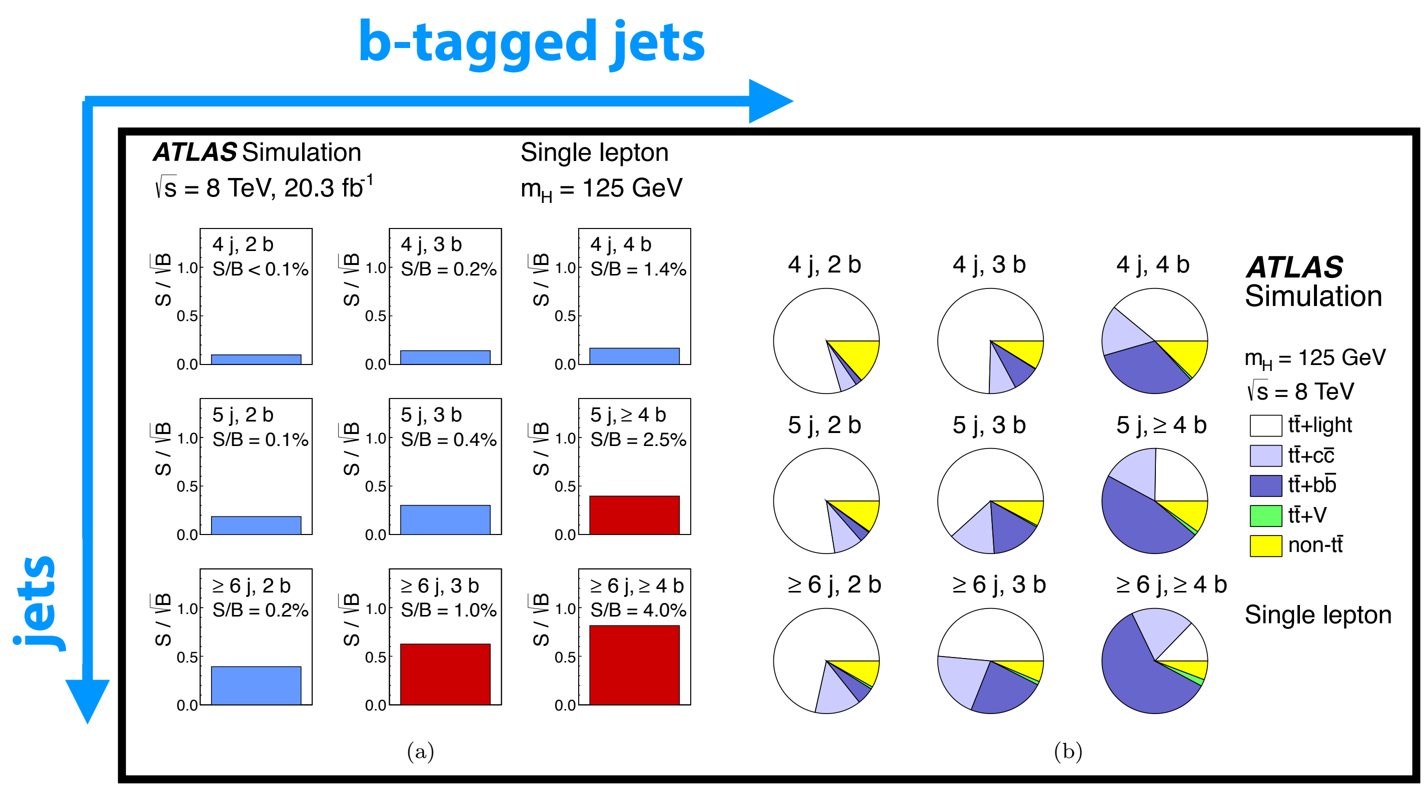
ttH **H→bb**

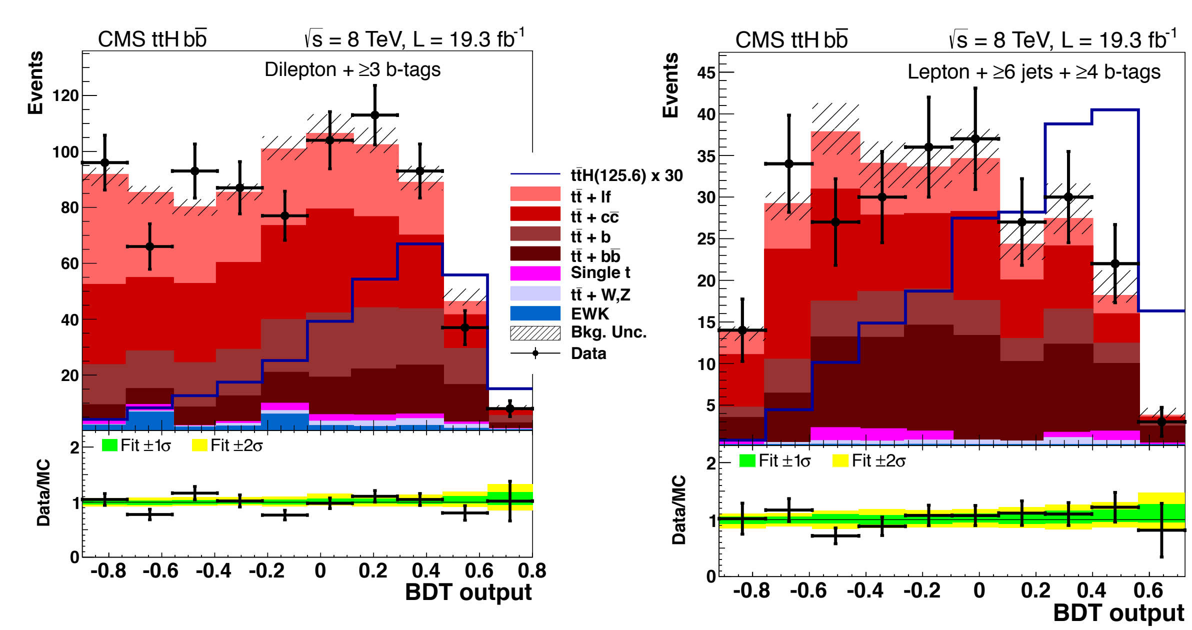
τ μ e b **t**

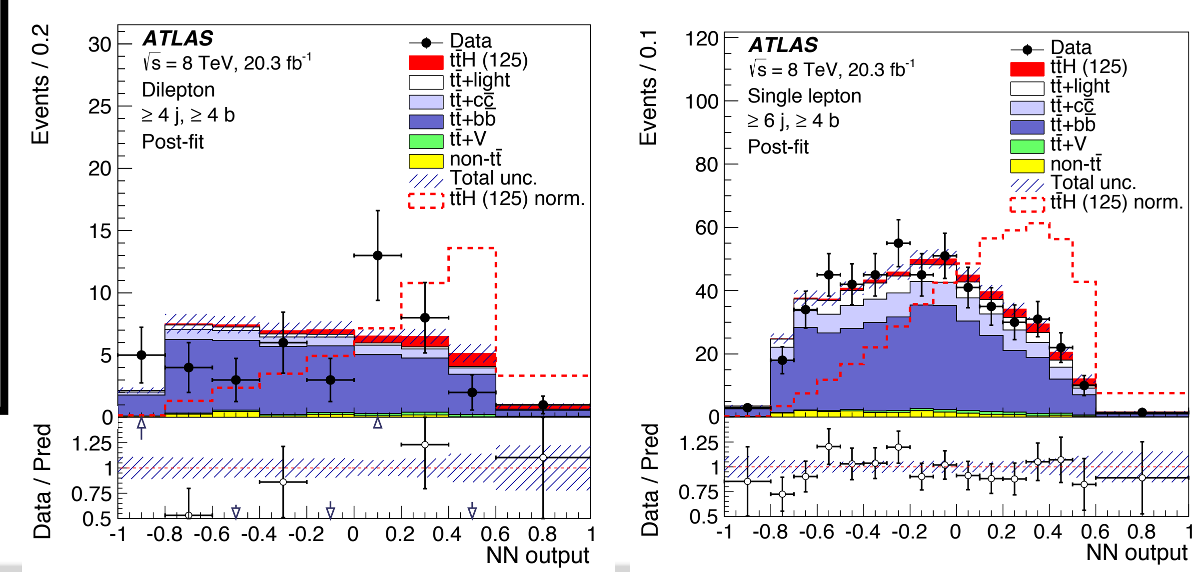
- **Single lepton** and **dilepton** selections to suppress large multi-jet background
- **Remaining backgrounds** from **tt+bb**, mis-tagged **tt+light** and **tt+cc, tt+V and single t**

- Categorise on jet and b-tagged jet multiplicity, multivariate discriminator for signal extraction

- **CMS**: 2 analyses: 1 BDT based, 1 matrix element method (MEM)
- **ATLAS**: Neural network with MEM input







$\hat{\mu} = 1.5 \pm 1.1$ @ 125.0 GeV | $\hat{\mu} = 0.7 \pm 1.9$ @ 125.6 GeV

ME Method

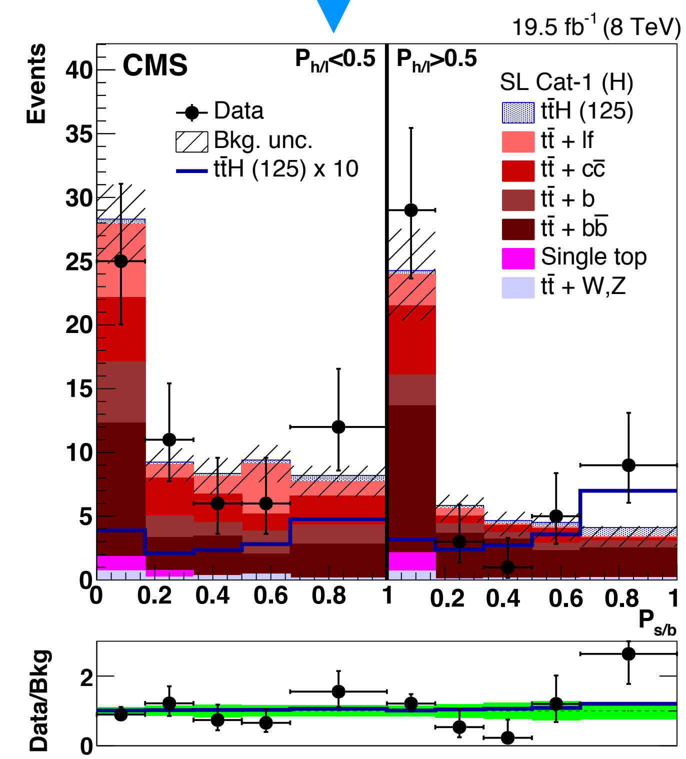
H→bb

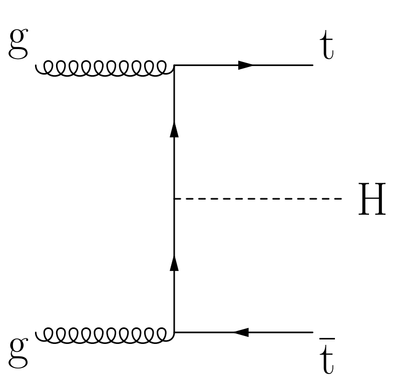
τ μ e b t

CMS Analysis:

- Fit 2D distribution of $\mathbf{P_{s/b}}$ and $\mathbf{P_{h/l}}$
  - $\mathbf{P_{s/b}}$**:** Ratio of signal **(ttH) and** bkg (**tt+bb**) likelihoods computed from **LO matrix elements** with transfer functions to model experimental resolution → similar ratio used in **ATLAS analysis**
  - $\mathbf{P_{h/l}}$**:** likelihood of b-tagging observables
- **~30% improved sensitivity** compared to BDT analysis

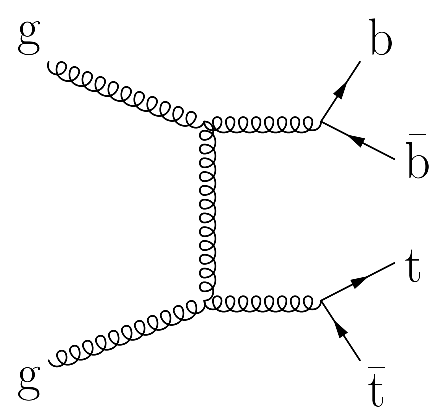
$$P_{\mathrm{h/l}} = \frac{f(\vec{\xi}|\mathrm{t\bar{t}+hf})}{f(\vec{\xi}|\mathrm{t\bar{t}+hf}) + k_{\mathrm{h/l}} f(\vec{\xi}|\mathrm{t\bar{t}+lf})}$$





ttH→bb

vs



tt + bb

$$P_{\mathrm{s/b}} = \frac{w(\vec{y}|\mathrm{t\bar{t}H})}{w(\vec{y}|\mathrm{t\bar{t}H}) + k_{\mathrm{s/b}} w(\vec{y}|\mathrm{t\bar{t}+b\bar{b}})}$$

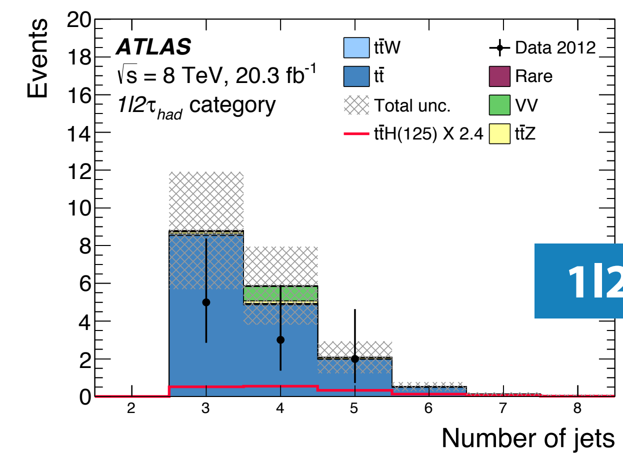
$\hat{\mu} = 1.2^{+1.6}_{-1.5}$ **@ 125.6 GeV**

ttH

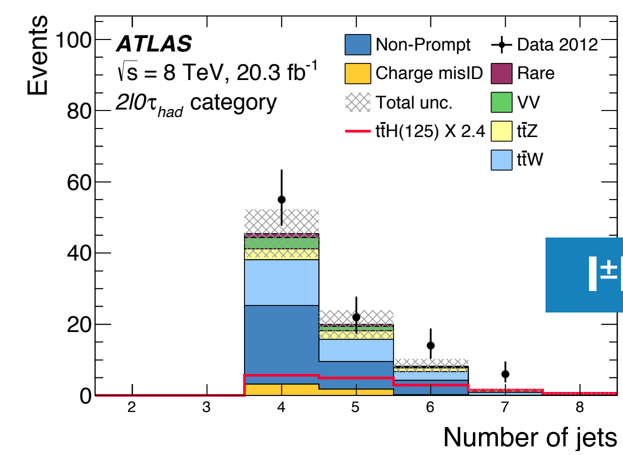
τ μ e b t

H→WW/ZZ/ττ

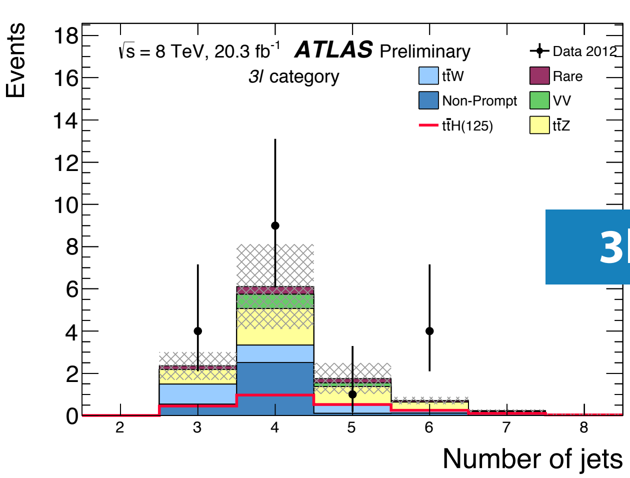
- **Categories:** 2l (same-sign), 3l, 4l, l+2τ_h
- **Backgrounds:** $t\bar{t}$/W/Z+jets with non-prompt leptons, $t\bar{t}$+V, VV



1l2τ_h

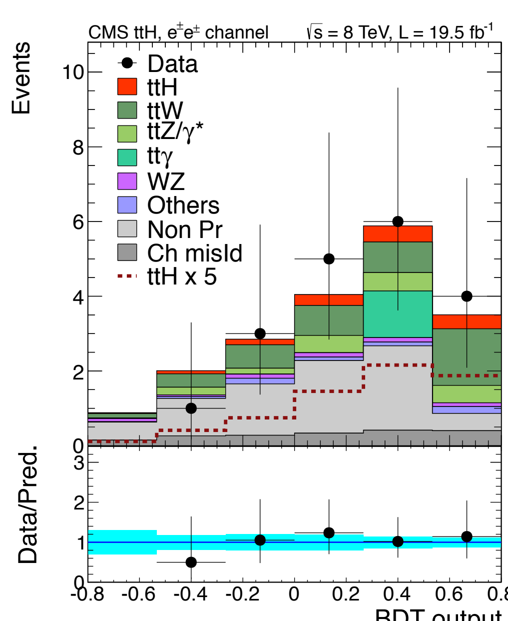


l±l±

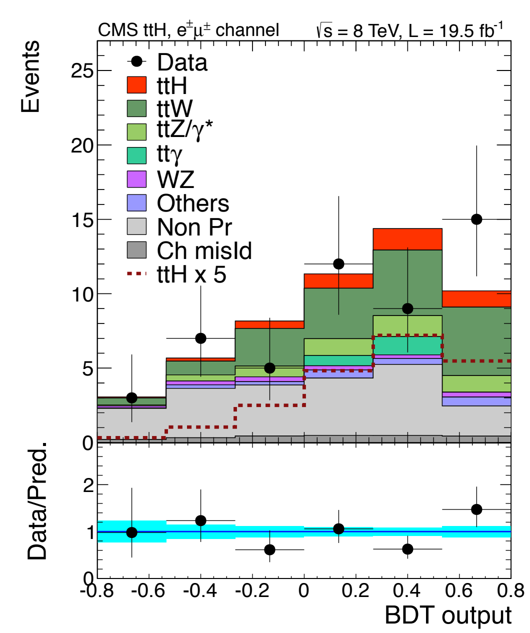


3l

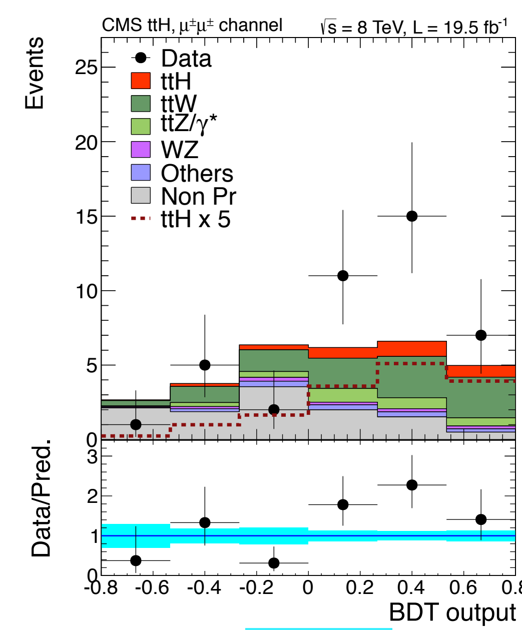
- **Signal Extraction**
  - **ATLAS:** Split di-lepton categories into events with **4 or ≥5 jets**. Simultaneous fit to data of yields in all categories.
  - **CMS:** Fit output of a **BDT discriminator** in 2- and 3-lepton categories. Excess of events visible in μ±μ± final state



e±e±



e±μ±



μ±μ±

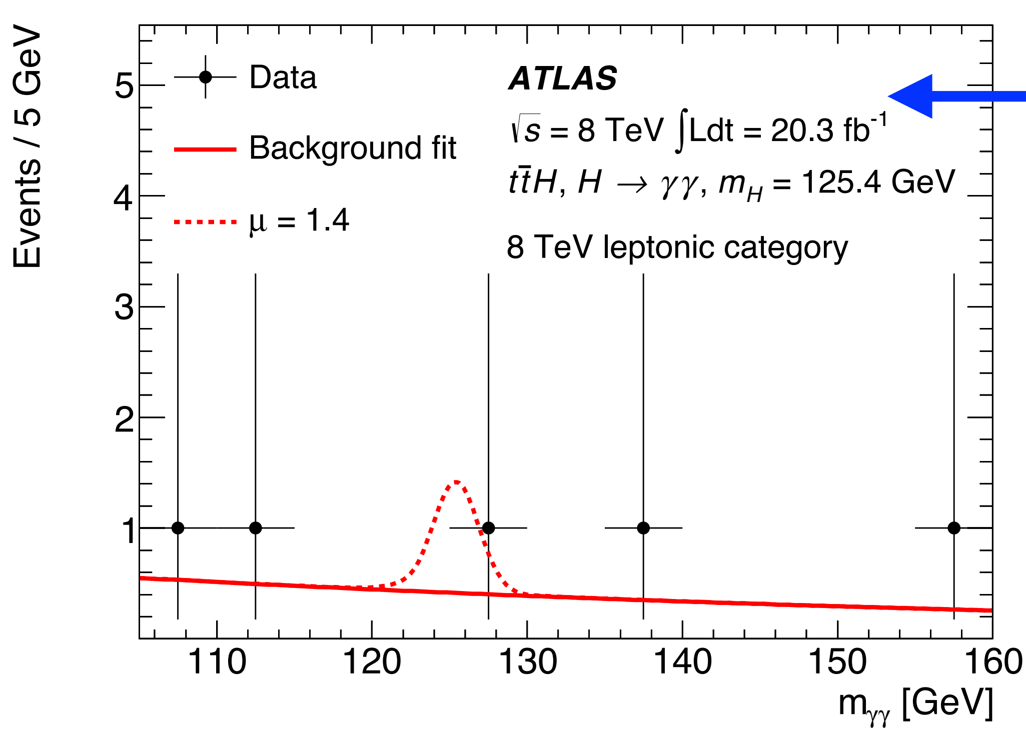
ttH

τ μ e b t

H→γγ

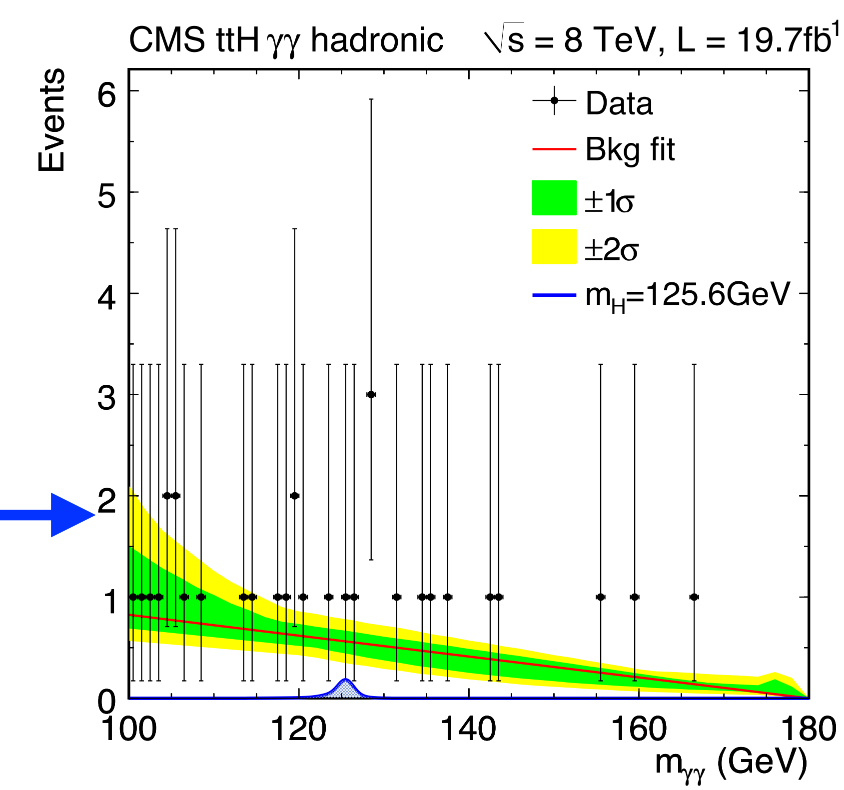
- Despite small H→γγ BF, exploit clean signature and excellent resolution of $m_{\gamma\gamma}$

- Categorise events based on **hadronic** and **leptonic** $t\bar{t}$ final states
- Selections on jet and b-tagged jet multiplicity
- **Signal extraction** from fit to $m_{\gamma\gamma}$
  - di-photon background modelled with smoothly falling functional form



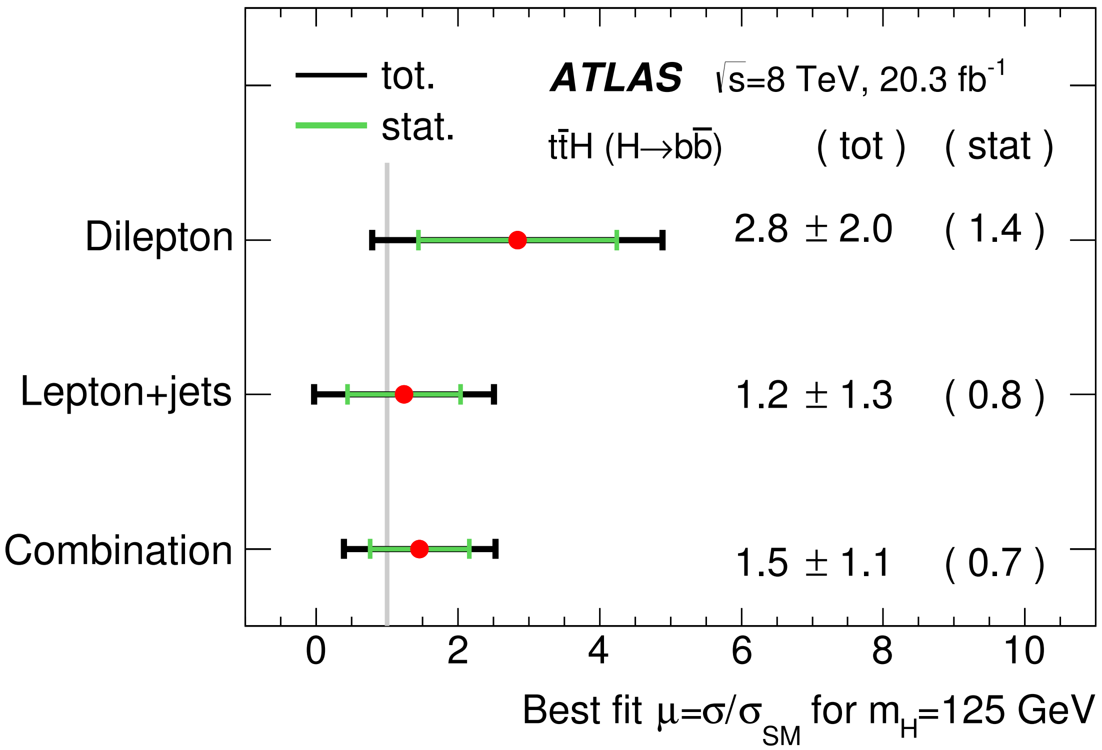
single or di-lepton tt channel
≥1 b-tagged jet

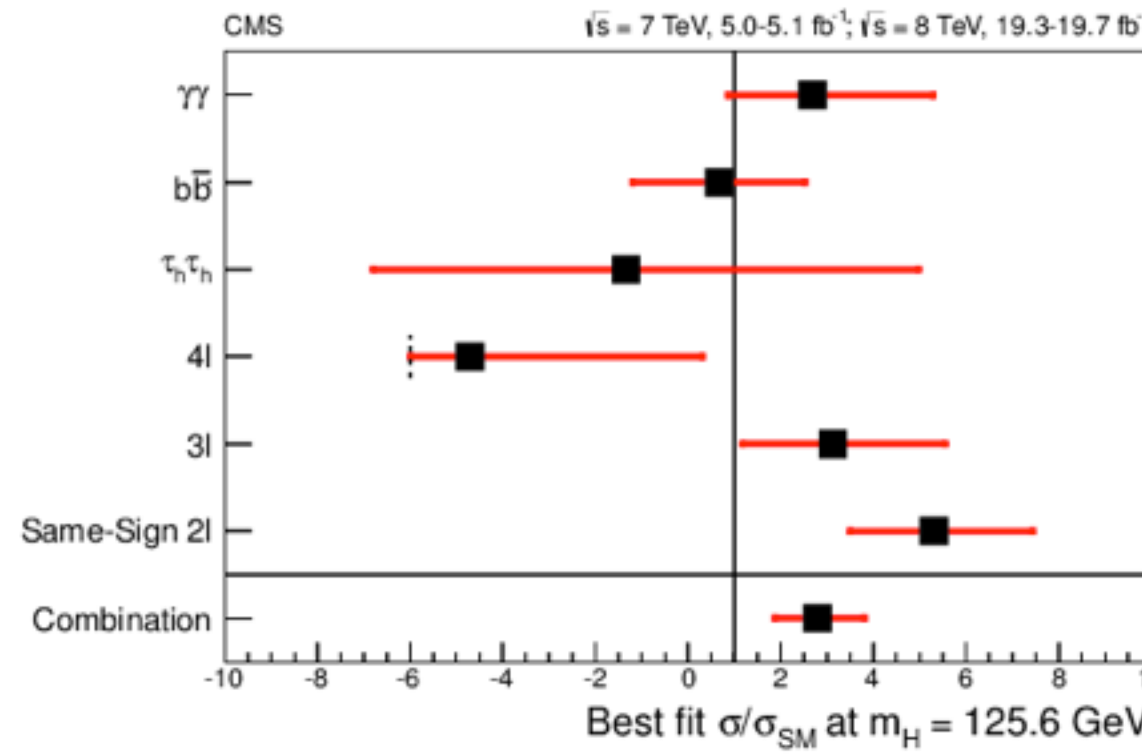
hadronic tt channel
4-6 jets, ≥1 b-tag

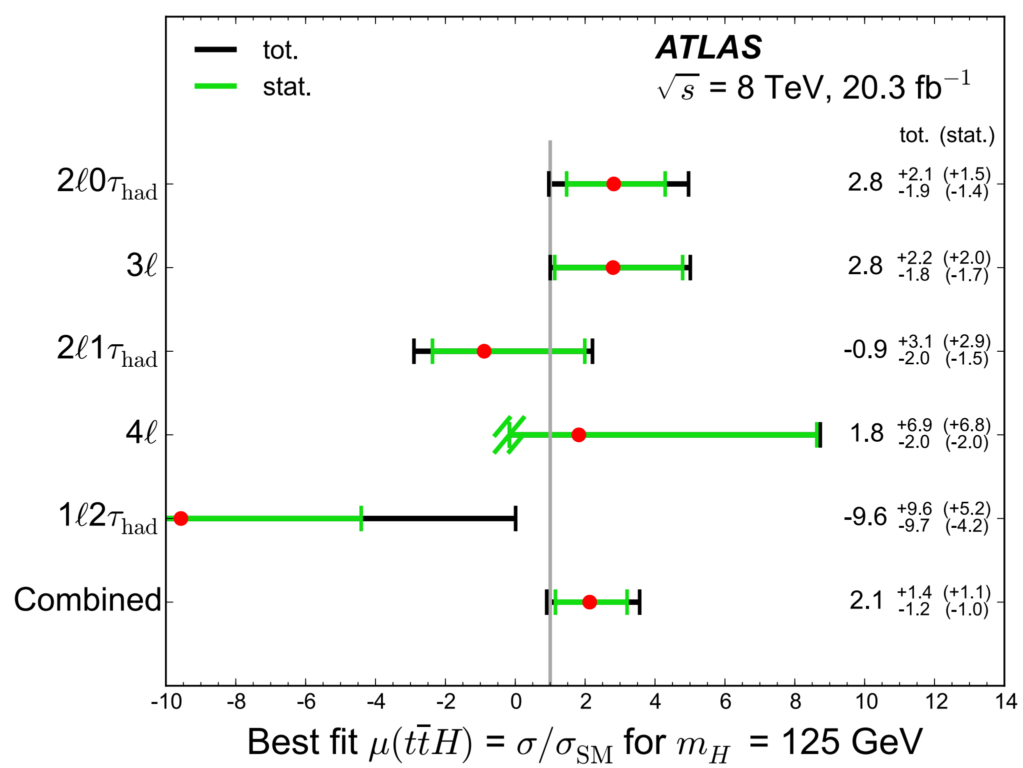


ttH - Results

τ μ e b t







- ttH signal strength from Higgs combinations (*):
- **CMS:** $\hat{\mu} = 2.9^{+1.1}_{-0.9}$ @ 125.0 GeV
- **ATLAS:** $\hat{\mu} = 1.81 \pm 0.80$ @ 125.36 GeV

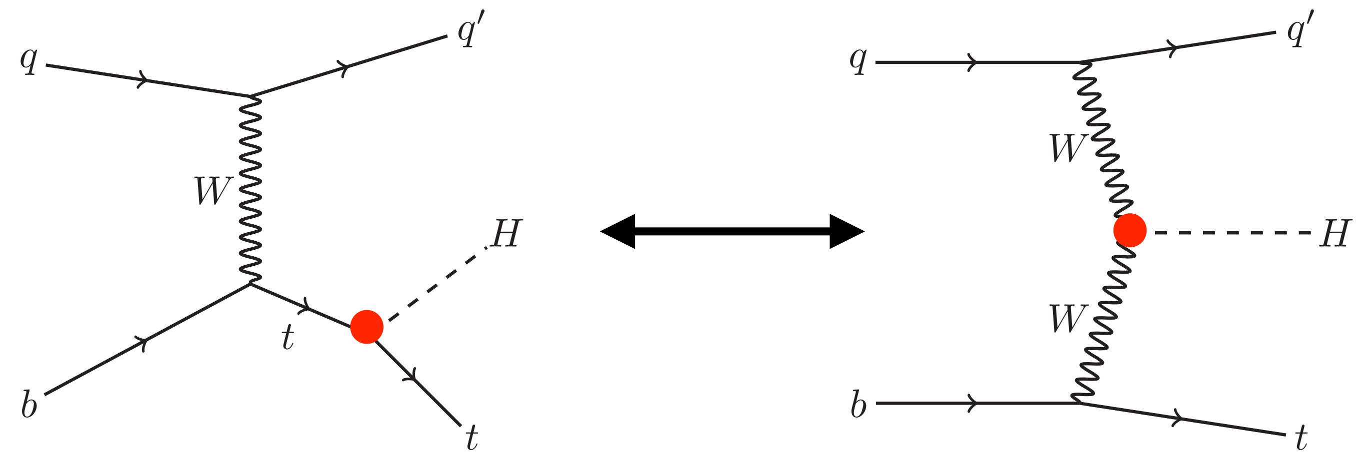
(*) **CMS** EPJ. C 75 (2015) 212
ATLAS arXiv:1507.04548

Single top + Higgs Production

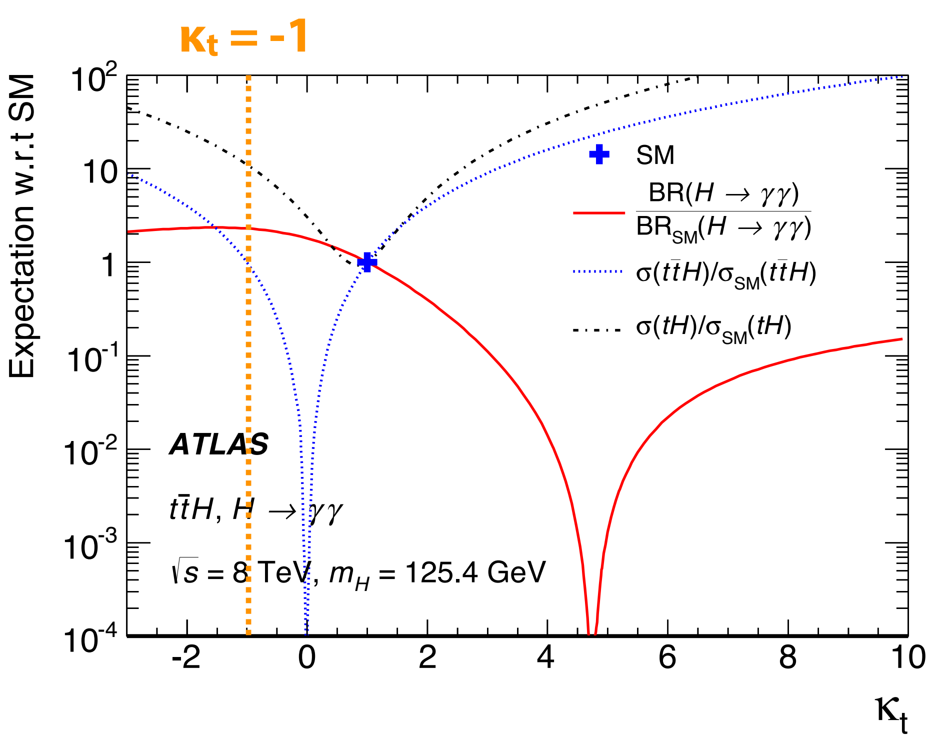
τ μ e b **t**

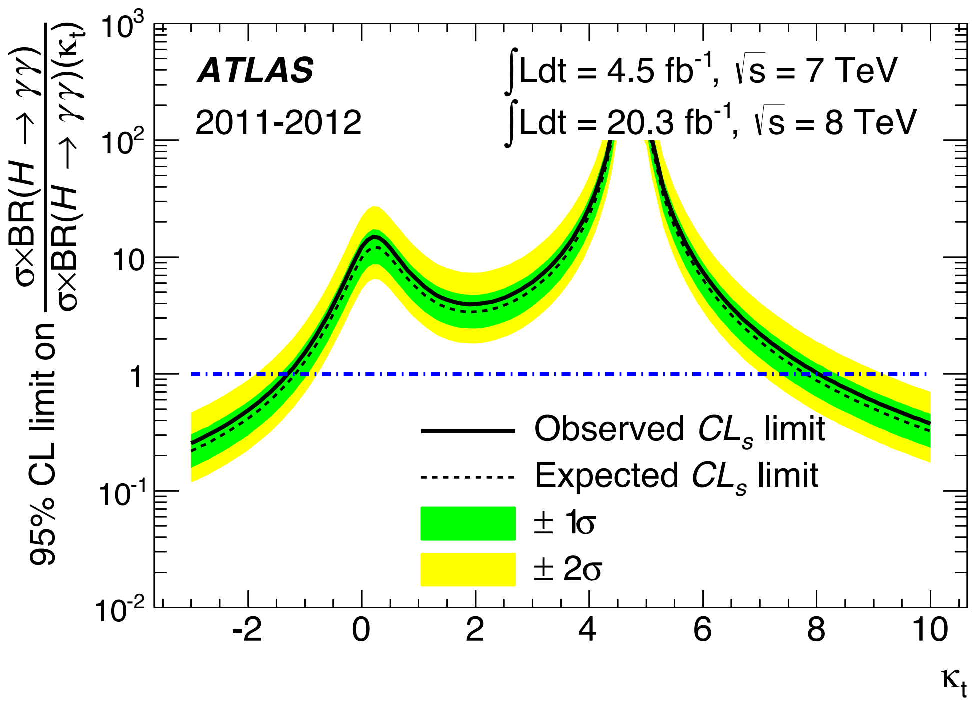
- Novel channel to probe the sign of k_t and search for new physics: **single top tHq production**

- t and W couple to H with opposite sign
- Destructive interference of main diagrams
- SM cross section of **~ 18 fb**
- **But enhanced by factor of 15 if y_t = -1**



- Utilised in ATLAS ttH→γγ analysis via effect on ttH and tH cross sections and BR(H→γγ)





Lower (upper) 95% CL limits of -1.3 (+8.0) on k_t

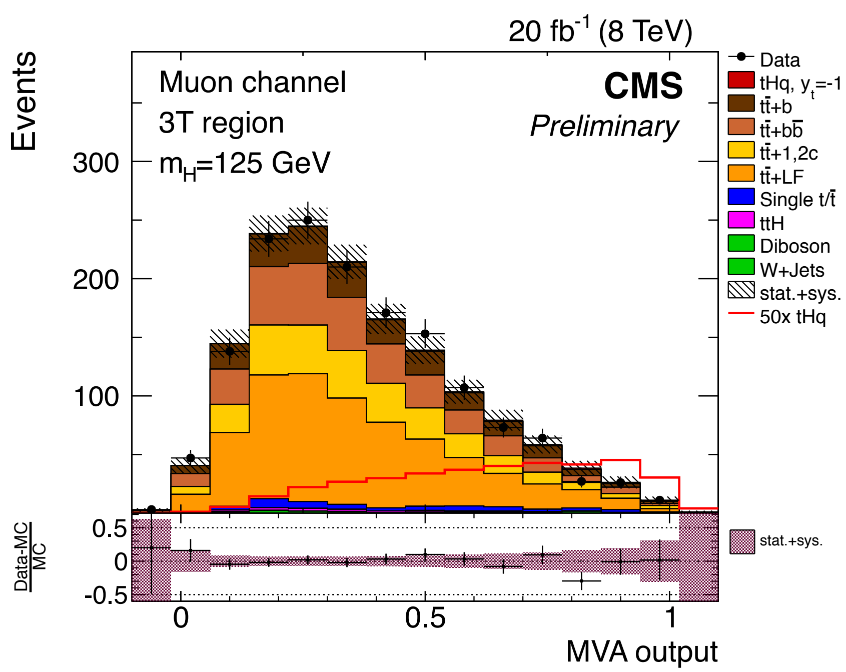
tH Production

CMS-HIG-14-026 (*leptons*)
CMS-HIG-14-015 (*bb*)
CMS-HIG-14-001 (*γγ*)

τ μ e b **t**

- **CMS**: Analyses target tHq production in three decay channels, **set limits on σ predicted for k_t = -1**

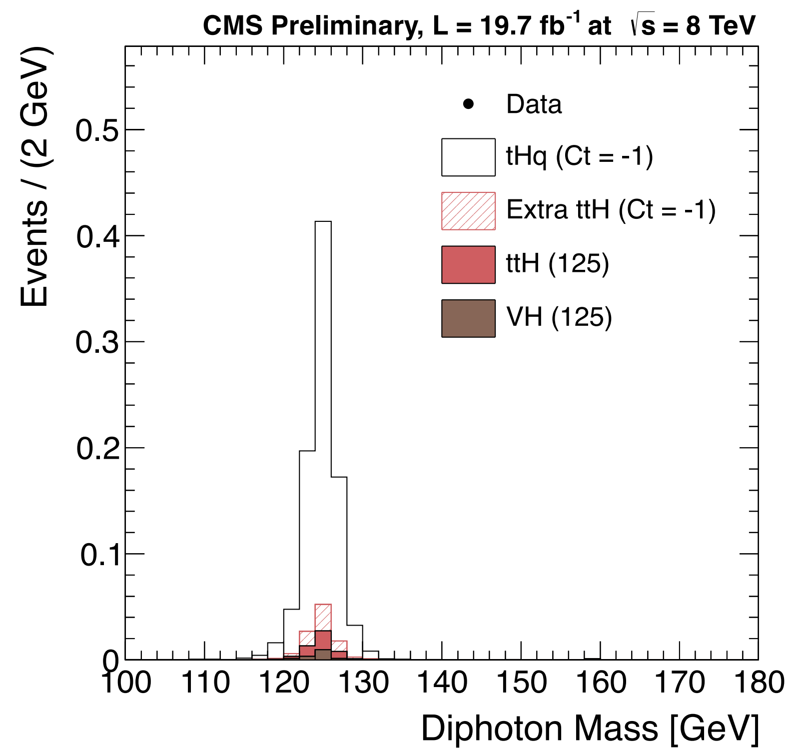
H→bb



- Significant tt+jets background reduced with MVA
- Fit neural network out in 3 b-tag and 4 b-tag categories

μ < 7.6 (5.2 exp) 95% CL

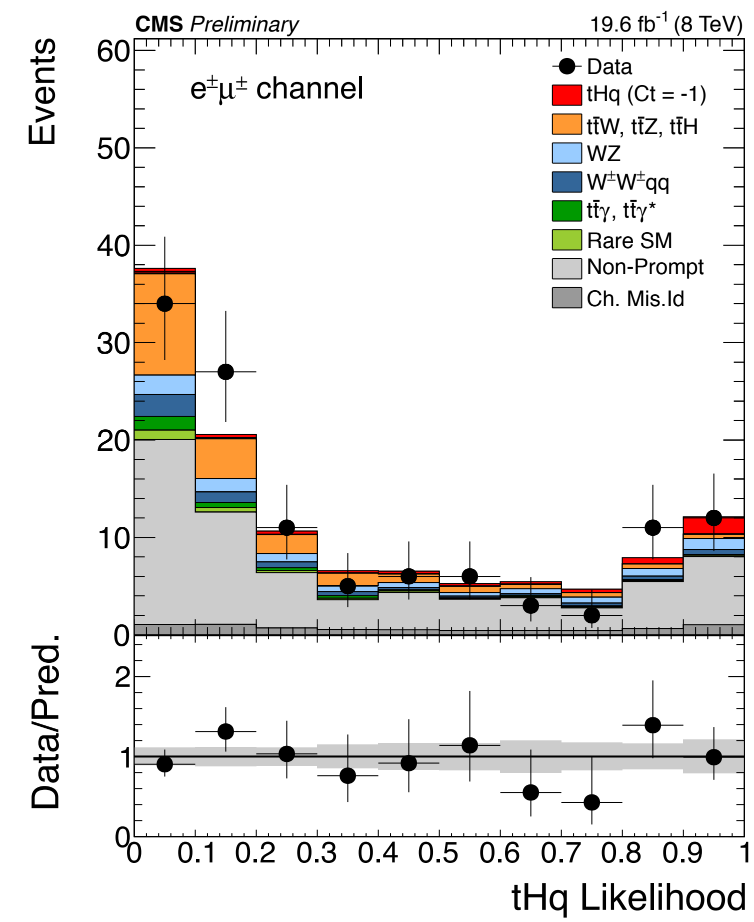
H→γγ



- Likelihood discriminator to separate ttH and tHq
- Zero events observed in signal region

μ < 4.1 (4.1 exp) 95% CL

H→leptons



- Likehood discriminator in 2 and 3 lepton selections

μ < 6.7 (5.0 exp) 95% CL

Combination Results

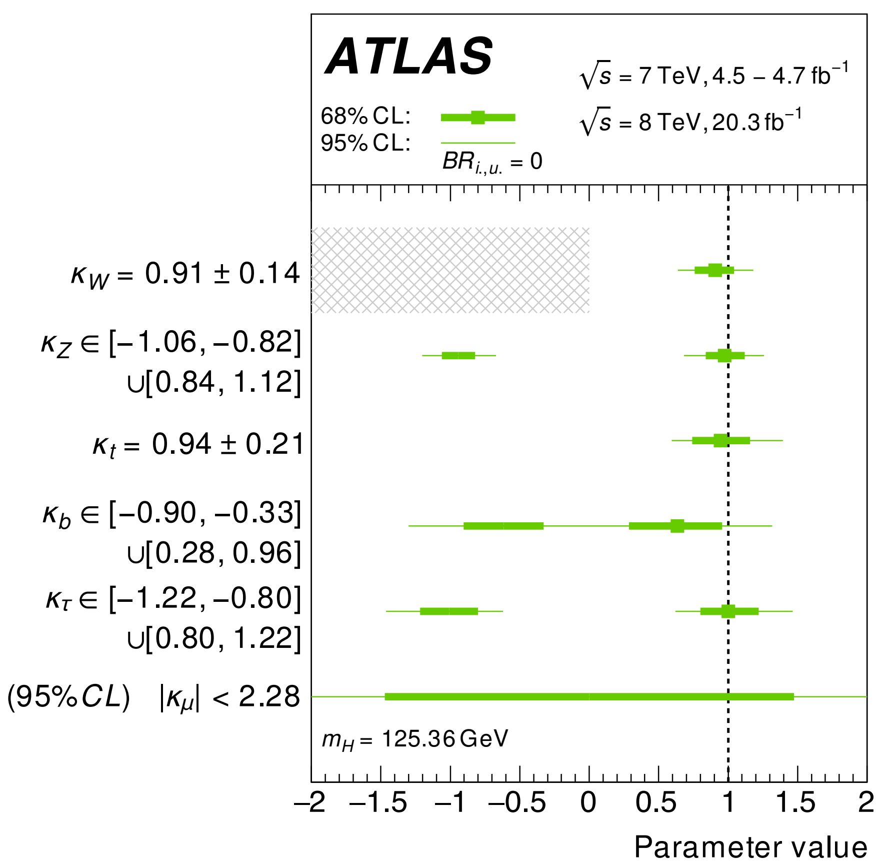
ATLAS arXiv:1507.04548
CMS EPJ. C 75 (2015) 212

- Assuming signal from a **single particle** and **narrow-width approximation** holds:

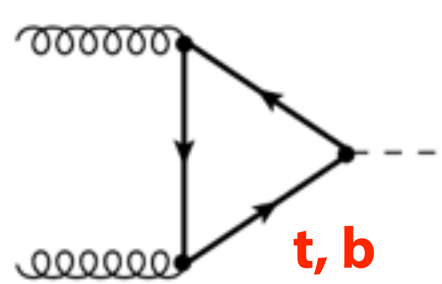
$$(\sigma \mathcal{B})(x \to \mathrm{H} \to yy) = \frac{\sigma_x \Gamma_{yy}}{\Gamma_{\mathrm{tot}}}$$

- Introduce parameters that allow for deviation with respect to SM values:

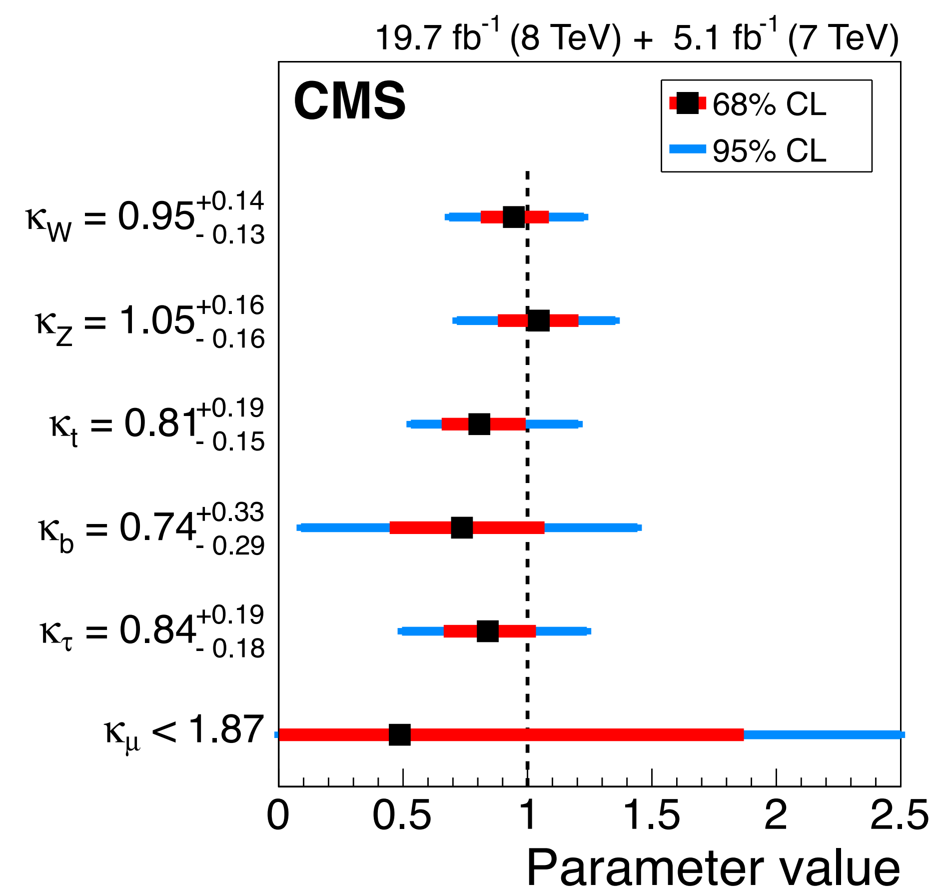
$$\kappa_i^2 = \sigma_i/\sigma_i^{\mathrm{SM}} \qquad \kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{\mathrm{SM}}$$



Loop processes (e.g. σ_{ggH}, $\Gamma_{\gamma\gamma}$) expressed in terms of SM coupling structure

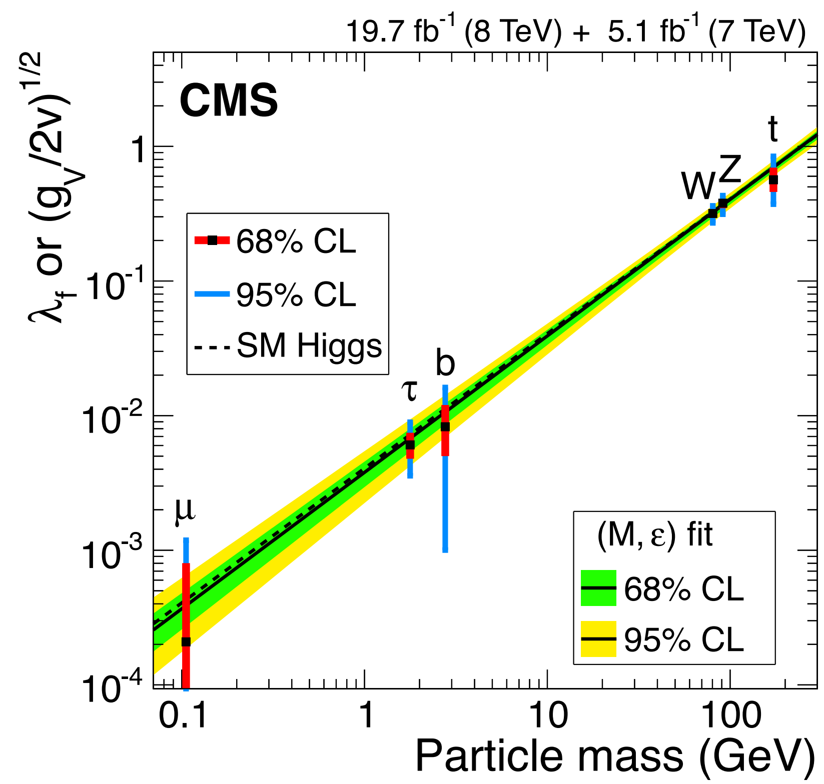


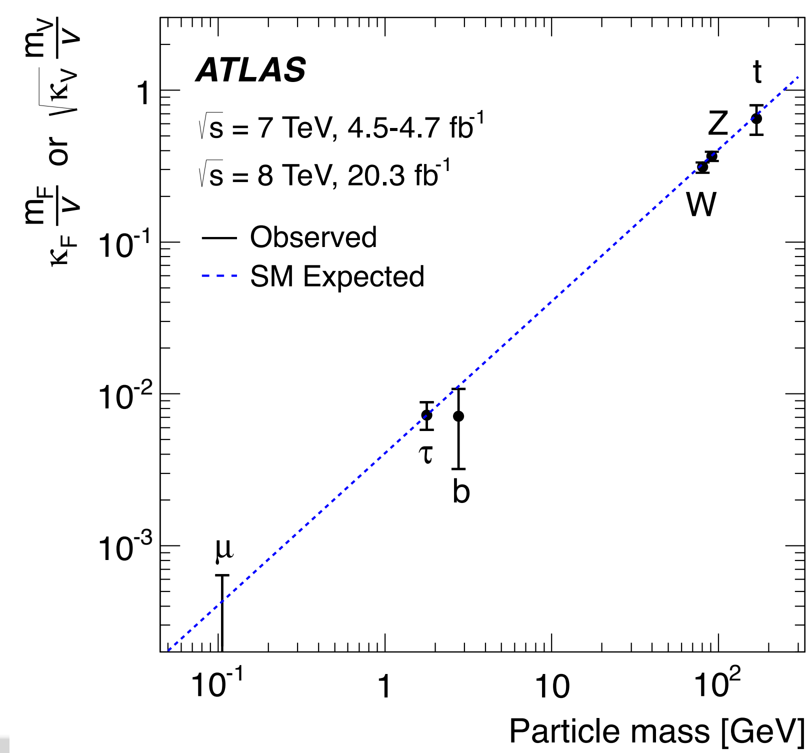
Top quark dominates ggH loop ⇒ extra constraint on κ_t



Summary

- **Evidence for Yukawa couplings** from H→ττ decays in both ATLAS and CMS analyses
- Non-detection of H→μμ/ee implies this coupling is **not lepton flavour universal**
- Excess of events in the H→bb and ttH searches compatible with SM expectation
- Limits set on the enhancement of tHq production
- Overall picture in combined coupling fits shows consistency with the SM





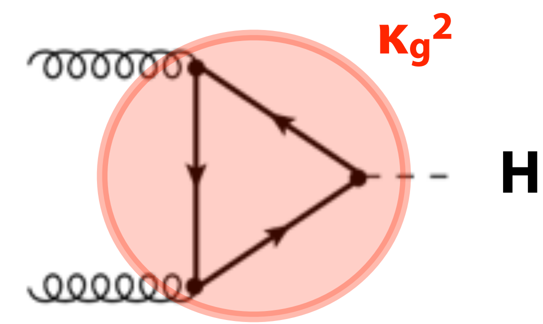
ATLAS arXiv:1507.04548
CMS EPJ. C 75 (2015) 212

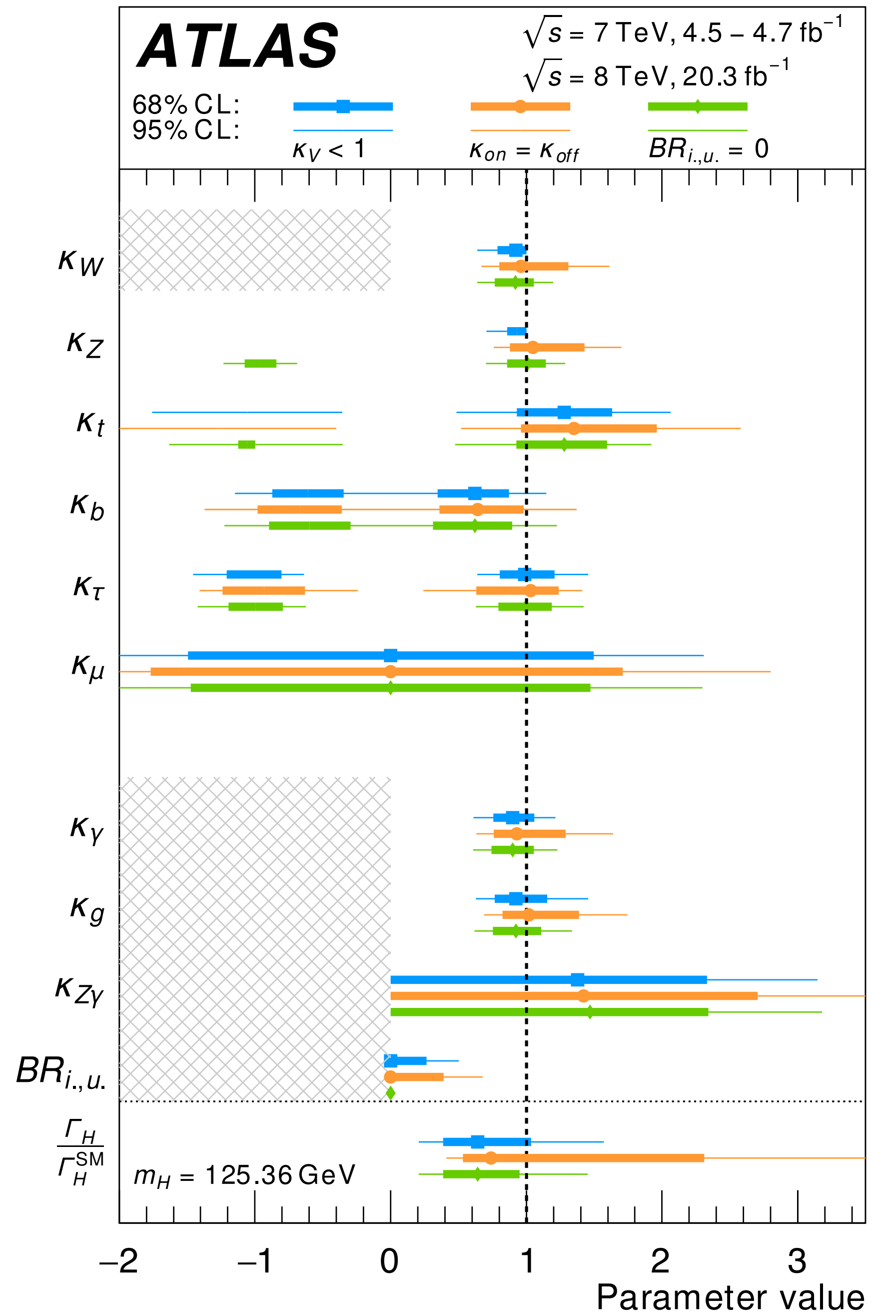
Backup

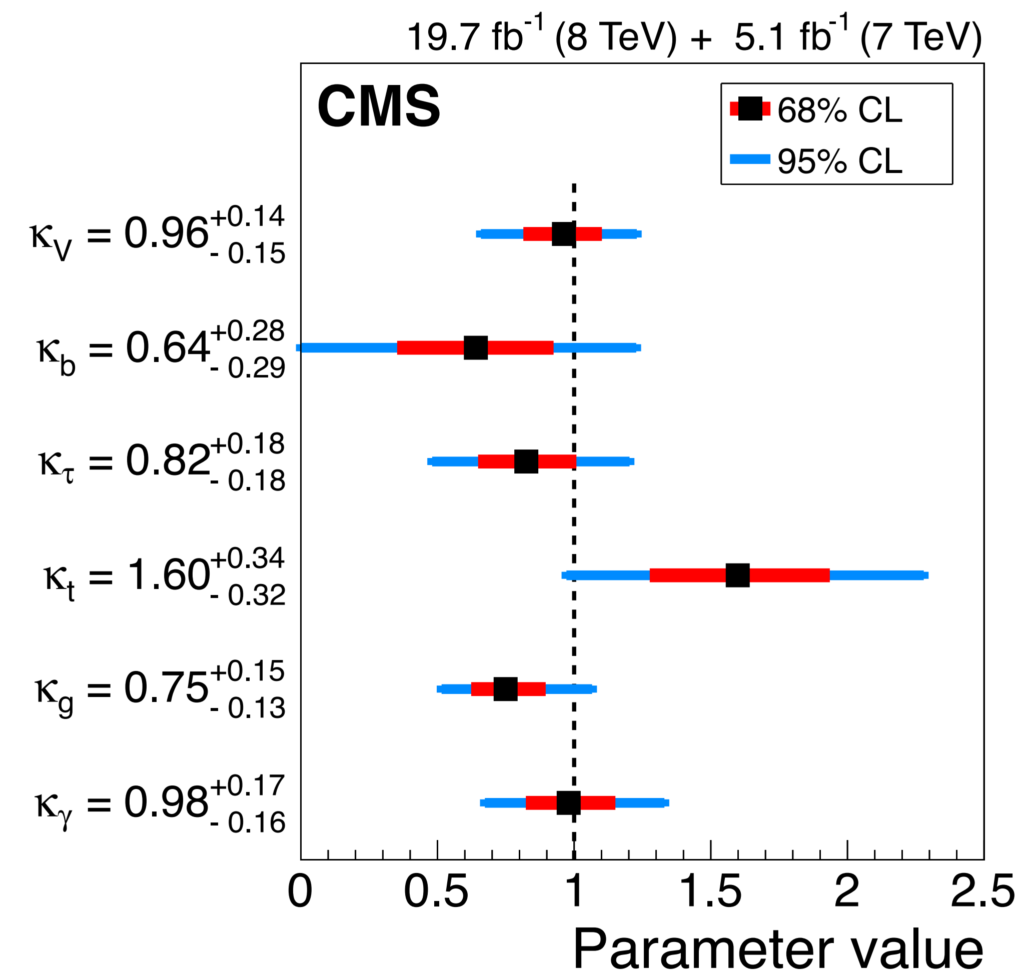
Combination Results

ATLAS arXiv:1507.04548
CMS EPJ. C 75 (2015) 212

- Alternatively parametrise loops with effective couplings, e.g.: κ_γ, κ_g
- Tests for presence of BSM particles in the loops
- Fermion couplings only from tree-level contributions







Combination Results

ATLAS arXiv:1507.04548
CMS EPJ. C 75 (2015) 212

- Assume $\kappa_V = \kappa_W = \kappa_V$, $\kappa_F = \kappa_b = \kappa_t = \kappa_\tau$
- Show 68% CL confidence regions for separate channels as well as the full combination
- Compatible with SM prediction $\kappa_F = \kappa_V = 1$