Search for the Higgs boson in fermionic channels using the ATLAS detector

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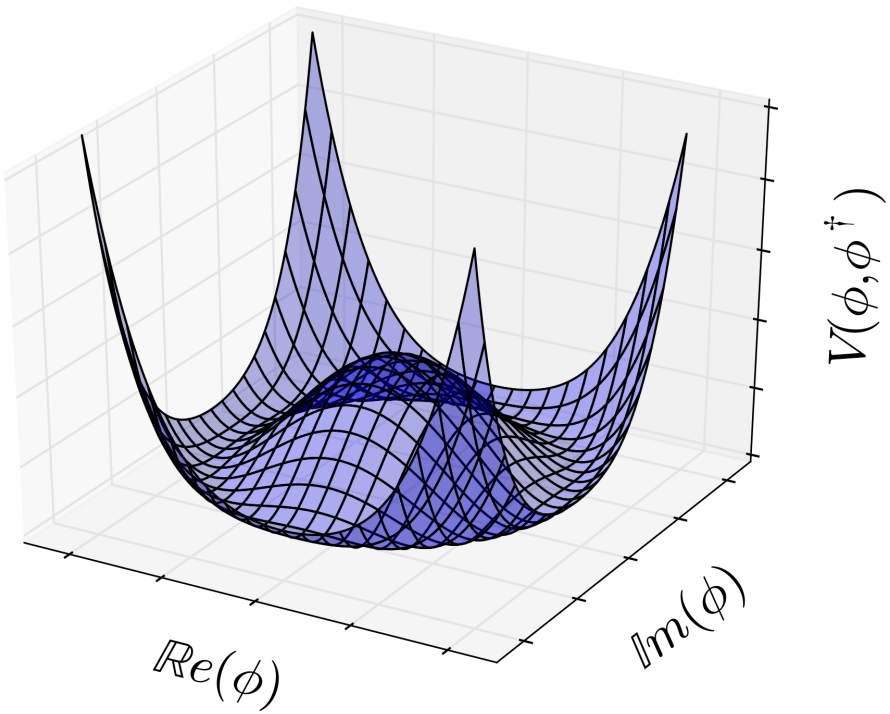
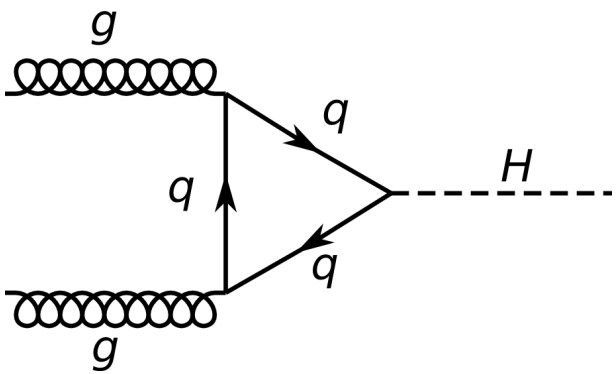
The SM Higgs Boson

- The BEH mechanism breaks the electroweak symmetry by introducing a new scalar field ϕ with potential $\mathbf{V}(\phi, \phi^\dagger)$
- 3 real d.o.f. of ϕ make the **$W^\pm$ and Z bosons massive**
- the 4th real d.o.f. becomes the **Higgs boson**
- The Higgs boson *can* have **Yukawa couplings to fermions**:
  - Coupling strength is proportional to the masses of the fermions
  - Replaces mass terms for fundamental fermions



$$\mathscr{L}_Y = -h_\psi \left(\bar{\psi}_R \phi^\dagger \psi_L + \bar{\psi}_L \phi \psi_R \right)$$

Relevant Production Modes

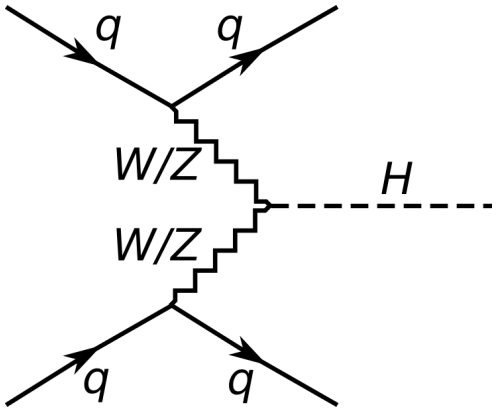


Gluon-gluon Fusion (ggF)

19.27pb

$m_H = 125\text{GeV}$

$\sqrt{s} = 8\text{TeV}$

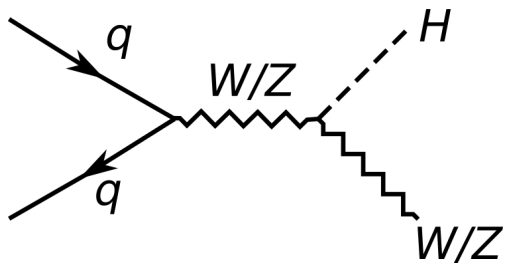


Vector Boson Fusion (VBF)

1.578pb

$m_H = 125\text{GeV}$

$\sqrt{s} = 8\text{TeV}$



Associated Production (VH)

1.12pb

$m_H = 125\text{GeV}$

$\sqrt{s} = 8\text{TeV}$

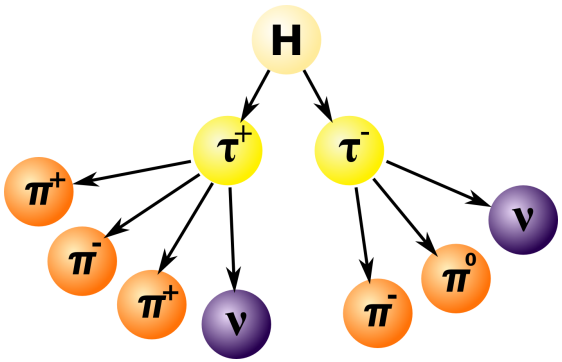
ATLAS Searches in the Fermionic Modes

	$H \to \tau\tau$	$H \to \mu\mu$	$H \to b\bar{b}$
Branching Fraction	6.32%	0.022%	57.7%
Most Difficult Background	$Z \to \tau\tau$	$Z \to \mu\mu$	$gg \to b\bar{b}$
Production Modes Exploited	VBF, ggF, *VH**	VBF, ggF	~~ggF~~, ~~VBF~~, VH, *ttH**
Strategy	Boosted Decision Trees (BDT)	Analytical Fits	Cut-based

*: Not discussed in this talk

$H \to \tau\tau$ Channels

The search is divided in three **channels**:

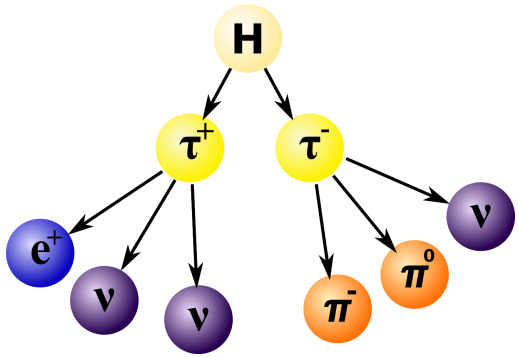


$\tau_{had}\tau_{had}$

hadronic-hadronic

42%

- 2 hadronic tau decays
- Missing E_T
- Any number of jets

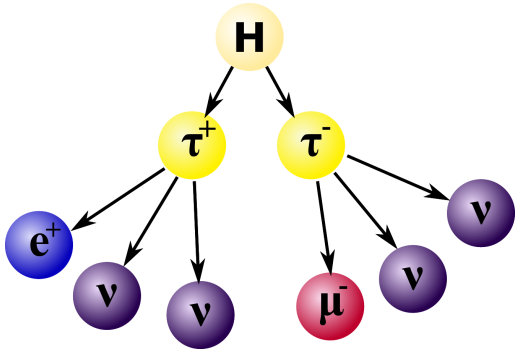


$\tau_{lep}\tau_{had}$

leptonic-hadronic

46%

- 1 hadronic tau decay
- 1 electron or muon
- Missing E_T
- Any number of jets



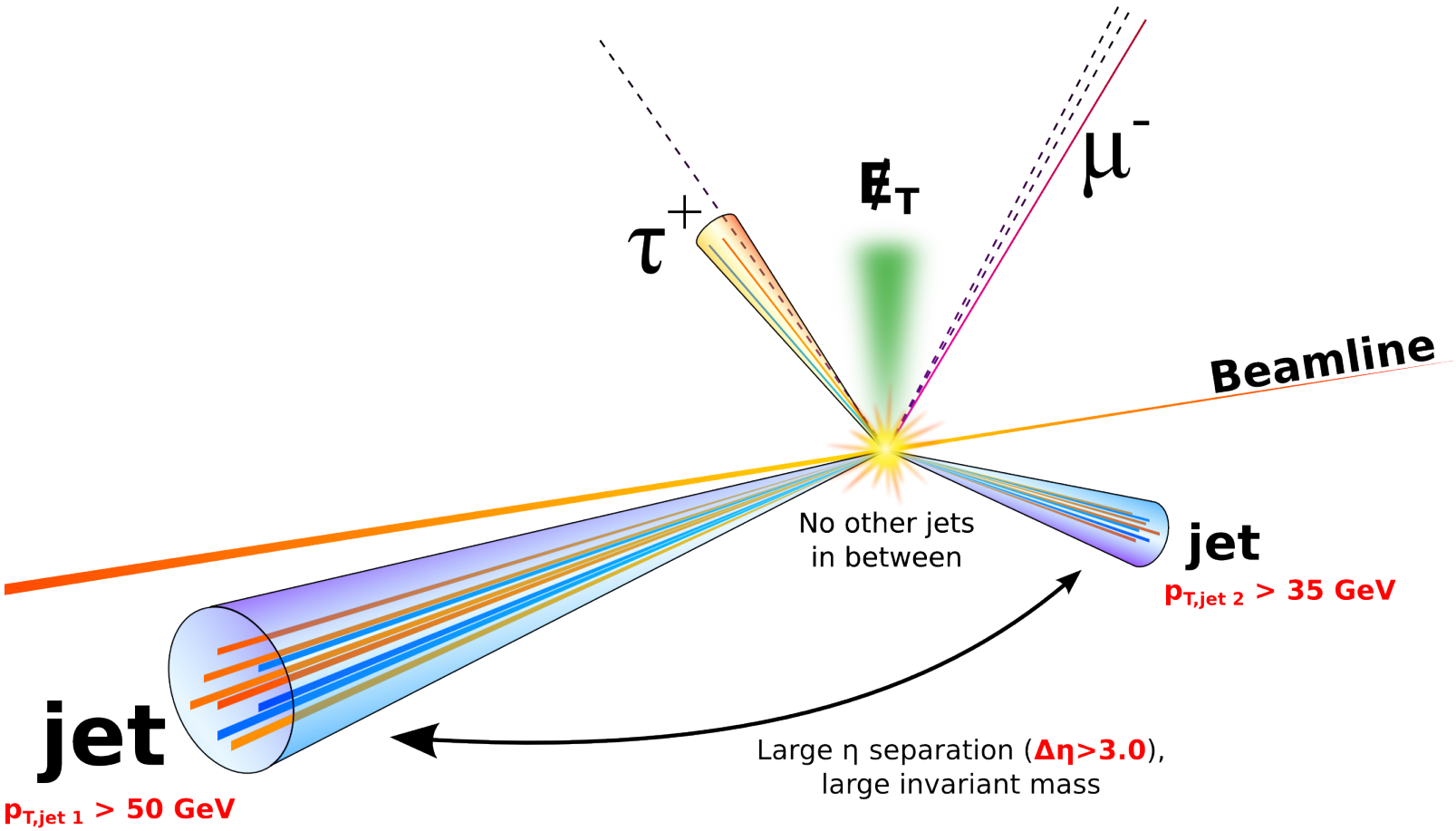
$\tau_{lep}\tau_{lep}$

leptonic-leptonic

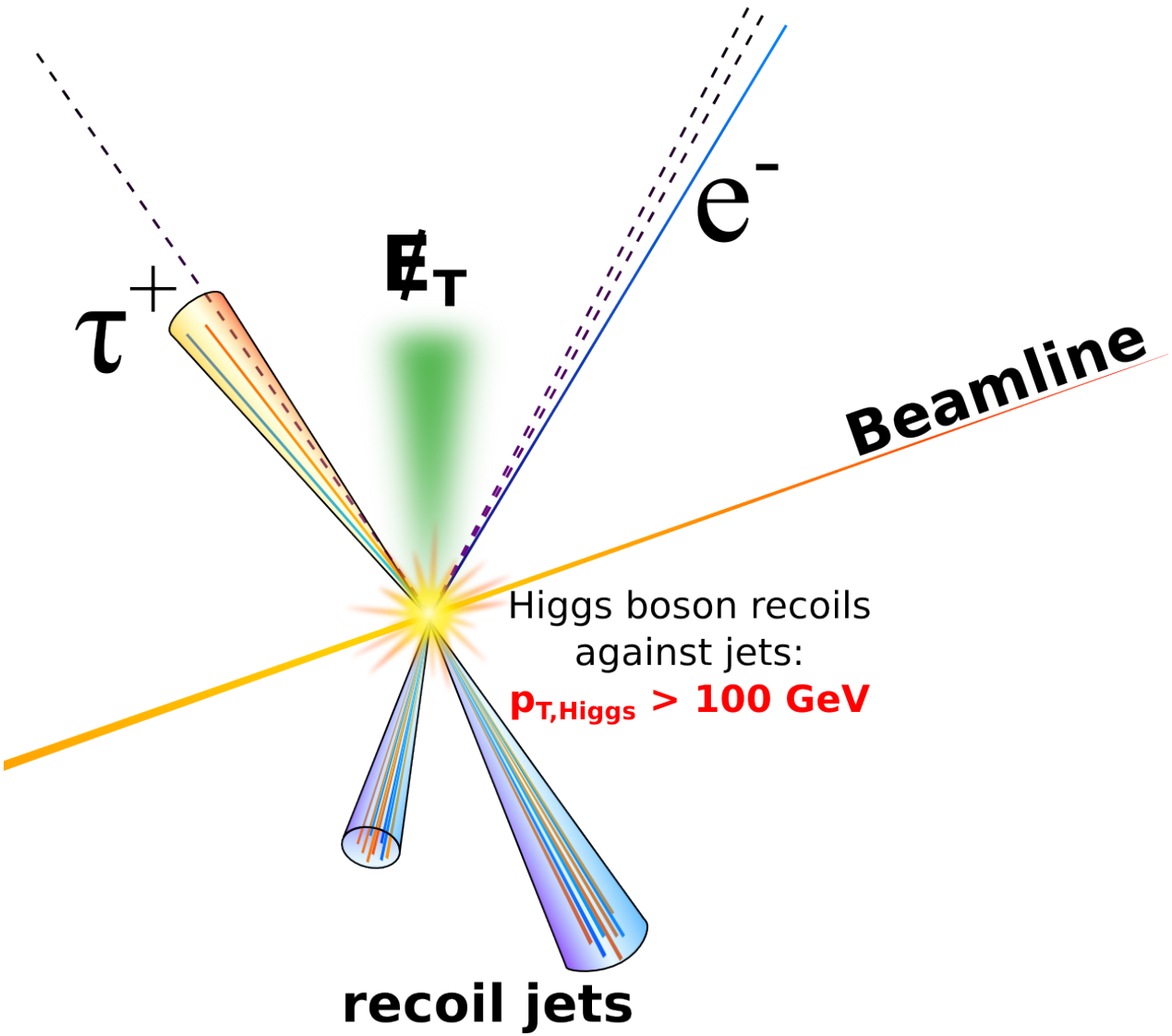
12%

- 2 electrons or muons
- More missing E_T
- Any number of jets

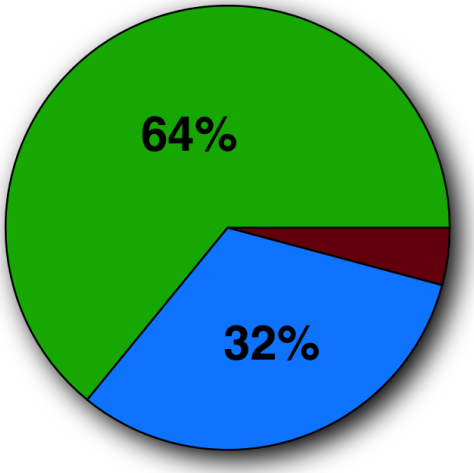
$H \to \tau\tau$ VBF Category: Definition and Topology



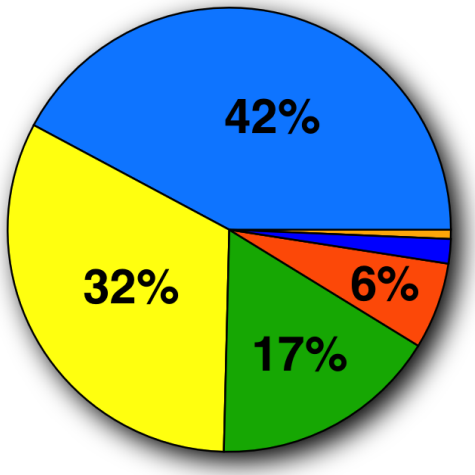
$H \to \tau\tau$ Boosted Category: Definition and Topology



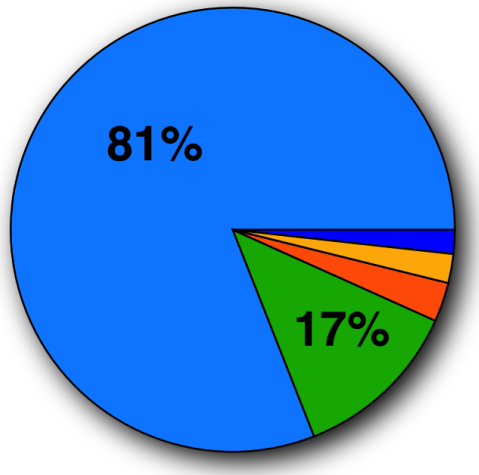
H $\rightarrow \tau\tau$ Backgrounds



$\tau_{had}\tau_{had}$



$\tau_{lep}\tau_{had}$



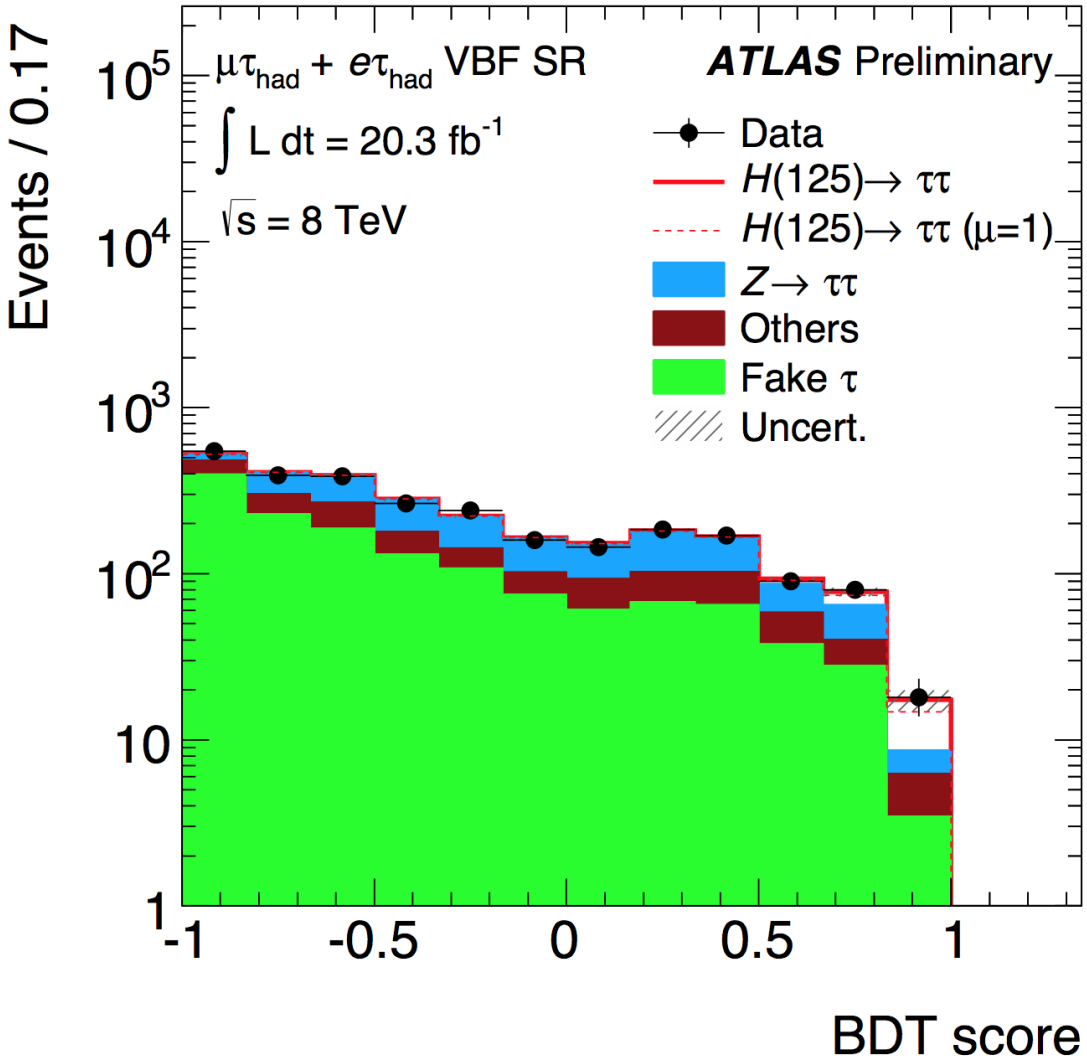
$\tau_{lep}\tau_{lep}$

- $Z\rightarrow\tau\tau$
- QCD multijets
- $W\rightarrow\ell\nu$
- $Z\rightarrow\ell\ell$
- VV
- Top
- Others (than $Z\rightarrow\tau\tau$ and QCD)

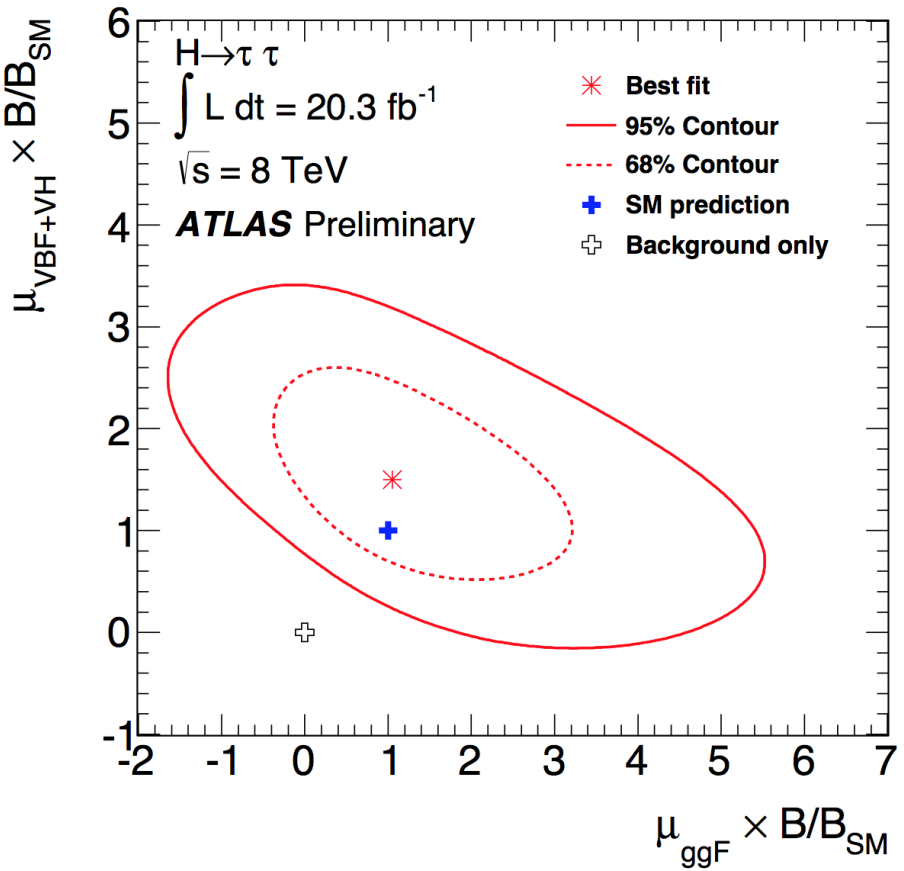
- $Z \rightarrow \tau\tau$: data-driven, $Z \rightarrow \mu\mu$ data events where $\mu \rightarrow \tau$ (simulated)
- QCD: data-driven or negligible
- Top: MC normalized to data
- W: data-driven or MC normalized to data
- Others: MC with theory cross-section

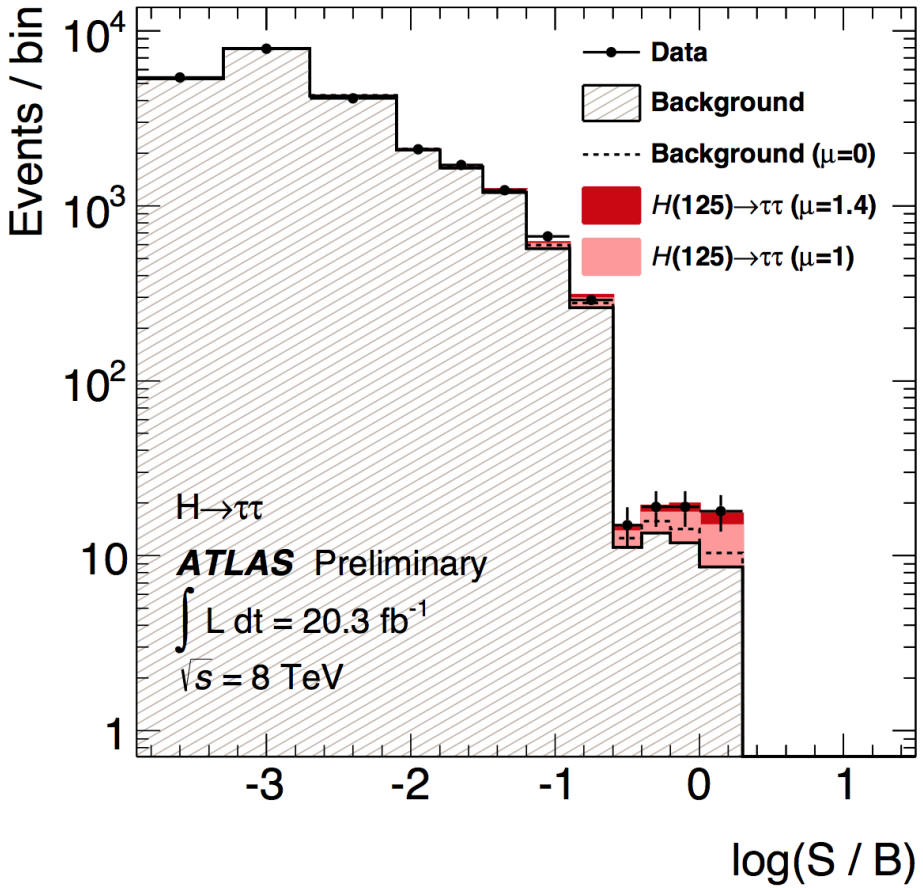
$H \to \tau\tau$ Hypothesis Testing

- Signal Hypothesis: The Higgs boson *already* found (with $\mathbf{m_H \sim 125\ GeV}$) decays to tau pairs
- Train 6 BDTs: for each channel/category
- Do a simultaneous fit on the 6 binned BDT scores + control regions
- Dominant uncertainties:
  - ggF cross-section
  - Jet energy scale
  - $Z \to \ell\ell$ and Top normalization



$H \to \tau\tau$ Results



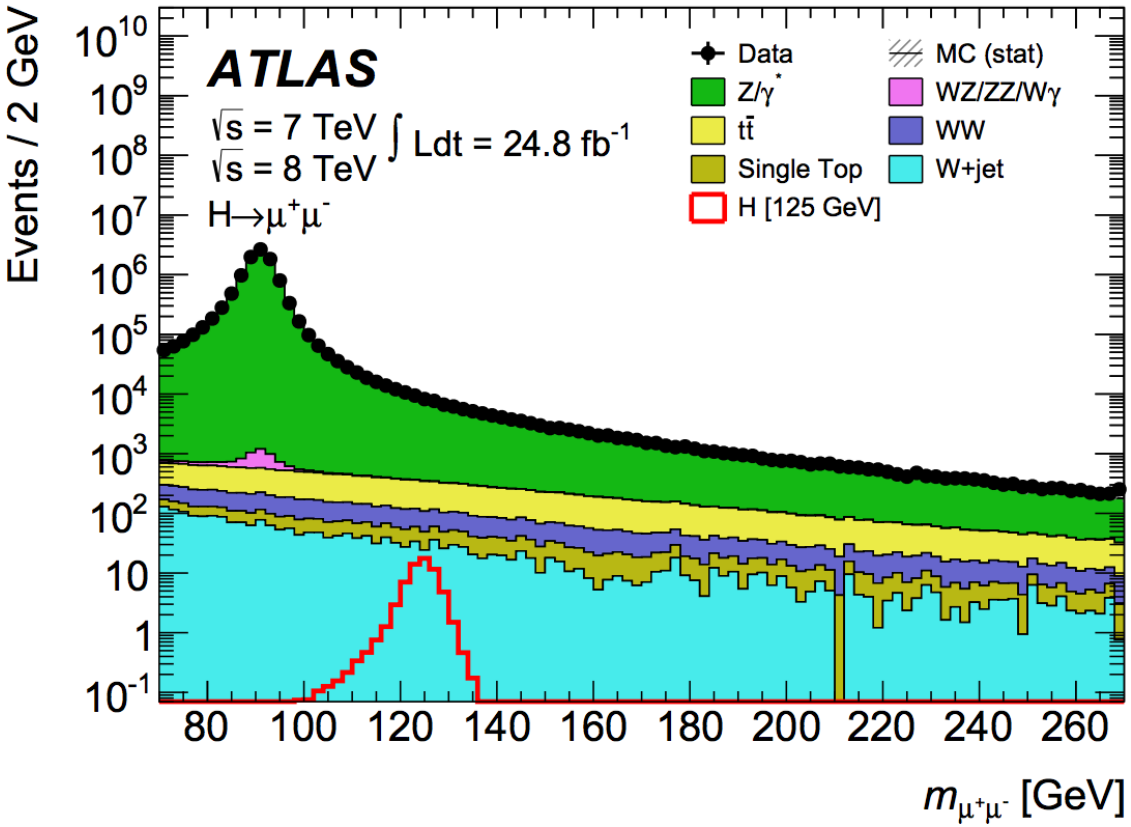


Current Run I Results:

Expected: 3.2σ **Observed:** 4.1σ $\sigma/\sigma_{\mathrm{SM}} = 1.4^{+0.3}_{-0.3}(\mathrm{stat.})^{+0.4}_{-0.3}(\mathrm{syst.})$

$H \to \mu\mu$ Strategy

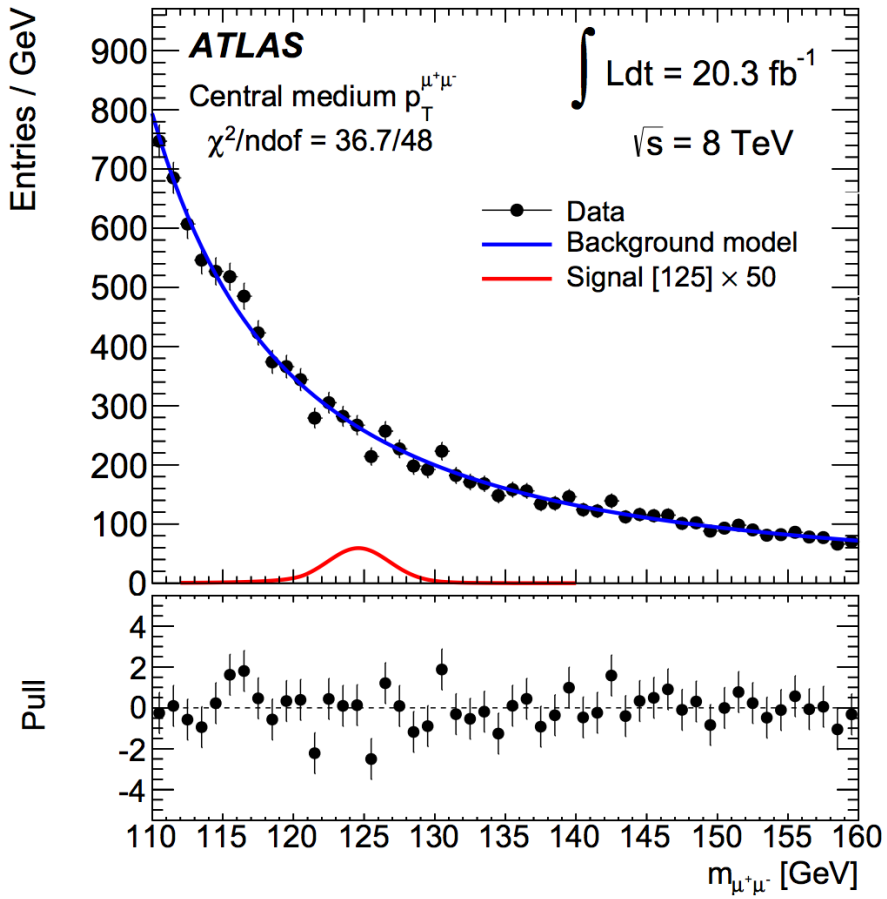
- Fit $m_{\mu\mu}$ distribution in 7 categories:
  - VBF category
  - 6 $p_{T,\mu\mu} - \eta_{\mu\mu}$ regions
- $110 < m_{\mu\mu} < 160$ GeV



- Minimal event selection with **55% signal acceptance**

$H \to \mu\mu$ Backgrounds

- The background and signal models are analytic:
  - **Background Model**: decreasing exponential/x^3 + Breit-Wigner with gaussian smearing *
  - **Signal**: Crystal Ball + Gaussian
- The backgrounds are fitted to data (MC used for studies and optimization only)
- The signal is fitted to Higgs MC samples, interpolated between available mass points

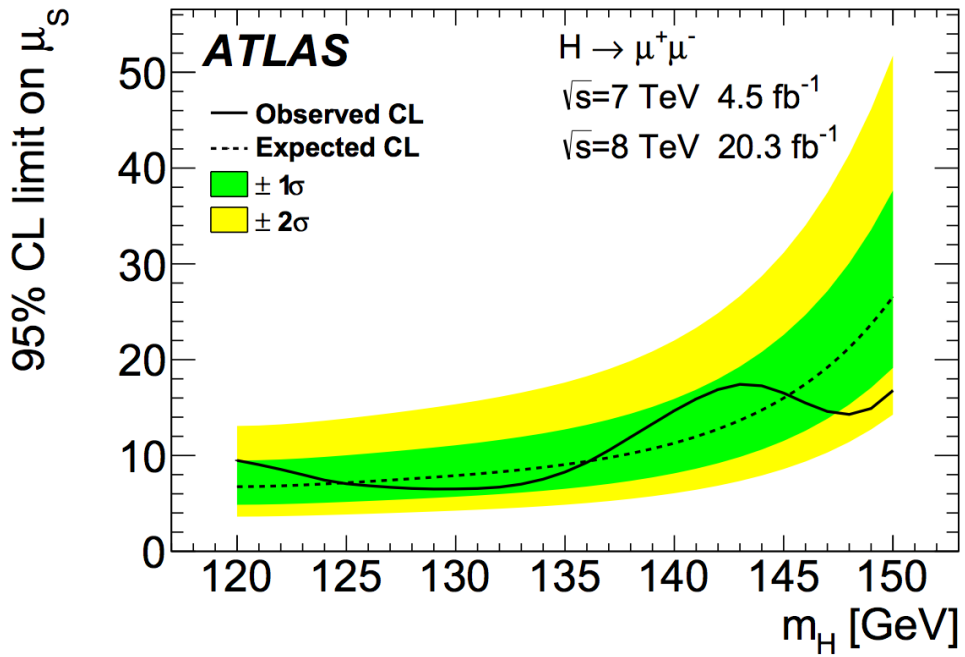


* different for VBF category

$H \to \mu\mu$ Results

Final Run I Results:

- **Expected:** $7.2 \times \sigma_{SM}$ 95% C.L.
- **Observed:** $7.1 \times \sigma_{SM}$ 95% C.L.
- Consistent with the Standard Model
- If Higgs lepton universality:
  - B.R.($\tau\tau$) = B.R.($\mu\mu$)
  - $H \to \mu\mu$ signal should be $\sim$ **283$\times$ larger!**
  - **Would have been seen** by this search



$H \to b\bar{b}$ Strategy

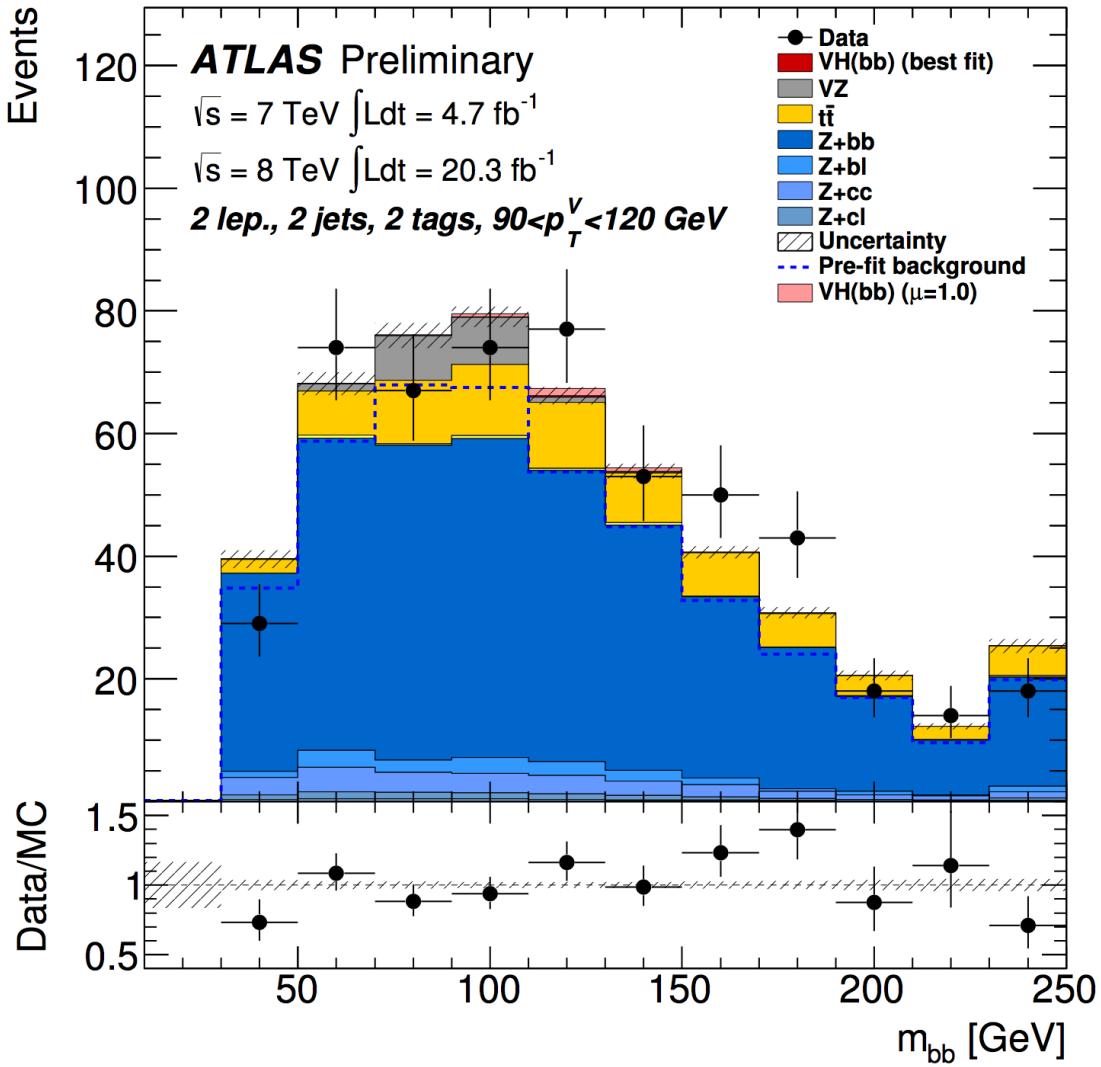
- $gg \to b\bar{b}$ **completely overwhelms** VBF and ggF Higgs production
- VH production provides objects to trigger on: E_T^{miss}, electrons and muons

$Z \to \nu\nu$	$W \to \ell\nu_\ell$	$Z \to \ell\ell$
0 leptons	1 lepton	2 leptons
Require two b-tagged jets $p_{T,j1} > 45$ GeV $\quad p_{T,j2} > 20$ GeV $\quad + \leq 1$ extra jet		
$E_T^{\text{miss}} > 120$ GeV	$E_T^{\text{miss}} > 25$ GeV	$E_T^{\text{miss}} < 60$ GeV
	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

- Further sub-categorization based on p_T^V, $\Delta R(b, \bar{b})$, E_T^{miss} and m_T^W: **26 signal regions**

$H \to b\bar{b}$ Strategy (2)

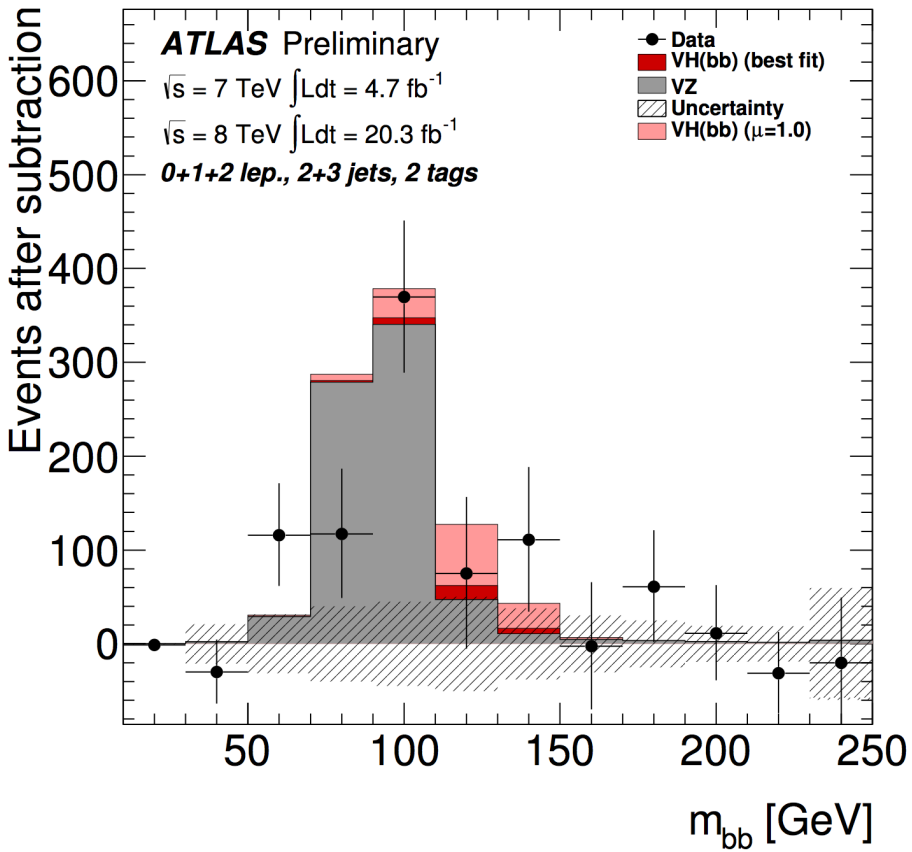
- Simultaneous fit on $m_{b\bar{b}}$ distributions in the 26 regions
- Also use regions with less than 2 b-tagged jets in the fit to constrain background model
- 2 highest p_T^V bins: 90% of the sensitivity

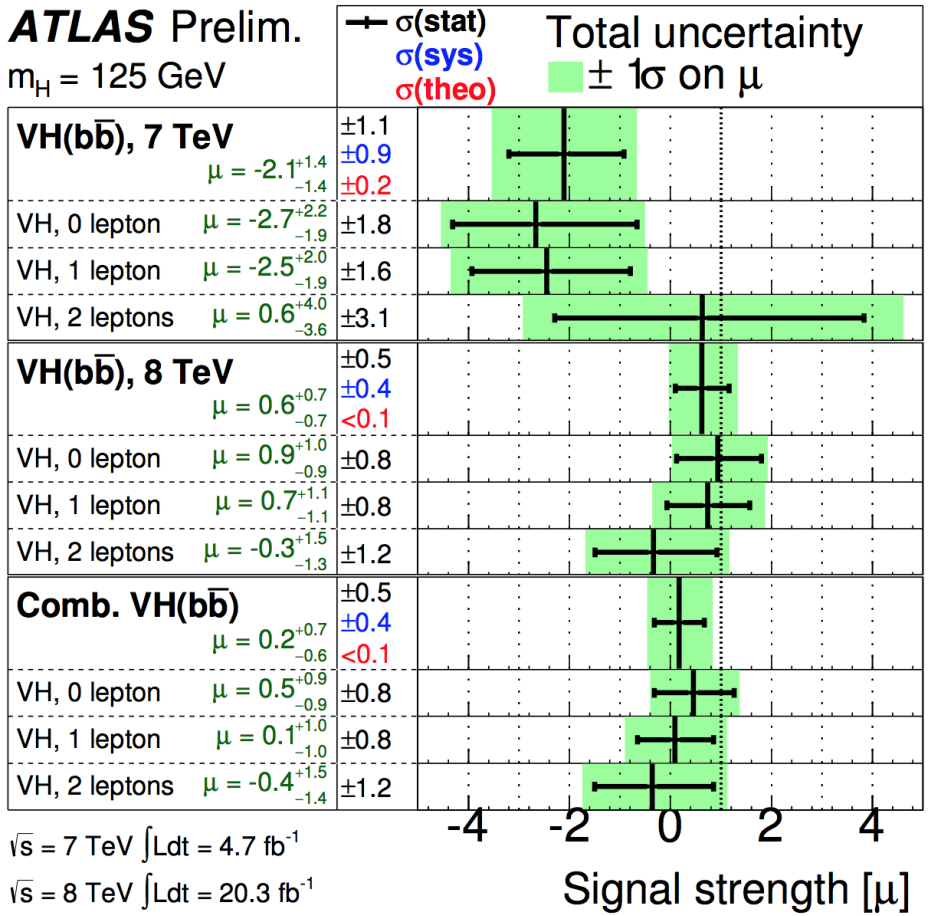


$H \to b\bar{b}$ Backgrounds

- The background composition varies quite a bit across categories
- QCD multijets background **estimated from data**:
  - $Z \to \nu\nu$: Normalization and shape extrapolation using 3 CRs
  - $W \to \ell\nu_\ell$: Extract QCD multijets template from CR: invert ℓ isolation
  - $Z \to \ell\ell$: Use $m_{\ell\ell}$ sidebands as CR to extract QCD multijets template
- Other backgrounds are **modelled with MC**:
  - Normalization of V+jets and $t\bar{t}$ backgrounds fitted to data using CRs
  - The rest are normalized using theoretical cross-sections
- Dominant uncertainty: dijet mass distribution for backgrounds

$H \to b\bar{b}$ Results





Current Run I Results:

Expected: $1.3 \times \sigma_{SM}$ 95% C.L. **Observed:** $1.4 \times \sigma_{SM}$ 95% C.L.

$\sigma/\sigma_{SM} = 0.2 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.})$

Summary

- **H $\to \tau\tau$**: Yukawa couplings to leptons have been directly observed
- **H $\to \mu\mu$**: The Higgs boson does not exhibit lepton universality, as expected

- **In Run II**:
  - $\sim$ **4**$\times$ the data ($25\text{fb}^{-1} \to 100\text{fb}^{-1}$)
  - **More than 2**$\times$ the Higgs production cross-section at 13 TeV
  - $\to$ **8 – 10**$\times$ more signal than Run I
- **Run II Goals**:
  - 5σ sensitivity for $H \to \tau\tau$, increased sensitivity for $H \to b\bar{b}$
  - Observation of VH production mode in the fermionic channels
  - CP measurement with $H \to \tau\tau$
  - more precise experimental branching fractions