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on behalf of the ATLAS Collaboration

Higgs Boson Decays to Leptons with the ATLAS Detector

37th International Conference on High Energy Physics

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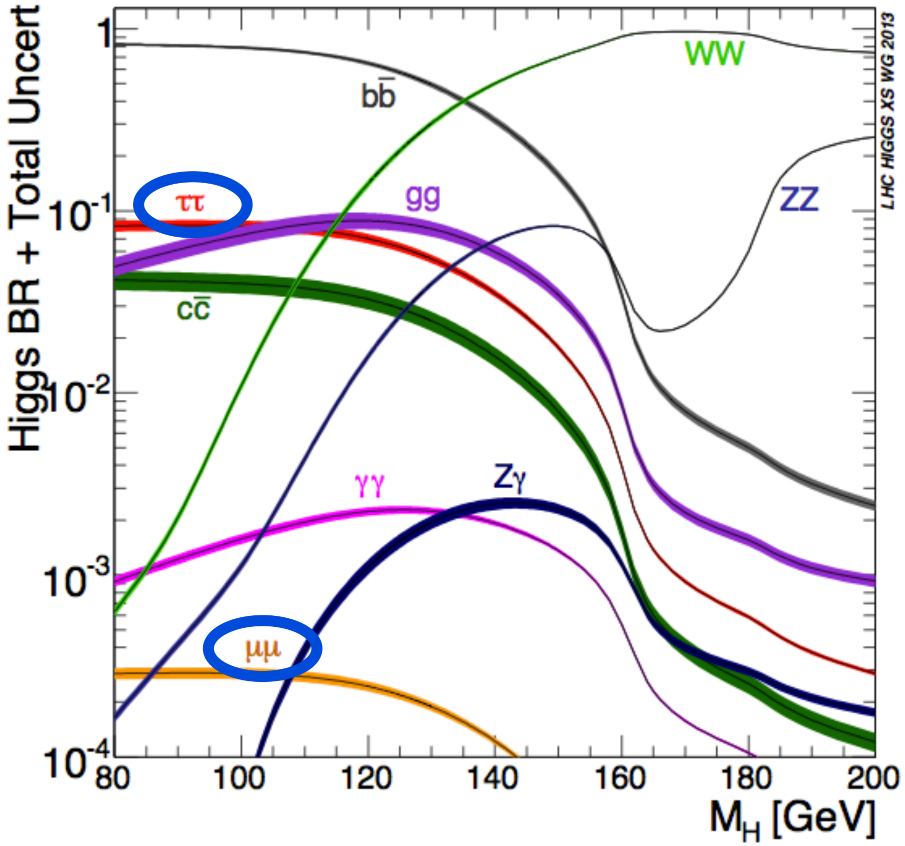
FSP 101 ATLAS

Bundesministerium für Bildung und Forschung

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

H→leptons

- Higgs signal strength consistent with SM in H→VV (γ,W,Z)
  - Does it couple to fermions?
  - Evidence for H→ττ at LHC one of the biggest headlines in the field in the past year
- H→ττ: Largest BR, challenging final state, poor mass resolution
  - ATLAS-CONF-2013-108
- H→μμ: Small BR, good mass resolution
  - arXiv: 1406.7663 – Submitted to Physics Letters B (NEW!)



BR(H→ττ)=6.24x10^{-2} for 125.5 GeV SM Higgs
BR(H→μμ)=2.16x10^{-4} (CERN-2013-004)

$H \rightarrow \tau\tau$

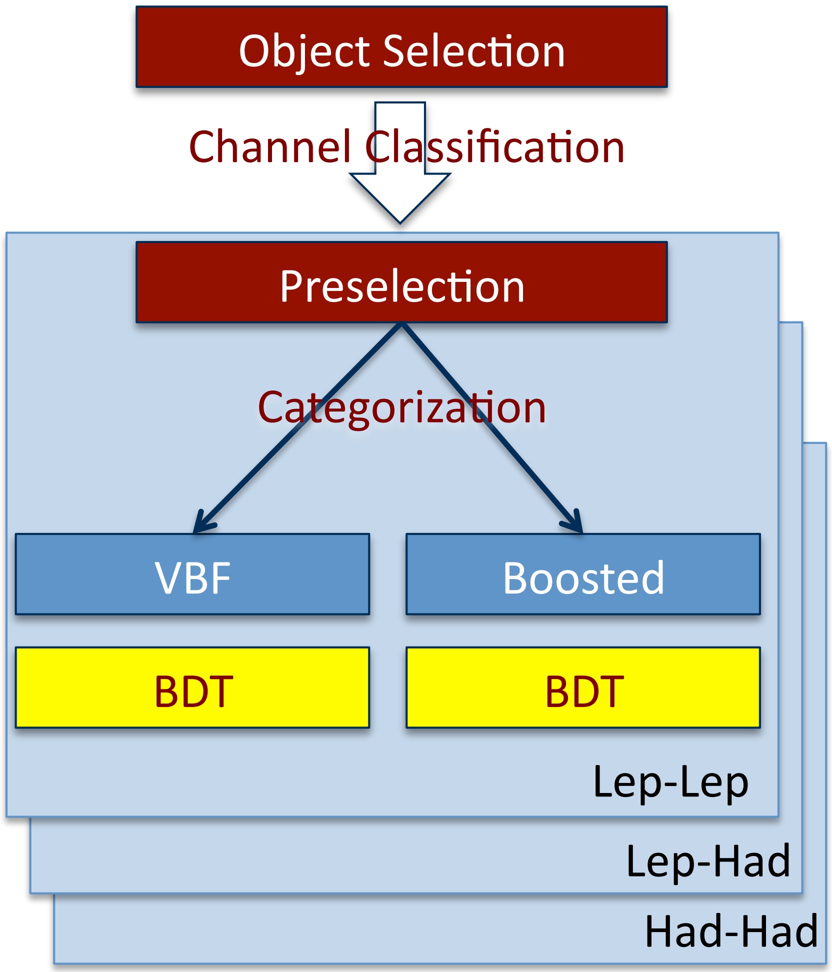
ATLAS-CONF-2013-108

$H \rightarrow \tau\tau$ – Analysis Concept

- Does the boson with $M_H \sim 125$ GeV decay to τ-lepton pairs?
- All final states of tau-decays considered
  - $H \rightarrow \tau\tau \rightarrow 2l + 4\nu$ (lep-lep channel; BR=12.4%)
  - $H \rightarrow \tau\tau \rightarrow l + \tau_{had} + 3\nu$ (lep-had channel; BR=45.6%)
  - $H \rightarrow \tau\tau \rightarrow 2\tau_{had} + 2\nu$ (had-had channel; BR=42%)
- Main backgrounds: $Z \rightarrow \tau\tau$, Fakes (W+jets, QCD multijet), $Z \rightarrow ll$, top
- Multivariate analysis, based on Boosted Decision Trees, BDTs
- Using all data collected by ATLAS in 2012 (8 TeV, 20.3 fb^{-1})

$H \rightarrow \tau\tau$ – Analysis Concept

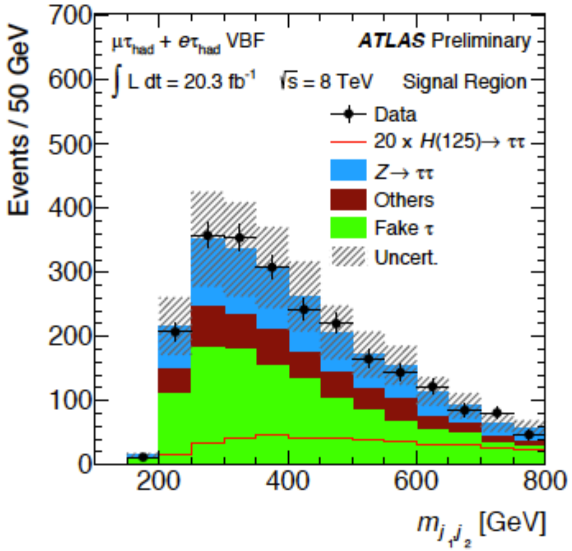
- Two categories per channel
  - VBF Category: 2 jets separated in η
    VBF signal fraction: 54-63%
  - Boosted Category: $p_T(H)$>100 GeV
    ggF signal fraction: 71-74%
- Separate BDTs trained for the 6 channel and category combinations

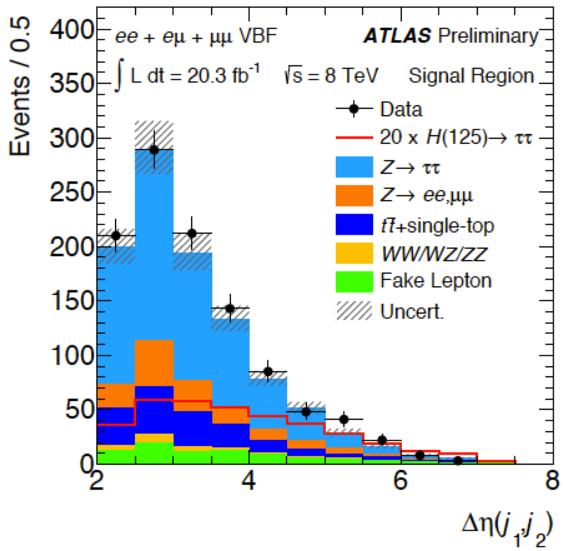


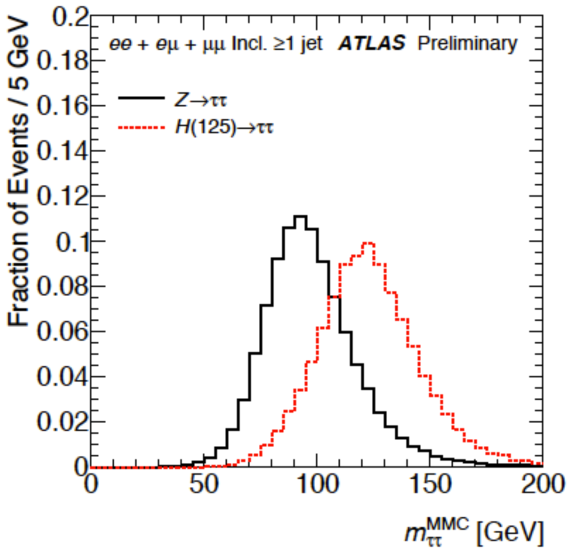
(Detailed Preselection & Categorization Cuts in Backup)

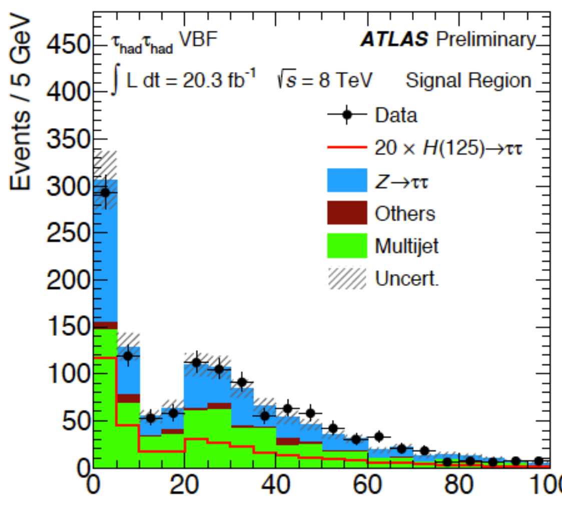
H→ττ – BDT Input Variables

- 6-9 variables used in the BDTs, exploiting:
  - Resonance properties: $m_{\tau\tau}$, $\Delta R_{\tau\tau}$, *etc*
  - Event activity: *scalar & vector* p_T*-sum, etc*
  - Event topology: m_T, $p_T(\tau_1)/p_T(\tau_2)$, *etc*
  - VBF topology: m_{jj}, $\Delta\eta_{jj}$
- Mass reconstruction: Use τ-decay PDFs to pick most likely di-τ invariant mass given visible decay products and E_T^{miss}







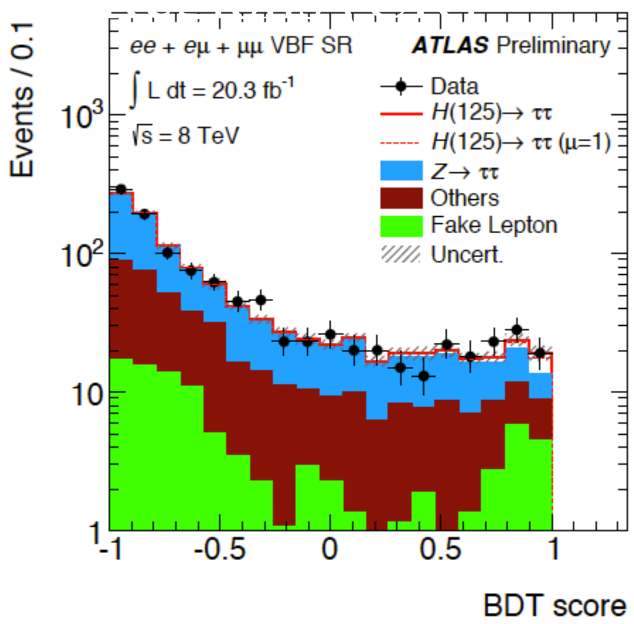


(Pre-fit plots)

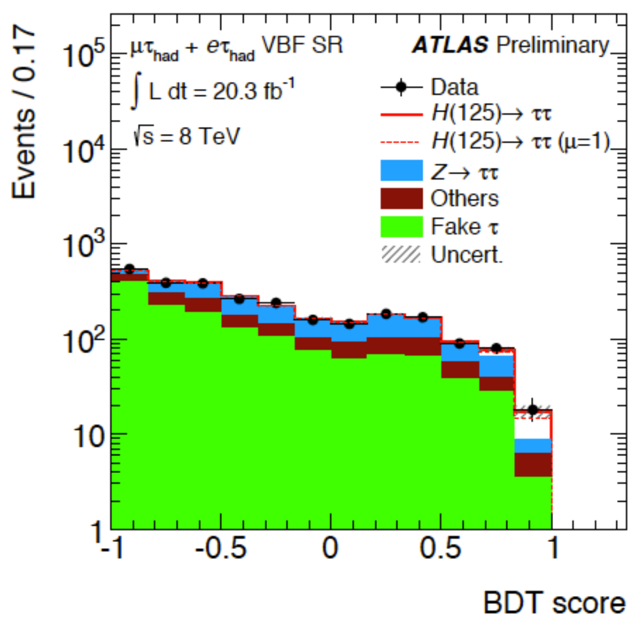
H→ττ

- BDT score distributions in the VBF category

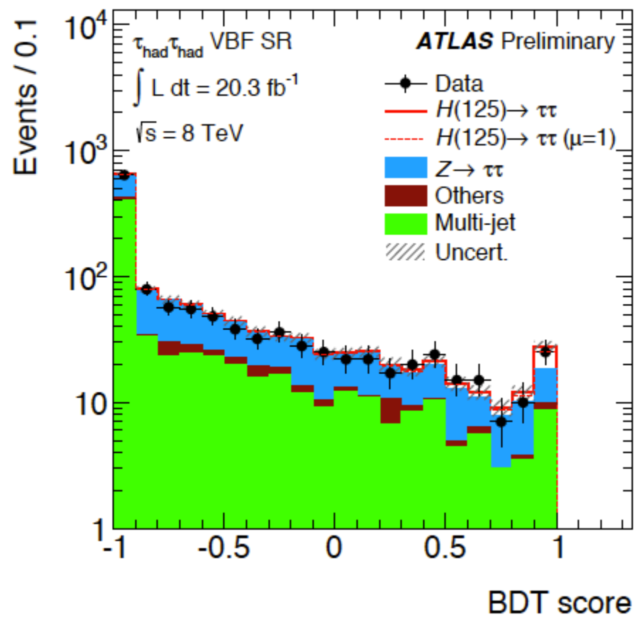
Lep-Lep



Lep-Had



Had-Had

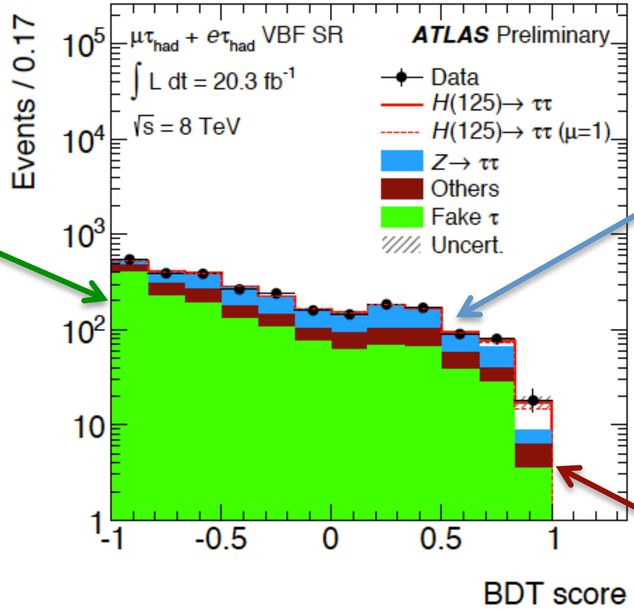


(Post-fit plots)

H→ττ

- Modelling of background processes crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions

Fake backgrounds:
Obtained though fully data-driven methods



Z→ττ:
Obtained from data-driven "embedding" procedure

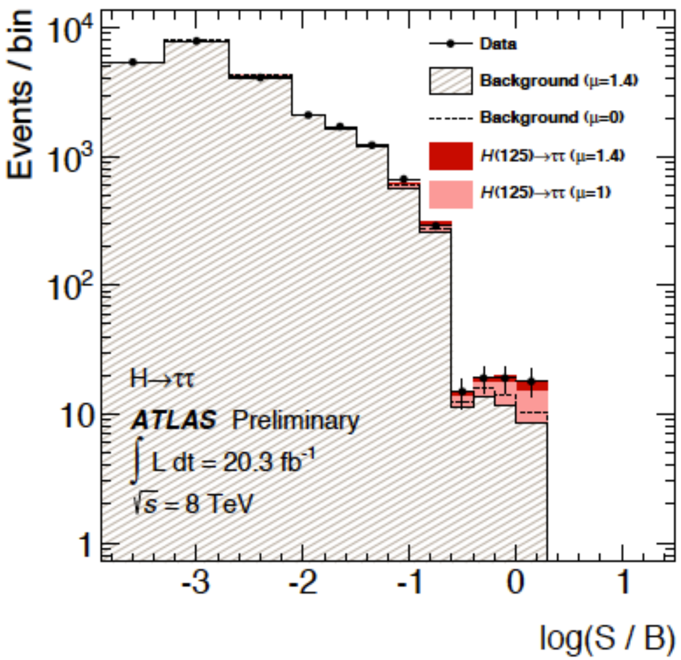
Others:
Z→ll, top normalized to data in control regions
Dibosons and H→WW from MC

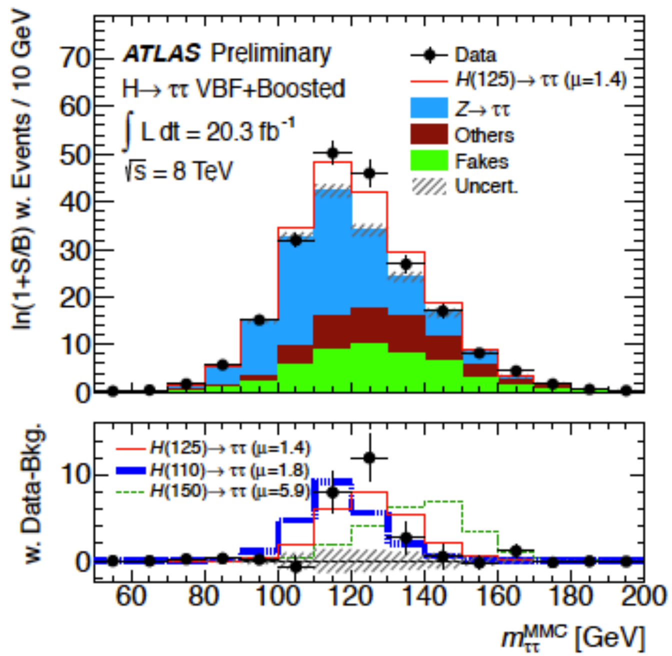
H→ττ

- Modelling of background processes crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions
- Signal extracted by fitting BDT shape with signal and background templates, simultaneously in the 6 Signal Regions (SR) + 9 Control Regions (CR)

ATLAS Evidence for H→ττ

- Excess of data events over the background prediction
  - Excess observed in all three channels
  - **Expected** significance at M_H=125 GeV: **3.2σ**
  - **Observed** significance at M_H=125 GeV: **4.1σ**
- Consistent with presence of Higgs boson at ~125 GeV

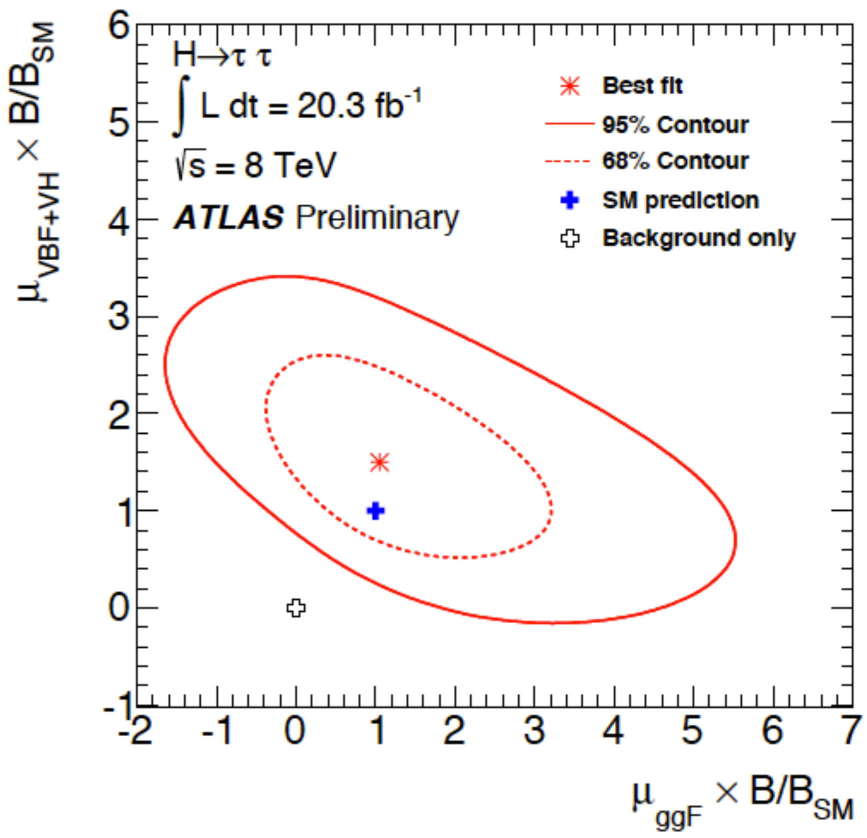


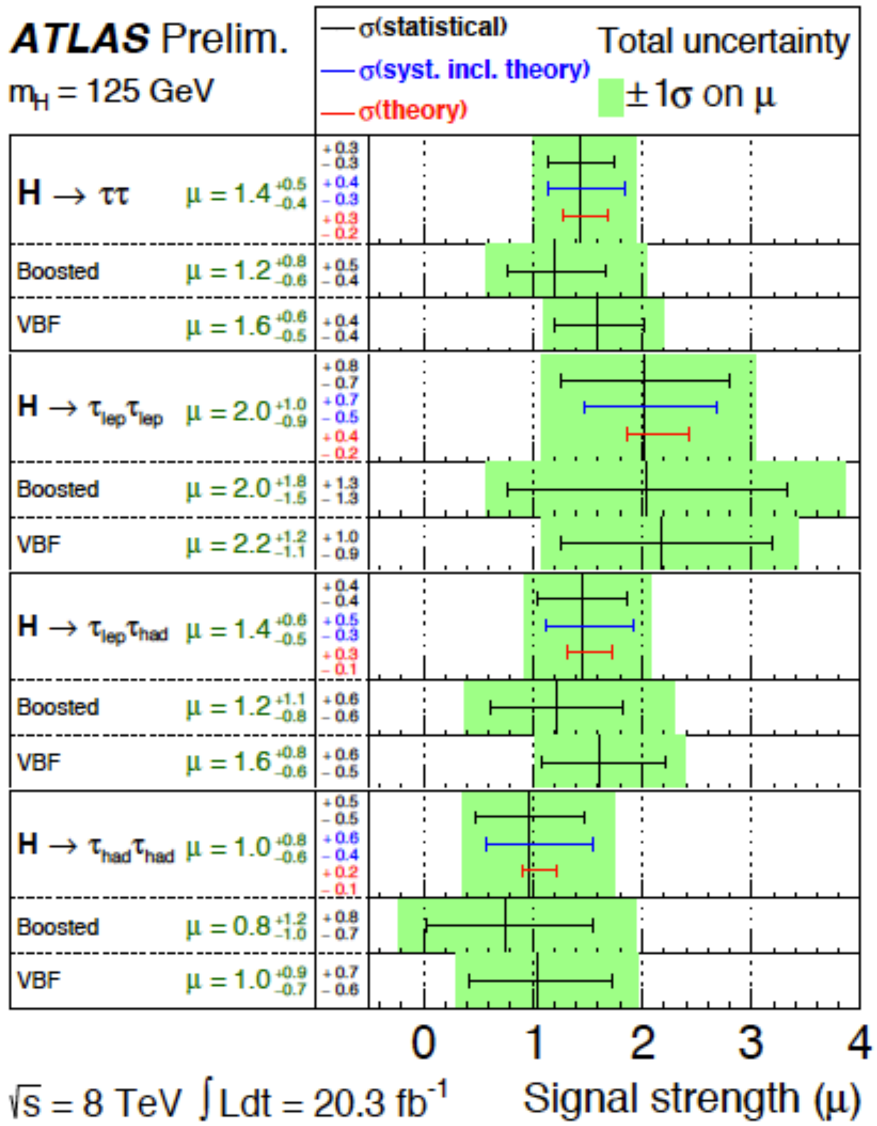


Events weighted by ln(1+S/B) of corresponding bin in BDT score

ATLAS Evidence for H→ττ

- Measured signal strength:
  $\mu = \sigma_{meas}/\sigma_{SM} = 1.4^{+0.5}_{-0.4}$





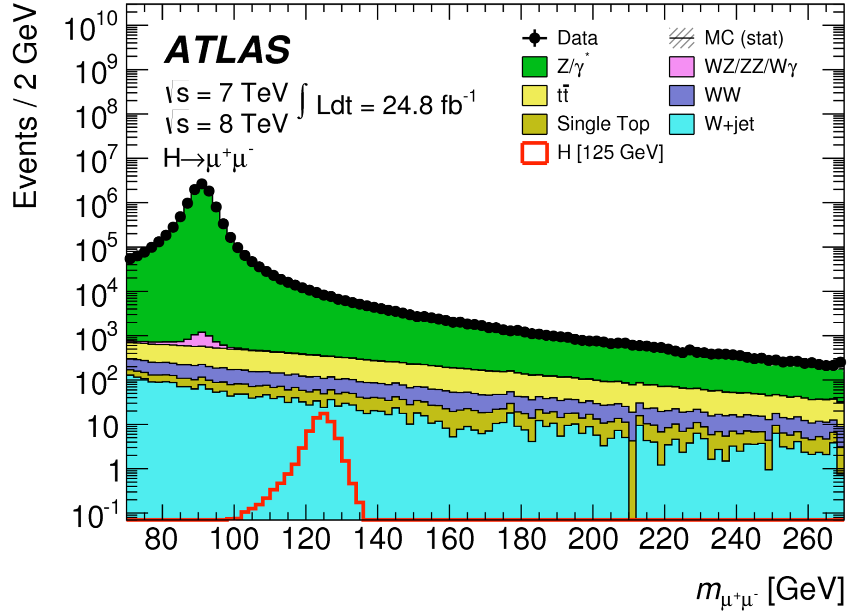
$H \rightarrow \mu\mu$

arXiv: 1406.7336

Submitted to Physics Letters B

H→μμ – Analysis Concept

- Strategy:
  - Search for a narrow H→μμ resonance
  - Fit $m_{\mu\mu}$ with analytical Signal+Bkg model
  - Fit in 110-160 GeV region
    - Determine background shape and normalization from sidebands
  - Using 7 TeV (4.5 fb^{-1}) and 8 TeV (20.3 fb^{-1}) ATLAS data



Event Selection

2 Isolated opposite-sign muons
$p_T(\mu_1)>25$ GeV; $p_T(\mu_2)>15$ GeV
$E_T^{miss}<80$ GeV

Categorization →

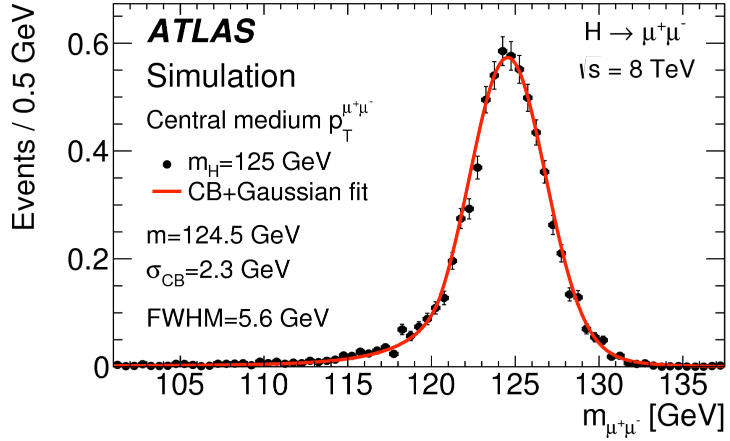
Fit

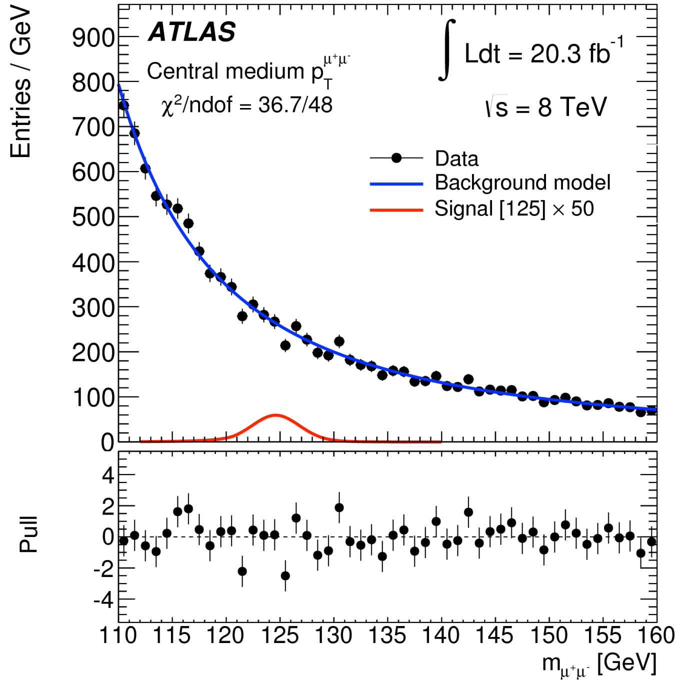
Central Muons, $p_T^{\mu\mu}<15$ GeV	Non-central Muons, $p_T^{\mu\mu}<15$ GeV	VBF ≥2 jets $M_{jj}>500$ GeV $\Delta\eta_{jj}>3$ $\eta_{j1}\times\eta_{j2}<0$
Central Muons, $15<p_T^{\mu\mu}<50$ GeV	Non-central Muons, $15<p_T^{\mu\mu}<50$ GeV	
Central Muons, $p_T^{\mu\mu}>50$ GeV	Non-central Muons, $p_T^{\mu\mu}>50$ GeV	

"Central"=Both muons have $|\eta|<1$; "Non-central"=One or both muons have $|\eta|>1$

H→μμ – Signal & Bkg Model

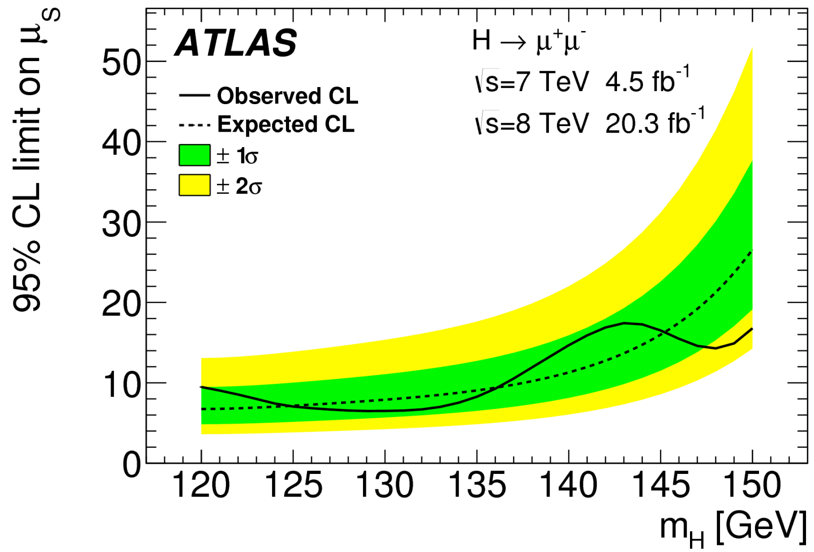
- Signal Model:
  - Sum of Gaussian and Crystal Ball functions
- Background Model:
  - Breit-Wigner convolved with a Gaussian, added to an exponential divided by x^3
  - In VBF category, product of Breit-Wigner and exponential function
  - Background models validated using high-stat samples





H→μμ – Results

- Data consistent with the expected background
- Observed (expected) limit for 125.5 GeV Higgs boson at 95% CL: 7.0xSM (7.2xSM)
- 95% CL limit on BR(H→μμ): 1.5×10^{-3}
  - Higgs does not decay to μ:s at the same rate as to τ:s
- Result limited by data statistics: lots of potential for Run-2



Summary

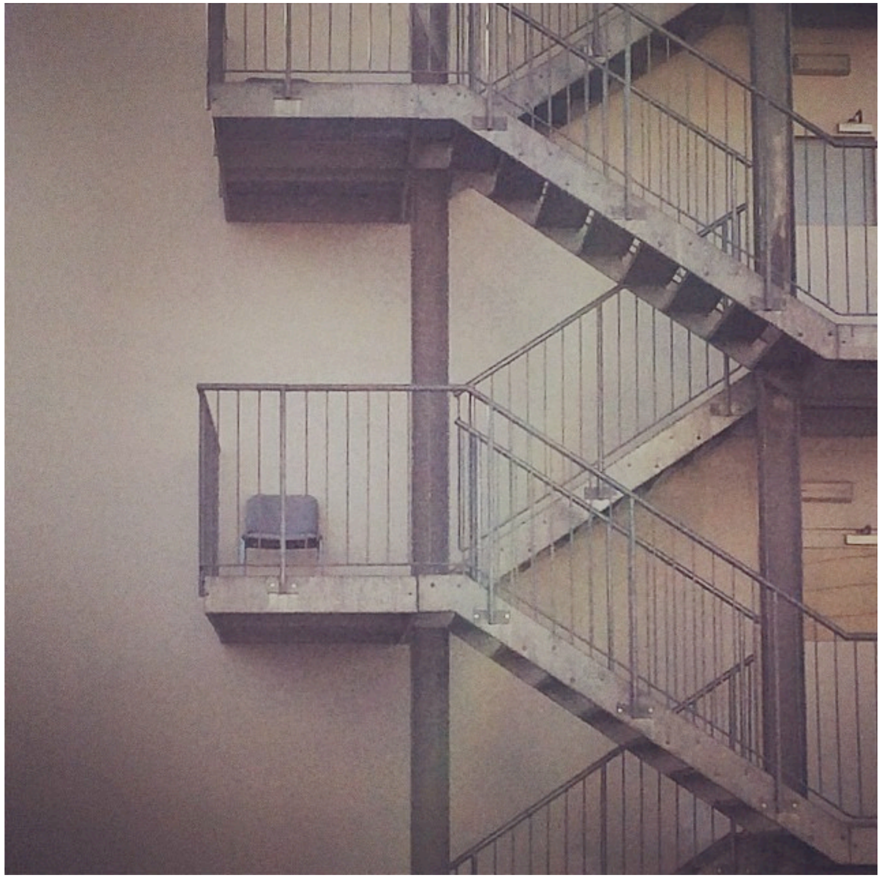
- Big question since discovery of Higgs boson: Does it couple to fermions?

- ATLAS sees evidence of $H \rightarrow \tau\tau$ decays
  - Observed (expected) significance: **4.1 (3.2) σ**
  - Signal strength $\boldsymbol{\mu = \sigma_{meas}/\sigma_{SM} = 1.4^{+0.5}_{-0.4}}$

- NEW Result in $H \rightarrow \mu\mu$ search
  - Observed (expected) limit: **7.0xSM (7.2xSM)**
  - Limit on $BR(H \rightarrow \mu\mu)$: $\mathbf{1.5 \times 10^{-3}}$

- ATLAS results confirm Higgs boson does not couple universally to leptons, consistent with the SM

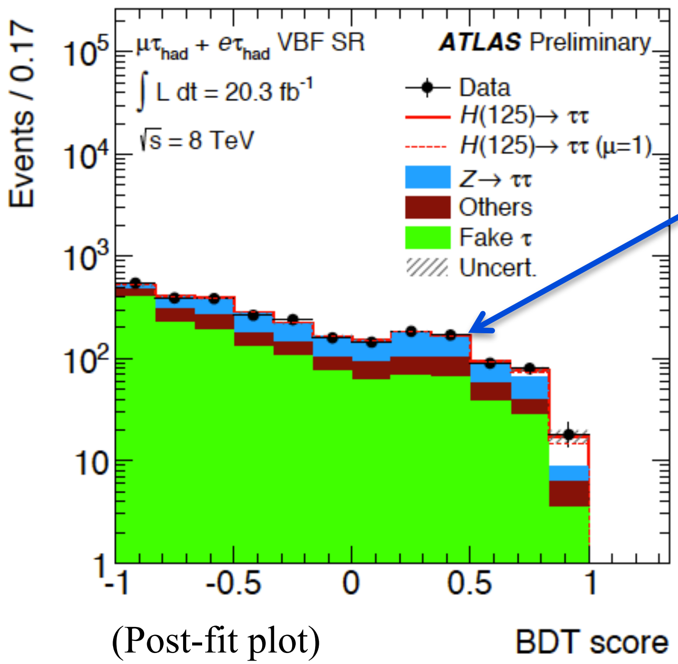
Backup Slides



Source: lonelychairsatcern.tumblr.com

H→ττ

- Signal extracted by fitting BDT shape with signal and background templates, simultaneously in the 6 Signal Regions (SR) + 9 Control Regions (CR)
- Modelling of background processes is crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions



(Post-fit plot)

$Z\to\tau\tau$:

Obtained from data-driven *"embedding"* procedure:

→ Select $Z\to\mu\mu$ events in data

→ Replace μ with a simulated τ

→ τ decayed using TAUOLA; polarization and spin-correlations taken into account

→ Normalization free parameter in the fit

$H \rightarrow \tau\tau$

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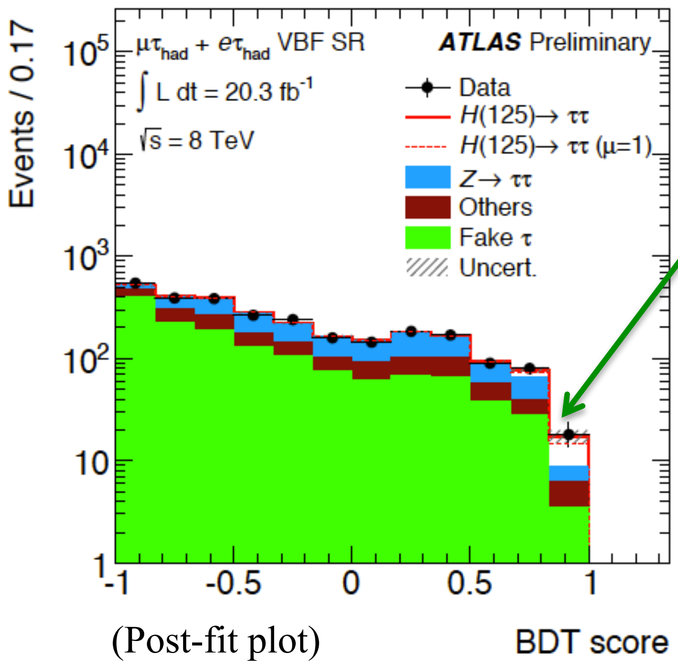
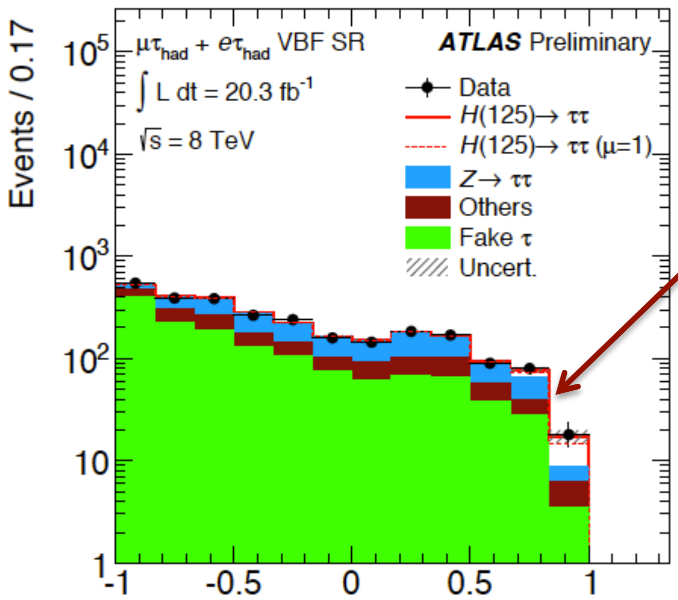


(Post-fit plot)

Fake backgrounds (e.g. W+jets, QCD multijets):
Obtained though fully data-driven methods
→ Lep-lep: Template fit in region of inverted lepton isolation.
→ Lep-had: τ_{had} candidates failing ID requirements, multiplied by process-dependent Fake Factors binned in p_T and track multiplicity.
→ Had-had: Invert opposite-sign requirement on two τ_{had} candidates. Normalization from the fit.

$H \to \tau\tau$

- Signal extracted by fitting BDT shape with signal and background templates, simultaneously in the 6 Signal Regions (SR) + 9 Control Regions (CR)
- Modelling of background processes is crucial
  - All major backgrounds either directly estimated from data, or normalized to data in control regions



(Post-fit plot)

Other Backgrounds:

→ Z→ll & top normalized to data in control regions in leptonic channels (where they are relevant)

→ Z→ll with lepton misidentified as τ_{had} candidate: scale by mis-ID factors obtained in dedicated tag&probe study

→ Diboson & H→WW: from MC

$H \rightarrow \tau\tau$ Preselection

Lep-Had

Exactly 1 electron or muon
Exactly 1 tau-jet
Opposite sign (lepton,τ)
mT(MET,lepton)<70 GeV

Had-Had

Exactly 2 tau-jets
Opposite sign
No electrons or muons
$0.8<\Delta R(\tau,\tau)<2.8$
$\Delta\eta(\tau,\tau)<1.5$
MET>20 GeV
MET between taus in ϕ or
min[$\Delta\phi$(MET,τ)]<π/2

Lep-Lep

Exactly 2 leptons, no tau-jet
Opposite sign
30<m(l,l)<75 GeV (SF)
30<m(l,l)<100 GeV (DF)
pT(l1)+pT(l2)>35 GeV
MET>40 GeV and
HPTO_MET>40 GeV (SF)
MET>20 GeV (DF)
0.1<x1,x2<1
$\Delta\phi$(l,l)<2.5

H→ττ Categorization

Category	Selection	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
VBF	$p_{\rm T}(j_1)$ (GeV)	40	50	50
	$p_{\rm T}(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	$b-$jet veto for jet $p_{\rm T}$ (GeV)	25	30	-
	$p_{\rm T}^H$ (GeV)	-	-	40
Boosted	$p_{\rm T}(j_1)$ (GeV)	40	-	-
	$p_{\rm T}^H$ (GeV)	100	100	100
	$b-$jet veto for jet $p_{\rm T}$ (GeV)	25	30	-

Table 2: Selection criteria applied in each analysis category for each channel. The numbers shown are lower thresholds. Only events that fail VBF category selection are considered for the boosted category. The $\Delta\eta(j_1, j_2)$ cut is applied on the two highest $p_{\rm T}$ jets in the event. Events in the $\tau_{\rm lep}\tau_{\rm had}$ VBF category must also satisfy $m_{\tau\tau}^{\rm vis} > 40$ GeV, and those that fail this requirement are not considered for the $\tau_{\rm lep}\tau_{\rm had}$ boosted category. The $p_{\rm T}(j_2)$ threshold in the $\tau_{\rm had}\tau_{\rm had}$ channel is 30 (35) GeV for jets within (outside of) $|\eta| = 2.4$.

H→ττ Variables in BDT

Variable	VBF			Boosted		
	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$m_{\tau\tau}^{\mathrm{MMC}}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1, j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1} \times \eta_{j_2}$		•	•			
$p_{\mathrm{T}}^{\mathrm{Total}}$		•	•			
sum p_{T}					•	•
$p_{\mathrm{T}}(\tau_1)/p_{\mathrm{T}}(\tau_2)$					•	•
$E_{\mathrm{T}}^{\mathrm{miss}}\,\phi$ centrality		•	•	•	•	•
$x_{\tau 1}$ and $x_{\tau 2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_{\mathrm{T}}^{\ell_1}$				•		
$p_{\mathrm{T}}^{j_1}$				•		
$E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell_2}$				•		
m_{T}		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\mathrm{jets}})$	•					
$j_3\ \eta$ centrality	•					
$\ell_1 \times \ell_2\ \eta$ centrality	•					
$\ell\ \eta$ centrality		•				
$\tau_{1,2}\ \eta$ centrality			•			

MMC Resolution in events with at least 1 jet

	Z→ττ
Lep-lep	21.4%
Lep-had	18.1%
Had-had	14.3%

H→ττ Systematics

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \to \ell\ell$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ boosted)	0.13
ggF $d\sigma/dp_T^H$	0.12
JES η calibration	0.12
Top normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ VBF)	0.12
Top normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ boosted)	0.12
$Z \to \ell\ell$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$ VBF)	0.12
QCD scale	0.07
di-τ_{had} trigger efficiency	0.07
Fake backgrounds ($\tau_{\text{lep}}\tau_{\text{lep}}$)	0.07
τ_{had} identification efficiency	0.06
$Z \to \tau^+\tau^-$ normalization ($\tau_{\text{lep}}\tau_{\text{had}}$)	0.06
τ_{had} energy scale	0.06

Table 7: The important sources of uncertainty on the measured signal strength parameter μ, given as absolute uncertainties on μ.

H→μμ Systematics & Signal Yields

Table 3: Main sources of experimental and theoretical uncertainty on the signal yield, excepting the error from mismodelling bias. "QCD scale" indicates the theoretical uncertainty on the Higgs boson production due to missing higher-order corrections estimated by varying the QCD renormalisation and factorisation scales, while "PDFs + α_s" indicates uncertainty due to parton distribution functions, as described in Ref. [13, 14]. The ranges for the uncertainties cover the variations among different categories and data-taking periods.

Source (experimental)	Uncertainty (%)
Luminosity	±1.8 (7 TeV), ±2.8 (8 TeV)
Muon efficiency	±1
Muon momentum res.	±1
Muon trigger	±1.5
Muon isolation	±1.1
Pile-up reweighting	±1
Jet energy scale	$^{+3.4}_{-4.5}$ (VBF)
Source (theory)	**Uncertainty (%)**
Higgs boson branching ratio	±7
QCD scale	±8 (ggF), ±1 (VBF, VH)
PDFs + α_s	±8 (ggF), ±4 (VBF, VH)
ggF uncert. in VBF	±22
Multi-parton inter. in VBF	±9 (ggF), ±4 (VBF)

Table 2: Expected signal yields (N_S) for m_H = 125 GeV and the ratio $N_S/\sqrt{N_B}$ using the simulated MC background yields (N_B) within a window of $|m_H - m_{\mu^+\mu^-}| \leq 2.5$ GeV for each of the event categories under study. In addition, the full width at half maximum (FWHM) of the signal $m_{\mu^+\mu^-}$ distribution, modelled as described in Section 5, is given. Also shown are χ^2/ndof of the fits to the $m_{\mu^+\mu^-}$ distribution described in Section 5.

$\sqrt{s}$ [TeV]	Category	N_S	$\frac{N_S}{\sqrt{N_B}}$	FWHM [GeV]	χ^2/ndof
8	non-cen. low $p_T^{\mu^+\mu^-}$	6.1	0.07	6.6	49.8/48
8	cen. low $p_T^{\mu^+\mu^-}$	2.6	0.06	5.5	52.8/48
8	non-cen. medium $p_T^{\mu^+\mu^-}$	10.4	0.15	6.6	45.1/48
8	cen. medium $p_T^{\mu^+\mu^-}$	4.7	0.13	5.6	36.7/48
8	non-cen. high $p_T^{\mu^+\mu^-}$	5.5	0.13	7.2	26.7/48
8	cen. high $p_T^{\mu^+\mu^-}$	2.6	0.10	6.0	32.3/48
8	VBF	0.8	0.09	7.0	18.6/19
7	non-cen. low $p_T^{\mu^+\mu^-}$	1.0	0.03	6.8	42.0/48
7	cen. low $p_T^{\mu^+\mu^-}$	0.5	0.03	5.3	43.5/48
7	non-cen. medium $p_T^{\mu^+\mu^-}$	1.8	0.06	6.9	41.2/48
7	cen. medium $p_T^{\mu^+\mu^-}$	0.8	0.05	5.5	34.4/48
7	non-cen. high $p_T^{\mu^+\mu^-}$	0.9	0.05	7.5	60.0/48
7	cen. high $p_T^{\mu^+\mu^-}$	0.5	0.05	5.9	56.2/48
7	VBF	0.1	0.05	6.9	6.2/19

$H \rightarrow \mu\mu$ Background Model

Breit-Wigner: Resonant part of Z/γ^*

Convolved with Gaussian: Account for detector resolution effects

$$P_B(x) = f \cdot [\mathrm{BW}(M_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}) * \mathrm{GS}(\sigma^{\mathrm{B}}_{\mathrm{GS}})](x) + (1-f) \cdot C \cdot e^{A \cdot x}/x^3,$$

Exponential: Correct for diboson and ttbar backgrounds

$1/x^3$: Correct for continuous part of Z/γ^* process

VBF Category: $$P_B(x) = \mathrm{BW}(M_{\mathrm{BW}}, \Gamma_{\mathrm{BW}}, x) \cdot e^{A \cdot x}$$