



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

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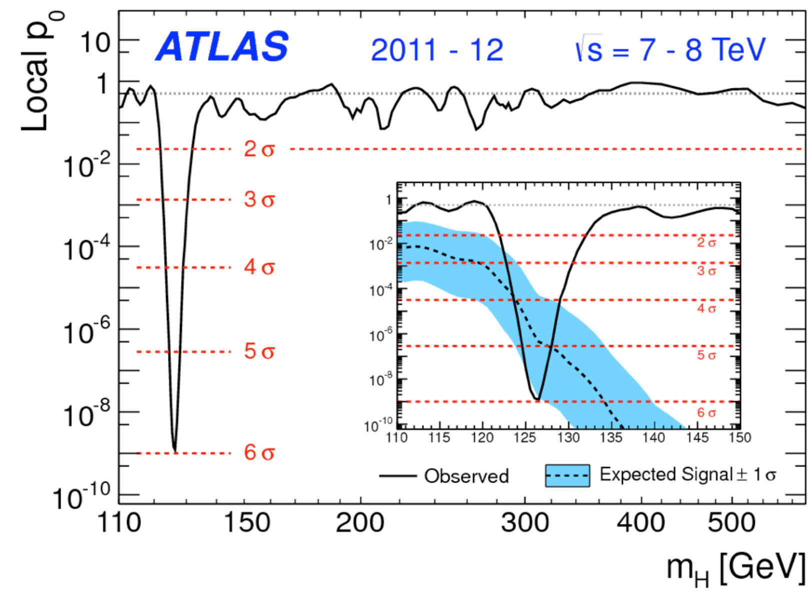
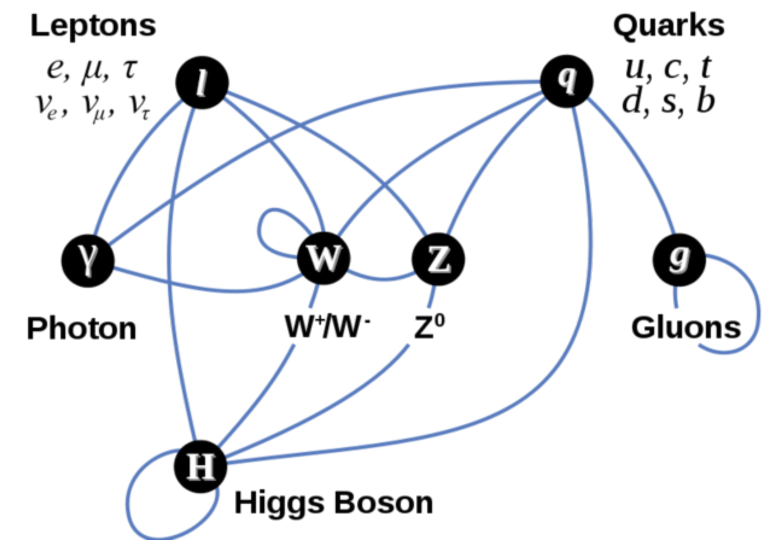
Introduction

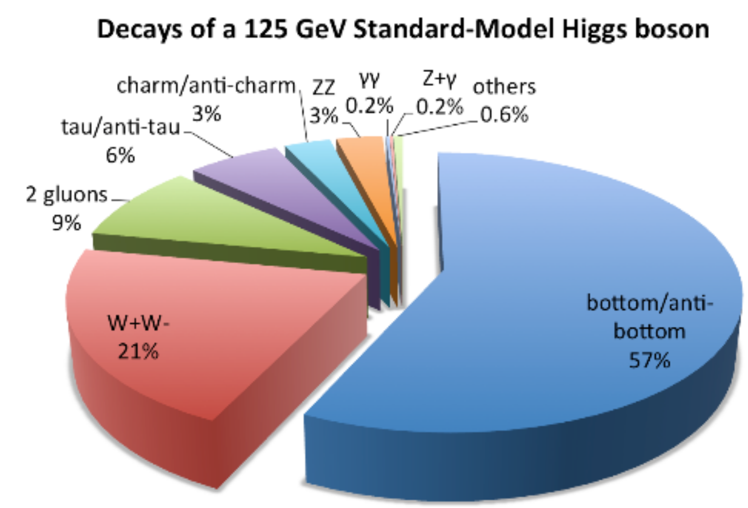
- The Higgs boson discovery in 2012 and subsequent measurements of its properties primarily focused on bosonic decay modes ($\gamma\gamma$, ZZ^*, WW^*). However, an important question for verification the discovered particle is a SM Higgs boson is whether the new particle also couples to fermions.
  - Dominant Higgs boson production mode at LHC (gluon-gluon fusion) is an indirect probe of the coupling to top quark
  - Coupling to down-type fermions require direct observation of its decays



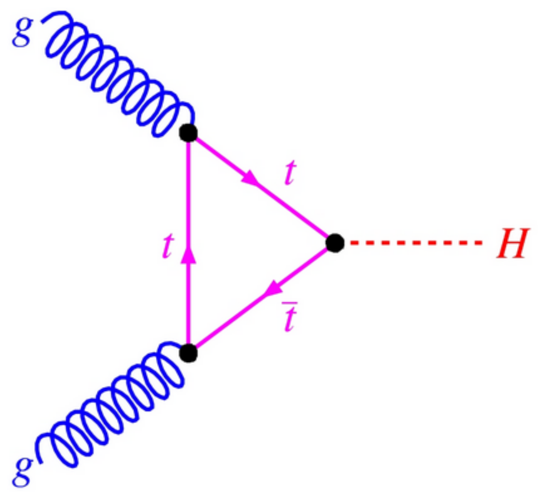
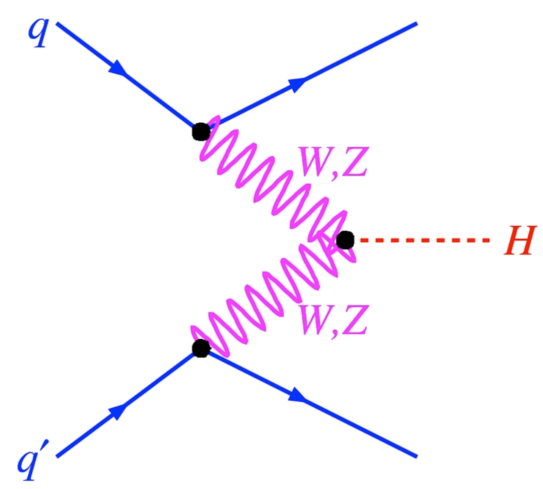
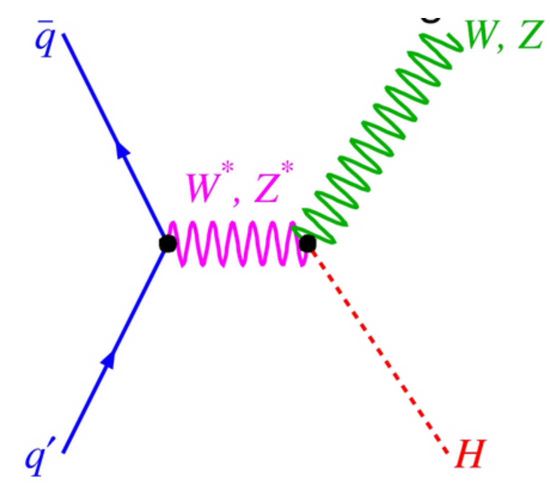
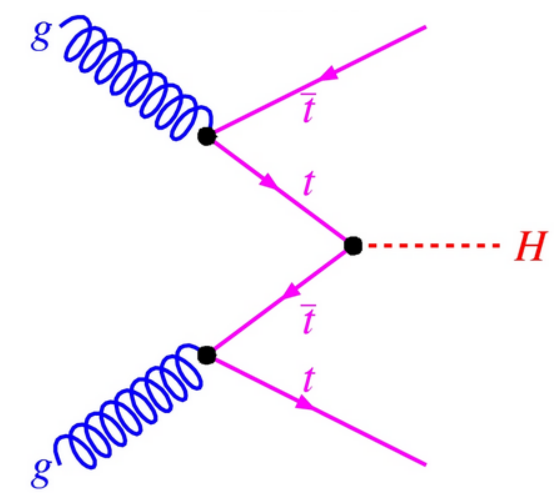
- At ATLAS we've thus far focused on the following channels:
  - $H\to b\bar{b}$ (57.7%), $H\to\tau\tau$ (6.32%), $H\to\mu\mu$ (0.0219%)
  - and in addition we can directly probe the top Yukawa coupling in associated ttH production via the various decay channels



- However, fermionic channels are particularly challenging at hadron colliders and require very high performance reconstruction of objects (e, μ, τ_{had}, jets (incl b-tagged) and $E_T$miss)



Higgs production mechanisms probed in fermionic decay channels

ggF	VBF	VH	ttH
			

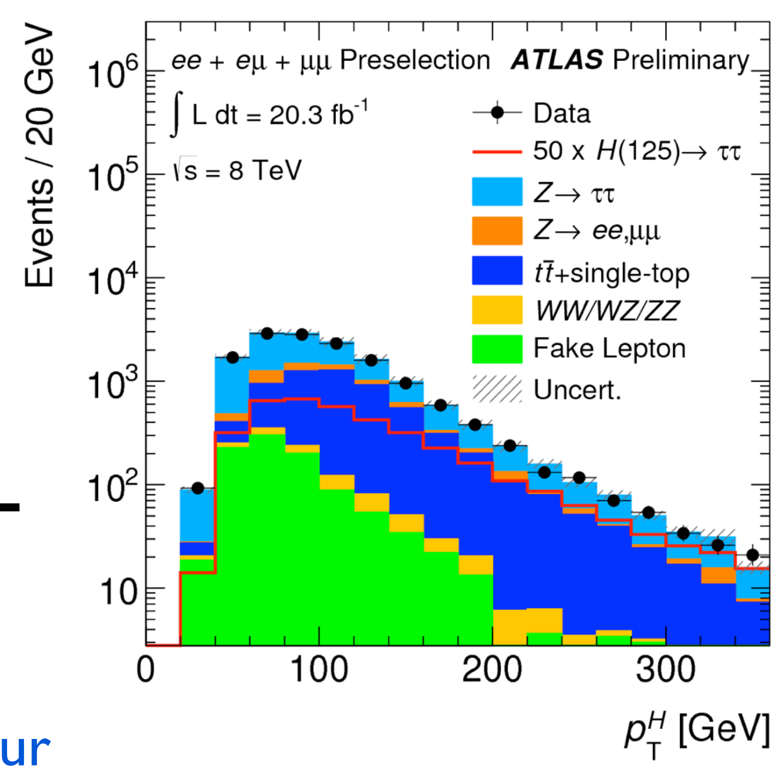
	ggF	VBF	VH	ttH
σ (m_H = 125 GeV)	15.13 pb @ 7 TeV 19.27 pb @ 8 TeV	1.22 pb @ 7 TeV 1.58 pb @ 8 TeV	0.58(W) 0.34(Z) pb @ 7 TeV 0.70(W) 0.42(Z) pb @ 8 TeV	0.09 pb @ 7 TeV 0.13 pb @ 8 TeV

	ggF	VBF	VH	ttH
$H\rightarrow\tau\tau$	20.3 fb^{-1} @ 8 TeV ATLAS-CONF-2013-108			-
$H\rightarrow b\bar{b}$	-	-	4.7 fb^{-1} @ 7 TeV + 20.3 fb^{-1} @ 8 TeV ATLAS-CONF-2013-079	20.3 fb^{-1} @ 8 TeV ATLAS-CONF-2014-011
$H\rightarrow\mu\mu$	20.7 fb^{-1} @ 8 TeV ATLAS-CONF-2013-010			

Search for $H \to \tau\tau$

- Multivariate analysis used to discriminate signal from background, with BDT score as final discriminant.
- Analysis covers 3 decay channels: lep/lep, lep/had, had/had and 2 categories: boosted ggF (p_T^H > 100 GeV) and VBF (2 jets with large $\Delta\eta$)

$H \to \tau_{lep}\tau_{lep}$ (BR 12.4%) Z, charm, bottom bg	$H \to \tau_{lep}\tau_{had}$ (BR 45.6%) W+jets bg	$H \to \tau_{had}\tau_{had}$ (BR 42%) multijet bg
exactly 2 OS leptons veto on τ_{had} E_T^{miss} > 40 (20) GeV for SF (DF) 30 < $m_{\tau\tau}^{vis}$ < 75 (100) GeV for SF (DF) $p_T^{\ell 1} + p_T^{\ell 2}$ > 35 GeV $\Delta\phi_{\ell\ell}$ < 2.5	1 lepton and 1 τ_{had} (OS) $m_T(\ell, E_T^{miss})$ > 70 GeV	2 OS high p_T τ_{had} candidates (one tight) e,μ veto E_T^{miss} > 20 GeV plus requirement on ϕ 0.8 < $\Delta R_{\tau\tau}$ < 2.8 $\Delta\eta_{\tau\tau}$ < 1.5



OS = Opposite Sign
SF = Same Flavour
DF = Different Flavour

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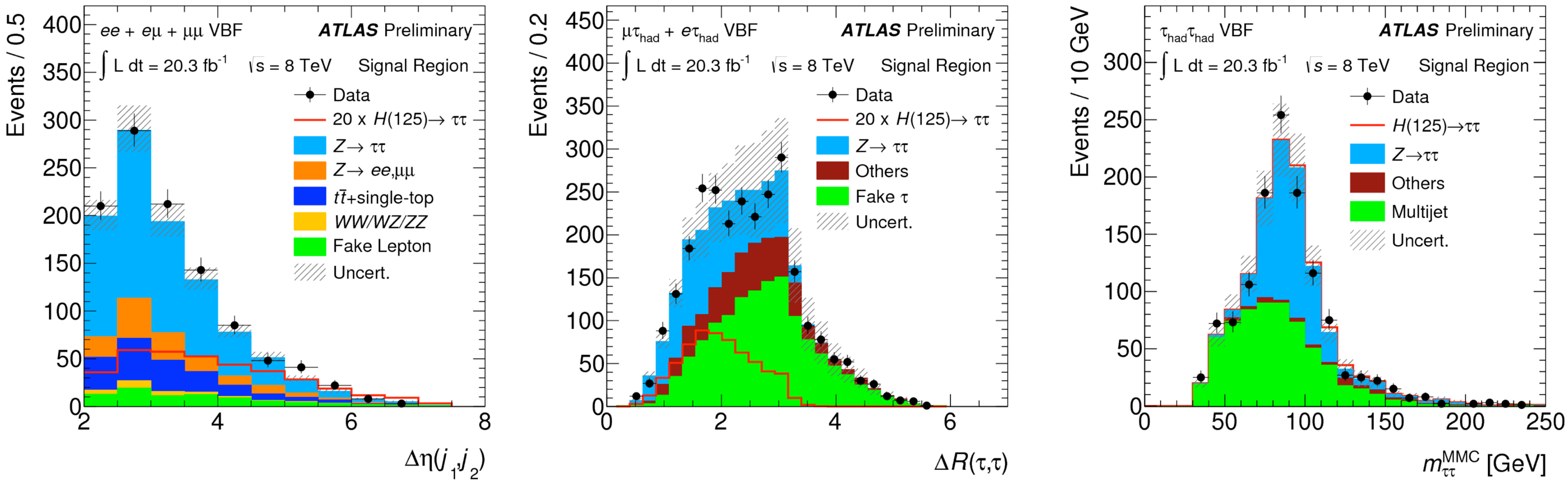
ATLAS EXPERIMENT

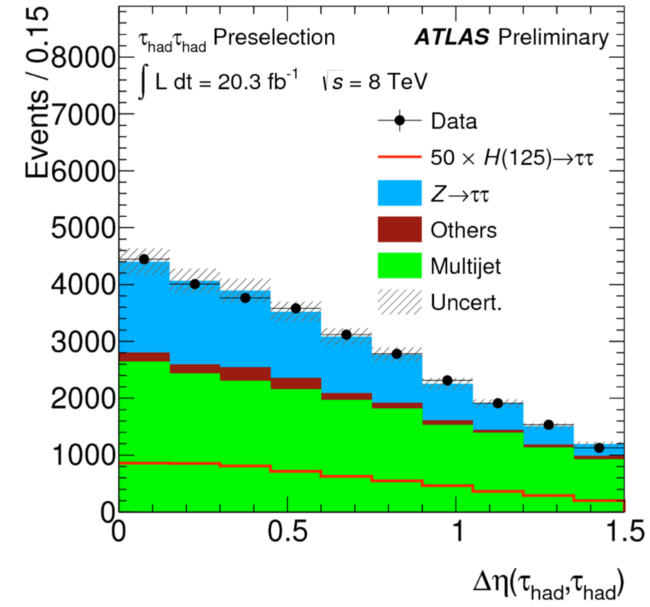
- Different BDTs are used to extract the Higgs boson signal from background, and trained separately to exploit differences in the event kinematics for each category and channel.
  - VBF category trained with VBF signal sample
  - Boosted category trained with ggF, VBF and VH signal samples
- Various input variables are used in the BDT depending on channel and category (though key variables are the same for all channels), covering event activity, event topology ($\Delta\eta_{jj}$), and resonance properties ($\Delta R_{\tau\tau}$)



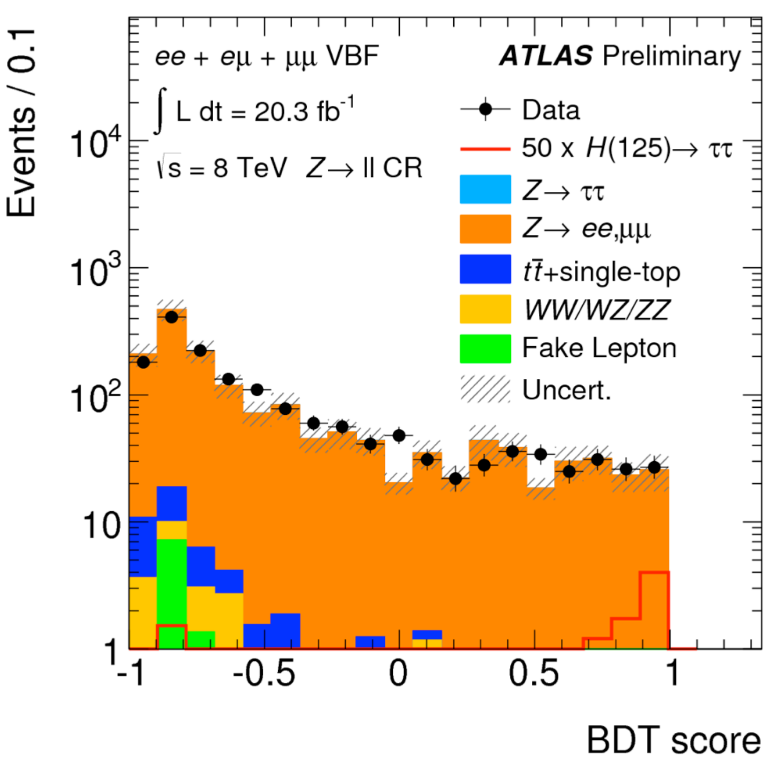
- Most important discriminating variable, used for all channels, is $m_{\tau\tau}$ reconstructed using the missing mass calculator (MMC)

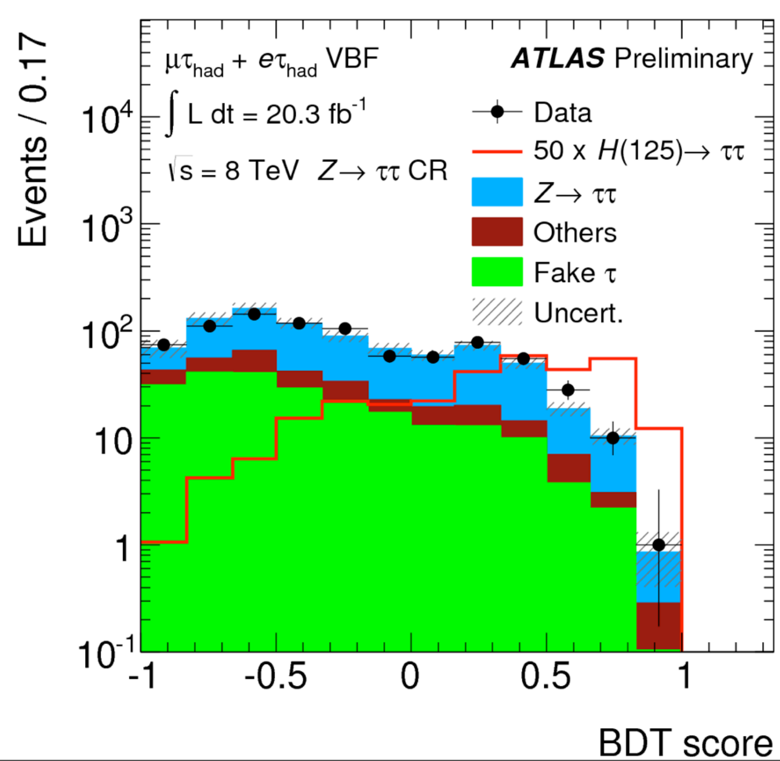
Background Estimation H→ττ

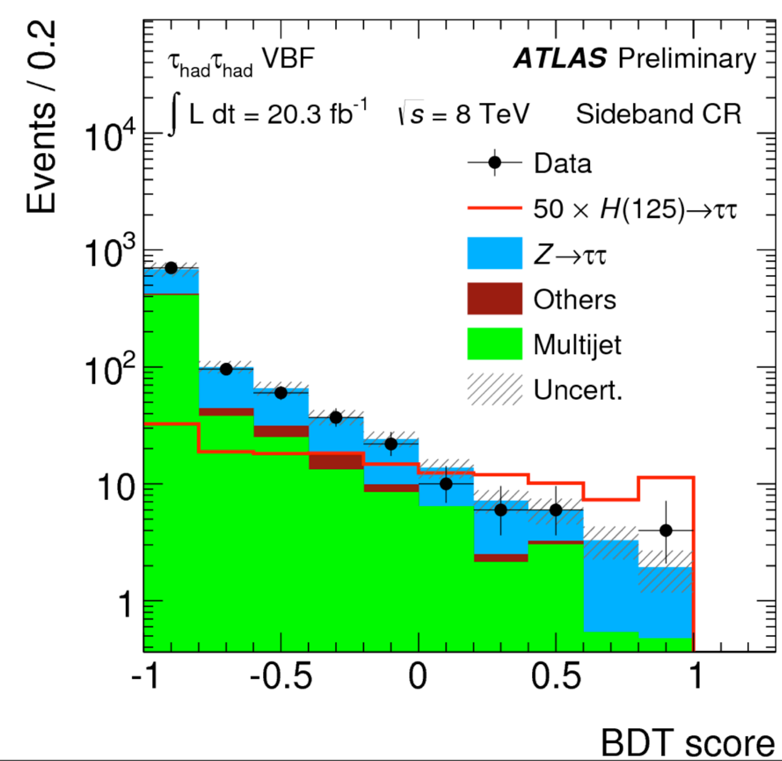
- Backgrounds are derived from a mixture of simulated and data-driven samples
- Dominant Z→ττ background uses a τ-embedded Z→μμ data sample, where only the τ decays and corresponding detector response are taken from simulation
- Data-derived background samples per category are as follows:



$H\to\tau_{lep}\tau_{lep}$	$H\to\tau_{lep}\tau_{had}$	$H\to\tau_{had}\tau_{had}$
Data sample using non-isolated leptons to model multijet, W +jets and semi-leptonic tt backgrounds	Data sample enriched in fake τ_{had} to derive estimates for multijet and W+jets	Data sample with same-sign tau candidates used as a template for multijet background







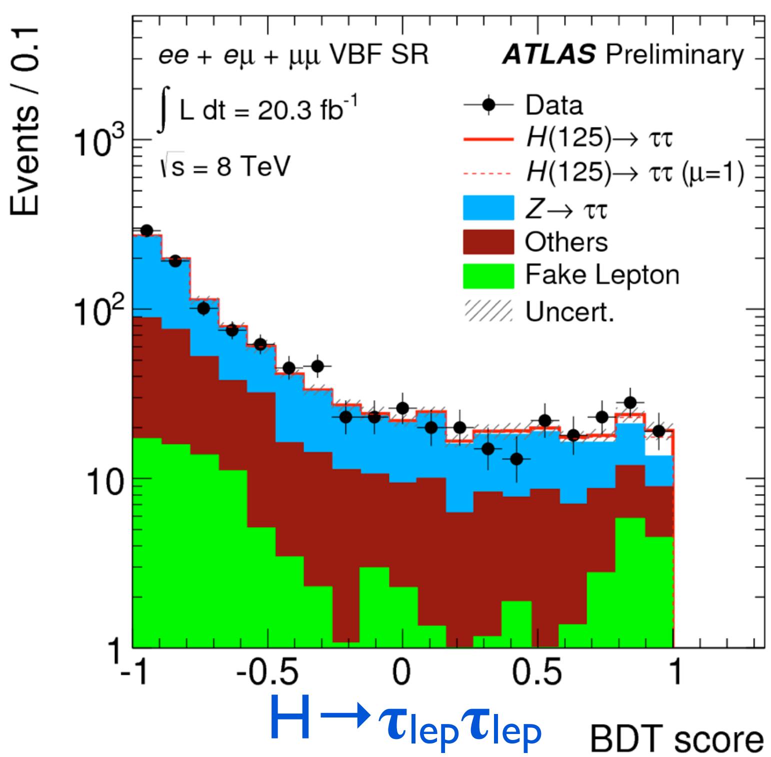
Signal Extraction

- Analysis uses a binned likelihood function with signal strength parameter μ
  - $Z\to\tau\tau$ background floats freely in the global fit

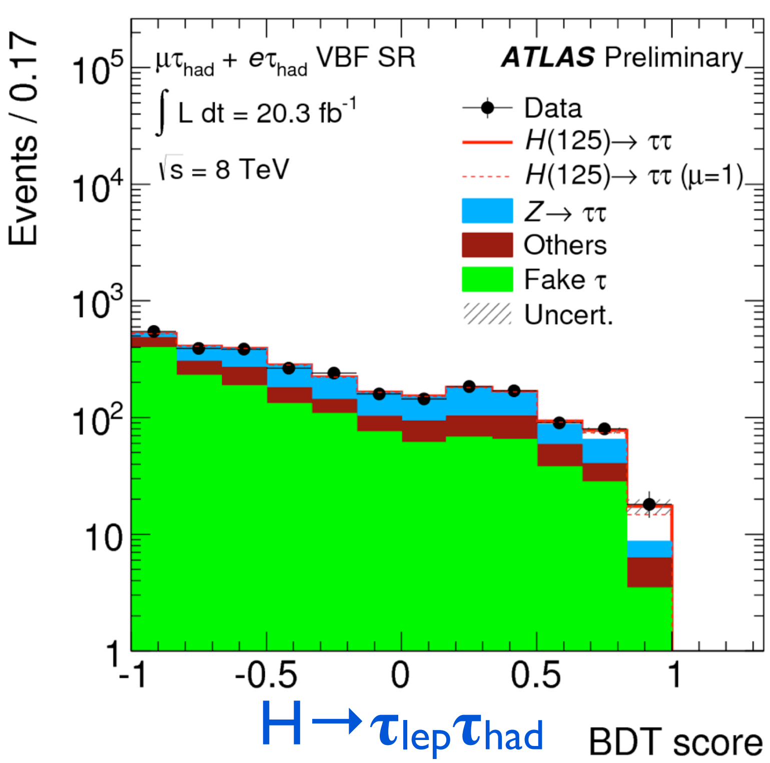
SR = Signal Region
CR = Control Region

Global fit input:	VBF			Boosted		
	lep/lep	lep/had	had/had	lep/lep	lep/had	had/had
BDT score (SR)	yes	yes	yes	yes	yes	yes
Top CR	yes	yes	-	yes	yes	-
$Z\to\ell\ell$ CR	yes	yes	-	yes	yes	-
Rest CR	-	-	$\Delta\eta_{\tau\tau}$ bins	-	-	$\Delta\eta_{\tau\tau}$ bins

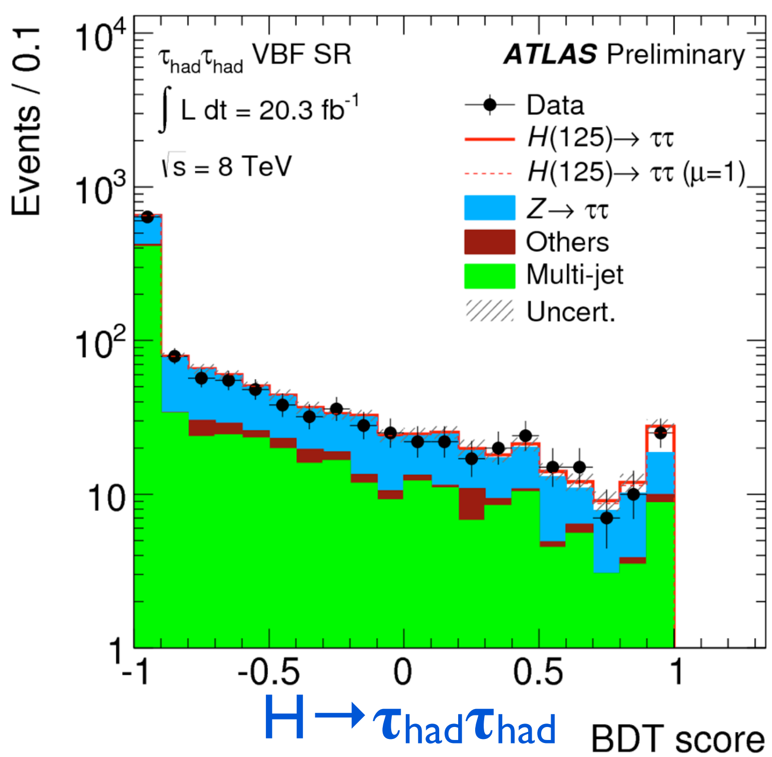
Rest CR: events that pass preselection but fail category selections, used for Z and multijet normalizations



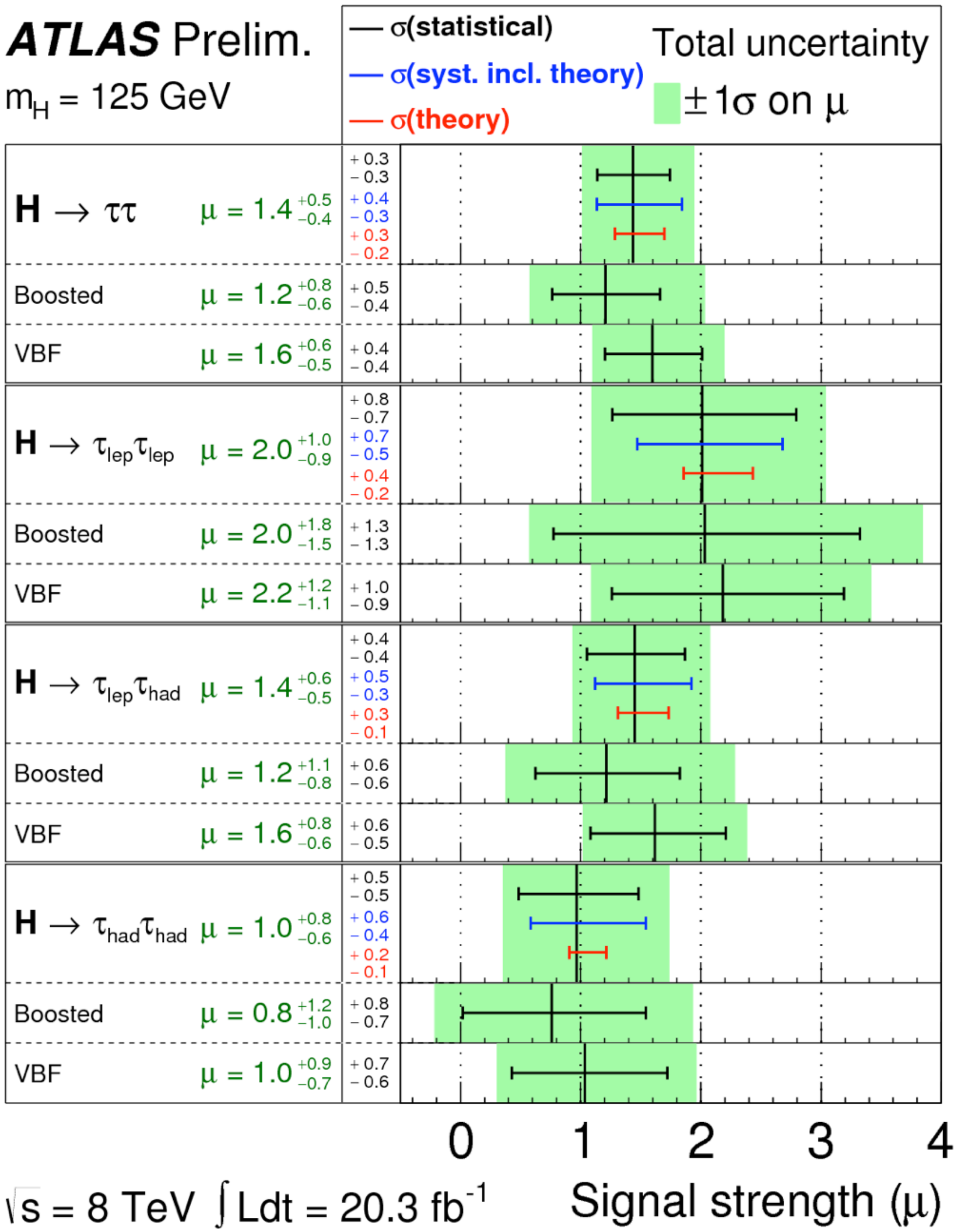
$H\to\tau_{lep}\tau_{lep}$



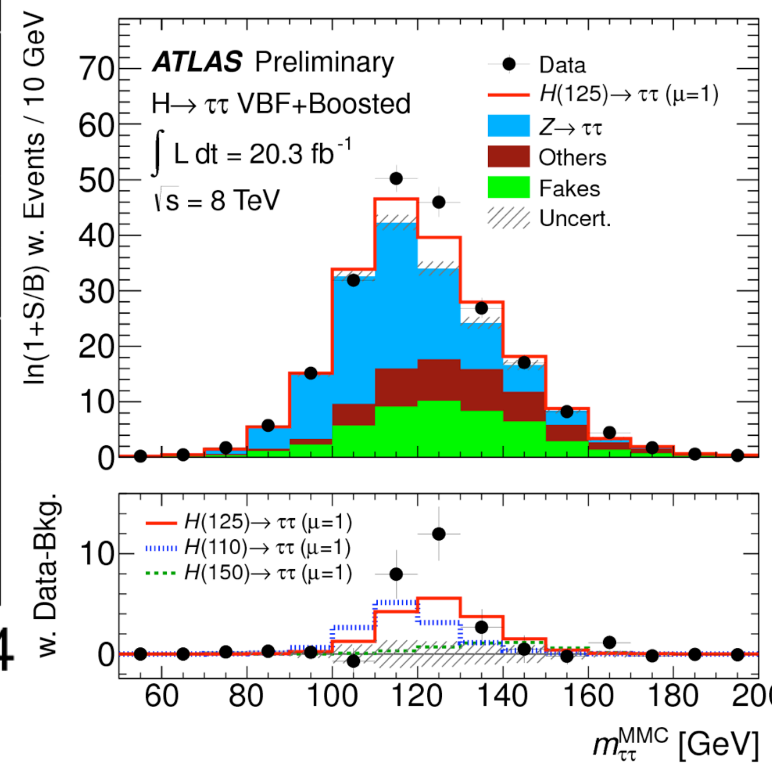
$H\to\tau_{lep}\tau_{had}$

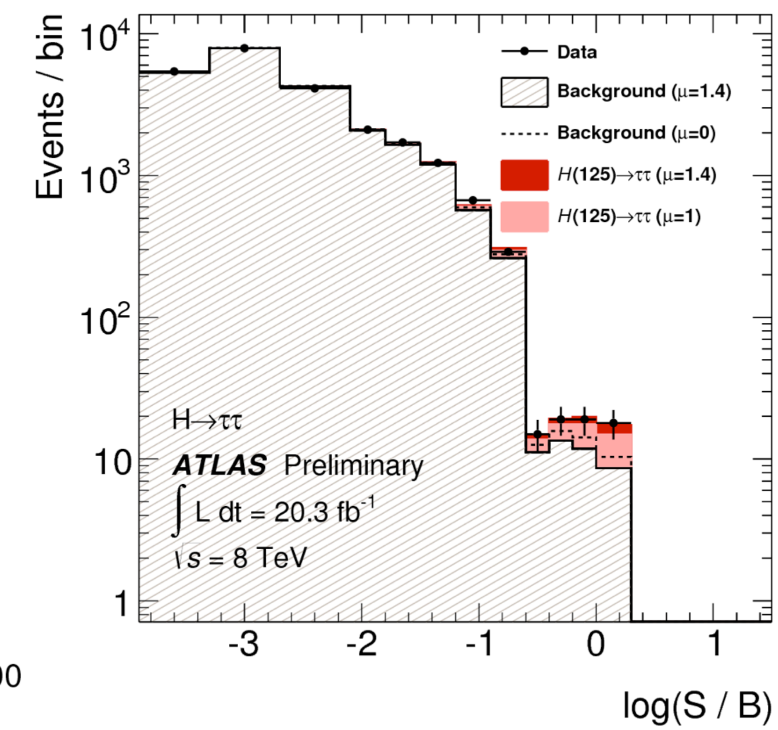


$H\to\tau_{had}\tau_{had}$



- Observed signal with a significance of 4.1σ at m_H = 125 GeV (expected significance: 3.2σ)
  - First direct evidence of decay of Higgs boson to fermions!
- Signal strength $\mu = \sigma_{obs}/\sigma_{SM} = 1.4^{+0.5}_{-0.4}$
  - compatible with SM expectation





Main sources of uncertainty on μ:

- Statistics (0.30)
- $Z\to\ell\ell$ normalization (0.13)
- ggF cross section, JES, Top normalization (0.12)

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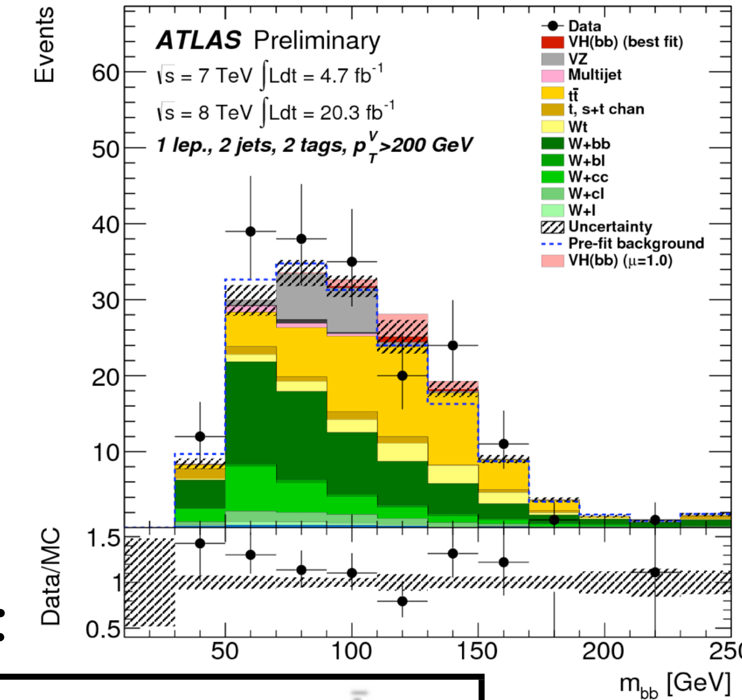
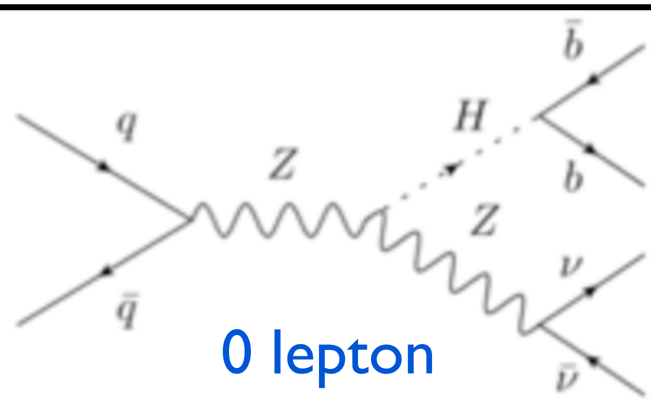
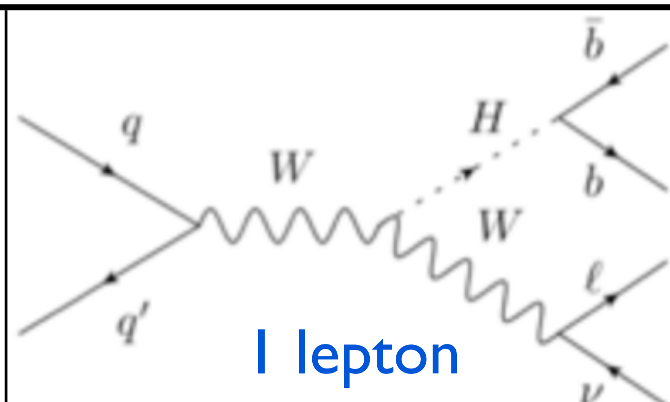
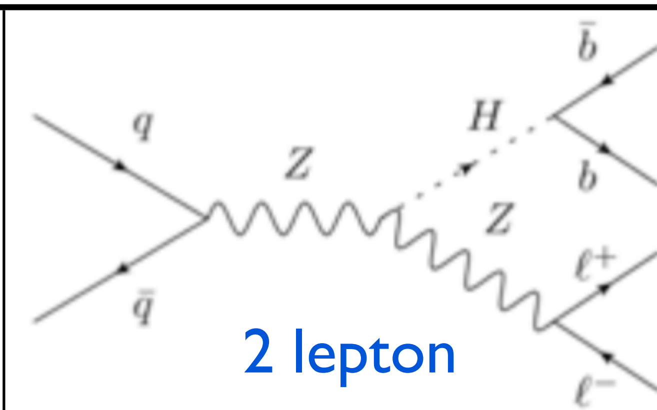
ATLAS EXPERIMENT

Search for VH→$b\bar{b}$

- H→$b\bar{b}$ has the highest branching ratio of all Higgs decays (m_H = 125 GeV)
  - only associated-production channels possible at hadron colliders due to large multijet background
- Cut-based analysis with profile likelihood fit to m_{bb}



- Event categorization by number of high pT isolated leptons (e,μ):

 0 lepton	 1 lepton	 2 lepton
2 b-tagged jets with p_T > 45 (20) GeV for leading (sub-leading) jet at most 1 extra jet		
0 loose leptons E_T^{miss} > 120 GeV p_T^{miss} > 30 GeV + directional cuts	1 tight, 0 loose leptons E_T^{miss} > 25 GeV 40 < m_T^W < 120 GeV	1 medium, 1 loose lepton E_T^{miss} < 60 GeV OS/SF leptons 83 < $m_{\ell\ell}$ < 99 GeV

p_T^{lep} (loose) > 10 GeV
p_T^{lep} (med,tight) > 25 GeV

OS = Opposite Sign
SF = Same Flavour

- Events are sub-categorized in bins of p_T^V and jet multiplicity, with further topological requirements to reduce the backgrounds in individual bins and increase overall sensitivity: (Signal Region, Control Region)

	2 jets 1 b-tag	2 jets 2 b-tags	3 jets 1 b-tag	3 jets 2 b-tags	≥2 jets 2 b-tags eμ events
0 lepton	3 p_T^V bins	3 p_T^V bins	3 p_T^V bins	3 p_T^V bins	-
1 lepton	5 p_T^V bins	5 p_T^V bins	5 p_T^V bins	5 p_T^V bins	-
2 lepton	5 p_T^V bins	5 p_T^V bins	5 p_T^V bins	5 p_T^V bins	5 p_T^V bins

p_T^V bins [GeV]:

- 0 - 90*
- 90 - 120*
- 120 - 160
- 160 - 200
- 200+

* not used in 0-lepton channel as below E_T^{miss} trigger threshold

- VZ, Z→$b\bar{b}$ production has a similar signature and is used to cross-check the analysis
  - main differences: softer p_T^{bb} spectrum and m_{bb} consistent with Z mass
  - Separate diboson fit (using same configuration as Higgs signal) to extract μ_{VZ}
    - μ_{VZ} = 0.9 ± 0.2 (4.8σ significance) consistent with SM

Global fit to following channels:

- m_{bb} distributions in 26 2-tag signal regions
- event yields in 26 1-tag control regions
- event yields in 5 top (eμ) control regions

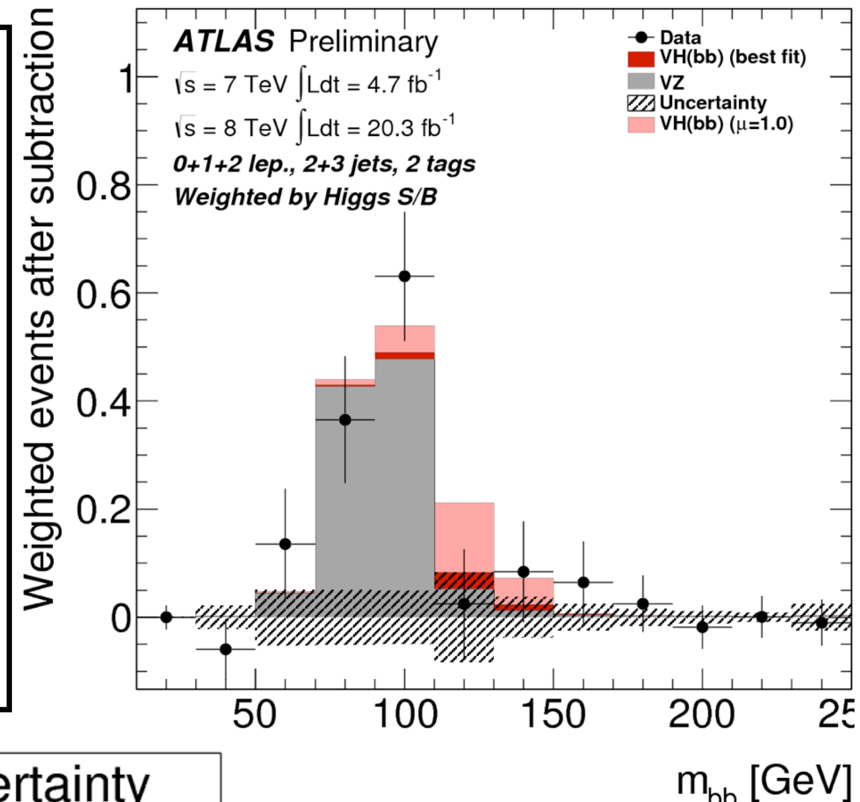
Results

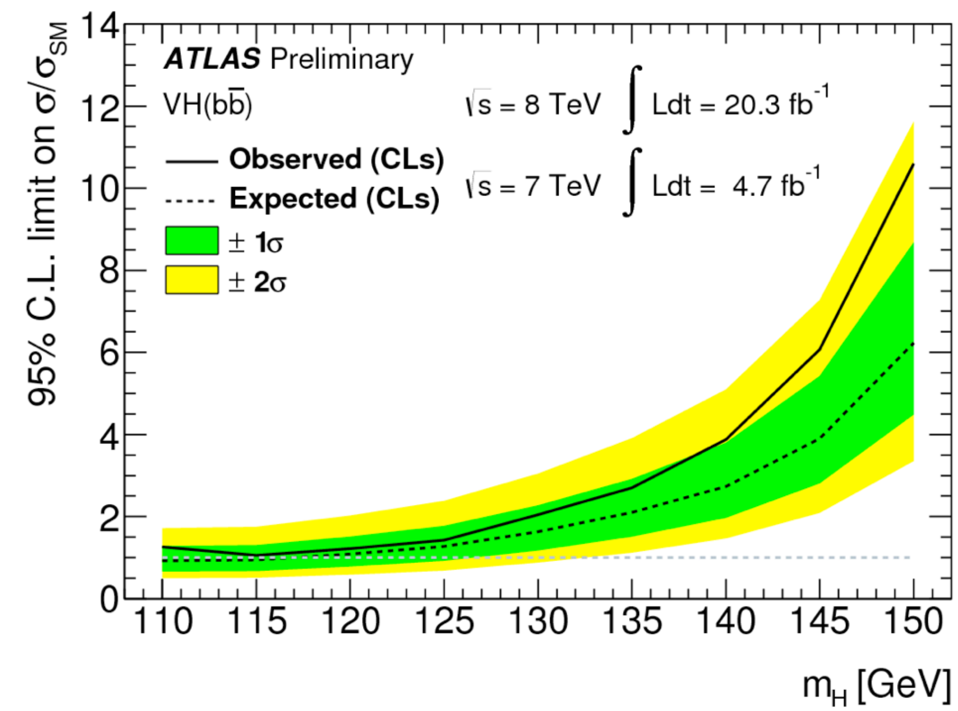
VH→$b\bar{b}$

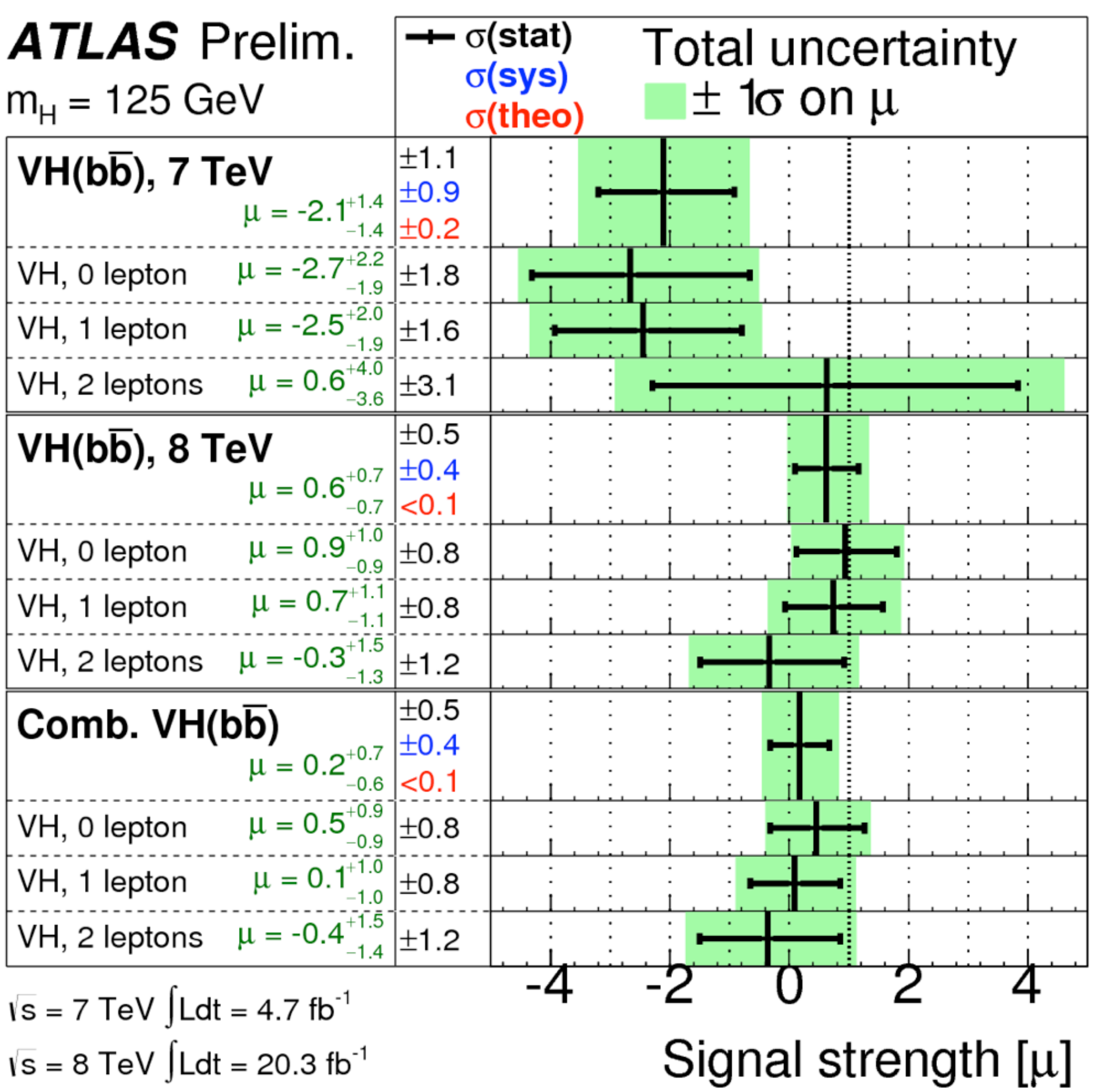
Dominant systematics:

- $t\bar{t}$ background modelling
- 2- to 3-jet ratio
- $p_T V$
- c-jet tagging efficiency
- multijet normalization
- signal acceptance

~ 3%(bg) and 12%(signal) after fit







- No significant excess observed
- Observed (expected) 95% CL upper limits on signal strength for m_H = 125 GeV:
  - 1.4 (1.3) x SM expectation
- Best-fit signal strength:
  - μ = 0.2 ± 0.5 (stat) ± 0.4 (sys)

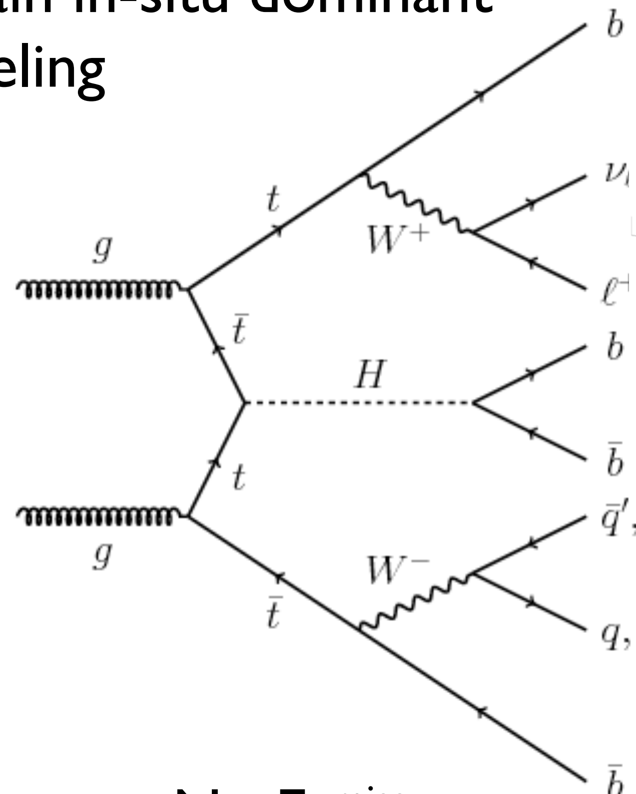
Claire Lee, DIS 2014, Warsaw

ATLAS EXPERIMENT

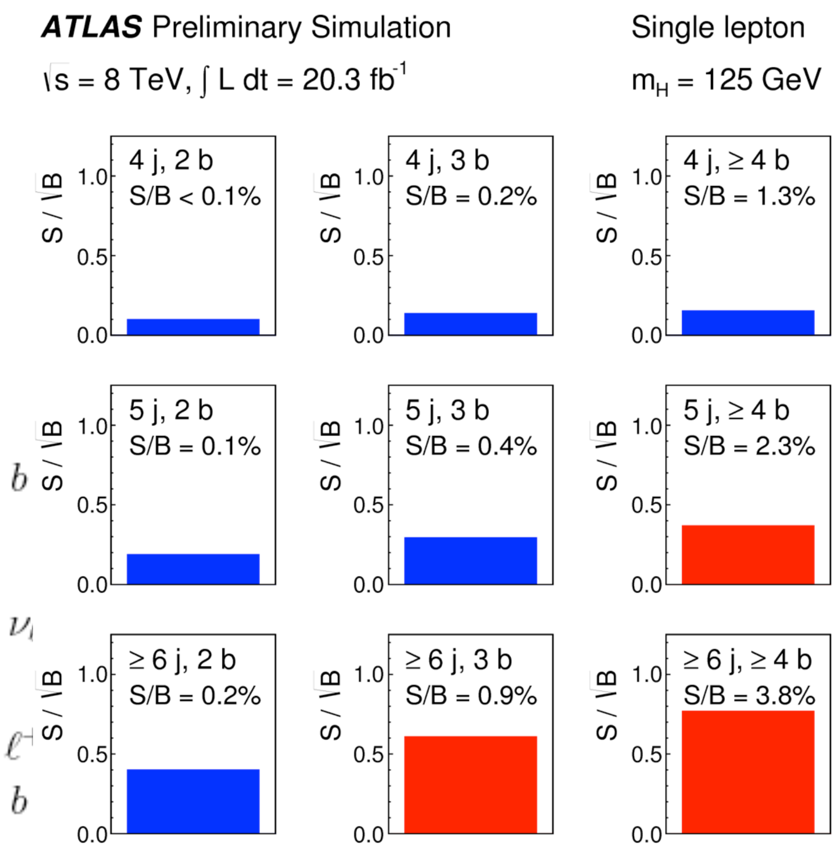
Search for ttH→bb̄

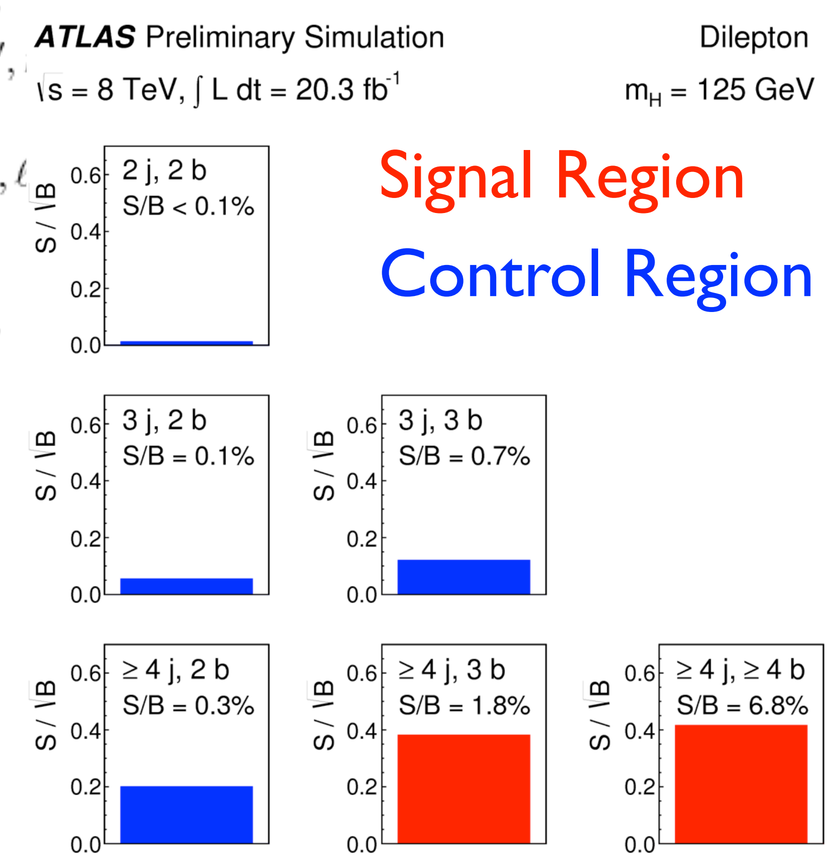
- Event preselection requiring 1 or 2 W bosons decaying leptonically
- Events categorized according to jet & b-tag multiplicities
- Multivariate analysis to discriminate signal from overwhelming tt+jets background
  - Signal-depleted channels used to constrain in-situ dominant systematic uncertainties on tt+jets modeling

1 lepton	2 lepton
exactly 1 lepton	exactly 2 leptons
p_T^{ℓ} > 25 GeV	p_T^{ℓ} > 25 (15) GeV
≥ 4 jets, ≥ 2 b-tags	≥ 2 jets, ≥ 2 b-tags
	H_T > 130 GeV (OF)
	$m_{\ell\ell}$ > 15 GeV and $\lvert m_{\ell\ell} - m_Z \rvert$ > 8 GeV (SF)



No E_T^{miss} requirement since after cuts background is dominated by tt+jets





Signal Region

Control Region

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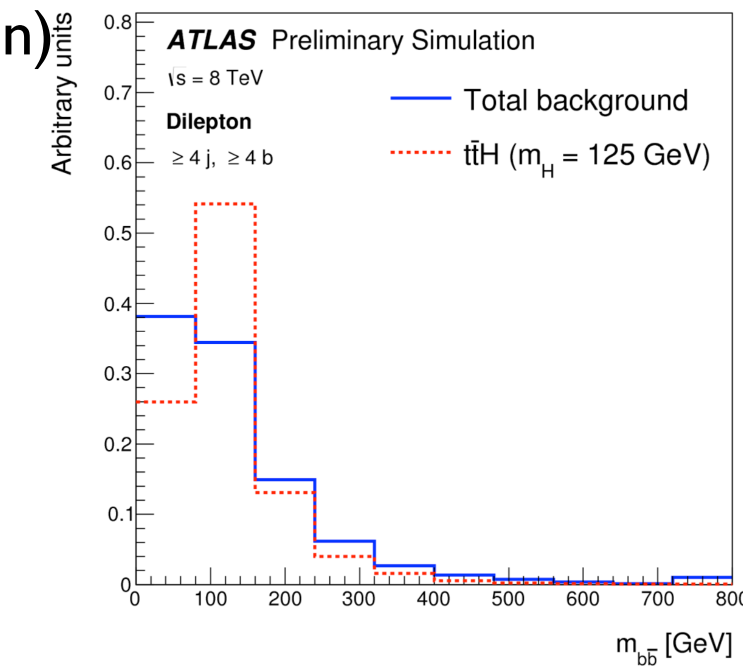
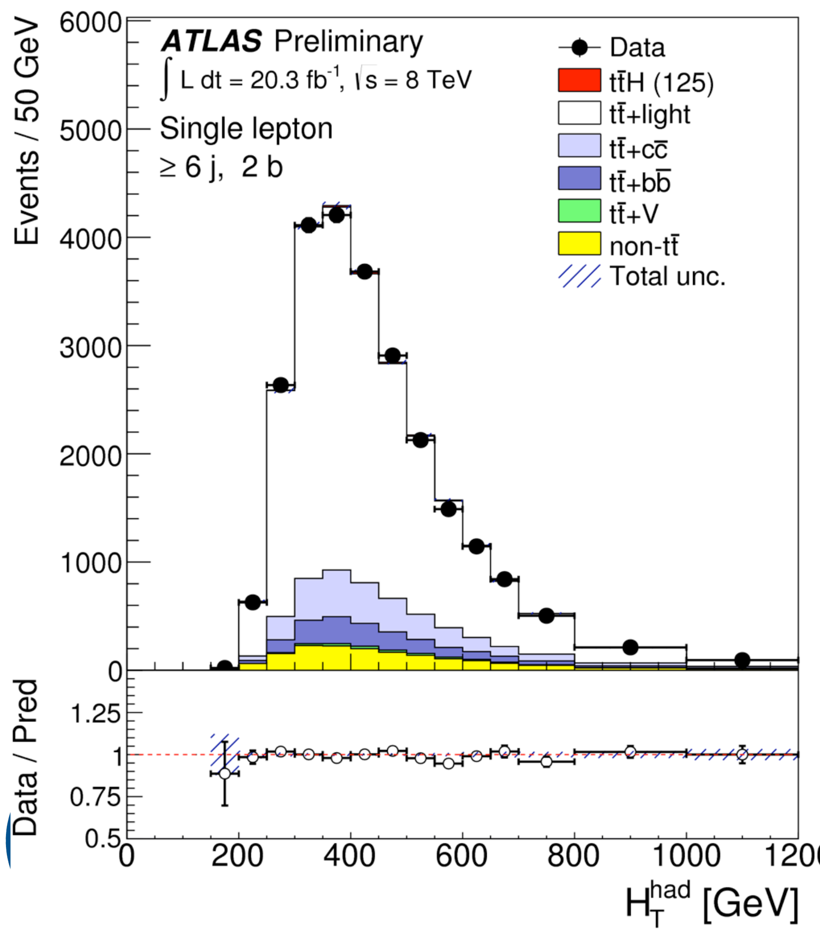
Analysis Method

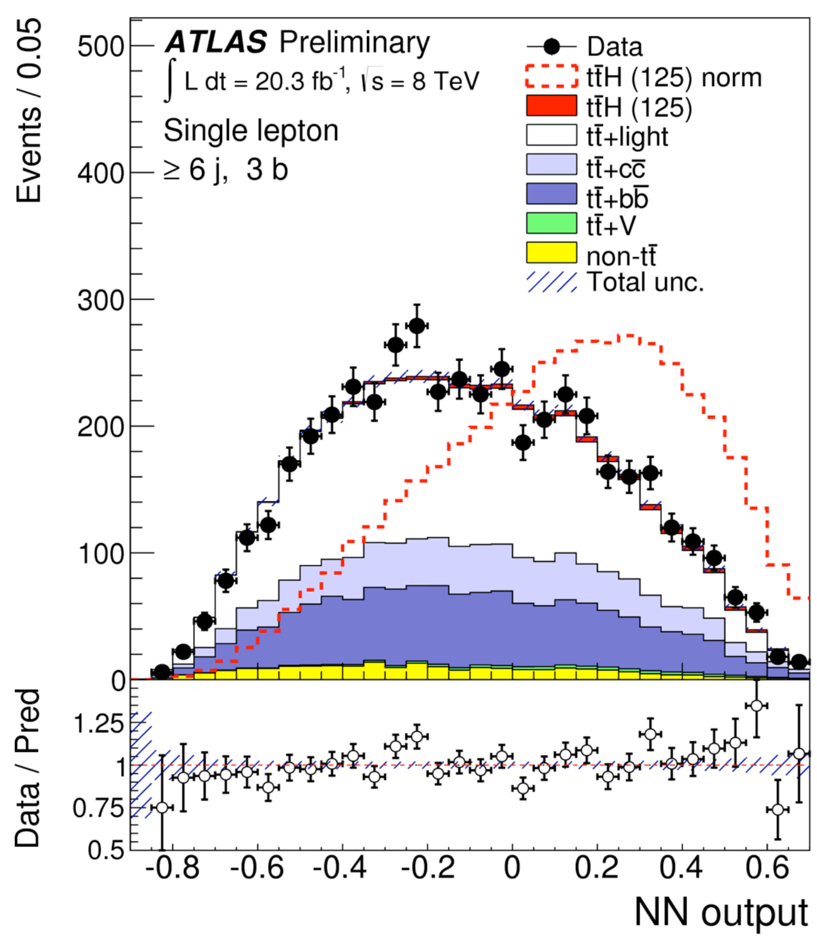
- Analysis uses a Neural Network to discriminate signal from background in signal regions
  - dedicated NN in 5j3b region trained to separate tt+light from tt+HF
  - signal-depleted regions use single variable: $\sum p_T^{jets}$ (+ $\sum p_T^{\ell}$ for dilepton)
- Variables used in NN:
  - Object kinematics
  - Global event variables
  - Event shape
  - Object pair properties

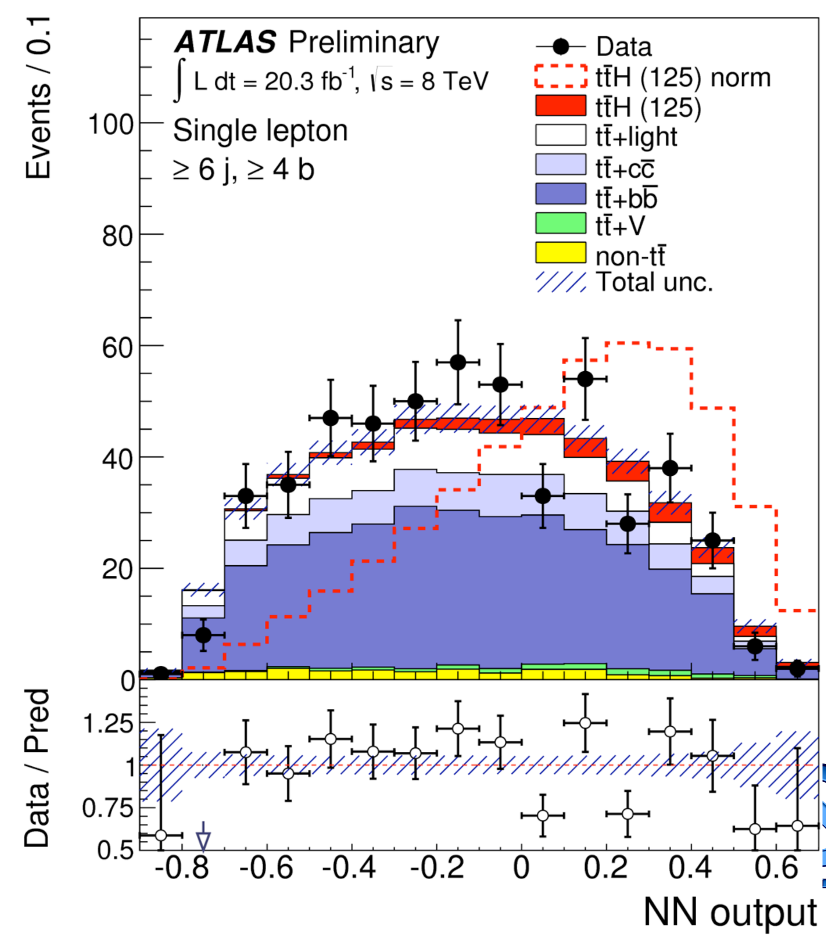
  } Variables used in one region are required to have well-described data/mc in other regions



- No kinematic reconstruction of ttH final state



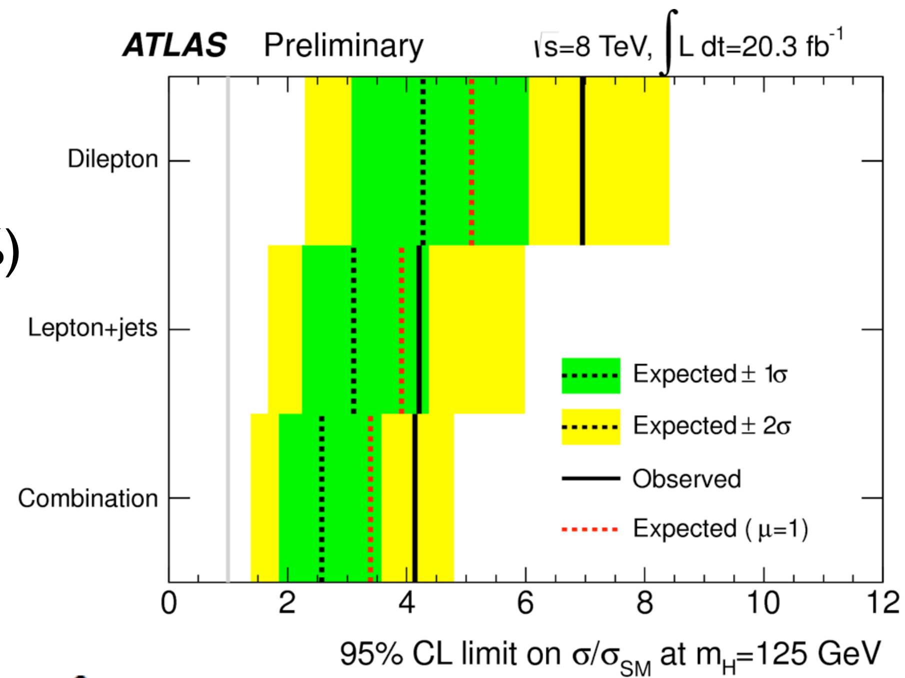


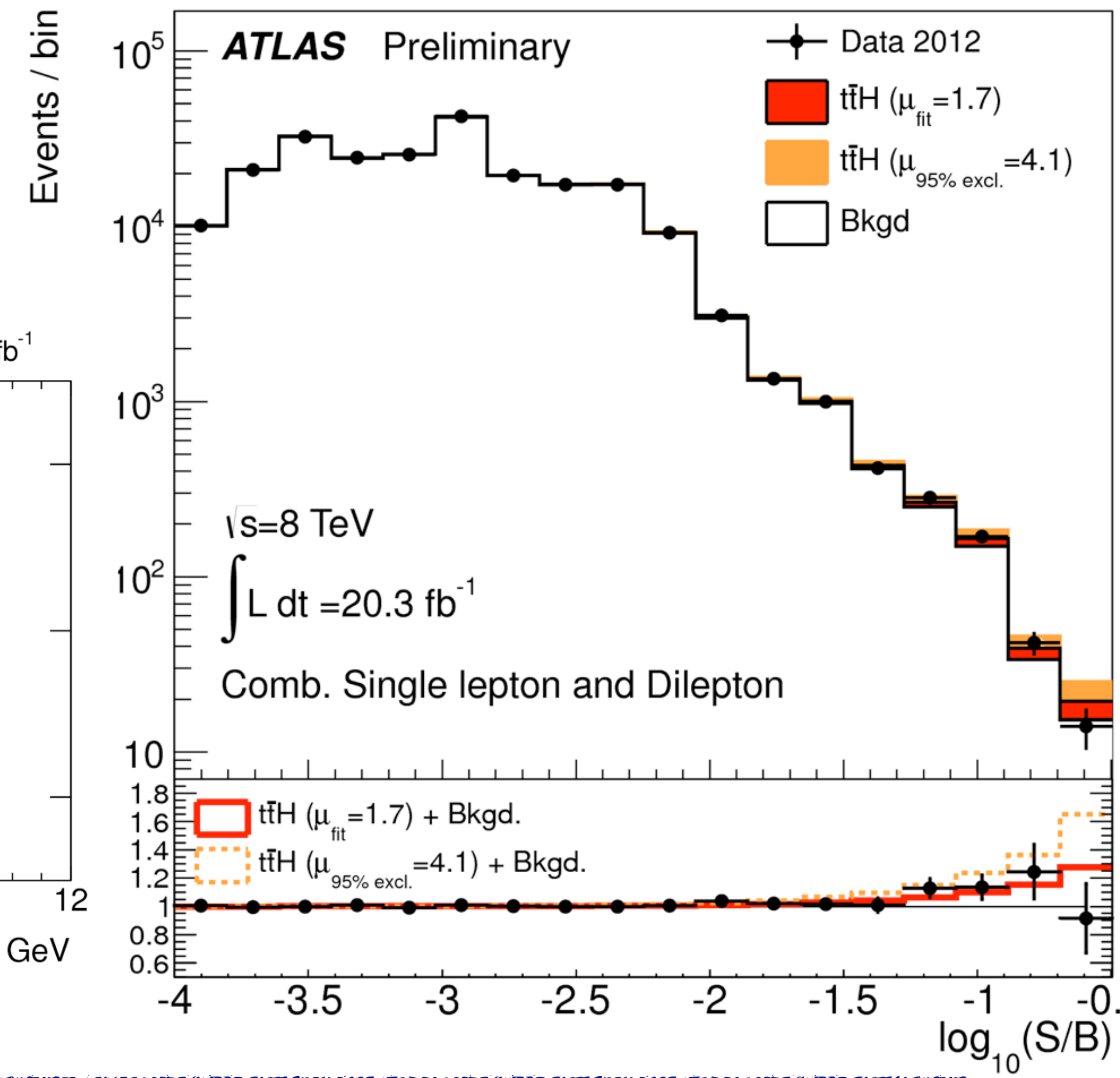


Results

$t\bar{t}H \rightarrow b\bar{b}$

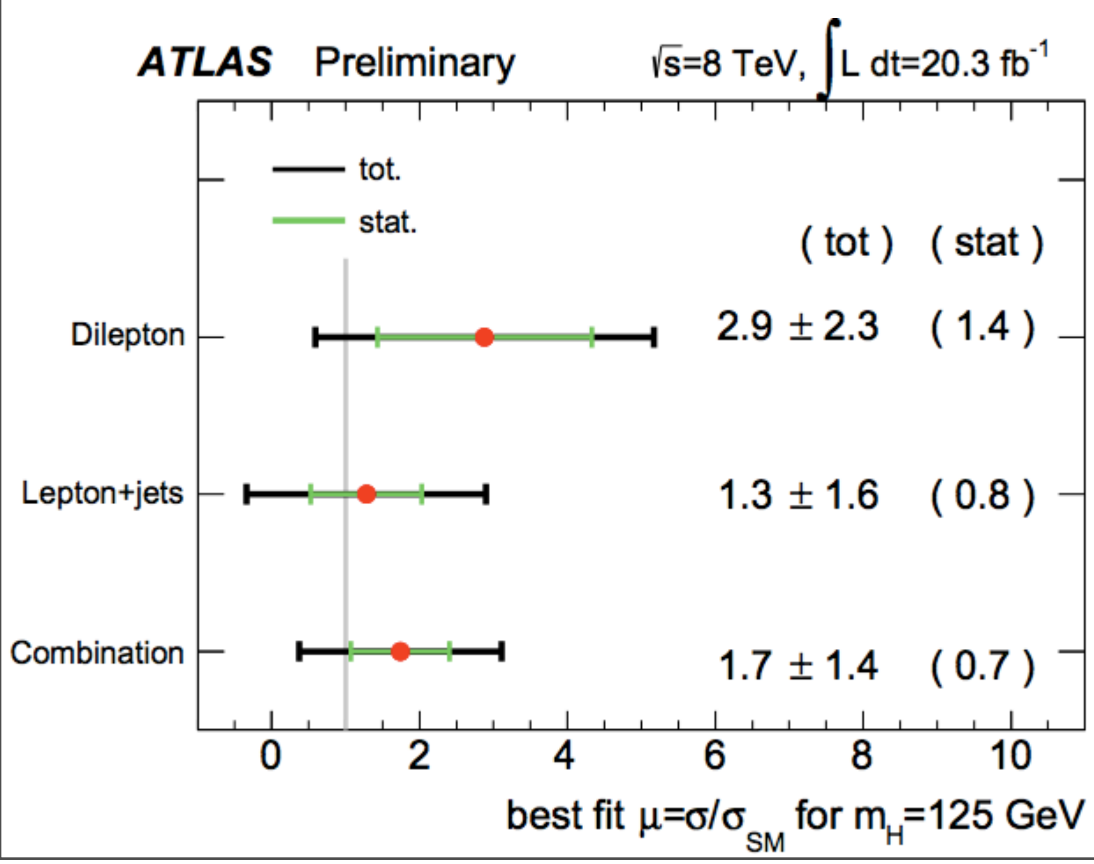
- Simultaneous binned likelihood fit to discriminants in 9+6 signal regions
- Fitted signal + background hypothesis where μ floats freely





Dominant systematics:

- tt+HF normalization (~ 50%)
- Flavour tagging efficiency
- tt reweighting
- Jet energy scale



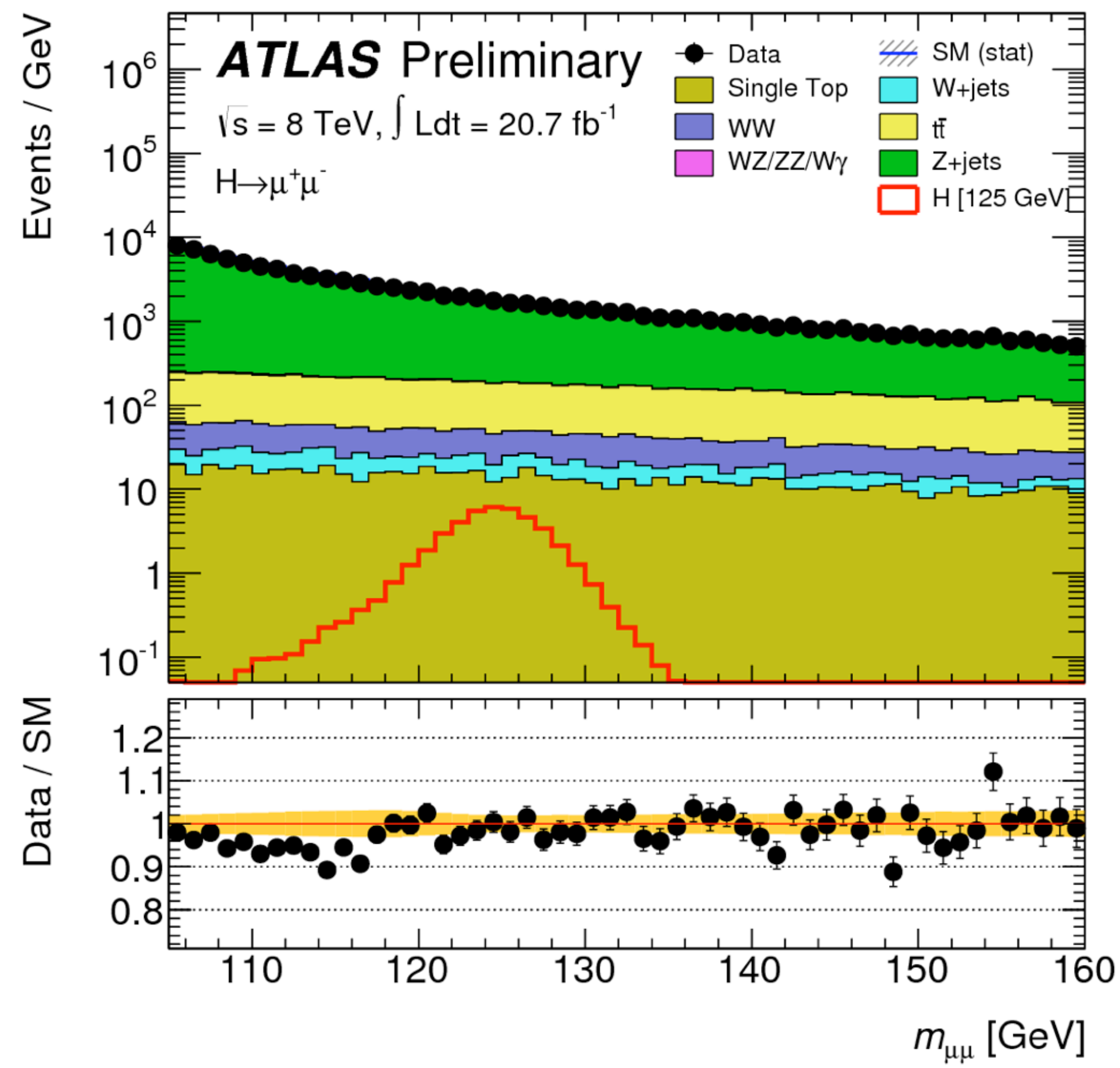
- Observed (expected) 95% CL upper limits on signal strength for m_H = 125 GeV:
  - 4.1 (2.6) x SM expectation
- Best-fit signal strength:
  - μ = 1.7 ± 1.4 (stat+sys)

Search for H→μμ

- Only channel for measuring the Higgs coupling to 2nd-generation fermions
- Inclusive search covering all production processes
- Clean final state, but small BR ($O \sim 10^{-5}$) and large SM backgrounds
- Cut-based analysis with a fit to $m_{\mu\mu}$ spectrum in the region $105 < m_{\mu\mu} < 160$ GeV

- Event Selection:
  - Exactly two OS muons with $p_T > 25$ (15) GeV for leading (sub-leading) muon
  - $p_T^{\mu 1 \mu 2} > 15$ GeV

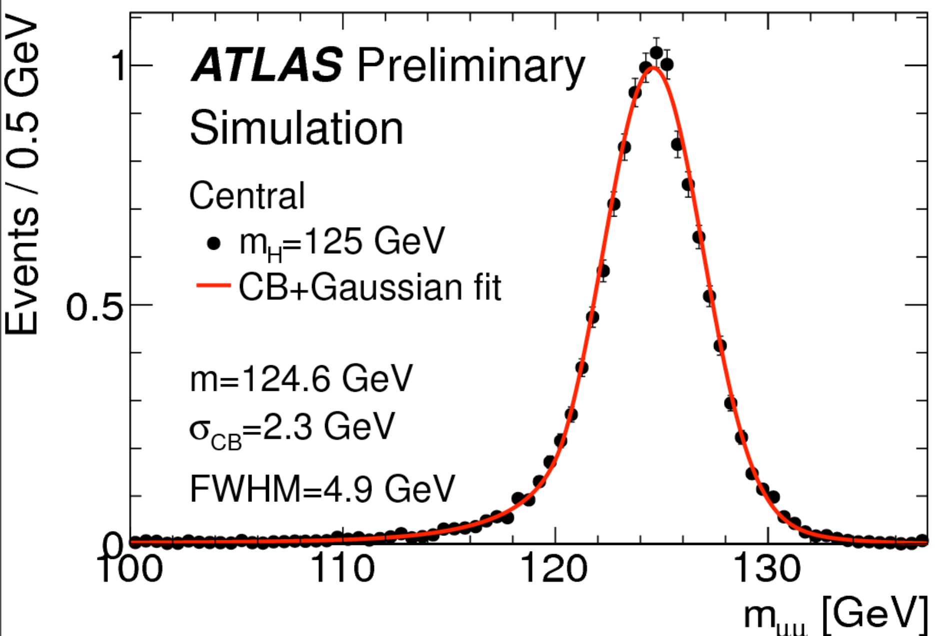
- Signal regions:
  - two categories: central ($|\eta_{\mu 1,\mu 2}| < 1$) and non-central
  - exploits the more precise muon p_T measurement in central region
- Control region:
  - events failing $p_T^{\mu 1 \mu 2} > 15$ GeV



Results

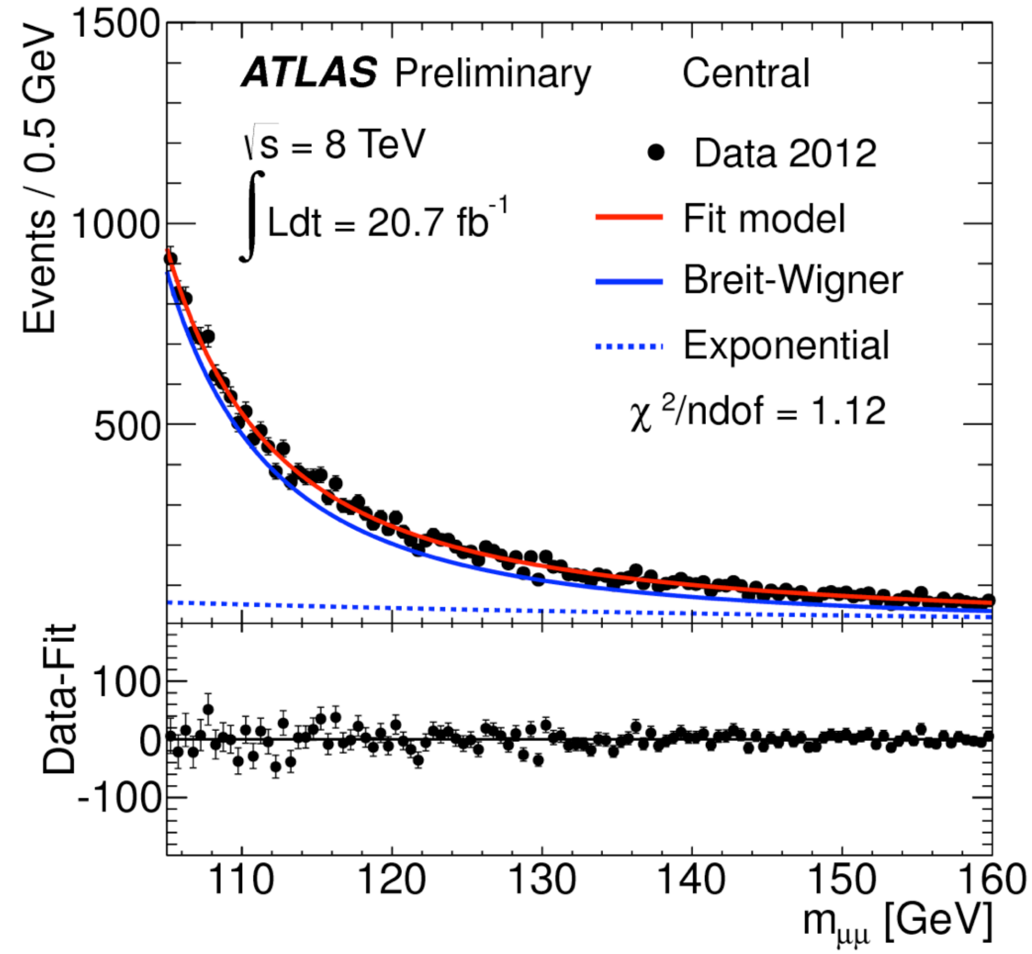
$H \rightarrow \mu\mu$

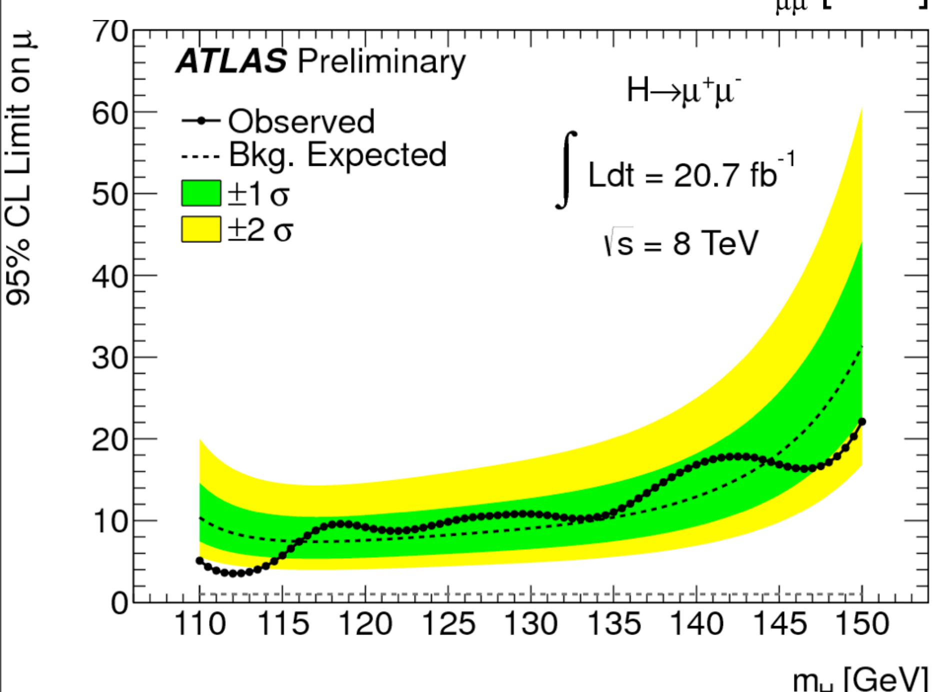
- Binned maximum likelihood fit performed on $m_{\mu\mu}$ in each category
- PDF_{signal}: Crystal Ball + Gaussian
  - obtained from Higgs signal MC samples with contributions from all four prod. processes
- PDF_{bg}: Breit-Wigner + exponential
  - BW mean, width fixed to world values for Z



Main systematic uncertainties:

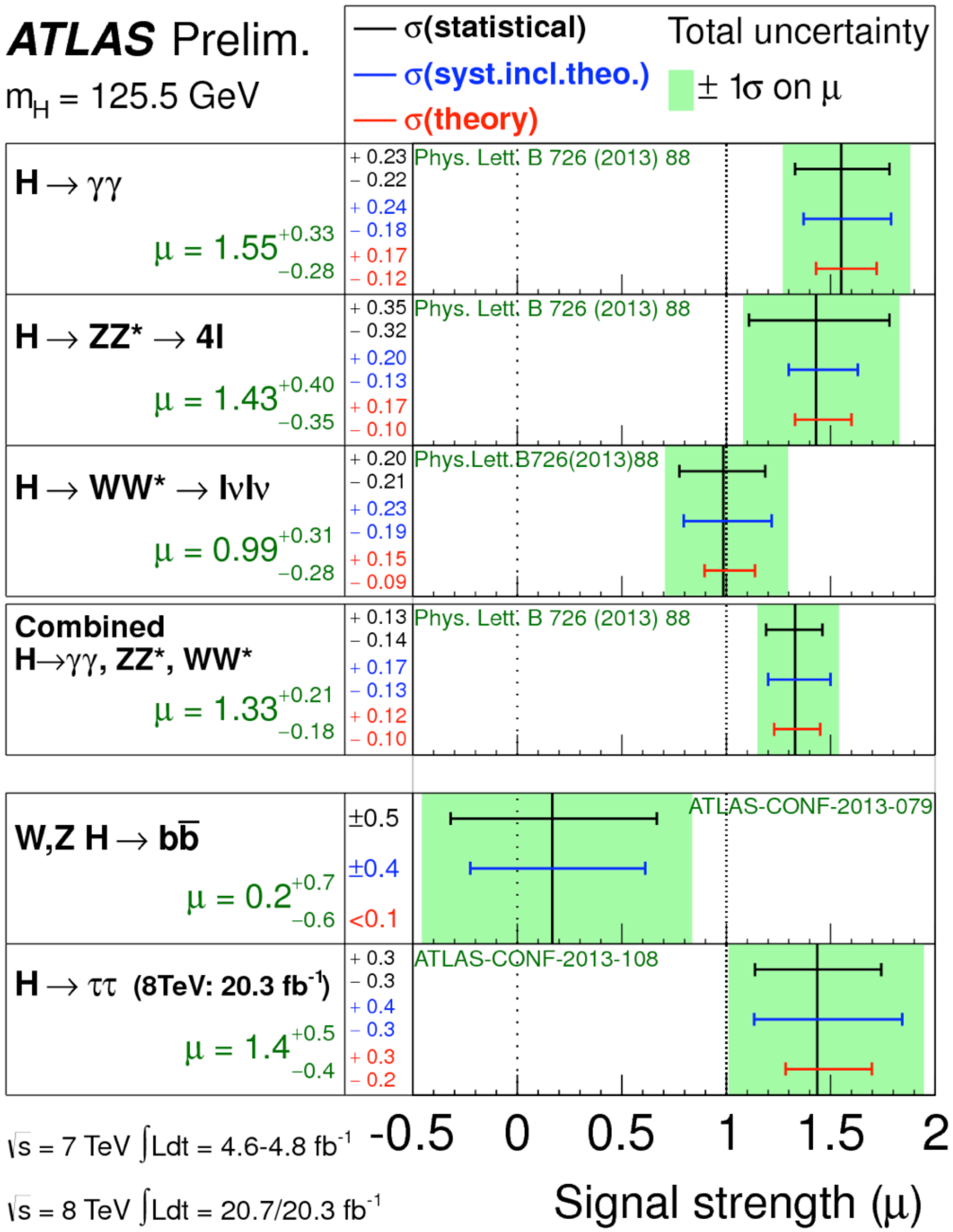
- cross-section: ~15% ggF, ~3% VBF
- BR: ~6%
- Acceptance: ~2.6% (th) and 4.2% (exp)
- Lumi: 3.6%





- No evidence of a signal observed
- Observed (expected) 95% CL upper limits on signal strength for m_H = 125 GeV:
  - 9.8 (8.2) x SM expectation

Conclusions



- A search for the Standard Model Higgs boson of mass 125 GeV via fermionic channels has been performed on 7 and 8 TeV data from LHC Run 1:
  - $H \rightarrow \tau\tau$: observed signal with 4.1σ significance
  - $H \rightarrow b\bar{b}$: no significant excess observed over background
    - VH: limit 1.4 (1.3) x SM
    - ttH: limit 4.1 (2.6) x SM
  - $H \rightarrow \mu\mu$: no significant excess observed over background
    - Incl: limit 9.8 (8.2) x SM
- Results show no significant deviations from the Standard Model.
- Improvements and updates to Run 1 analyses are in progress, and we look forward to Run 2!

Backup

Trigger	p_T threshold(s) [GeV]	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Electron	24	•	•	
Muon	24		•	
Di-electron	12 ; 12	•		
Di-muon	18 ; 8	•		
Electron + Muon	12 ; 8	•		
Electron + τ_{had}	18 ; 20		•	
Muon + τ_{had}	15 ; 20		•	
Di-τ_{had}	29 ; 20			•

Table 1: Triggers used for each channel. When more than one trigger is used, a logical OR of the triggers is taken and the trigger efficiency is calculated accordingly. The electron+τ_{had} and muon+τ_{had} triggers are used for the $\tau_{lep}\tau_{had}$ channel at preselection, but not in the VBF and boosted categories as defined in Section 7.

Category	Selection	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
VBF	$p_T(j_1)$ (GeV)	40	50	50
	$p_T(j_2)$ (GeV)	30	30	30/35
	$\Delta\eta(j_1, j_2)$	2.2	3.0	2.0
	b–jet veto for jet p_T (GeV)	25	30	-
	p_T^H (GeV)	-	-	40
Boosted	$p_T(j_1)$ (GeV)	40	-	-
	p_T^H (GeV)	100	100	100
	b–jet veto for jet p_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_T jets in the event. Events in the $\tau_{lep}\tau_{had}$ VBF category must also satisfy $m_{\tau\tau}^{vis} > 40$ GeV, and those that fail this requirement are not considered for the $\tau_{lep}\tau_{had}$ boosted category. The $p_T(j_2)$ threshold in the $\tau_{had}\tau_{had}$ channel is 30 (35) GeV for jets within (outside of) $|\eta| = 2.4$.

H→ττ

Variable	VBF			Boosted		
	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm lep}$	$\tau_{\rm lep}\tau_{\rm had}$	$\tau_{\rm had}\tau_{\rm had}$
$m_{\tau\tau}^{\rm MMC}$	•	•	•	•	•	•
$\Delta R(\tau,\tau)$	•	•	•		•	•
$\Delta\eta(j_1,j_2)$	•	•	•			
m_{j_1,j_2}	•	•	•			
$\eta_{j_1}\times\eta_{j_2}$		•	•			
$p_{\rm T}^{\rm Total}$		•	•			
sum $p_{\rm T}$					•	•
$p_{\rm T}(\tau_1)/p_{\rm T}(\tau_2)$					•	•
$E_{\rm T}^{\rm miss}\,\phi$ centrality		•	•	•	•	•
$x_{\tau1}$ and $x_{\tau2}$						•
$m_{\tau\tau,j_1}$				•		
m_{ℓ_1,ℓ_2}				•		
$\Delta\phi_{\ell_1,\ell_2}$				•		
sphericity				•		
$p_{\rm T}^{\ell_1}$				•		
$p_{\rm T}^{j_1}$				•		
$E_{\rm T}^{\rm miss}/p_{\rm T}^{\ell_2}$				•		
$m_{\rm T}$		•			•	
$\min(\Delta\eta_{\ell_1\ell_2,\rm jets})$	•					
$j_3\ \eta$ centrality	•					
$\ell_1\times\ell_2\ \eta$ centrality	•					
$\ell\ \eta$ centrality		•				
$\tau_{1,2}\ \eta$ centrality			•			

Table 3: Discriminating variables used for each channel and category. The filled circles identify which variables are used in each decay mode. Note that variables such as $\Delta R(\tau,\tau)$ are defined either between the two leptons, between the lepton and $\tau_{\rm had}$, or between the two $\tau_{\rm had}$ candidates, depending on the decay mode.

Table 4: Predicted event yields in the $\tau_{\rm lep}\tau_{\rm lep}$ channel for m_H = 125 GeV in the three highest bins of the BDT distributions. The background normalizations, signal normalization, and uncertainties reflect the preferred values from the global fit. The uncertainties on the total background and total signal reflect the full statistical+systematic uncertainty, while the uncertainties on the individual background components reflect the full systematic uncertainty only.

Process/Category	VBF			Boosted		
BDT score bin edges	0.684-0.789	0.789-0.895	0.895-1.0	0.667-0.778	0.778-0.889	0.889-1.0
ggF	0.53 ± 0.26	0.8 ± 0.4	0.7 ± 0.4	5.3 ± 2.1	5.2 ± 2.0	1.7 ± 0.7
VBF	1.15 ± 0.35	2.0 ± 0.6	5.0 ± 1.5	1.01 ± 0.33	1.5 ± 0.5	0.67 ± 0.22
WH	< 0.05	< 0.05	< 0.05	0.71 ± 0.22	0.64 ± 0.20	0.16 ± 0.05
ZH	< 0.05	< 0.05	< 0.05	0.36 ± 0.11	0.32 ± 0.10	0.06 ± 0.02
$Z \to \tau^+\tau^-$	7.6 ± 0.8	9.0 ± 0.9	4.6 ± 0.6	97 ± 7	61.5 ± 3.2	13.6 ± 1.3
Fake	2.8 ± 0.7	5.8 ± 2.0	4.5 ± 1.7	10.1 ± 3.1	15 ± 5	0.79 ± 0.29
Top	4.0 ± 0.9	2.9 ± 0.7	1.8 ± 0.4	28 ± 7	15 ± 4	3.5 ± 0.9
Others	1.97 ± 0.26	3.3 ± 0.4	2.7 ± 0.4	24.7 ± 1.9	8.8 ± 0.6	2.34 ± 0.24
Total Background	16.3 ± 1.5	20.9 ± 2.4	13.5 ± 2.4	160 ± 7	101 ± 4	20.2 ± 1.8
Total Signal	1.7 ± 0.5	2.9 ± 0.9	5.7 ± 1.7	7.4 ± 2.4	7.7 ± 2.5	2.6 ± 0.8
S/B	0.10	0.14	0.42	0.05	0.08	0.13
Data	23	28	19	156	128	20

- lep/lep candidate event

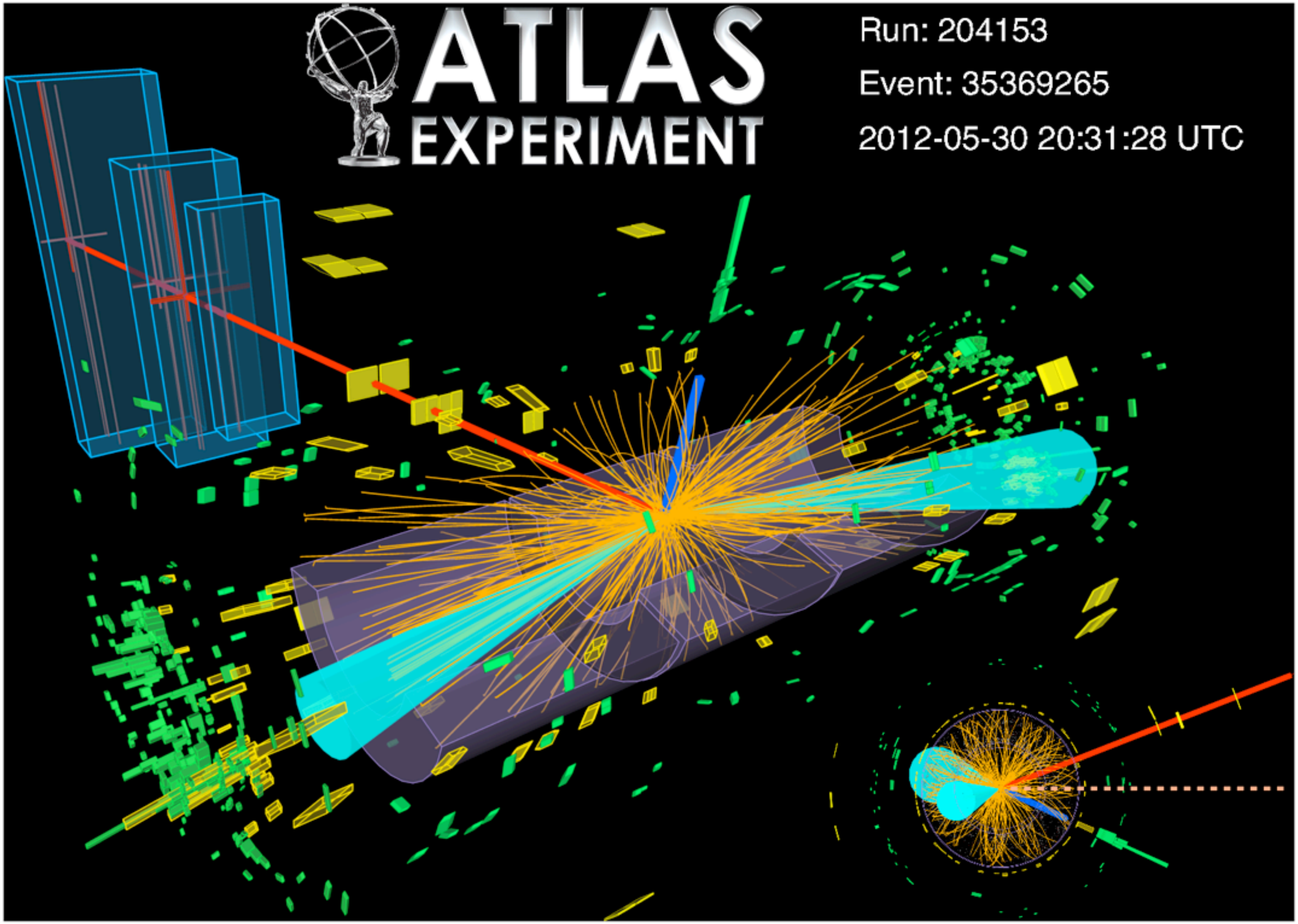


Table 5: Predicted event yields in the $\tau_{lep}\tau_{had}$ channel for $m_H = 125$ GeV in the three highest bins of the BDT distributions. The background normalizations, signal normalization, and uncertainties reflect the preferred values from the global fit. The uncertainties on the total background and total signal reflect the full statistical+systematic uncertainty, while the uncertainties on the individual background components reflect the full systematic uncertainty only.

Process/Category	VBF			Boosted		
BDT score bin edges	0.5-0.667	0.667-0.833	0.833-1.0	0.6-0.733	0.733-0.867	0.867-1.0
ggF	2.2 ± 0.9	3.5 ± 1.5	1.2 ± 0.6	7.7 ± 2.9	6.3 ± 2.3	5.5 ± 2.1
VBF	4.1 ± 1.2	9.2 ± 2.7	7.5 ± 2.2	1.7 ± 0.5	1.5 ± 0.5	1.3 ± 0.4
WH	< 0.05	< 0.05	< 0.05	0.95 ± 0.29	0.85 ± 0.26	0.81 ± 0.25
ZH	< 0.05	< 0.05	< 0.05	0.42 ± 0.13	0.47 ± 0.14	0.41 ± 0.12
$Z \to \tau^+\tau^-$	28.6 ± 1.4	25.0 ± 1.6	2.41 ± 0.35	48.3 ± 3.4	26.1 ± 2.7	18.4 ± 2.0
Fake	37.7 ± 1.8	27.9 ± 2.1	3.5 ± 0.5	27 ± 4	10.8 ± 1.8	5.8 ± 1.4
Top	6.5 ± 0.7	4.1 ± 0.8	1.5 ± 0.4	7.0 ± 0.9	5.7 ± 0.8	2.23 ± 0.33
Diboson	2.9 ± 0.4	3.0 ± 0.5	0.23 ± 0.04	4.8 ± 0.5	4.0 ± 0.5	1.69 ± 0.23
$Z \to \ell\ell(j \to \tau_{had})$	8.7 ± 1.7	3.3 ± 0.5	0.40 ± 0.10	3.8 ± 0.5	0.71 ± 0.07	< 0.05
$Z \to \ell\ell(\ell \to \tau_{had})$	2.8 ± 1.2	1.9 ± 1.2	0.7 ± 0.6	9.4 ± 1.9	4.9 ± 1.1	3.8 ± 1.2
Total Background	87.2 ± 2.7	65 ± 5	8.7 ± 2.5	101 ± 6	52 ± 4	32 ± 4
Total Signal	6.3 ± 1.8	12.7 ± 3.5	8.7 ± 2.4	10.7 ± 3.3	9.2 ± 2.8	8.0 ± 2.5
S/B	0.07	0.20	1.0	0.11	0.18	0.25
Data	90	80	18	103	64	34

- lep/had candidate event

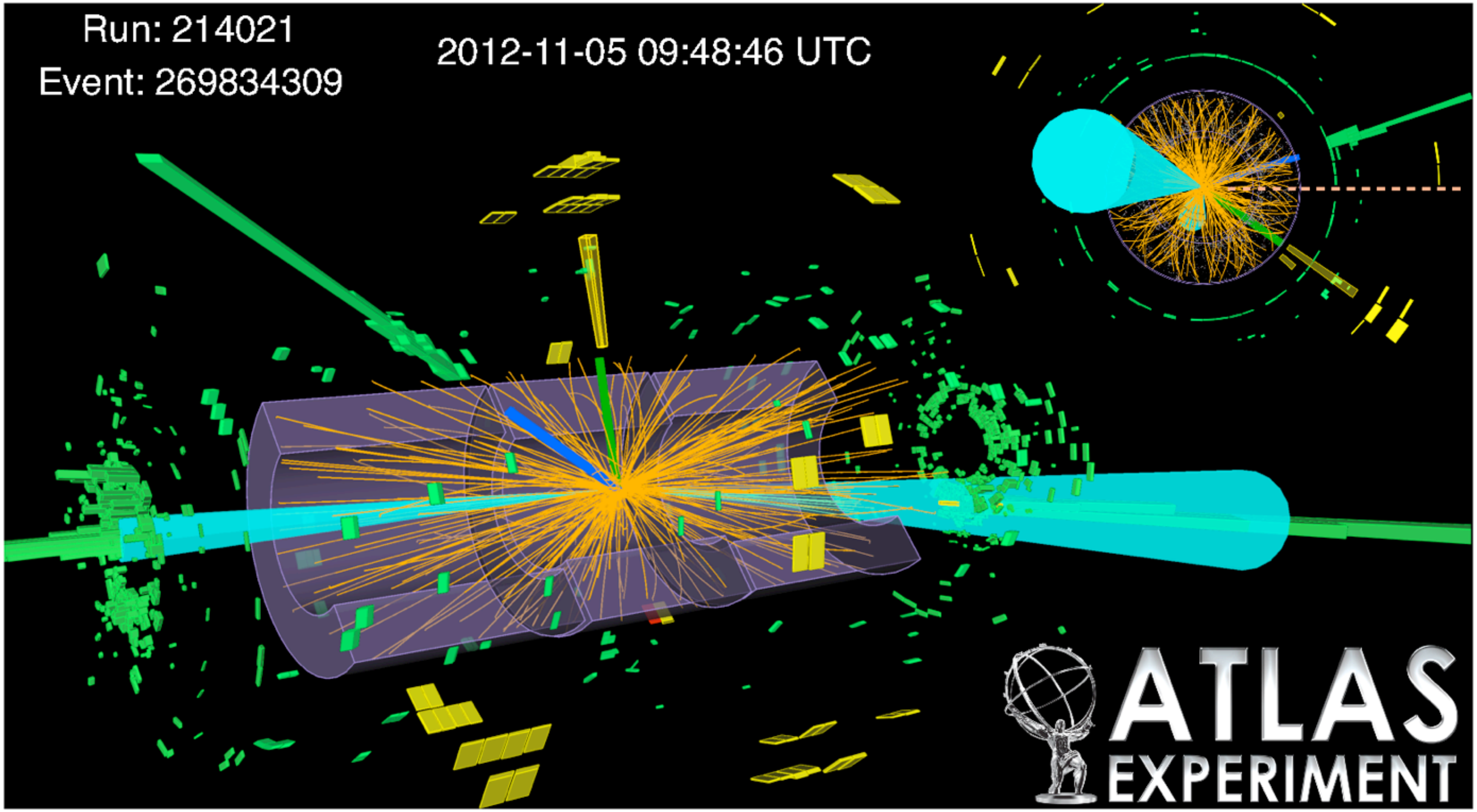
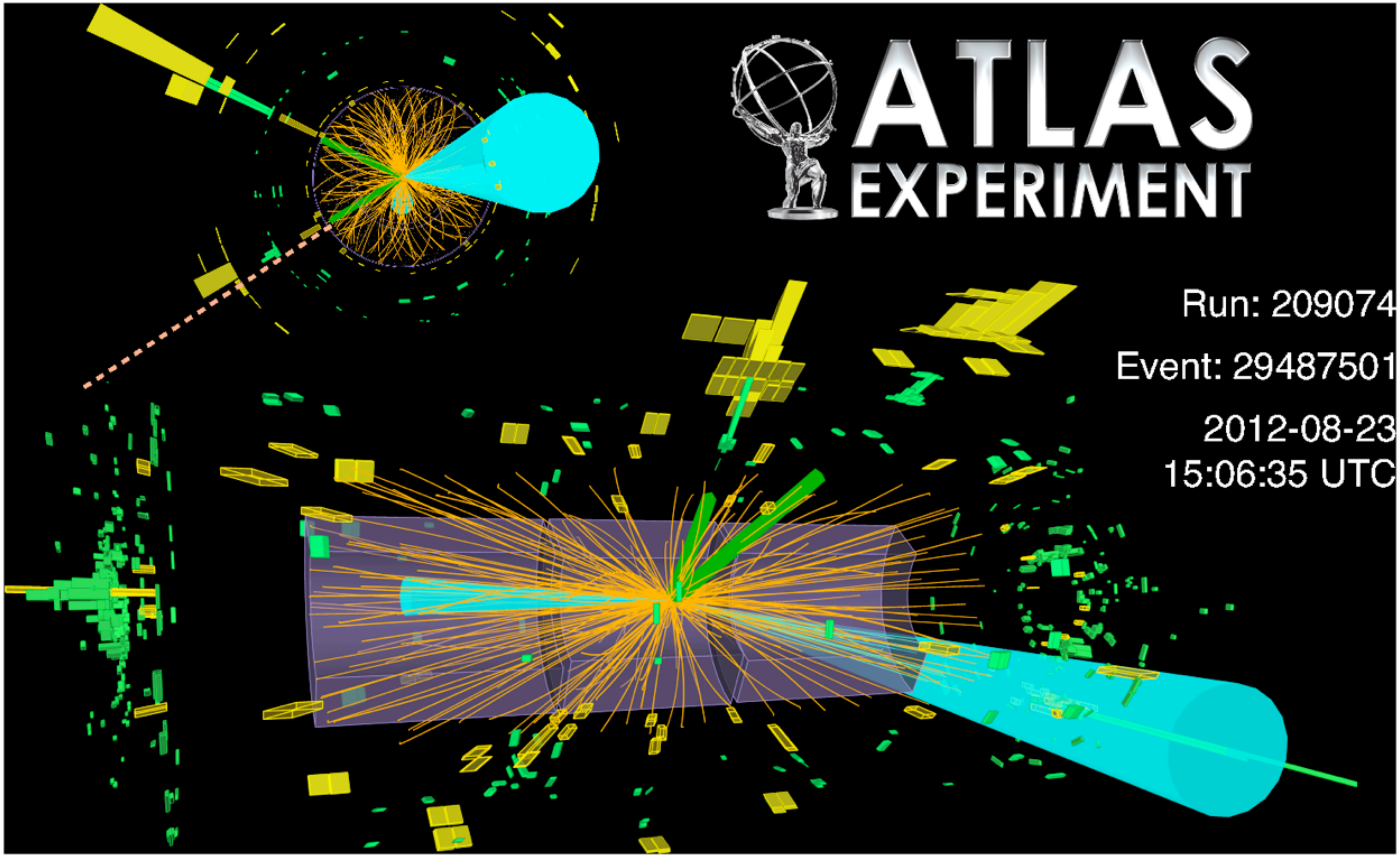


Table 6: Predicted event yields in the $\tau_{had}\tau_{had}$ channel for m_H = 125 GeV in the three highest bins of the BDT distributions. The background normalizations, signal normalization, and uncertainties reflect the preferred values from the global fit. The uncertainties on the total background and total signal reflect the full statistical+systematic uncertainty, while the uncertainties on the individual background components reflect the full systematic uncertainty only.

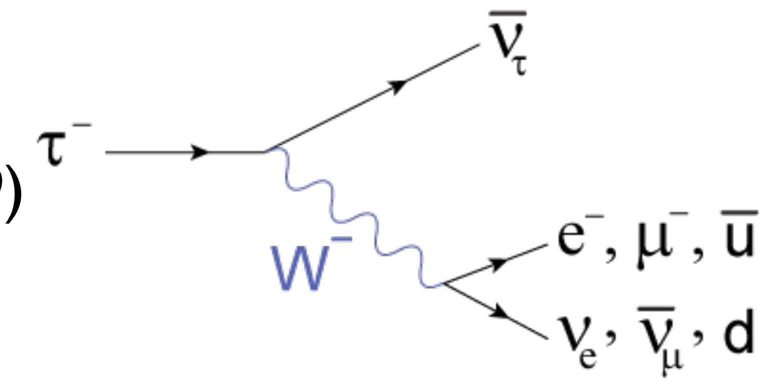
Process/Category	VBF			Boosted		
BDT score bin edges	0.85-0.9	0.9-0.95	0.95-1.0	0.85-0.9	0.9-0.95	0.95-1.0
ggF	0.39 ± 0.17	0.35 ± 0.16	2.0 ± 0.9	2.2 ± 0.8	2.5 ± 1.0	2.3 ± 0.9
VBF	0.57 ± 0.18	0.72 ± 0.22	5.9 ± 1.8	0.55 ± 0.17	0.61 ± 0.19	0.57 ± 0.17
WH	< 0.05	< 0.05	< 0.05	0.34 ± 0.11	0.40 ± 0.12	0.44 ± 0.14
ZH	< 0.05	< 0.05	< 0.05	0.22 ± 0.07	0.22 ± 0.07	0.22 ± 0.07
$Z \to \tau^+\tau^-$	3.2 ± 0.6	3.4 ± 0.7	5.3 ± 1.0	15.7 ± 1.7	12.3 ± 1.8	9.7 ± 1.6
Multijet	3.3 ± 0.6	2.9 ± 0.6	5.9 ± 0.9	5.2 ± 0.6	3.7 ± 0.5	1.40 ± 0.22
Others	0.38 ± 0.09	0.49 ± 0.12	0.64 ± 0.13	1.49 ± 0.27	2.8 ± 0.5	0.07 ± 0.02
Total Background	6.9 ± 1.3	6.8 ± 1.3	11.8 ± 2.6	22.4 ± 2.5	18.8 ± 2.8	11.2 ± 1.9
Total Signal	0.97 ± 0.29	1.09 ± 0.31	8.0 ± 2.2	3.3 ± 1.0	3.8 ± 1.2	3.6 ± 1.1
S/B	0.14	0.16	0.67	0.15	0.2	0.32
Data	6	6	19	20	16	15

- had/had candidate event



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.



- Relatively new method to estimate di-tau invariant mass
  - A. Elagin, P. Murat, A. Pranko, A. Safonov (NIM A654 (2011), 481-489)
- In a τ decay, a fraction of the energy is carried by the neutrinos
- Full reconstruction requires solving for 6-8 unknowns:
  - x,y,z components of ν_τ's
  - $\nu_{e,\mu}$ invariant mass if W decays leptonically
- Practically, can use MET x,y components and visible masses of τ's to find constraints on missing parameters, but system is underconstrained
- Extra parameters:
  - angular distance between ν_τ & visible decay products

$$\not{E}_{T_x} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$
$$\not{E}_{T_y} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$
$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$
$$M_{\tau_2}^2 = m_{\text{mis}_2}^2 + m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$

- For each possible solution a reconstructed mass is created weighted by the output of a Likelihood function
  - Choose the mass with highest probability

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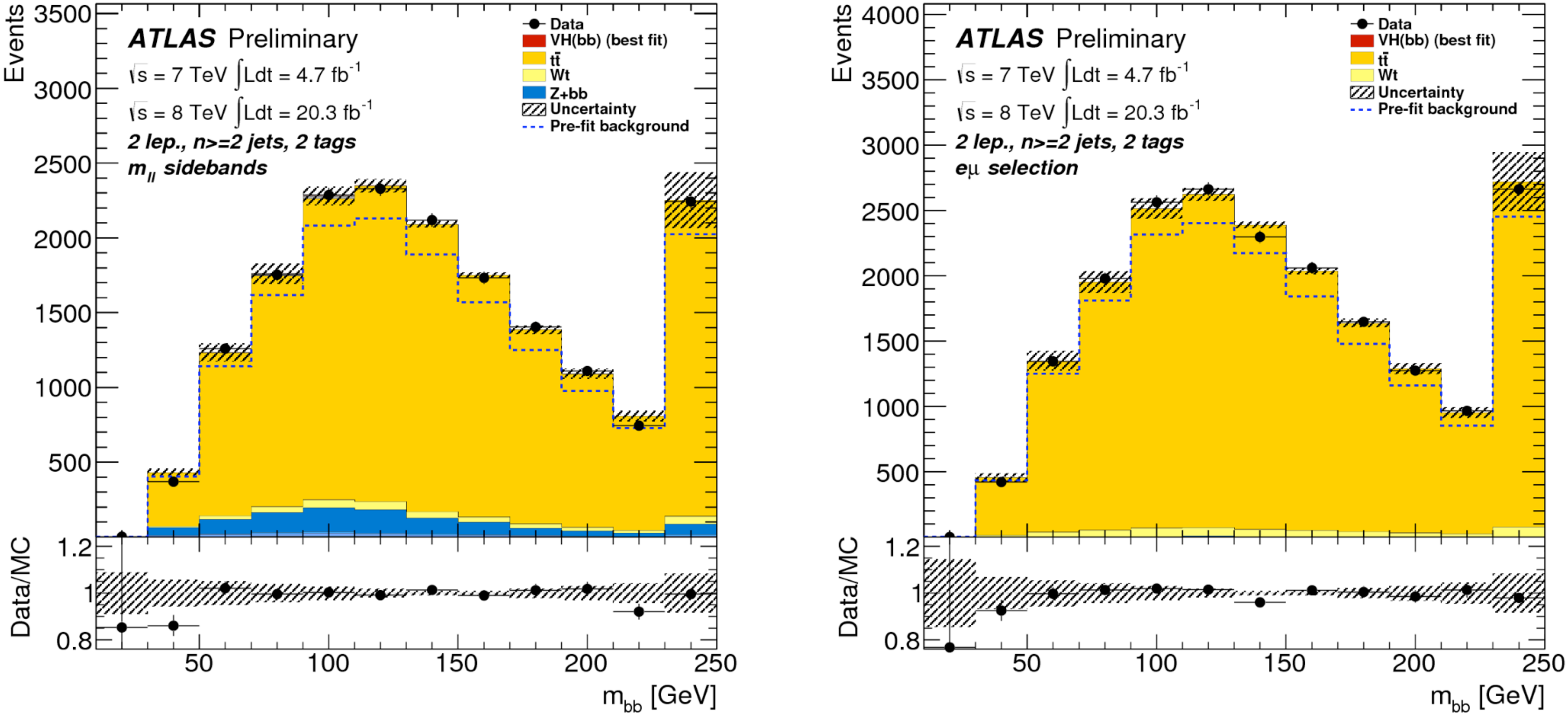
Table 1: The basic event selection for the three channels.

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_T^{\mathrm{jet}_1} > 45$ GeV $p_T^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_T^{\mathrm{miss}} > 120$ GeV $p_T^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_T^{\mathrm{miss}}, \boldsymbol{p}_T^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_T^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_T^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_T^{\mathrm{miss}} > 25$ Gev	$E_T^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_T^W < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

Table 2: Further topological criteria in p_T^V intervals. The 0-lepton channel does not use the lowest two p_T^V intervals.

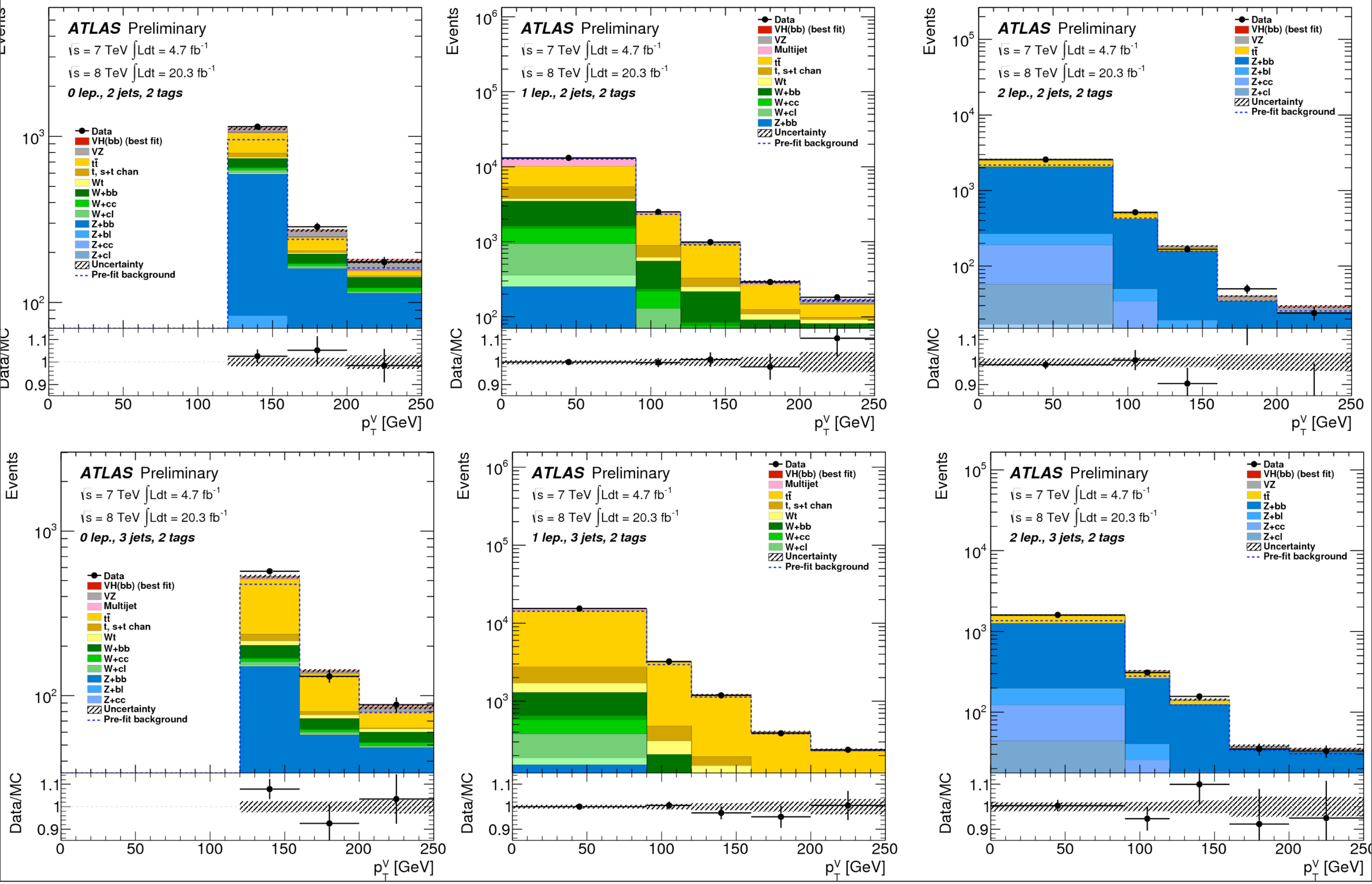
	p_T^V [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b, \bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	E_T^{miss} [GeV]	>25				>50
	m_T^W [GeV]	40-120			<120	

- The m_{bb} distribution in data and simulation for the top validation and control regions of the 2-lepton channel, with all p_T^V intervals combined. The validation region is defined by the mll sidebands (left), and the control region by the eμ selection (right); they are inclusive in jet multiplicity (n >= 2 jets).

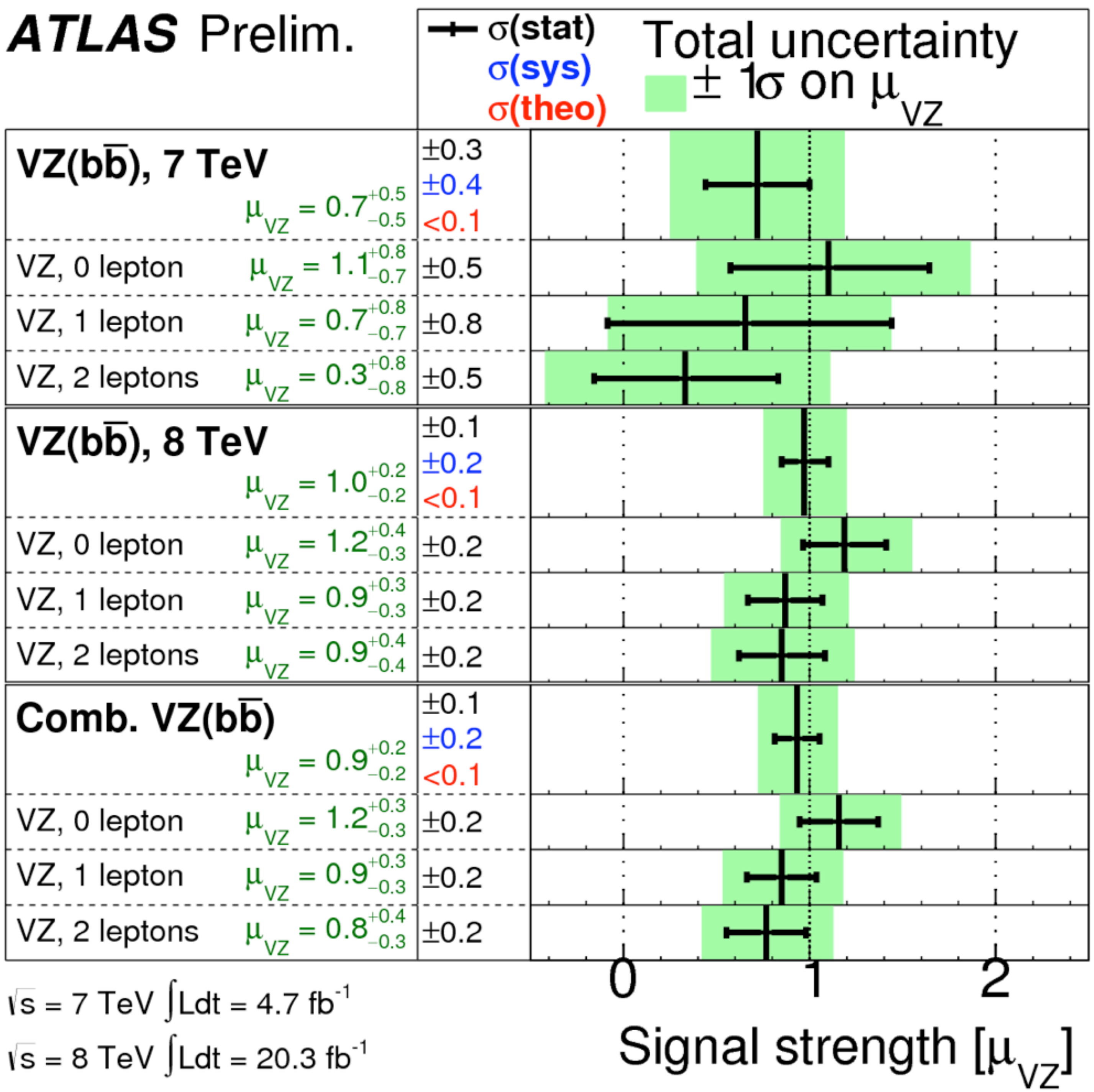


VH→bb

- p_T^V distributions for the 0,1,2 lepton channels, 2 jets (top) and 3 jets (bottom)



- The fitted diboson signal strength μ_{VZ} for the 7 TeV, 8 TeV, and combined datasets, and for the three channels separately and combined. The individual μ_{VZ}-values for the lepton channels are obtained from a simultaneous fit with the signal strength for each floating independently.



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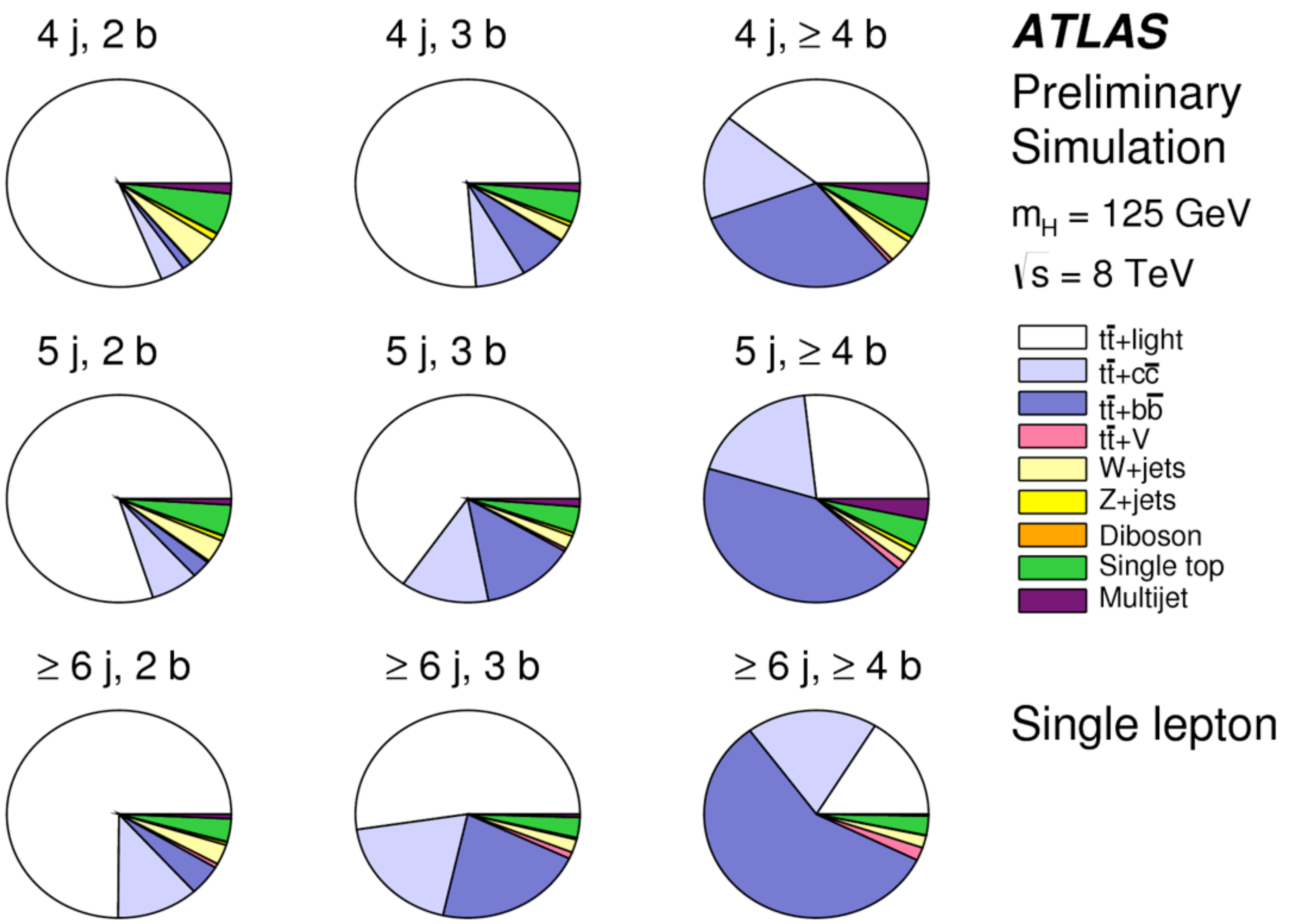
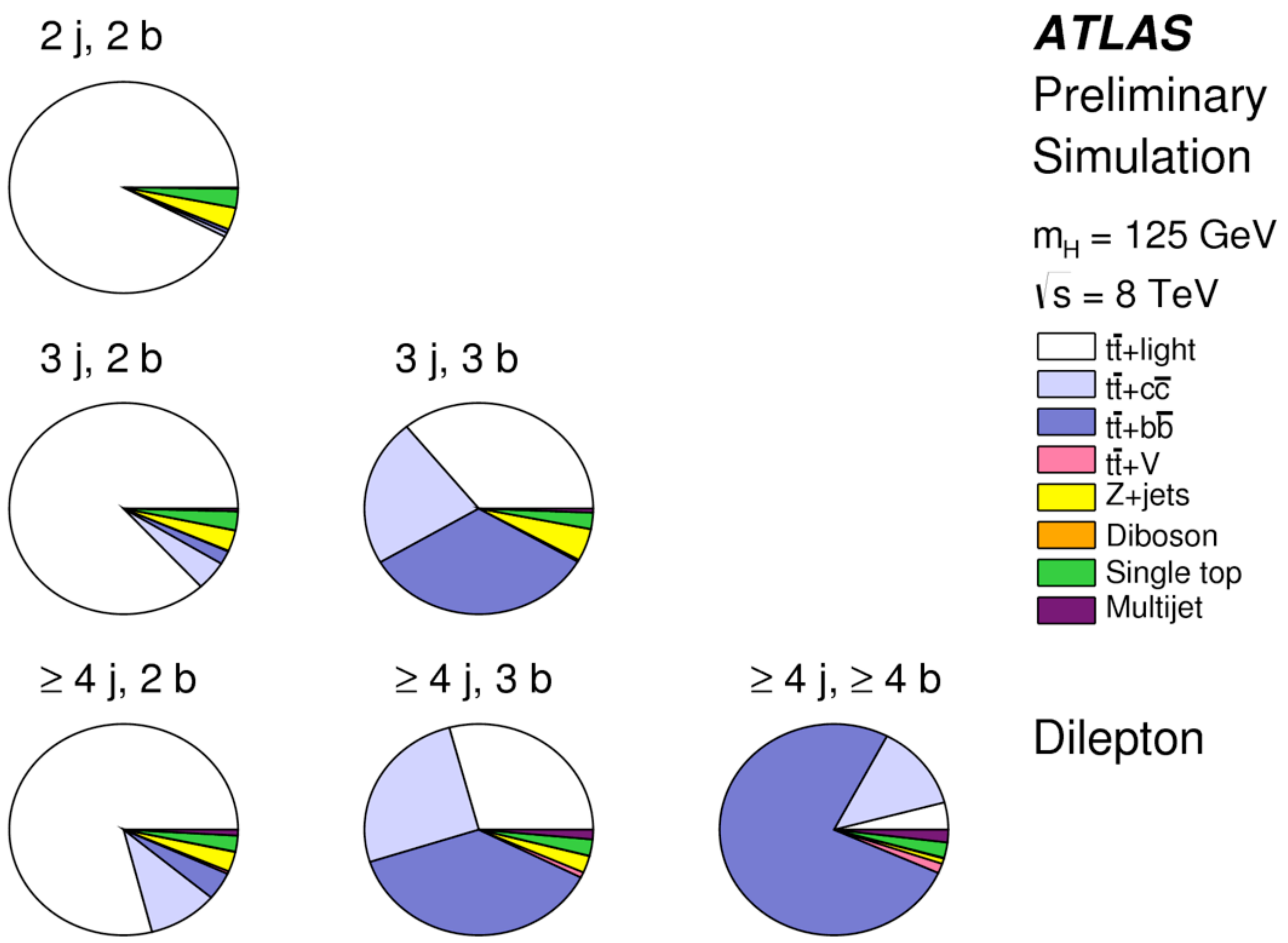
ATLAS EXPERIMENT

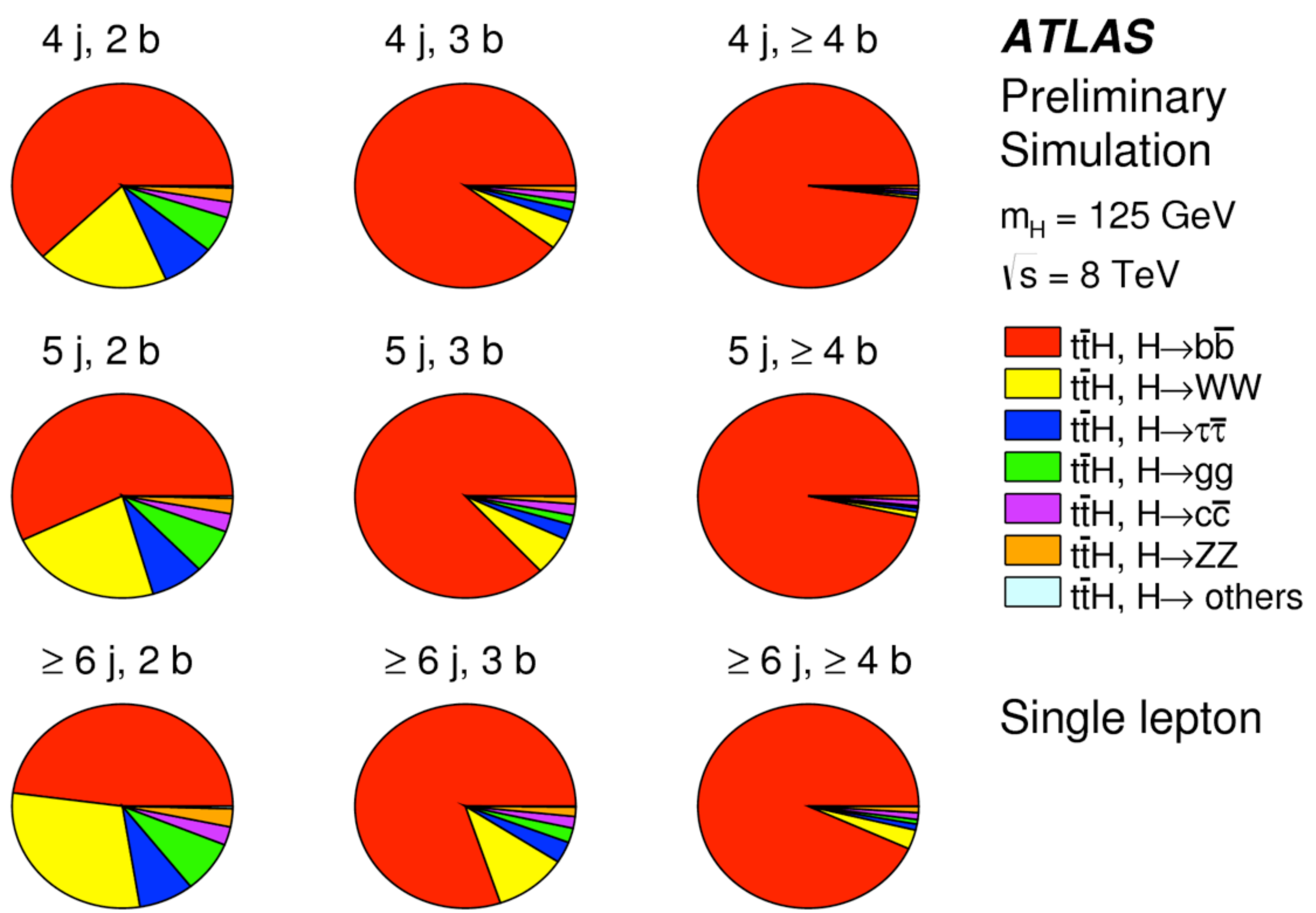
- The fractional contributions of the various backgrounds to the total background prediction in the single lepton selection



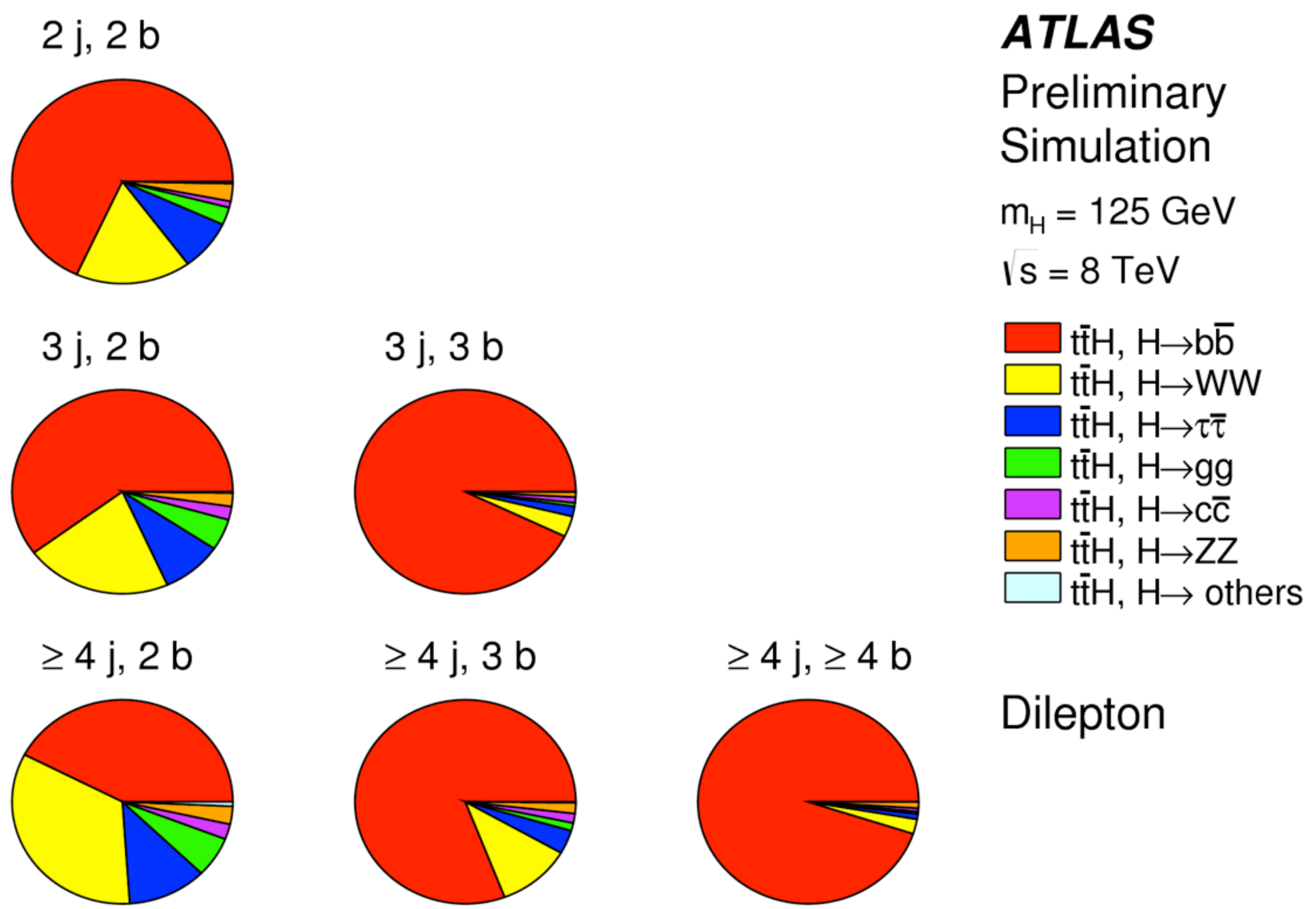
- The fractional contributions of the various backgrounds to the total background prediction in the dilepton channel.



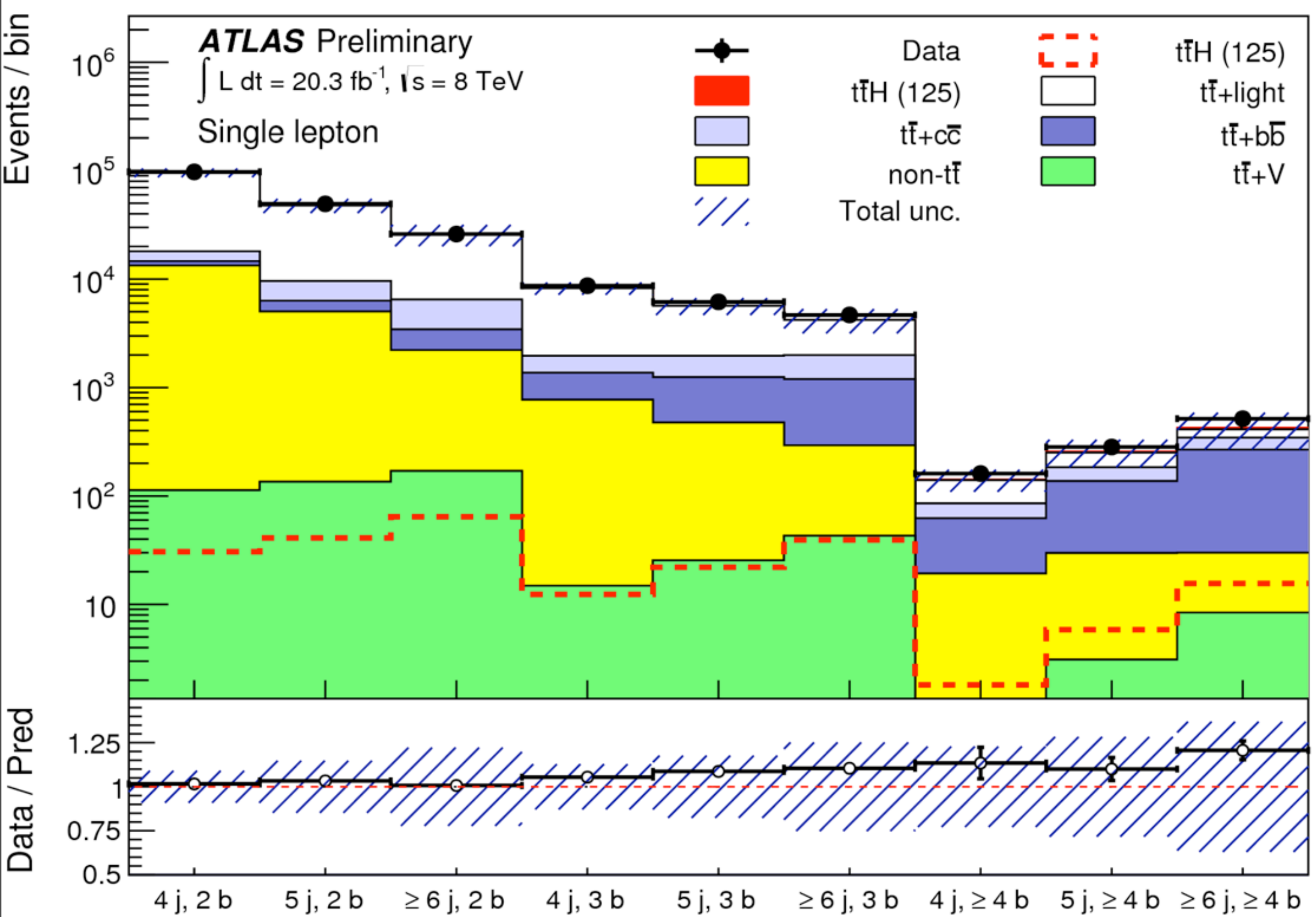
- Contribution of various Higgs boson decay modes to the analysis regions in the single lepton channel.

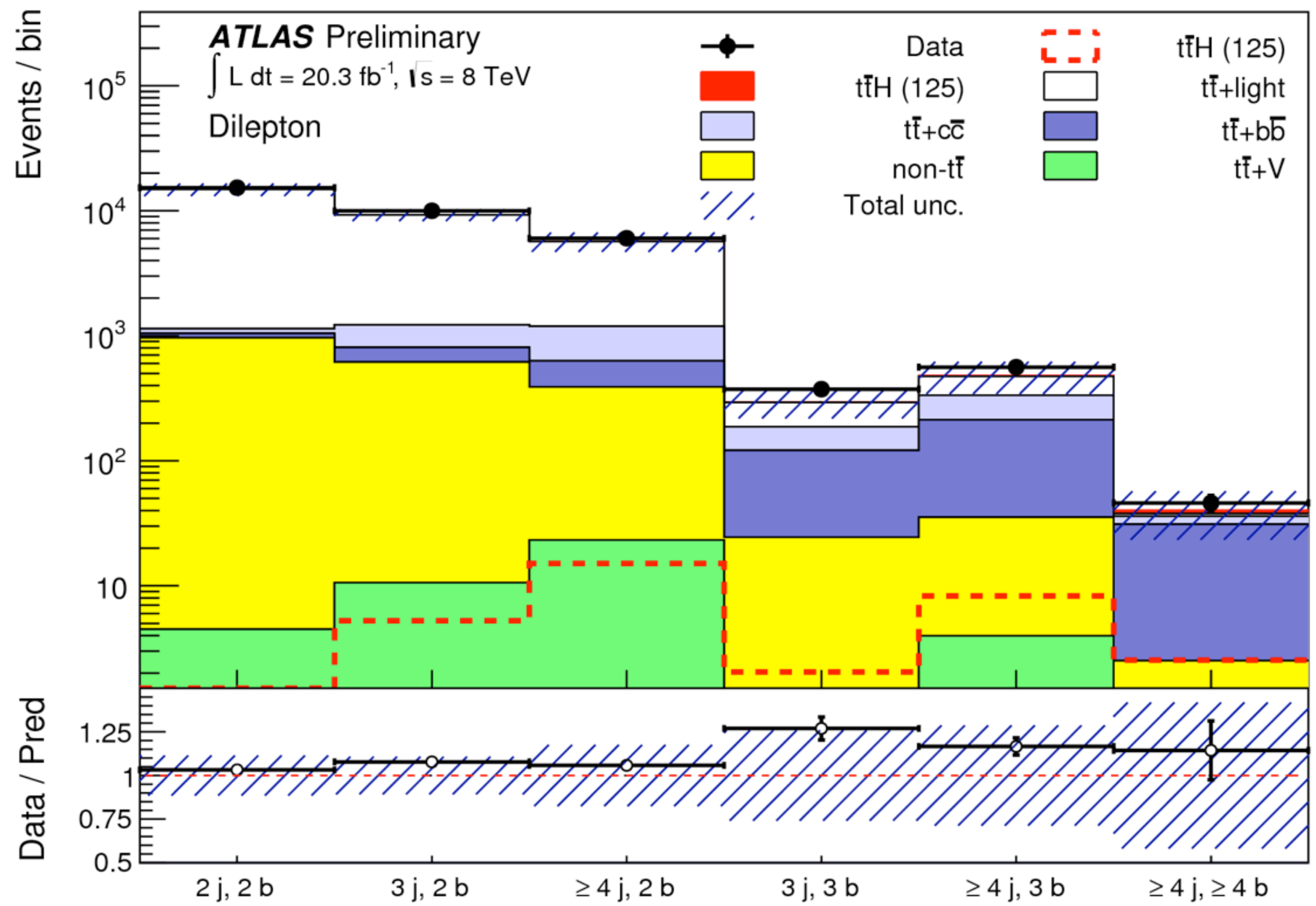


- Contribution of various Higgs boson decay modes to the analysis regions in the dilepton channel.

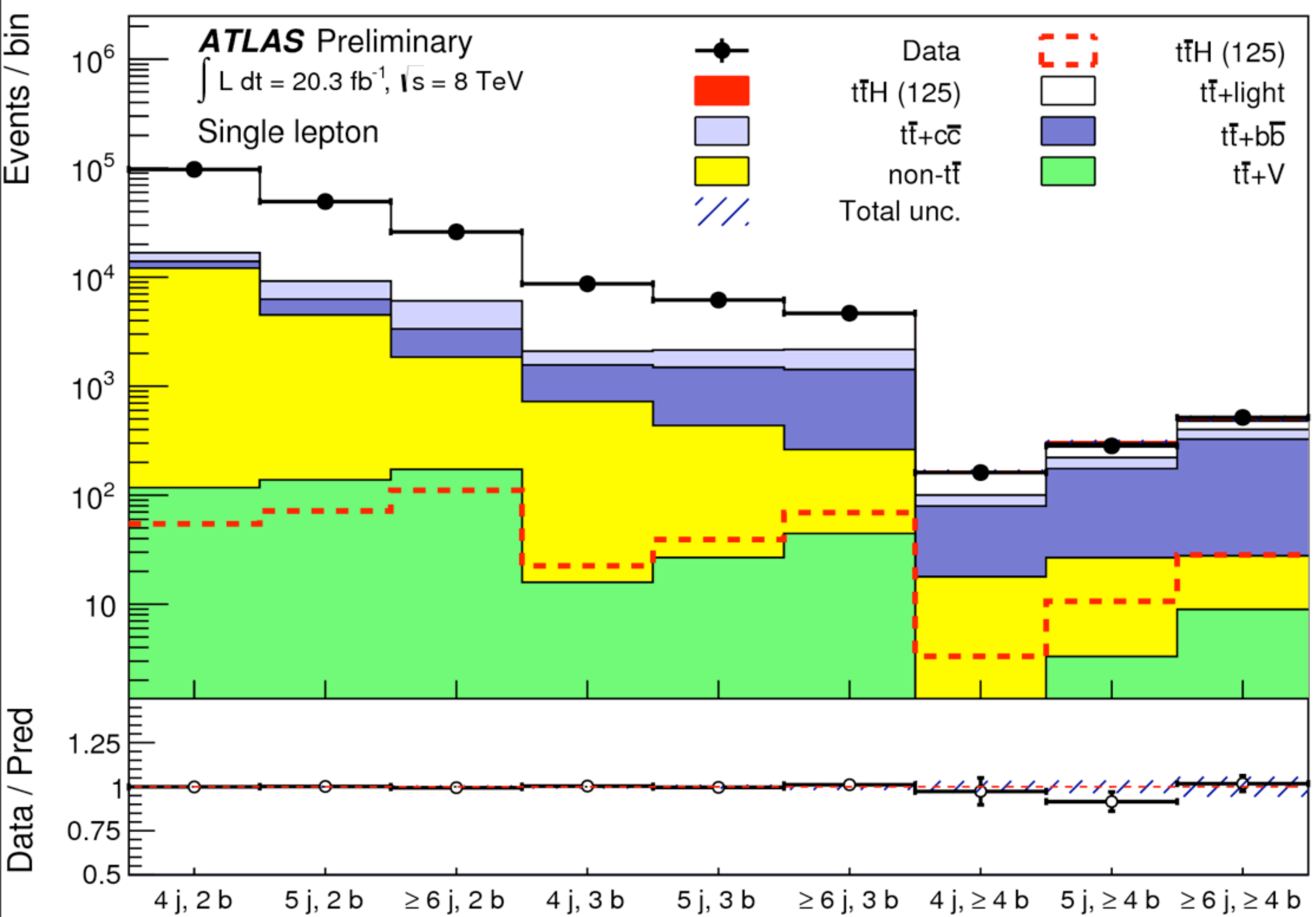


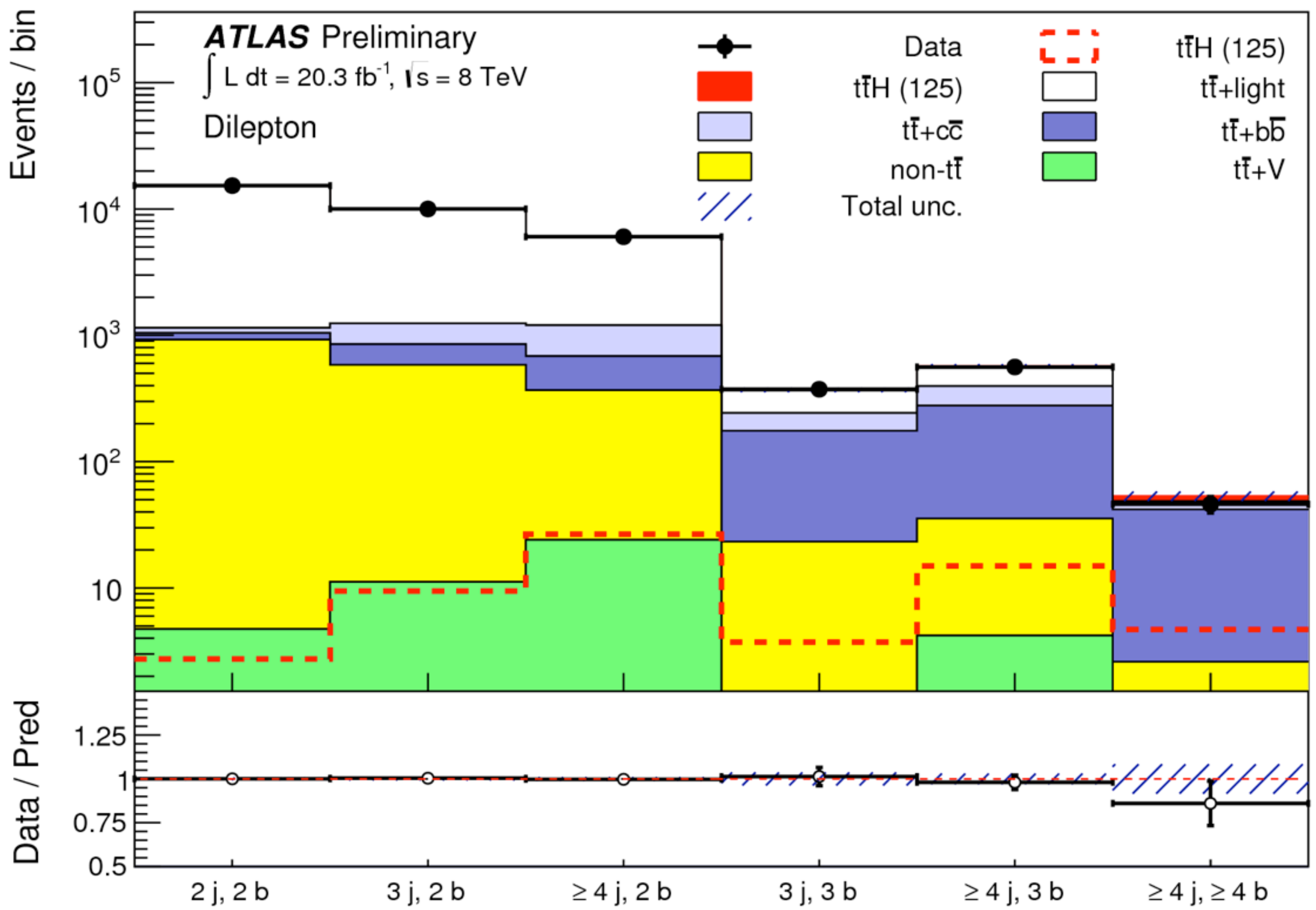
- Comparison of prediction to data in all analysis regions before the fit to data in the single lepton (left) and dilepton (right) channel





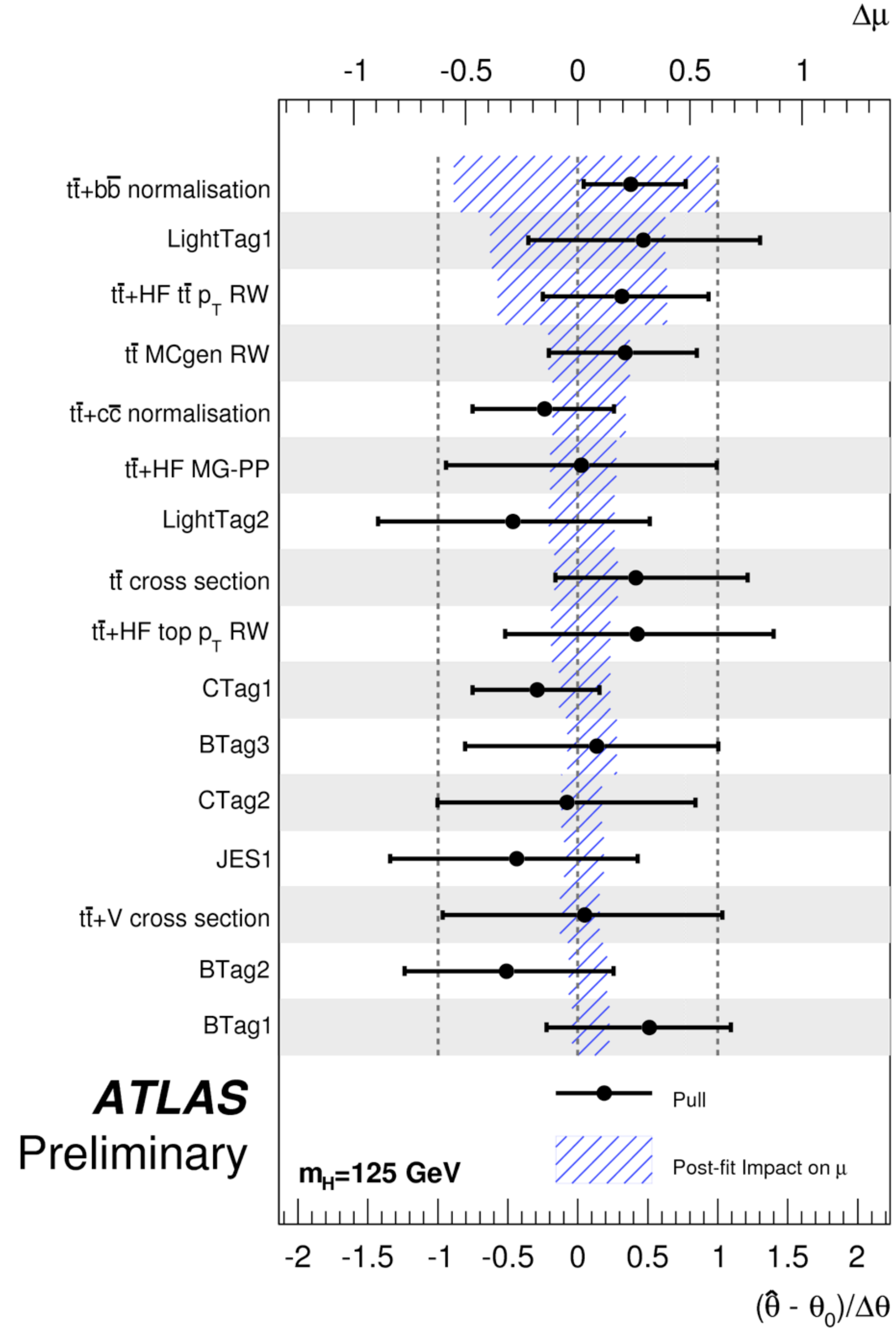
- Event yields in all analysis regions in the single lepton (left) and dilepton (right) channels after the combined fit to data under the signal-plus-background hypothesis





Systematic uncertainty	Type	Components
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	6
Light jet-tagging efficiency	SN	12
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	2
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}$+heavy-flavour: HF reweighting	SN	2
$t\bar{t}$+heavy-flavour: generator	SN	5
W+jets normalisation	N	3
W p_T reweighting	SN	1
Z+jets normalisation	N	2
Z p_T reweighting	SN	1
Multijet normalisation	N	3
Multijet shape dilepton	S	1
Single top cross section	N	1
Dibosons cross section	N	1
$t\bar{t}V$ cross section	N	1
Signal Model		
$t\bar{t}H$ modelling	SN	2

Table 8: List of systematic uncertainties considered. An "N" means that the uncertainty is taken as normalisation-only for all processes and channels affected, whereas an "S" denotes systematics that are considered shape-only in all processes and channels. An "SN" means that the uncertainty is taken on both shape and normalisation. Some of the systematic uncertainties are split into several components for a more accurate treatment (number indicated under the column labelled as "Components").



Spares

ATLAS vs CMS: differences in selection

	CMS	ATLAS
Lepton p_T	30 GeV	25 GeV
Muon η	$\lvert\eta\rvert < 2.1$	$\lvert\eta\rvert < 2.5$
Jet algo	anti-k_T 0.5	anti-k_T 0.4
Jet η	$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.5$
3 leading jets	$p_T > 40$ GeV	$p_T > 25$ GeV
Other jets	$p_T > 30$ GeV	$p_T > 25$ GeV
Other cuts	No E_T^{miss}, no M_T^W	No E_T^{miss}, no M_T^W
B-tagging	70% / 20% / 2%	70% / 20% / 1%

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Spares

ATLAS vs CMS: Pre-fit yields comparison

Single lepton	5 j, $\geq$ 4 b		$\geq$ 6 j, $\geq$ 4 b	
	CMS	ATLAS	CMS	ATLAS
$t\bar{t}H$	5.3	5.8	8.3	16
$t\bar{t}$+light	79	70	71	70
$t\bar{t}+c\bar{c}$	32	50	52	80
$t\bar{t}+b\bar{b}$	67	110	111	200
S/B	2.7%	2.3%	3.5%	4%
$S/\sqrt{B}$	0.37	0.36	0.54	0.84

Dilepton	CMS	ATLAS		
	$\geq$ 3 j, $\geq$ 3 b	3 j, 3 b	$\geq$ 4 j, 3 b	$\geq$ 4 j, $\geq$ 4 b
$t\bar{t}H$	11.2	2.0	8.3	2.5
$t\bar{t}$+light	289	105	138	1.6
$t\bar{t}+c\bar{c}$	147	70	120	5
$t\bar{t}+b\bar{b}$	229	100	180	29
S/B	0.02	0.01	0.02	0.06
$S\sqrt{B}$	0.43	0.12	0.39	0.40

Spares

ATLAS vs CMS: differences in systematic model

- Many differences in the systematic model
- HF normalisation
  - CMS: 50% on $t\bar{t}+b\bar{b}$, 50% on $t\bar{t}+b$, 50% on $t\bar{t}+c\bar{c}$ and additional 50% on $t\bar{t}$+HF
  - ATLAS: 50% on $t\bar{t}+b\bar{b}$,50% on $t\bar{t}+c\bar{c}$
- Modelling
  - CMS: using Madgraph sample, top p_T reweighting ON/OFF, 1 Madgraph scale variation uncorrelated in $t\bar{t}+b\bar{b}$, $t\bar{t}+b$, $t\bar{t}+c\bar{c}$ and $t\bar{t}$+light
  - ATLAS: using Powheg+Pythia, 9 components from top p_T and $t\bar{t}$ p_T measurements for $t\bar{t}$+light; reweighting ON/OFF for $t\bar{t}$+HF uncorrelated; parton shower; generator (comparison with Madgraph)
- Jet energy scale
  - CMS: 1 JES
  - ATLAS: 22 JES components
- *b*-tagging
  - CMS: fully continuous MVA spectrum; linear and parabolic shape distortions; no calibration for *c*-jets
  - ATLAS: components for *b*, *c* and light jets (6/6/12)
- Checked ATLAS sensitivity only mildly-dependent on assumed systematics model.
- Difference in sensitivity primarily originates from the better $S/\sqrt{B}$. Also helpful is the higher background statistics in the signal-depleted regions, which allows greater constraining power of systematic uncertainties.

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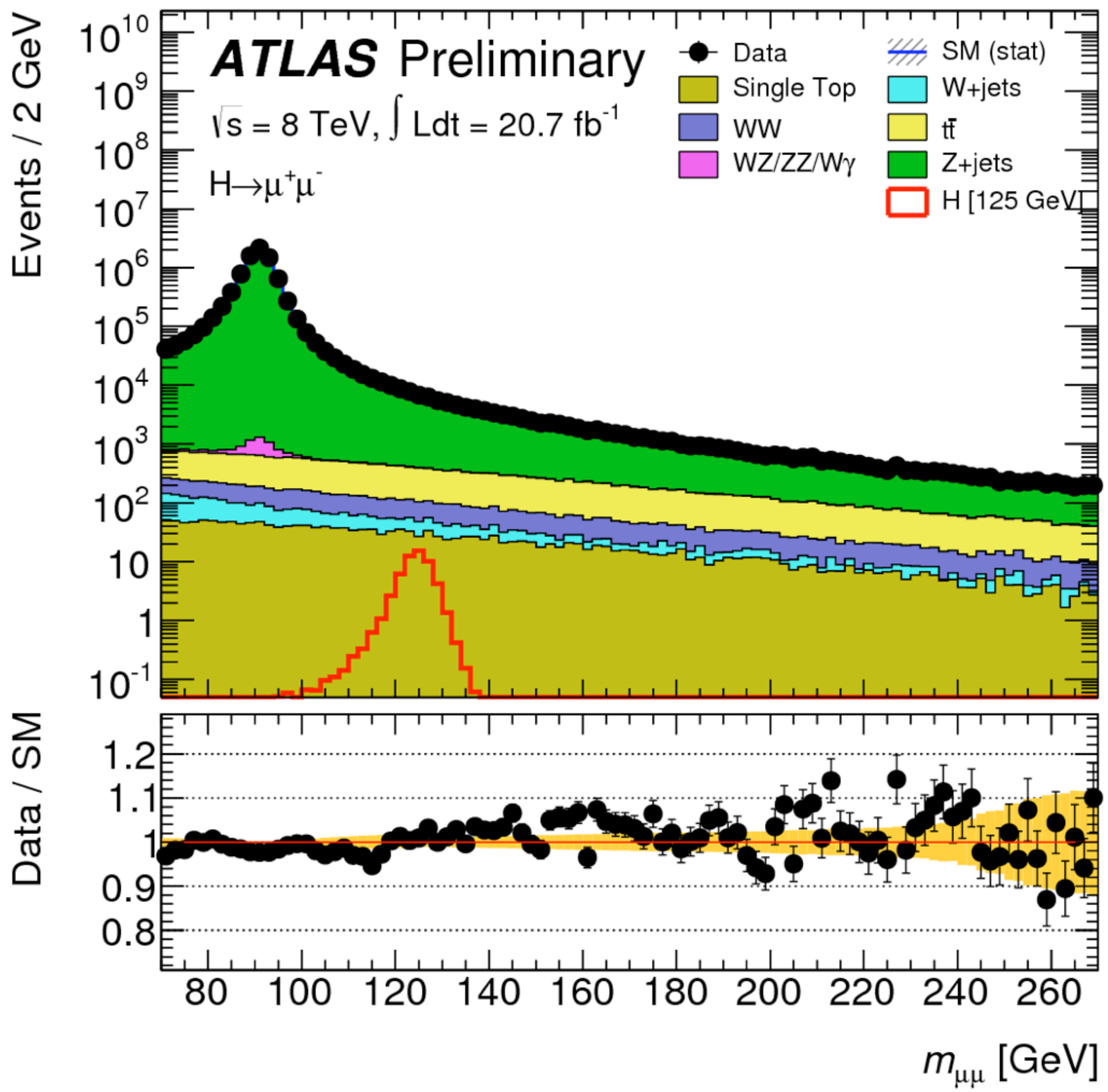
H→μμ



ATLAS Preliminary
√s = 8 TeV, ∫ Ldt = 20.7 fb-1
H→μ+μ-
Data
Single Top
WW
WZ/ZZ/Wγ
SM (stat)
W+jets
tt̄
Z+jets
H [125 GeV]
Events / 2 GeV
Data / SM
m_μμ [GeV]

	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

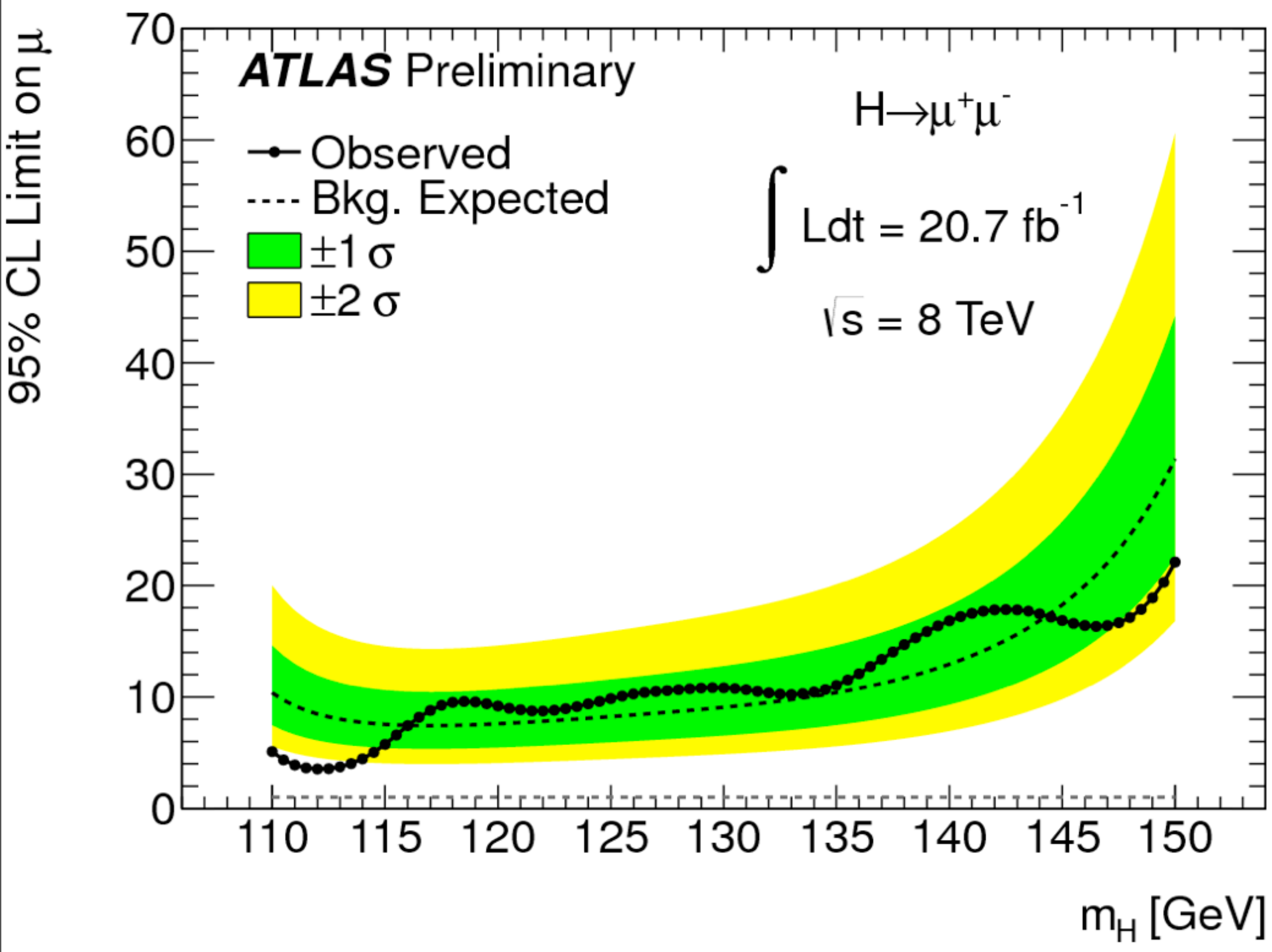
Table 1: Number of expected signal events for $m_H = 125$ GeV, number of the expected MC background events and number of the observed data events within $\lvert m_H - m_{\mu^+\mu^-}\rvert \leq 5$ GeV window after all selection criteria applied. Only statistical uncertainties are given. The numbers shown in this table have been rounded.

Uncertainty	Upward [%]	Downward [%]
Ren./Fac. Scale	0.1	-0.3
ISR	1.3	-2.5
FSR	-0.4	0.1
PDF	0.2	0.2
Total inclusive	+1.3	-2.6

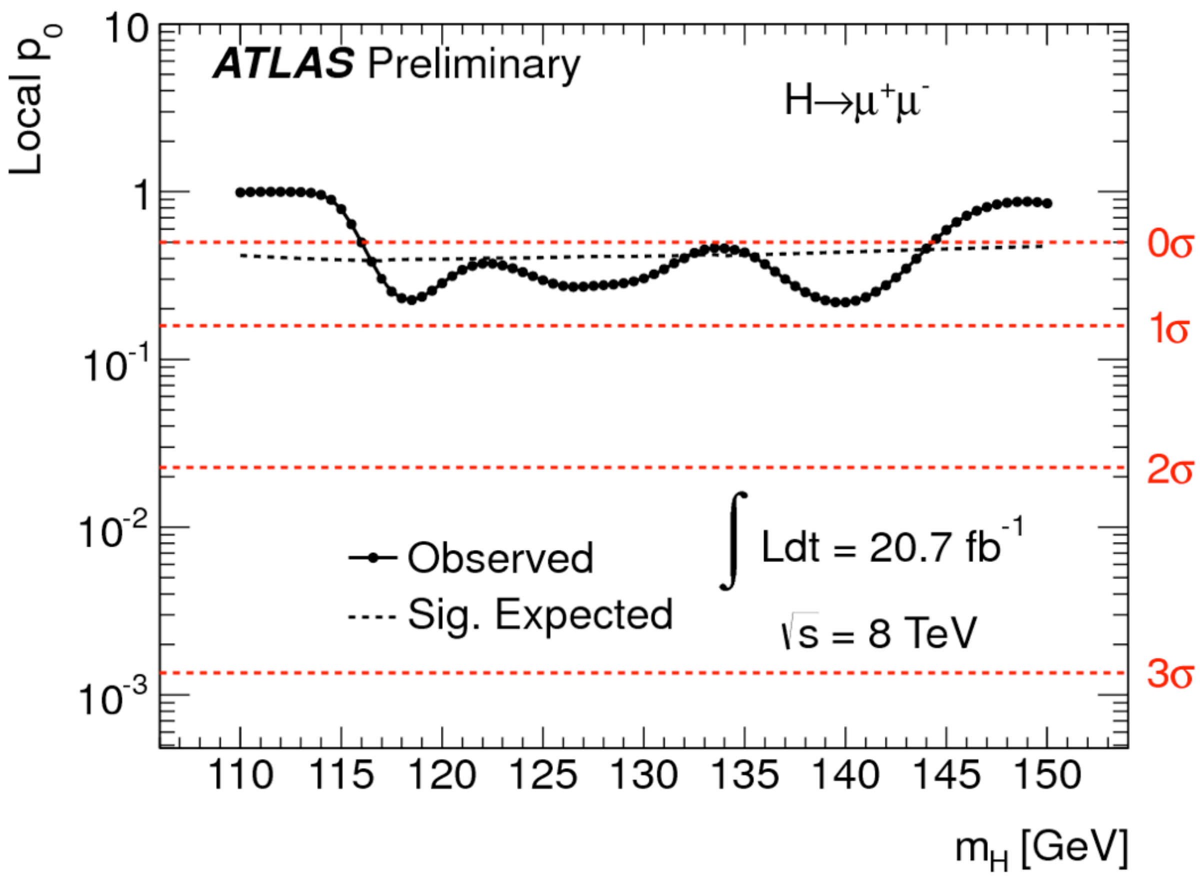
Table 3: Summary of signal acceptance uncertainties due to theoretical sources.

Source of Uncertainty	Treatment in the analysis
Luminosity	3.6%
Muon Selection Efficiency	0.3-1% as a function of η and p_T
Muon Momentum Scale and Resolution	$<$ 1%
Muon Trigger	$<$ 1%
Muon Track Isolation	$<$ 1%
Pile-up reweighting	$<$ 1%

Table 4: Summary of signal normalization uncertainties due to experimental sources.



- Main systematic uncertainties:
  - cross-section: ~15% ggF, ~3% VBF
  - BR: ~6%
  - Acceptance: ~2.6% (th) and 4.2% (exp)
  - Lumi: 3.6%



ttH production with H→γγ (ATLAS-CONF-2013-080)

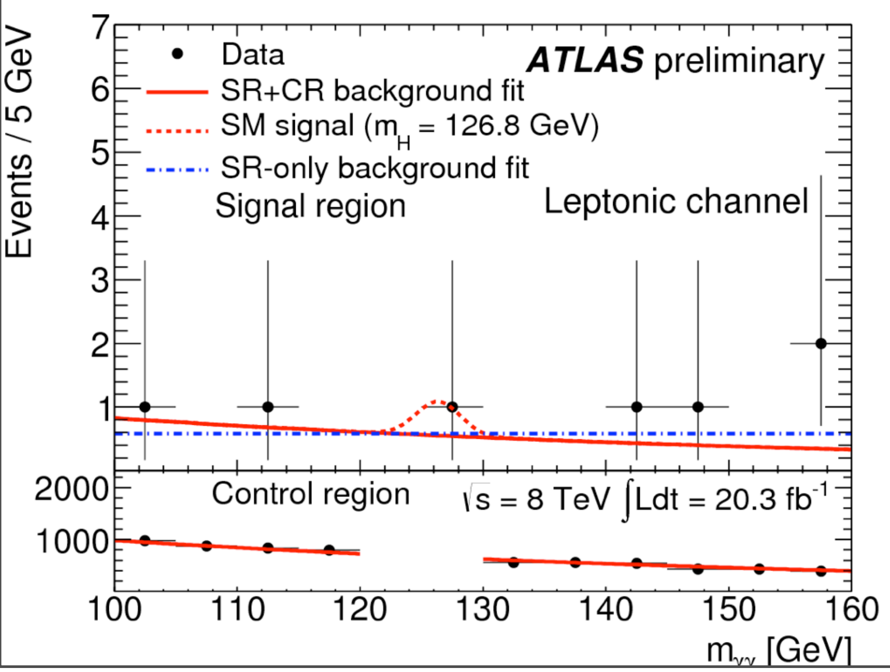
- 20.3 fb^{-1} 8 TeV data
- Analysis covers leptonic (single and dilepton) and hadronic channels of tt decay
- Cut-based analysis with profile likelihood fit to $m_{\gamma\gamma}$
  - Signal: Crystal Ball + Gaussian
  - Background: exponential

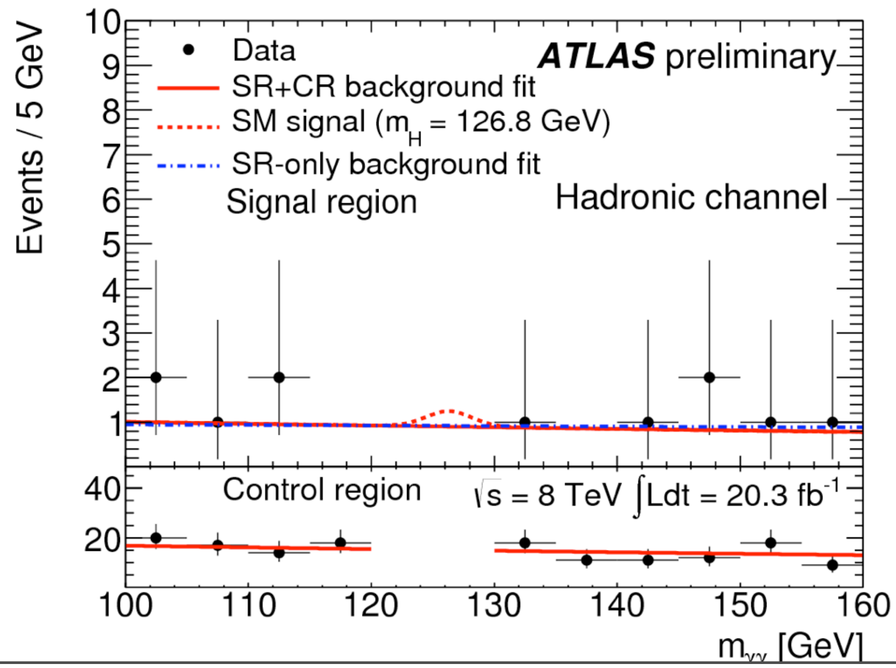
Leptonic	Hadronic
p_T^γ > 40 (30) GeV for leading (subleading) photon	
at least 1 *e* (μ) > 15 (10) GeV at least 1 b-tagged jet ETmiss > 20 GeV	no leptons at least 6 jets at least 2 b-tagged jets

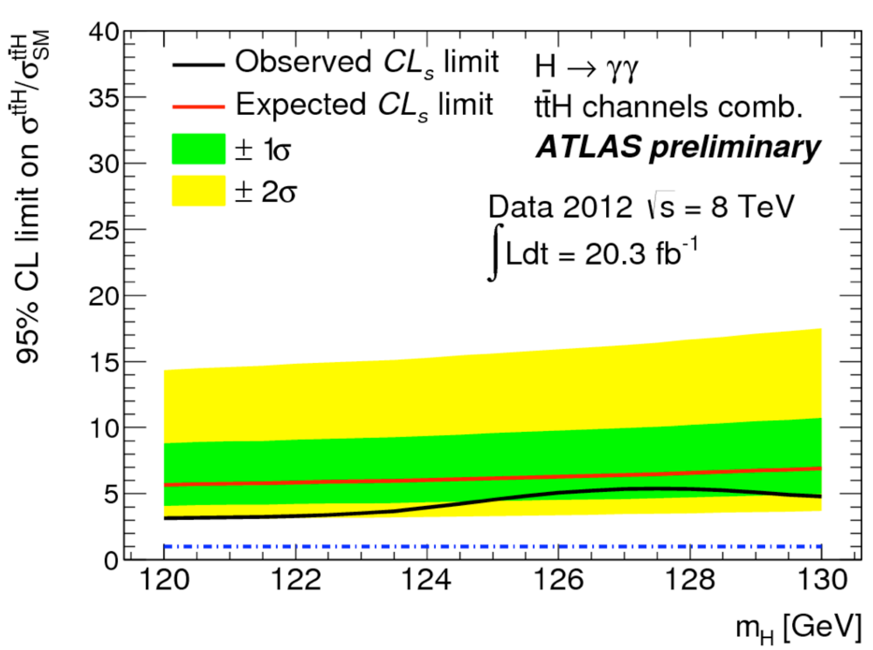
Dominant systematics:

	Leptonic	Hadronic
xsec:	~ 12 %	
BR:	~5 %	
QCD scale:	~3 %	~10 %
Lumi:	~ 2.8 %	

- Overall no excess above predicted background
- Observed (expected) 95% CL upper limits on signal strength for m_H = 126.8 GeV:
  - 5.3 (6.4) x SM expectation







Higgs Production Cross Sections and BR's