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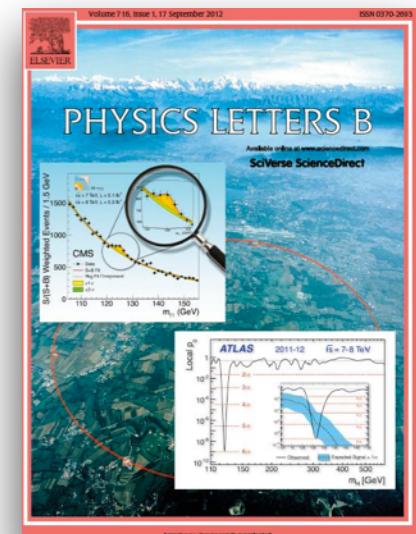
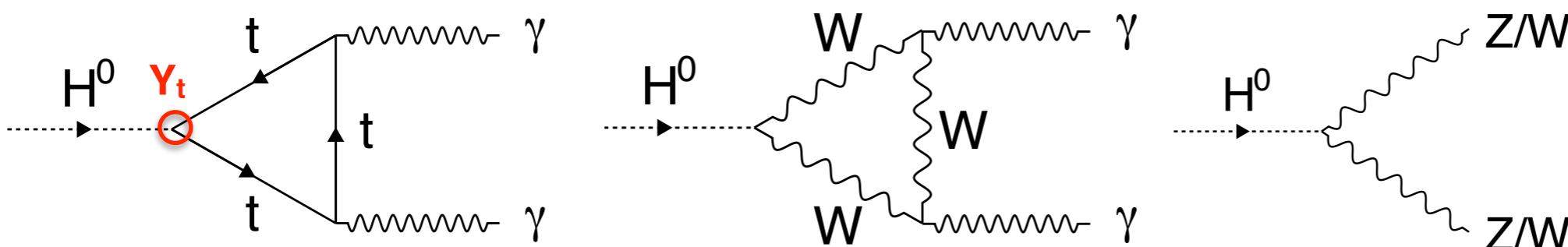
Search for the Higgs boson in fermionic channels using the ATLAS detector

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on the behalf of the ATLAS Collaboration**

**Phenomenology 2014
05/May/2014**

Introduction

- Summer 2012 : ATLAS/CMS experiment made great success,
“Discovery of Higgs boson with mass ~125.5GeV”
- Observation by “only” Bosonic mode : $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$
- Result of property measurement compatible with SM Higgs.



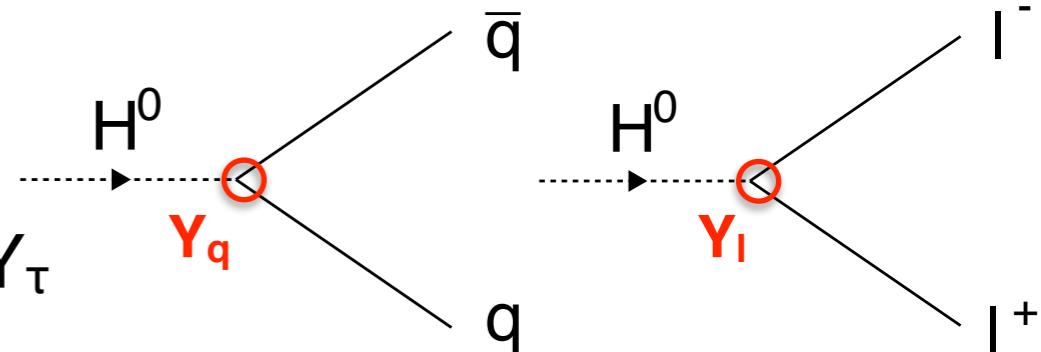
- Important question: **Does discovered Higgs boson couple to fermion?**
- Higgs-Quark coupling**

Indirectly confirmed by $H \rightarrow \gamma\gamma$ and gluon fusion Higgs production.

Direct measurement is necessary: Y_t , Y_b

- Higgs-Lepton coupling**

Only possible by direct measurement : Y_μ , Y_τ



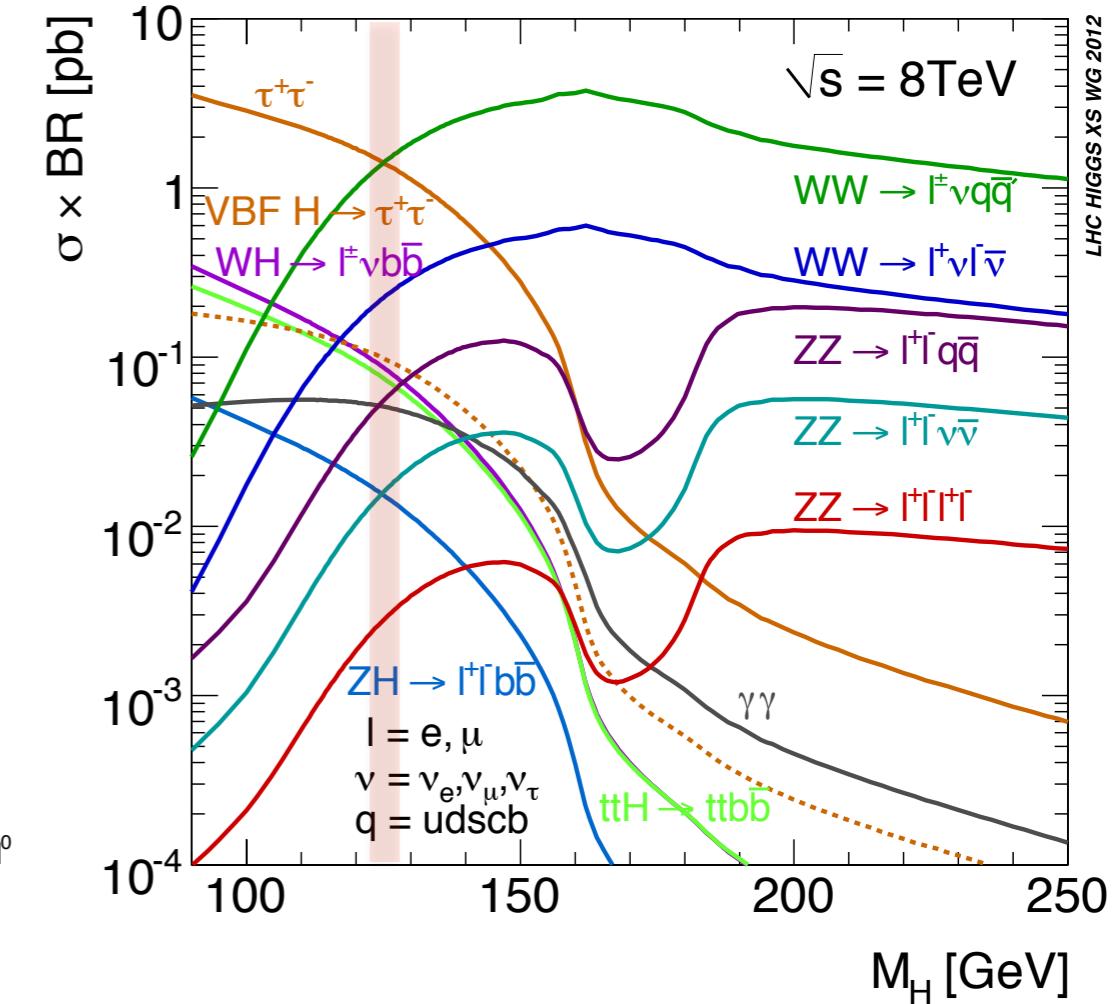
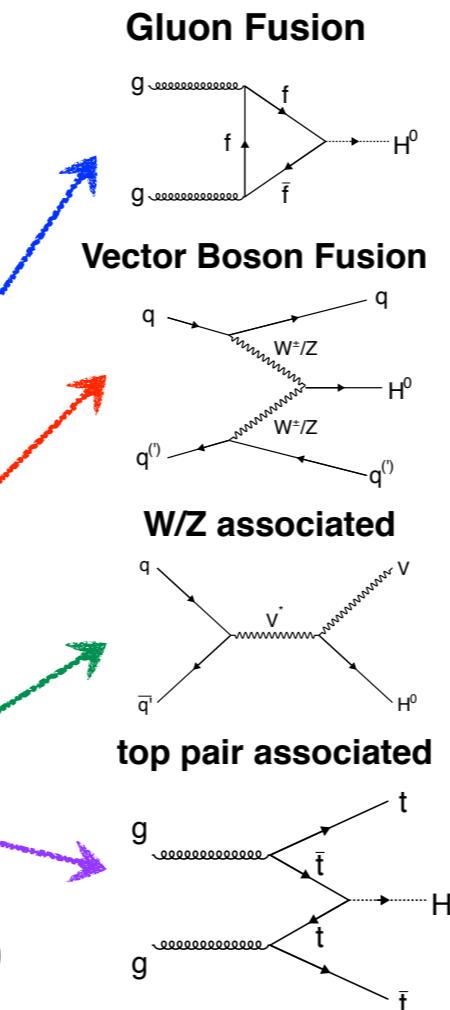
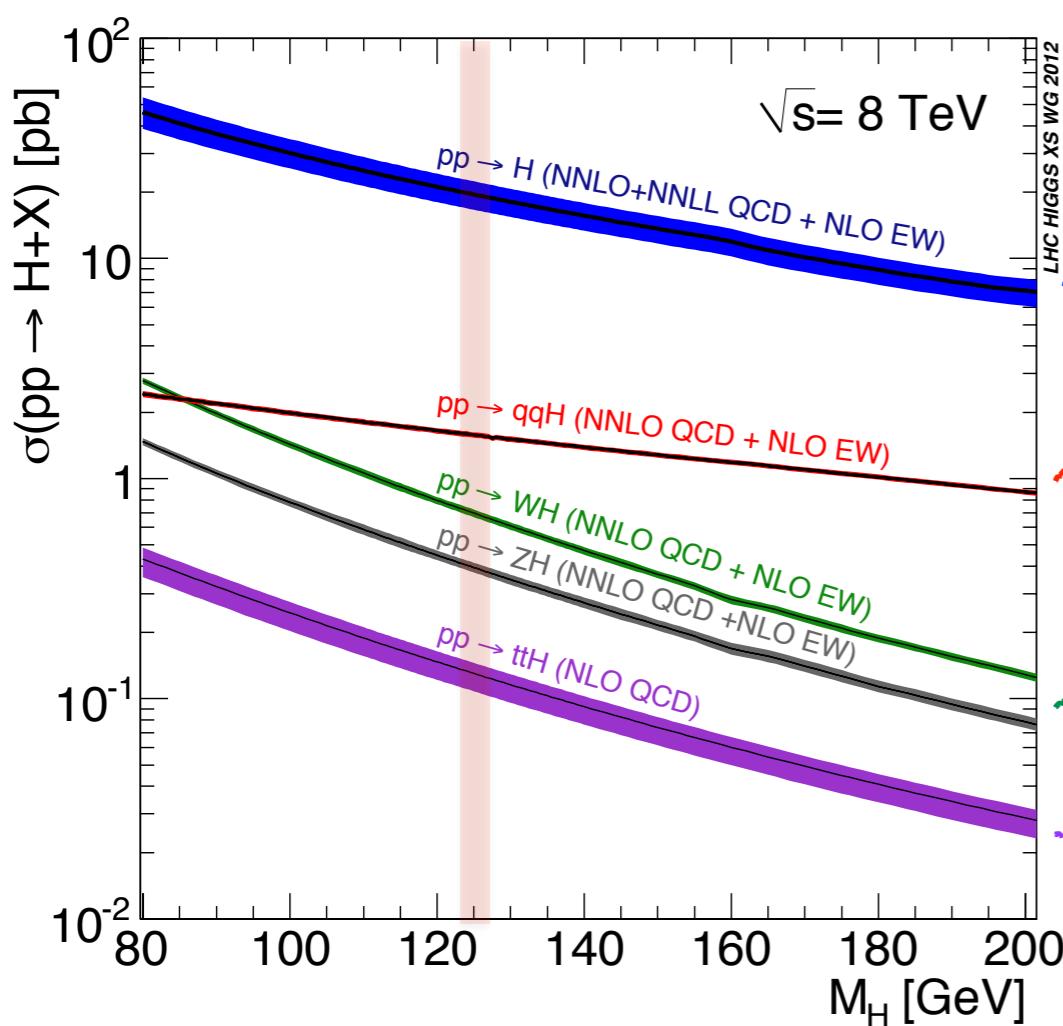
Contents

- **Higgs Boson Searches in Fermionic channels**
 - ▶ VH ($H \rightarrow b\bar{b}$) Search with 7 + 8TeV (2011+2012) data
ATLAS-CONF-2013-079
 - ▶ $t\bar{t}H(H \rightarrow b\bar{b})$ Search with 8TeV (2012) data
ATLAS-CONF-2014-011
 - ▶ $H \rightarrow \mu\mu$ Search with 8TeV (2012) data
ATLAS-CONF-2013-010
 - ▶ $H \rightarrow \tau\tau$ Search with 8TeV (2012) data
ATLAS-CONF-2013-108

Other Higgs Talks

- ▶ Higgs Properties by James Saxon & Kathleen Whalen
- ▶ BSM Higgs by Daniel Pelikan

Higgs “Phenomenology” in LHC



- **Gluon Fusion (ggH)** : most dominant production, $H \rightarrow \tau\tau/\mu\mu$
- **Vector Boson Fusion (VBF)** :
good separation by 2 forward jets, main channel in $H \rightarrow \tau\tau$
- **W/Z associated (VH)** :
main channel in $H \rightarrow b\bar{b}$, clean signature by lepton from W/Z
- **top pair associated (ttH)** :
important channel for top Yukawa (Y_t) with $H \rightarrow b\bar{b}$ decay

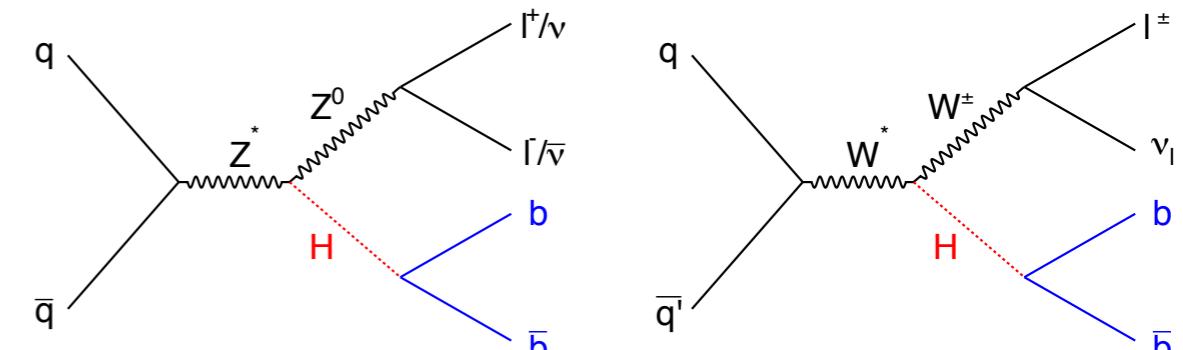
channel	$\sigma \times B.R$ [pb]
$H \rightarrow \tau\tau$	~1.3
$VH \rightarrow b\bar{b}$	~0.1
$t\bar{t}H \rightarrow b\bar{b}$	~0.07
$H \rightarrow \mu\mu$	~0.0002

VH ($H \rightarrow b\bar{b}$) : Overview

- Associated production with W/Z boson decaying leptonically.
- Define **3 channels** according to the number of leptons.

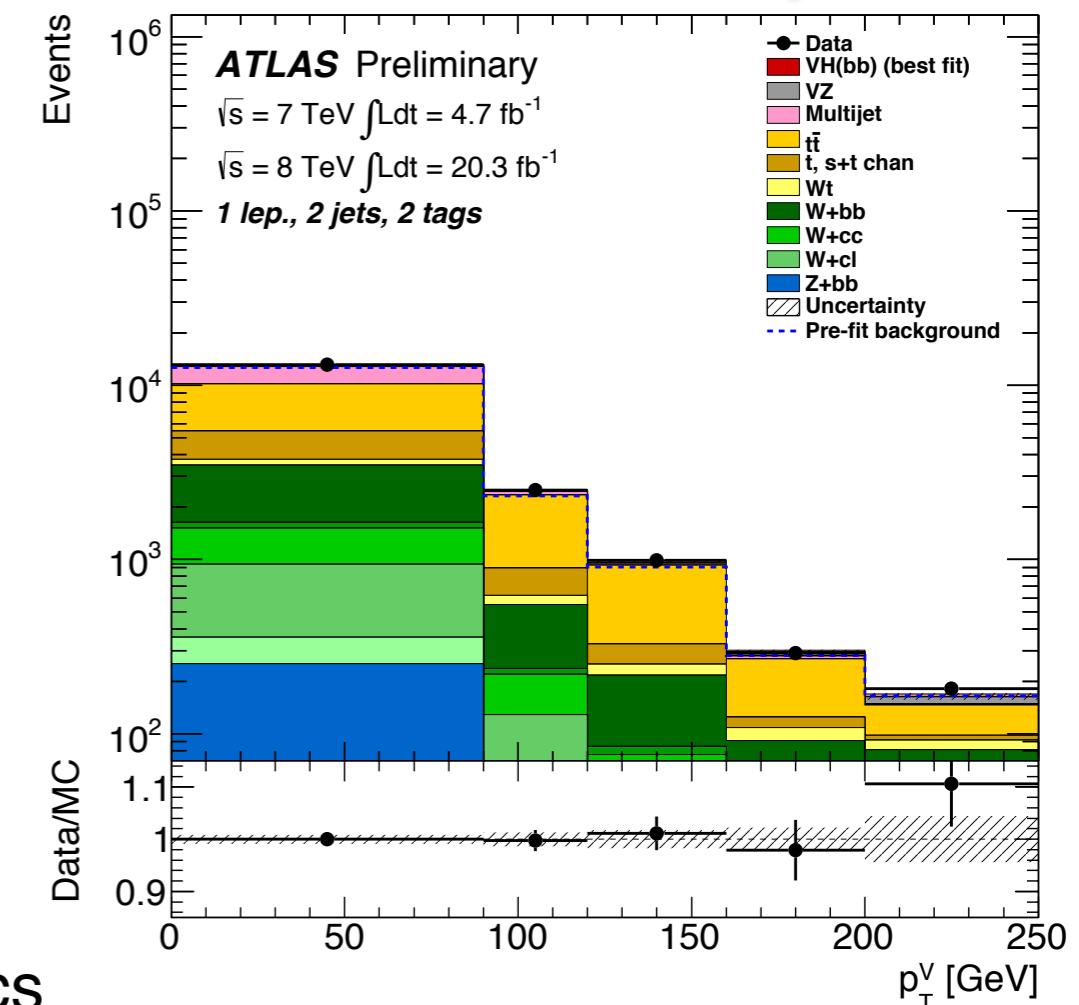
	2 lepton	1 lepton	0 lepton	2 lepton : $ZH \rightarrow ll + b\bar{b}$ 0 lepton : $ZH \rightarrow v\bar{v} + b\bar{b}$	1 lepton : $WH \rightarrow lv + b\bar{b}$
Process	$ZH \rightarrow ll + b\bar{b}$	$WH \rightarrow lv + b\bar{b}$	$ZH \rightarrow v\bar{v} + b\bar{b}$		
Event selection	2 b-tag jets 2 or 3 jets 2 OS leptons	2 b-tag jets 2 or 3 jets 1 lepton MET	2 b-tag jets 2 or 3 jets Large MET		
Main background	$Z + \text{jets}$	$\text{top}, W/Z + \text{jets}$	$\text{top}, W + \text{jets}$		

- Categorization by bins of N_{jets} and p_T^V to maximize sensitivity.
- Search signal excess in invariant mass of **2 b-tag jets (M_{bb})** for each category.
- Simultaneous fit in 26 signal regions and (26 1 b-tag + 5 top) control regions.
 \rightarrow normalize background & constrain systematics

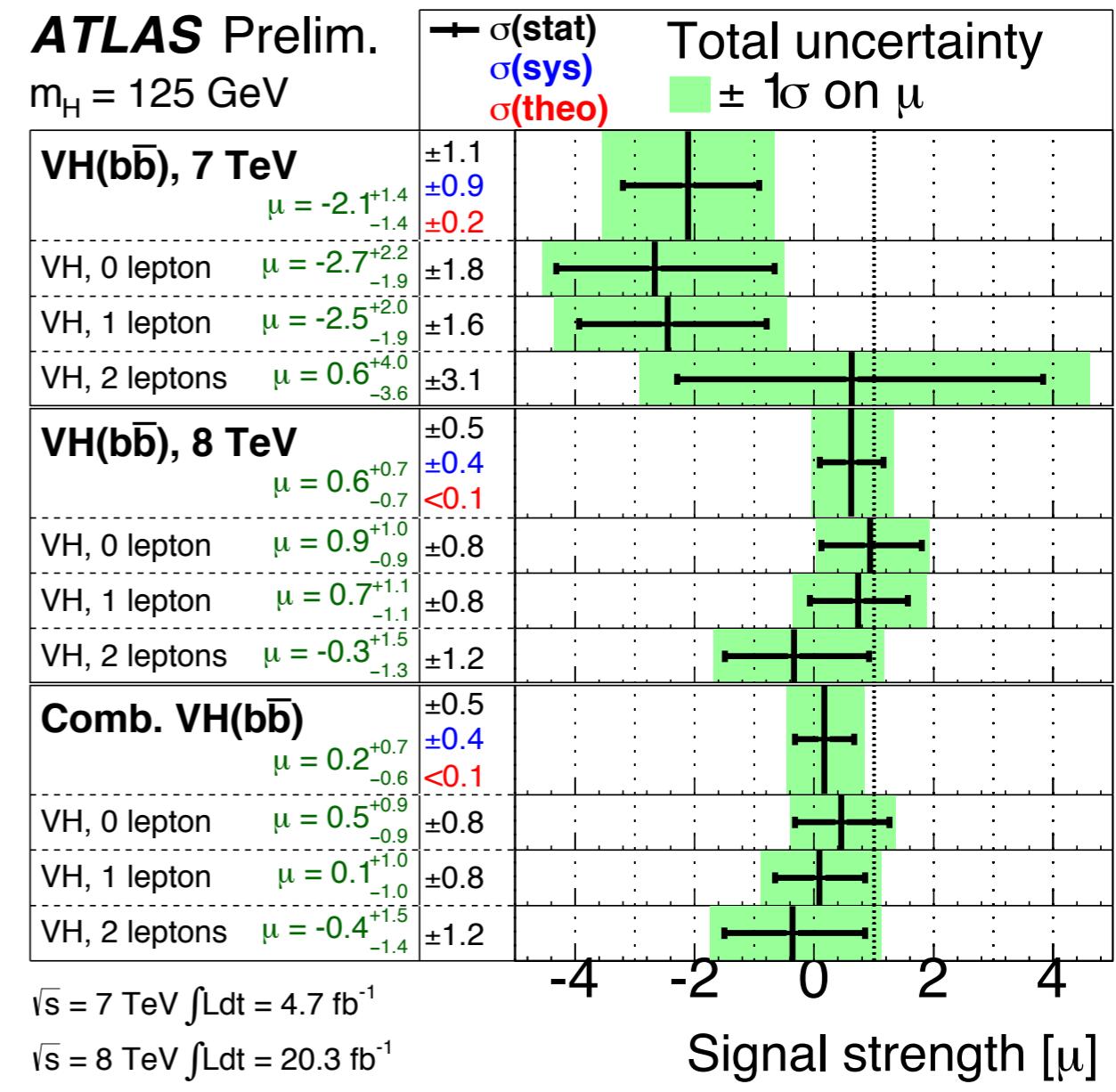
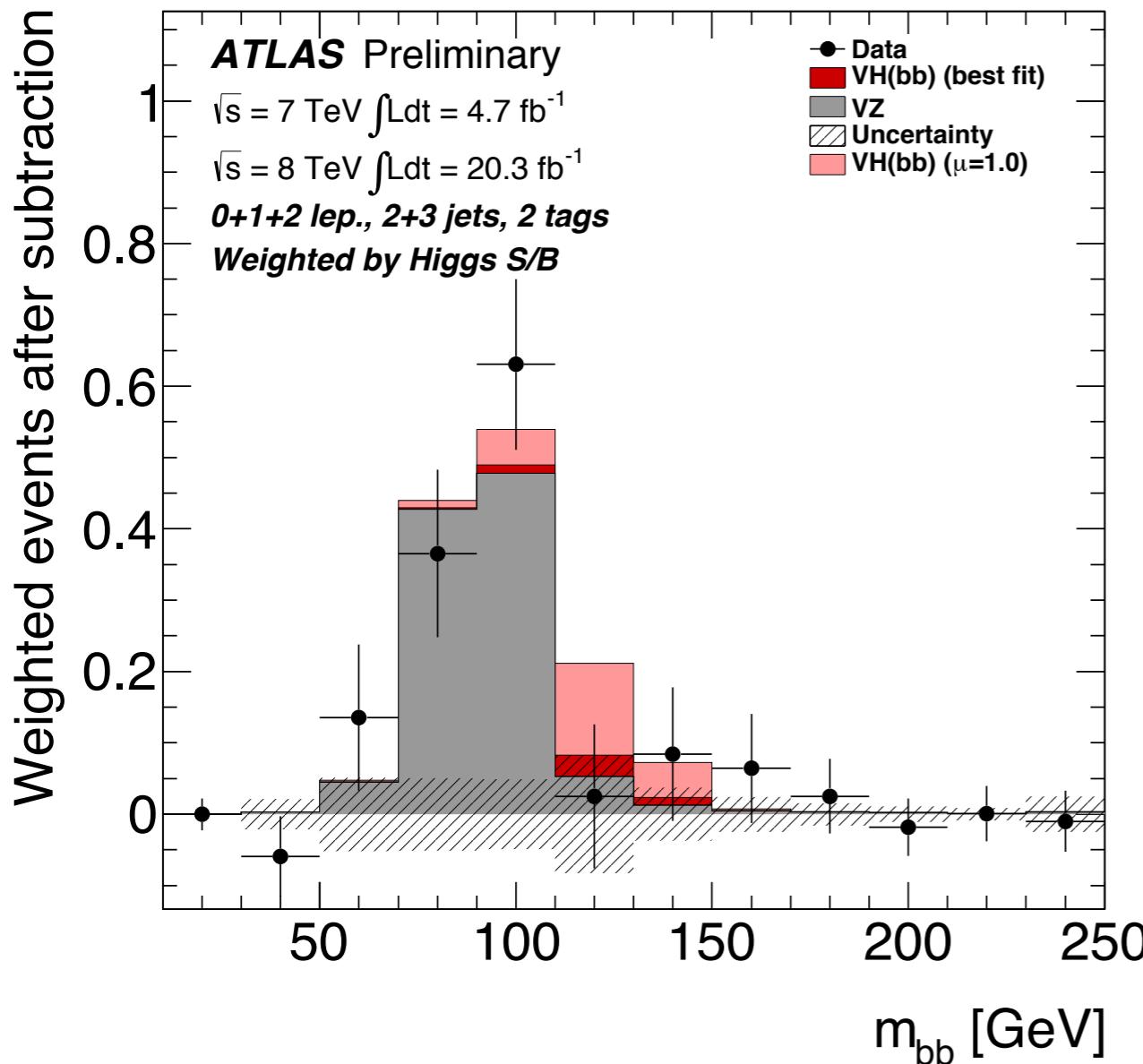


2 lepton : $ZH \rightarrow ll + b\bar{b}$
0 lepton : $ZH \rightarrow v\bar{v} + b\bar{b}$

1 lepton : $WH \rightarrow lv + b\bar{b}$



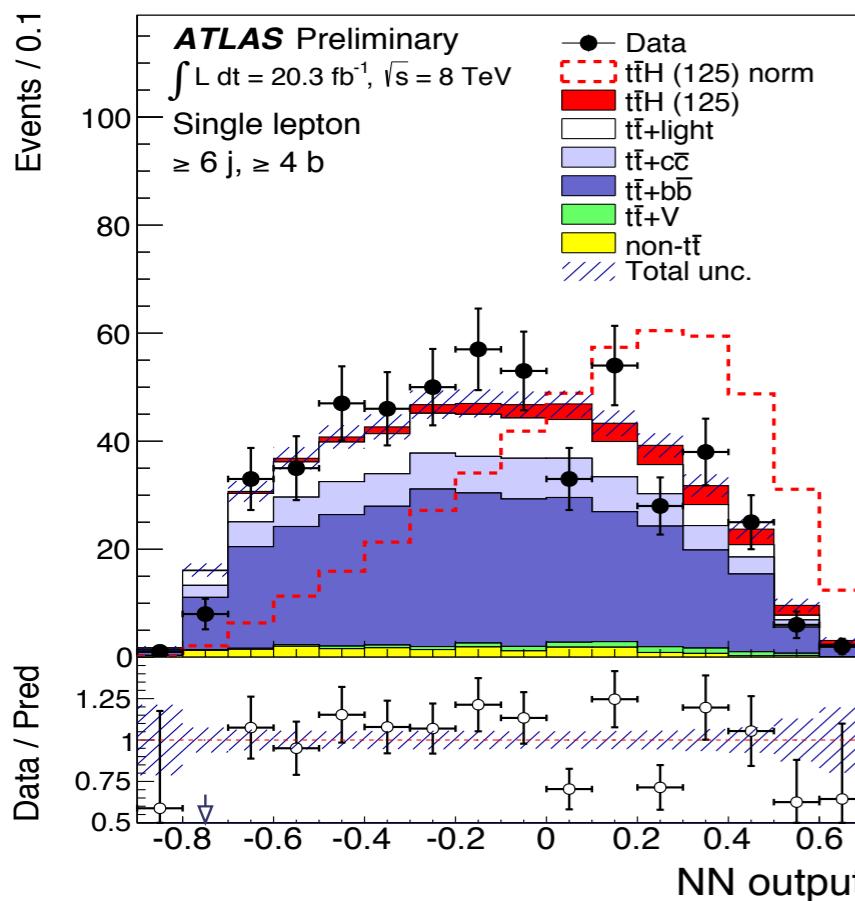
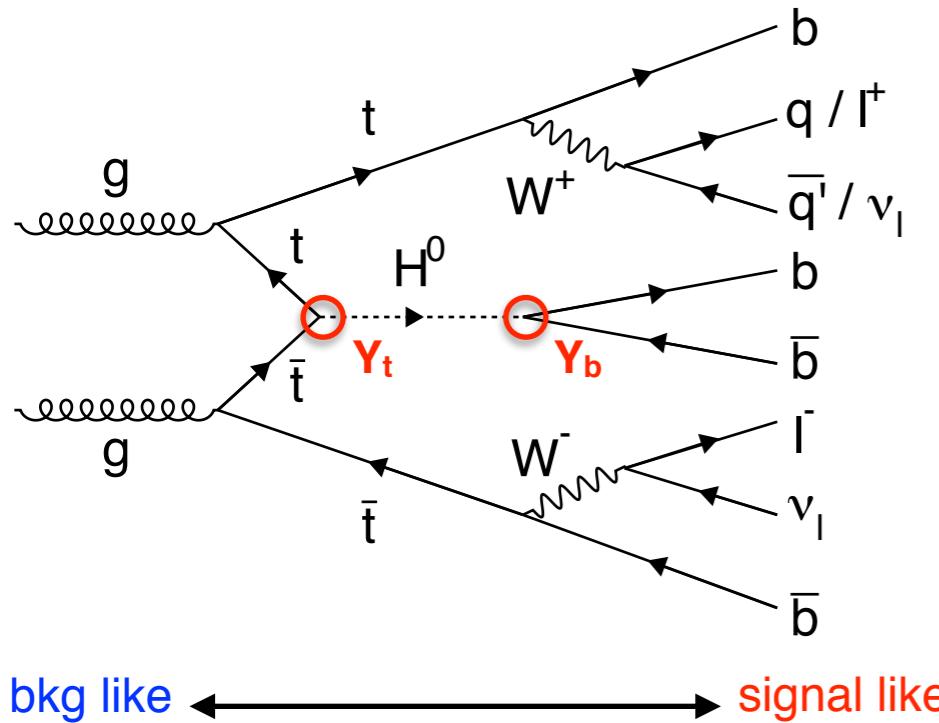
VH ($H \rightarrow b\bar{b}$) : Result



95% CL limit @125 GeV: observed (expected) $1.4 (1.3) \times \sigma_{\text{SM}}$
Signal strength μ ($=\sigma/\sigma_{\text{SM}}$) @125GeV: $\mu = 0.2 +0.7 -0.6$

Current result is consistent with S+B and B-only hypotheses

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

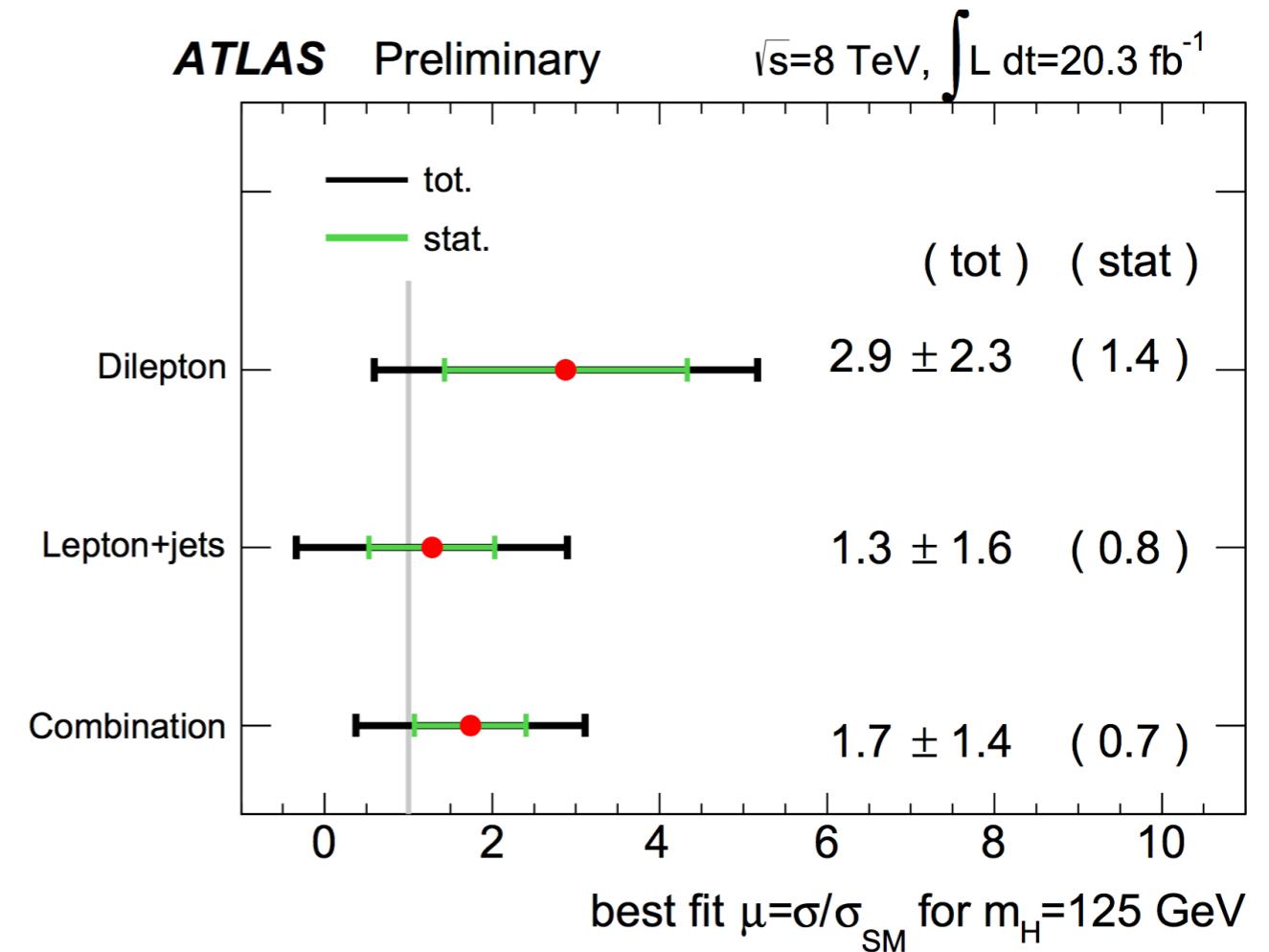
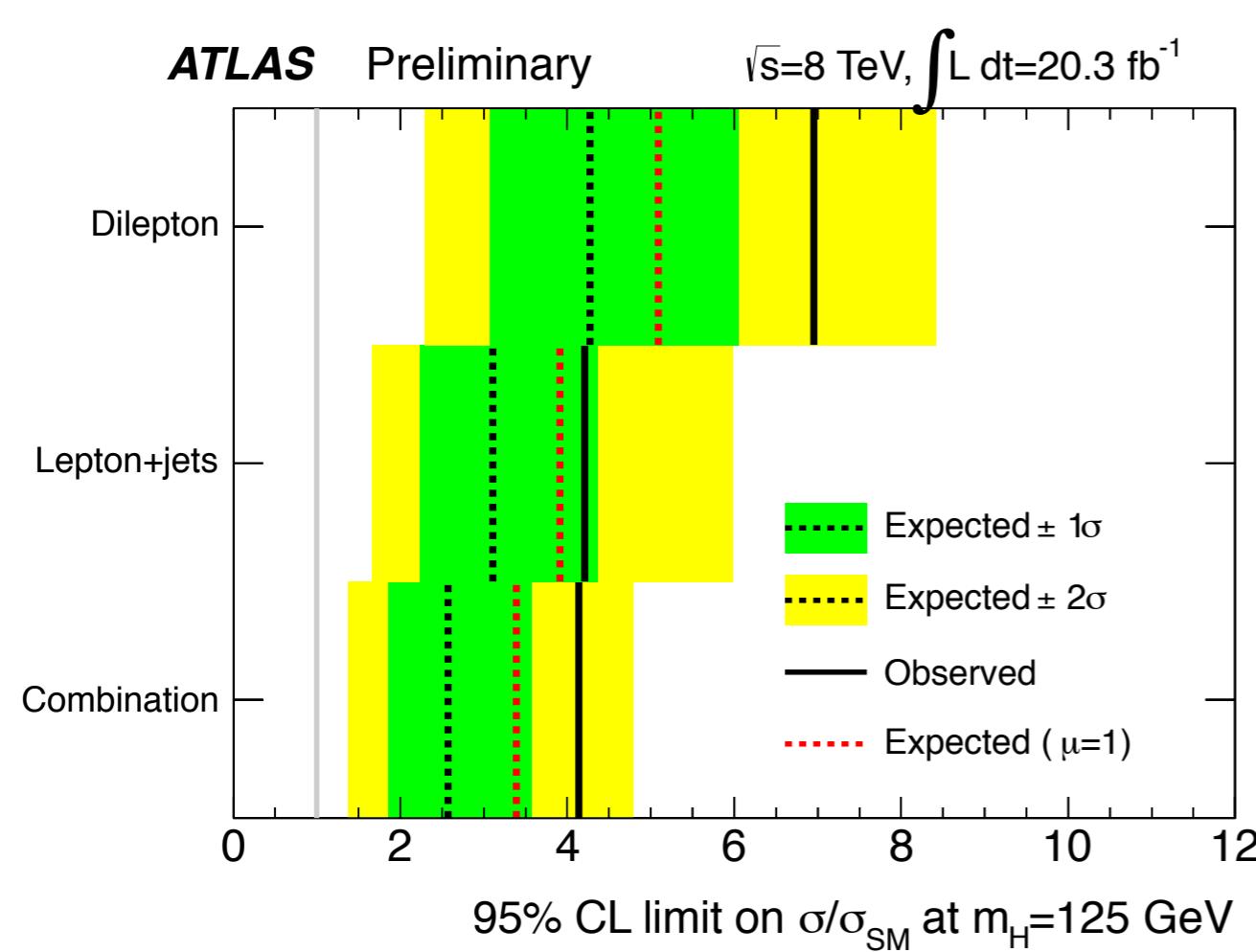


- $t\bar{t}H(H \rightarrow b\bar{b})$ with one or both W boson decaying leptonically.
- Possible to **probe 2 fermionic coupling** at the same time in both production (Y_t) and decay (Y_b).
- Categorization depending on N_{jet} and $N_{\text{b-jet}}$.

channel	lepton+jets	di-lepton
Event Selection	exactly 1 lepton 4 , 5 , ≥ 6 jets 2 , 3 , ≥ 4 b-tag	2 OS lepton Z mass window cut 2 , 3 , ≥ 4 jets 2 , 3 , ≥ 4 b-tag
Backgrounds		$t\bar{t}+\text{jets}$ (especially $t\bar{t}+b\bar{b}$)

- Choose **6 signal regions**(high S/B), perform Multi-Variate Analysis: **Neural Network(NN)** to maximize sensitivity.
- Optimize input variables for each category
Event kinematics : H_T , $M_{b\bar{b}}^{\min \Delta R}$, Centrality , ...
10 inputs for each NN.
- Other regions (control regions) are used to normalize background and to constrain common systematics.
→ Total 15 regions for simultaneous fitting.

tt>H (H→bb>) : Result



No significant signal excess is observed over predicted backgrounds.

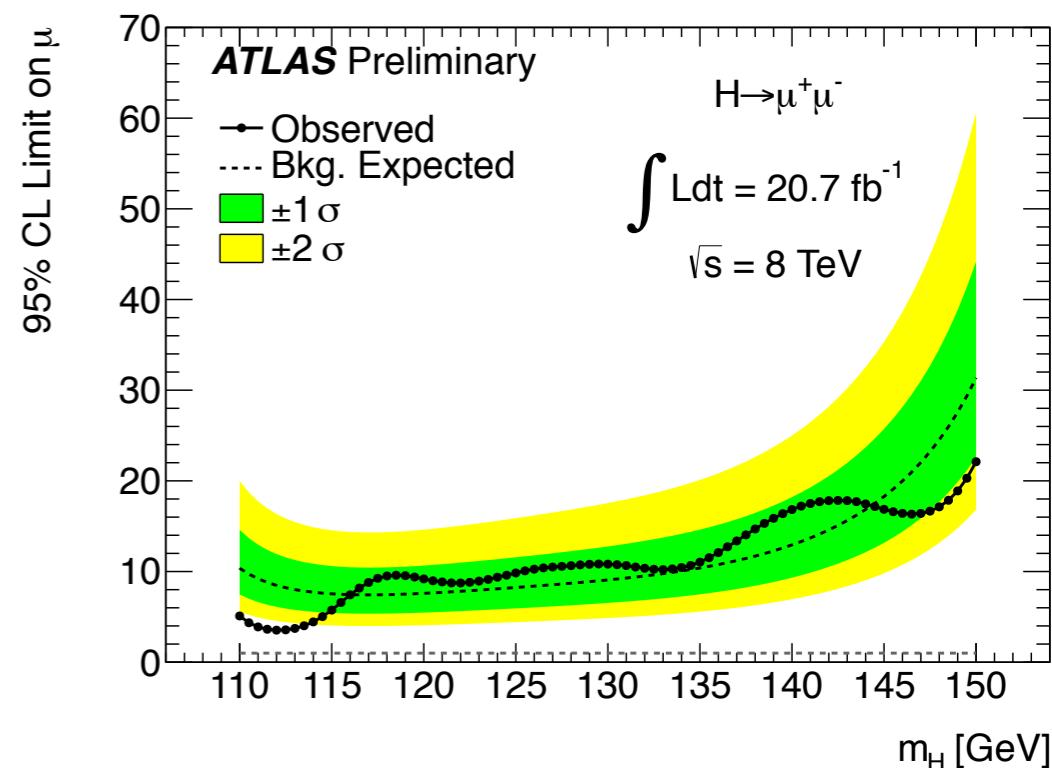
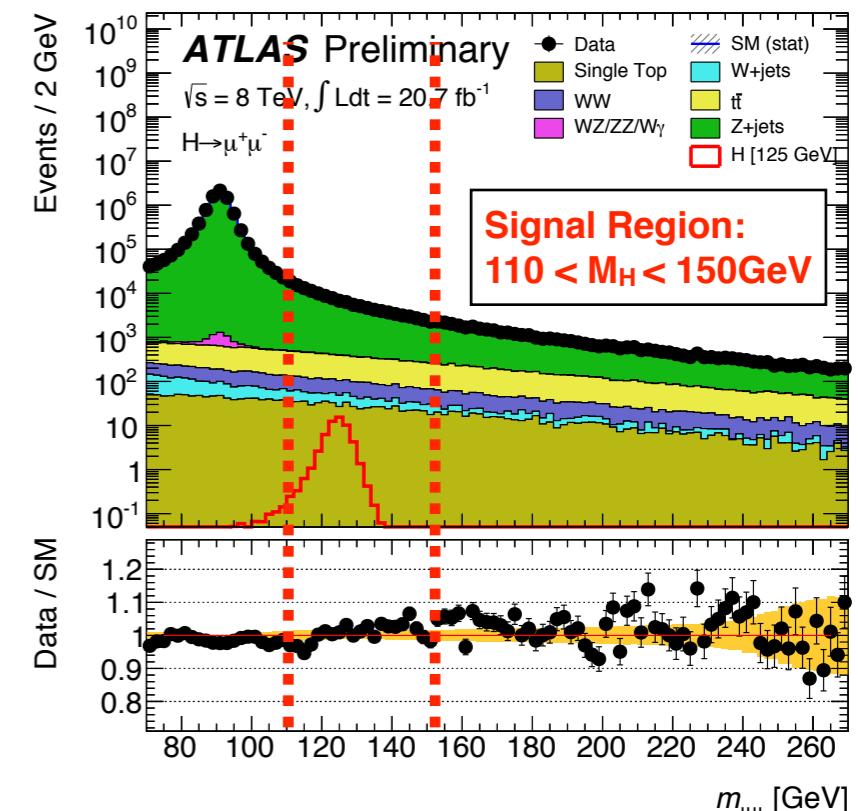
- 95% C.L $\sigma \times B.R$ limit @ 125GeV : observed (expected) : $4.1(2.6) \times \sigma_{\text{SM}}$
- Signal strength μ ($=\sigma/\sigma_{\text{SM}}$) @ 125GeV : $\mu = 1.7 \pm 1.4$
 → Systematics part is improved by simultaneous fitting with control regions.

Other Higgs decay modes ($H \rightarrow \gamma\gamma/\tau\tau/\dots$) can improve the sensitivity for Y_{top} .

Current results consistent with S+B and B-only hypotheses

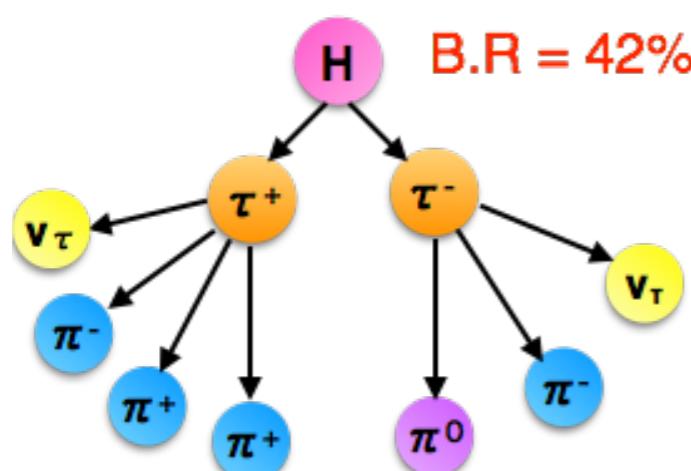
H \rightarrow $\mu\mu$: Overview & Result

- H \rightarrow $\mu\mu$ is only channel to measure coupling of 2nd generation fermions in ATLAS.
- Final State is very clean, but challenging.
small B.R and large Z \rightarrow $\mu\mu$ background
- Select 2 isolated opposite sign muons.
- Categorize 2 signal regions:
central / non central
- Fit M $_{\mu\mu}$ with signal + background shape.
Signal : Crystal-Ball + Gaussian
Background : Breit-Wigner + Exponential
- No significant excess, set 95% C.L $\sigma \times$ B.R limit@125GeV :
observed: 9.8 \times σ_{SM} / expected: 8.2 \times σ_{SM}



H \rightarrow $\tau\tau$: Strategy & Selection

- H \rightarrow $\tau\tau$ is **most sensitive** mode in fermionic(leptonic) channels.
- Perform analysis with **3 channels** according to τ decay.

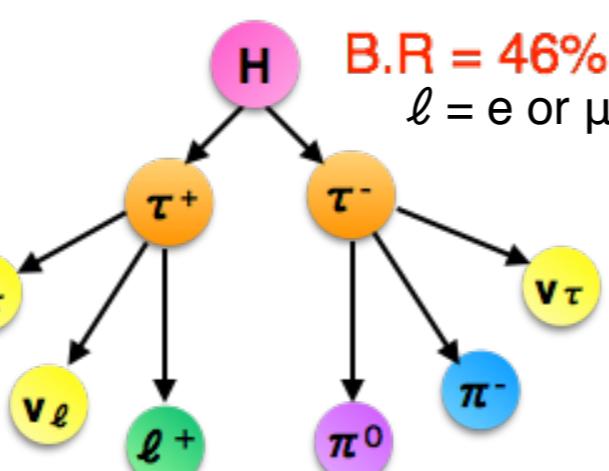


$\tau_{\text{had}}\text{-}\tau_{\text{had}}$ channel

Large B.R

High multi-jet background

2 OS hadronic τ

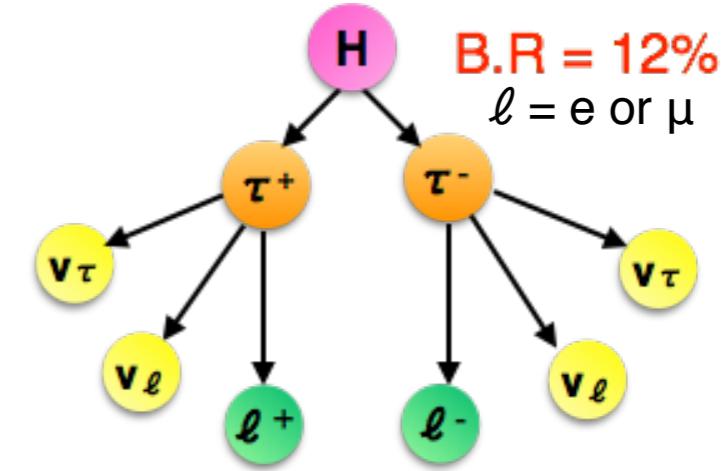


$\tau_{\text{lep}}\text{-}\tau_{\text{had}}$ channel

Large B.R

Clean Signature

1 lepton + 1 hadronic τ (OS)



$\tau_{\text{lep}}\text{-}\tau_{\text{lep}}$ channel

Small B.R

Very Clean Signature

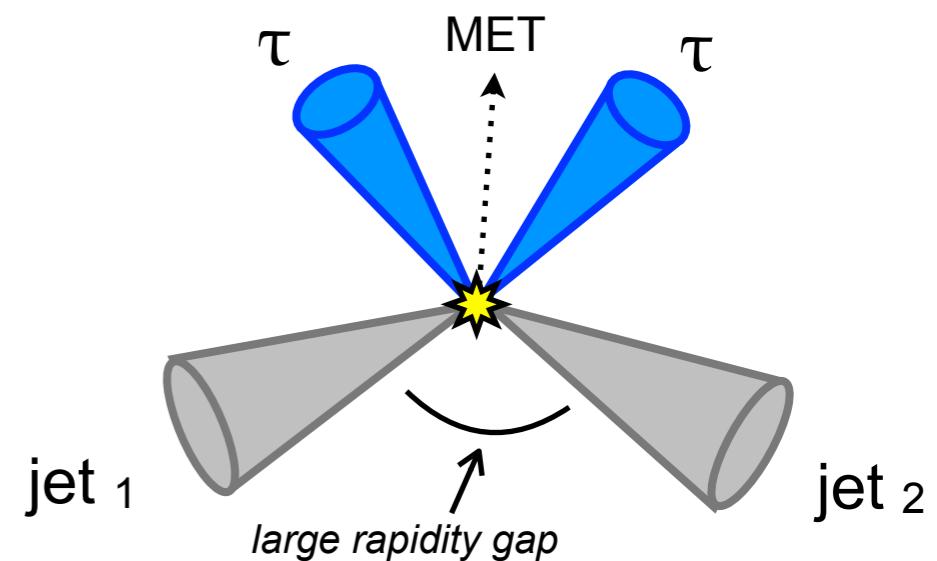
2 OS leptons

- **2 categories** according to signal topology

VBF : 2 jets with large pseudo-rapidity gap

Boost : High Higgs($\tau\tau$ system) momentum

- Use **BDT(Boosted Decision Tree)** to maximize sensitivity.



H \rightarrow $\tau\tau$: Strategy & Selection

- **Background estimation**

Z \rightarrow $\tau\tau$ (main) : **Embedding technique**

Directory taken from Z \rightarrow $\mu\mu$ data

Replaced μ to simulated τ

Fake τ : Multi-jet , W+jets

Data driven method (Fake rate / template fits)

Others : Z \rightarrow ee/ $\mu\mu$, top , di-boson

Normalized to data by dedicated control regions.

- **BDT strategy**

Different BDTs for each channel/category.

Optimize ~10 input variables for each BDTs

Resonance properties : M $_{\tau\tau}$, $\Delta R(\tau, \tau)$, ...

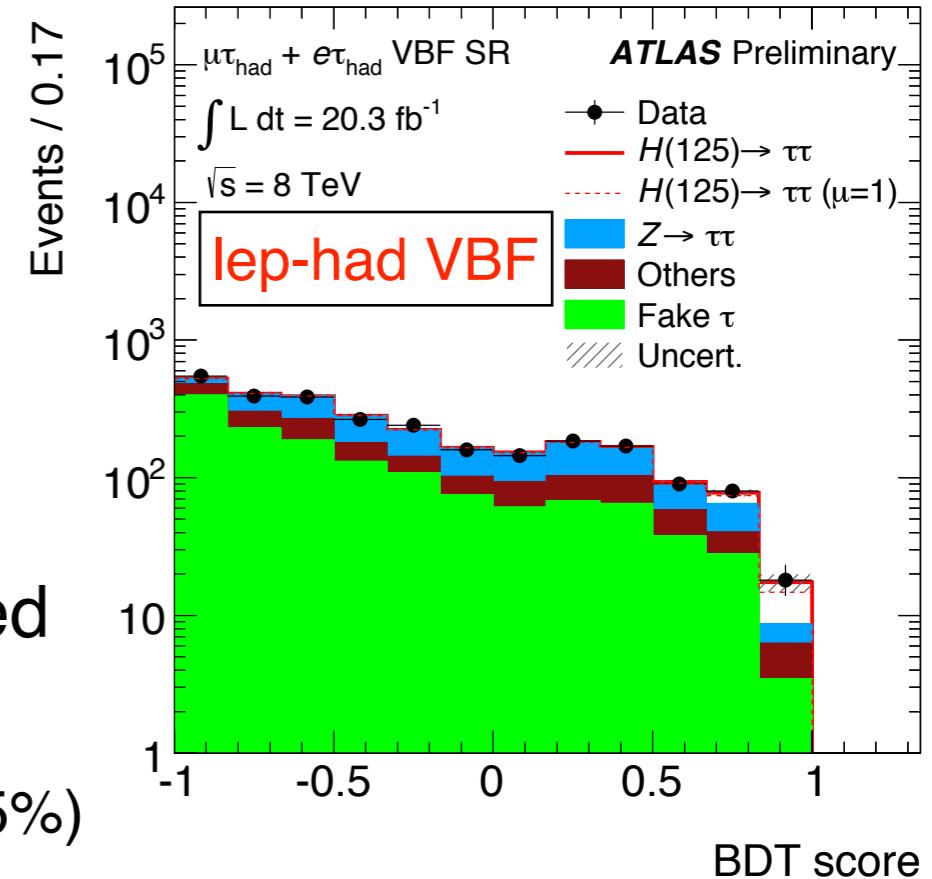
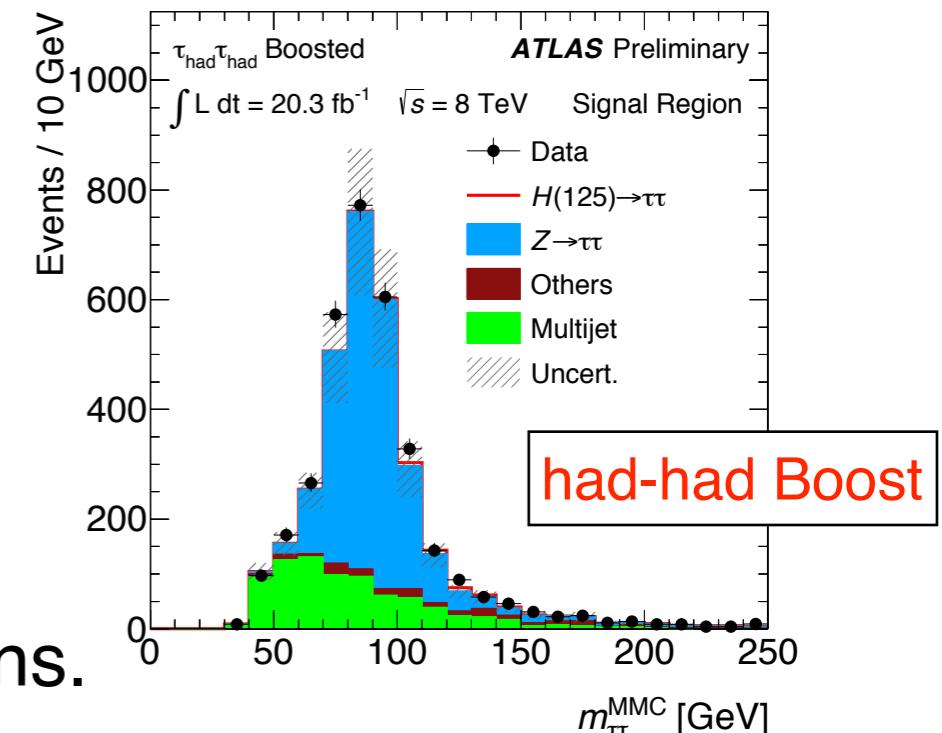
Event topology : M T , MET , centrality ...

VBF topology : M $_{jj}$, $\Delta\eta_{jj}$, ...

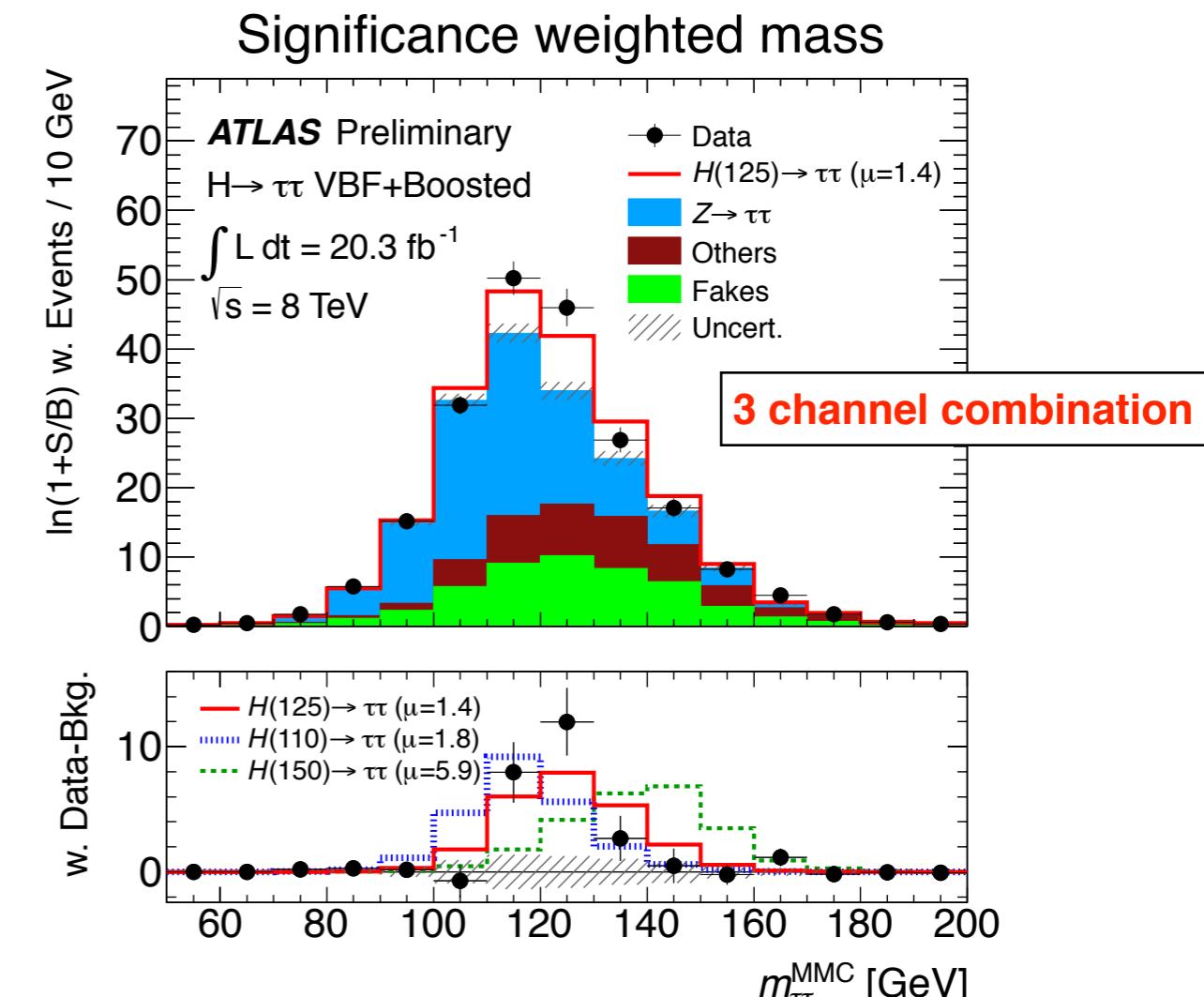
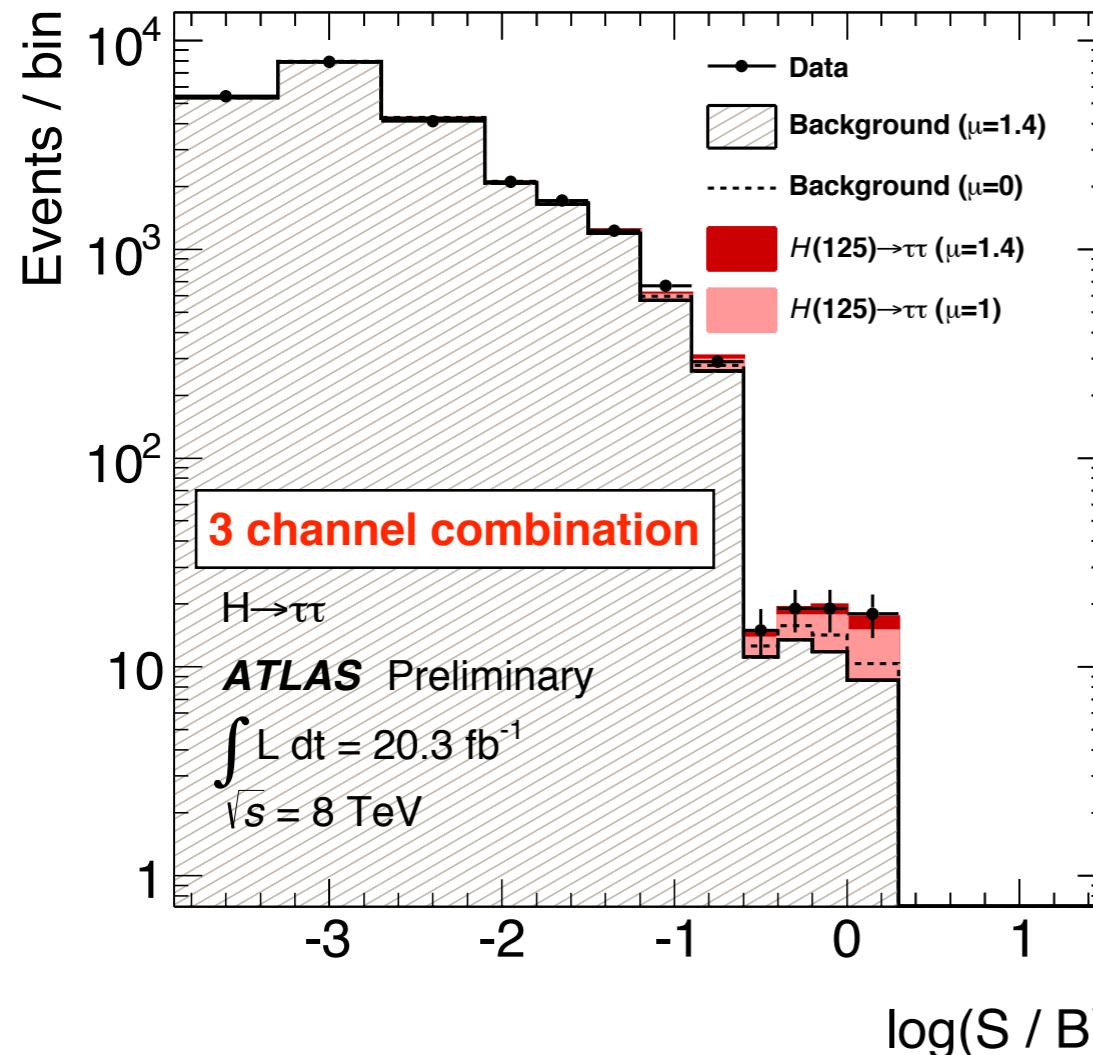
Most important input variable : M $_{\tau\tau}$ is reconstructed

by **Missing Mass Calculator (MMC)**

→ Precise mass estimator by kinematic likelihood ($\sigma \sim 15\%$)



H \rightarrow $\tau\tau$: Result



Significant excess is observed in all channel at high S/B region.

Observed (expected) significance @M_H=125 GeV: **4.1 σ (3.2 σ)**

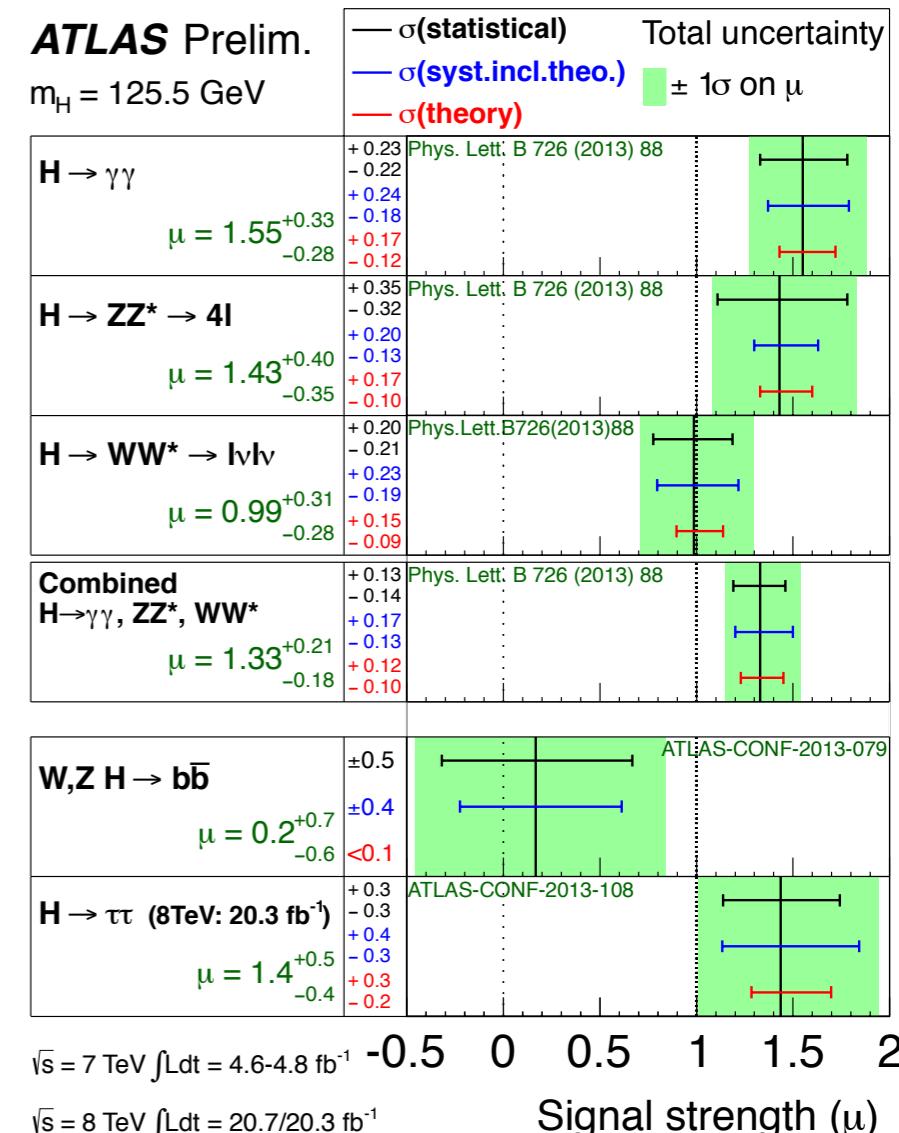
Signal strength $\mu = \sigma/\sigma_{SM} = \mathbf{1.4 +0.5 -0.4}$

The mass is comparable with discovered Higgs (M_H = 125GeV)

Direct evidence of the Higgs boson in the fermionic channel !

Conclusion

- Higgs search in fermionic channels is one of most important in ATLAS Higgs analysis and has high activity!
- $H \rightarrow \mu\mu$: no excess over background observed observed (expected) limit: $9.8 (8.2) \times SM$
- VH ($H \rightarrow b\bar{b}$): no excess over background observed observed (expected) limit: $1.4 (1.3) \times SM$
signal strength $\mu = 0.2 +0.7 -0.6$
- $t\bar{t}H(H \rightarrow b\bar{b})$: no excess over background observed observed (expected) limit: $4.1 (2.6) \times SM$
signal strength $\mu = 1.7 \pm 1.4$
- $H \rightarrow \tau\tau$:
observed (expected) $4.1 (3.2) \sigma$ evidence
signal strength $\mu = 1.4 +0.5 -0.4$
- There are some rooms to improve, will be updated by papers.

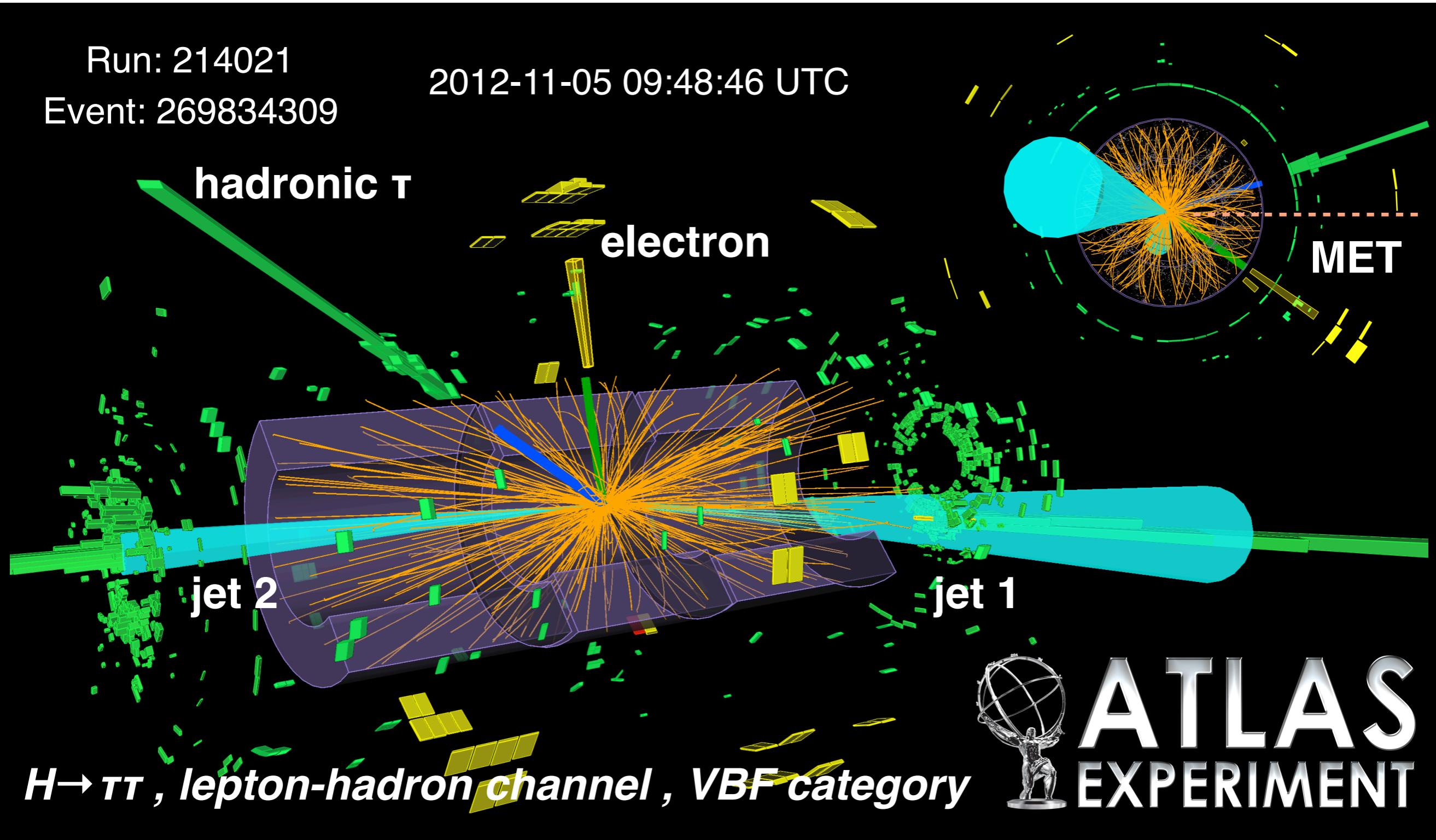


BACKUP

$H \rightarrow \tau\tau$: Event Display

Run: 214021
 Event: 269834309

2012-11-05 09:48:46 UTC



VH \rightarrow bb : Selection & Control Region

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

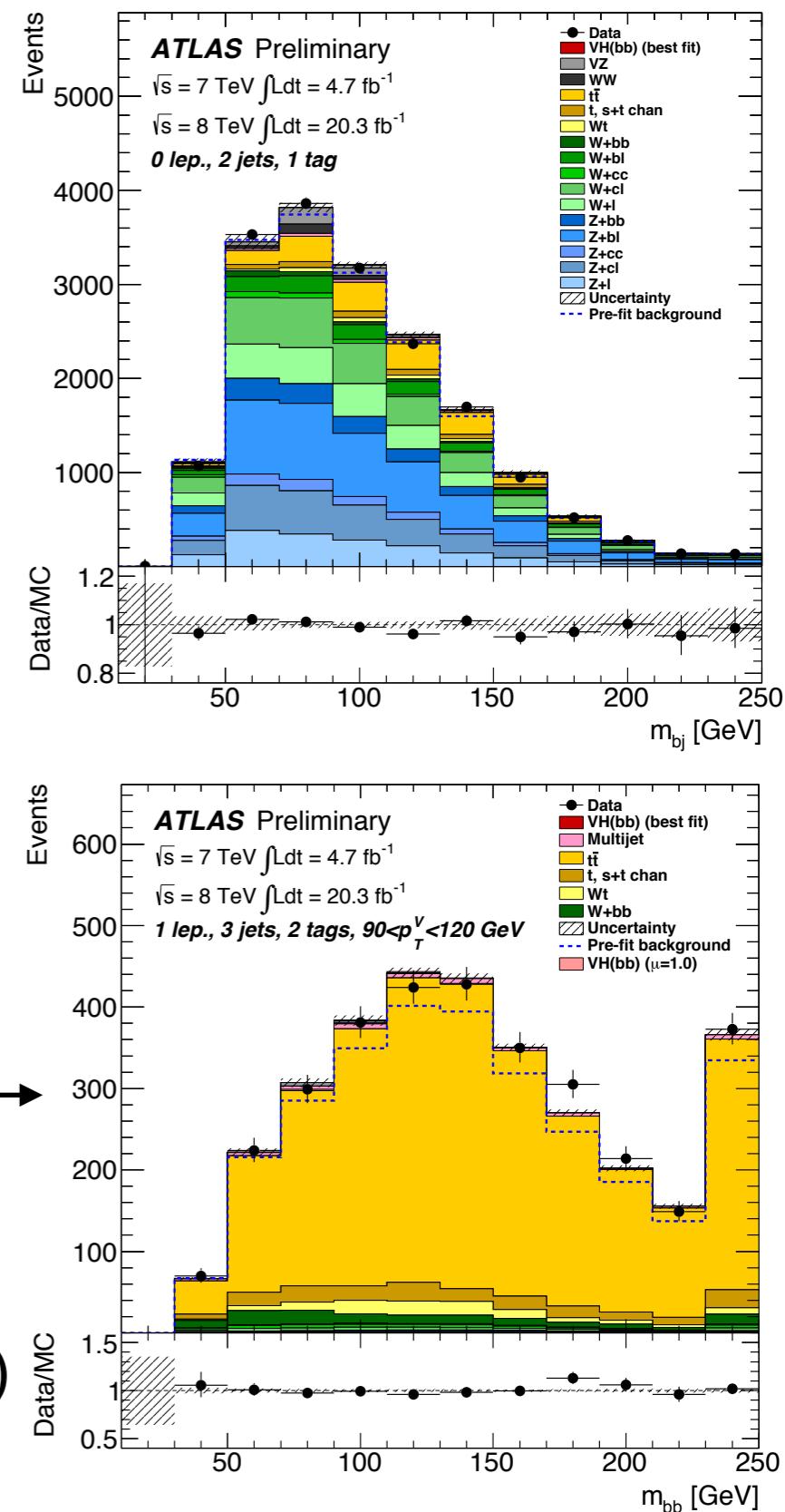
Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets		2 b-tags $p_T^{\text{jet}_1} > 45 \text{ GeV}$ $p_T^{\text{jet}_2} > 20 \text{ GeV}$ + ≤ 1 extra jets	
Missing E_T	$E_T^{\text{miss}} > 120 \text{ GeV}$ $p_T^{\text{miss}}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

	p	2 jets 1 b-tag	3 jets 1 b-tag	2 jets 2 b-tag	3 jets 2 b-tag	$e + \mu$ ≥ 3 jets 2 b-tag
0 lep	3 bin	CR	CR	SR	SR	—
1 lep	5 bin	CR	CR	SR	SR	—
2 lep	5 bin	CR	CR	SR	SR	Top CR →

Simultaneous fit in

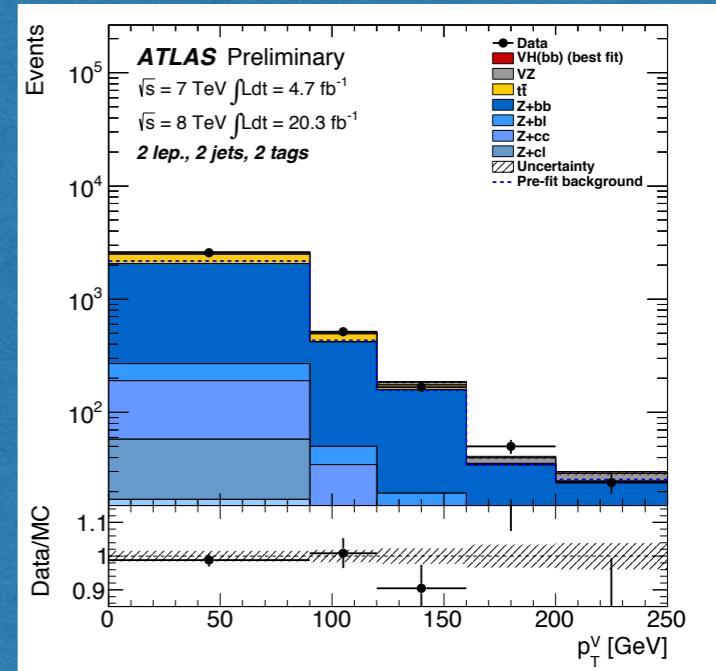
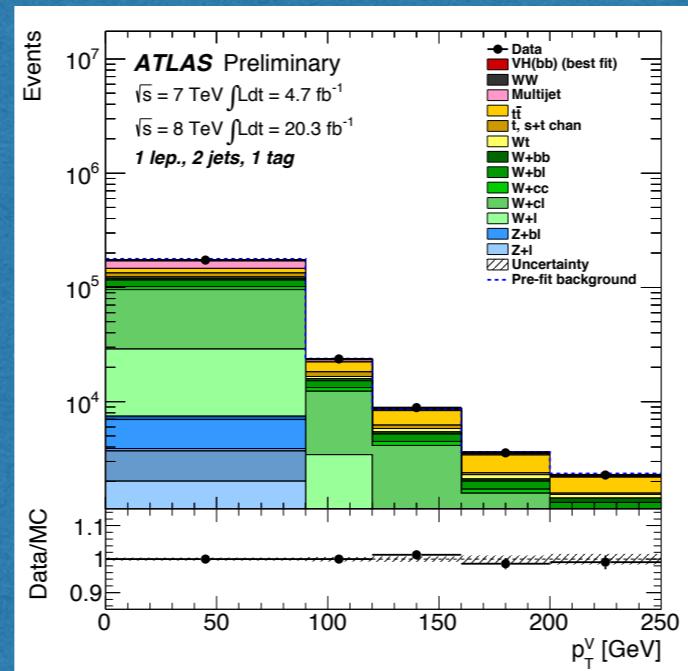
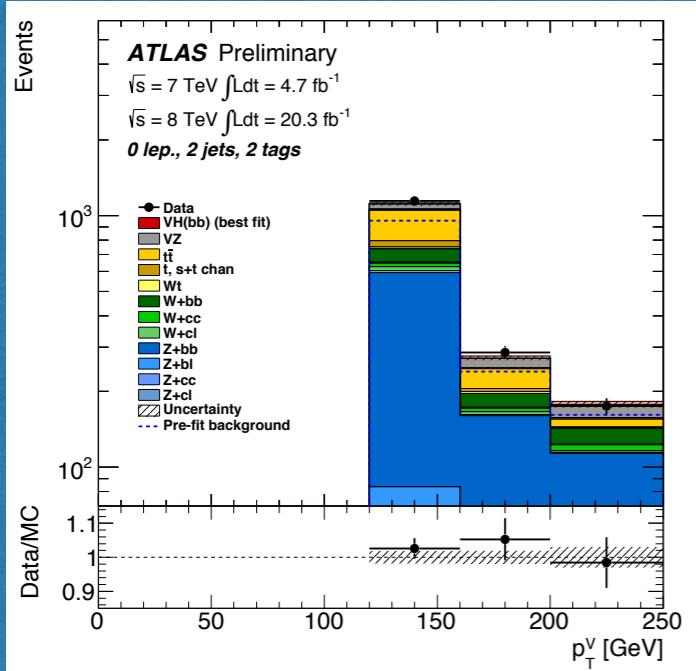
26 SR's + 26 1 b-tag CR's + 5 Top CR's

Common nuisance parameters (systematic uncertainties)
across SR's and CR's and channels/categories

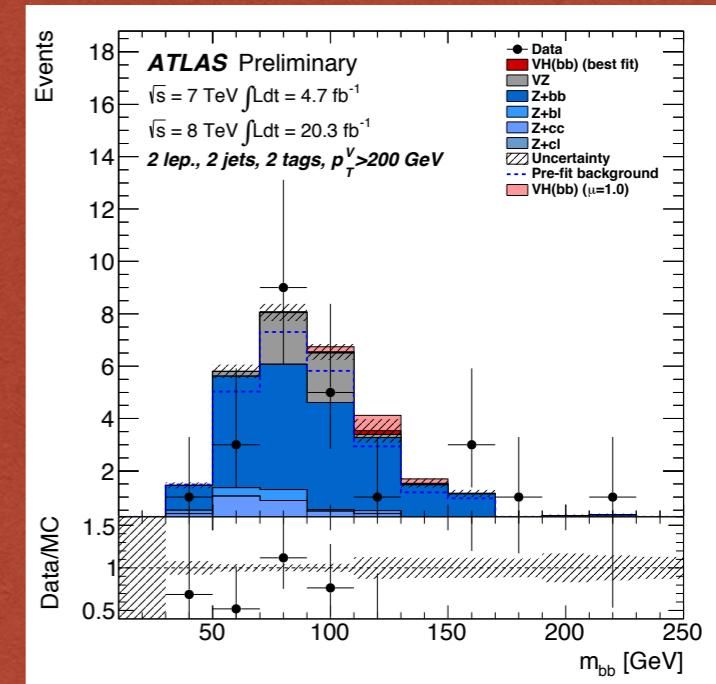
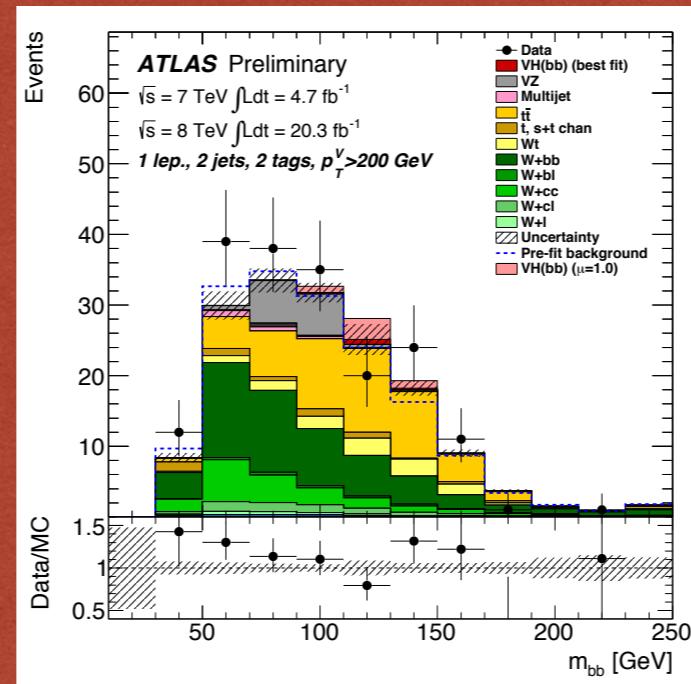
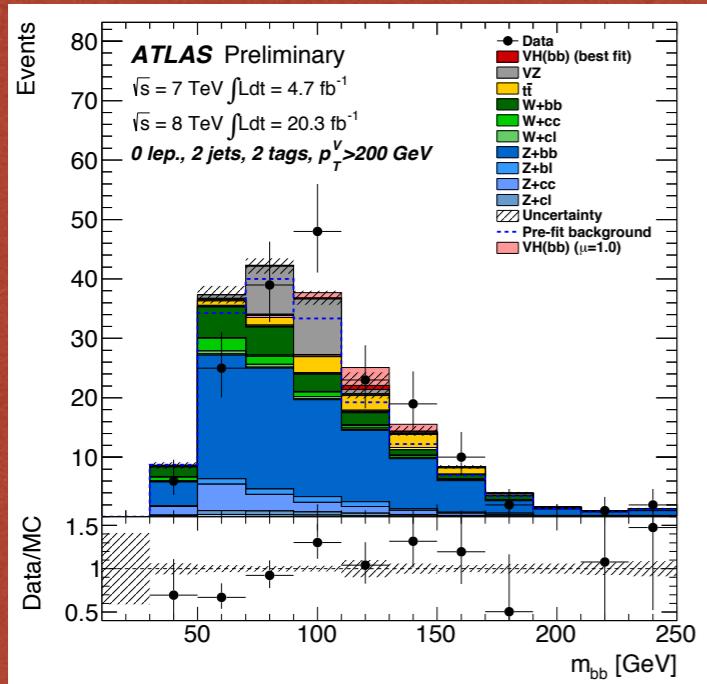


VH \rightarrow b \bar{b} : Control plots

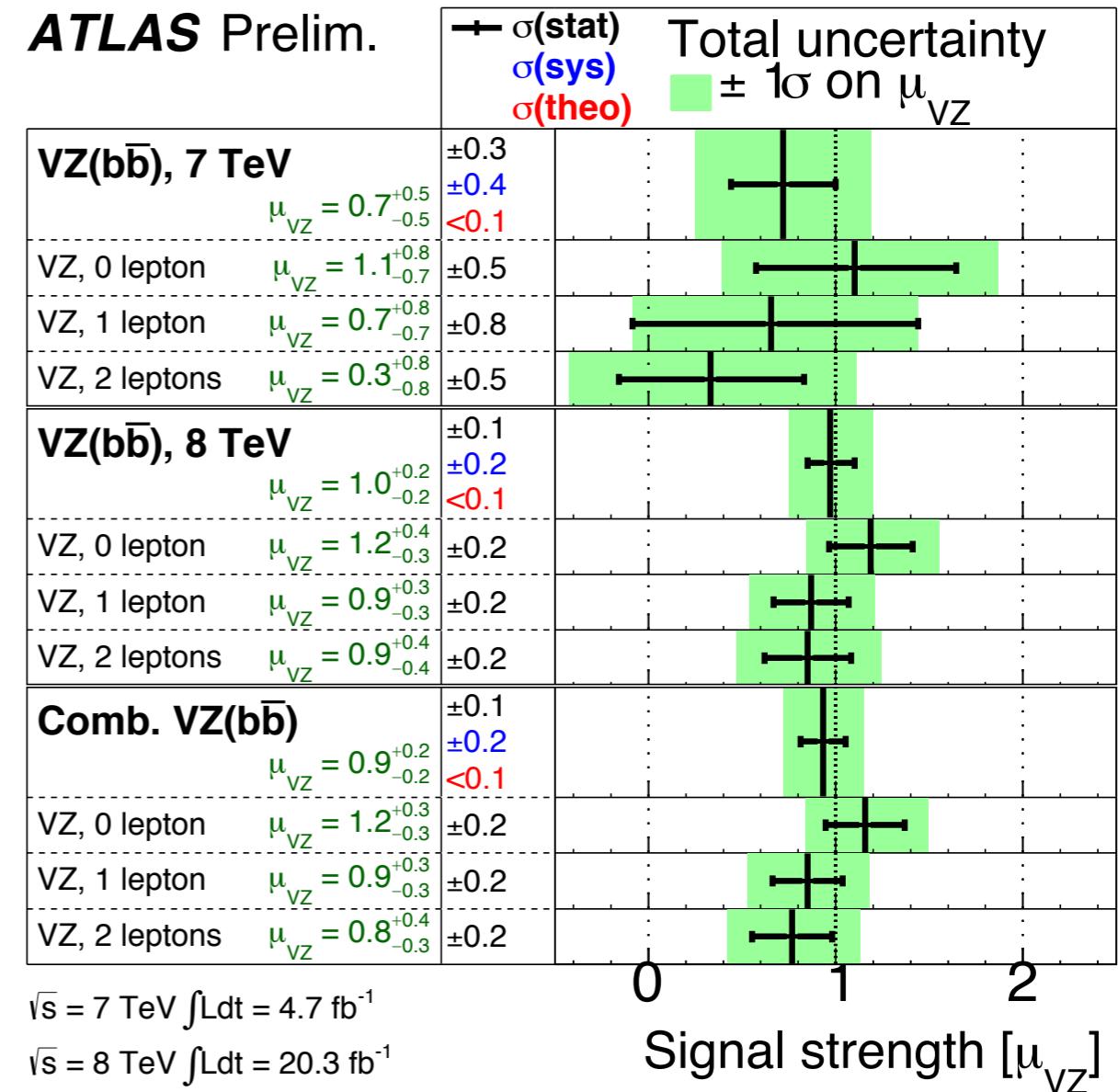
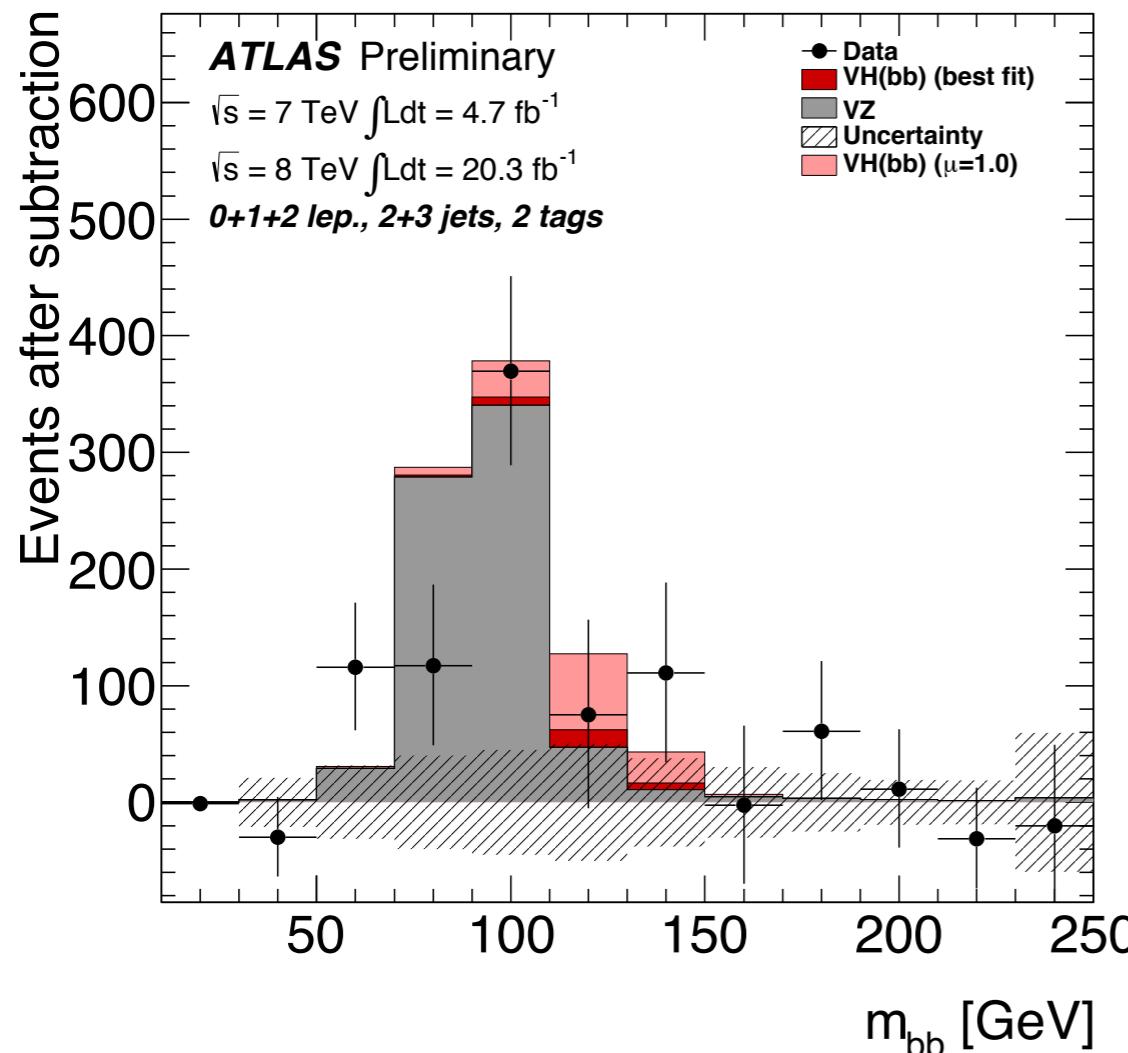
p_T^V plots : 2-jets , 2 b-tag jets



Mbb plots : 2-jets , 2 b-tag jets , p_T^V > 200GeV



VH \rightarrow b \bar{b} : VZ(\rightarrow b \bar{b}) cross check

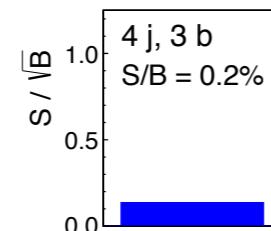
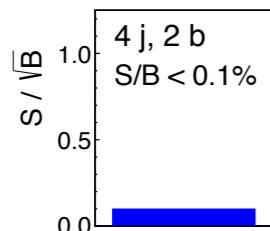


VZ \rightarrow b \bar{b} has the same signature of events selected by VH \rightarrow b \bar{b} .
M $_{bb}$ peak of VZ \rightarrow b \bar{b} is lower values than VH \rightarrow b \bar{b} .
Measure μ_{VZ} by separate fitting from Higgs signal extraction for cross check.
 $\mu_{VZ} = 0.9 \pm 0.2$ \rightarrow Consistent with SM.

$t\bar{t}H \rightarrow b\bar{b}$: Signal Region

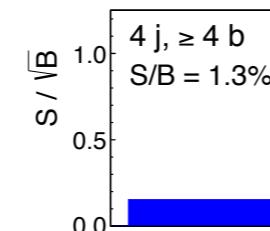
ATLAS Preliminary Simulation

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.3 \text{ fb}^{-1}$



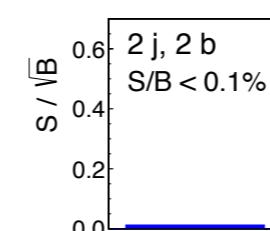
Single lepton

$m_H = 125 \text{ GeV}$



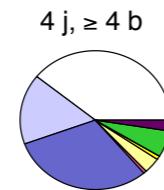
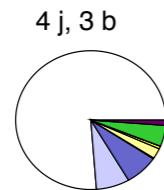
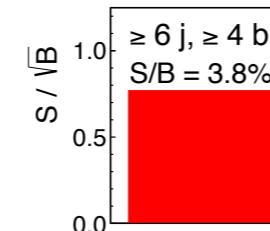
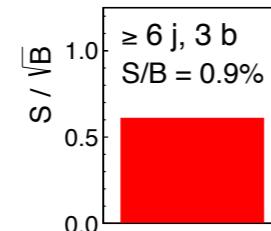
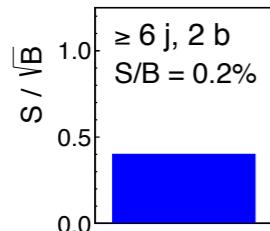
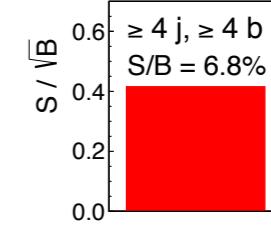
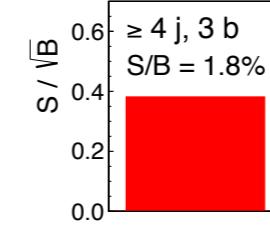
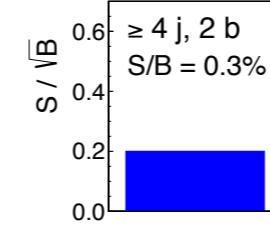
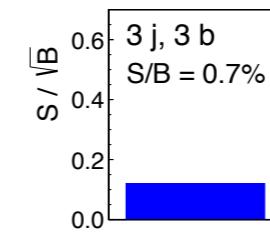
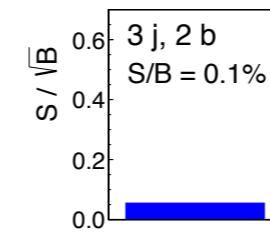
ATLAS Preliminary Simulation

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 20.3 \text{ fb}^{-1}$



Dilepton

$m_H = 125 \text{ GeV}$



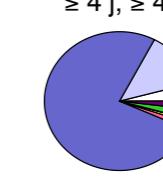
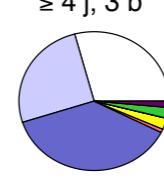
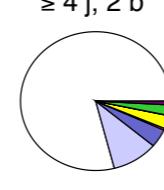
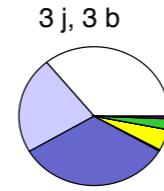
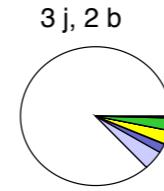
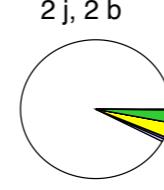
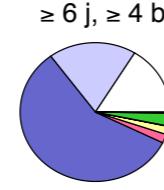
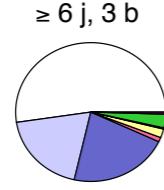
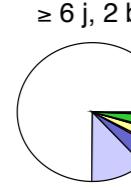
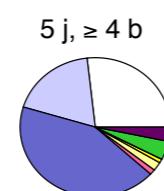
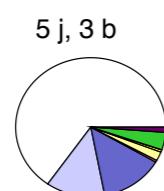
ATLAS
Preliminary
Simulation

$m_H = 125 \text{ GeV}$
 $\sqrt{s} = 8 \text{ TeV}$



- [white] $t\bar{t} + \text{light}$
- [light blue] $t\bar{t} + c\bar{c}$
- [dark blue] $t\bar{t} + b\bar{b}$
- [pink] $t\bar{t} + V$
- [yellow] $W + \text{jets}$
- [orange] $Z + \text{jets}$
- [red] Diboson
- [green] Single top
- [purple] Multijet

Single lepton



ATLAS
Preliminary
Simulation

$m_H = 125 \text{ GeV}$
 $\sqrt{s} = 8 \text{ TeV}$



- [white] $t\bar{t} + \text{light}$
- [light blue] $t\bar{t} + c\bar{c}$
- [dark blue] $t\bar{t} + b\bar{b}$
- [pink] $t\bar{t} + V$
- [yellow] $Z + \text{jets}$
- [orange] Diboson
- [green] Single top
- [purple] Multijet

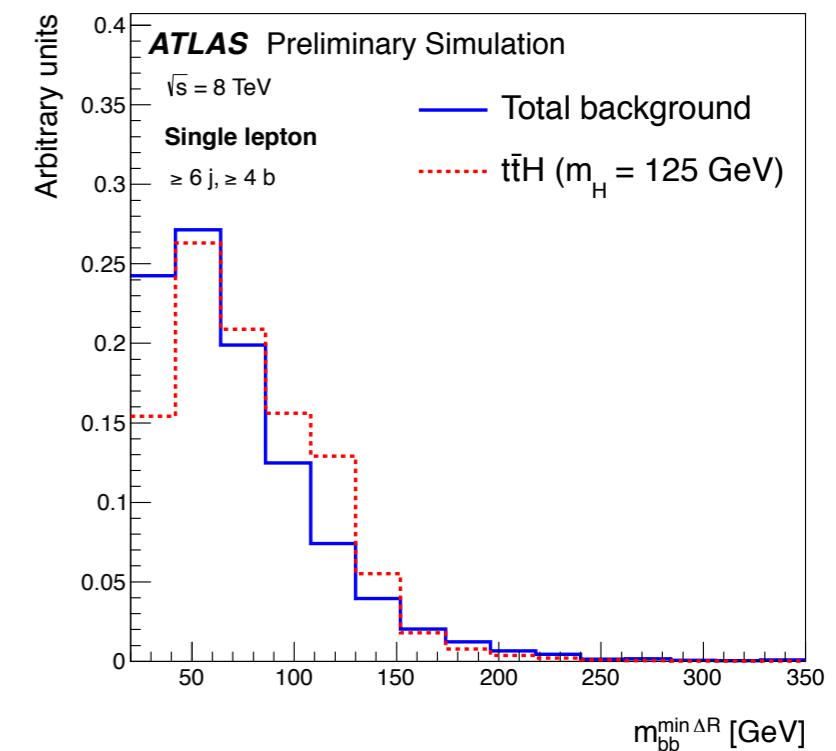
Dilepton

$t\bar{t}H \rightarrow b\bar{b}$: Input variables

Variable	Definition
Centrality	Sum of the p_T divided by sum of the E for all jets and the lepton
H1	Second Fox-Wolfram moment computed using all jets and the lepton
$m_{bb}^{\min \Delta R}$	Mass of the combination of two b -tagged jets with the smallest ΔR
N_{40}^{jet}	Number of jets with $p_T \geq 40$ GeV
$\Delta R_{bb}^{\text{avg}}$	Average ΔR for all b -tagged jet pairs
$m_{jj}^{\max p_T}$	Mass of the combination of any two jets with the largest vector sum p_T
Aplanarity _{b-jet}	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with only b -tagged jets
H_T^{had}	Scalar sum of jet p_T
$m_{jj}^{\min \Delta R}$	Mass of the combination of any two jets with the smallest ΔR
$\Delta R_{\text{lep}-bb}^{\min \Delta R}$	ΔR between the lepton and the combination of two b -tagged jets with the smallest ΔR
$m_{bj}^{\min \Delta R}$	Mass of the combination of a b -tagged jet and any jet with the smallest ΔR
$m_{bj}^{\max p_T}$	Mass of the combination of a b -tagged jet and any jet with the largest vector sum p_T
$m_{uu}^{\min \Delta R}$	Mass of the combination of two untagged jets with the smallest ΔR
$p_T^{\text{jet}5}$	Fifth leading jet p_T
$\Delta R_{bb}^{\max p_T}$	ΔR between two b -tagged jets with the largest vector sum p_T
$m_{bb}^{\max m}$	Mass of the combination of two b -tagged jets with the largest invariant mass
$p_{T,uu}^{\min \Delta R}$	Scalar sum of the p_T 's of the pair of untagged jets with the smallest ΔR
m_{ijj}	Mass of the jet triplet with the largest vector sum p_T
$\Delta R_{uu}^{\min \Delta R}$	Minimum ΔR between two untagged jets
$m_{bb}^{\max p_T}$	Mass of the combination of two b -tagged jets with the largest vector sum p_T

Table 4: List of variables used in the NN in the single lepton channel in at least one region. From the list, 10 variables are chosen in each region.

Variable	$(\geq 6j, \geq 4b)$	$(\geq 6j, 3b)$	$(5j, \geq 4b)$	$(5j, 3b)$
$\Delta R_{bb}^{\text{avg}}$	1	5	5	-
$m_{bb}^{\min \Delta R}$	2	9	3	1
Centrality	3	2	1	-
H1	4	3	2	-
$p_T^{\text{jet}5}$	5	8	-	-
Aplanarity _{b-jet}	6	-	7	-
$m_{uu}^{\min \Delta R}$	7	7	-	2
$\Delta R_{bb}^{\max p_T}$	8	-	-	-
$\Delta R_{\text{lep}-bb}^{\min \Delta R}$	9	10	10	-
$m_{bj}^{\max p_T}$	10	6	-	-
N_{40}^{jet}	-	1	4	-
$m_{bj}^{\min \Delta R}$	-	4	-	-
$m_{jj}^{\max p_T}$	-	-	6	-
p_T^{had}	-	-	8	-
$m_{jj}^{\min \Delta R}$	-	-	9	-
$m_{bb}^{\max m}$	-	-	-	3
$p_{T,uu}^{\min \Delta R}$	-	-	-	4
m_{ijj}	-	-	-	5
$\Delta R_{uu}^{\min \Delta R}$	-	-	-	6
$m_{bb}^{\max p_T}$	-	-	-	7



Variable	$(\geq 4j, \geq 4b)$	$(\geq 4j, 3b)$	$(3j, 3b)$
$\Delta \eta_{jj}^{\max \Delta \eta}$	1	1	1
$m_{bb}^{\min \Delta R}$	2	8	-
$m_{b\bar{b}}$	3	-	-
$\Delta R_{hl}^{\min \Delta R}$	4	5	-
N_{30}^{Higgs}	5	2	5
$\Delta R_{bb}^{\max p_T}$	6	4	8
Aplanarity _{jet}	7	7	-
$m_{jj}^{\min m}$	8	3	2
$\Delta R_{hl}^{\max \Delta R}$	9	-	-
m_{jj}^{closest}	10	-	10
H_T	-	6	3
$\Delta R_{bb}^{\max m}$	-	9	-
$\Delta R_{lj}^{\min \Delta R}$	-	10	-
Centrality	-	-	7
$m_{jj}^{\max p_T}$	-	-	9
H4	-	-	4
$p_T^{\text{jet}3}$	-	-	6

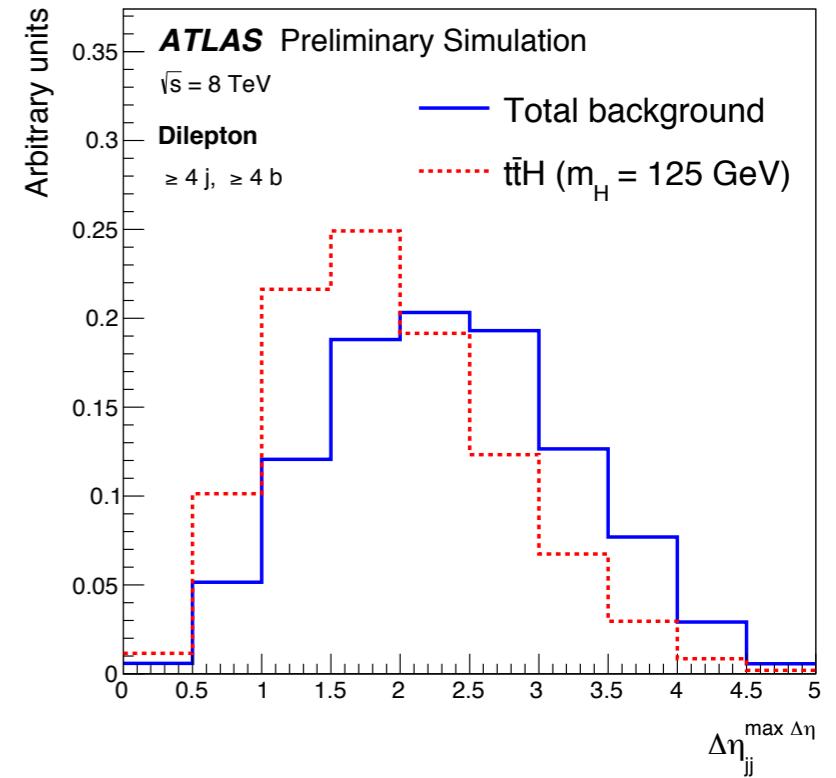
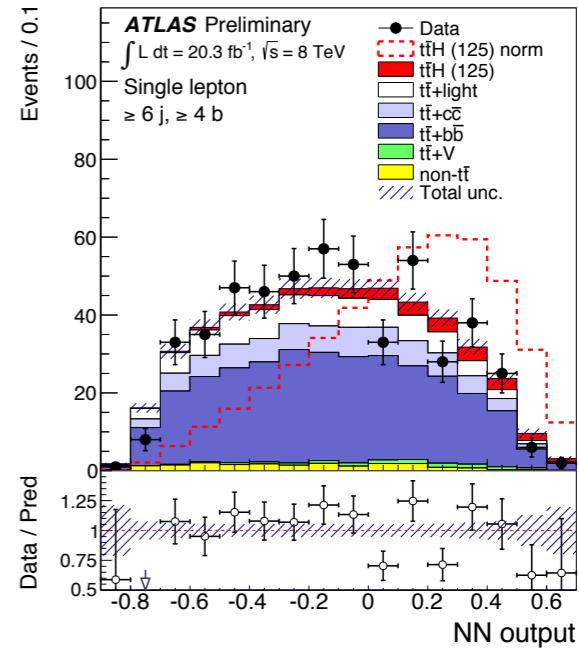
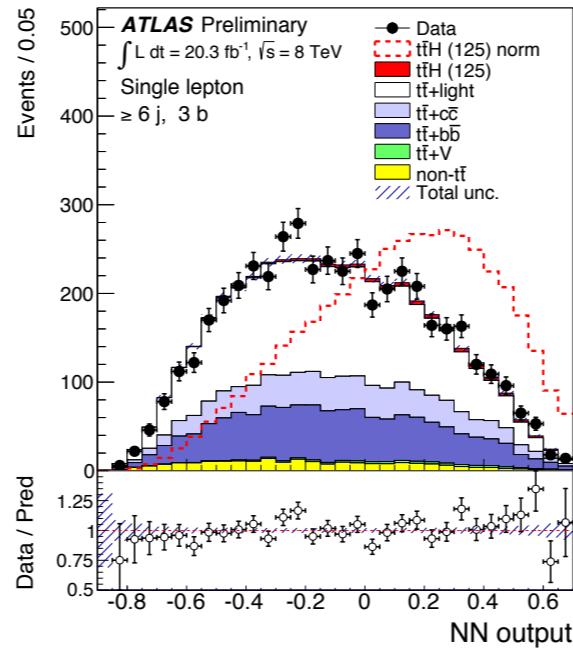
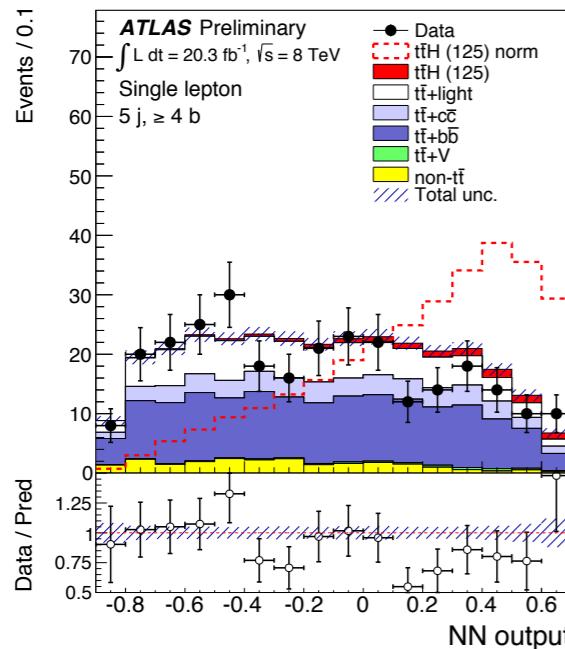
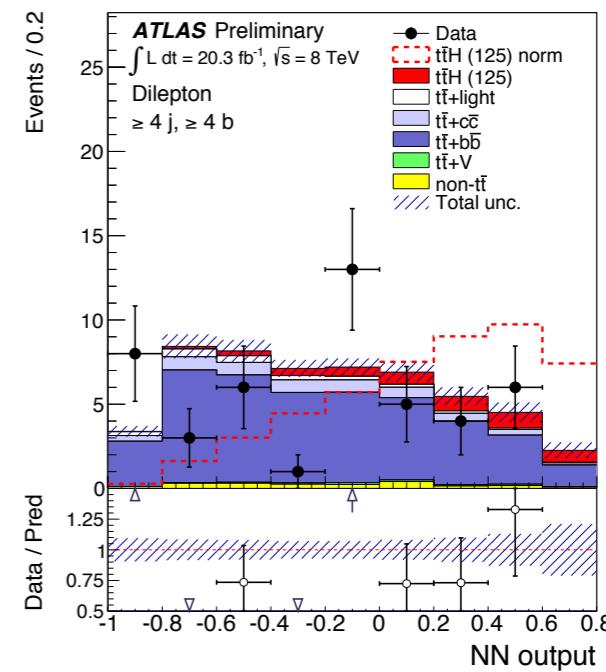
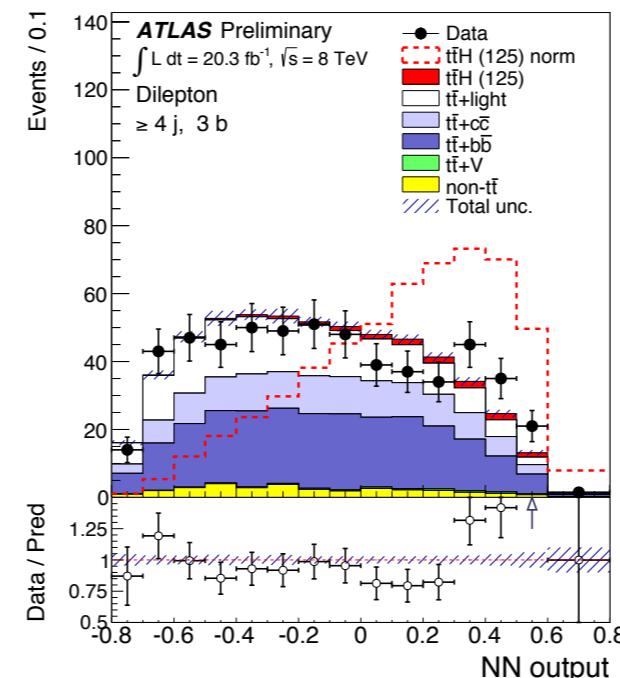
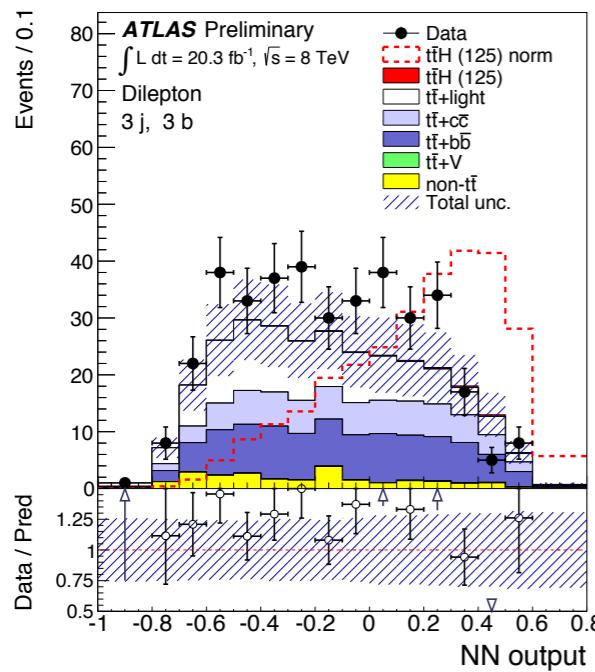


Table 5: List of variables used in the NN in the dilepton channel in at least one region. From the list, 10 variables are chosen in each region.

Lepton + Jets channel



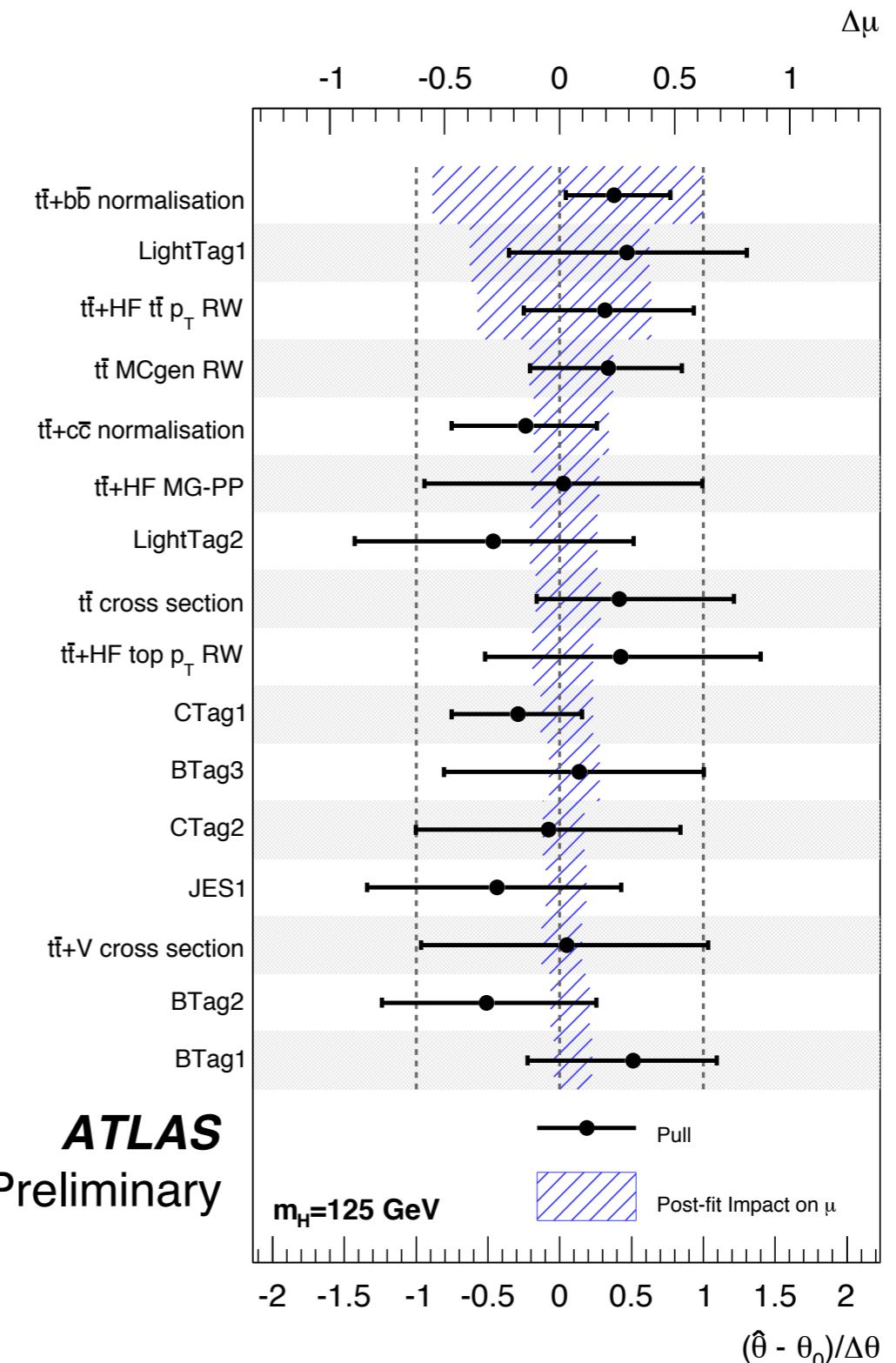
Di-lepton channel



$t\bar{t}H \rightarrow b\bar{b}$: Systematic Uncertainty

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
<i>b</i> -tagging efficiency	SN	6
<i>c</i> -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

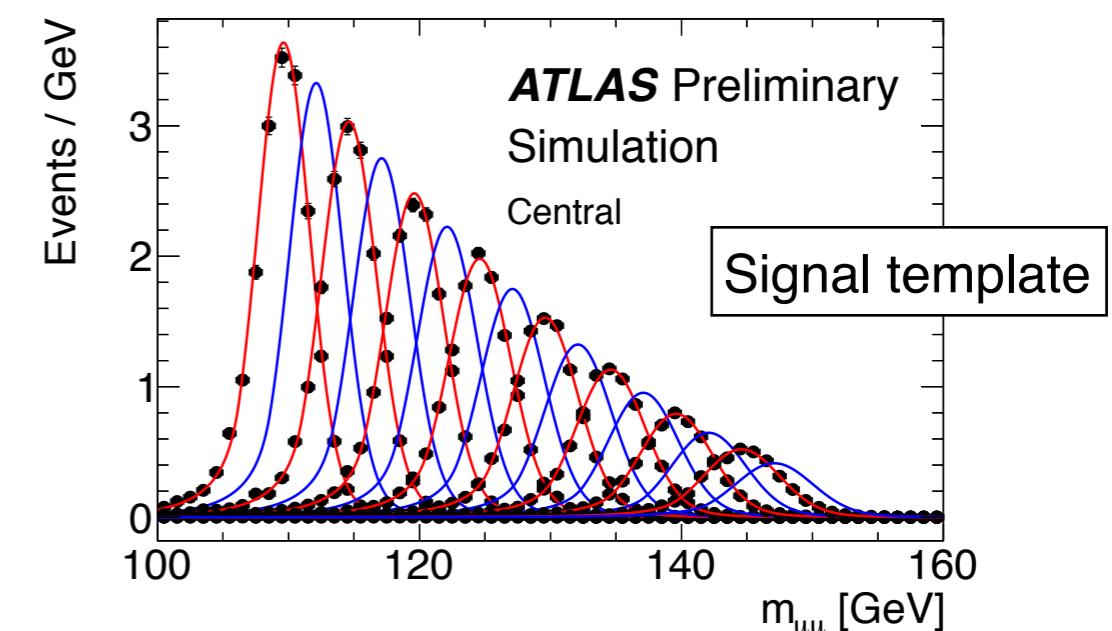
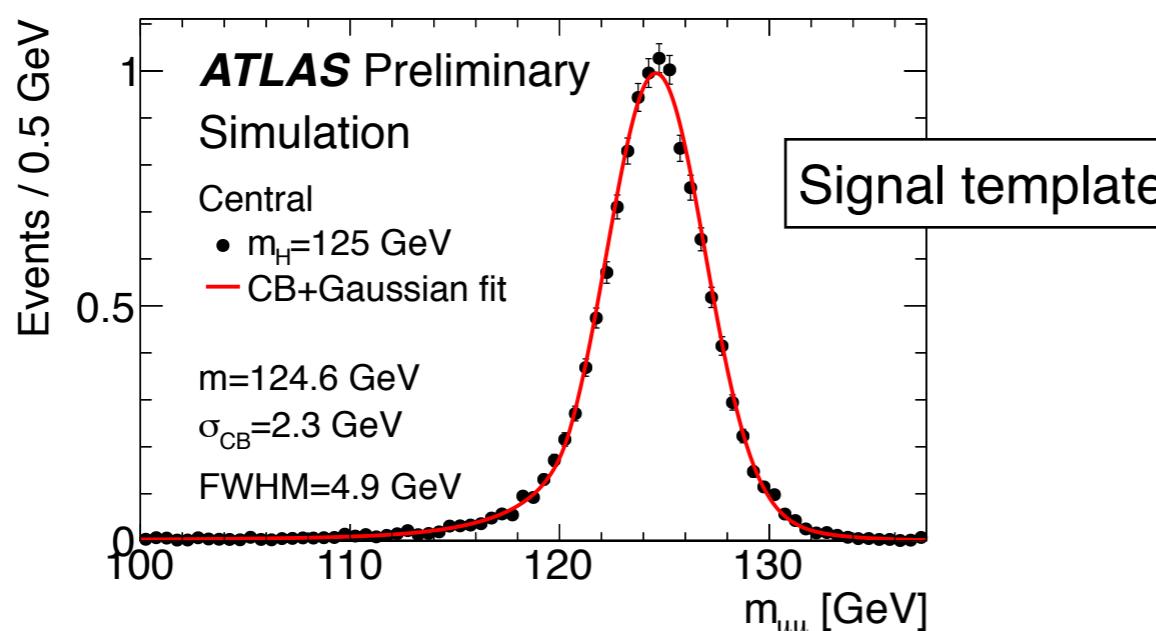
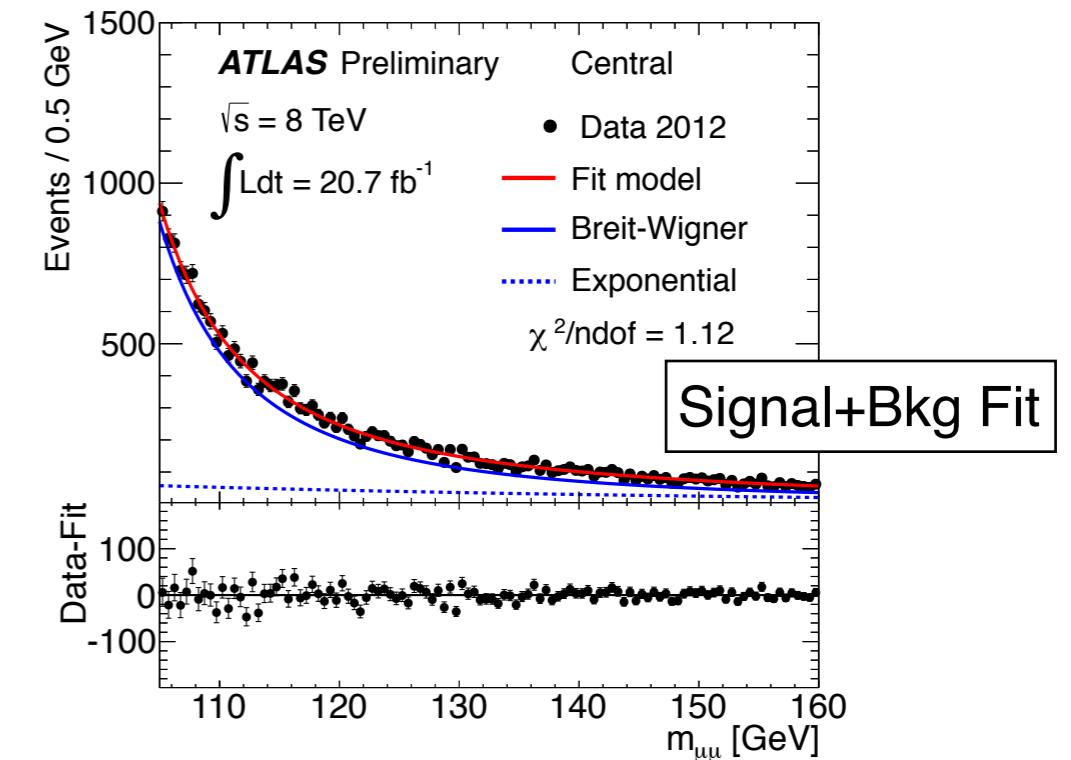
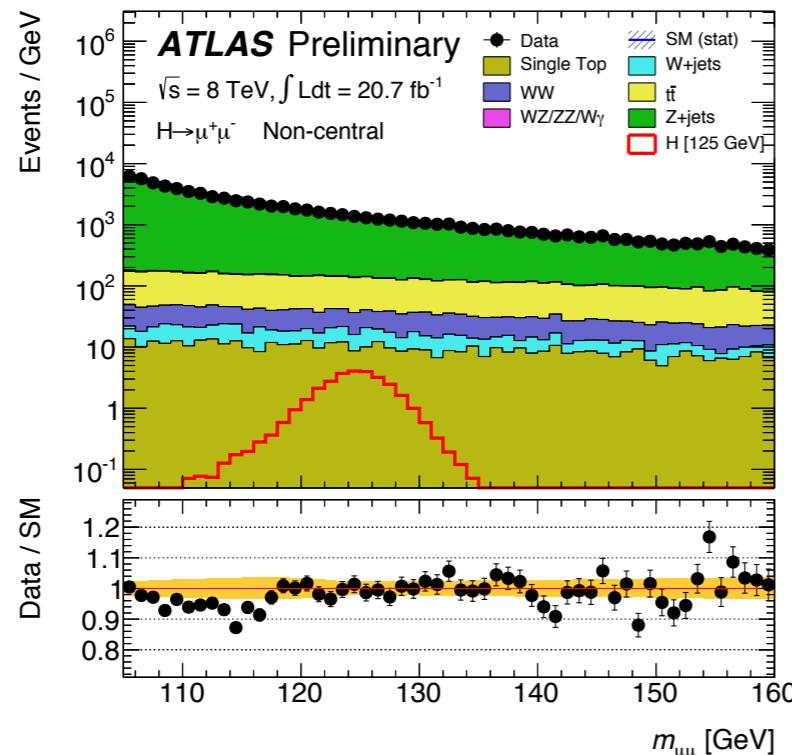
Table 8: List of systematic uncertainties considered. An “N” means that the uncertainty is taken as normalisation-only for all processes and channels affected, whereas an “S” denotes systematics that are considered shape-only in all processes and channels. An “SN” means that the uncertainty is taken 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”).



$H \rightarrow \mu\mu$: Fit template

$$P_{BG}(x) = f_{BW} \cdot BW(x, M_Z, \Gamma_Z) + (1 - f_{BW}) \cdot P(e^{B \cdot x}),$$

$$P_S(x) = f_{CB} \cdot CB(x, m, \sigma_{CB}, \alpha, n) + (1 - f_{CB}) \cdot GS(x, m, \sigma_G)$$



H \rightarrow $\mu\mu$: Systematic Uncertainty

m_H [GeV]	σ [pb]	gluon fusion		vector boson fusion		BR			
		uncertainty [%]		σ [pb]	uncertainty [%]		BR($H \rightarrow \mu^+\mu^-$)	uncertainty [%]	
		up	down		up	down		up	down
110	25.04	+15.3	-14.9	1.809	+2.7	-3.0	2.76×10^{-4}	+7.0	-6.8
115	22.96	+15.0	-14.9	1.729	+2.7	-3.0	2.63×10^{-4}	+6.7	-6.6
120	21.13	+14.8	-14.8	1.649	+2.8	-3.0	2.44×10^{-4}	+6.4	-6.3
125	19.52	+14.7	-14.7	1.578	+2.8	-3.0	2.20×10^{-4}	+6.0	-5.9
130	18.07	+14.6	-14.6	1.511	+2.8	-2.9	1.90×10^{-4}	+5.5	-5.4
135	16.79	+14.4	-14.7	1.448	+2.8	-2.9	1.55×10^{-4}	+5.0	-4.9
140	15.63	+14.3	-14.5	1.389	+2.7	-2.9	1.22×10^{-4}	+3.7	-3.8
145	14.59	+14.1	-14.4	1.333	+2.8	-2.8	9.06×10^{-5}	+3.4	-3.4
150	13.65	+14.1	-14.4	1.280	+2.8	-2.9	6.19×10^{-5}	+3.1	-3.2

Table 2: SM Higgs production cross sections at 8 TeV and SM Higgs branching ratios BR($H \rightarrow \mu^+\mu^-$) with associated uncertainty [6, 7].

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.

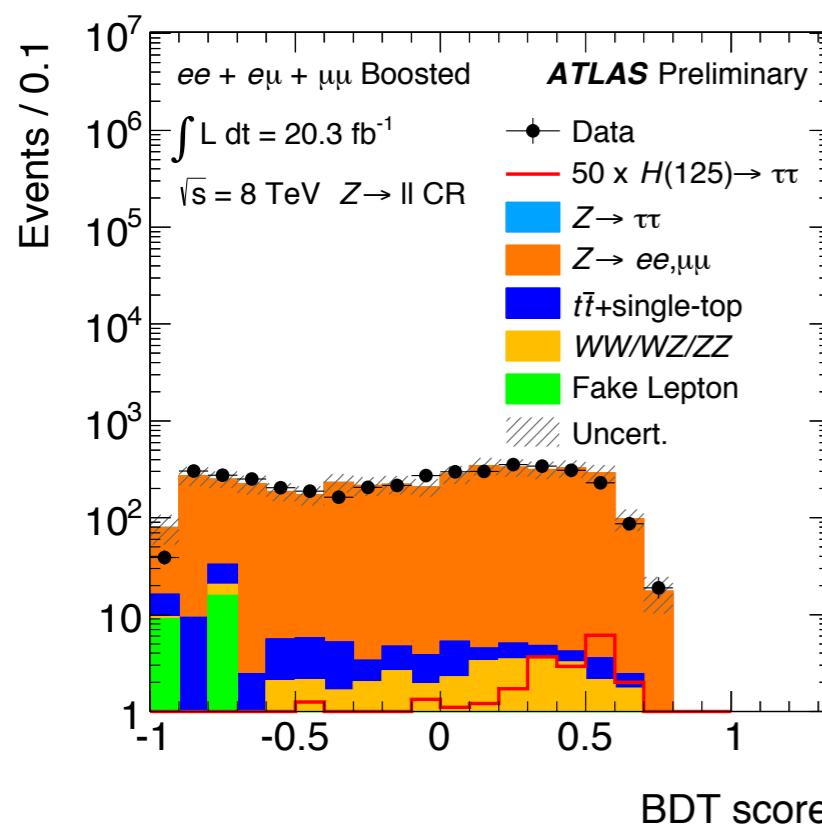
Source of Uncertainty	Treatment in the analysis
Luminosity	3.6%
Muon Selection Efficiency	0.3-1% as a function of η and p_T
Muon Momentum Scale and Resolution	< 1%
Muon Trigger	< 1%
Muon Track Isolation	< 1%
Pile-up reweighting	< 1%

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

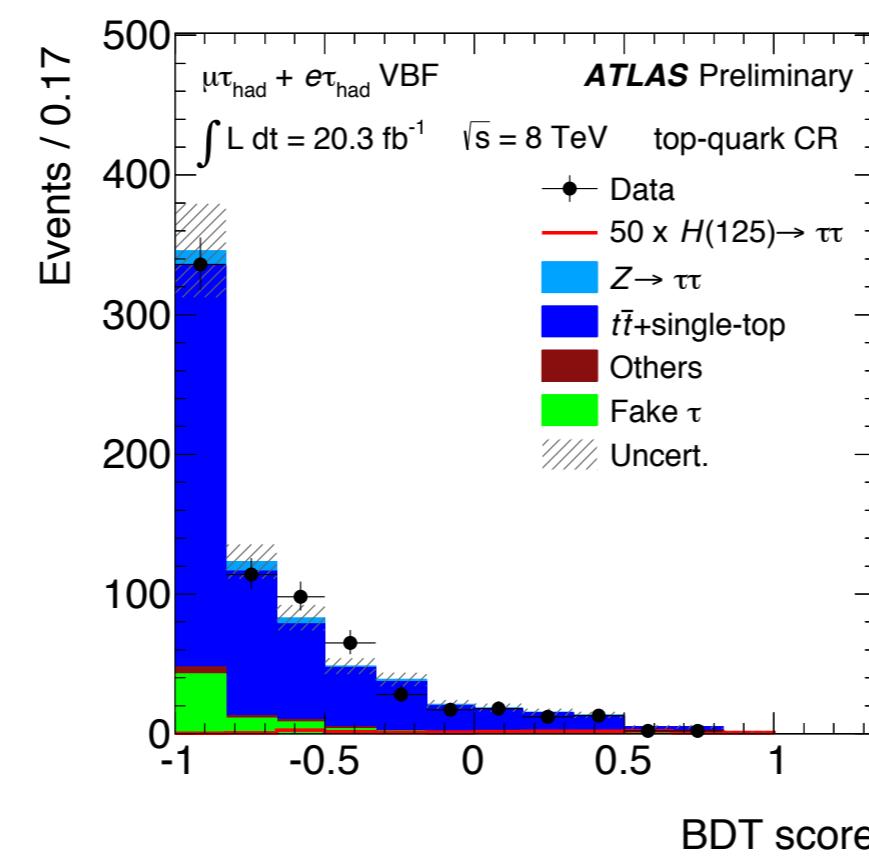
H \rightarrow TT : Control Region

	VBF Category		Boosted Category		Rest Category
	SR	CR	SR	CR	CR
H \rightarrow T _{lept} T _{lept}	✓	✓ Z \rightarrow ll (1 bin) & Top (1 bin)	✓	✓ Z \rightarrow ll (1 bin) & Top (1 bin)	✗
H \rightarrow T _{lept} T _{had}	✓	✓ Z \rightarrow ll (1 bin) & Top (1 bin)	✓	✓ Z \rightarrow ll (1 bin) & Top (1 bin)	✗
H \rightarrow T _{had} T _{had}	✓	✗	✓	✗	✓ $\Delta\eta(\tau_1, \tau_2)$ (shape)

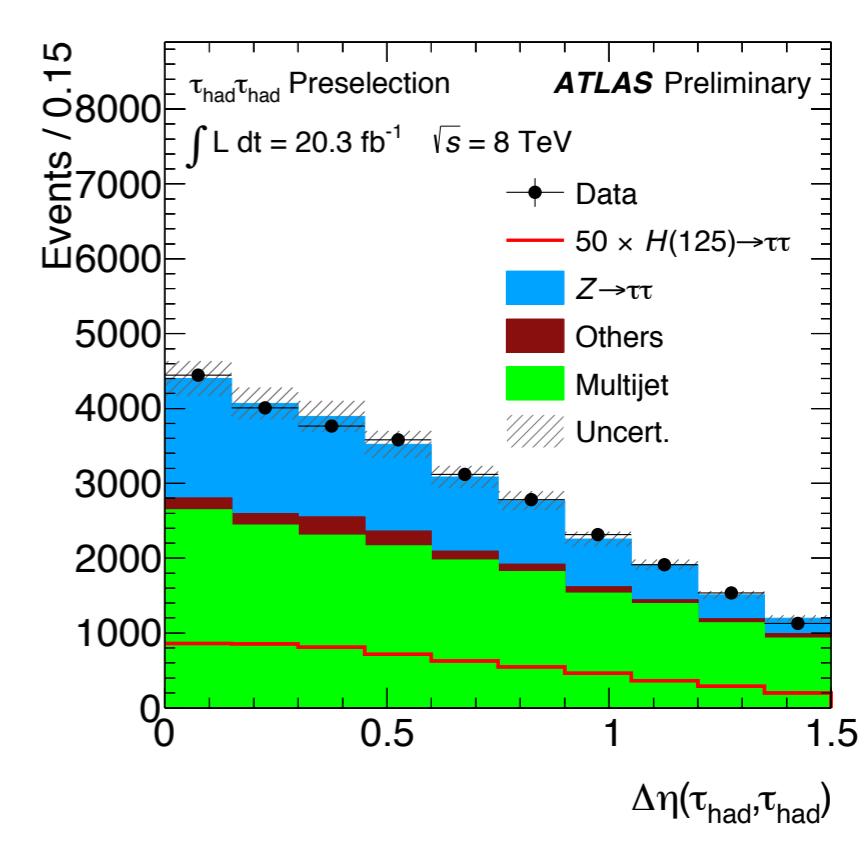
T_{lept}-T_{lept} Z \rightarrow ll CR



T_{lept}-T_{lept} Top CR



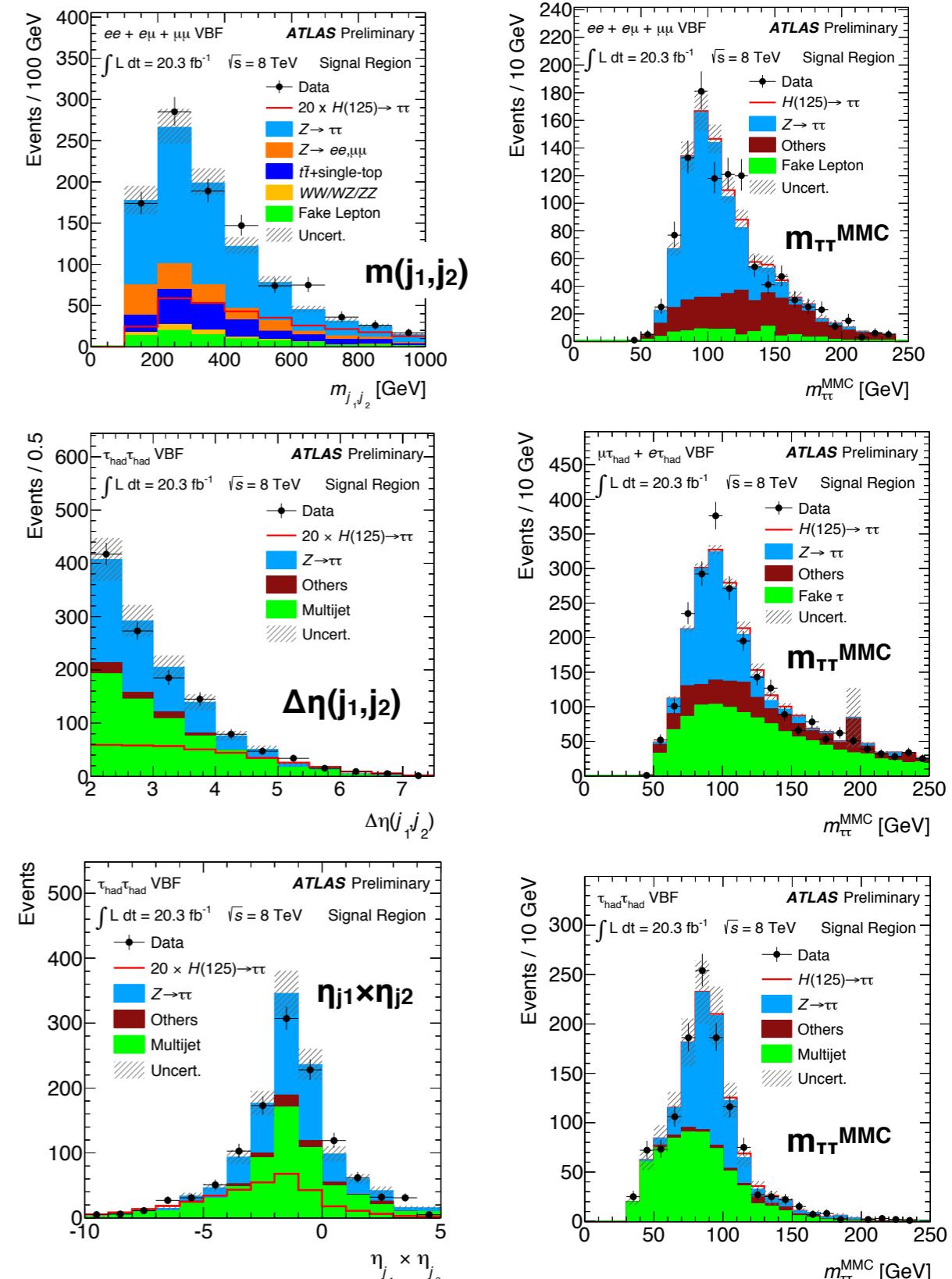
T_{had}-T_{had} Δη(τ₁,τ₂) CR



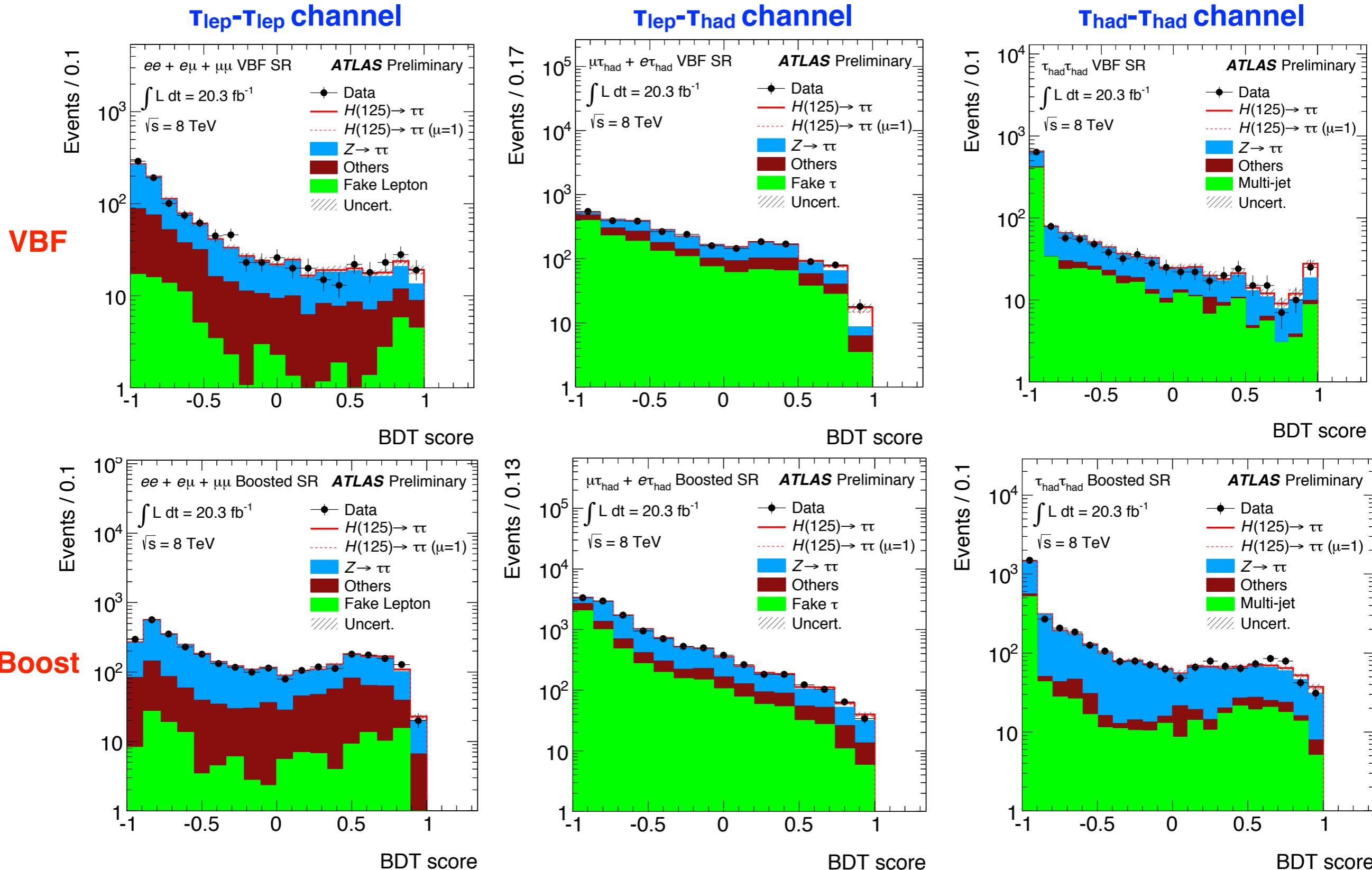
H \rightarrow $\tau\tau$: Input Variables

Variable	VBF			Boosted		
	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{lep}}$	$\tau_{\text{lep}}\tau_{\text{had}}$	$\tau_{\text{had}}\tau_{\text{had}}$
$m_{\tau\tau}^{\text{MMC}}$	●	●	●	●	●	●
$\Delta R(\tau, \tau)$	●	●	●	●	●	●
$\Delta\eta(j_1, j_2)$	●	●	●			
m_{j_1, j_2}	●	●	●			
$\eta_{j_1} \times \eta_{j_2}$		●	●			
p_T^{Total}		●	●			
sum p_T				●	●	
$p_T(\tau_1)/p_T(\tau_2)$				●	●	●
$E_T^{\text{miss}}\phi$ 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			●			
$p_T^{\ell_1}$			●			
$p_T^{j_1}$			●			
$E_T^{\text{miss}}/p_T^{\ell_2}$			●			
m_T		●		●		
$\min(\Delta\eta_{\ell_1 \ell_2 \text{jets}})$	●					
$j_3 \eta$ 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 τ_{had} , or between the two τ_{had} candidates, depending on the decay mode.



H \rightarrow TT : BDT Scores



H \rightarrow $\tau\tau$: Systematic Uncertainty

Source of Uncertainty	Uncertainty on μ
Signal region statistics (data)	0.30
$Z \rightarrow \ell\ell$ 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
$Z \rightarrow \ell\ell$ 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
$Z \rightarrow \tau^+\tau^-$ 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 .