HEAVY HIGGS BOSON SEARCHES IN THE ZZ AND WW CHANNELS WITH ATLAS

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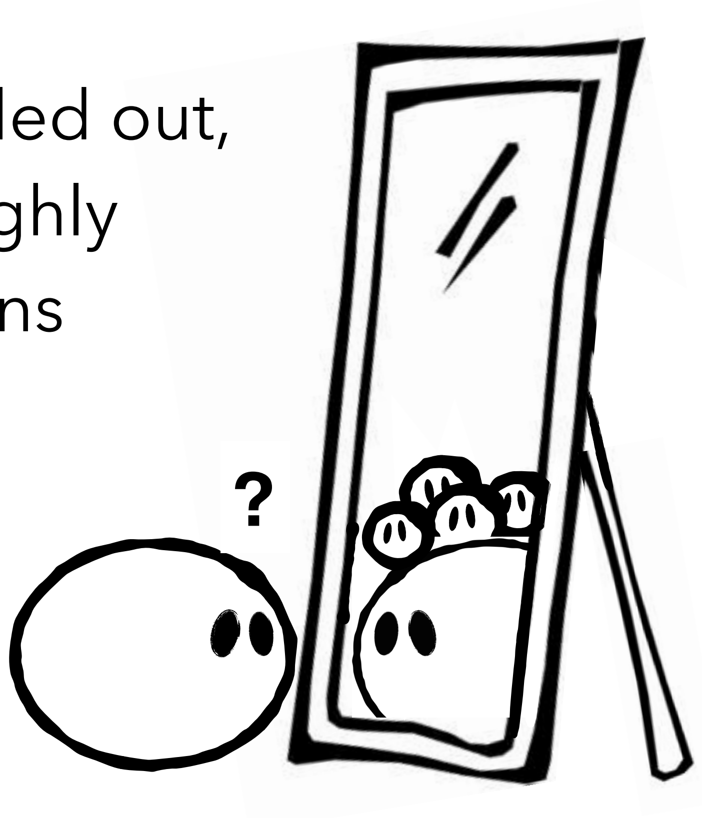
INTRODUCTION

The existence of an extended Higgs sector is not ruled out, although our recently discovered Higgs boson is highly compatible with the Standard Model (SM) predictions



Overview

- Theoretical motivation
  - 2HDM
  - EWS
- The $H \to ZZ$ searches
- The $H \to WW$ searches
- Results
- Outlook and summary

Will present an overview of the ATLAS searches for heavy Higgs bosons in the ZZ and WW channels with $\sqrt{s}$ = 8 TeV data

THEORETICAL MOTIVATION

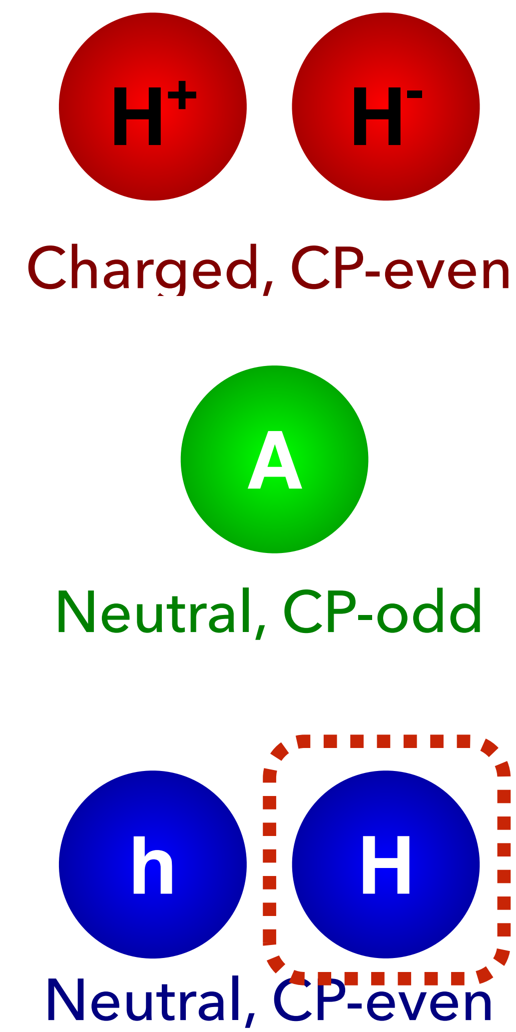
Models with extended Higgs sector

- 2 Higgs Doublet Model (2HDM)
- Electroweak Singlet (EWS)

EXTENDED HIGGS SECTORS – 2HDM

The Higgs sector contains 2 complex doublets (Φ_1, Φ_2), resulting in 5 Higgs bosons after spontaneous symmetry breaking

- Interpret the 125 GeV Higgs as h – search for the heavier H



Parameters of 2HDM

- Masses of the bosons
- tan(β): ratio of vacuum expectation values of doublets
- α: mixing angle of doublets

Several types of 2HDM

- Type-1: Φ_2 couples to all quarks and leptons
- Type-2: Φ_1 couples to down-type quarks and leptons, Φ_2 couples to up-type quarks

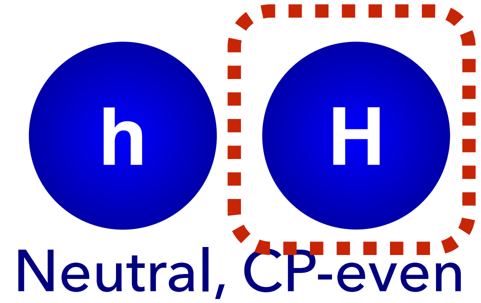
The width of the heavy Higgs is highly dependant on the 2HDM parameters

- Results in narrow width over large part of the 2HDM parameter space

The H→ZZ channel presents a 2HDM interpretation (type-1 and -2)

EXTENDED HIGGS SECTORS – EWS

Simple extension to SM Higgs sector with an additional singlet, resulting in 2 Higgs bosons after spontaneous symmetry breaking



Couplings of both Higgs scales in relation to SM couplings

- Preserves unitary in vector boson scattering

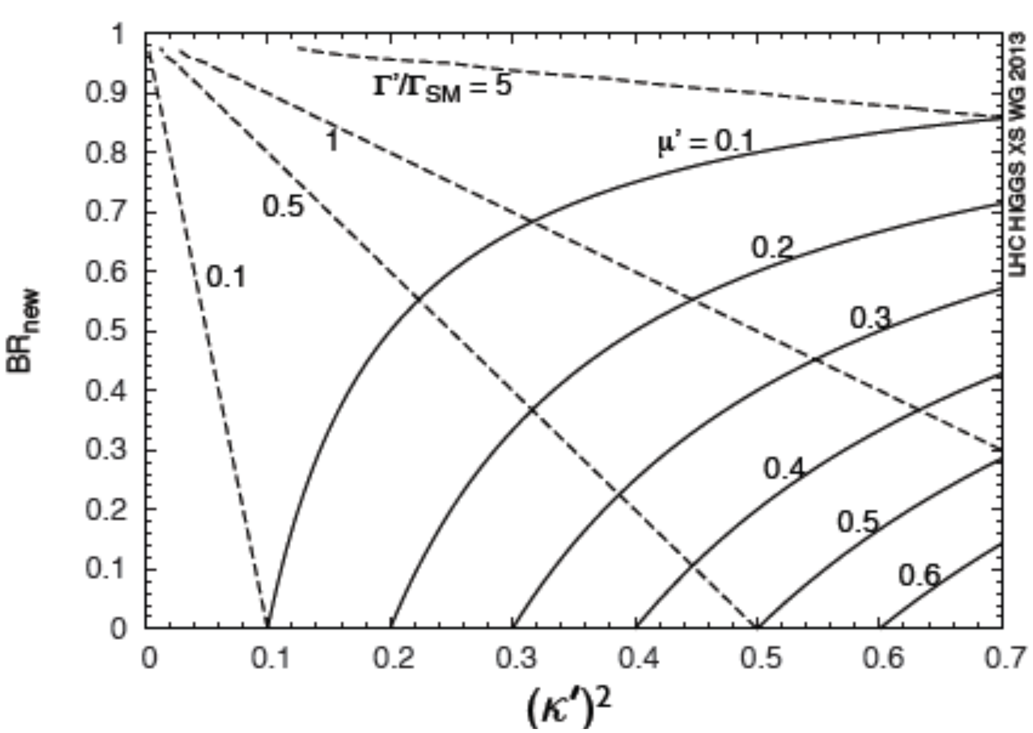
$$\kappa^2(h) + \kappa'^2(H) = 1$$

H can have non-SM decays

- Branching ratio to non-SM decays given by BR_{new}

H width varies as function of couplings and BR_{new}

$$\Gamma' = \frac{\kappa'^2}{(1 - BR_{new})}\Gamma_{SM}$$



Given current measurements of signal strength for light Higgs, if $BR_{new} = 0$, H will have small width

The H→WW channel presents a EWS-like interpretation by scanning over multiple widths

OVERVIEW OF SEARCHES

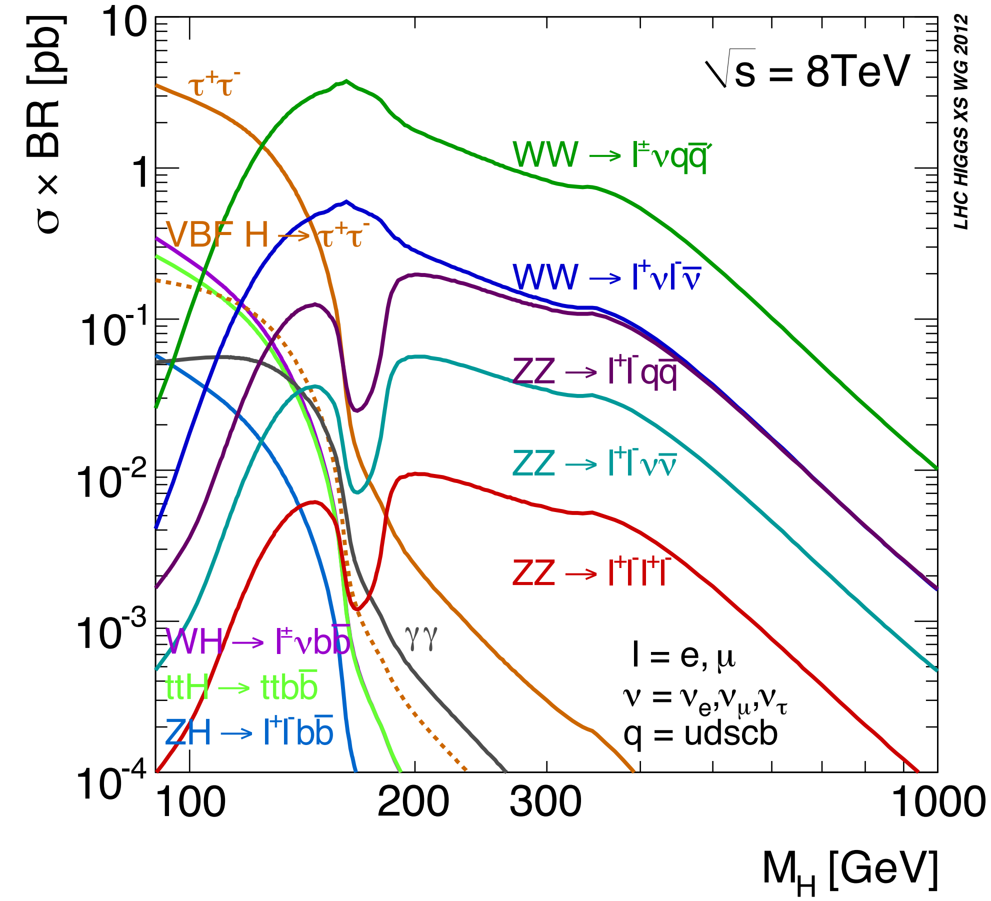
THE ZZ AND WW SEARCHES

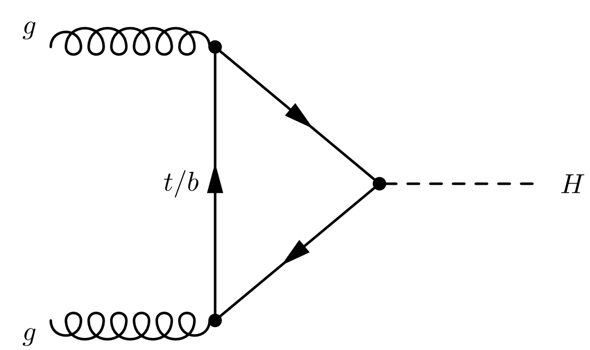
The ZZ and WW high mass searches rely on 20.3 fb^{-1} recorded at $\sqrt{s}$ = 8 TeV

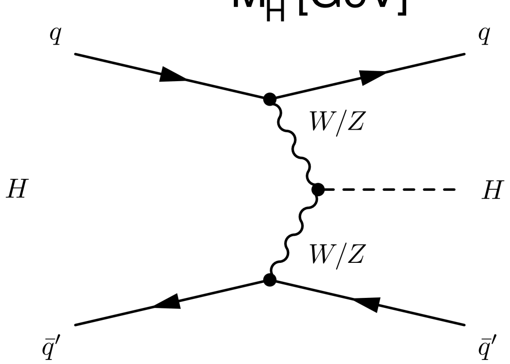
Both channels search in multiple final states, which are then statistically combined to provide a combined limit

Both channels classify events according to production mode

- ggF- or VBF-like
    - Determined from jet multiplicity
- A signal strength parameter is defined for each production mode (μ_{ggF}, μ_{VBF})







Channel	Final states
ZZ	4l, llvv, llqq, vvqq
WW	lvlv, lvqq

SIGNAL SCENARIOS

Different results are produced, depending on the various signal scenarios

Narrow Width Approximation (NWA)

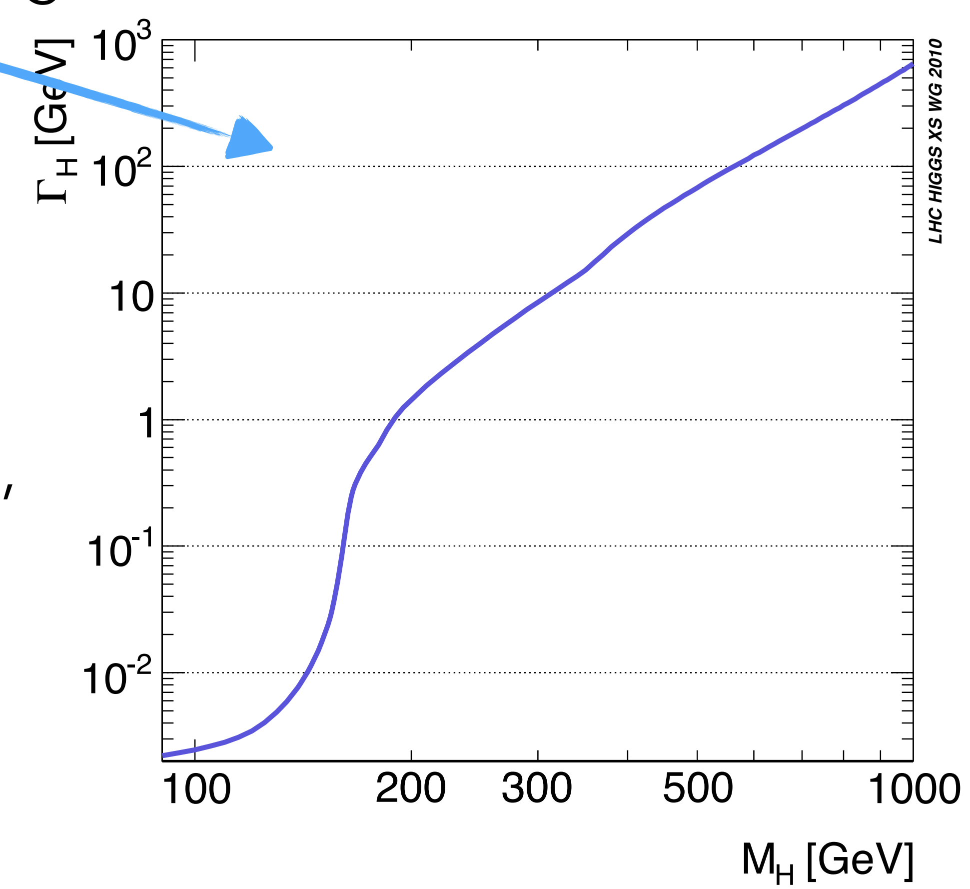
- Signal modelled as a narrow resonance with Γ_H = 4 MeV ($\Gamma_{SM\ h@125\ GeV}$)
  - Width fixed as function of mass
- Interference with light Higgs and diboson continuum neglected
- ***Used for pseudo-model independent results and 2HDM interpretation***

Complex Pole Scheme (CPS)

- Lineshape derived with full complex Higgs propagator
- Width identical to SM higgs, $\Gamma_H(m_H) = \Gamma_{SM}(m_H)$
- Interference with diboson continuum included
- ***Used for SM-like results***

Intermediate width

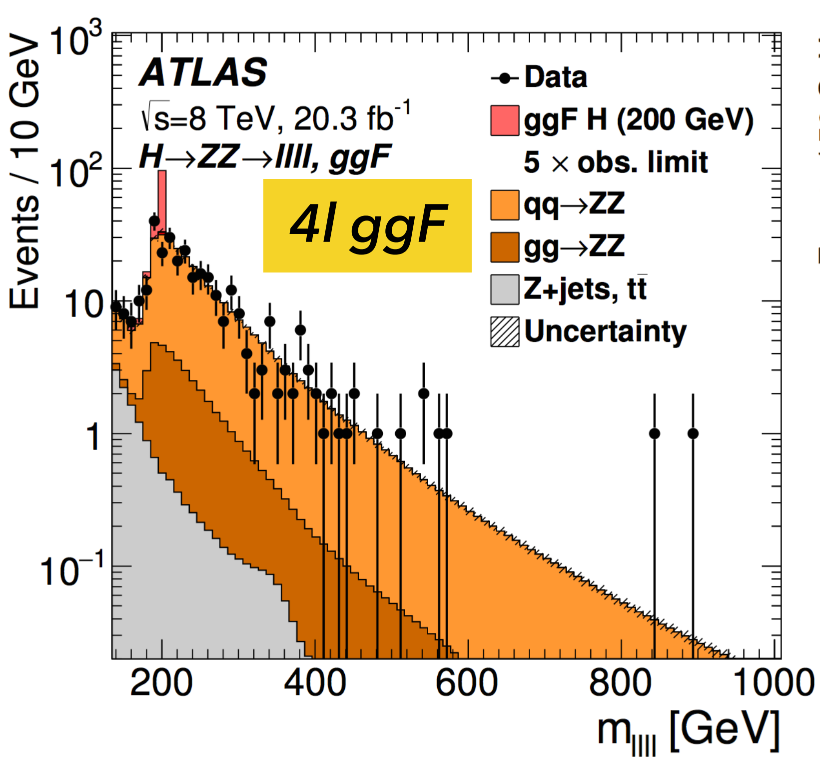
- Width of CPS samples scaled down to 20%, 40%, and 80% of Γ_{SM}
- ***Used for EWS-like results***

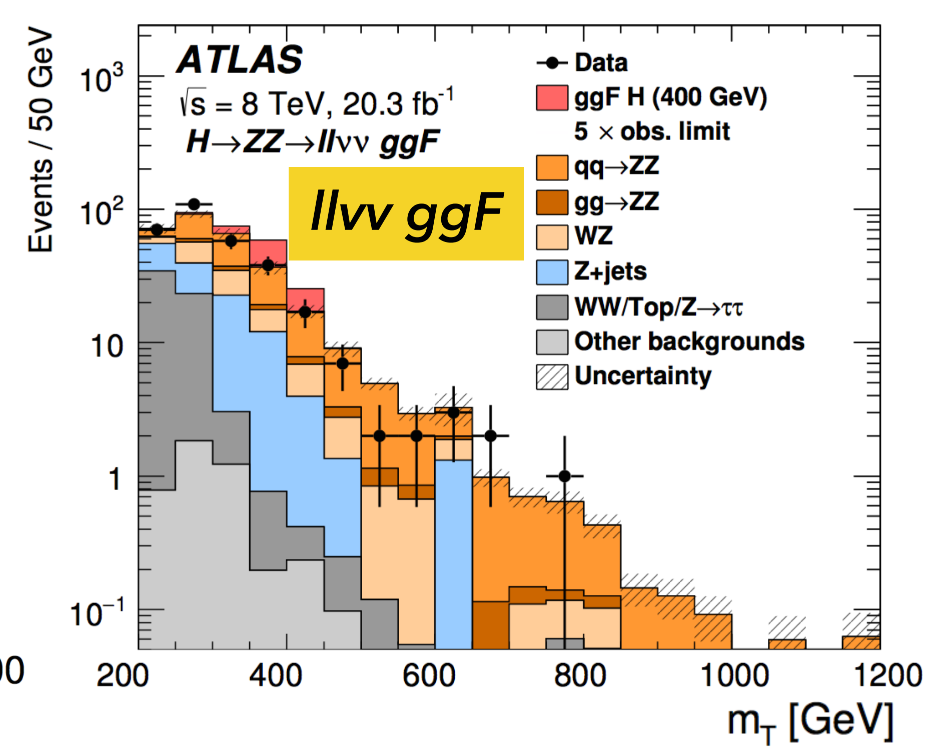


THE H→ZZ SEARCHES

arXiv:1507.05930

Final state	Selected final state objects*	Discriminant	Event categories	Main backgrounds
4l	2 lepton pairs**	m_{4l}	ggF/VBF/VH	ZZ
llvv	1 lepton pair** E_T^{miss}	m_T	ggF/VBF	ZZ, WZ
llqq	1 lepton pair** 1 or 2 jets	$m_{llj(j)}$	ggF/VBF	Z+jets, top, diboson
vvqq	E_T^{miss} 1 or 2 jets	m_T	ggF	Z+jets, W+jets, tt





* Ignoring jets for VBF tagging

** $\mu^+\mu^-$ or e^+e^-

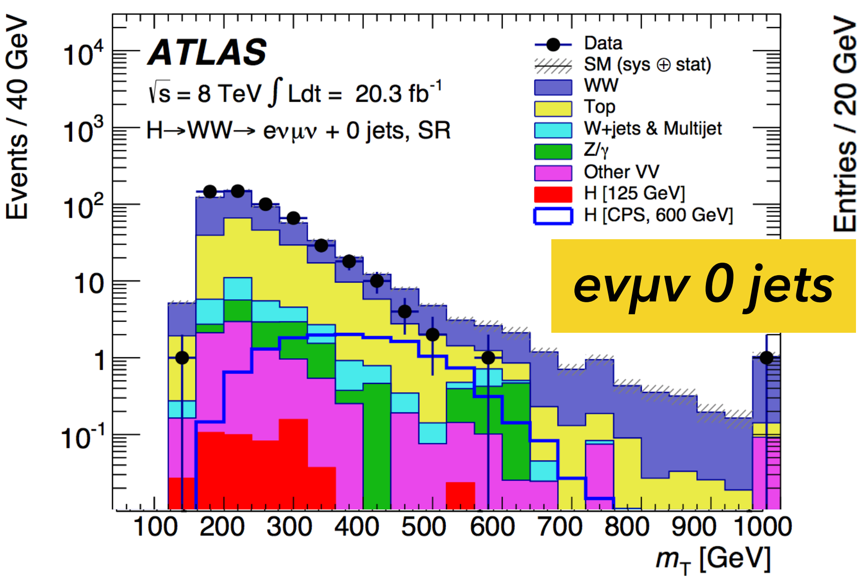
*** More details in backup

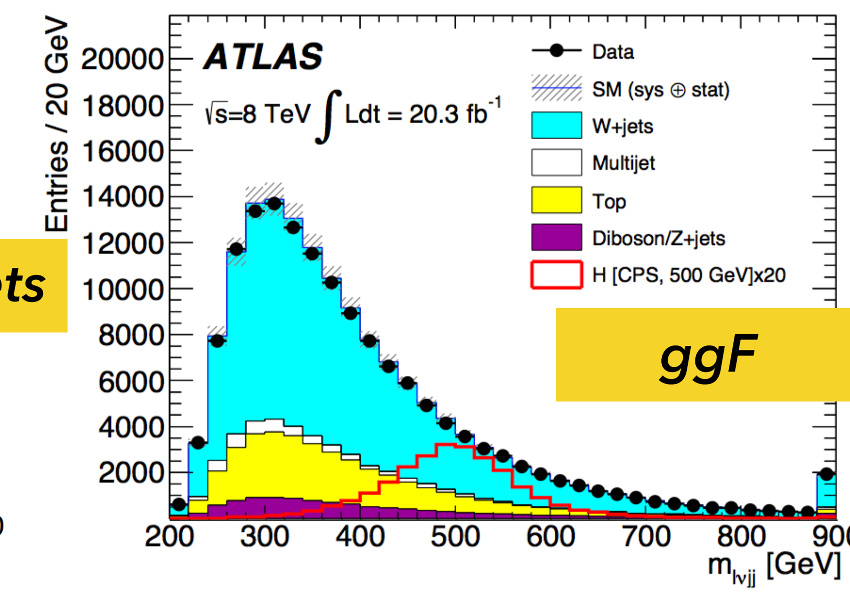
Channels have vastly different experimental resolution (O(1) - O(100) GeV) and sensitivity across different mass ranges

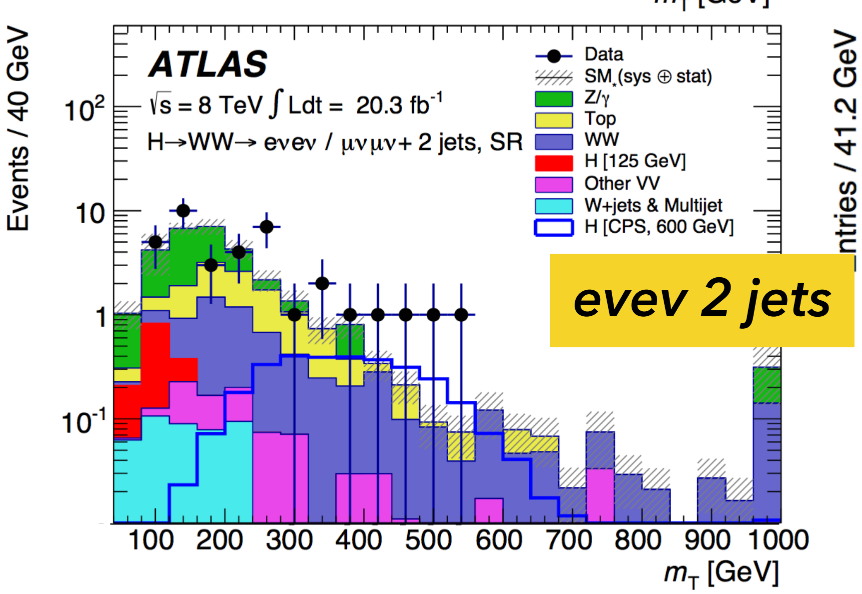
THE H→WW SEARCHES

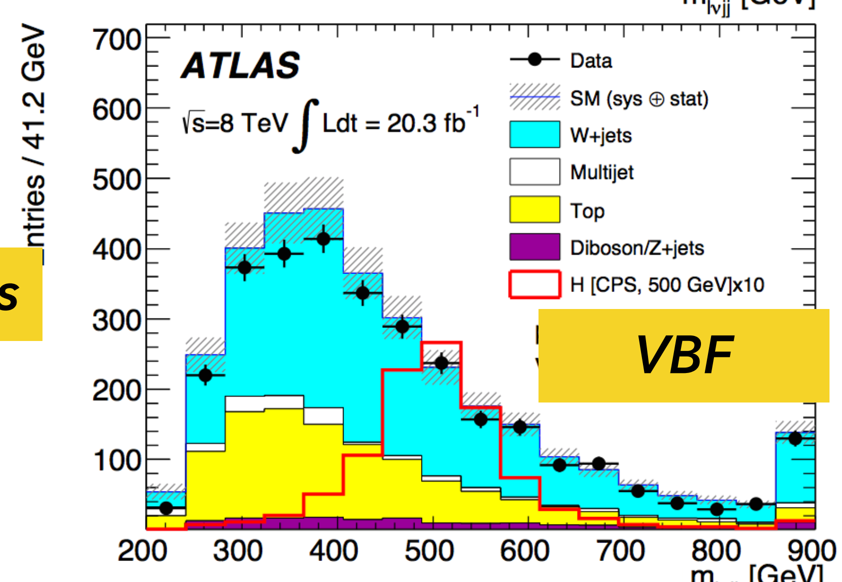
arXiv:1509.00389

Final state	Selected final state objects*	Discriminant	Event categories	Main backgrounds
lvlv	2 leptons** E_T^{miss}	m_T	ggF/VBF	WW, top
lvqq	1 lepton** E_T^{miss} 2 jets	m_{lvjj}	ggF/VBF	W+jets, top









* Ignoring jets for VBF tagging

** μ or e

*** More details in backup

Sensitivity of final states differs across mass range

- Low mass: lvlv dominates
  - Less background
- High mass: lvqq dominates
  - Higher BR and better experimental resolution

RESULTS

Pseudo-model independent limits on $\sigma_H \times BR$

- $H \to ZZ$, Narrow Width Approximation
- $H \to WW$, Narrow Width Approximation

Model-specific scenarios

- $H \to ZZ$, constraints on 2HDM type-1 parameter space
- $H \to WW$, limits in EWS-like scenario

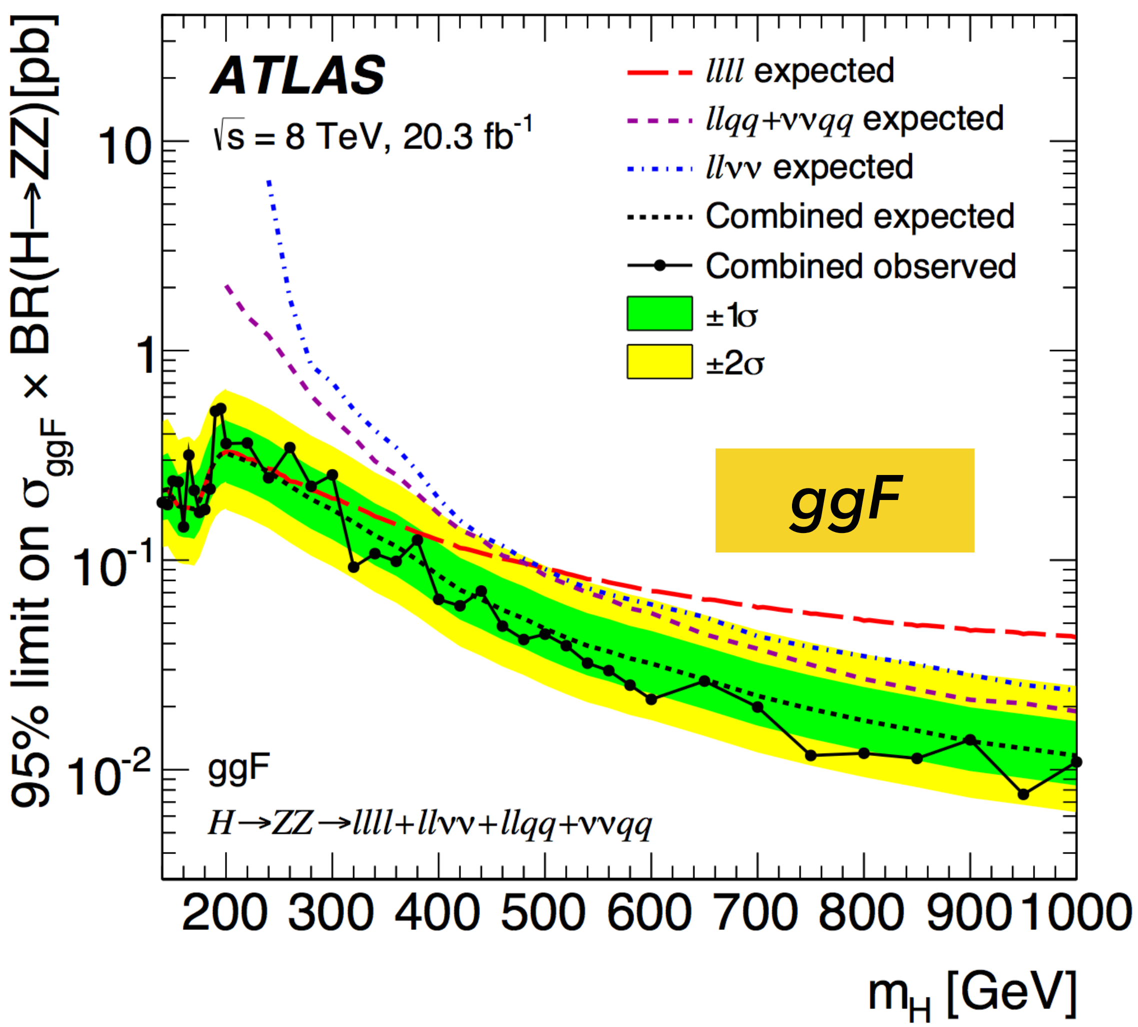
In backup

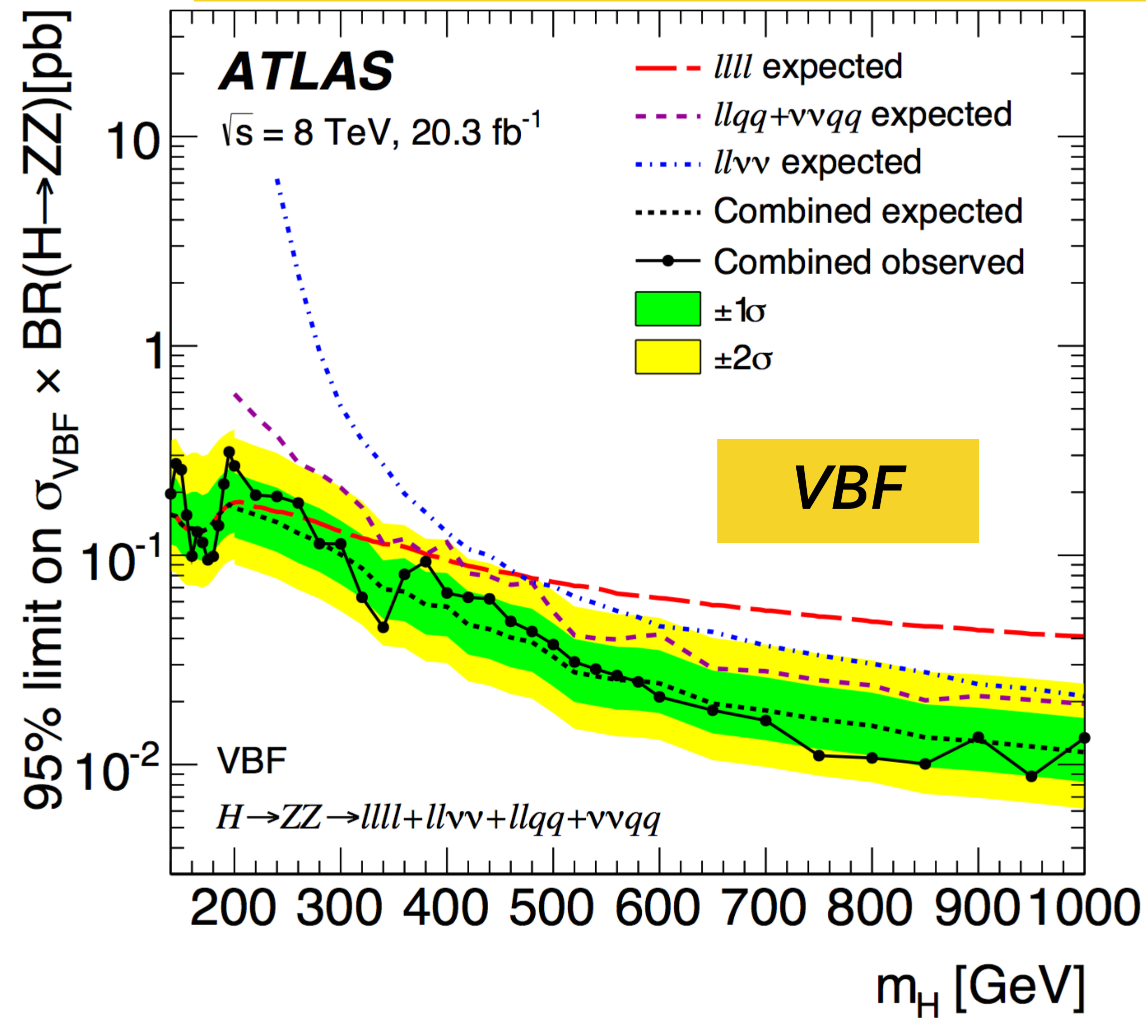
- $H \to WW$, Complex Pole Scheme
- $H \to ZZ$, constraints on 2HDM type-2 parameter space

LIMITS ON $\sigma_H \times BR(H \to ZZ)$

arXiv:1507.05930

$H \to ZZ$ Narrow Width Approximation





Pseudo-model independent limits obtained by setting limits separately for μ_{ggF} and μ_{VBF}

- Avoid model-specific assumptions about ggF/VBF ratio
- In observed limits, the μ not being fitted is profiled

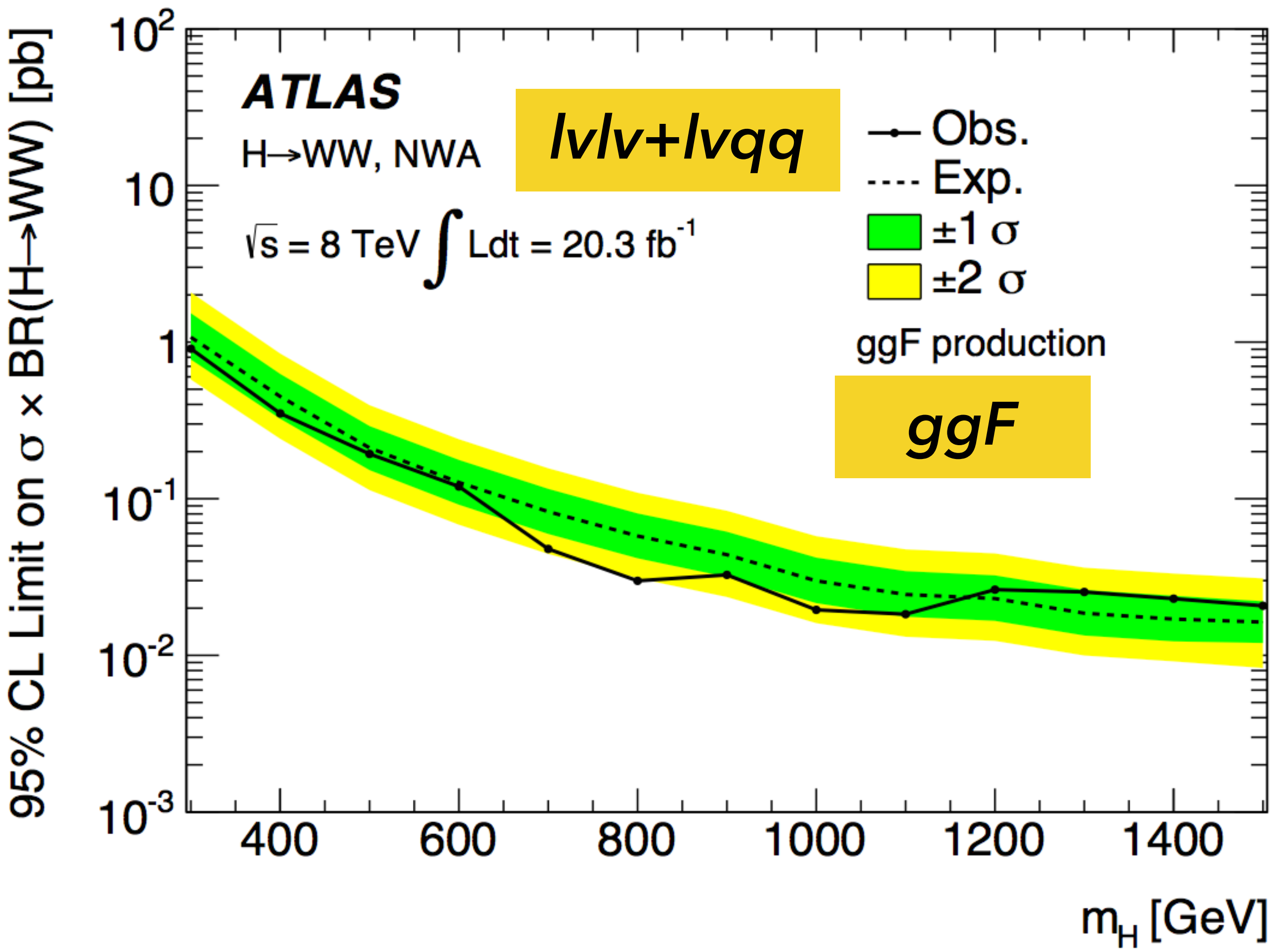
No indications of a heavy Higgs

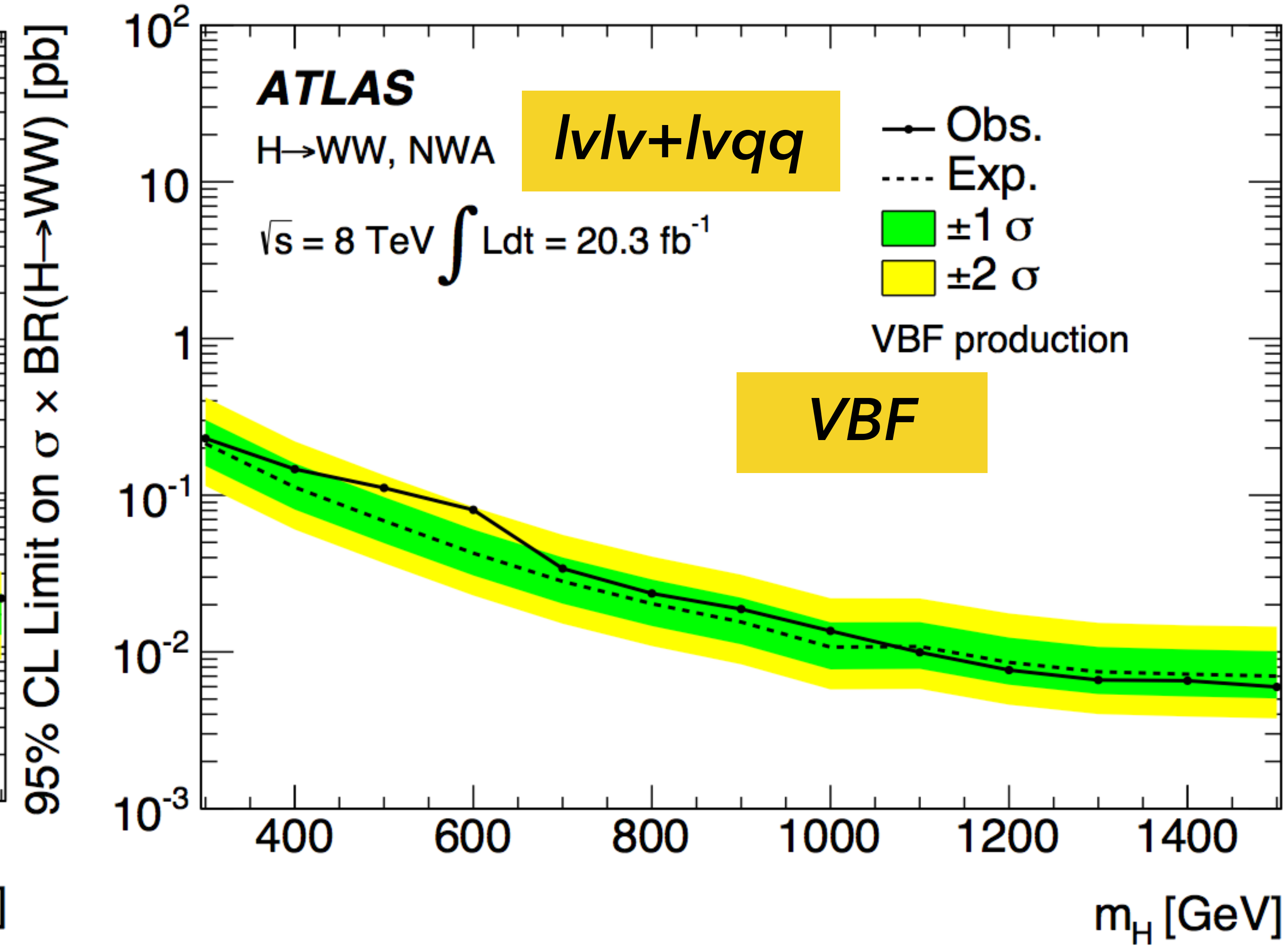
- Upper limits on ggF: 0.53 pb – 0.008 pb
- Upper limits on VBF: 0.31 pb – 0.009 pb

LIMITS ON $\sigma_H \times BR(H \rightarrow WW)$

arXiv:1509.00389

H→WW Narrow Width Approximation





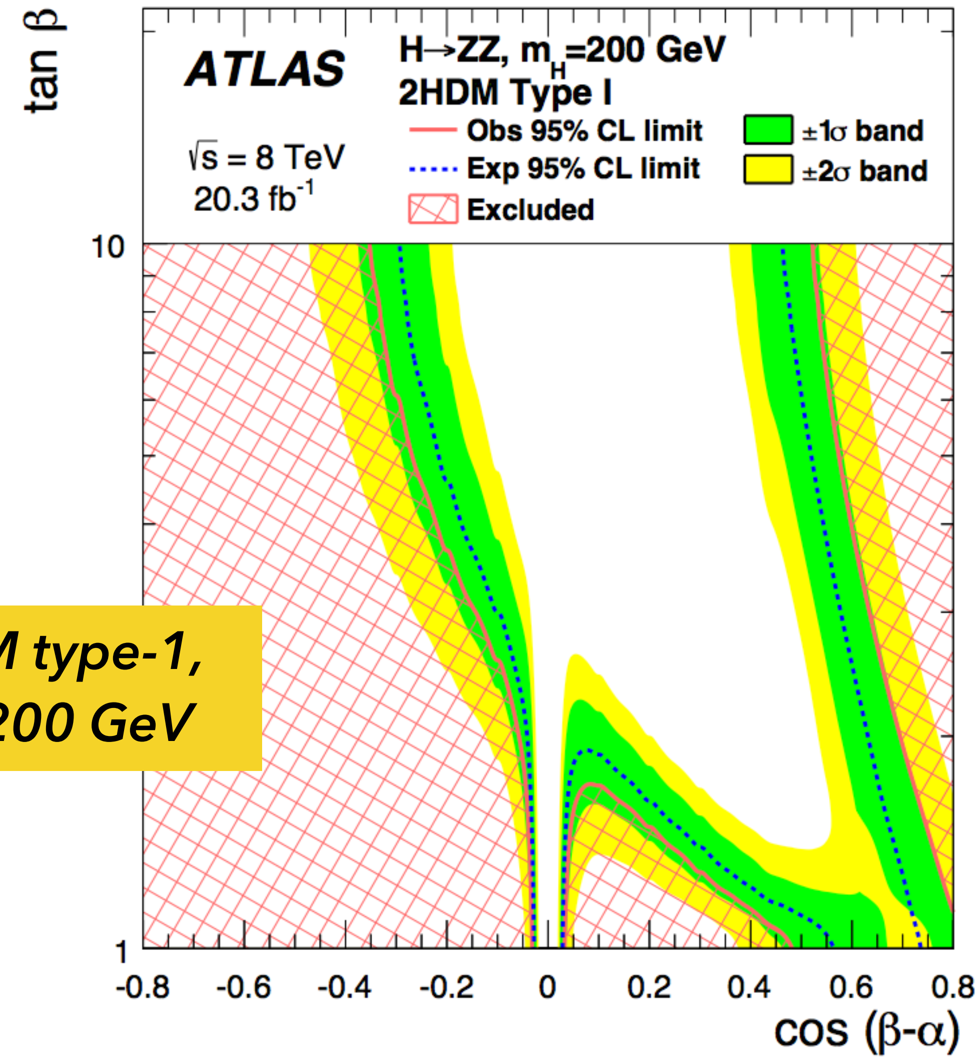
No indications of a heavy Higgs

- Upper limits on ggF: 0.91 pb – 0.021 pb
- Upper limits on VBF: 0.23 pb – 0.006 pb

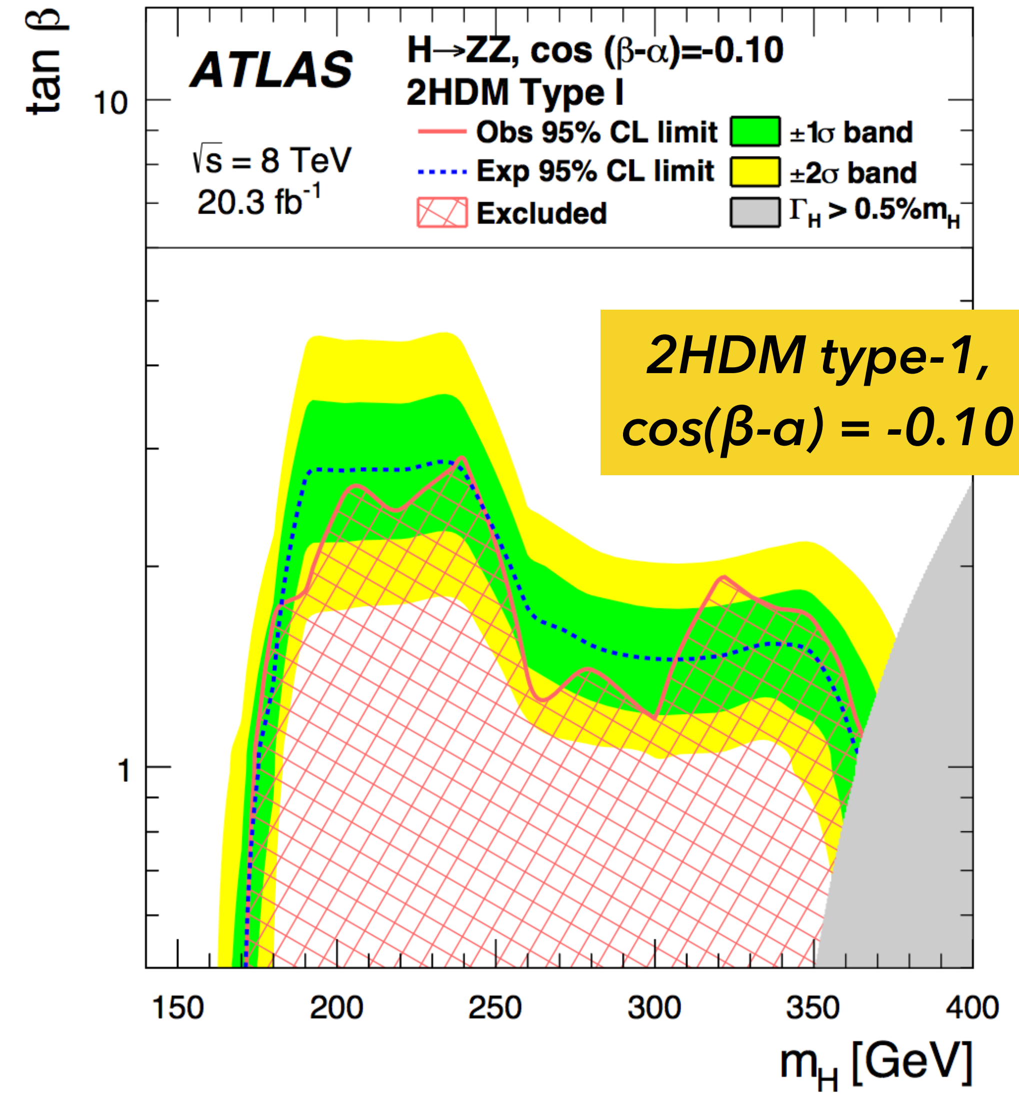
CONSTRAINTS ON 2HDM

arXiv:1507.05930

H→ZZ Narrow Width Approximation



2HDM type-1, m_H=200 GeV



2HDM type-1, cos(β-α) = -0.10

Constraints on 2HDM parameter space obtained by fixing ggF/VBF ratio according to values of cos(β-α) and tan(β)

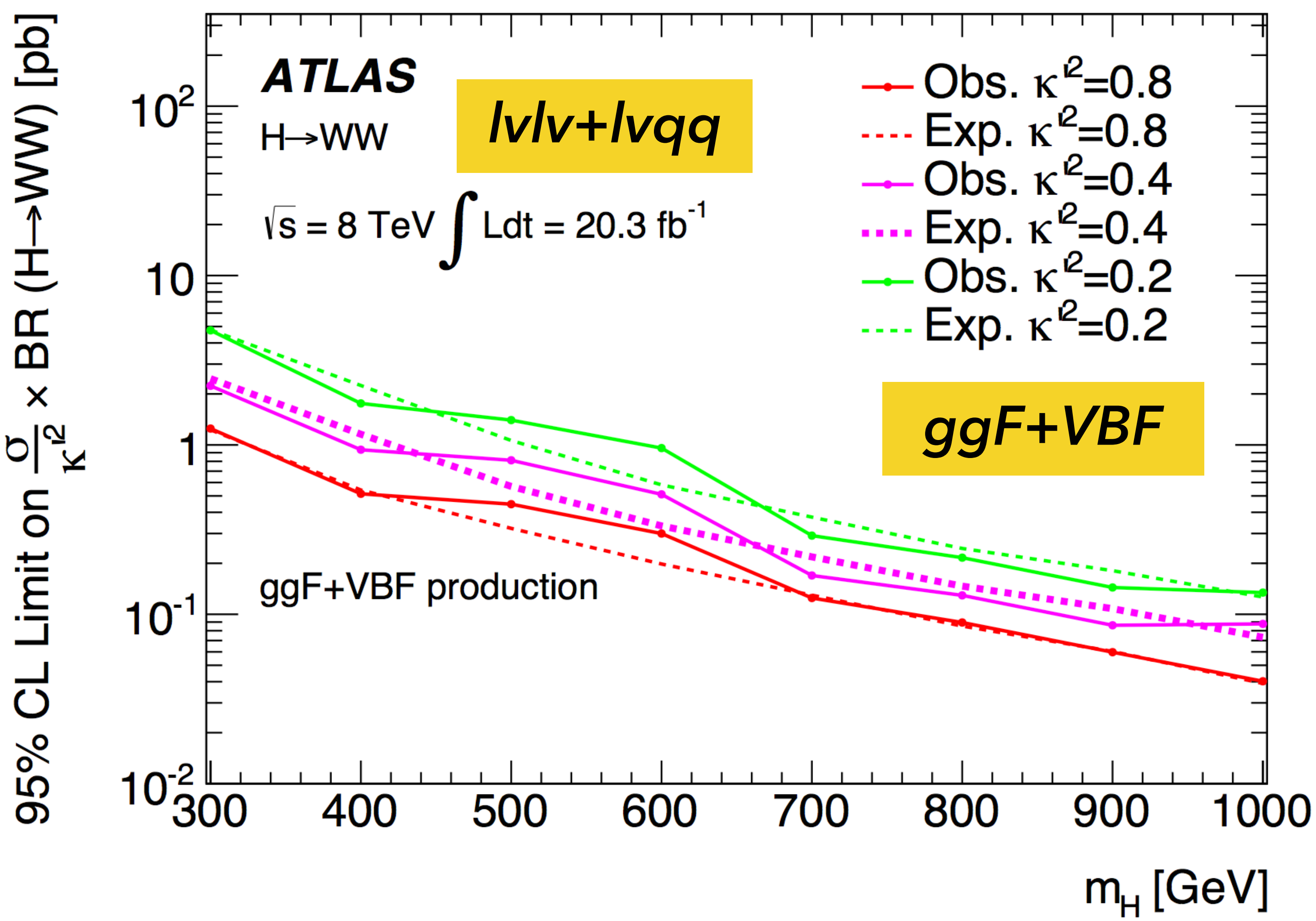
The range of cos(β-α) and tan(β) is limited to the region where the Narrow Width Approximation is valid

Similar plots with type-2 in backup

LIMITS IN EWS-LIKE SCENARIO

arXiv:1509.00389

H→WW intermediate width scenario



Assume scale factor k'^2 between SM and EWS scenario

- ***Limits set for different values of*** k'^2

$$\sigma_H = \kappa'^2 \times \sigma_{H,\mathrm{SM}}$$
$$\Gamma_H = \kappa'^2 \times \Gamma_{H,\mathrm{SM}}$$
$$\mathrm{BR}_i = \mathrm{BR}_{\mathrm{SM},i}$$

The parameters of a true EWS are constrained by measurements of the 125 GeV Higgs

- This approach allows a greater spectrum of possible widths to be explored

ggF/VBF ratio assumed to follow that in the SM

- Limits set on the global signal strength μ

SUMMARY

SUMMARY

ATLAS presented searches for heavy Higgs bosons with the run-1 dataset in the ZZ and WW channels

- No indications of additional Higgs bosons observed so far

$H\to ZZ$ interpretations done on the basis of the Narrow Width Approximation

- Pseudo-model independent limits on $\sigma_H \times BR(H\to ZZ)$
- Constraints on the 2HDM parameter space in type-1 and type-2 2HDM

The $H\to WW$ channel presents results with three different signal scenarios

- Pseudo-model independent limits on limits on $\sigma_H \times BR(H\to WW)$
  - Performed with both Narrow Width Approximation and Complex Pole Scheme
- EWS-like limits on $\sigma_H \times BR(H\to WW)$
  - Intermediate-width scenario

OUTLOOK

Sensitivity expected to increase rapidly at $\sqrt{s}$ = 13 TeV and become comparable to Run-1 analyses with as little as ~5 fb^{-1}

Significance, H→ZZ→4l, ggF		
m_H [GeV]	Run-1	Run-2 5 fb^{-1}
200	6.25	6.05
600	4.59	7.01
1000	1.3	2.01

C. Gwilliam

Significance, H→ZZ→llqq, ggF			
m_H [GeV]	Run-1	Run-2 5 fb^{-1}	Run-2 30 fb^{-1}
200	1.2	1.24	3.04
600	3.6	5.64	13.81
1000	0.7	1.21	3.25

C. Gwilliam

S/B H→WW→lvqq, ggF			
m_H [GeV]	Run-1	Run-2 5 fb^{-1}	Run-2 10 fb^{-1}
300	3.95	3.99	5.65

S. Diglio

Stay tuned for early Run-2 analyses!

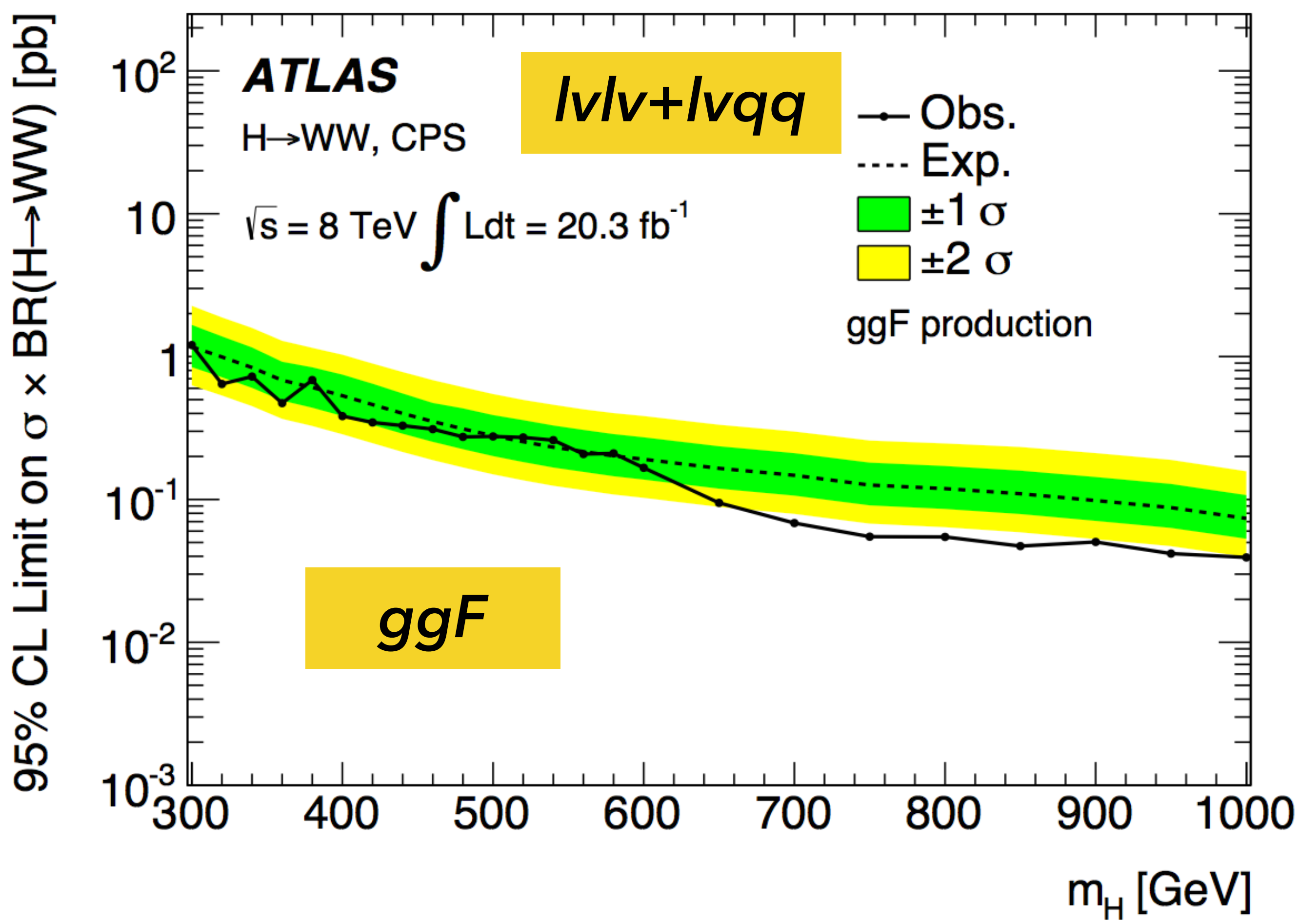
THANKS FOR YOUR ATTENTION

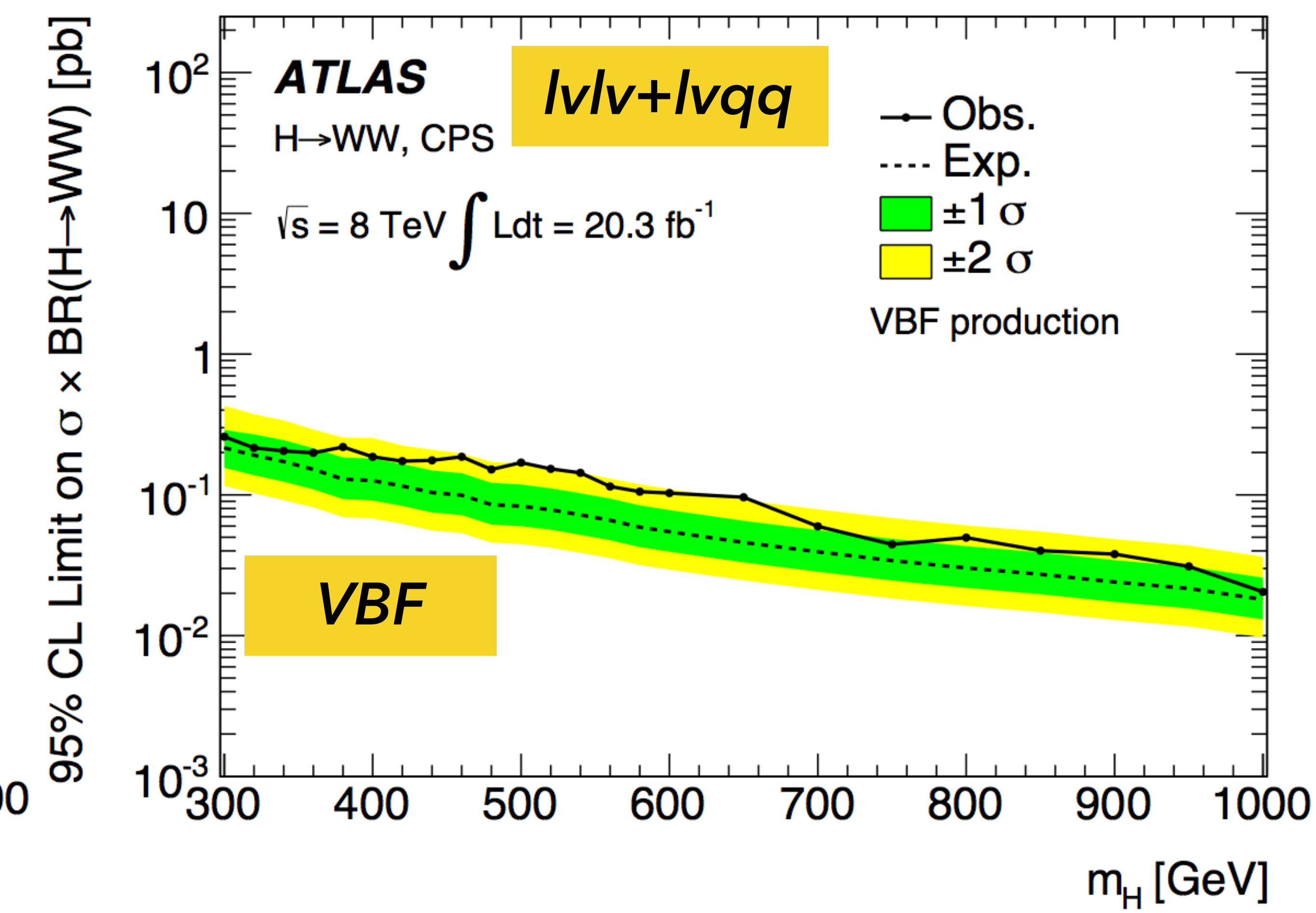
BACKUP

LIMITS ON $\sigma_H \times BR(H \rightarrow WW)$

arXiv:1509.00389

H→WW Complex Pole Scheme (SM-like scenario)





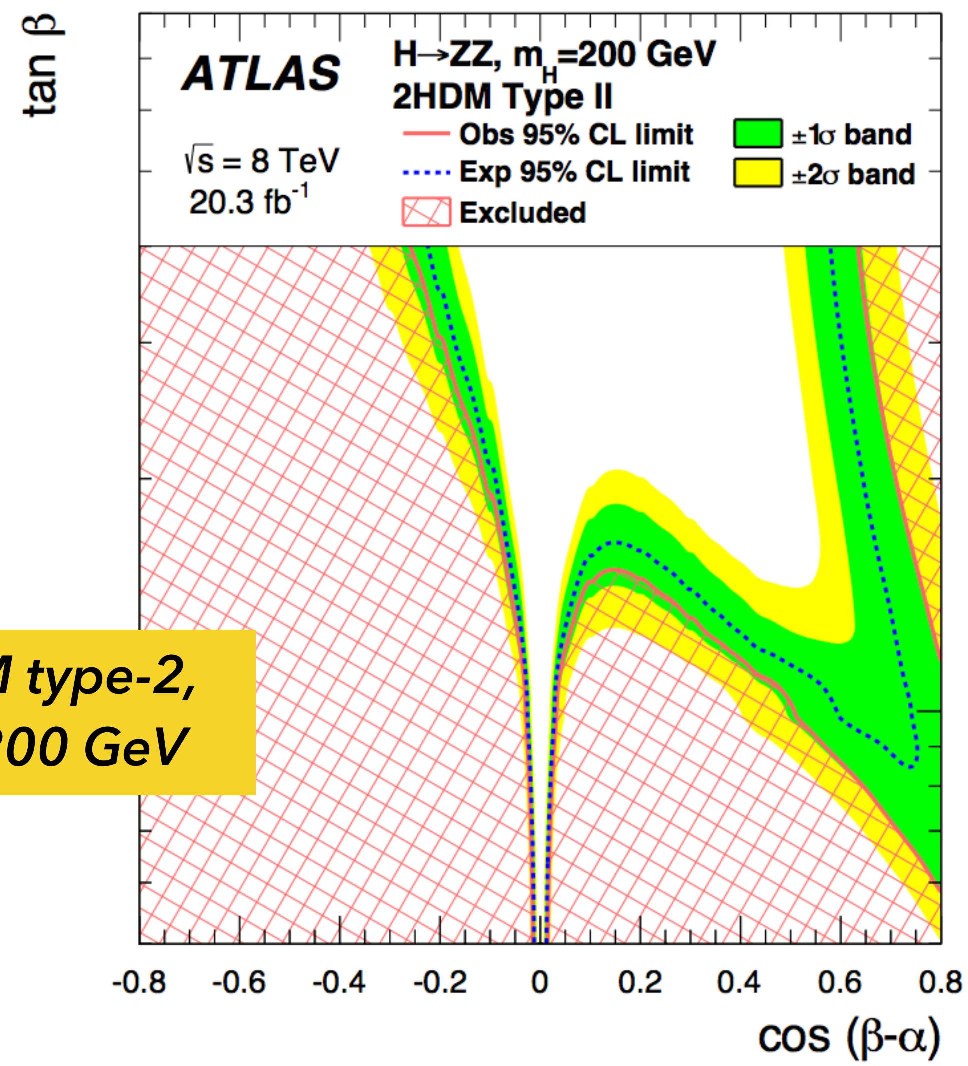
No indications of a heavy Higgs

- Upper limits on ggF: 1.20 pb – 0.040 pb
- Upper limits on VBF: 0.26 pb – 0.020 pb

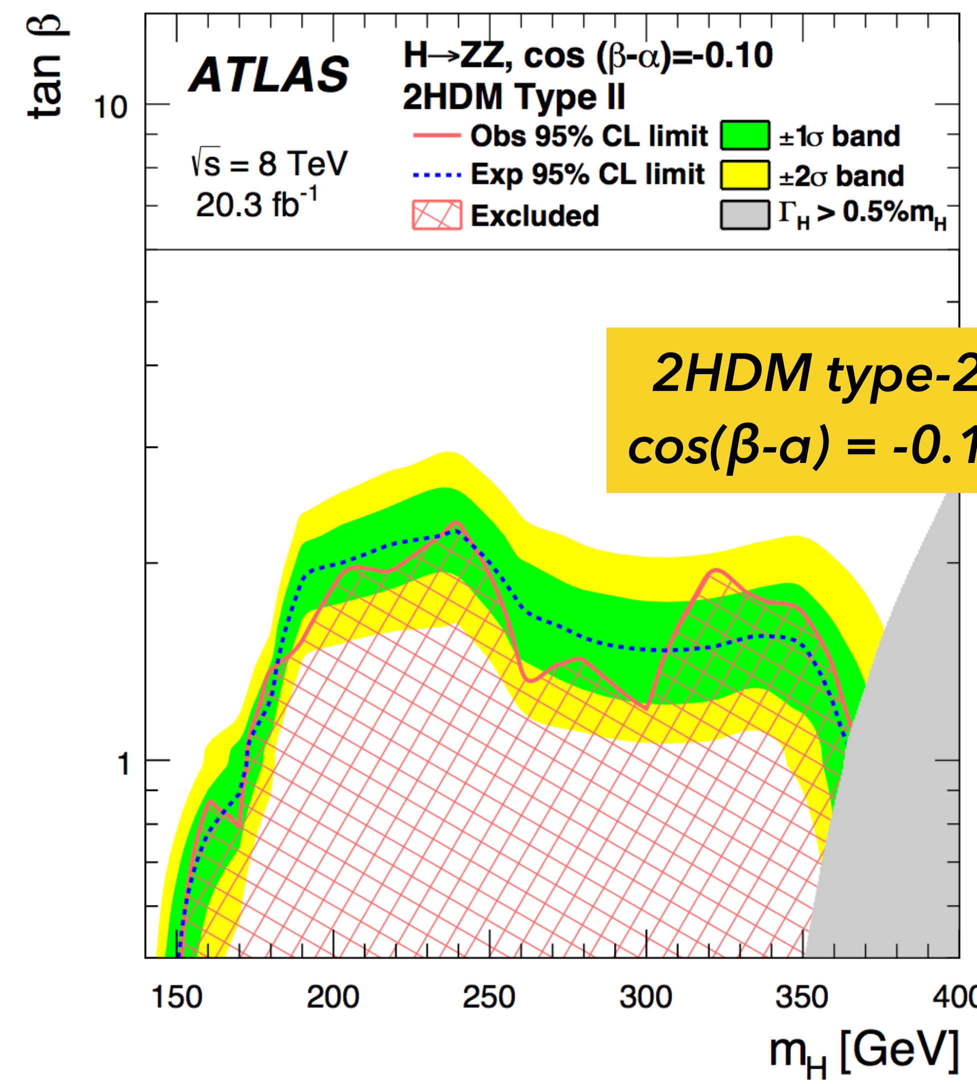
CONSTRAINTS ON 2HDM

arXiv:1507.05930

H→ZZ Narrow Width Approximation



2HDM type-2, m_H=200 GeV

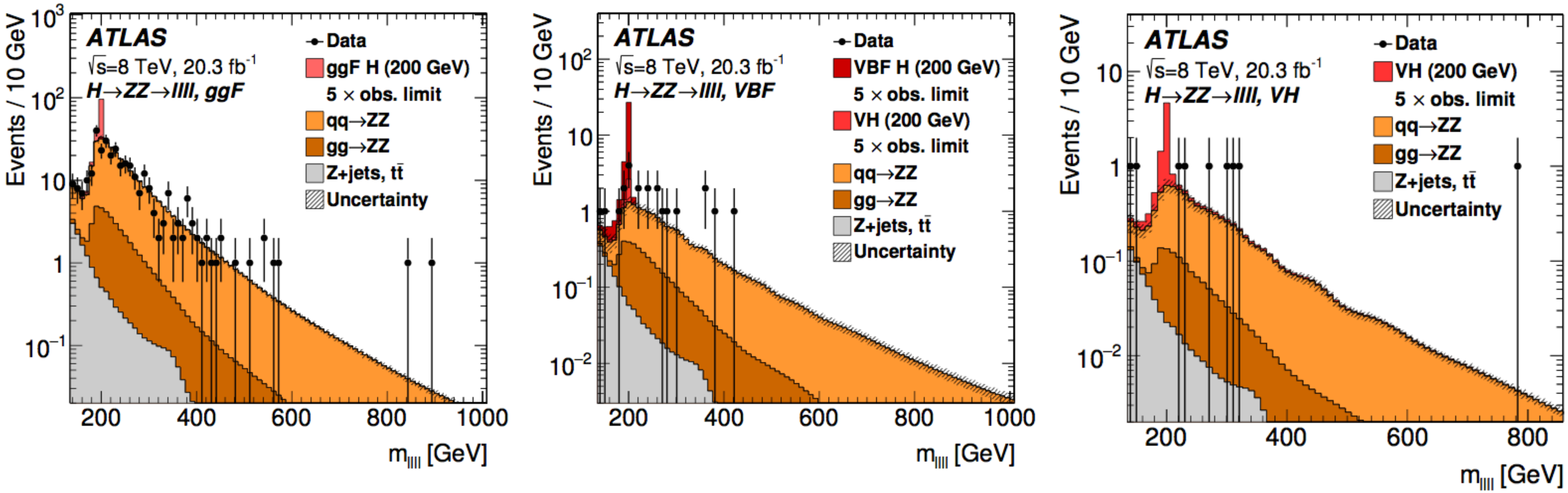


2HDM type-2, cos(β-α) = -0.10

Constraints on 2HDM parameter space obtained by fixing ggF/VBF ratio according to values of cos(β-α) and tan(β)

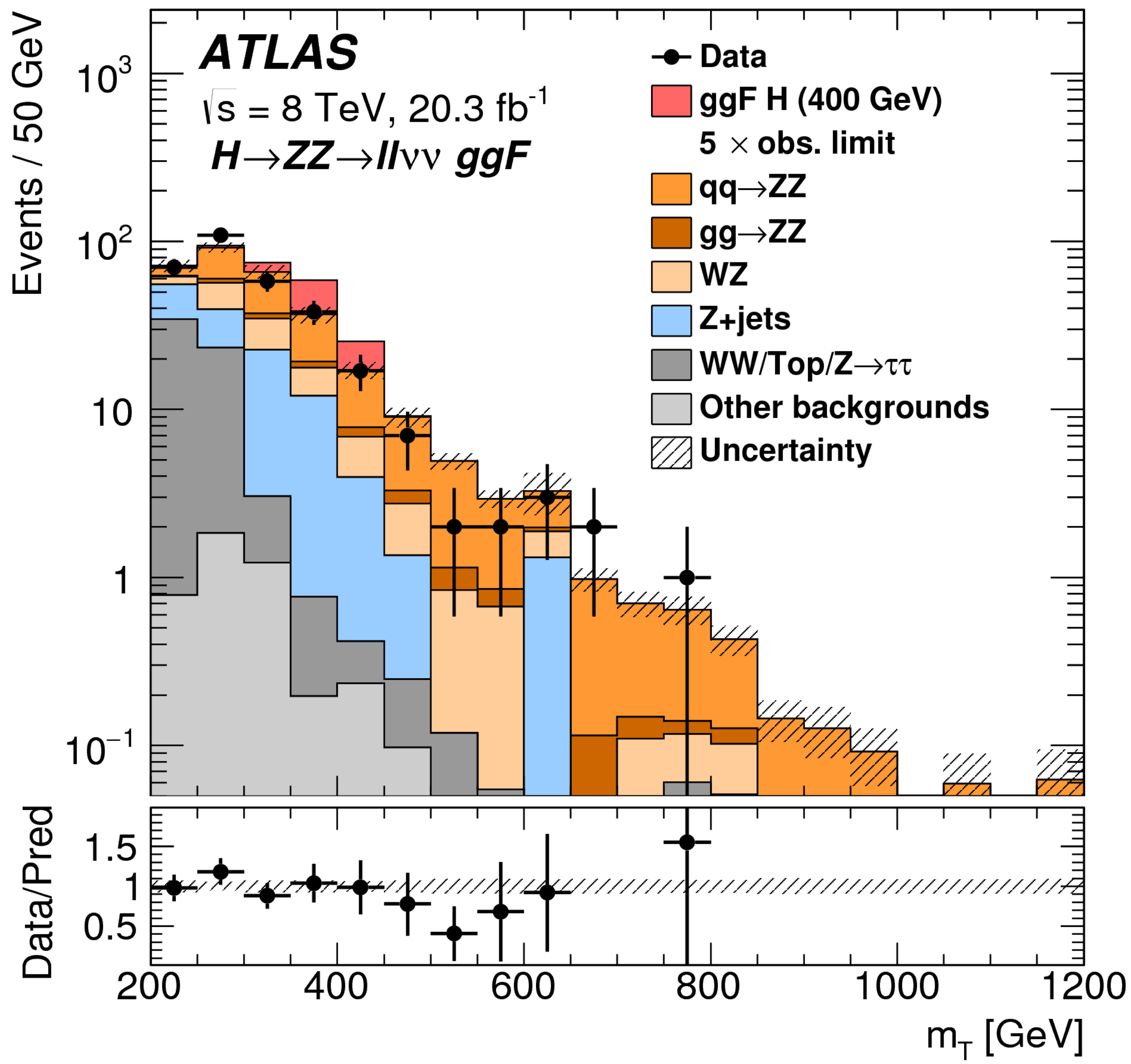
The range of cos(β-α) and tan(β) is limited to the region where the Narrow Width Approximation is valid

H→ZZ→4l


ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, ggF
Data
ggF H (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt̄
Uncertainty
Events / 10 GeV
m_llll [GeV]
ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, VBF
Data
VBF H (200 GeV)
5 × obs. limit
VH (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt̄
Uncertainty
Events / 10 GeV
m_llll [GeV]
ATLAS
√s=8 TeV, 20.3 fb-1
H→ZZ→llll, VH
Data
VH (200 GeV)
5 × obs. limit
qq→ZZ
gg→ZZ
Z+jets, tt̄
Uncertainty
Events / 10 GeV
m_llll [GeV]

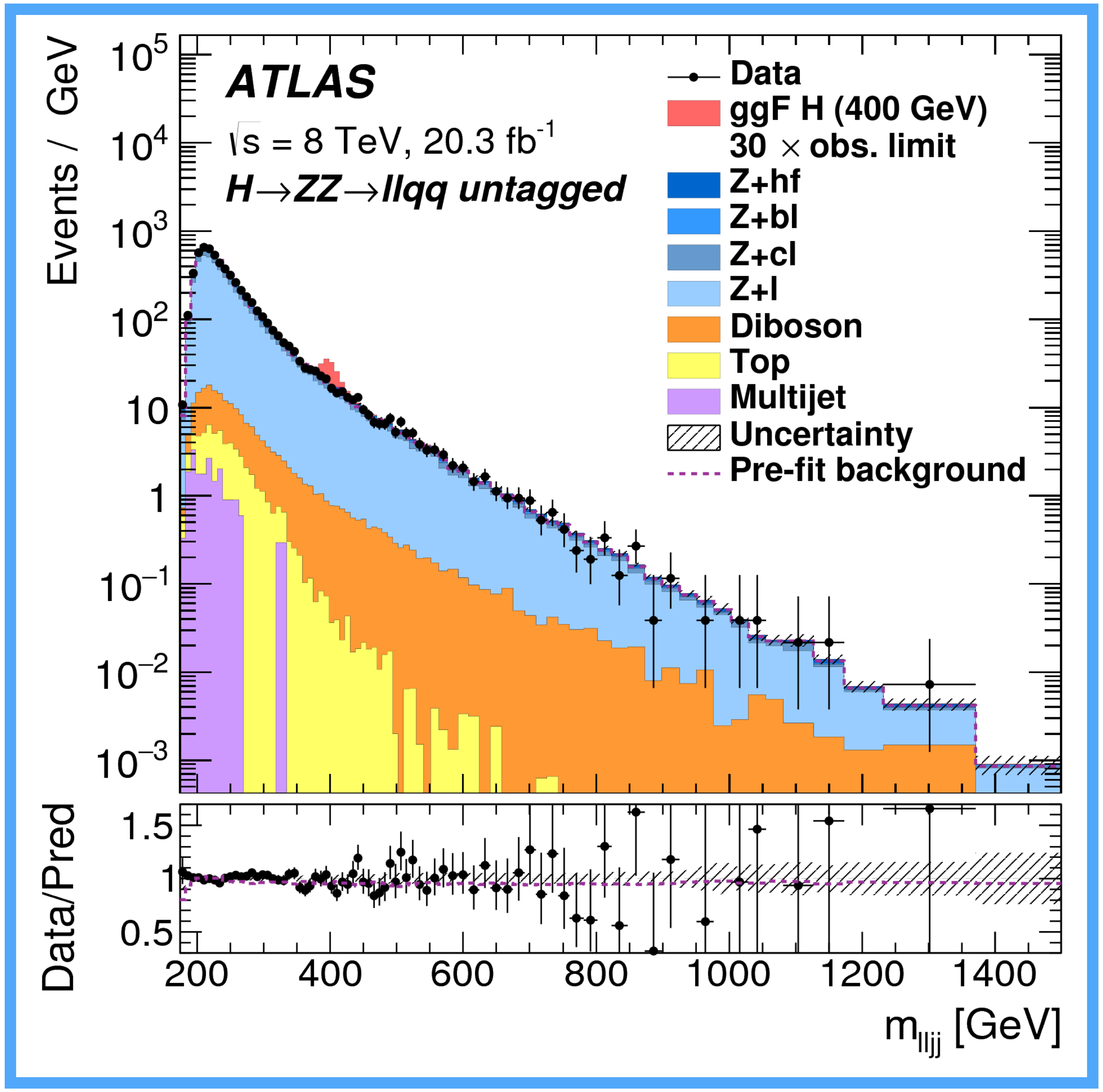
H→ZZ→llvv

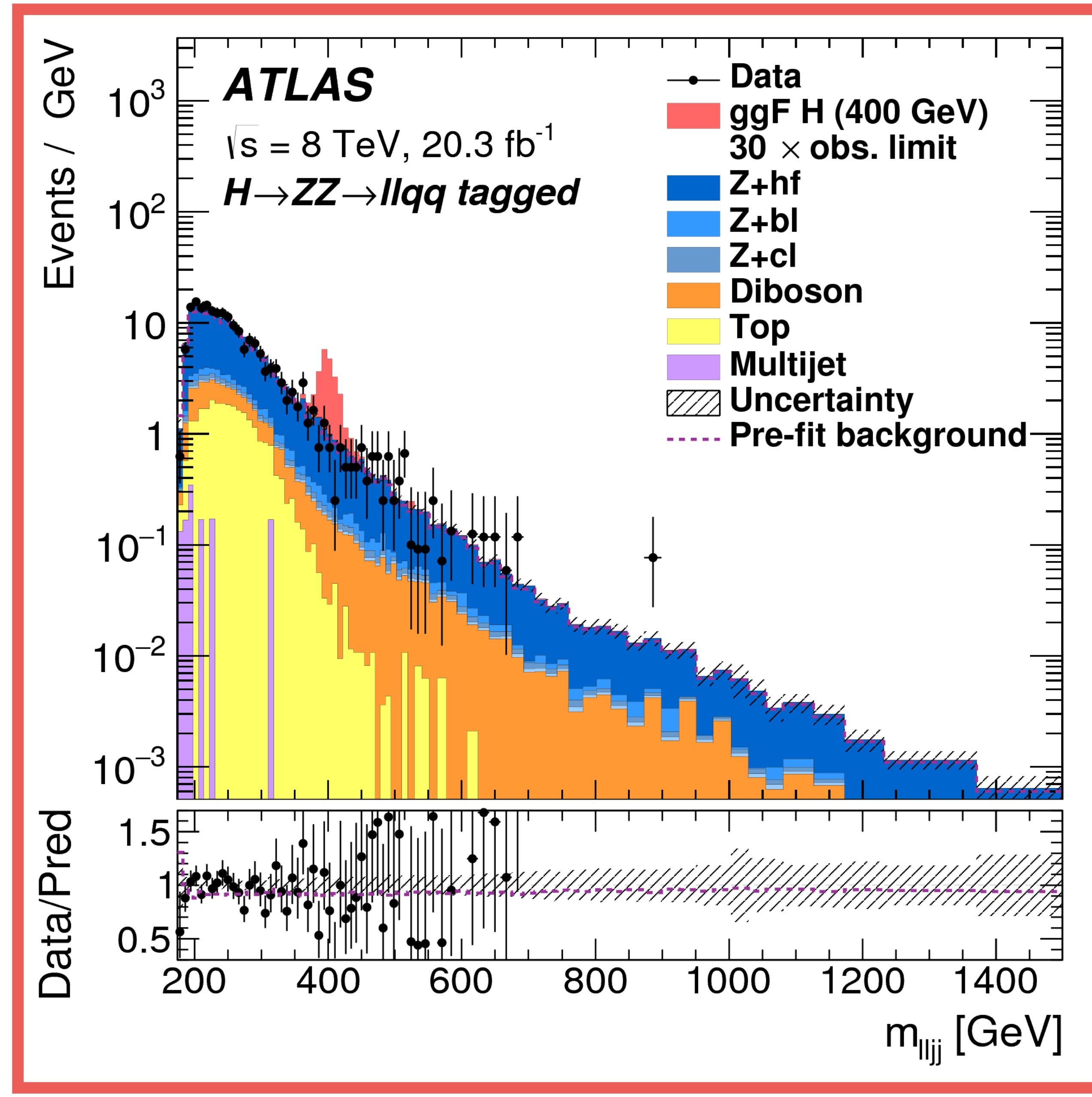
Transverse mass is defined as $$(m_T^{ZZ})^2 \equiv \left(\sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{miss}|^2}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2$$



H→ZZ→llqq

$N_{b-\text{tag}}$	Categories						
	ggF			Merged		VBF	
	m_{jj} SR	m_{jj} CR	$e\mu$ CR	m_j SR	m_j CR	m_{jj} SR	m_{jj} CR
0 b-tag	m_{lljj}	MV1cSum	–	m_{llj}	m_{llj}	m_{lljj}	m_{lljj}
1 b-tag			–				
2 b-tag	m_{lljj}	MV1cSum	m_{lljj}				



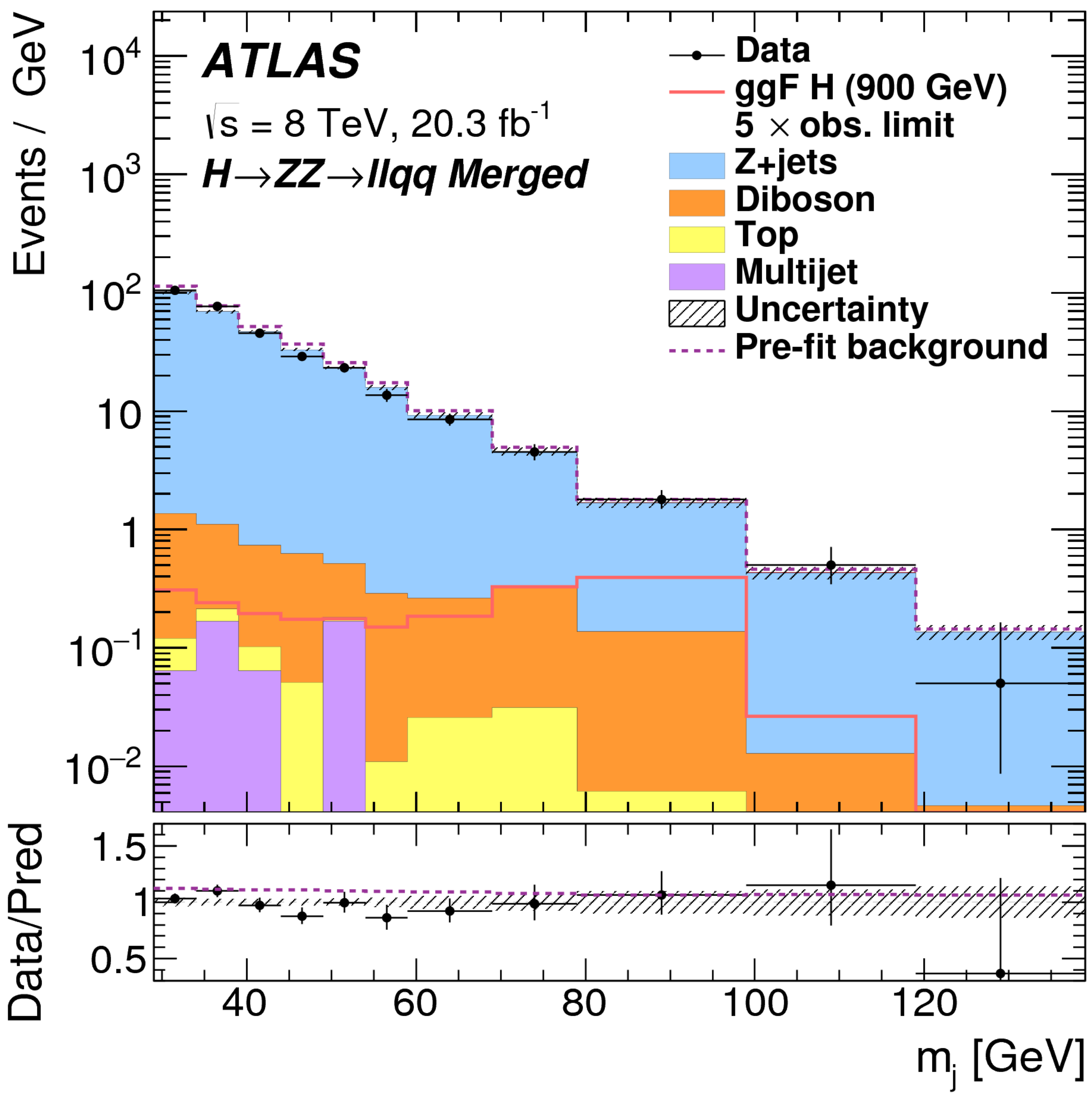


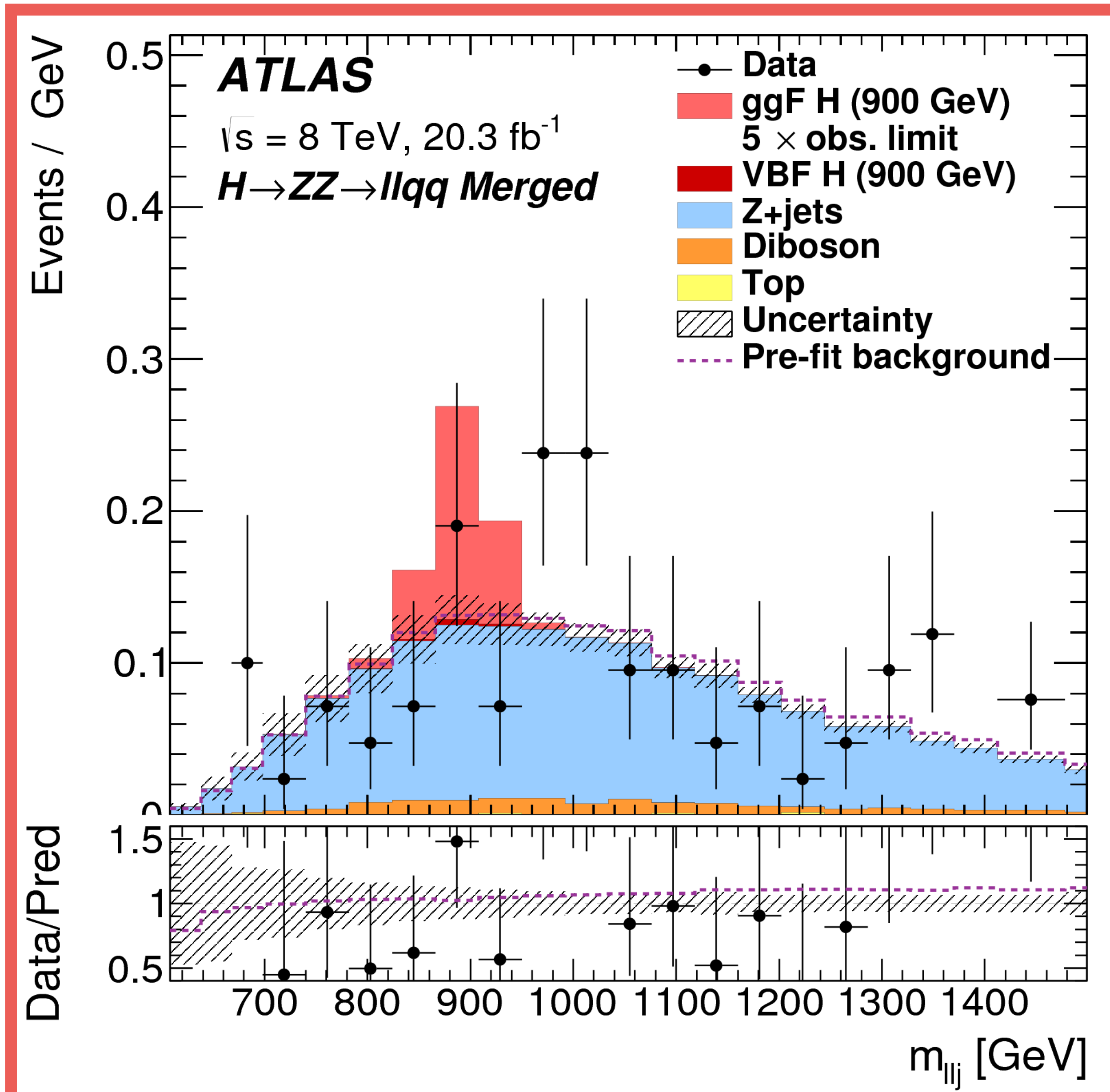
H→ZZ→llqq

Merged category

m_H >700 GeV

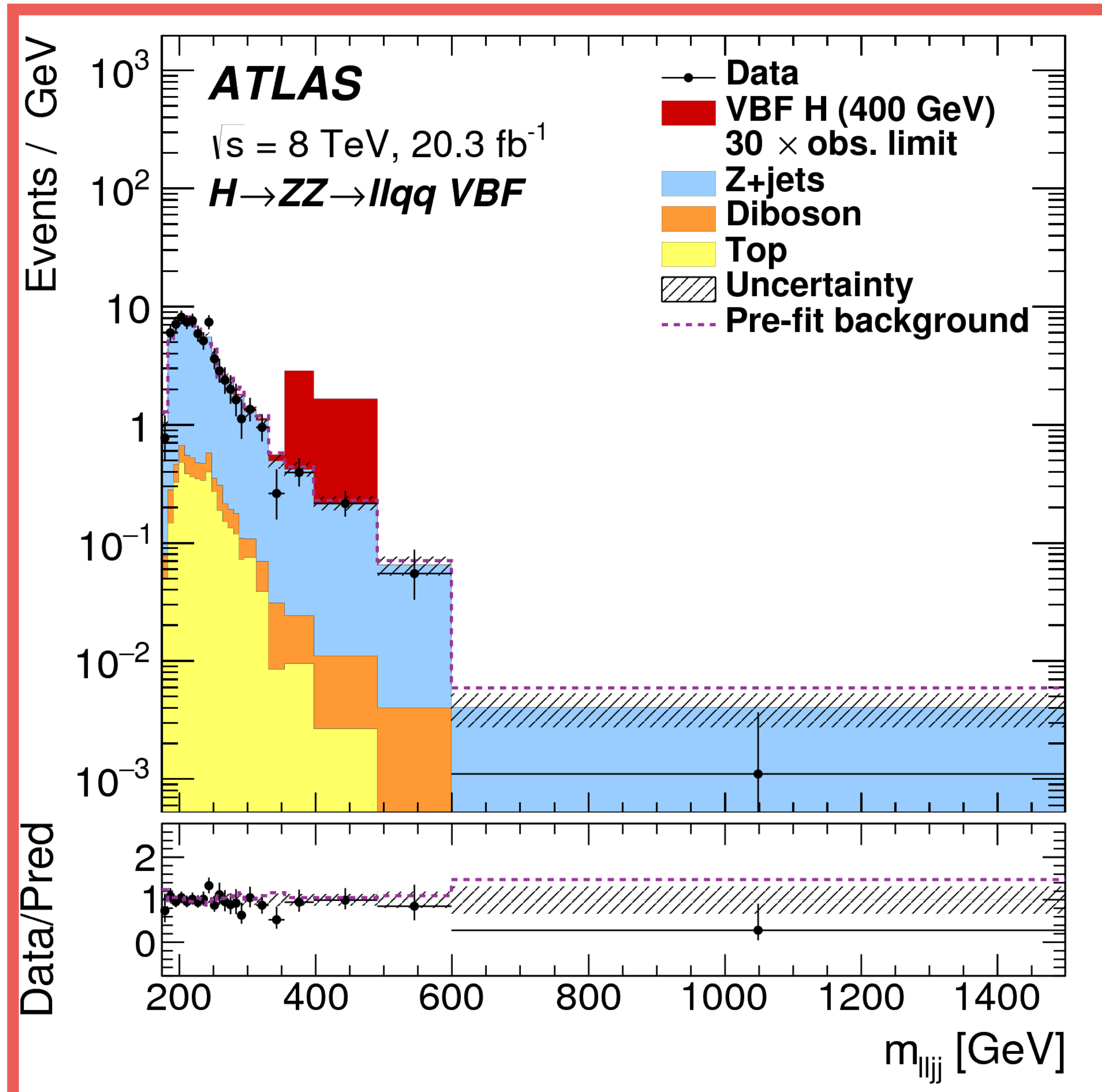
N_{b-tag}	Categories						
	ggF			Merged		VBF	
	m_{jj} SR	m_{jj} CR	$e\mu$ CR	m_j SR	m_j CR	m_{jj} SR	m_{jj} CR
0 b-tag	m_{lljj}	MV1cSum	–	m_{llj}	m_{llj}	m_{lljj}	m_{lljj}
1 b-tag			–				
2 b-tag	m_{lljj}	MV1cSum	m_{lljj}				





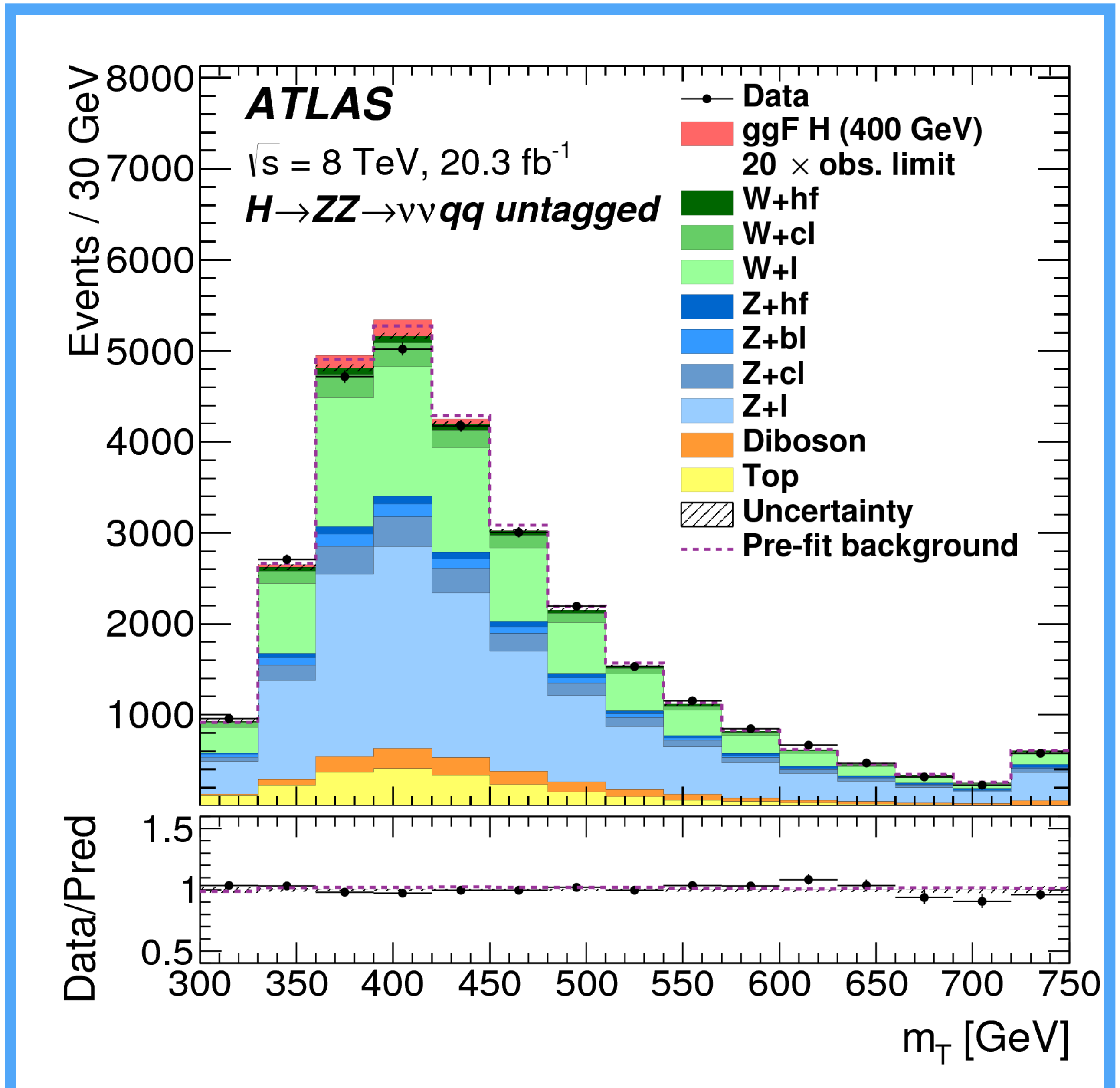
H→ZZ→llqq

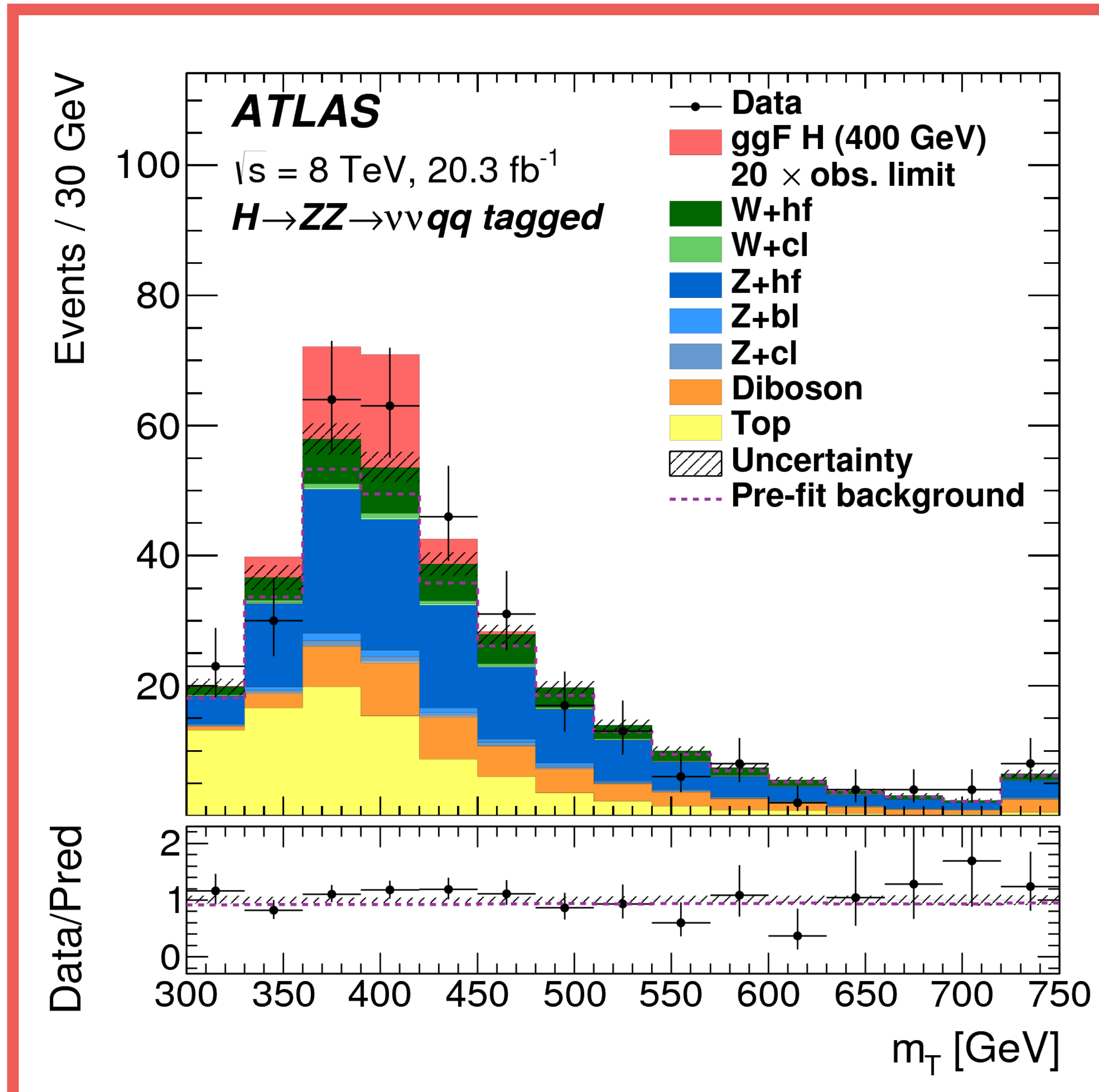
$N_{b-\text{tag}}$	Categories						
	ggF			Merged		VBF	
	m_{jj} SR	m_{jj} CR	$e\mu$ CR	m_j SR	m_j CR	m_{jj} SR	m_{jj} CR
0 b-tag	m_{lljj}	MV1cSum	–	m_{llj}	m_{llj}	m_{lljj}	m_{lljj}
1 b-tag			–				
2 b-tag	m_{lljj}	MV1cSum	m_{lljj}				



H→ZZ→ννqq

Channel	SR	CR, ttbar	CR, W+jets	CR, Z+jets
0-tag	M_T	-	MV1cSum	MV1cSum
1-tag	M_T	-	MV1cSum	MV1cSum
2-tag	M_T	M_{lljj}	-	MV1cSum





$H \to WW \to l\nu l\nu$

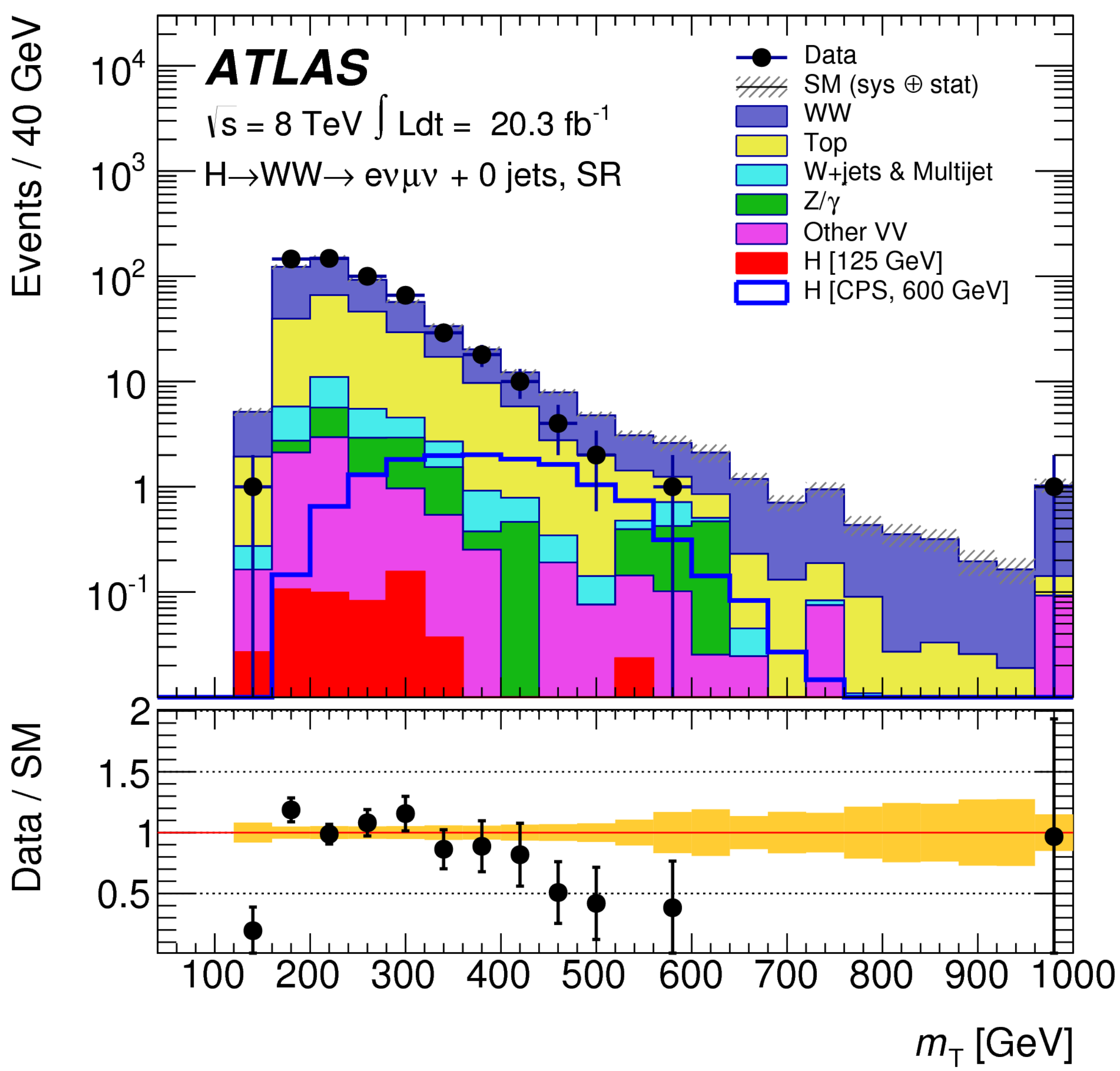
Category	$N_{jet} = 0$	$N_{jet} = 1$	$N_{jet} \geq 2$
Preselection	Two isolated leptons ($\ell = e, \mu$) with opposite charge $p_T^{lead} > 22$ GeV, $p_T^{sublead} > 10$ GeV DF: $m_{\ell\ell} > 10$ GeV SF: $m_{\ell\ell} > 12$ GeV, $\lvert m_{\ell\ell} - m_Z \rvert > 15$ GeV		
Lepton p_T	$p_T^{lead} > 60$ GeV $p_T^{sublead} > 30$ GeV	$p_T^{lead} > 55$ GeV $p_T^{sublead} > 35$ GeV	$p_T^{lead} > 45$ GeV $p_T^{sublead} > 20$ GeV
Missing transverse momentum	DF: $p_T^{miss} > 45$ GeV SF: $E_{T,rel}^{miss} > 45$ GeV SF: $p_{T,rel}^{miss} > 65$ GeV	DF: $p_T^{miss} > 35$ GeV SF: $E_{T,rel}^{miss} > 45$ GeV SF: $p_{T,rel}^{miss} > 70$ GeV	DF: $E_{T,calo}^{miss} > 25$ GeV SF: $E_{T,calo}^{miss} > 45$ GeV -
General selection	- $p_T^{\ell\ell} > 60$ GeV	$N_{b\text{-jet}} = 0$ -	$N_{b\text{-jet}} = 0$ $p_T^{tot} < 40$ GeV
VBF topology	- - - -	- - - -	$m_{jj} > 500$ GeV $\Delta y_{jj} > 4.0$ No jet ($p_T > 20$ GeV) in rapidity gap Both ℓ in rapidity gap
$H \to WW \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} > 60$ GeV $\Delta\eta_{\ell\ell} < 1.35$	$m_{\ell\ell} > 65$ GeV $\Delta\eta_{\ell\ell} < 1.35$	DF: $m_{\ell\ell} > 60$ GeV, SF: $m_{\ell\ell} > 45$ GeV $\Delta\eta_{\ell\ell} < 1.85$

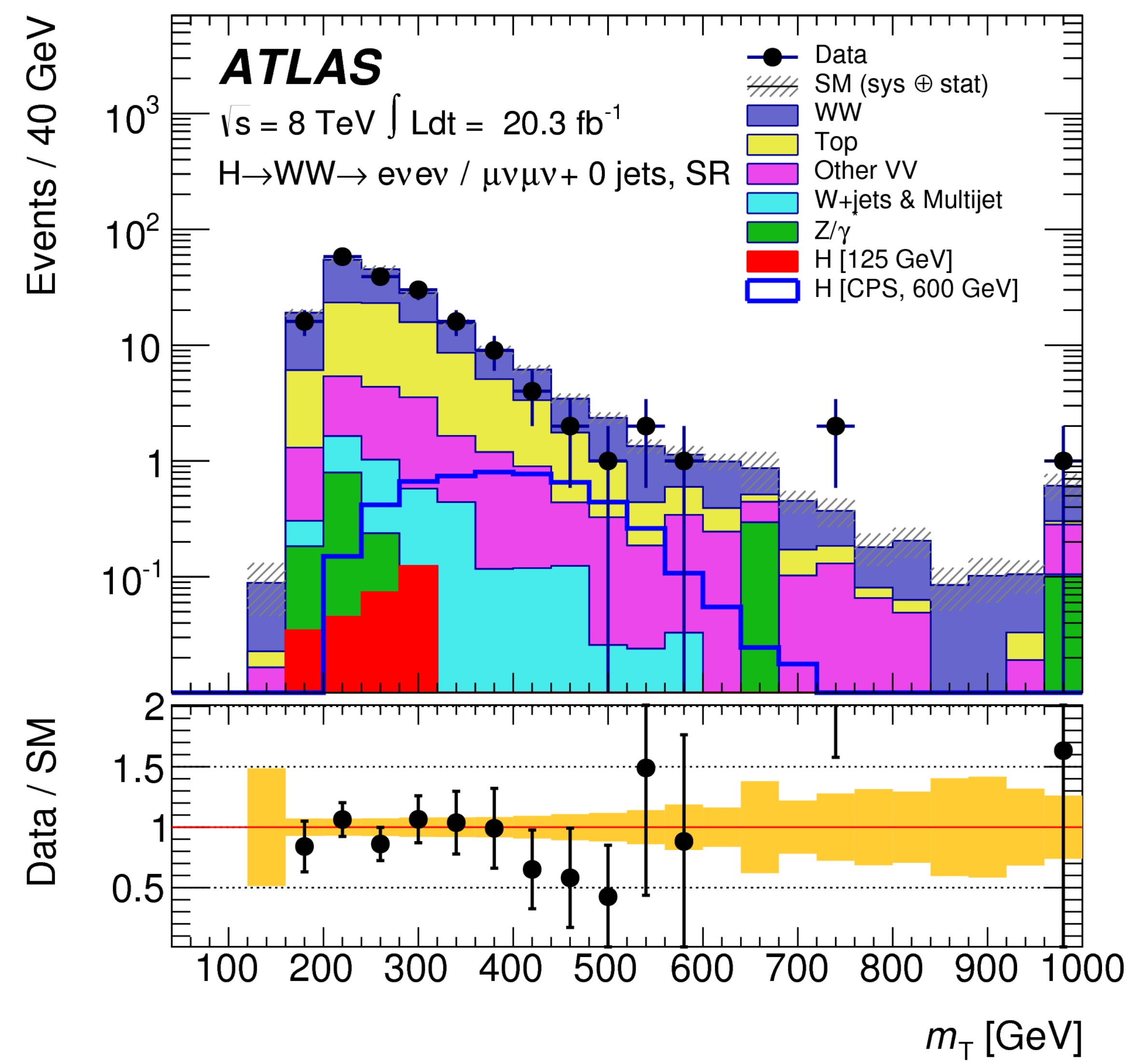
H→WW→lvlv

Transverse mass is defined as

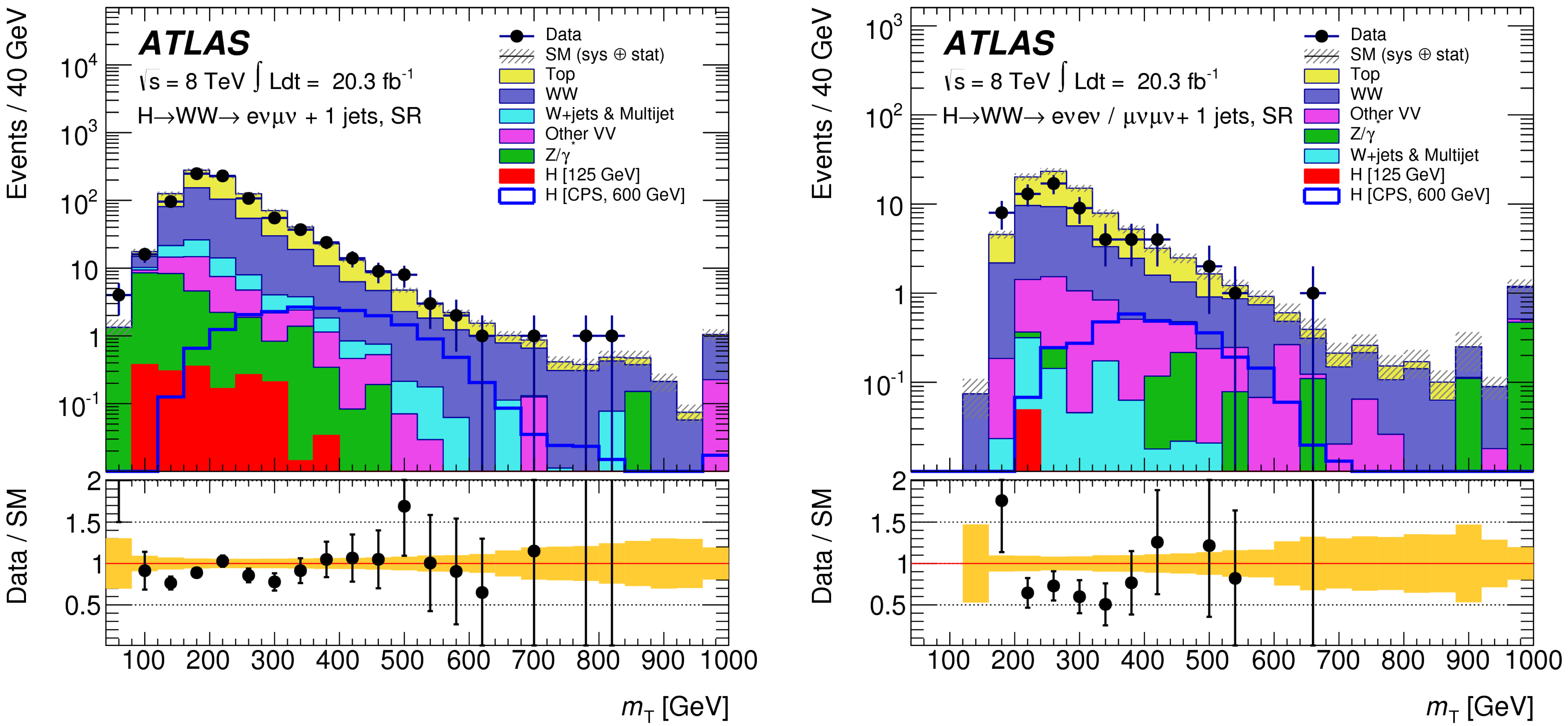
$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{E}_T^{miss}|^2}$$

$$E_T^{\ell\ell} = \sqrt{|\mathbf{p}_T^{\ell\ell}|^2 + m_{\ell\ell}^2}$$

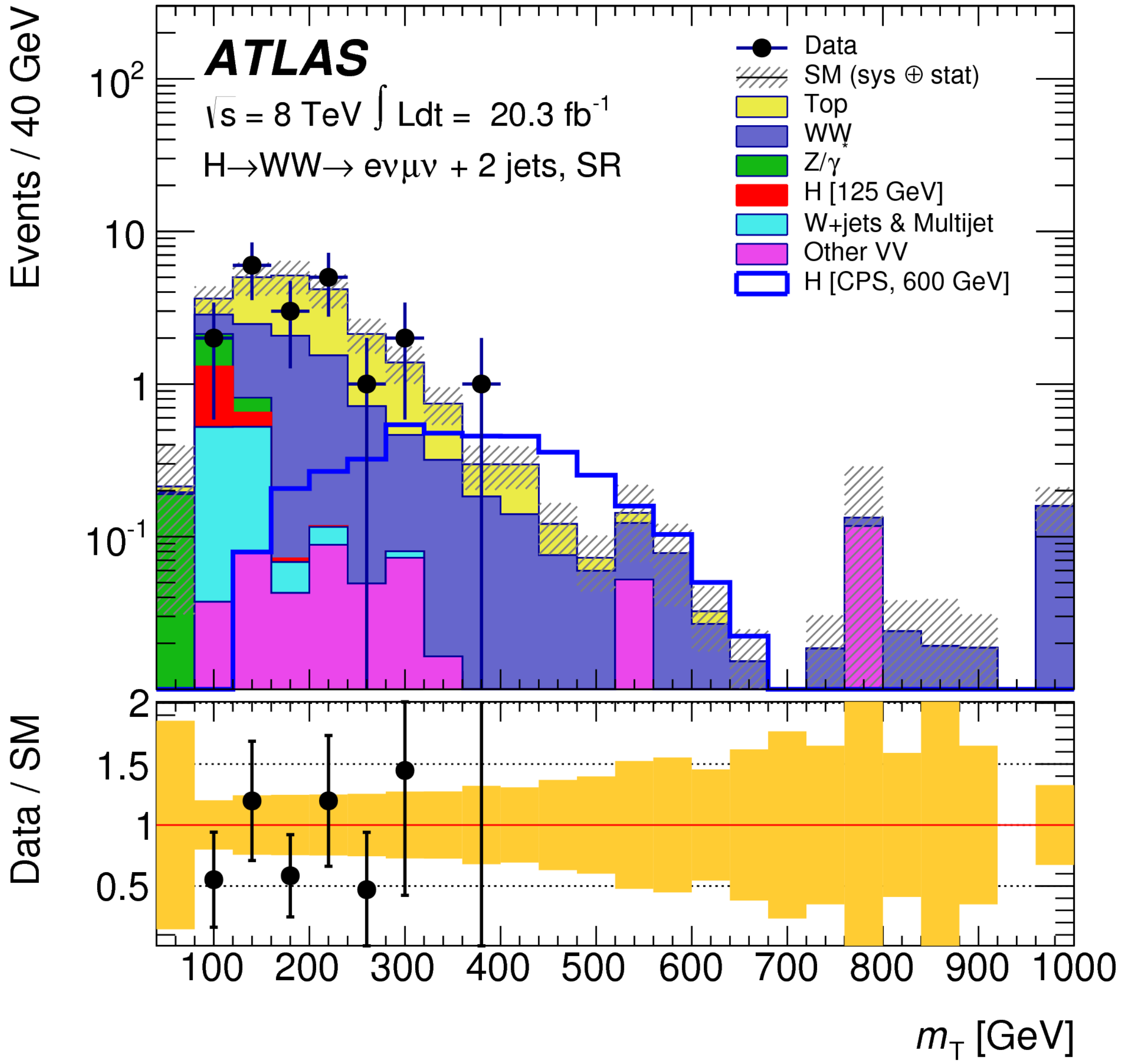




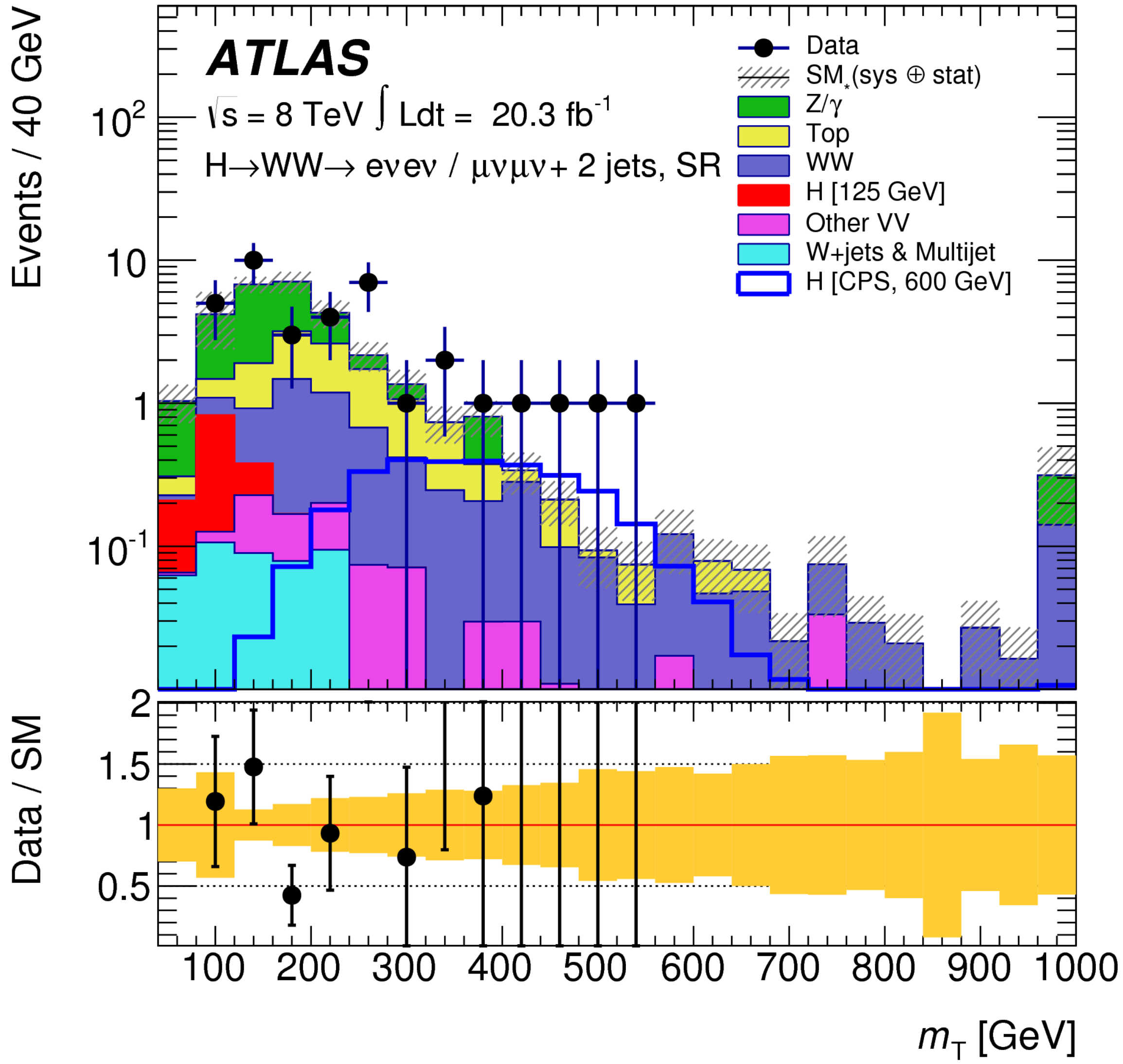
H→WW→lvlv


ATLAS
$\sqrt{s}$ = 8 TeV ∫ Ldt = 20.3 fb^{-1}
H→WW→ eνμν + 1 jets, SR
Data
SM (sys ⊕ stat)
Top
WW
W+jets & Multijet
Other VV
Z/γ*
H [125 GeV]
H [CPS, 600 GeV]
Events / 40 GeV
Data / SM
m_T [GeV]
ATLAS
$\sqrt{s}$ = 8 TeV ∫ Ldt = 20.3 fb^{-1}
H→WW→ eνeν / μνμν+ 1 jets, SR
Data
SM (sys ⊕ stat)
Top
WW
Other VV
Z/γ*
W+jets & Multijet
H [125 GeV]
H [CPS, 600 GeV]
Events / 40 GeV
Data / SM
m_T [GeV]

H→WW→lνlν



ATLAS
√s = 8 TeV ∫ Ldt = 20.3 fb⁻¹
H→WW→ eνμν + 2 jets, SR
Data
SM (sys ⊕ stat)
Top
WW
Z/γ
H [125 GeV]
W+jets & Multijet
Other VV
H [CPS, 600 GeV]
Events / 40 GeV
Data / SM
m_T [GeV]

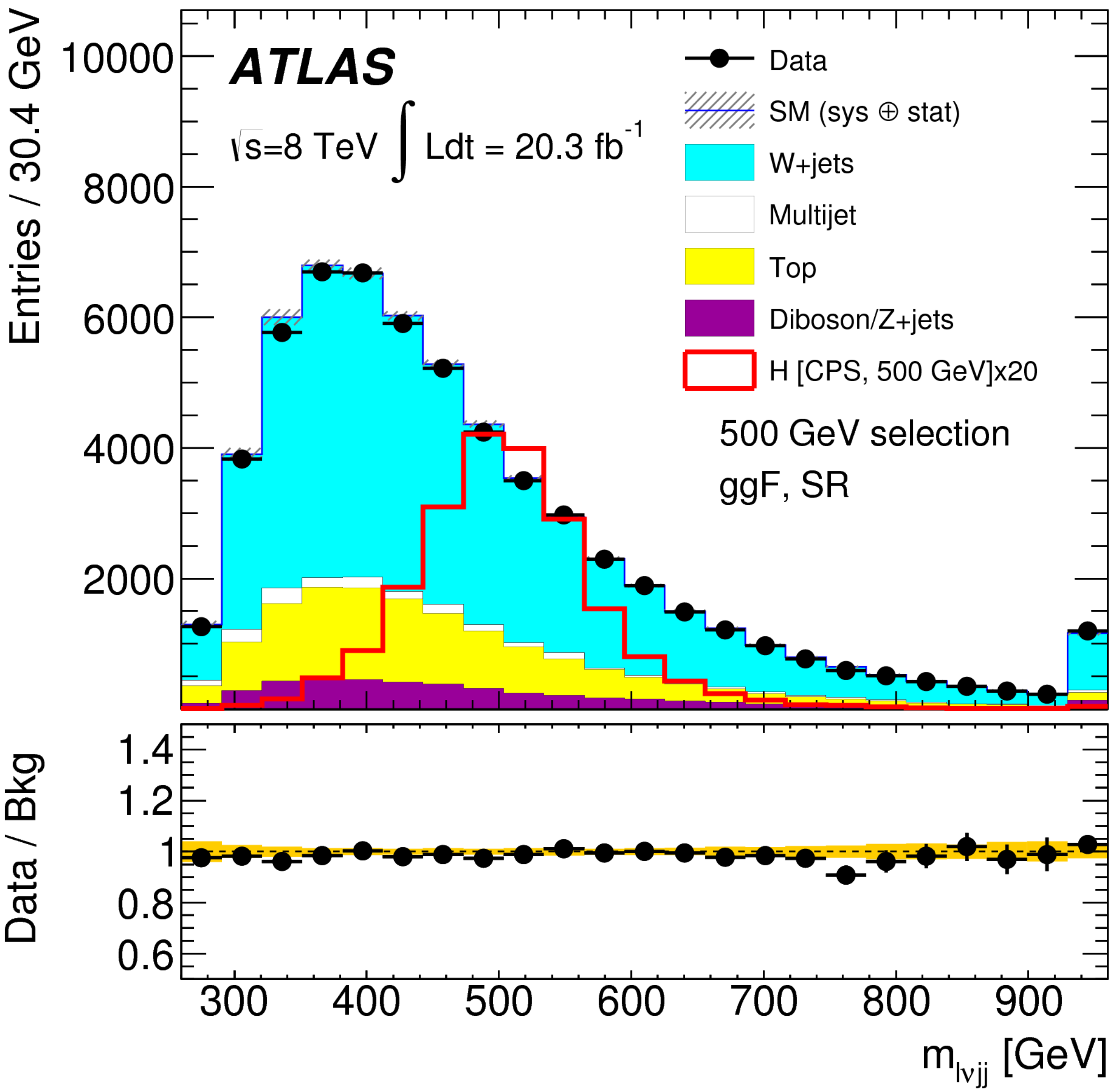


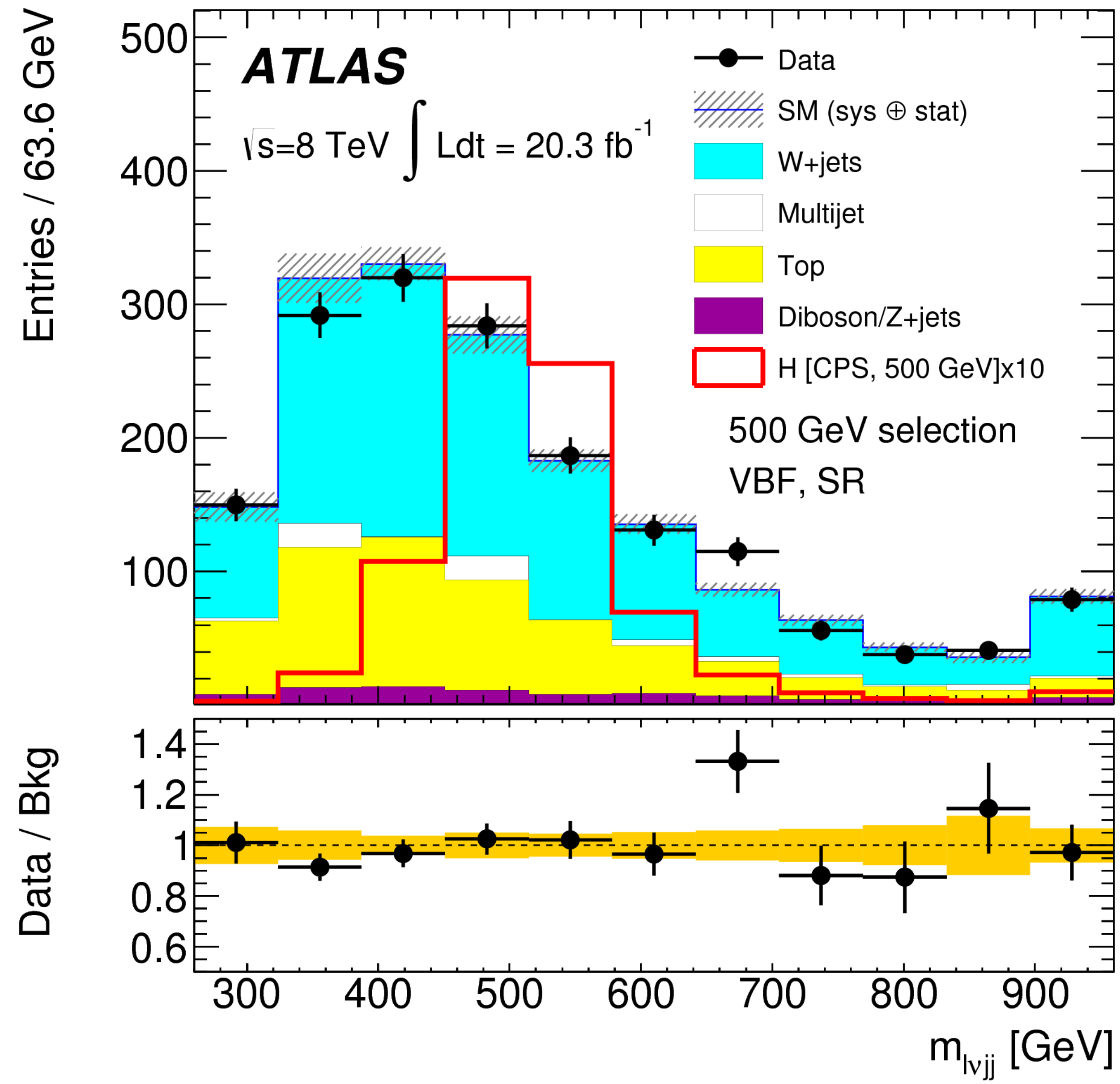
ATLAS
√s = 8 TeV ∫ Ldt = 20.3 fb⁻¹
H→WW→ eνeν / μνμν+ 2 jets, SR
Data
SM (sys ⊕ stat)
Z/γ
Top
WW
H [125 GeV]
Other VV
W+jets & Multijet
H [CPS, 600 GeV]
Events / 40 GeV
Data / SM
m_T [GeV]

H→WW→lvqq

Object selection	1 isolated charged lepton (e or μ): $p_T > 25$ GeV, $\|\eta\| < 2.4$	
	$E_{T,calo}^{miss} > 60$ GeV	
	jet: $p_T > 30$ GeV, $\|\eta\| < 4.5$	
	large-R jet: $p_T > 100$ GeV, $\|\eta\| < 1.2$	
VBF selection	(≥ 4 jets) or (≥ 2 jets + ≥ 1 large-R jets)	
	$m_{j_1,j_2} > 600$ GeV	
	$p_T^{j_1} > 40$ GeV	
	$\Delta y(j_1, j_2) > 3.0$	
ggF selection	not VBF tagged and (≥ 2 jets or ≥ 1 large-R jet)	
Further selection, hadronic W boson reconstructed as:	jet pair	large-R jet
Decay topology	$p_T^{j_{lead}} > 60$ GeV	-
	$\Delta\phi(jj) < 2.5$	-
	$\Delta\phi(j, \ell) > 1.0$	$\Delta\phi(J, \ell) > 1.0$
	$\Delta\phi(j, E_{T,calo}^{miss}) > 1.0$	$\Delta\phi(J, E_{T,calo}^{miss}) > 1.0$
	$\Delta\phi(\ell, E_{T,calo}^{miss}) < 2.5$	
b-tagging veto events with:	both W candidate jets *b*-tagged	*b*-tagged jet with $\Delta R(j, J) > 0.4$
	or any other jet *b*-tagged	-
W-mass window	65 GeV $\leq m_{jj} \leq$ 96 GeV	65 GeV $\leq m_J \leq$ 96 GeV

H→WW→lνqq


ATLAS
$\sqrt{s}$=8 TeV $\int$ Ldt = 20.3 fb^{-1}
Data
SM (sys ⊕ stat)
W+jets
Multijet
Top
Diboson/Z+jets
H [CPS, 500 GeV]x20
500 GeV selection
ggF, SR
Entries / 30.4 GeV
Data / Bkg
$m_{l\nu jj}$ [GeV]


ATLAS
$\sqrt{s}$=8 TeV $\int$ Ldt = 20.3 fb^{-1}
Data
SM (sys ⊕ stat)
W+jets
Multijet
Top
Diboson/Z+jets
H [CPS, 500 GeV]x10
500 GeV selection
VBF, SR
Entries / 63.6 GeV
Data / Bkg
$m_{l\nu jj}$ [GeV]

H→ZZ SYSTEMATICS

ggF mode Systematic source	Effect [%]	VBF mode Systematic source	Effect [%]
$m_H = 200$ GeV			
$gg \to ZZ$ K-factor uncertainty	27	$gg \to ZZ$ acceptance	13
Z+hf $\Delta\phi$ reweighting	5.3	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	13
Luminosity	5.2	$gg \to ZZ$ K-factor uncertainty	13
Jet energy resolution ($\ell\ell qq/\nu\nu qq$)	3.9	Z + jets $\Delta\phi$ reweighting	7.9
QCD scale $gg \to ZZ$	3.7	Jet energy scale η modelling ($\ell\ell qq/\nu\nu qq$)	5.3
$m_H = 400$ GeV			
$qq \to ZZ$ PDF	21	Z + jets estimate ($\ell\ell\nu\nu$)	34
QCD scale $qq \to ZZ$	13	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	6.5
Z + jets estimate ($\ell\ell\nu\nu$)	13	VBF Z + jets $m_{\ell\ell jj}$	5.5
Signal acceptance ISR/FSR ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	7.8	Jet flavour composition ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	5.3
$Z + b\bar{b}$, $Z + c\bar{c}$, $p_{\mathrm{T}}^{\ell\ell}$	5.6	Jet vertex fraction ($\ell\ell qq/\nu\nu qq$)	4.8
$m_H = 900$ GeV			
Jet mass scale ($\ell\ell qq$)	7	Z + jets estimate ($\ell\ell\nu\nu$)	19
$Z + jj$ p_{T}^{Z} shape ($\nu\nu qq$)	5.6	Jet mass scale ($\ell\ell qq$)	8.7
$qq \to ZZ$ PDF	4.3	$Z + jj$ $p_{\mathrm{T}}^{\ell\ell}$ shape	7.3
QCD scale $qq \to ZZ$	3.5	Jet energy resolution ($\ell\ell\ell\ell/\ell\ell\nu\nu$)	4.4
Luminosity	2.6	Jet flavour composition (VV/Signal)	2.6