# High Mass Searches for Standard Model-Like Higgs Boson at the LHC

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On behalf of the ATLAS and CMS Experiments

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Introduction

- ATLAS and CMS discovered a new particle m~125 GeV, with measured coupling and properties compatible with the SM Higgs boson

- Is it the SM Higgs boson ?

  - Or is this particle part of an extended scalar sector postulated by several extensions to the SM ?

- The discovery of additional Higgs-like particles will be an unambiguous sign of NEW PHYSICS !
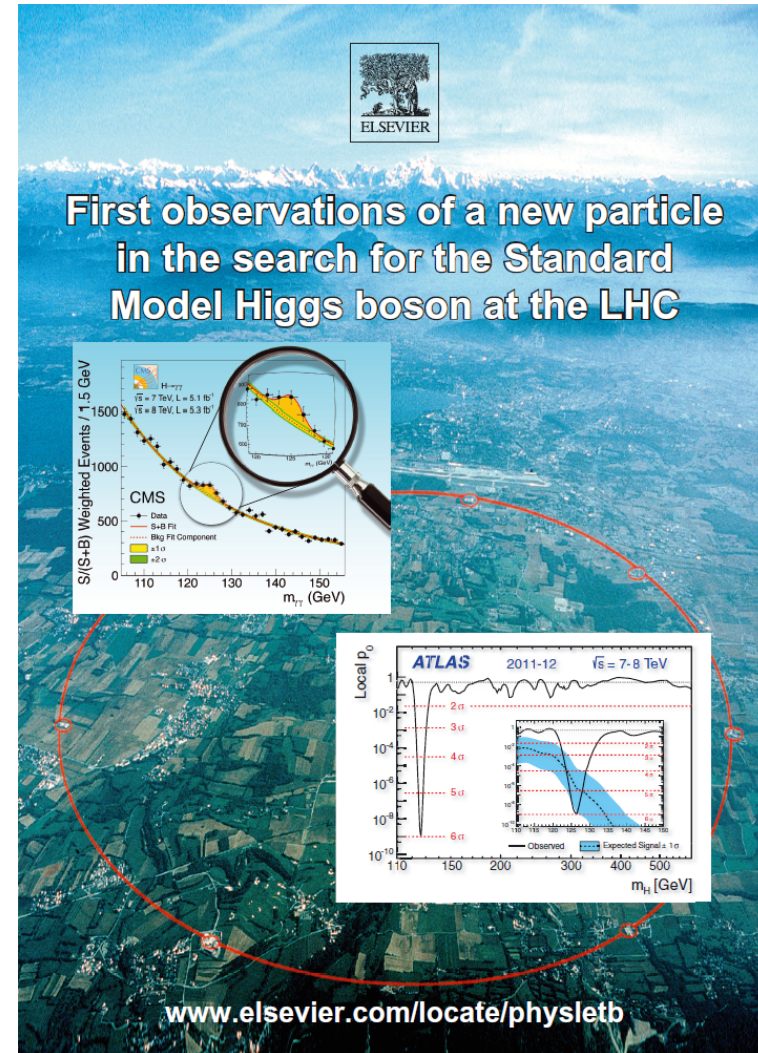
Electroweak Singlet Model

- Simplest extension to SM Higgs sector
- Involves addition of an EW singlet which mixes with the SM doublet state, resulting 2 CP-even Higgs bosons h and H

	h	H
σ	$C^2 \times \sigma_{h,SM}$	$C'^2 \times \sigma_{H,SM}$
Γ	$C^2 \times \Gamma_{h,SM}$	$(C'^2/(1-BR_{H,new})) \times \Gamma_{H,SM}$
BR_i	$BR_{h,SM,i}$	$(1-BR_{H,new}) \times BR_{H,SM,i}$

- Assume couple to fermions and vector bosons in same way as SM Higgs boson, but strength reduced by common scale factor :
  - $C \rightarrow h$
  - $C' \rightarrow H$
- Unitarity constraint :
  - $C^2 + C'^2 = 1$

- Free parameters :
  - C, C' , BR_{new} , mH
  - BR_{new} : branching fraction of H to new decay modes.

Two Higgs Doublet Model (2HDM)

- Add second EW doublet to Higgs sector

  - => five Higgs bosons
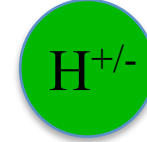

CP-even neutral Higgs   CP-odd neutral Higgs   Charged Higgs

- Higgs sector of 2HDM described by :

  - 4 Higgs masses

  - $\tan\beta$: ratio of vacuum expectation values

  - mixing angle α between the two CP-even states h and H

- Different types of 2HDM scenarios satisfy the Glashow-Weinberg condition (to avoid FCNC)

  - Type I : One Higgs doublet couples to vector bosons and the other couples to fermions (fermiophobic)

  - Type II : (MSSM like) one doublet couples to up-type quarks, and the other couples to down-type quarks and leptons

 - Type III and IV are not discussed

Overview of Searches

- Talk focus on searches for high mass neutral Higgs (decay to vector bosons)
- Other BSM searches in the Higgs sector at LHC:

- **Experimental BSM Higgs boson status:**
  - Pawel Bruckman de Renstrom
- **Searches for neutral Higgs bosons of 2HDM, MSSM and NMSSM at the LHC:**
  - Matthias Schroeder

- **Searches for Charged Higgs boson at LHC**
  - Pietro Vischia
- **Rare & Exotic decays of the Higgs boson at LHC**
  - Yuta Takahashi
- **Search for invisible decays of Higgs boson at LHC**
  - Andrew White

| Decay	Final State	ATLAS	CMS
$H \to \gamma\gamma$	$\gamma\gamma$	8 TeV (20.3 fb^{-1}) $65 < m_H < 600$ GeV PRL 113, 171801 (2014)	8 TeV (19.7 fb^{-1}) $150 < m_H < 850$ GeV arXiv:1506.02301
$H \to WW$	$l\nu l\nu$	8 TeV (20.3 fb^{-1}) $220 < m_H < 1000$ GeV $300 < m_H < 1500$ GeV HIGG-2013-19	7 TeV (5.1 fb^{-1}) + 8 TeV(19.7 fb^{-1}) $145 < m_H < 1000$ GeV arXiv:1504.00936
	$l\nu qq$		
$H \to ZZ$	$llll$	8 TeV (20.3 fb^{-1}) $140 < m_H < 1000$ GeV arXiv:1507.05930	7 TeV (5.1 fb^{-1}) + 8 TeV(19.7 fb^{-1}) $145 < m_H < 1000$ GeV arXiv:1504.00936
	$ll\nu\nu$		
	$llqq$		
	$\nu\nu qq$		

H→γγ

- Select events with two isolated photons
- Main background :
  - di-photon continuum
  - γ+jet , di-jet (jet fakes photon)
  - Drell-Yan $(γ^*/Z)$ (electron fakes photon)
- Search for a mass peak over a smooth $m_{γγ}$ spectrum
- Fit $m_{γγ}$ spectrum with analytical description of signal and background

h(125) contribution is included in background
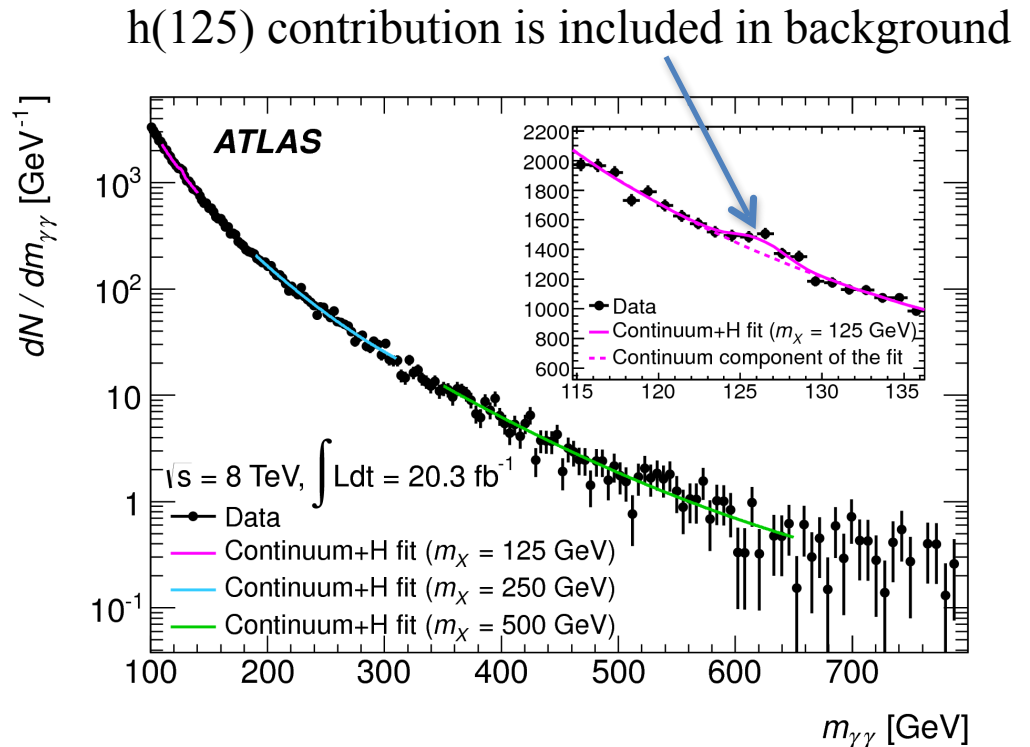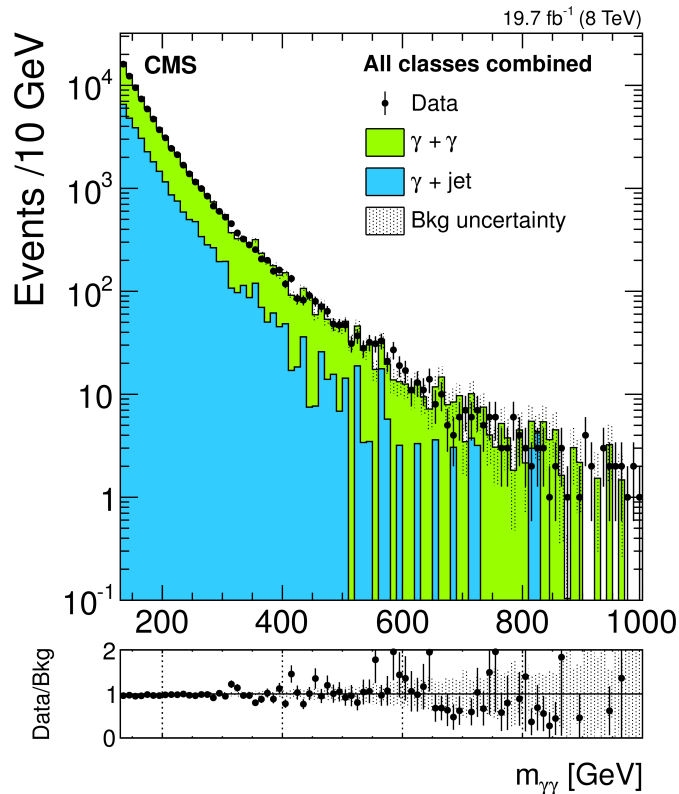
H→γγ : Results

- ATLAS : Search for narrow resonance (Γ_X=0.09 GeV + 0.01m_X)
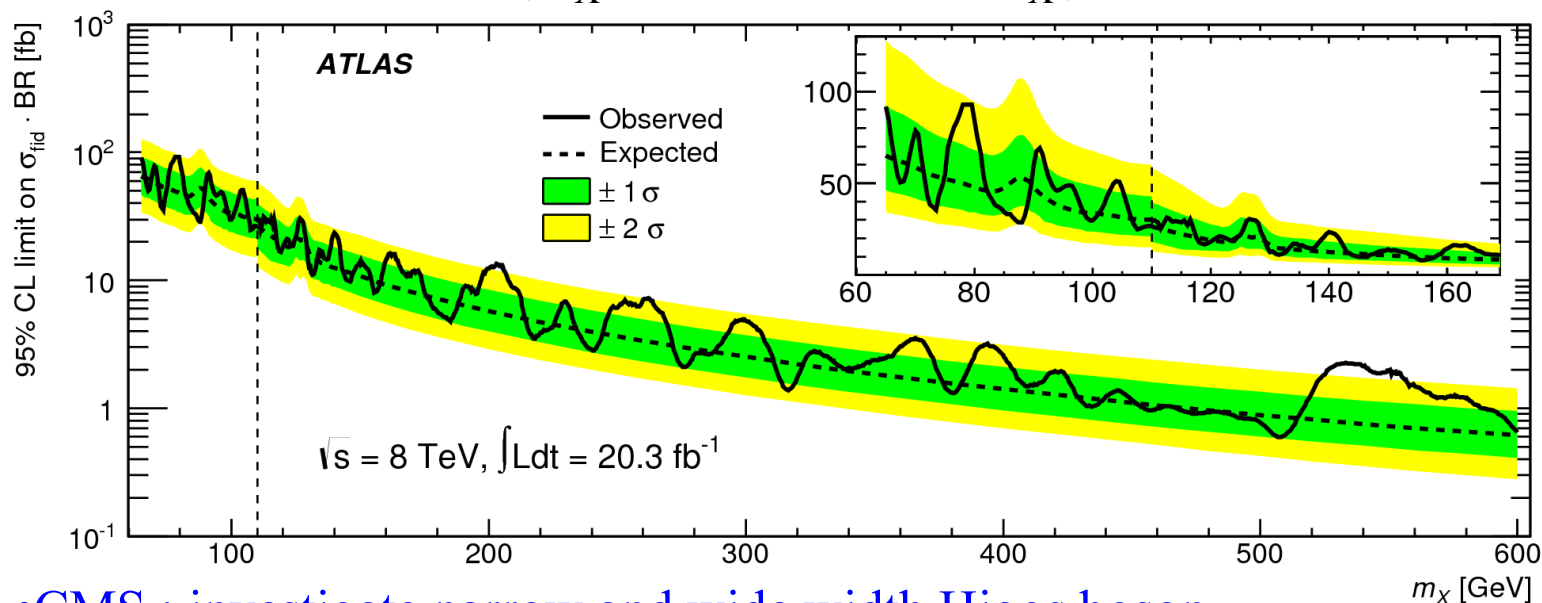
Width assumed smaller than mass resolution

- CMS : investigate narrow and wide width Higgs boson

Narrow (Γ_X=0.1 GeV)   Wide (Γ_X=0.1 m_X) m_X=840 GeV

Limit degrades with increase in width

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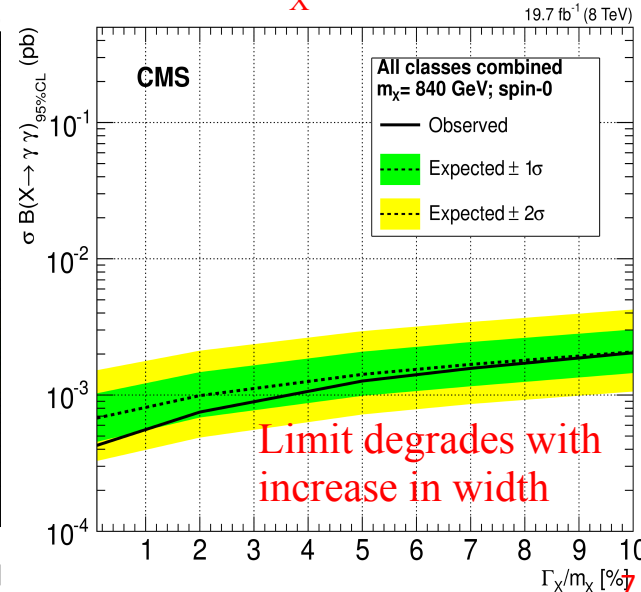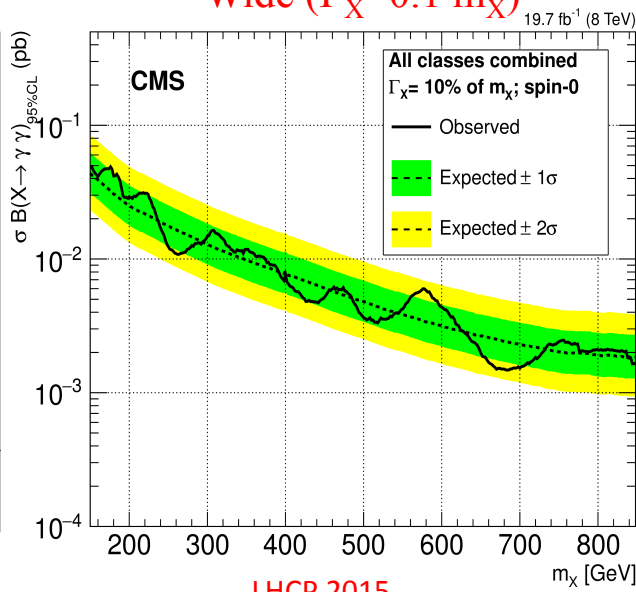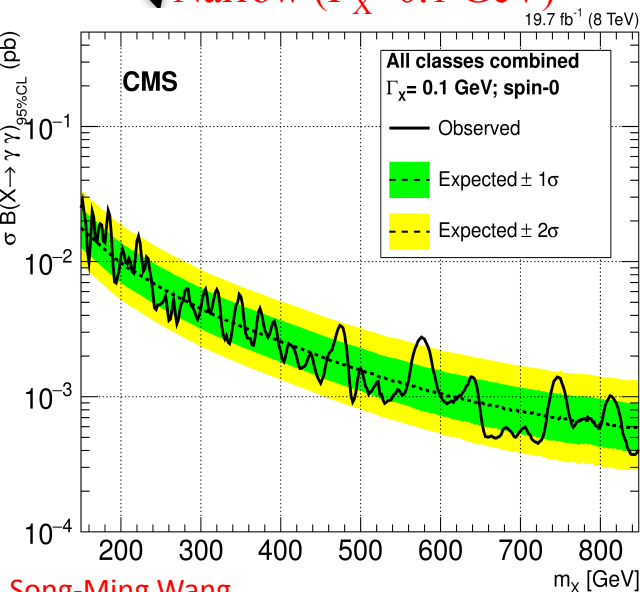
H→WW

- Search for high mass CP-even Higgs in the H→WW decay channel
- Two final states are used :

H→WW→lνlν

- Two leptons , mass m_{ll} (e^+e^-, $\mu^+\mu^-$) , outside Z mass window
- Large MET (due to escaping neutrinos)
- Veto events with 3rd lepton (reject WZ,ZZ) and b-tag jets (reject Top)
- Separate events into 0,1 and ≥2 jets
 - ≥2 jets events are optimized to select VBF Higgs production (large m_{jj} , $\Delta\eta_{jj}$)

CMS 19.5 fb^{-1} (8 TeV)

H → WW → ℓν ℓν
0-jet, DF

Observed
h(125)
W+jets
V+Z/γ*
VVV
Top quark
Z/γ*
WW
Uncertainty
H(400) x 5

eνμν , 0-jet

ATLAS Preliminary
√s = 8 TeV ∫ Ldt = 20.3 fb^{-1}
H→WW→ eνμν + 2 jets, SR

Data
SM (sys ⊕ stat)
Top
WW
Z/γ
H SM-like [125 GeV]
W+jets & Multijet
Other VV
H SM-like [600 GeV]

eνμν , 2-jet VBF
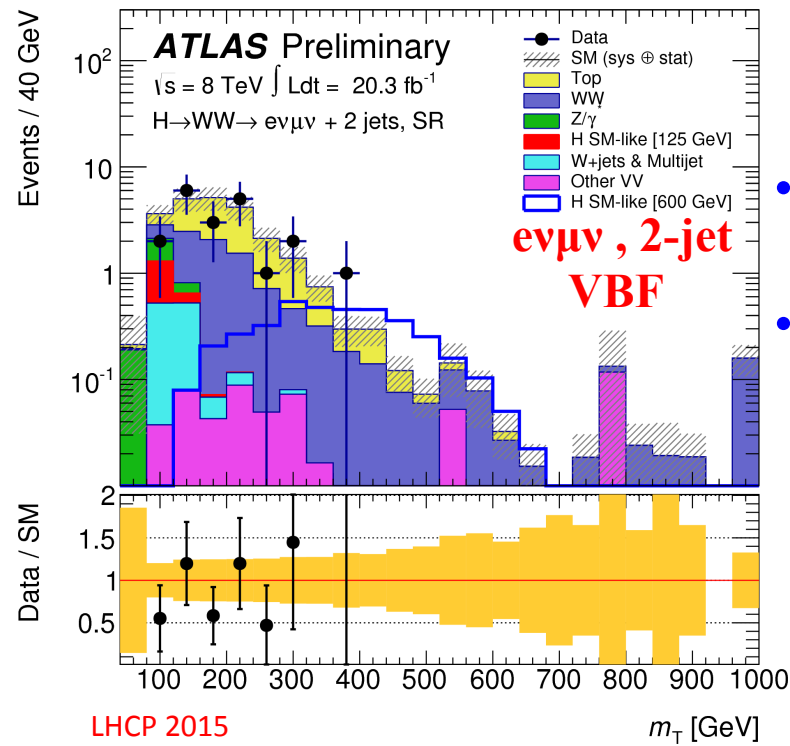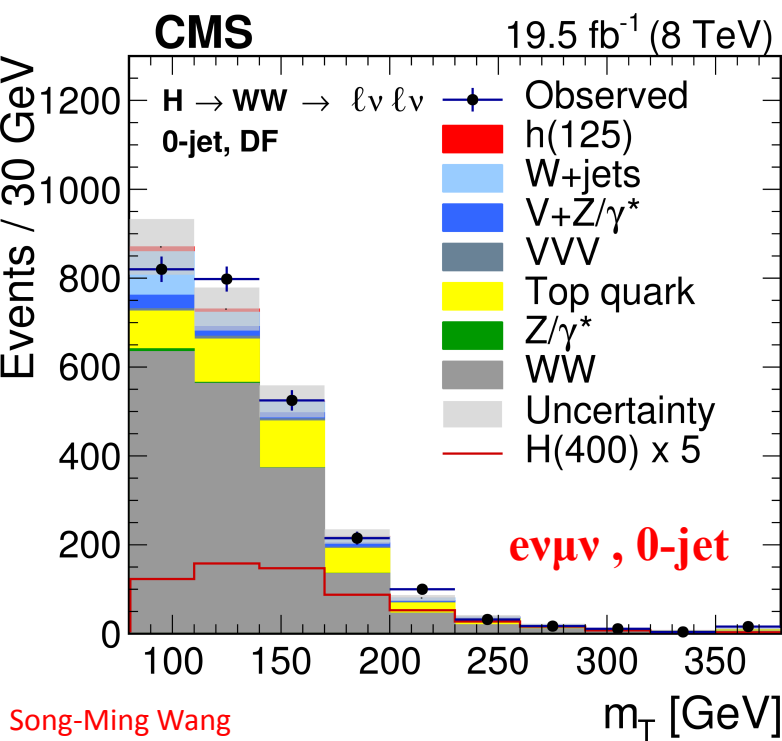
- m_T :discrimina ting var.
- Dominant background:
  - WW
  - Top

H→WW

- **H→WW→lνqq**
- At high Higgs mass, two jets from W decay can merge to form large-R jet (J)
  - Perform search in "resolved" & "merged" channels
- Selection:
  - One lepton (e,μ) , some MET, veto events with extra lepton or b-tag jets
  - Separate events into VBF or non-VBF tagged
    - **VBF :** ≥4 jets   or   ≥2 jets + 1 large-R jet.   Require 2 jets tagged as VBF jets
    - **Non-VBF (mostly ggF) :** ≥2 jets   or   1 large-R jet (failed VBF selection)
  - Require mass m_{jj} (resolved) or m_J (merged) consistent with W mass
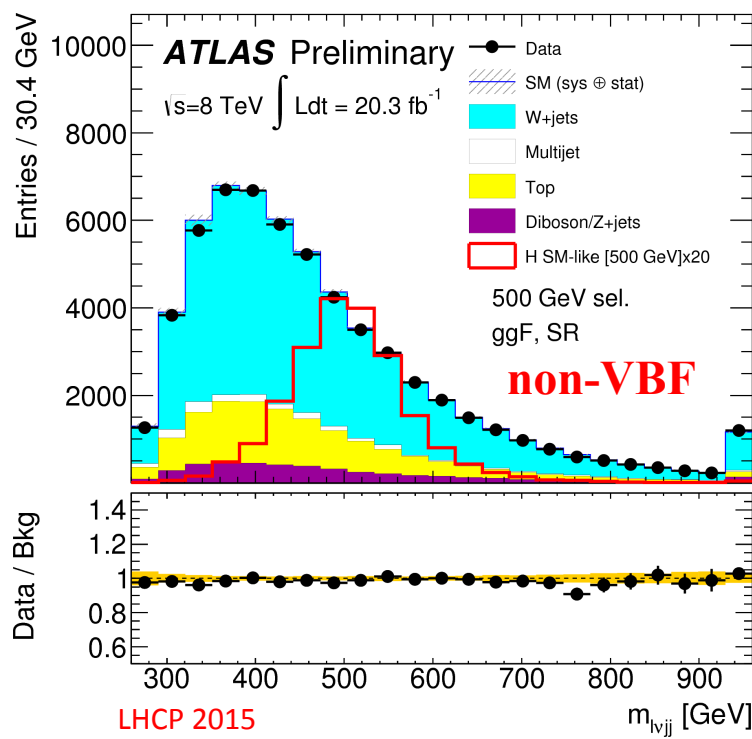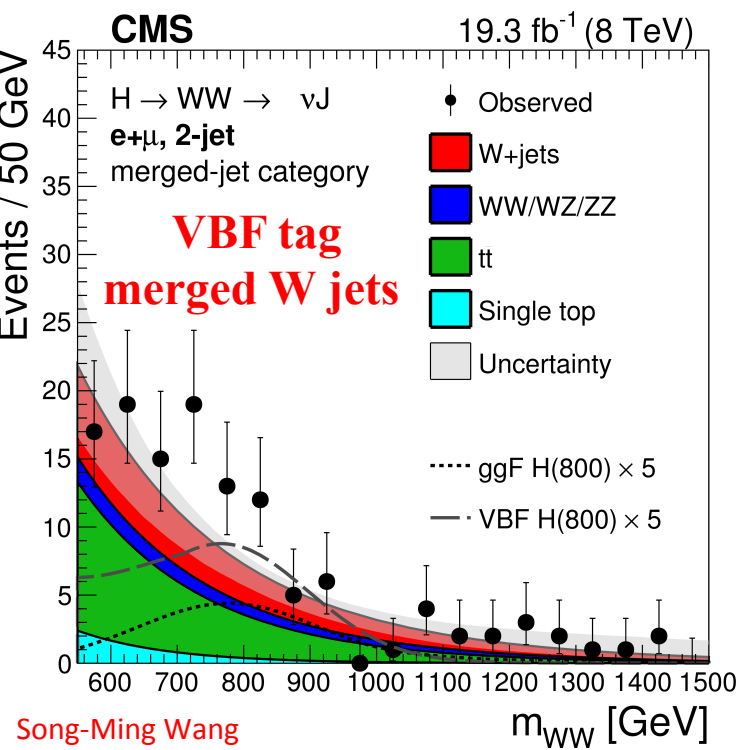
- Dominant background:
  - W+jets
  - Top
  - Diboson

H→WW : Results

- CMS and ATLAS perform search in several scenarios

- **<u>SM-Like</u>**

- Width gets large at high mass
  - $\Gamma \sim 650$ GeV @ mH=1 TeV
- Account for interference between signal and non-resonance WW BG

CMS

Observed

Expected

$H \rightarrow WW \rightarrow 2\ell 2\nu$

$H \rightarrow WW \rightarrow \ell\nu\, qq$

Combined (WW+ZZ)

$H \rightarrow WW$

95% CL limit on σ/σ_{SM} vs m_H [GeV]

- Dominant sensitivity :
  - Low m_H : $2l2\nu$
  - High m_H : $l\nu qq$

ATLAS Preliminary
H→WW, SM-like
$\sqrt{s} = 8$ TeV $\int Ldt = 20.3$ fb^{-1}
Obs. / Exp. / $\pm 1\sigma$ / $\pm 2\sigma$ / SM
ggF production

ATLAS Preliminary
H→WW, SM-like
$\sqrt{s} = 8$ TeV $\int Ldt = 20.3$ fb^{-1}
Obs. / Exp. / $\pm 1\sigma$ / $\pm 2\sigma$ / SM
VBF production
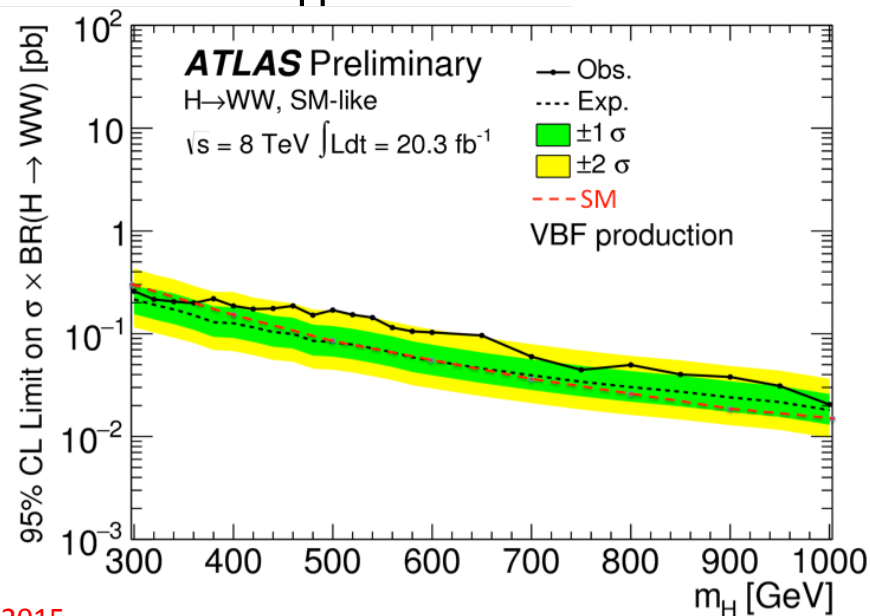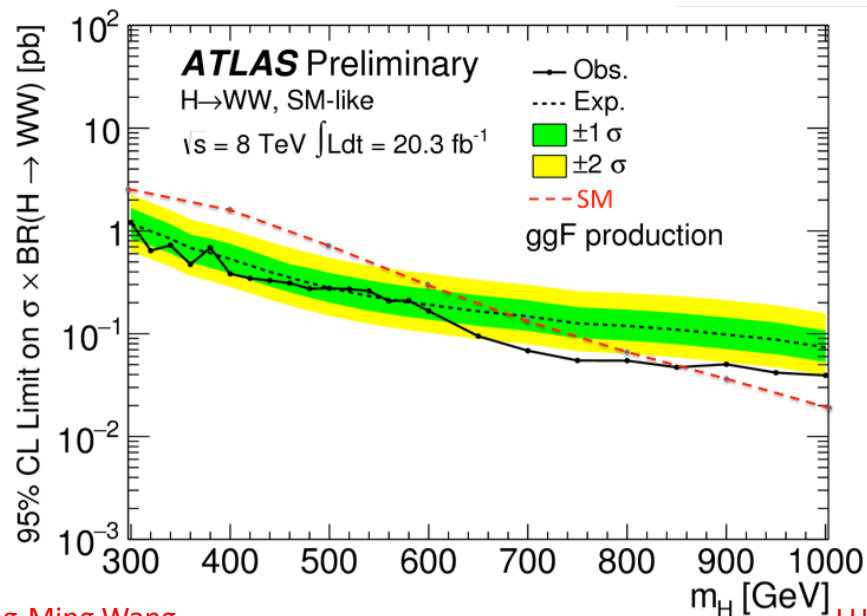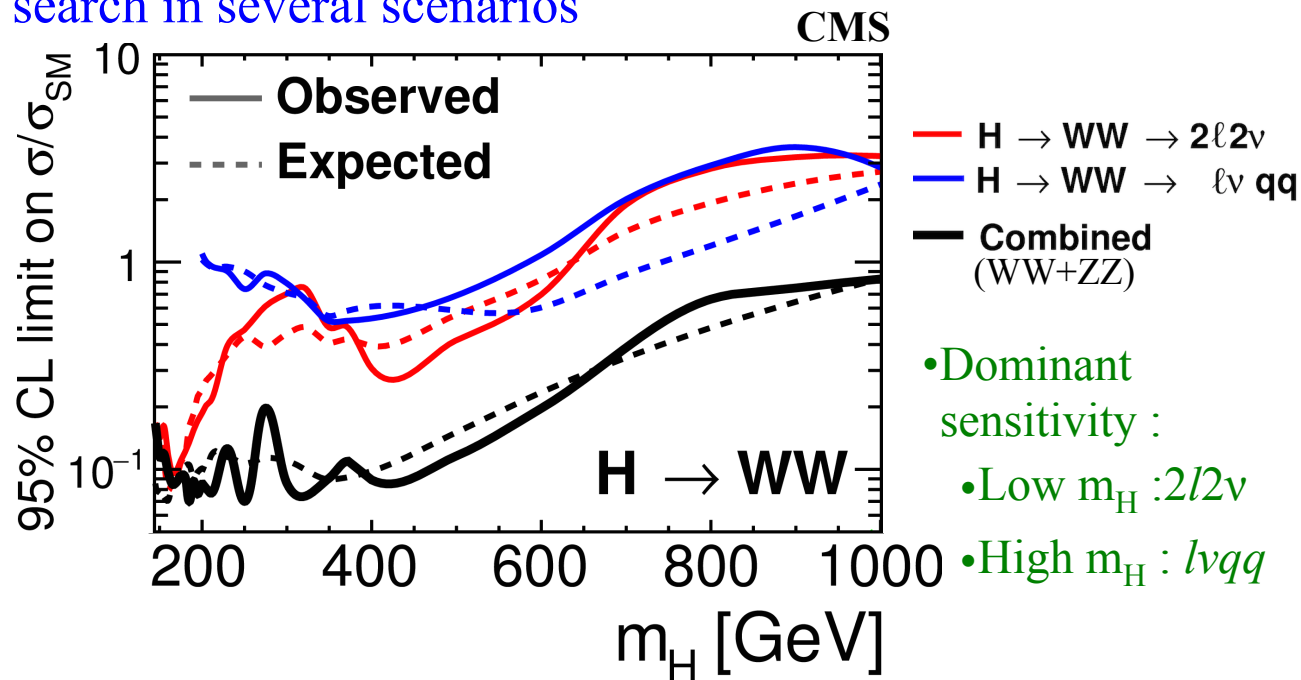
H→WW : Results

- **Narrow Width** (negligible effect from interference)
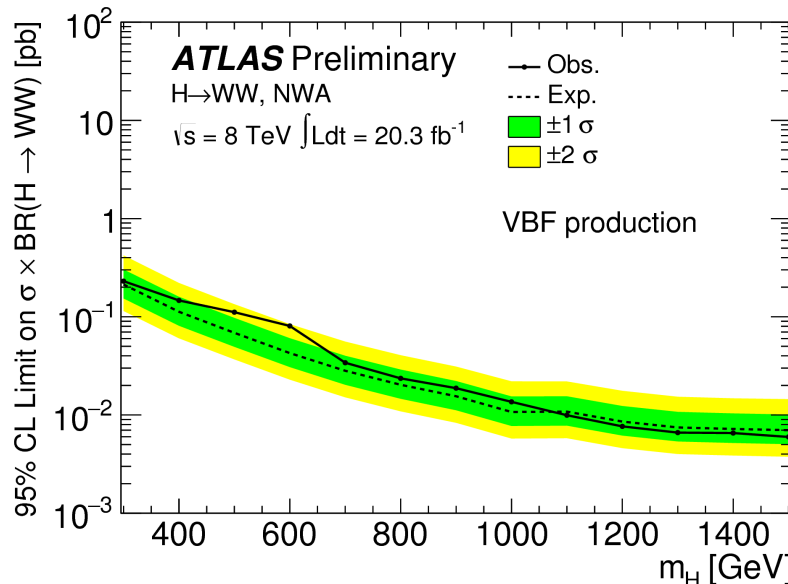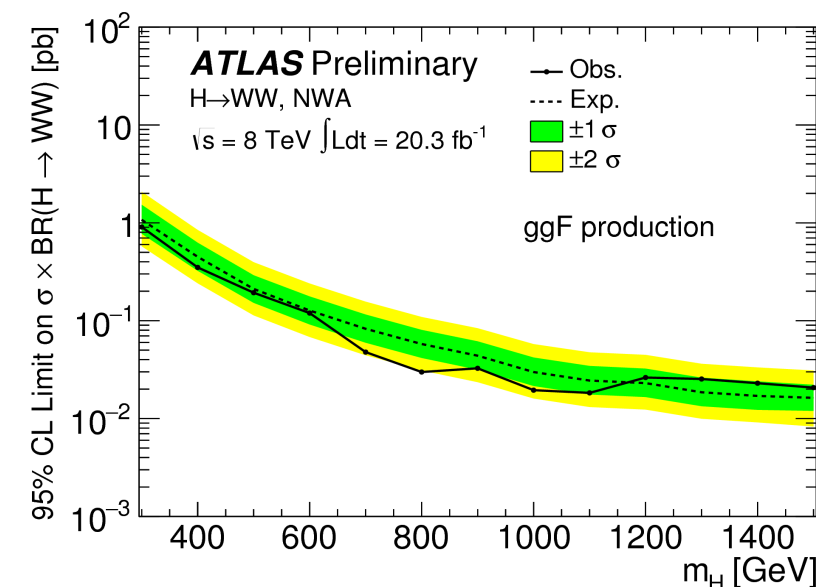
- *Extend search to mH=1.5 TeV !*

- **Intermediate Width**
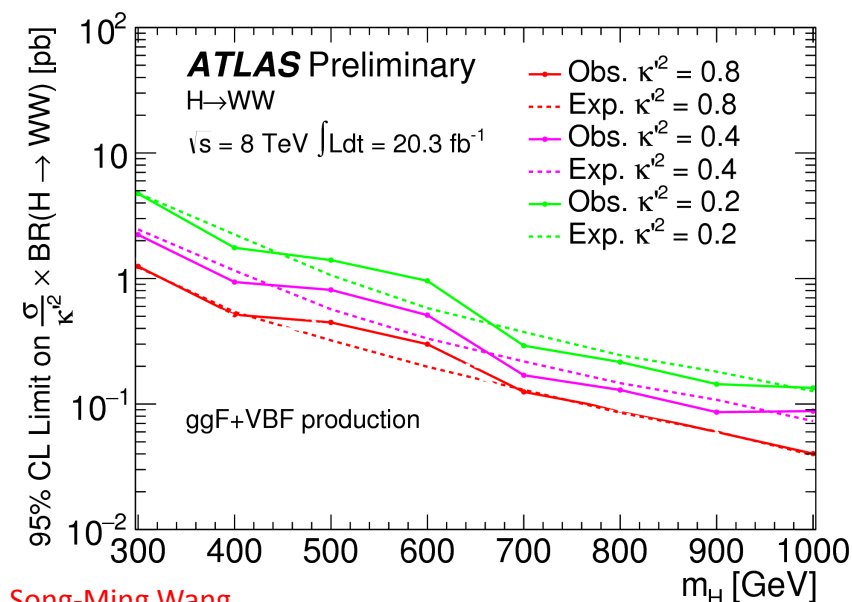
- Motivated by EW singlet model
- Assume production cross section and partial width of heavy H is related to SM Higgs by a single constant SF
- Not considering new decay modes ($BR_{new}=0$)
- Results not sensitive to width of H

H→ZZ

- Perform search in various decay combinations
  - *llll* : good mass resolution, well suited for narrow resonant search
  - *llvv , llqq, vvqq* : high branching ratio, good sensitivity at high mass

- **H→ZZ→2l2l**
- 4 isolated leptons (*l=e* or μ)
  - CMS also considers $2l2\tau$
- Good S/B
- m_{4l} : discriminant variable
- Dominant background :
  - Continuum ZZ, Z+jets
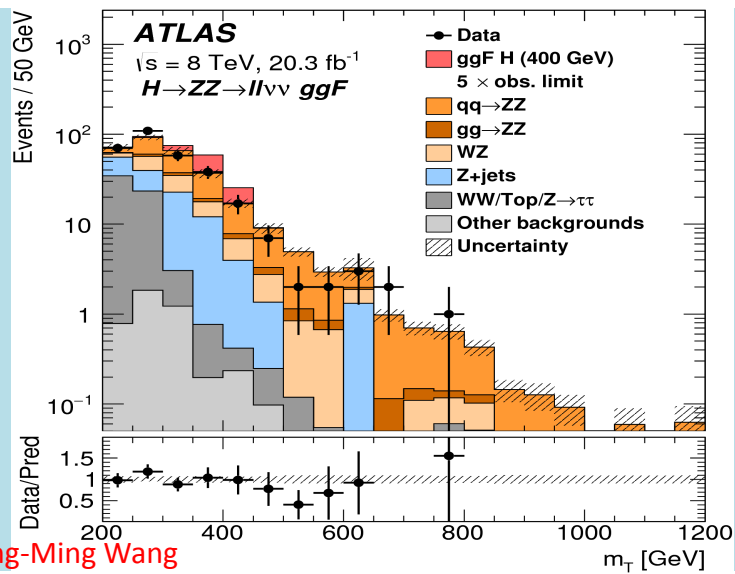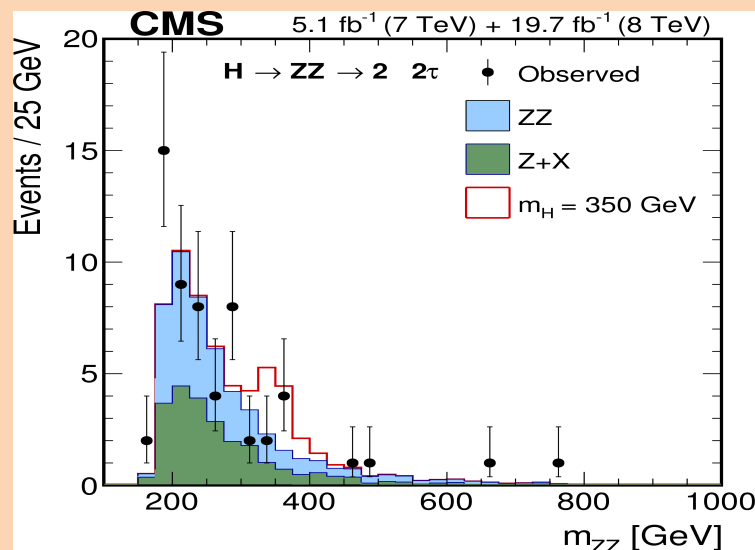
- **H→ZZ→llvv**
- l^+l^- (*l=e* or μ) , large MET
- Veto events with b-tagged jet or extra lepton
- Require high pT objects and MET well separated to suppress events where MET is mis-measured
- Also separate events into VBF and non-VBF categories

H→ZZ

• H→ZZ→*llqq*

- At high Higgs mass jets from Z→qq may merge (J : merged jet)
  - Perform search in "resolved" & "merged" channels
- l^+l^- ($l=e$ or μ) , m_{ll} consistent with Z mass
- Separate events into VBF, non-VBF, resolved and merged categories
- Mass of m_{jj} , m_J be consistent with Z mass
- Non-VBF events further classified into 0, 1, 2 b-tagged events (to improve sensitivity)
  - b-jets occur more often in signal (~21%) than in dominant Z+jets BG (~2%)
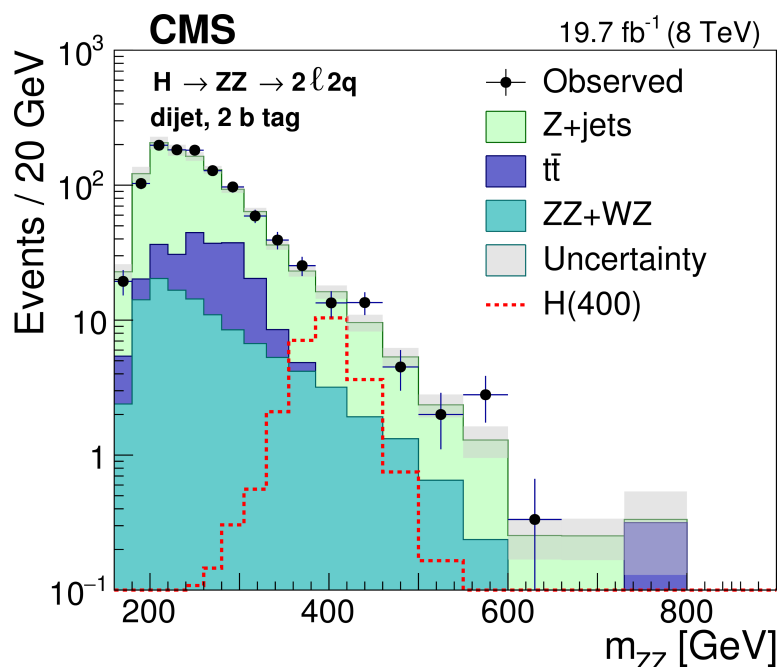
- Dominant background: Z+jets, Top, Diboson

H→ZZ
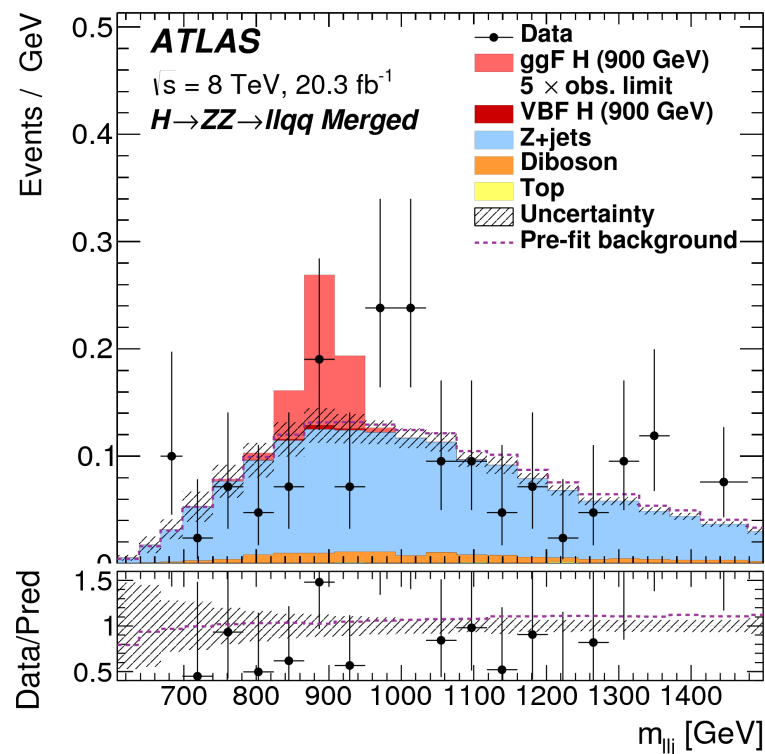
•H→ZZ→νν*qq*

•Only considered in ATLAS, has large BR, but also large background

•No reconstructed lepton, large MET

•Reject fake MET events to suppress multi-jet BG

•No separation into VBF and non-VBF categories

•Mass of m_{jj} be consistent with Z mass

•Classify events into 0, 1, 2 b-tagged events

•Dominant background:
  •Z+jets, W+jets, Top, Diboson

ATLAS
√s = 8 TeV, 20.3 fb⁻¹
H→ZZ→νν*qq* tagged

- Data
- ggF H (900 GeV) 30 × obs. limit
- W+hf
- Z+hf
- Z+bl
- Diboson
- Top
- Uncertainty
- Pre-fit background
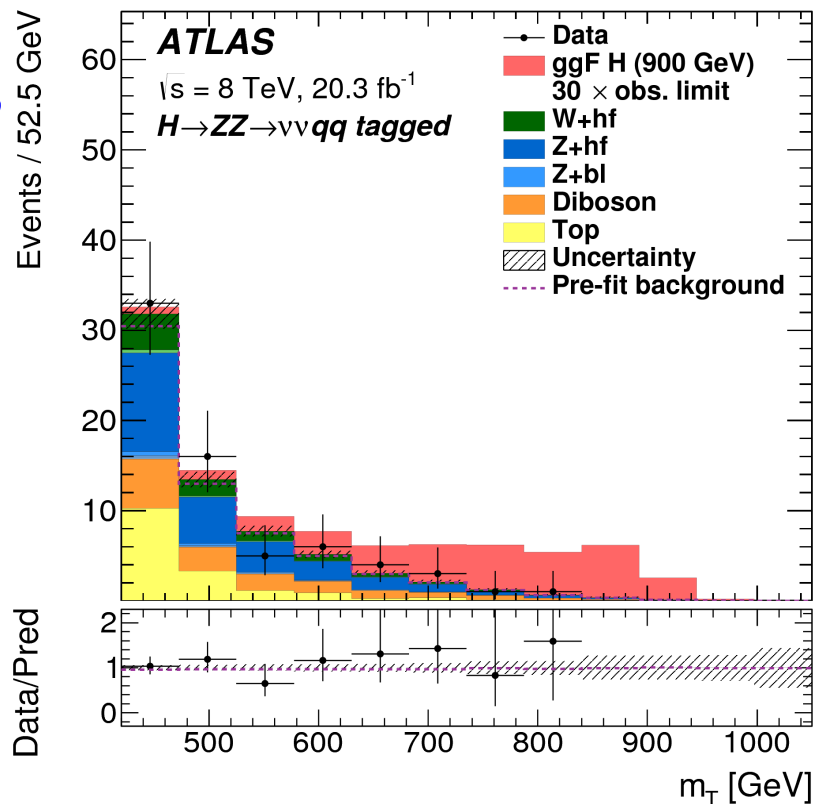
H→ZZ : Results

- **ATLAS :**
  Narrow Width

- Higgs width much smaller than detector resolution
  - $\sigma(4l) \sim 1.5\text{-}3.5\%$
- Interference not accounted
- Best sensitivity:
  - Low mass: $4l$
  - High mass : $llqq$ $+\nu\nu qq$
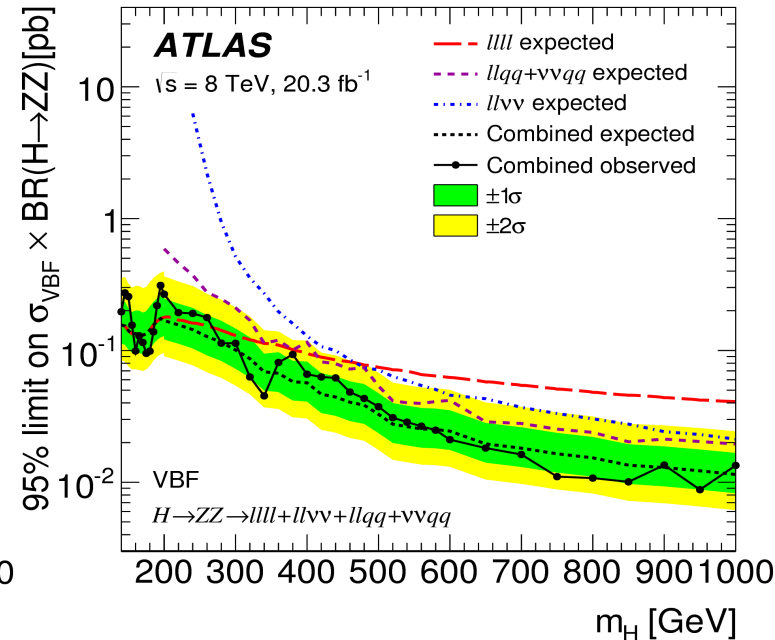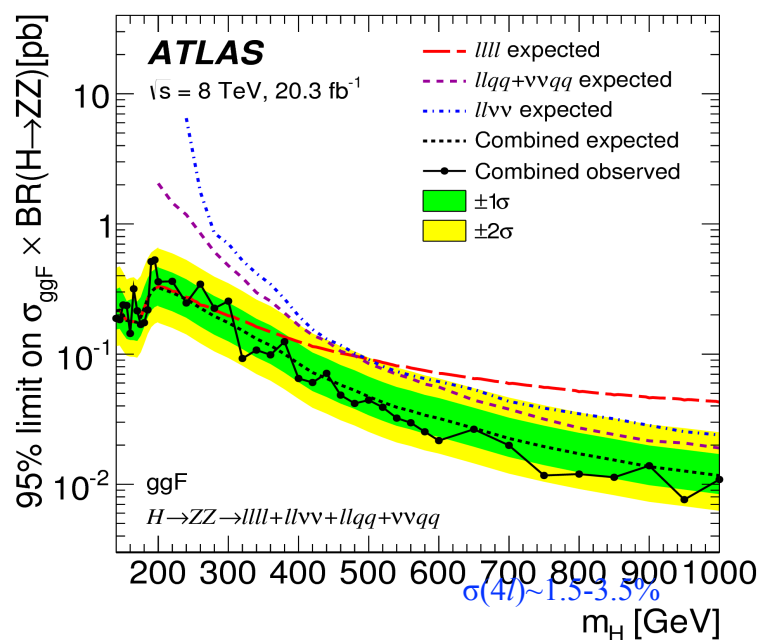
- **CMS : SM-Like**
  - Interference is accounted
  - Best sensitivity:
    - Low mass: $4l$
    - High mass : $2l2\nu$
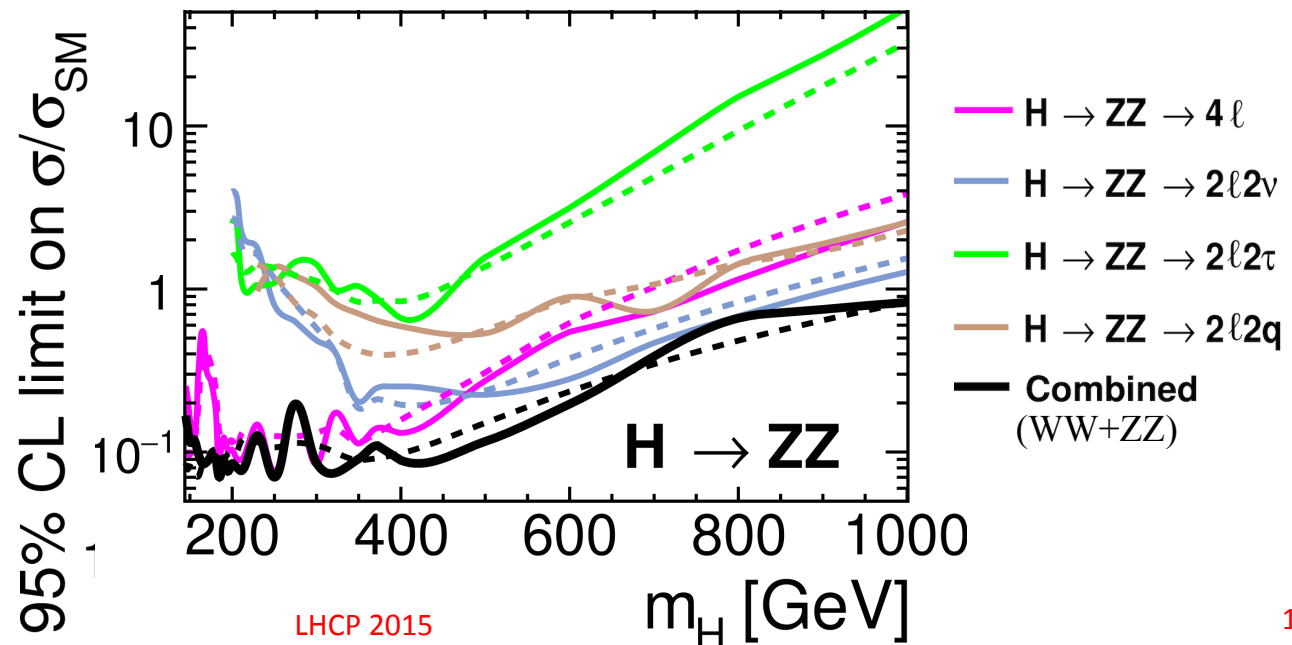
H→ZZ : Results

•ATLAS :
2HDM

•Chosen mH and ranges of tan β and cos(β-α) are limited to region where the assumption of heavy narrow width Higgs boson with negligible interference is valid.

Type-I

Type-II

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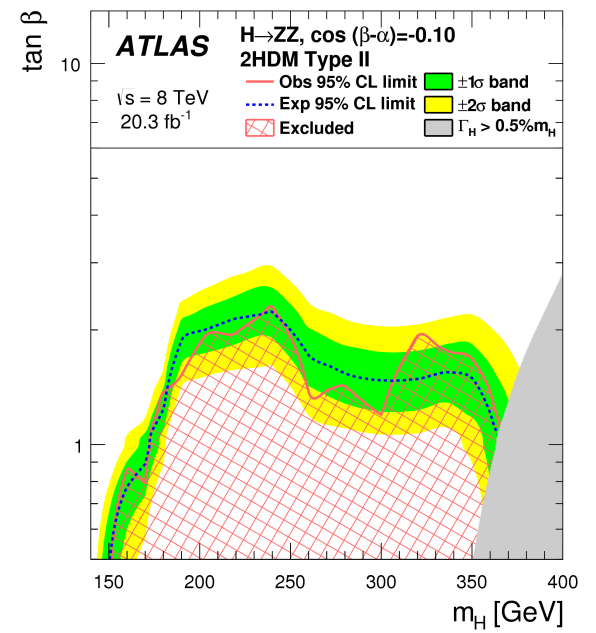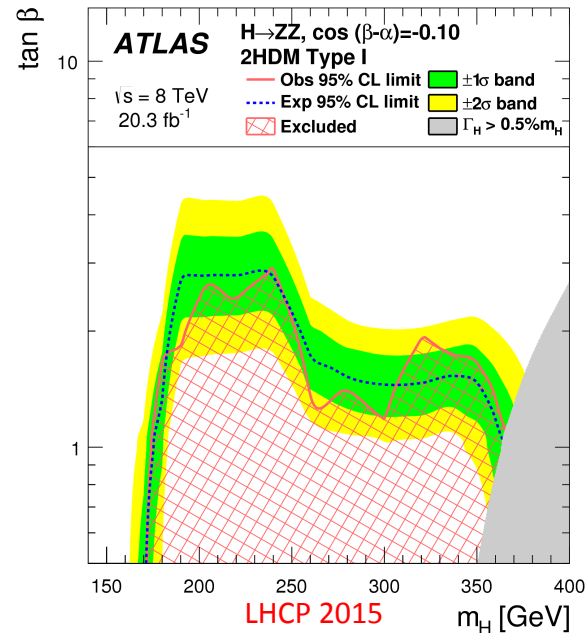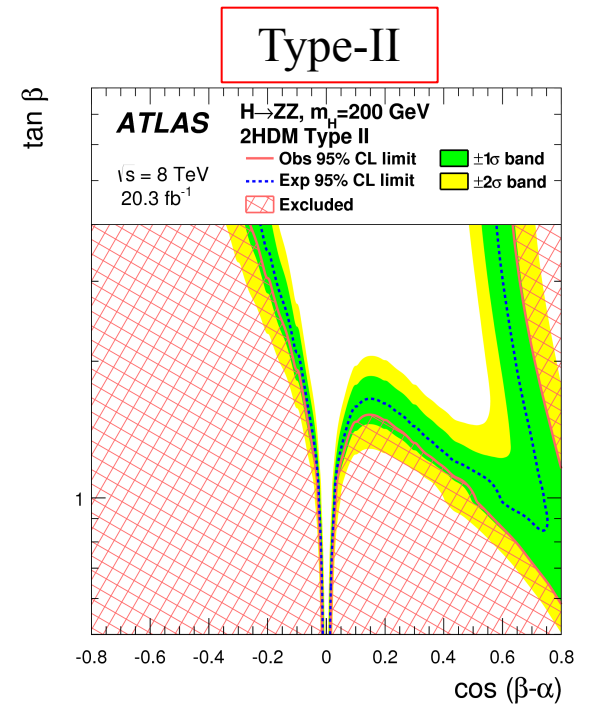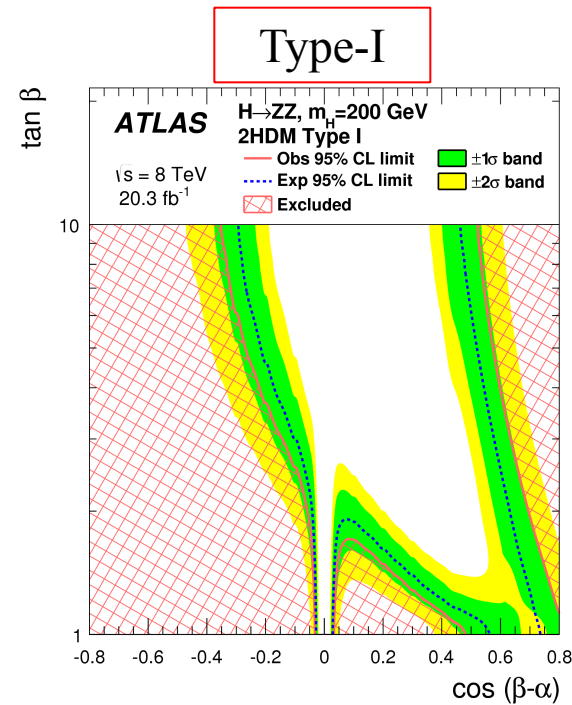
Combine H→WW + H→ZZ (CMS)

SM-Like

CMS up to 5.1 fb⁻¹ (7 TeV) + up to 19.7 fb⁻¹ (8 TeV)

Legend:
- Combined
- Combined (exp. ± 2σ)
- $H \to WW \to 2\ell2\nu$
- $H \to WW \to \ell\nu\,qq$
- $H \to ZZ \to 2\ell2\nu$
- $H \to ZZ \to 4\ell$
- $H \to ZZ \to 2\ell2\tau$
- $H \to ZZ \to 2\ell2q$

y-axis: 95% CL limit on σ/σ_{SM}
x-axis: m_H [GeV]
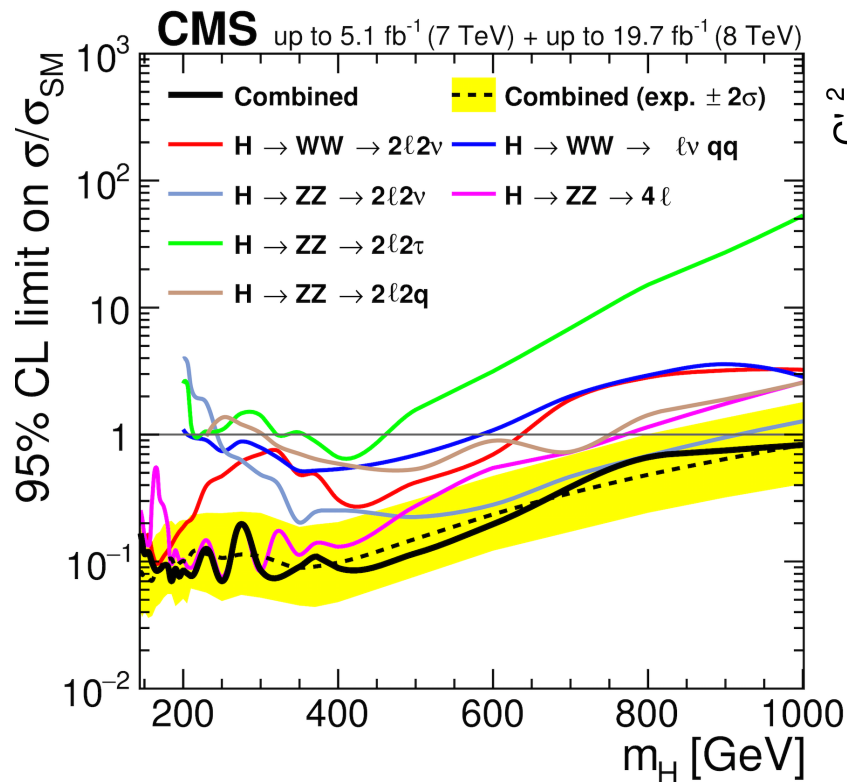
- Exclude $145 < m_H < 1000$ GeV

EW Singlet

CMS up to 5.1 fb⁻¹ (7 TeV) + up to 19.7 fb⁻¹ (8 TeV)

Legend:
- Obs., $B_{new} = 0.0$
- Exp., $B_{new} = 0.0$
- Obs., $B_{new} = 0.2$
- Exp., $B_{new} = 0.2$
- Obs., $B_{new} = 0.5$
- Exp., $B_{new} = 0.5$

$\Gamma = \Gamma_{SM}\,(B_{new} = 0.5)$

$\mu_{h(125)} = 1.00 \pm 0.14$

y-axis: C'^2
x-axis: m_H [GeV]
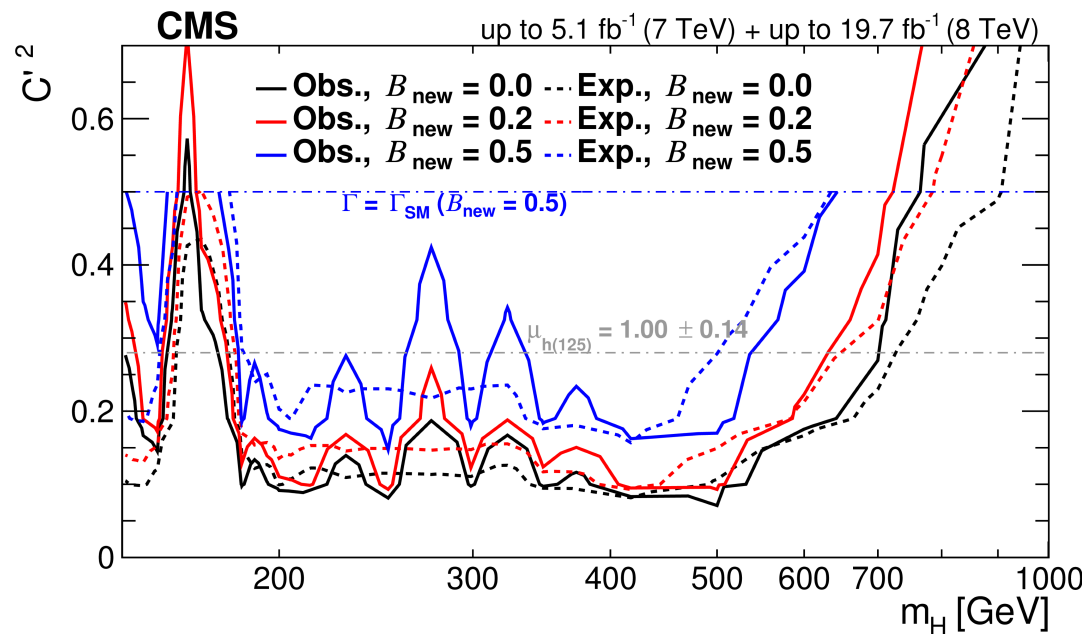
- Large region of C'^2 vs m_H is excluded for various values of B_{new}

Summary

- CMS and ATLAS have searched for high mass Higgs boson with Run 1 data
  - No excess is found over SM prediction
- Run 2 data taking has just started
  - Increased collision energy may open new doors to BSM
- Understanding detector performances and background will be critical to searches at the new energy frontier

Back Up

Two Higgs Doublet Model (2HDM)

•Different types of 2HDM scenarios satisfy the Glashow-Weinberg condition (to be absence of FCNC)

- •Type I : One Higgs doublet couples to vector bosons and the other couples to fermions (fermiophobic)

- •Type II : (MSSM like) one doublet couples to up-type quarks, and the other couples to down-type quarks and leptons

- •Type III : (lepton-specific) quarks couple to one doublet and leptons to the other

- •Type IV : ("flipped") up-type quarks and leptons couple to one doublet and down-type quarks couple to the other

H→γγ : Results

•CMS : Limits on narrow width resonance decaying into two photons
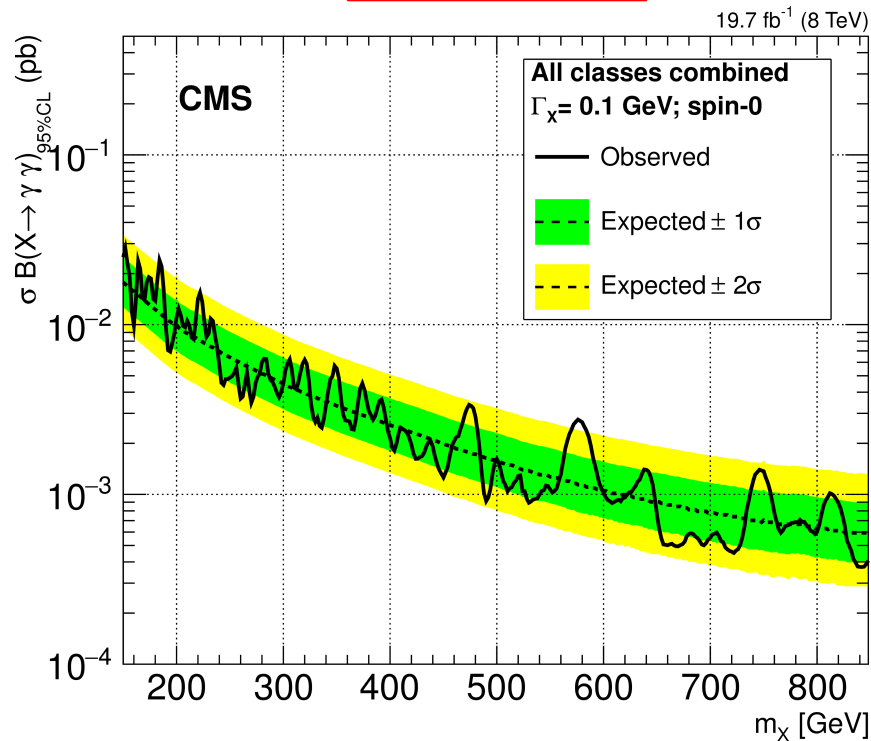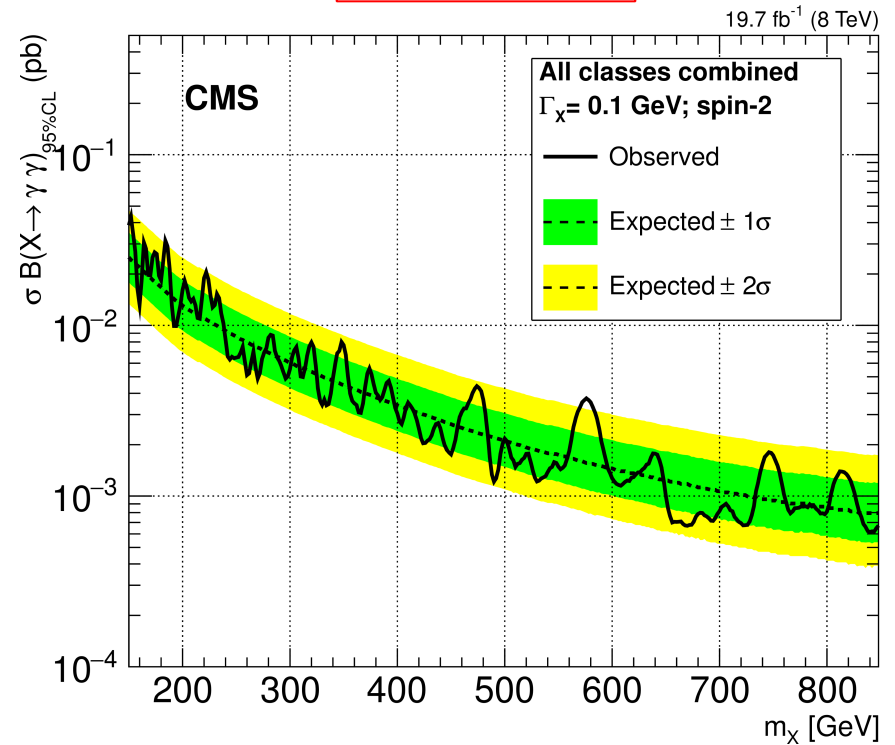
H→γγ : Results

• CMS : Limits on width vs mass mH

Observed
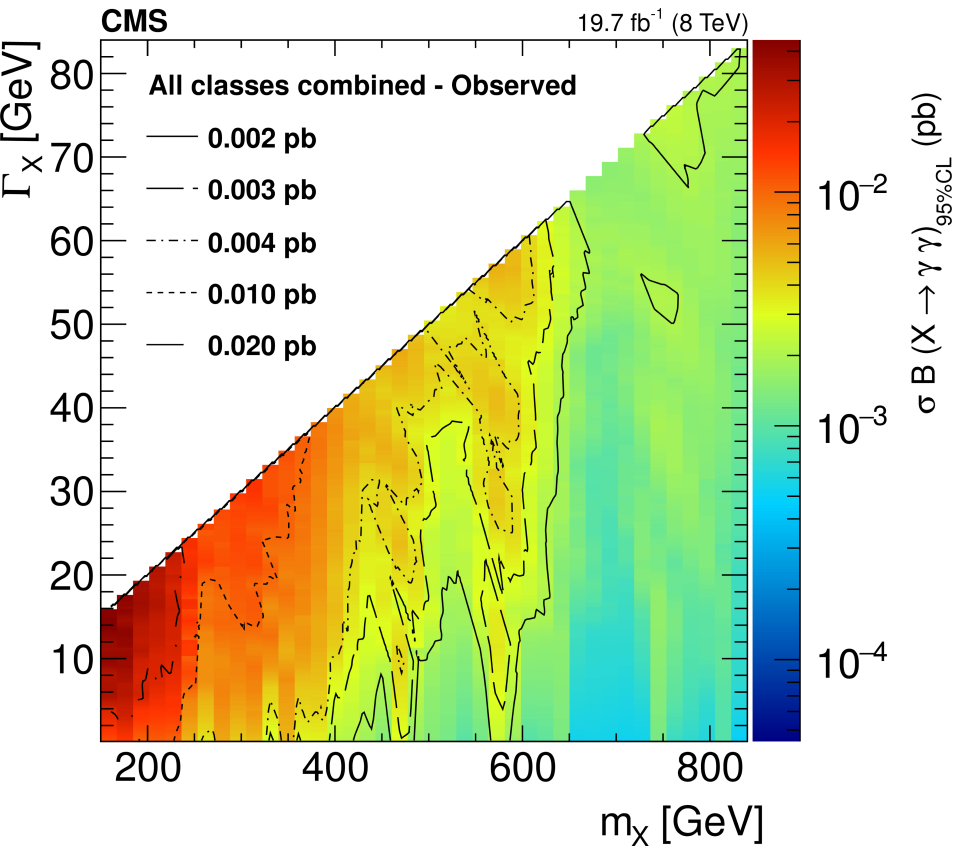
Expected
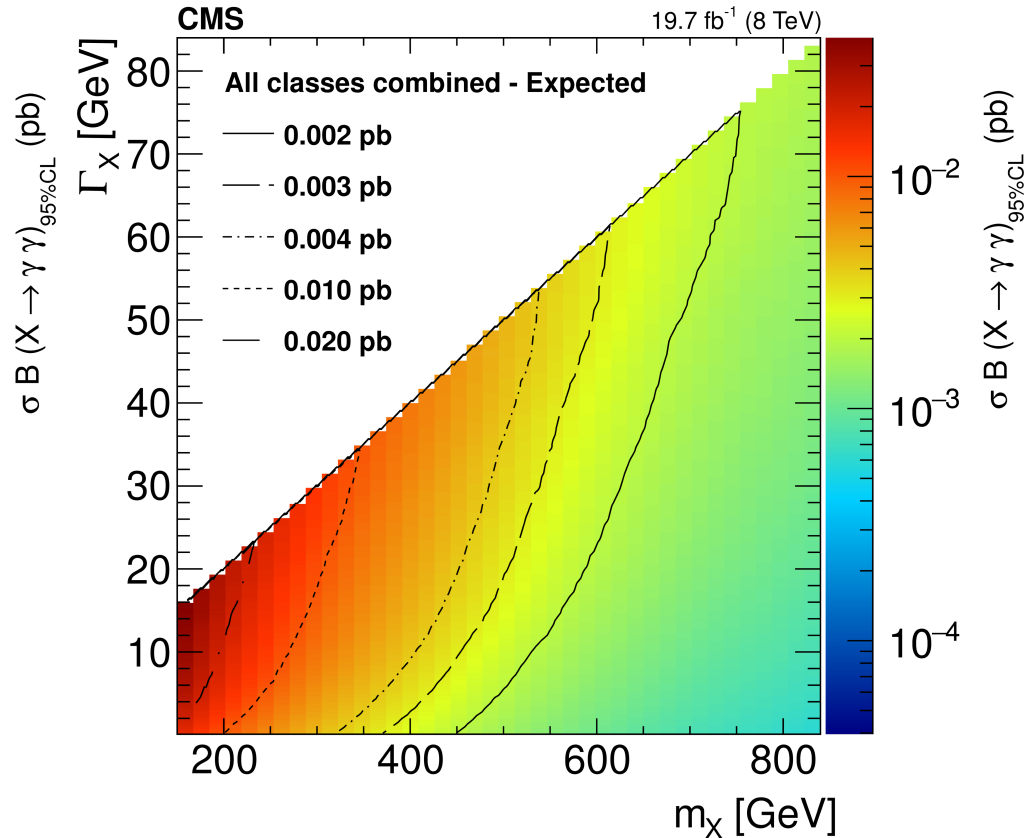
H→γγ : Results

- CMS : interpret results in 2HDM Type I model in A→γγ
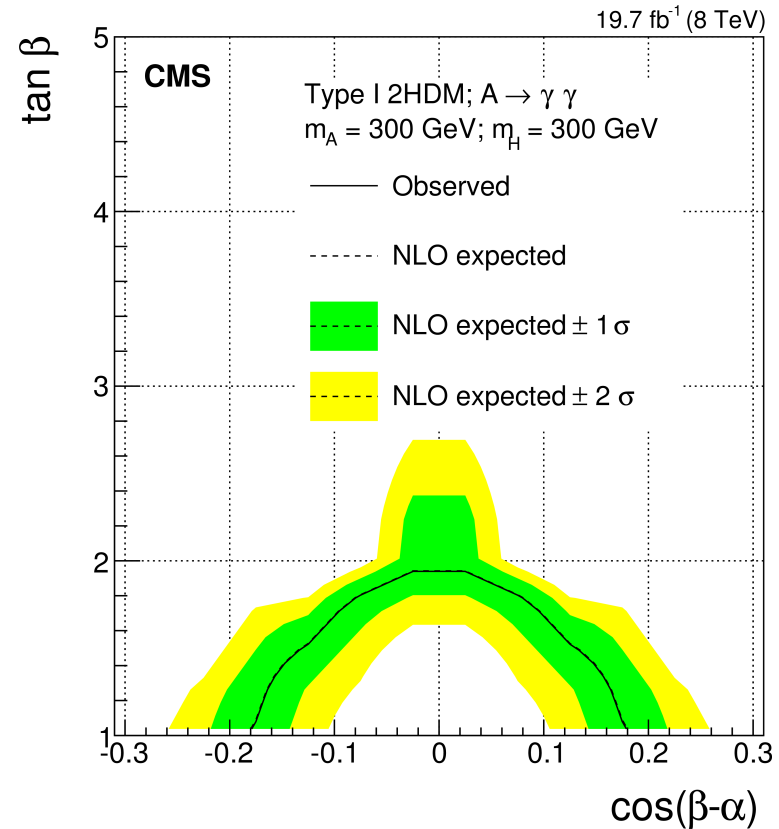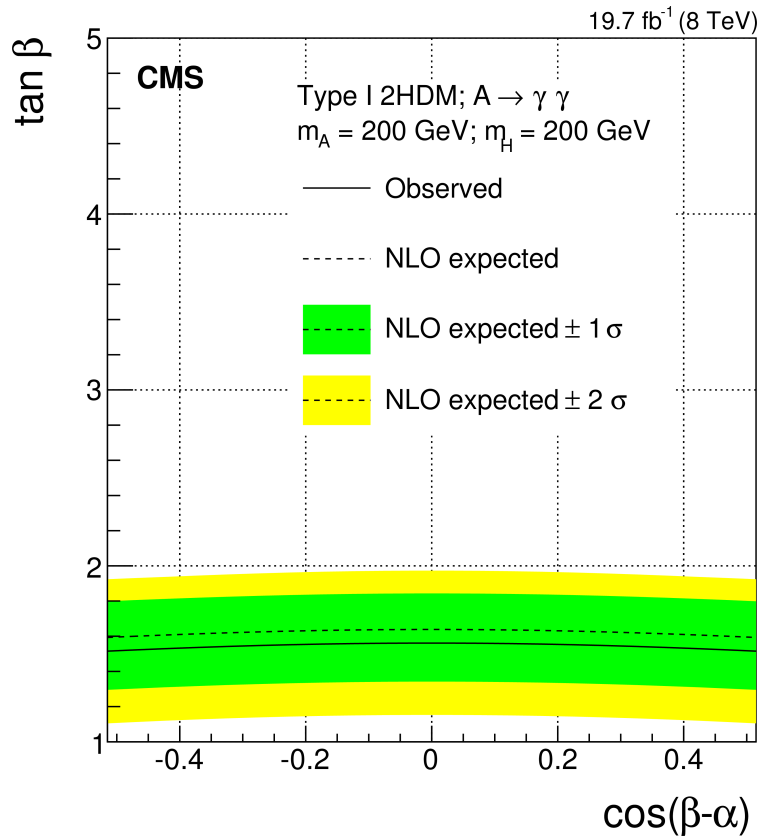
- Region below curves are excluded

H→WW : Results

- ATLAS : SM-Like
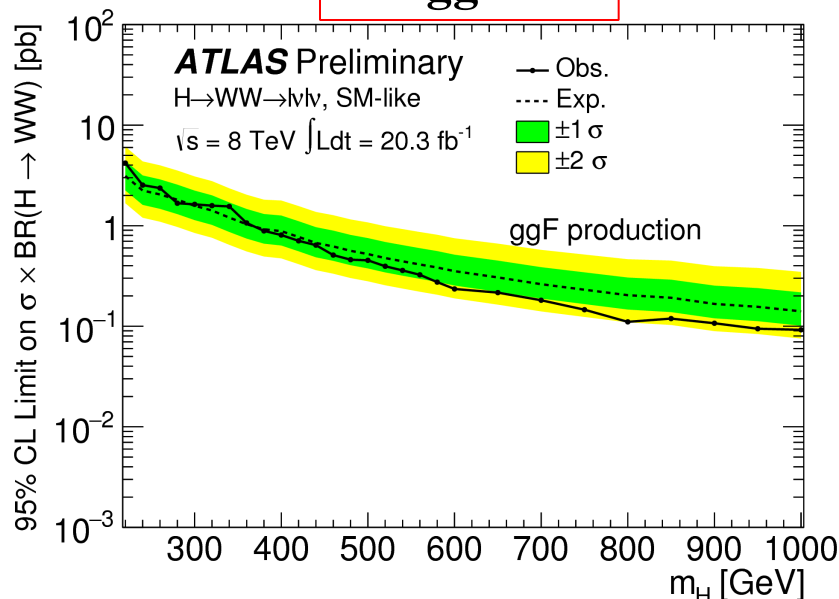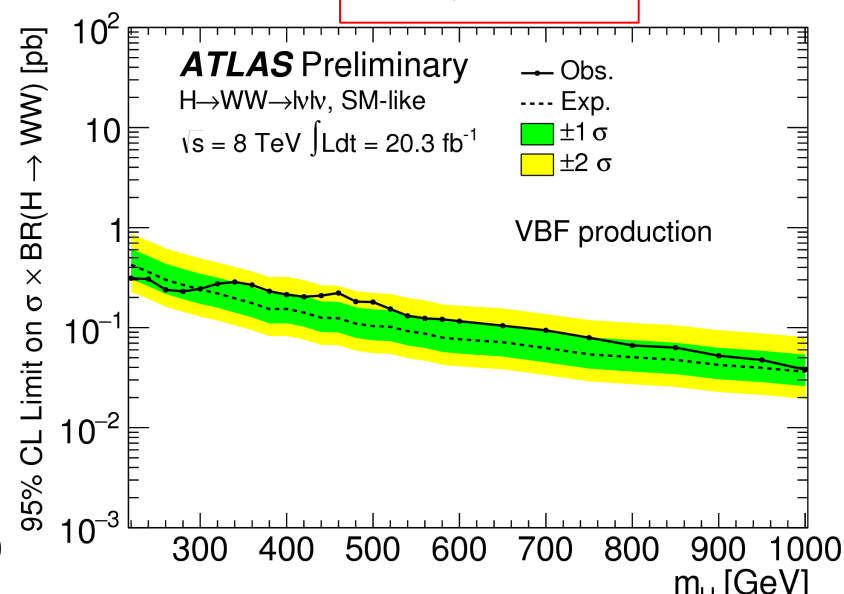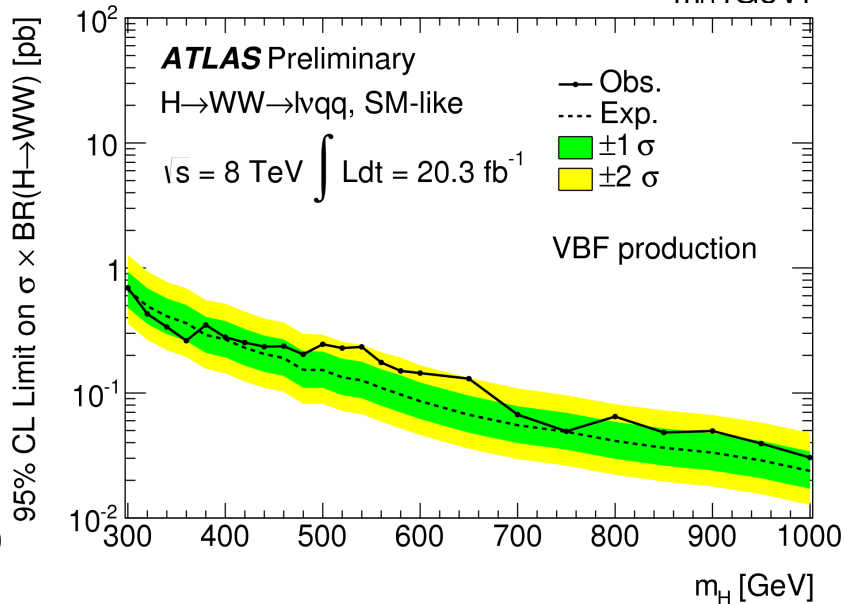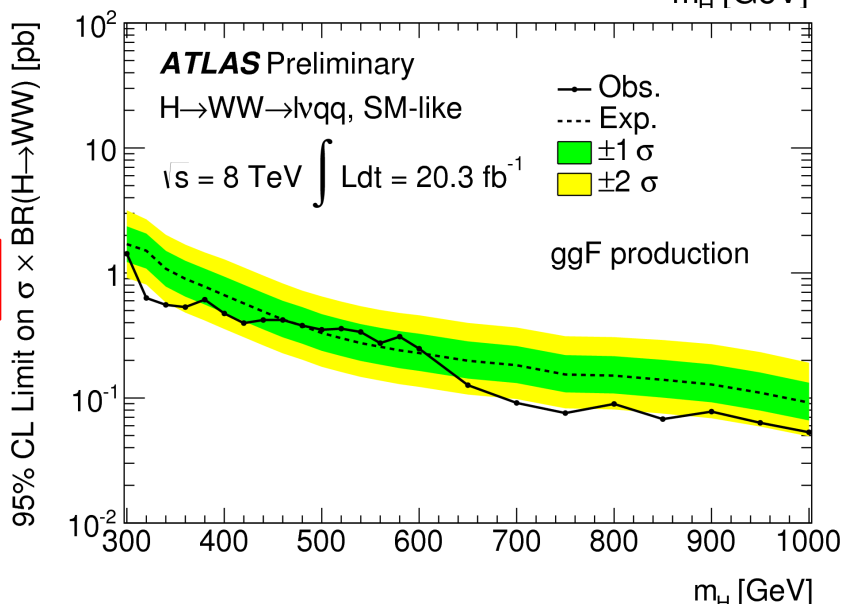
H→WW : Results

•ATLAS : Narrow Width
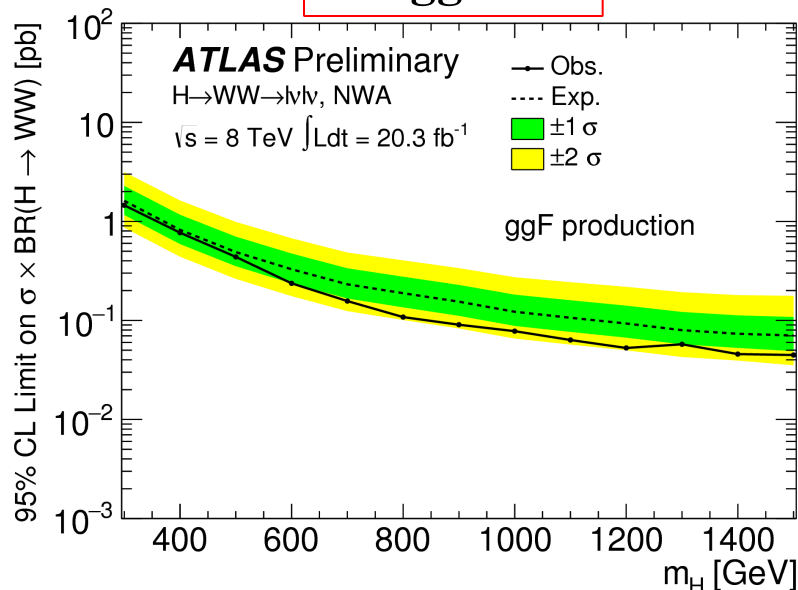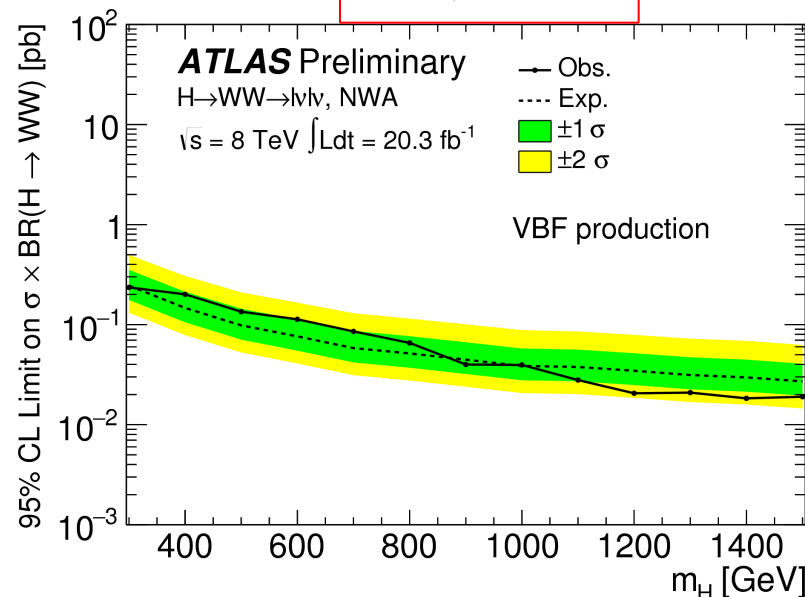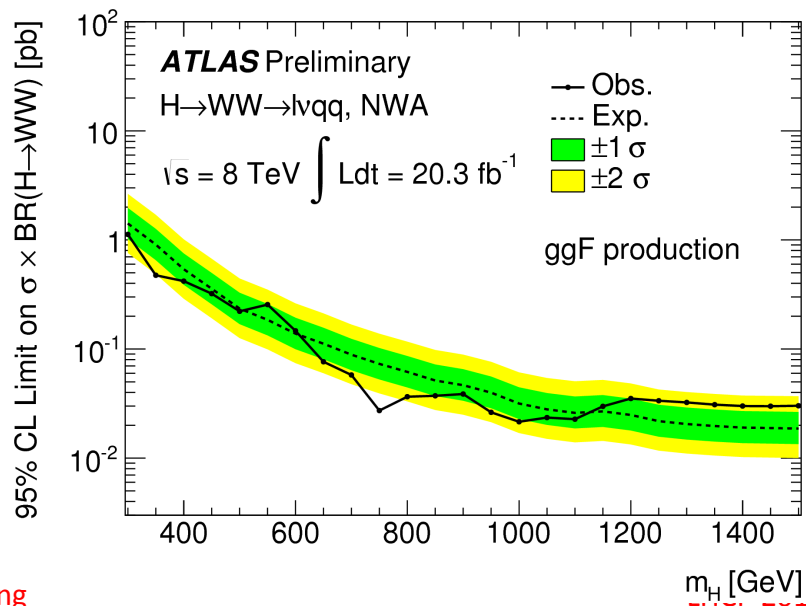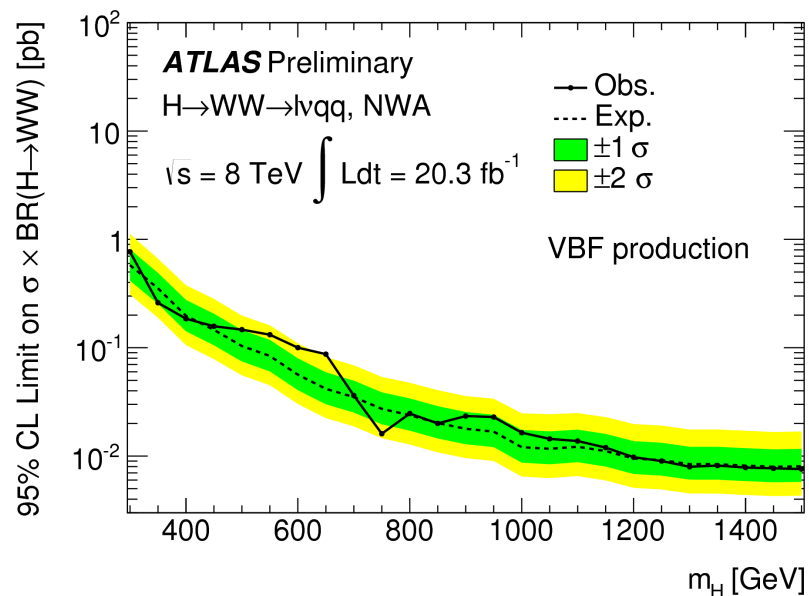
H→WW, ZZ : Results

- CMS : Electroweak Singlet Extension

H→ZZ : Results

•ATLAS :

ggF

VBF
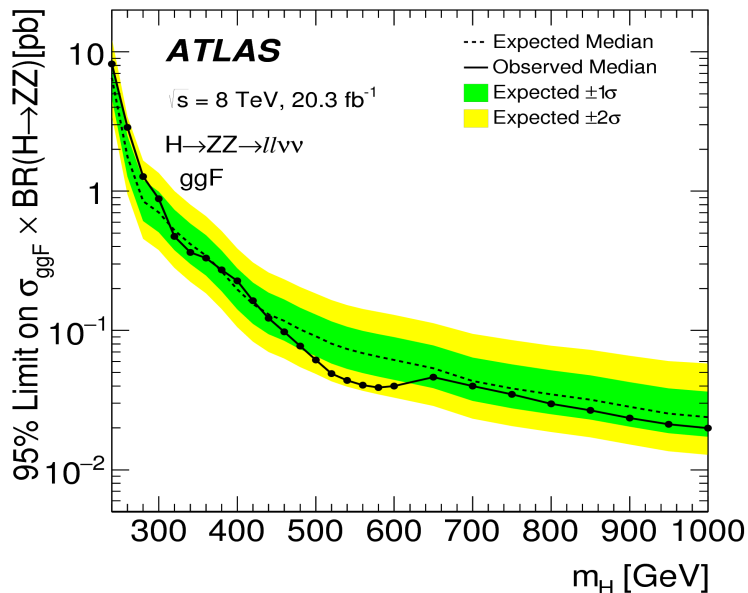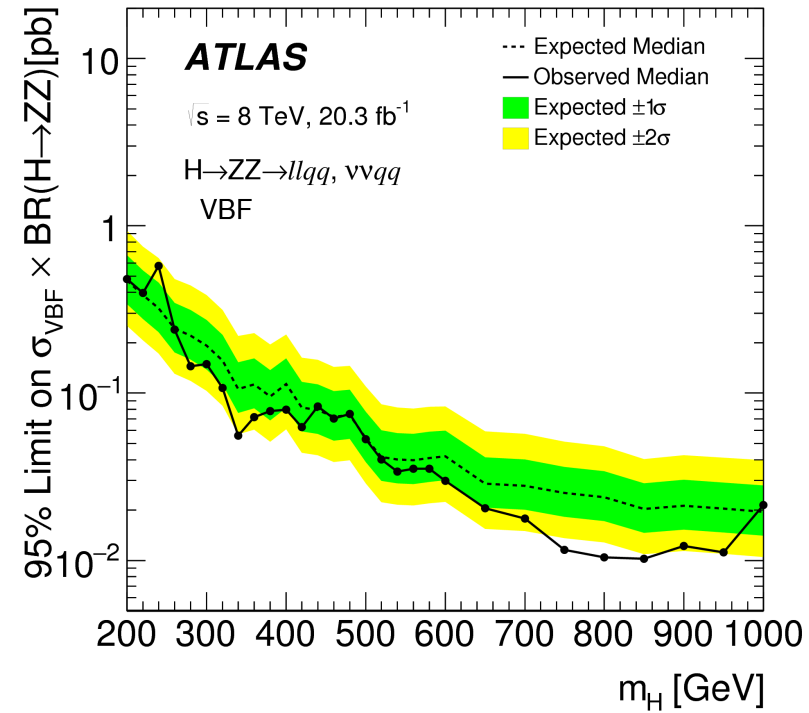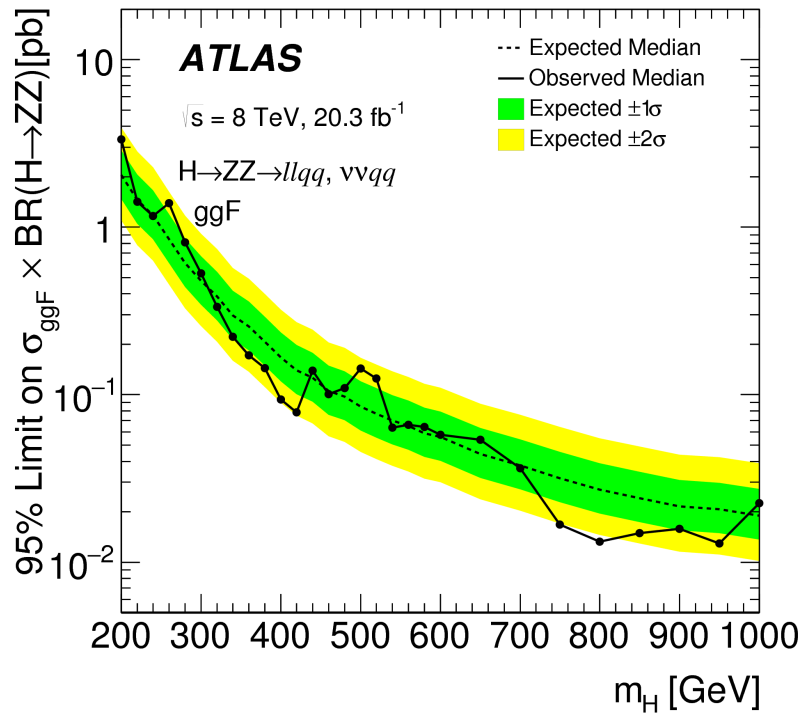
4*l*

llνν
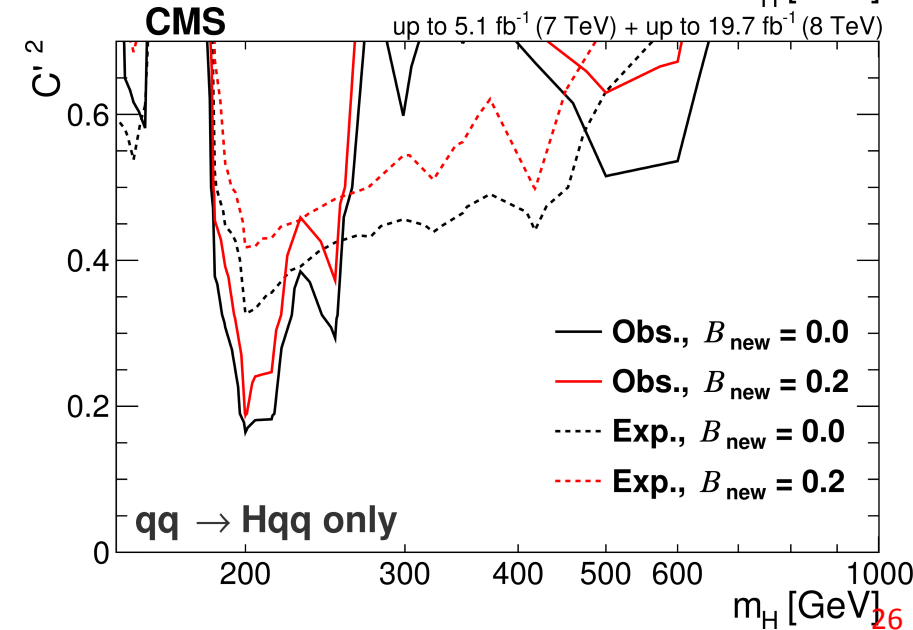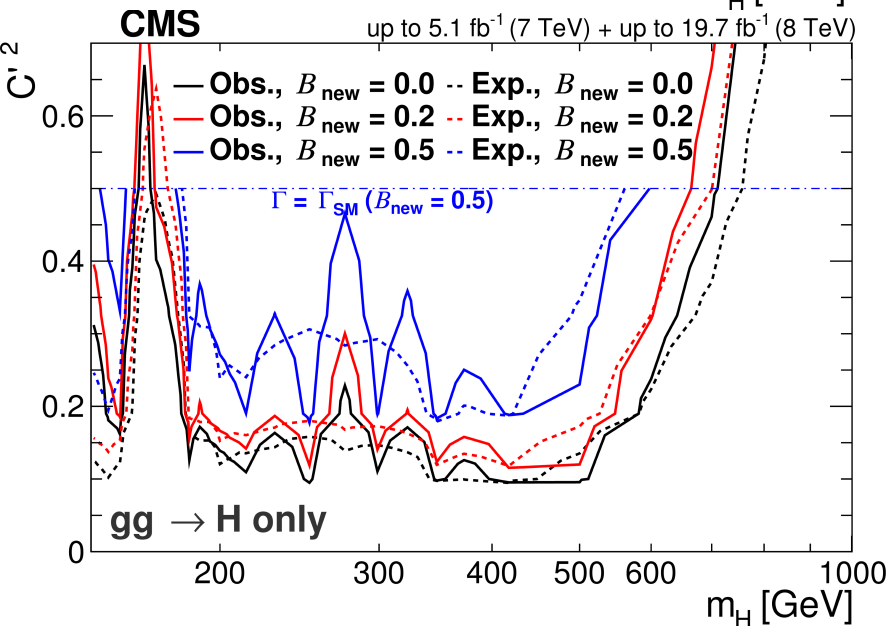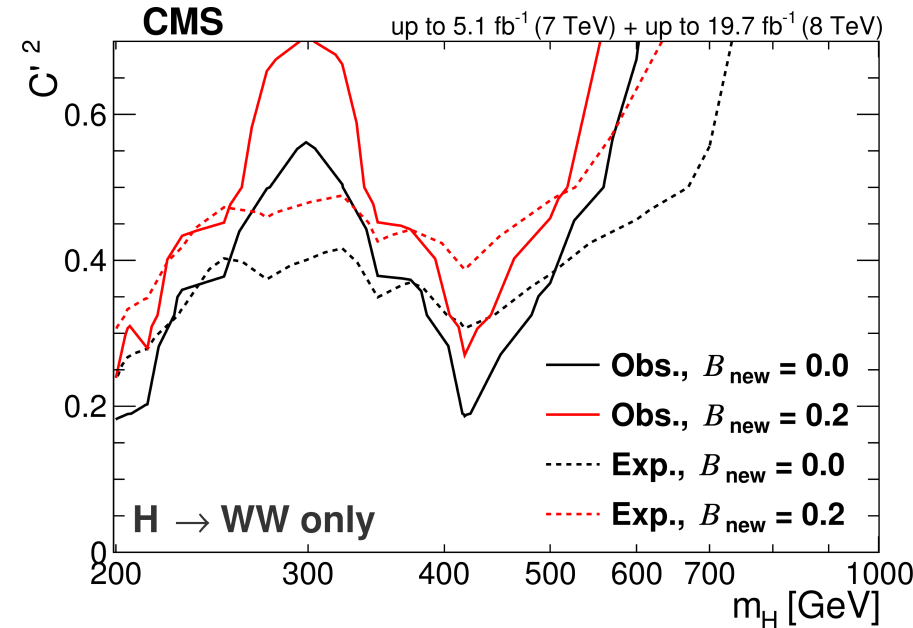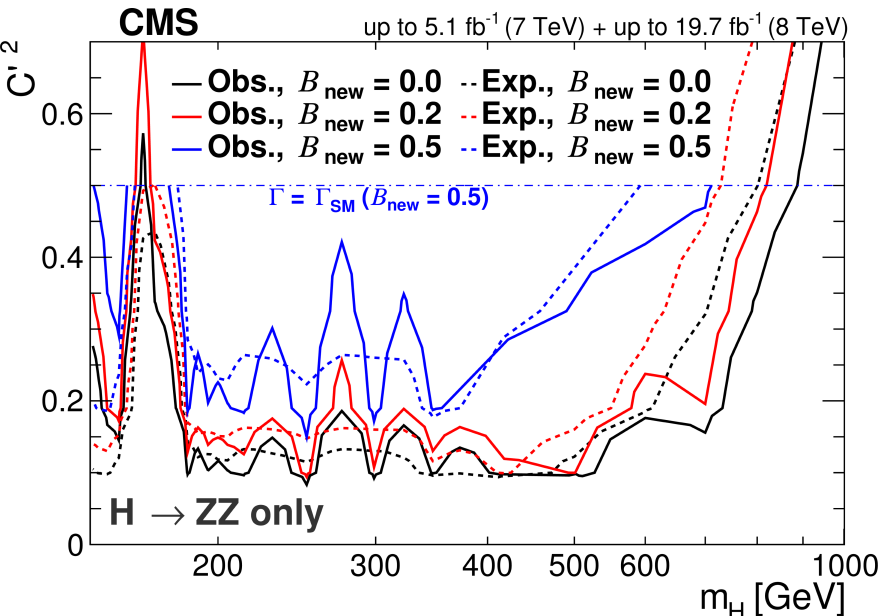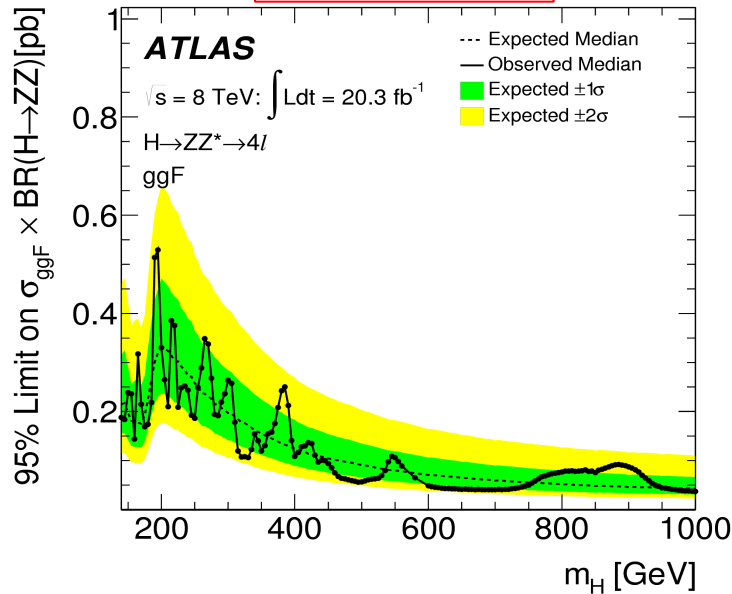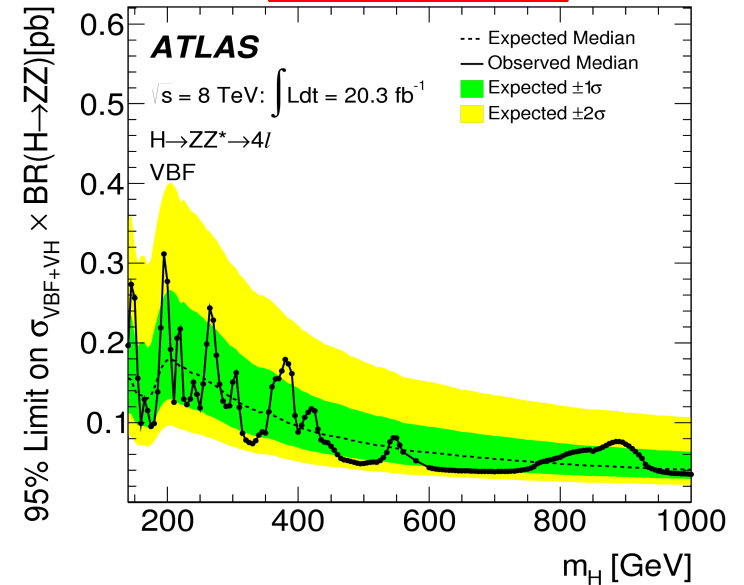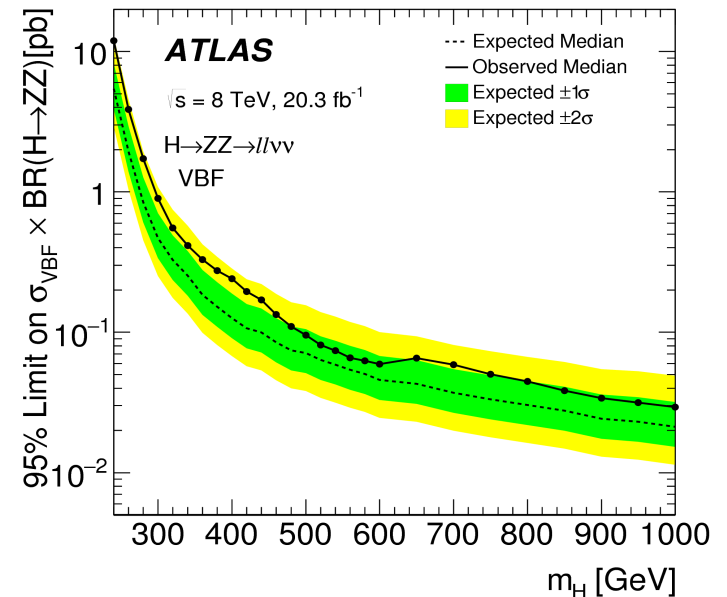
H→ZZ : Results

• ATLAS :

ggF

VBF

llqq + vvqq

H→WW : Results

- CMS and ATLAS perform search in several scenarios

- **<u>SM-Like</u>**

- Width gets large at high mass
  - $\Gamma \sim 650$ GeV @ mH=1 TeV

- Account for interference between signal and non-resonance WW BG

- Better expected sensitivity :
  - Low m_H : $2l2\nu$
  - High m_H : $l\nu qq$

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