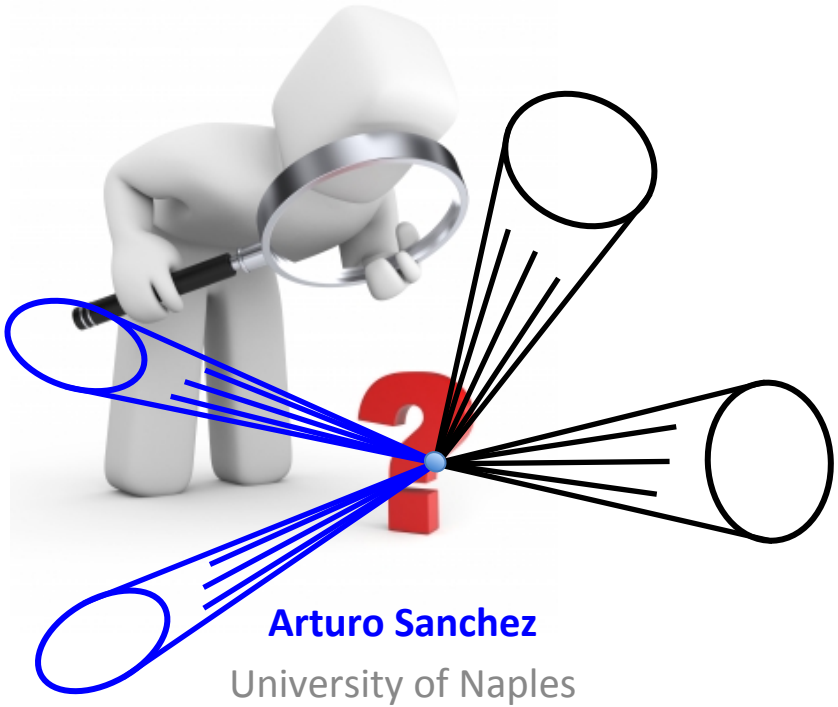
# Ricerca di un bosone di Higgs pesante nel canale di decadimento H→ZZ con l'esperimento ATLAS



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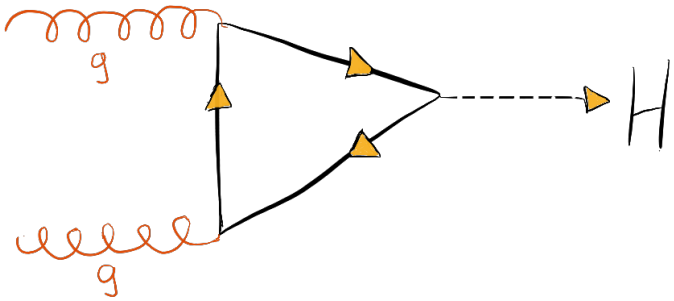
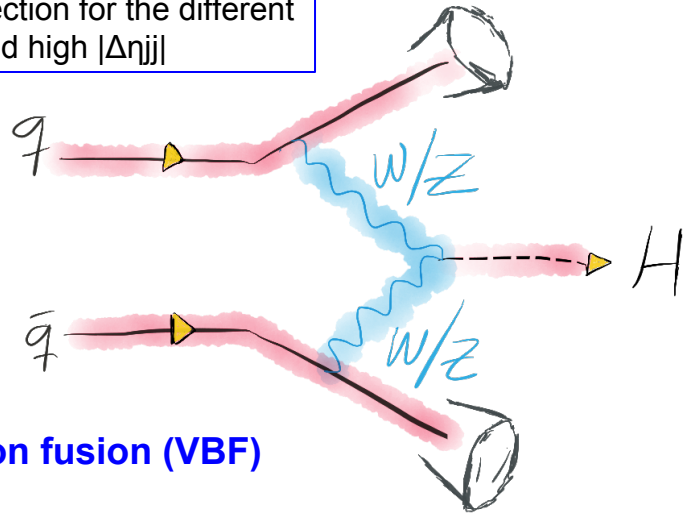
# Introduction

**This presentation resumes the different analysis searches of an additional heavy Higgs boson decaying into two Z bosons in the ATLAS Collaboration during the Run 1 period and their ongoing Run 2 status**

Events are split according to the number of jets in order to optimise the selection for the different production mechanisms: **VBF category** is based on ≥2 jets with high mjj and high |Δηjj|




**gluon-gluon fusion (ggF)**




**vector boson fusion (VBF)**

The principal reference to those analyses is http://arxiv.org/abs/1507.05930
Where the production mechanisms of this hypothetical heavy Higgs boson are the gluon-gluon fusion (ggF) and the vector boson fusion (VBF)

# Motivations

The Higgs mechanism makes the SM consistent. But extensions of the theory predict that the existence of more that one scalar field

**Electroweak Singlet**

an additional Electroweak Singlet which mixes to the SM Higgs doublet: two CP-even bosons should be there - features are mainly SM-like

| | h | H |
|---|---|---|
| **cross section** | $C^2 \times \sigma_{SM}$ | $C'^2 \times \sigma_{SM}$ |
| **width** | $C^2 \times \Gamma_{SM}$ | $C'^2/(1-B_{new}) \times \Gamma_{SM}$ |
| **branching ratio** | $BR_{h,SM}$ | $(1-B_{new}) \times BR_{h,SM}$ |

$C^2$ and $C'^2$ are scaling constants wrt/ the SM quantities
from unitarity: $C^2 + C'^2 = 1$
Free parameters: $B_{new}$, $C^2$ and $C'^2$ $m_H$

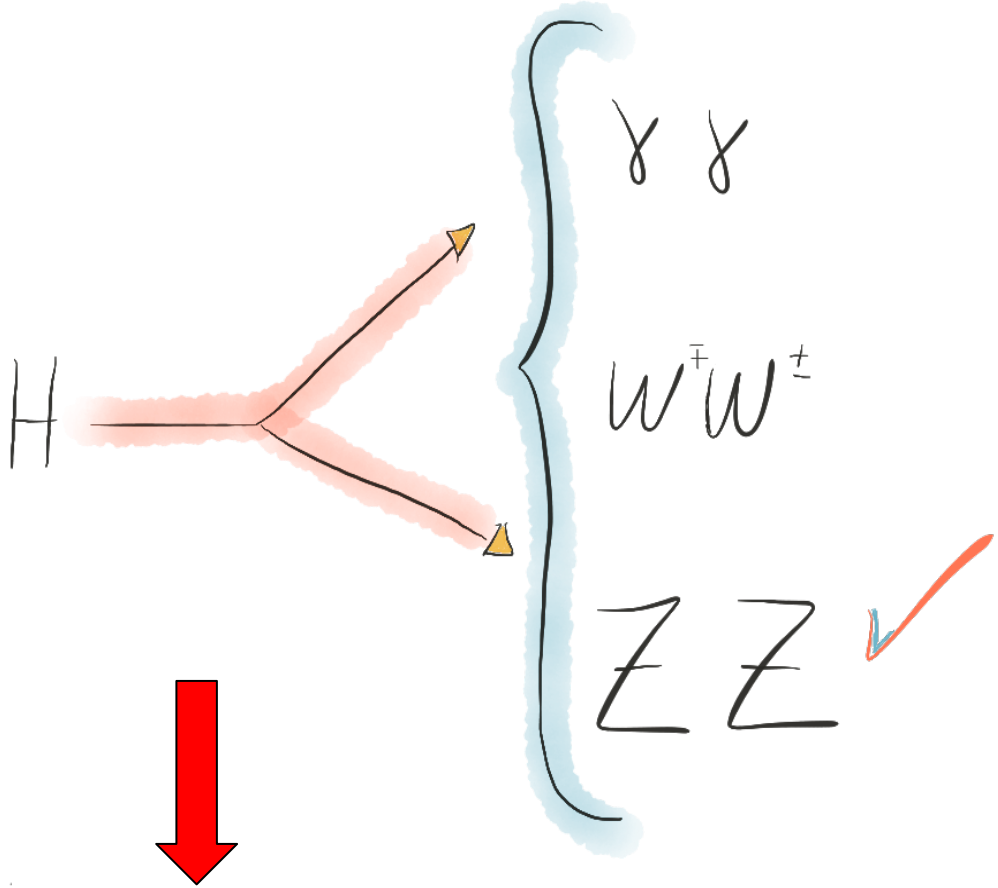
**2 Higgs Doublet Model**

Higgs-like mechanism achieved with two doublets: 5 Higgs-like bosons are there
2 CP-even: h and H / a neutral CP-odd: A / two charged bosons: $H^+$ and $H^-$
Free parameters are:

- the masses of the bosons
- tanβ - the ratio between the vacuum expectation values of the doublets
- α - the mixing angle between the two doublets

- different types of 2HDM models are obtained with different assumptions on the symmetry of the Lagrangian

# Searches of heavy Higgs→di-boson

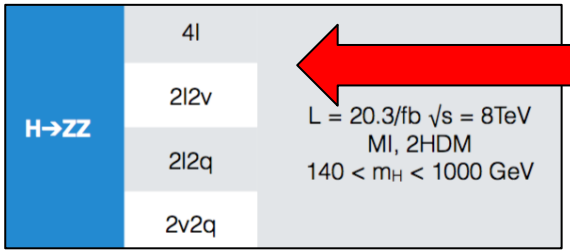



The searches for Higgs boson like high mass resonances have been performed in those three bosonic decay channels:

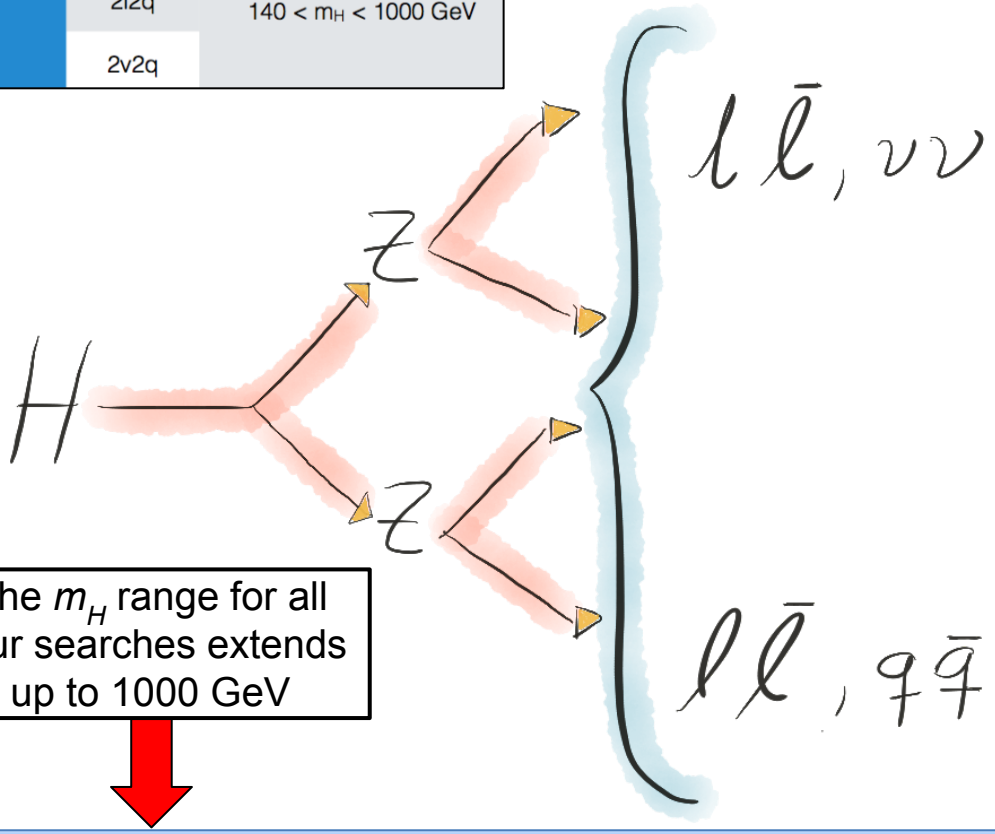
- $\gamma\gamma$: http://arxiv.org/abs/1407.6583
- WW: http://arxiv.org/abs/1509.00389
- ZZ: http://arxiv.org/abs/1507.05930
- W/Z+$\gamma$: http://arxiv.org/abs/1407.8150

We will focus the attention in the ZZ decay mode for the rest of the presentation

# Searches of heavy Higgs→ZZ




In the next plots and results, the total luminosity in use is the total 8 TeV Run1 dataset of 20.3 $fb^{-1}$



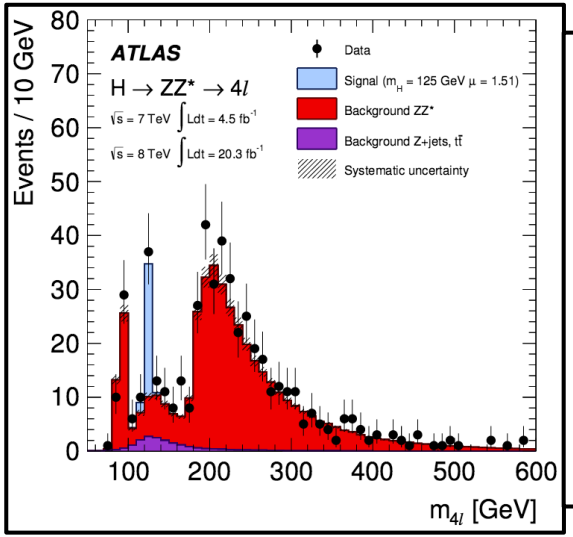

The $m_H$ range for all four searches extends up to 1000 GeV

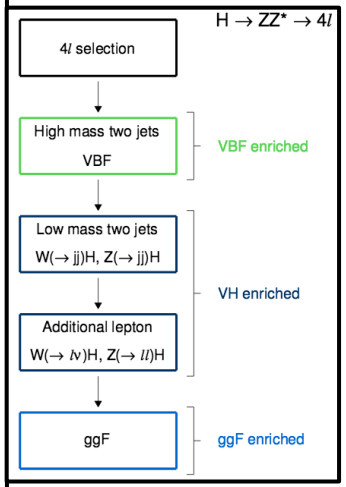
**The main ATLAS analyses in H→ZZ search are divided into four:**

- **H→ZZ→llll (*or* 4lep) analysis**
- **H→ZZ→llqq analysis**
- **H→ZZ→ll*νν* analysis**
- **H→ZZ→*νν*qq analysis**

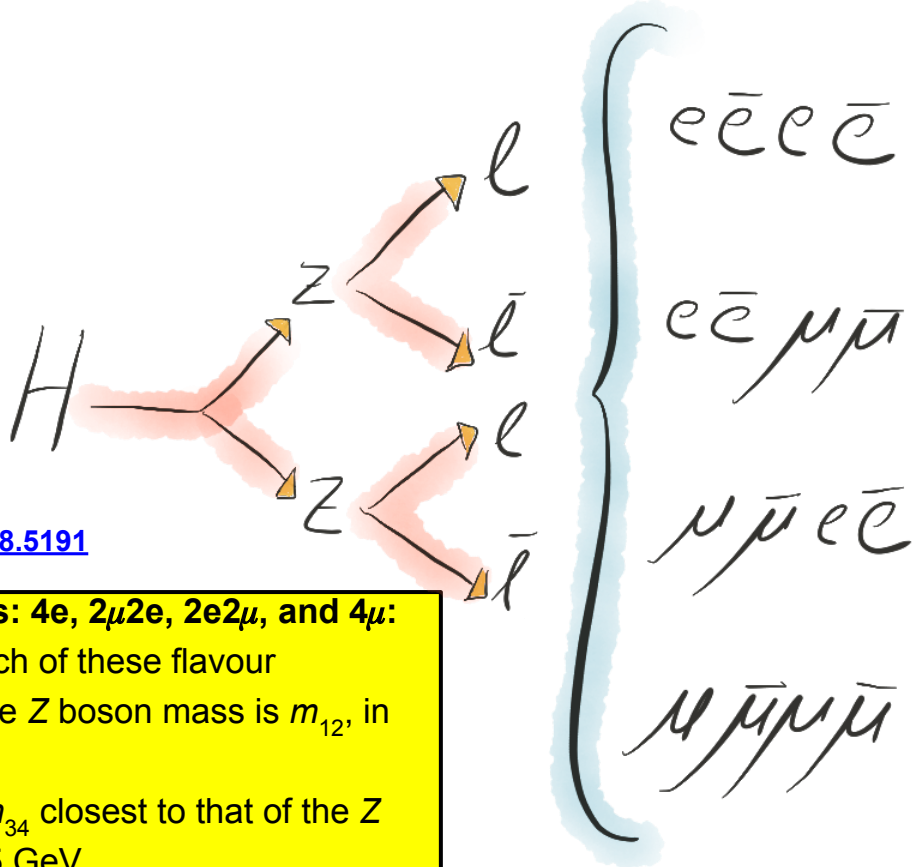
**In all of then, the Z bosons are requested to be real. Each of the analyses have sub-divisions or *channels:***

# Searches of heavy Higgs→ZZ→*llll*



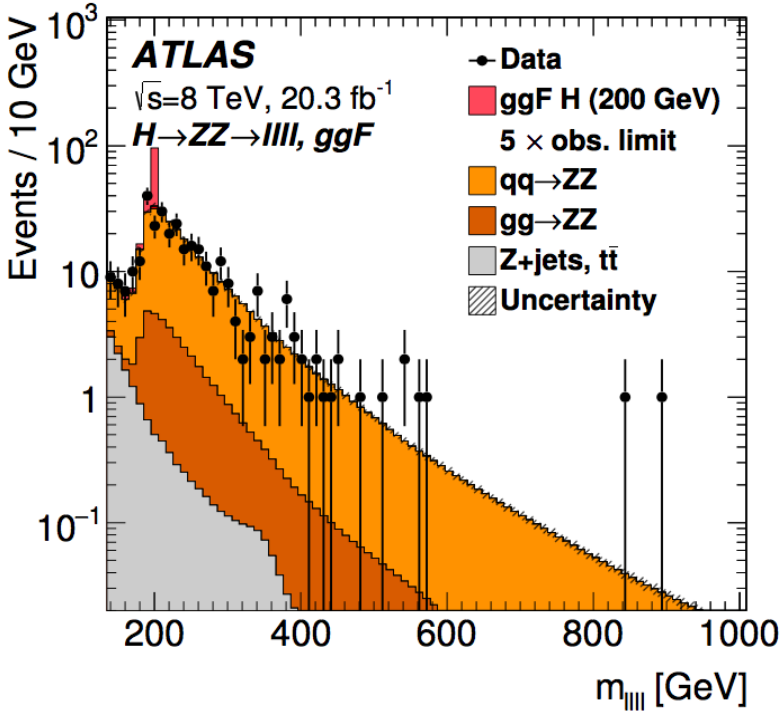

Ref: [http://arxiv.org/abs/1408.5191](http://arxiv.org/abs/1408.5191)



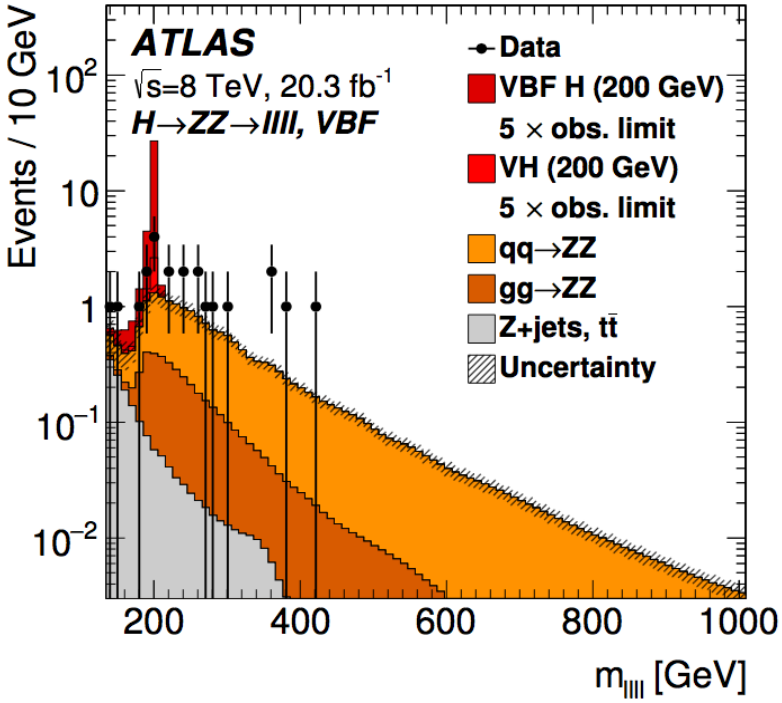

**The H→ZZ→llll analysis has been divided into 4 channels: 4e, 2μ2e, 2e2μ, and 4μ:**

- The selection of lepton pairs is made separately for each of these flavour combinations; the pair with invariant mass closest to the *Z* boson mass is $m_{12}$, in the range 50–106 GeV.
- The subleading, pair from the remaining leptons with $m_{34}$ closest to that of the *Z* boson in the range a $m_{min}$ (12 to 50 GeV) < *m*34 < 115 GeV.
- Is the only decay mode that includes the VH production mode, due to its relevant for Higgs masses < 200 GeV.

# Searches of heavy Higgs→ZZ→*llll*




(a) ggF




(b) VBF

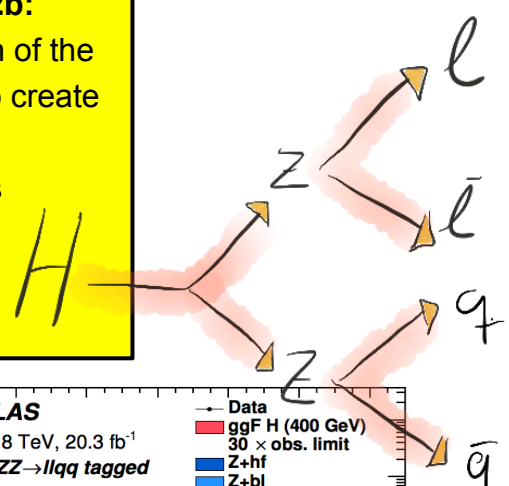
**Ref:** http://arxiv.org/abs/1408.5191

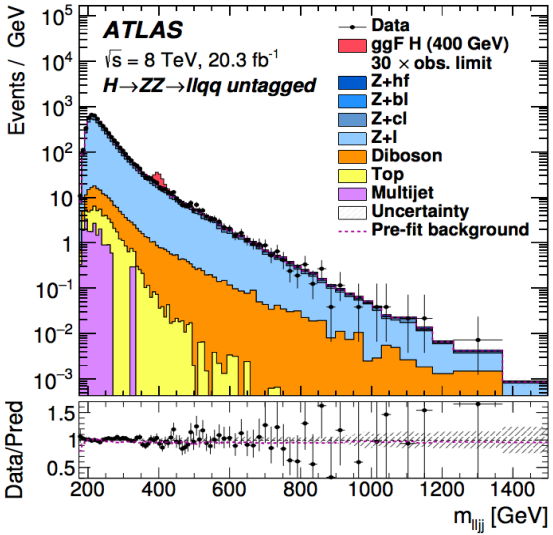
**The distributions used in the likelihood fit (*see results later on*) of the four-lepton invariant mass $m_{llll}$ for the $H \to ZZ \to l^+l^-l^+l^-$ search in the (a) ggF production mode and (b) VBF mode.**

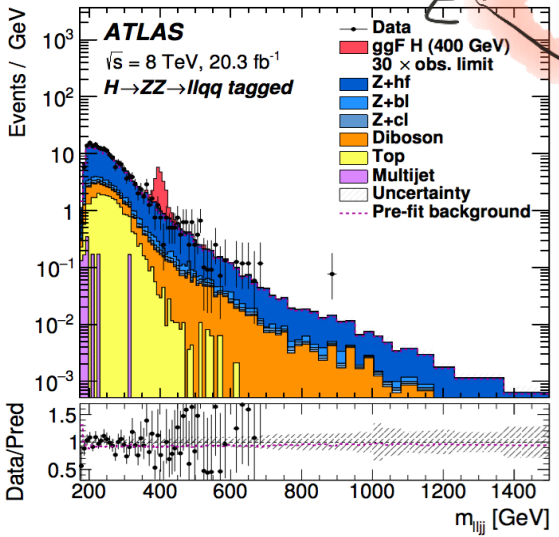
# Searches of heavy Higgs→ZZ→*llqq*

**The H→ZZ→llqq analysis has been divided into 4 channels for the ggF: 2e2j, 2$\mu$2j, 2e2b, and 2$\mu$2b:**

- In the case of the VBF the is not distinction of the jet flavour of those objects that are used to create the jj couple.
- Apart of the VBF, the **merged regime** was explored too: or Higgs masses >700 GeV looking for a single jet that containing the **Z→qq**




$e\bar{e}jj$

$\mu\bar{\mu}jj$

$e\bar{e}b\bar{b}$

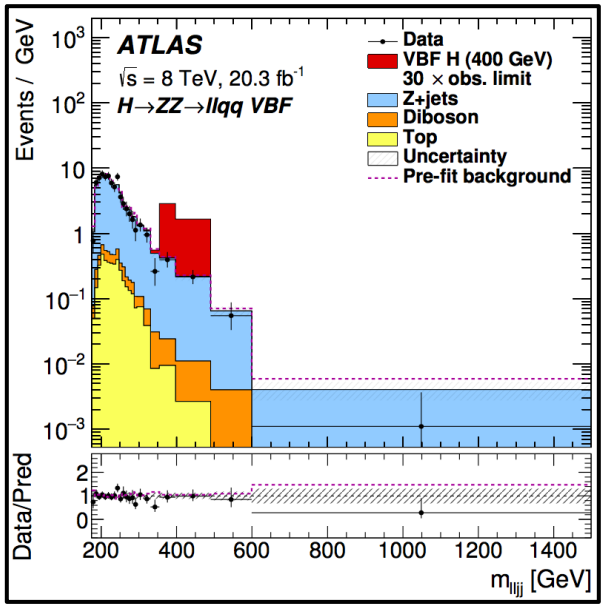
$\mu\bar{\mu}b\bar{b}$

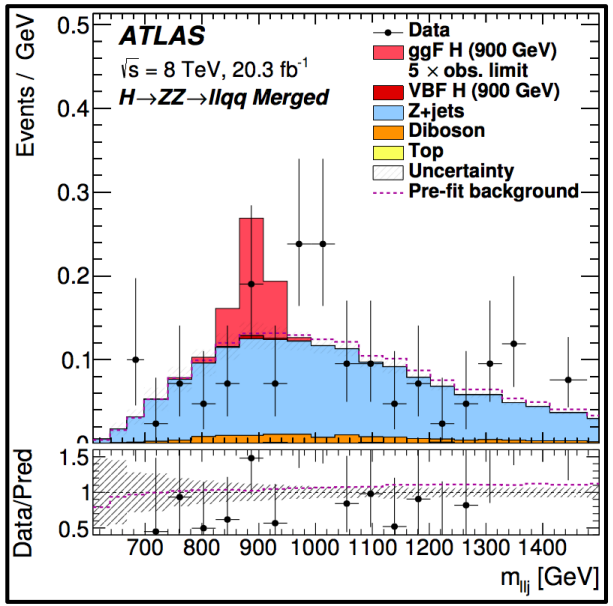
This is the so-called ***untagged*** channel, where the jet-couple contains < 2*b*-tagged jets

This is the so-called ***tagged*** channel, where the jet-couple contains exactly 2*b*-tagged jets

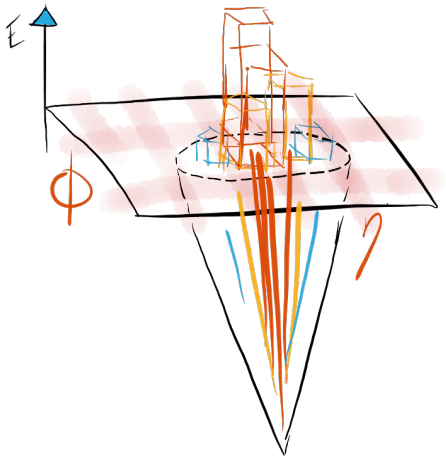
**Ref:** http://arxiv.org/abs/1408.5191

# Searches of heavy Higgs→ZZ→*llqq*




**The merged regime search to improve the sensitivity at very high masses looking for the Z boson into a single *small-R* jet** (not *quark-flavour* discriminate used)



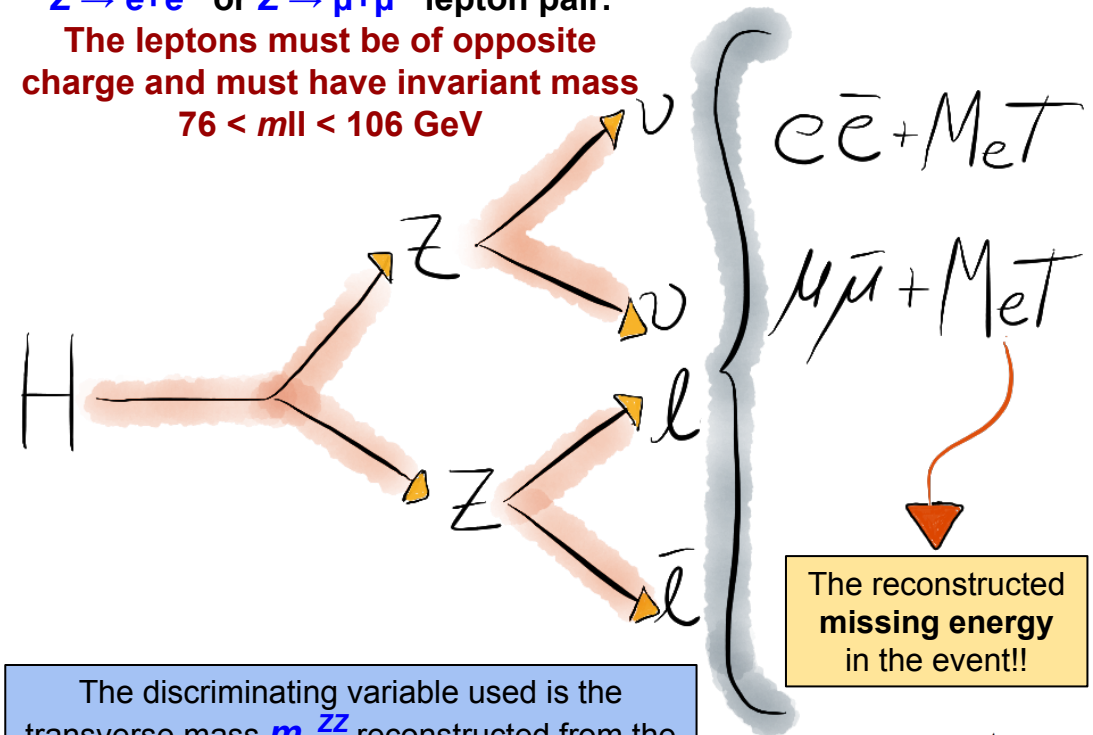
**Ref:** [http://arxiv.org/abs/1408.5191](http://arxiv.org/abs/1408.5191)

**The H→ZZ→llqq analysis has been divided into ggF and VBF production mechanism:**

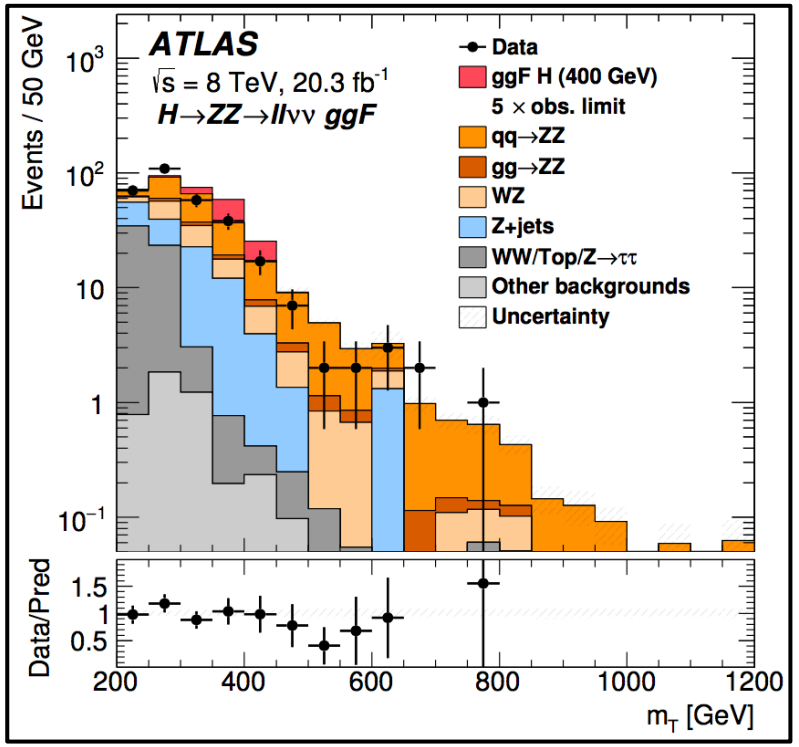
- In the case of the VBF the is not distinction of the jet flavour of those objects that are used to create the jj couple. Looking for 2 extra jets in the forward region (left).
- The **merged regime** is part of the ggF "collection" (right) And is a first view of the current Boosted region, uses for many analysis working with hadronic decays inside and outside the Higgs group into the ATLAS collaboration.

# Searches of heavy Higgs→ZZ→*llvv*

**The event selection for the $H \to ZZ \to l^+l^-\nu\bar{\nu}$ ($llvv$) search starts with the reconstruction of either a $Z \to e^+e^-$ or $Z \to \mu^+\mu^-$ lepton pair. The leptons must be of opposite charge and must have invariant mass $76 < m_{ll} < 106$ GeV**




The reconstructed **missing energy** in the event!!




**Ref:** http://arxiv.org/abs/1408.5191

The discriminating variable used is the transverse mass $m_T^{ZZ}$ reconstructed from the momentum of the dilepton system and the missing transverse momentum, defined by:

$$(m_{\mathrm{T}}^{ZZ})^2 \equiv \left( \sqrt{m_Z^2 + \left|p_{\mathrm{T}}^{\ell\ell}\right|^2} + \sqrt{m_Z^2 + \left|E_{\mathrm{T}}^{\mathrm{miss}}\right|^2} \right)^2 - \left| \vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{E}_{\mathrm{T}}^{\mathrm{miss}} \right|^2$$

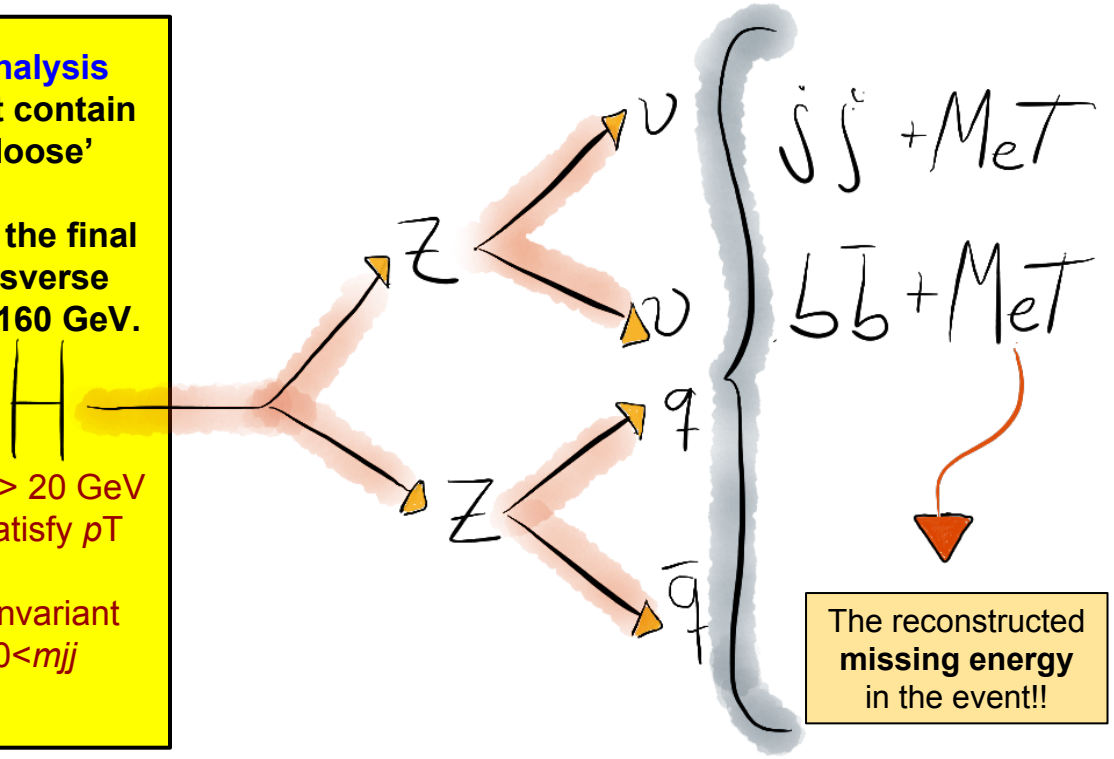
# Searches of heavy Higgs→ZZ→*vvqq*

**In the second of the *not leptons* analysis the events selected for this search must contain no electrons or muons in their defined 'loose' lepton selection of the *llqq* search.**

**To select events with neutrinos in the final state, the magnitude of the missing transverse momentum vector must satisfy $E_{T}^{miss}$ > 160 GeV.**

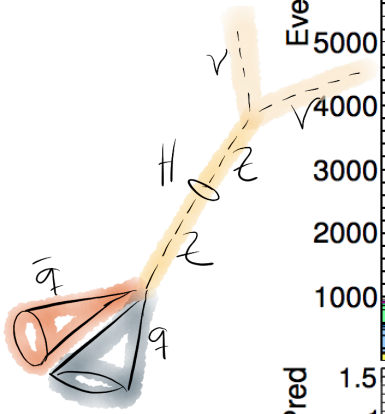
Events must have at least two jets with *p*T > 20 GeV and |η| < 2.5; the leading jet must further satisfy *p*T > 45 GeV.

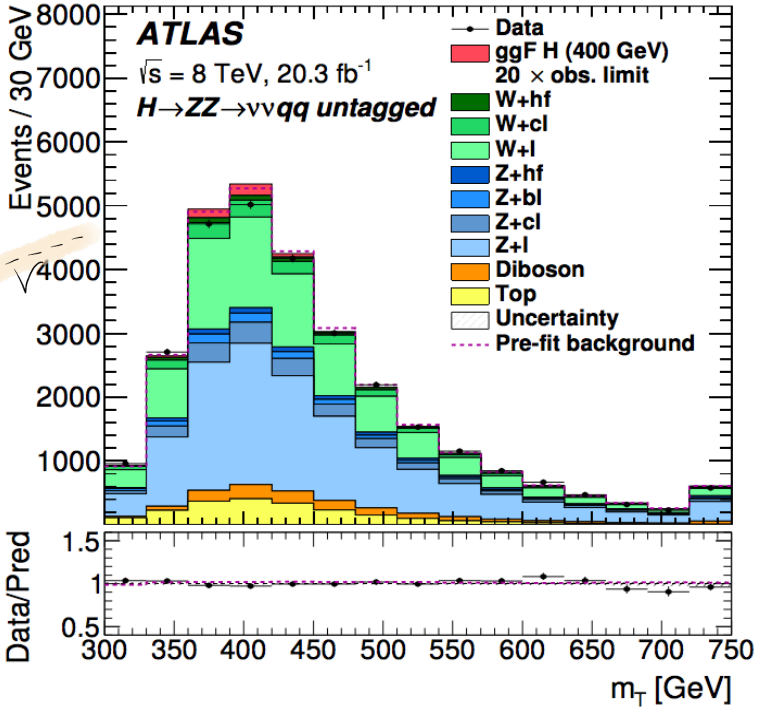
To select a candidate $Z \rightarrow q\bar{q}$ decay, the invariant mass of the leading two jets must satisfy 70<*mjj*<105 GeV.

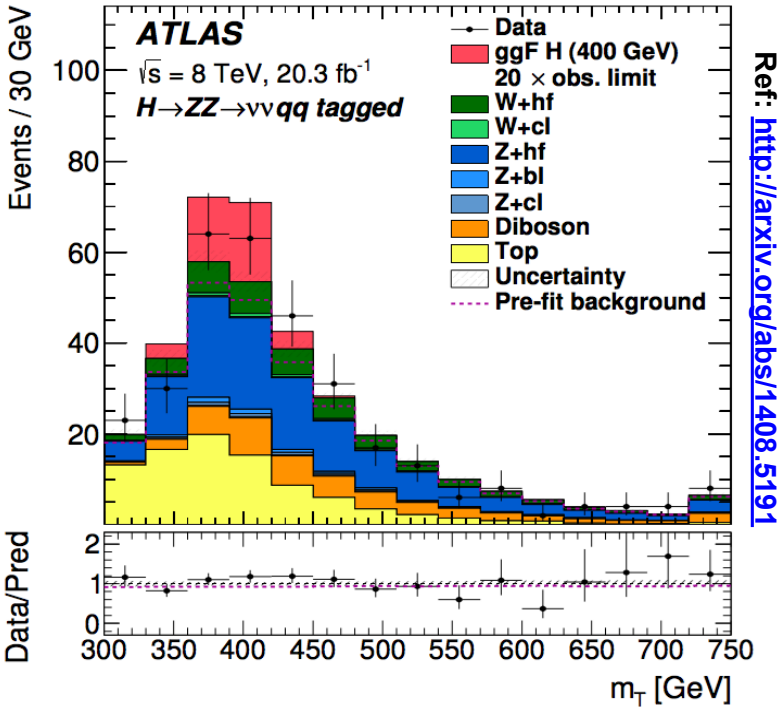



The discriminating variable used is the transverse mass $m_T^{ZZ}$ reconstructed from the momentum of the dilepton system and the missing transverse momentum, defined as in the slide before, but replacing the the leptonic Z decay for the **hadronic ($Z \rightarrow jj$)** one!

# Searches of heavy Higgs→ZZ→*vvqq*



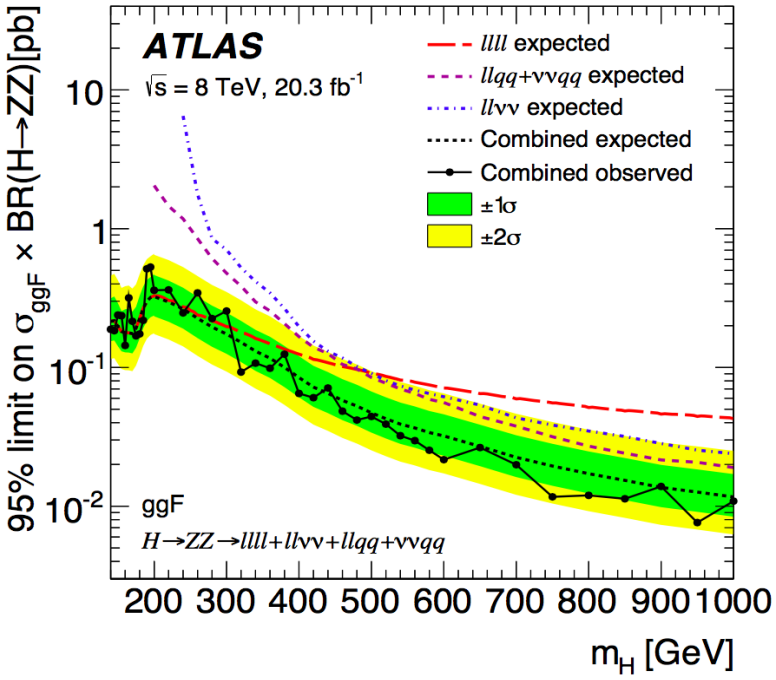


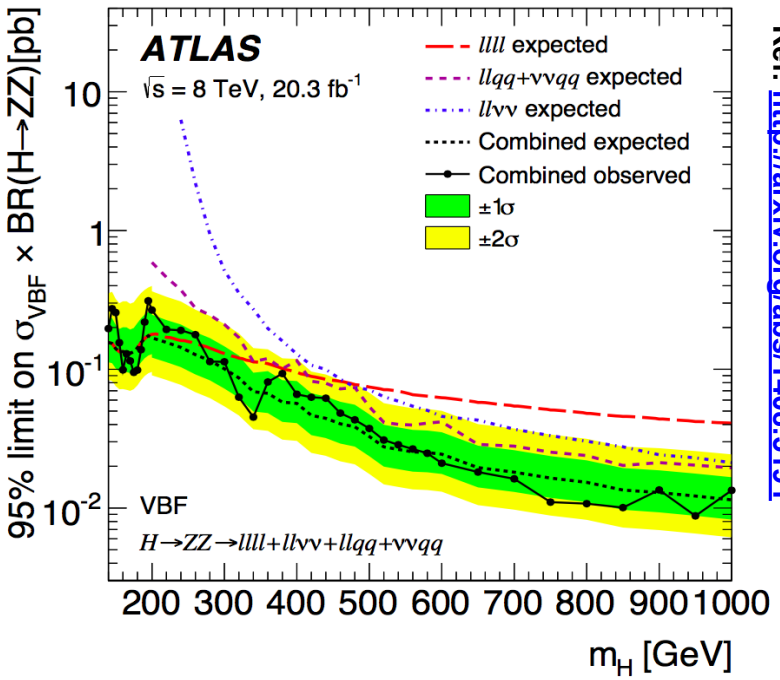




Ref: http://arxiv.org/abs/1408.5191

**The distributions of $m_T$, the transverse mass of the $Z(\nu\nu)Z(jj)$ system, used in the likelihood fit for the $H \rightarrow ZZ \rightarrow \nu\nu qq$ search in the untagged (left) and tagged (right) channels, for Higgs boson mass hypotheses of $m_H$ = 400 GeV.The dashed line shows the total background used as input to the fit for the results (next slide).** For this $m_H$ = 400 GeV hypothesis the simulated signal is normalized to a cross-section corresponding to twenty times the observed limit.

# **Run 1 Results:** Model independent

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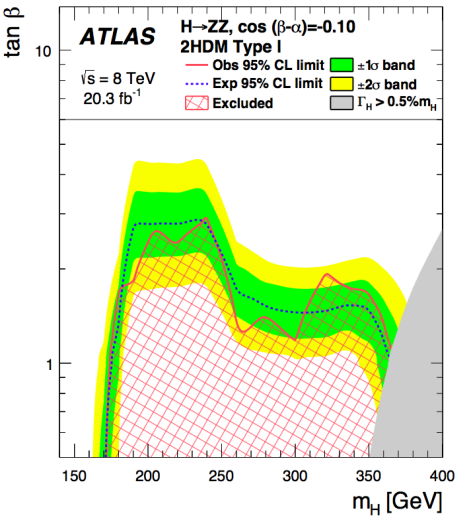
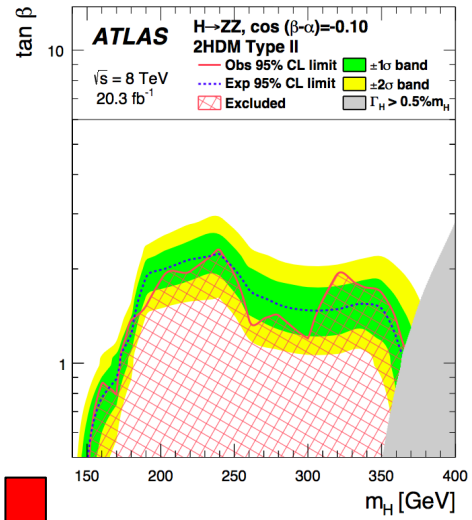
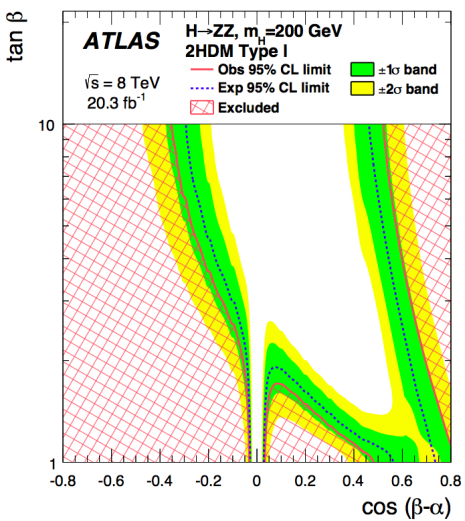
**Model independent (with narrow resonance):** 95% CL upper limits on σ × BR(***H → ZZ***) as a function of $m_H$, resulting from the combination of all of the searches in the **ggF** (left) and **VBF** (right) channels.

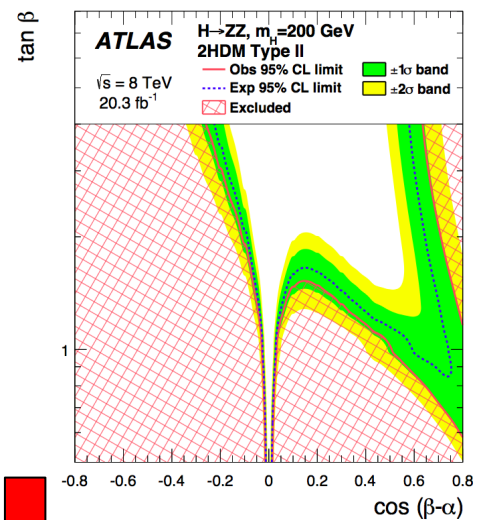
- The solid black line and points indicate the observed limit. The dashed black line indicates the expected limit and the bands the 1-σ and 2-σ uncertainty ranges about the expected limit.
- The dashed coloured lines indicate the expected limits obtained from the individual searches; for the ***llqq*** and ***vvqq*** searches, only the combination of the two is shown as they share control regions.

# **Run 1 Results:** Higgs→ZZ 2HDM




**Ref:** [http://arxiv.org/abs/1408.5191](http://arxiv.org/abs/1408.5191)

**95% CL exclusion contours in the 2HDM (left) Type-I and (right) Type-II models for cos(β − α) = −0.1, shown as a function of the heavy Higgs boson mass *mH* and the parameter tanβ.**

- The shaded area shows the observed exclusion, with the black line denoting the edge of the excluded region.
- The blue line represents the expected exclusion contour and the shaded bands the 1-σ and 2-σ uncertainties on the expectation.

**95% CL exclusion contours in the 2HDM (left) Type-I and (right) Type-II models for *mH* = 200 GeV, shown as a function of the parameters cos(β − α) and tan β.**

- The red hashed area shows the observed exclusion, with the solid red line denoting the edge of the excluded region.
- The dashed blue line represents the expected exclusion contour and the shaded bands the 1-σ and 2-σ uncertainties on the expectation.

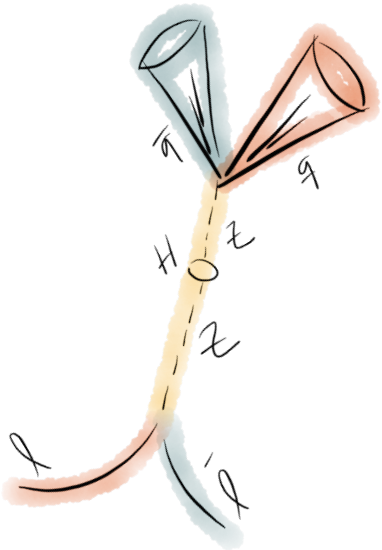
# Summary

**A search is presented for a high-mass Higgs boson in the $H \rightarrow ZZ \rightarrow llll$, $H \rightarrow ZZ \rightarrow ll\nu\bar{\nu}$, $H \rightarrow ZZ \rightarrow llq\bar{q}$, and $H \rightarrow ZZ \rightarrow \nu\bar{\nu}q\bar{q}$ decay modes using the ATLAS detector at the CERN Large Hadron Collider using the proton–proton collision data at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of 20.3 $fb^{-1}$:**

- The results of the search are interpreted in the scenario of a heavy Higgs boson with a width that is small compared with the experimental mass resolution. The Higgs boson mass range considered extends up to 1 TeV for all four decay modes and down to as low as 140 GeV, depending on the decay mode.

- **No significant excess of events over the Standard Model prediction is found. Limits on production and decay of a heavy Higgs boson to two *Z* bosons are set separately for gluon-fusion and vector-boson-fusion production modes.**

- For the combination of all decay modes, 95% CL upper limits range from 0.53 pb at $mH$ = 195 GeV to 0.008 pb at $mH$ = 950 GeV for the gluon-fusion production mode and from 0.31 pb at $mH$ = 195 GeV to 0.009 pb at $mH$ = 950 GeV for the vector-boson-fusion production mode.



# Summary

- **The results are also interpreted in the context of Type-I and Type-II two-Higgs-doublet models**:
  - With exclusion contours given in the $\cos(\beta - \alpha)$ versus $\tan\beta$ and $m_H$ versus $\tan\beta$ planes for $m_H$ = 200 GeV.
  - This $m_H$ value is chosen so that the assumption of a narrow-width Higgs boson is valid over most of the parameter space.
  - The two-Higgs-doublet model exclusion presented here is considerably more stringent for Type-I with $\cos(\beta - \alpha) < 2$ and $0.5 < \tan\beta < 2$, and for Type-II with $0.5 < \tan\beta < 2$

- **The Run 2 is now ongoing and the different analysis are sharing this the beginning all the possible common tools and selections in order to perform a coherent search and fast but significant combination of the different channels.**
- **Some of the key tools are relative to the implementation of the boosted regime for the cases of analysis using Jets, since this is already increasing the sensitivity for high and very high masses.**
- **At this moment the efforts are focus in perform similar analysis like those in Run1 and adding the most recent techniques and better performance in order to obtain better objects to be use in the reconstruction of the possible new Particle.**