# Search for the High-Mass Standard Model Higgs Boson with the ATLAS Detector

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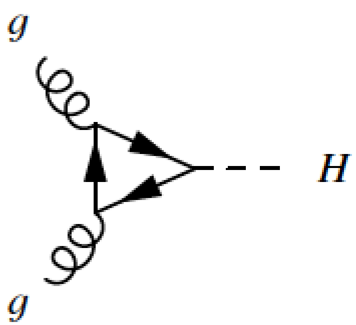
**on behalf of the**
***ATLAS* collaboration**

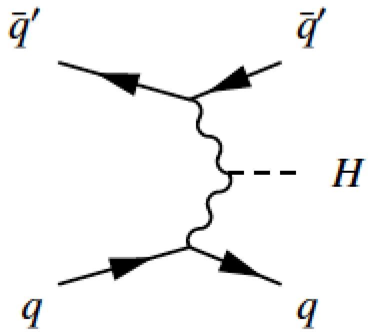
**SEARCH 2012 Workshop**
**17/03/2012**

# Introduction

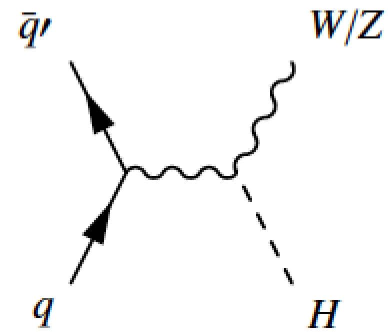
**gluon gluon fusion (ggF)**



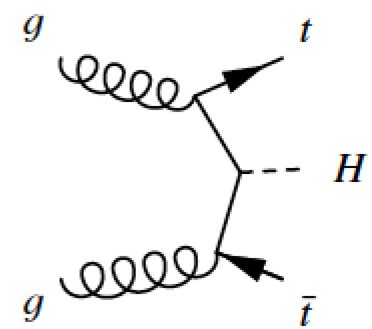

**vector boson fusion (VBF)**

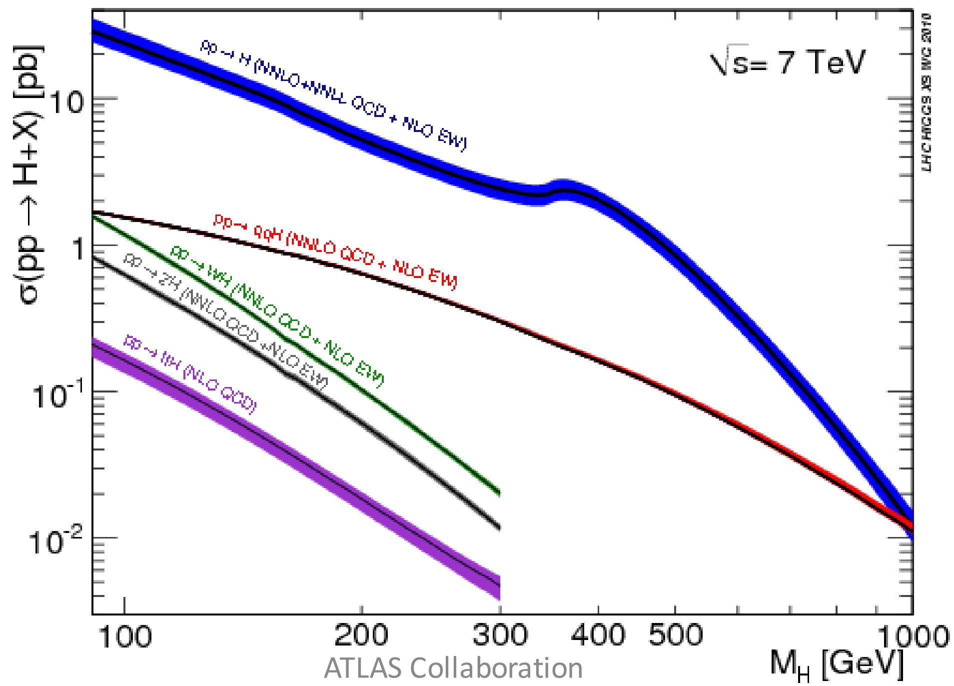



**associated production with W/Z**




**associated production With ttbar**






https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

# Introduction

## SM High Higgs masses?

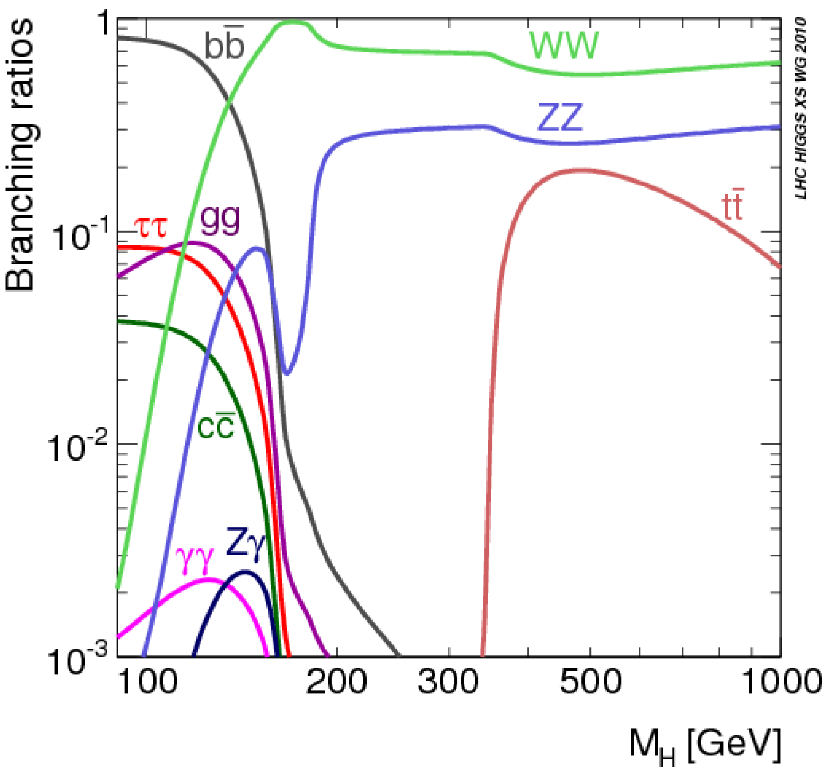
- For some reason (!), people tend to focus on low-mass Higgs searches these days... ;-)

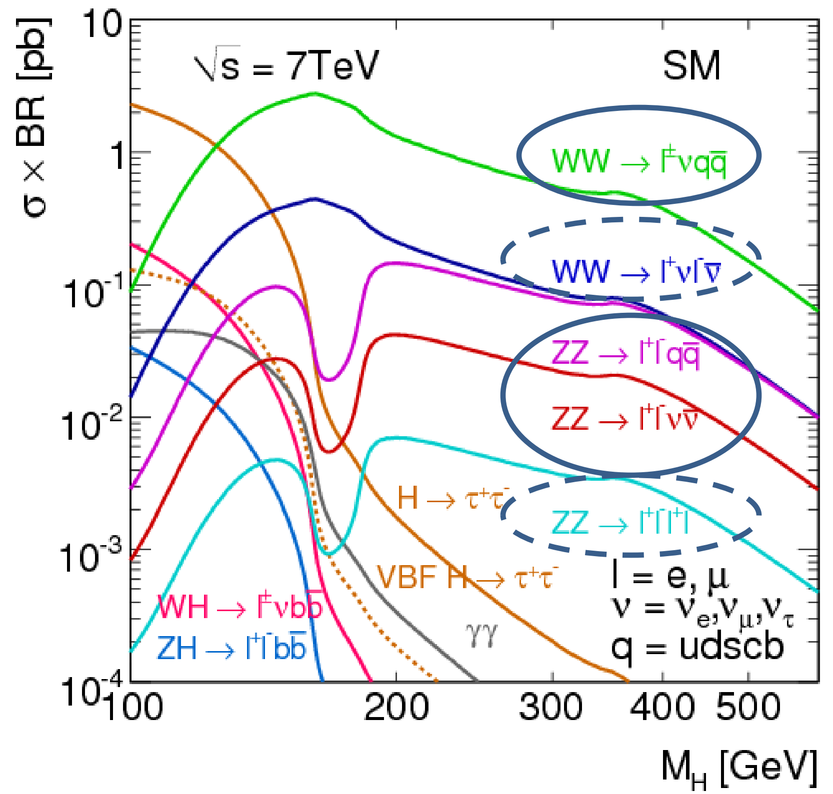
- **We have to not forget to look at the high-mass region!**

- *The region above 600 GeV is still an unexplored territory!*

# Introduction

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections




In this talk:

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

$$H \to ZZ \to ll\nu\nu$$

$$H \to ZZ \to llqq$$

In Bertrand Brelier's talk:

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

$$H \to ZZ \to llll$$

# Some Generalities

## Signal MC

- We use PowHeg + Pythia for ggF and VBF
- Higgs $p_T$ is reweighted (QCD corrections/QCD soft gluon resummations -using HqT 2.0)
- Typical uncertainty on signal production cross-section :

  -15-20% ggF

  - 3-9% VBF
- Uncertainty on the cross section to cover the Higgs line shape and SM background interference uncertainties (applied only for $m_H$ > 300 GeV): $1.5 \times (m_H)^3$

## Limit Extraction :

- We use Profile likelihood ratio to test $\mu=\sigma/\sigma_{SM}$ (Eur.Phys.J.C71:1554,2011)
- Exclusion limits on $\mu$ are set at a 95% CL using the $CL_s$ method (J. Phys. G 28 (2002) 2693-2704)

# $H \rightarrow WW \rightarrow l\nu qq$: 300-600 GeV

# $H \to WW \to l\nu qq$ 300-600

## Interesting at High masses:

- High decay branching fraction, reasonable background (W+jets)
- W energetic enough to be adequately reconstructed
- Presence of $E_t^{miss}$ in signal
- Can fully reconstruct the Higgs' mass.

## What's new this winter?

- Updated to full 2011 dataset (4.7 $fb^{-1}$)
- Added specific VBF search
- ATLAS-CONF-2012-018

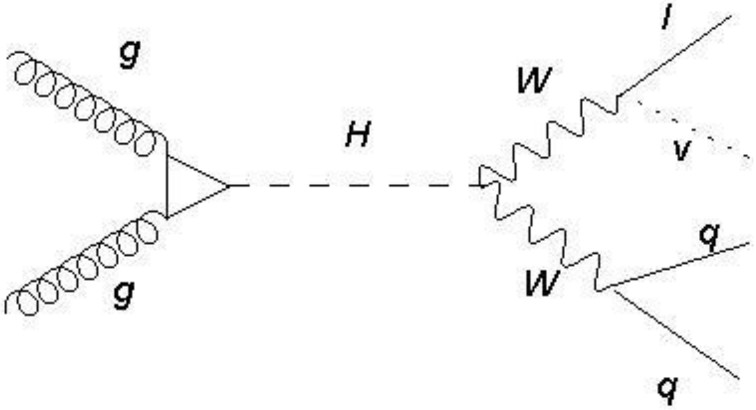
## Previous public results:

Phys.Rev.Lett. 107 (2011) 231801 (1.04 $fb^{-1}$)

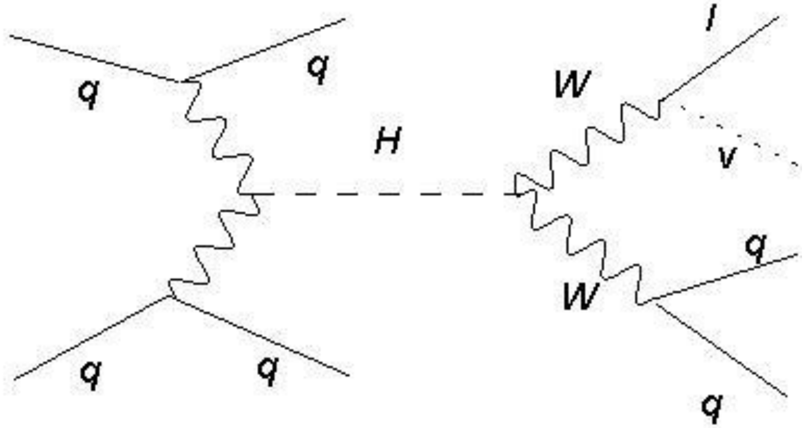
# $H \to WW \to l\nu qq$ 300-600

## Feynman Diagrams

gluon gluon fusion




vector boson fusion



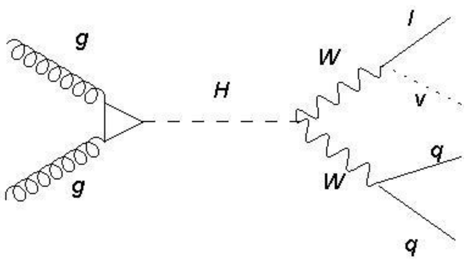

## Analysis Method

- Channels:
  - -H + 0 or 1 jets (**ggF**) and H+2jets (**VBF**)
  - -Electrons and muons
- Fit the $m_{WW} = m_{l\nu jj}$ (Higgs) shape

# H→WW→lνqq 300-600

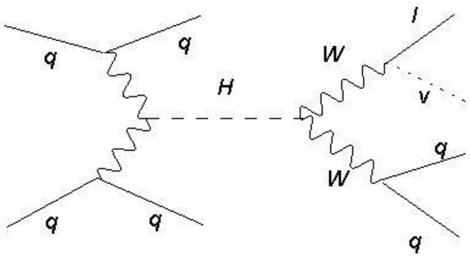
## Selections

**gluon gluon fusion: H + 0 or 1 jet**




- Exactly 1 lepton with $p_T > 40$ GeV
- $E_T^{miss} > 40$ GeV *(presence of neutrino)*
- 2 or 3 jets
- 2 closest jet to W mass with $71 < m_{jj} < 91$ GeV
- Most energetic jet $E_T > 60$ GeV
- No b-tag jets *(top background)*
- $\Delta R_{jj} < 1.3$ *(W + jet background)*
- $\Delta R_{lnu} < 1.3$

**vector boson fusion: H + 2 jets**




- Exactly 1 lepton with $p_T > 30$ GeV
- $E_T^{miss} > 30$ GeV *(presence of neutrino)*
- At least 4 jets
- 2 closest jet to W mass with $71 < m_{jj} < 91$ GeV
- 2 other jets *(VBF tag jets)*
  - $\eta_1 * \eta_2 < 0$ *(opposite hemispheres)*
  - $\Delta\eta > 3$ *(well separated in pseudo-rapidity)*
  - $m_{jj} > 600$ GeV
- No more jets with $|\eta| < 3.2$
- Lepton between the 2 tag jets in $\eta$
- No b-tag jets

# $H \rightarrow WW \rightarrow l\nu qq$ 300-600

## Main Background processes

- **W + jets (main)**
- Z + jets
- Multijets from QCD
- top
- dibosons (WW, WZ, ZZ)

- ***MC to motivate shape functions***
- ***Data control samples used to validate background fit.***

*•MC & Data-driven method are used to understand the background composition.*

## Fit the $M_{l\nu jj}$ shape

Background

*•H + 0 or 1 jet channel:*

$$f(x) = \frac{1}{1 + |a(x-m)|^b} e^{-c(x-200)}$$

where x is the WW invariant mass in GeV

*•H + 2 jets channel:* **sum of two exponential functions**

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Signal

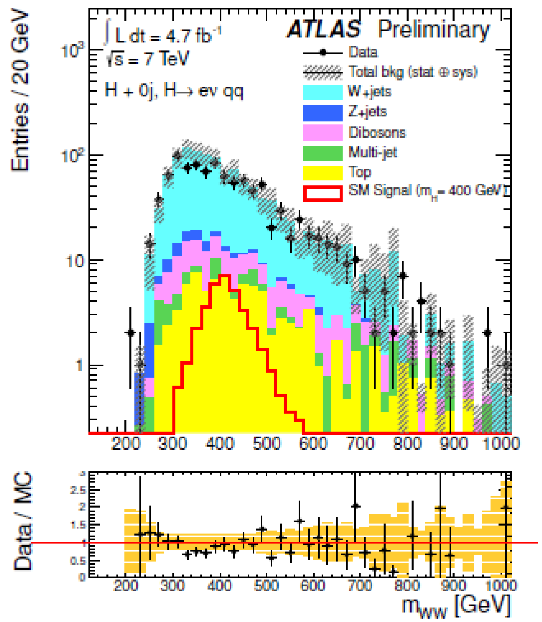
$$f(x) = \frac{1}{a + (x-m_1)^2 + b(x-m_2)^4}$$

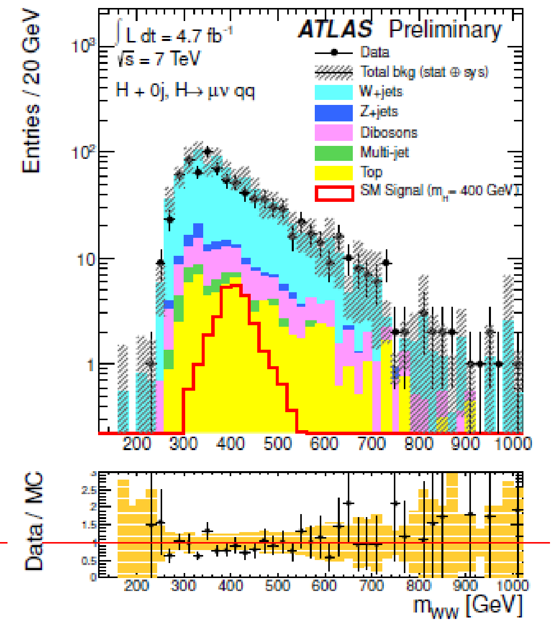
[*using constraint* $m_{l\nu}=m_W$]

# H→WW→lνqq 300-600

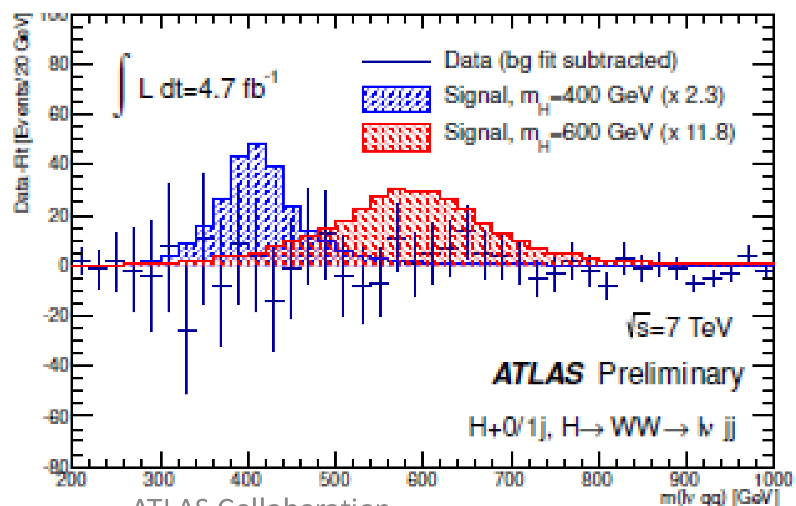
## Results

ggF H + 0 jet



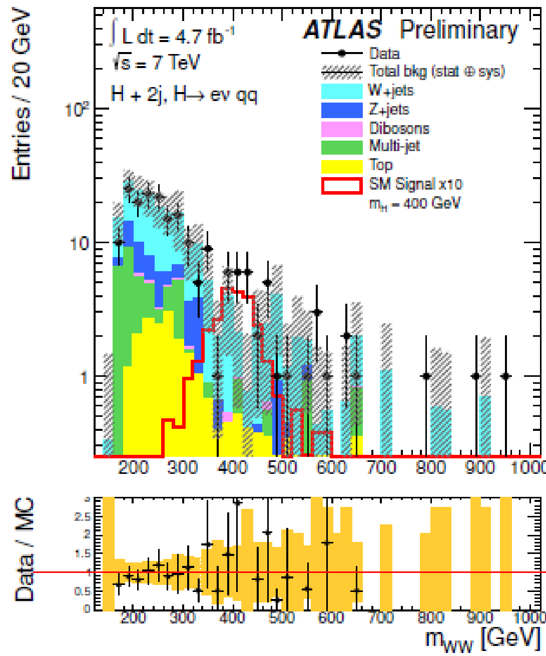

ggF H + 0 or 1 jet

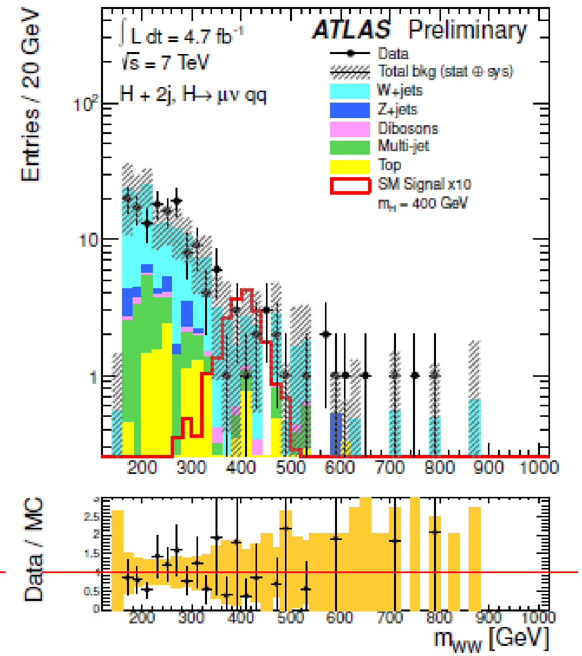


# H→WW→lνqq 300-600

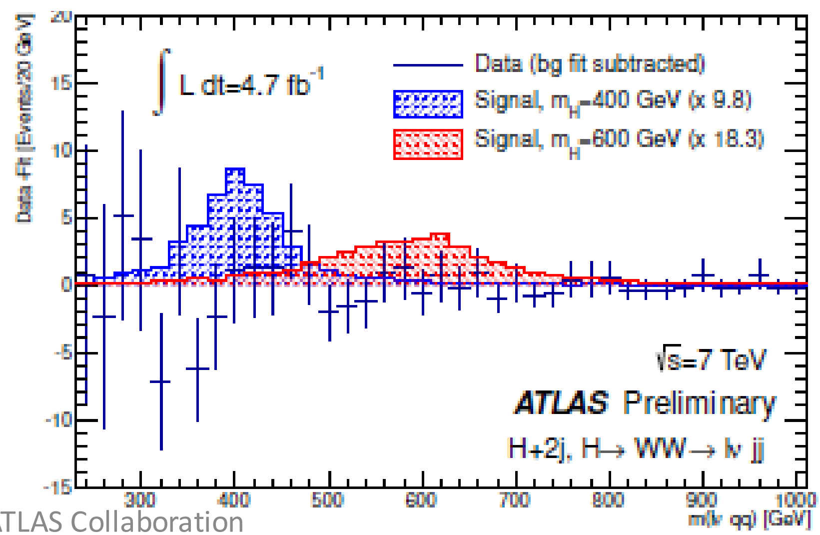
## Results

**VBF H + 2 jets**



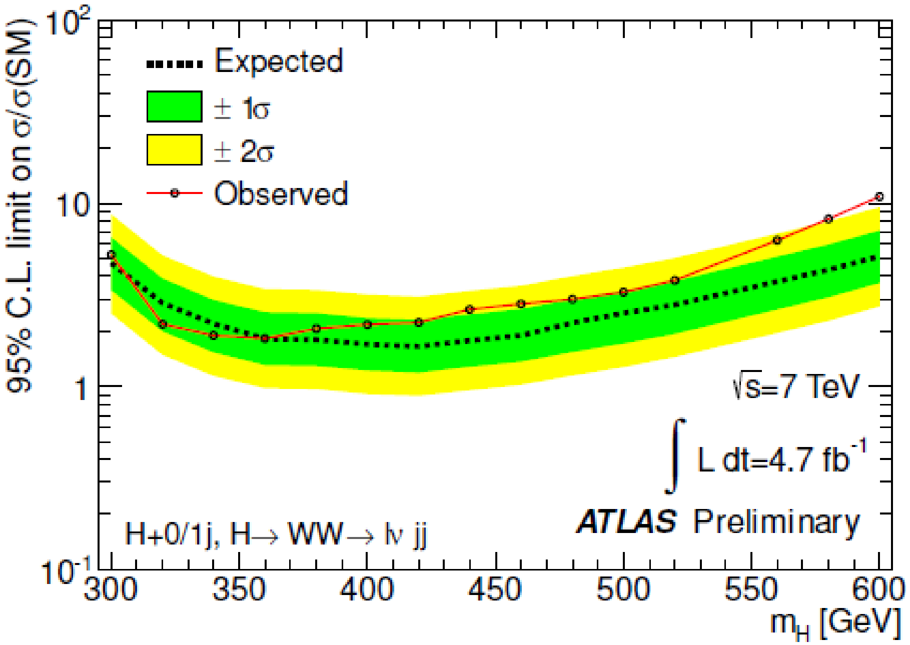



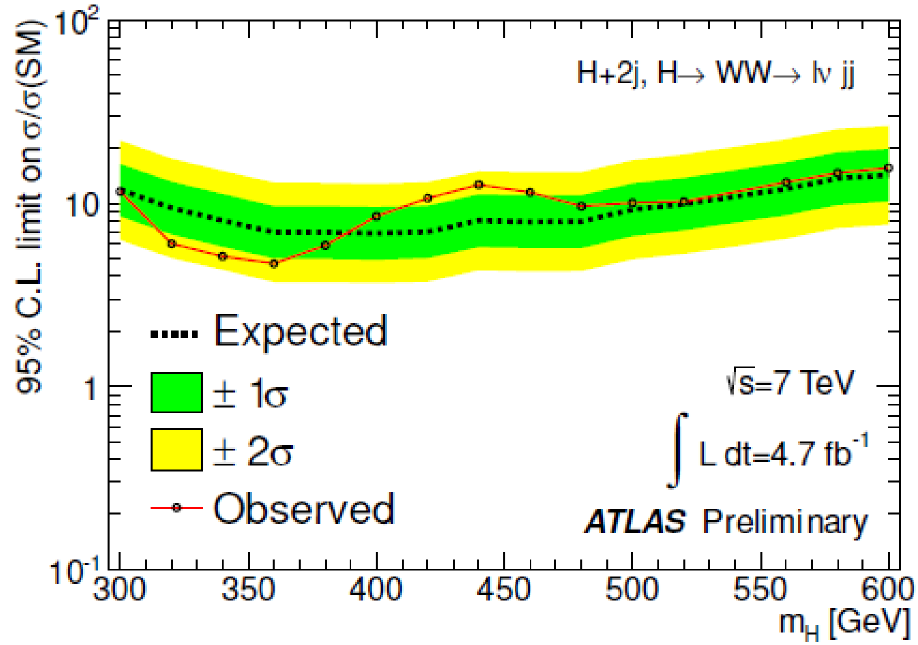

**VBF H + 2 jets**



# H→WW→lνqq 300-600

## Results




**ggF**, for mH = 400 GeV:

**Upper bound at 2.2 times the SM cross-section**

*(expected if no SM signal: 1.7)*

**VBF**, for mH = 400 GeV :

**Upper bound at 8.5 times the SM cross-section**

*(expected if no SM signal: 6.9)*

# $H \to ZZ \to llqq$: 200-600 GeV

# H→ZZ→llqq: 200-600 GeV

## Interesting at High masses:

- Cross-section & branching ratios important
- Have to deal with high Z+jets background

## What's new this winter?

- Updated to full 2011 dataset (4.7 $fb^{-1}$)
- Improved b-tagging
- ATLAS-CONF-2012-017

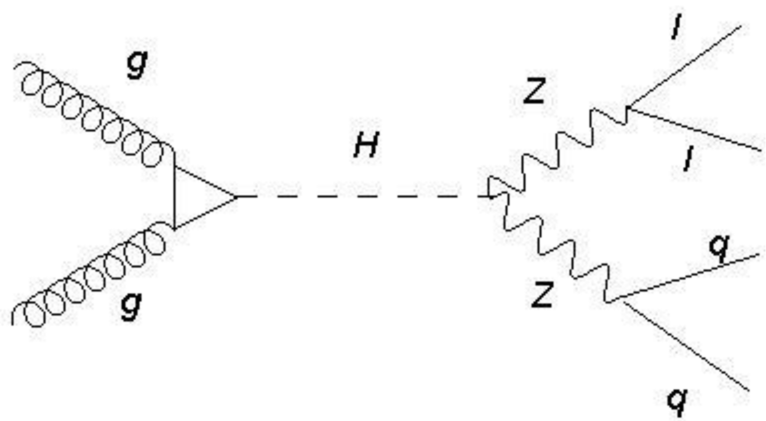
## Previous public results:

- ATLAS-CONF-2011-026 (35$pb^{-1}$)
- Phys.Lett.B 707 (2012) 27-45 (1.04 $fb^{-1}$)
- ATLAS-CONF-2011-150 (2.05 $fb^{-1}$ )

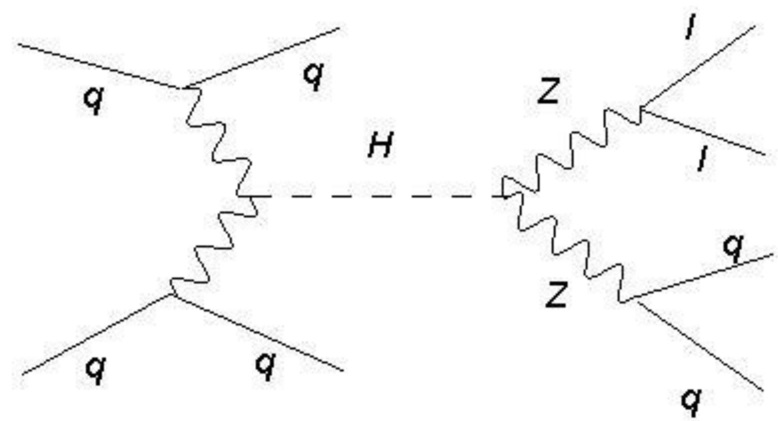
# $H \to ZZ \to llqq$: 200-600 GeV

## Feynman Diagrams

gluon gluon fusion




vector boson fusion

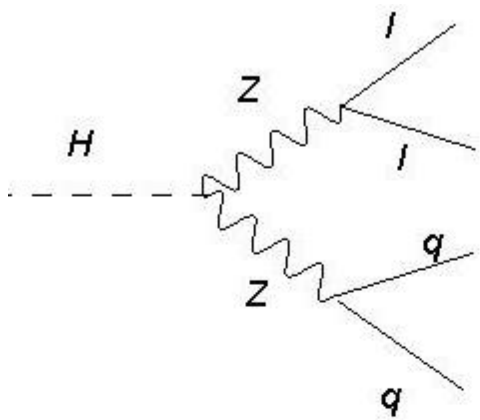



## Analysis Method

- Channels:
  - low mass (< 300 GeV), high mass (≥ 300 GeV)
  - “tagged” (2 b-tags) and “untagged”(<2b-tags)
- Use the $m_{lljj}$ shape

# $H \to ZZ \to llqq$: 200-600 GeV

## Selections



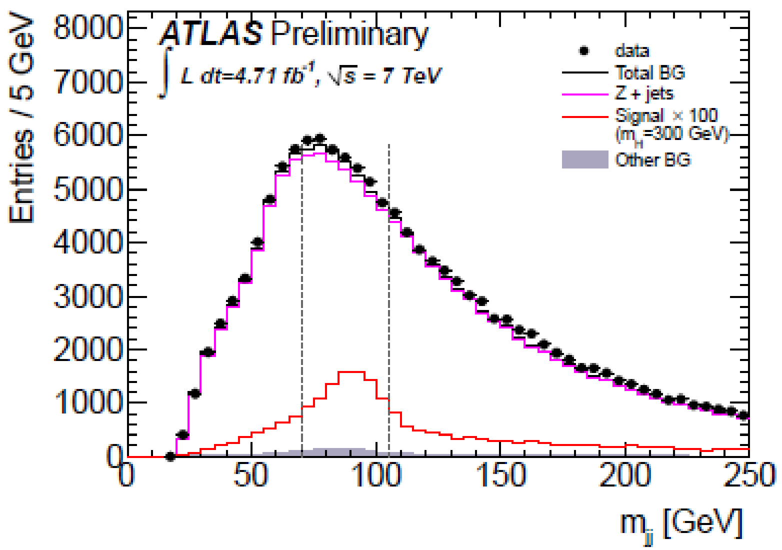

- Exactly 2 leptons with $83 < m_{ll} < 99$ GeV *(compatible with the Z decay)*
- $E_T^{miss} < 50$ GeV *(no neutrino, reduces top background)*
- At least 2 jets with $70 < m_{jj} < 105$ GeV , $\Delta R_{jj} > 0.7$ *(compatible with Z decay)*
- For $m_H \geq 300$: $p_T$ jet > 45 GeV, $\Delta\phi_{ll} < \pi/2$ and $\Delta\phi_{jj} < \pi/2$ *(boosted leptons)*
- Constrain $m_{jj}$ to $m_Z$ when setting the limits

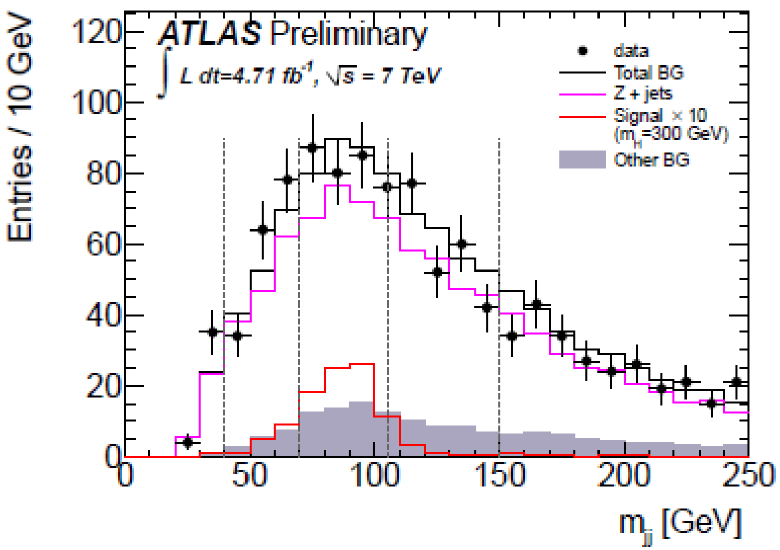
# $H \rightarrow ZZ \rightarrow llqq$: 200-600 GeV

- **Main Background processes**
  - **Z + jets**
  - top
  - dibosons (WW, WZ, ZZ)

- *Background shapes taken from MC predictions. Various data control samples are used to validate/normalize the MC behavior where needed.*
  - $-m_{jj}$ sidebands (Z+jets)
  - $-m_{ll}$ sidebands and $E_T$Miss reversed (top)
- *data only:* Electron ID relaxed (QCD)
- *dibosons uses MC predictions*

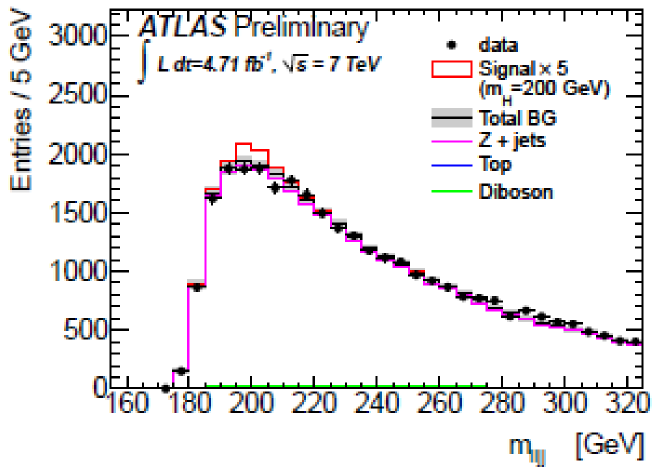
*$m_{jj}$ distributions (before the $m_{jj}$ requirement)*



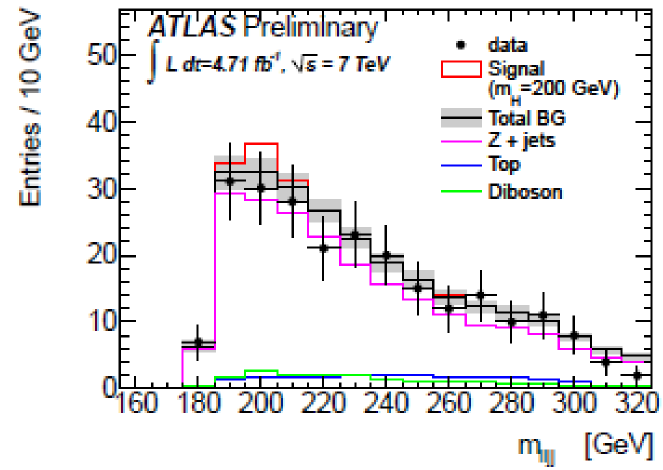



# H→ZZ→llqq: 200-600 GeV

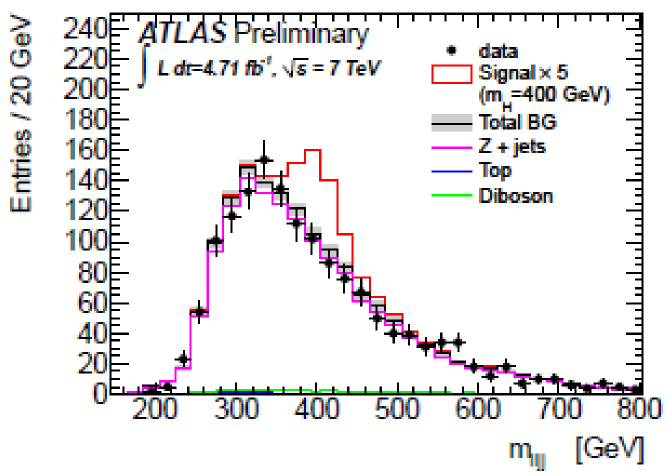
## Results



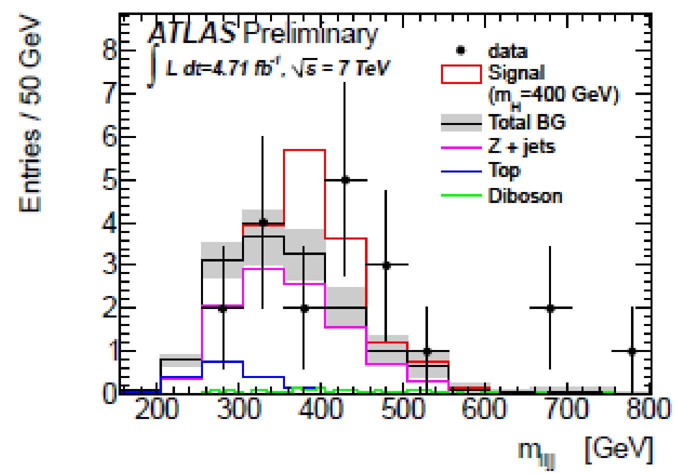

(a) Low-$m_H$, untagged selection.




(b) Low-$m_H$, tagged selection.



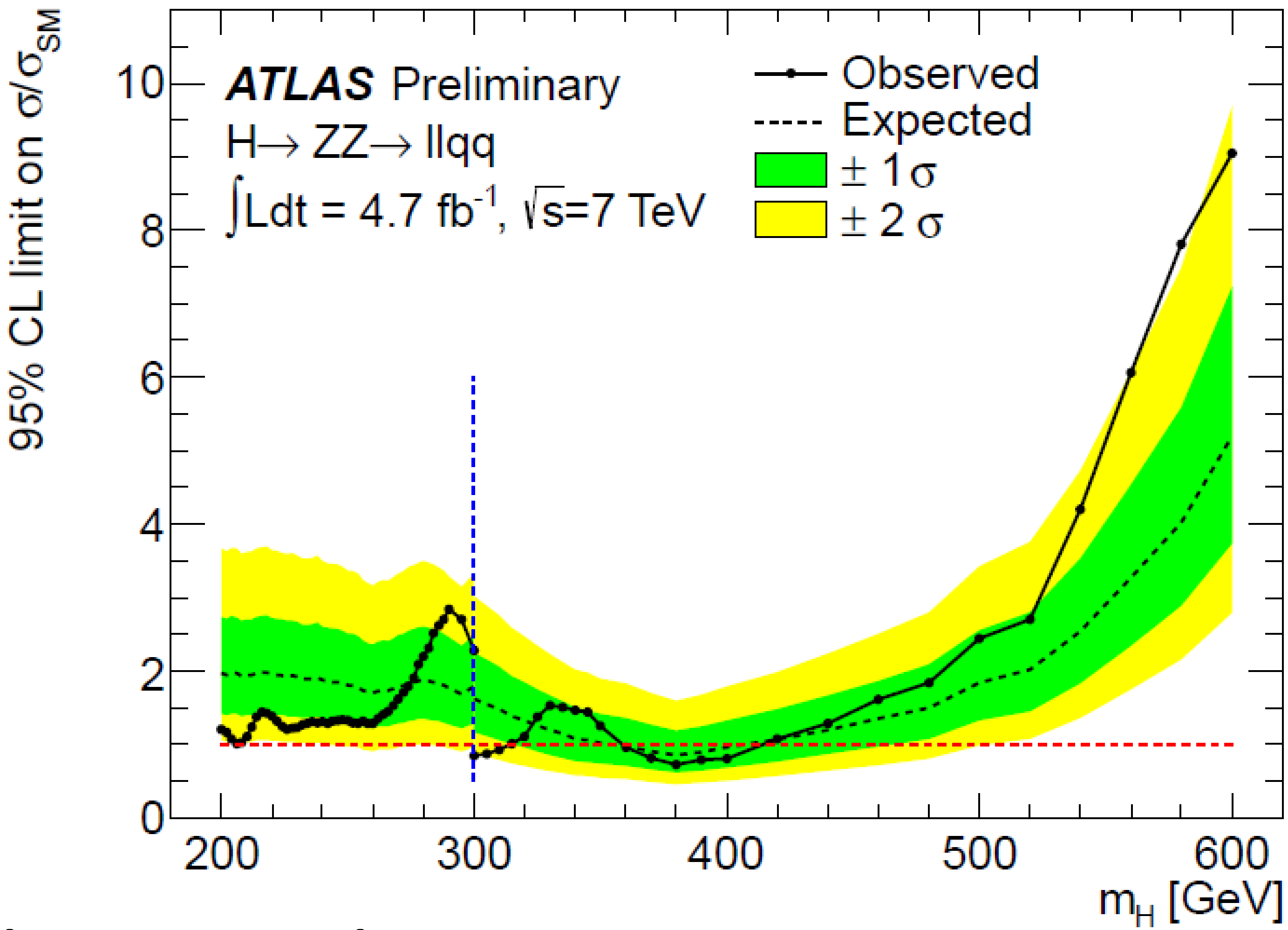

(c) High-$m_H$, untagged selection.




(d) High-$m_H$, tagged selection.

# H→ZZ→llqq: 200-600 GeV

## Results




**95%CL Excluded: 300-310 and 360-400 GeV**

Expected to be excluded if no SM signal: 360-400 GeV

# $H \rightarrow ZZ \rightarrow ll\nu\nu$: 200-600 GeV

# $H \rightarrow ZZ \rightarrow ll\nu\nu$: 200-600 GeV

## Most sensitive channel at high mass

- Fairly high cross-sections and branching fractions
- Good background rejection (high lepton $p_T$, high $E_T^{miss}$)

## What's new this winter?

- Updated to full 2011 dataset (4.7 $fb^{-1}$)
- Improved b-tagging, z+jet background rejection under high pile-up conditions
- ATLAS-CONF-2012-016

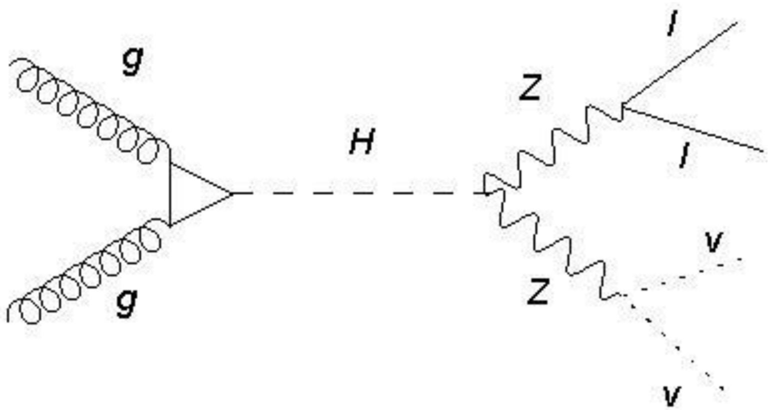
## Previous public results:

- ATLAS-CONF-2011-026 (35$pb^{-1}$)
- Phys. Rev. Lett. 107 (2011 ) 221802 (1.04 $pb^{-1}$)
- ATLAS-CONF-2011-148 (2.05$fb^{-1}$)

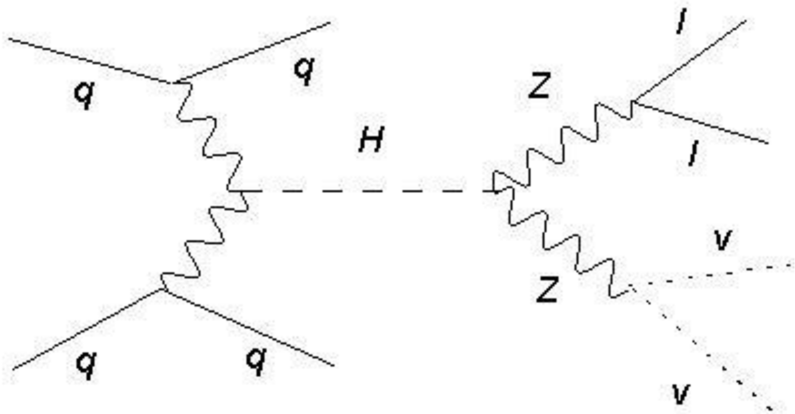
# H→ZZ→llνν: 200-600 GeV

## Feynman Diagrams

gluon gluon fusion




vector boson fusion

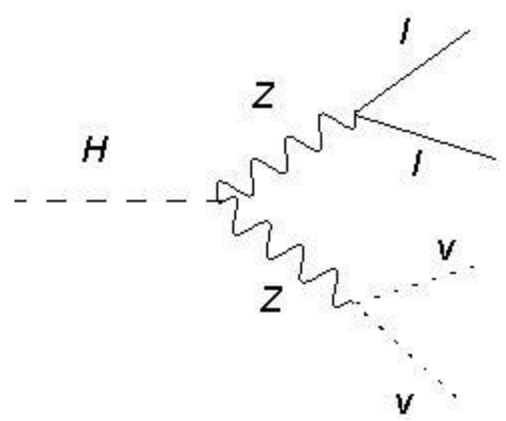



## Analysis Method

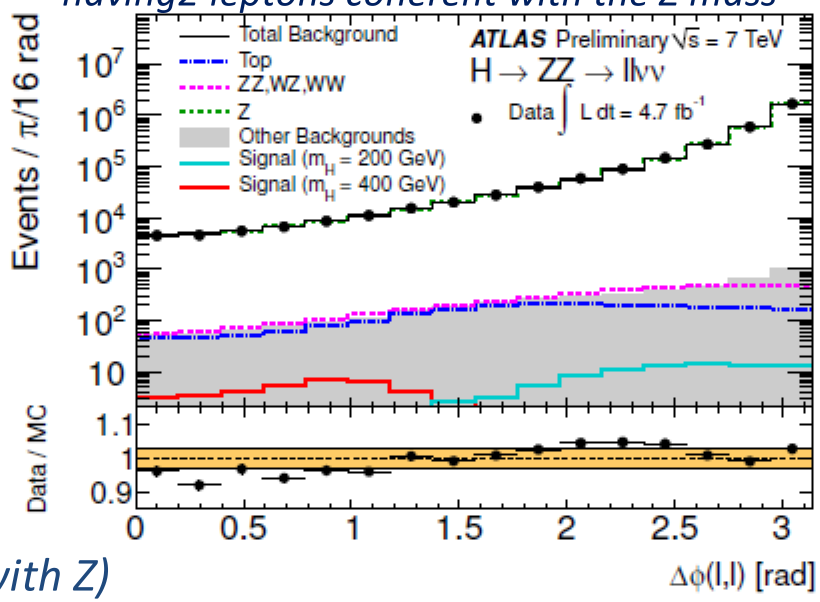
- Channels:
  - low mass (< 280 GeV), high mass (≥ 280 GeV)
  - low pile-up, high pile-up conditions
  - Electrons and muons
- Use the $m_T$ shape $$m_T^2 \equiv \left[\sqrt{m_Z^2 + |\vec{p}_T^{\,\ell\ell}|^2} + \sqrt{m_Z^2 + |\vec{p}_T^{\,\mathrm{miss}}|^2}\right]^2 - \left[\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,\mathrm{miss}}\right]^2$$

# $H \to ZZ \to ll\nu\nu$: 200-600 GeV

## Selections




*Azimuthal separation between leptons for events having2 leptons coherent with the Z mass*




- Exactly 2 leptons, $|m_{ll} - m_Z| < 15$ GeV *(coherent with Z)*
- No b-tag jets *(against top background)*

| | **for $m_H < 280$GeV** | **for $m_H \geq 280$GeV** |
|---|---|---|
| *Presence of neutrinos* | $E_T^{miss} > 66$ GeV | $E_T^{miss} > 82$ GeV |
| *Boosted Z* | $1 < \Delta\phi_{ll} < 2.64$ | $\Delta\phi_{ll} < 2.25$ |
| *Zs back to back* | - | $\Delta\phi_{p_T ll, p_T Miss} \geq 1$ |
| *Background with fake $E_T^{miss}$* | $\Delta\phi_{jet, p_T Miss} > 1.5$ | $\Delta\phi_{jet, p_T Miss} > 0.5$ |

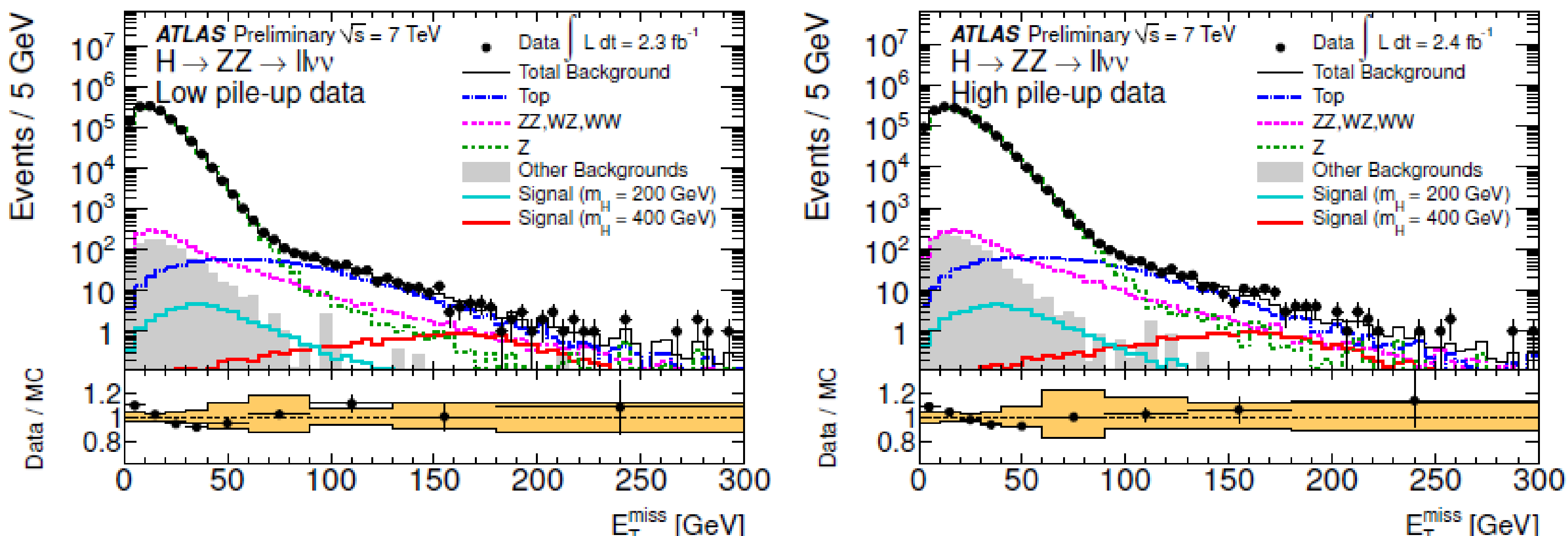
# $H \rightarrow ZZ \rightarrow ll\nu\nu$: 200-600 GeV

**Main Background processes**

- Z + jets
- top
- dibosons (WW, WZ, ZZ)

- *Background shapes taken from MC predictions. Various data control samples are used to validate/normalize the MC behavior where needed.*
  - 3 leptons (WZ)
  - $m_{ll}$ sidebands + b-tag or e/mu pairs (top)
  - $m_{ll}$ sidebands + same sign ee/emu + no b-jets (W+jets)
  - Electron ID relaxed (QCD)
  - $\Delta \phi_{jet,p_T Miss}$ + reverted after MET cut (Z+jets)
- *ZZ and WW uses MC predictions*

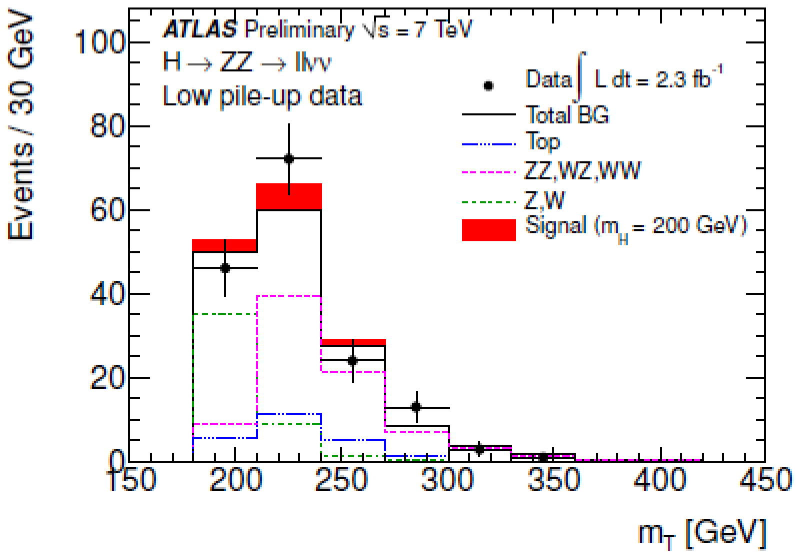
*$E_T^{miss}$ distributions for events with 2 leptons coherent with the Z mass*

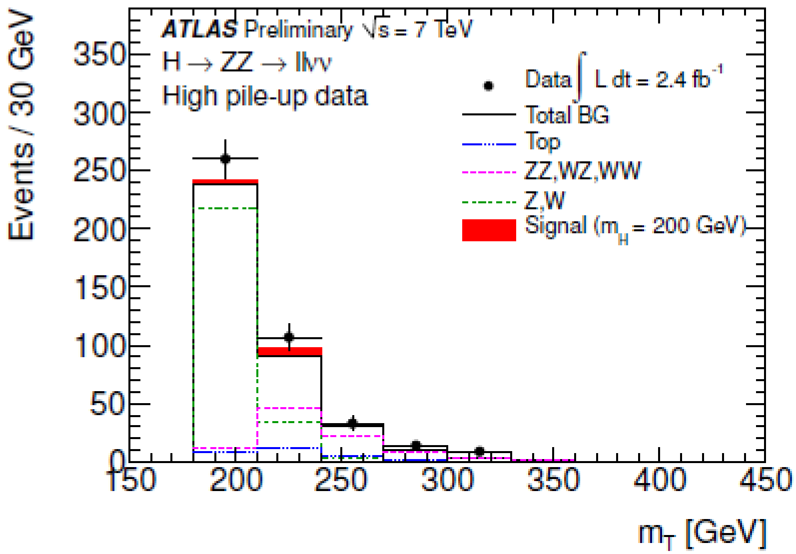


# H→ZZ→llνν: 200-600 GeV

## Results

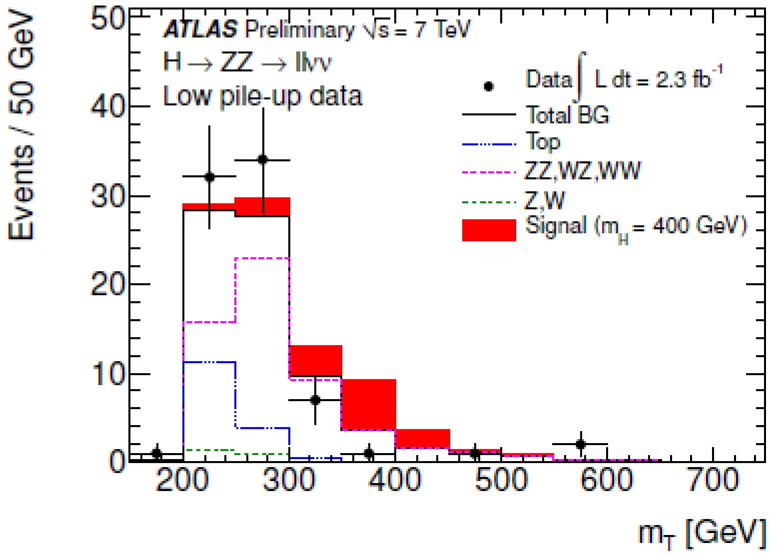
$m_H = 200$ GeV

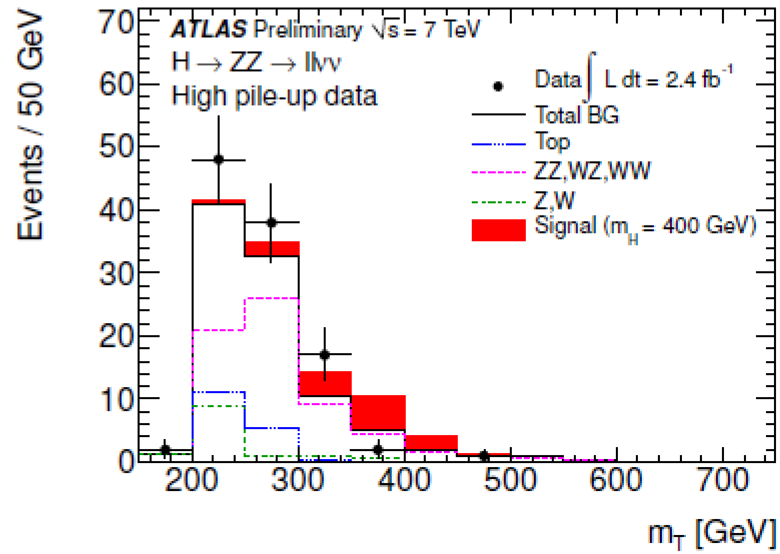


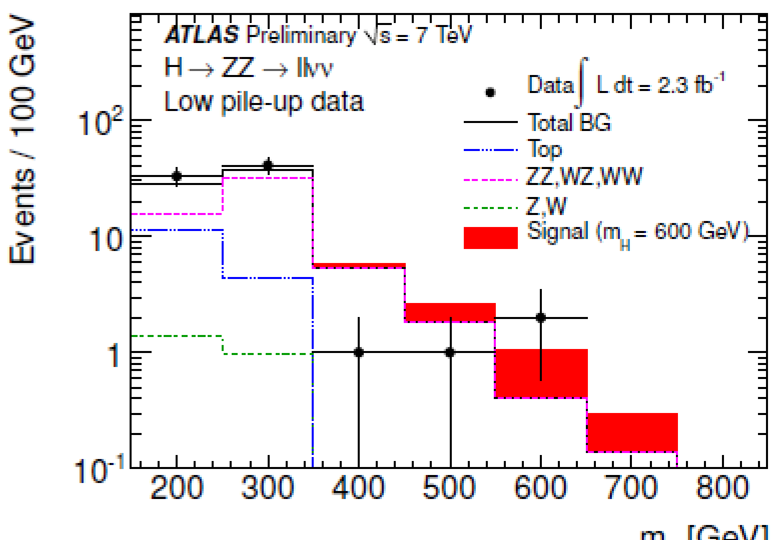
# $H \rightarrow ZZ \rightarrow ll\nu\nu$: 200-600 GeV

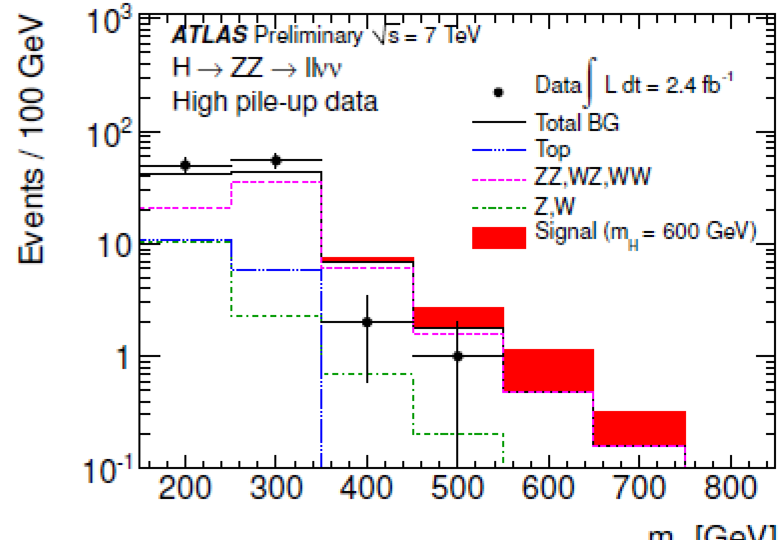
$m_H$ = 400 GeV



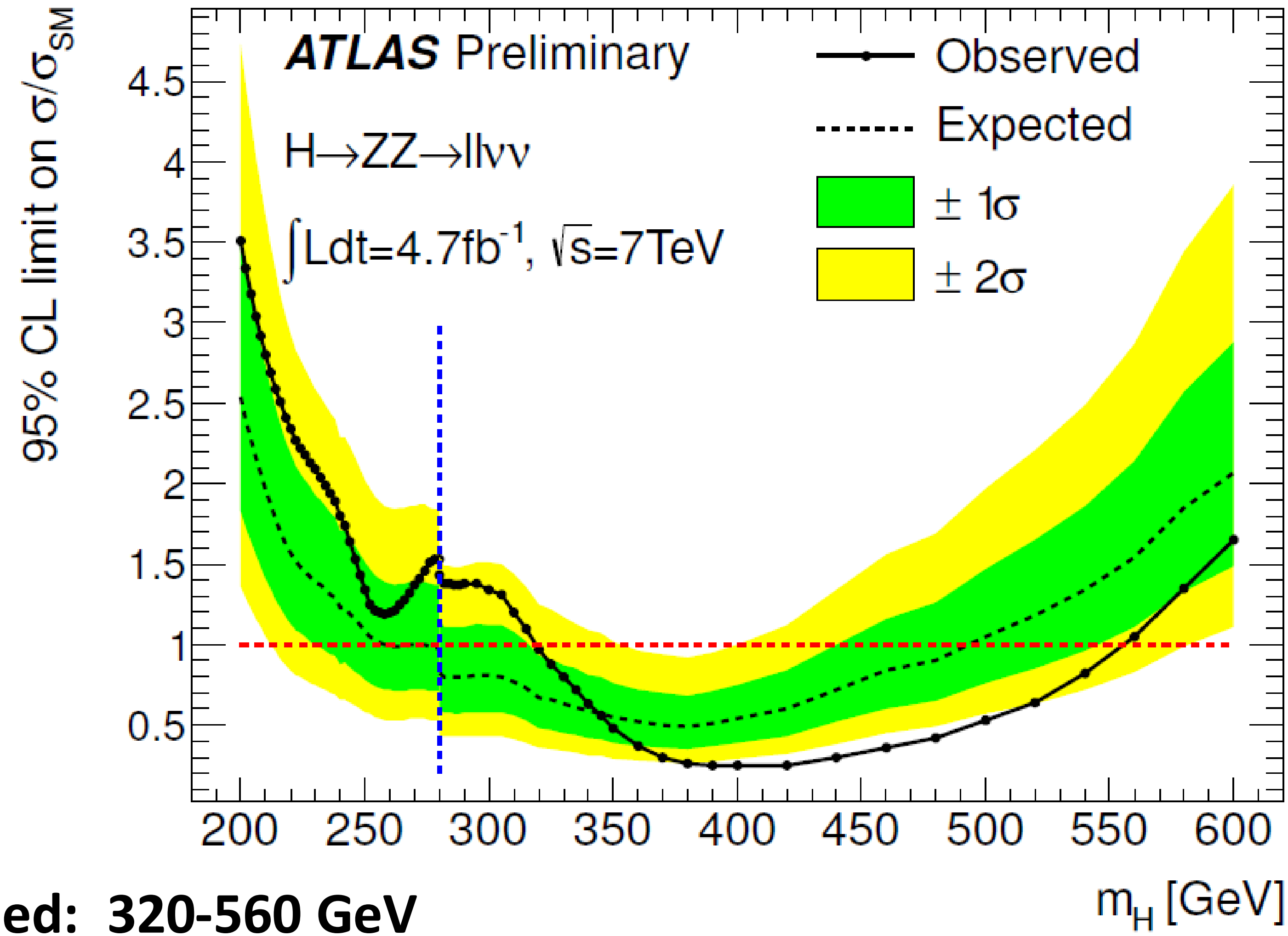

$m_H$ = 600 GeV



# H→ZZ→llνν: 200-600 GeV

## Results




**95%CL Excluded: 320-560 GeV**

Expected to be excluded if no SM signal: 260-490 GeV

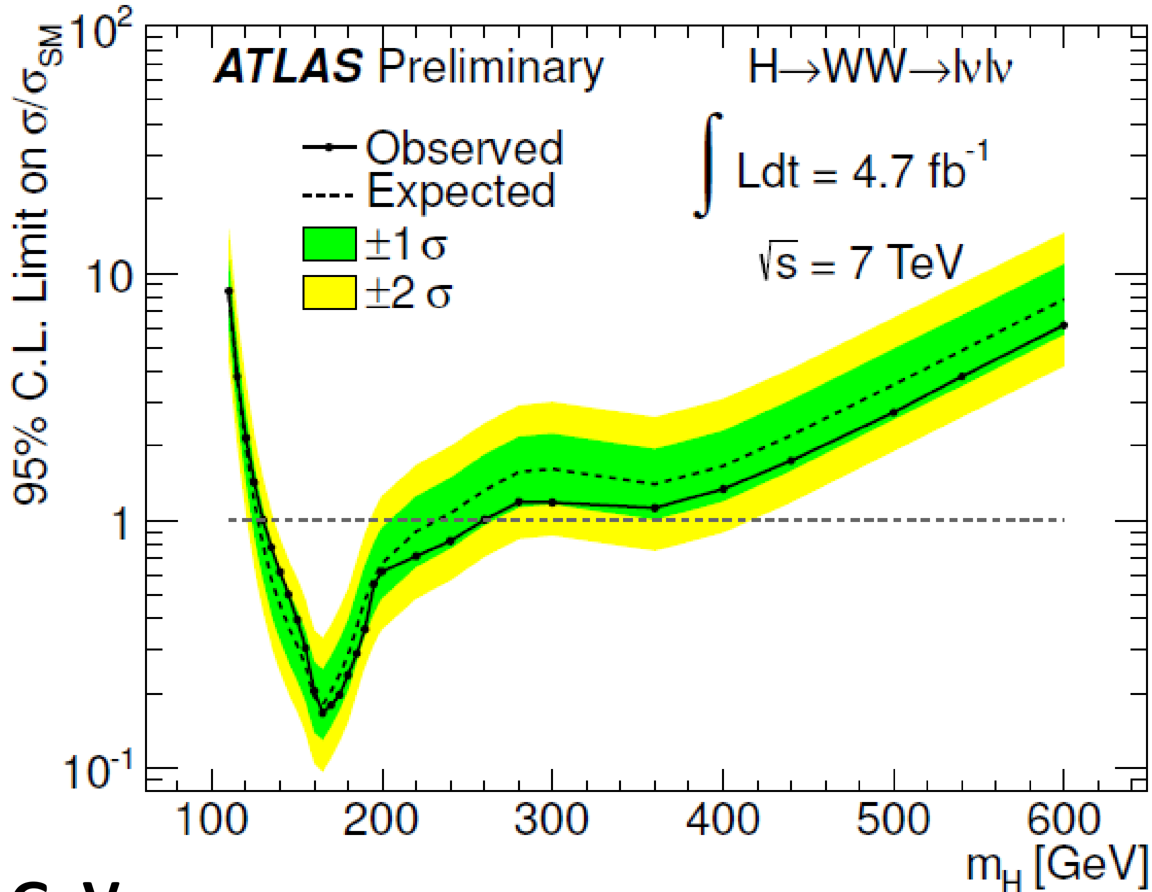
# $H \to WW \to l\nu l\nu$ : 110-600 GeV

# H→WW→lνlν : 110-600 GeV

- Presented in details in Bertrand Brelier's talk

Updated to full 2011 dataset (4.7 fb$^{-1}$), added VBF specific search

[ATLAS-CONF-2012-12]()




**95%CL Excluded: 130-260 GeV**

Expected to be excluded if no SM signal: 127-234 GeV

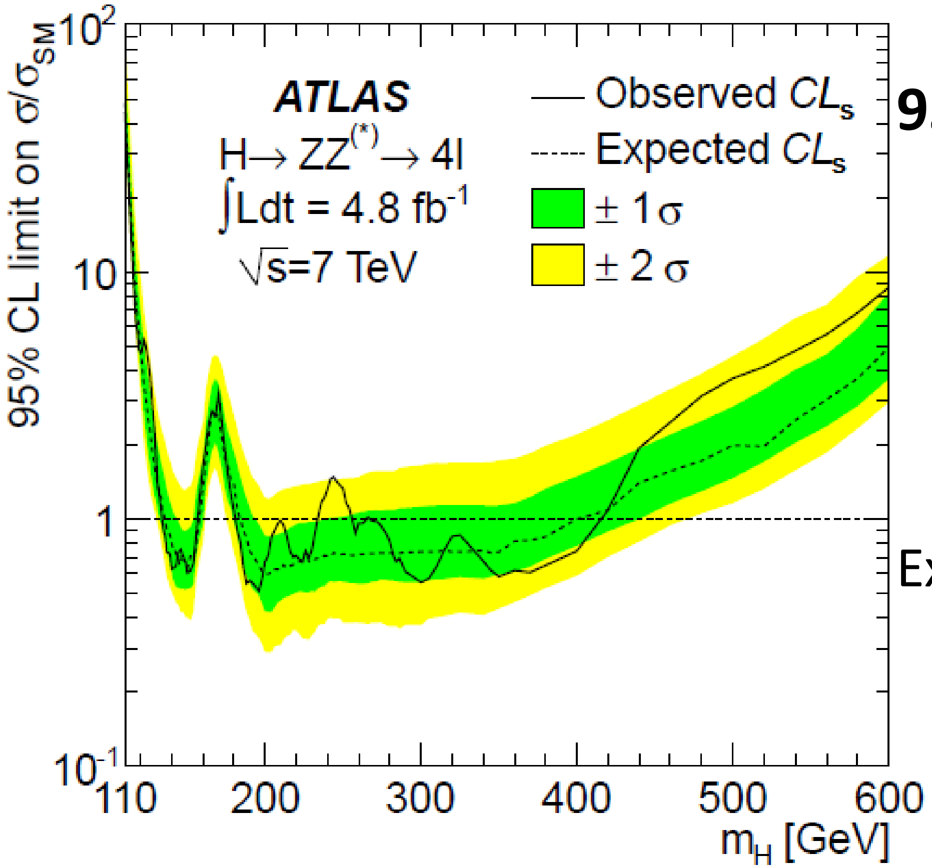
# $H \rightarrow ZZ \rightarrow llll$: 110-600 GeV

# H→ZZ→llll (110-600)

- **Presented in details in Bertrand Brelier's talk**

Quite sensitive at high mass

[arXiv:1202.1415](arXiv:1202.1415) (submitted to Physics Letters B)




**95%CL Excluded:**

- **134-156 GeV**
- **182-233 GeV**
- **256-265 GeV**
- **268 -415 GeV**

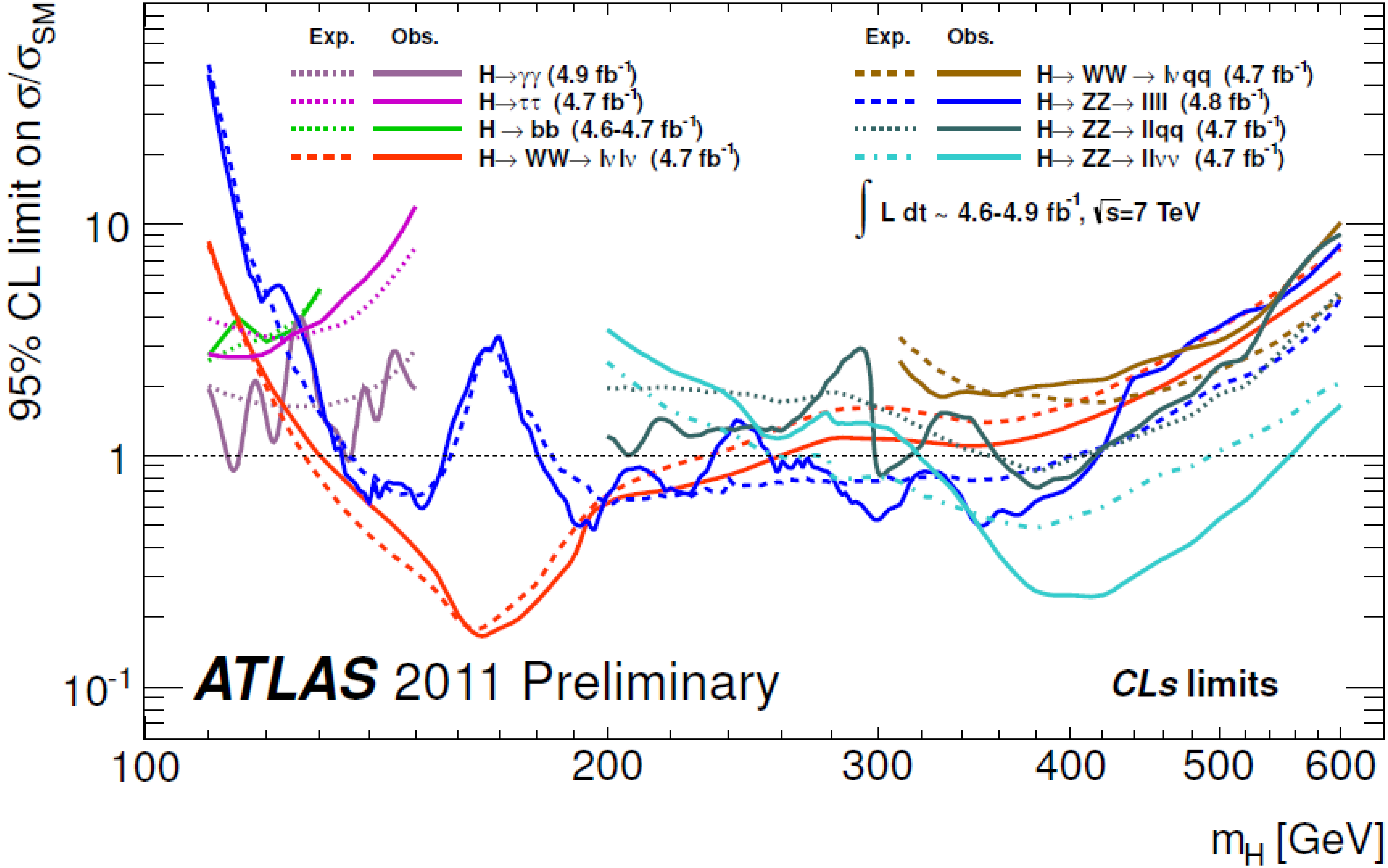
Expected to be excluded if no SM signal:

- 136-157 GeV
- 184-400 GeV

# Combination

# Combination

- ATLAS-CONF-2012-019



# Combination

**95%CL Excluded:**

- **110-117.5 GeV**
- **118.5-122.5 GeV**
- **129-539 GeV**

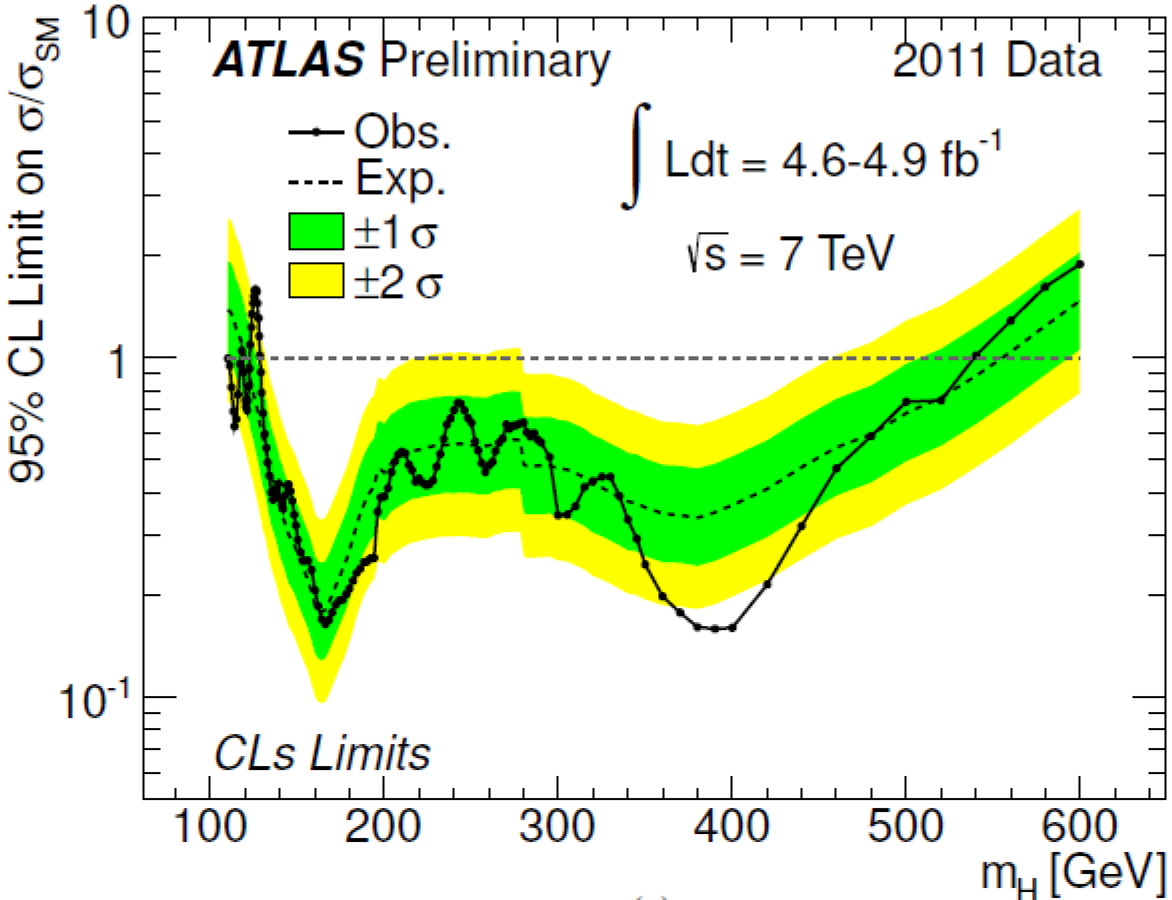
Expected to be excluded if no SM signal: 120-555 GeV

99% CL Excluded:

- 130-486 GeV

Excess seen at 126 GeV

- local significance of 2.5σ
- probability of fluctuation in the 110-146 GeV range: 10%



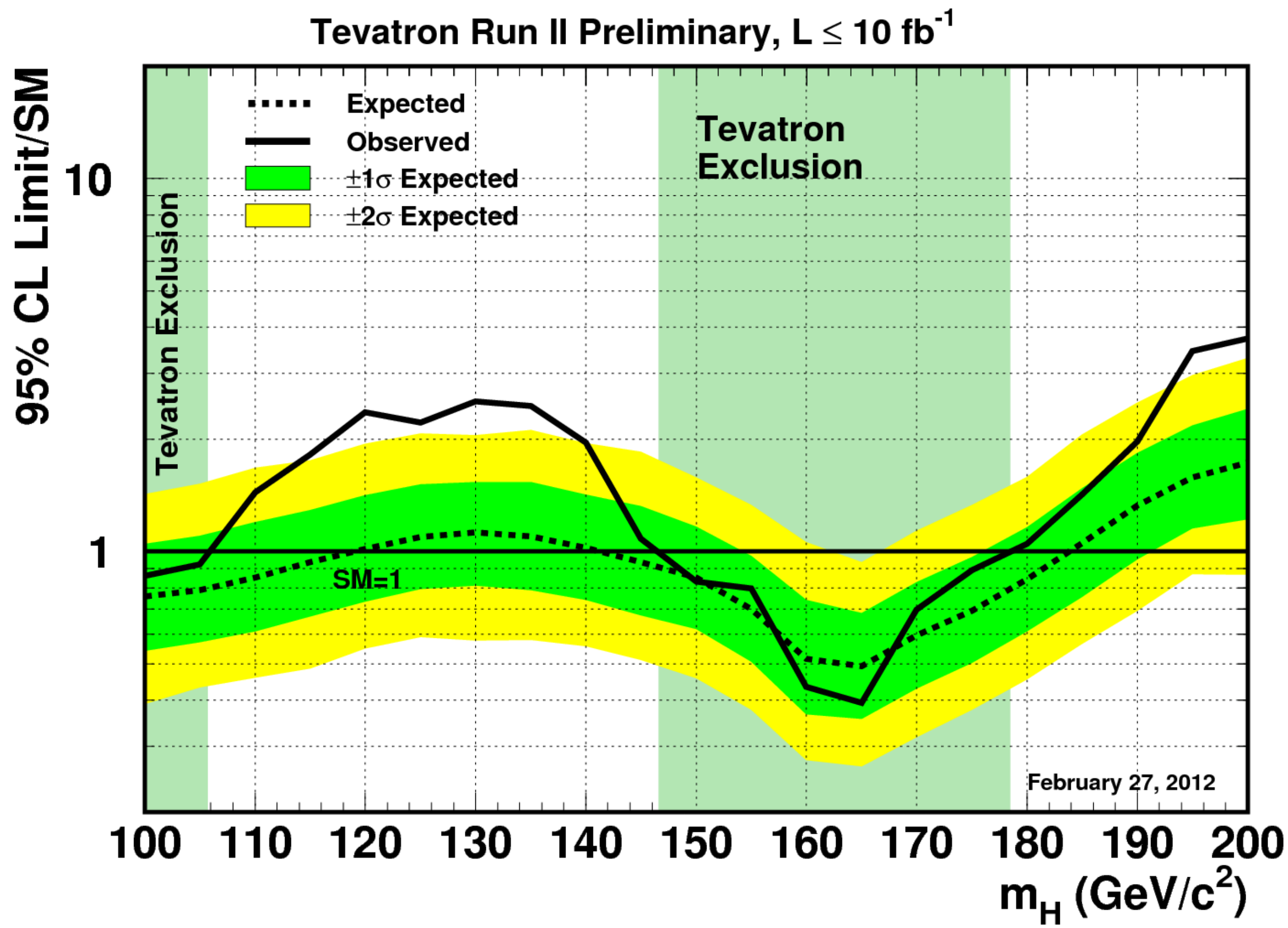

(a)

# Moriond 2012

## Tevatron

**Excluded: 147 - 179 GeV**

Expected: 141 - 184 GeV

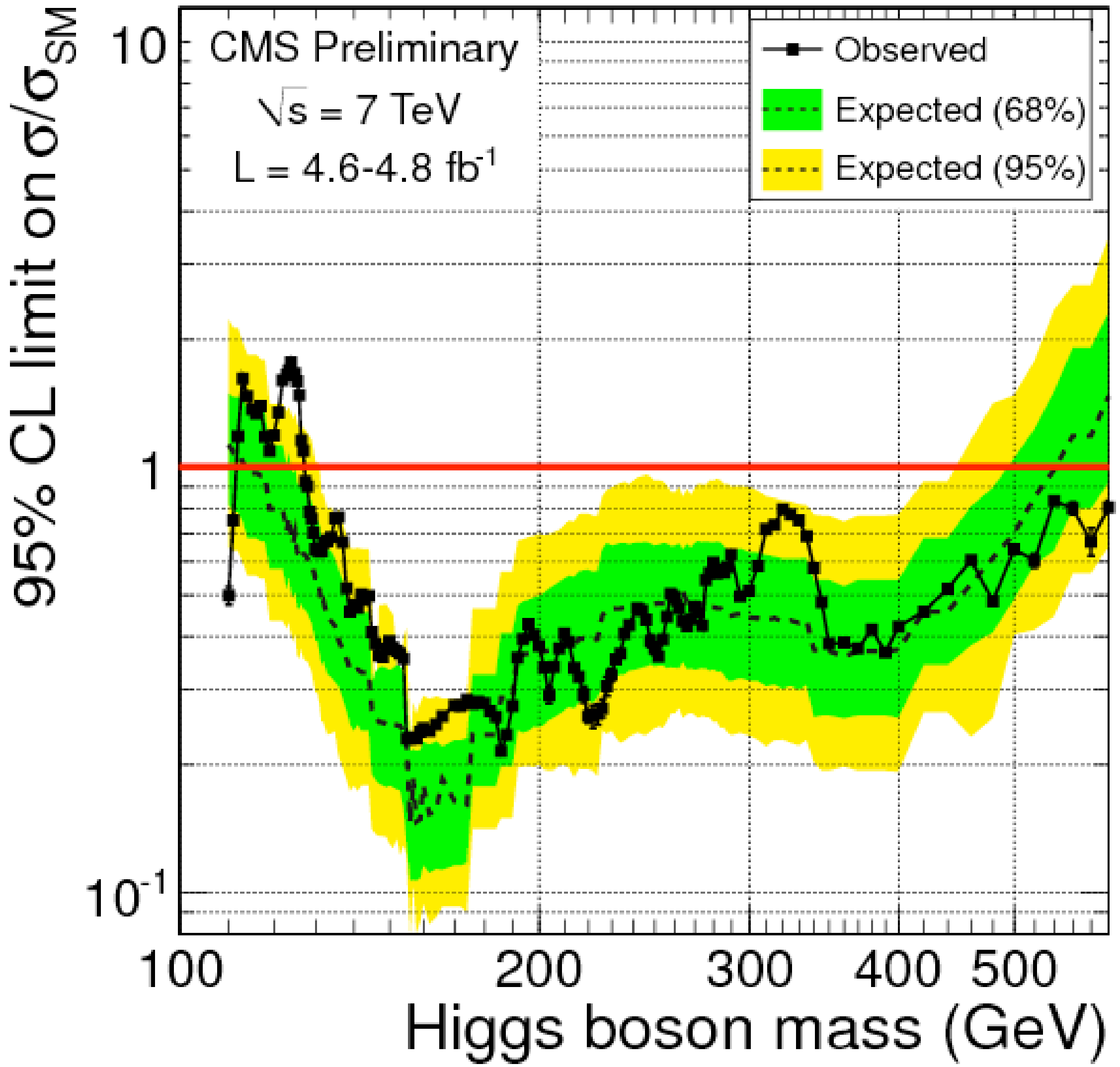


# Moriond 2012

## CMS

**95%CL Excluded:**
- **127.5-600**

Expected to be excluded if no SM signal: 114.5-543 GeV



# Going Higher?

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- **Experiments have the data points beyond 600 GeV... We need theoretical predictions & uncertainties ;-)**

- ***What is the best strategy to go beyond 600 GeV in 2012?***
  - Still SM-like boson searches? Does it make sense? As a baseline?
  - Model-independent approach (arbitrary mass and width) ?
  - Specific model dependent?

# Going Higher?

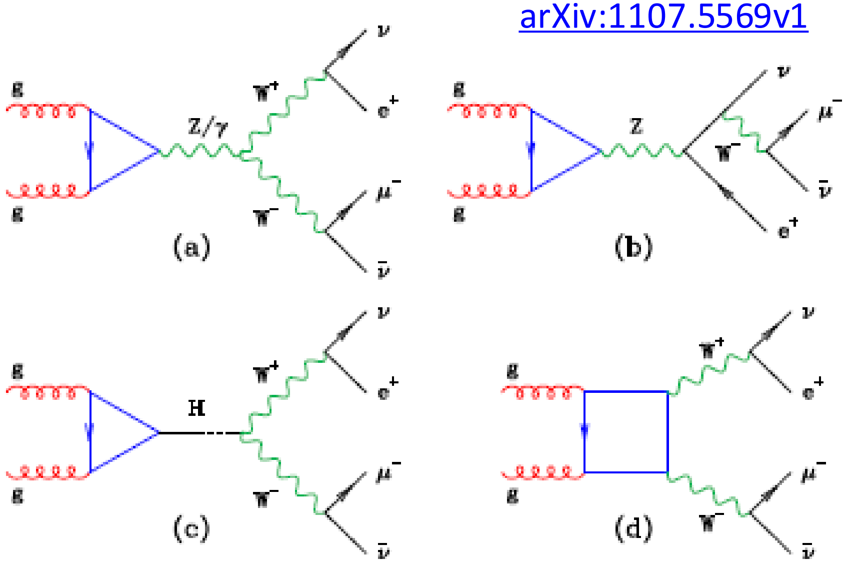
*LHC Higgs cross-section working group* **is working on important aspects of the question:**

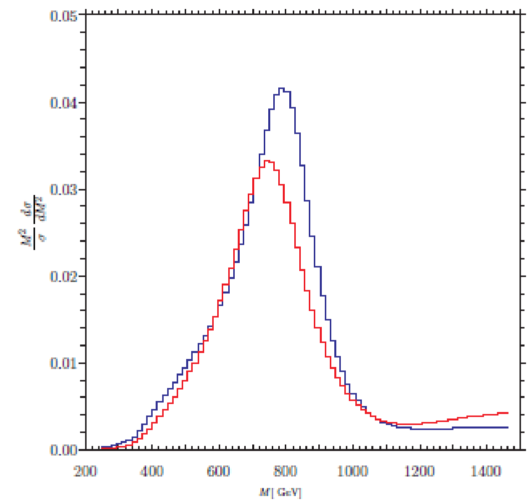
- Interference effects with SM backgrounds
- Lineshape
- Uncertainties on these
- Tools
- Anything else?

**Lots of work still to be done- if you have free time!**

**Effects not restricted only at high masses!**

arXiv:1107.5569v1




arXiv:1112.5517v1 Normalized BW (red) and complex-pole—scheme (blue) for mH=800 GeV

# Going Higher?

**Workshops at CERN in May about these issues**
**(but efforts very welcome before that since new data are knocking at our doors!)**

**The case of a large-mass Higgs** (S. Frixione and C. Anastasiou)
**CERN, May 14-15 2012**
**https://indico.cern.ch/conferenceDisplay.py?confId=174430**

**LHC Higgs Cross Section Working Group Workshop**
**CERN, May 24-25 2012**

# Summary & Outlook

- ATLAS "High-mass" Higgs boson modes updated in time for Moriond using the full 2011 dataset:
  - $H \to WW \to l\nu qq$
  - $H \to ZZ \to llqq$
  - $H \to ZZ \to ll\nu\nu$
  - ($H \to ZZ \to llll$ & $H \to WW \to l\nu l\nu$)

- ATLAS Combination excludes "high-mass" SM Higgs boson up to 539 GeV @ 95% CL.

- Getting Higher: Theory and Experiments meet again! What can be done? What's the best way to go?

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- ATLAS "High-mass" Higgs boson modes updated in time for Moriond using the full 2011 dataset:
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  - ($H \rightarrow ZZ \rightarrow llll$ & $H \rightarrow WW \rightarrow l\nu l\nu$)

Exciting year(s) ahead!!!

- ATLAS Combination excludes "high-mass" SM Higgs boson up to 539 GeV @ 95% CL.

- Getting Higher: Theory and Experiments meet again! What can be done? What's the best way to go?