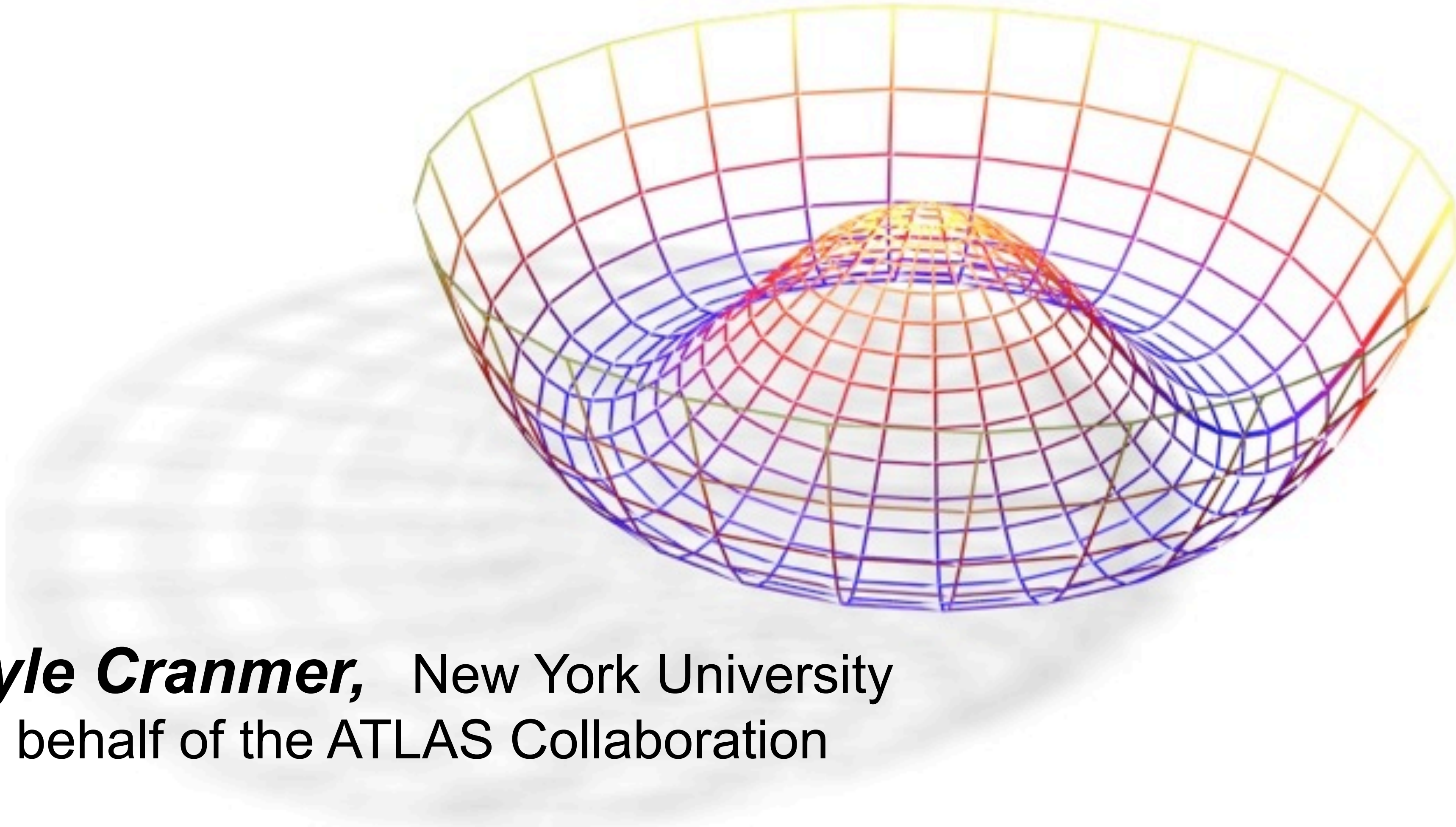
Center for Cosmology and Particle Physics

# Combined ATLAS Standard Model Higgs Search with 1 fb$^{-1}$ of Data at 7 TeV



**Kyle Cranmer,** New York University
on behalf of the ATLAS Collaboration

# Introduction

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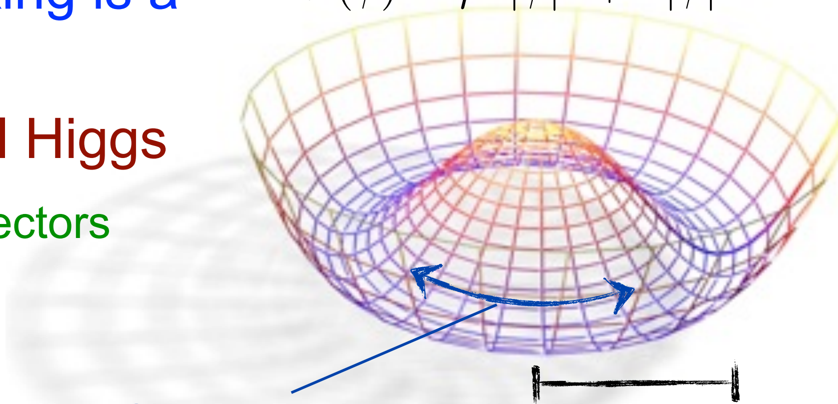
Understanding of electroweak symmetry breaking is a major goal of the LHC physics program

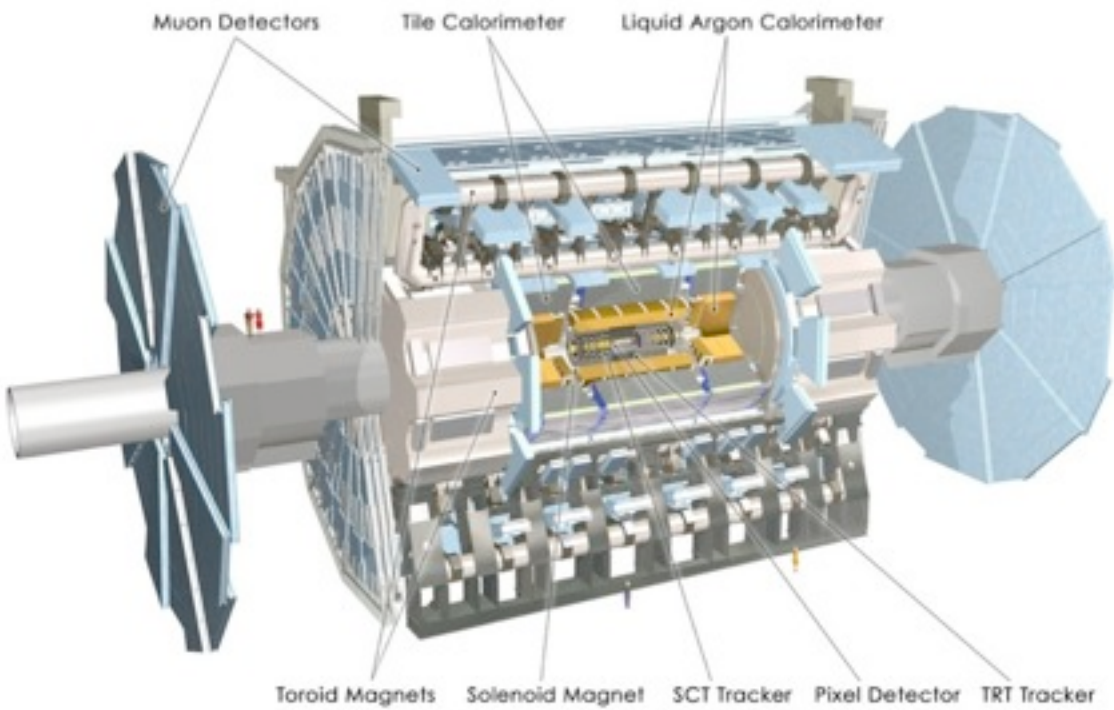
- Initial focus: search for the Standard Model Higgs
  - drove the design of both the ATLAS and CMS detectors
  - stresses every major sub-system

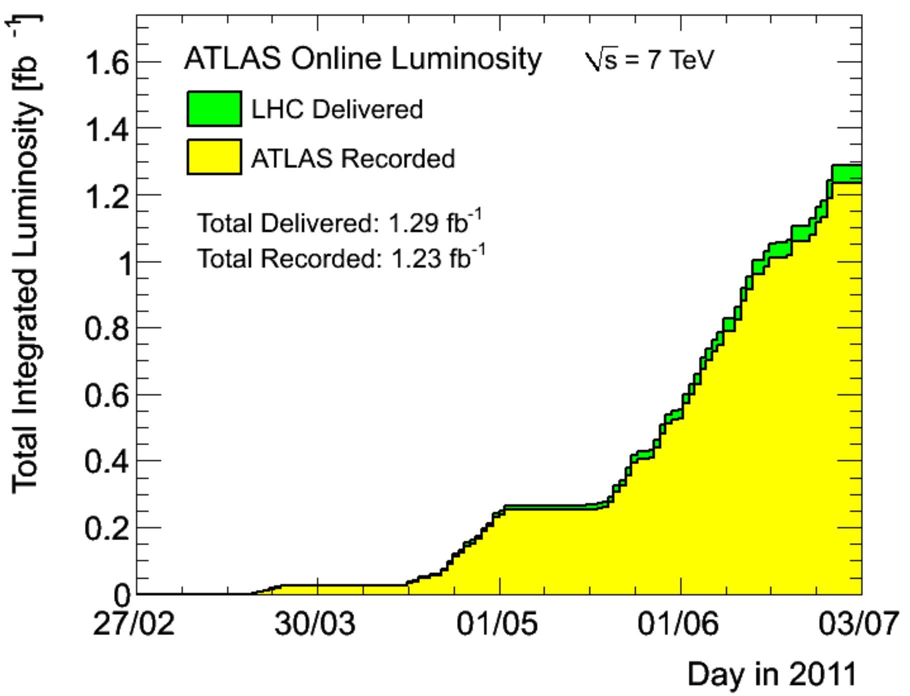
$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$




ATLAS and LHC are running great!

- Analyses here are based on up to 1.2 $fb^{-1}$
- High pile-up environment



# Channels Included in the Combination

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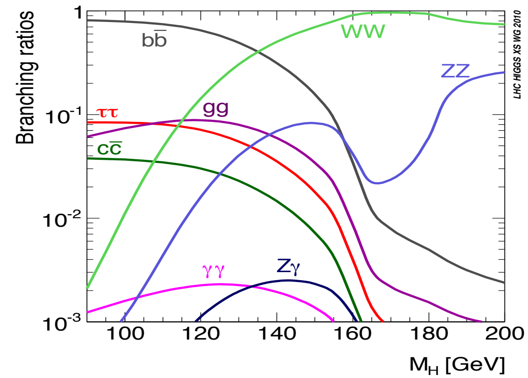
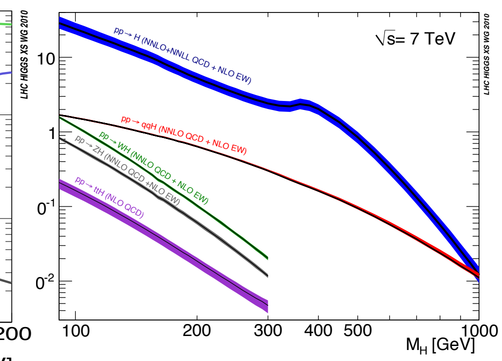
Enhance sensitivity by combining all available searches channels in the context of the SM Higgs hypothesis

- some channels are composed of sub-channels and include control samples




| Channel | | btag (veto) | Jets | MET (GeV) | Shape | Mass Range (GeV/c²) | Main backgrounds |
|---|---|---|---|---|---|---|---|
| γγ | | | | | $M_{gg}$ | 110-150 | γγ (from sidebands) |
| WH | | ✓ | 2 | | $M_{bb}$ | 110-130 | Top (3j - high $M_{bb}$) and W+jets (low $M_{bb}$) |
| ZH | | ✓ | 2 | | $M_{bb}$ | 110-130 | Z+jets (low $M_{bb}$) |
| WW (lνlν) | 0-jet | | 0 | >30 | | 110-240 | WW (control region $M_{ll}$) |
| | 1-jet | veto | 1 | >30 | | 110-240 | Top (from reverse btag) and WW ($M_{ll}$ CR) |
| WW (lνqq) | 0-jet | | 0 | >30 | $M_{WW}$ | 200-600 | W+jets (sidebands) |
| | 1-jet | veto | 1 | >30 | $M_{WW}$ | 200-600 | W+jets (sidebands) |
| ZZ (llνν) | | ✓ | | >30 | $M_T$ | 200-600 | VV(from MC) and top (MC and checks) |
| ZZ (llqq) | | ✓ | 2 | <50 | $M_{llqq}$ | 200-600 | Z+jets (from MC) and top (from MC) |
| ZZ (4l) | | IP | | | $M_{4l}$ | 110-600 | ZZ (from MC), Z+jets (MC) and top (CR) |

# Detailed presentations on the channels



### Higgs search in the Higgs to bb channel

inside **Higgs and New Physics**

View details | Export

11:30 - 11:45

**Room:** *Dauphine*
**Location:** *Alpes Congrès - Alpexpo*
**Presenter(s):** *GONCALO, Ricardo*

*The decay of the Standard Model-like Higgs boson into bb is the dominant decay process in the region of low Higgs boson masses. The Hig[gs] search in this channel requirese an associated heavy objec...*

### Search for Higgs to ZZ (llll,llnunu,llqq)

inside **Higgs and New Physics**

View details | Export

12:15 - 12:35

**Room:** *Dauphine*
**Location:** *Alpes Congrès - Alpexpo*
**Presenter(s):** *NIKOLOPOULOS, Konstantinos*

*The search for the Standard Model-like Higgs boson via its decays into two Z bosons is presented, based on the ATLAS data collected in 2011. The results obtained in the fully leptonic 'golden' deca...*

### Higgs search in the Higgs to gammagamma channel

inside **Higgs and New Physics**

View details | Export

11:45 - 12:00

**Room:** *Dauphine*
**Location:** *Alpes Congrès - Alpexpo*
**Presenter(s):** *KADO, Marumi*

*The search for the Standard Model-like Higgs boson decaying to two photons is one of the best ways to identify a low mass Higgs boson at LHC. The results of the search in this channel are presente...*

### Search for Higgs to WW (lnulnu,lnuqq)

inside **Higgs and New Physics**

View details | Export

14:30 - 14:45

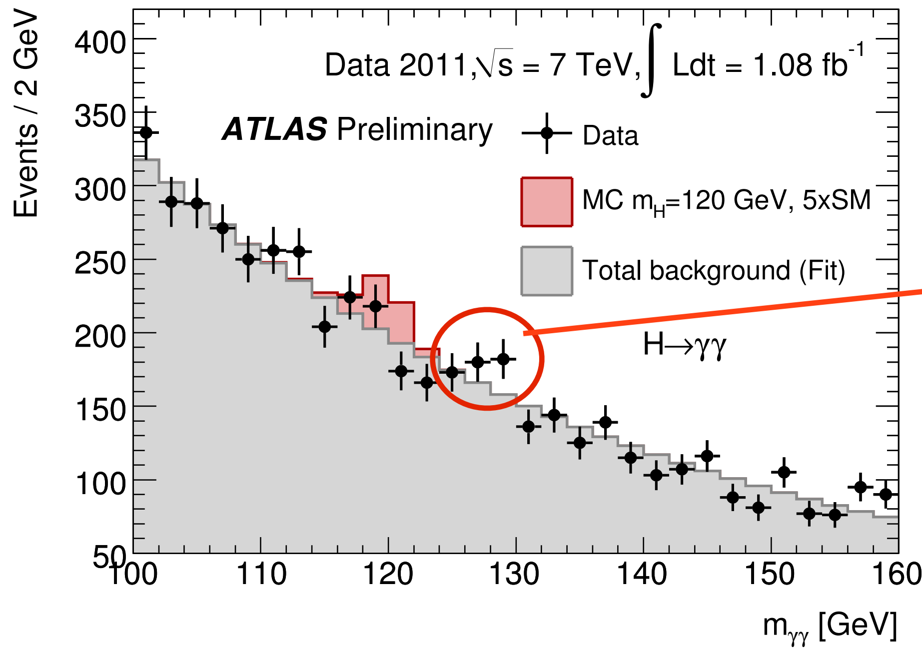
**Room:** *Dauphine*
**Location:** *Alpes Congrès - Alpexpo*
**Presenter(s):** *STRANDBERG, Jonas*

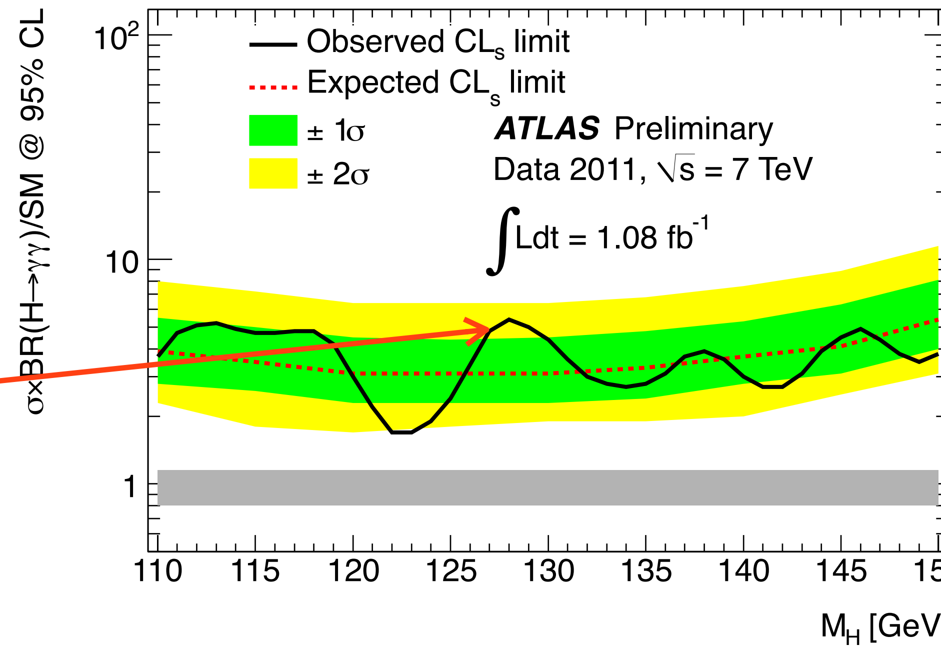
*The search for the Standard Model-like Higgs boson via its decays into two W bosons is presented, based on the ATLAS data collected in 2011. The search in the dilepton final state is more powerful...*

# Low mass channels

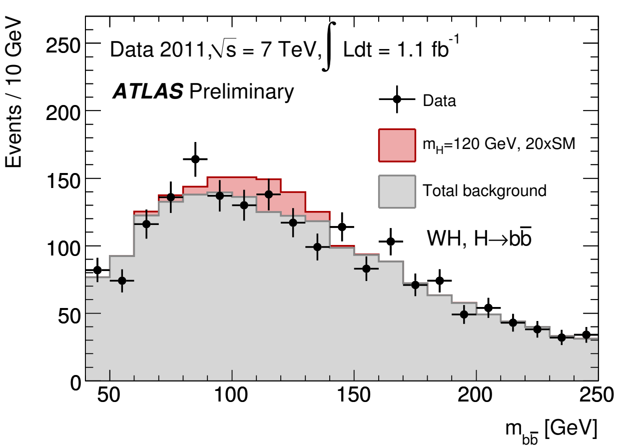


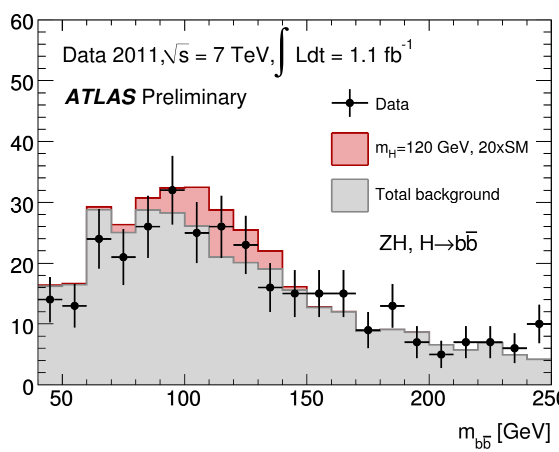
## H→γγ (110-150)

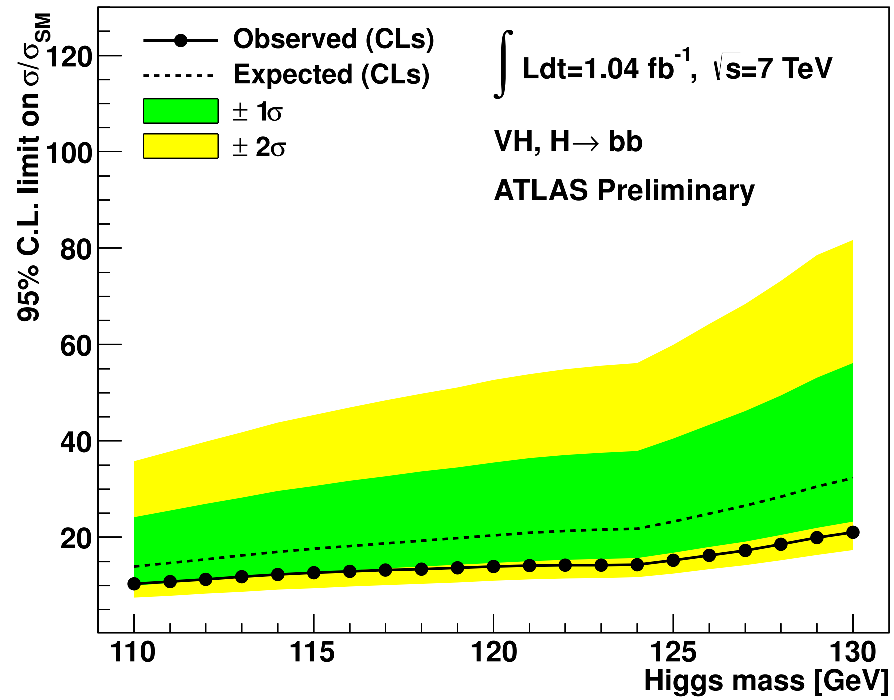


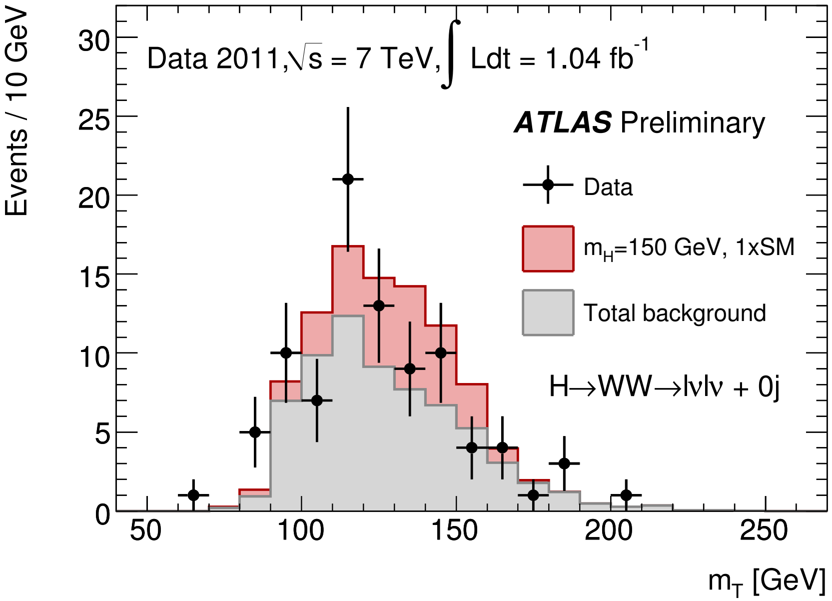

## WH and ZH, H→bb (110-130)

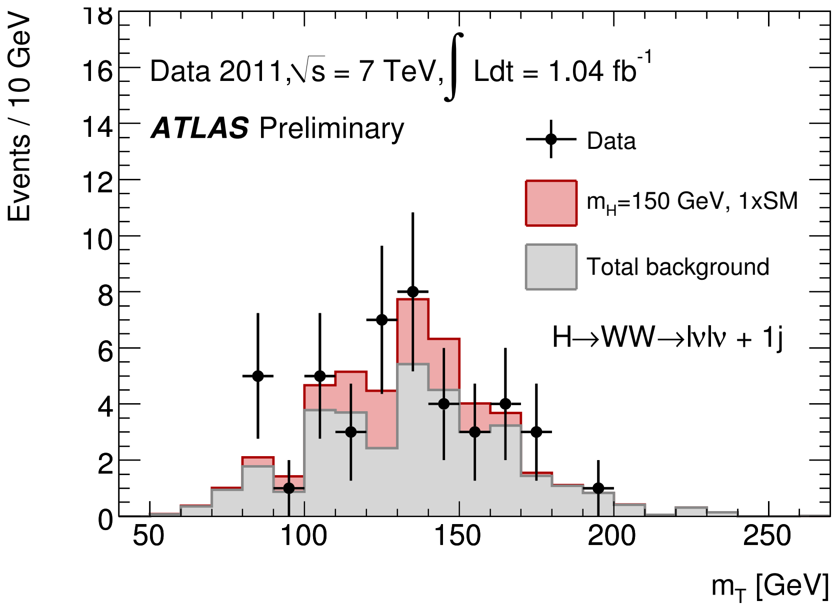


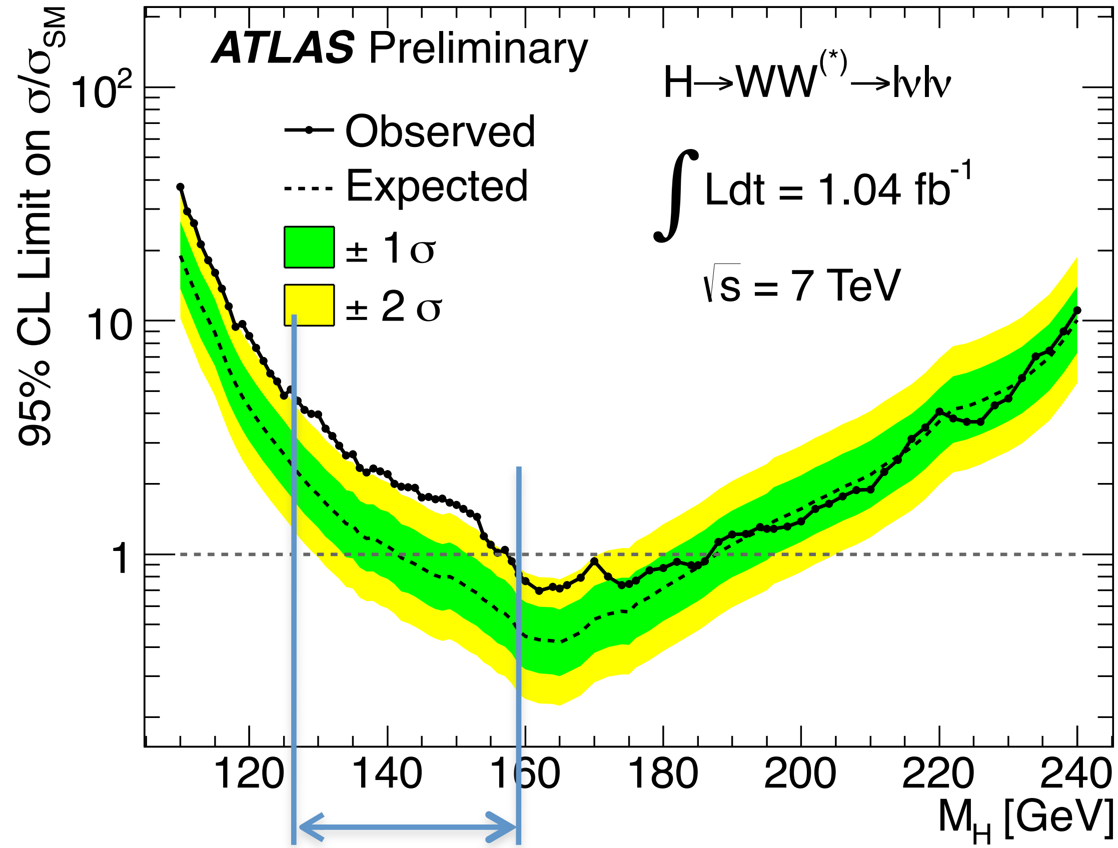



# The H→ WW → lνlν Channels

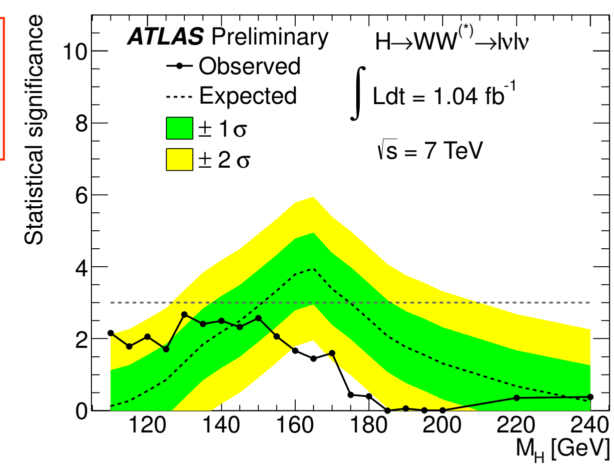



$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2},$$

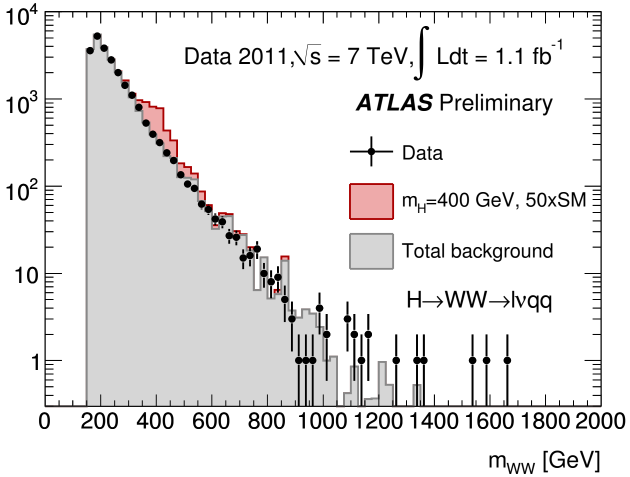


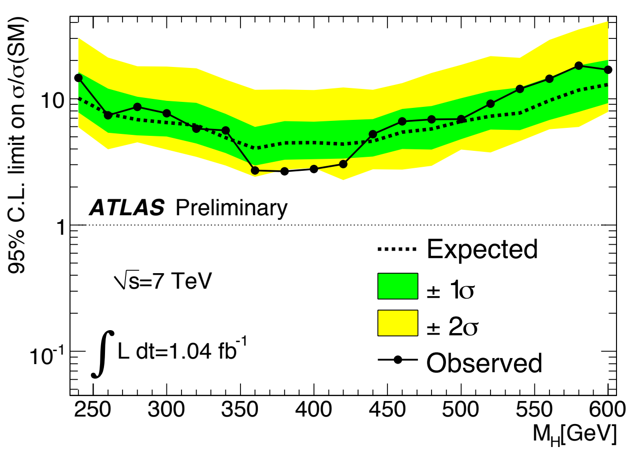

Broad excess >2σ
$126 < m_H < 158$ GeV/c$^2$



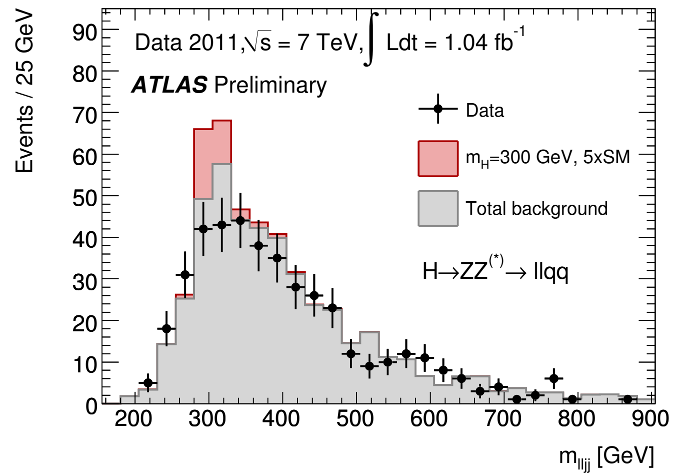
# The High Mass Channels

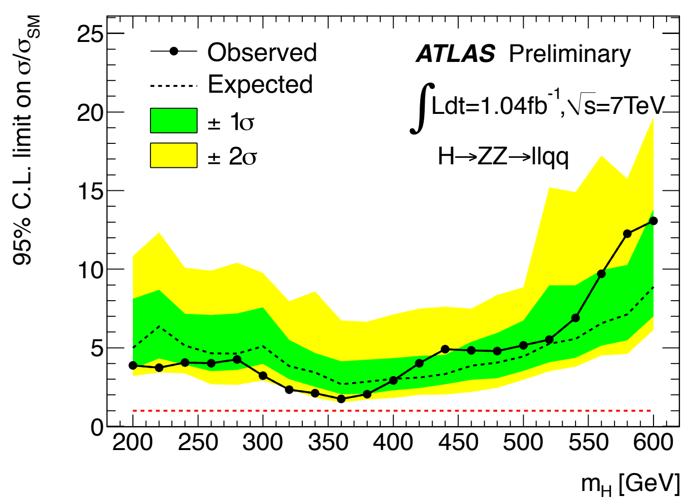
## H→ WW → lνqq



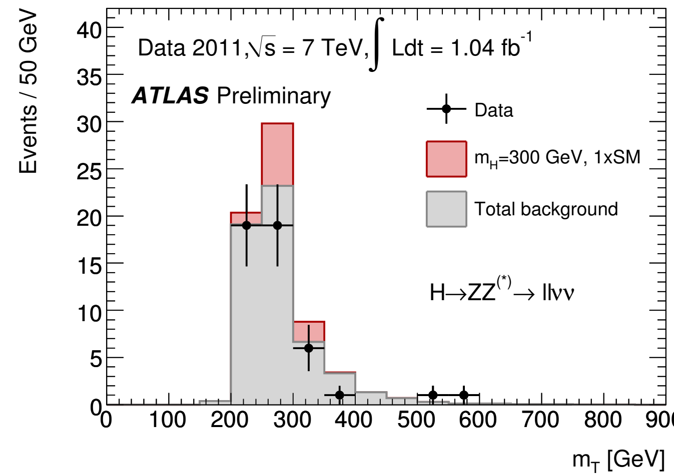



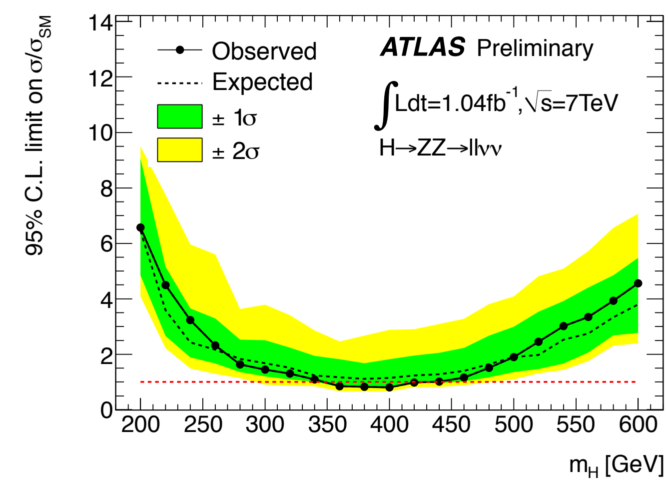

## H→ ZZ → llqq




## H→ ZZ → llνν

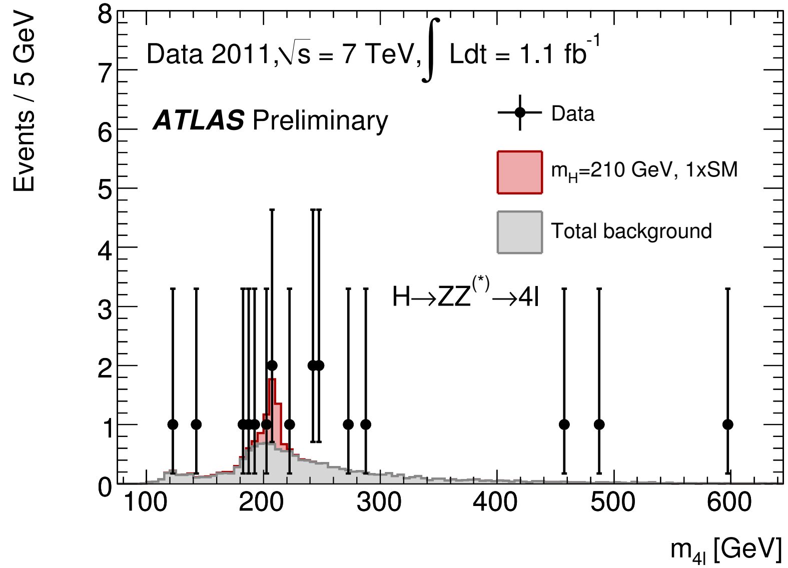


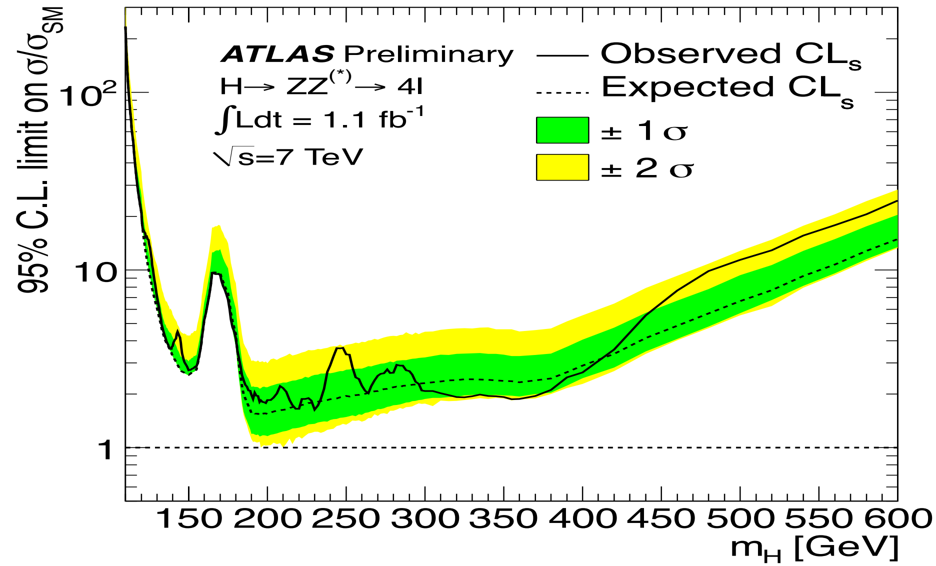



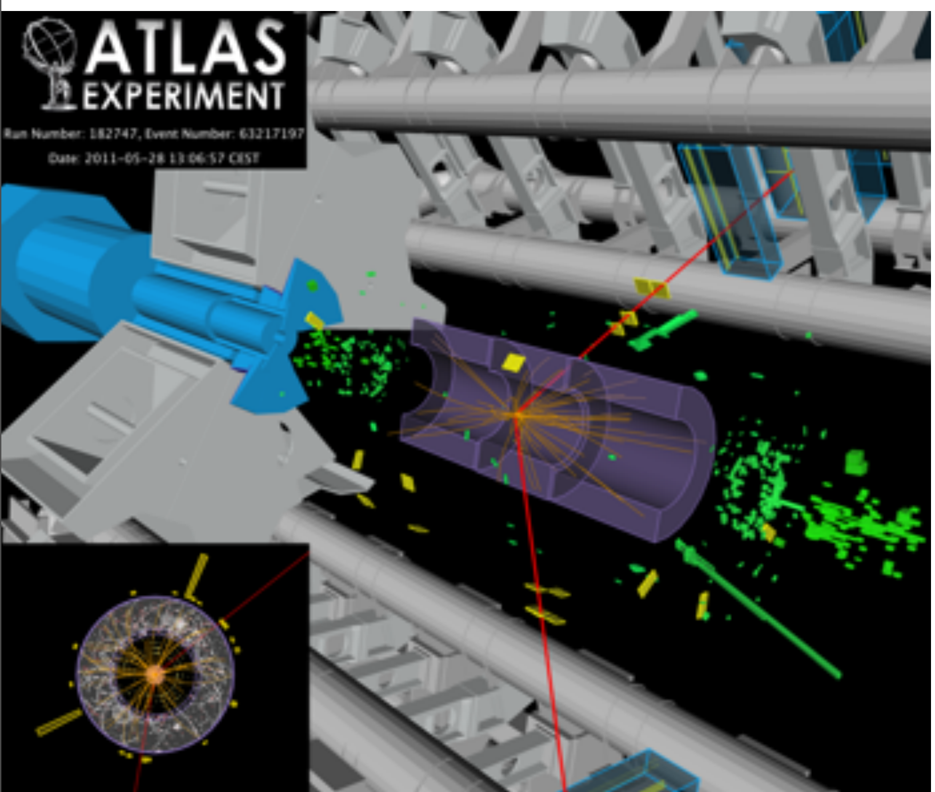

**H→ZZ channels able to exclude high-mass SM Higgs**

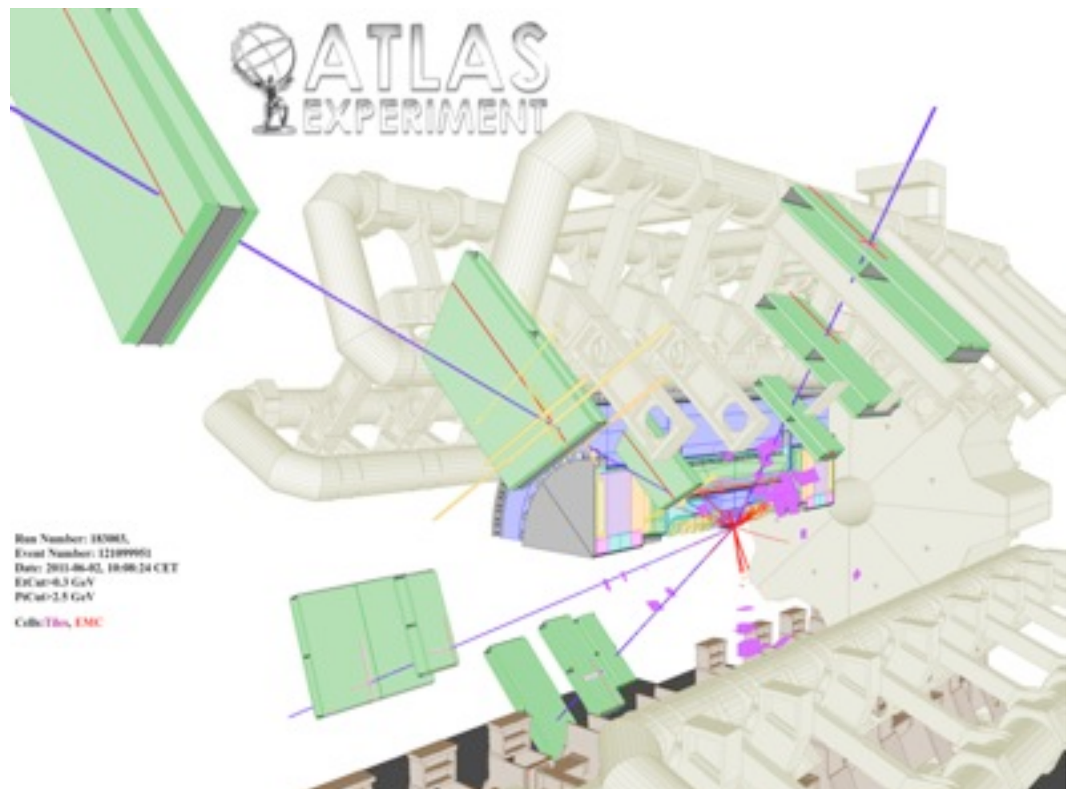
# The H→ ZZ → 4l Channel (110 < $M_H$ < 600)





# *Summary of individual channels' limits*

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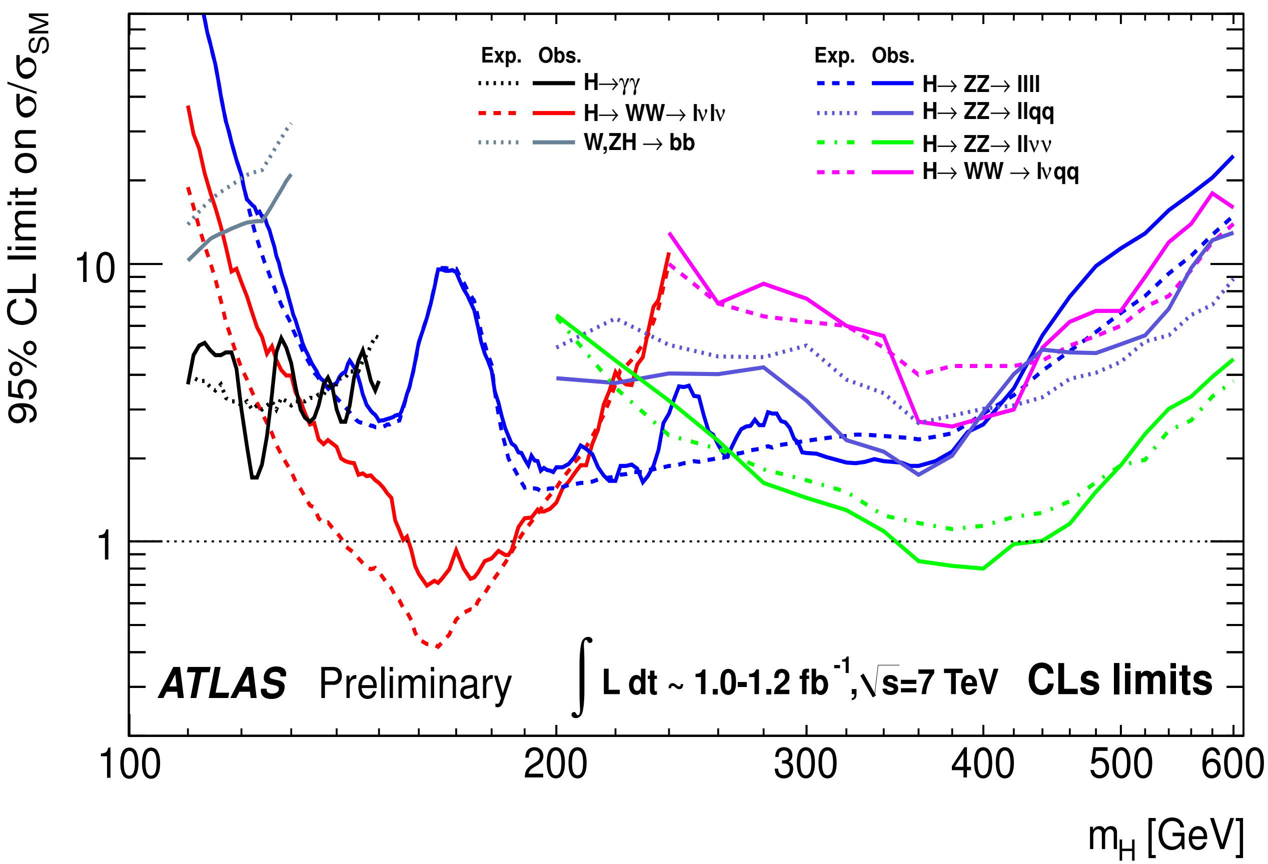
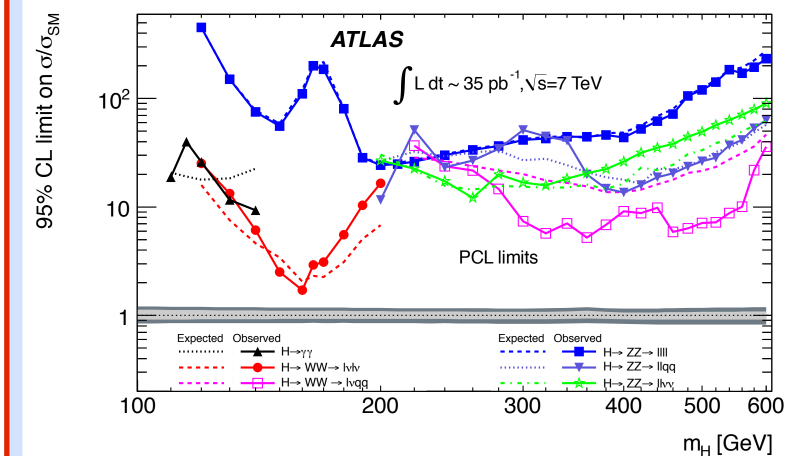
## The situation prior to the combination

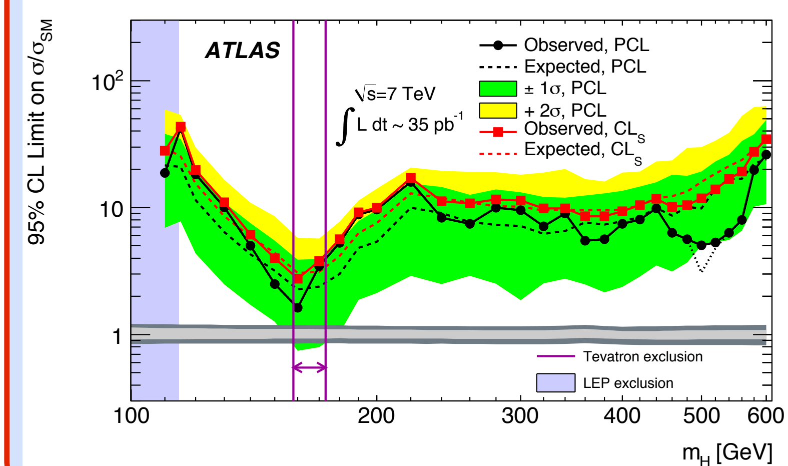
- Two individual channels are able to exclude by themselves




**ATLAS w/ 35 pb$^{-1}$**

[arXiv:1106.2748]



# Systematics

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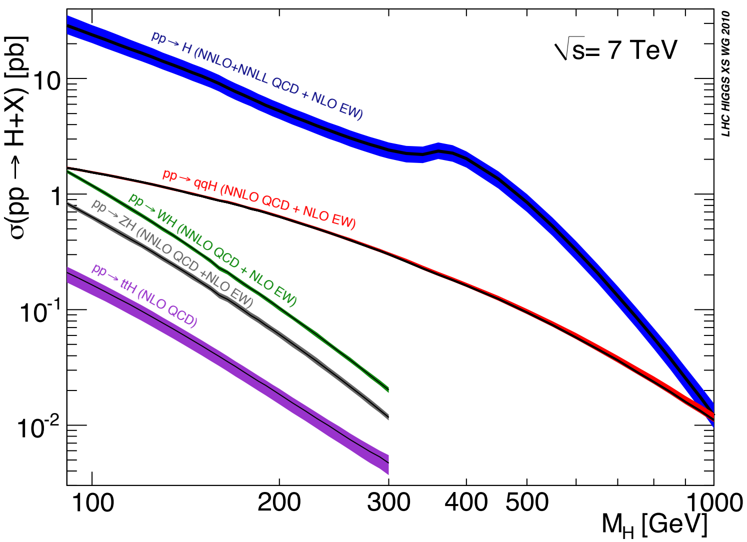
The channels utilize three main strategies for addressing systematic uncertainties:

- **data-driven techniques:** eliminates dominant impact of uncertainty leaving uncertainties associated with extrapolation from control to signal region
- **implicit parametrization:** parametrized functions flexible enough to describe effect of uncertainty on distribution (eg. exponential + Crystal ball in $H\to\gamma\gamma$)
- **explicit parametrization:** variational histograms obtained from modifying simulated samples according to variations the source of uncertainty (eg. $H\to ZZ$)

Uncertainties in normalization described by log-normal distributions

The combination requires relations between rates of different channels, thus it is subject to theoretical uncertainties. Prescription agreed upon by LHC-HCG & Higgs cross-section working group.




| | $H\to\gamma\gamma$ | $H\to b\bar{b}$ | $H\to WW^{(*)}$ $\ell\nu\ell\nu$ | $H\to WW^{(*)}$ $\ell\nu qq$ | $H\to ZZ^{(*)}$ $\ell\ell\ell\ell$ | $H\to ZZ^{(*)}$ $\ell\ell\nu\nu$ | $H\to ZZ^{(*)}$ $\ell\ell qq$ |
|---|---|---|---|---|---|---|---|
| Luminosity | $\pm3.7$ | $\pm3.7$ | $\pm3.7$ | $\pm3.7$ | $\pm3.7$ | $\pm3.7$ | $\pm3.7$ |
| e/$\gamma$ efficiency | $^{+11.6}_{-10.4}$ | $\pm2.3$ | $\pm1.4$ | $^{+0.9}_{-0.8}$ | $\pm1.9$ | $\pm1.2$ | $\pm1.1$ |
| e/$\gamma$ energy scale | - | $^{+1.5}_{-1.6}$ | $^{+0.1}_{-0.4}$ | - | - | $^{+0.8}_{-1.1}$ | |
| e/$\gamma$ resolution | - | $^{+2.1}_{-1.5}$ | $^{+0.0}_{-0.5}$ | - | - | - | |
| $\mu$ efficiency | - | $^{+1.1}_{-2.0}$ | $^{+0.6}_{-0.6}$ | $\pm0.3$ | $\pm1.2$ | $^{+0.8}_{-0.7}$ | $\pm0.6$ |
| $\mu$ resolution | - | $\pm5.8$ | $^{+4.2}_{-4.5}$ | - | - | - | |
| Jet/MET energy scale | - | $^{+21}_{-17}$ | $^{+4.6}_{-7.9}$ | $^{+15}_{-18}$ | - | $^{+5.9}_{-4.0}$ | $^{+3.7}_{-10.4}$ |
| Jet resolution | - | $\pm2.5$ | - | $^{+8.2}_{-9.0}$ | - | - | $^{+2.1}_{-0.0}$ |
| MET | - | $^{+5.5}_{-6.1}$ | - | - | - | $^{+6.6}_{-4.2}$ | - |
| $b$-tag efficiency | - | $^{+37}_{-33}$ | - | - | - | $^{+4.3}_{-4.4}$ | - |
| Theory | $^{+15.0}_{-20.0}$ | $\pm5$ | $^{+15.0}_{-20.0}$ | $^{+15.0}_{-20.0}$ | $^{+15.0}_{-20.0}$ | $^{+15.0}_{-20.0}$ | $^{+15.0}_{-20.0}$ |

# Statistical Procedure

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The full complexity of individual channels' likelihood functions are packaged using RooFit/RooStats workspaces, and a combined probability model is formed by identifying nuisance parameters $\nu$ associated to common systematic effects

- the common parameter of interest is a cross-section scale factor: $\boldsymbol{\mu} = \boldsymbol{\sigma} / \boldsymbol{\sigma_{SM}}$

The profile likelihood ratio is used as a test statistic: $\lambda(\mu) = L_{s+b}(\mu, \hat{\hat{\nu}}) / L_{s+b}(\hat{\mu}, \hat{\nu})$

- nuisance parameters are "profiled" based on the data
- one-sided variants of the test statistic are used for upper-limits and discovery

The distribution of the test statistic is obtained in two ways:

- Ensemble tests with toy Monte Carlo using a fully frequentist procedure
  - randomize auxiliary measurements instead of randomizing nuisance parameters
- Using asymptotic distribution of likelihood ratio
  - used for primary result

Cowan, Cranmer, Gross, Vitells
Eur.Phys.J. C71 (2011)

Primary result based CLs, conservatism introduced to protect against downward fluctuations

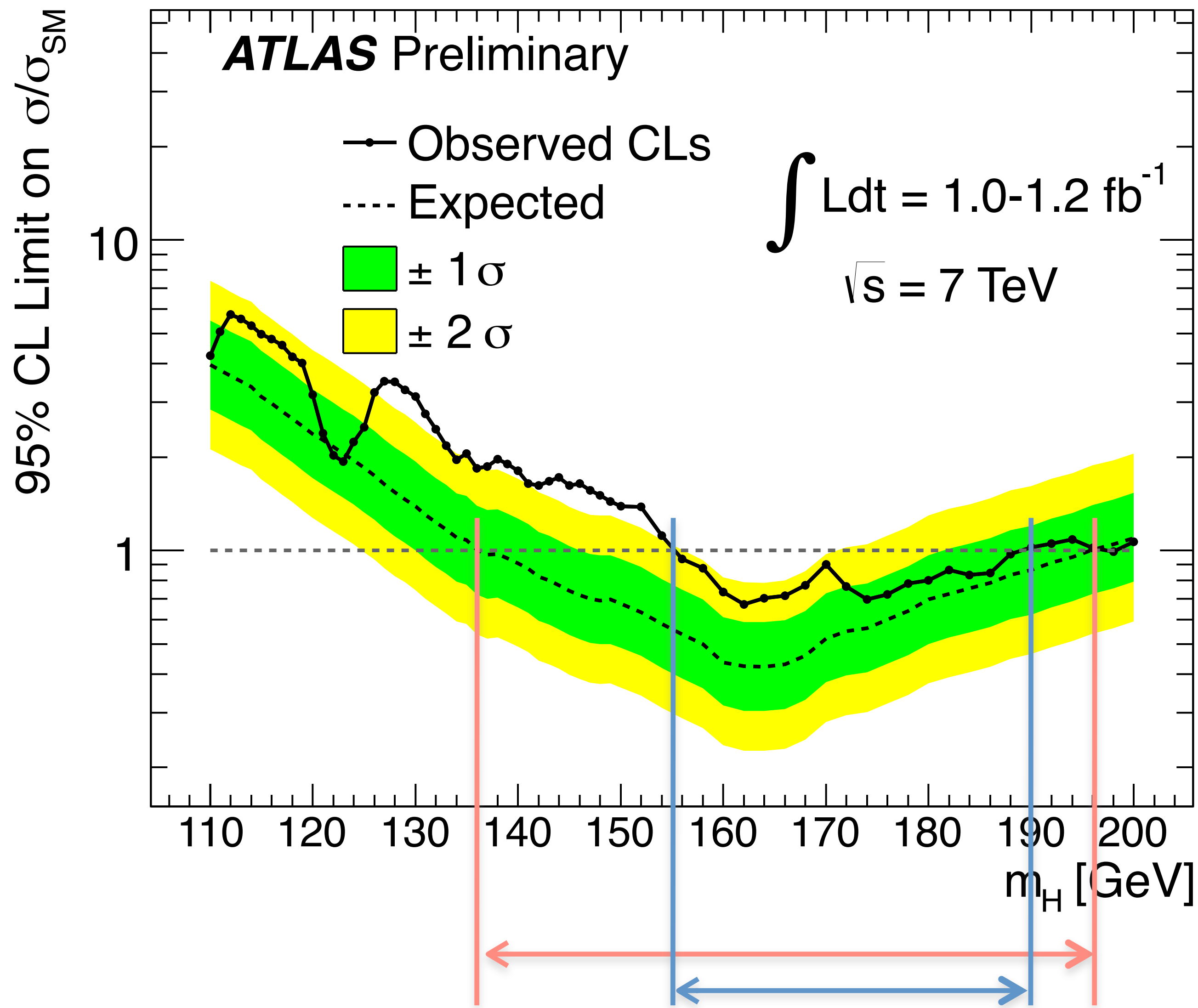
- results based on power-constrained CLs+b ("PCL") in backup
- Additional comparisons with Bayesian procedure with a uniform prior on $\mu$

# Limits in the low mass range



Impressive sensitivity to a Higgs boson in the mass range 135-200 GeV

Excess in H→ WW → lνlν leads to weaker-than-expected limits near $M_H$ = 130-160 GeV




155<$m_H$<190 GeV/$c^2$ excluded at 95% CL

# *Limits in the low mass range*

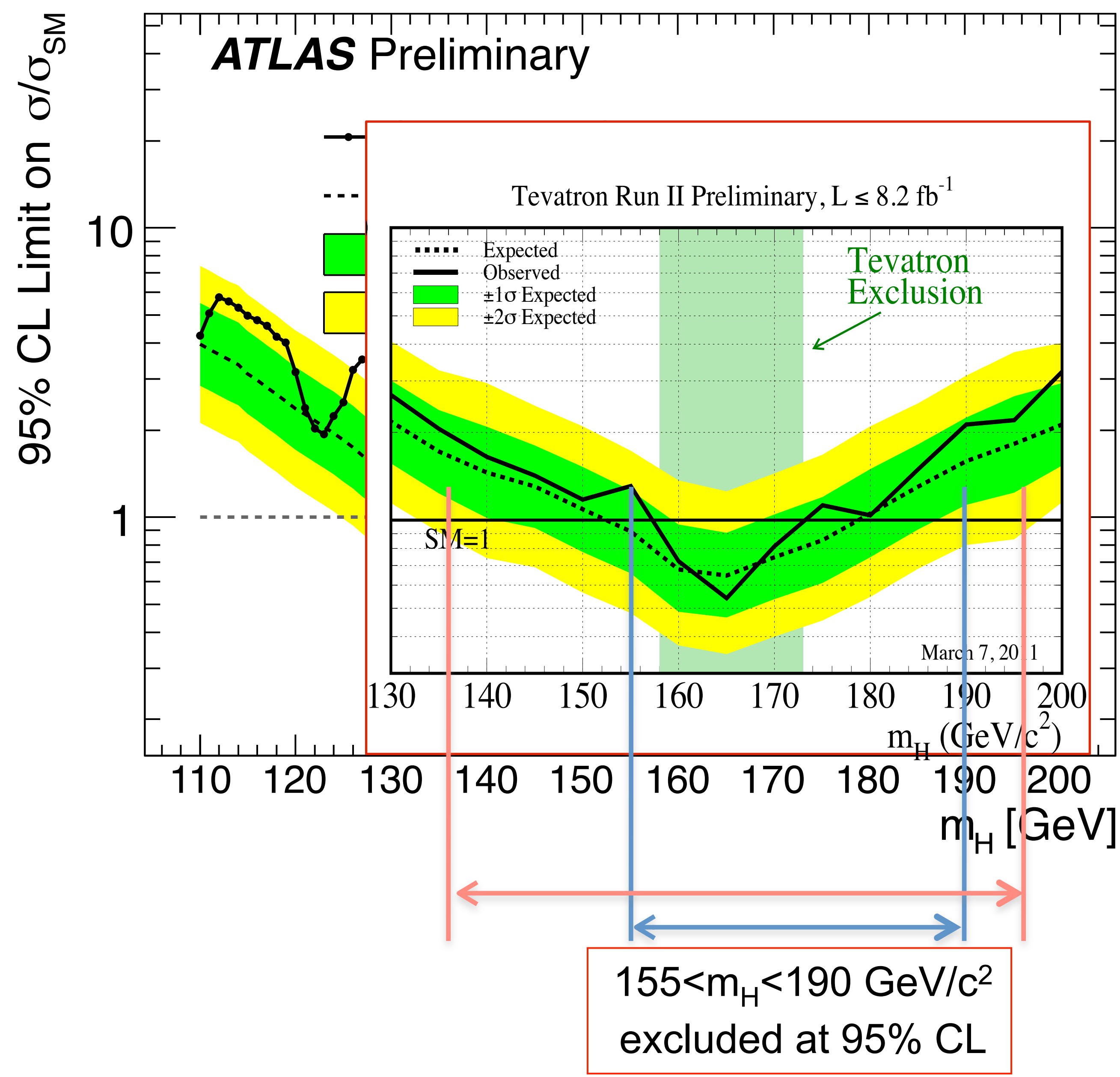


Impressive sensitivity to a Higgs boson in the mass range 135-200 GeV

Excess in H→ WW → lνlν leads to weaker-than-expected limits near $M_H$ = 130-160 GeV

Extends exclusion range significantly beyond Tevatron from ~175 to 190

Not yet competitive near LEP limit



# *Background-only p-values at low-mass*

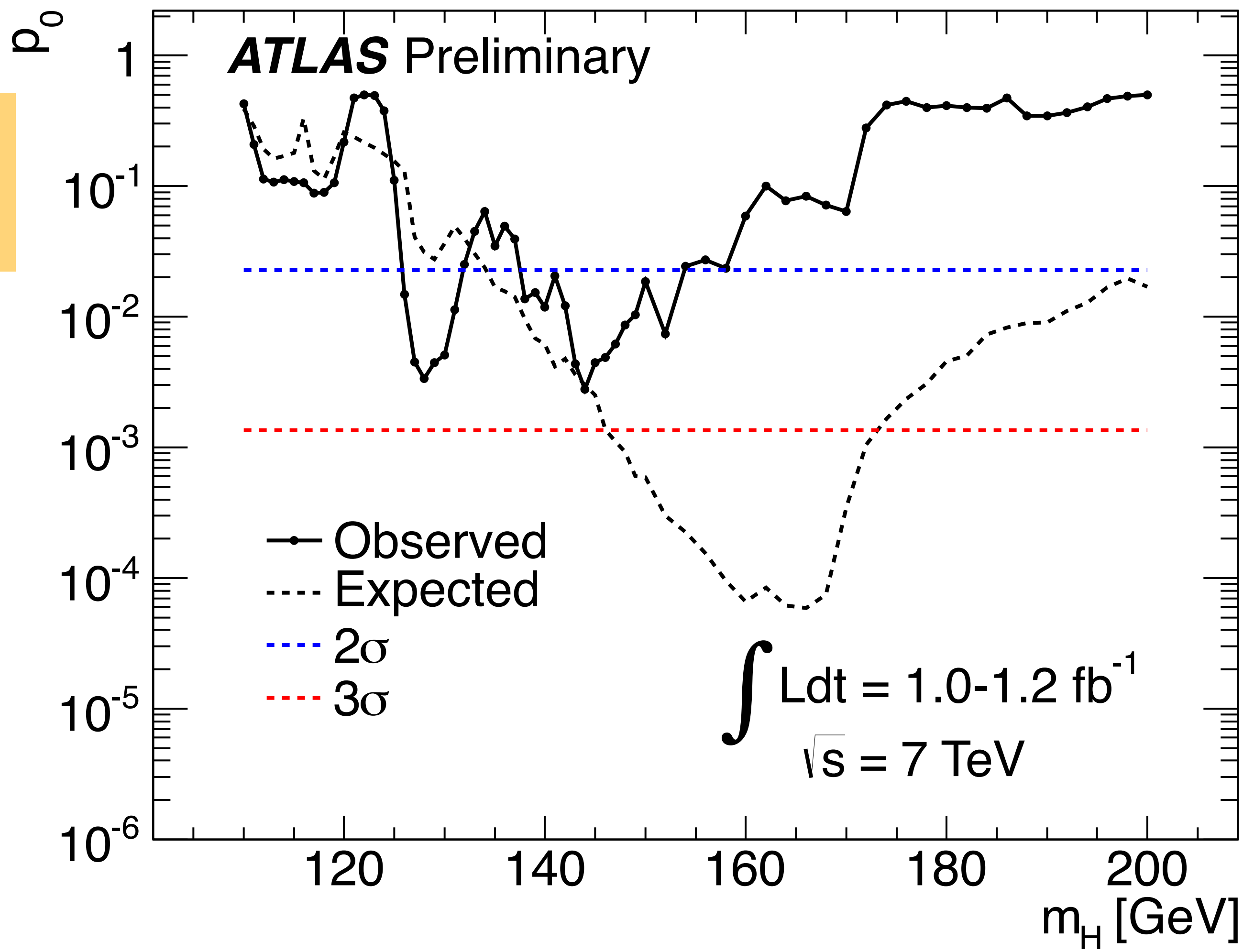


## Broad WW excess is modulated by local fluctuations in $\gamma\gamma$ and 4l

- local significance, no look-elsewhere effect correction applied

Test statistic defined such that downward fluctuation gives $p_0$=50%

Largest excess has approximately 2.8σ significance



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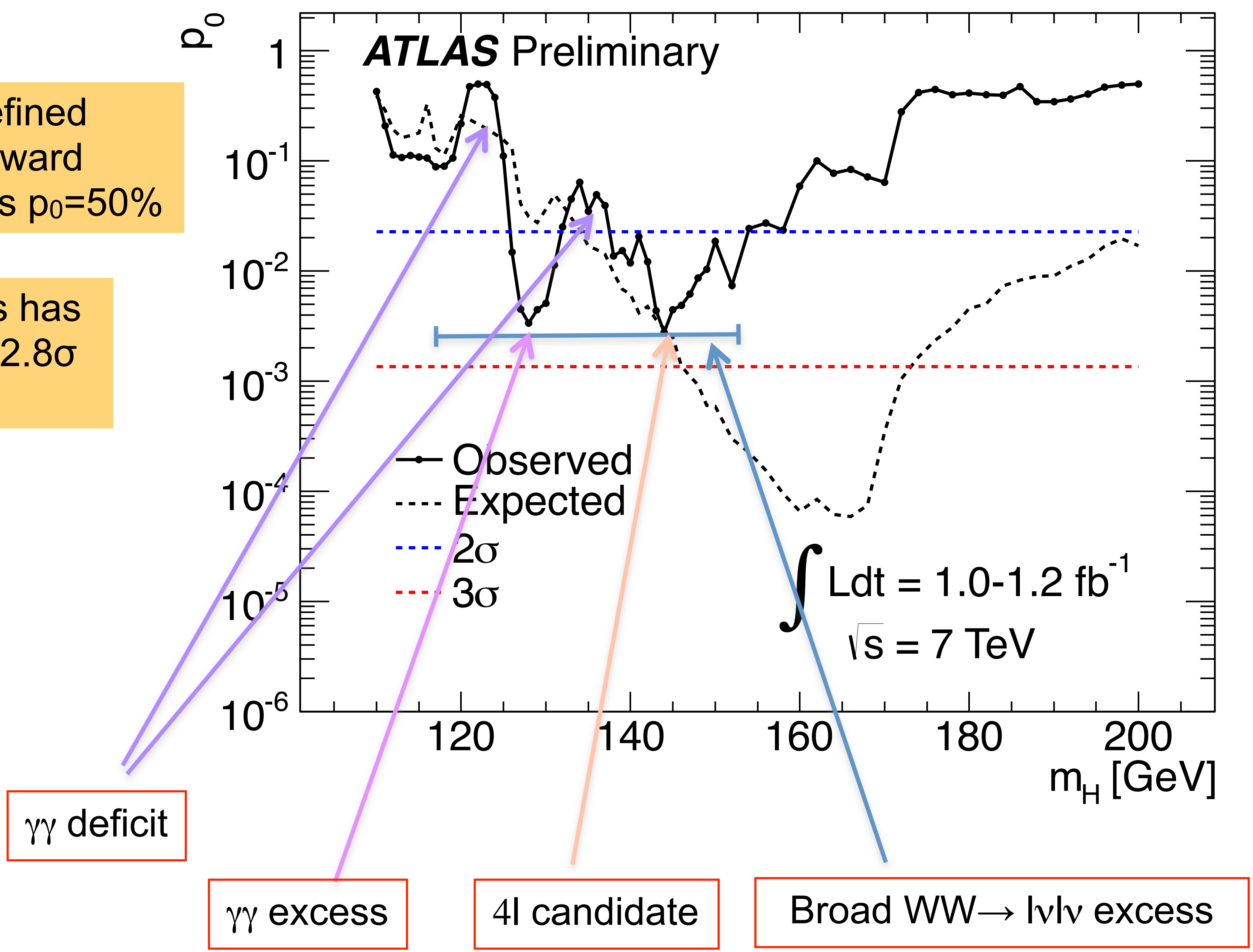
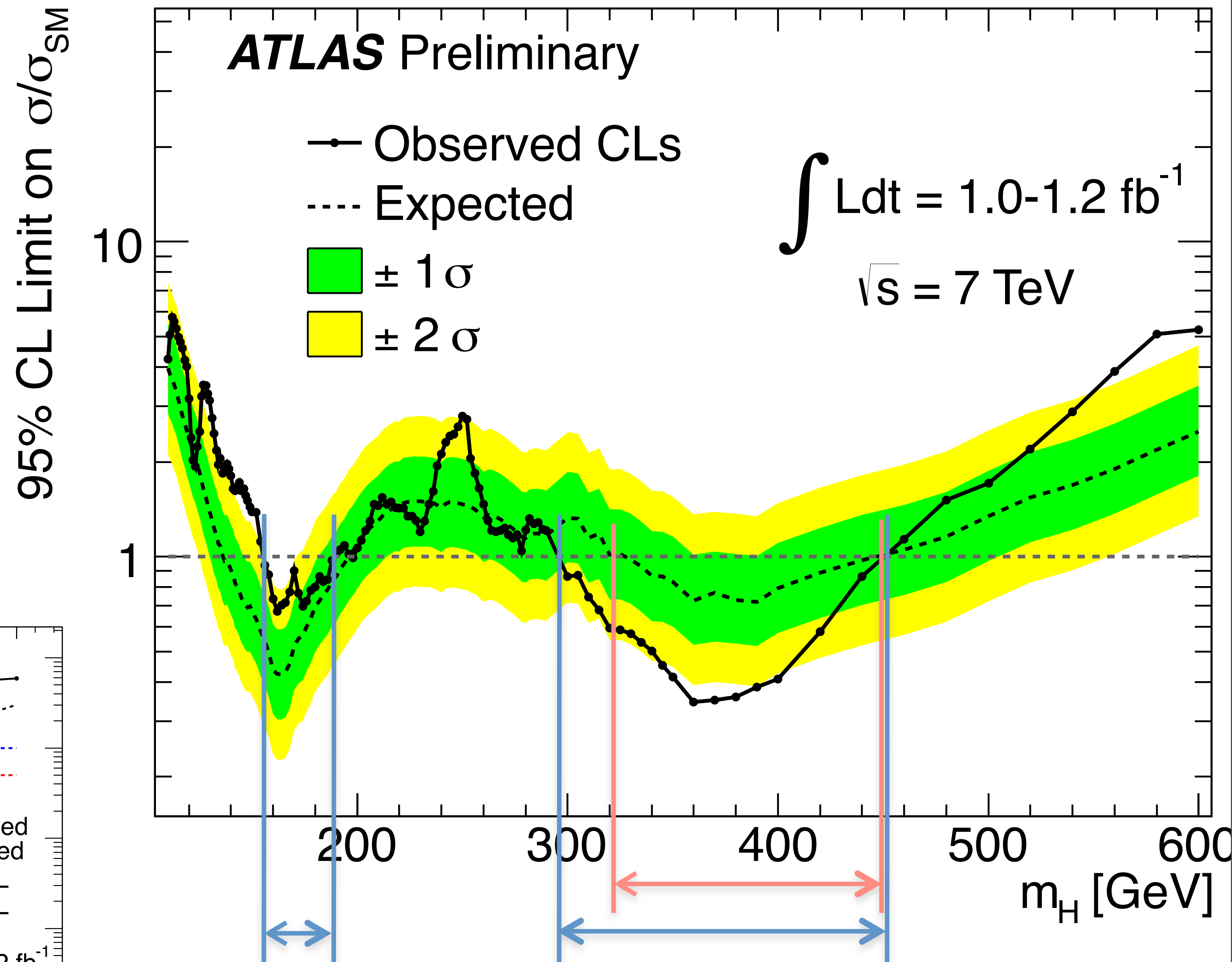


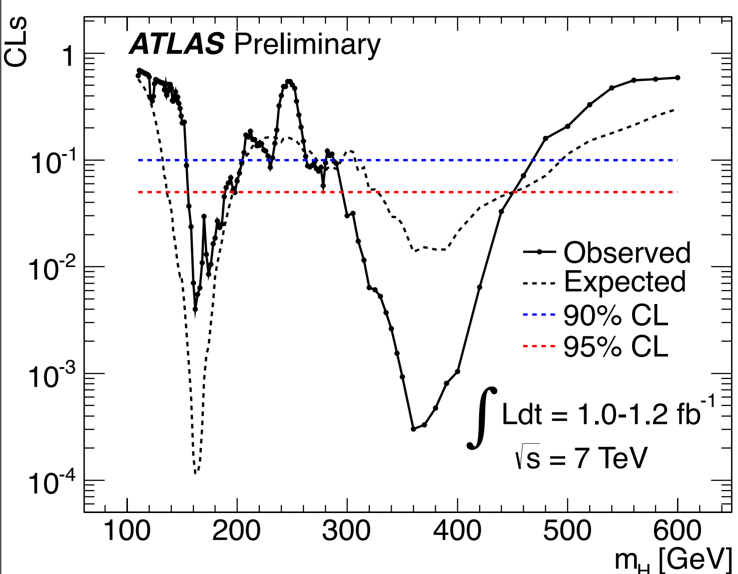
# Limits full mass range



Additional High-mass channels extend the $H \rightarrow ZZ \rightarrow ll\nu\nu$ exclusion

Noticeable excess around 250 GeV from $H \rightarrow ZZ \rightarrow 4l$ candidates



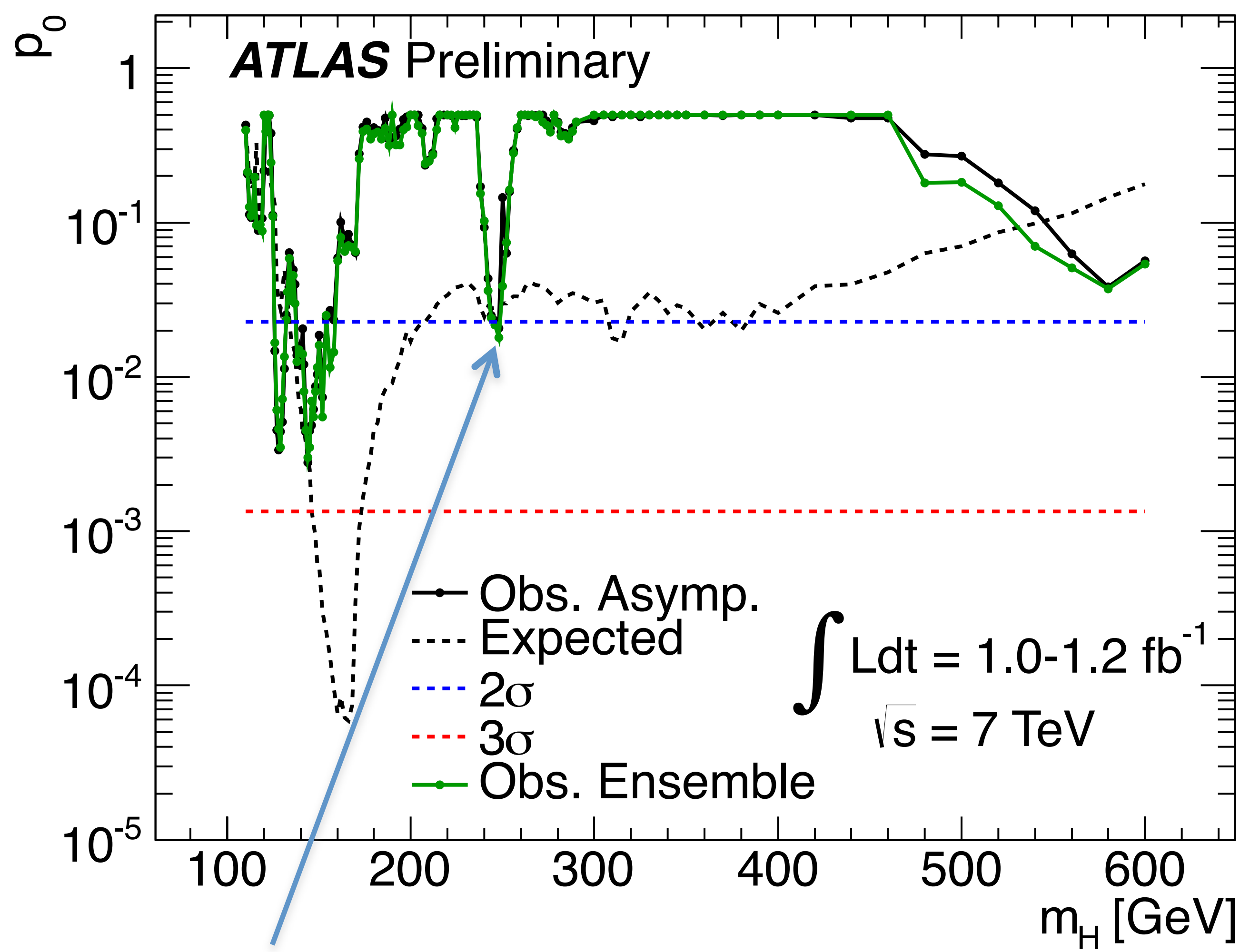

$155 < M_H < 190$ and $295 < M_H < 450$ GeV/$c^2$ excluded at @ 95% CL

# p-values full mass range

Approximately 8% chance of background-only fluctuation this large anywhere in range

No combined excess beyond 3σ is observed

Asymptotic approximation in good agreement with ensemble tests




H→ZZ→ 4l candidates

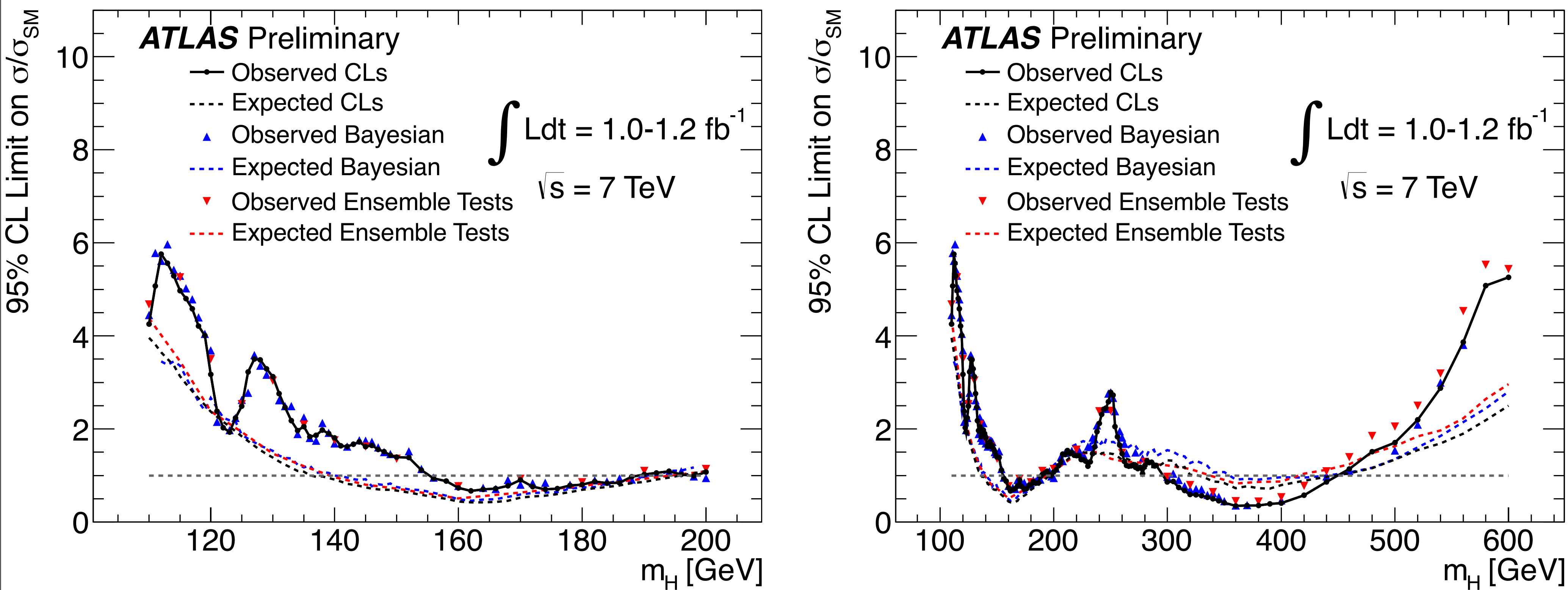
# Cross-checks



The full limit procedure was performed with toys to confirm the asymptotic distributions of the profile likelihood ratio

- Toy Monte Carlo is significantly more computationally intensive and sensitive to fit failures etc. Asymptotic results are robust

In addition, a Bayesian procedure, which is known to reproduce the CLs limit in simple problems, also yielded consistent results.



# Conclusions



Thanks to the excellent LHC operations, ATLAS has collected more than 1 $fb^{-1}$ of 7 TeV data leading to substantial gains in sensitivity to the Standard Model Higgs

- In the low-mass range (120 − 140 GeV) an excess of events with a significance of approximately 2.8σ is observed.

ATLAS has extended the 95% CL excluded region around $2M_W$ to $155<M_H<190$ GeV and excluded a new range from $295<M_H<450$ GeV

We congratulate the LHC for terrific performance and look forward to more successful running in 2011!

We also look forward to the results from CMS and the upcoming ATLAS+CMS Higgs combination

# Backup

# Results with PCL

Center for Cosmology and Particle Physics

While CLs is well a established technique in our field, it is considered a non-standard procedure by statistician mixing notions of power and coverage

- it intentionally over-covers to protect against setting limits beyond the experiments sensitivity due to downward fluctuations

An alternative approach (PCL) is based on purely frequentist CLs+b together with a “power-constraint” at the experiments sensitivity achieves the same protection without mixing the notions of coverage and power