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# Overview of Higgs results from the ATLAS experiment

**21st International Conference on SuperSymmetry and Unification of Fundamental Interactions**
**August 26th- 31st, 2013**

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on behalf of the ATLAS collaboration

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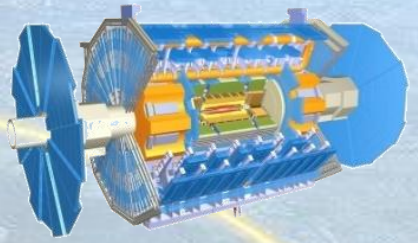
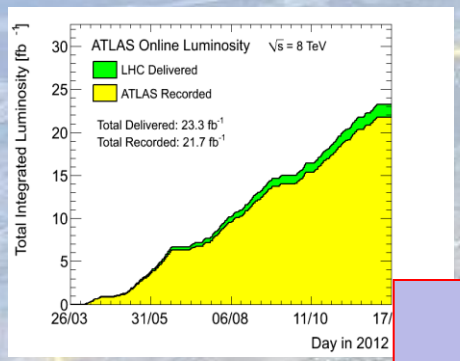
# ATLAS and the LHC: Run I performance

**The LHC has performed very well**

**Peak luminosity: 7.7 x $10^{33}$ $cm^{-2}s^{-1}$**

**More than 25 $fb^{-1}$ delivered to ATLAS and CMS.**



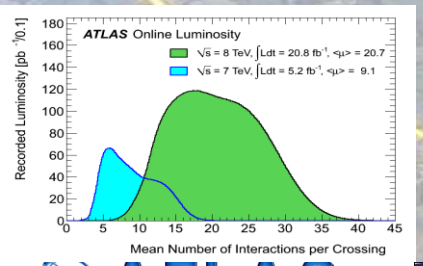



**ATLAS has collected data efficiently**

**Collecting good data 95% of the time**

**High quality data for physics analysis:**

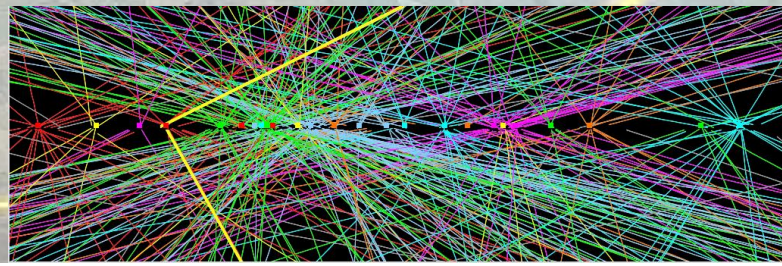
**4.7 - 4.9 $fb^{-1}$ at √s = 7 TeV and 20.3 $fb^{-1}$ at √s = 8 TeV**




**Pile-up has been higher than foreseen**

**Well modelled**

**Not a major issue for analysis**



# What has happened since the discovery?

Combination of results $H\to\gamma\gamma$, $H\to ZZ^*$ & $H\to WW^*$ with full data (25 $fb^{-1}$) to determine

⇒ mass and couplings (arXiv:1307.1427)

⇒ spin and parity (arXiv:1307.1432)

Preliminary results:

⇒ $H\to\gamma\gamma$ differential cross-sections (25 $fb^{-1}$) (ATLAS-CONF-2013-072)

⇒ VH with $H\to bb$ (25 $fb^{-1}$) (ATLAS-CONF-2013-079)

⇒ $H\to\tau\tau$ (18 $fb^{-1}$) (ATLAS-CONF-2012-160)

⇒ ttH with $H\to\gamma\gamma$ (20 $fb^{-1}$) (ATLAS-CONF-2013-080)

⇒ $H\to\mu\mu$ (21 $fb^{-1}$) (ATLAS-CONF-2013-010)

⇒ $H\to Z\gamma$ (25 $fb^{-1}$) (ATLAS-CONF-2013-009)

⇒ VH with $H\to WW$ (25 $fb^{-1}$) (ATLAS-CONF-2013-075)

⇒ ZH with $H\to$invisible (18 $fb^{-1}$) (ATLAS-CONF-2013-011)

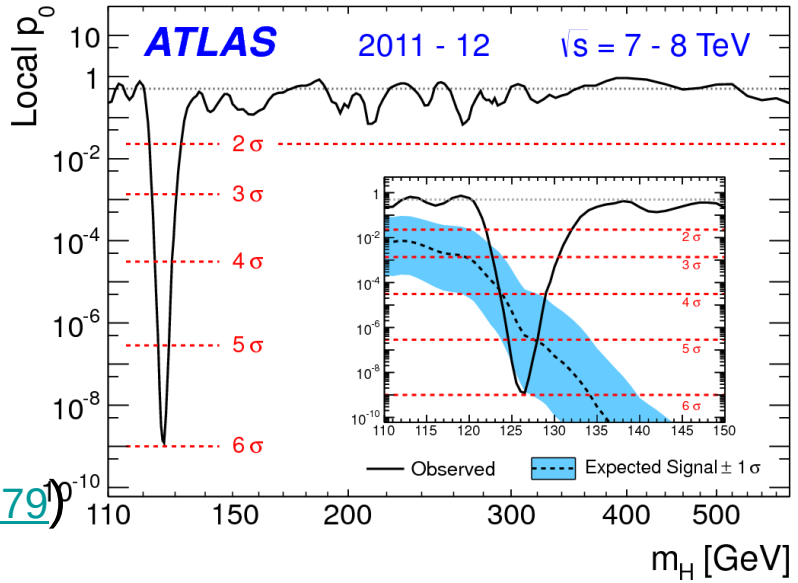
⇒ High mass Higgs (25 $fb^{-1}$)

⇒$H\to ZZ\to 4$ leptons (ATLAS-CONF-2013-013)

⇒$H\to WW\to e\nu\mu\nu$ (ATLAS-CONF-2013-067)

**4th July 2012**

*Phys. Lett. B 716 (2012) 1-29*

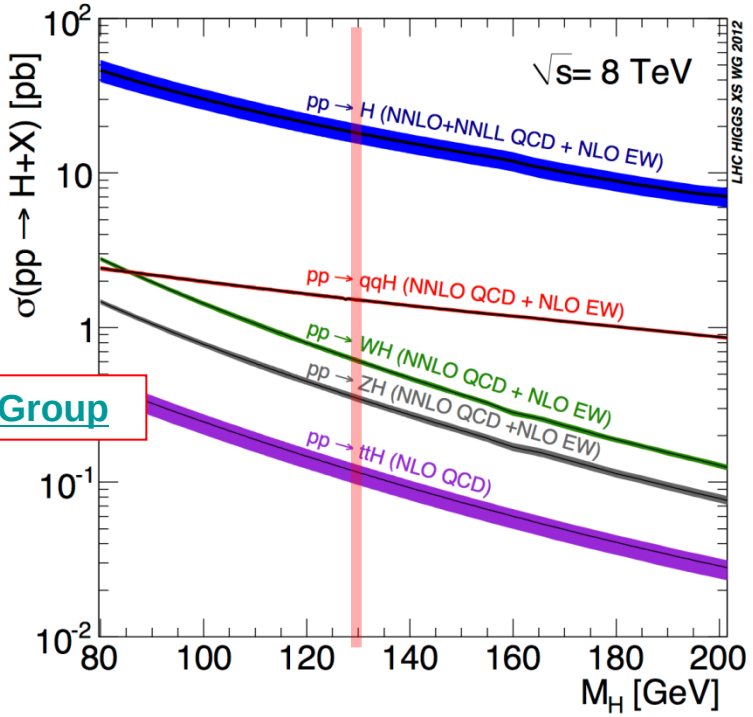



Cross section limits/significances presented are based on the signal confidence level ($CL_S$) determined using the profile likelihood method (arXiv:1007.1727). For more details see e.g. ATLAS-CONF-2013-034.

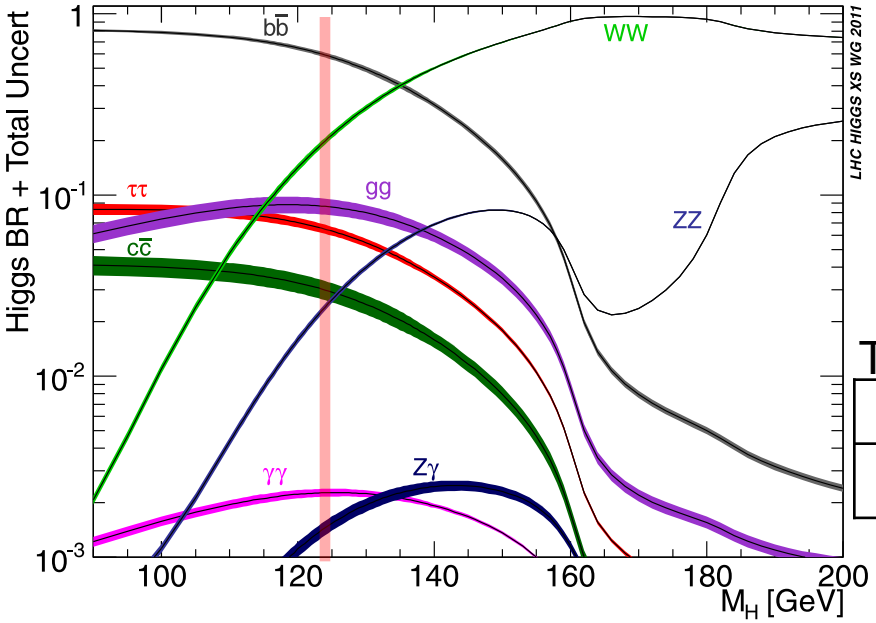
# Production and decay modes at the LHC

Cross sections SM Higgs 125.5 GeV @ 8 TeV

- Gluon-gluon fusion (ggF): 19 pb
- Vector boson fusion(VBF) 1.6 pb
- Associated production:
  WH: 0.70 pb / ZH: 0.41 pb / ttH: 0.13 pb




**LHC Higgs Cross Section Working Group**




The decay modes of a 125.5 GeV SM Higgs

| bb | WW* | ττ | ZZ* | γγ | Zγ | μμ |
|---|---|---|---|---|---|---|
| 57% | 22% | 6.2% | 2.8% | 0.23% | 0.16% | 0.02% |

Many have contributed to the calculation cross section branching ratios. For a detailed description and a complete set of references see CERN Yellow Reports I, II and III (arXiv:1101.0593, arXiv:1201.3084 and arXiv:1307.1347)

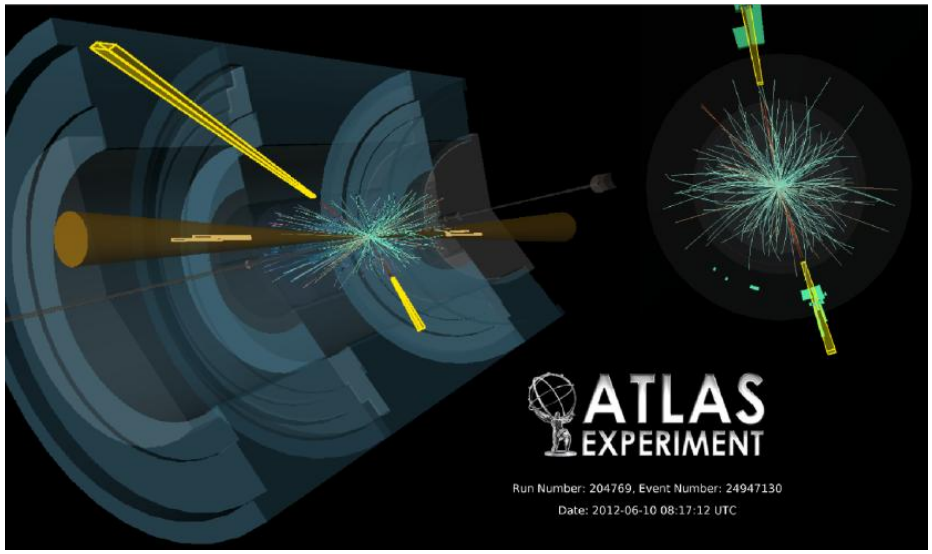
# Higgs decays to bosons
# $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^* \rightarrow 4l$, $H\rightarrow WW^* \rightarrow l\nu l\nu$

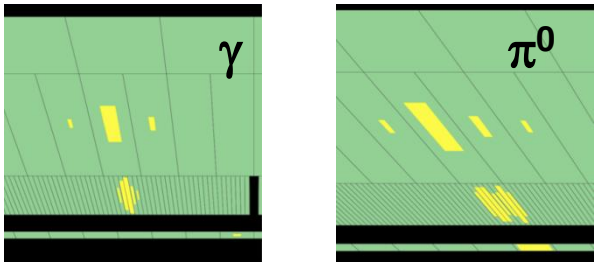
# $H \rightarrow \gamma\gamma$

arXiv:1307.1427

Small branching fraction, but excellent mass resolution.

Sensitivity to spin ($0^+/2^+$) / excludes spin 1 (Landau-Yang)

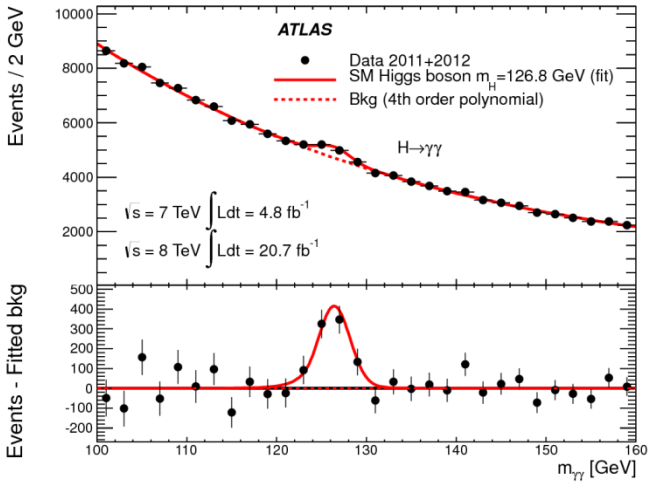



Excellent $\gamma$-jet separation in 1st layer of Liquid Argon calorimeter.

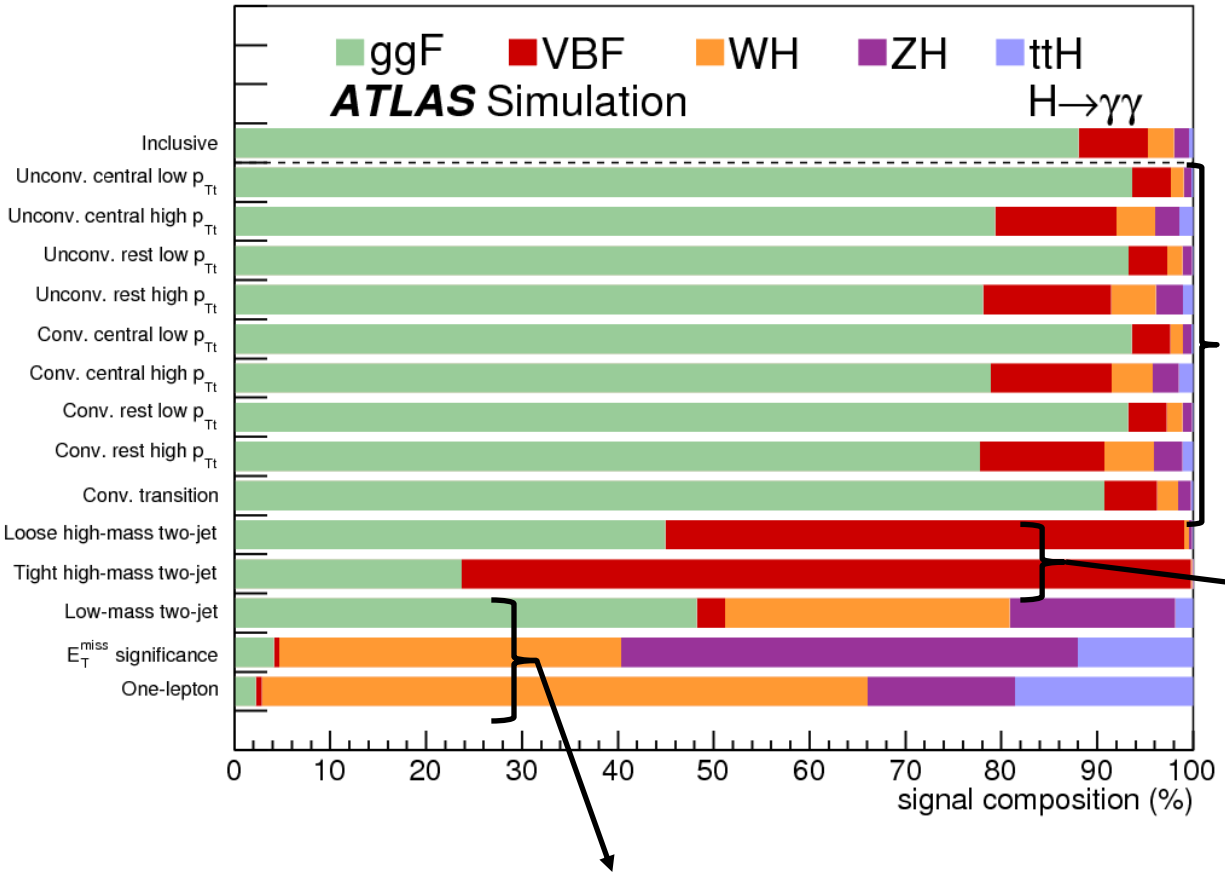
Only ~25% of background is from jet-jet or $\gamma$-jet events

Extract signal in simultaneous fit of signal and background.



# H→γγ search categories

arXiv:1307.1427

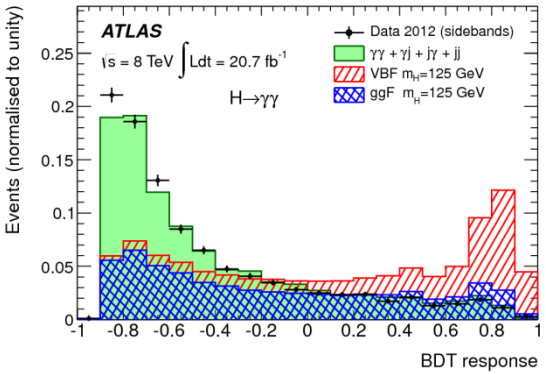



**9 combinations of:**

- converted/unconverted
- forward/central
- $p_T$ range

**2 VBF enhanced categories**

- high mass jet pair and BDT cut




**3 VH enhanced categories:**

- low mass jet pair
- 1 lepton and/or missing $E_T$

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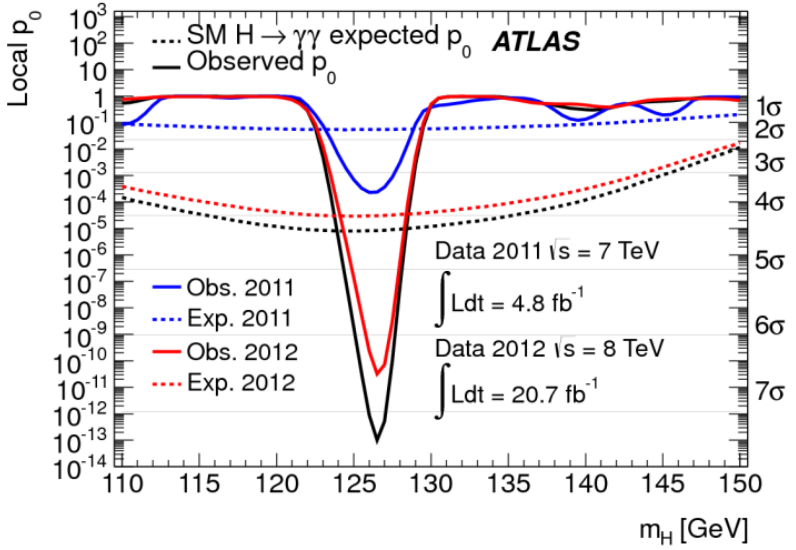
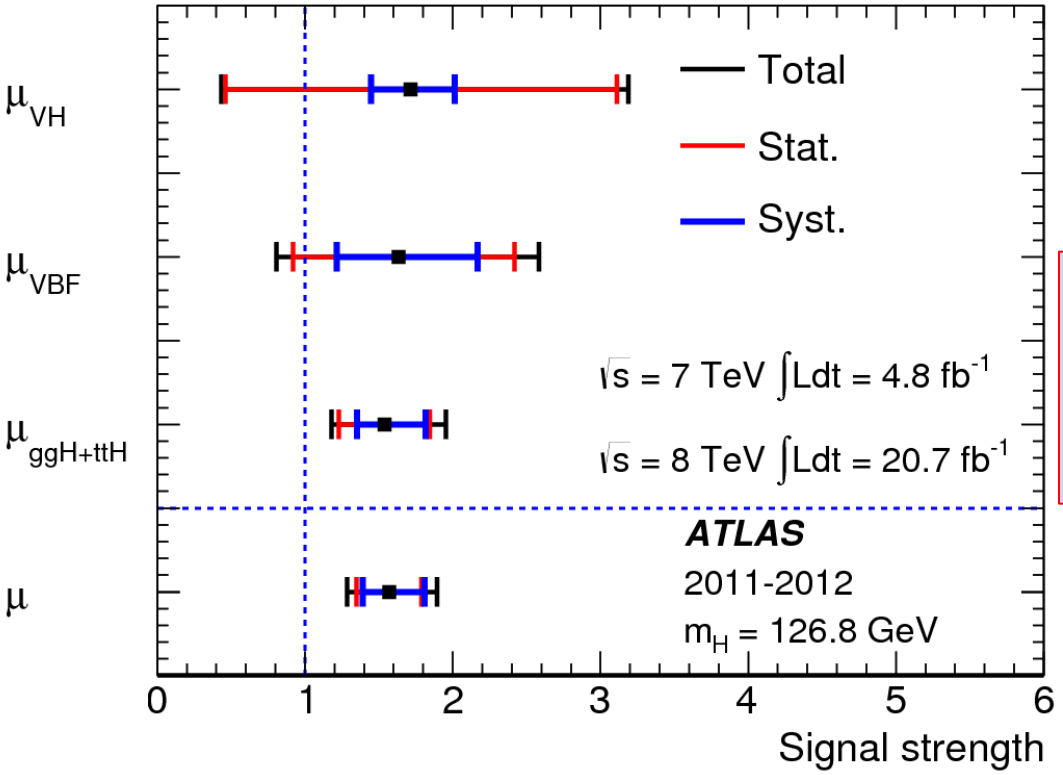
arXiv:1307.1427

# H→γγ results

**Overall signal significance:**
**7.4σ (4.3σ exp.)**




**Best fit signal strength:**

$$\mu = 1.55^{+0.33}_{-0.28}$$

where: $\mu = \dfrac{\sigma \times BR}{(\sigma \times BR)_{SM}}$

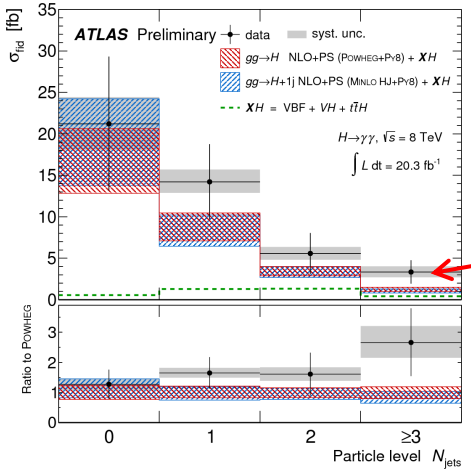
# NEW: H→γγ differential cross sections

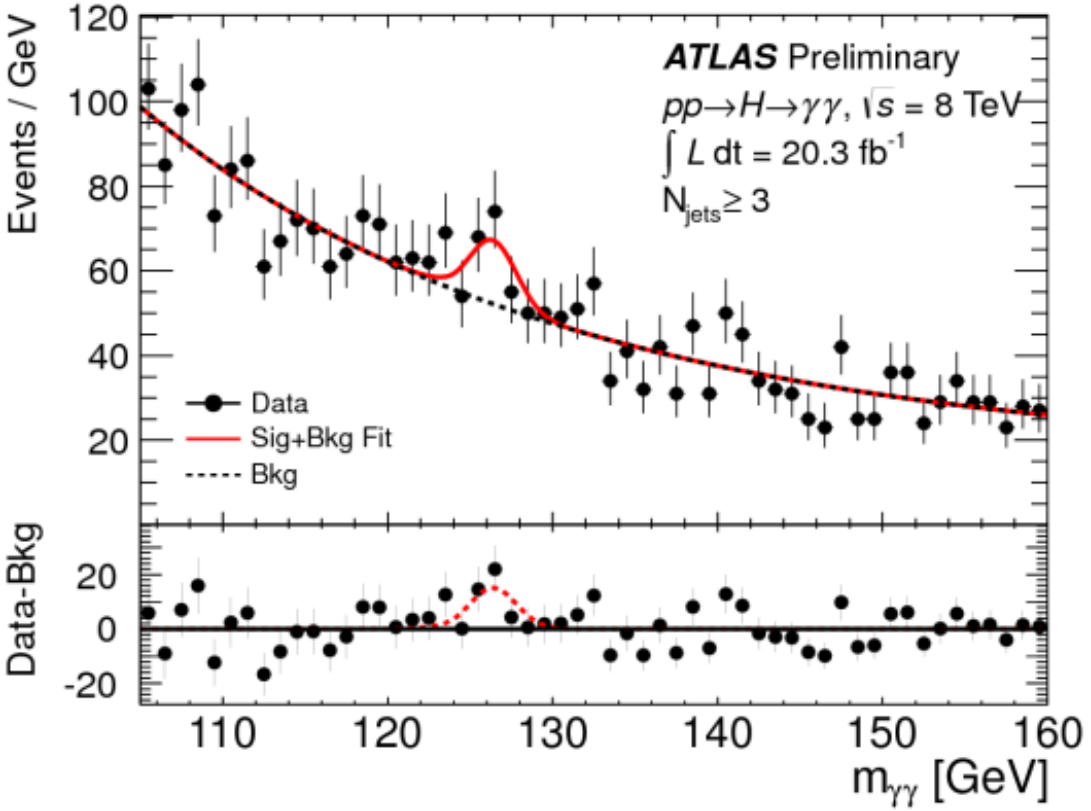
ATLAS-CONF-2013-072

Repeat fit to extract signal in each bin

(Signal model: ggF + VBF + VH + ttH @ $m_H$=126.8GeV)

example:≥ 3 jets

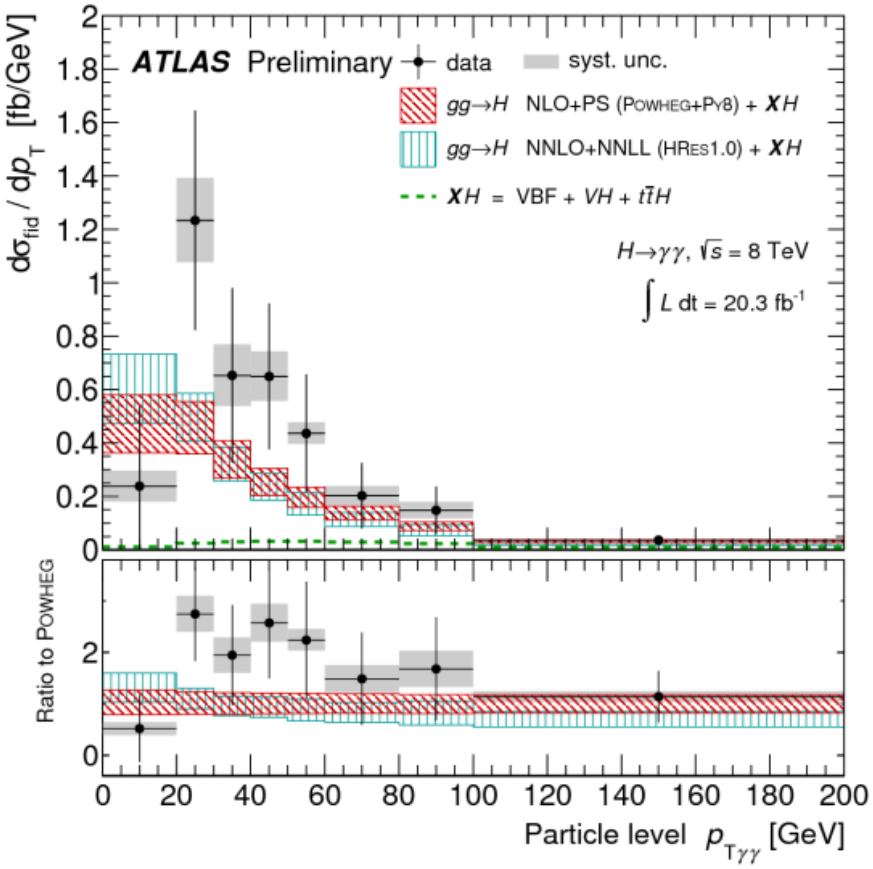


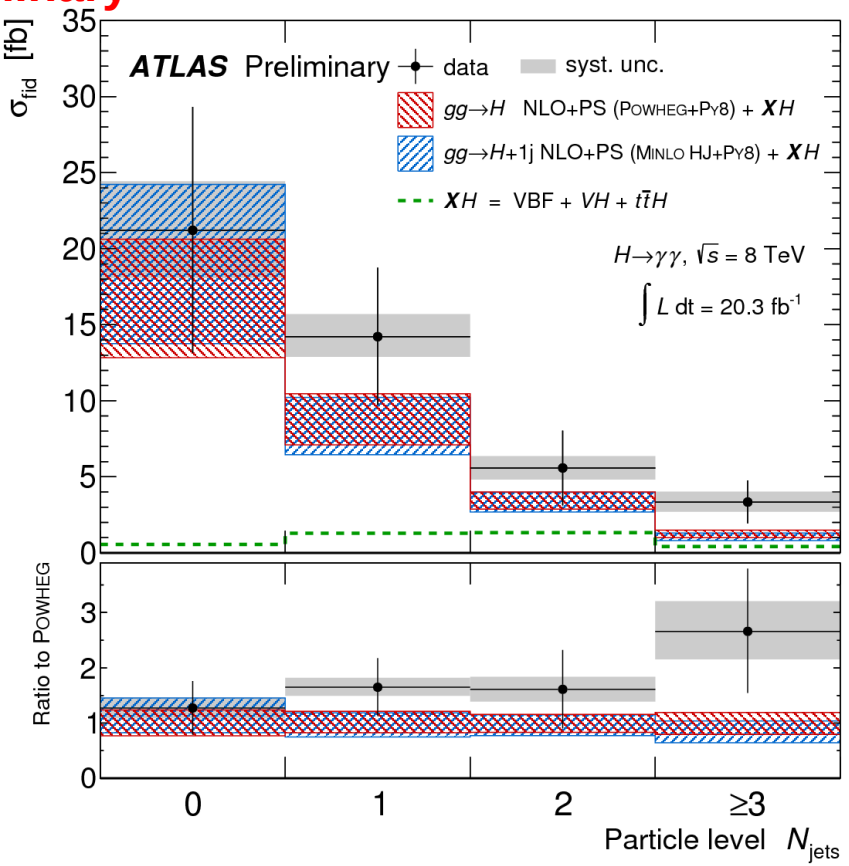



# NEW: H→γγ differential cross sections

ATLAS-CONF-2013-072

**Preliminary**



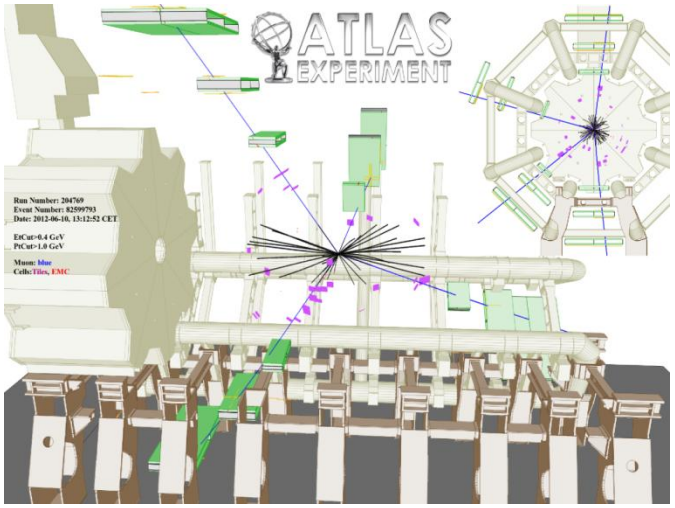

⇒ for other distributions see ATLAS-CONF-2013-072

$P_T$ spectrum in data appears harder but errors (stat & theory) are still large.

No significant disagreements with expectation SM Higgs

# H→ZZ* → 4 leptons

arXiv:1307.1427

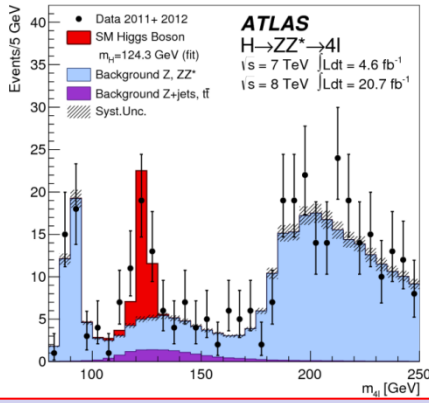


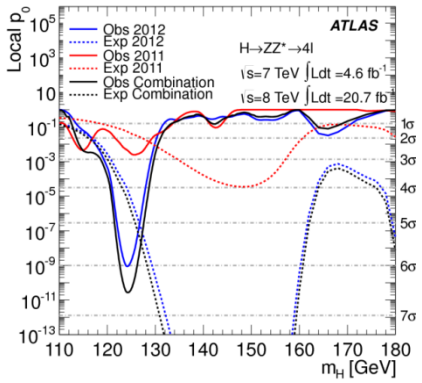

Small branching fraction, but very clean and good mass resolution.

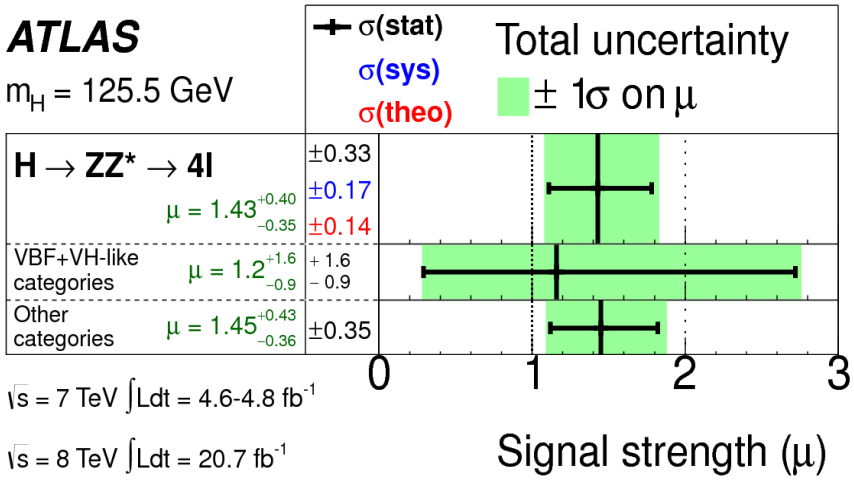
Good sensitivity to spin and parity ($0^+/0^-/1^+/1^-/2^+$)

Analysis subcategories

- VBF enhanced: high mass jet pair ($|\Delta\eta|>3$)
- VH enhanced: additional lepton
- ggF dominated: inclusive




**Overall signal significance**

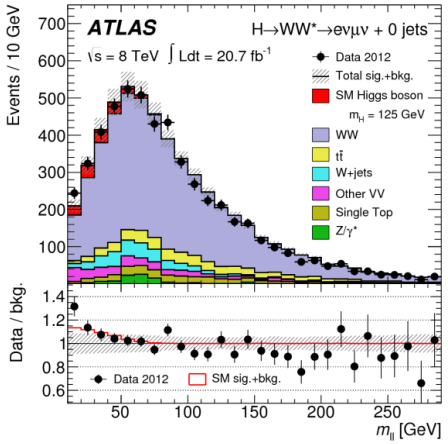
**6.6σ (4.4σ exp.)**

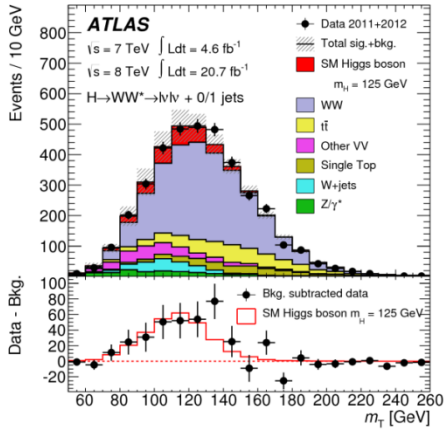
# H→WW* →lνlν

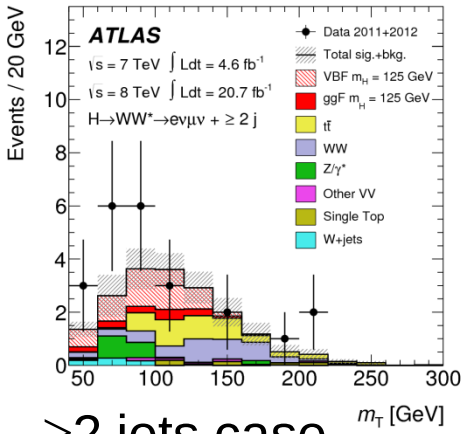
arXiv:1307.1427

High branching fraction, but limited mass resolution and significant backgrounds.

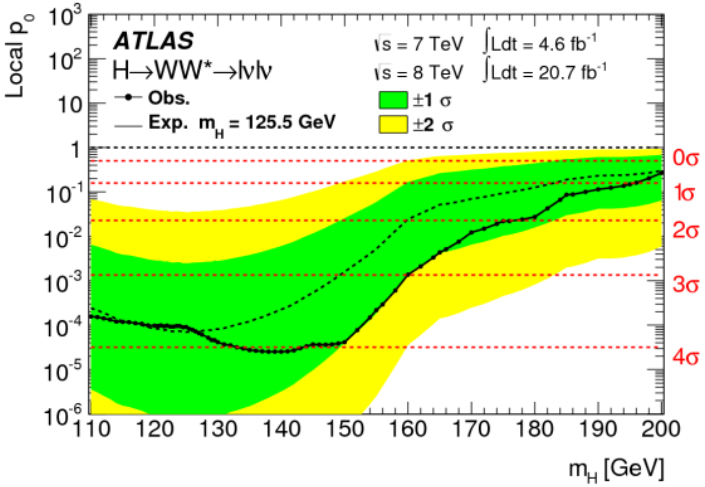
Analysis categories
- ee, μμ or eμ pair
- 0,1 or ≥2 jets

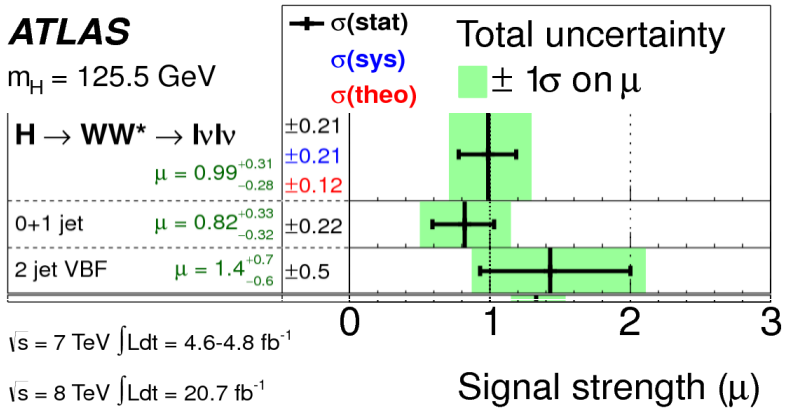



≥2 jets case optimised for VBF



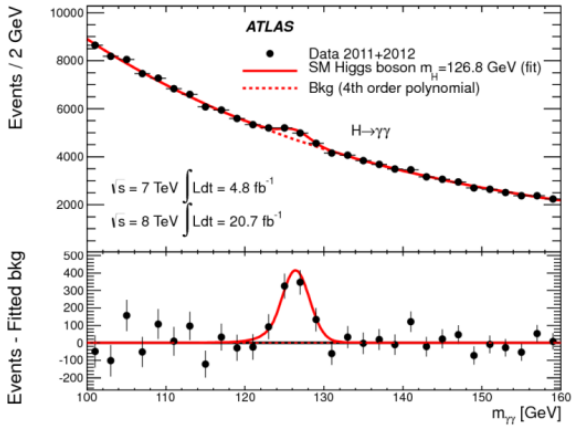

**Evidence for a Higgs (over broad range of masses)**
**3.8σ excess observed (3.8 σ expected) for $m_H$=125.5 GeV**

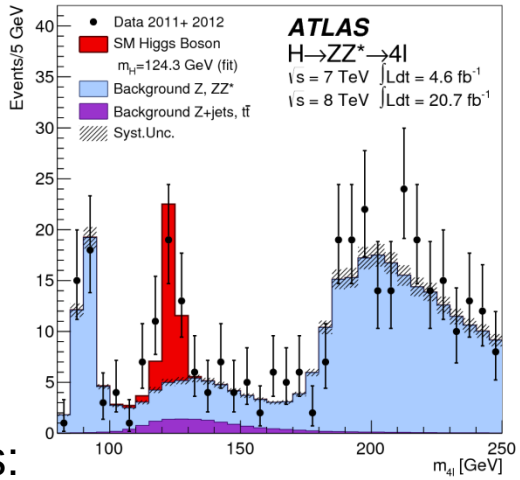
# $H \rightarrow \gamma\gamma$,ZZ*,WW* combined

Mass
Couplings
Spin and parity

# Higgs mass
# (H→γγ / H→ZZ* → 4l)

arXiv:1307.1427



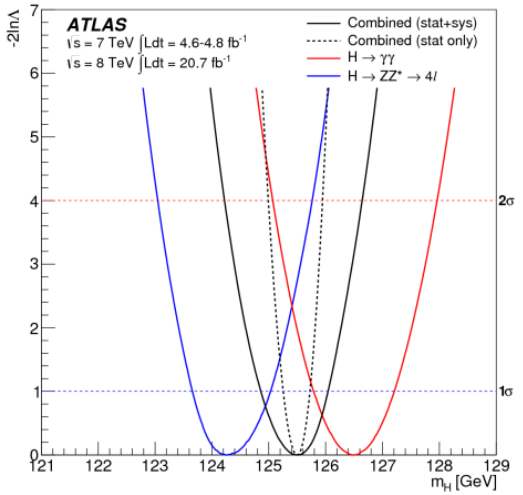

H→γγ : $m_H$ determined from combined fit in all categories.

$$m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})\,\text{GeV}$$

H →4 leptons:
$m_H$ determined from unbinned likelihood fit

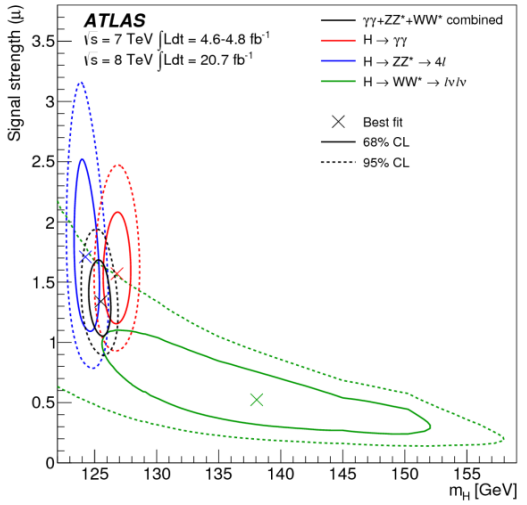
$$m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})\,\text{GeV}$$

Mass difference 2.4σ, which has a ~1.5% probability to occur.
(increases to 8% if we assume a flat prior for the energy scale uncertainties)




Combined mass

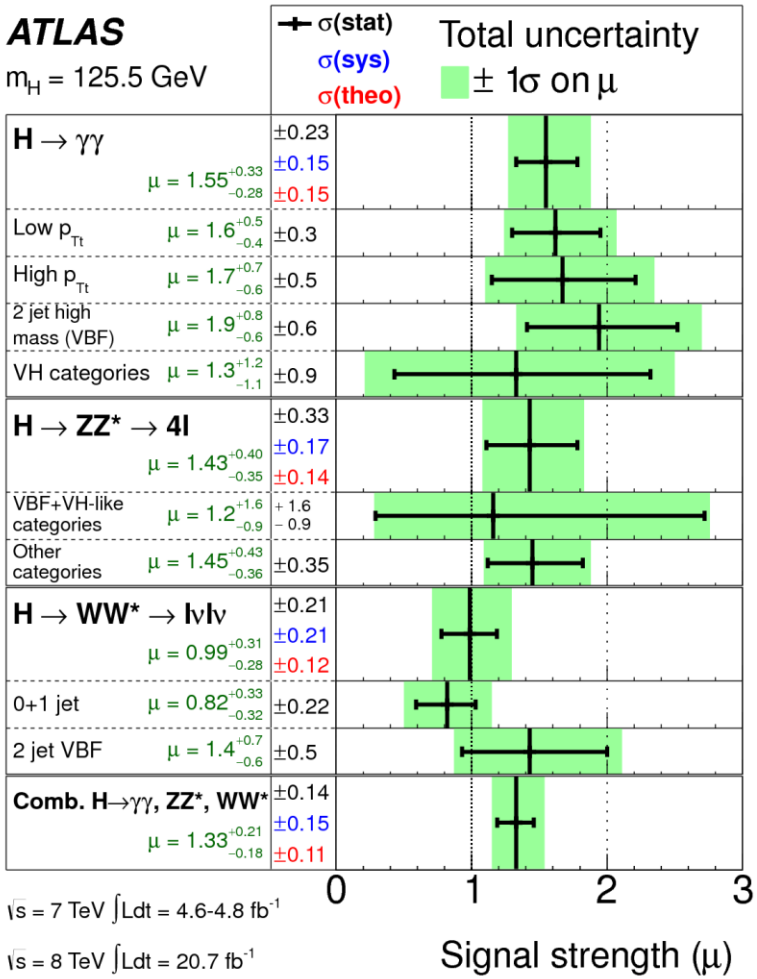
$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\,\text{GeV}$$



# Couplings combination

arXiv:1307.1427

Combined results H→γγ, H→ZZ*→4l, H→WW*→lνlν channels, including VBF or VH enhanced cases.




**Overall signal strength:**

$$\mu = 1.33^{+0.21}_{-0.18}$$

Statistical, systematic and theory uncertainties are already comparable.

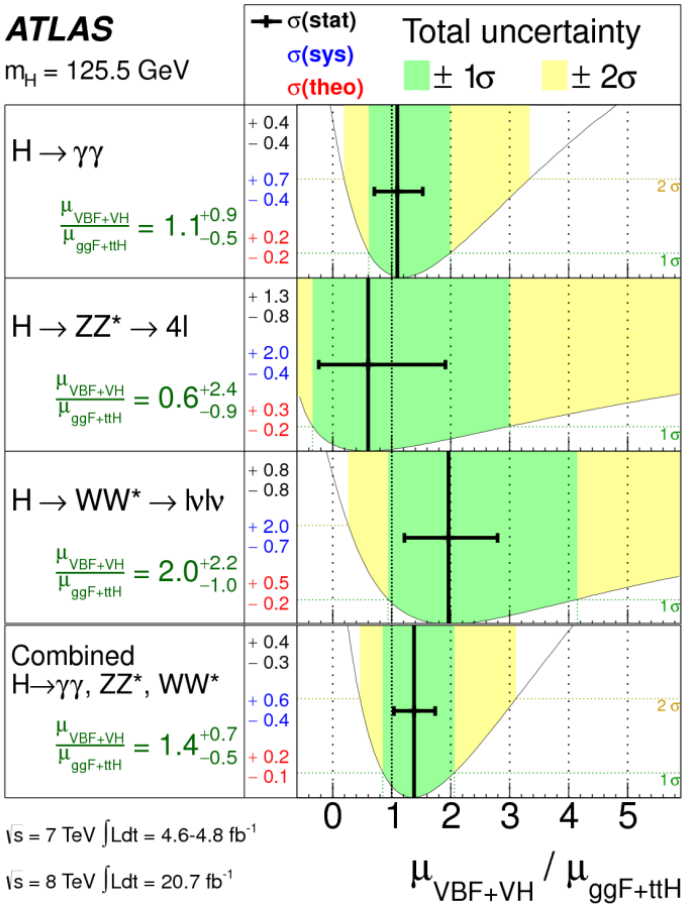
# Evidence for Higgs production via vector-boson fusion

arXiv:1307.1427

VBF enhanced analyses in $H\to\gamma\gamma$, $H\to ZZ^*\to 4l$ and $H\to WW^*\to l\nu l\nu$ all find a VBF component consistent with the SM expectation.

Combined the VBF(+VH) to ggF(+ttH) ratio is

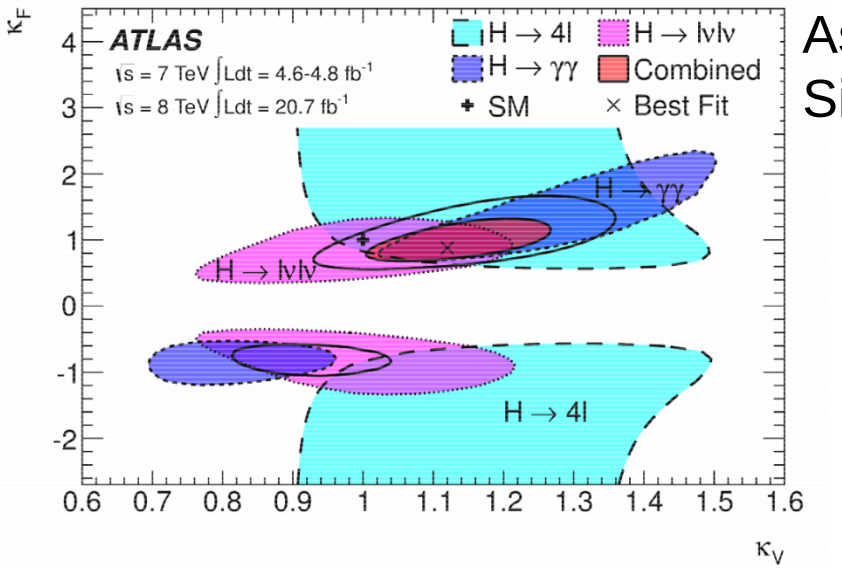
$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.4^{+0.7}_{-0.5}$$



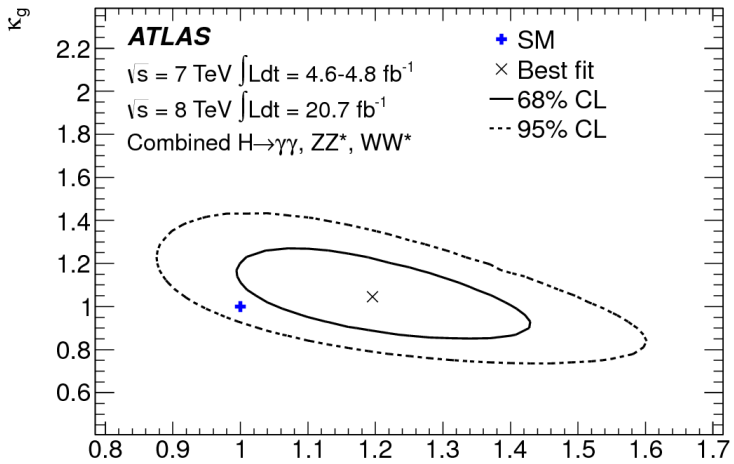

**3.3 σ evidence that a non-zero fraction of Higgs events is produced via vector boson fusion**

# Coupling parameters

arXiv:1307.1427




Assumption:
Single narrow resonance with m=125.5GeV




$\kappa_F$ $\kappa_V$ : scale factors fermion/boson couplings
$\kappa_F$ = 0 (fermiophobic H) excluded at >5σ CL
Negative $\kappa_F$ still allowed at ~2σ level
68% CL intervals:

$$\kappa_F \in [0.76,\ 1.18]$$
$$\kappa_V \in [1.05,\ 1.22]$$

$\kappa_g$ $\kappa_\gamma$ : scale factors for gg→H and H→γγ loops

$$\kappa_g = 1.04 \pm 0.14$$
$$\kappa_\gamma = 1.20 \pm 0.15$$

Custodial symmetry
$\lambda_{WZ}$ : ratio scale factors for W and Z couplings
($\lambda_{WZ}$ =1 in SM)

$$\lambda_{WZ} = 0.82 \pm 0.15$$

# Spin and Parity of the candidate boson

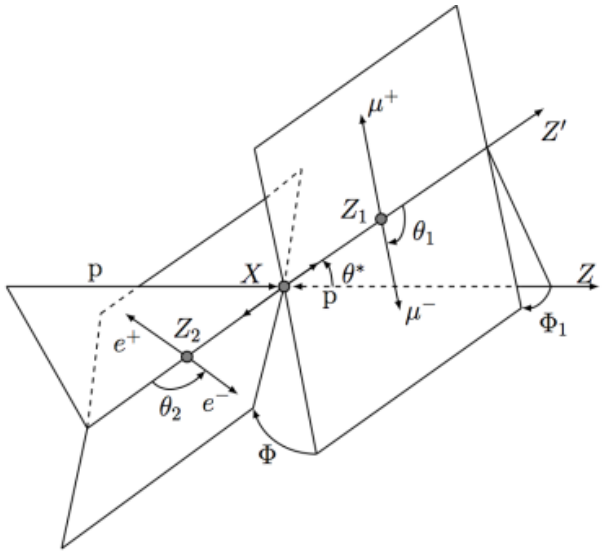
Test various options ($J^p=0^-$, $0^+$,$1^-$,$1^+$,$2^+$) using angular and kinematic distributions in $H\rightarrow\gamma\gamma$,$H\rightarrow ZZ^*\rightarrow 4l$ and $H\rightarrow WW^*\rightarrow l\nu l\nu$.

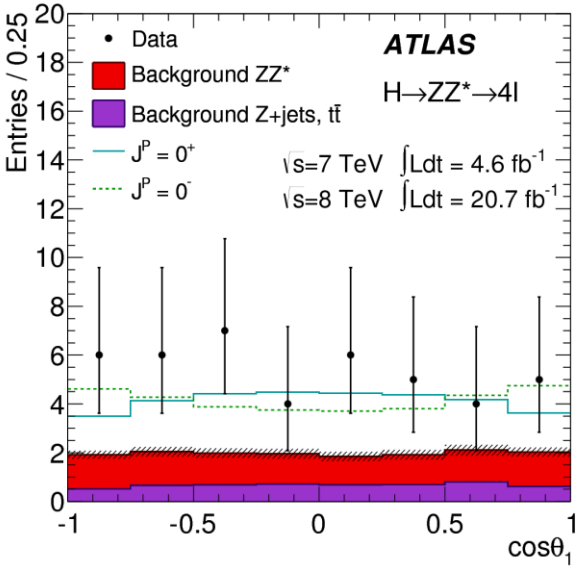
For a detailed description of the used theoretical calculations and a complete set of references see:

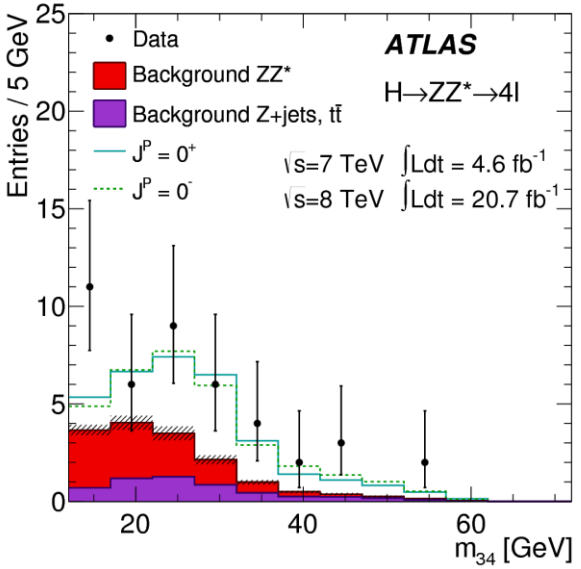
**CERN Yellow Report III (arXiv:1307.1347)**

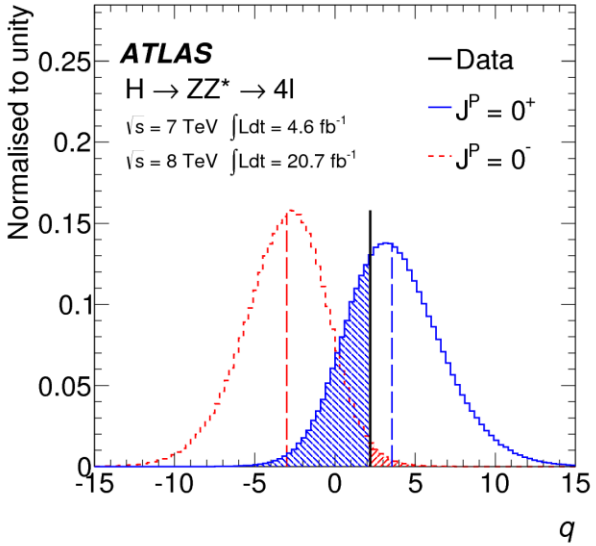
# $J^p=0^+$ vs $0^-$ ($H\to ZZ^*\to 4l$)

arXiv:1307.1432




Measure the log likelihood ratio q

$$q = \log \frac{L(J^p = 0^+)}{L(J^p = 0^-)}$$

and compare to the expected distributions.

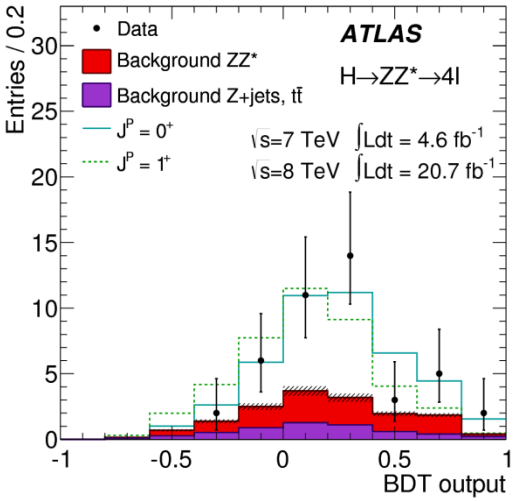
**Data agree with $0^+$ hypothesis,**
**$0^-$ hypothesis is excluded at 97.8% CL**

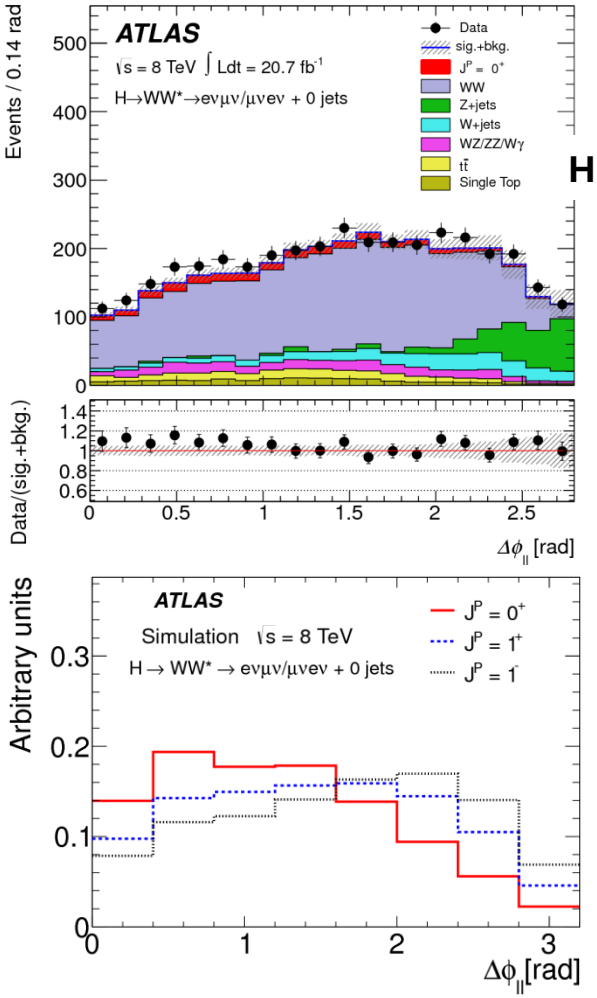
# $J^p=0^+$ vs $1^+/1^-$ ($H\to ZZ^*\to 4l$ / $H\to WW^*\to l\nu l\nu$)

arXiv:1307.1432

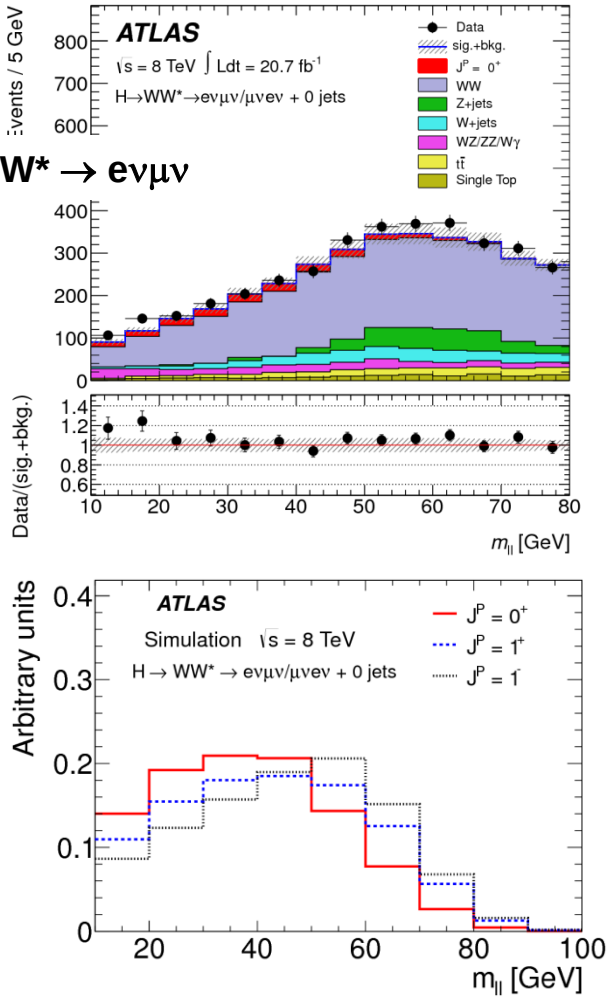
**Observation $H\to\gamma\gamma$ decay prohibits spin 1 option (Landau-Yang) for on-shell particle.**

**$H\to ZZ^*\to 4$ leptons**




**$H\to WW^*\to e\nu\mu\nu$**

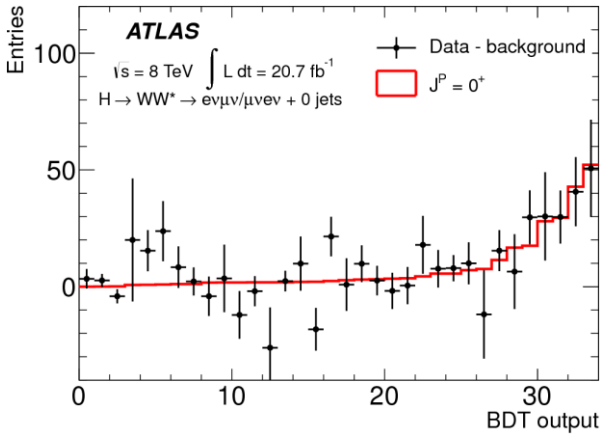


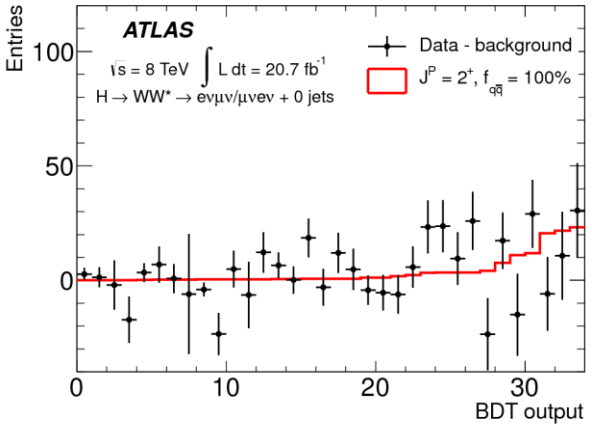

**Combined ZZ*/WW*data agree with $0^+$ hypothesis,**
**$J^p = 1^+$ hypothesis is excluded at 99.97% CL**
**$J^p = 1^-$ hypothesis is excluded at 99.7% CL**

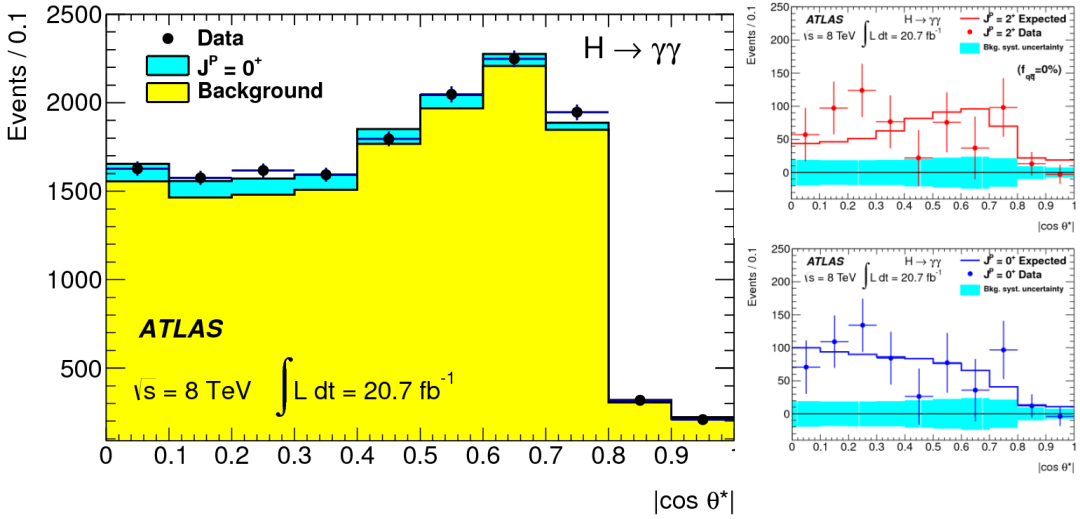
# $J^p=0^+$ vs $2^+$ ($H\to\gamma\gamma$ / $H\to ZZ^*\to 4l$ / $H\to WW^*\to l\nu l\nu$)

arXiv:1307.1432

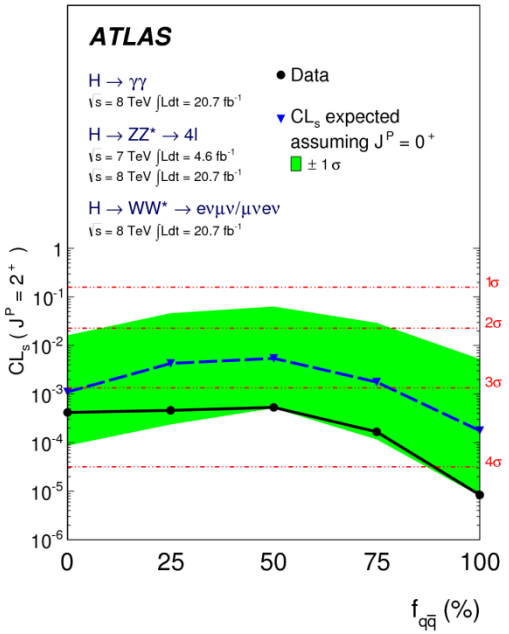
**BDT output based on WW* variables**




We vary the production mode for a $2^+$ boson from fully gluon induced ($f_{qq}$=0%) to fully quark induced ($f_{qq}$=100%)




**Data agree with $0^+$ hypothesis for all $f_{qq}$**
**$2^+$ hypothesis is excluded at >99.9% CL for all $f_{qq}$**

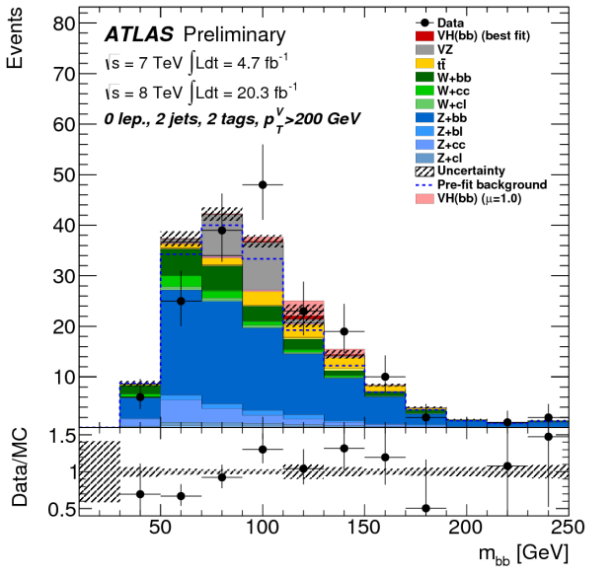
# Higgs decays to fermions
# $H \to bb$, $H \to \tau\tau$

# VH with H to bb

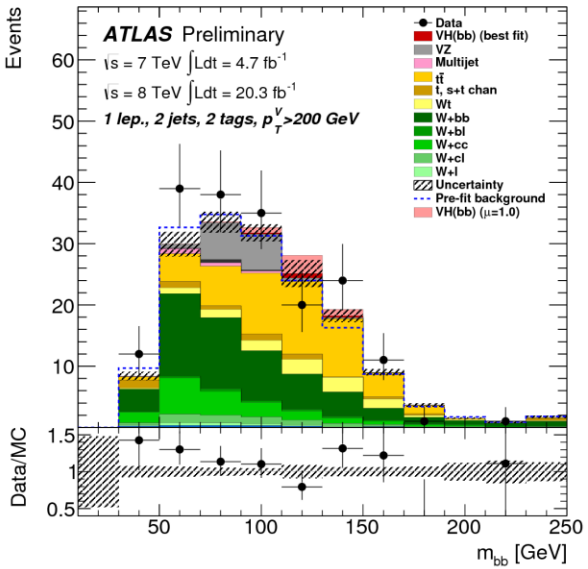
Abundant channel with difficult backgrounds.
Flavour composition of the main backgrounds is determined from data.

Analysis split in to many categories:
number of leptons = 0 / 1 / 2
number of jets (b-jets) = 2(2) / 3(2) / 2(1) / 3(1)
$p_T^V$ = [< 90 GeV] / [90..120 GeV] / [120..160 GeV] / [160..200 GeV] / [> 200 GeV]

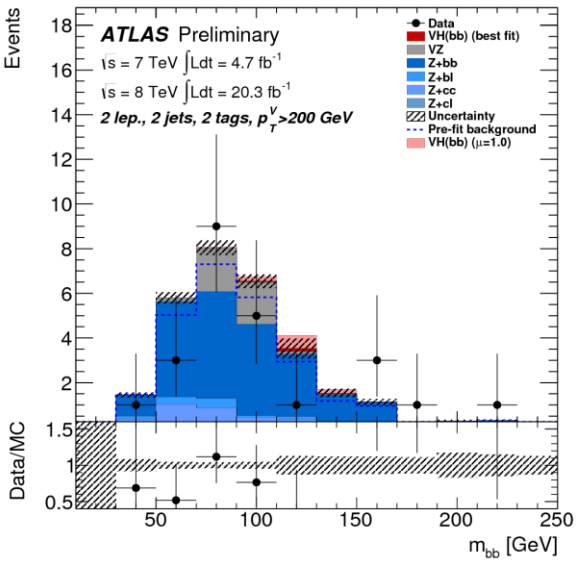
**0 leptons (ZH→νν̄bb̄)**




**1 lepton (WH→lνbb̄)**

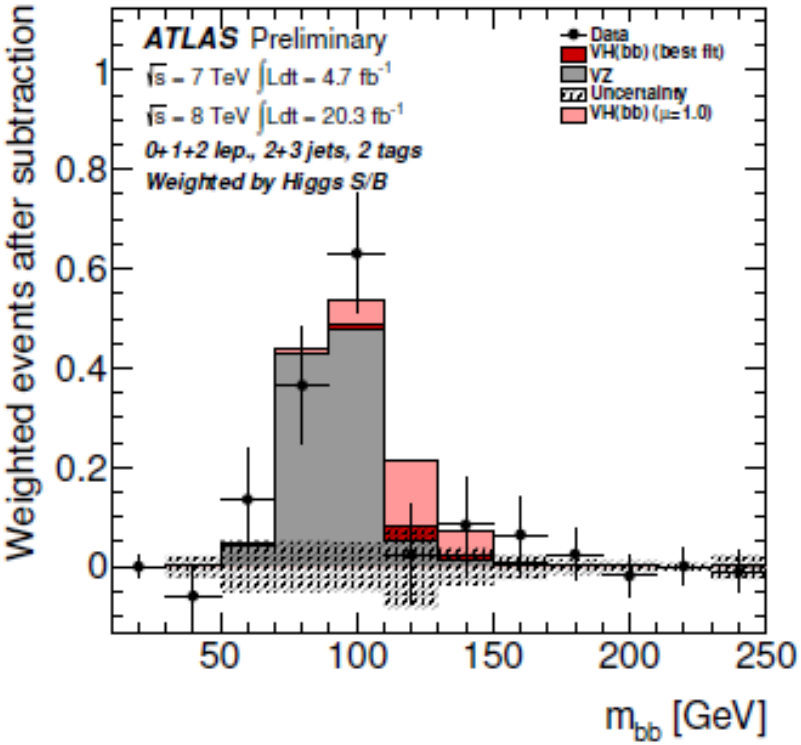



**2 leptons (ZH→llbb̄)**

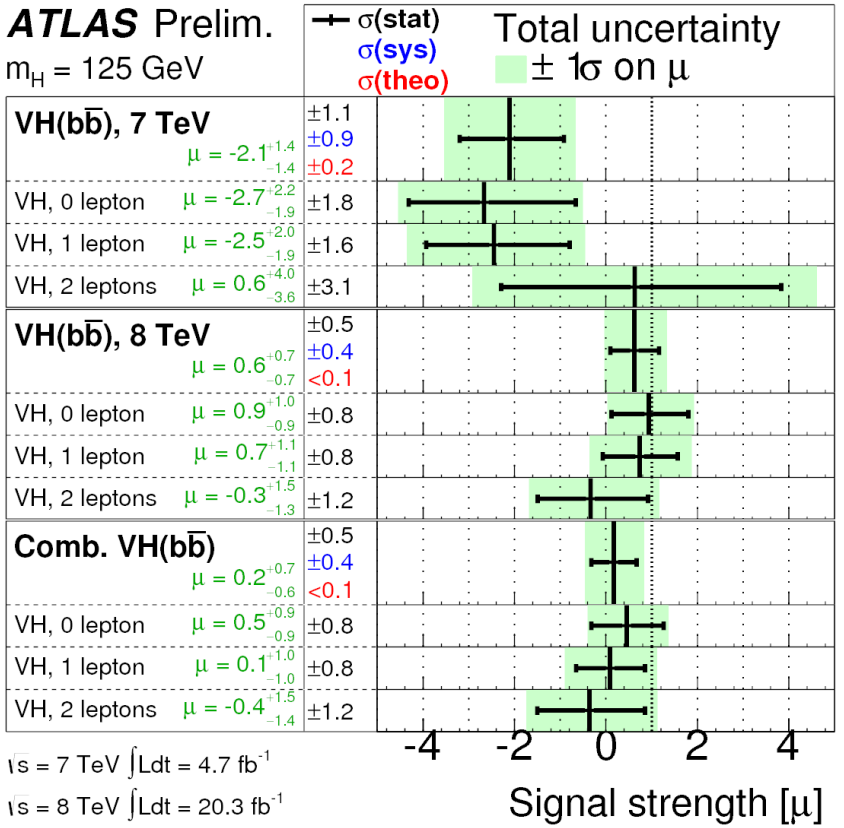


# VH with H to bb

ATLAS-CONF-2013-079




**Background subtracted $m_{bb}$ distribution, combining all regions with S/B based weighting**




preliminary

**Combined 2011 + 2012 result :**
**data are consistent with either SM backgrounds only backgrounds + Higgs**

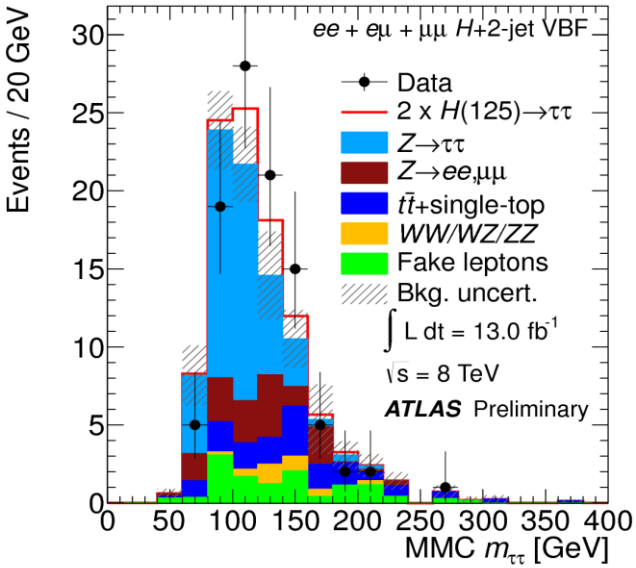
**Best fit signal strength:** $\mu = 0.2^{+0.7}_{-0.6}$

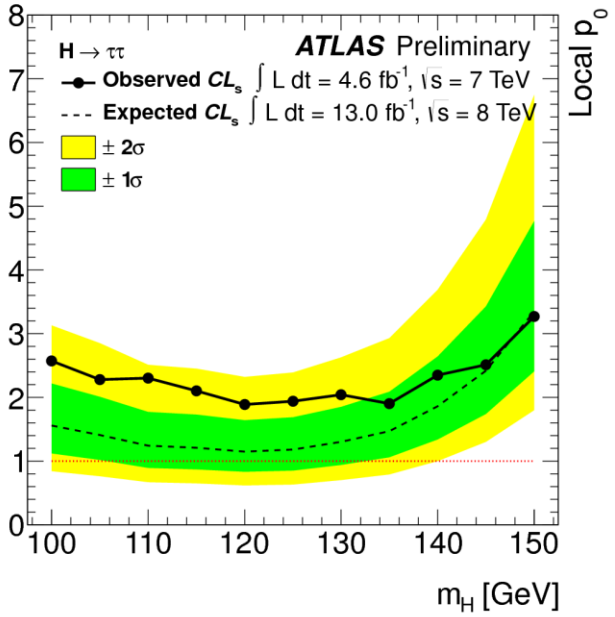
# H→ττ

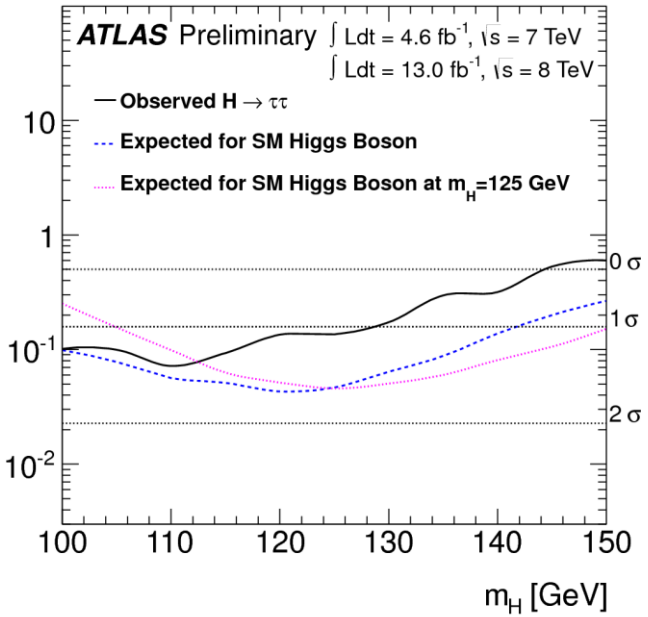
ATLAS-CONF-2012-160

Search in lep-lep, lep-had and had-had channels

Analysis split in 0,1, 2 jet case (2 jet case optimised for VBF/VH)




Result 2011 and part of 2012 data:
1.1σ excess over SM background
Best fit: μ=0.7±0.7

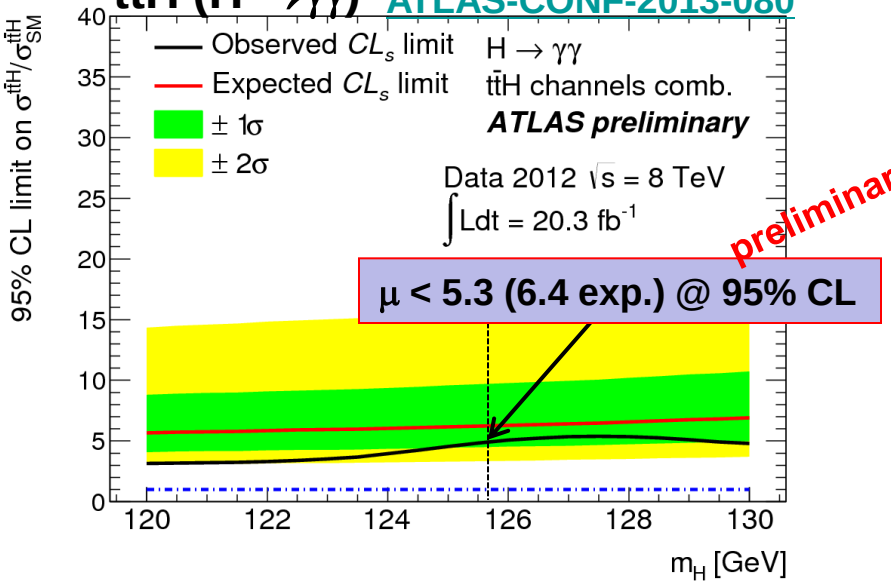
preliminary

**Analysis with full 2012 data still to come.**

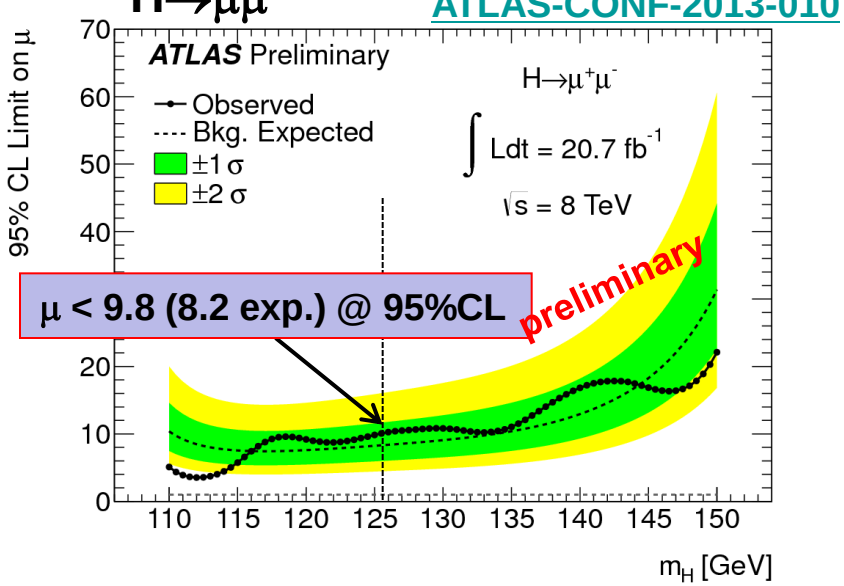
# Rare production and/or decay modes

# Rare production/decay modes

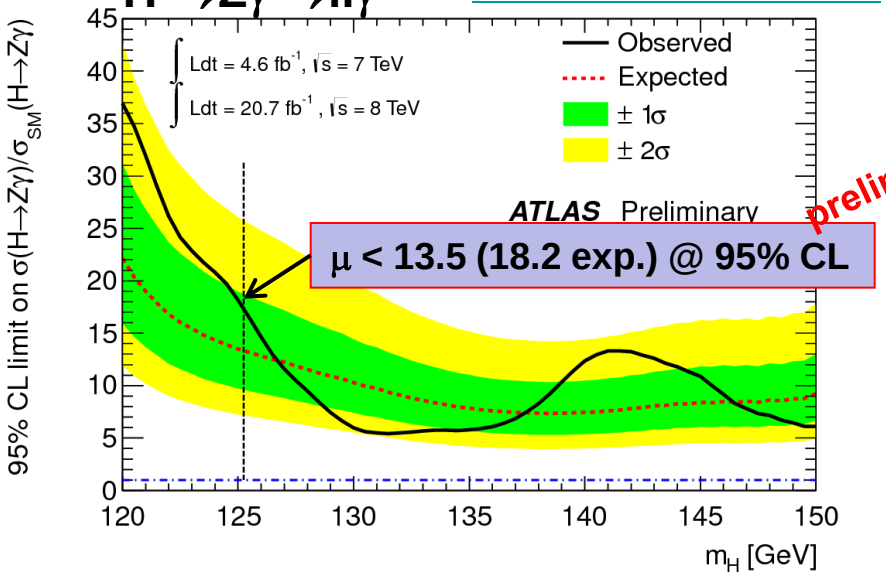
## ttH (H →γγ) ATLAS-CONF-2013-080



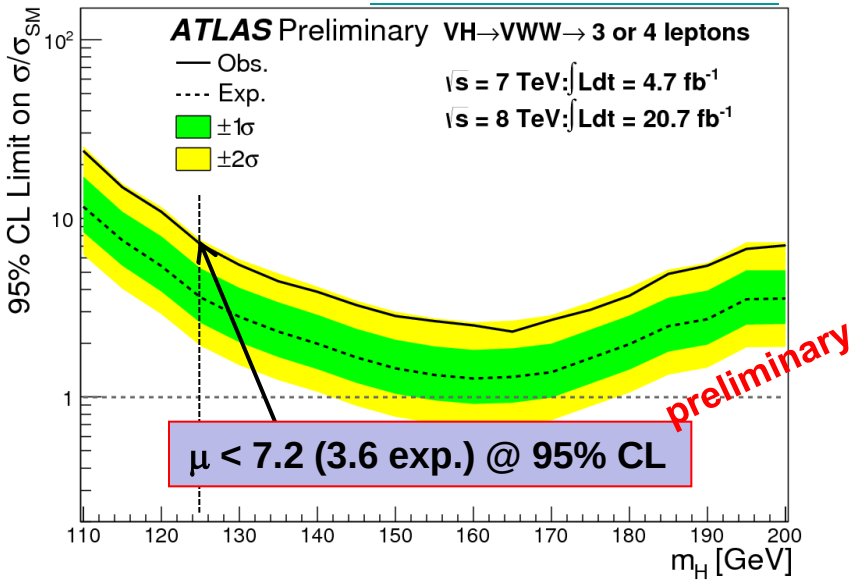

## H→μμ ATLAS-CONF-2013-010




## H →Zγ →llγ ATLAS-CONF-2013-009




## VH→VWW ATLAS-CONF-2013-027

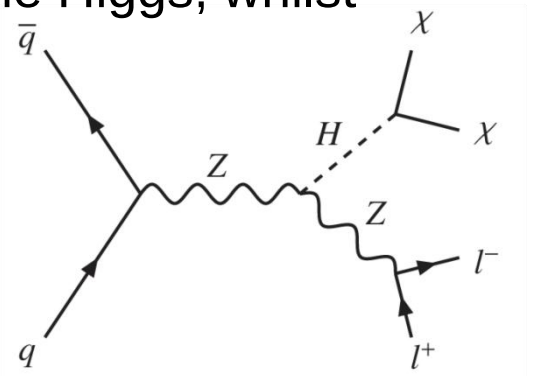


# BSM Higgs

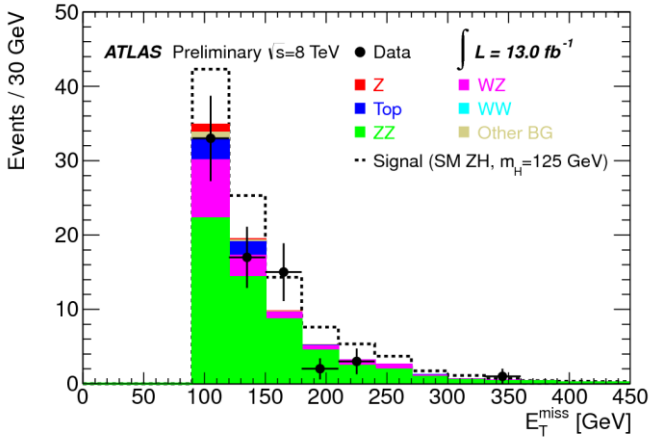
## A few recent results

# Invisible decays of the Higgs: ZH→ ll + inv

Rate expected in SM (H→ZZ→νννν) negligible
Channel is sensitive to any new particle coupling to the Higgs, whilst invisible to our detectors (dark matter candidates).




Search for an excess of events with
2 leptons + high missing $E_T$
Extract limit from the missing $E_T$ distribution




preliminary

**Result 2011 and part 2012 data:**
**BR(H(125 GeV)→inv) < 65% (84% exp.) @ 95%CL**

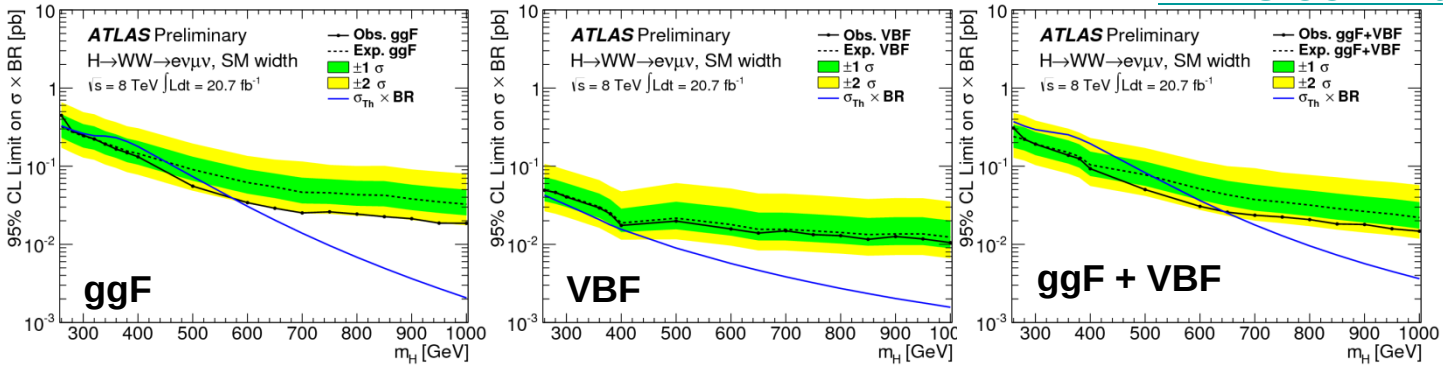
# Search for a high mass Higgs

Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes.
Preliminary results H→ZZ→4l available in ATLAS-CONF-2013-013

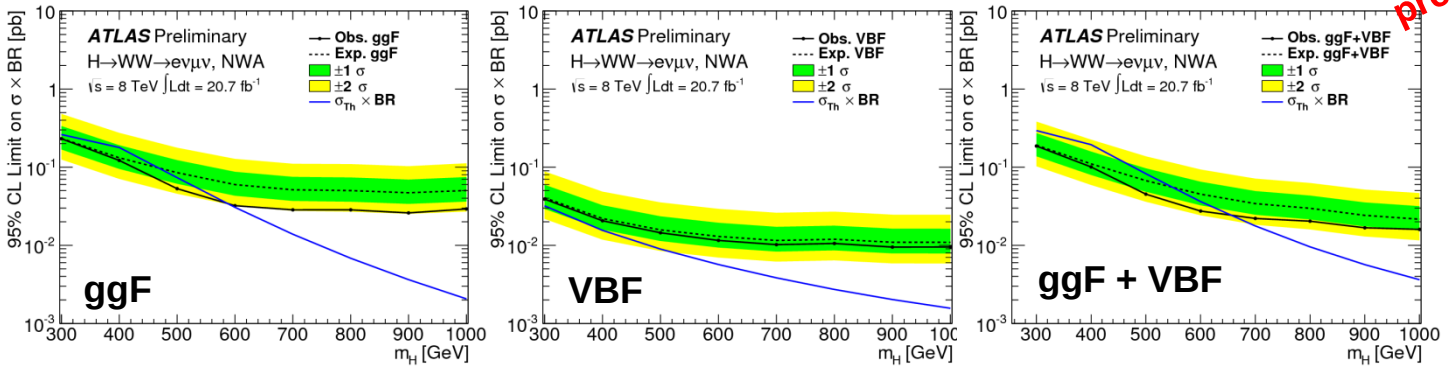
New: H→WW→eνμν search for a SM-like high mass Higgs.
Signal: SM like Higgs with full description of the width and of interference effects.
Vary width between a narrow width and that expected for a high mass SM Higgs.

ATLAS-CONF-2013-067

SM width




Narrow width




preliminary

Full combination to come. More WW/ZZ decay channels to be included:
H→ZZ→llνν, H→ZZ→llqq, H→WW→lνqq

# More BSM Higgs

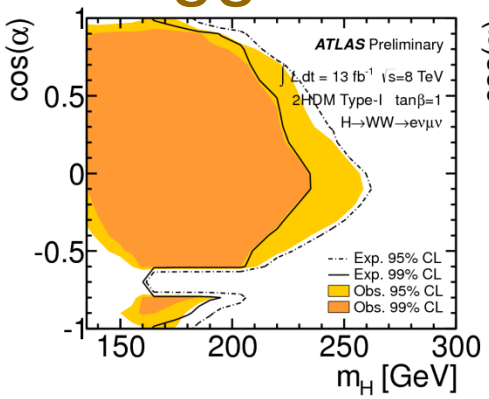
ATLAS-CONF-2013-027

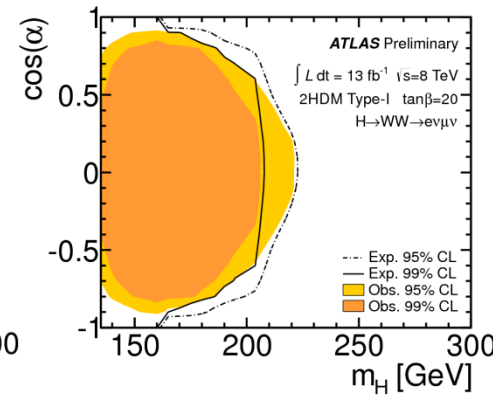
**2HDM Higgs**

H→WW→eνμν

(similar analysis to that on previous slide)

- 0 jets (ggF) and 2 jets (VBF)
- assume 125 GeV Higgs candidate is h and look for H in mass range 135 – 300 GeV
- No indication of a signal, set limits in $m_H$ – cos (α) plane for varying values of tan(β)



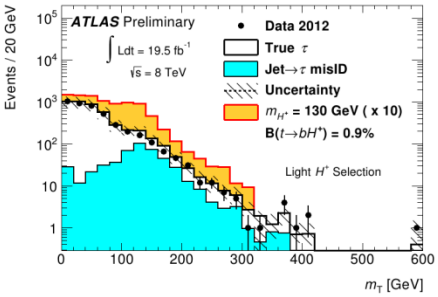

## Search for $H^{\pm} \rightarrow \tau\upsilon$ + jets

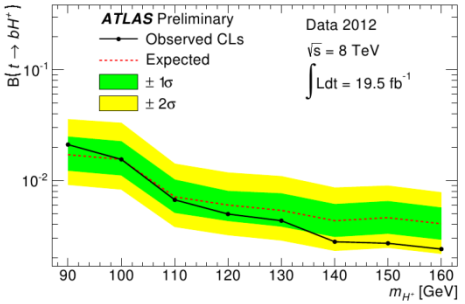
**Released today!** ATLAS-CONF-2013-090

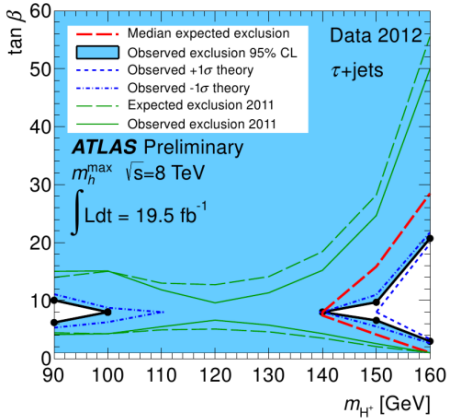
Low mass ($m_H^{\pm} < m_t$)

$m_H^{\pm}$: 90 – 160 GeV

ttbar → $H^{\pm}$bWb



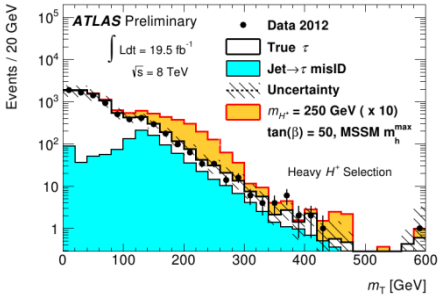



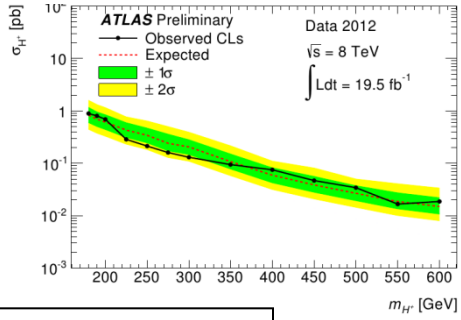



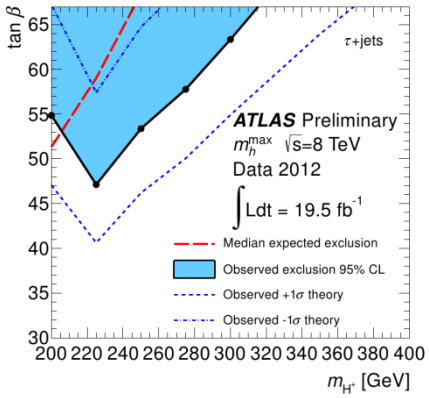

High mass ($m_H^{\pm} > m_t$)

$m_H^{\pm}$: 180 – 600 GeV

- Associated t$H^{\pm}$ production




**More on these results in parallel talk Alessandro Manfredini**

# Summary

LHC Run I (2010-2013) a great success for ATLAS

Discovery of a new boson, and first measurement of its mass, .. $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\,\text{GeV}$

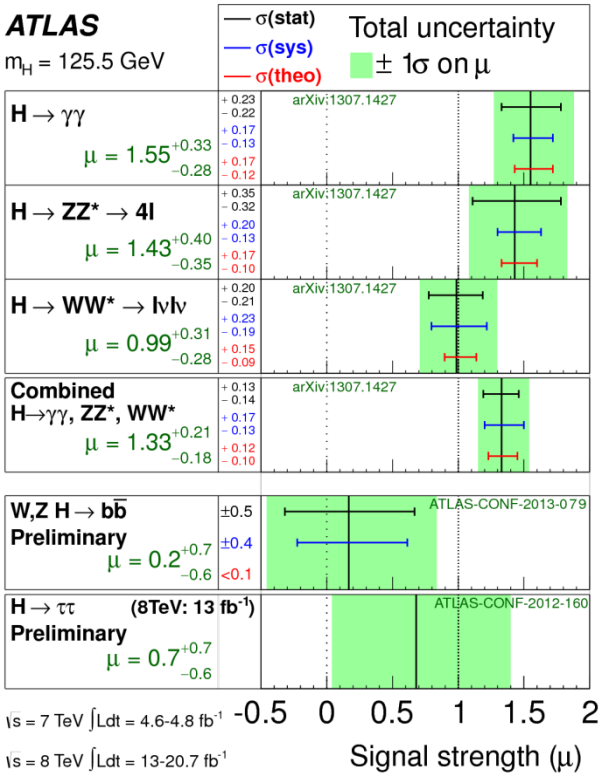
its coupling parameters (all consistent with a SM Higgs)

and its spin and parity .. Strong evidence $J^P = 0^+$

No significant evidence yet for fermionic decays, but results are consistent with SM Higgs hypothesis

$H \to bb$ : $\mu = 0.2^{+0.7}_{-0.6}$

$H \to \tau\tau$: 1.1 sigma excess, best fit $\mu = 0.7 \pm 0.7$




First results on various rare production decay modes (more data needed to observe these modes)

Direct limit on H → invisible particles BR(H→inv) < 65%

Search for high mass Higgs and SM and narrow width approach.

Many analyses of Run I data are ongoing, so more results to come ....

# Outlook

ATLAS is preparing for LHC run II: $\sqrt{s}$=13/14 TeV and up to 80 interactions on average per bunch crossing.

Improvements on electronics, an extra b-tagging layer and improved forward muon tracking are ongoing.

Major upgrades are being planned for HL-LHC running to ultimately get to ~3000$fb^{-1}$ per experiment.

Very exciting times ahead ..