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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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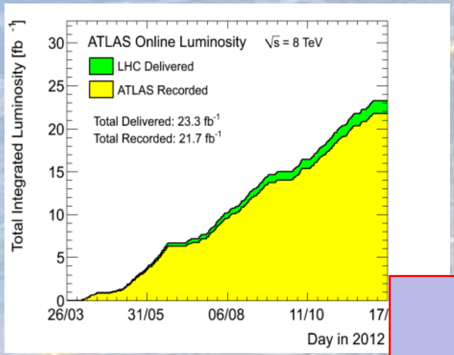
on behalf of the ATLAS collaboration

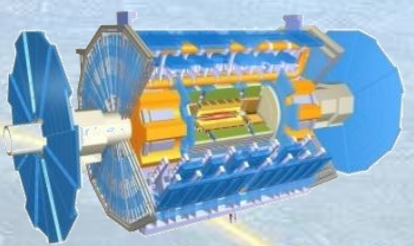
ATLAS and the LHC: Run I performance

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.



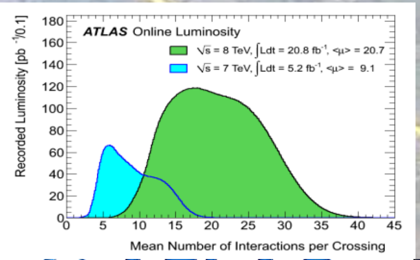


ATLAS has collected data efficiently

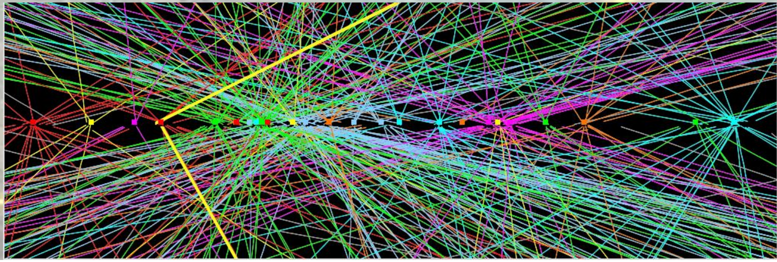
Collecting good data 95% of the time

High quality data for physics analysis:

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



Pile-up has been higher than foreseen
Well modelled
Not a major issue for analysis



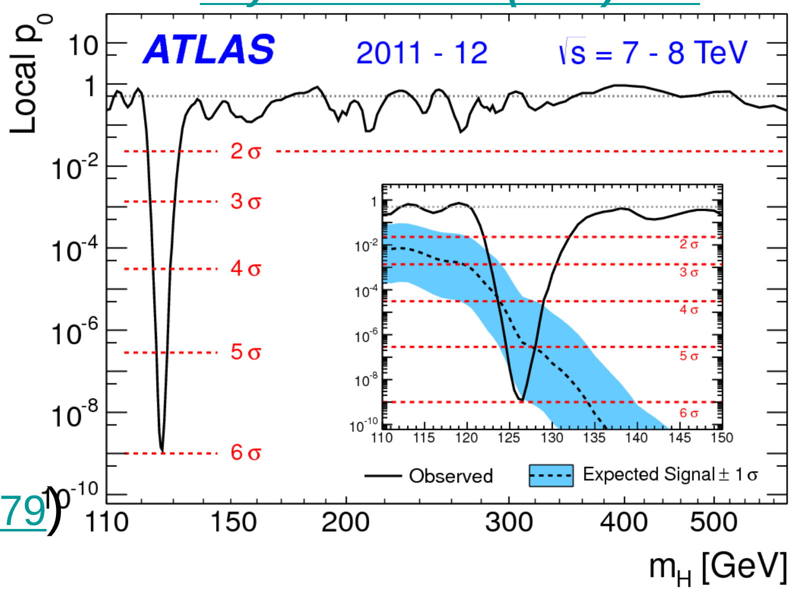
ATLAS EXPERIMENT

UNIVERSITY OF LIVERPOOL

What has happened since the discovery?

4th July 2012

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



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

⇒ mass and couplings (arXiv:1307.1427)

⇒ spin and parity (arXiv:1307.1432)

Preliminary results:

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

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

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

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

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

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

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

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

⇒ High mass Higgs (25 fb^{-1})

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

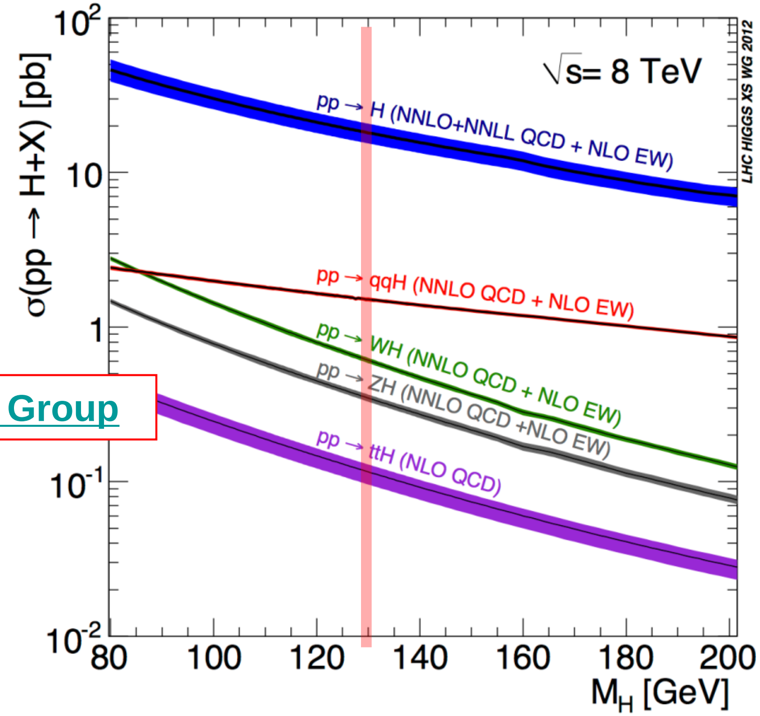
⇒ $H\rightarrow WW\rightarrow e\nu\mu\nu$ (ATLAS-CONF-2013-067)

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.

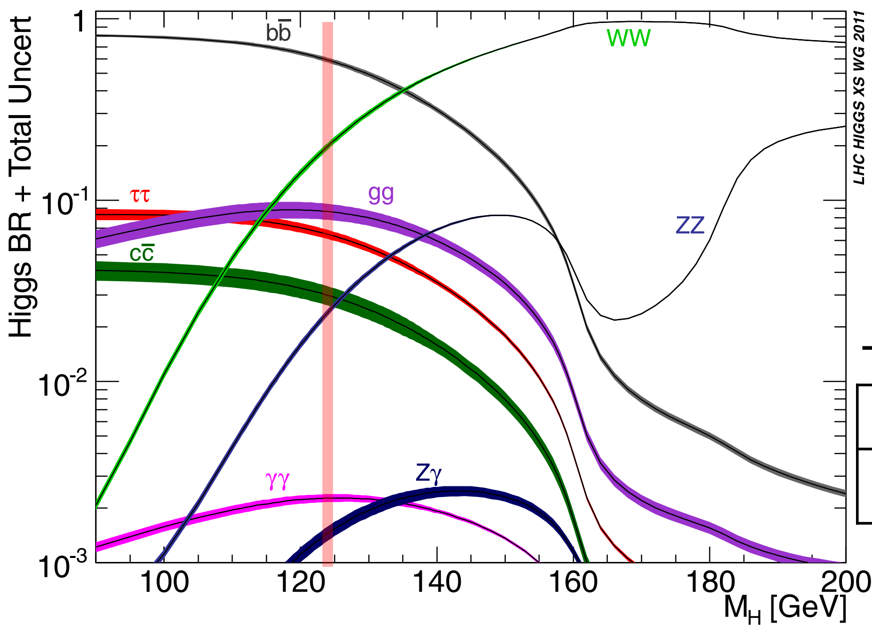
Production and decay modes at the LHC

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

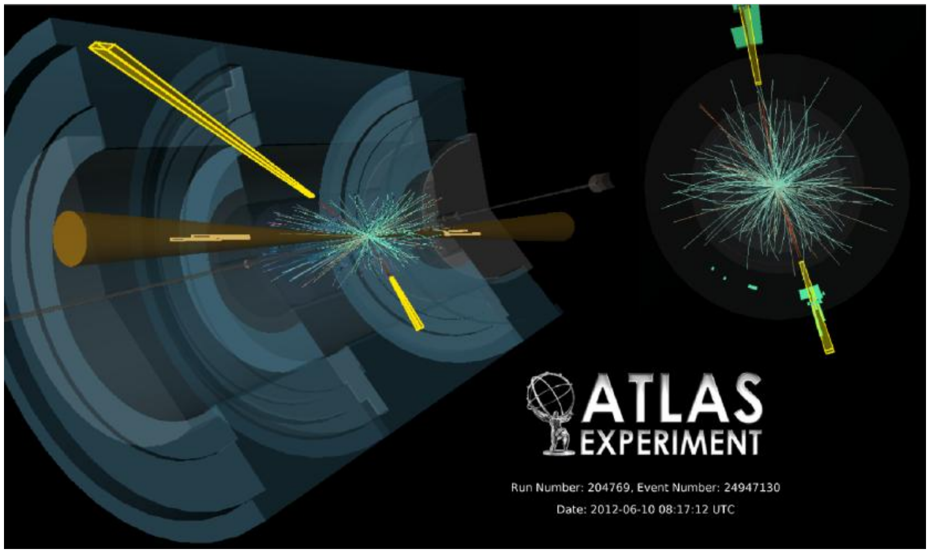
$H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^* \rightarrow 4l$, $H\rightarrow WW^* \rightarrow l\nu l\nu$

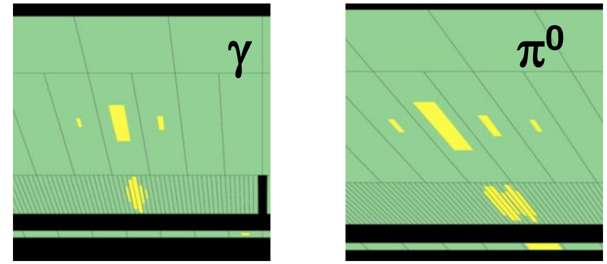
$H \to \gamma\gamma$

arXiv:1307.1427

Small branching fraction, but excellent mass resolution.

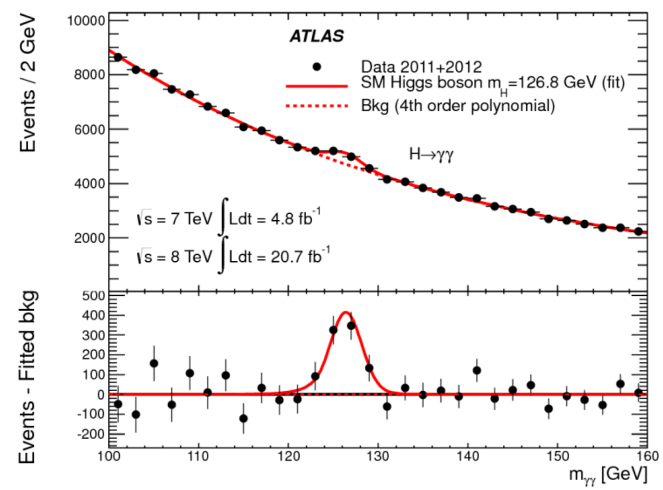
Sensitivity to spin ($0^+/2^+$) / excludes spin 1 (Landau-Yang)





Excellent γ-jet separation in 1st layer of Liquid Argon calorimeter.

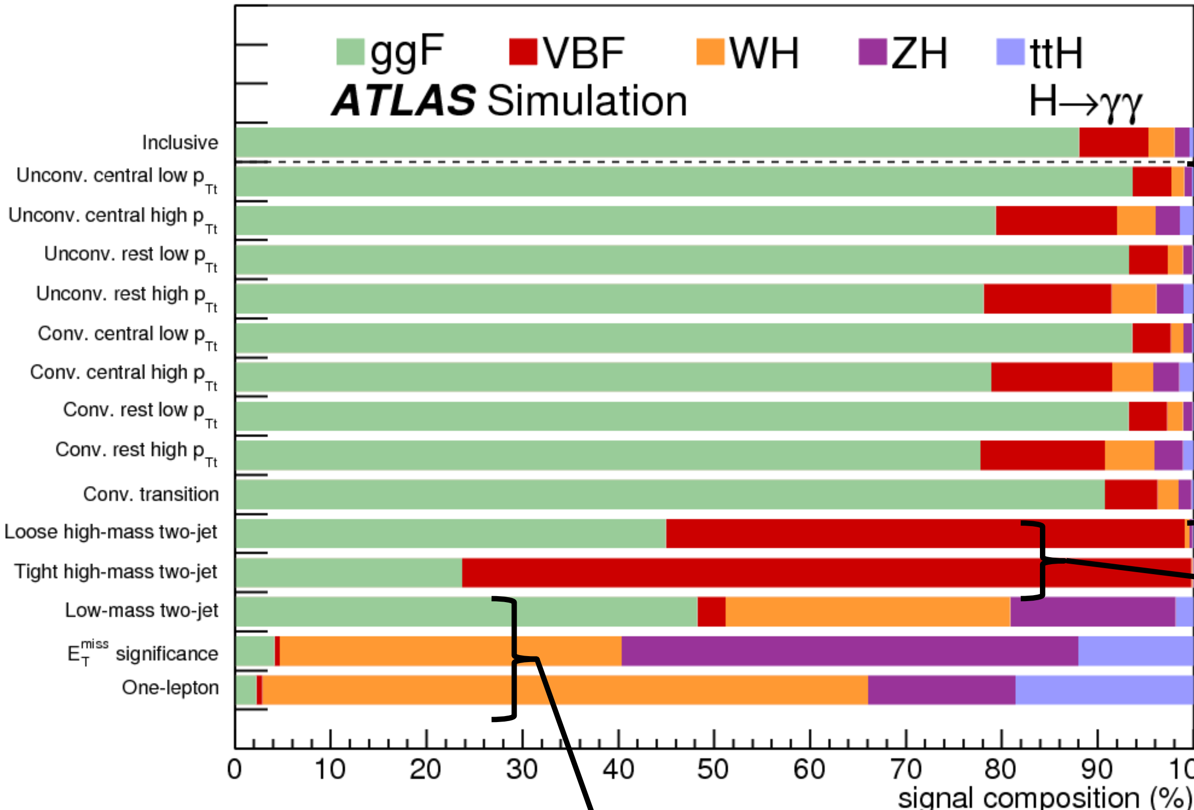
Only ~25% of background is from jet-jet or γ-jet events



Extract signal in simultaneous fit of signal and background.

H→γγ search categories

arXiv:1307.1427



9 combinations of:

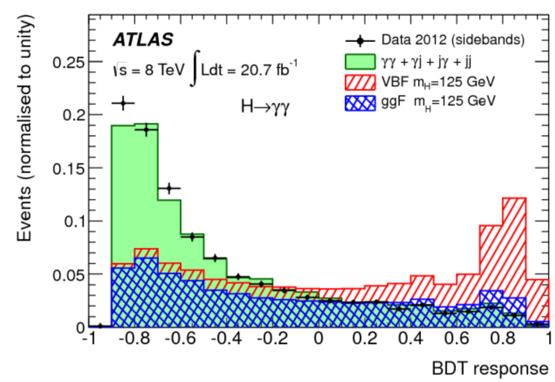
- converted/unconverted
- forward/central
- p_T range

2 VBF enhanced categories

- high mass jet pair and BDT cut

3 VH enhanced categories:

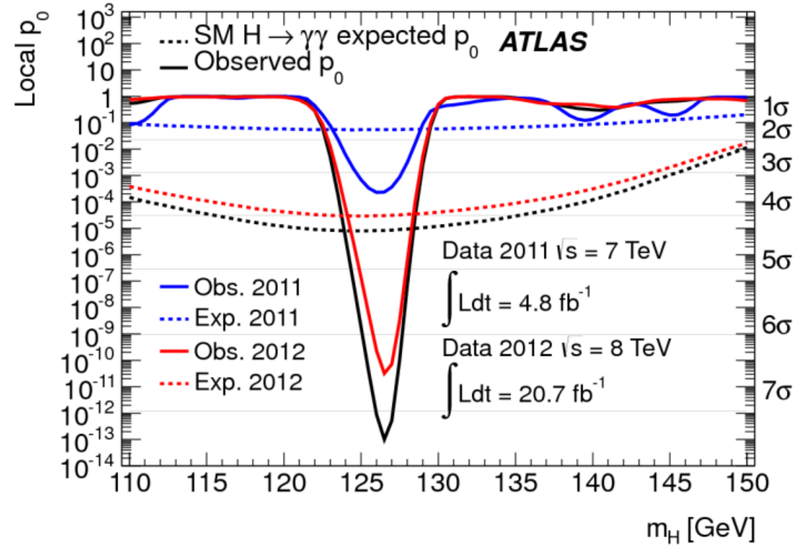
- low mass jet pair
- 1 lepton and/or missing E_T

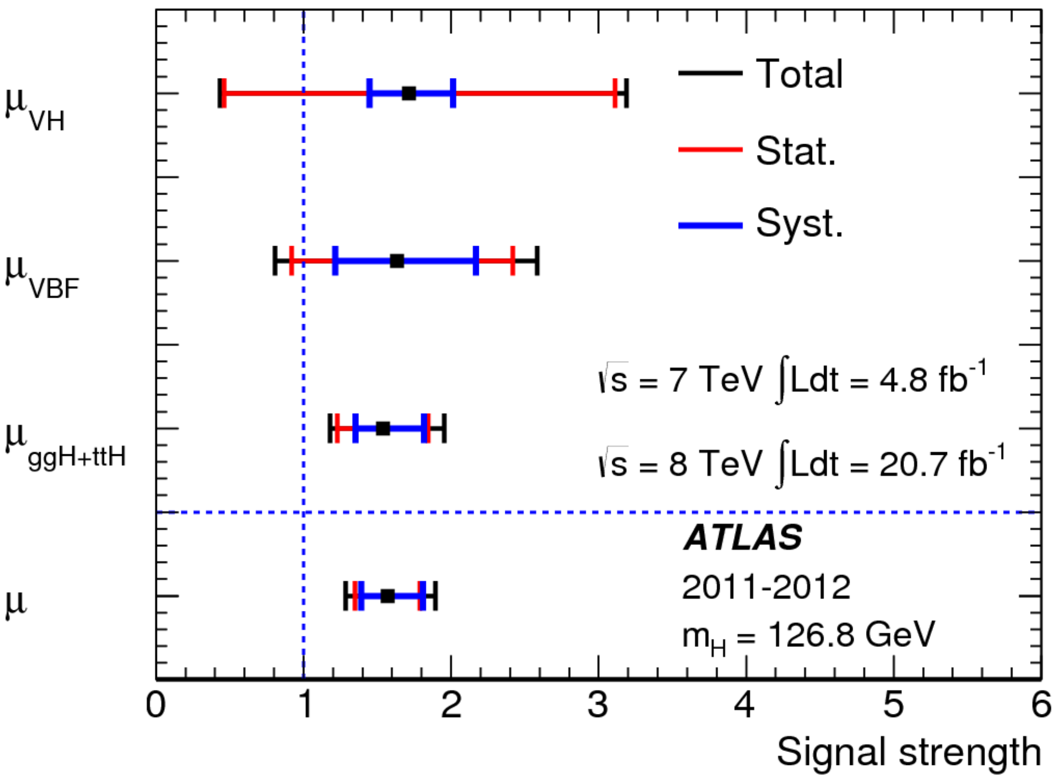


arXiv:1307.1427

H→γγ results

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





Best fit signal strength:

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

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

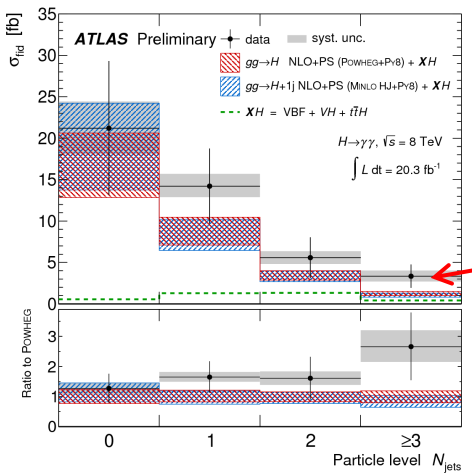
NEW: H→γγ differential cross sections

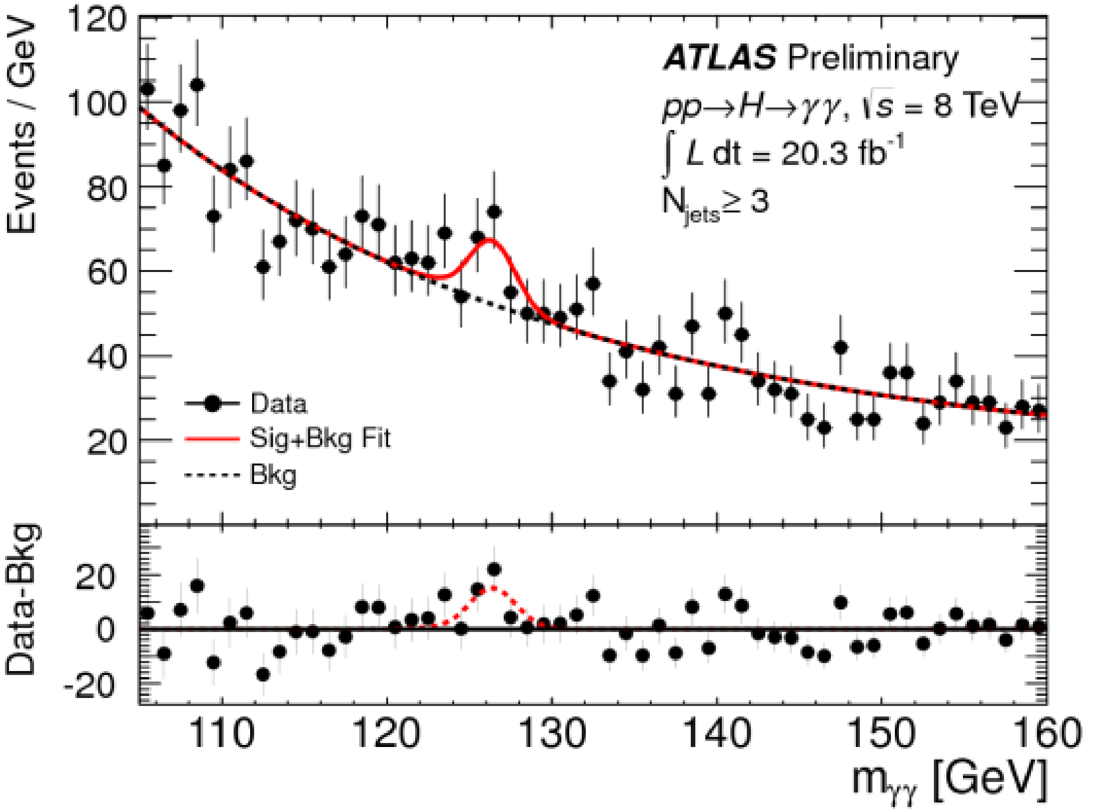
ATLAS-CONF-2013-072

Repeat fit to extract signal in each bin

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

example:≥ 3 jets

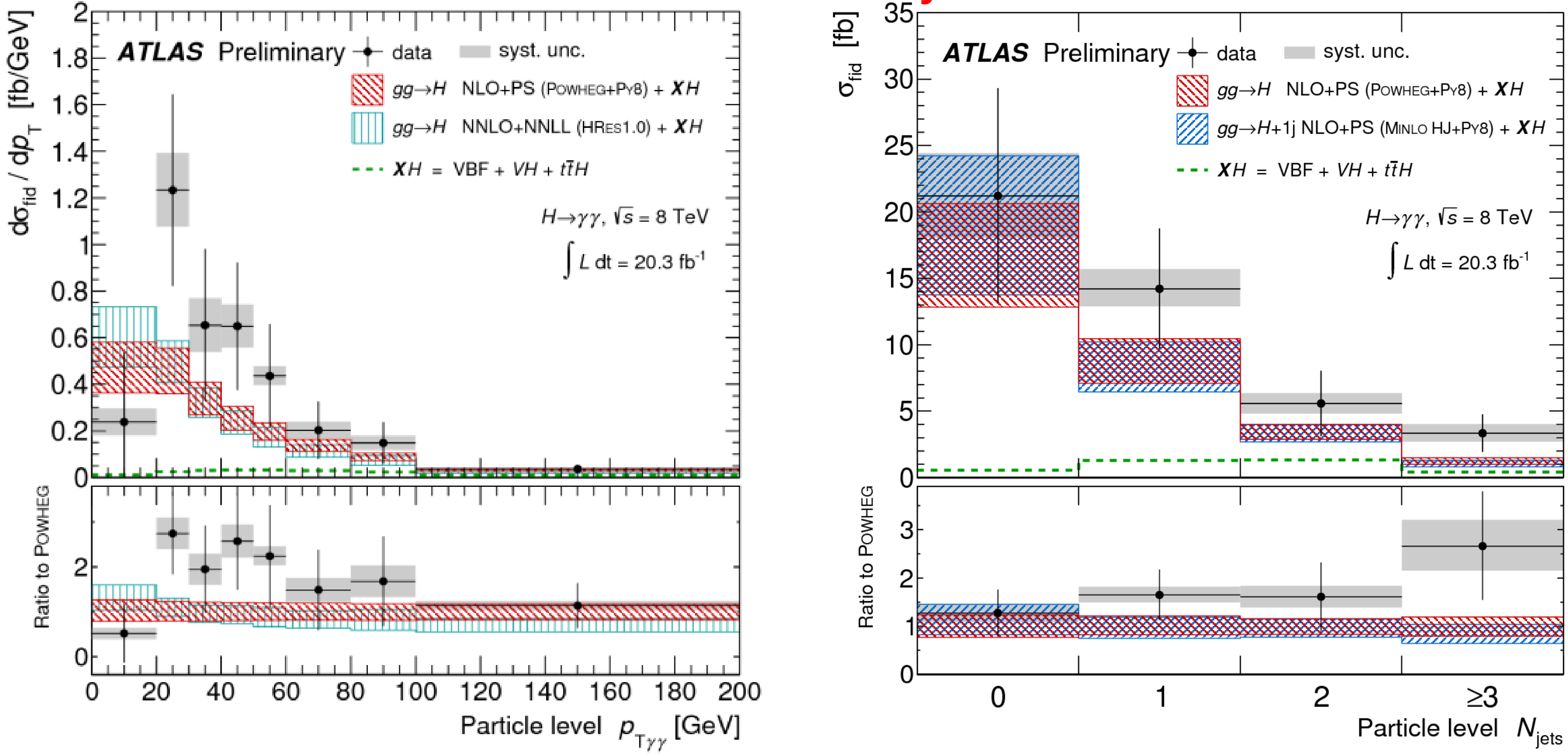




NEW: H→γγ differential cross sections

ATLAS-CONF-2013-072

Preliminary



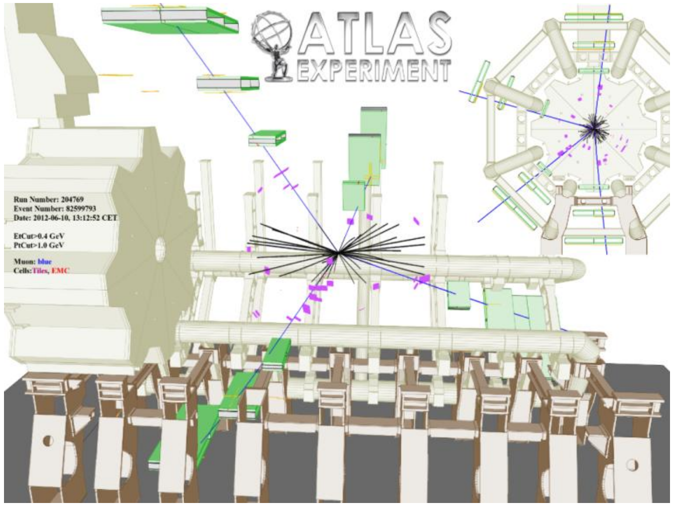
⇒ for other distributions see ATLAS-CONF-2013-072

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

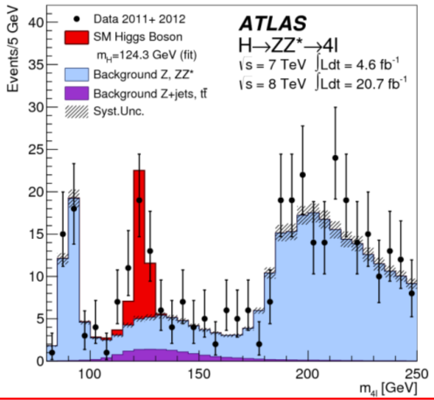


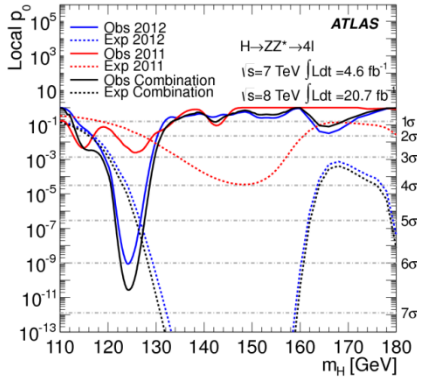
Small branching fraction, but very clean and good mass resolution.

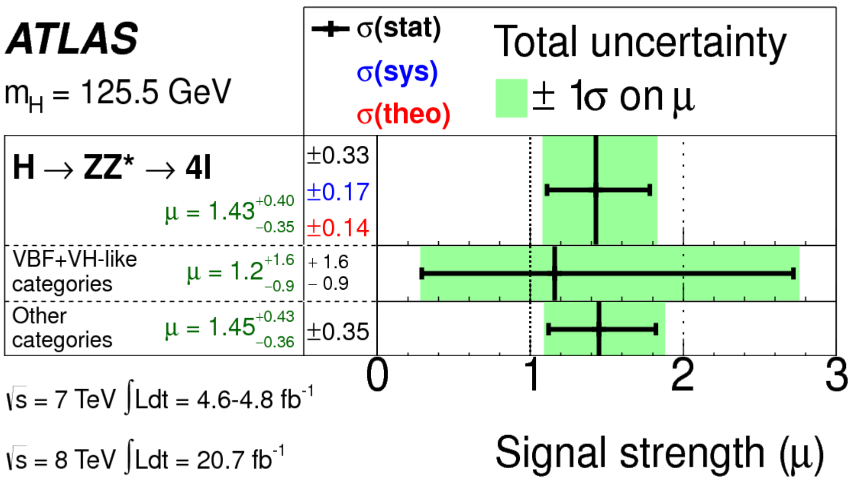
Good sensitivity to spin and parity ($0^+/0^-/1^+/1^-/2^+$)

Analysis subcategories

- VBF enhanced: high mass jet pair (|Δη|>3)
- VH enhanced: additional lepton
- ggF dominated: inclusive







Overall signal significance 6.6σ (4.4σ exp.)

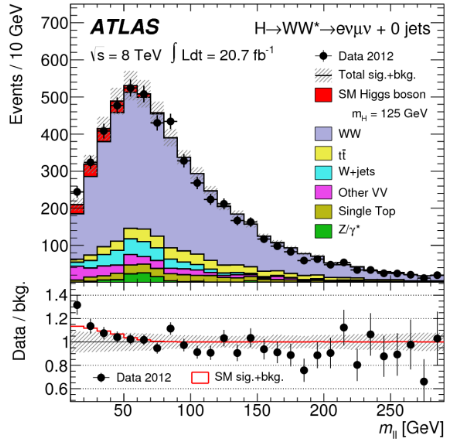
arXiv:1307.1427

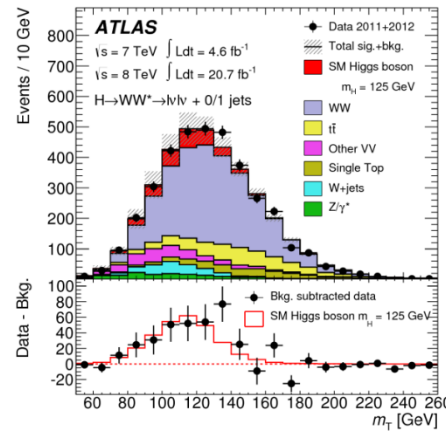
$H \to WW^* \to l\nu l\nu$

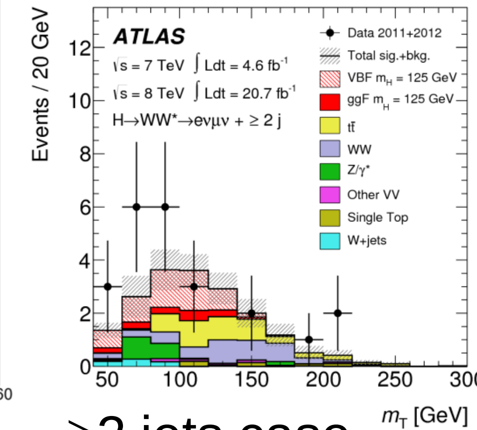
High branching fraction, but limited mass resolution and significant backgrounds.

Analysis categories

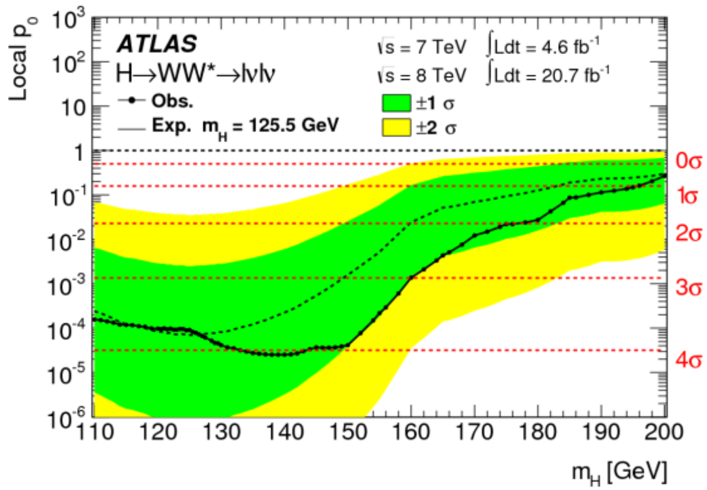
- ee, $\mu\mu$ or eμ pair
- 0,1 or ≥2 jets

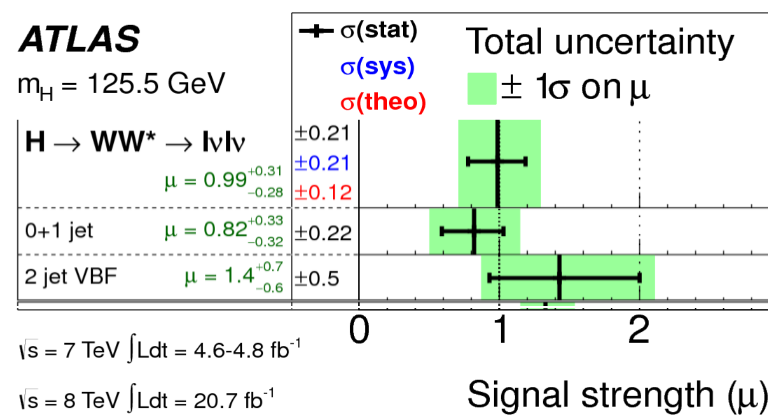






≥2 jets case optimised for VBF





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

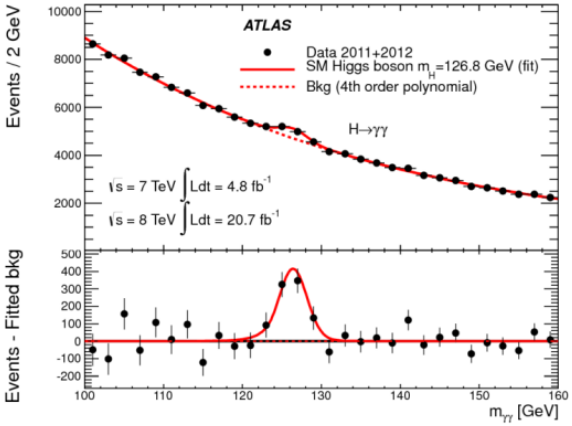
Mass

Couplings

Spin and parity

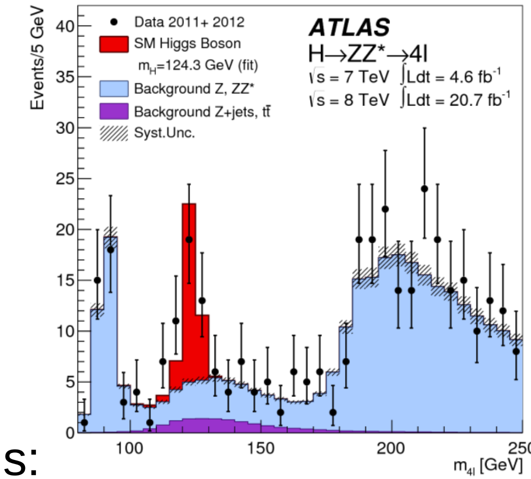
Higgs mass
(H→γγ / H→ZZ* → 4l)

arXiv:1307.1427



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

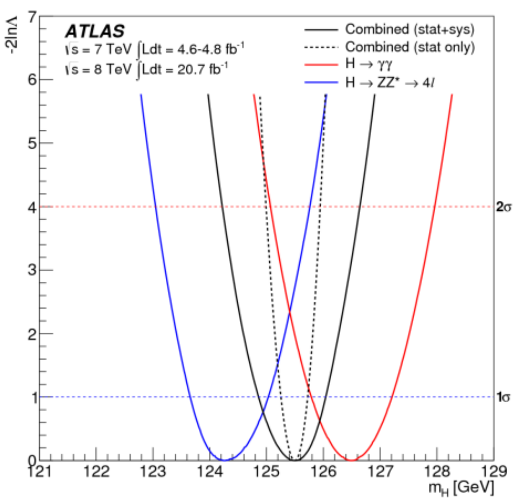
$$m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})\,\text{GeV}$$



H →4 leptons:
m_H determined from unbinned likelihood fit

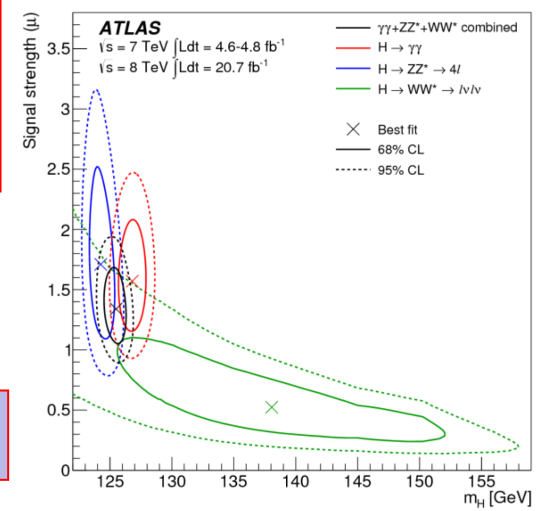
$$m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{sys})\,\text{GeV}$$

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

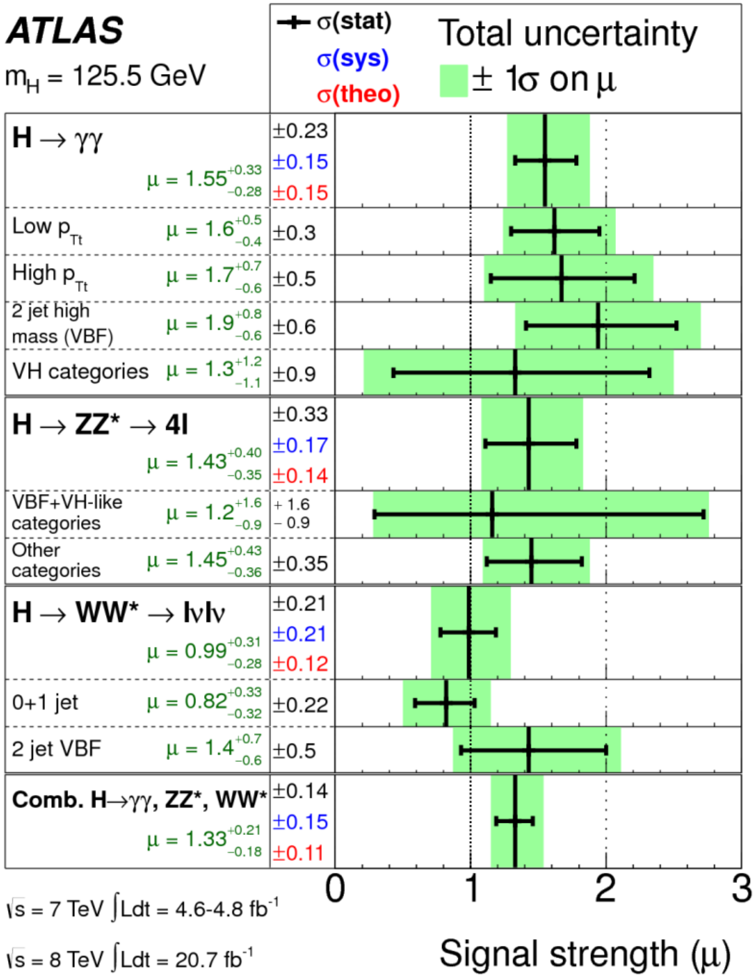
$$\boxed{m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})\,\text{GeV}}$$



arXiv:1307.1427

Couplings combination

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.

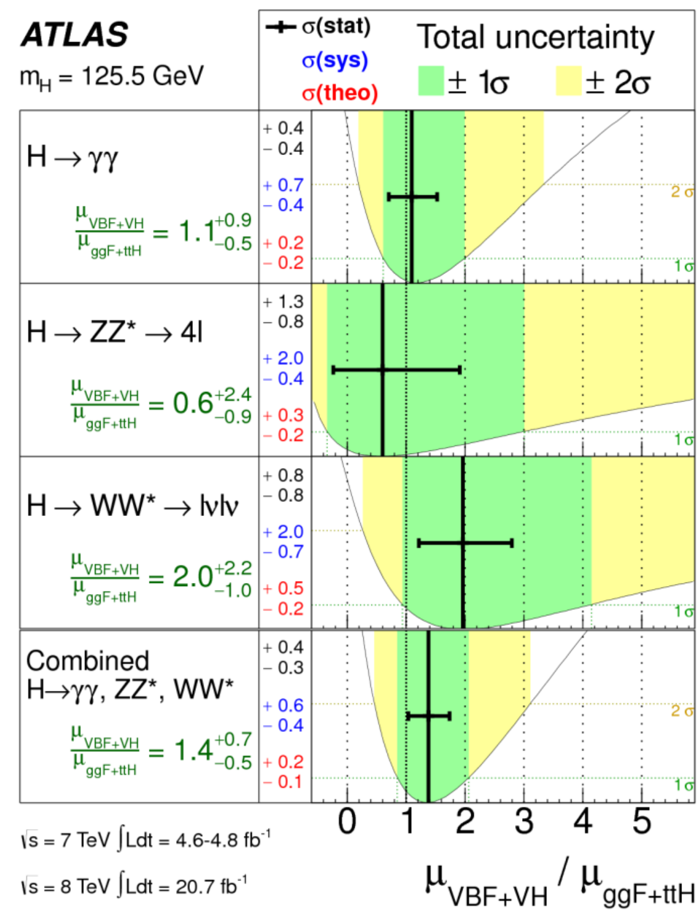
Evidence for Higgs production via vector-boson fusion

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

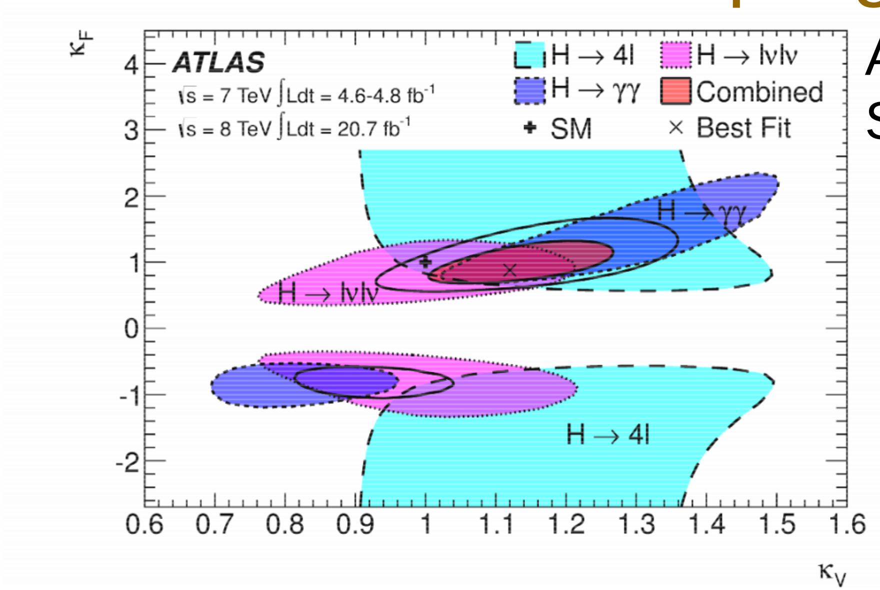
$$\frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}} = 1.4^{+0.7}_{-0.5}$$



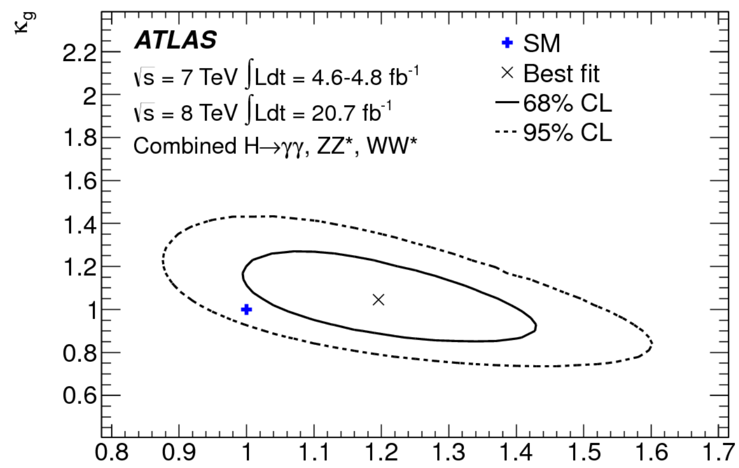
3.3 σ evidence that a non-zero fraction of Higgs events is produced via vector boson fusion

Coupling parameters

arXiv:1307.1427



Assumption:
Single narrow resonance with m=125.5GeV



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

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

κ_g κ_γ : 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
λ_{WZ} : ratio scale factors for W and Z couplings
(λ_{WZ} =1 in SM)

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

Spin and Parity of the candidate boson

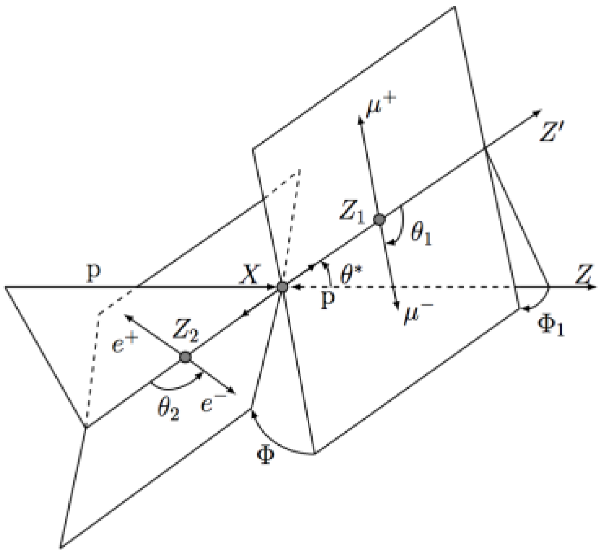
Test various options ($J^p=0^-, 0^+, 1^-, 1^+, 2^+$) using angular and kinematic distributions in $H\rightarrow\gamma\gamma$, $H\rightarrow ZZ^*\rightarrow 4l$ and $H\rightarrow WW^*\rightarrow l\nu l\nu$.

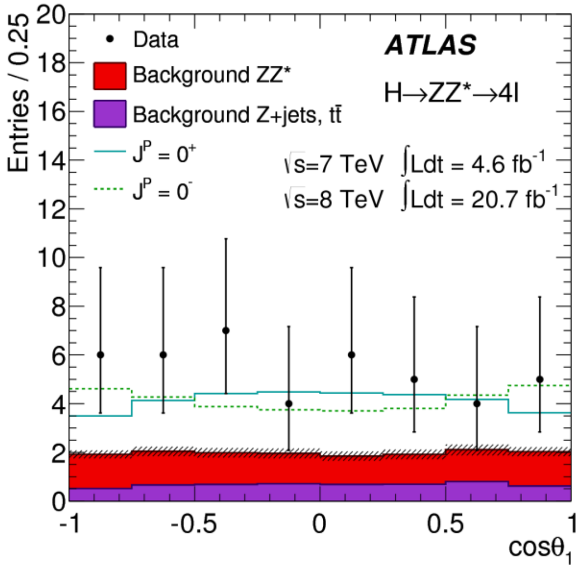
For a detailed description of the used theoretical calculations and a complete set of references see:

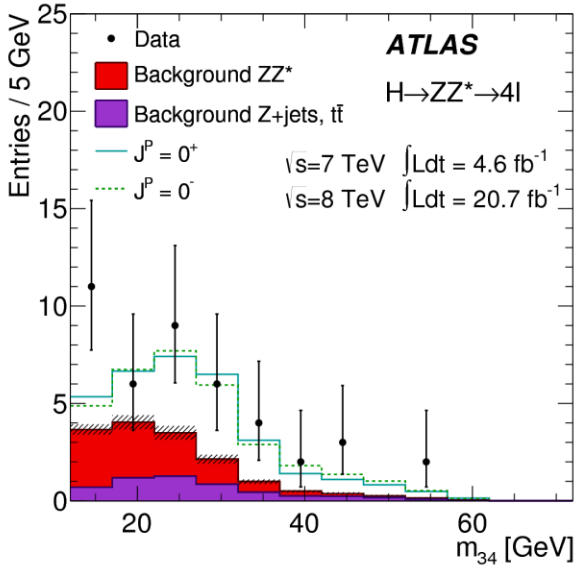
CERN Yellow Report III (arXiv:1307.1347)

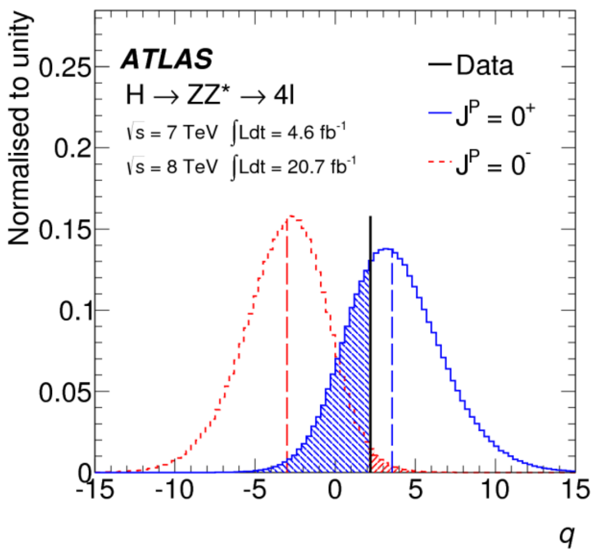
$J^p=0^+$ vs 0^- ($H\rightarrow ZZ^*\rightarrow 4l$)

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.

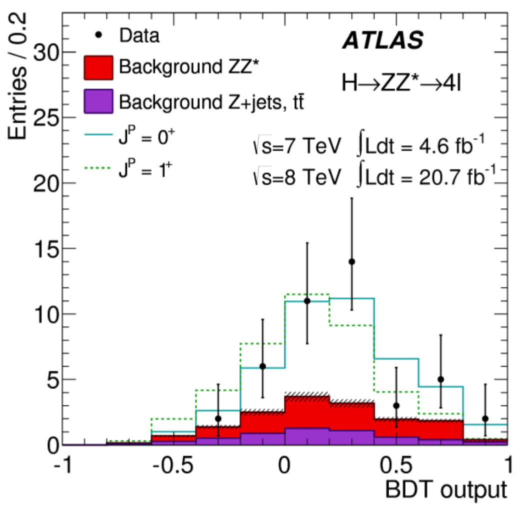
Data agree with 0^+ hypothesis,
0^- hypothesis is excluded at 97.8% CL

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

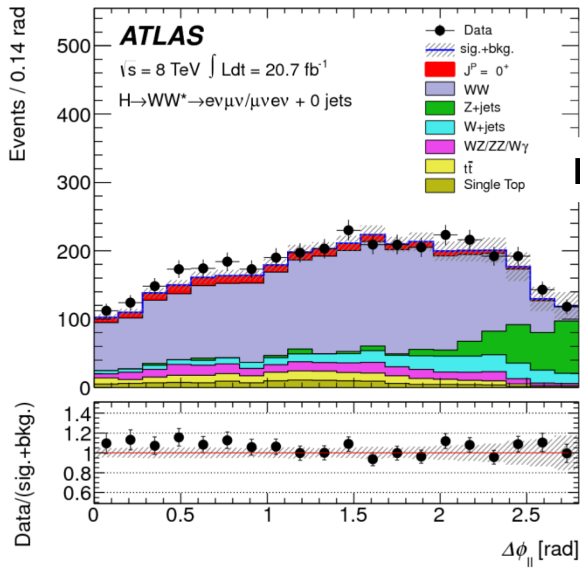
arXiv:1307.1432

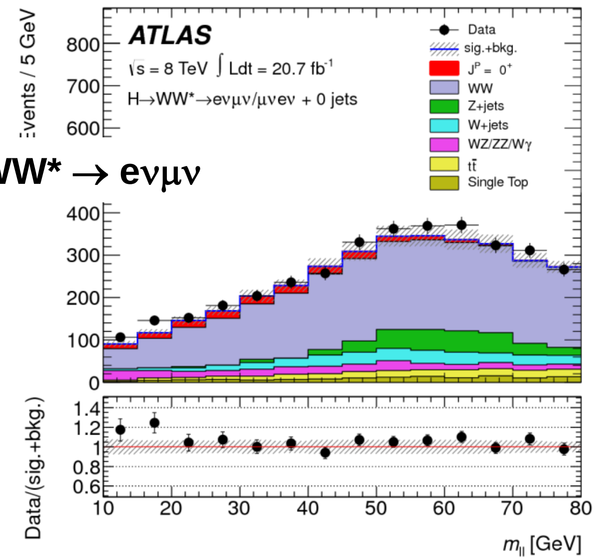
Observation $H\rightarrow\gamma\gamma$ decay prohibits spin 1 option (Landau-Yang) for on-shell particle.

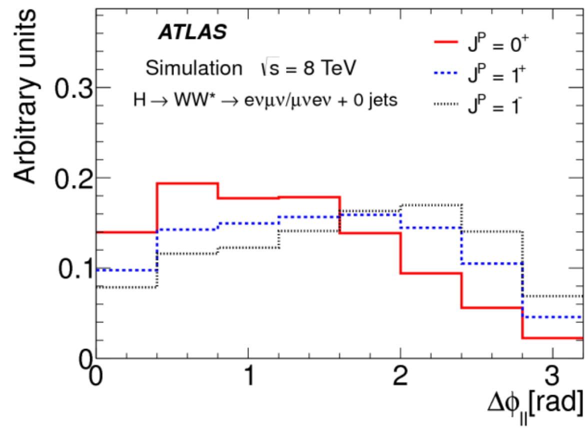
$H\rightarrow ZZ^* \rightarrow$ 4 leptons

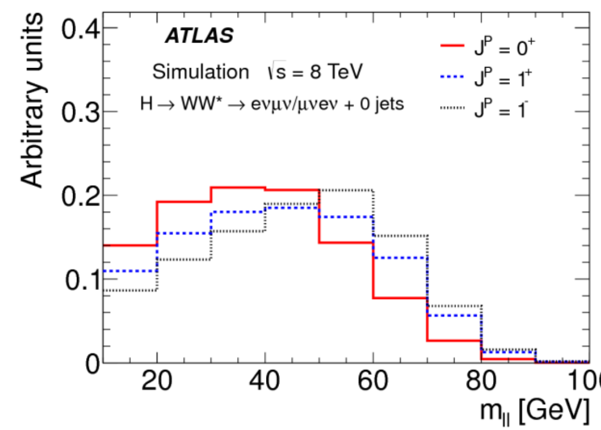


$H\rightarrow WW^* \rightarrow e\nu\mu\nu$







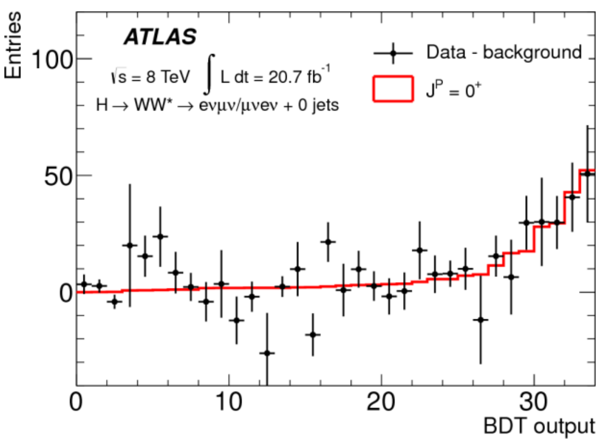


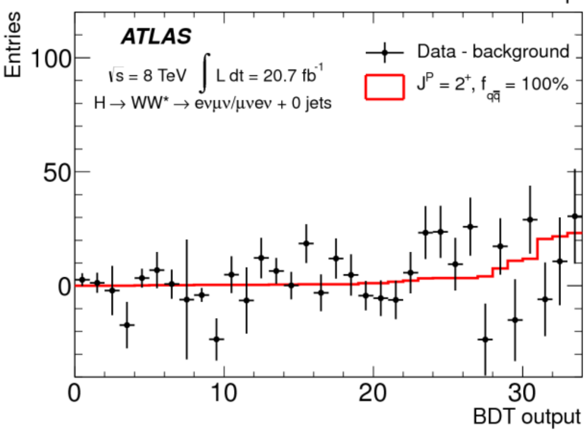
Combined ZZ*/WW*data agree with 0^+ hypothesis,
$J^p = 1^+$ hypothesis is excluded at 99.97% CL
$J^p = 1^-$ hypothesis is excluded at 99.7% CL

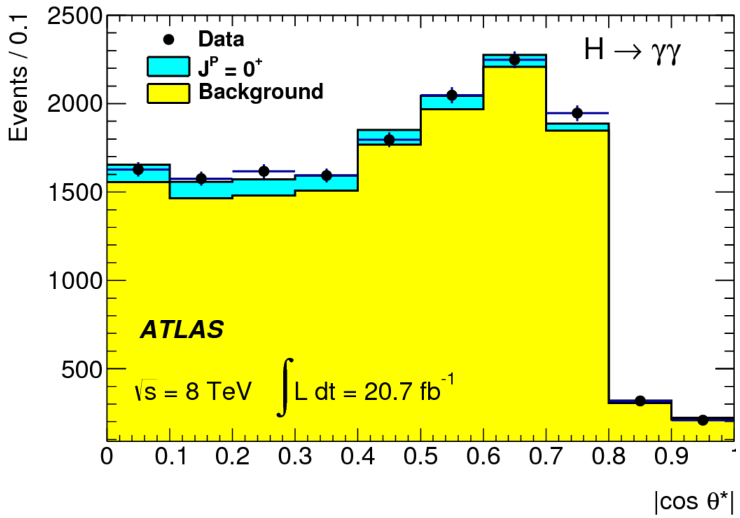
$J^p=0^+$ vs 2^+ ($H\rightarrow\gamma\gamma$ / $H\rightarrow ZZ^*\rightarrow 4l$ / $H\rightarrow WW^*\rightarrow l\nu l\nu$)

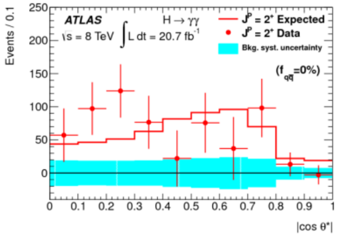
arXiv:1307.1432

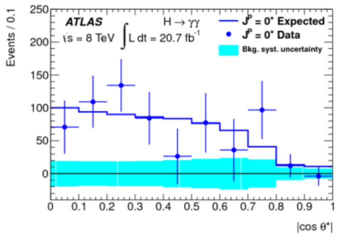
BDT output based on WW* variables



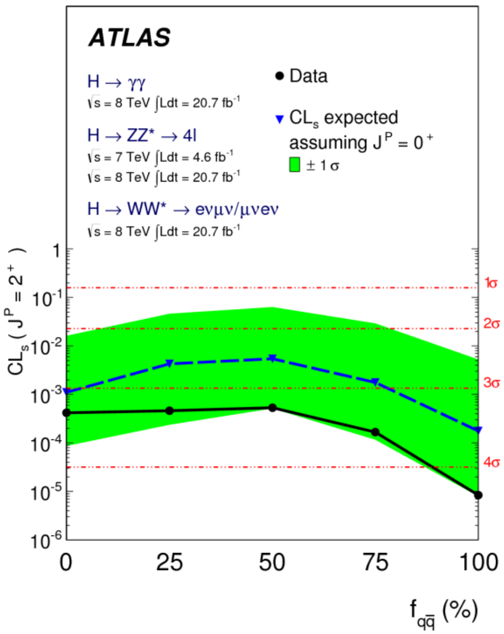








We vary the production mode for a 2^+ boson from fully gluon induced (f_{qq}=0%) to fully quark induced (f_{qq}=100%)



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
$H \rightarrow bb$, $H \rightarrow \tau\tau$

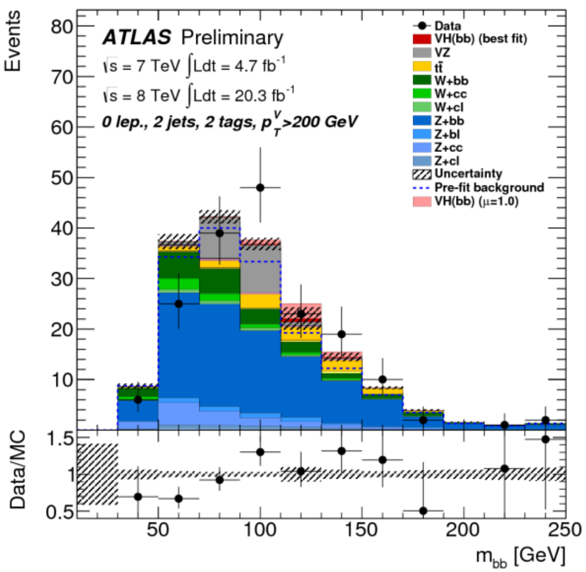
ATLAS-CONF-2013-079

VH with H to bb

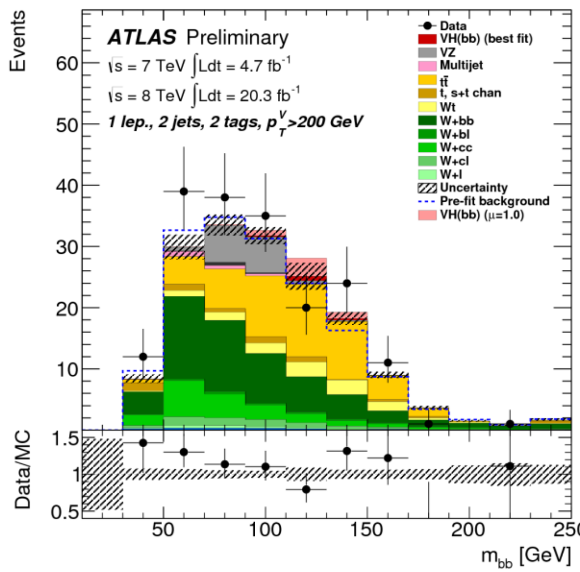
Abundant channel with difficult backgrounds.
Flavour composition of the main backgrounds is determined from data.

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]

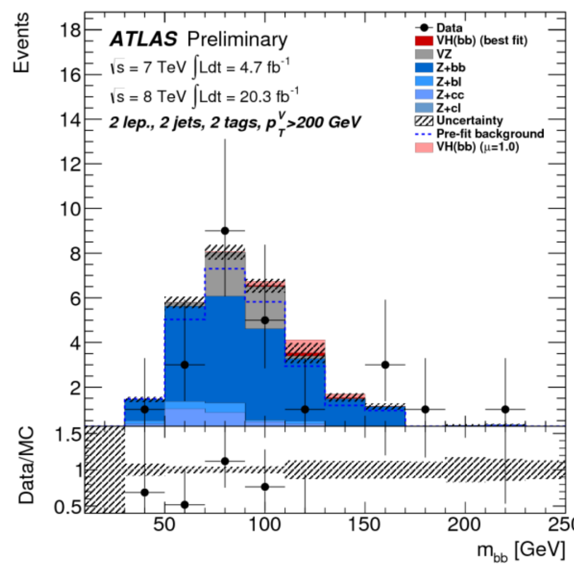
0 leptons (ZH→ννbb)



1 lepton (WH→lνbb)

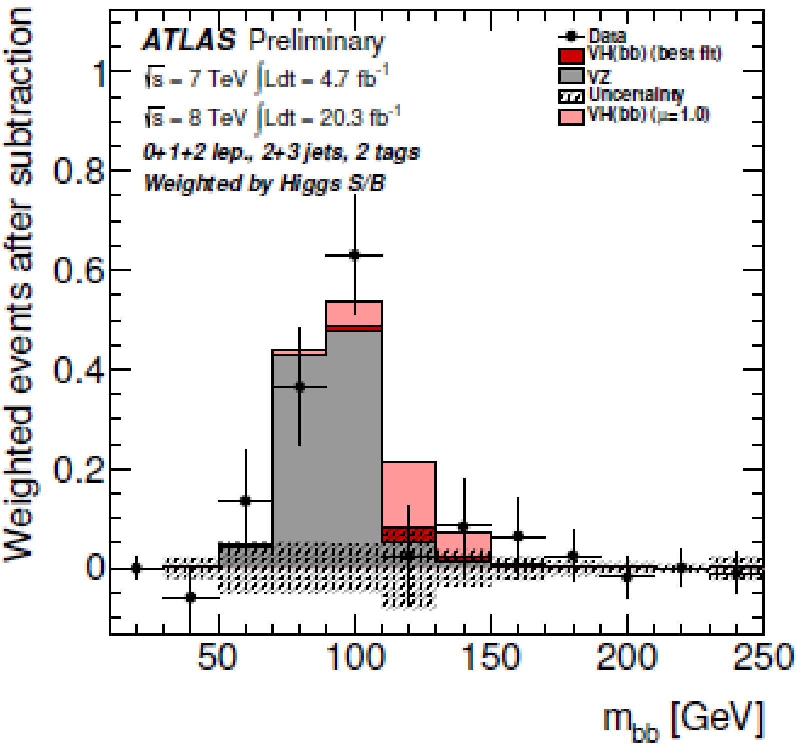


2 leptons (ZH→llbb)

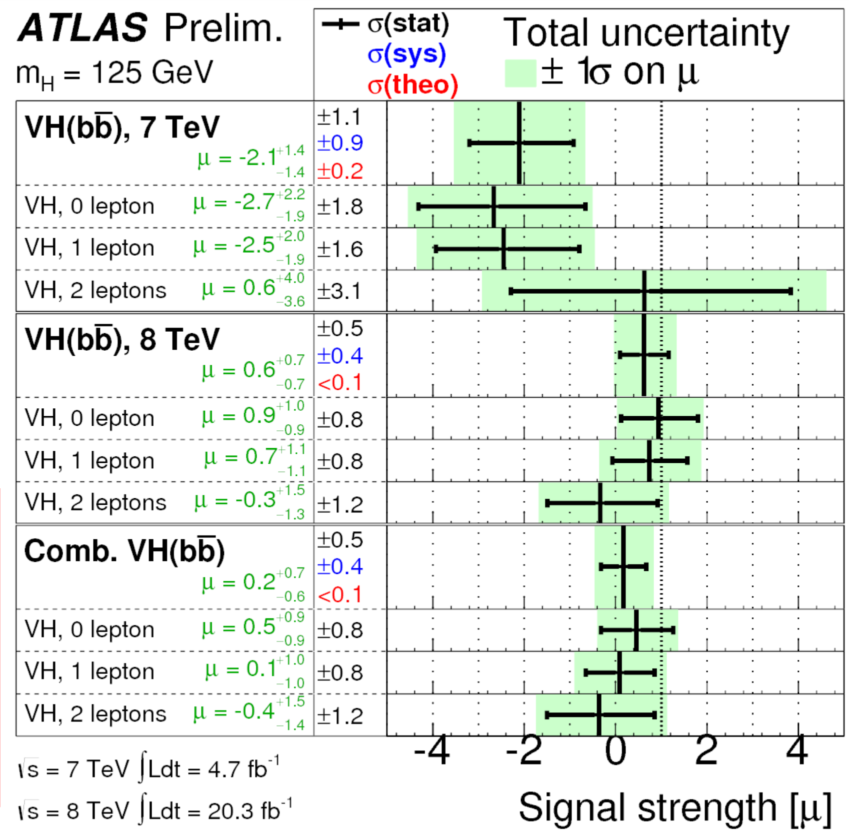


VH with H to bb

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

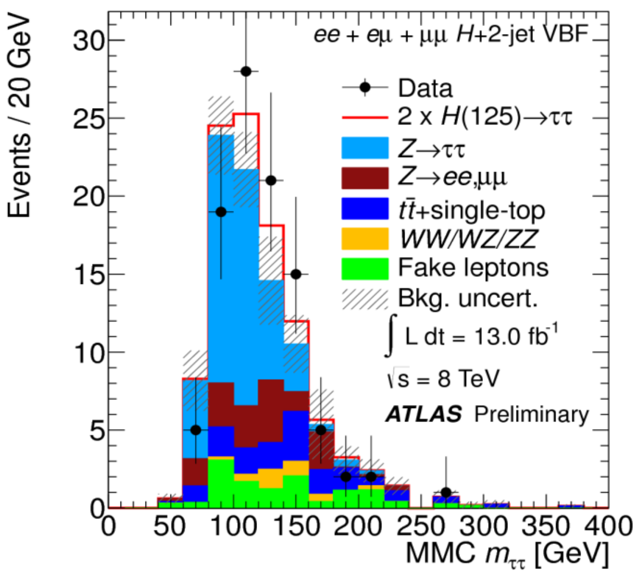
Best fit signal strength: $\mu = 0.2^{+0.7}_{-0.6}$

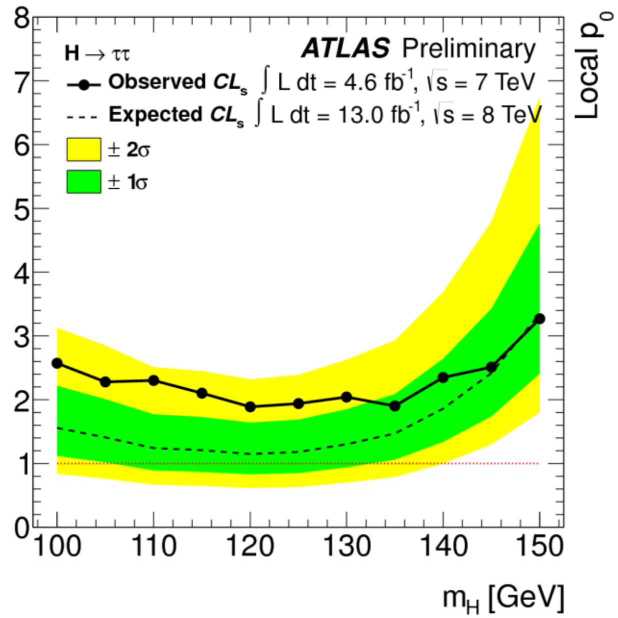
$H \to \tau\tau$

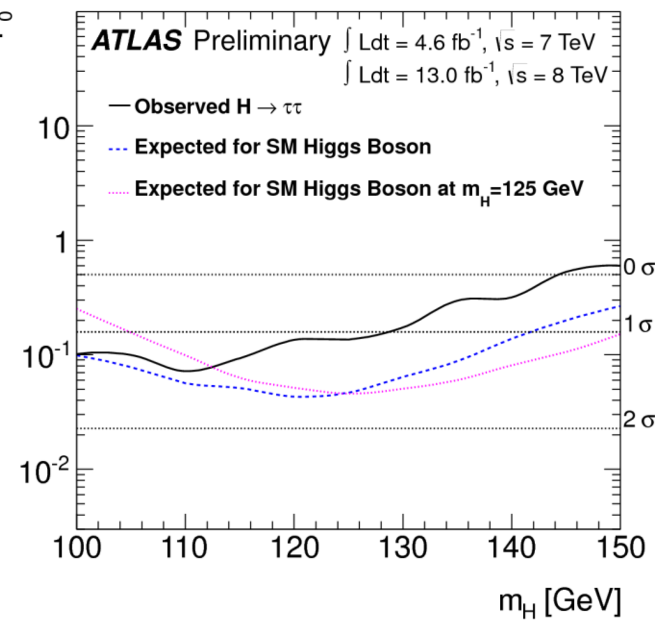
ATLAS-CONF-2012-160

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

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







Result 2011 and part of 2012 data:
1.1σ excess over SM background
Best fit: $\mu=0.7\pm0.7$

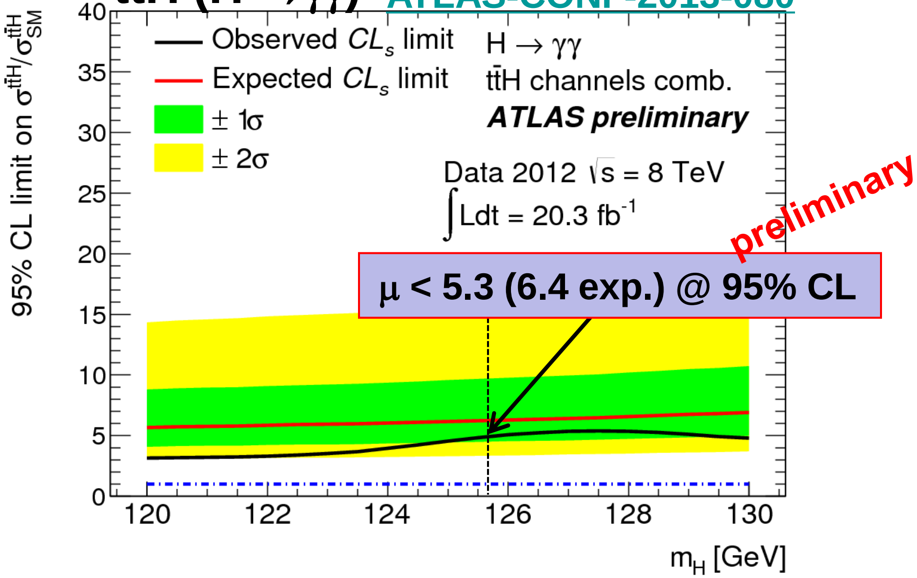
preliminary

Analysis with full 2012 data still to come.

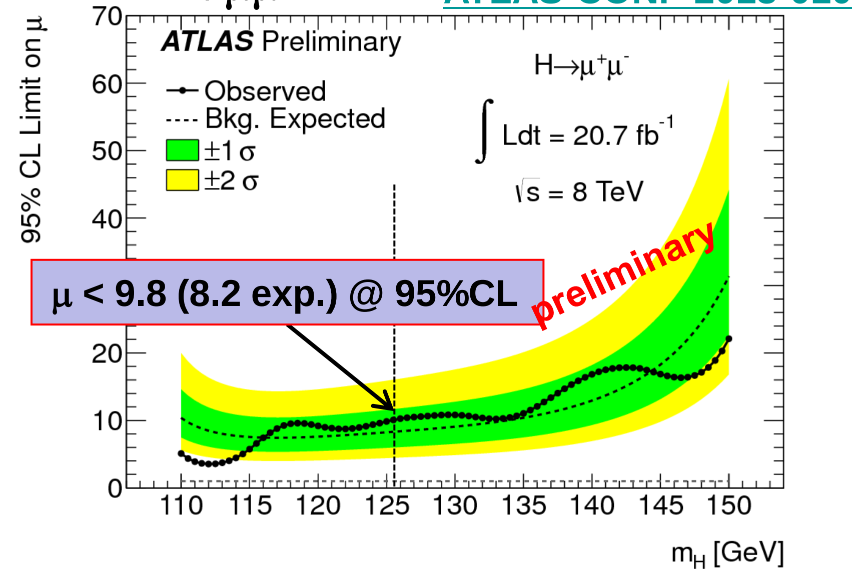
Rare production and/or decay modes

Rare production/decay modes

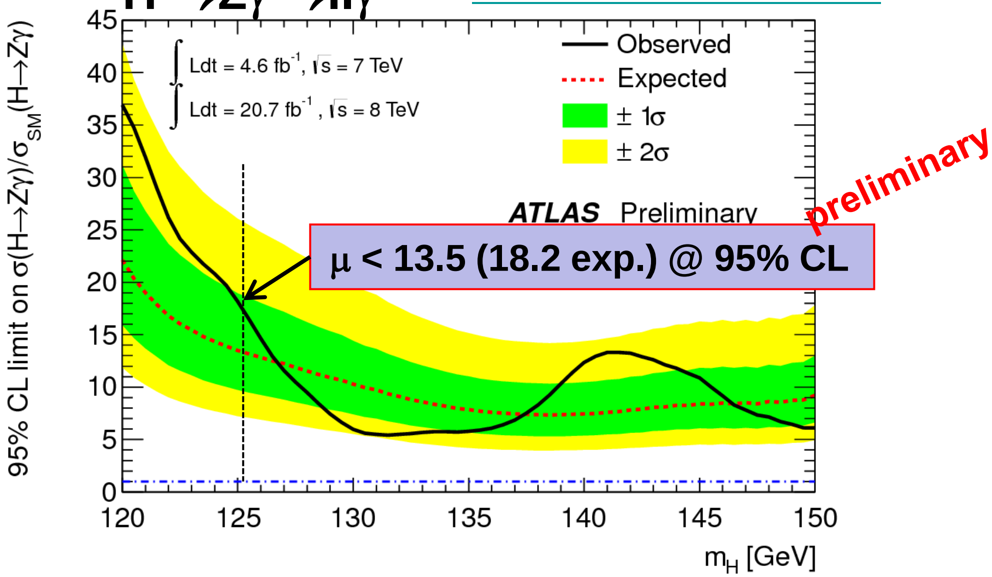
ttH (H →γγ) ATLAS-CONF-2013-080



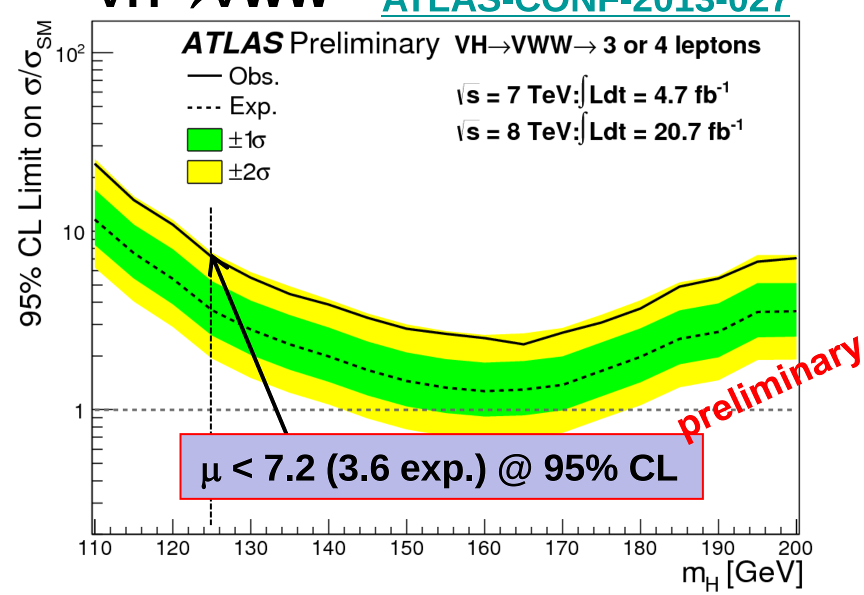
H→μμ ATLAS-CONF-2013-010



H →Zγ →llγ ATLAS-CONF-2013-009



VH→VWW ATLAS-CONF-2013-027

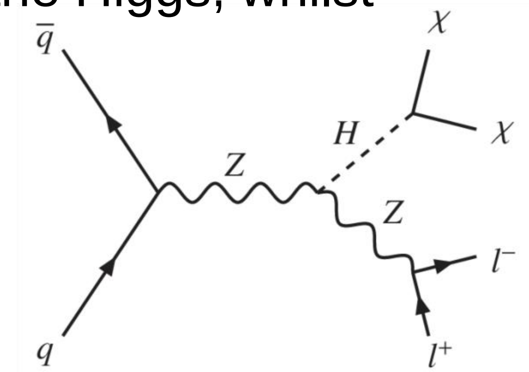


BSM Higgs

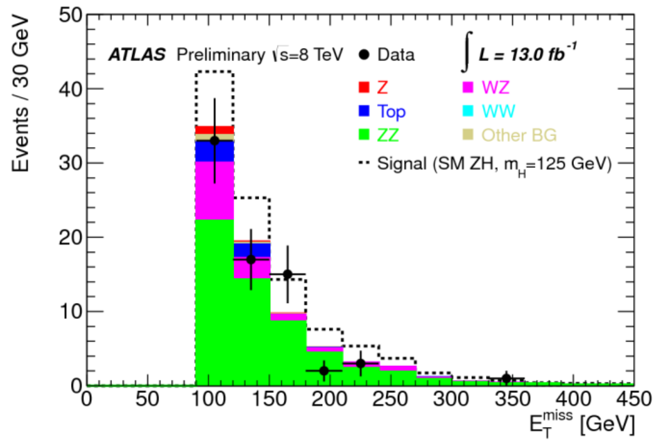
A few recent results

Invisible decays of the Higgs: ZH→ ll + inv

Rate expected in SM ($H \to ZZ \to \nu\nu\nu\nu$) 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

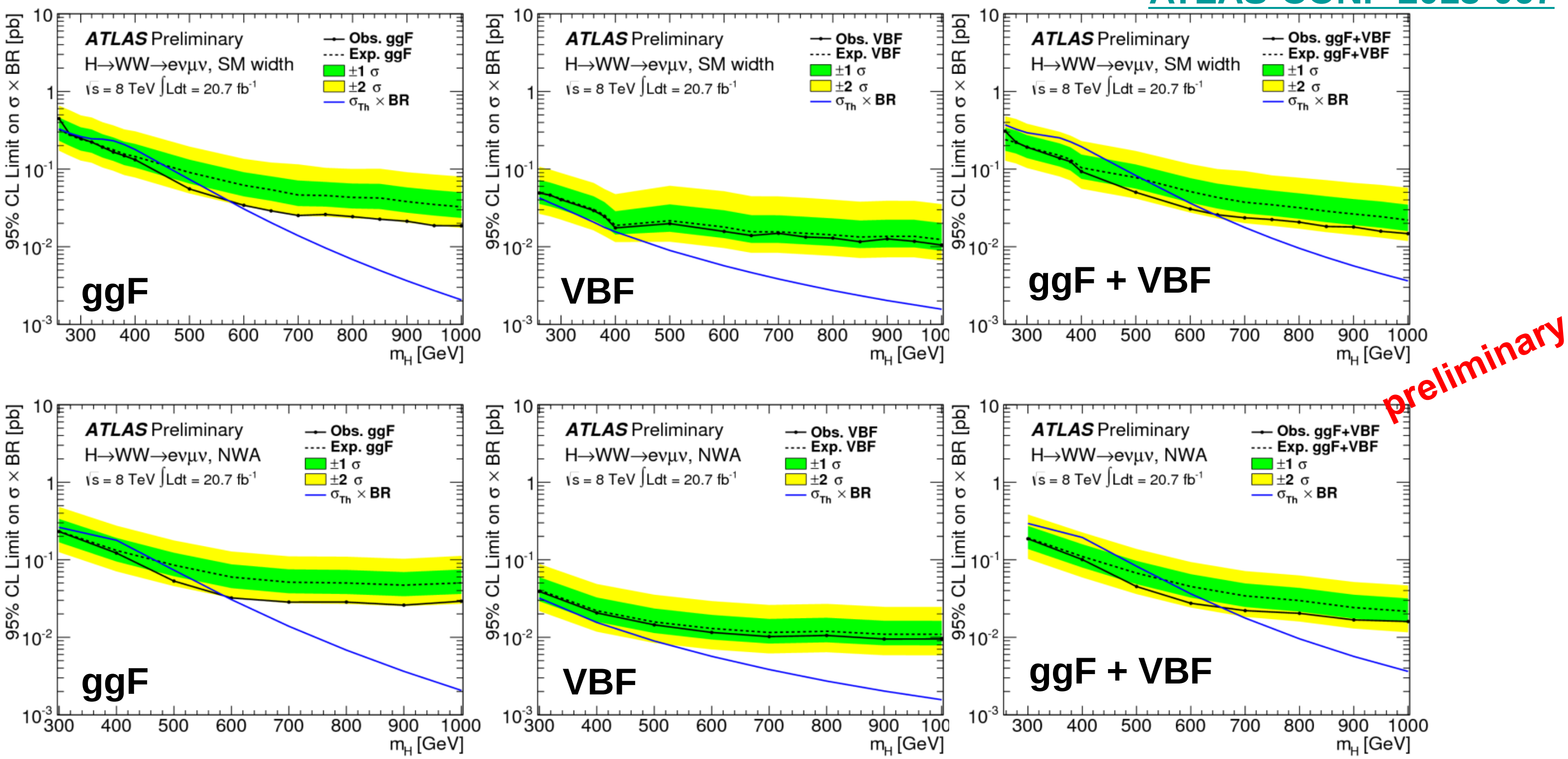
Search for a high mass (additional) neutral Higgs in the ZZ and WW decay modes.
Preliminary results $H\to ZZ\to 4l$ available in ATLAS-CONF-2013-013

New: $H\to WW\to e\nu\mu\nu$ 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



Full combination to come. More WW/ZZ decay channels to be included:
$H\to ZZ\to ll\nu\nu$, $H\to ZZ\to llqq$, $H\to WW\to l\nu qq$

More BSM Higgs

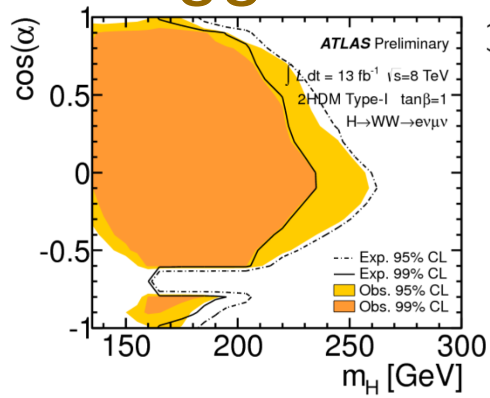
ATLAS-CONF-2013-027

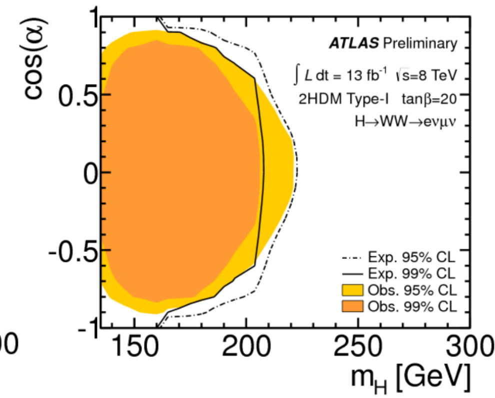
2HDM Higgs

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 $H^\pm \to \tau\upsilon$ + jets in mass range 180 – 600 GeV

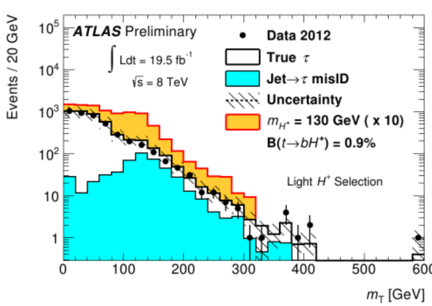
Released today!

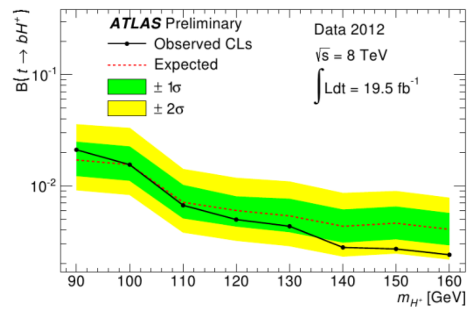
ATLAS-CONF-2013-090

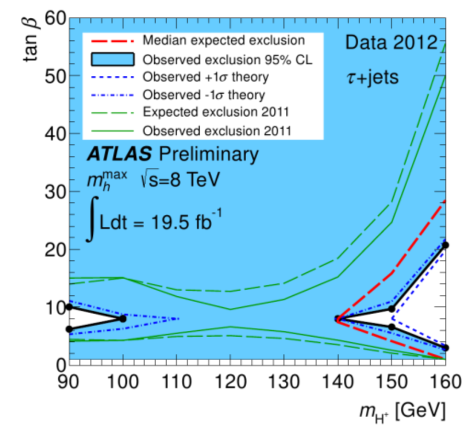
Low mass

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

ttbar → $H^\pm$bWb



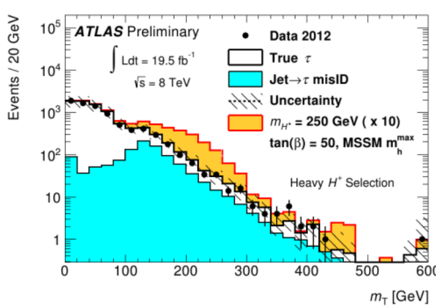


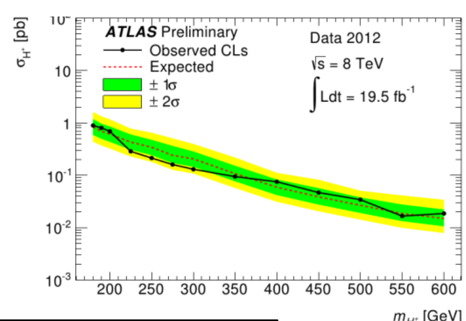


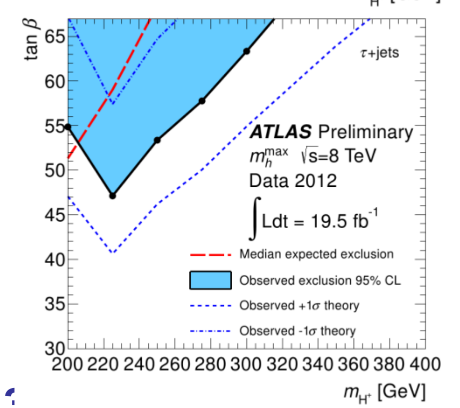
High mass

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

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

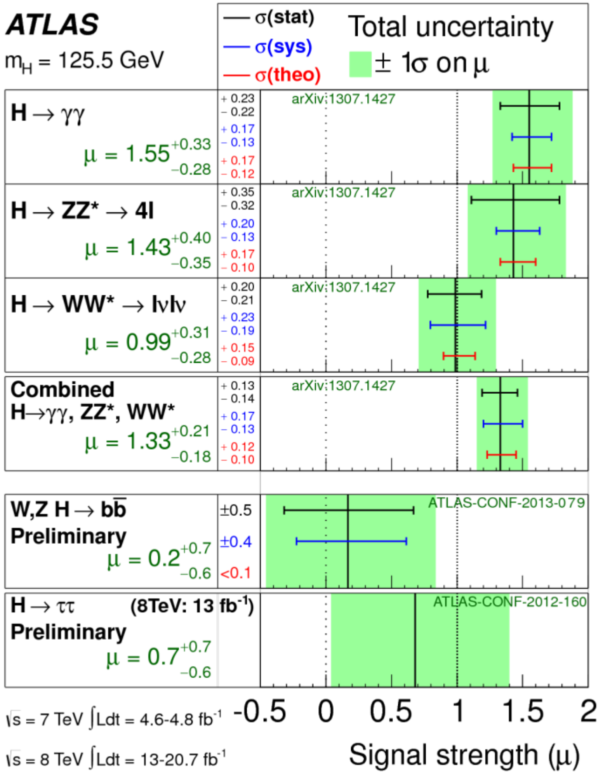
its coupling parameters (all consistent with a SM Higgs)

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

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

$H \rightarrow \tau\tau$: 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 $H \rightarrow$ invisible particles BR($H \rightarrow$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 ~3000fb^{-1} per experiment.

Very exciting times ahead ..