Search for a Standard Model Higgs Boson in Vector Boson Fusion in the $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ Decay with the ATLAS Detector

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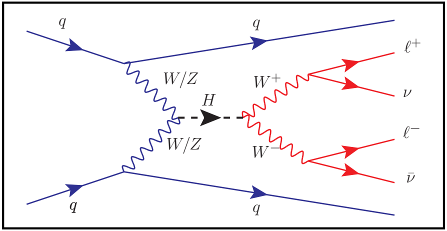

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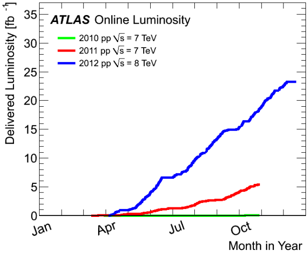
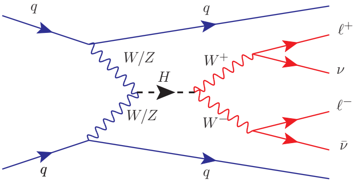
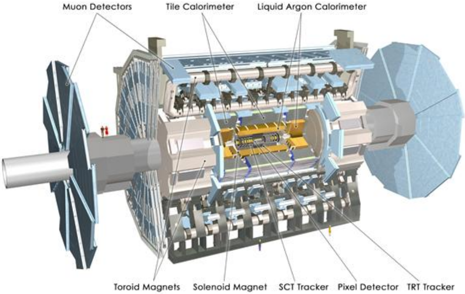
LHC and ATLAS

- ATLAS is a multi purpose detector located at the Large Hadron Collider (LHC) at CERN.

- The LHC has delivered a integrated luminosity of over 20 fb^{-1} of data from proton proton collisions at a center of mass energy of $\sqrt{s} = 8\,\text{TeV}$ (and 5 fb^{-1} at $\sqrt{s} = 7\,\text{TeV}$).
- I will focus on the Higgs results from 2012!
  - more specific: on the decay $H \to WW \to \ell\nu\ell\nu$
  - even more specific: in the Vector Boson Fusion (VBF) Higgs production mode.







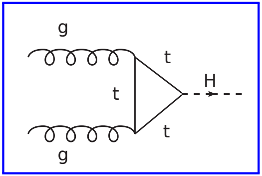
Production Mechanisms of a Standard Model Higgs Boson at the LHC

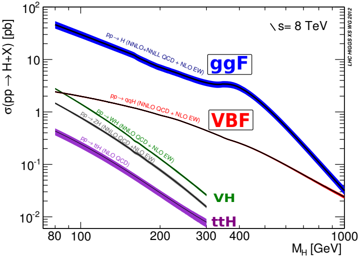
Gluon fusion (ggF):

- σ_{ggF} **dominant** cross section at LHC.

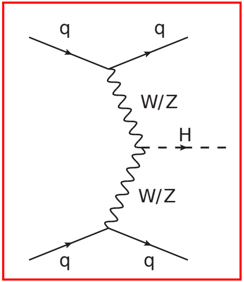
Vector Boson Fusion (VBF):

- $\sigma_{VBF} \approx 1/10 \cdot \sigma_{ggF}$
- Very clear signature with two forward jets.

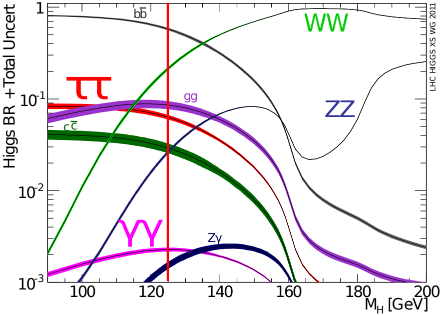




arXiv:101.0593



Why is $H \to WW$ such an interesting channel



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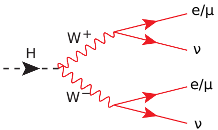
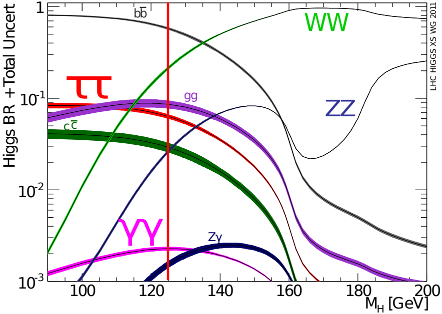


- **Higgs decay in two W Bosons is dominant branching fraction for $m_H > 2 \cdot m_W$!**
- Important at lower masses: $H \to \gamma\gamma$ and $H \to ZZ$.

The $H \to WW$ decay signature

- Two hard leptons (e, μ) and two neutrinos $\to$ missing transverse energy E_T^{miss}. $\Rightarrow$ Very low mass resolution!
- transverse Higgs mass from dilepton-E_T^{miss} system.
- Spin s $= 0 \to$ Small dilepton opening angle.



- **Higgs decay in two W Bosons is** **dominant branching fraction** **for** $m_H > 2 \cdot m_W$ **!**
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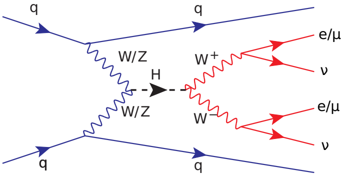
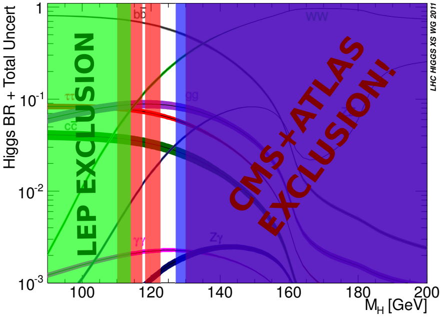


The VBF Topology

- Two energetic jets:
  - in the forward region of the detector.
  - in opposite hemispheres.
- Exploiting VBF Topology →
  - Very good background rejection.
  - BUT small statistics.



arXiv:101.0593

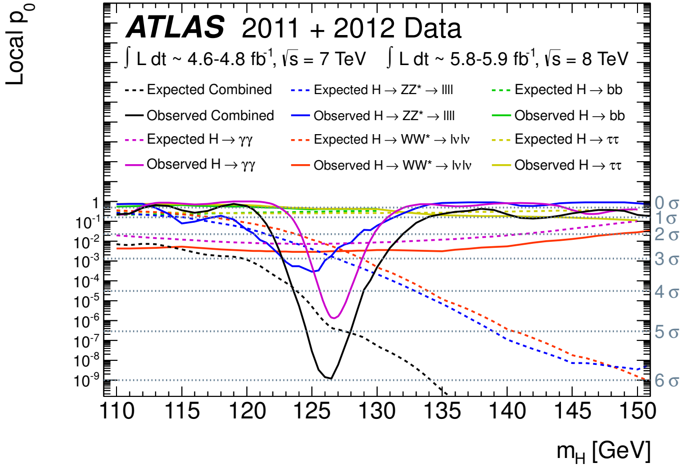
Already 2011 with 5fb^{-1} @ 7TeV:

- **ATLAS exclusion (95% CL)**:
  $110.0\,\text{GeV} < m_H < 117.5\,\text{GeV}$,
  $118.5\,\text{GeV} < m_H < 122.5\,\text{GeV}$,
  $129\,\text{GeV} < m_H < 539\,\text{GeV}$.
- **CMS exclusion (95% CL)**:
  $127\,\text{GeV} < m_H < 600\,\text{GeV}$
- **LEP exclusion**:
  $m_H < 114\,\text{GeV}$

Low mass range ($m_H < 600$ GeV) almost completely excluded already with data from 2011!
except: $122\,\textbf{GeV} < m_H < 127\,\textbf{GeV}$

Local P_0: Probability that a background only hypothesis produces a more signal like result than the observation (expected from signal + background)

- The smaller the local P_0 the lower the probability, that we observe only background.



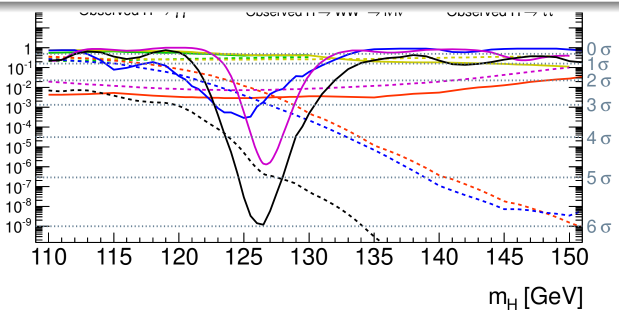
Compatibility with a background fluctuation at $m_H = 125\text{GeV}$: $1.7 \times 10^{-9} \rightarrow 5.9\ \sigma$

Discovery of a non charged scalar Boson,

- with mass ≈ 125 GeV that couples to Bosons (decay in γ/Z/W).

What we still don't know:

- It's exact mass and it's spin (s = 0 or 2) (Not in this talk!)
- Does it decay to Fermions (τ and b)? (Not in this talk!)
- Coupling strength and cross section.
  - Measure rate in different decay channels. (**WW in this talk!**)
  - Measure rate in different production mechanism. (**VBF in this talk!**)

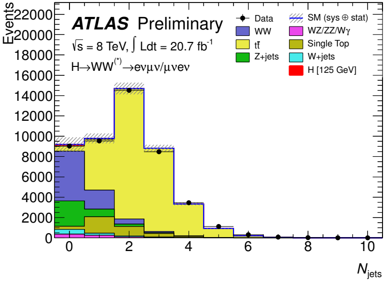


Compatibility with a background fluctuation at m_H = 125GeV: $1.7 \times 10^{-9} \rightarrow 5.9\ \sigma$

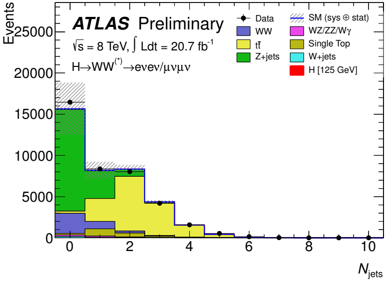
The $H \to WW$ Analysis: the backgrounds

Jet multiplicity after requiring 2 oppositely charged leptons and large E_T^{miss}

Different flavor (DF): $e\mu + \mu e$



Same flavor (SF): $ee + \mu\mu$

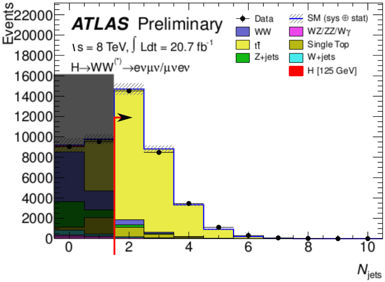


	DF ($e\mu + \mu e$)	SF ($ee + \mu\mu$)
no jets	WW (■) ,Z+jets ($Z \to \tau\tau$) (■)	Z+jets ($Z \to ee/Z \to \mu\mu$) (■),WW (■)
1 jet	Top (■/■), WW (■)	Z+jets (■), Top (■/■)
$\geq$ 2 jets	Top (■/■)	Top (■/■),Z+jets (■)

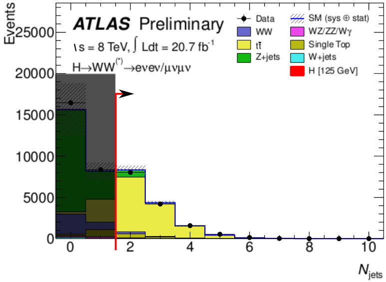
- Non WW Diboson processes, WZ/ZZ/Wγ (■): small cross section and at least one additional lepton.
- W+jet (■) process has large cross section but only one real lepton.

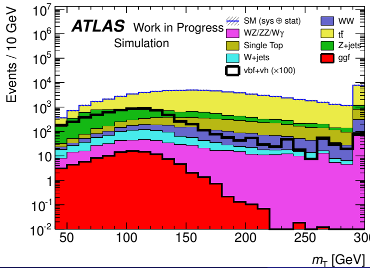
Jet multiplicity after requiring 2 oppositely charged leptons and large E_T^{miss} and 2 jets

Different flavor (DF): $e\mu + \mu e$



Same flavor (SF): $ee + \mu\mu$



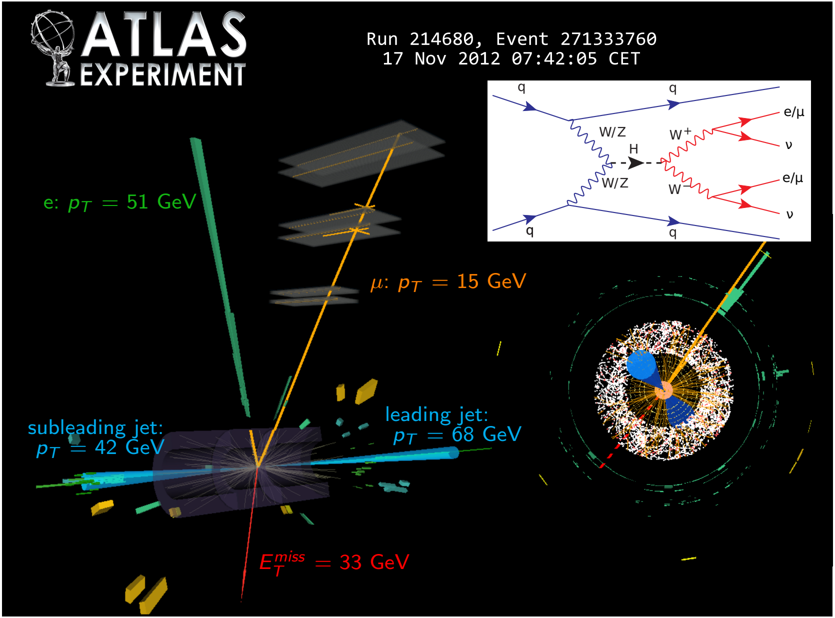


$\Leftarrow m_T$ distribution after preselection.

- **2 jet analysis** is the **VBF search channel**!
- VBF signal @ 125 GeV
  - here: (black line) $\times$ 100.
- ggf signal @ 125 GeV (■)
  - **is part of the background**.

The $H \to WW$ VBF analysis and the full results with 20fb^{-1} will be shown in the following.

A prime example of a VBF Candidate

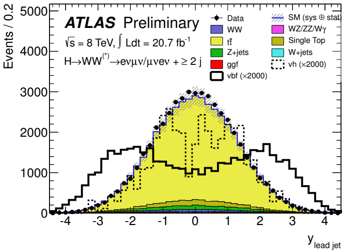


The Selection

VBF jets are energetic, forward, in opposite hemispheres and mostly from light (u,d,s) quarks!

- Veto on b jet (jet from a b-quark) → Top rejection!
- Central Jet Veto (CJV): no jet between the two leading (tagging) jets.
- Outside lepton veto: Higgs decay products (Leptons) in between the tagging jets.

Rapidity distribution of the leading jet



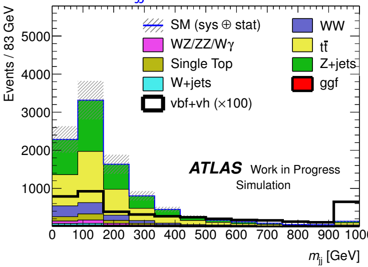
Exploiting the VBF Topology

The Selection

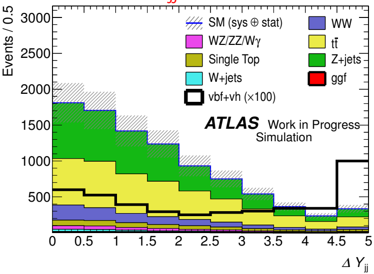
VBF jets are energetic, forward, in opposite hemispheres and mostly from light (u,d,s) quarks!

- Veto on b jet (jet from a b-quark) → Top rejection!
- Central Jet Veto (CJV): no jet between the two leading (tagging) jets.
- Outside lepton veto: Higgs decay products (Leptons) in between the tagging jets.
- High invariant Di-jet mass: $m_{jj} > 500$ GeV.
- Large rapidity gap between tagging jets: $\Delta Y_{jj} > 2.8$

$m_{jj} > 500$ GeV

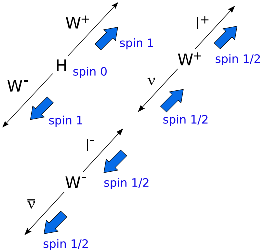


$\Delta Y_{jj} > 2.8$

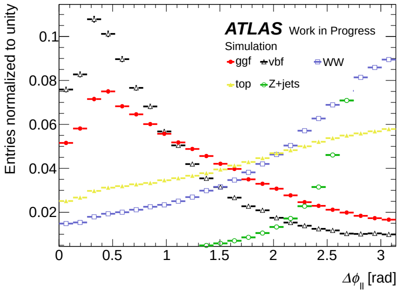


- For $s_{\text{Higgs}} = 0$ $\rightarrow$ $\vec{s}_W$ are back to back.
- $m_H \leq 2 \times m_W$ $\rightarrow$ W's at rest $\rightarrow$ $\ell\nu$-pair back to back!
- $\bar{\nu}$, from $W^- \rightarrow \ell^- \bar{\nu}$ decay, is right handed
  - $\rightarrow$ $\vec{p}_{\bar{\nu}} \parallel \vec{s}_{\bar{\nu}}$ (opposite for ν from $W^+ \rightarrow \ell^+ \nu$)
  - $\rightarrow$ $\vec{p}_{\bar{\nu}} \parallel \vec{p}_{\nu} \Rightarrow \vec{p}_{\bar{\ell}} \parallel \vec{p}_{\ell}$
  - $\rightarrow$ Small opening angle between the leptons.

$\Delta\phi(\ell\ell) < 1.8$



$\Delta\phi(\ell\ell)$ after selection of 2 oppositely charged leptons



- For $s_{Higgs} = 0$ $\rightarrow \vec{s}_W$ are back to back.
- $m_H \leq 2 \times m_W$ $\rightarrow$ W's at rest $\rightarrow$ $\ell\nu$-pair back to back!
- $\bar{\nu}$, from $W^- \rightarrow \ell^- \bar{\nu}$ decay, is right handed
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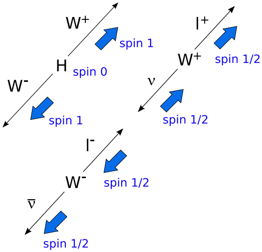
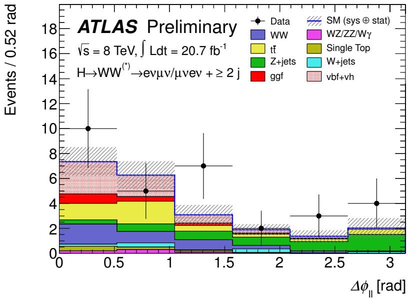
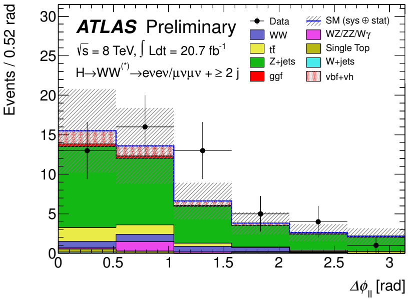
$$\Delta\phi(\ell\ell) < 1.8$$



Different flavor



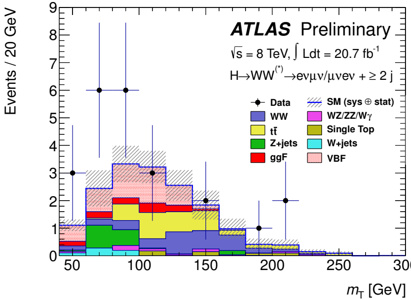
Same flavor



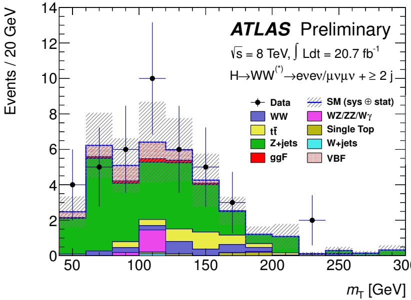
What is left at the end

m_T distribution after all cuts are applied.

Different flavor



Same flavor



- Very good signal to background ratio ($\approx$ S/B = 1/2) for different flavor.
- Same flavor final state less sensitive due to extra $Z \to ee/Z \to \mu\mu$ background.
- Excess of events over bkg only hypothesis observed (Quantification of excess 2 slides later)
- Signal and background m_T shape are very similar

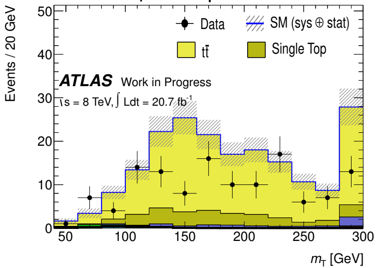
  $\to$ **Need to understand the background very well.**

  $\to$ **Exemplary: data driven Top bkg estimation in next slides**

Top Background Modelling and Estimation in Data driven Control region

- VBF cuts select only 0.008% of all Top.
  - $\Rightarrow$ We select rare/unnatural Top events
  - $\Rightarrow$ Can't rely on modelling by simulation!
- Top-decay: $t \rightarrow Wb$
- Definition of Top control region (CR):
  - b veto inversion.
  - All cuts applied except: $m_{\ell\ell}$, $\Delta\phi(\ell\ell)$, m_T

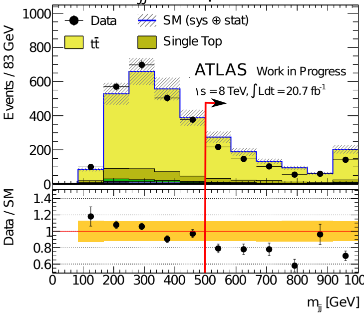
m_T in Top CR:



- $\rightarrow$ **Correction factor of 0.6 on the Top bkg Monte-Carlo prediction!**

- Cause of large correction:
  - Modelling of VBF (Di-jet) variables (m_{jj}, ΔY_{jj}, central jet veto ...)

m_{jj} in Top CR



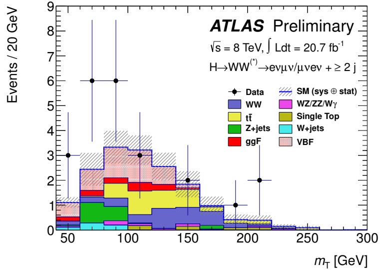
Measurement of VBF rate in $H \to WW$

- ggf is part of the background!
- Probability p_0, that bgk. only fluctuates to larger values then:
  - we expect from bkg + sig: **0.05 ∼ 1.6 σ**
  - we observe: **0.007 ∼ 2.5 σ**
- Signal strength μ ($\sim$ rate $\sigma_{\mathrm{VBF}} \times \mathcal{B}_{H\to WW}$):

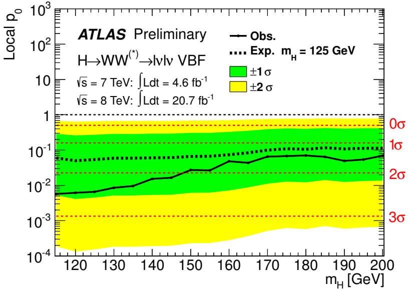
$$\mu_{\mathrm{obs,VBF}} = 1.66 \pm 0.67(\mathrm{stat.}) \pm 0.42(\mathrm{syst.})$$

- All numbers are given for $m_H = 125$ GeV!

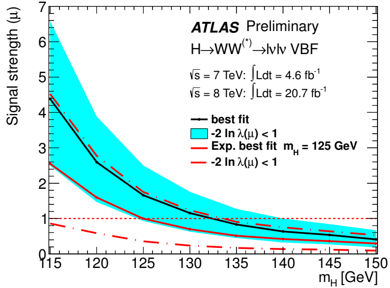
m_T distribution (DF) **2 jets**



Local p_0 for VBF signal only



Signal strength ∼ VBF production rate



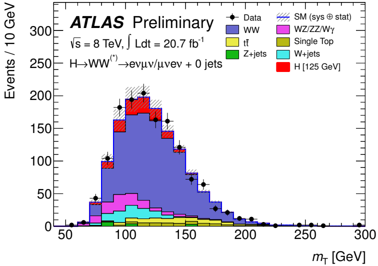
Measurement of rate in $H \to WW$ from VBF + ggf

- $H \to WW$ 0, 1, 2 jet combination (ggf + VBF)
- Probability p_0, that bgk. only fluctuates to larger values then:
  - we expect from bkg + sig: $1 \times 10^{-4} \sim 3.7\ \sigma$
  - we observe: $8 \times 10^{-5} \sim 3.8\ \sigma$
  - we observe: $2 \times 10^{-5} \sim 4.1\ \sigma$ @ 140GeV
- Signal strength μ ($\sim$ rate $\sigma_{\text{VBF}} \times \mathcal{B}_{H \to WW}$):

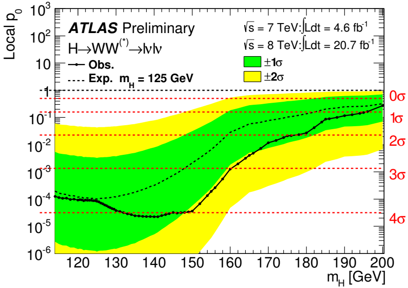
$$\mu_{\text{obs}} = 1.01 \pm 0.21(\text{stat.}) \pm 0.23(\text{syst.})$$

- All numbers are given for $m_H = 125$ GeV!

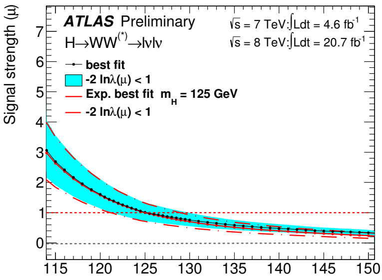
m_T distribution (DF) **0 jet**



Local p_0 for 0,1,2 jet combined



Signal strength 0,1,2 jet combined



Summary

- The ATLAS $H \to WW$ analysis was motivated and introduce,

  with emphasis on the VBF part of the analysis.
- An excess of events is observed (2.5σ) compatible with Standard Model Higgs production via VBF.
- The overall $H \to WW$ analysis observes an excess of 3.8σ compatible with the Standard Model prediction.

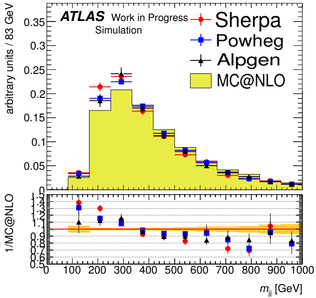
Thank You!

Backup

Comparing different Top generators

- Data/Simulation disagreement in VBF variables in Top CR by nominal generator MC@NLO
  ⇒ Large correction factor on Top prediction in signal region (SR)
- Requirement to apply correction derived in CR to SR:
  - **Data/simulation differences should be of same order in CR and SR.**
  - Impossible to check in SR due to other backgrounds and signal contamination.

  ⇒ Compare to other generators that model diet kinematics differently.



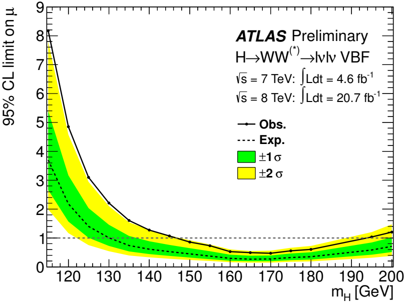
- Differences between generators in Top CR: ≈ 50%

  ⇒ Large correction understandable.
- Quantifying our lack of knowledge :
  - Derive individual correction factor for each generator.
  - Apply to generator prediction in SR.
  - Compare generators in SR after correction application.
  - 15% Difference between Alpgen/Powheg/MC@NLO

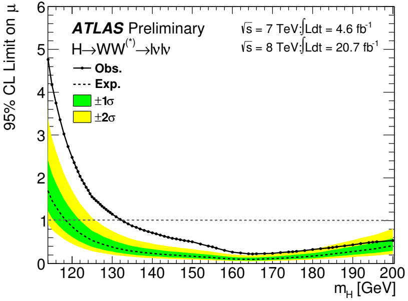
⇒ 15% syst. uncertainty applied to the Top prediction from the CR to SR extrapolation!

95% CLs upper limit vs. m_H

VBF limits

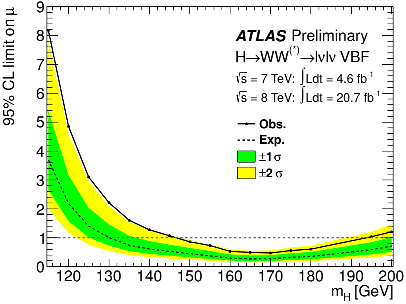


0, 1, 2-jet combined limits

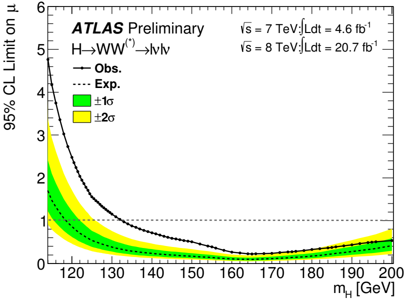


95% CLs upper limit vs. m_H

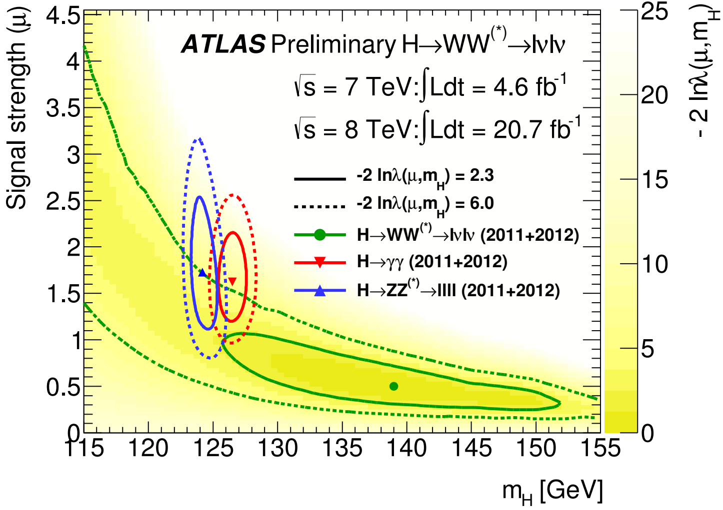
VBF limits



0, 1, 2-jet combined limits

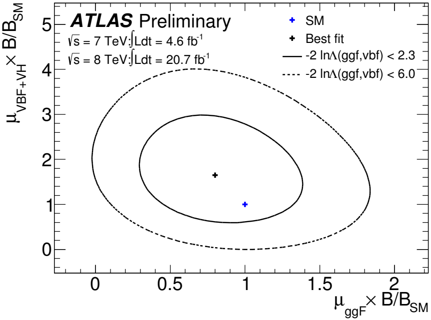


Combination with other Higgs decay channels



95% CLs upper limit vs. m_H

Likelihood contour μ_{ggf} vs. μ_{VBF}



$\mu_{VBF}/\mu_{\mathrm{ggf}}$ Likelihood curve