Higgs boson measurements in the $H \to WW^* \to \ell\nu\ell\nu$ channel with ATLAS

Experimental Particle Physics Seminar
University of Pennsylvania

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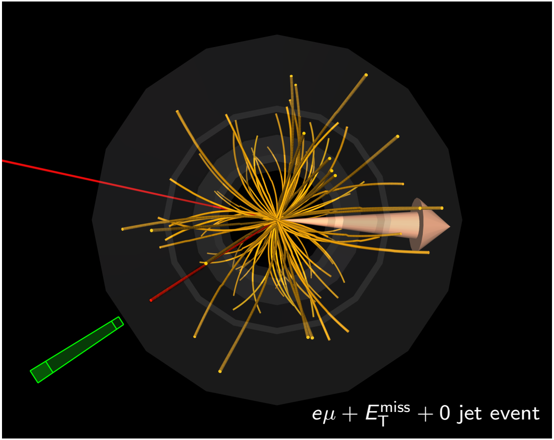
Outline

I will present the measurements of the Higgs boson in the $H \to WW^* \to \ell\nu\ell\nu$ decay, using all *pp* data collected by ATLAS during the first run of the LHC

- Physics motivation
- ATLAS experiment
- $H \to WW^* \to \ell\nu\ell\nu$
- Backgrounds
- Measuring Higgs production
- Higgs boson couplings
- Prospects

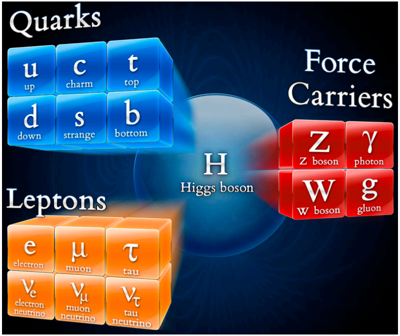


Phys. Lett. B 726 (2013), pp. 88-119; ATLAS-CONF-2013-030; ATLAS-CONF-2014-009

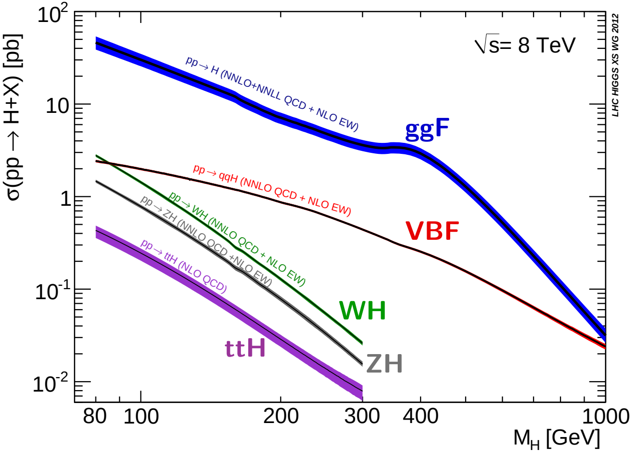
Physics Motivation

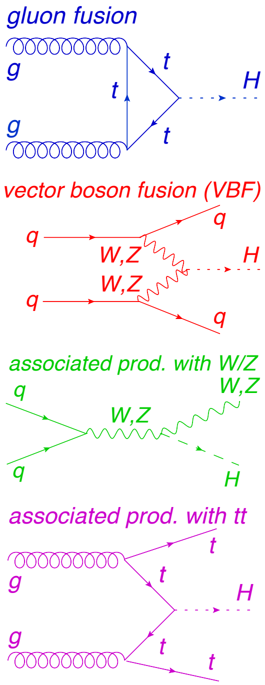
Standard Model Higgs boson

- Standard Model: unified description of fundamental particles and forces
- Based on local gauge invariance of the SU(3) $\times$ SU(2) $\times$ U(1) group
- Remarkable agreement between theory and experiment!
- But mass terms for gauge bosons are forbidden...
- Unless symmetry is spontaneously broken: Higgs mechanism
- Gain spin-0 scalar massive particle: the Higgs boson
- Higgs boson observed by ATLAS and CMS at the LHC with $m_H \sim 125$ GeV
- Prof. Peter Higgs and Prof. François Englert awarded the Nobel Prize in 2014



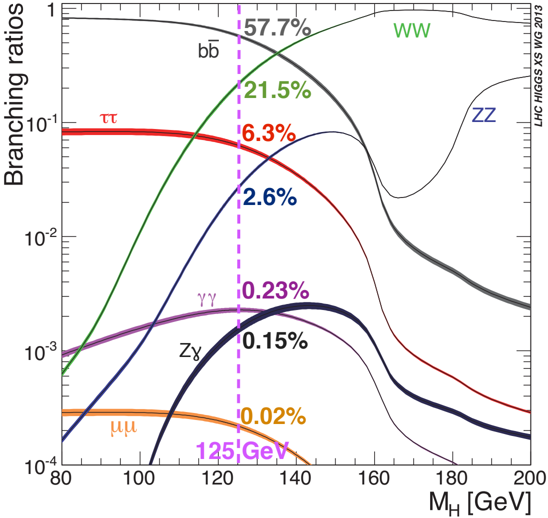
Producing the Higgs at the LHC





- **ggF** largest x-section, ∼ 10% uncertainty
- **VBF** distinct signature, ∼ 3% uncertainty
- **WH** clean event tag to probe e.g. $H \to b\bar{b}$
- **ttH** very low x-section, direct probe of top Yukawa

Higgs boson decays



Analysis strategy needs to take into account Higgs branching ratios, final state signatures, production x-sections and background processes

Bosonic modes (discovery)

- $H \to WW^* \to \ell\nu\ell\nu$
  more ahead!
- $H \to ZZ^* \to \ell\ell\ell\ell$
  low BR but very high S/B
  good mass resolution
- $H \to \gamma\gamma$
  very low BR
  good mass resolution

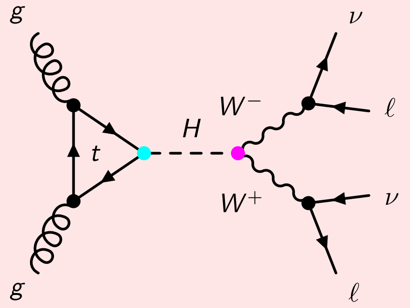
Fermionic decays

- $H \to b\bar{b}$
  needs VH
- $H \to \tau\tau$
  needs VBF

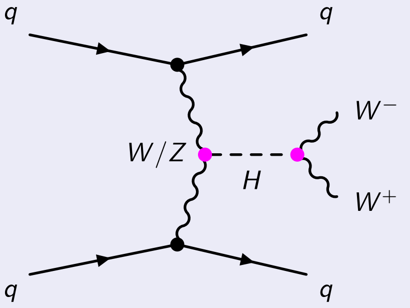
Why $H \to WW^* \to \ell\nu\ell\nu$?

- Observing $H \to WW^*$ decay is fundamental test of the theory
- Sizable $W \to e\nu/\mu\nu$ decays provide clean signature: probe ggF and VBF
- Two neutrinos in the final state: no mass sensitivity
- But second highest BR for $m_H = 125$ GeV: high event rate
- $H \to WW^* \to \ell\nu\ell\nu$ provides powerful measurements of production rates
- Important constraints to fermion and vector boson couplings
- Can also probe spin and parity properties (but I won't address that...)

ggF $H \to WW^* \to \ell\nu\ell\nu$

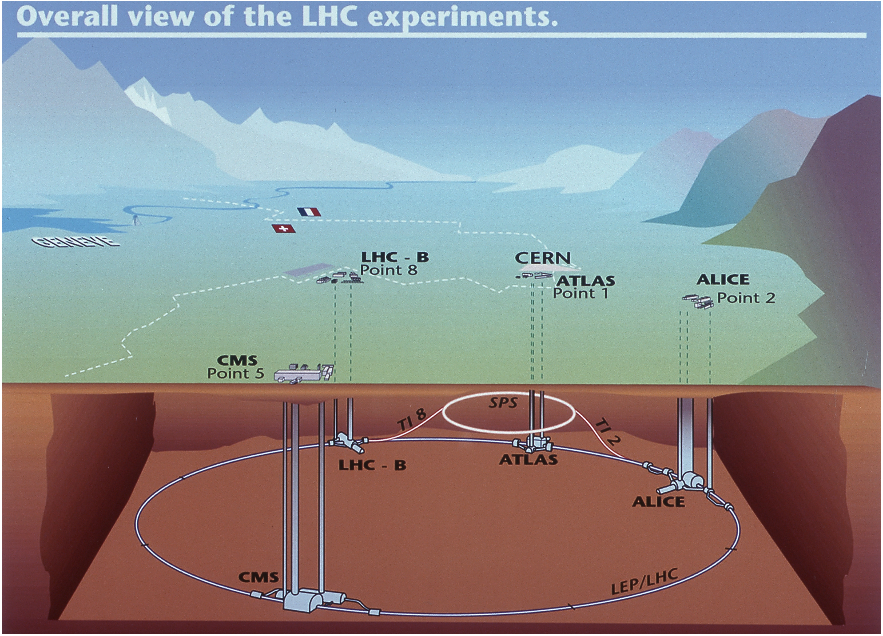


VBF $H \to WW^*$



The ATLAS Experiment

LHC: Large Hadron Collider



ATLAS: A Toroidal LHC ApparatuS

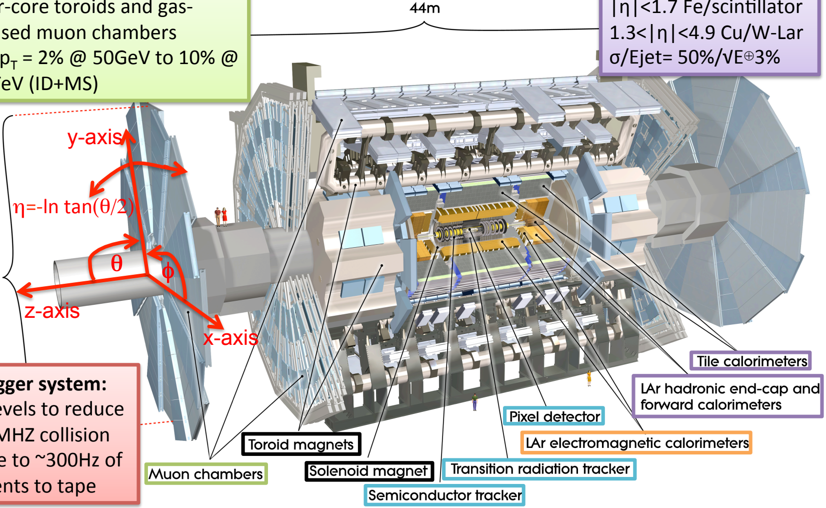
Magnet system:
B=2T in ID from solenoid
B=0.5-1T from toroid

Inner Detector: $|\eta|<2.5$
Si pixels/strips
Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\ (\text{GeV}) \oplus 1\%$

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

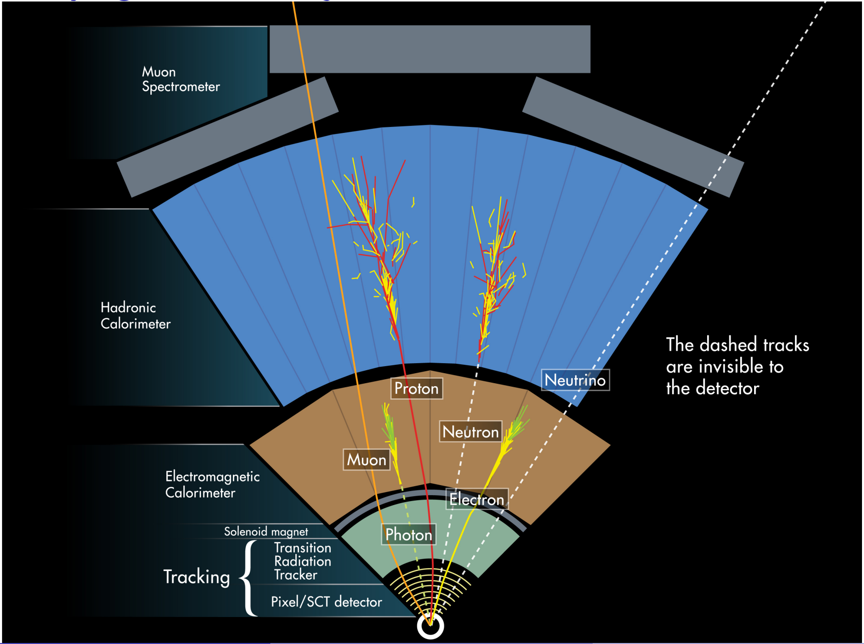
Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$



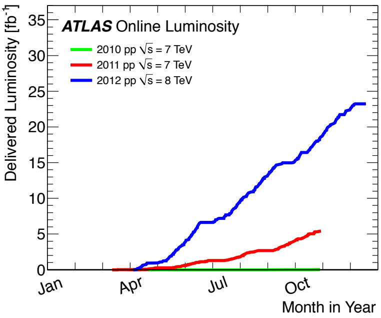
Trigger system:
3 levels to reduce 20MHZ collision rate to ~300Hz of events to tape

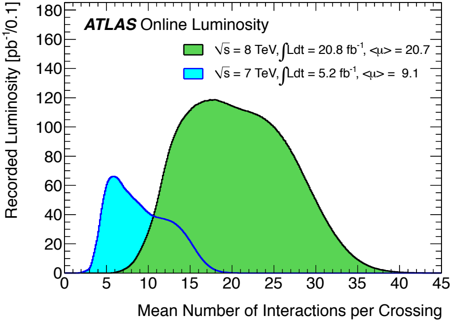
Identifying different objects



The dashed tracks are invisible to the detector

Recording pp collision data



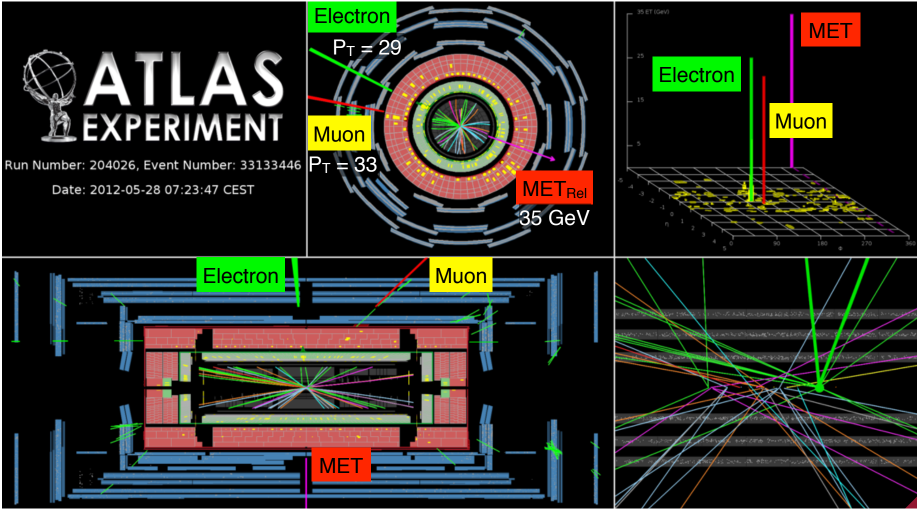


	2011	2012
Center-of-mass energy	7 TeV	8 TeV
Peak luminosity	3.65×10^{33} cm^{-2}s^{-1}	7.73×10^{33} cm^{-2}s^{-1}
Integrated luminosity	5.25 fb^{-1}	21.7 fb^{-1}
Average interaction rate	9.1/crossing	20.7/crossing
Data taking efficiency	93.5%	93.5 %

- Much more data in 2012 w.r.t. 2011.
- The challenge: handling pile-up!

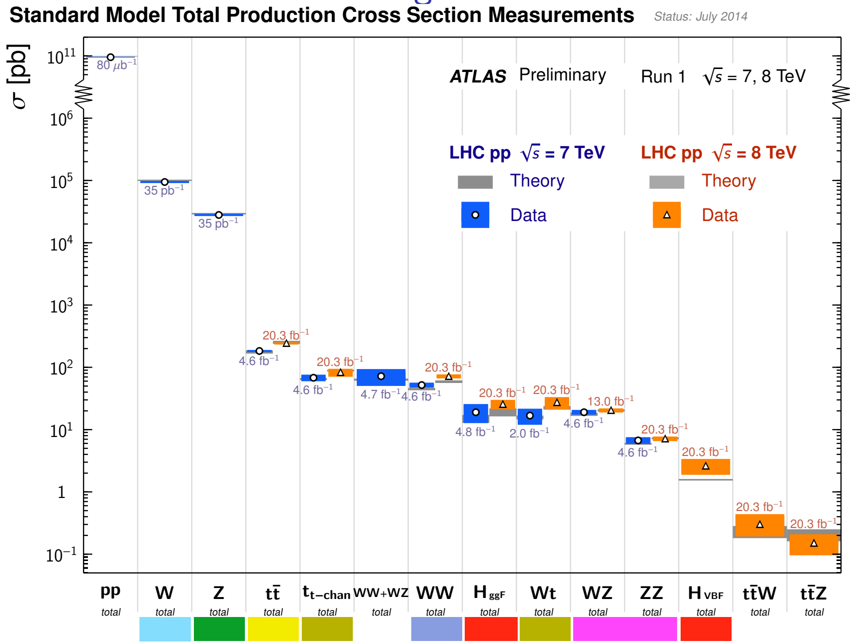
The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis

$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ signature



- 2 opposite-charge leptons + missing transverse energy final state
- No mass peak, signal manifests as broad excess in transverse mass m_T
- Accurate and precise estimation of different background sources is essential!

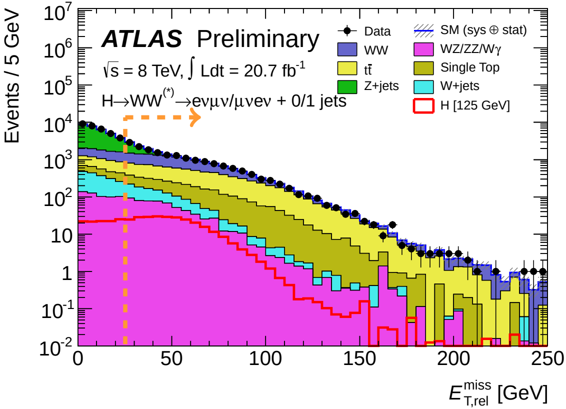
All these are sources of background

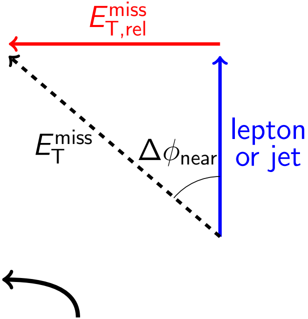


Missing transverse energy

- Select events with missing transverse energy: $E_T^{miss} = -\sum p_T$
- Relative-E_T^{miss}: better measurement in events with mismeasured leptons/jets

$$E_{T,rel}^{miss} = \begin{cases} E_T^{miss} \times \sin \Delta\phi_{near} \text{ , if } \Delta\phi_{near} > \pi/2 \\ E_T^{miss} \text{ , otherwise} \end{cases}$$



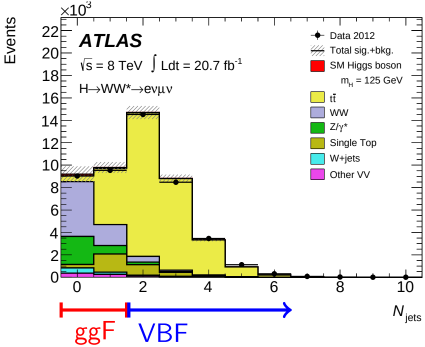


Calorimeter-based measurement of missing transverse energy

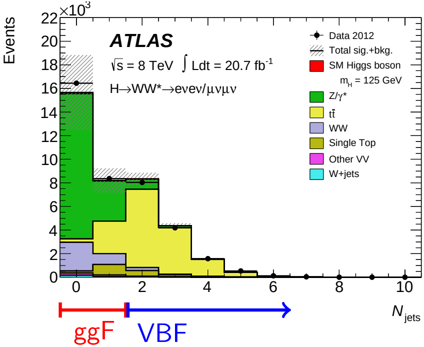
- $E_{T,rel}^{miss} > 25$ (45) GeV for $e\mu$ ($ee + \mu\mu$) events

Event categories

$e\mu$ - different flavor leptons

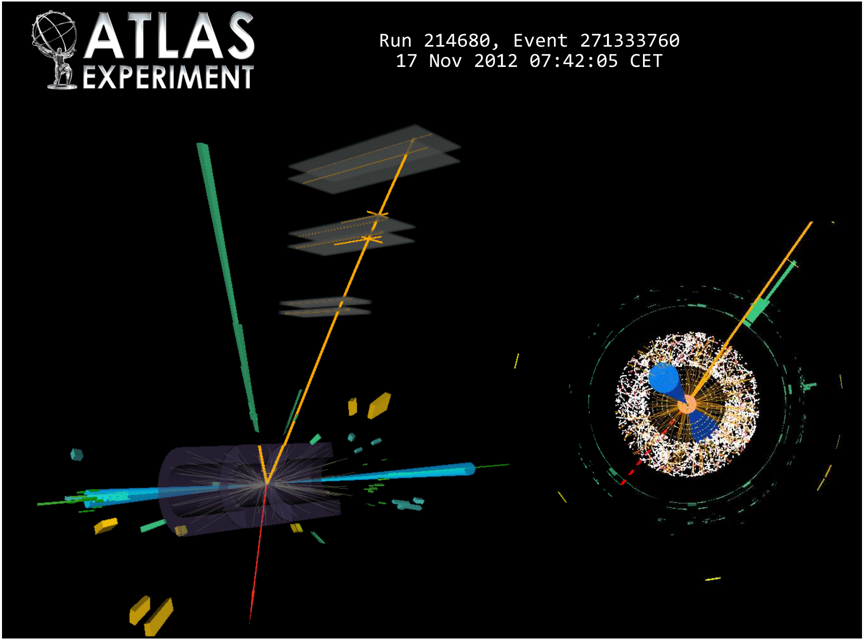


$ee + \mu\mu$ - same flavor leptons

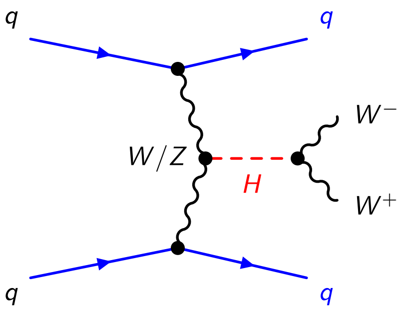


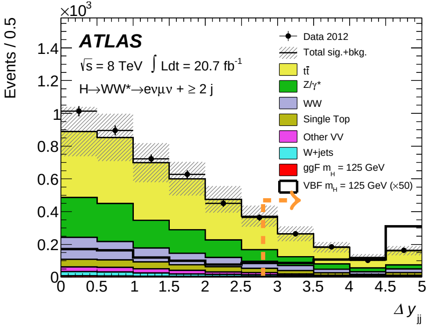
- Event categories with different background compositions: better sensitivity!
- Lepton flavor split:
  - $ee + \mu\mu$ suffers from large Z/γ^* contamination, $e\mu$ has better sensitivity
- N_{jets} split (anti-k_t 0.4, $p_T > 25$ (30) GeV):
  - use $N_{\text{jets}} \leqslant 1$ and $N_{\text{jets}} \geqslant 2$ to probe ggF and VBF production modes

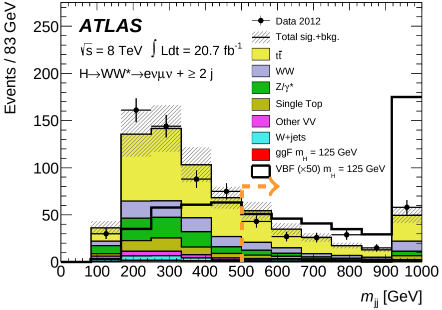
VBF $H \to WW^* \to \ell\nu\ell\nu$ signature with forward jets



The VBF topology

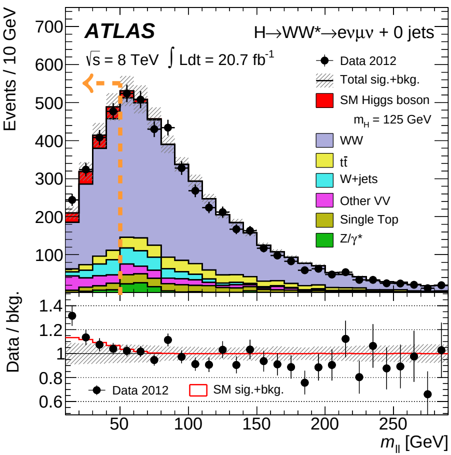


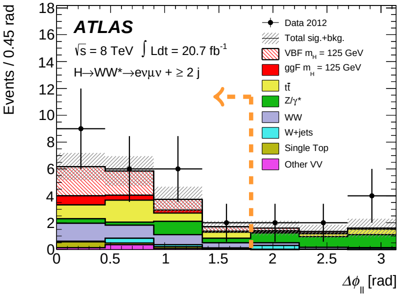


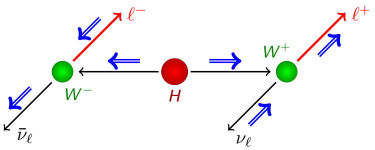


- Two forward widely separated jets:
  - $|\Delta y_{jj}| > 2.8$
  - $m_{jj} > 500$ GeV
  - no *b*-jets to suppress top
- Central Higgs boson:
  - No other jets in the gap
  - Require leptons in the gap

Selecting Higgs candidates



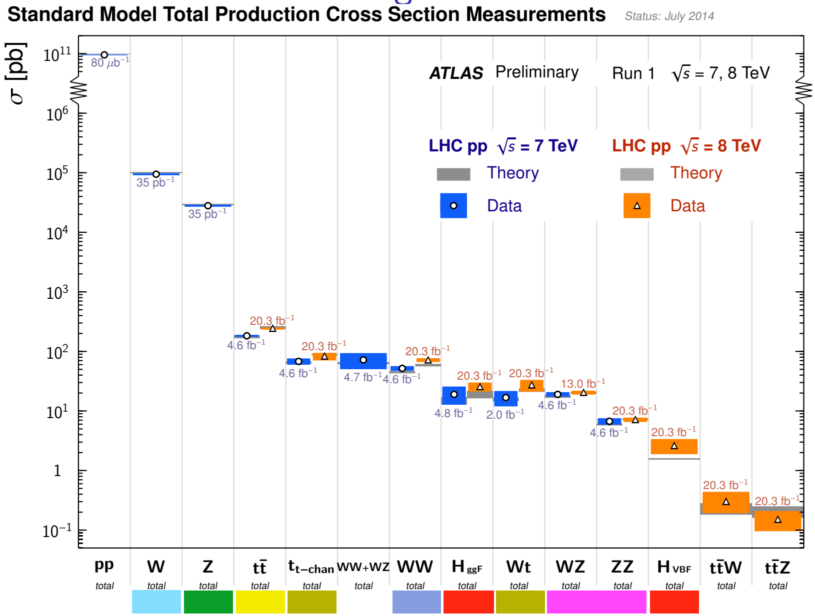




- Exploit spin-0 of SM Higgs and V-A weak decay of W bosons
- Low invariant mass of dilepton system: $\boldsymbol{m_{\ell\ell} < 50}$ **GeV**
- Small azimuthal separation between two leptons: $\boldsymbol{\Delta\phi_{\ell\ell} < 1.8}$ **rad**

Backgrounds

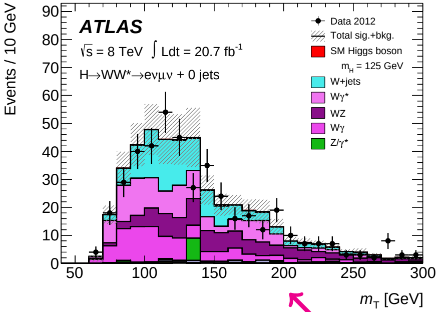
All these are sources of background



Use data to normalize/validate/replace MC result as much as possible!

W+jets

- Mimics signal when jet fakes lepton
- Essential to have good lepton identification and isolation
- Very hard to model fakes with MC
- Estimated entirely from data
- Validated with same charge dilepton
- $\sim 30\%$ uncertainty



$W\gamma$, $W\gamma^*$, WZ taken from MC and validated with same charge sample ($\sim 20\%$ unc.)

Fake factor method

1. $W+$jets control sample with id + anti-id leptons:

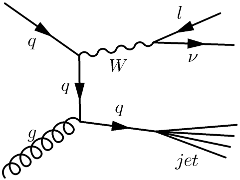
$$N^{W+\text{jets}}_{\text{id+anti-id}}$$

2. Determine fake factor from high statistics dijet data:

$$f_{\text{fake}}(p_T, \eta) = N_{\text{id}}/N_{\text{anti-id}}$$

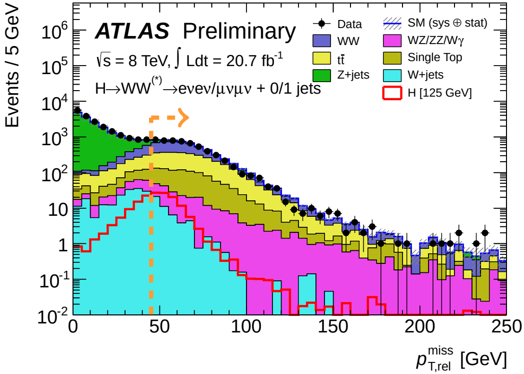
3. Extract $W+$jets contamination in signal region:

$$N^{W+\text{jets}}_{\text{id+id}} = f_{\text{fake}} \times N^{W+\text{jets}}_{\text{id+anti-id}}$$



Drell-Yan in 0- and 1-jet same flavour channels

- Large $Z/\gamma^* \to ee/\mu\mu$ contamination in $ee + \mu\mu$ channels
- Pile-up degrades $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution: more fake $E_{\mathrm{T}}^{\mathrm{miss}}$
- Z/γ^* contamination in 2012 increased by ~ 5 w.r.t. 2011



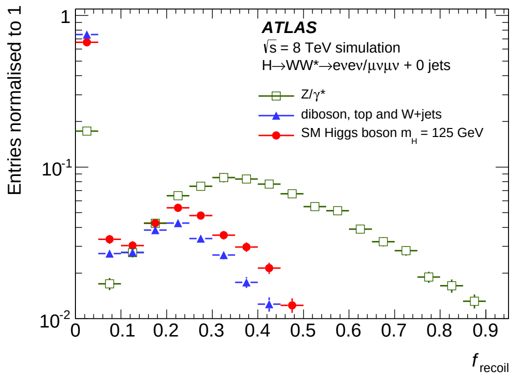
- Independent measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$ using inner detector tracks - $p_{\mathrm{T}}^{\mathrm{miss}}$:

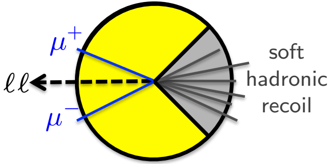
+ Stability with pile-up

− No information on neutrals

- Apply tight selections on both calorimeter- and track-based measurements:
  - $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ GeV and $p_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ GeV

Soft hadronic recoil to further suppress Drell-Yan



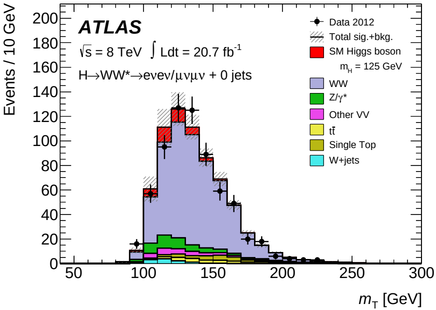


$$f_{\text{recoil}} = \frac{\left|\sum |\text{JVF}| \times \vec{p_{\text{T}}}\right|}{p_{\text{T}}^{\ell\ell}}$$

- Remember: looking at events with low $m_{\ell\ell}$, small $\Delta\phi_{\ell\ell}$ and no jets
- Z/γ^* events have two close-by leptons and no neutrinos (fake $E_{\text{T}}^{\text{miss}}$)
- $\ell\ell$ must be balanced by very soft jets not passing veto threshold
- Define f_{recoil} to measure soft hadronic activity opposite to $\ell\ell$-axis
- Clear separation between Z/γ^* and processes with true $E_{\text{T}}^{\text{miss}}$ including signal
- Apply tight f_{recoil} selection: $f_{\text{recoil}} < 0.05$ (0.2) for 0-jet (1-jet)
  - $\epsilon^{Z/\gamma^*} \sim 25\%$ and $\epsilon^{\text{non-}Z/\gamma^*} \sim 75\%$

Data-driven method to estimate Drell-Yan

- Challenging environment for $ee + \mu\mu$:
  - $E_{\mathrm{T}}^{\mathrm{miss}}$ is complex object
  - Fake $E_{\mathrm{T}}^{\mathrm{miss}}$ very hard to model
  - Soft jets: non-perturbative QCD
  - Pile-up just complicates more
- Estimate Z/γ^* from data: Pacman
- Z/γ^* suppressed to reasonable level
- 60% (80%) uncertainty on 0-jet (1-jet)



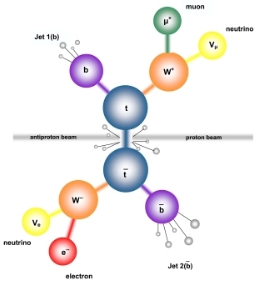
Pacman method

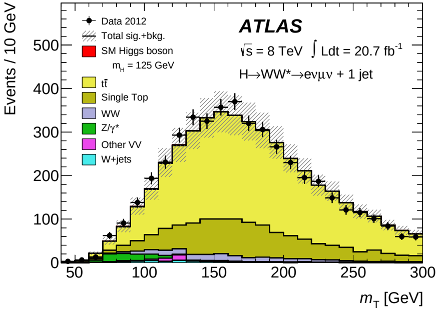
1. Measure efficiencies of f_{recoil} selection in data: ϵ^{Z/γ^*} and $\epsilon^{\text{non-}Z/\gamma^*}$
2. Use data passing and failing f_{recoil} cut directly in the signal region
   - measuring efficiencies so still insensitive to the presence of signal!
3. Invert matrix and solve for $N_{\mathrm{pass}}^{Z/\gamma^*}$ to obtain Z/γ^* estimate in the SR

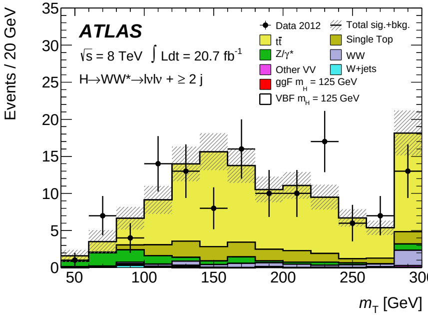
$$\begin{bmatrix} N_{\mathrm{pass}}^{\mathrm{data}} \\ N_{\mathrm{pass+fail}}^{\mathrm{data}} \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1/\epsilon^{Z/\gamma^*} & 1/\epsilon^{\text{non-}Z/\gamma^*} \end{bmatrix} \begin{bmatrix} N_{\mathrm{pass}}^{Z/\gamma^*} \\ N_{\mathrm{pass}}^{\text{non-}Z/\gamma^*} \end{bmatrix}$$

Top backgrounds in 1- and 2-jet channels

- Top-quark backgrounds produce $WW + b$-jets
- Suppress $t\bar{t}$ and single top by vetoing on b-jets
- Use events with 1 b-jet as control regions
- Used to normalize top background directly to data
- For 2-jet apply VBF topology selections



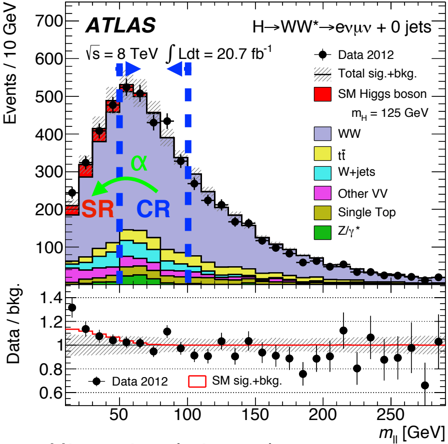




$\mathrm{NF}^{\mathrm{top}}_{\mathrm{1jet}} = 1.04 \pm 0.02$ (stat.)
$\sim 30\%$ uncertainty

$\mathrm{NF}^{\mathrm{top}}_{\mathrm{VBF}} = 0.59 \pm 0.07$ (stat.)
$\sim 40\%$ uncertainty

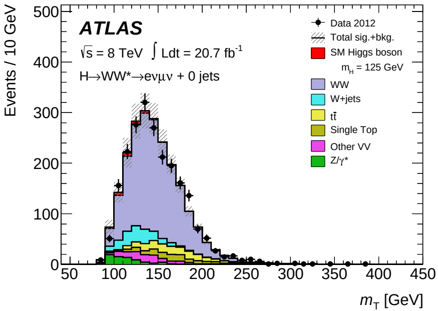
Continuum *WW* for 0- and 1-jet channels



- Higgs signal sits at low $m_{\ell\ell}$
- *WW* control region at high $m_{\ell\ell}$
- Normalize *WW* to data in CR

$$NF^{WW}_{0\text{jet}} = 1.16 \pm 0.04 \text{ (stat.)}$$
$$NF^{WW}_{1\text{jet}} = 1.03 \pm 0.06 \text{ (stat.)}$$

$50 < m_{\ell\ell} < 100$ GeV *WW* CR

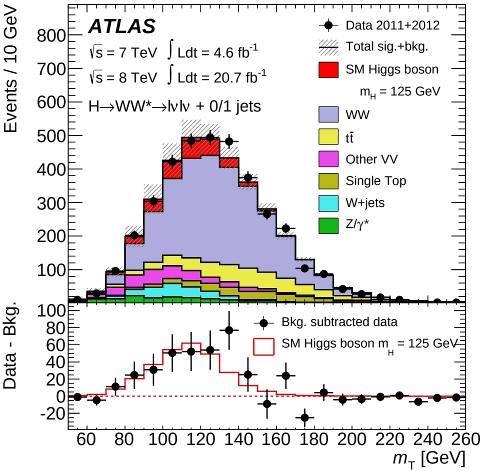


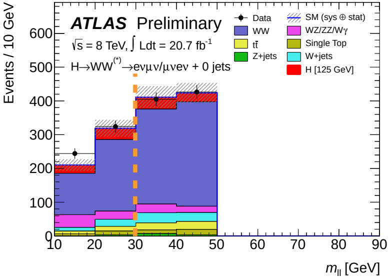
- *WW* is main background
- Uncertainties from MC on CR-to-SR extrapolation α
- Important to keep them small
- Reduce by choosing CR close to SR
- $\sim 2\%$ uncertainty on α
- $\sim 7\%$ total uncertainty for 0-jet

Measuring the Higgs Production

Not the full mass, but still something

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





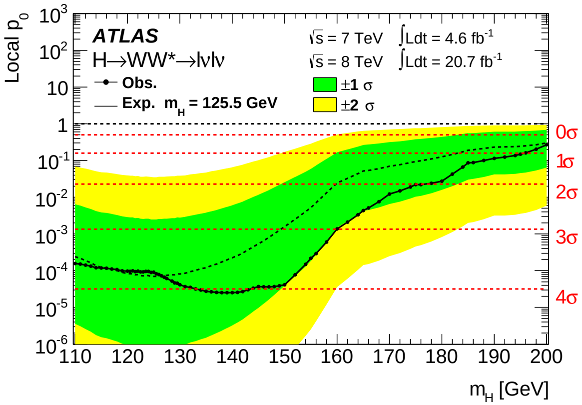
- Further sensitivity by splitting $e\mu$ events in $m_{\ell\ell}$

	$N_{\mathrm{jet}} = 0$	$N_{\mathrm{jet}} = 1$	$N_{\mathrm{jet}} \geq 2$
Observed	831	309	55
Signal	100 ± 21	41 ± 14	10.9 ± 1.4
Total background	739 ± 39	261 ± 28	36 ± 4
WW	551 ± 41	108 ± 40	4.1 ± 1.5
Other VV	58 ± 8	27 ± 6	1.9 ± 0.4
Top-quark	39 ± 5	95 ± 28	5.4 ± 2.1
Z+jets	30 ± 10	12 ± 6	22 ± 3
W+jets	61 ± 21	20 ± 5	0.7 ± 0.2

- m_{T} fitted to extract Higgs
- Excess in data consistent with SM Higgs

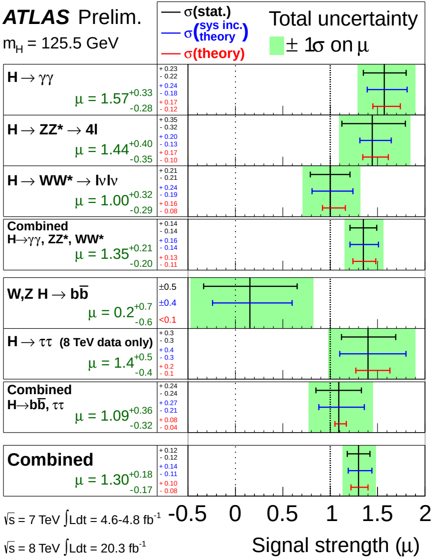
Note: yields quoted in m_{T} window

Significance of the excess



- Probability for background-only to produce observed excess at 125.5 GeV
  - 8×10^{-5}
- Significance of the observed excess at 125.5 GeV:
  - 3.8σ
- Evidence of Higgs boson in $H \to WW^*$ decay

Measuring the total production rate



- Signal strength compares observed rate to SM-predicted rate

$$\mu_{\text{obs}} = \frac{(\sigma \times \text{BR})_{\text{obs}}}{\sigma_{\text{SM}} \times \text{BR}_{\text{SM}}}$$

- 30% precision on μ!
- Excess compatible with 125.5 GeV Higgs

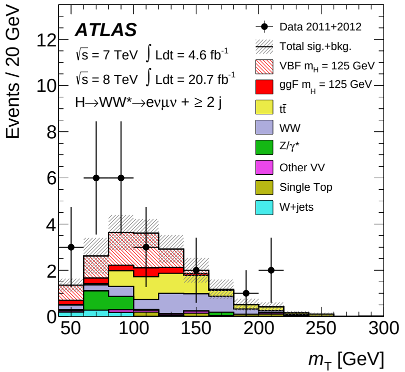
$$\boldsymbol{\mu_{\text{obs}} = 1.00 \pm 0.21\ (\text{stat.})\ {}^{+0.16}_{-0.08}\ (\text{theo.})\ {}^{+0.18}_{-0.17}\ (\text{expt.}) = 1.00^{+0.32}_{-0.29}}$$

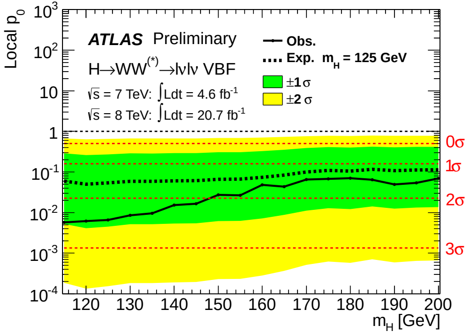
Breakdown of uncertainties on μ

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	$W+$ jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29

- Uncertainties impacting μ: half statistics, half systematics
- Half the systematics are from theory
- Dominant experimental systematics from jet energy scale, *b*-tagging and data-driven background estimates

Measuring VBF

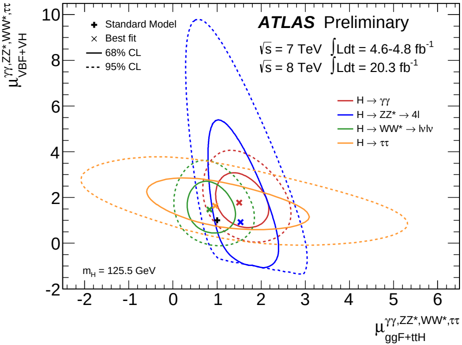


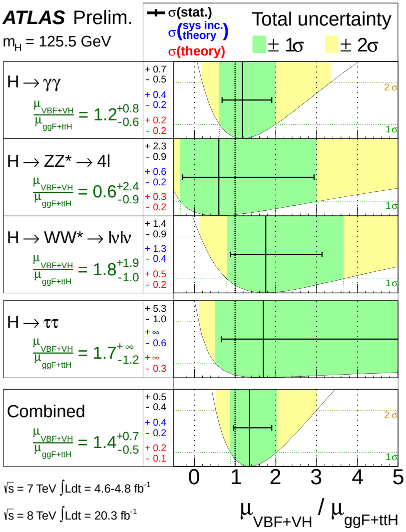


- Use 2-jet category to measure VBF
- ggF considered background

- 2.5σ excess observed in data
- $\mu_{\mathrm{VBF}}^{\mathrm{obs}} = 1.66 \pm 0.79$

ggF vs. VBF





- 2D contour of $\mu_{\mathrm{ggF+ttH}}$ vs. $\mu_{\mathrm{VBF+VH}}$
- All channels compatible with SM
- Take ratio for combination
- 4.1σ evidence that a fraction of Higgs production occurs through VBF

Higgs Boson Couplings

Translating rates into SM Higgs couplings

Why?

- Higgs couplings are exactly determined in the SM:

$$g_{HVV} = 2m_V^2/\text{vev} \qquad g_{\text{Yukawa}} = m_f/\text{vev}$$

- Essential to measure them as precisely as possible
- Any deviations will be a sign of new physics

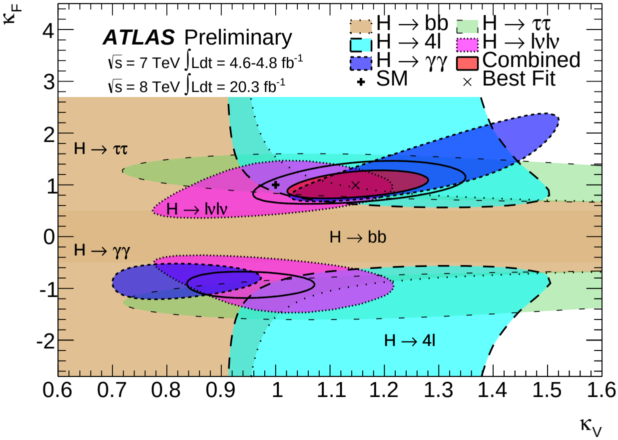
How?

- Scaling factors κ, such that $\sigma \sim \kappa^2$ and $\Gamma \sim \kappa^2$, with $\kappa = 1$ for SM
- Take common fermion and vector boson scaling factors: κ_F and κ_V
  - heavy quarks in ggF loop: $\sigma_{\text{ggF}} \sim \kappa_F^2$
  - vector bosons in VBF: $\sigma_{\text{VBF}} \sim \kappa_V^2$
  - $H \to WW$ decay: $\Gamma_{WW} \sim \kappa_V^2$
  - Higgs total width: $\Gamma_H \sim 0.25\kappa_V^2 + 0.75\kappa_F^2$

Result

- $\sigma(gg \to H) \times \text{BR}(H \to WW) = \sigma_{\text{ggF}} \frac{\Gamma_{WW}}{\Gamma_H} \sim \frac{\kappa_F^2 \kappa_V^2}{0.25\kappa_V^2 + 0.75\kappa_F^2}$
- $\sigma(qq \to qqH) \times \text{BR}(H \to WW) = \sigma_{\text{VBF}} \frac{\Gamma_{WW}}{\Gamma_H} \sim \frac{\kappa_V^2 \kappa_V^2}{0.25\kappa_V^2 + 0.75\kappa_F^2}$

Fermion vs. vector boson couplings



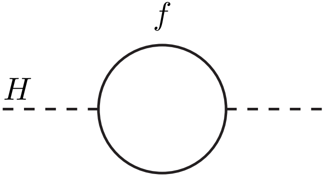
- Assuming only SM contributions to the Higgs total width
- Relative sign between κ_F and κ_V probed only in $H \to \gamma\gamma$ loop
- Combination of all channels favors SM-like positive sign

$$\kappa_V = 1.15 \pm 0.08 \qquad \kappa_F = 0.99^{+0.17}_{-0.15}$$

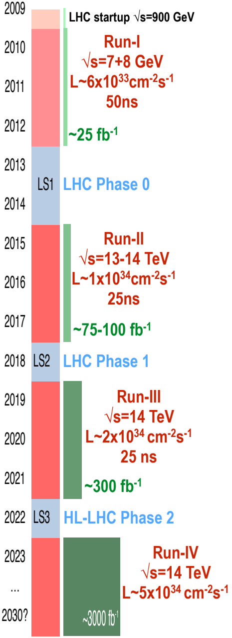
What's next?

Prospects for the future

- Remarkable agreement between SM and data but...
  - dark matter and dark energy?
  - SM does not explain everything
- Found the Higgs but...
  - Low mass is unnatural, hierarchy problem arises
  - Loop corrections to scalar Higgs mass are divergent
  - With a cut-off $\Lambda \sim 10^{19}$ GeV (Plank scale), a striking cancellation with the bare mass m_0 needs to occur!
  - Λ can be smaller, but then there should be new physics at the TeV scale



$$m_H^2 = m_0^2 + \Delta m_H^2, \text{ with } \Delta m_H^2 \propto -\Lambda^2$$

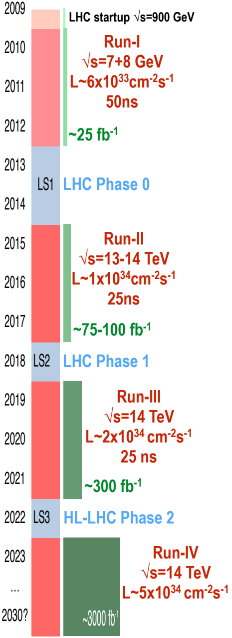


Prospects for the future

- Maybe it's SUSY?
  - Cures hierarchy problem & offers dark matter candidate
  - So far no signs of it at the LHC
  - But the phase space to cover is large

fermion and boson contributions to m_H^2 have opposite signs and cancel out

- More data and energy for Run-II!
  - Look directly for new physics
  - Or look for deviations to the SM
  - Last energy boost we'll get in a while: the time is now!



Summary and conclusions

- Very rich Higgs physics program for Run-I of the LHC!
- $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ provides powerful measurements of Higgs production and couplings
- New and improved $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ results will be out soon
- And Run-II is about to begin, bringing a lot more energy and data, and hopefully some new physics?

Prof. Peter Higgs (as confirmed by the name tag!) cornered when coming out of the bathroom at the EPS-HEP conference in Stockholm

Back-up slides

MC simulation

Signal	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
ggF	POWHEG [30]+PYTHIA8 [31]	0.44
VBF	POWHEG+PYTHIA8	0.035
VH	PYTHIA8	0.13

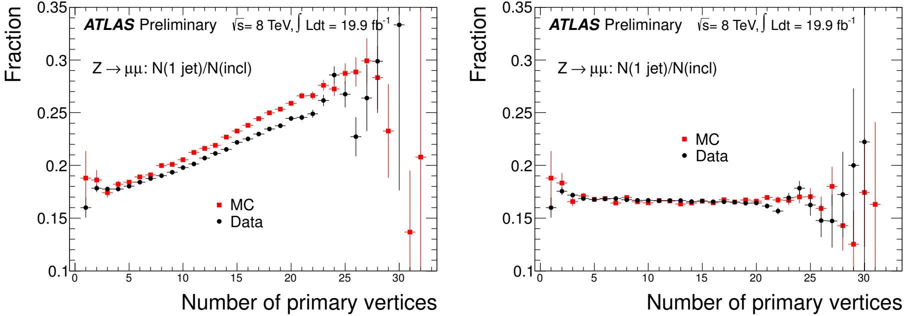
Background	MC generator	$\sigma \cdot \mathcal{B}$ (pb)
$q\bar{q}, gq \to WW$	POWHEG+PYTHIA6 [32]	5.7
$q\bar{q}, gq \to WW{+}2j$	Sherpa [33] with no $O(\alpha_s)$ terms	0.039
$gg \to WW$	GG2WW 3.1.2 [34, 35]+HERWIG [36]	0.16
$t\bar{t}$	MC@NLO [37]+HERWIG	240
Single top: tW, tb	MC@NLO+HERWIG	28
Single top: tqb	AcerMC [38]+PYTHIA6	88
Z/γ^*, inclusive	ALPGEN+HERWIG	16000
$Z^{(*)} \to \ell\ell + 2j$	Sherpa processes up to $O(\alpha_s)$	1.2
$Z^{(*)}Z^{(*)} \to 4\ell$	POWHEG+PYTHIA8	0.73
$WZ/W\gamma^*, m_{Z/\gamma^*}{>}7$	POWHEG+PYTHIA8	0.83
$W\gamma^*, m_{\gamma^*} \leq 7$	MadGraph [39–41]+PYTHIA6	11
$W\gamma$	ALPGEN+HERWIG	370

Production	Symbol	Mechanism	Cross-section [pb] $\sqrt{s} = 8$ (7) TeV, $m_H = 125$ GeV	Theory Uncertainties [%] QCD scale	PDFs + α_s
Gluon fusion	ggF	$gg \to H$	19.27 (15.13)	$^{+7.2}_{-7.8}$ ($^{+7.1}_{-7.8}$)	$^{+7.5}_{-6.9}$ ($^{+7.6}_{-7.1}$)
Vector boson fusion	VBF	$qq \to qqH$	1.58 (1.22)	± 0.2 (± 0.3)	$^{+2.6}_{-2.8}$ ($^{+2.5}_{-2.1}$)
Higgs-stralung	WH	$qq \to WH$	0.70 (0.58)	± 1.0 (± 0.9)	± 2.3 (± 2.6)
	ZH	$qq/gg \to ZH$	0.42 (0.34)	± 3.1 (± 2.9)	± 2.4 (± 2.7)
Associated w/ top	ttH	$gg \to t\bar{t}H$	0.13 (0.09)	$^{+3.8}_{-9.3}$ ($^{+3.2}_{-9.3}$)	± 8.1 (± 8.4)

$H \to WW^* \to \ell\nu\ell\nu$ event selection

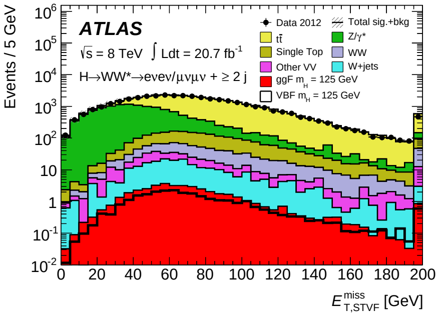
Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Pre-selection	Two isolated leptons ($\ell = e, \mu$) with opposite charge Leptons with $p_{\text{T}}^{\text{lead}} > 25$ and $p_{\text{T}}^{\text{sublead}} > 15$ $e\mu + \mu e$: $m_{\ell\ell} > 10$ $ee + \mu\mu$: $m_{\ell\ell} > 12$, $\lvert m_{\ell\ell} - m_Z \rvert > 15$		
Missing transverse momentum and hadronic recoil	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.05$	$e\mu + \mu e$: $E_{\text{T,rel}}^{\text{miss}} > 25$ $ee + \mu\mu$: $E_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $p_{\text{T,rel}}^{\text{miss}} > 45$ $ee + \mu\mu$: $f_{\text{recoil}} < 0.2$	$e\mu + \mu e$: $E_{\text{T}}^{\text{miss}} > 20$ $ee + \mu\mu$: $E_{\text{T}}^{\text{miss}} > 45$ $ee + \mu\mu$: $E_{\text{T,STVF}}^{\text{miss}} > 35$ -
General selection	- $\lvert \Delta\phi_{\ell\ell,MET} \rvert > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30$	$N_{b\text{-jet}} = 0$ - $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto	$N_{b\text{-jet}} = 0$ $p_{\text{T}}^{\text{tot}} < 45$ $e\mu + \mu e$: $Z/\gamma^* \to \tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj} > 500$ $\lvert \Delta y_{jj} \rvert > 2.8$ No jets ($p_{\text{T}} > 20$) in rapidity gap Require both ℓ in rapidity gap
$H \to WW^{(*)} \to \ell\nu\ell\nu$ topology	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 50$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ $e\mu + \mu e$: split $m_{\ell\ell}$ Fit m_{T}	$m_{\ell\ell} < 60$ $\lvert \Delta\phi_{\ell\ell} \rvert < 1.8$ - Fit m_{T}

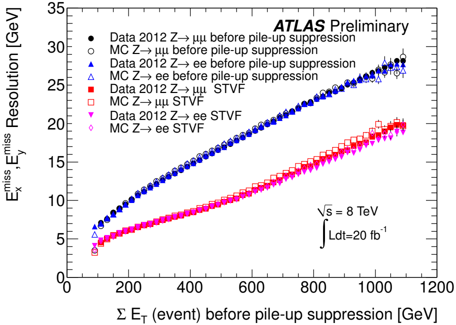
Jets, jet vertex fraction and pile-up



- Fraction of $Z \to \mu\mu + 1$ jet to all $Z \to \mu\mu$ candidates versus number of primary vertices, before and after JVF requirement
- Jet vertex fraction (JVF) defined at $\sum p_{\mathrm{T}}$ of associated tracks that can be matched to the primary vertex
- In $H \to WW^* \to \ell\nu\ell\nu$ we require $|\mathrm{JVF}| > 0.5$ for jets with $p_{\mathrm{T}} < 50$ GeV

$E_{T,STVF}^{miss}$ for $ee + \mu\mu$ VBF



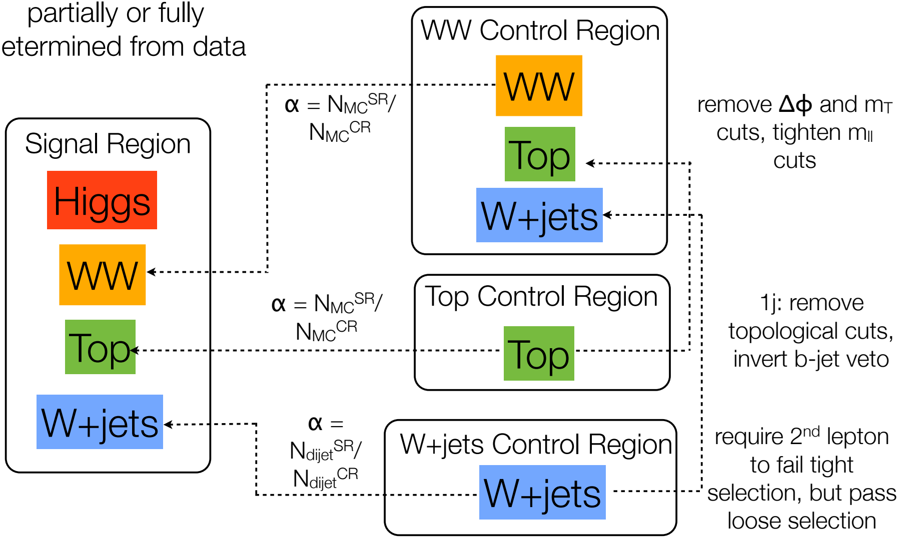


$$E_{x(y)}^{\text{miss,calo}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss},\mu}$$

- For STVF the soft term is weighted by $\sum p_T$ of associated tracks that can be matched to the primary vertex

Schematics of backgrounds estimates

Backgrounds either partially or fully determined from data



*0j: estimate top background from b-jet survival probability

Summary of backgrounds estimates

Table 3: Background treatment listing. The estimation procedures for various background processes are given in four categories: normalised using a control region (CR); data-derived estimate (Data); normalised using the MC (MC); and normalised using the MC, but validated in a control region (MC + VR). The "$(e\mu + \mu e)$" terms denote that for the $ee + \mu\mu$ channel in the same N_{jet} mode, the $e\mu + \mu e$ region is used instead, for reasons of purity and/or statistics. The "(merged)" terms indicate that the fully combined $e\mu + \mu e + ee + \mu\mu$ control region is used for all channels.

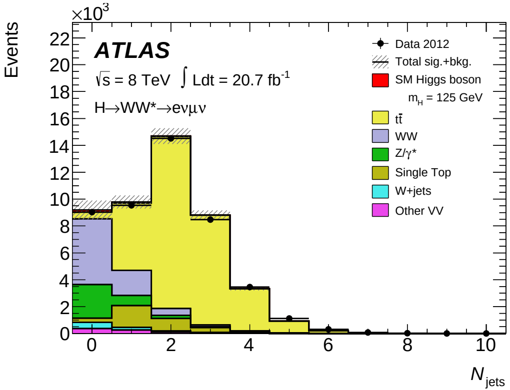
Channel	WW	Top	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \ell\ell$	W+ jets	VV
$N_{\text{jet}} = 0$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR $(e\mu + \mu e)$	CR $(e\mu + \mu e)$	CR $(e\mu + \mu e)$	Data	Data	MC + VR
$N_{\text{jet}} = 1$						
$e\mu + \mu e$	CR	CR	CR	MC	Data	MC + VR
$ee + \mu\mu$	CR $(e\mu + \mu e)$	CR $(e\mu + \mu e)$	CR $(e\mu + \mu e)$	Data	Data	MC + VR
$N_{\text{jet}} \geq 2$						
$e\mu + \mu e$	MC	CR (merged)	CR	MC	Data	MC
$ee + \mu\mu$	MC	CR (merged)	CR $(e\mu + \mu e)$	Data	Data	MC

- Generally use $e\mu$ CRs, with higher stats and higher purity

Cutflow in control regions

Estimate	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
WW									
$N_{jet} = 0$	2224	1970 ± 17	31 ± 0.7	1383 ± 9.3	100 ± 6.8	152 ± 4.4	107 ± 4.3	68 ± 10	160 ± 3.6
$N_{jet} = 1$	1897	1893 ± 17	1.9 ± 0.3	752 ± 6.8	88 ± 5.5	717 ± 9.5	243 ± 6.7	37 ± 7.5	56 ± 2.5
$Z/\gamma^* \to \tau\tau$									
$N_{jet} = 0$	1935	2251 ± 31	2.5 ± 0.2	61 ± 1.9	8.5 ± 1.1	4.5 ± 0.8	2.7 ± 0.6	2113 ± 31	61 ± 3.8
$N_{jet} = 1$	2884	3226 ± 34	7.5 ± 0.3	117 ± 2.7	22 ± 3.1	570 ± 8.4	50 ± 3	2379 ± 32	88 ± 4.3
$N_{jet} \geq 2$	212	224 ± 7	0.6 ± 0.1	13 ± 1	4 ± 1	44 ± 3	5 ± 1	148 ± 6	9 ± 1
Top									
$N_{jet} = 1$	4926	4781 ± 26	12 ± 0.5	184 ± 3.7	43 ± 9.5	3399 ± 20	1049 ± 13	72 ± 3.1	35 ± 2.2
$N_{jet} \geq 2$	126	201 ± 5	1.6 ± 0.1	6.4 ± 0.4	1.0 ± 0.3	157 ± 4	26 ± 2	9 ± 1	0.3 ± 0.4

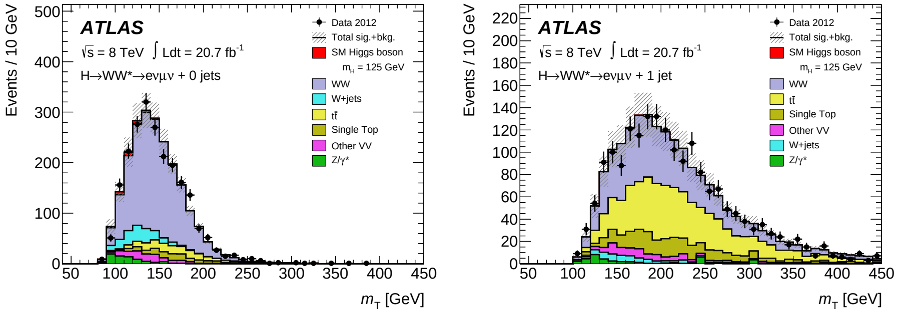
Jet Veto Survival Probability for top in 0-jet



$$N^{0j}_{\mathrm{top,est}} = N^{\mathrm{incl.}}_{\mathrm{data}} \times \frac{N^{0\mathrm{j}}_{\mathrm{MC}}}{N^{\mathrm{incl.}}_{\mathrm{MC}}} \times \left(\frac{P^{1b\text{-tag}}_{\mathrm{data}}}{P^{1b\text{-tag}}_{\mathrm{MC}}} \right)^2$$

- $P^{1b\text{-tag}}$ is the jet veto survival probability ($N^{0j}/N^{\mathrm{incl.}}$) in a sample with at least one b-tagged jet
- $\mathrm{NF}^{top}_{\mathrm{0jet}} = 1.07 \pm 0.03$ (stat.), $\sim 13\%$ on estimated yield

WW control regions

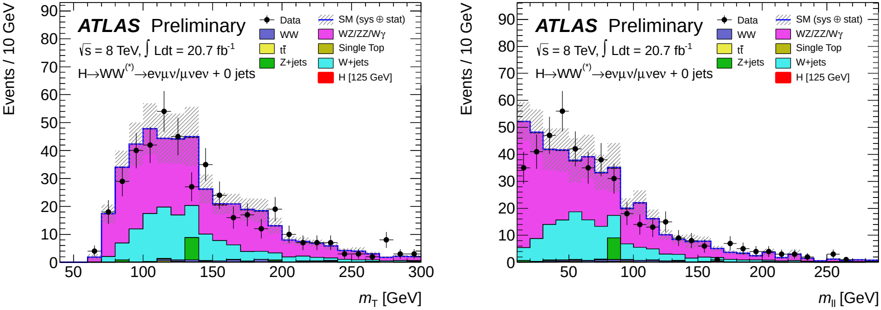


- WW 0-jet CR: $50 < m_{\ell\ell} < 100$ GeV
- WW 1-jet CR: $m_{\ell\ell} > 80$ GeV

WW CR α extrapolation uncertainties

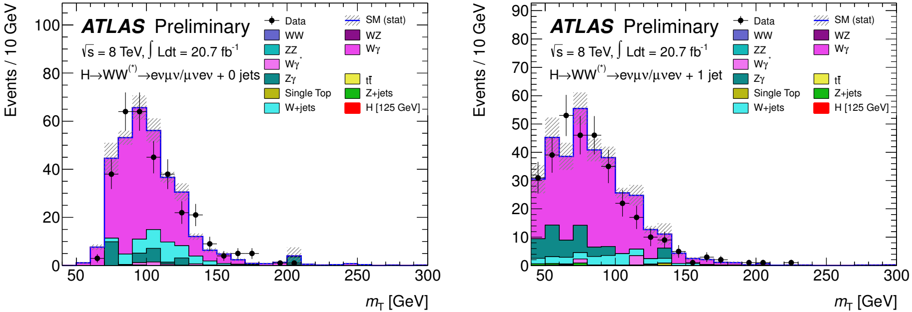
Channel	Range (GeV)	QCD scale (%)	PS, UE (%)	PDF (%)	Modelling (%)
$N_{\mathrm{jet}} = 0$					
$e\mu + \mu e$	$10 < m_{\ell\ell} < 30$	0.9	0.2	1.5	−1.2
$e\mu + \mu e$	$30 \leq m_{\ell\ell} < 50$	0.9	0.8	1.1	−1.4
$ee + \mu\mu$	$12 < m_{\ell\ell} < 50$	1.0	0.3	1.1	1.7
$N_{\mathrm{jet}} = 1$					
$e\mu + \mu e$	$10 < m_{\ell\ell} < 30$	1.6	0.5	2.0	−5.1
$e\mu + \mu e$	$30 \leq m_{\ell\ell} < 50$	1.5	0.5	1.8	−5.0
$ee + \mu\mu$	$12 < m_{\ell\ell} < 50$	1.4	0.6	1.7	−3.1

Same sign validation regions



- W+jets determined entirely from data
- $W\gamma$, WZ, $W\gamma^*$ and ZZ taken from simulation
- $W\gamma$ and $W\gamma^*$ normalized to NLO prediction of MCFM
- All processes validated with same sign dilepton events

$W\gamma$ validation region



- The simulation of the $W\gamma$ is validated with modified same-sign dilepton events, in which the electron selection criteria that remove photon conversions are reversed.

Uncertainties on background yields estimated from CRs

Estimate	Stat. (%)	Theory (%)	Expt. (%)	Crosstalk (%)	Total (%)
WW					
$N_{\text{jet}} = 0$	2.9	1.6	4.4	5.0	7.4
$N_{\text{jet}} = 1$	6	5	4	36	37
Top					
$N_{\text{jet}} = 1$	2	8	22	16	29
$N_{\text{jet}} \geq 2$	10	15	29	19	39

$$N^{\text{SR}}_{\text{bkg,est}} = \underbrace{\frac{N^{\text{CR}}_{\text{data}} - N^{\text{CR}}_{\text{other}}}{N^{\text{CR}}_{\text{bkg,MC}}}}_{\text{NF}_{\text{bkg}}} \times N^{\text{SR}}_{\text{bkg,MC}} = (N^{\text{CR}}_{\text{data}} - N^{\text{CR}}_{\text{other}}) \times \underbrace{\frac{N^{\text{SR}}_{\text{bkg,MC}}}{N^{\text{CR}}_{\text{bkg,MC}}}}_{\alpha^{\text{bkg}}_{\text{SR}}}$$

0-jet cutflow

(a) $e\mu + \mu e$ channel

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} = 0$	9024	9000 ± 40	172 ± 2	4900 ± 20	370 ± 10	510 ± 10	310 ± 10	2440 ± 30	470 ± 10
$\mid \Delta\phi_{\ell\ell,MET} \mid > \frac{\pi}{2}$	8100	8120 ± 40	170 ± 2	4840 ± 20	360 ± 10	490 ± 10	310 ± 10	1690 ± 30	440 ± 10
$p_{\text{T}}^{\ell\ell} > 30$	5497	5490 ± 30	156 ± 2	4050 ± 20	290 ± 10	450 ± 10	280 ± 10	100 ± 10	320 ± 5
$m_{\ell\ell} < 50$	1453	1310 ± 10	124 ± 1	960 ± 10	110 ± 6	69 ± 3	46 ± 3	18 ± 7	100 ± 2
$\mid \Delta\phi_{\ell\ell} \mid < 1.8$	1399	1240 ± 10	119 ± 1	930 ± 10	107 ± 6	67 ± 3	44 ± 3	13 ± 7	88 ± 2

(b) $ee + \mu\mu$ channel

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} = 0$	16446	15600 ± 200	104 ± 1	2440 ± 10	190 ± 5	280 ± 6	175 ± 6	12300 ± 160	170 ± 10
$\mid \Delta\phi_{\ell\ell,MET} \mid > \frac{\pi}{2}$	13697	12970 ± 140	103 ± 1	2430 ± 10	190 ± 5	280 ± 6	174 ± 6	9740 ± 140	160 ± 10
$p_{\text{T}}^{\ell\ell} > 30$	5670	5650 ± 70	99 ± 1	2300 ± 10	170 ± 5	260 ± 6	167 ± 5	2610 ± 70	134 ± 4
$m_{\ell\ell} < 50$	2314	2390 ± 20	84 ± 1	760 ± 10	64 ± 3	53 ± 3	42 ± 3	1410 ± 20	62 ± 3
$p_{\text{T,rel}}^{\text{miss}} > 45$	1032	993 ± 10	63 ± 1	650 ± 10	42 ± 2	47 ± 3	39 ± 3	200 ± 5	19 ± 2
$\mid \Delta\phi_{\ell\ell} \mid < 1.8$	1026	983 ± 10	63 ± 1	640 ± 10	41 ± 2	46 ± 3	39 ± 3	195 ± 5	18 ± 2
$f_{\text{recoil}} < 0.05$	671	647 ± 7	42 ± 1	520 ± 10	30 ± 2	19 ± 2	22 ± 2	49 ± 3	12 ± 1

1-jet cutflow

(a) $e\mu + \mu e$ channel

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{jet} = 1$	9527	9460 ± 40	97 ± 1	1660 ± 10	270 ± 10	4980 ± 30	1600 ± 20	760 ± 20	195 ± 5
$N_{b\text{-jet}} = 0$	4320	4240 ± 30	85 ± 1	1460 ± 10	220 ± 10	1270 ± 10	460 ± 10	670 ± 10	160 ± 4
$Z \to \tau\tau$ veto	4138	4020 ± 30	84 ± 1	1420 ± 10	220 ± 10	1220 ± 10	440 ± 10	580 ± 10	155 ± 4
$m_{\ell\ell} < 50$	886	830 ± 10	63 ± 1	270 ± 4	69 ± 5	216 ± 6	80 ± 4	149 ± 5	46 ± 2
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	728	650 ± 10	59 ± 1	250 ± 4	60 ± 4	204 ± 6	76 ± 4	28 ± 3	34 ± 2

(b) $ee + \mu\mu$ channel

Selection	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{jet} = 1$	8354	8120 ± 90	54 ± 1	820 ± 10	140 ± 10	2740 ± 20	890 ± 10	3470 ± 80	60 ± 10
$N_{b\text{-jet}} = 0$	5192	4800 ± 80	48 ± 1	720 ± 10	120 ± 10	720 ± 10	260 ± 10	2940 ± 70	40 ± 10
$m_{\ell\ell} < 50$	1773	1540 ± 20	38 ± 1	195 ± 4	35 ± 2	166 ± 5	65 ± 3	1060 ± 10	20 ± 2
$p_{T,rel}^{miss} > 45$	440	420 ± 10	21 ± 1	148 ± 3	21 ± 1	128 ± 5	52 ± 3	64 ± 4	5.1 ± 0.8
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	430	410 ± 10	20 ± 1	143 ± 3	20 ± 1	125 ± 5	51 ± 3	63 ± 4	4.5 ± 0.7
$f_{recoil} < 0.2$	346	320 ± 10	16 ± 1	128 ± 3	17 ± 1	97 ± 4	44 ± 3	25 ± 2	3.1 ± 0.6

VBF cutflow

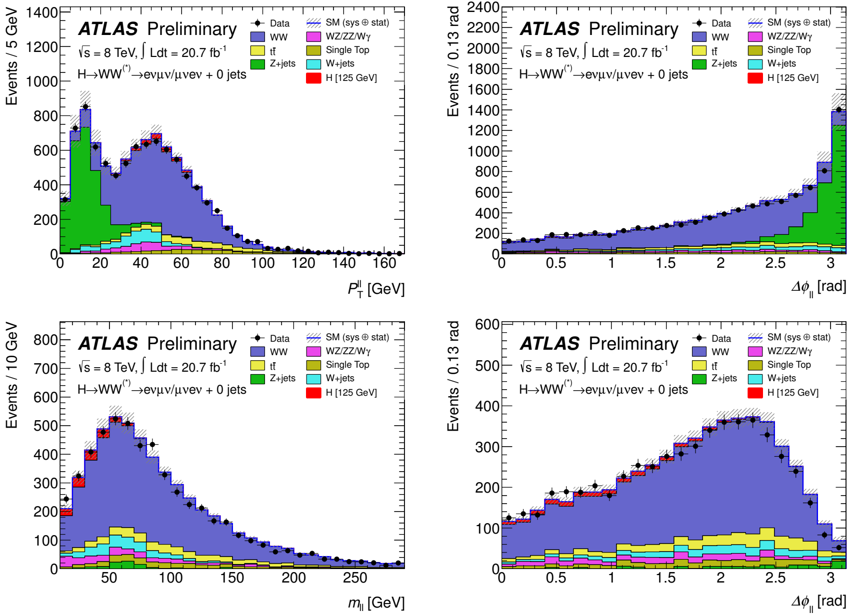
(a) $e\mu + \mu e$ channel

Selection	N_{obs}	N_{bkg}	$N_{\text{sig,VBF}}$	$N_{\text{sig,ggF}}$	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} \geq 2$	48723	47740 ± 80	43 ± 1	67 ± 1	940 ± 10	300 ± 20	41800 ± 70	2370 ± 20	1800 ± 30	440 ± 10
$N_{b\text{-jet}} = 0$	5852	5690 ± 30	31 ± 1	49 ± 1	690 ± 10	200 ± 10	2930 ± 20	350 ± 10	1300 ± 20	171 ± 5
$p_{\text{T}}^{\text{tot}} < 45$	4790	4620 ± 30	27 ± 1	41 ± 1	590 ± 10	160 ± 10	2320 ± 20	290 ± 10	1100 ± 20	126 ± 4
$Z \to \tau\tau$ veto	4007	3840 ± 30	25 ± 1	38 ± 1	540 ± 10	140 ± 10	2150 ± 20	260 ± 10	600 ± 20	108 ± 4
$\lvert\Delta y_{jj}\rvert > 2.8$	696	680 ± 10	12 ± 0.2	9.5 ± 0.3	100 ± 2	25 ± 3	380 ± 10	55 ± 3	95 ± 5	19 ± 2
$m_{jj} > 500$	198	170 ± 4	7.5 ± 0.1	2.9 ± 0.2	34 ± 1	5.6 ± 0.6	93 ± 3	11 ± 1	19 ± 2	4.4 ± 0.7
No jets in y gap	92	77 ± 2	6.3 ± 0.1	1.7 ± 0.2	25 ± 1	2.8 ± 0.4	30 ± 2	5.2 ± 0.8	9 ± 1	3.1 ± 0.6
Both ℓ in y gap	78	59 ± 2	6.1 ± 0.1	1.6 ± 0.1	19 ± 1	2.1 ± 0.3	22 ± 1	4.3 ± 0.7	7 ± 1	2.4 ± 0.5
$m_{\ell\ell} < 60$	31	16 ± 1	5.5 ± 0.1	1.5 ± 0.1	3.8 ± 0.4	0.7 ± 0.2	4.5 ± 0.7	0.7 ± 0.3	4.4 ± 0.8	1.0 ± 0.4
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	23	12 ± 1	5.1 ± 0.1	1.3 ± 0.1	3.5 ± 0.4	0.6 ± 0.2	3.7 ± 0.7	0.7 ± 0.3	1.9 ± 0.5	0.6 ± 0.3

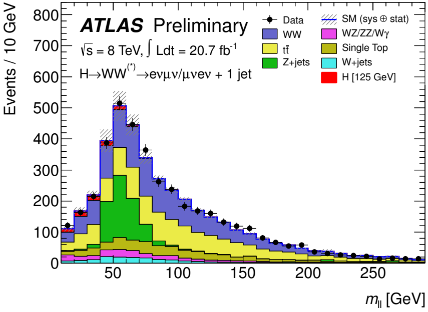
(b) $ee + \mu\mu$ channel

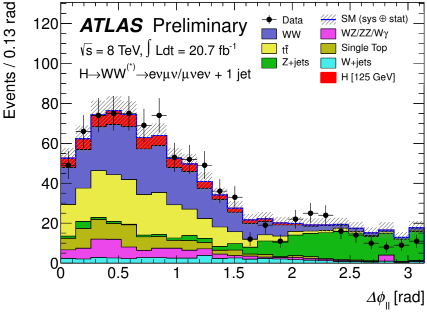
Selection	N_{obs}	N_{bkg}	$N_{\text{sig,VBF}}$	$N_{\text{sig,ggF}}$	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	$N_{W+\text{jets}}$
$N_{\text{jet}} \geq 2$	32877	32300 ± 100	26 ± 0.7	40 ± 1	540 ± 6	180 ± 10	24540 ± 60	1390 ± 20	5420 ± 90	190 ± 10
$N_{b\text{-jet}} = 0$	65388	6370 ± 80	19 ± 0.6	30 ± 1	390 ± 5	130 ± 10	1750 ± 20	200 ± 10	3810 ± 80	58 ± 4
$p_{\text{T}}^{\text{tot}} < 45$	4903	4830 ± 70	17 ± 0.5	24 ± 1	340 ± 4	92 ± 5	1370 ± 10	170 ± 10	2790 ± 70	43 ± 3
$\lvert\Delta y_{jj}\rvert > 2.8$	958	930 ± 30	8.1 ± 0.2	6.2 ± 0.3	61 ± 2	12 ± 1.3	252 ± 6	35 ± 2	560 ± 30	6 ± 1
$m_{jj} > 500$	298	245 ± 6	5.5 ± 0.1	2.1 ± 0.2	23 ± 1	4.1 ± 1.1	62 ± 3	9 ± 1	142 ± 5	1.4 ± 0.6
No jets in y gap	147	119 ± 4	4.7 ± 0.1	1.1 ± 0.1	17 ± 1	2.8 ± 1.1	19 ± 1	4.1 ± 0.7	74 ± 3	0.7 ± 0.4
Both ℓ in y gap	108	85 ± 3	4.5 ± 0.1	0.9 ± 0.1	12 ± 1	2.3 ± 1.1	14 ± 1	3.1 ± 0.6	51 ± 3	0.3 ± 0.3
$m_{\ell\ell} < 60$	52	40 ± 2	4.0 ± 0.1	0.8 ± 0.1	3.2 ± 0.3	1.6 ± 1.1	3.7 ± 0.6	0.8 ± 0.3	30 ± 2	0.1 ± 0.2
$\lvert\Delta\phi_{\ell\ell}\rvert < 1.8$	42	34 ± 2	3.7 ± 0.1	0.7 ± 0.1	2.8 ± 0.3	1.6 ± 1.1	3.3 ± 0.5	0.7 ± 0.3	25 ± 2	0.1 ± 0.2

0-jet $e\mu$ kinematics

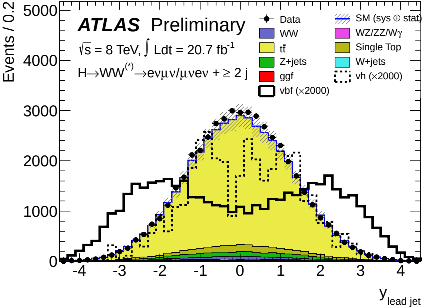


1-jet $e\mu$ kinematics

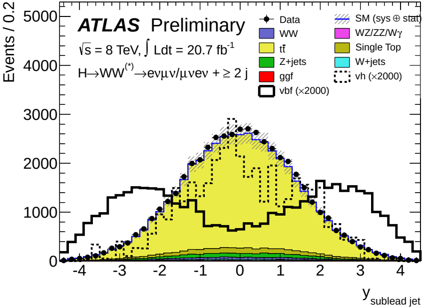




VBF jets

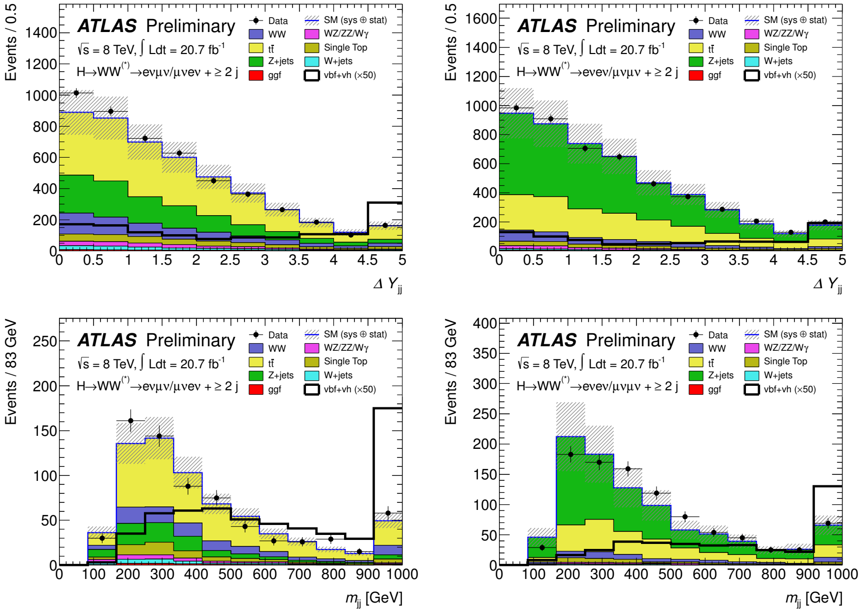


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 20.7 fb^{-1}
H→WW$^{(*)}$→eνμν/μνeν + ≥ 2 j
Data
WW
tt̄
Z+jets
ggf
vbf (×2000)
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
vh (×2000)
Events / 0.2
y lead jet

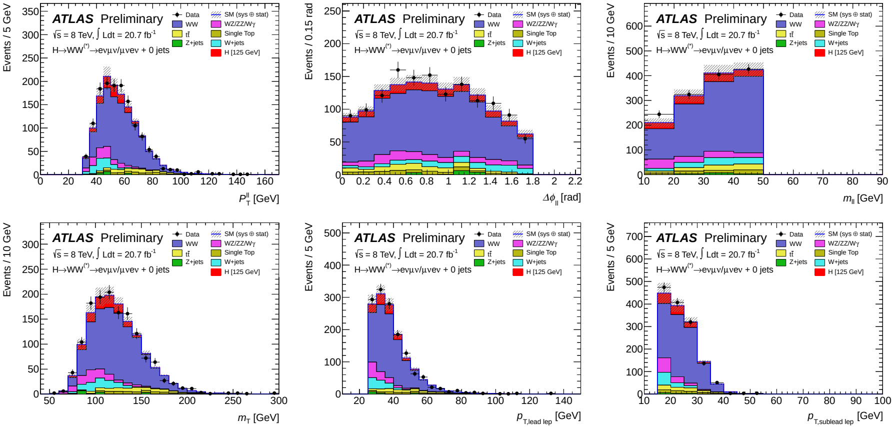


ATLAS Preliminary
$\sqrt{s}$ = 8 TeV, $\int$ Ldt = 20.7 fb^{-1}
H→WW$^{(*)}$→eνμν/μνeν + ≥ 2 j
Data
WW
tt̄
Z+jets
ggf
vbf (×2000)
SM (sys ⊕ stat)
WZ/ZZ/Wγ
Single Top
W+jets
vh (×2000)
Events / 0.2
y sublead jet

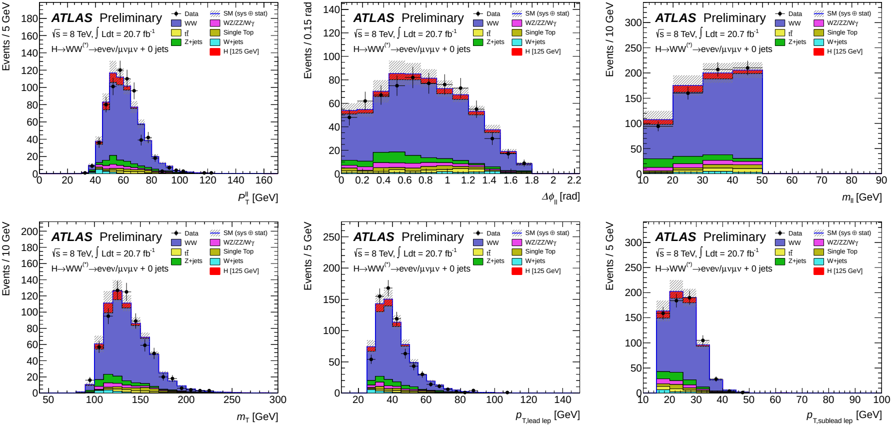
VBF kinematics



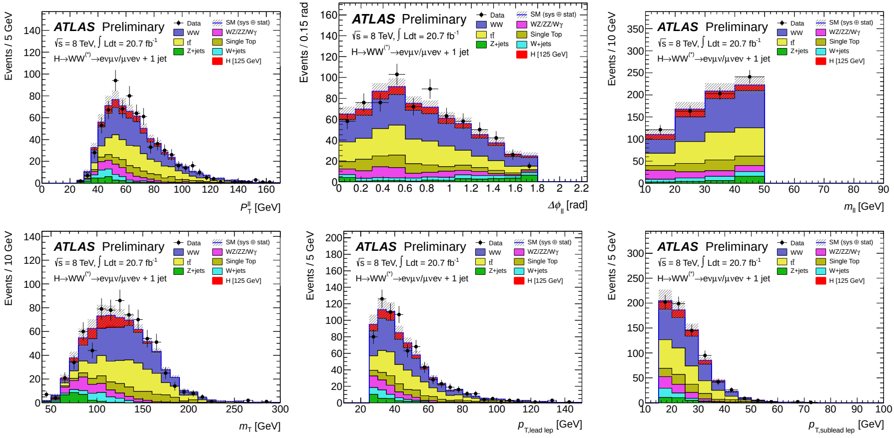
0-jet DF signal region



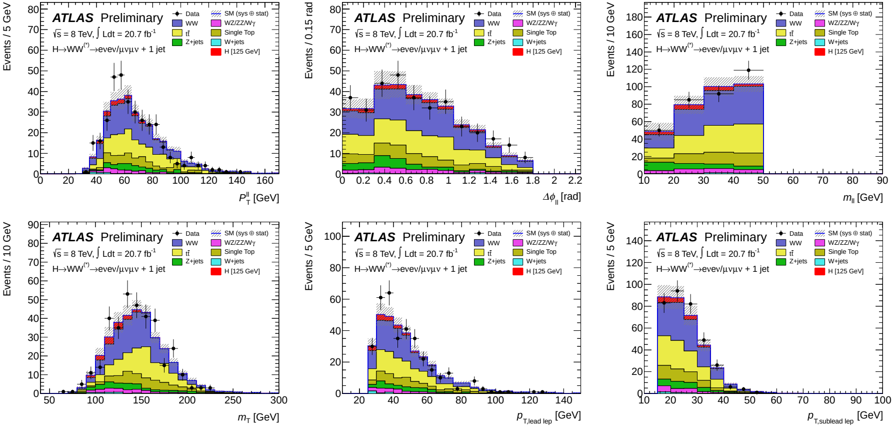
0-jet SF signal region



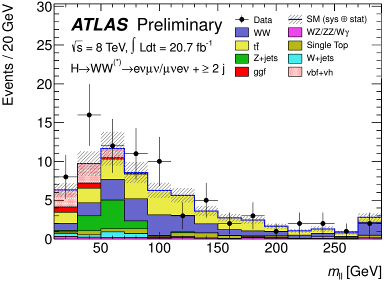
1-jet DF signal region

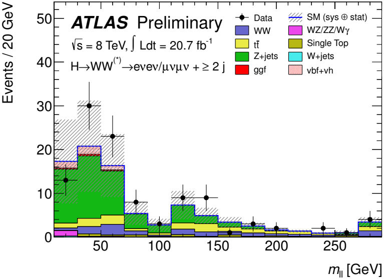


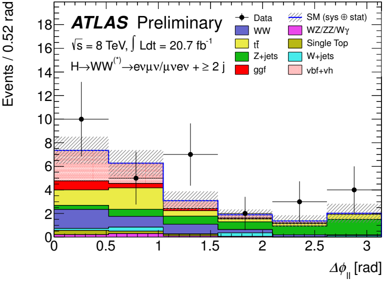
1-jet SF signal region

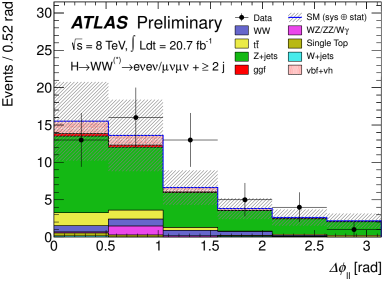


VBF signal region

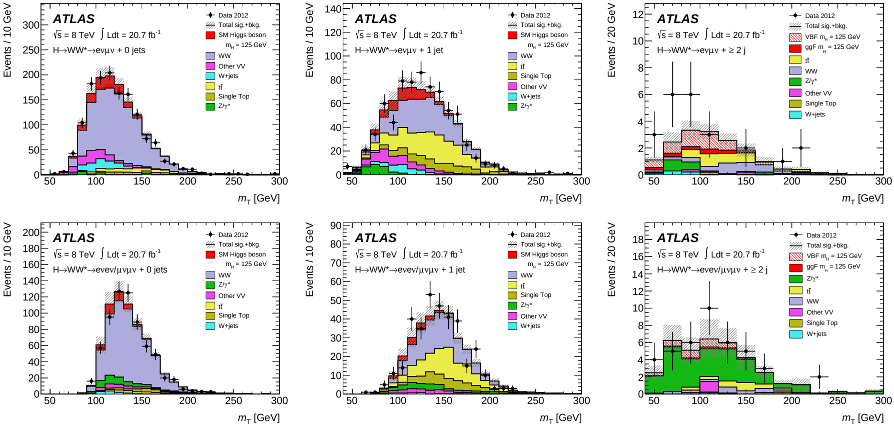








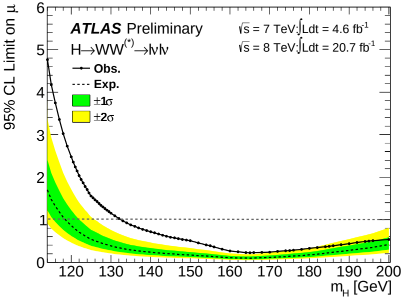
Signal region m_T distributions

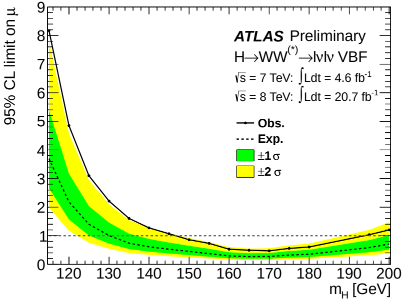


Systematic uncertainties on predicted signal and background yields

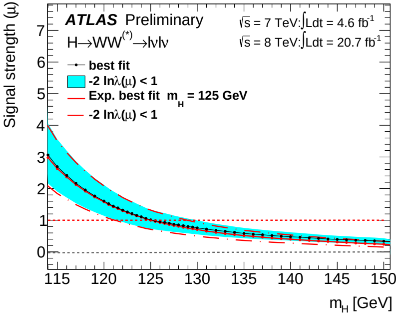
Source	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$
Theoretical uncertainties on total signal yield (%)			
QCD scale for ggF, $N_{\text{jet}} \geq 0$	+13	-	-
QCD scale for ggF, $N_{\text{jet}} \geq 1$	+10	−27	-
QCD scale for ggF, $N_{\text{jet}} \geq 2$	-	−15	+4
QCD scale for ggF, $N_{\text{jet}} \geq 3$	-	-	+4
Parton shower and underlying event	+3	−10	±5
QCD scale (acceptance)	+4	+4	±3
Experimental uncertainties on total signal yield (%)			
Jet energy scale and resolution	5	2	6
Uncertainties on total background yield (%)			
WW transfer factors (theory)	±1	±2	±4
Jet energy scale and resolution	2	3	7
b-tagging efficiency	-	+7	+2
f_{recoil} efficiency	±4	±2	-

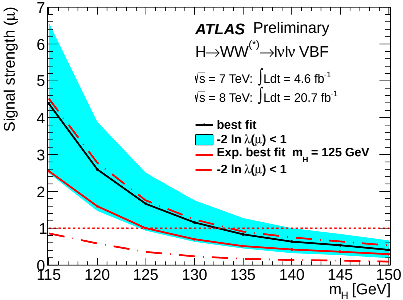
Exclusion


ATLAS Preliminary
H→WW(*)→lνlν
√s = 7 TeV:∫Ldt = 4.6 fb-1
√s = 8 TeV:∫Ldt = 20.7 fb-1
Obs.
Exp.
±1σ
±2σ
95% CL Limit on μ
mH [GeV]
0
1
2
3
4
5
6
120
130
140
150
160
170
180
190
200

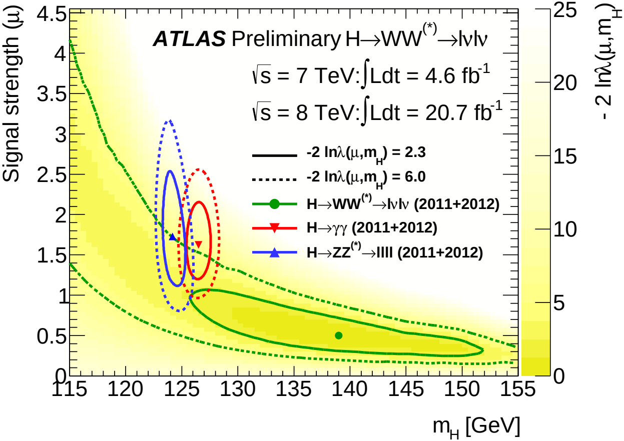

ATLAS Preliminary
H→WW(*)→lνlν VBF
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
Obs.
Exp.
±1 σ
±2 σ
95% CL limit on μ
mH [GeV]
0
1
2
3
4
5
6
7
8
9
120
130
140
150
160
170
180
190
200

Signal strength





The banana plot



SUSY after Run-I