Measurement of Higgs-boson properties in $H \to WW^*$ events

ICHEP 2018

Dominik Duda (Max-Planck-Institut für Physik)

on behalf of the ATLAS collaboration

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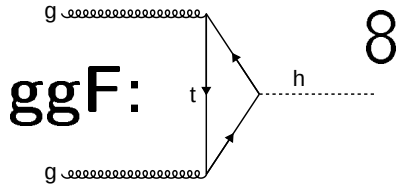
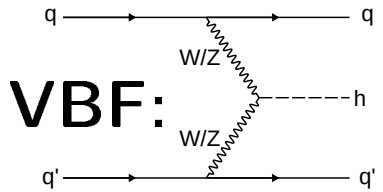
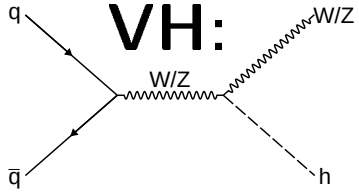
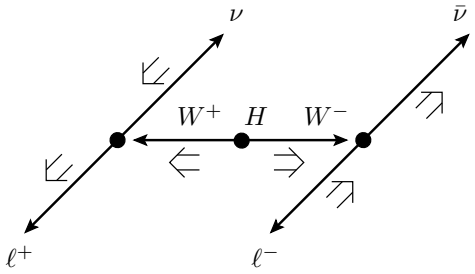
$H \to WW^*$

- Present measurements in $H \to WW^*$ candidate events
  - Production cross section times branching ratio
  - Spin and parity in the decay vertex (Run I)
- ggF production is dominant, but other processes have cleaner signatures
  - VBF: two jets with large m_{jj} and $\Delta\eta_{jj}$
  - VH: Additional lepton(s), high E_{T}^{mis} or jets
- $H \to WW^* \to \ell\nu\ell\nu$ (for $\ell = e, \mu, \tau \to \ell\nu\nu$) is with 1.5% one of the most frequent decay modes
  - Cleaner signature wrt $H \to b\bar{b}$
  - Higher statistics than $H \to ZZ^*$ or $H \to \gamma\gamma$
- Characteristics of $H \to WW^* \to \ell\nu\ell\nu$ decay:
  - Two oppositely charged leptons with small opening angle and invariant mass m_{ll}
  - Presence of neutrinos prevents direct measurement of invariant mass m_H









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Measurement of the ggF and VBF production cross sections

http://cds.cern.ch/record/2308392
ATLAS-CONF-2018-004

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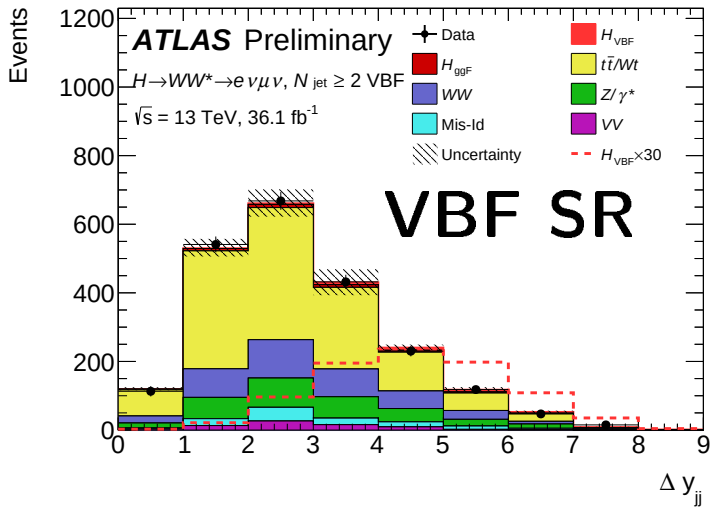
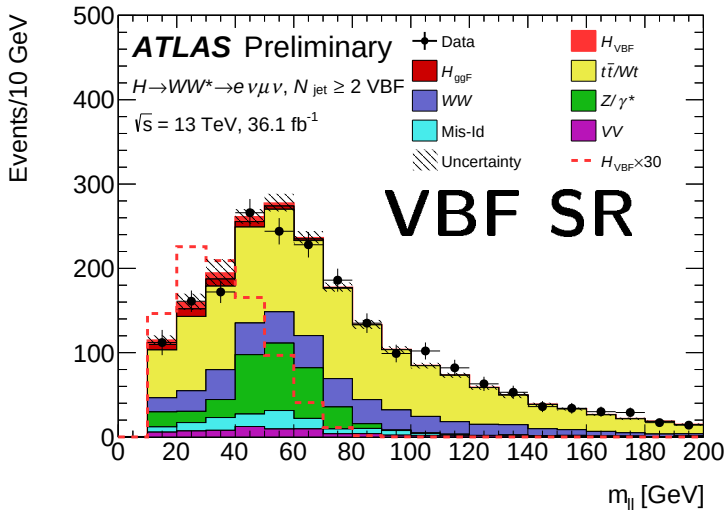
Analysis strategy (event selection)

- Select events with different-flavour leptons ($\ell = e, \mu$) and opposite charge
  - $p_{\mathrm{T}}^{\mathrm{lead}} > 22\,GeV$ and $p_{\mathrm{T}}^{\mathrm{sublead}} > 15\,GeV$
- Classify events according to multiplicity of jets with $p_T > 30\,\mathrm{GeV}$
  - $N^{jets} = 0$ and $N^{jets} = 1$ categories target the ggF production mode
  - $N^{jets} \geq 2$ category targets VBF production
- Reduce main backgrounds:
  - Veto events containing a heavy-flavour jet with $p_T > 20\,GeV$
  - Select events with low $m_{\ell\ell}$ and $\Delta\Phi_{\ell\ell}$ (ggF)
  - Central jet and outside lepton veto (VBF)
- Further enhance VBF signal using a MVA
  - Trained using eight input quantities: m_{jj}, ΔY_{jj}, $m_{\ell\ell}$, $\Delta\Phi_{\ell\ell}$, $m_{\mathrm{H,T}}$, ...





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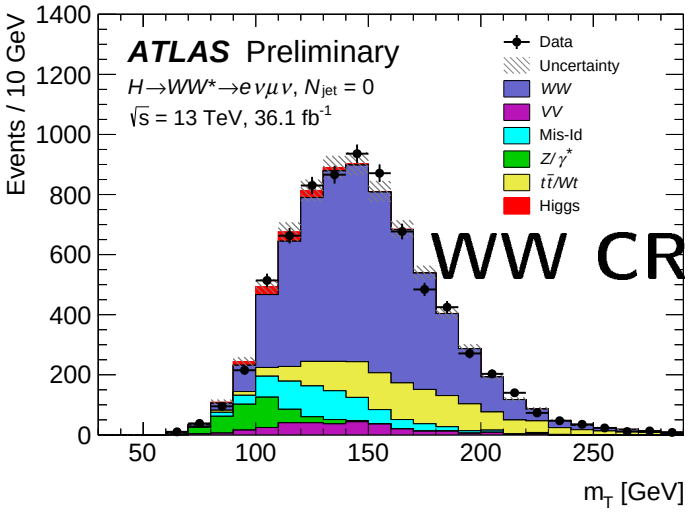
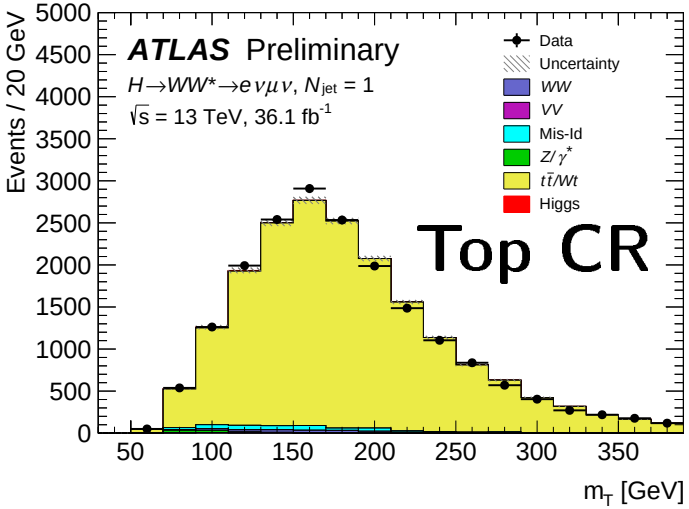
Analysis strategy (background estimation)

- Smaller backgrounds such as WZ, ZZ, $W\gamma$ or $Z\gamma$ are entirely taken from the simulation
- Constrain normalisation of most important backgrounds via **control regions in data**
  - WW, $t\bar{t} + Wt$ and $Z\gamma^* +$ jets
- **Data-driven estimation of mis-identified lepton backgrounds** (W+jets/multijet):
  - **Define control sample using events with**
    - One well-defined lepton
    - One lepton failing nominal object definitions requirements but passing looser requirements (anti-identified)
  - Contribution to signal region is estimated by scaling control sample via p_T/η dependent extrapolation factors
  - Extrapolation factor is ratio of well-defined leptons to anti-identified leptons





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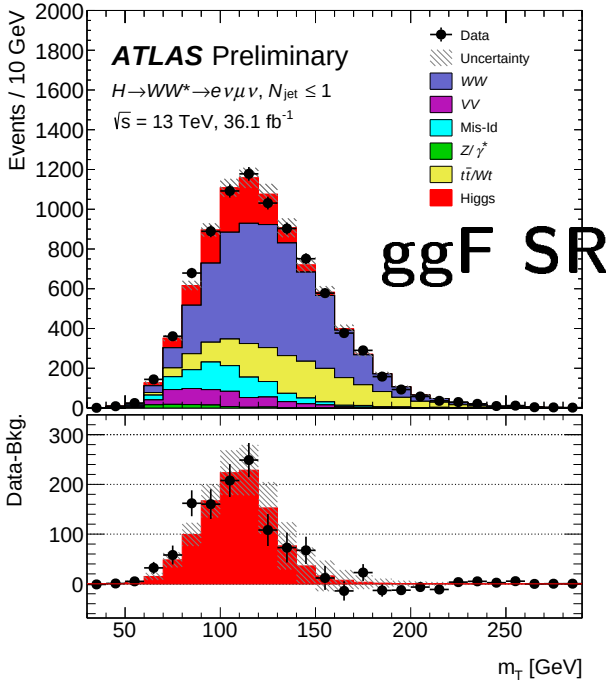
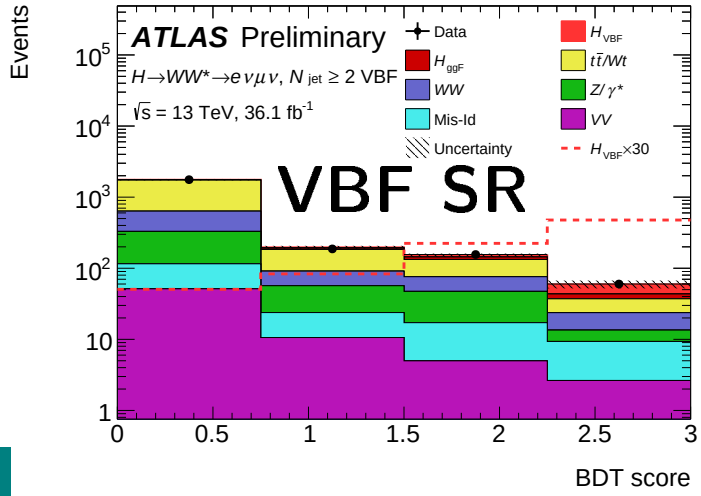
Details on the likelihood procedure

- ggF and VBF cross sections are obtained by a simultanious fit to control and signal regions (maximising a likelihood function)
- Input variables for the fit:
  - **ggF: transverse mass $m_{\mathrm{H,T}}$**
    - Subdivide phase space using $m_{\ell\ell}$ as well as p_{T} and flavour of subleading lepton
  - **VBF: score of a boosted decision tree**
- Systematic uncertainties enter as nuisance parameters in the likelihood function
  - Consider correlations
  - Dominant uncertainties are:
    - Modelling (±8% ggF, ±21% VBF)
    - Data statistics (±8% ggF, ±46% VBF)
    - MC statistics (±5% ggF, ±23% VBF)
    - *b*-tagging (±5% ggF, ±6% VBF)





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Results

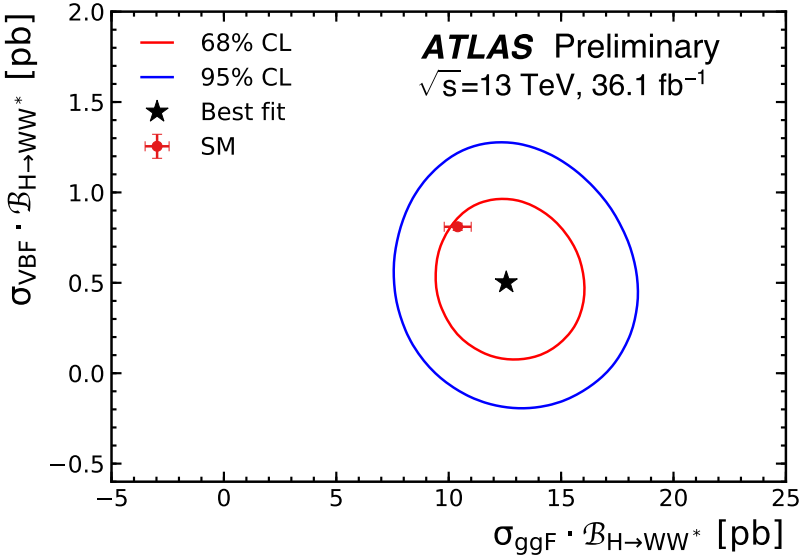
- **Measured cross section times branching ratio:**

$$\sigma_{ggF} \times \mathcal{BR}(H \to WW^*) = 12.6^{+1.3}_{-1.2}(stat.)^{+1.9}_{-1.8}(sys.)\,\mathrm{pb}$$

$$\sigma_{VBF} \times \mathcal{BR}(H \to WW^*) = 0.5^{+0.24}_{-0.23}(stat.) \pm 0.18(sys.)\,\mathrm{pb}$$

- **Prediction:** $10.4 \pm 0.6\,\mathrm{pb}$ (for ggf) and $0.81 \pm 0.02\,\mathrm{pb}$ (for VBF)
- ggF measurement is dominated by systematics now (30% improved wrt Run-I)

- **Observed (expected) significances are**:
  - 6.3 (5.2) standard deviations for ggF
  - 1.9 (2.7) standard deviations for VBF
- Profile ggF production when determine significance of VBF production, and vice-versa



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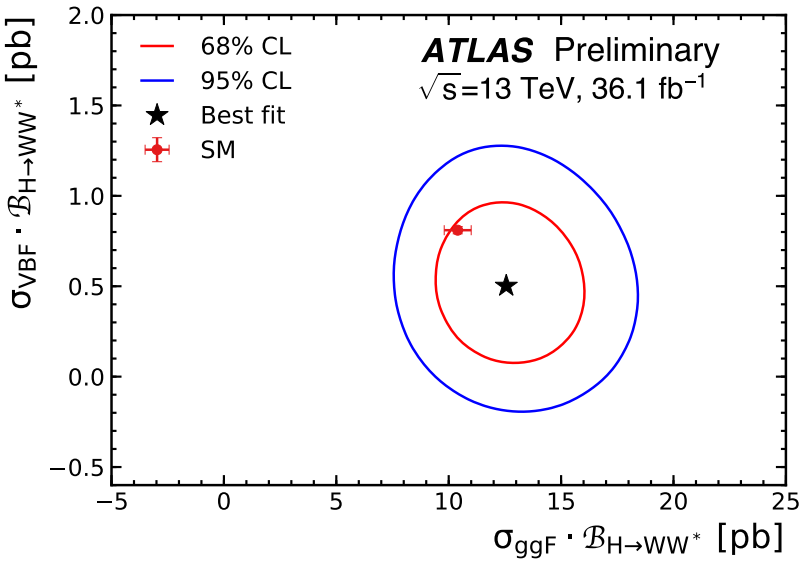
- **Predictions:** $10.4 \pm 0.6\,\mathrm{pb}$ (for ggf) and $0.81 \pm 0.02\,\mathrm{pb}$ (for VBF)

- **Signal strength parameter:**

$$\mu_{ggF} = 1.21^{+0.12}_{-0.11}(stat.)^{+0.18}_{-0.17}(syst.)$$

$$\mu_{VBF} = 0.62^{+0.30}_{-0.28}(stat.) \pm 0.22(syst.)$$

- **Results are consistent with SM prediction within one standard deviation**



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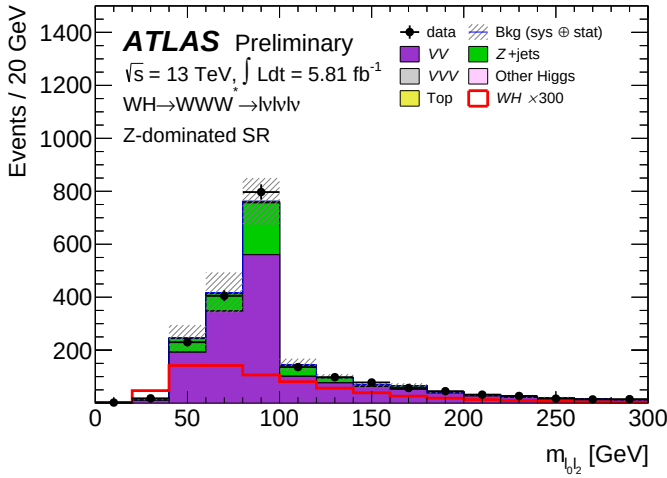
Measurement of the WH production cross section

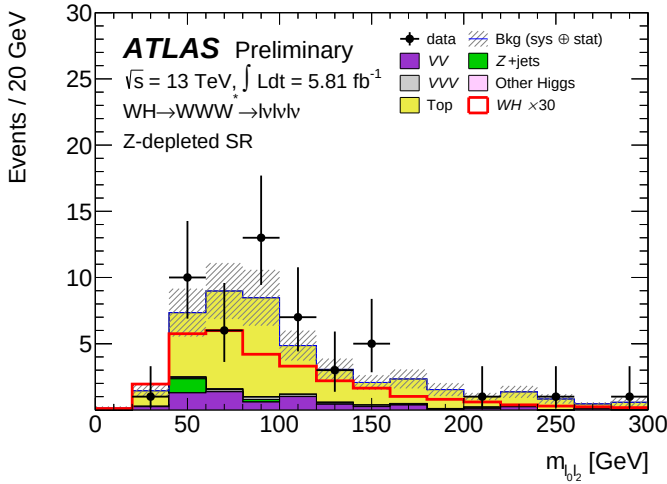
http://cds.cern.ch/record/2231811/
ATLAS-CONF-2016-112

Based on partial 2015+2016 ATLAS dataset
Measurement will be updated in the next months

Analysis strategy

- Classify $N^{\ell} = 3$ events according to lepton pairing
  - ≥ 1 Same-flavour opposite charge pair (Z-dominated): $S/B \approx 0.14$
  - No same-flavour opposite charge pair (Z-depleted): $S/B \approx 0.36$
- Normalisation of the dominant backgrounds is taken from control regions
  - $WZ/W\gamma^*$, $Z\gamma$, Z+jets and $t\bar{t}/Wt/t\bar{t}+V/...$
- Determine σ_{WH} via simultaneous fits to all signal and control regions
- Systematic uncertainties enter as nuisance parameters in the likelihood function
  - Dominant uncertainties are:
    - Data ($\sim 120\%$) & MC statistics ($\sim 70\%$)
    - pile-up activity ($\sim 24\%$), Jet energy resolution ($\sim 23\%$)
    - Modelling of most dominant backgrounds ($\sim 20\%$ for $t\bar{t}$ gen.)





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Results

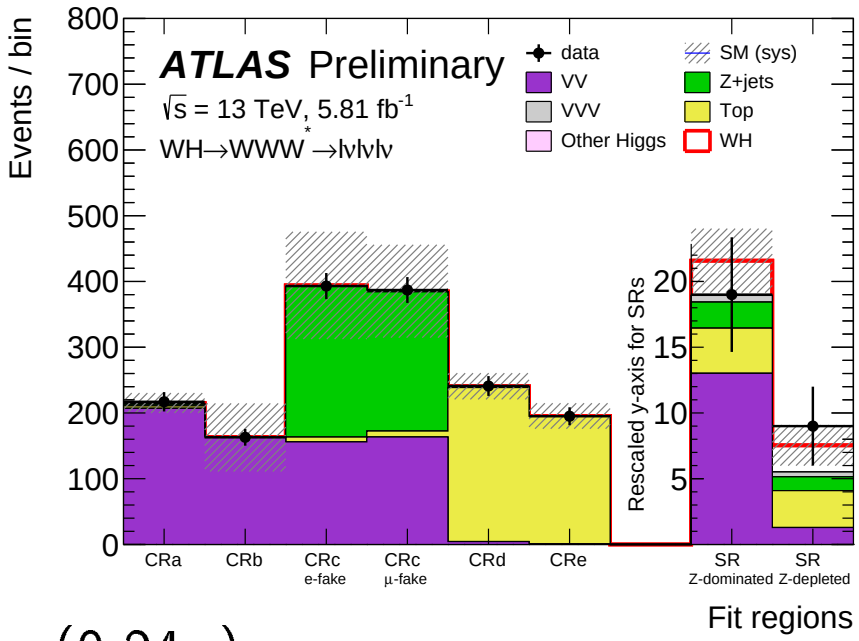
- **Measured cross section times branching ratio:**

$$\sigma_{WH} \times \mathcal{BR}(H \to WW^*) = 0.9^{+1.1}_{-0.9}(stat.)^{+0.7}_{-0.8}(sys.)\,\mathrm{pb}$$

- **Predictions:** $0.293 \pm 0.007\,\mathrm{pb}$
- **Signal strength parameter:**

$$\mu_{WH} = 3.2^{+3.7}_{-3.2}(stat.)^{+2.3}_{-2.7}(syst.)$$

- **Measurements are consistent with the SM prediction**



- Observed (expected) significance is 0.77σ (0.24σ)
- Upper limits at the 95% confidence level computed using the modified frequentist method CL_S: $3.3\,\mathrm{pb}$

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Determination of spin and parity of the Higgs-boson

Eur. Phys. J. C75 (2015) 231

Based on full Run-I ATLAS dataset

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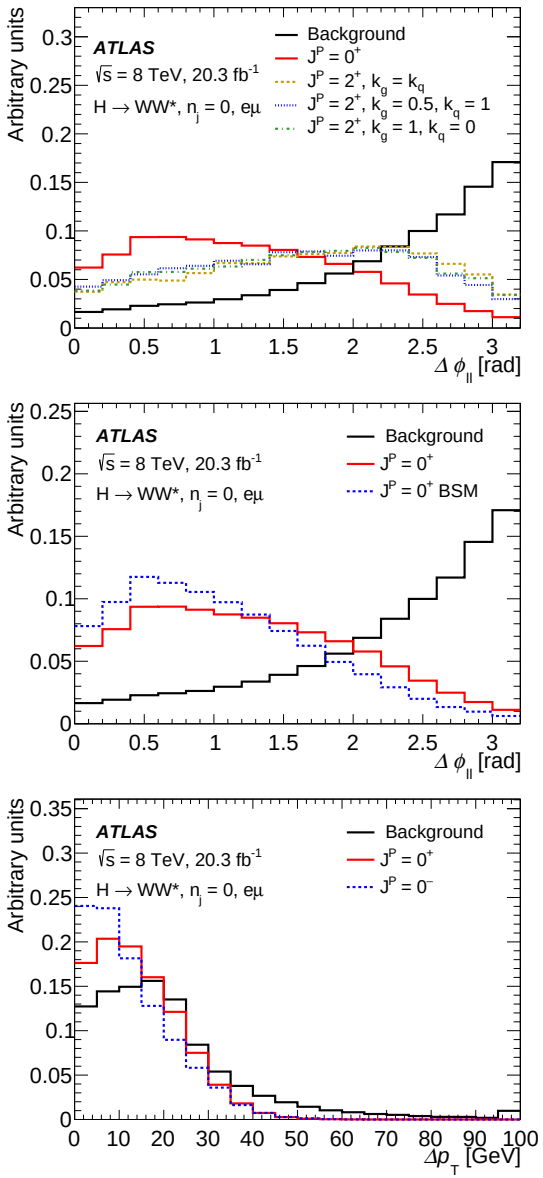
Analysis strategy

- Similar event selection as for σ_{ggF} measurement
- Train boosted decision trees to distinguish between the SM and BSM Higgs-boson hypotheses as well as the SM backgrounds
  - Exploit kinematical differences of Higgs-boson decay products
- **Perform hypothesis tests**
  - SM vs. Spin-2 ($J^P = 2^+$)
  - SM vs. CP odd ($J^P = 0^-$)
  - SM vs. BSM CP even ($J^P = 0^+$)
- **Scan CP mixing scenarios**
  - Angle α describes the mixing between CP-even and CP-odd states
  - κ_{HWW} and κ_{AWW} are the BSM CP-even and CP-odd coupling parameters
- **Results are only based on shape information**



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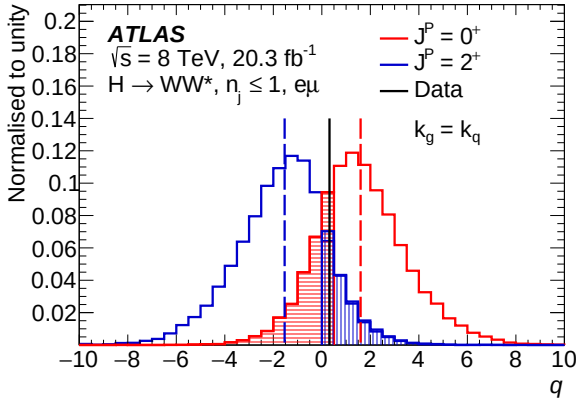
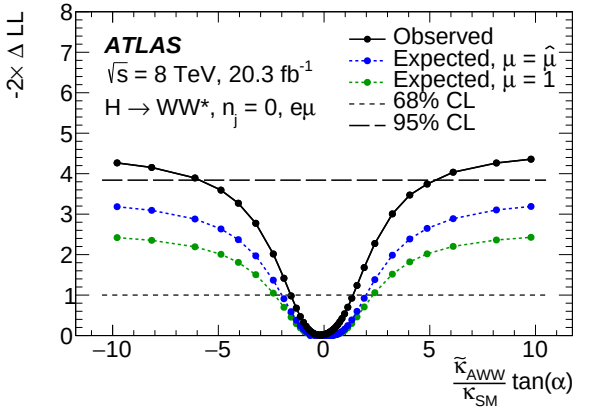
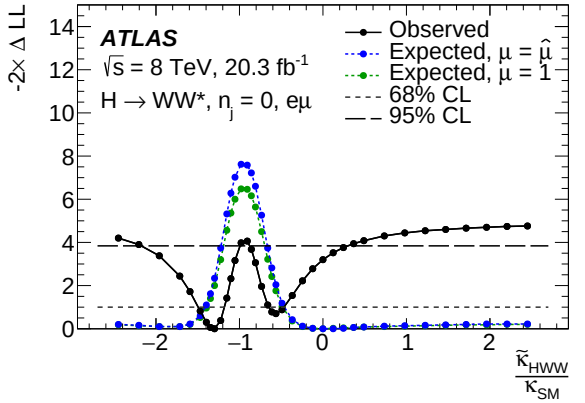
Results

- **Fit input: enrolled two-dimensional $BDT_0 \times BDT_{2/CP}$ distribution**
- **Hypothesis tests:**
  - SM hypothesis is favoured in all tests
  - **Exclude:**
    - Spin-2 hypothesis with non-universal couplings at 92.5% CL
    - Pure CP odd Higgs-boson at 96.5% CL
  - **Disfavour:**
    - Spin-2 hypothesis for universal couplings at a 84.5% CL
    - A BSM CP even Higgs-boson at a 70.8% CL
- **CP-mixing scan:**
  - Exclude $(\tilde{\kappa}_{AWW}/\kappa_{SM}) \cdot \tan\alpha$ values below -6 and above 5 at a 95% CL
  - Exclude $(\tilde{\kappa}_{HWW}/\kappa_{SM})$ values above 0.4 and below -2.2 at a 95% CL







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Summary and outlook

- Presented the latest measurements of the cross section times branching ratios for Higgs-bosons decaying via $H \to WW^*$:
  - In the ggF and VBF production modes for the data collected by ATLAS in 2015 & 2016
    - Cross sections are compatible to SM predictions within one standard deviation
  - In the WH production mode for a partial 2015+2016 dataset
    - Upper cross section limit at a 95% CL was set to be 3.3 pb
    - Results corresponding to the combined 2015 and 2016 data periodes will be published soon
- Also summarised the measurement of the Spin and parity of the Higgs-boson in $H \to WW^*$ events (Run I)
  - A pure CP odd Higgs-boson can be excluded at 96.5% CL
  - A BSM CP even Higgs-boson is disfavoured at 70.8% CL
  - Spin-2 hypothesis with universal couplings is disfavoured at 84.5% CL
  - Spin-2 hypothesis with non-universal couplings is excluded 92.5% CL
- Measurements of Higgs boson properties with Run II data ongoing in Higgs + 2 jets events (in both ggF and VBF production modes)
  - Exploit angle between jets $\Delta\Phi_{jj}$ to study parity and coupling strength to polarised vector bosons

Back-up

Event selection (signal regions)

Category	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$, VBF
Preselection	Two isolated, different-flavour, leptons ($\ell = e, \mu$) with opposite charge $p_{\text{T}}^{\text{lead}} > 22\ GeV$, $p_{\text{T}}^{\text{sublead}} > 15\ GeV$ $m_{\ell\ell} > 10\ GeV$ $E_{\text{T}}^{\text{miss, track}} > 20\ GeV$		
Background rejection	$\Delta\phi(\ell\ell, E_{\text{T}}^{\text{miss}}) > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30\ GeV$	$N_{b\text{-jet},(p_{\text{T}}>20\ \text{GeV})} = 0$ $\max\left(m_{\text{T}}^{\ell}\right) > 50\ GeV$ $m_{\tau\tau} < m_Z - 25\ GeV$	
$H \to WW^* \to e\nu\mu\nu$ topology	$m_{\ell\ell} < 55\ GeV$ $\Delta\phi_{\ell\ell} < 1.8$		Central Jet Veto Outside Lepton Veto
Discriminant Variable BDT input variables	m_{T}		BDT m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_{T}, $\sum C_{\ell}$, $\sum_{\ell,j} m_{\ell j}$, $p_{\text{T}}^{\text{tot}}$

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Event selection (control regions)

CR	$N_{\text{jet}} = 0$	$N_{\text{jet}} = 1$	$N_{\text{jet}} \geq 2$, VBF
WW	$55 < m_{\ell\ell} < 110\ GeV$ $\Delta\phi_{\ell\ell} < 2.6$	$m_{\ell\ell} > 80\ GeV$ $\lvert m_{\tau\tau} - m_Z \rvert > 25\ GeV$	
	b-jet veto		
		$m_{\text{T}}^{\ell} > 50\ GeV$	
Top-quark	$N_{b\text{-jet},(20\ \text{GeV} < p_{\text{T}} < 30\ \text{GeV})} > 0$ $\Delta\phi(\ell\ell, E_{\text{T}}^{\text{miss}}) > \pi/2$ $p_{\text{T}}^{\ell\ell} > 30\ GeV$ $\Delta\phi_{\ell\ell} < 2.8$	$N_{b\text{-jet},(p_{\text{T}} > 30\ \text{GeV})} = 1$ $N_{b\text{-jet},(20\ \text{GeV} < p_{\text{T}} < 30\ \text{GeV})} = 0$ $\max\left(m_{\text{T}}^{\ell}\right) > 50\ GeV$	$N_{b\text{-jet},(p_{\text{T}} > 20\ \text{GeV})} = 1$ Central Jet Veto
		$m_{\tau\tau} < m_Z - 25\ GeV$	
			Outside Lepton Veto
$Z \to \tau\tau$	no $E_{\text{T}}^{\text{miss, track}}$ requirement		Outside Lepton Veto Central Jet Veto
	$m_{\ell\ell} < 80\ GeV$		
	$\Delta\phi_{\ell\ell} > 2.8$	$m_{\tau\tau} > m_Z - 25\ GeV$ $N_{b\text{-jet},(p_{\text{T}} > 20\ \text{GeV})} = 0$	

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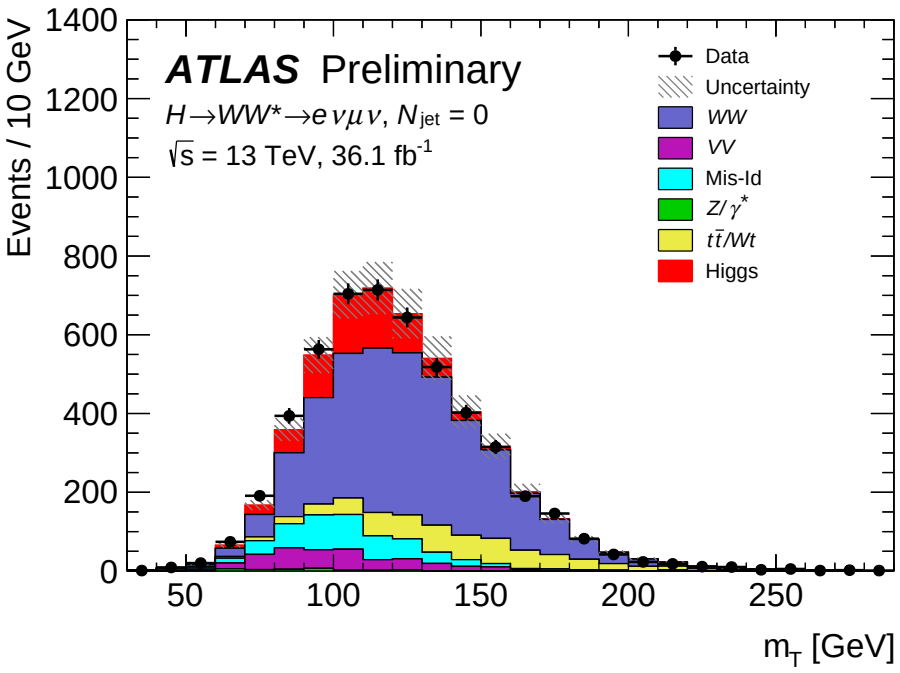
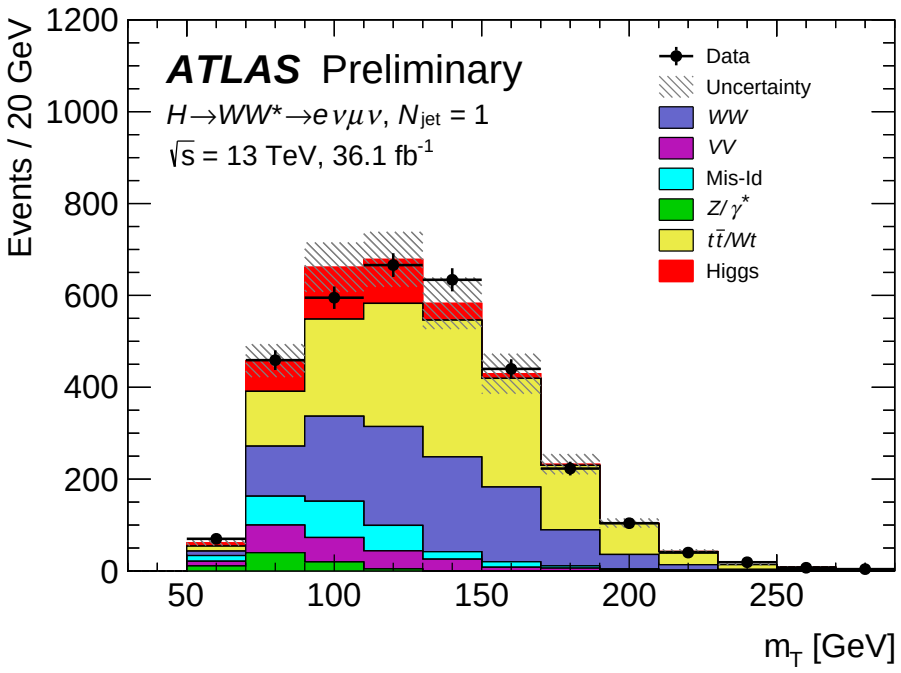
Distribution in signal region (ggF)





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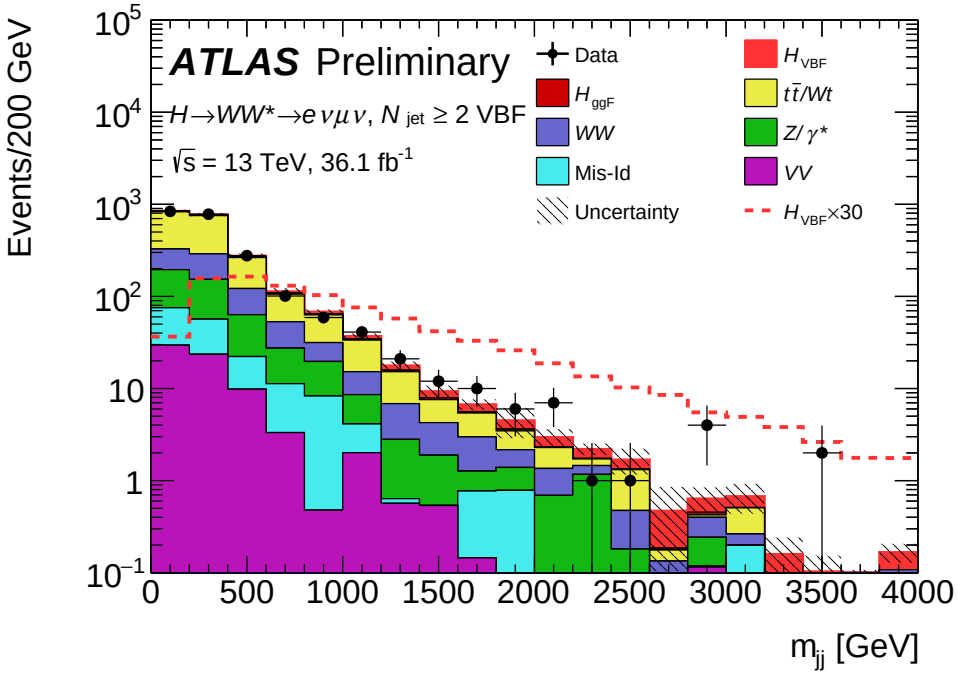
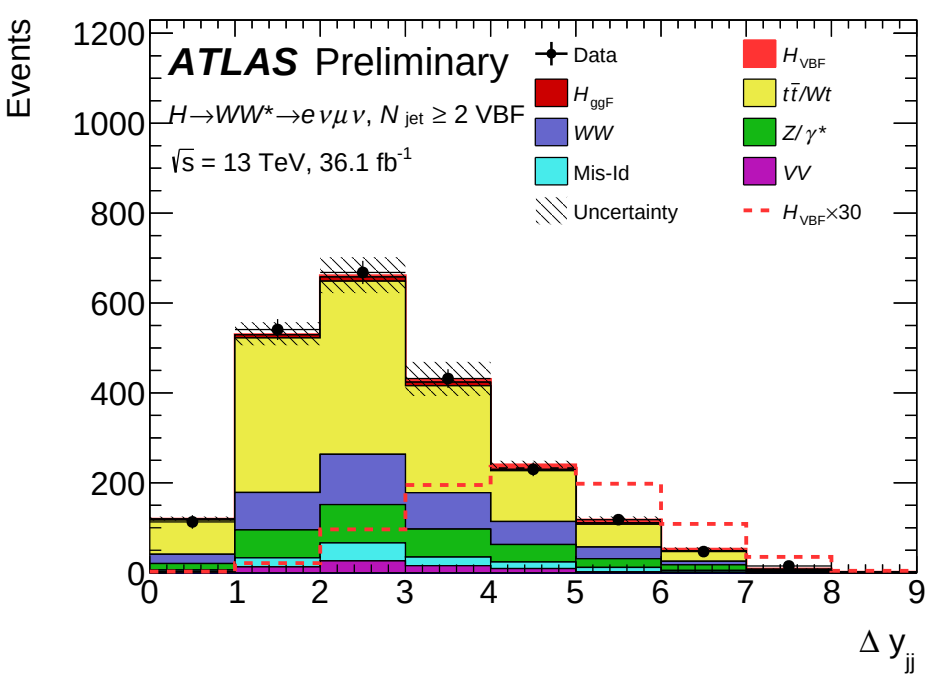
Distribution in signal region (VBF)





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Event yields

Process	$N_{\text{jet}} = 0$ SR	$N_{\text{jet}} = 1$ SR	$N_{\text{jet}} \geq 2$ VBF SR
ggF	680 ± 110	303 ± 52	37 ± 13
VBF	6.8 ± 0.8	30.0 ± 1.9	30 ± 16
WW	2960 ± 670	1020 ± 390	386 ± 59
VV	323 ± 34	204 ± 30	71 ± 14
$t\bar{t}/Wt$	580 ± 128	1400 ± 180	1234 ± 89
Mis-Id	471 ± 80	246 ± 50	109 ± 38
Z/γ^*	27 ± 10	76 ± 22	298 ± 42
Total	5062 ± 67	3290 ± 51	2138 ± 47
Observed	5089	3264	2164

Breakdown of uncertainties

Source	$\frac{\Delta\sigma_{\mathrm{ggF}}}{\sigma_{\mathrm{ggF}}}$ [%]	$\frac{\Delta\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}}$ [%]
Data statistics	± 8	± 46
CR statistics	± 8	± 9
MC statistics	± 5	± 23
Theoretical uncertainties	± 8	± 21
ggF signal	± 5	± 15
VBF signal	<1	± 15
WW	± 5	± 12
Top-quark	± 4	± 4
Experimental uncertainties	± 9	± 8
b-tagging	± 5	± 6
Pile-up	± 5	± 2
Jet	± 3	± 4
Electron	± 3	<1
Misidentified leptons	± 5	± 9
Luminosity	± 2	± 3
TOTAL	± 17	± 59

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Details on Monte Carlo generators

Process	Matrix Element (Alternative)	PDF	PS (Alternative)	Precision σ
ggF	POWHEG-BOX v2 NNLOPS [4,5,6] (MG5_aMC@NLO [22,23])	PDF4LHC15 NNLO [7]	PYTHIA 8 [8] (HERWIG 7 [24])	N^3LO QCD + NLO EW
VBF	POWHEG-BOX v2 (MG5_aMC@NLO)	PDF4LHC15 NLO	PYTHIA 8 (HERWIG 7)	NNLO QCD + NLO EW
VH	POWHEG-BOX v2 [25]	PDF4LHC15 NLO	PYTHIA 8	NNLO QCD + NLO EW
$qq \to WW$	SHERPA 2.2.2 [29,29,30] (POWHEG-BOX v2, MG5_aMC@NLO)	NNPDF3.0NNLO [31]	SHERPA 2.2.2 [32,33] (HERWIG++ [24])	NLO [34]
$gg \to WW$	SHERPA 2.1.1 [34]	CT10 [35]	SHERPA 2.1	NLO [36]
WZ/Vγ^*/ZZ	SHERPA 2.1	CT10	SHERPA 2.1	NLO [34]
Vγ	SHERPA 2.2.2 (MG5_aMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.2 (CSS variation [32,37])	NLO [34]
$t\bar{t}$	POWHEG-BOX v2 [38] SHERPA 2.2.1	NNPDF3.0NLO	PYTHIA 8 [39] (HERWIG 7)	NNLO+NNLL [40]
Wt	POWHEG-BOX v1 [41] (MG5_aMC@NLO)	CT10 [35]	PYTHIA 6.428 [42] (HERWIG++)	NLO [41]
Z+jets	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	NLO [43]

Event selection *WH*

Category	Z-dominated SR ≥ 1 SFOS pair	Z-depleted SR no SFOS pair
Preselection	Three isolated leptons (p_{T} >15 GeV) total charge $= \pm 1$ ≥ 1 lepton matches to the trigger	
Background Rejection	$N_{\mathrm{jet}} \leq 1$, $N_{b\text{-jet}} = 0$	
	$E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV	–
	$\lvert m_{\ell^+\ell^-} - m_Z \rvert > 25$ GeV	$Z/\gamma^* \to ee$ veto
	$m_{\ell^+\ell^-}^{\mathrm{max}} < 200$ GeV	
	$m_{\ell^+\ell^-}^{\mathrm{min}} > 12$ GeV	$m_{\ell^+\ell^-}^{\mathrm{min}} > 6$ GeV
$H \to WW^* \to \ell\nu\ell\nu$ topology	$\Delta R_{\ell_0\ell_1} < 2.0$	

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Analysis strategy

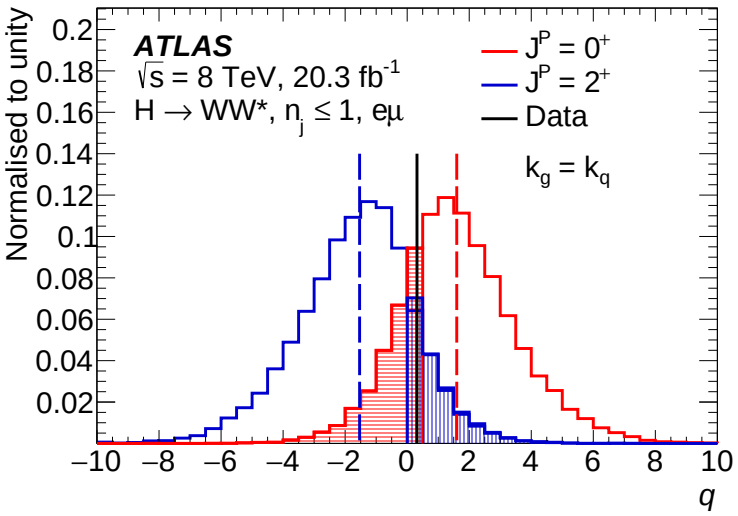
- Effective field theory (Higgs characterisation model) approach used to describe (B)SM hypothesis
  - EFT lagrangian describing interaction between Spin-0 resonance and W-bosons:

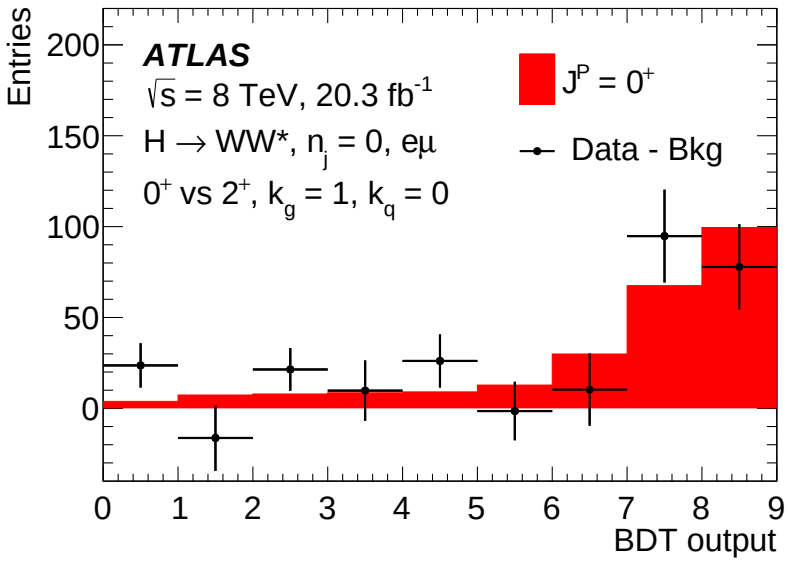
$$\mathcal{L}_0^W = \cos\alpha\kappa_{SM}\left(g_{HWW}W_\mu^+W^{-\mu}\right)X_0 - \frac{1}{2\Lambda}\left(\cos\alpha\kappa_{HWW}W_{\mu\nu}^+W^{-\mu\nu} + \sin\alpha\kappa_{AWW}W_{\mu\nu}^+\tilde{W}^{-\mu\nu}\right)X_0 + \ldots \quad (1)$$

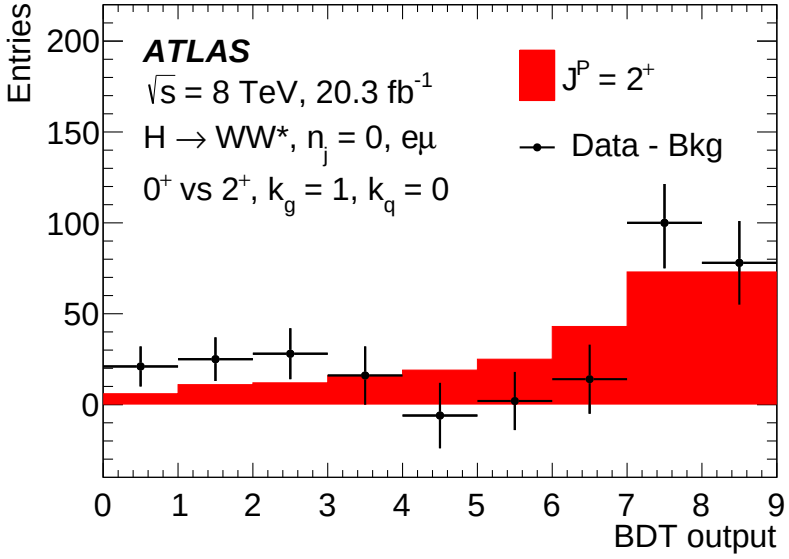
  - Angle α describes the mixing between CP-even and CP-odd states
  - κ_{SM} describes the deviation of the Higgs-boson coupling to vector bosons wrt the SM predictions
  - κ_{HWW} and κ_{AWW} are the BSM CP-even and CP-odd coupling parameters
  - Λ is the scale where new physics is expected (set to $1\,\mathrm{TeV}$)
- Test four hypothesis vs. data
  - SM vs. BSM CP even ($\kappa_{SM} = \kappa_{AWW} = 0$ and $\kappa_{AWW} = \cos\alpha = 1$)
  - SM vs. CP odd ($\kappa_{SM} = \kappa_{HWW} = \cos\alpha = 0$ and $\kappa_{AWW} = 1$)
  - Scan over $\tan\alpha$ ($\kappa_{SM} = \kappa_{AWW} = 1$ and $\kappa_{HWW} = 0$)
  - Scan over κ_{HWW} ($\kappa_{SM} = \cos\alpha = 1$ and $\kappa_{AWW} = 0$)

Results on Spin measurement

- **Perform hypothesis tests**
  - Based on enrolled two-dimensional $BDT_0 \times BDT_2$ distribution
- Hypothesis tests:
  - SM hypothesis is favoured in all tests
  - Spin-2 hypothesis is disfavoured for universal couplings at a 84.5% CL
  - Spin-2 hypothesis with non-universal couplings is excluded 92.5% CL







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