Measurement of cross sections and couplings of the SM Higgs boson in the WW decay channel using the ATLAS detector

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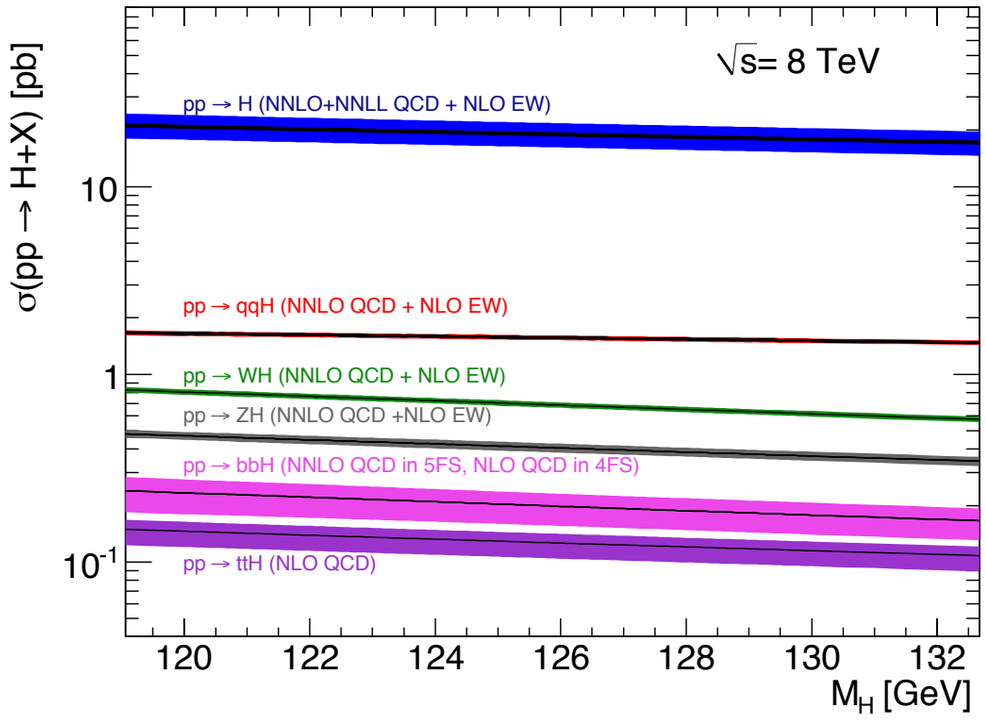
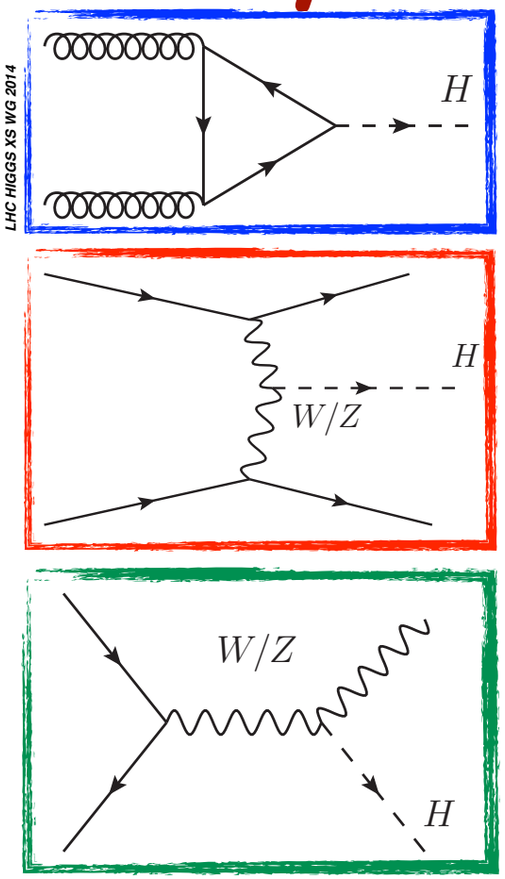
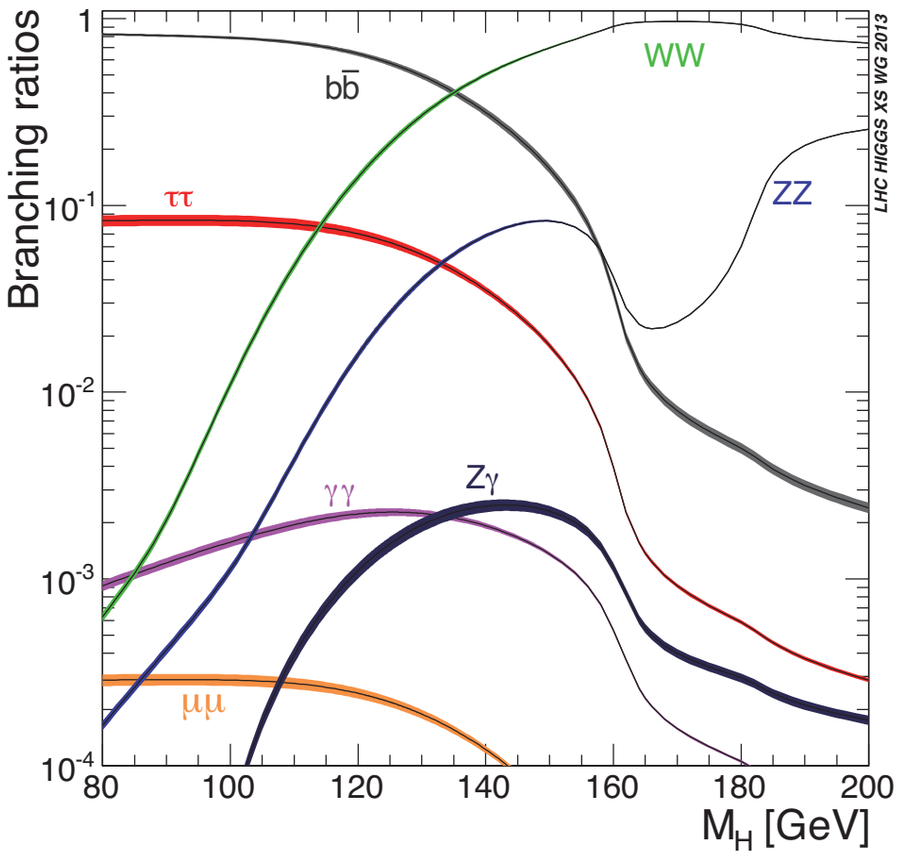
on behalf of ATLAS Collaboration

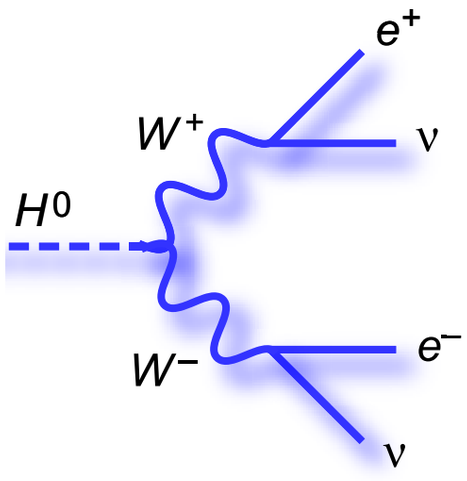
Higgs boson production/decay

- Higgs boson couplings measurement essential SM consistency test
- Search for rare production modes
  - Continue search for additional states at high mass in parallel



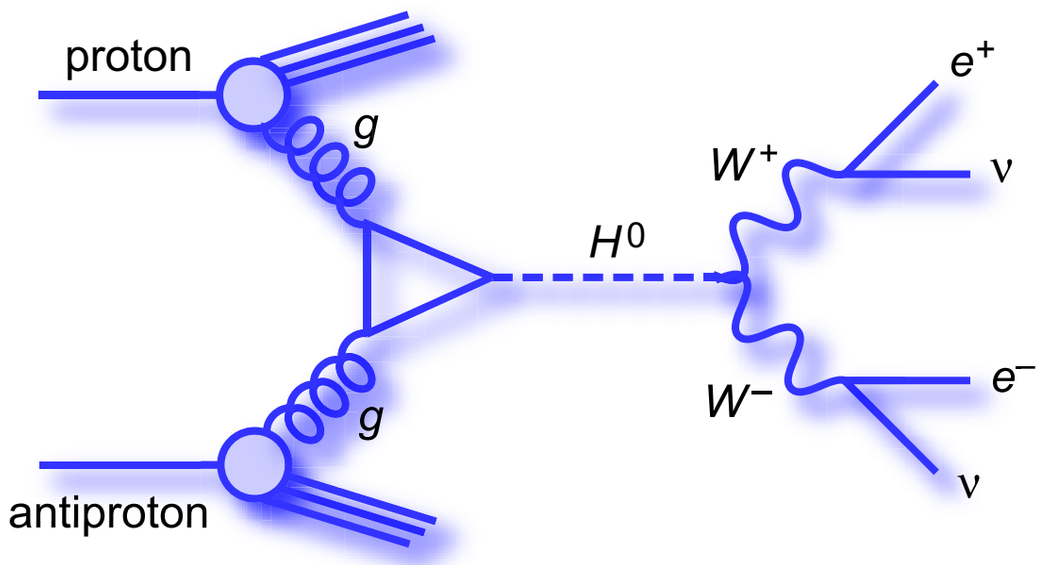






- WW channel well-suited to exploring rare production modes and searching at high-mass
  - Large branching ratio: **22 %**
  - Good S/B from clean dilepton signature

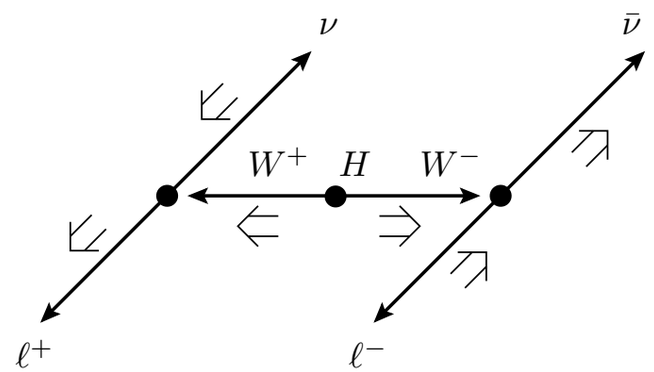
H→WW*→lνlν Signature



Final state:

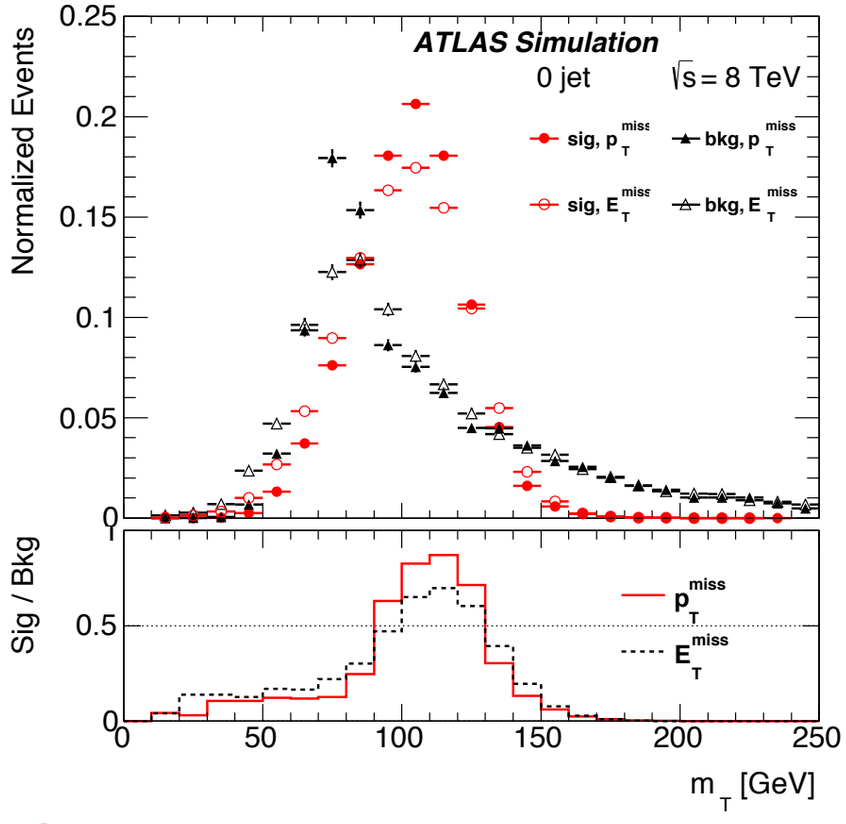
- 2 charged leptons
- 2 neutrinos
- njets depend on the production mode

Spin zero Higgs: charged leptons prefer to point in same direction



- Signal process can not be fully reconstructed → presence of neutrino
  - A transverse mass m_T can be calculated without the unknown longitudinal neutrino momenta

$$M_T^2 = (E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\,\text{miss}})^2$$



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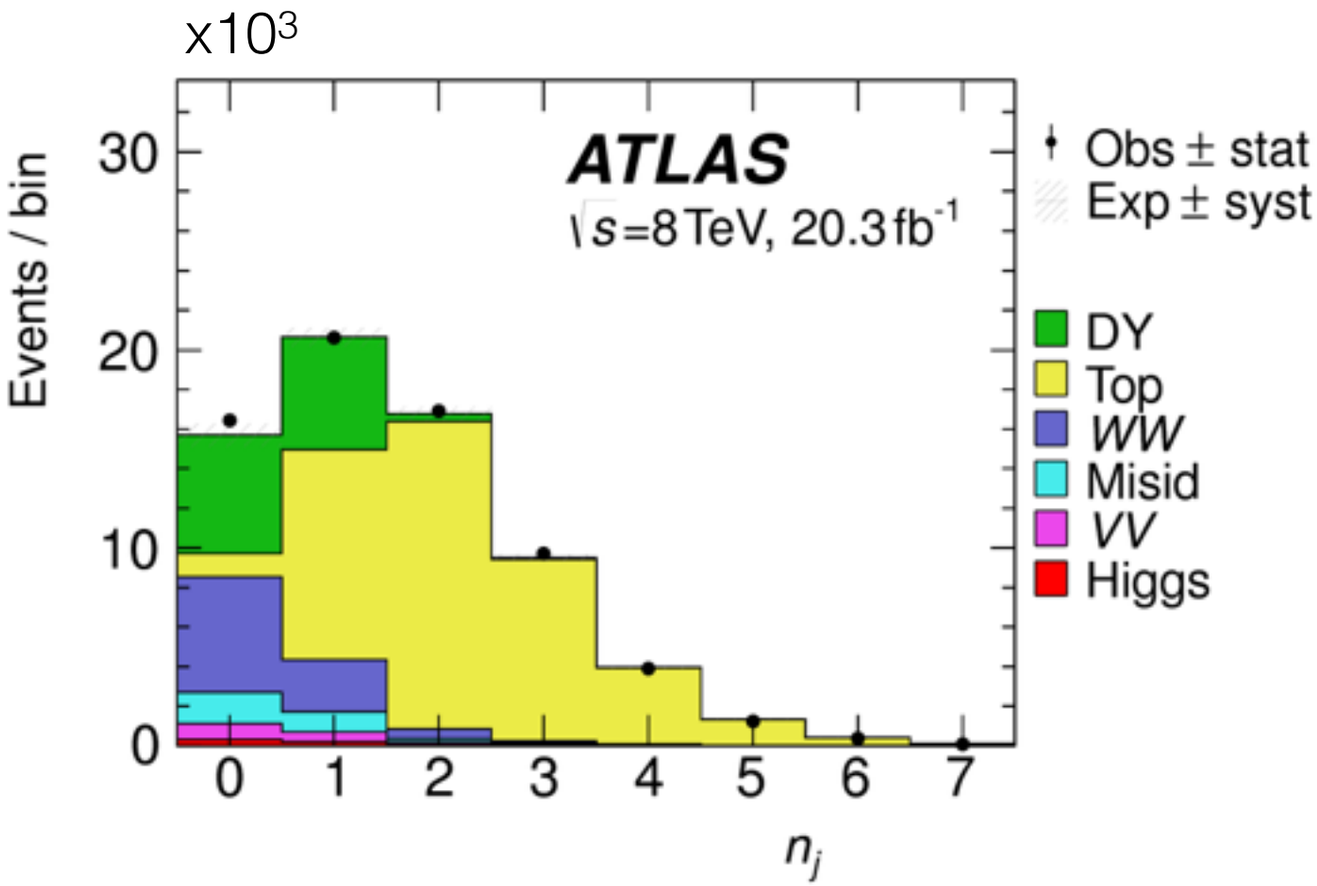
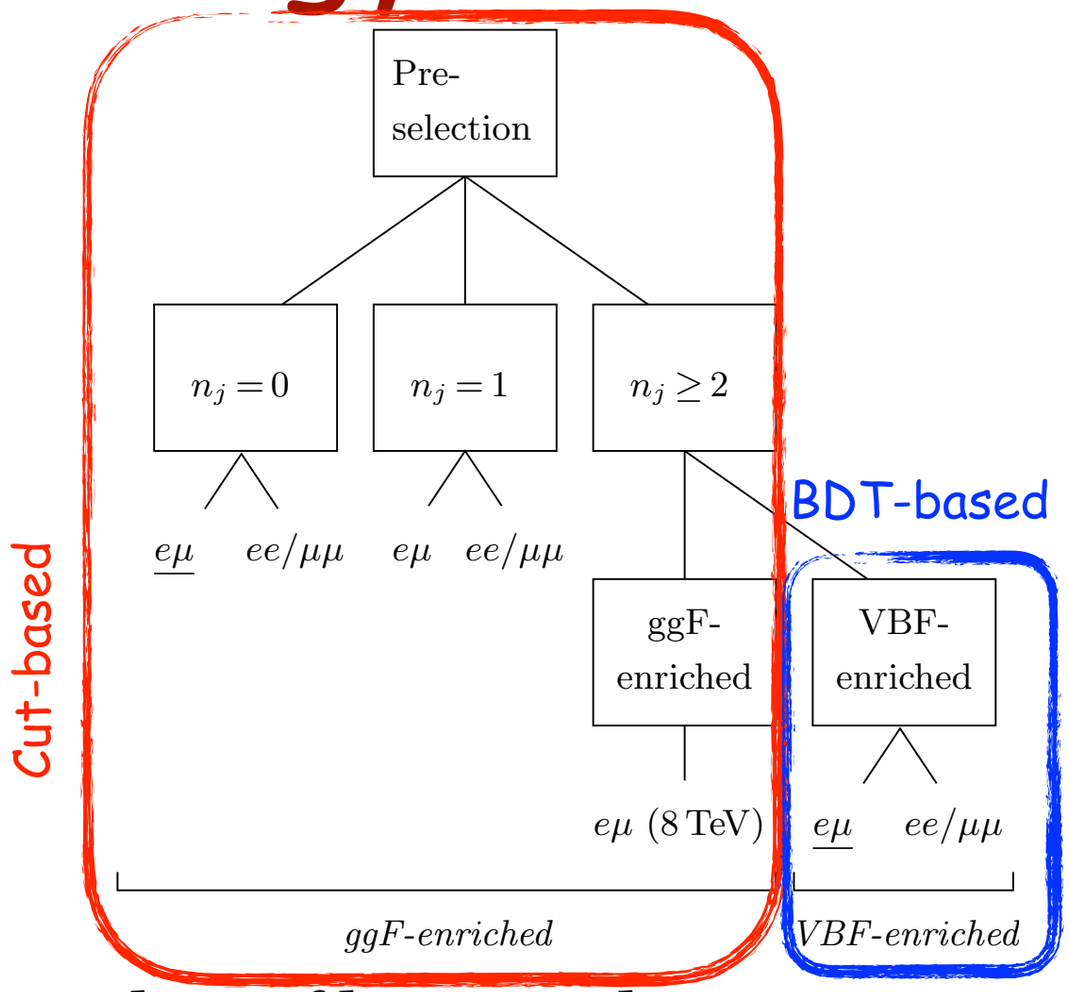
Analysis strategy





- Categorise events by number of jets, number of leptons, lepton flavors
- Separate by production mode and background composition
- Cut away backgrounds and normalise to control regions enriched in a particular background but orthogonal to the signal region

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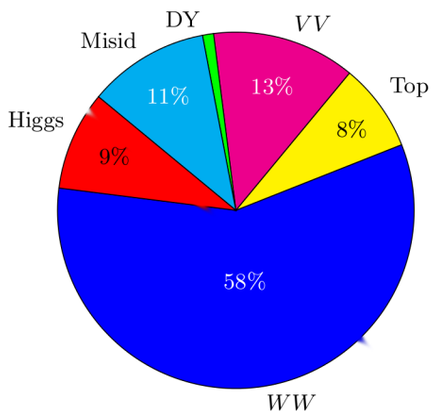
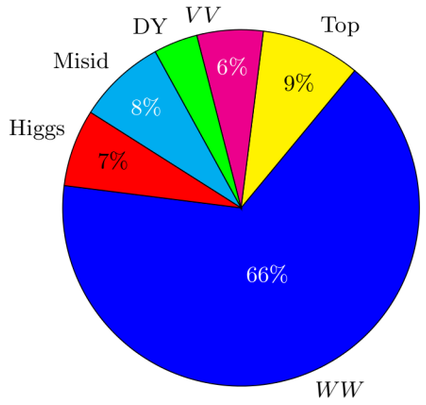
Backgrounds

GGF 0jets

(a) $n_j = 0$, $e\mu$

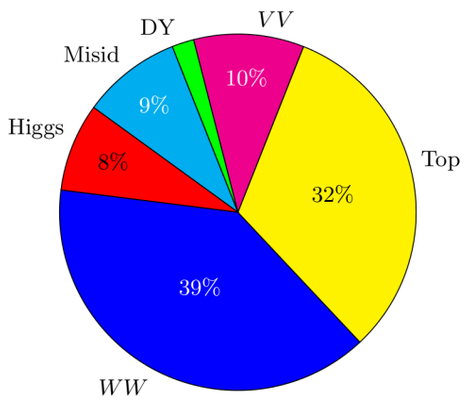


(b) $n_j = 0$, $ee/\mu\mu$

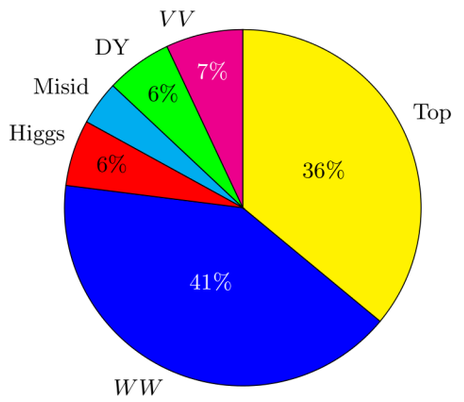


GGF 1jet

(c) $n_j = 1$, $e\mu$

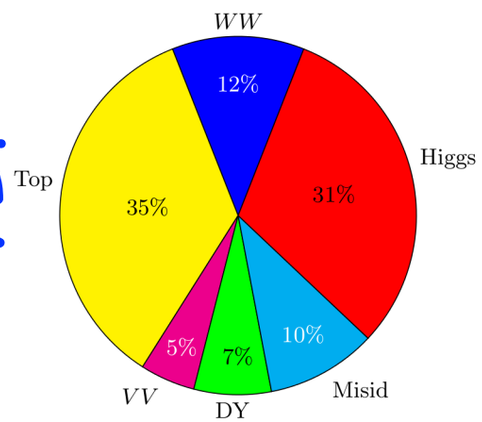


(d) $n_j = 1$, $ee/\mu\mu$

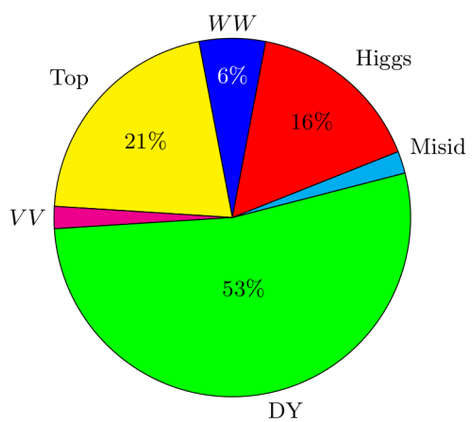


VBF

(a) $n_j \geq 2$ VBF, $e\mu$



(b) $n_j \geq 2$ VBF, $ee/\mu\mu$



- **WW**: dominant ggF background → almost irreducible
- **Top**: coming from unidentified b-quark
- **DY**:
  - Z/γ* → ee/μμ: Misidentified missing energy
  - Z/γ* → τ τ: Irreducible
- **Misid**: jet misidentified as lepton
  - "fake" leptons, particularly muons, are often true leptons from heavy-flavor hadron decays
  - dijet data samples are use to obtain the fake factor
    - 40-45% uncertainty on fake factor from sample composition

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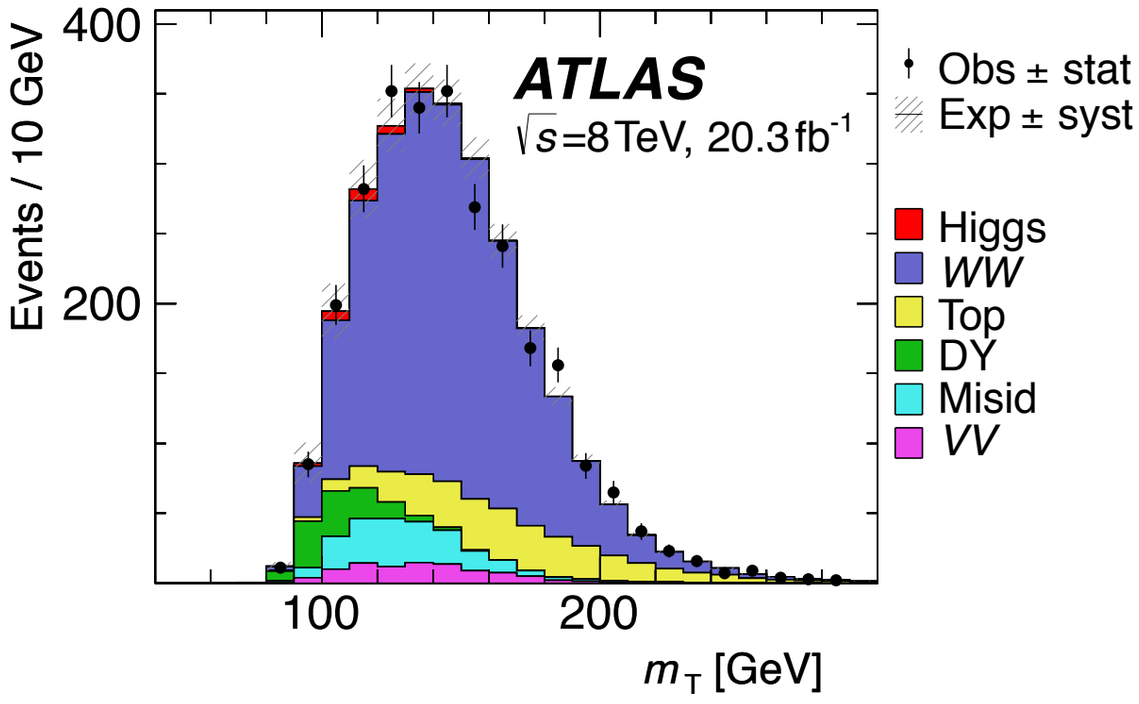
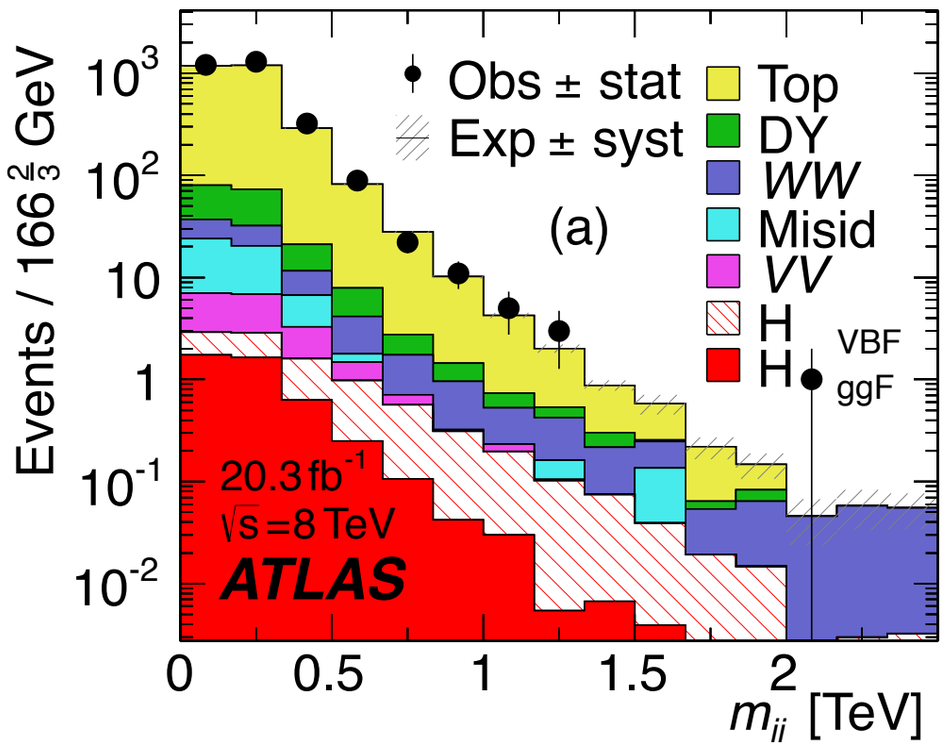
Backgrounds

WW background



- $N_{Jets}<2$ analyses use m_{ll} to define the CR
  - process characterised by two lepton with bigger angle wrt Higgs process
  - Invariant mass of the charged leptons combines angular information with the kinematic information associated with Higgs boson mass —> powerful discriminant

Top background



- $N_{Jets}>1$ categories have a large contribution from top-quark background
- Light-quark et from initial-state radiation and a b-quark jet that is not identified by the b -tagging algorithm
- CR requires exactly one b-tagged jet to mimic this topology

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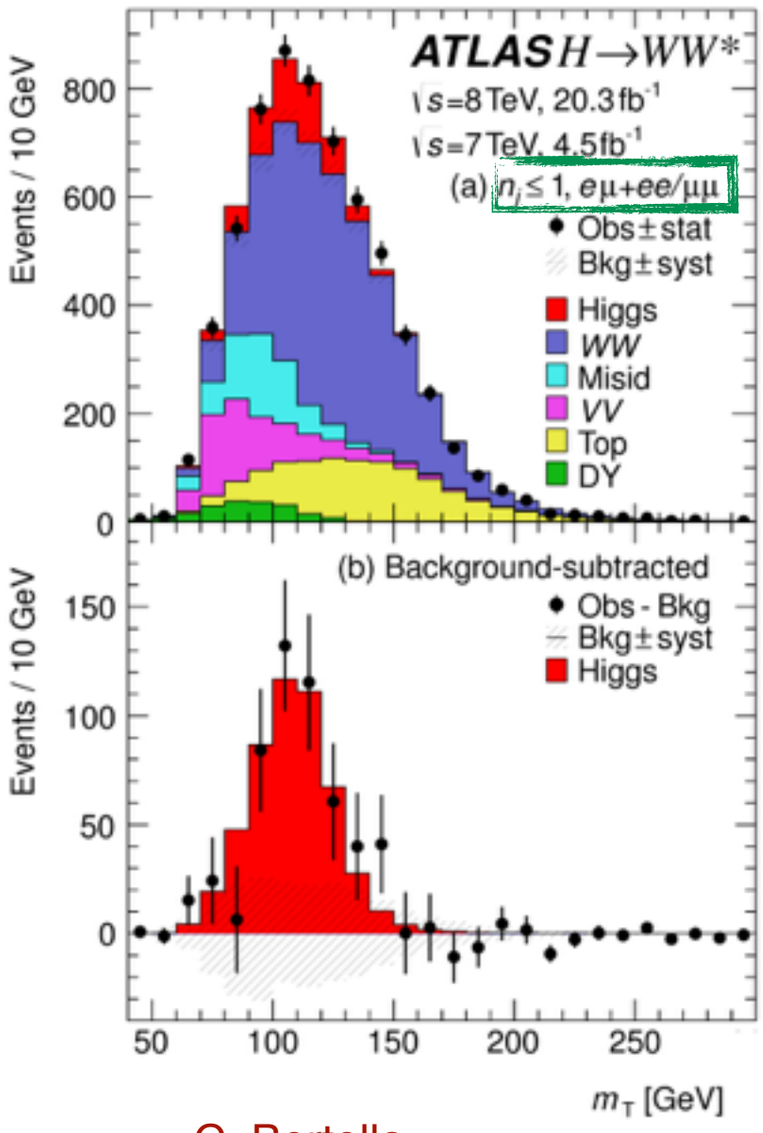
H→WW*→lvlv signal strength

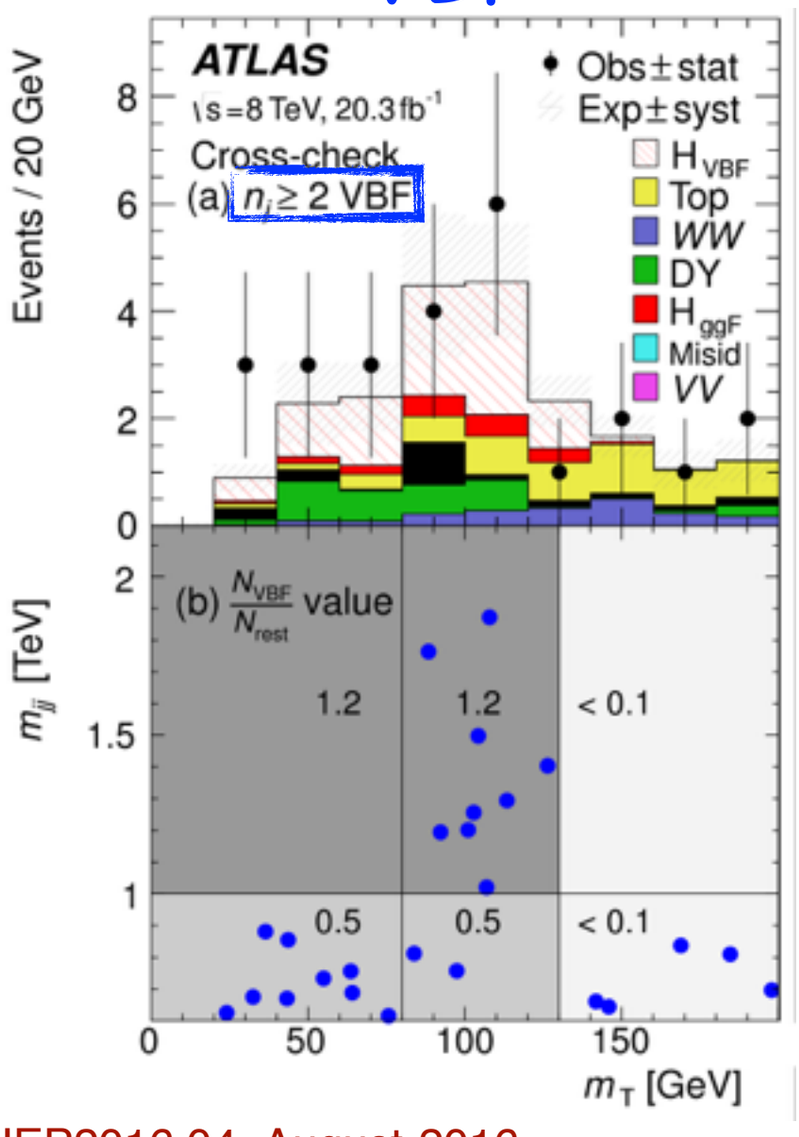
$$\mu_{\mathrm{ggF}} = 1.02 \pm 0.19\ ^{+0.22}_{-0.18} = 1.02\ ^{+0.29}_{-0.26}$$
$$\mu_{\mathrm{VBF}} = 1.27\ ^{+0.44}_{-0.40}\ ^{+0.30}_{-0.21} = 1.27\ ^{+0.53}_{-0.45}\cdot$$
(stat) (syst)

$$\sigma^{7\mathrm{TeV}}_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 2.0 \pm 1.7\ ^{+1.2}_{-1.1} = 2.0\ ^{+2.1}_{-2.0}\ \mathrm{pb}$$
$$\sigma^{8\mathrm{TeV}}_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 4.6 \pm 0.9\ ^{+0.8}_{-0.7} = 4.6\ ^{+1.2}_{-1.1}\ \mathrm{pb}$$
$$\sigma^{8\mathrm{TeV}}_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.51\ ^{+0.17}_{-0.15}\ ^{+0.13}_{-0.08} = 0.51\ ^{+0.22}_{-0.17}\ \mathrm{pb}.$$
(stat) (syst)

ggF



VBF



- $\mu = \sigma/\sigma_{SM}$ //measured cross section $\sigma = \mu * \sigma_{SM}$
  - Fiducial cross section not affected by the theoretical uncertainties on the total signal yield
- Confirmed Higgs boson decay to W bosons —> rate consistent with the Standard Model : observed significance of 5.8 standard deviations
- Evidence of VBF production in this channel —> observed significance of 3.2 standard deviations

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VH → WW Signal Regions

Clean 3-lepton (WH) and 4- lepton (ZH) signatures, additional info on HWW vertex (complement to VBF mode) —> pure HWW or HZZ

WH → 3-leptons

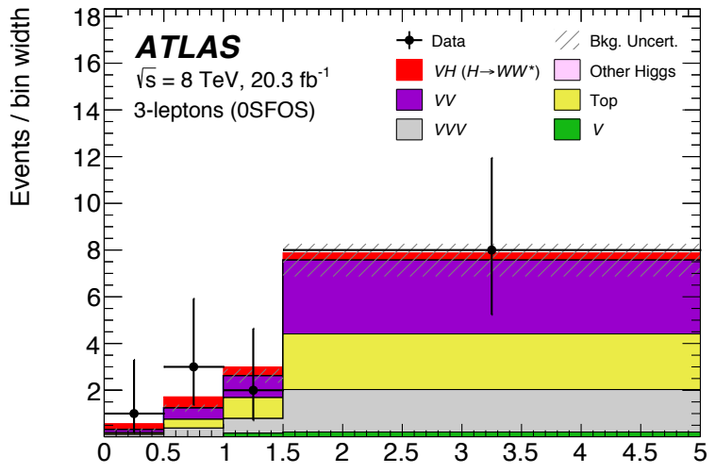
- Major backgrounds are WZ/Wγ*, ZZ*, VVV
- Split into Z enriched and Z depleted regions using number of same flavour (SF) opposite sign (OS) lepton pairs

ΔR_{l0l1}

(Z depleted region)

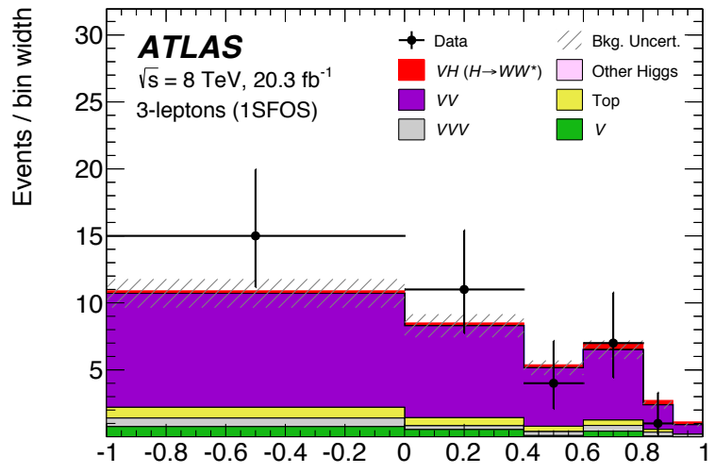
l_0: lepton with unique charge

l_1: lepton closest l_0



BDT score

(1SFOS SR)

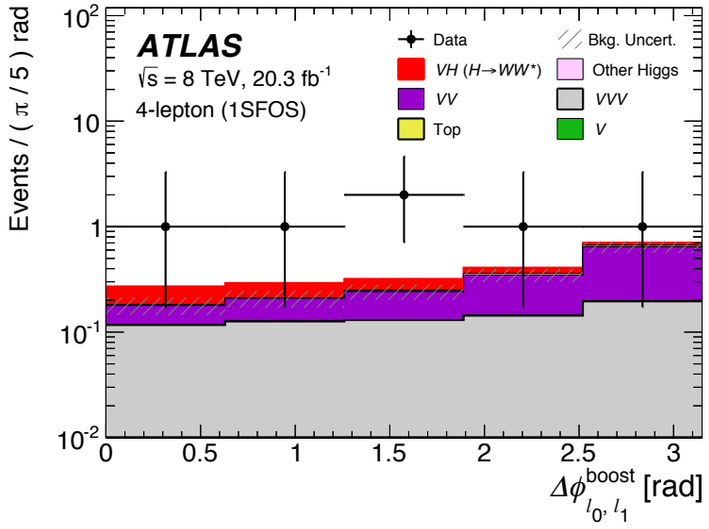


ZH → 4-leptons:

- 2 OS pairs, one with |mll - mZ| < 10 GeV 1 event expected, S/B ~ 1/5 zero observed
- Main background is ZZ*
- Split SR into 1SFOS and 2SFOS to better control ZZ* bkg

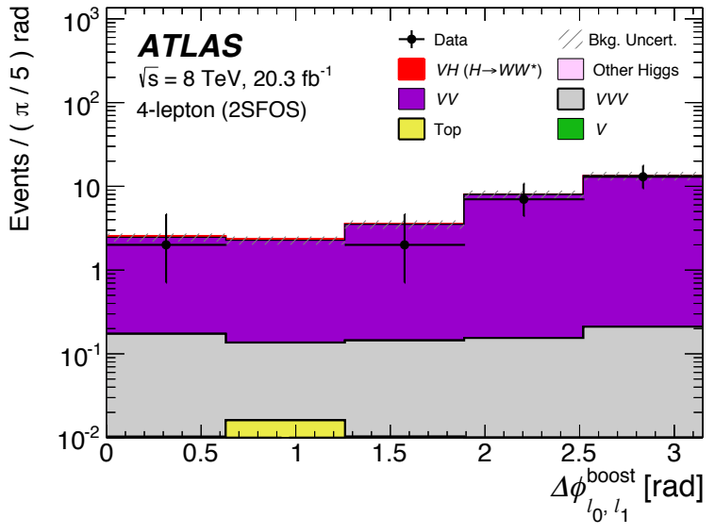
$\Delta\varphi_{l0l1}$ in 1SFOS SR

l_0l_1: Higgs boson decay lepton



$\Delta\varphi_{l0l1}$ in 2SFOS SR

l_0l_1: Higgs boson decay lepton



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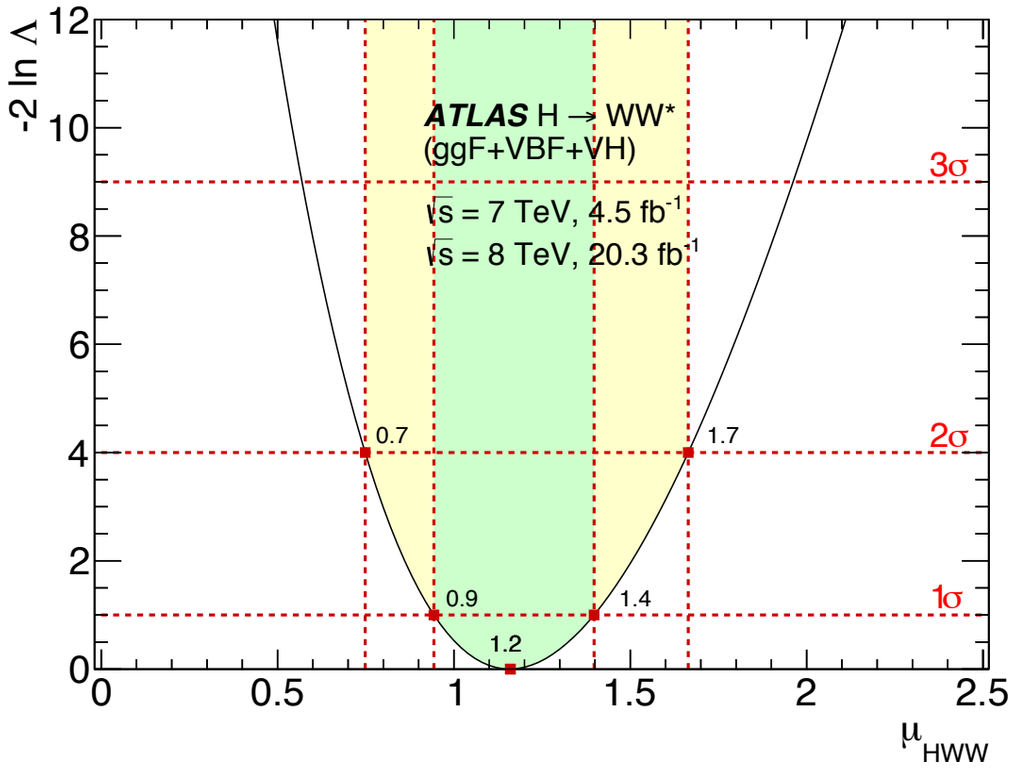
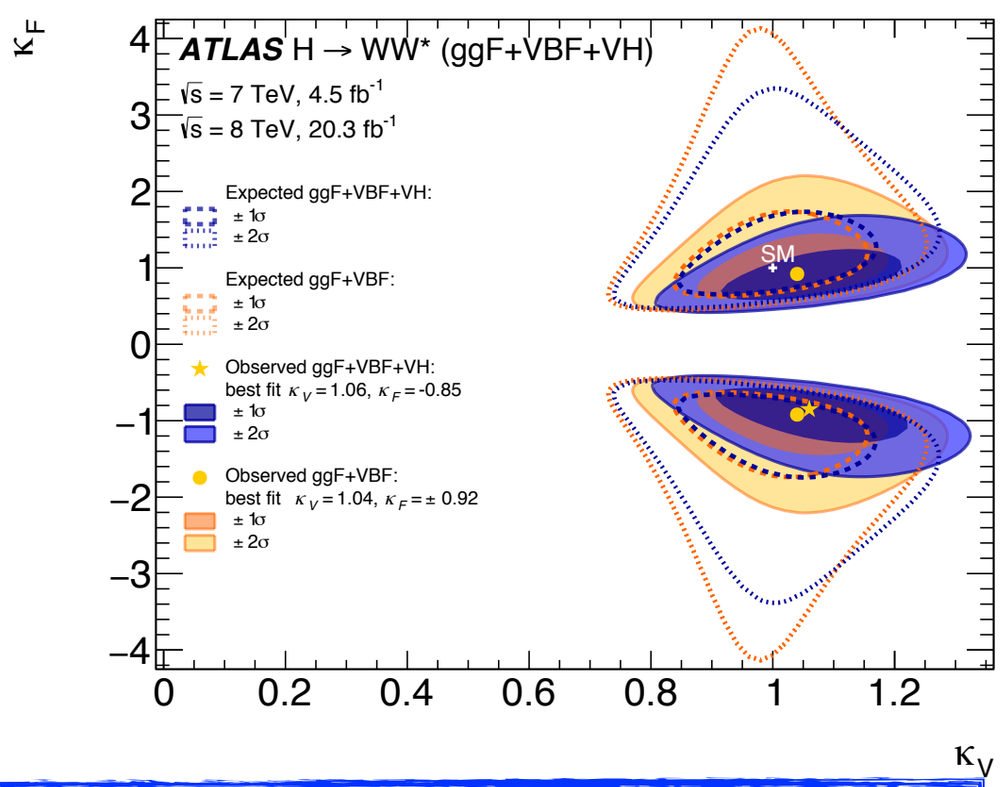
Combined H → WW Results (mH = 125.36 GeV)

Category	Signal significance Z_0 Exp. Z_0	Obs. Z_0	Observed signal strength μ μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −
ggF	4.4	4.2	**0.98**	0.29	0.26	0.22	0.18
VBF	2.6	3.2	**1.28**	0.55	0.47	0.32	0.25
VH	0.93	2.5	**3.0**	1.6	1.3	0.95	0.65
WH only	0.77	1.4	**2.1**	1.9	1.6	1.2	0.79
ZH only	0.30	2.0	**5.1**	4.3	3.1	1.9	0.89
ggF+VBF+VH	5.9	6.5	**1.16**	0.24	0.21	0.18	0.15





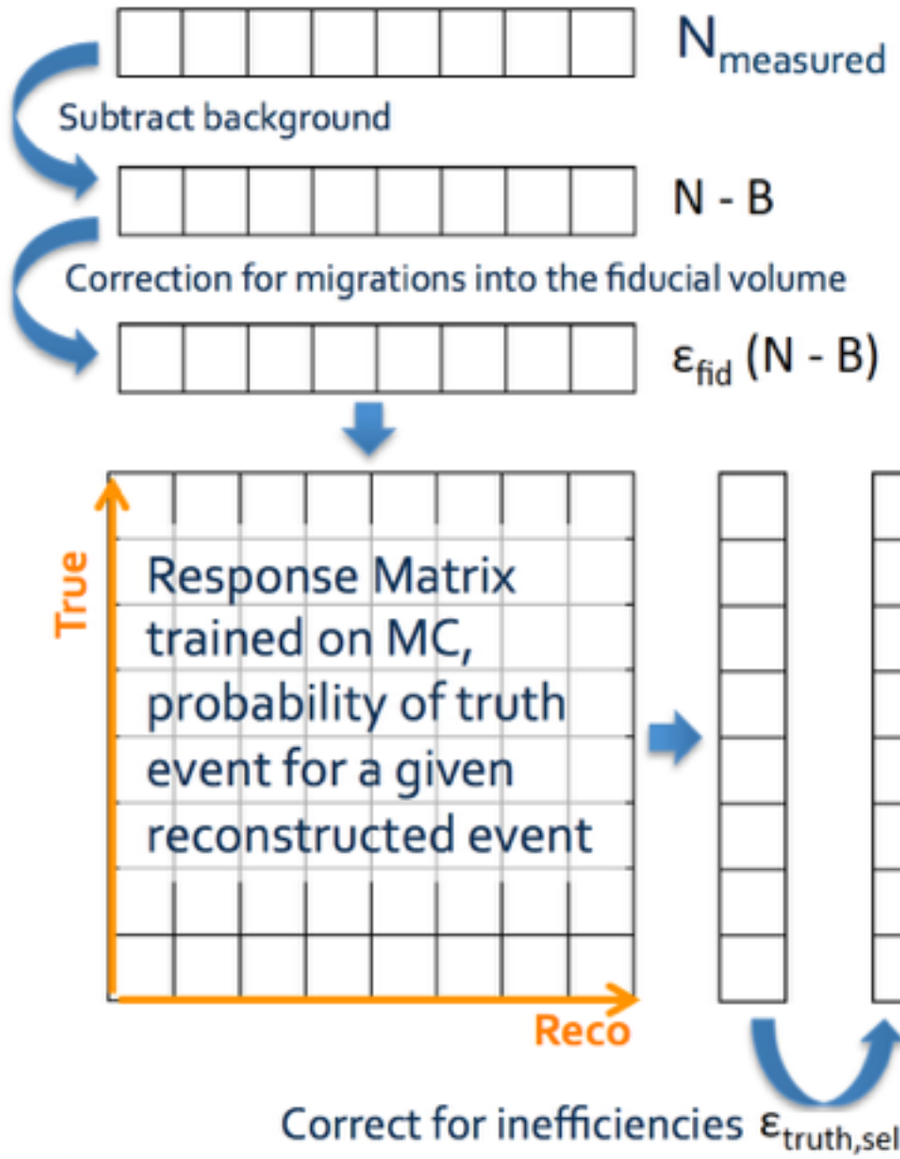
- Observed significance for the combined VH production is 2.5 standard deviations
- Significance of 0.9 standard deviations is expected in the SM Higgs boson hypothesis

arXiv:1604.02997

Differential Cross Sections

- Possible to directly measure several kinematic distributions in a close to model independent way
  - Compare to theoretical models and provide constrains on QCD and PDF calculation
  - Sensitive to new physics
- Analysis performed only on different flavour
- Use control region to extract background and subtract the predicted background in the signal region from the data
- Correction/extrapolation of the event yields from the reconstructed signal region to the truth-level fiducial volume
- Unfolding corrects measured distribution for detector effects and brings it from the signal (reconstructed)to the fiducial (particle level) volume

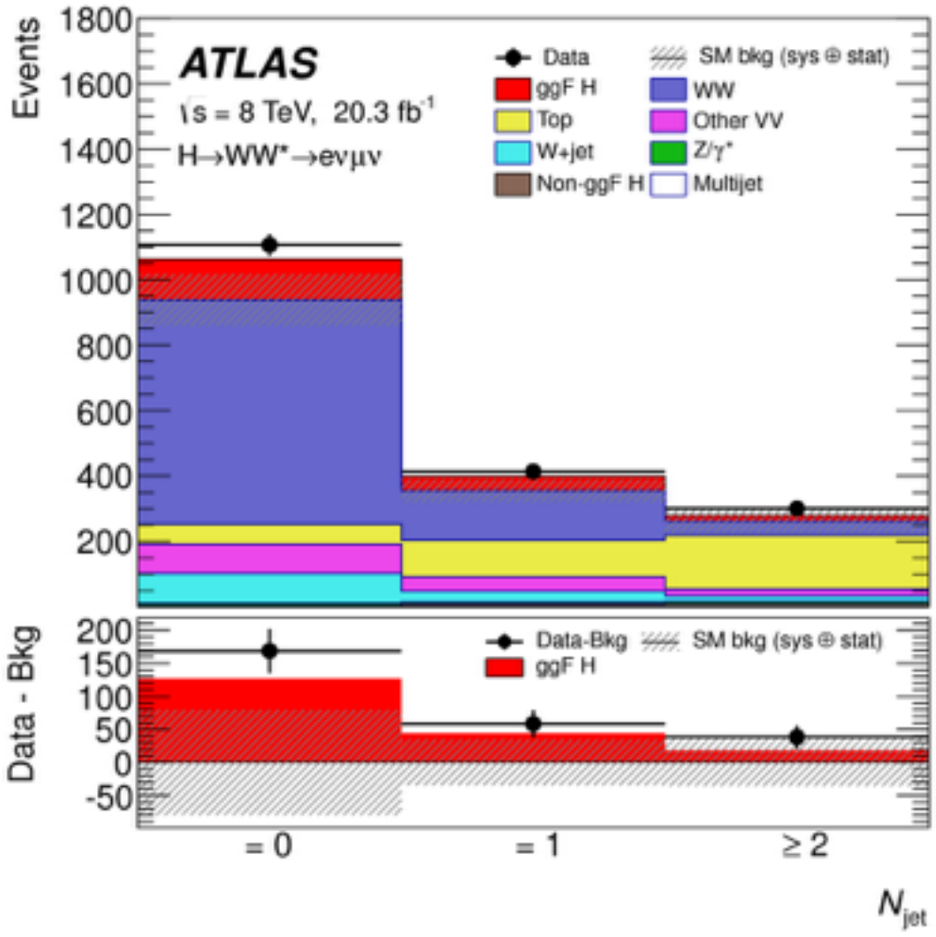
$$\frac{d\sigma}{dX_i} = \frac{1}{\mathcal{L} * BR} \frac{M_{ji}^{-1} \epsilon_{fid,j}}{\epsilon_{truth,sel,i}} (N_j - B_j)$$

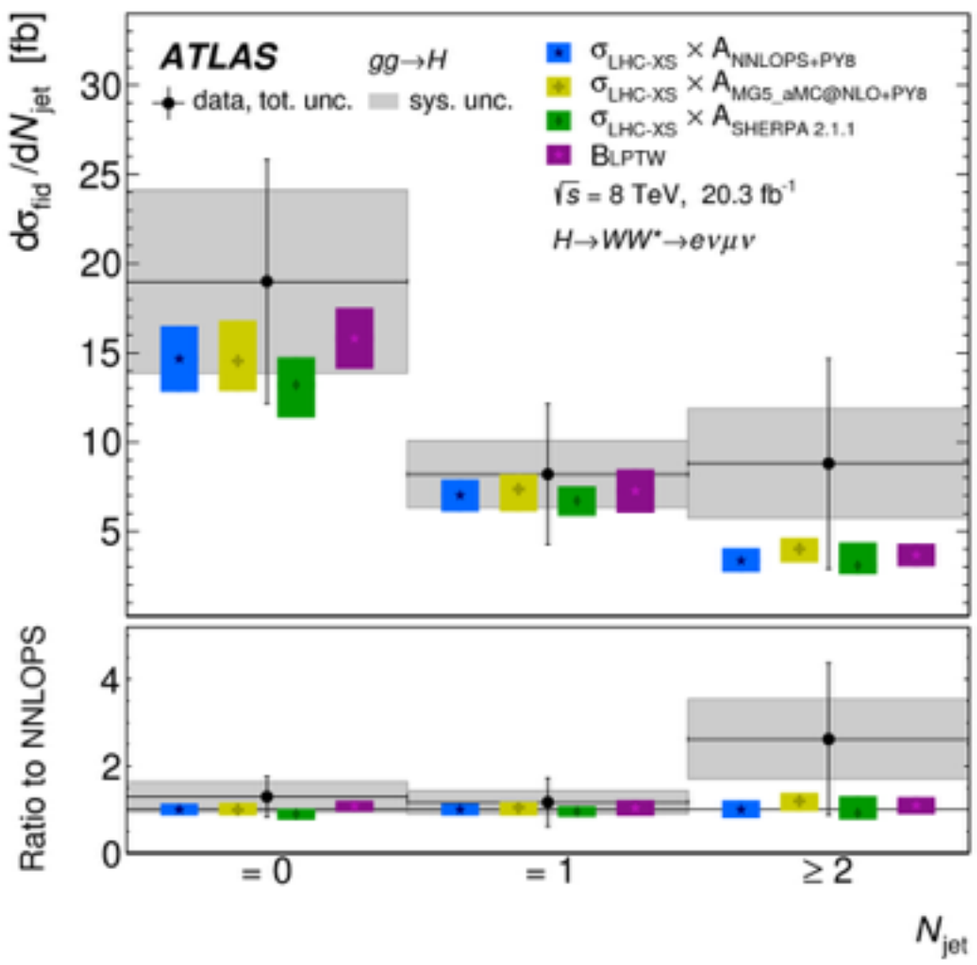


Differential Cross Sections

- Jet multiplicity N_{jets}: a measure of the QCD radiative process in the initial state. Reflects the hard QCD process, calculations lack precise prediction for the high N_{jets}

- Statistical uncertainties (25%-75%) still dominate all the differential measurements



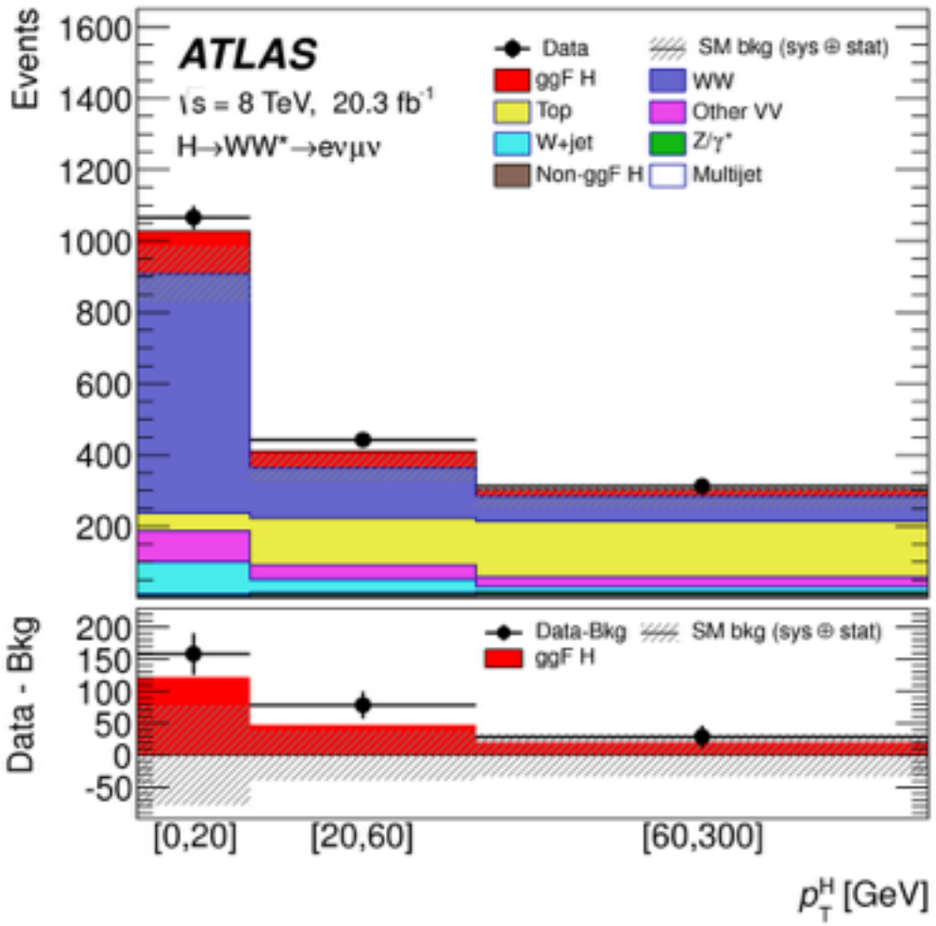


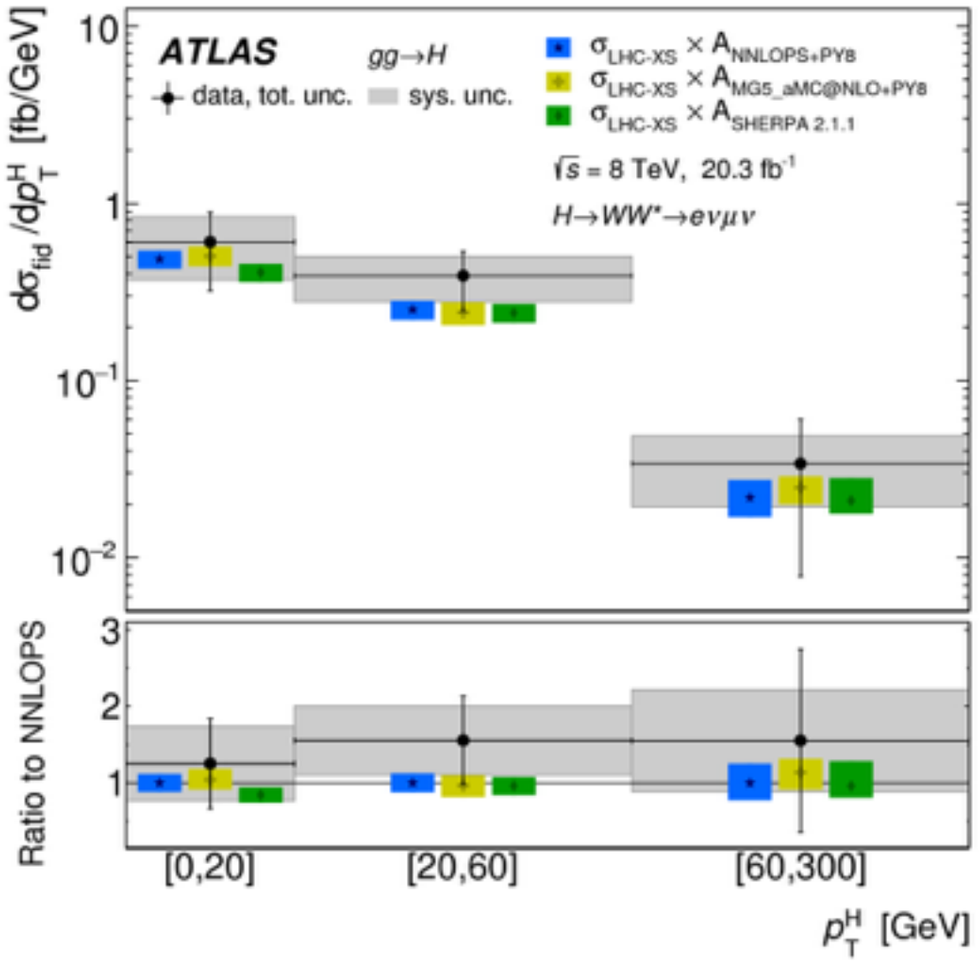
arXiv:1604.02997

Differential Cross Sections

- Transverse momentum p_T^H directly probes perturbative/soft QCD, sizeable uncertainties at low p_T

- Statistical uncertainties (25%-75%) still dominate all the differential measurements





Summary

- WW was essential to discovery, combined rate measurement, and connecting the new particle to electroweak symmetry breaking

- WW channel can be very useful in investigation the Higgs boson nature

  - Good S/B and large branching ratio

  - Challenging backgrounds in ggF and VBF

  - ggF and VBF modes key inputs to coupling measurement combinations

    - Search for rarer production modes: WH, ZH

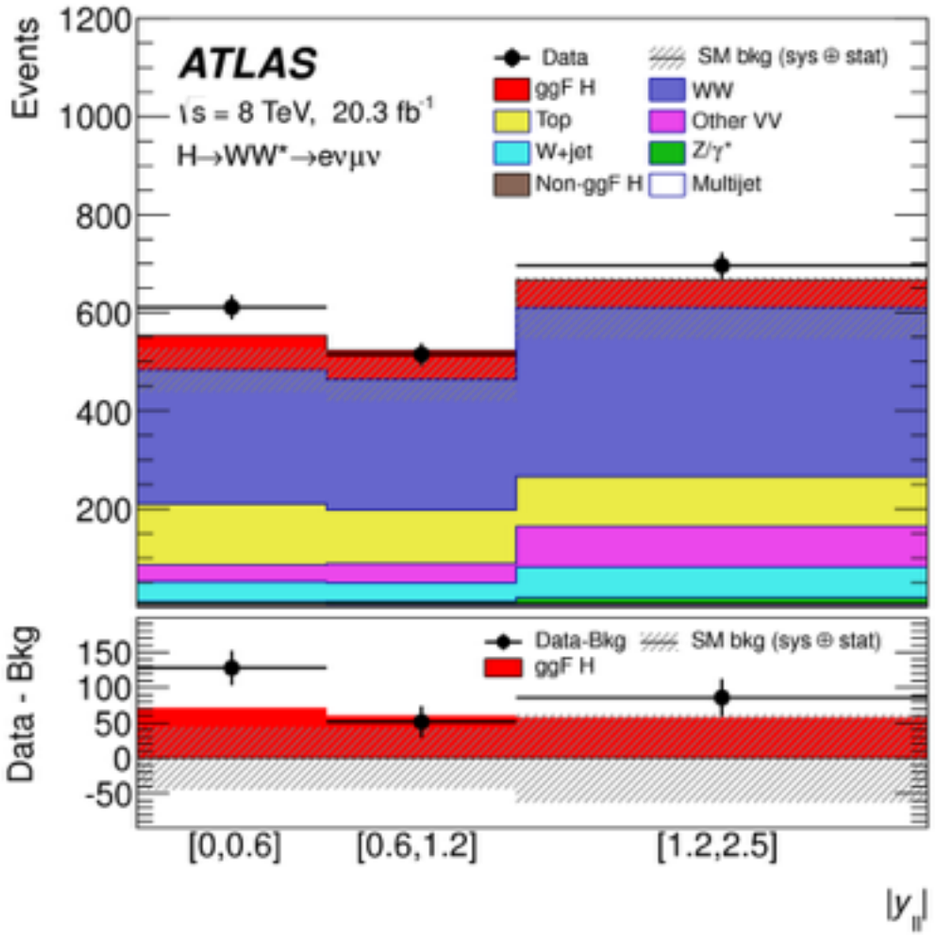
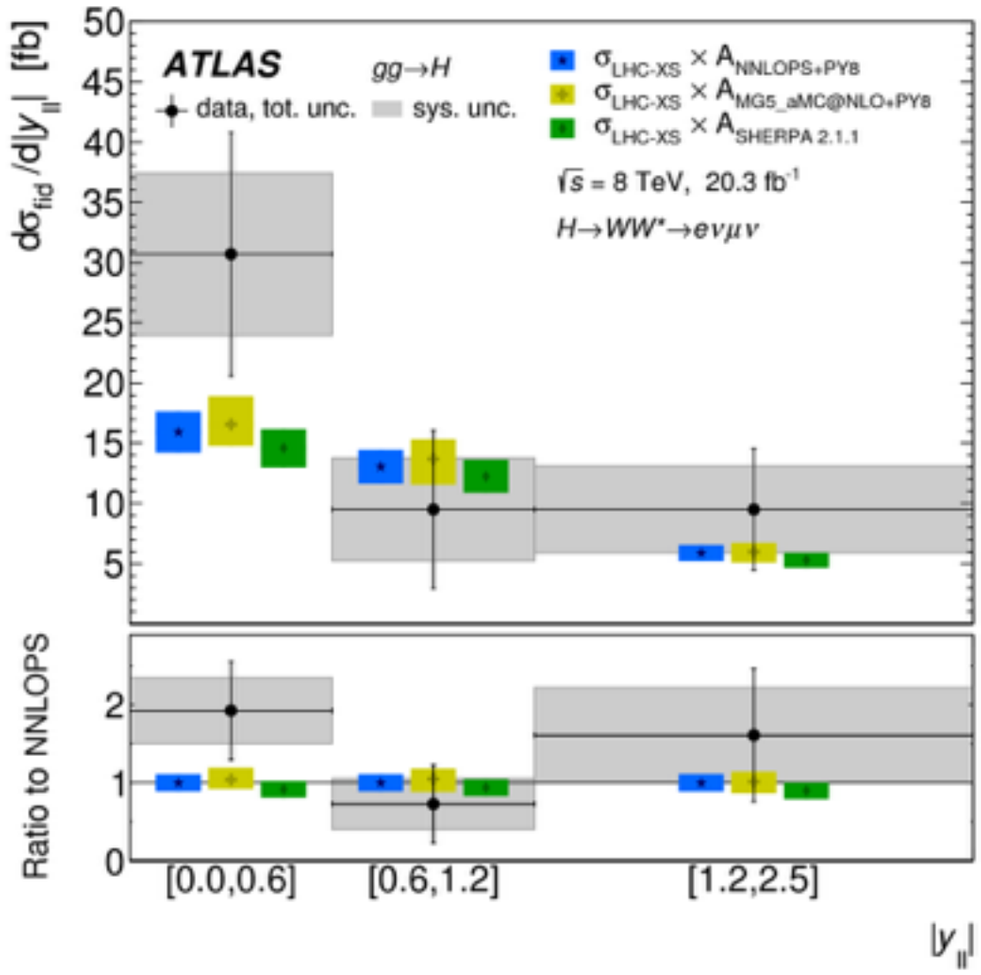
    - Total fiducial cross BR is obtained by summing the three bins on the Njet distribution

$$\sigma_{\mathrm{ggF}}^{\mathrm{fid}} = 36.0 \pm 7.2(\mathrm{stat}) \pm 6.4(\mathrm{sys}) \pm 1.0(\mathrm{lumi})\ \mathrm{fb}$$

- *The Run 2 data will significantly reduce the statistical uncertainties on the measurements. Future precise measurement will provide more stringent tests of the SM predictions of the Higgs boson properties*

Backup

Differential Cross Sections

- Longitudinal angle Y_{ll}: depends on QCD radiative corrections and PDF. Substantial uncertainties on gluon PDFs for low x, high x and high Q^2

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