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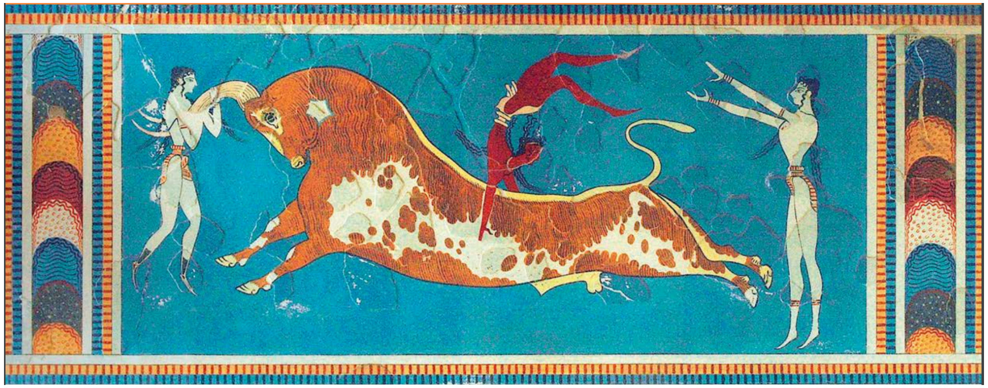
Higgs Physics at ATLAS

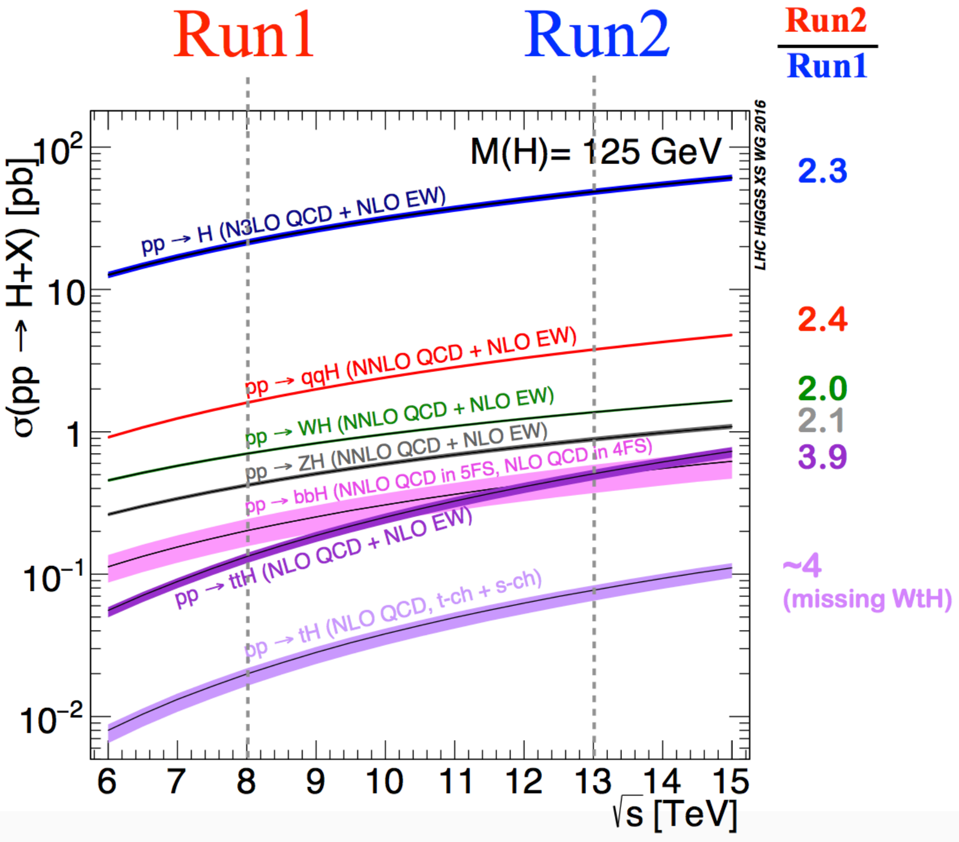
Diane Cinca

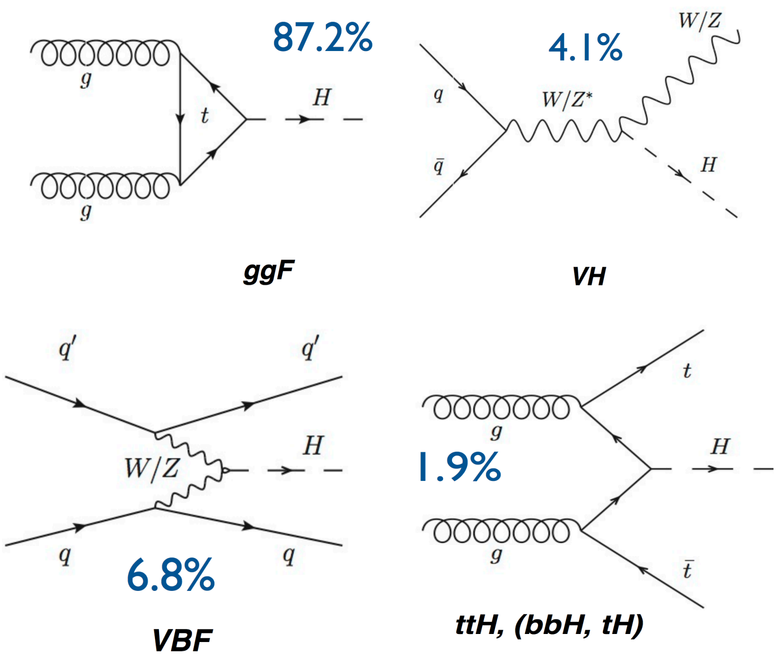
on behalf of the ATLAS collaboration



7th International Conference on New Frontiers in Physics (ICNFP 2018)

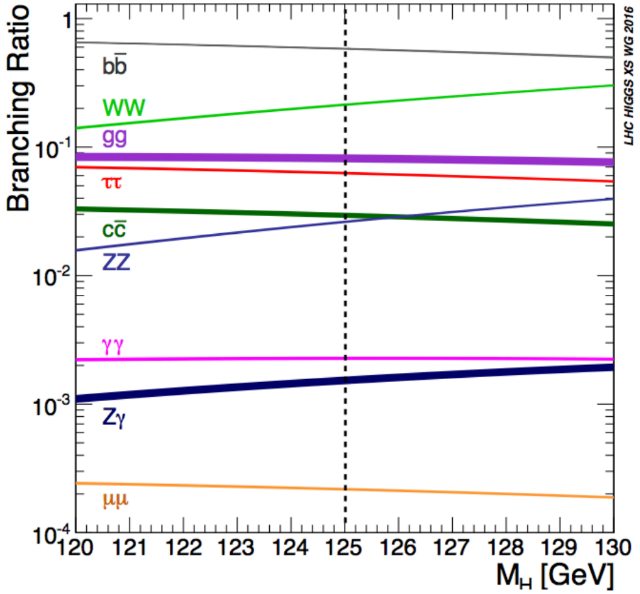
The Higgs at the LHC

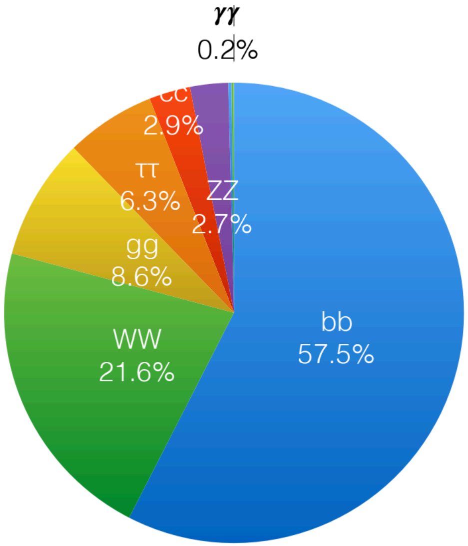




- ggF has the highest cross-section but can have large backgrounds
- VH, ttH and VBF topologies rely strongly on b-tagging algorithms
- ttH production is directly sensitive to t-Yukawa coupling

Higgs decays



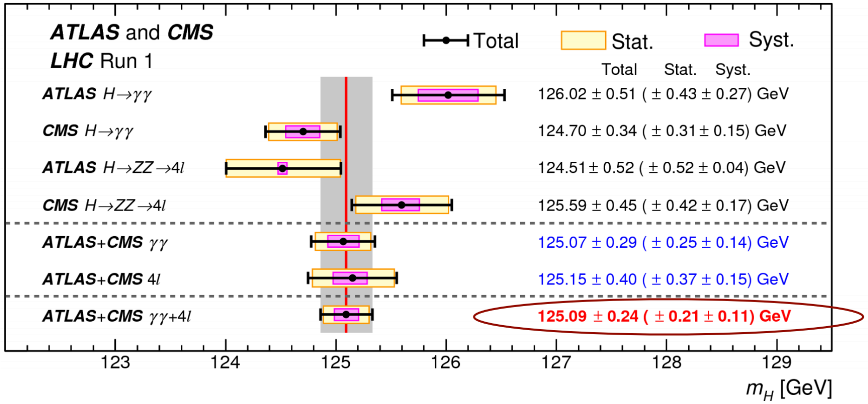


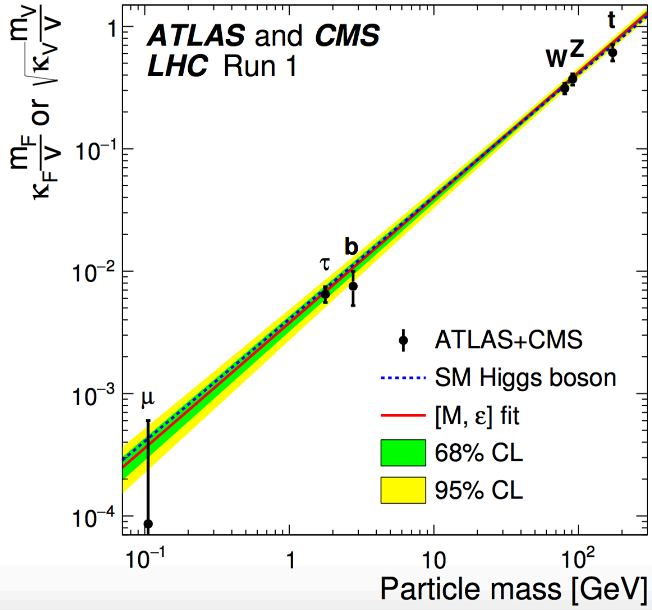
- Higgs branching ratios depend strongly on m_H in the SM.

- For mH = 125 GeV:
  - **bb** - largest BR with but very large backgrounds from multijets.
  - **WW**: large BR, poor mass resolution in the leptonic channels
  - **ττ** - missing energy from neutrinos, $m_{\tau\tau}$ reconstruction, background from jets faking τ
  - **ZZ**(→ 4l) – *discovery channel* – small BR but good mass resolution
  - **γγ** – *discovery channel* – small BR but good mass resolution
  - **cc** – small BR, dependent on c-tagging
  - **μμ** - rare process, analysis progressing towards observation

Legacy of Run1

PRL 114 (2015) 191803





- Run1:
  - Discovery of the Higgs boson
  - First measurement of its properties
- Run 2:
  - Establish discovery in remaining decay channels /production modes (e.g. H → bb, ttH, …)
  - Higher precision in Higgs boson properties measurements

JHEP 08 (2016) 045

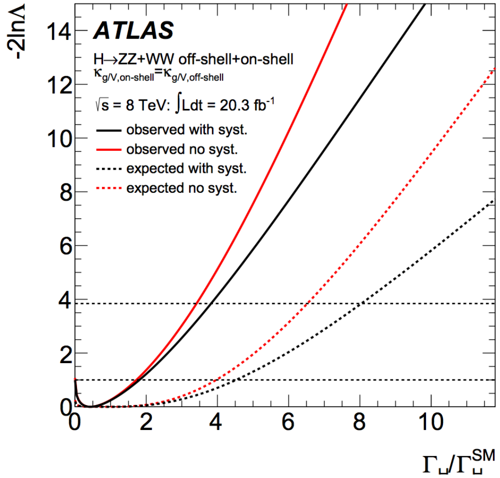
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

Run1 Higgs boson properties

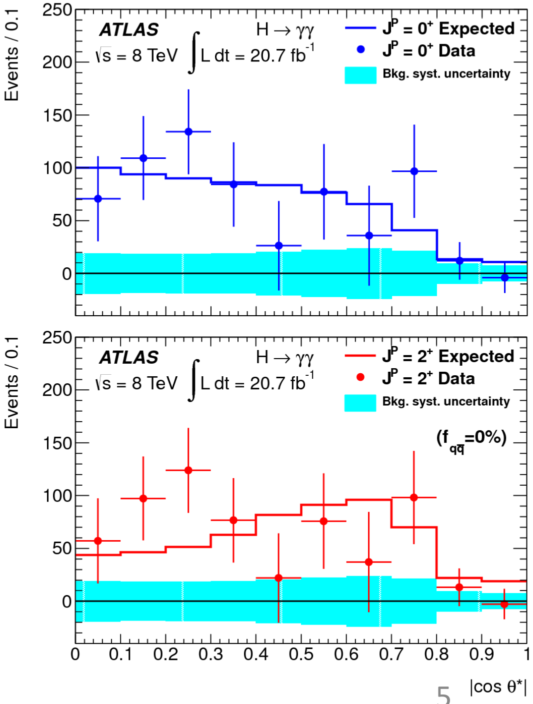
- Width **Eur. Phys. J. C (2015) 75:335**
  - SM predicts Γ_H ~ 4 MeV → too low to be measured before HL-LHC (resolution ~1-2 GeV)
  - Indirect constraint on Γ_H by studying off-shell Higgs boson production in diboson final states:
    - when $m_{VV} >> m_H$, the cross-section doesn't depend on Γ_H
    - by assuming same on-shell and off-shell couplings:

$$\mu_{off-shell} = \mu_{on-shell} \cdot \boxed{\Gamma_H} / \Gamma_{H,SM}$$

→ $\Gamma_H < 22.7$ MeV @ 95%CL (<33 MeV exp.)



- Spin/CP **Run-I: Eur. Phys. J. C75 (2015) 476**
  Run-II: CERN-EP-2017-288, JHEP03 (2018) 095
  - Spin and Parity of the Higgs boson measured in γγ/WW*/ZZ* final states using Run1 data (~25 fb^{-1}). SM Higgs boson hypothesis, JP = 0+, tested against alternative spin scenarios, which were excluded at 99.9% C.L.
  - In Run2 Higgs boson spin-CP tested, e.g. in γγ decays, with angle distributions of photons and jets sensitive to these properties



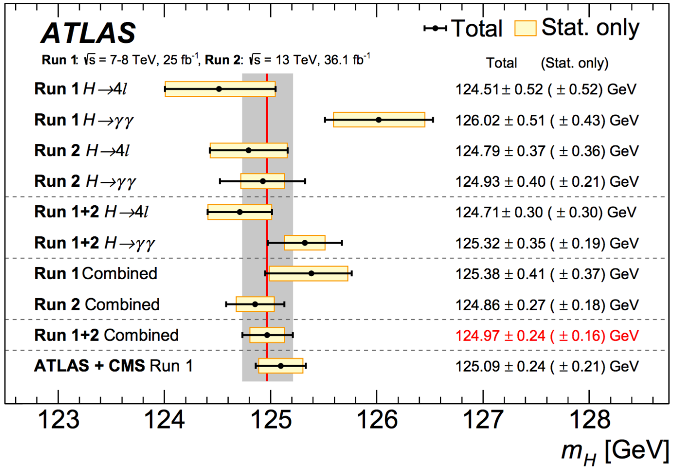
- All measurements compatible with a SM Higgs boson

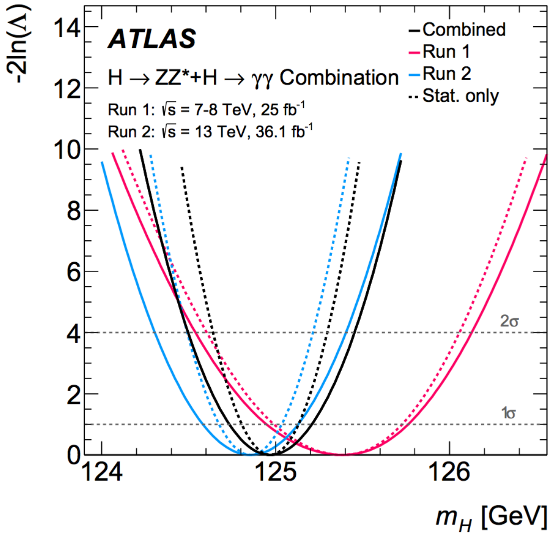
NEW

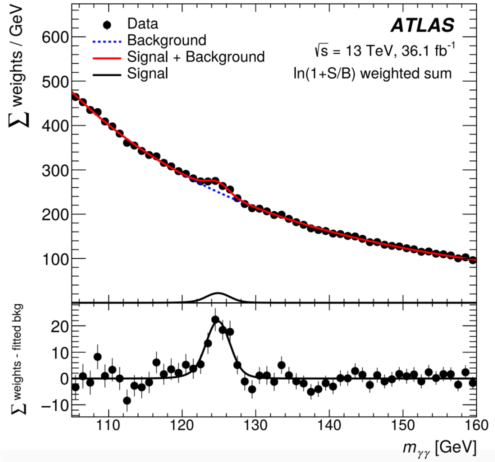
Higgs boson mass

CERN-EP-2018-085

Run1 + 36.1 fb^{-1}







mH = 124.97 +/- 0.24 GeV (Run1+Run2)

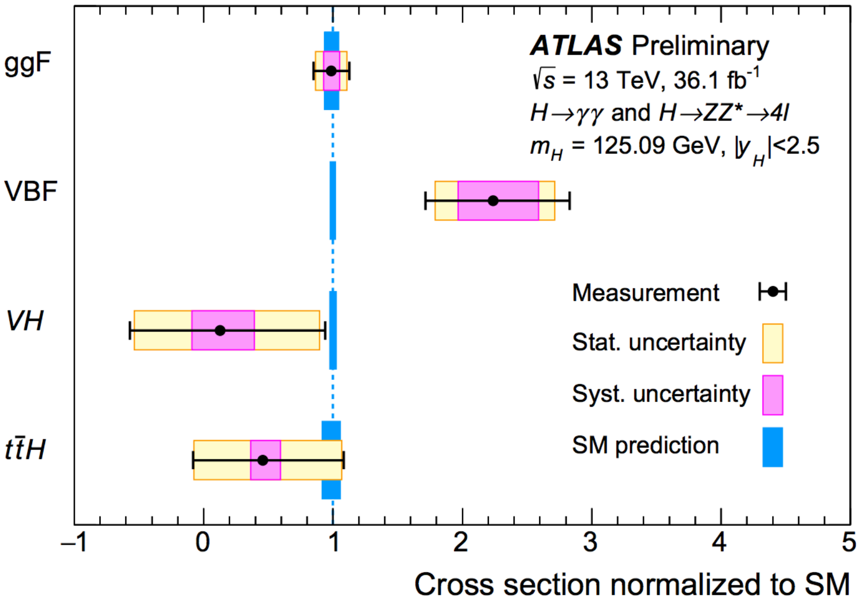
- Precise measurement with excellent detector performance : σ(m$_H$)/m$_H$ ~ 0.17%.

- While 4l analysis is still statistics dominated, γγ analysis is becoming systematics dominated. Improving the γγ measurement will require detailed understanding of the photon calibration.
- ATLAS current measurement has now a precision comparable to ATLAS+CMS Run-1 combination.

γγ+4l signal strength measurement

ATLAS-CONF-2017-047

36.1 fb^{-1}



- Global signal strength ATLAS+CMS Run1 (all channels included):

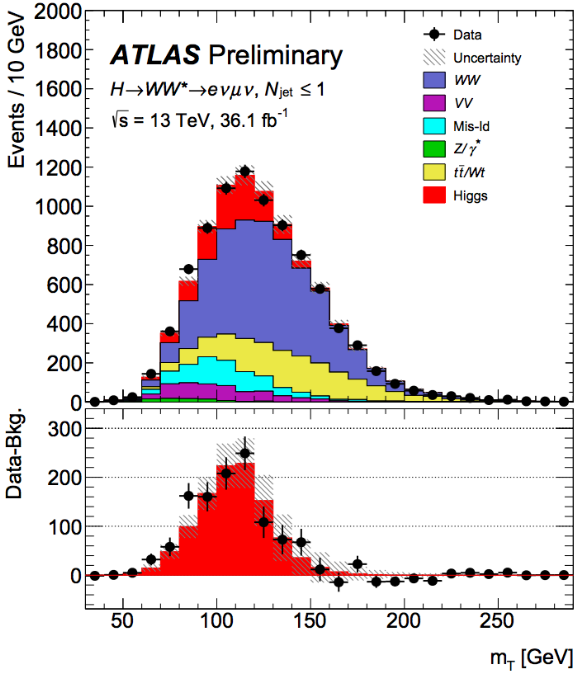
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

- ATLAS Run2 global signal strength (γγ+4l) has been measured to:

$$\mu = 1.09\ \pm 0.12 = 1.09 \pm 0.09\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{exp.})\ ^{+0.06}_{-0.05}\ (\text{th.}).$$

- Single experiment measurement is getting as good as Run1 combination.
- Systematic uncertainties are greater than statistical one for ggF and VBF.

WW* signal strength measurement



ATLAS-CONF-2018-004

36.1 fb^{-1}

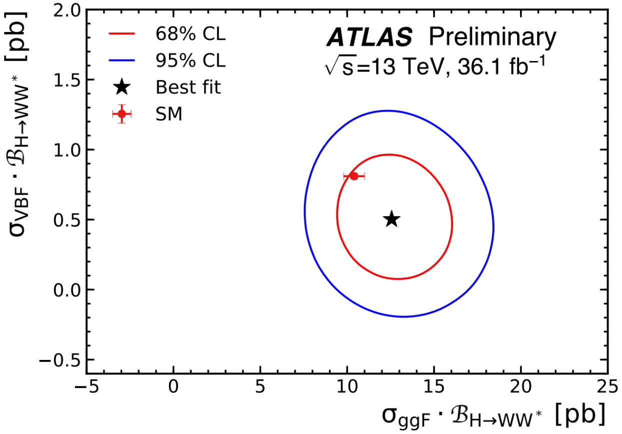
- Analysis performed in the $e\nu\mu\nu$ channel with single and dilepton triggers
- 3 categories: N_{jets} = 0, 1 (ggF), N_{jets}= 2 (VBF)

- mT variable as final discriminant for ggF, BDT for VBF (to enhance discrimination power btw ggF and VBF)

- Signal strength has been measured as:

$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW^*} = 12.6^{+1.3}_{-1.2}(\mathrm{stat.})^{+1.9}_{-1.8}(\mathrm{sys.})\ \mathrm{pb} = 12.6^{+2.3}_{-2.1}\ \mathrm{pb}$$
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.23}(\mathrm{stat.}) \pm 0.18(\mathrm{sys.})\ \mathrm{pb} = 0.50^{+0.30}_{-0.29}\ \mathrm{pb}$$

- Dominant systematics are JES, JER and b-tagging eff.
- Both measurements are compatible with Standard Model.
- WW* is observed with 6.3σ (ggF+VBF)



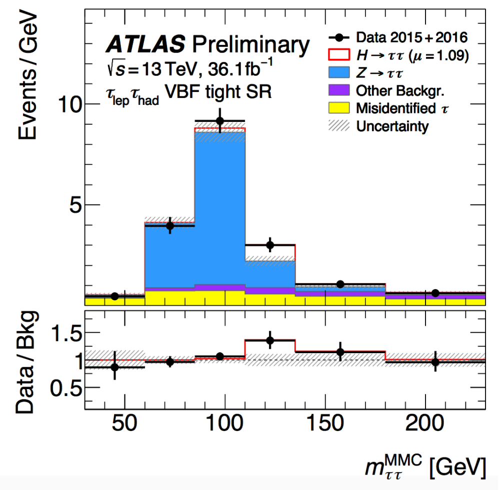
NEW

H→ττ observation

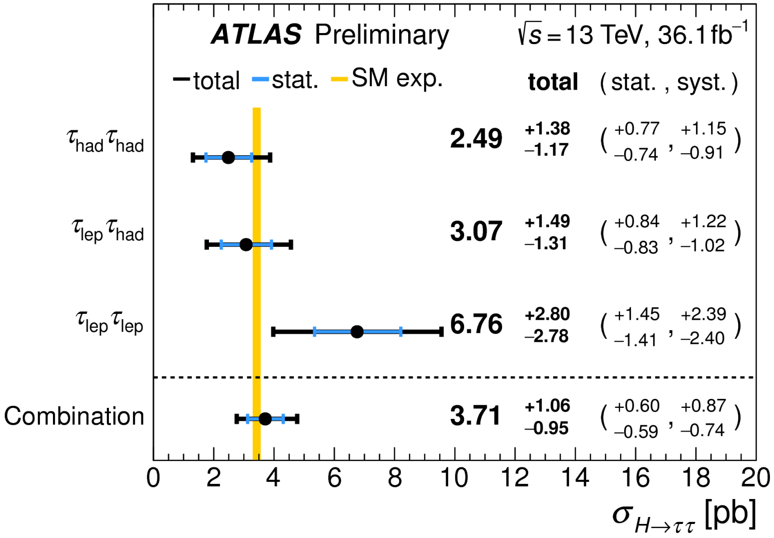
ATLAS-CONF-2018-021

36.1 fb^{-1}

- Use all combinations of hadronic and leptonic τ decays in 2 categories: VBF and boosted (mostly ggF)
- Cut-based analysis using fit to mττ distribution in 13 signal regions
- Estimate of Z→ττ using Sherpa NLO
- Largest backgrounds from Z+jets and from jets faking τ (W+jets and multi-jet) (in $t_{had}\tau_{had}$ category)
- Largest uncertainties: data and MC statistics, signal modelling and jets



- Obs. (exp.) significance of 4.4σ (4.1σ)
- Combination with Run 1: obs. (exp.) sign. of 6.4σ (5.4σ)
- Combined measurement of cross sections for VBF and ggF productions:
  - σ_{ggF} = 3.0 ± 1.0 (stat.) -1.2+1.6 (syst.) pb
  - σ_{VBF} = 0.28 ± 0.09 (stat.) ± 0.10 (syst.) pb
- Agreement with SM prediction within 1σ



NEW

Search for H-> bb (VBF)

CERN-EP-2018-140

30.6 fb^{-1}

- 3 channels:
  - 2 central b-tagged jets + >= 1 fw VBF jet (qqH)
  - 2 central b-tagged jets + 2 central VBF jets (qqH)
  - 1 γ + 2 central b-tagged jets + 2 VBF jets (new channel qqHγ, suppresses large non-resonant background, not sensitive to ggF)

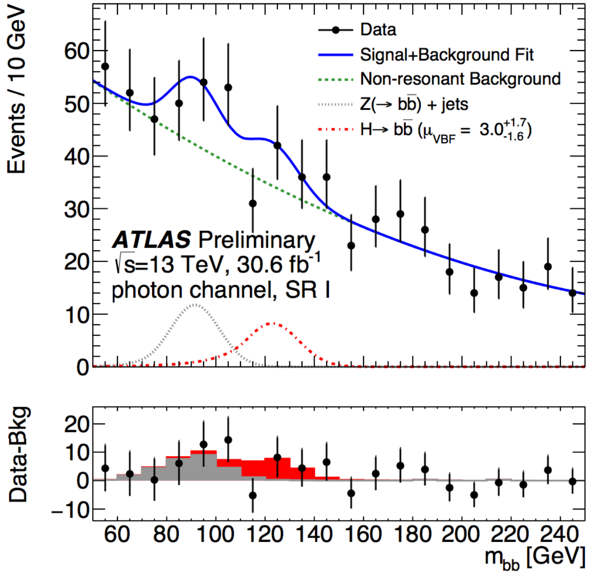
- Use dedicated VBF triggers to record events (separate trigger for central and forward jets)
- Dedicated BDT (based on jet kinematics) in each channel to define SRs, m_{bb} as final discriminant

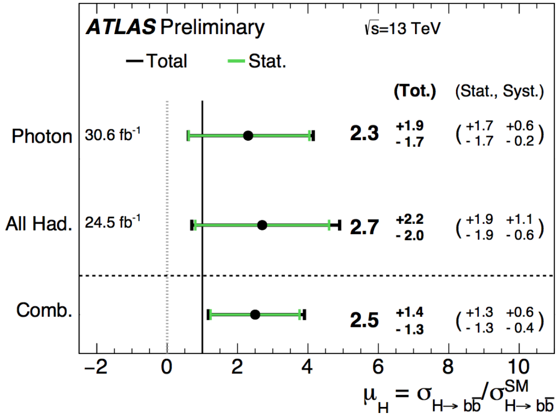
- Fit analytical background function to data in sidebands
- Z(→bb)+jets has large contribution in low m_{bb} and affects bkg estimation. Left floating in the different BDT regions.

- Largest uncertainties: jet energy scale and resolution, Z estimate, signal modelling and flavour tagging

- Obs. (exp.) significance of 1.9σ (0.9σ) for inclusive Higgs
- Obs. (exp.) limits: $\mu_{Hbb} < 4.8$ (2.5)

  $\mu_{VBF} < 5.9$ (3.0) at 95% C.L.





Evidence for H-> bb (VH)

JHEP12 (2017) 024

36.1 fb^{-1}

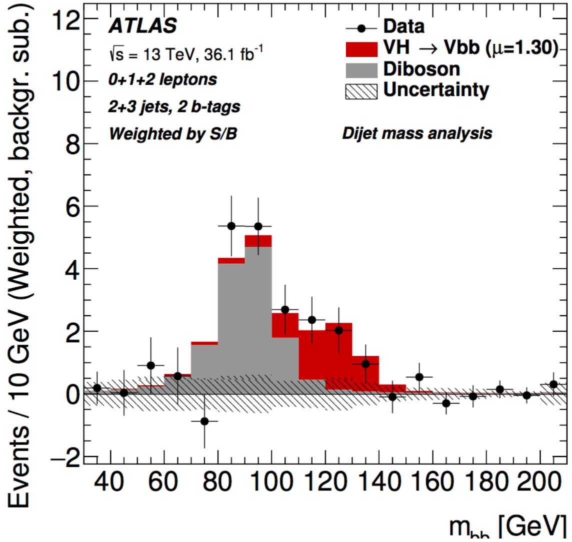
- Require 2 b-tagged jets + 0 (Z→νν), 1 (W→lν) or 2 (Z→ll) leptons
- Dedicated b-jet calibration to improve m_{bb} resolution
- Use BDT to classify events in all signal regions

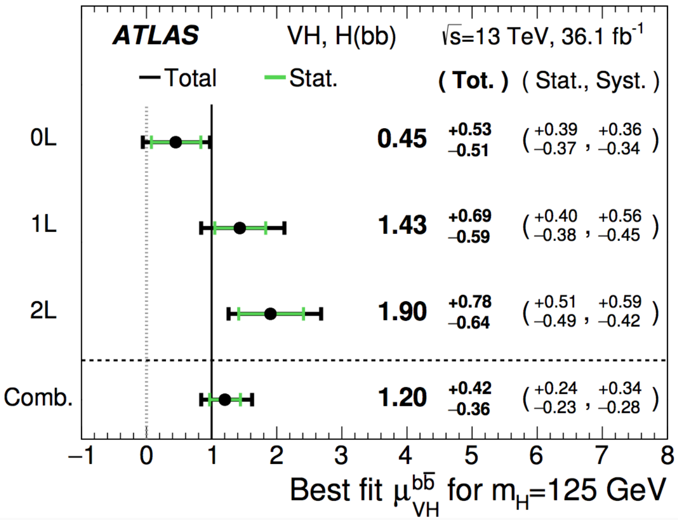
- Largest background from Z+HF (0- and 2-lepton) and ttbar (1-lepton)
- Irreducible background from VZ with Z→bb
- Diboson analysis targeting VZ(→bb) as validation for VH result. VZ signal strength measured as:

$$\mu_{VZ} = 1.11^{+0.12}_{-0.11}(\text{stat.})^{+0.22}_{-0.19}(\text{syst.})$$

- Obs. (exp.) sign. of 3.5σ (3.0σ)
- Combination with Run 1:

  obs. (exp.) significance of 3.6σ (4.0σ)



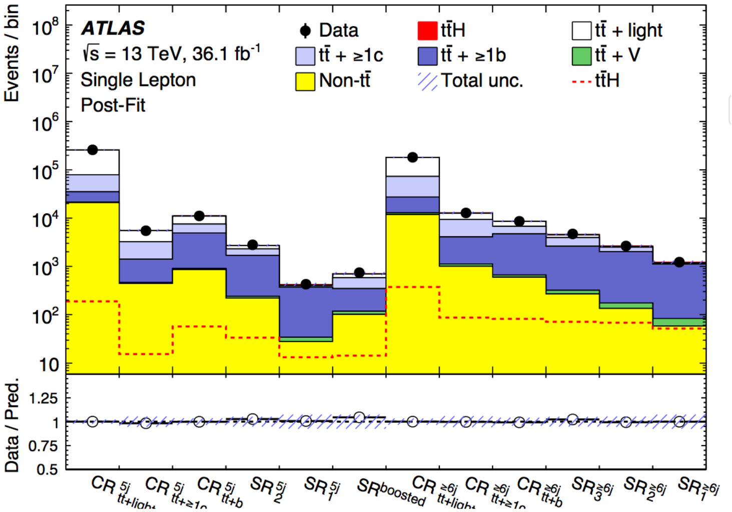


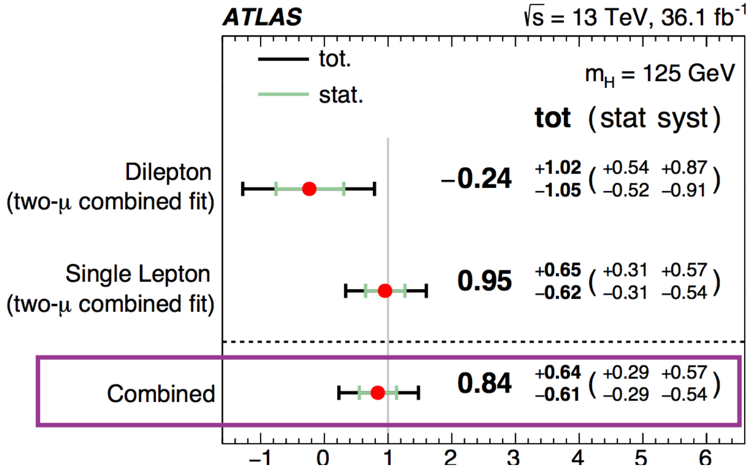
Search for ttH, H->bb

Phys. Rev. D 97 (2018) 072016

36.1 fb^{-1}

- Target topologies with 1-2 leptons + 4 b-jets
- Largest background from ttbar + HF jets
- Categorise events by N_{lep}, N_{jets} and b-tag score into multiple signal and control regions
- Use BDT to associate jets to top quark and Higgs candidates + dedicated BDTs for each signal region to classify signal and background events (using MEM)
- Extract signal from combined likelihood fit to MVA distribution in all signal and control regions
- Largest uncertainties: **ttbar+HF modelling (46%)**, data and MC statistics, and flavour tagging
- Observed significance: 1.4 σ (expected 1.6 σ)
- The analysis requires both experimental and theoretical improvements on the ttbar+HF modelling



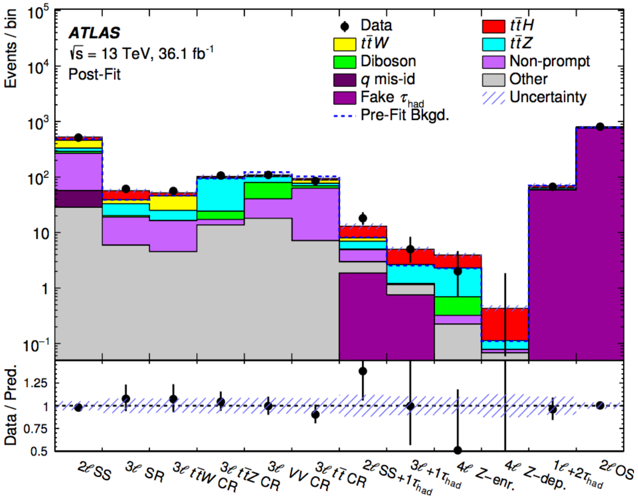


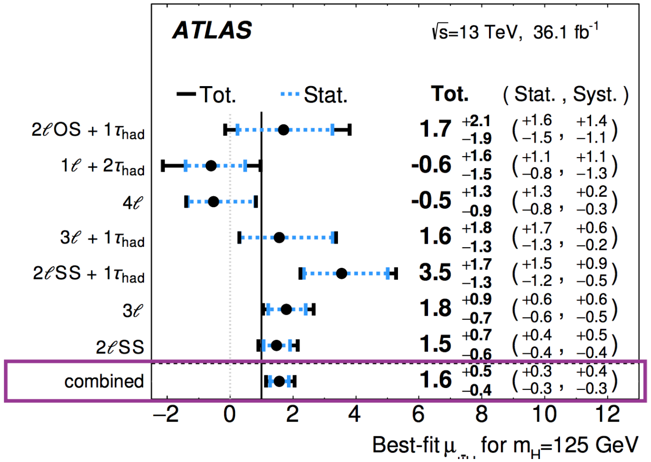
Search for ttH, H->ML

Phys. Rev. D 97 (2018) 072003

36.1 fb^{-1}

- Target ttH + all Higgs decays with leptons in final state: H->ττ, H→WW* and H→ZZ*
- Categorise events based on number of hadronic τ and light leptons
- Large backgrounds from ttV, non-prompt leptons and jets faking τ depending on region
- Dedicated BDTs to reject non-prompt leptons and charge mis-identification of electrons.
- Dedicated control regions for ttV backgrounds.
- Largest uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate.
- Obs. (exp.) significance of 4.1σ (2.8σ) for mH = 125 GeV





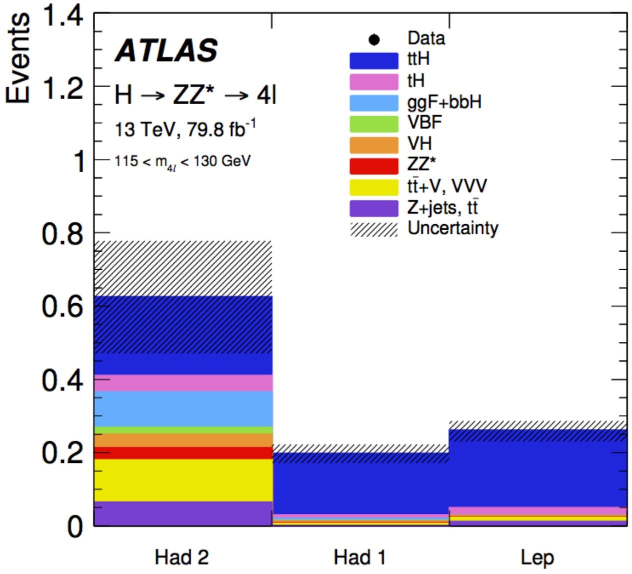
NEW

Search for ttH, H→ZZ→4l

CERN-EP-2018-138

80 fb^{-1}

- Update with 79.8fb^{-1}
- Improved sensitivity by analysis improvements like separation of leptonic and hadronic categories with BDT (in hadronic categories)
- Simultaneous fit of all categories
- No event was observed for an expected of 1.2σ
- Observed limit < 900 (68% C.L.)



NEW

Search for ttH, H→γγ

CERN-EP-2018-138

80 fb^{-1}

- Update with 79.8fb^{-1}

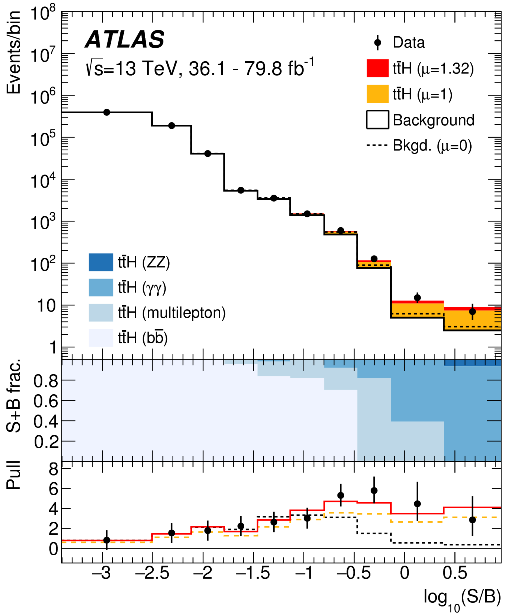
- Analysis strategy:
  - Categorisation based on ttbar decay - leptonic (≥1l) and hadronic (0l) categories
  - Further categorisation based on XGBoost BDT discriminant value - 4 hadronic and 3 leptonic categories (events w/ low BDT scores rejected).

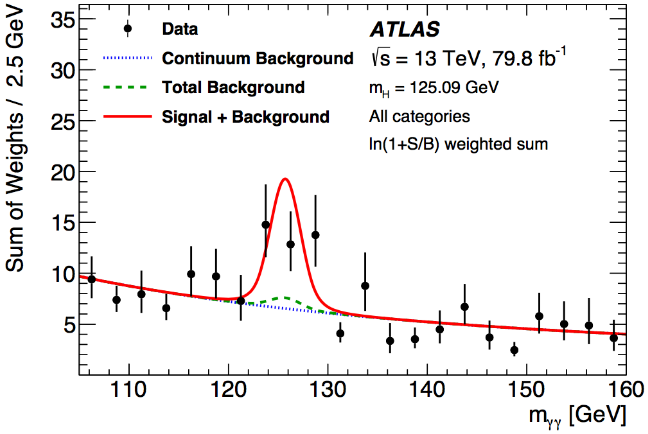
- Input variables to XGBoost BDT (mass independent variables):
  - 4-vector information of photons (pT/mγγ), jets, MET (both cat.), lepton(s) (lep cat), and b-tag (had cat)
  - Training ttH (from simulation) vs. main background - γγ, ttγγ (from data CRs), other H (from simulation).

→ Improvement of 50% in sensitivity

- Main systematics:
  - ttH parton shower model (8%)
  - photon isolation, energy resolution & scale (8%)
  - Jet energy scale & resolution (6%)

- Observed significance: 4.1 σ (expected 3.7 σ)



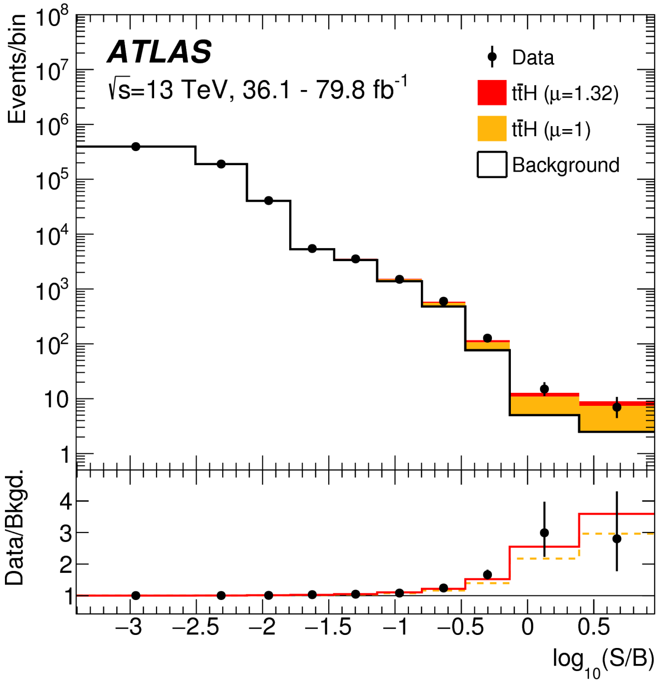


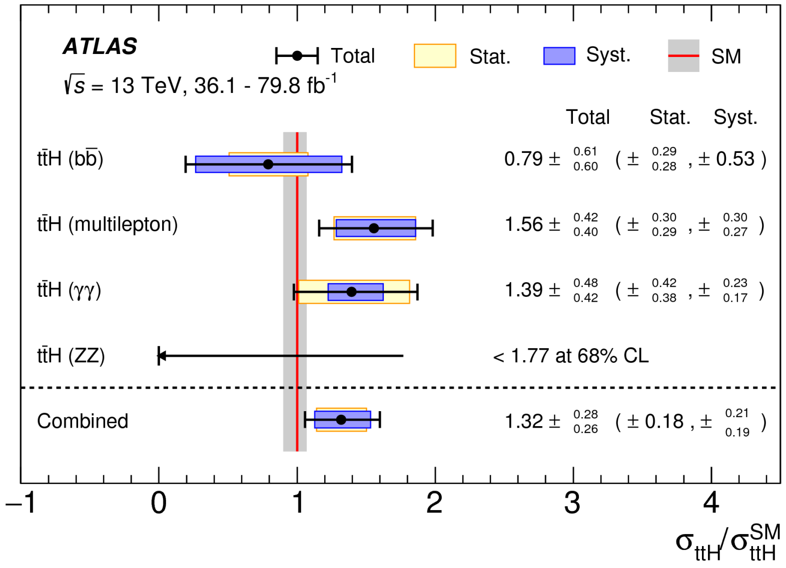
NEW

ttH observation

CERN-EP-2018-138

Run1 + 36.1 – 80 fb^{-1}





- Combine measurements of all final states sensitive to ttH: H→bb, H→ττ, H→WW*, H→ZZ* and H→γγ in Run1 and Run2.

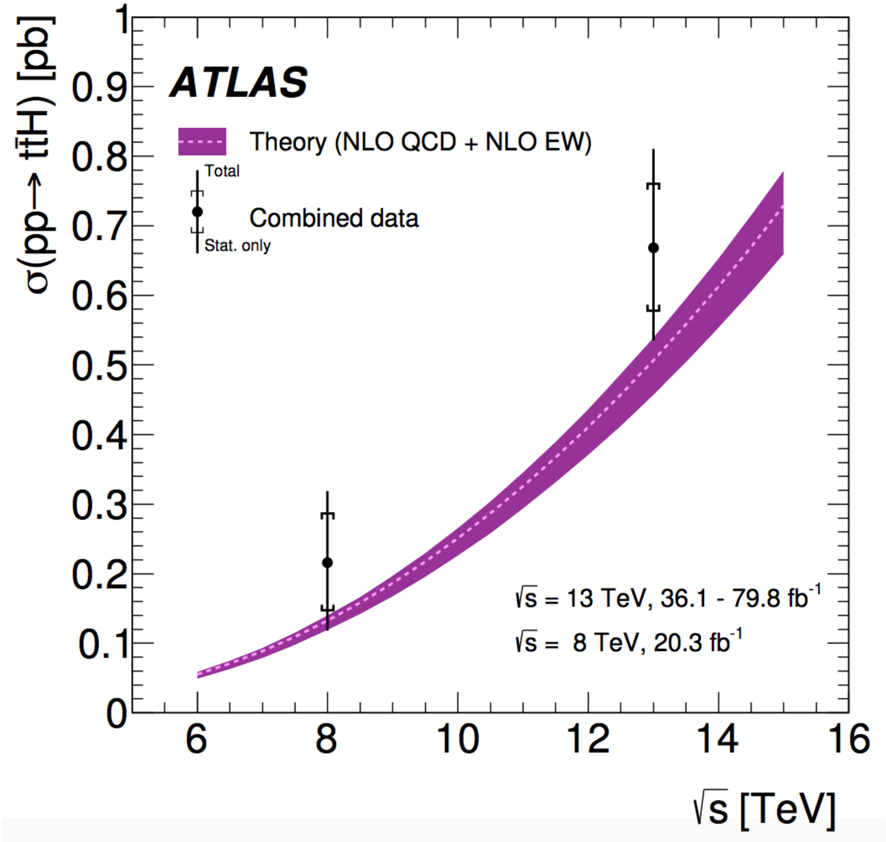
- Observation of ttH production with:
  - Run-2 alone: 5.8 σ significance (4.9 σ expected)
  - Run-1 and Run-2 combined: 6.3 σ significance (5.1 σ expected)

ttH XS measurement

NEW

CERN-EP-2018-138

Run1 + 36.1 – 80 fb^{-1}



Dominant systematics

- ttbar+HF modelling (9.9%)
- ttH modelling (6%)
- Non-prompt leptons (5.2%)

ttH (13TeV) = 670 ± 90(stat) + 110 - 100(sys) fb
ttH,SM (13TeV) = 507 + 35 - 50 fb

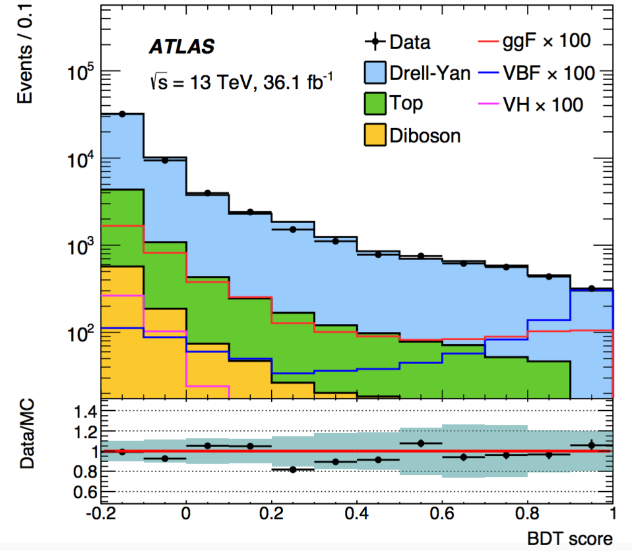
Compatible with the SM prediction

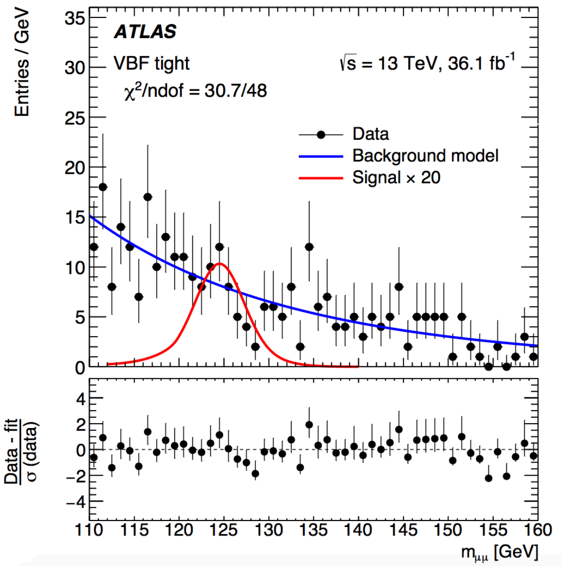
Search for H→μμ

PRL 119(2017) 051802

36.1 fb^{-1}

- Loose event selection requiring two isolated OS muons and veto b-jets
- Use BDT to select events in 2 VBF categories (m_{jj}, $p_T^{\mu\mu}$, $|\Delta\eta jj|$, ΔRjj, etc.)
- All other events are categorised in 6 ggF categories based on cuts on $p_T^{\mu\mu}$ and $|\Delta\eta\ \mu|$
- Large background from Drell-Yan and smaller background from top quarks
- Signal and background described by analytical functions, fit to di-muon mass distribution in all signal regions
- Obs. (exp.) upper limit on $\mu < 3.0$ (3.1) at 95% C.L.
- Combined with Run 1 data: $\mu < 2.8$ (2.9) at 95% C.L.





Search for H->cc

CERN-EP-2017-334

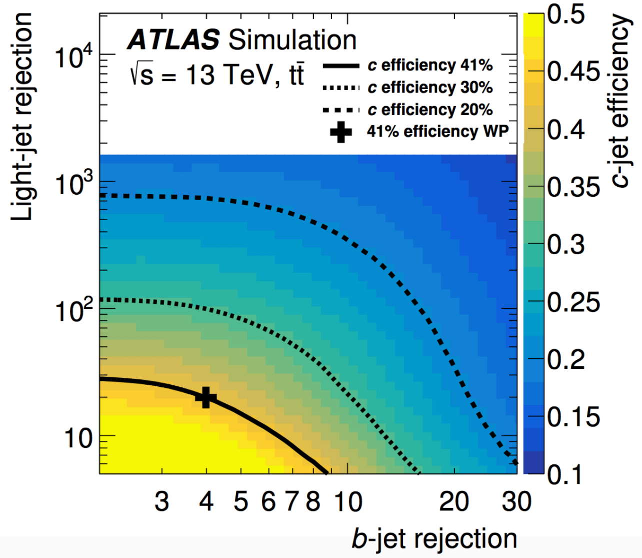
36.1 fb^{-1}

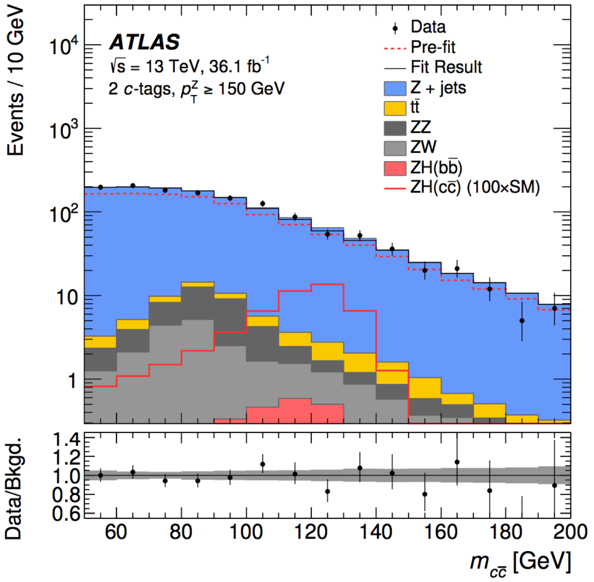
- Hcc coupling was previously searched with $J/\psi\ \gamma$ channel in Run 1.
- Search for the coupling with c-tagging is new.

- Similar approach as search for VH, $H\rightarrow bb$
- 1 or 2 c-tagged jets and 2 leptons with $81 < m_{ll} < 101$GeV

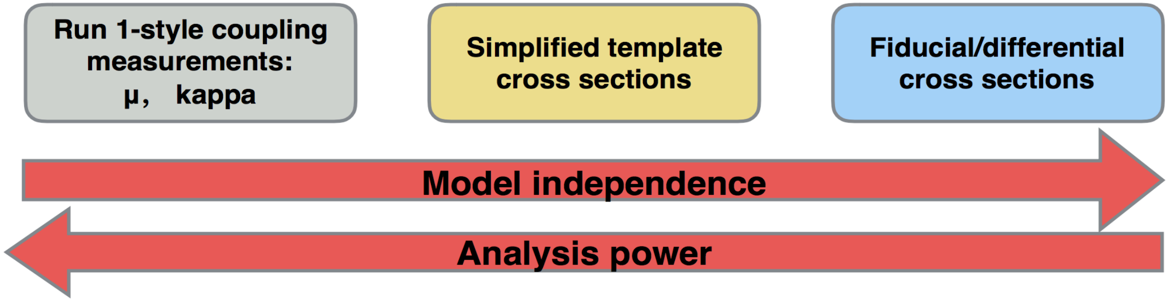
- Largest background from Z + HF jets (used as calibrating tool), other backgrounds from ttbar and diboson
- Maximum likelihood fit to m_{cc} distribution in 4 signal regions based on Nc-jets and pT V
- Largest uncertainties: flavour tagging and data statistics

- Measurement of irreducible background from ZV with a significance of 1.4σ (2.2σ): $\mu_{ZV} = 0.6 - 0.4 + 0.5$
- Obs. (exp.) upper limit on $\mu_{Hcc} < 110$ (150) at 95% C.L.





Higgs couplings



Run 1-style coupling measurements: μ, kappa

Simplified template cross sections

Fiducial/differential cross sections

Model independence

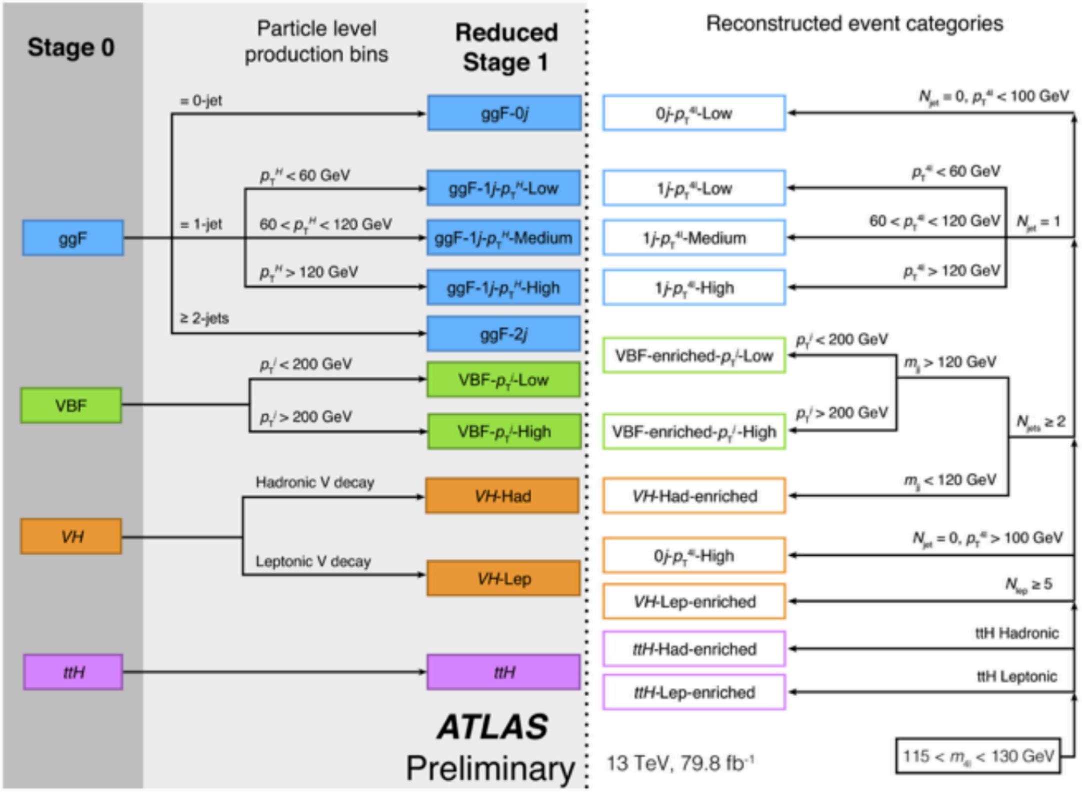
Analysis power

ggF→

VBF→

VH→

tt̄H→



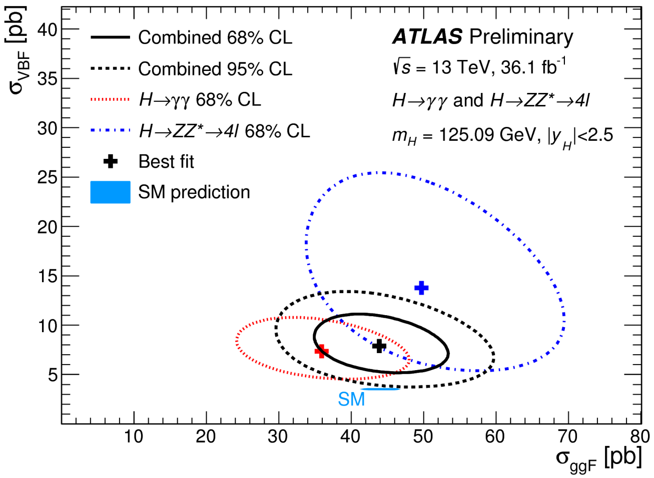
Kappa framework

ATLAS-CONF-2017-047

36.1 fb^{-1}

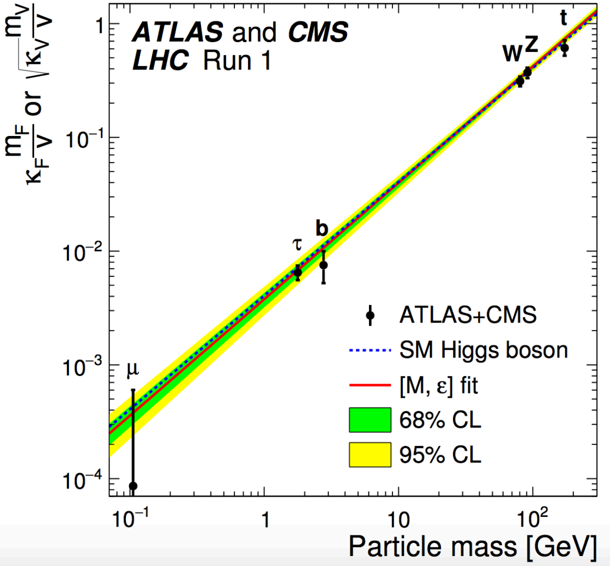
- Assumptions:
  - Single state, spin 0 and CP-even.
  - Narrow-width approximation: $(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \dfrac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
- Methodology: parameterize deviations with coupling scale factors $\{\kappa_x\}$

Model with vector boson and fermion coupling separation



- Two fundamental options:
  - Allow undetected/invisible decays or only SM decays
  - Allow BSM particles in the loops or resolve the loop assuming SM field only
- Many models present in the combination
- Good agreement with the SM predictions

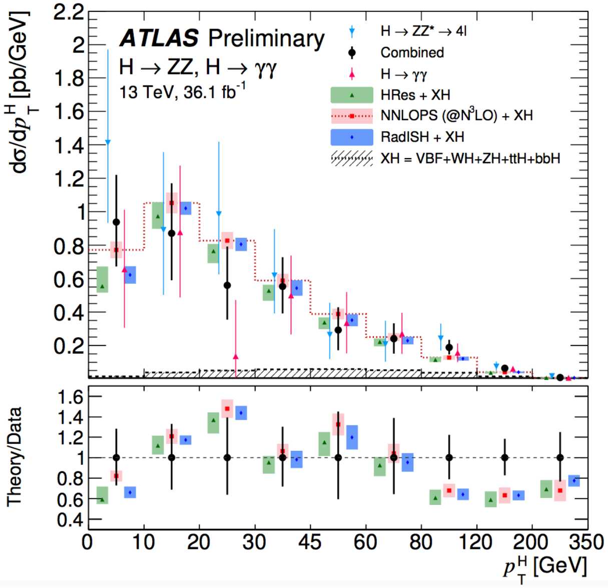
Mass dependence



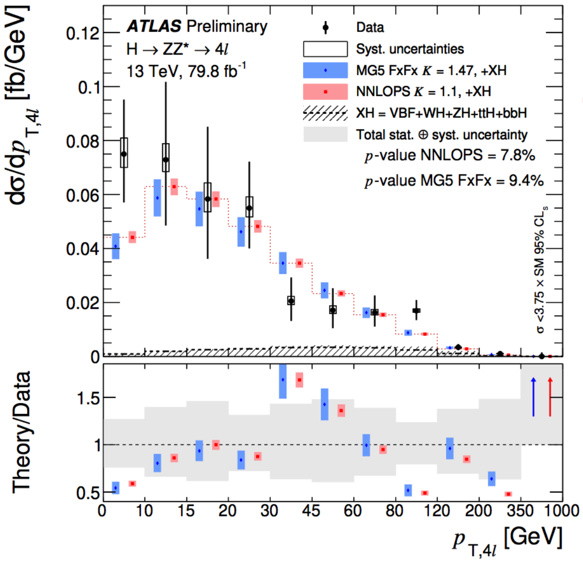
Differential cross section

ATLAS-CONF-2018-002 36.1 fb^{-1}

ATLAS-CONF-2018-018 80 fb^{-1} NEW



- Kinematic distributions (Higgs pT, y, number of jets & jet pT) are important probes:
  - To check the validity of the perturbative QCD
  - To understand/improve the Monte Carlo generators.



NEW

- Higgs pT and jets pT of are also sensitive to physics beyond the Standard Model

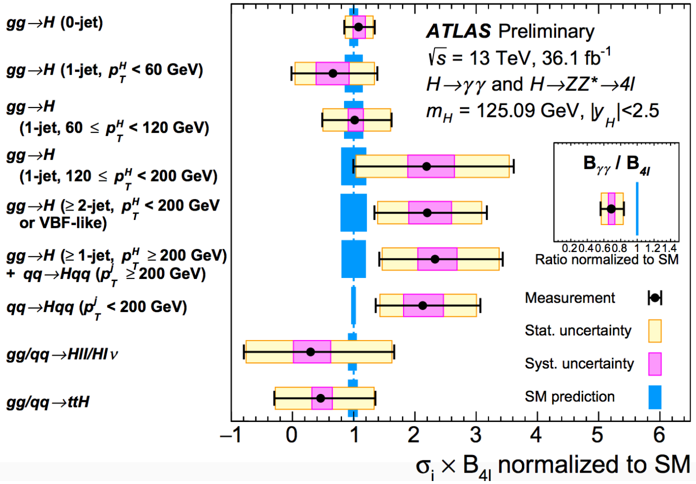
- All measurements are in agreement with SM predictions.

Simplified Template Cross Section (STXS)

ATLAS-CONF-2017-047 | 36.1 fb^{-1}

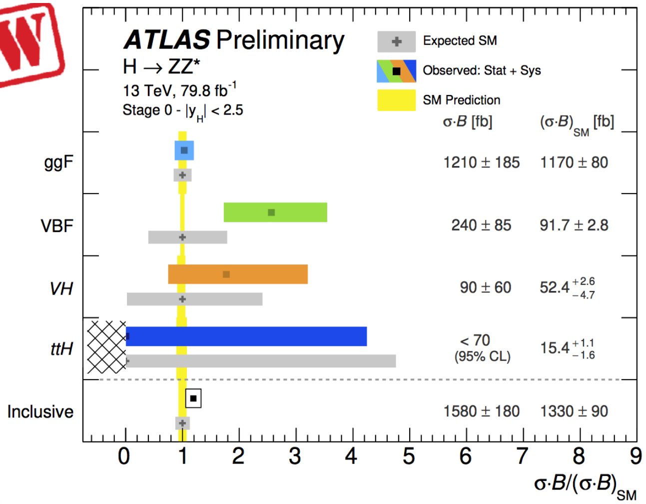
ATLAS-CONF-2018-018 | 80 fb^{-1} NEW

- STXS targets maximum sensitivity while keeping theoretical dependence as small as possible. New approach compared to Run1.



- Cross sections can be split by very simple fiducial regions for each production mode & common between ATLAS, CMS, and theory.
- Inclusive in Higgs decays, designed for combination

NEW

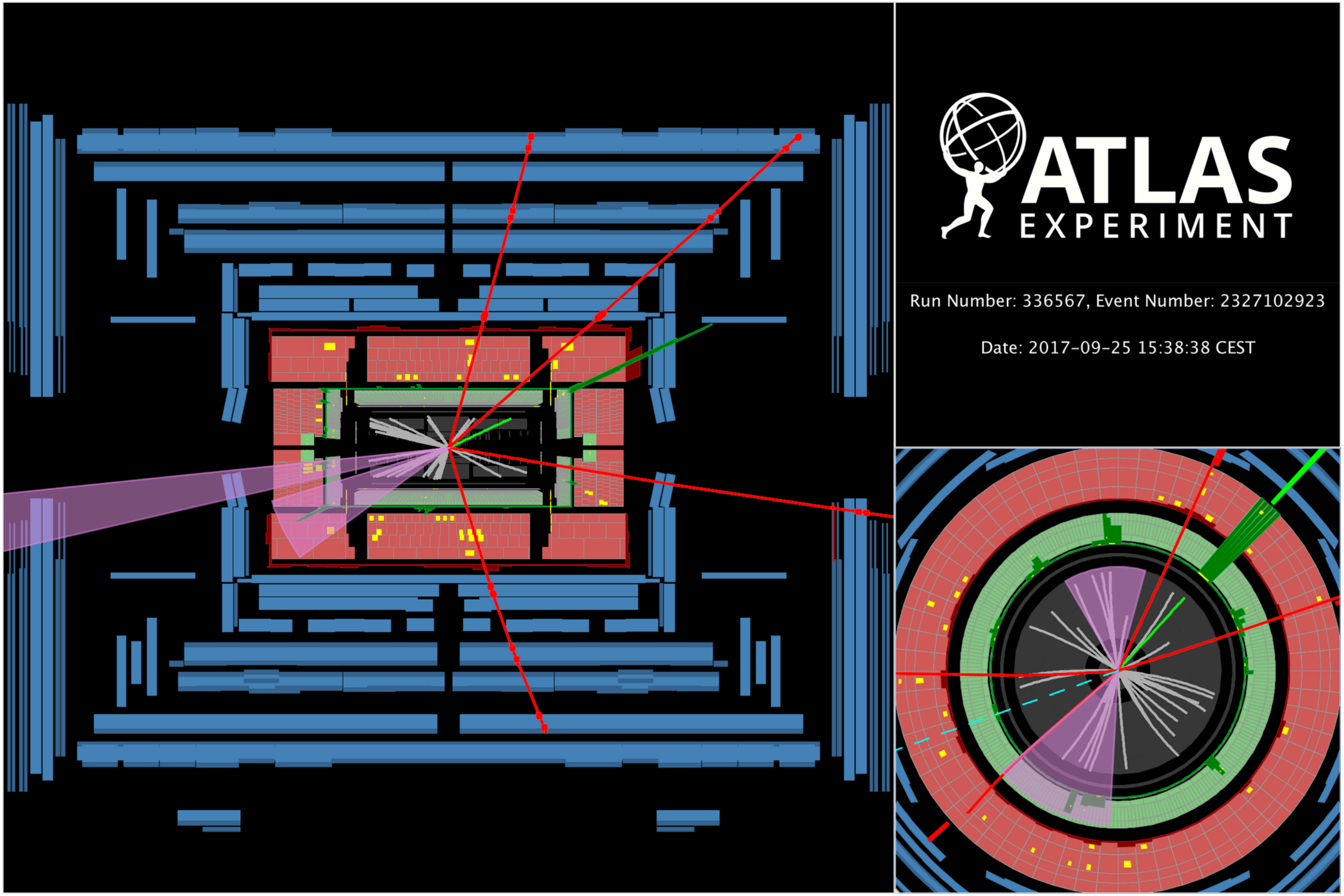


- Latest result from H→ZZ*→4l channel:

  stage 0 inclusive $(\sigma^*B)_{SM}$ = 1330 ± 90 fb

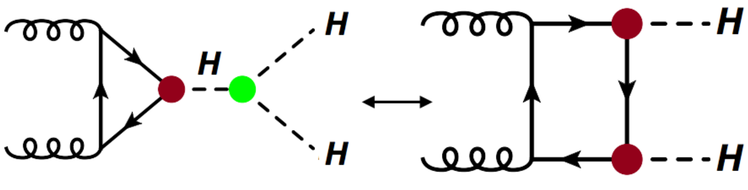
80 fb^{-1}

NEW



W(→eν)H(→4μ) candidate, S/B ~7, m_{4l} = 124.6 GeV

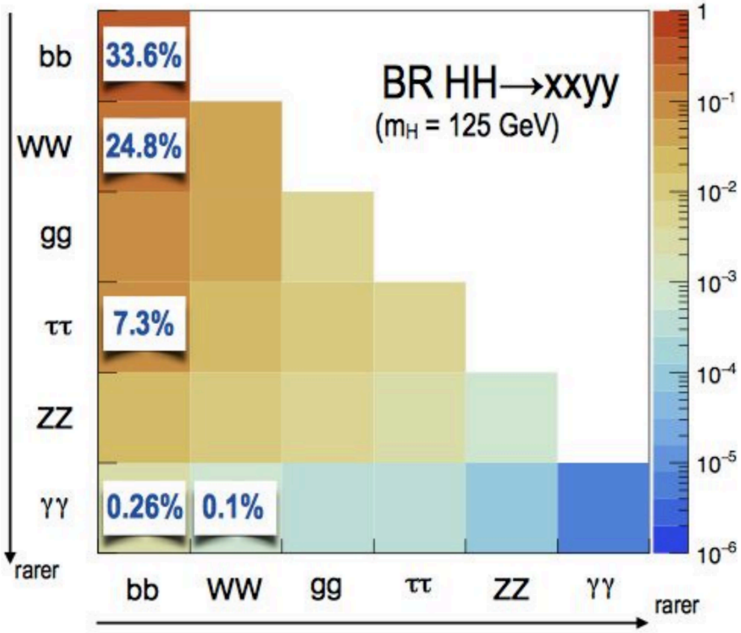
Di-Higgs search



Destructive Interference

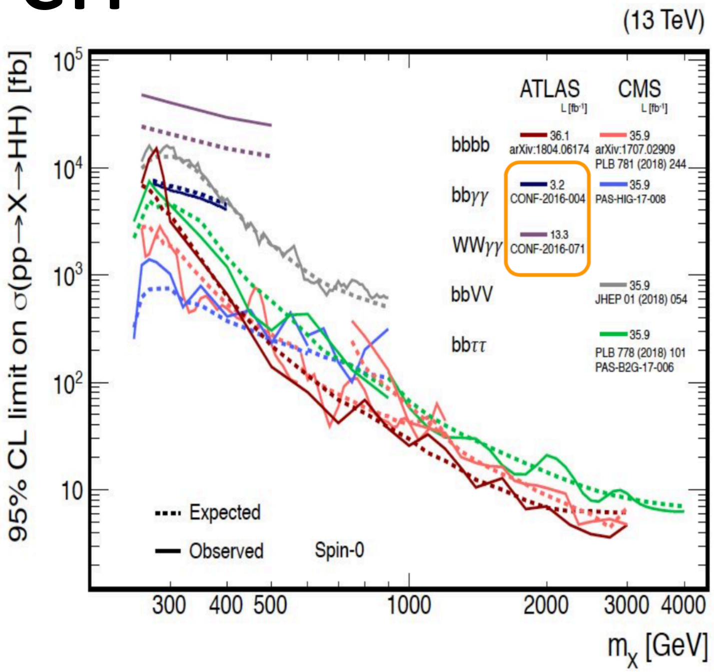
- SM cross section @ 13 TeV not accessible with the Run2 data but we need to estimate challenges and future sensitivities.

- BSM effects lead to:
  - the presence of resonant HH process.
  - the enhancement of the non-resonant HH production cross section and the modification of the kinematics of the decays.
- Very different theoretical motivation, but similar experimental signature

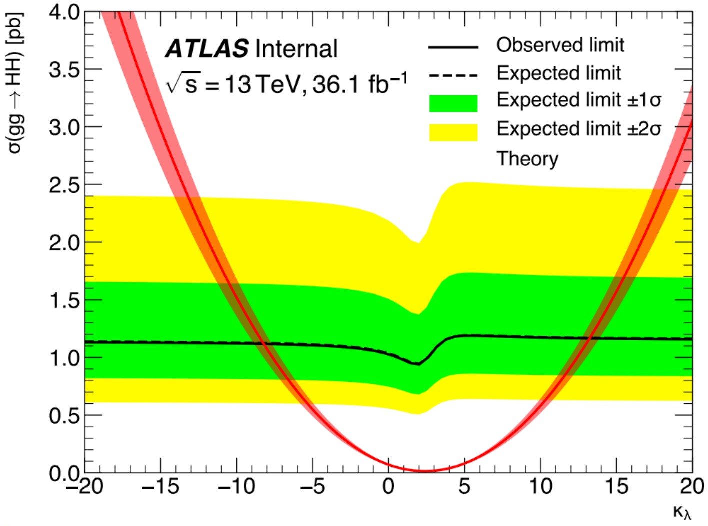


Di-Higgs search

- bbbb : high BR but large multijet background (dominant at high mass)
- bbVV: high BR, large irreducible ttbar background
- bbγγ and bbττ: similar sensitivity at low mass
- WWγγ: new result



Channel	σ/σ_{SM}		
bbbb	< 13	CERN-EP-2018-029	36.1 fb^{-1}
bbγγ	< 22	HIGG_2016_15	36.1 fb^{-1}
WWγγ	< 230	HIGG_2016_20	36.1 fb^{-1}



- bbγγ study: $-8.2 < \kappa_\lambda < 13.2$ @ 95% CL

Conclusion

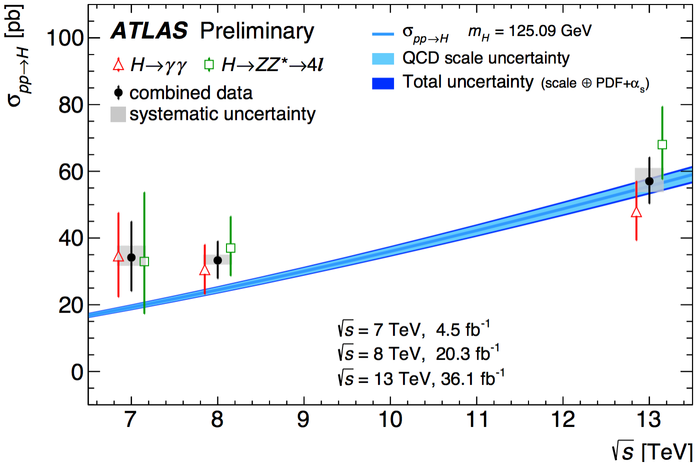
- The Higgs discovery at Run1 opened a new field both for precise measurements and new physics search.
- Already many important results in Run2:
  - More details & improved precision in cross section & coupling measurements
  - Evidence for H→bb
  - Observation of H→ττ
  - Observation of ttH production
  - Uncertainty on the signal strength of H→μμ is below SM strength
- More to come with the full Run 2 data to be taken until the end of this year.

- Run3 is coming next with new potential of discoveries and precision measurements. Stay tuned !

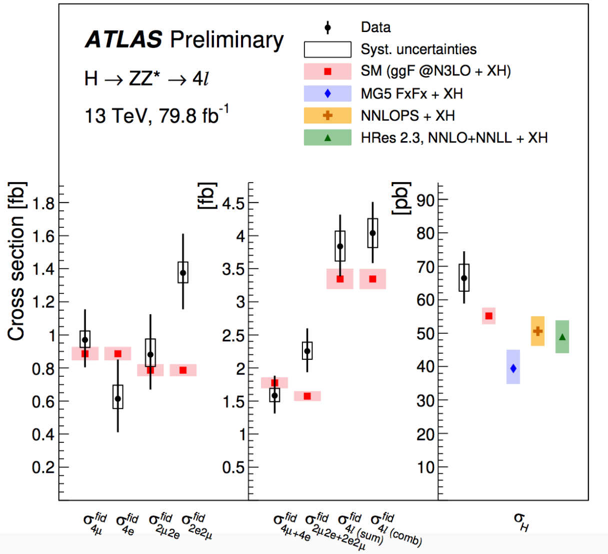
BACKUP

Fiducial cross sections: H->yy/ZZ

ATLAS_CONF_2017_047



σ_{fid} [fb]/13TeV	H→γγ	H→ZZ
ATLAS	55±9(stat)±4(syst)±0.1(th)	$3.62\pm0.5(\mathrm{stat})^{+0.25}_{-0.20}(\mathrm{sys})$
SM	64±2	2.91±0.13



All measurements (in different fiducial volumes) agree well with SM predictions.

WW* signal strength measurement

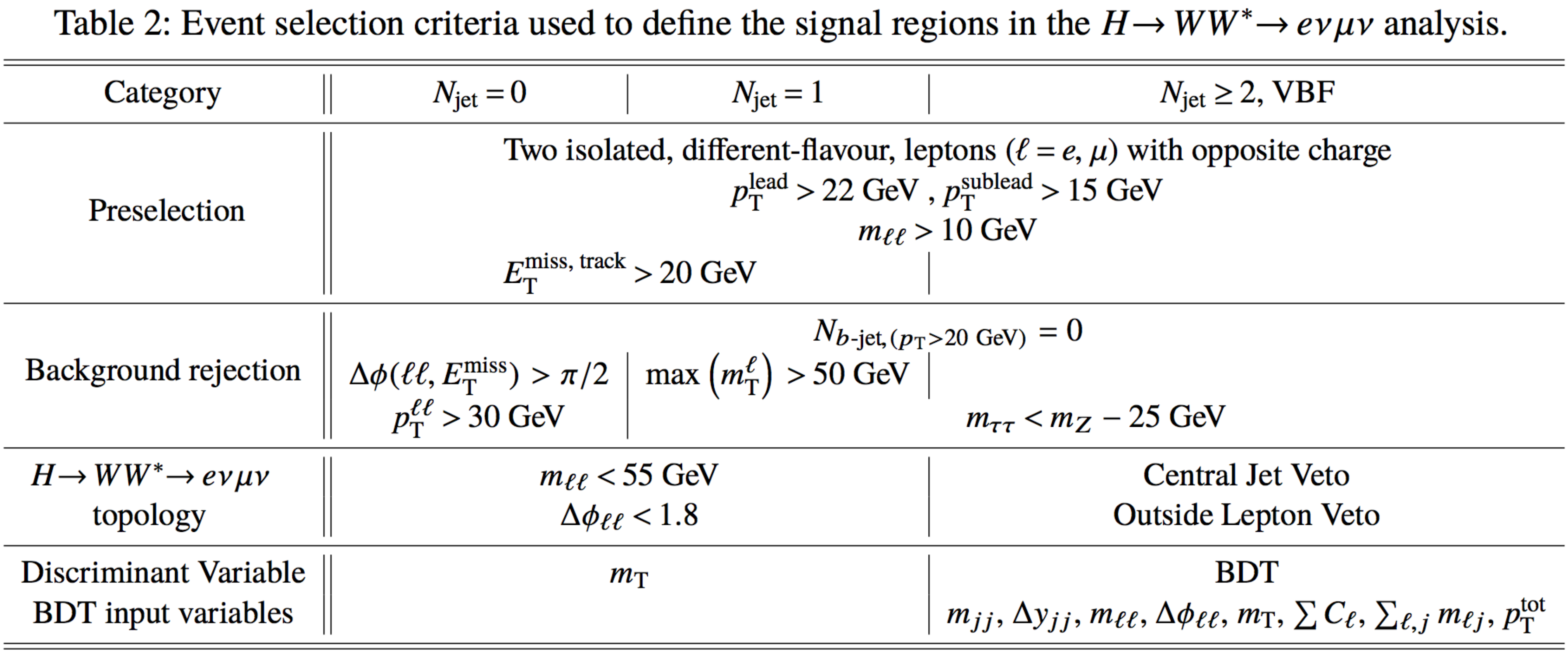


Table 2: Event selection criteria used to define the signal regions in the $H \to WW^* \to e\nu\mu\nu$ analysis.

<table>
<tr><th>Category</th><th>$N_{\text{jet}} = 0$</th><th>$N_{\text{jet}} = 1$</th><th>$N_{\text{jet}} \geq 2$, VBF</th></tr>
<tr><td rowspan="4">Preselection</td><td colspan="3">Two isolated, different-flavour, leptons ($\ell = e, \mu$) with opposite charge</td></tr>
<tr><td colspan="3">$p_{\text{T}}^{\text{lead}} > 22$ GeV , $p_{\text{T}}^{\text{sublead}} > 15$ GeV</td></tr>
<tr><td colspan="3">$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="2">$E_{\text{T}}^{\text{miss, track}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="3">$N_{b\text{-jet}, (p_{\text{T}} > 20 \text{ GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi(\ell\ell, E_{\text{T}}^{\text{miss}}) > \pi/2$
$p_{\text{T}}^{\ell\ell} > 30$ GeV</td><td>$\max\left(m_{\text{T}}^{\ell}\right) > 50$ GeV</td><td></td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$H \to WW^* \to e\nu\mu\nu$ topology</td><td colspan="2">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td>Central Jet Veto
Outside Lepton Veto</td></tr>
<tr><td>Discriminant Variable
BDT input variables</td><td colspan="2">m_{T}</td><td>BDT
$m_{jj}, \Delta y_{jj}, m_{\ell\ell}, \Delta\phi_{\ell\ell}, m_{\text{T}}, \sum C_{\ell}, \sum_{\ell,j} m_{\ell j}, p_{\text{T}}^{\text{tot}}$</td></tr>
</table>