Higgs physics results by ATLAS and CMS

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The Higgs Boson in the Standard Model

Responsible for electroweak symmetry breaking

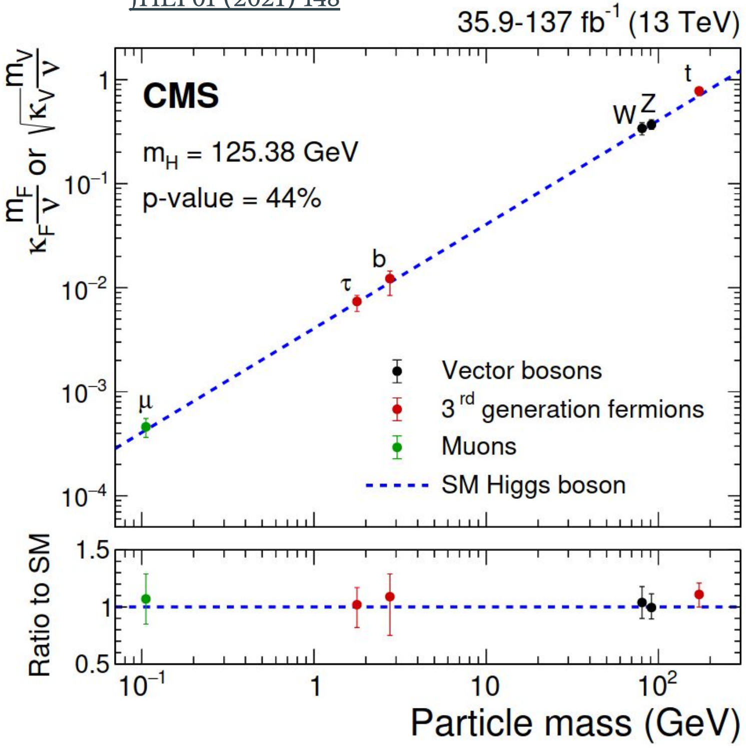
$$\mathcal{L}_\phi = (D^\mu \phi)^\dagger (D_\mu \phi) - \sum_f g_f (\bar{\psi}_L \phi \psi_R + h.c.) - V(\phi)$$

Gives mass to vector bosons through gauge couplings and vev

Fermion masses determined by Yukawa couplings

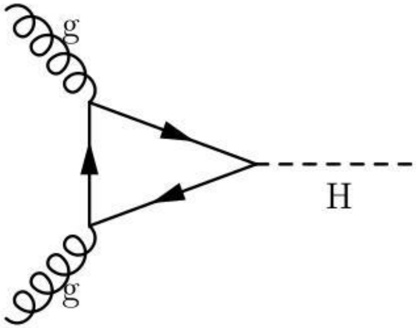
Stability of vacuum at high energies depends on m_H and m_{top}

JHEP01 (2021) 148

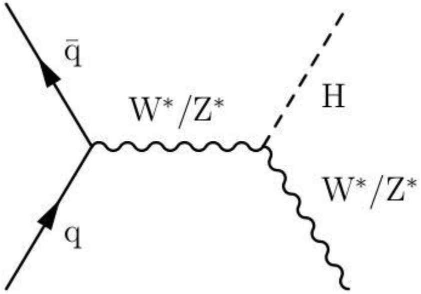


Higgs Production Mechanisms at the LHC

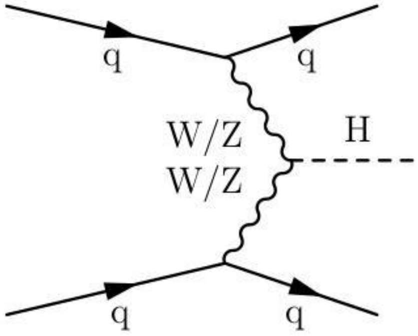
Cross-section values at 13 TeV from LHC Higgs WG



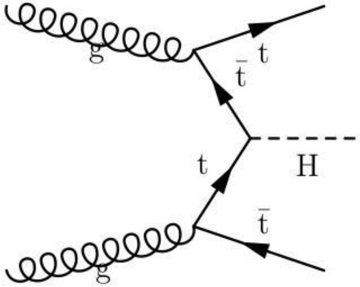
gluon-gluon fusion
48.6 pb



production in association with a vector boson
2.3 pb



vector boson fusion
3.8 pb



production in association with a top quark pair
0.5 pb

Higgs Decay Channels

Branching fractions fixed by the Higgs mass

- values from LHC Higgs WG

Golden channels:

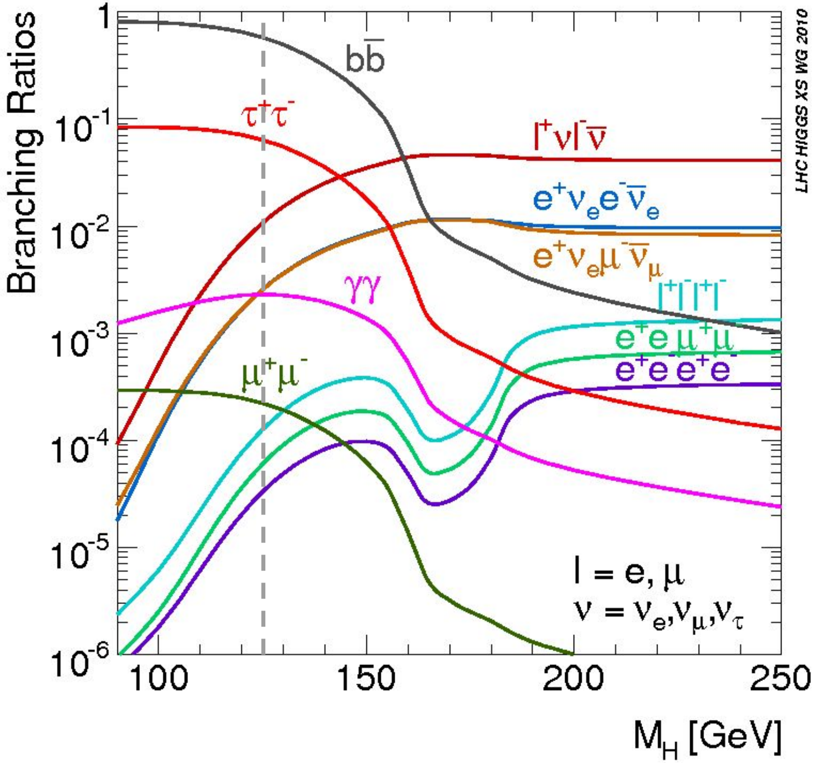
- H → ZZ (2.6%)
- H → γγ (0.23%)

Other di-boson or third-generation decay channels:

- H → WW (21.5%)
- H → ττ (6.3%)
- H → bb (57.7%)

More challenging channels:

- H → μμ (0.02%)
- H → cc (2.9%)
- H → Zγ (0.15%)
- H → γγ* (0.01%)



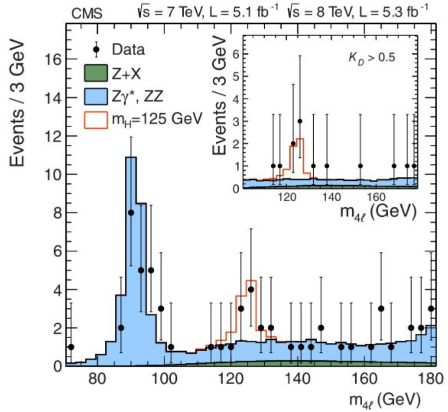
Current Status

About 7.7 millions Higgs bosons produced during Run 2 by each experiment

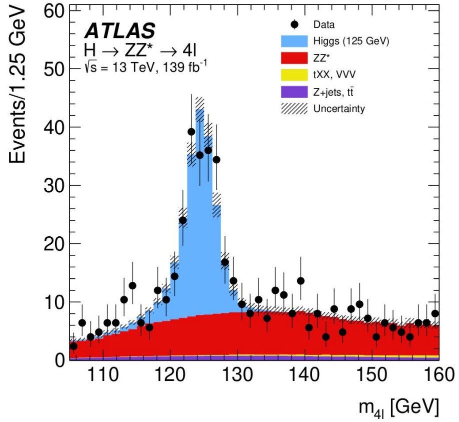
Enough data for precision measurements and search for rare decays:

- Main production modes and decay channels studied in detail
  - decays to bosons and third-generation fermions
  - fiducial, differential measurements, and STXS
  - challenging phase spaces
- Starting the inspection of second-generation fermions
  - evidence for $H \to \mu\mu$ and search for $H \to cc$
- And also other rare decays
  - $H \to \gamma\gamma^*$ or $H \to Z\gamma$
- Double Higgs production
  - key to study self-coupling and the structure of the scalar Higgs field potential

Phys. Lett. B 716 (2012) 30



Eur. Phys. J. C 81, 488 (2021)



Mass Measurements

Only Higgs free parameter, fixes all other properties

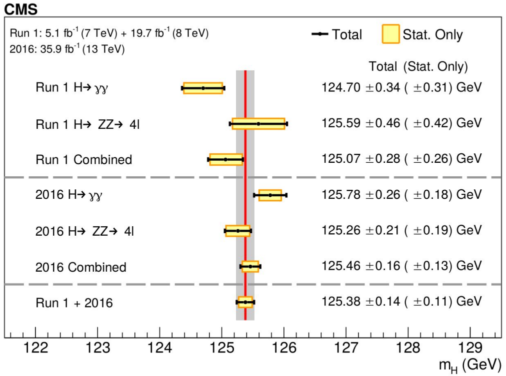
- measured using the golden channels
  - they provide the best resolution

- Energy and momentum calibrations are key
  - detector calibration and alignment
  - constraints to Z mass

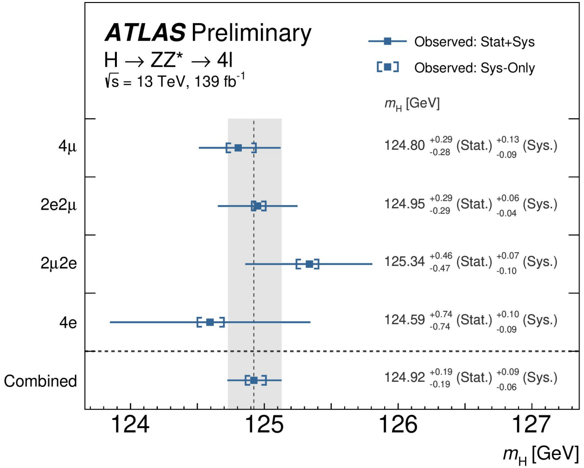
- CMS: combination of $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$ results using Run 1 and 2016 data
  - 125.38 ± 0.14 GeV
  - 0.11% uncertainty

- ATLAS: $H \rightarrow ZZ$ result using full Run 2 dataset
  - $124.92 \pm 0.19\ (\text{stat.})^{+0.09}_{-0.06}\ (\text{syst.})$
  - 0.2% uncertainty

10.1016/j.physletb.2020.135425

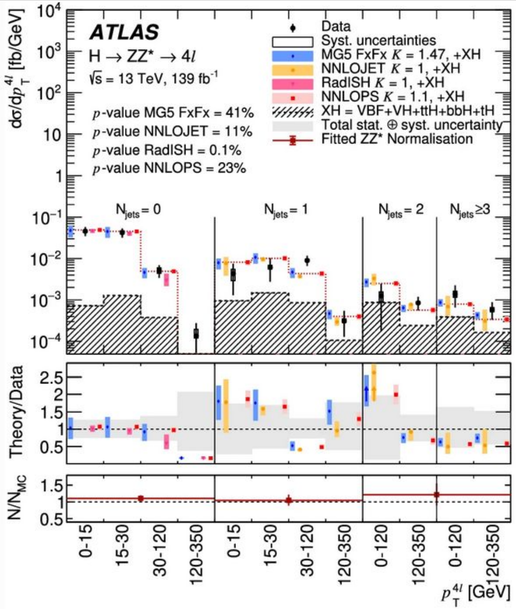


ATLAS-CONF-2020-005



$H \rightarrow ZZ$

Eur. Phys. J. C 80 (2020) 942

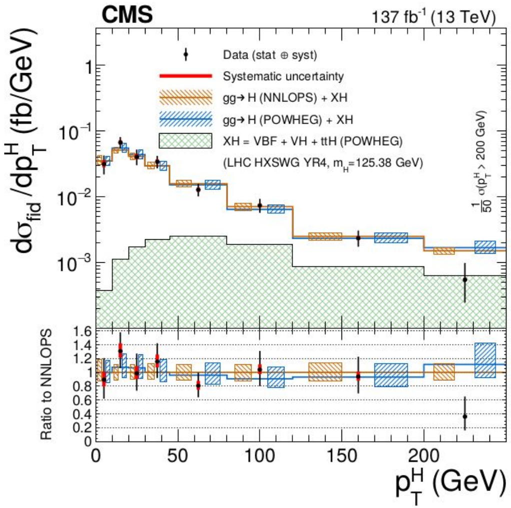


Final state with two pairs of opposite-sign, same-flavour leptons

Cross-section measurement performed in a fiducial volume that closely matches the reconstruction level selection

- reduced model dependence
- integrated fiducial cross section and differential cross sections

Eur. Phys. J. C 81, 488 (2021)



Fiducial cross-section results:

CMS:

- $\sigma_{fid} = 2.84\ ^{+0.23}_{-0.22}\ \text{(stat)}\ ^{+0.26}_{-0.21}\ \text{(syst) fb}\ \ (\sigma_{fid}^{SM} = 2.84 \pm 0.15\ \text{fb})$

ATLAS:

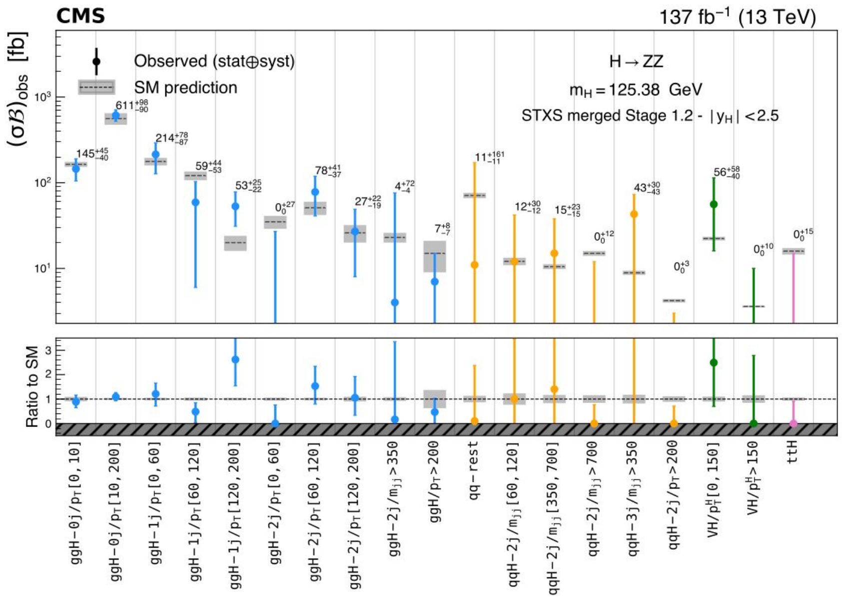
- $\sigma_{fid} = 3.28 \pm 0.32\ \text{fb}\ \ (\sigma_{fid}^{SM} = 3.41 \pm 0.18\ \text{fb})$

$H \rightarrow ZZ$

Measurement of different production mechanisms in mutually exclusive regions (STXS)

- CMS uses a finer categorization
- ATLAS categorization optimized to reduce correlation among measurements

Eur. Phys. J. C 81 (2021) 488



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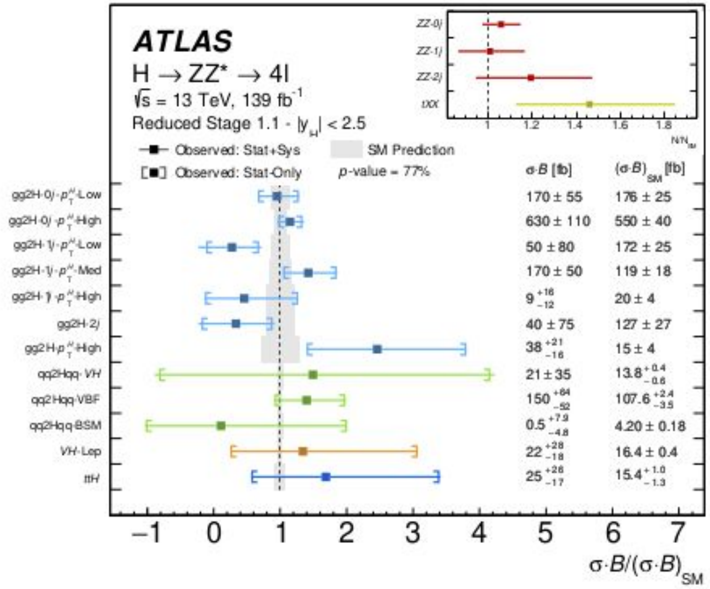
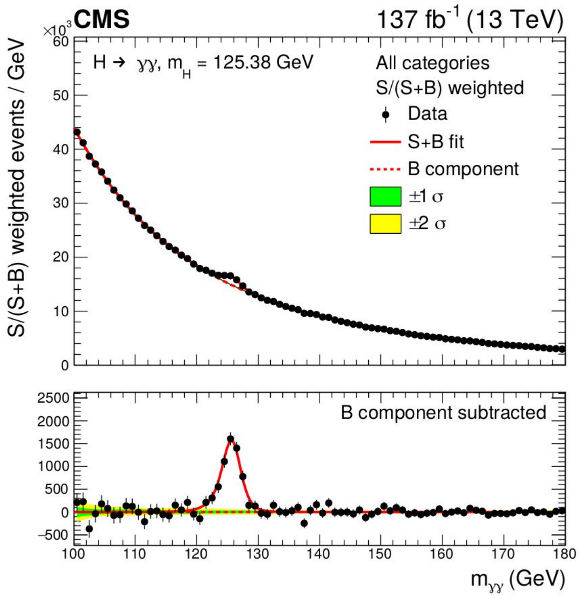


$H \rightarrow \gamma\gamma$

JHEP07 (2021) 027

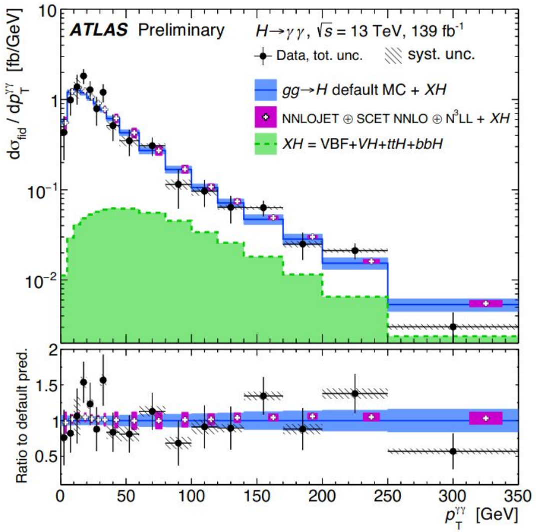


Large background from non-resonant photon pairs estimated through a fit to data

Both ATLAS and CMS presented inclusive and STXS results

- ATLAS published also differential measurements

ATLAS-CONF-2019-029, ATLAS-CONF-2020-026



Inclusive cross-section results:

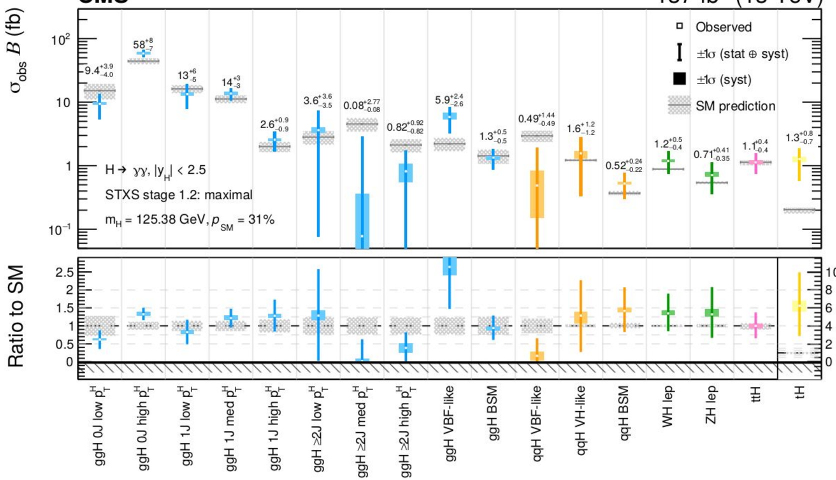
- ATLAS (fiducial):
  - $(\sigma \times B_{\gamma\gamma})_{obs} = 127 \pm 10$ fb $(\sigma \times B_{\gamma\gamma}{}^{SM} = 116 \pm 5$ fb$)$
- CMS (inclusive):
  - $\mu = \sigma/\sigma_{SM} = 1.12^{+0.07}_{-0.06}(\text{stat.}) \pm 0.03(\text{syst.}) \pm 0.06\ (\text{theo.})$

H → γγ

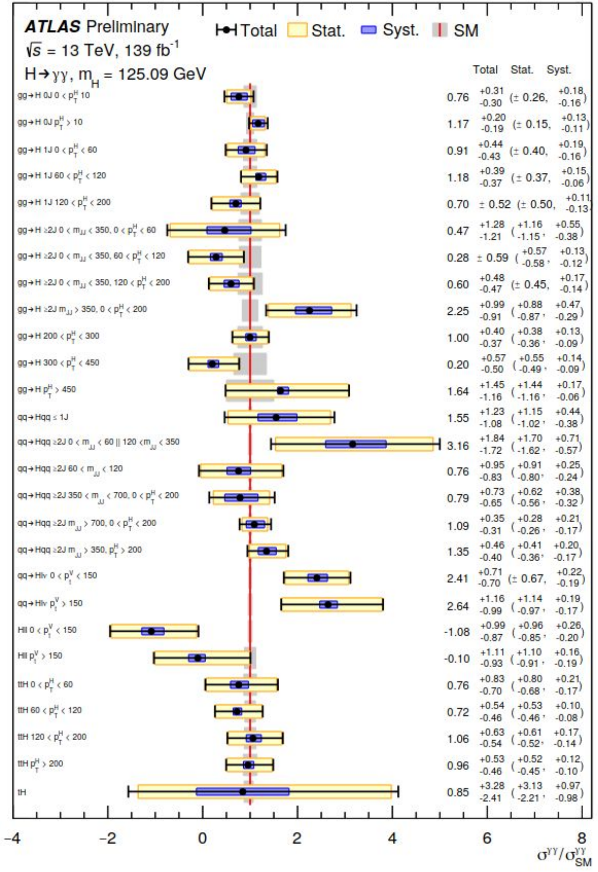
STXS results are also provided in bins targeting different production mechanisms:

- ggH, VBF, VH, ttH, and tH

[JHEP07 (2021) 027](#)



[ATLAS-CONF-2020-026](#)



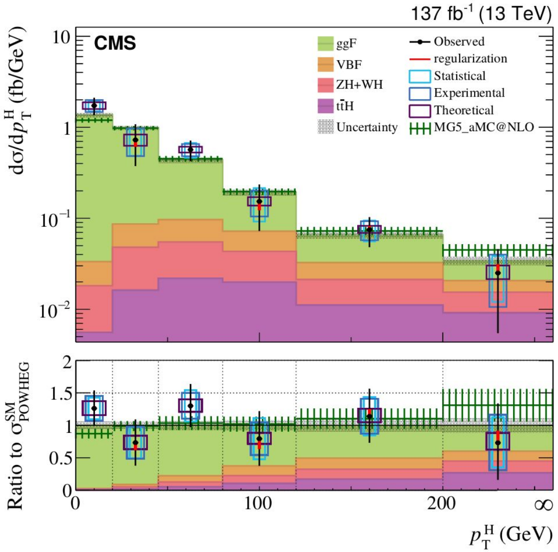
H → WW

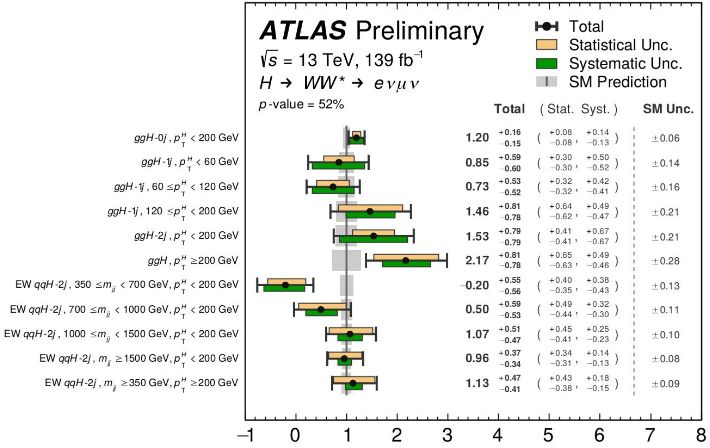
JHEP03 (2021) 003

Clean leptonic final state but neutrinos spoil mass resolution

ATLAS:

- ggH and VBF total (σ x BR) measurements
  - ggH: $\sigma_{obs} = 12.4 \pm 1.5$ pb ($\sigma_{SM} = 10.4 \pm 0.6$ pb)
  - VBF: $\sigma_{obs} = 0.79\ ^{+0.19}_{-0.16}$ pb ($\sigma_{SM} = 0.81 \pm 0.02$ pb)
- STXS in 11 categories





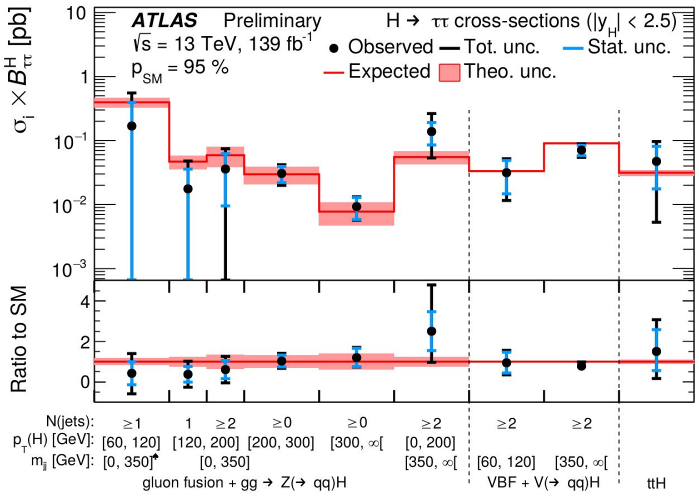
ATLAS CONF 2021 014 σ / σ_{SM}

CMS:

- integrated fiducial cross section
  - $\sigma_{fid} = 86.5 \pm 9.5$ fb ($\sigma_{fid}^{SM} = 82.5 \pm 4.2$ fb)
- differential cross-section
  - p_T(H) and nJets

$H \to \tau\tau$

ATLAS-CONF-2021-044

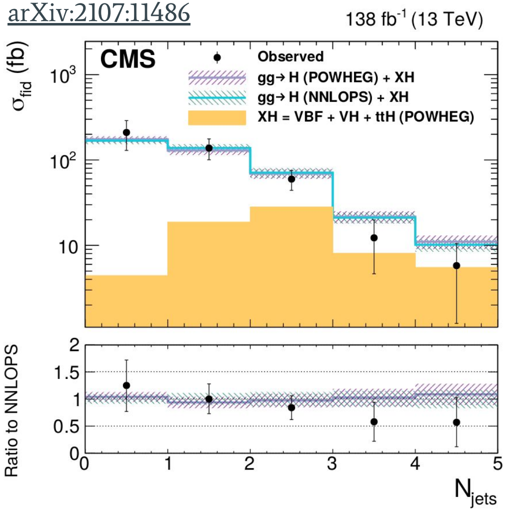


Final state with at least one hadronically-decaying τ lepton

CMS:

- inclusive fiducial cross-section
  - $\sigma_{fid} = 426 \pm 102$ fb ($\sigma_{fid}^{SM} = 408 \pm 27$ fb)
- differential cross-section
  - nJets, p_T(Higgs), leading jet p_T

arXiv:2107:11486



ATLAS:

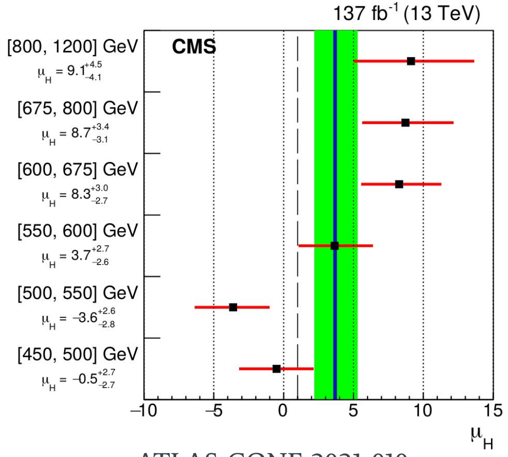
- inclusive cross-section times BR for $|y_H| < 2.5$:
  - $\sigma_{obs} = 2.89 \pm 0.21\ (\text{stat.})\ ^{+0.37}_{-0.32}\ (\text{syst.})$ pb ($\sigma_{SM} = 3.14 \pm 0.08$ pb)
  - also individual measurements per production mode
- STXS in 9 categories

$H \to bb$

JHEP12 (2020) 085

Targets a highly-boosted final state, with two b jets merged into a single large-radius jet

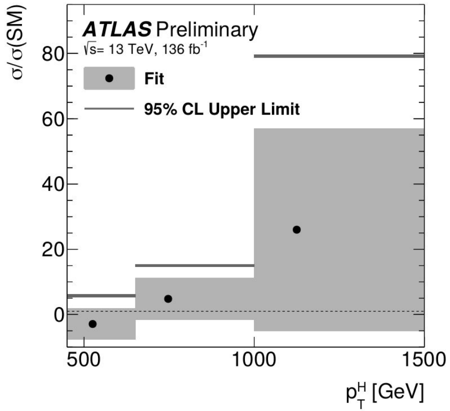
- p_T(Higgs) > 450 GeV
- analysis strategy validated with $Z \to bb$ decay
- both inclusive cross-section measurement and differential as a function of p_T(Higgs)



CMS:

- $\mu_H = 3.7 \pm 1.2\ (\text{stat})\ ^{+0.8}_{-0.7}\ (\text{syst})\ ^{+0.8}_{-0.5}\ (\text{theo})$

ATLAS-CONF-2021-010



ATLAS:

- σ_{obs} (p_T(Higgs) > 450 GeV) = 13 ± 57 (stat) ± 22 (syst) ± 3 (theo) fb

Both results in agreement with the SM

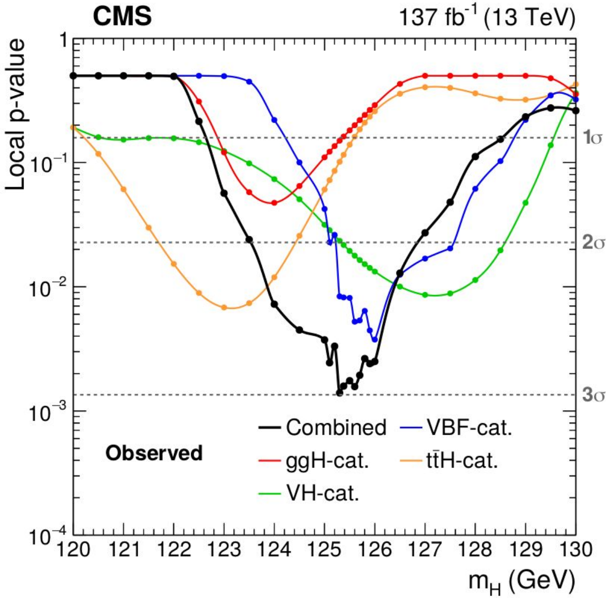
H → μμ

[JHEP01 (2021) 148]

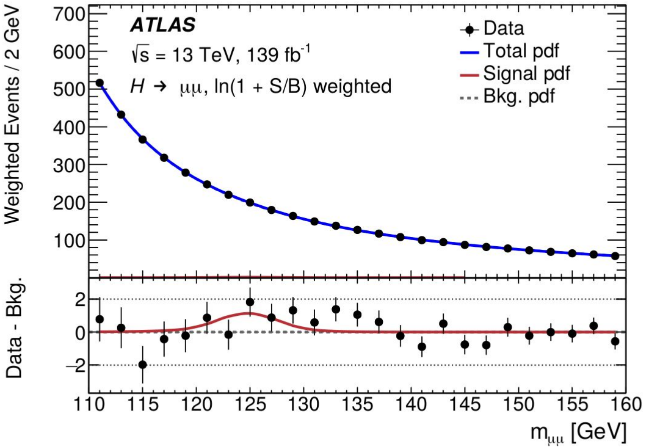
Evidence for Higgs coupling to second-generation fermions

Fit to data to distinguish the signal peak above the dominant Z → μμ smoothly-falling distribution

- CMS uses template-based approach for the VBF category to enhance sensitivity with a DNN



[Phys. Lett. B 812 (2021) 135980]



Results (significance):

- CMS: 3 σ obs (2.5 σ exp)
- ATLAS: 2 σ obs (1.7 σ exp)

H → cc

Use of multivariate analysis techniques to identify jets produced by c quarks

Targeting VH associate production to trigger interesting events and suppress backgrounds:

- ZH → ννcc, WH → lνcc, and ZH → llcc
- at least one c tagged jet

Analysis strategy validated in VW (→ cq) and VZ(→ c$\bar{c}$) channels:

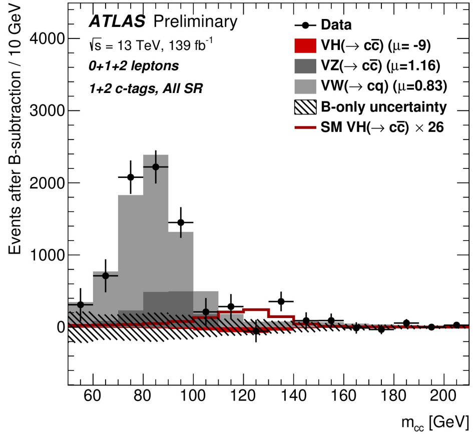
- good agreement with SM

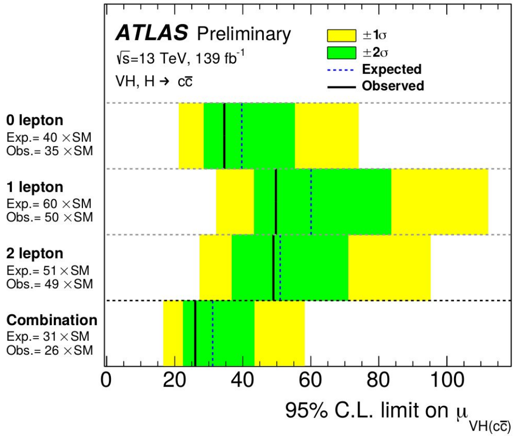
Upper limits:

- σ x BR < 26 (31^{+12}_{-8}) SM at 95% CL (full Run 2 data)
- $|k_c|$ < 8.5 (12.4) at 95% CL

CMS results (2016 data only): JHEP03 (2020) 131

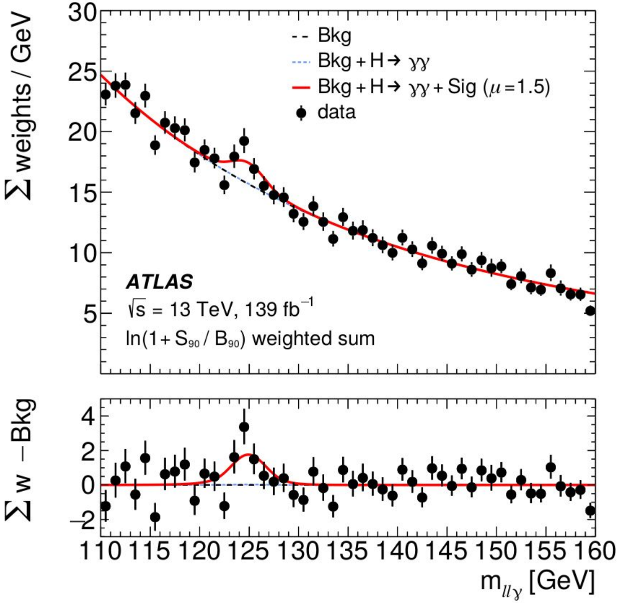
ATLAS-CONF-2021-021





H → llγ

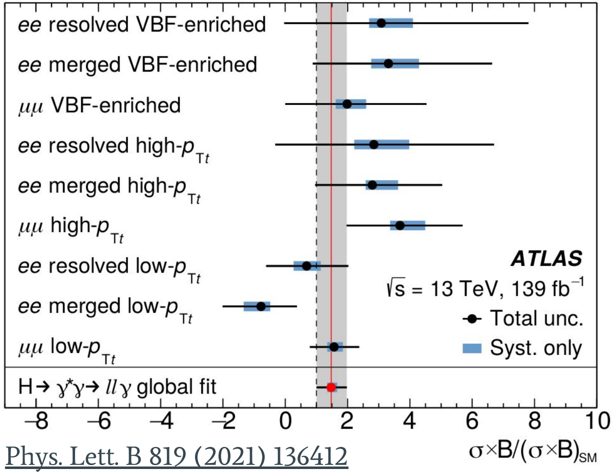
Phys. Lett. B 819 (2021) 136412



Mainly driven by H → γγ*, with contribution from H → Zγ

Fit to llγ invariant mass to distinguish signal from non-resonant background:

- m_{ll} < 30 GeV to suppress events from Z decay
- dedicated triggers for close-by electrons



Phys. Lett. B 819 (2021) 136412

ATLAS full Run 2 results:

- Evidence for H → llγ
  - 3.2 σ obs (2.1 σ exp)
- Results also for H → Zγ
  - m_{ll} ~ m_Z
  - 2.2 σ obs (1.2 σ exp)

CMS results (2016 data only): JHEP 11 (2018) 152

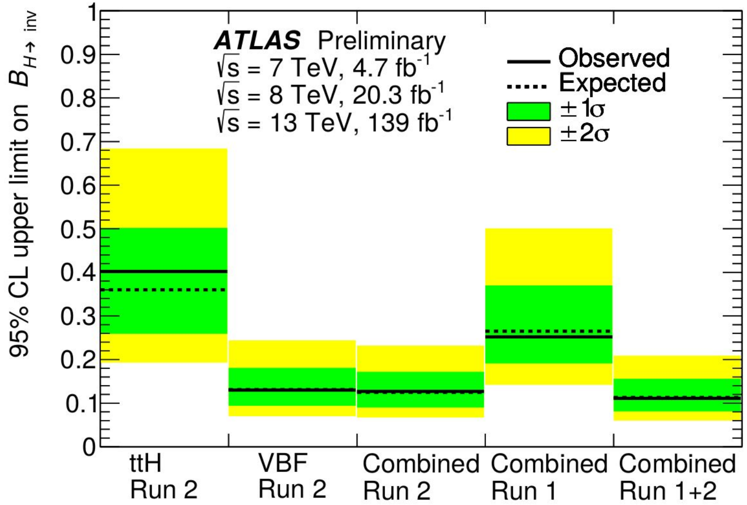
H decay to invisible particles

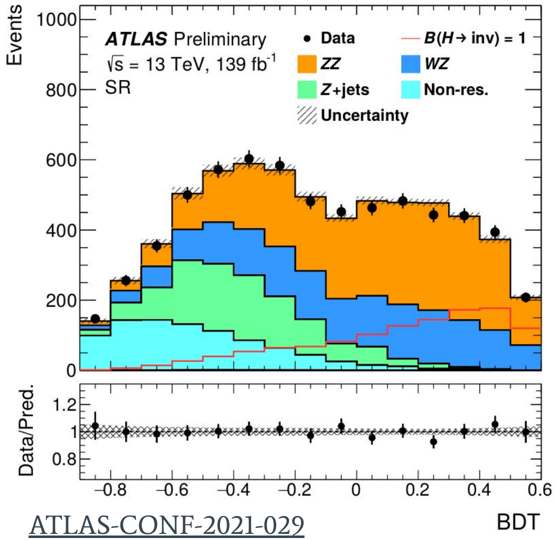
ATLAS-CONF-2020-052

Reinterpretation in terms of Higgs couplings with Dark Matter or Higgs exotic decays

Latest results:

- $ZH \rightarrow ll + E_T^{miss}$
- cut on E_T^{miss} significance + fit to BDT discriminant





ATLAS-CONF-2021-029

Results:

- ZH: $B(H \rightarrow inv) < 18\%$ obs (18% exp) at 95% CL
- combination of previous ATLAS analyses (VBF and ttH): $B(H \rightarrow inv) < 11\%$ obs. (11% exp.) at 95% CL

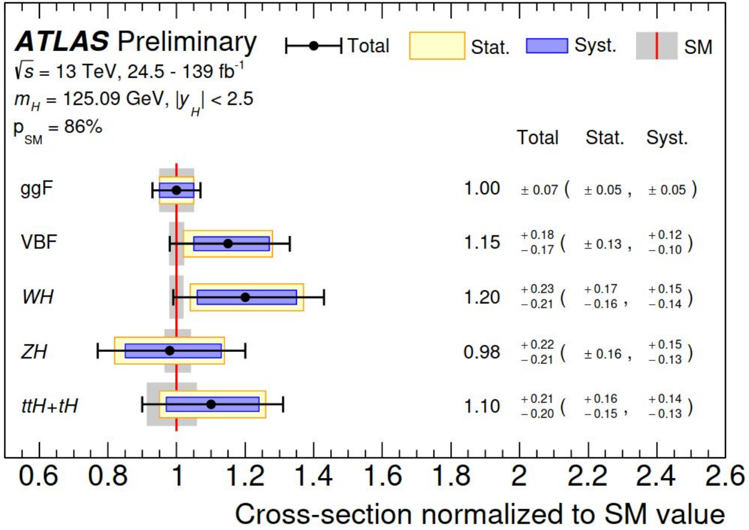
CMS results (2016 data only): Phys. Lett. B 793 (2019) 520

Combination of Higgs Results

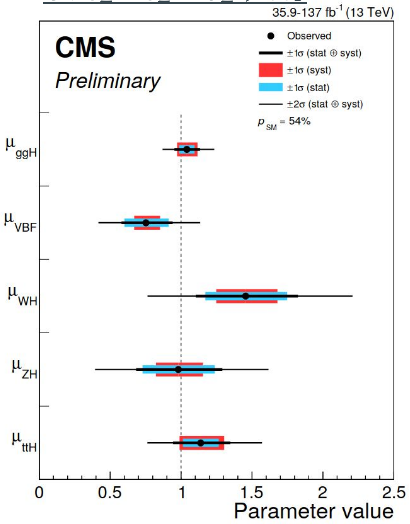
Both ATLAS and CMS presented a combination of their Higgs results at 13 TeV:

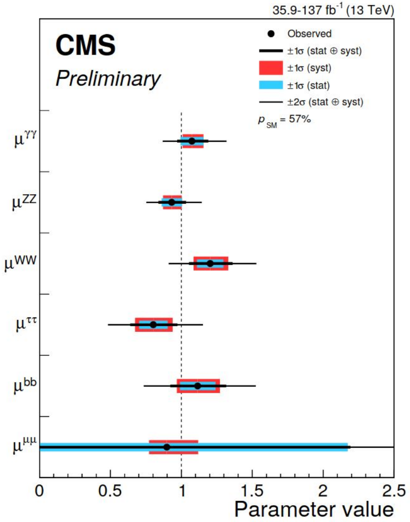
- using γγ, ZZ, WW, ττ, bb, and μμ results
- interesting to set limits on anomalous couplings values
- all results in agreement with SM

ATLAS-CONF-2020-027



CMS_PAS_HIG_19-005

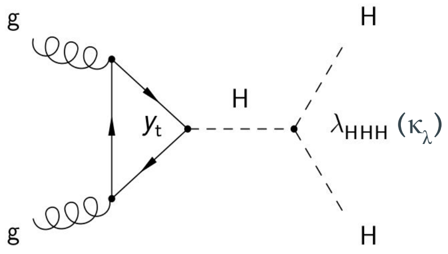


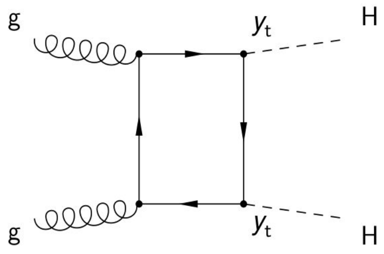


Double-Higgs searches

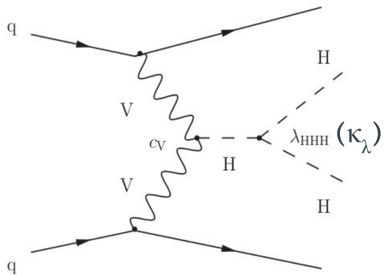
Possibility to directly inspect the Higgs self coupling and the shape of the potential

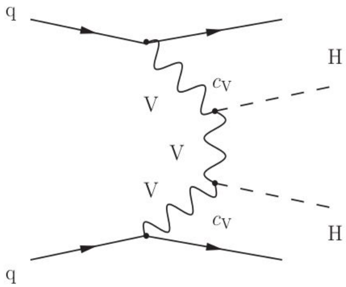
- cross-section values at 13 TeV from LHC HH WG

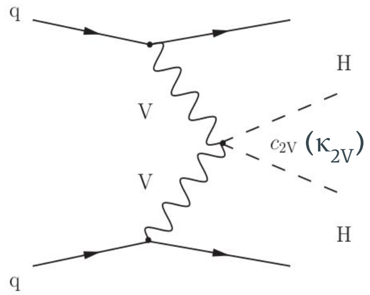




gluon-gluon fusion
31.1 fb







vector-boson fusion
1.726 fb

HH → bb bb

ATLAS full Run 2 results: JHEP 07 (2020) 108

Largest branching fraction (34%)

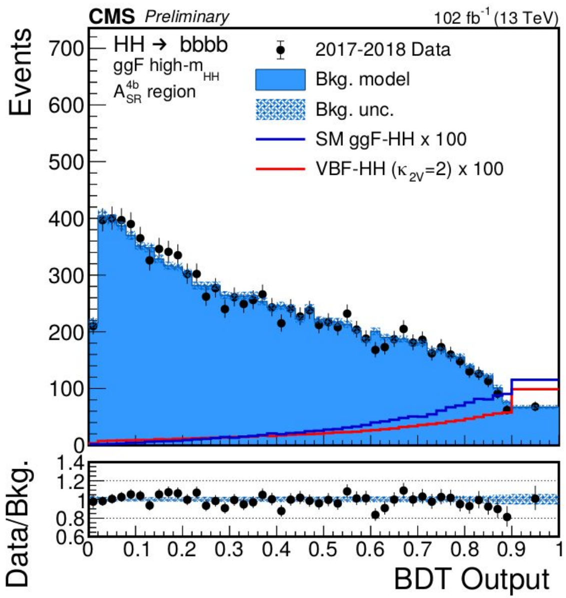
Targets both ggF and VBF production mechanisms

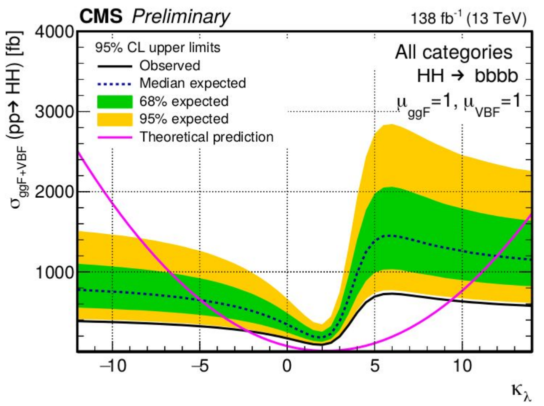
- Dominant QCD and top backgrounds estimated in control regions
- Signal extracted through fit to BDT discriminant or m_{4b}

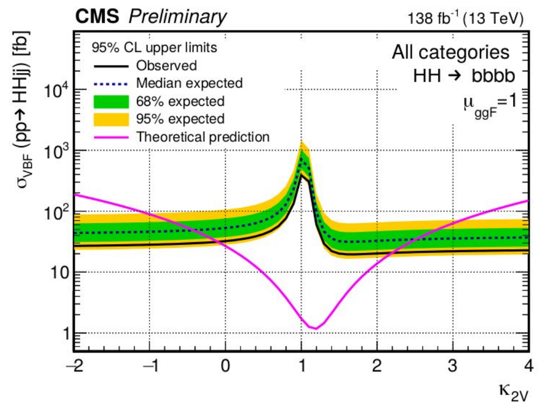
CMS results:

- $\sigma(pp \to HH \to 4b) < 3.6\ (7.3) \times$ SM obs (exp)
- $-2.3 < \kappa_\lambda < 9.4\ (-5.0 < \kappa_\lambda < 12.0)$
- $-0.1 < \kappa_{2V} < 2.2\ (-0.4 < \kappa_{2V} < 2.5)$

CMS PAS HIG-20-005







HH → bb bb (boosted)

CMS PAS B2G-21-001

Targets non-resonant VBF HH production to measure κ_{2V}

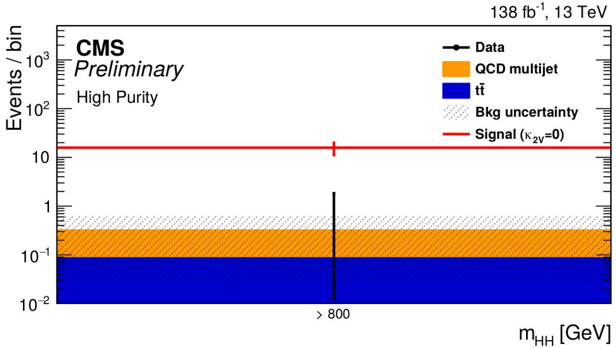
Boosted topology:

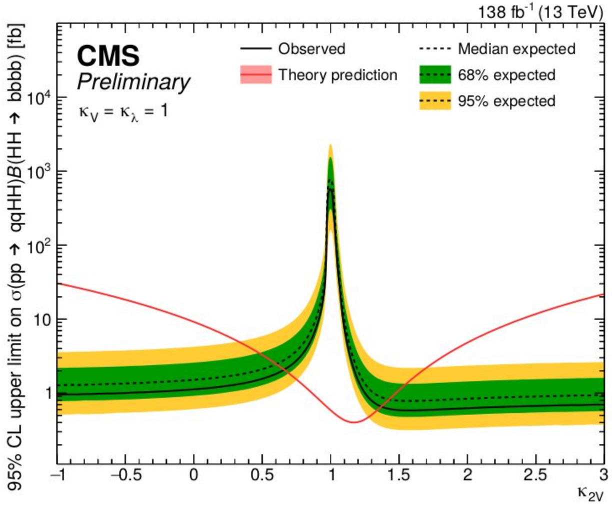
- each H → bb candidate reconstructed as a large-radius jet
- multivariate classifier based on graph convolutional networks and mass regression to identify signal events

Leading top and QCD backgrounds estimated in control regions

Results:

- $0.6 < \kappa_{2V} < 1.4$ (obs and exp) at 95% CL





HH → bb γγ

ATLAS-CONF-2021-016

Small BR but clean final state with good resolution

BDT discriminant and invariant mass categorization to separate signal from main backgrounds:

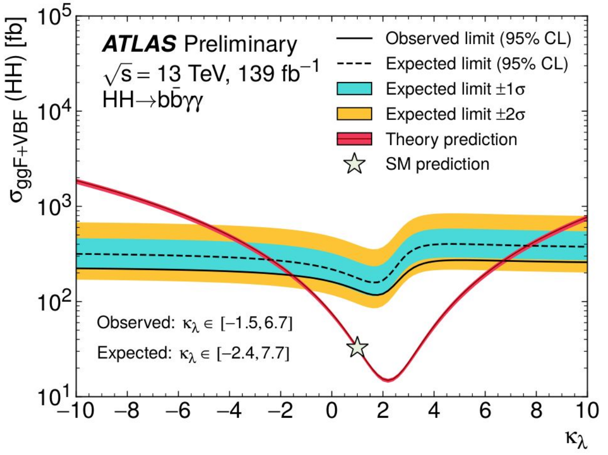
- $m^*_{bb\gamma\gamma} = m_{bb\gamma\gamma} - m_{bb} - m_{\gamma\gamma} + 250$ GeV
- Fit to $m_{\gamma\gamma}$

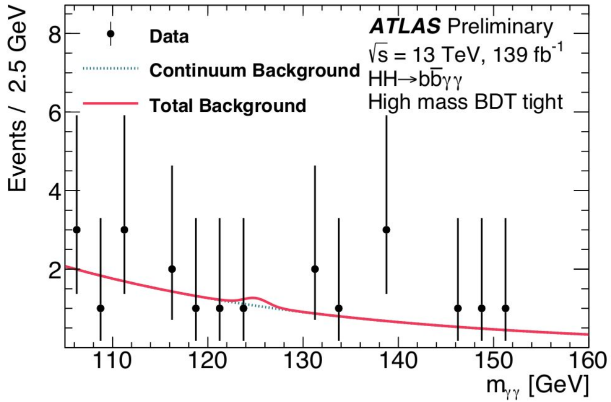
Resonant (ggF) and non-resonant (VBF) strategies

Results:

- $\sigma(HH \to bb\gamma\gamma) < 4.1$ (5.5) × SM obs (exp)
- $-1.5 < \kappa_\lambda < 6.7$ obs ($-2.4 < \kappa_\lambda < 7.7$ exp)
- at 95% CL

CMS full Run 2 results: JHEP03 (2021) 257





HH → bb ττ

Compromise between BR and background contamination

Search is optimised for maximum sensitivity to cross-section measurement

At least one τ_{had} in each event

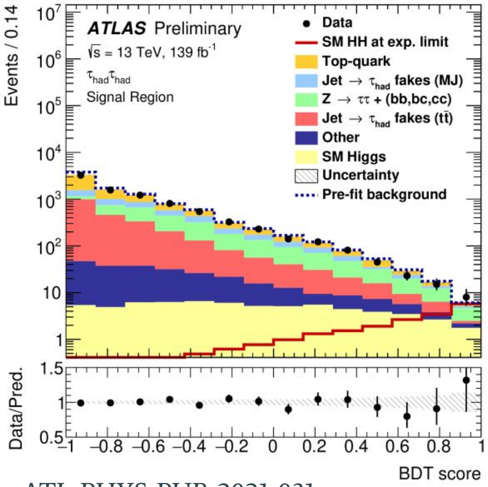
Signal extracted from fits to multivariate discriminants

Results:

- σ(HH → bbττ) < 4.7 (3.9) × SM obs (exp) at 95% CL

CMS results (2016 data only): Phys. Lett. B 778 (2018) 101

ATLAS-CONF-2021-030



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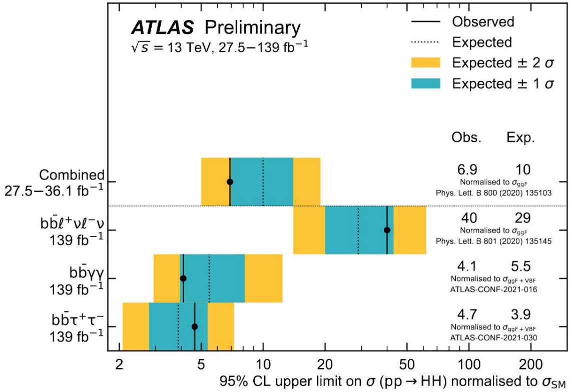


Conclusions

Recent Higgs results from ATLAS and CMS using full Run 2 dataset

- golden channels, vector bosons, and third generation fermions established
- effort to explore decays to second generation fermions and rarer final states
- inclusive, fiducial, and STXS measurements
- limits on HH measurements are more stringent and already close to SM expectations

The forthcoming Run 3 will help improving current results and prepare the high-luminosity phase

Higgs Talks in Parallel Sessions

More details in the Higgs talks during parallel sessions:

- Measurement of Higgs differential distributions at the LHC - Arun Kumar
- Higgs couplings to fermions and bosons - Serhat Ordek
- Probing Higgs couplings to light quarks via Higgs pair production - Lina Alasfar
- Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC - Juan Rojo
- Higgs rare and exotic decays - Miha Muskinja
- Double Higgs production - Louis Portales

BACK-UP

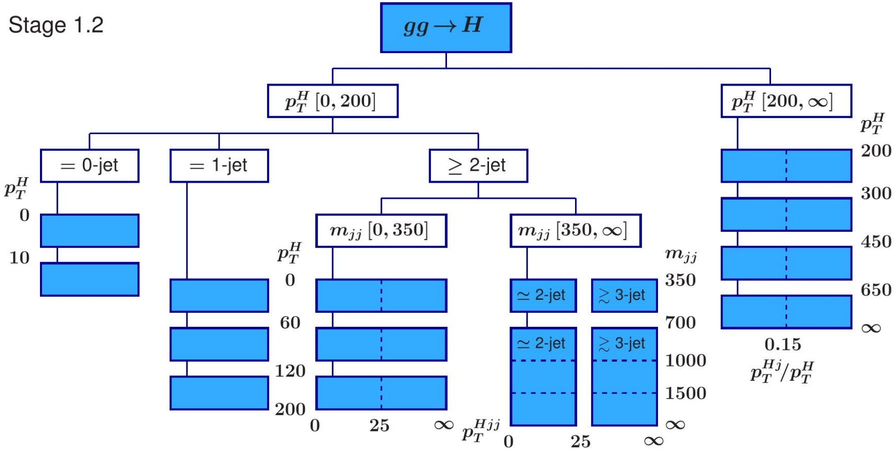
Simplified Template Cross-Section (STXS)

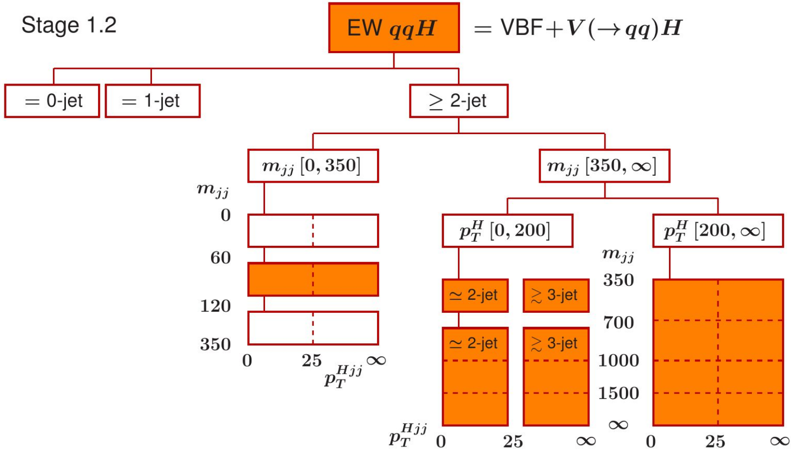
STXS TWiki

Main goals of the STXS framework:

- increase the re-interpretability of the precision H boson measurements
- minimize the theory dependence

This is achieved by defining exclusive kinematic regions in the H boson production phase space.





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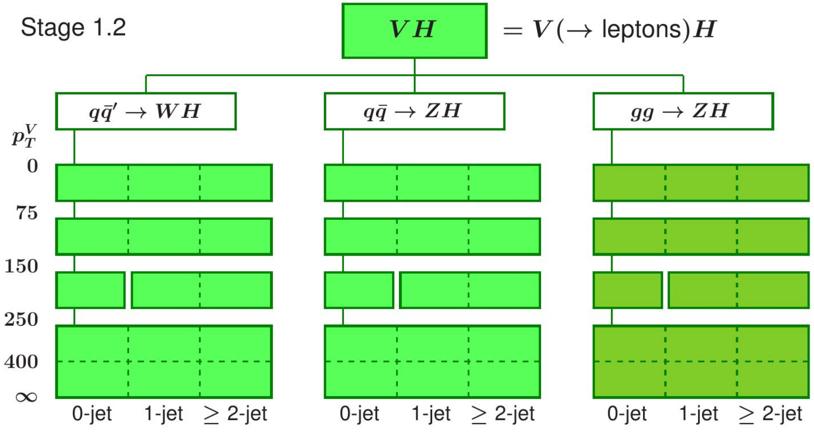
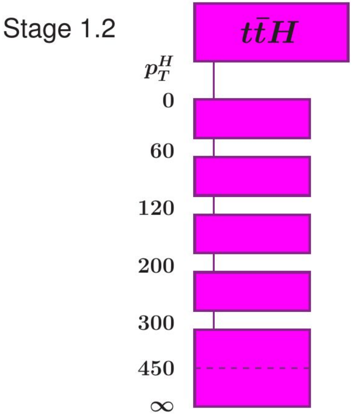


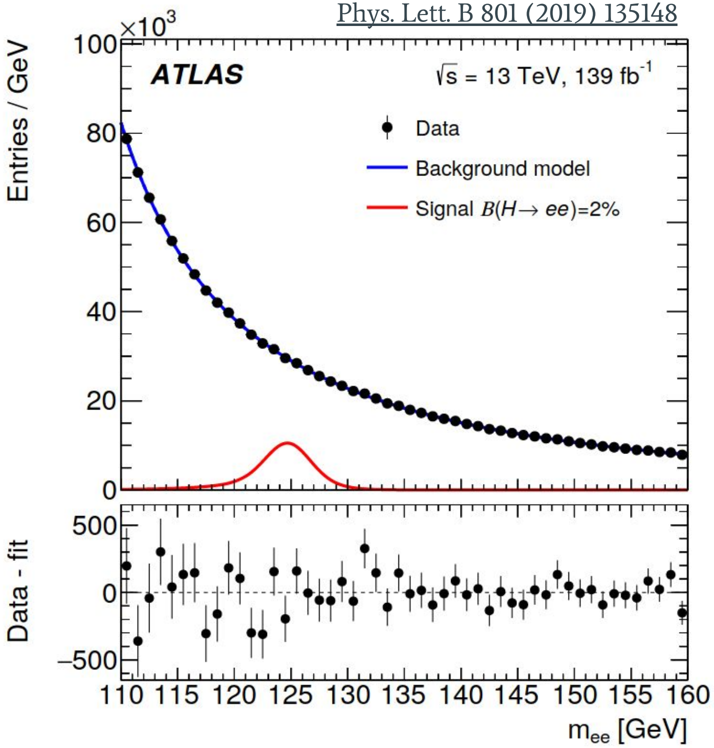


$H \longrightarrow ee$

ATLAS produced a search for the Higgs boson decay to pair of electrons:

- the main challenge is given by the small branching ratio ($\sim 5 \times 10^{-9}$)
- analysis strategy similar to $H \rightarrow \mu\mu$
  - fit to data in several categories with different signal-to-background ratios
- upper limit on branching fraction:
  - BR ($H \rightarrow ee$) < 3.6×10^{-4} (3.5×10^{-4}) obs (exp)

Phys. Lett. B 801 (2019) 135148



H $\longrightarrow$ ZZ - CMS Fiducial Volume Definition

Requirements for the $\mathrm{H} \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_{T}	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$
Next-to-leading lepton p_{T}	$p_{\mathrm{T}} > 10\,\mathrm{GeV}$
Additional electrons (muons) p_{T}	$p_{\mathrm{T}} > 7(5)\,\mathrm{GeV}$
Pseudorapidity of electrons (muons)	$\lvert\eta\rvert < 2.5$ (2.4)
Sum of scalar p_{T} of all stable particles within $\Delta R < 0.3$ from lepton	$< 0.35 p_{\mathrm{T}}$
Event topology	
Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m_{\mathrm{Z}_1} < 120\,\mathrm{GeV}$
Inv. mass of the Z_2 candidate	$12 < m_{\mathrm{Z}_2} < 120\,\mathrm{GeV}$
Distance between selected four leptons	$\Delta R(\ell_i, \ell_j) > 0.02$ for any $i \neq j$
Inv. mass of any opposite sign lepton pair	$m_{\ell^+ \ell'^-} > 4\,\mathrm{GeV}$
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140\,\mathrm{GeV}$

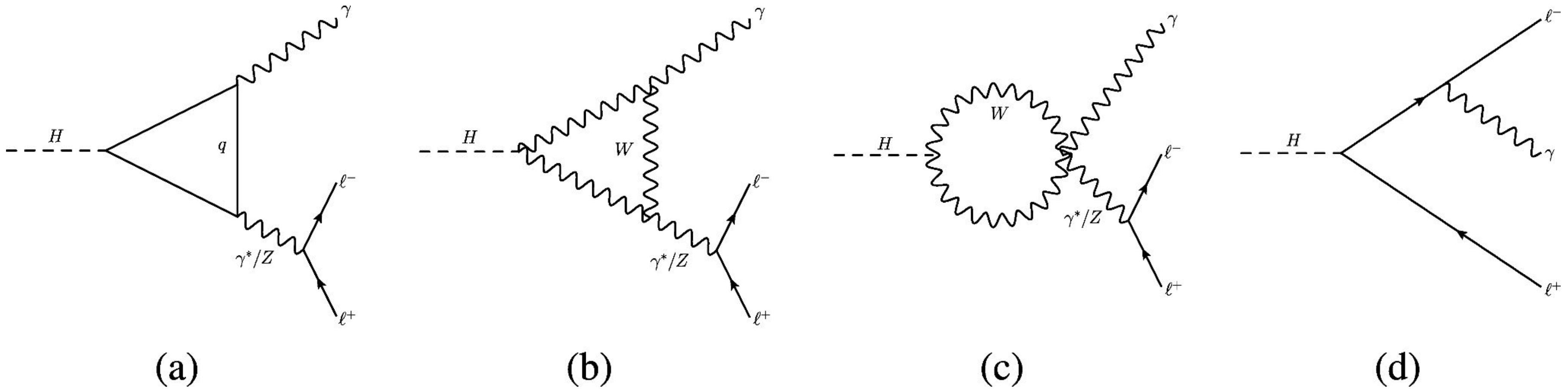
H → ZZ - ATLAS Fiducial Volume Definition

Table 3 List of event selection requirements which define the fiducial phase space for the cross-section measurement. SFOC lepton pairs are same-flavour opposite-charge lepton pairs

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets	$p_T > 30$ GeV, $\lvert y\rvert < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV $< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \mathrm{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

$H \rightarrow ll\gamma$

Feynman diagrams for $H \rightarrow ll\gamma$ production



Phys. Lett. B 819 (2021) 136412