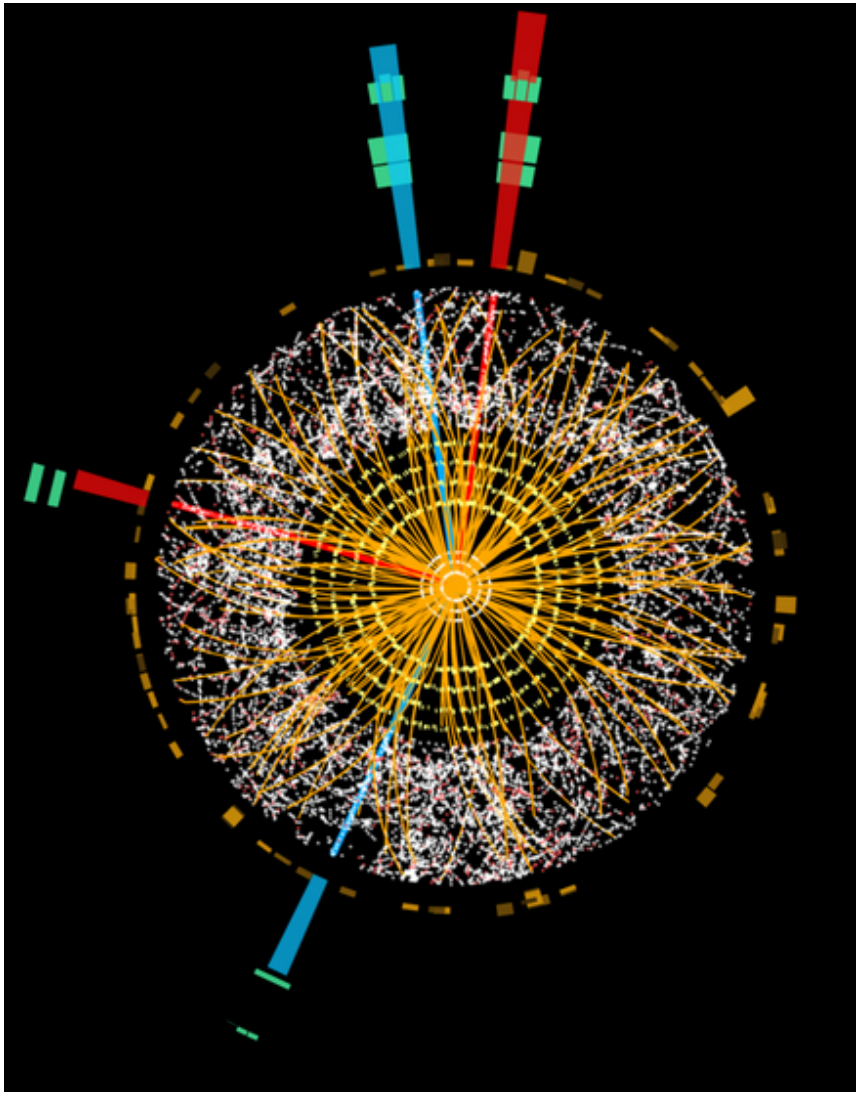
Higgs Measurements



EPS 2021

July 27, 2021

Kerstin Tackmann
(DESY and Universität Hamburg)

on behalf of the ATLAS and CMS collaborations

[JHEP 01 (2021) 148, arXiv:1205.6497 [hep-ph], arXiv:1312.5672 [hep-ph]]

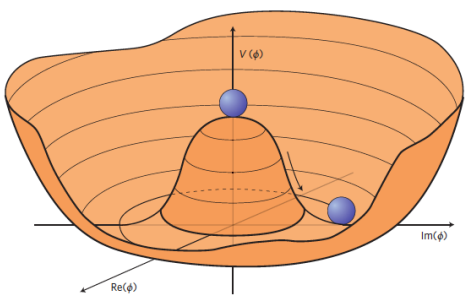
The Higgs boson in the SM.

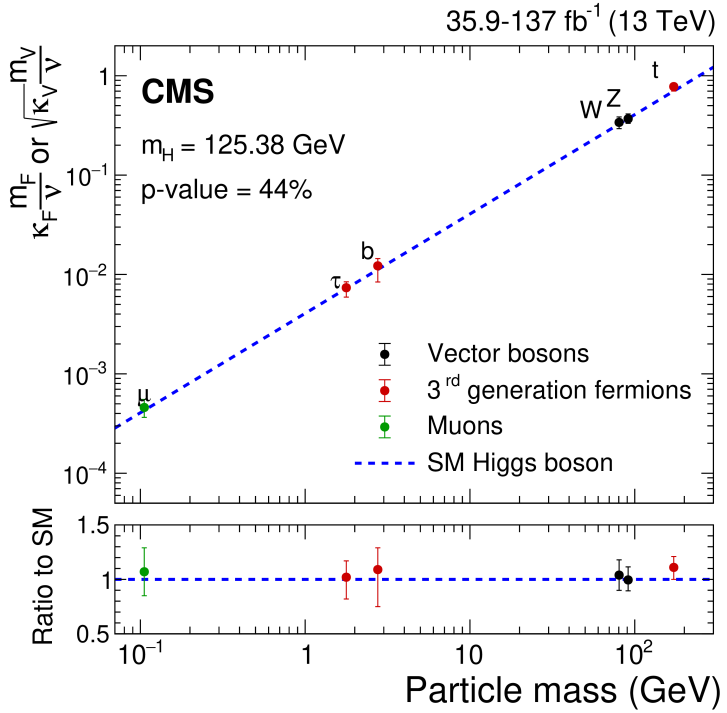
$$\mathcal{L}_\phi = (D^\mu\phi)^\dagger(D_\mu\phi) - \sum_f g_f(\bar{\psi}_L\phi\psi_R + \text{h.c.}) - V(\phi)$$

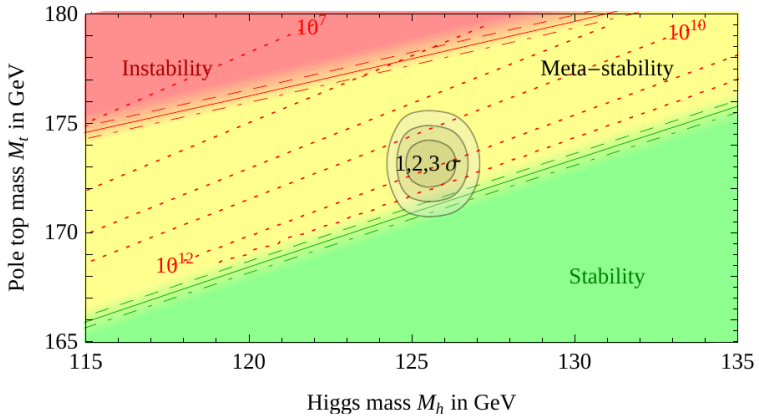
- W and Z masses determined from gauge couplings and Higgs vev
- Fermion masses from Yukawa couplings
  - ⋆ Not needed for EWSB, but convenient
  - ⋆ Only interaction in the SM that distinguishes between generations

$$V(\phi) = \mu^2|\phi|^2 + \lambda|\phi|^4$$

- Stability of vacuum at high energies depends on m_H and m_t

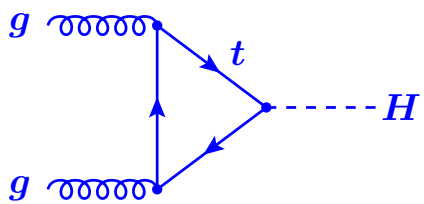






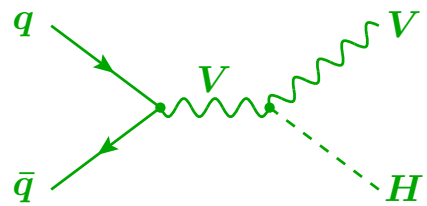
Main Higgs boson production modes at the LHC.

Gluon fusion: 48.6 pb



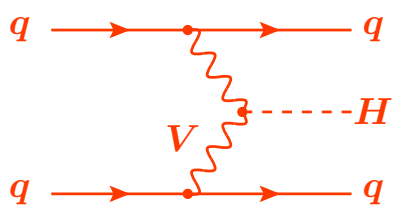
Higgs tends to have low p_T

Associated production with V: 2.3 pb



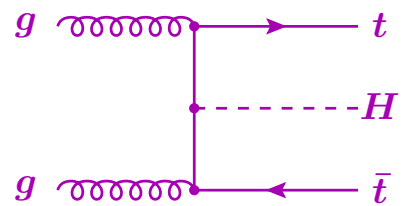
Clear signature: reconstruct W and Z in leptonic and/or hadronic decays

Vector boson fusion: 3.8 pb



Distinct signature with 2 forward jets and little hadronic activity in between

Associated production with $t\bar{t}$: 0.5 pb



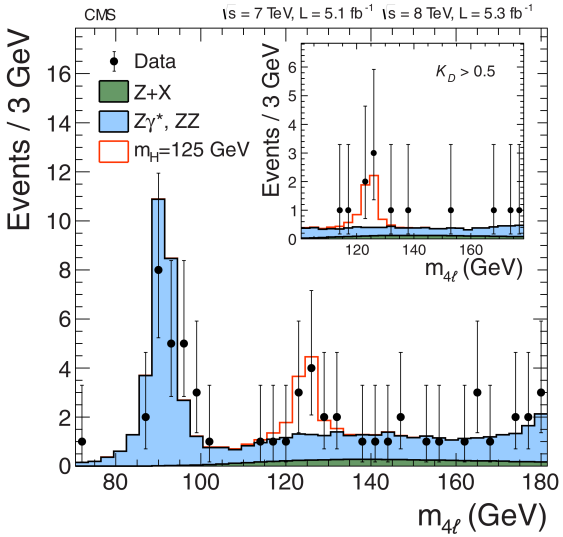
Tag presence of two top quarks

Predicted production cross sections given at m_H =125 GeV and $\sqrt{s}$ =13 TeV

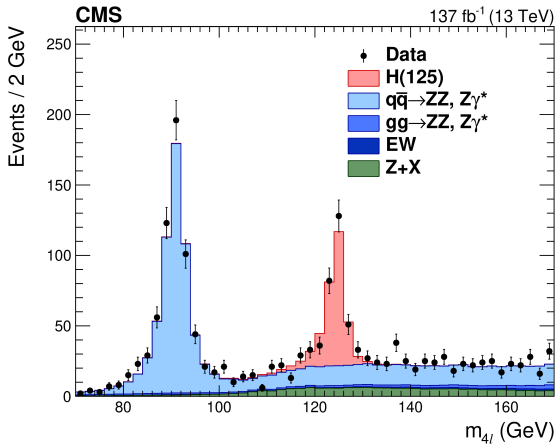
[Summarized by LHC Higgs Working Group]

Higgs in 2021.

2012



2021



7.7 million Higgs produced in Run2 per experiment

- All main production processes and decay channels established
  - ⋆ Decays to bosons and third-generation fermions
- Measurements now more differential, exploring also more extreme kinematics
- Searches for decays to second-generation fermions and other rare decays
- Searches for HH production → constraints on Higgs potential

Predicted decay branching fractions

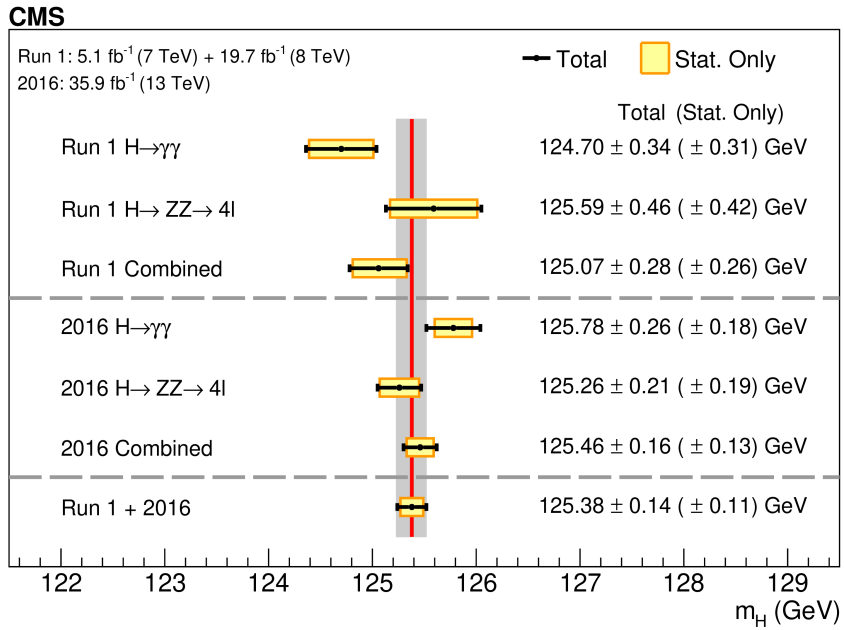
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.3%
$H \to c\bar{c}$	2.9%
$H \to ZZ^*$	2.6%
$H \to \gamma\gamma$	0.23%
$H \to Z\gamma$	0.15%
$H \to \mu\mu$	0.02%
$H \to \gamma^*\gamma$	0.01%

[Phys. Lett. B 805 (2020) 135425, ATLAS-CONF-2020-005]

Higgs mass.

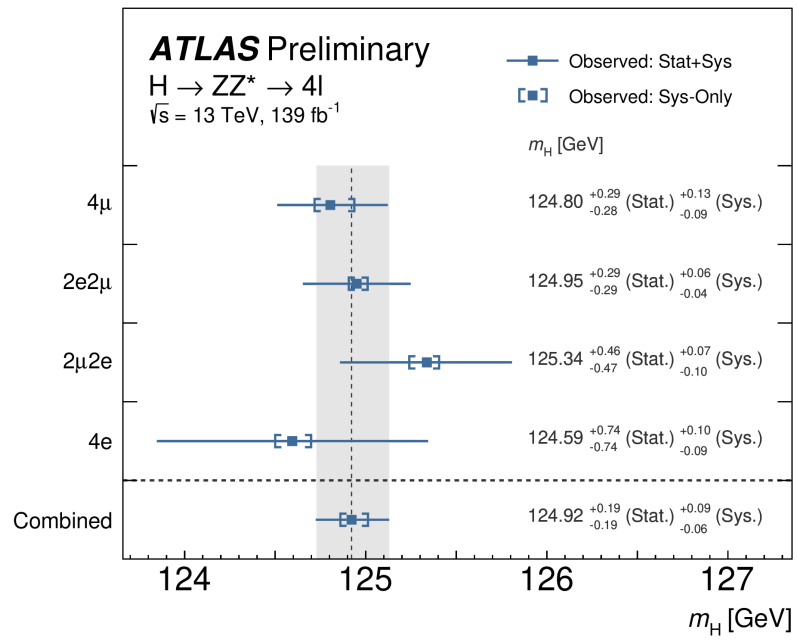
Only free parameter, fixes all other Higgs properties

- Measurement in decay channels with good resolution: $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$
  - ⋆ Relies on precise energy/momentum calibration



$H \to 4\ell$ and $H \to \gamma\gamma$ Run1+2016 data (CMS): 0.11% uncertainty

$H \to 4\ell$ full Run2 (ATLAS): 0.2% uncertainty

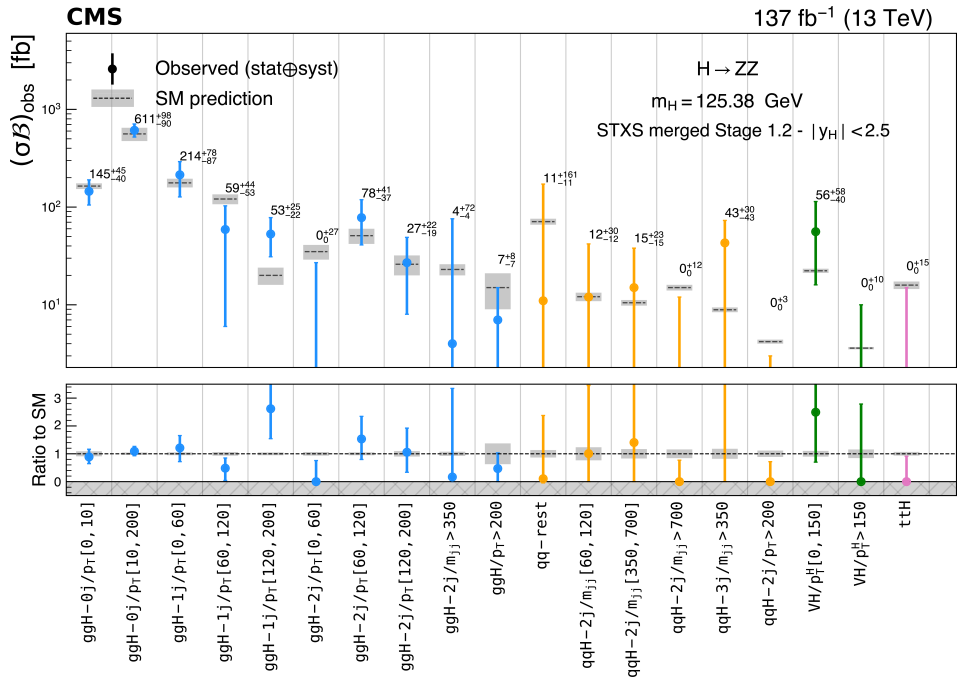


- Precision not a limiting factor for other Higgs measurements, nor for constraints on SUSY

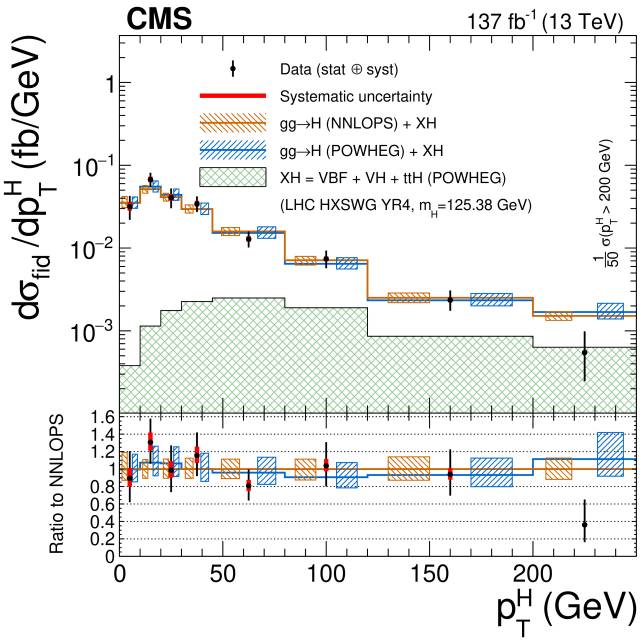
$H \to ZZ^* \to 4\ell$.

Very clean final state

[Eur. Phys. J. C 81 (2021) 488]
[ATLAS: Eur. Phys. J. C 80 (2020) 957, Eur. Phys. J. C 80 (2020) 942]



- Main ZZ background estimated from simulation
- Measurements of ggH, VBF, VH and $t\bar{t}H$ in various kinematic regions ("simplified template cross sections")



- Measurements inclusive in production process in fiducial volume defined by lepton kinematics
  - ★ Less model dependent
  - ★ More detailed kinematic information

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

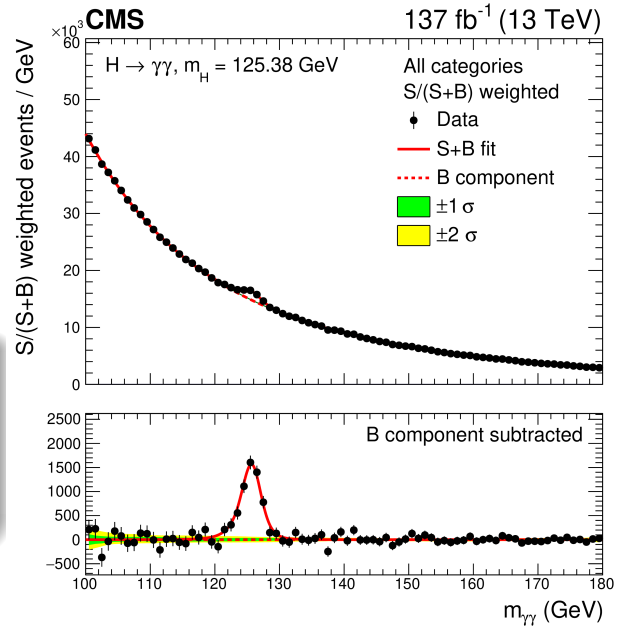
[JHEP 07 (2021) 027, ATLAS-CONF-2020-026]

$H \to \gamma\gamma$.

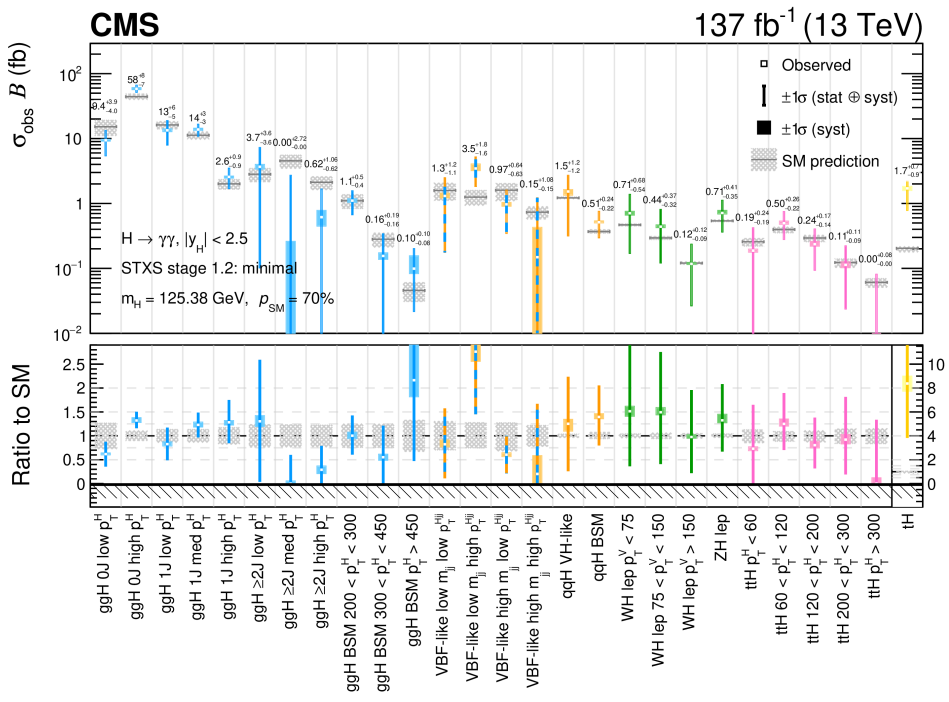
Larger backgrounds, but robust subtraction using parametrization

Inclusive signal strength

$$\mu = \sigma/\sigma^{\mathrm{SM}} = 1.12^{+0.07}_{-0.06}(\mathrm{stat})^{+0.03}_{-0.03}(\mathrm{syst})^{+0.06}_{-0.06}(\mathrm{theo})$$



- Measurements of various kinematic regions in ggH, VBF, VH, $t\bar{t}H$ and tH
  - ⋆ Five bins in Higgs p_T in $t\bar{t}H$



Limit on tH

- 14 (8)×SM at 95% CL obs. (exp.) (CMS)
- 8×SM at 95% CL (ATLAS)

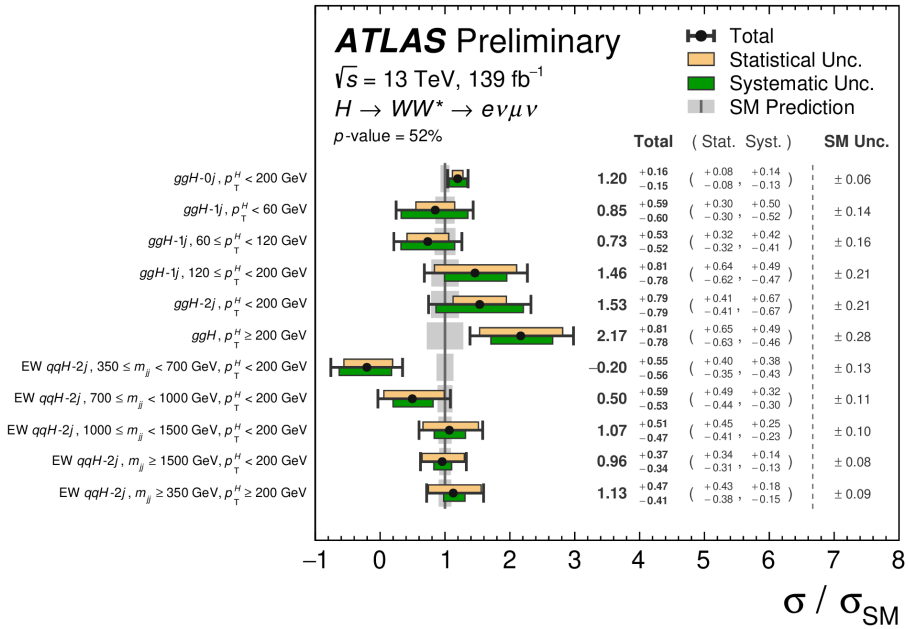
[ATLAS-CONF-2021-014, CMS-PAS-HIG-19-017]

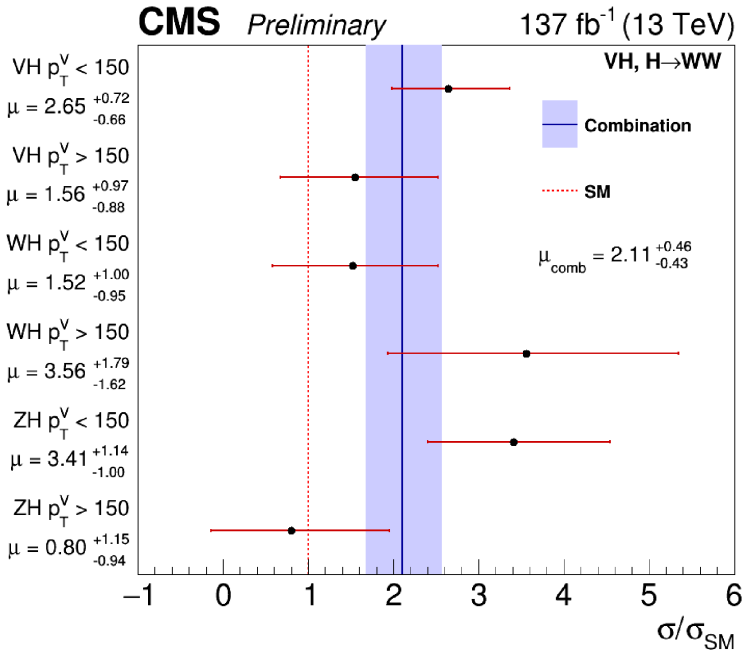
[CMS: PLB 791 (2019) 96, ATLAS: Phys. Lett. B 798 (2019) 134949]

$H \to WW^* \to 2\ell 2\nu$.

Larger branching fraction, but worse resolution due to ν

- Signature: $e + \mu + E_{\mathrm{T}}^{\mathrm{miss}}$
- Main backgrounds: WW, $t\bar{t}$, Z+jets from CRs
- Measurements in various kinematic regions for ggH and VBF
- Theory uncertainties can be important





- Measurement of VH in final states with 2, 3, or 4 leptons
- Main backgrounds: VV, fake leptons

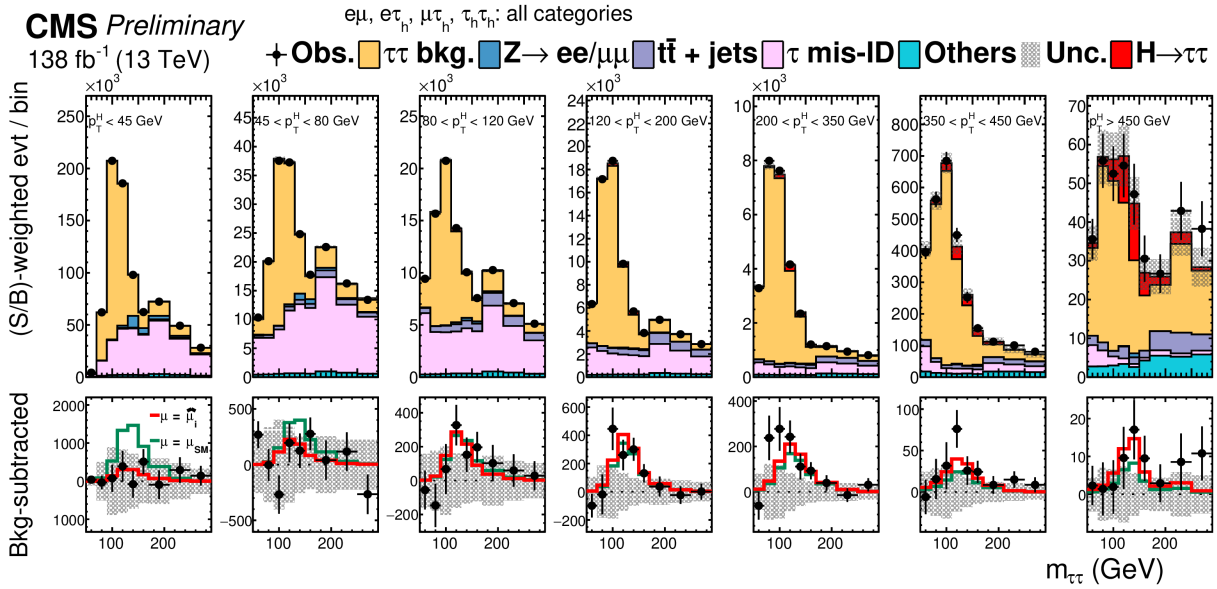
Significance for inclusive VH

4.7 σ obs. (2.8 σ exp.)

$H \to \tau\tau$.

Higgs coupling to third-generation fermions

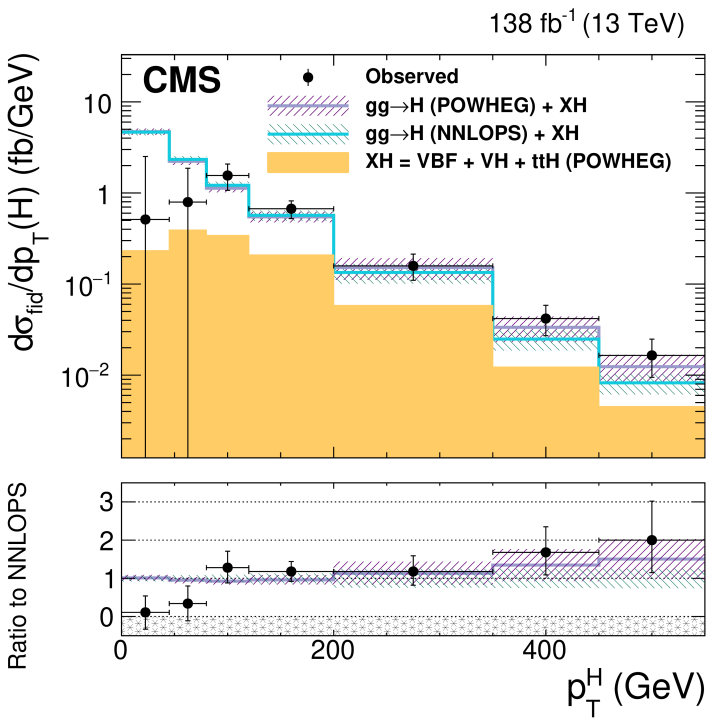
- Main backgrounds: $Z \to \tau\tau$, fake τ
- Good sensitivity at high p_T and for VBF topology



- Differential measurements in fiducial volume defined by kinematics of visible τ decay products

Inclusive fiducial measurement
(by summing N_{jet} bins)

$$\sigma_{\text{fid}} = 426 \pm 102 \text{ fb}$$
$$\sigma_{\text{fid}}^{\text{SM}} = 408 \pm 27 \text{ fb}$$

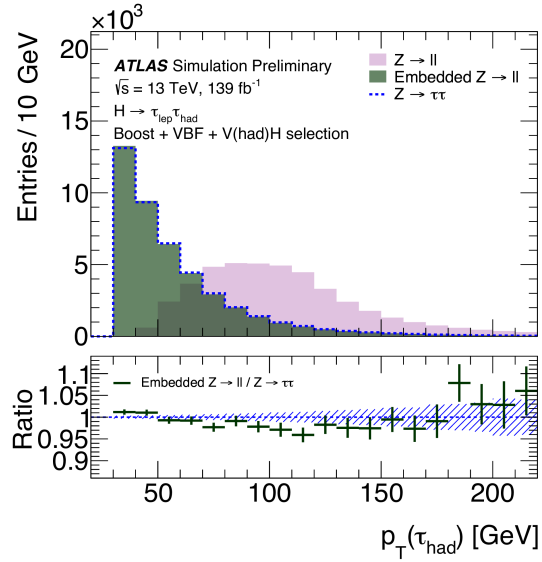


$H \to \tau\tau$.

New for this conference

[ATLAS-CONF-2021-044]
[CMS: CMS-PAS-HIG-19-010]

- New: MC $Z \to \tau\tau$ background estimate validated with $Z \to \ell\ell$ data events with simulation-based corrections to kinematics (four vectors) and efficiencies



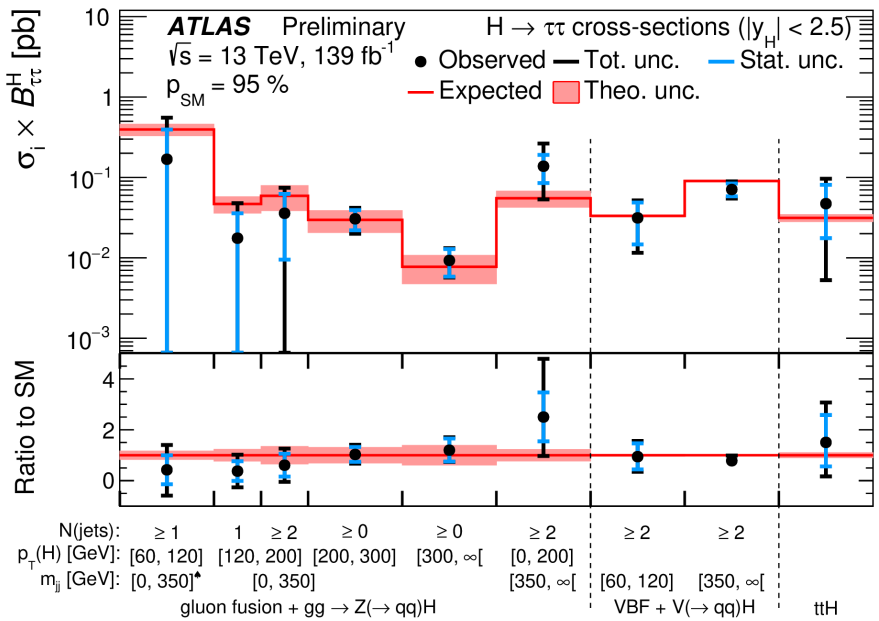
Inclusive cross section ($|y_H| < 2.5$)

$\sigma = 2.89^{+0.21}_{-0.21}(\text{stat})^{+0.37}_{-0.32}(\text{syst})$ pb

$\sigma^{\text{SM}} = 3.14 \pm 0.08$ pb

- Uncertainty improved by factor of 2-2.5 (stat. and syst.)
- Systematic uncertainties dominated by signal modeling

- Measurements of various kinematic regions in ggH, VBF/VH, and all-hadronic $t\bar{t}H$



Significance for ggH

$3.9\,\sigma$ obs. ($4.6\,\sigma$ exp.)

Significance for VBF

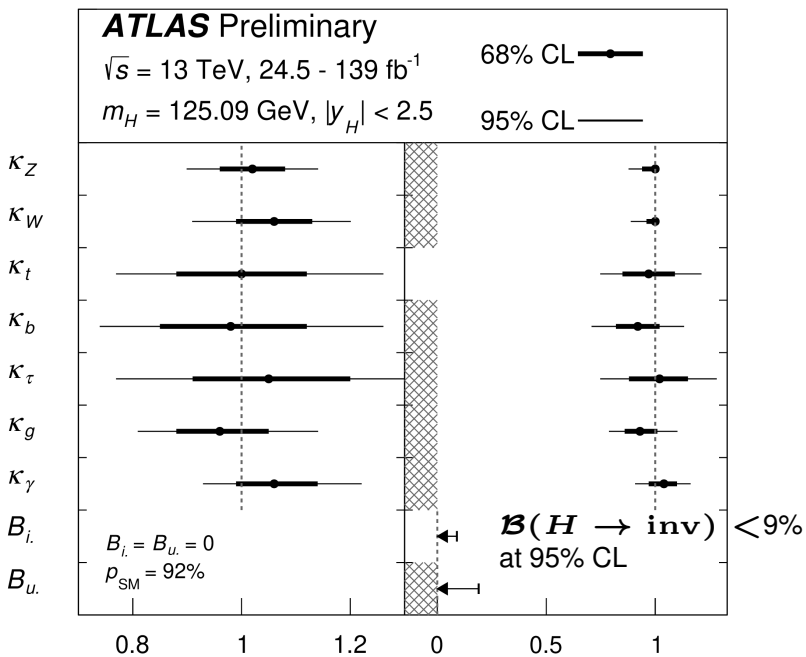
$5.3\,\sigma$ obs. ($6.2\,\sigma$ exp.)

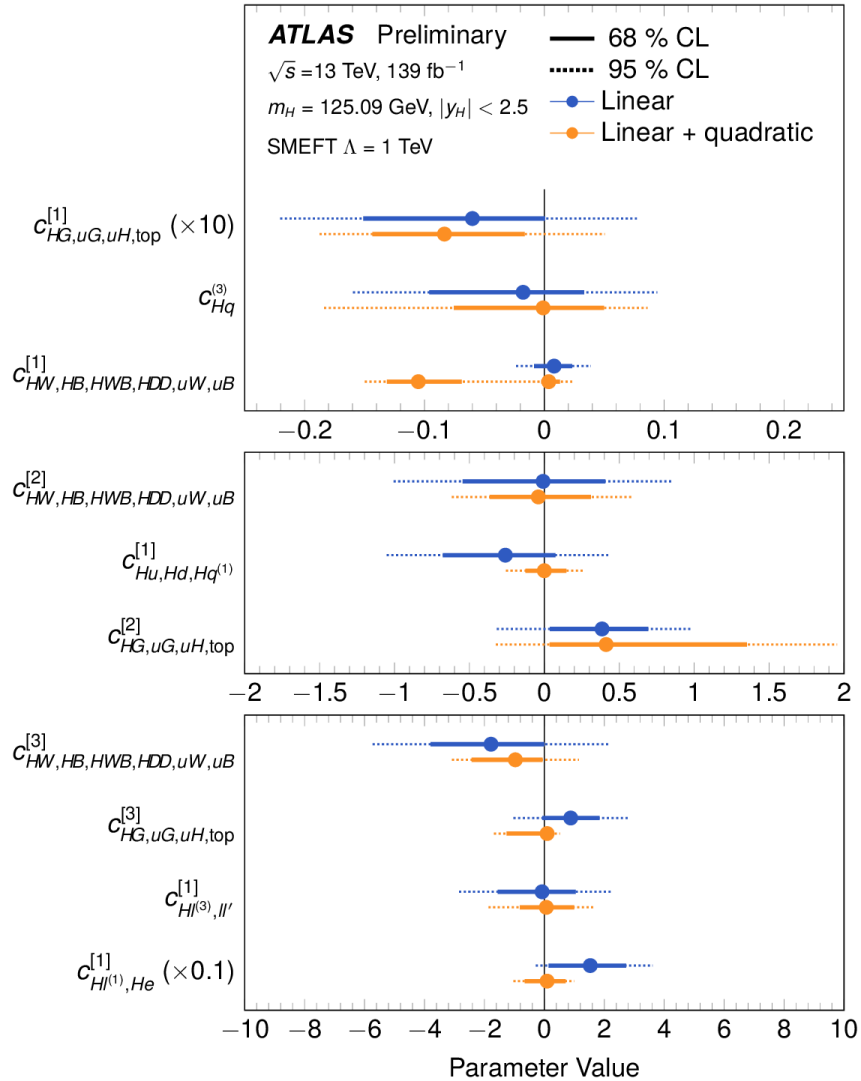
Combination.

[ATLAS-CONF-2020-027, ATLAS-CONF-2020-053]
[CMS: CMS-PAS-HIG-19-005]

Most precise measurements and interpretations obtained from statistical combination of production processes and decay channels

- Interpretation in terms of coupling scaling factors κ
  - ⋆ Typical precision 6-15%
- Interpretation in terms of 10 linear expressions of EFT coefficients in SMEFT





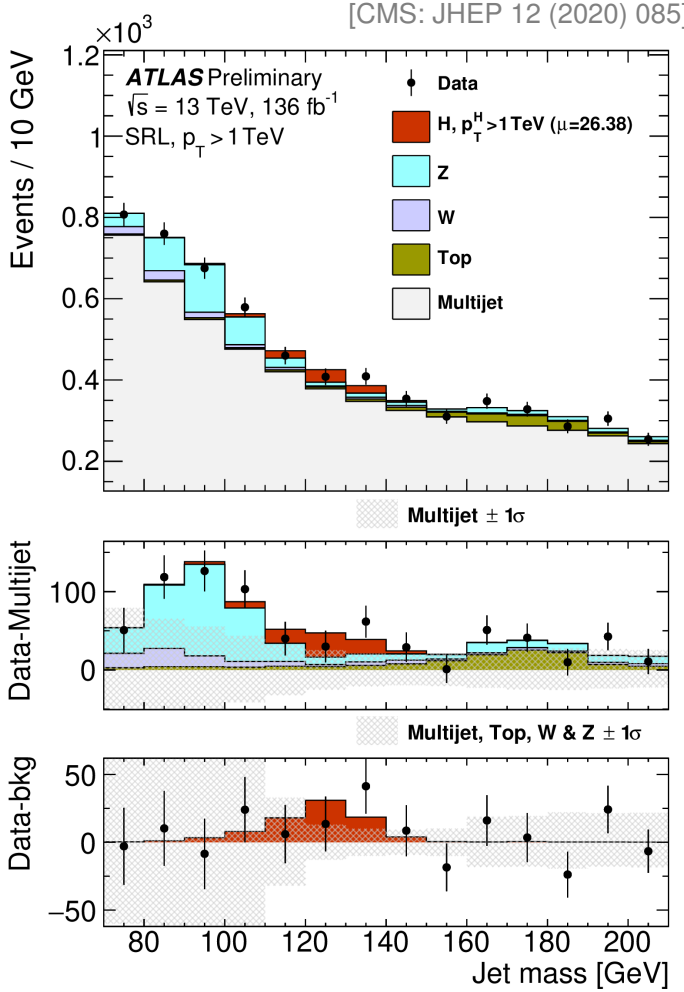
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{c_{HB}}{\Lambda^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \cdots$$

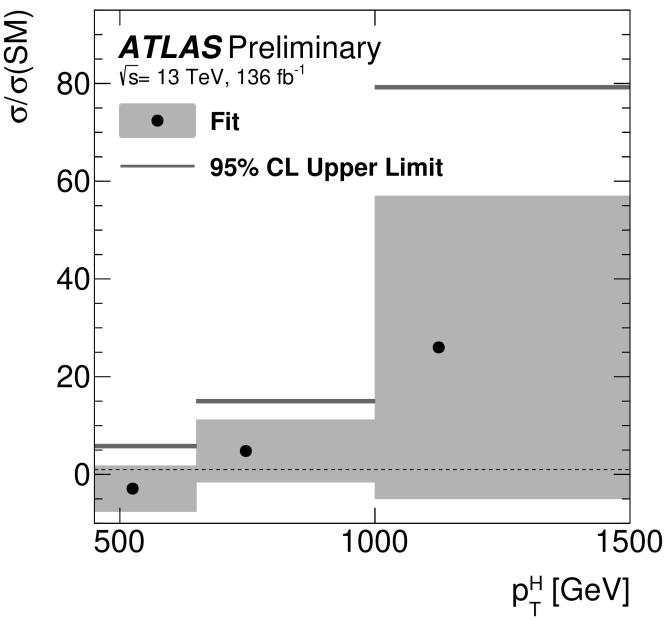
High-p_T Higgs.

[ATLAS-CONF-2021-010]
[CMS: JHEP 12 (2020) 085]

Study extreme regions of phase space in most abundant Higgs decay

- $H \to b\bar{b}$ candidate reconstructed from single large-R jet, b-tagging applied to contained track jets
- Large backgrounds: multijet parametrized using a VR, V+jets and $t\bar{t}$ from CRs
- Analysis method validated with $Z \to b\bar{b}$





Limit on fiducial cross section for p_T >1 TeV
10.3 fb at 95% CL

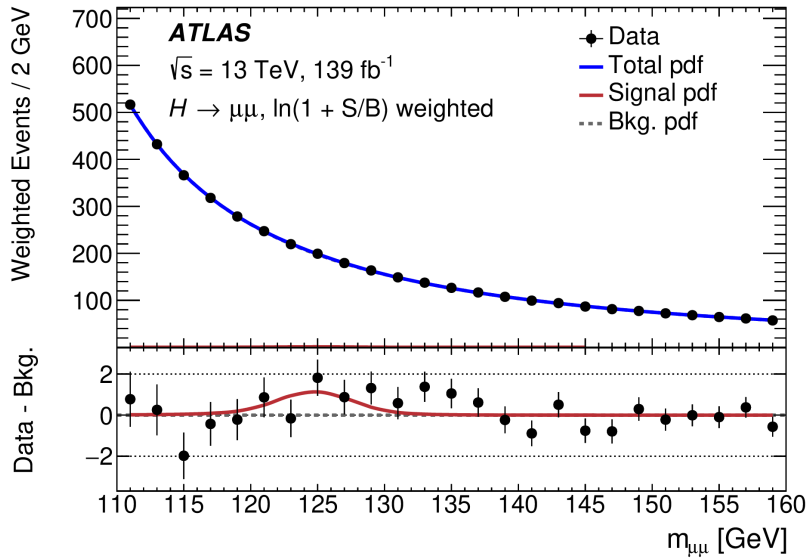
- Differential measurement in several p_T bins

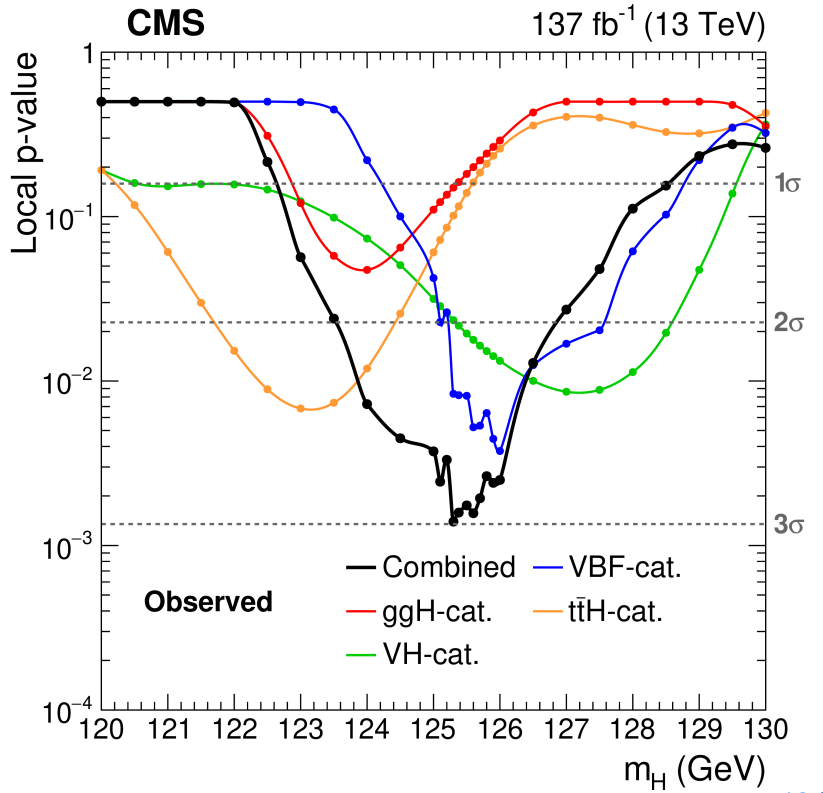
[JHEP 01 (2021) 148, Phys. Lett. B 812 (2021) 135980]

$H \to \mu\mu$.

Higgs couplings to second generation leptons

- Good signal resolution, smoothly falling background dominated by $Z \to \mu\mu$
- $m_{\mu\mu}$ shape parametrized
  - ⋆ Exception: VBF categories use shape of DNN discriminant in CMS





CMS: significance: 3 σ obs. (2.5 σ exp.) at $m_H = 125.38$ GeV

ATLAS: significance: 2 σ obs. (1.7 σ exp.)

- Evidence for Higgs coupling to second generation leptons

[ATLAS-CONF-2021-021]

[CMS: JHEP 03 (2020) 131]

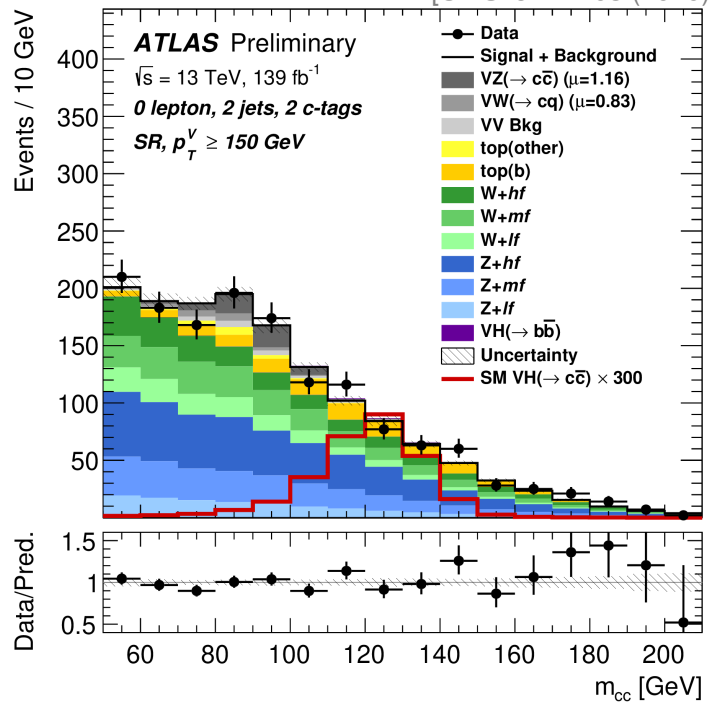
$H \to c\bar{c}$.

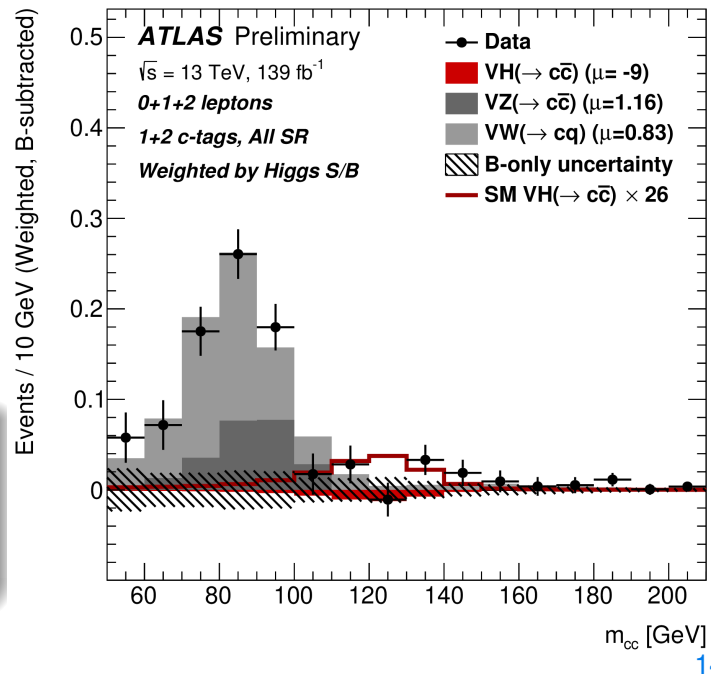
Higgs couplings to second generation quarks

- Target VH production to suppress backgrounds and trigger
- Challenges:
  - ⋆ c-tagging: multivariate algorithm
  - ⋆ Large backgrounds: categorize in terms of number of leptons, number of c-tags, p_{T}^{V}
- Simultaneous measurement of $VW(\to c\bar{q})$ and $VZ(\to c\bar{c})$ as control channels
  - ⋆ 3.8 σ (4.6 σ) and 2.6 σ (2.2 σ) obs. (exp.) significance

Limit on $H \to c\bar{c}$: $26\ (31^{+12}_{-8})$ × SM 95% CL

$|\kappa_c| < 8.5\ (12.4)$ obs. (exp.) at 95% CL





[Phys. Lett. B 819 (2021) 136412]
[CMS: JHEP 11 (2018) 152]

$H \to \ell\ell\gamma$.

Searching for rare decays

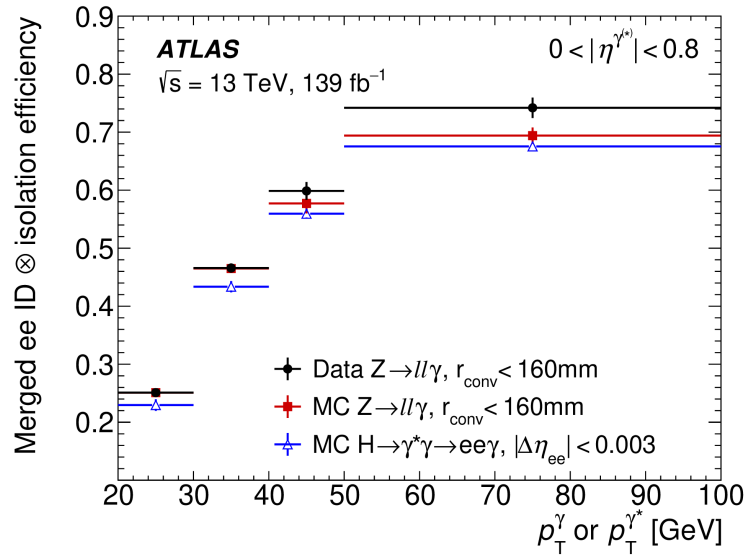
- Low invariant mass range: $m_{\ell\ell} < 30$ GeV, dominated by $H \to \gamma^*\gamma$
- Dedicated trigger and identification of low-$m_{\ell\ell}$ electron pairs
  - ⋆ Overlapping showers in electromagnetic calorimeter
  - ⋆ Performance validated with low-R converted photons
- Background parametrized by analytic functions

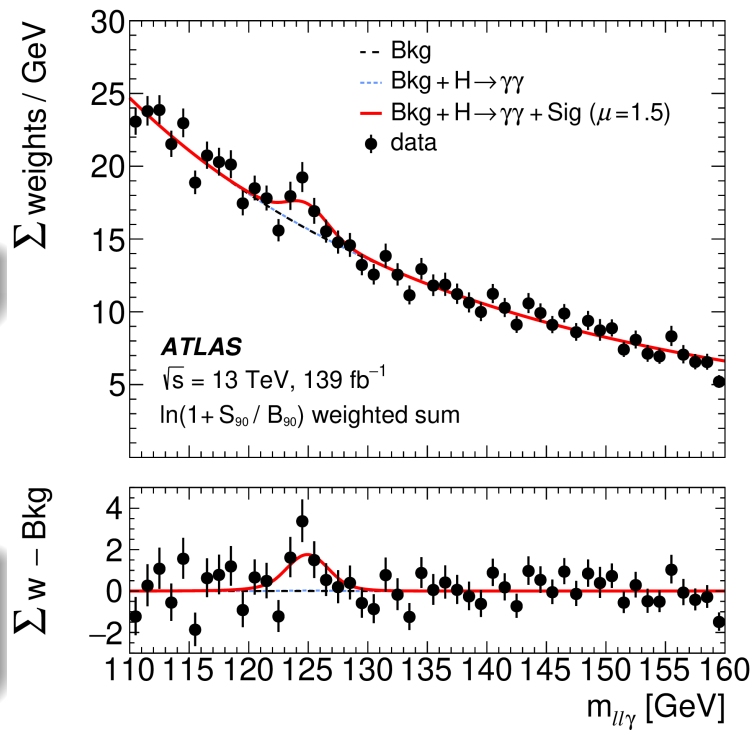
Significance: 3.2 σ obs. (2.1 σ exp.)

- Evidence for $H \to \ell\ell\gamma$

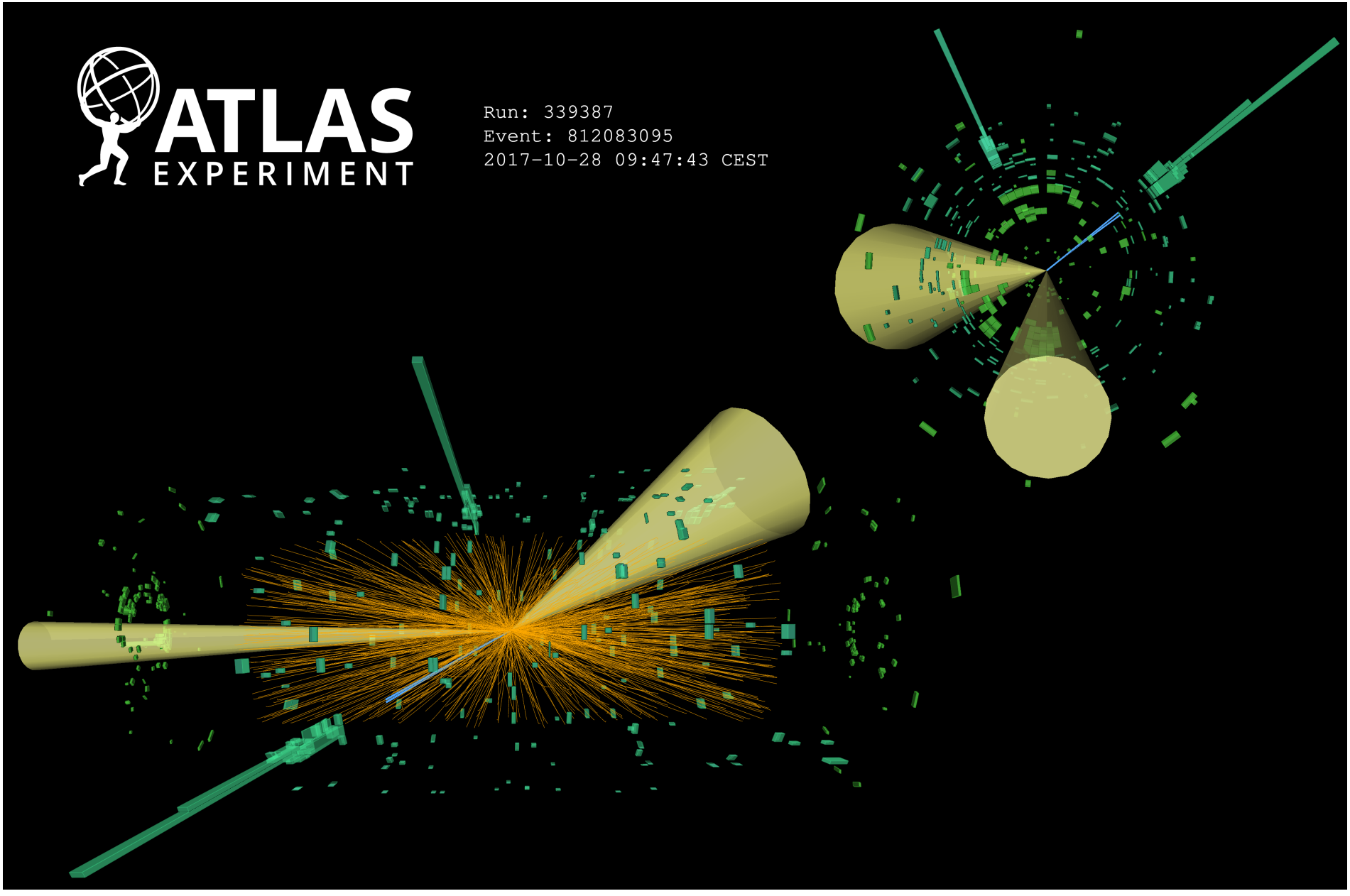
Complementary result for $H \to Z\gamma$ ($m_{\ell\ell} \sim m_Z$)

Significance: 2.2 σ obs. (1.2 σ exp.)





$H \to e^+e^-\gamma$ candidate event.



[arXiv:2104.12152 [hep-ex]]

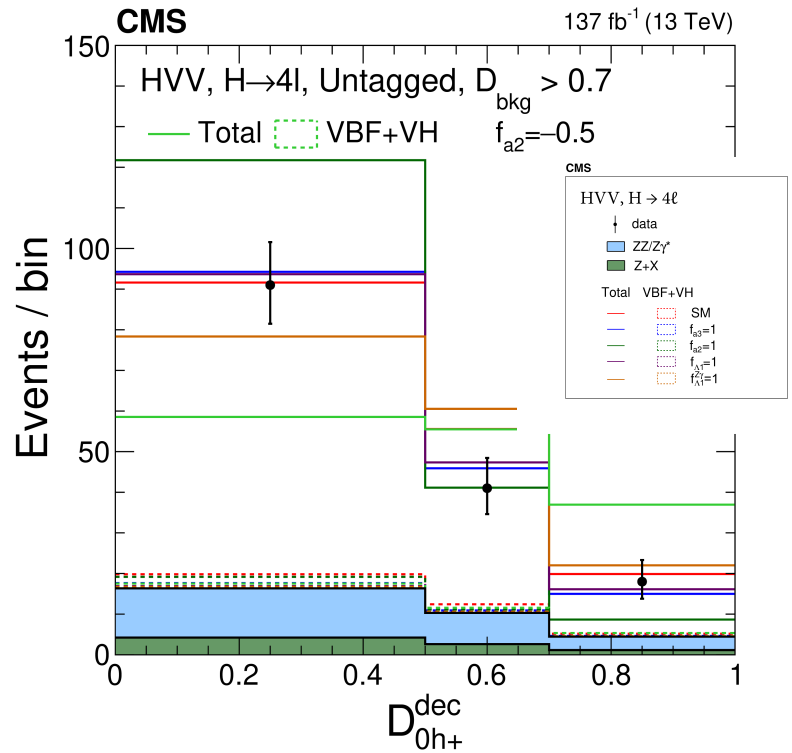
[ATLAS: Eur. Phys. J. C 80 (2020) 957]

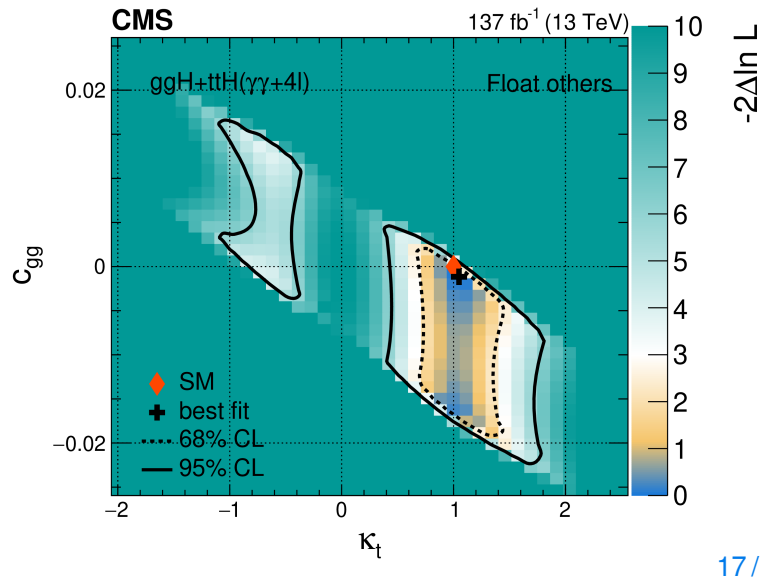
CP and anomalous couplings in $H \to 4\ell$.

Studying the structure of Higgs couplings

- Using ggH+2j, VBF, VH, $t\bar{t}H$ and $H \to 4\ell$ decay
- Two dedicated categorizations:
  - ⋆ effects in HVV vertices: joint analysis of four anomalous couplings
  - ⋆ effects in $Ht\bar{t}$ and effective Hgg vertices: CP even and CP odd couplings
    - ▶ Includes also recent analysis of $t\bar{t}H(\to \gamma\gamma)$

No indication of non-SM couplings





New for this conference

[ATLAS-CONF-2021-029, ATLAS-CONF-2020-052]
[CMS: Eur. Phys. J. C 81 (2021) 13]

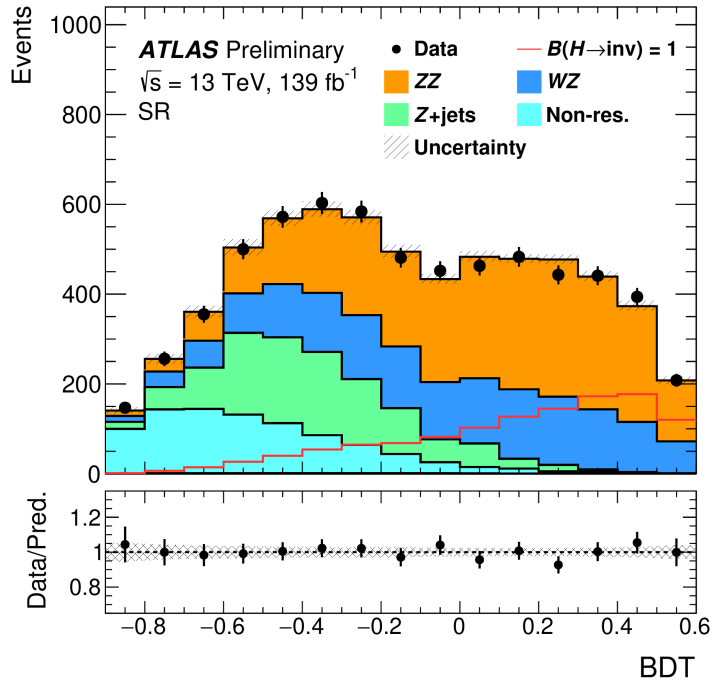
$ZH(\rightarrow\text{inv})$.

Coupling of Higgs to dark matter?

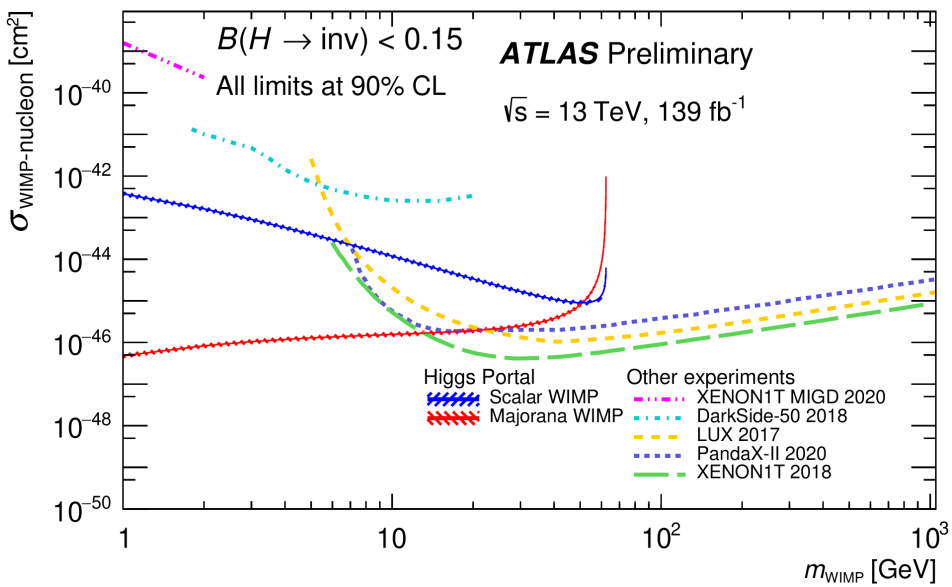
- Experimental signature: $Z \rightarrow \ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$
- ZZ background estimated from $ZZ \rightarrow 4\ell$ CR

$\mathcal{B}(H \rightarrow \mathrm{inv}) <$ 18% obs. (18% exp.) at 95% CL

ATLAS combined limit (Run1+prev. full Run2):
$\mathcal{B}(H \rightarrow \mathrm{inv}) <$ 11% obs. (11% exp.) at 95% CL



- Interpretation as limit on WIMP-nucleon scattering in Higgs portal model
  - ⋆ DM assumed to be scalar or Majorana fermion
- Complementary to direct DM searches



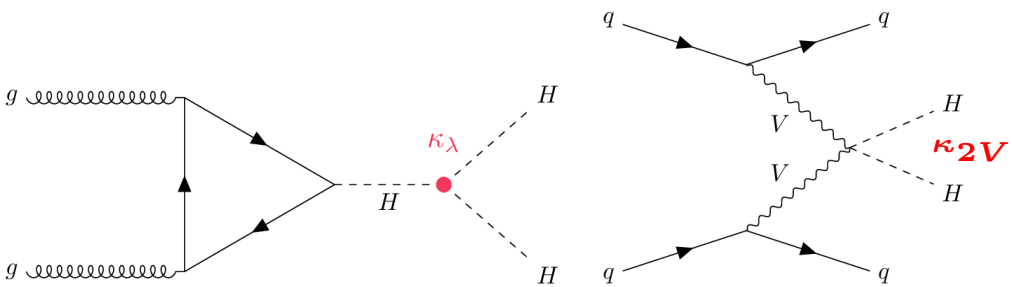
[CMS-PAS-HIG-20-005]

[ATLAS: JHEP 07 (2020) 108, JHEP 01 (2019) 030]

$HH \to 4b$.

Testing the Higgs potential with largest $\mathcal{B} = 34\%$

- HH produced via ggH and VBF
  - ⋆ $\sigma(pp \to HH)^{\mathrm{SM}} = 32.8$ fb
- Sensitivity to Higgs self-coupling and $VVHH$ coupling

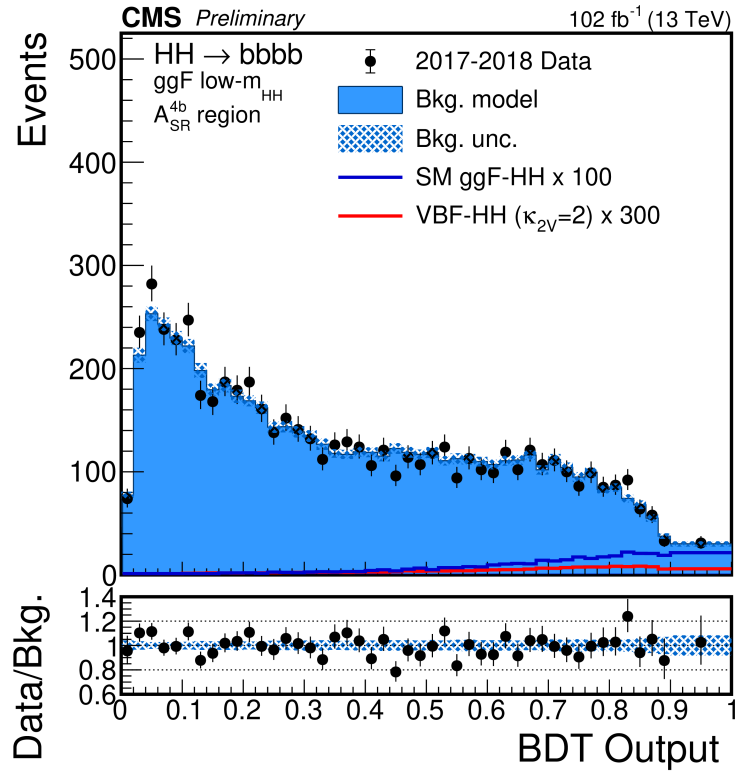


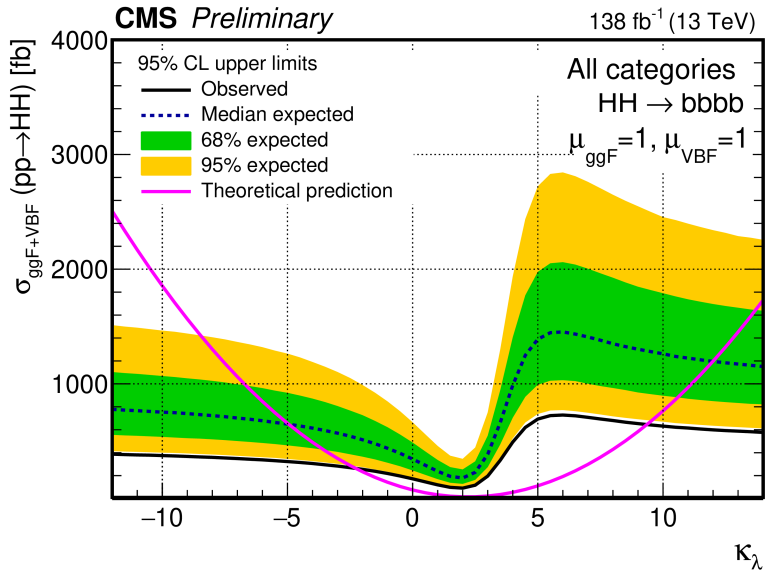
- Large and difficult backgrounds from multijet and $t\bar{t}$ estimated from CRs

$\sigma(pp \to HH \to 4b) < 3.6\ (7.3) \times$SM obs. (exp.)

$-2.3 < \kappa_\lambda < 9.4$ ($-5.0 < \kappa_\lambda < 12.0$) and $-0.1 < \kappa_{2V} < 2.2$ ($-0.4 < \kappa_{2V} < 2.5$)

all at 95% CL



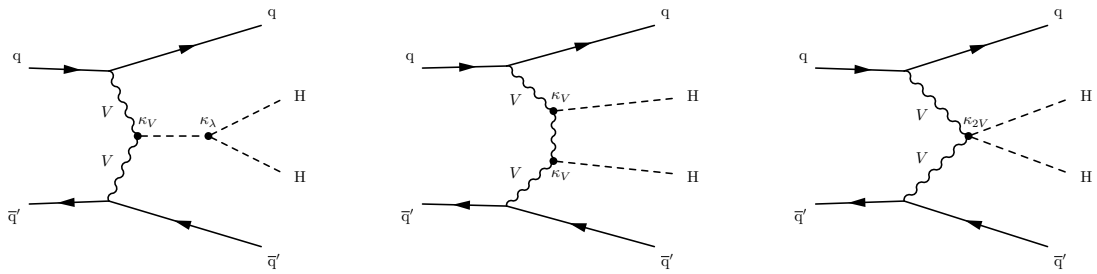


New for this conference

[CMS-PAS-B2G-21-001]

VBF $HH \to 4b$ boosted.

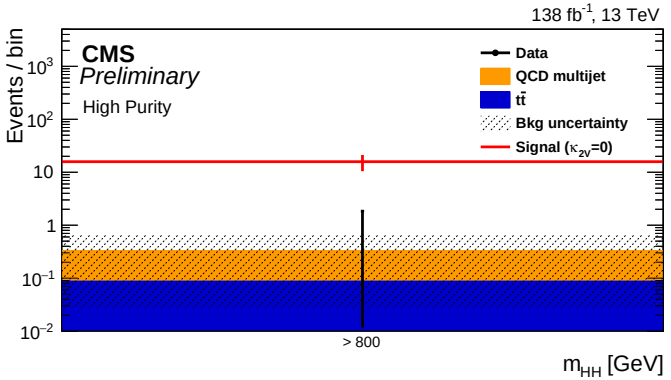
Testing the $VVHH$ coupling in boosted topology

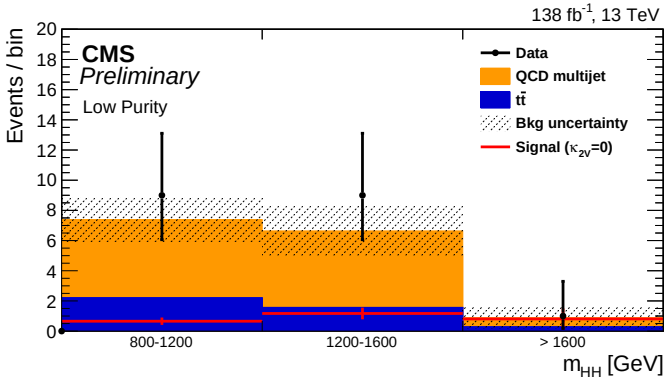


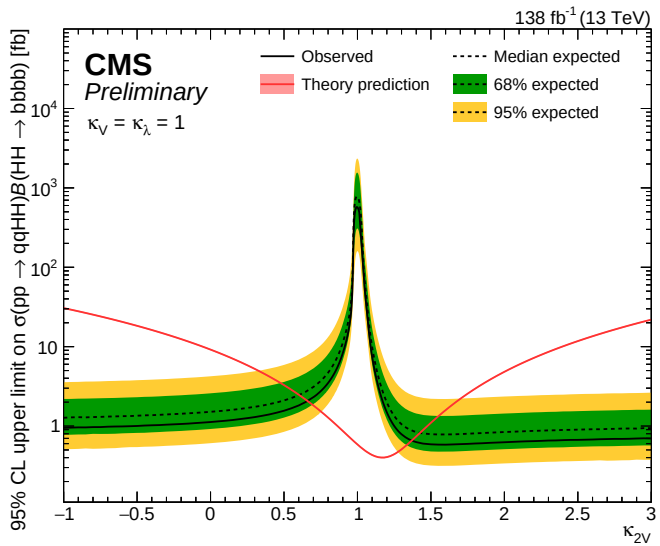
- $H \to b\bar{b}$ candidates reconstructed from large-R jets
- $H \to b\bar{b}$ identification and mass regression with graph convolutional neural networks
- Multijet and $t\bar{t}$ backgrounds estimated from CRs and MC
- Data agree with background-only hypothesis

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

$\kappa_{2V} = 0$ excluded at more than 95% CL for $\kappa_V > 0.5$ and all other $\kappa = 1$





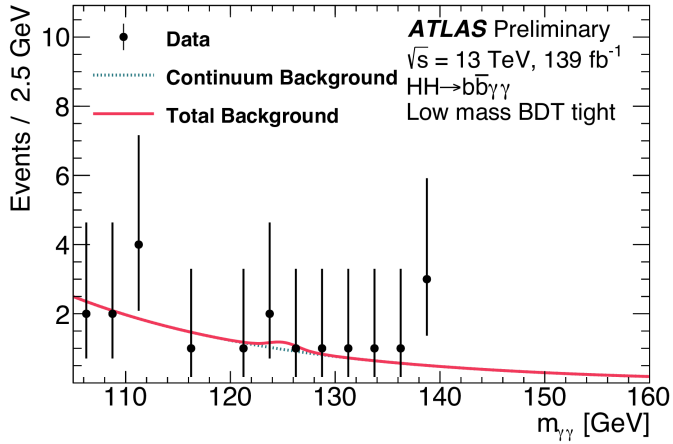


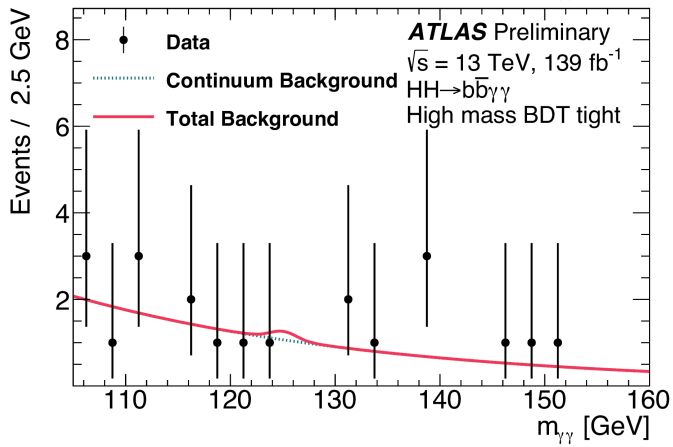
[ATLAS-CONF-2021-016]
[CMS: JHEP 03 (2021) 257]

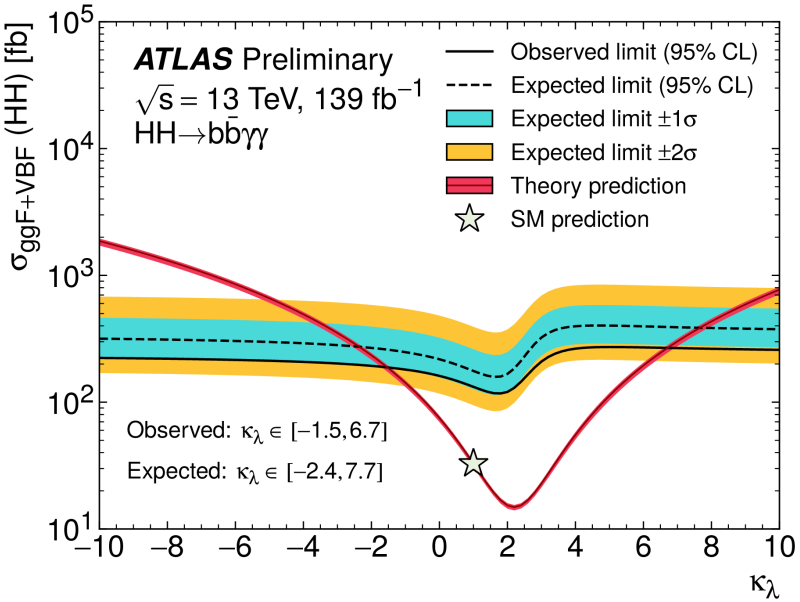
$HH \to b\bar{b}\gamma\gamma$.

Very rare, but cleaner final state ($\mathcal{B} = 0.26\%$)

- HH produced via ggH and VBF
- Events categorized by $m_{b\bar{b}\gamma\gamma}$ and a multivariant discriminant
  - ⋆ Low and high $m_{b\bar{b}\gamma\gamma}$ regions sensitive to large and smaller $|\kappa_\lambda|$
- Signal and background parametrized in $m_{\gamma\gamma}$







$\sigma(pp \to HH \to b\bar{b}\gamma\gamma) < 4.1\ (5.5) \times$SM
obs. (exp.) at 95% CL

$-1.5 < \kappa_\lambda < 6.7$ obs.
$(-2.4 < \kappa_\lambda < 7.7$ exp.) at 95% CL

New for this conference [ATLAS-CONF-2021-030, ATL-PHYS-PUB-2021-031]
[CMS: Phys. Lett. B 778 (2018) 101]

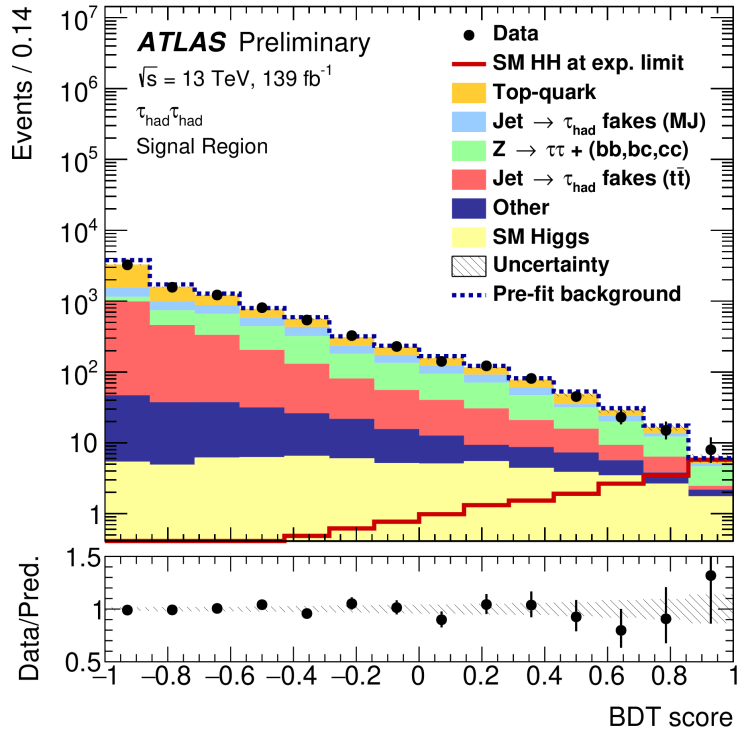
$HH \to b\bar{b}\tau\tau$.

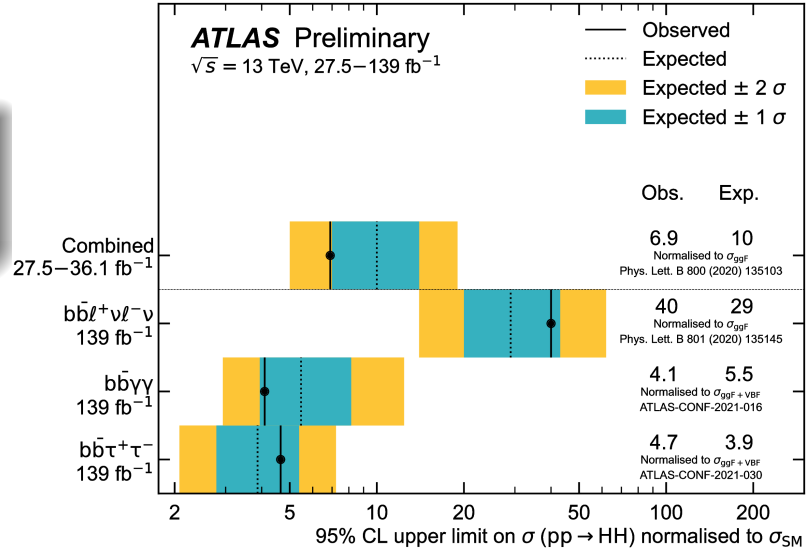
Sizeable branching fraction, not too large backgrounds ($\mathcal{B} = 7.3\%$)

- Using $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{lep}}$ decay channels with significantly improved τ_{had} efficiencies
- Variety of sizeable backgrounds: $t\bar{t}$, V+jets, VV, multijet, single Higgs, fake τ
  - ⋆ Estimated from simulation and data
- Signal extracted from fits to multivariate discriminants

$\sigma(pp \to HH \to b\bar{b}\tau\tau) < 4.7\ (3.9) \times \text{SM}$
obs. (exp.) at 95% CL

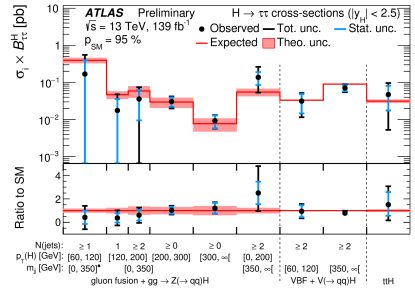
- Limits from new $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau\tau$ already better than 36 fb^{-1} combination

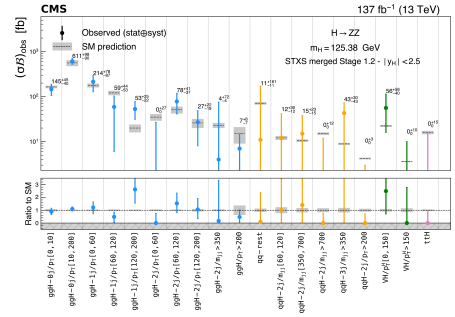


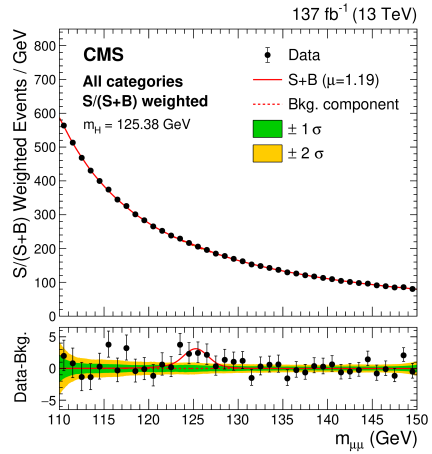


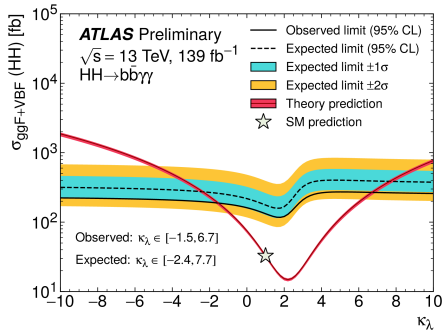
Conclusion.

- Recent measurements and searches use full Run2 dataset
- Measurements in main production processes and decay channels becoming more precise and more differential
  - ⋆ Inclusive cross section measured with 9% precision (in $H \to 4\ell$)
  - ⋆ Probing Higgs p_T >1 TeV (in $H \to b\bar{b}$)
- Searches for decays to second-generation fermions and other rare decays starting to be sensitive
  - ⋆ Evidence for $H \to \mu\mu$ and $H \to \ell\ell\gamma$
- Searches for HH production getting closer to SM predictions
  - ⋆ Individual channels limit cross section to a few times SM









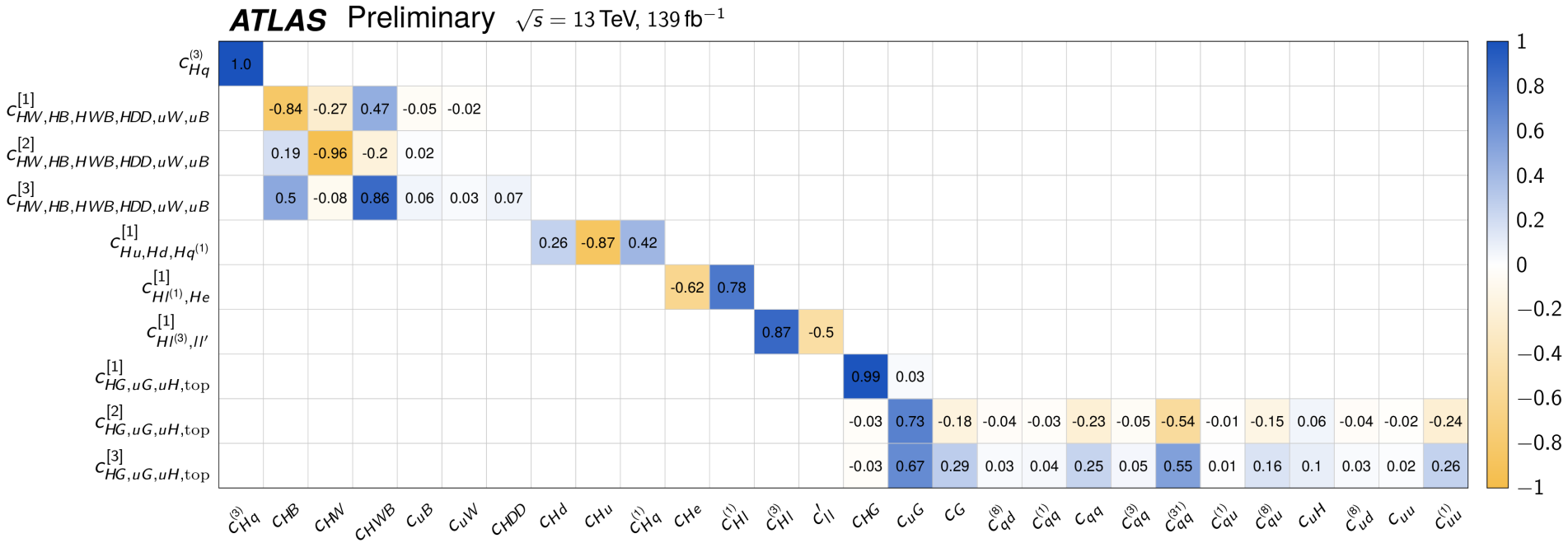
SM and BSM Higgs talks in parallel sessions

- Measurements and interpretations of Simplified Template Cross Sections, differential and fiducial cross sections in Higgs boson decays to two photons with the ATLAS detector (Eleonora Rossi) Monday morning
- Measurements and interpretations of Simplified Template Cross Sections and differential and fiducial cross sections in Higgs boson decays to two W bosons with the ATLAS detector (Yun-Ju Lu) Monday morning
- Measurements and interpretations of Simplified Template Cross Sections, differential and fiducial cross sections in Higgs boson decays to four leptons with the ATLAS detector (Christos Anastopoulos) Monday morning
- Measurements of Higgs boson cross sections and differential distributions in bosonic final states (CMS) (Jonathon Langford) Monday morning
- Combined measurements of Higgs boson production and decays with the ATLAS detector (Yanping Huang) Monday morning
- Studies of the CP properties of the Higgs boson at the ATLAS experiment (William Leight) Monday morning
- Measurements and interpretations of Higgs boson production using decays to two b-quarks with the ATLAS detector (Karol Krizka) Monday afternoon
- Higgs boson coupling to second generation fermions with the ATLAS detector (Marko Stamenkovic) Monday afternoon
- Measurements of Higgs production and decay in final states involving quarks (CMS) (Aliya Nigamova) Monday afternoon
- Measurements of Higgs boson production in decays to two tau leptons with the ATLAS detector (Michaela Mlynarikova) Monday afternoon
- Measurements of Higgs boson cross sections and differential distributions in leptonic final states (CMS) (Andrew Loeliger) Monday afternoon
- Search for rare decays of the Higgs boson with the ATLAS detector (Artem Basalaev) Monday afternoon
- Measurements of Higgs boson properties and couplings at CMS (Ulascan Sarica) Monday afternoon
- Searches for rare Higgs boson decays (CMS) (Silvio Donato) Monday afternoon
- Searches for Higgs invisible (CMS) (Vukasin Milosevic) Monday afternoon
- Searches for Higgs boson pair production with the full LHC Run-2 dataset in ATLAS (Valentina Cairo) Tuesday morning
- Searches for non-resonant and resonant HH production at CMS (Agni Bethani) Tuesday morning
- Searches for additional Higgs bosons at CMS (Mariarosaria D'Alfonso) Monday afternoon
- Searches for additional Higgs bosons at ATLAS (Maria Florencia Daneri) Monday afternoon
- Searches for exotic decays of the Higgs boson with the ATLAS detector (Ben Nachman) Monday afternoon
- Searches for Higgs exotic decays and additional (pseudo)scalars at CMS (Antoine Lesauvage) Monday afternoon

I show here a selection of SM Higgs results, more and more details can be found in parallel session talks and posters on under ATLAS public results and CMS public results.

Backup

EFT basis rotation.



- Rotation of EFT coefficients guided by physics and experimental sensitivity
- Experimental sensitivity estimated from Fisher information matrix derived from covariance matrix of STXS measurements

VBF $HH \to 4b$ boosted 2d results.

- $\kappa_{2V} = 0$ at more than 95% CL for $\kappa_V > 0.5$ and all other $\kappa = 1$