FPCP2023: 21st Conference on Flavor Physics and CP Violation

Higgs flavor and lepton flavor violation in Higgs

Ka Wa, Ho [*]
On behalf of the ATLAS and CMS collaboration

[*] University of Notre Dame

Higgs Flavor

UNIVERSITY OF NOTRE DAME

Higgs Flavor

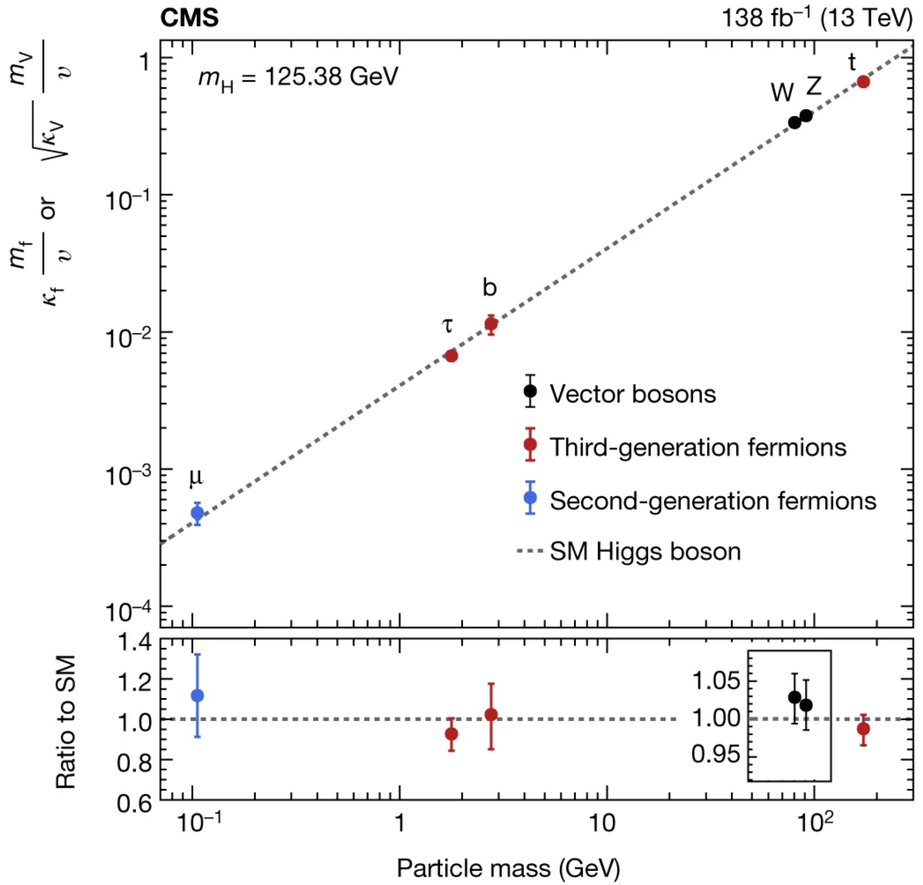
ATLAS EXPERIMENT

CMS

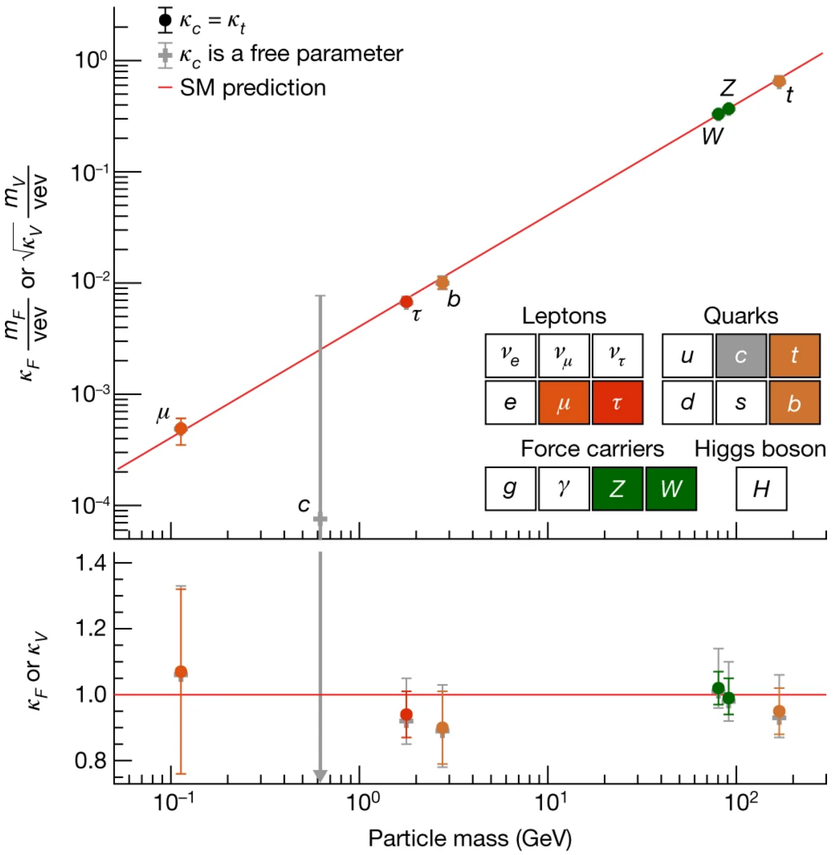
- Couplings of the Higgs boson (H) with (charged) fermions have been studied extensively since its discovery
- Couplings with the 3rd generation fermions ($t,\ b,\ \tau$) have been measured to be consistent with the Standard Model (SM) prediction
- There is also progress on the search for the couplings with the 1st and 2nd generation fermions:
  - First evidence of $H \to \mu^+\mu^-$ is established
  - Constraints on $H \to e^+e^-$ and $H \to c\bar{c}$ have improved significantly
- Today's talk will focus on analyses of proton-proton collision data of ~138 fb^{-1} collected by CMS and ATLAS during Run II of the LHC at $\sqrt{s} = 13$ TeV

Combination Results

Nature 607 (2022) 60



Nature 607 (2022) 52



- The combination results also set a 95% CL observed limit on the branching ratio of undetected H decays to be:
  - < 0.16 from CMS
  - < 0.12 from ATLAS

Combine fit of the H couplings to μ, τ, b, W, Z, t (, and c) relative to the SM predictions (κ_i), assuming no invisible or undetected beyond-the-SM (BSM) H decays. Result of the Run II data collected by the CMS (ATLAS) experiment is shown on the left (right).

Search for $H \rightarrow \mu^+\mu^-$

Search for $H \rightarrow \mu^+\mu^-$: Event Topology

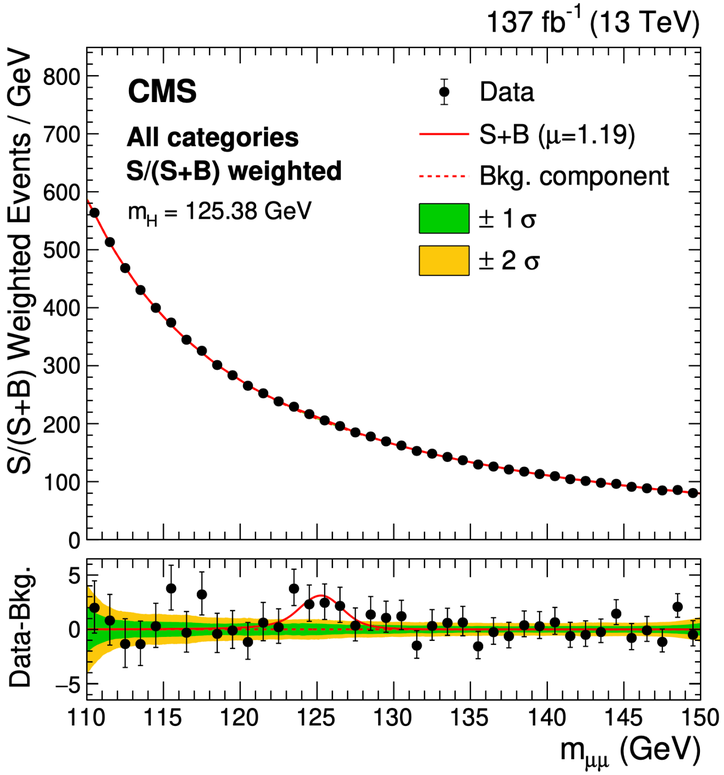
- Both CMS (JHEP 01 (2021) 148) and ATLAS (Phys.Lett.B 812 (2021) 135980) focused on similar production modes:

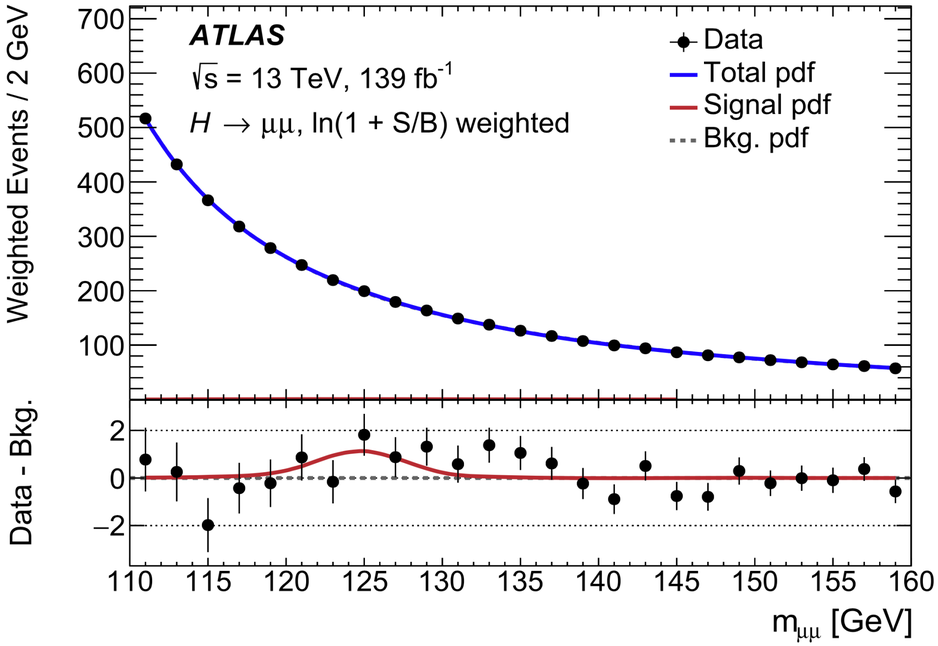
  1. ggH, VBF dominated by Drell-Yan (DY) backgrounds
  2. $Z(ll)/W(l\nu)H$, where $l = e, \mu$ dominated by WZ and ZZ backgrounds
  3. $t\bar{t}H$ (hadronic, semi-leptonic, fully-leptonic) dominated by $t\bar{t}$ and $t\bar{t}Z$ backgrounds

, with hadronic $t\bar{t}H$ being a unique channel in the CMS search

Search for $H \to \mu^+\mu^-$: Strategies

- General:
  - A “bump-hunting” search in the $m_{\mu\mu}$ spectrum
  - Categories are optimized with Boosted Decision Trees (BDT)
  - Background approximated from data directly
- VBF in CMS:
  - Deep neural network (DNN) to identify signal-like events
  - Maximum likelihood (ML) fit of the DNN score of the simulated signal and backgrounds to the data

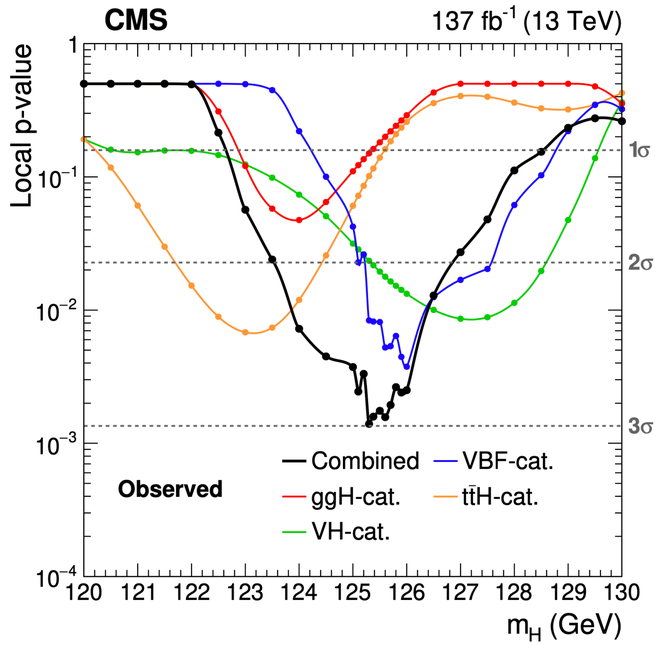




Search for $H \to \mu^+\mu^-$: Results

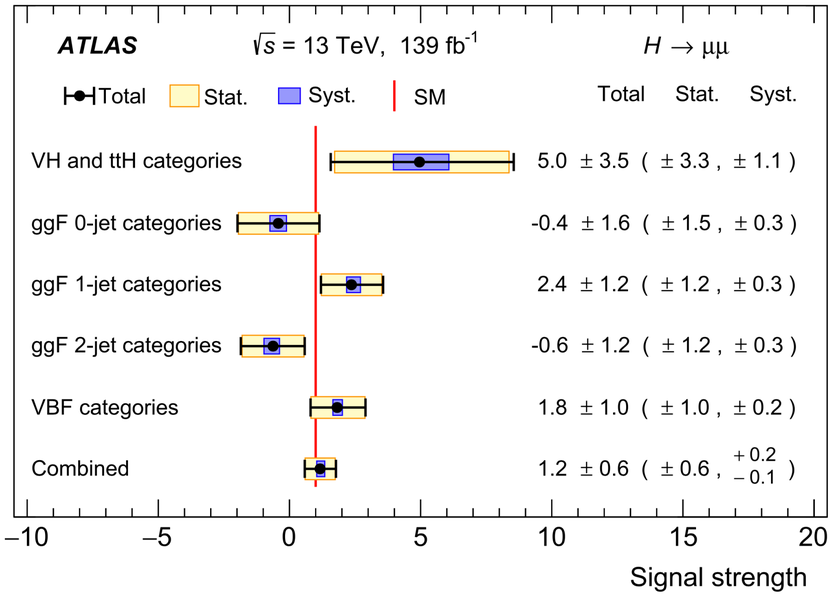
CMS (JHEP 01 (2021) 148)

- An observed (expected) excess of 3.0 (2.5) σ significance is reported, establishing the first evidence of $H \to \mu^+\mu^-$
- A combination with the 7 and 8 TeV data gives a measured signal strength of $1.19^{+0.40}_{-0.39}\ (\text{stat})\ ^{+0.15}_{-0.14}\ (\text{syst})$ relative to the SM prediction



ATLAS (Phys.Lett.B 812 (2021) 135980)

- An observed (expected) excess of 2.0 (1.7) σ significance is reported
- Best fit of the signal strength is $1.2 \pm 0.6\ (\text{stat})\ ^{+0.2}_{-0.1}\ (\text{syst})$ relative to the SM prediction



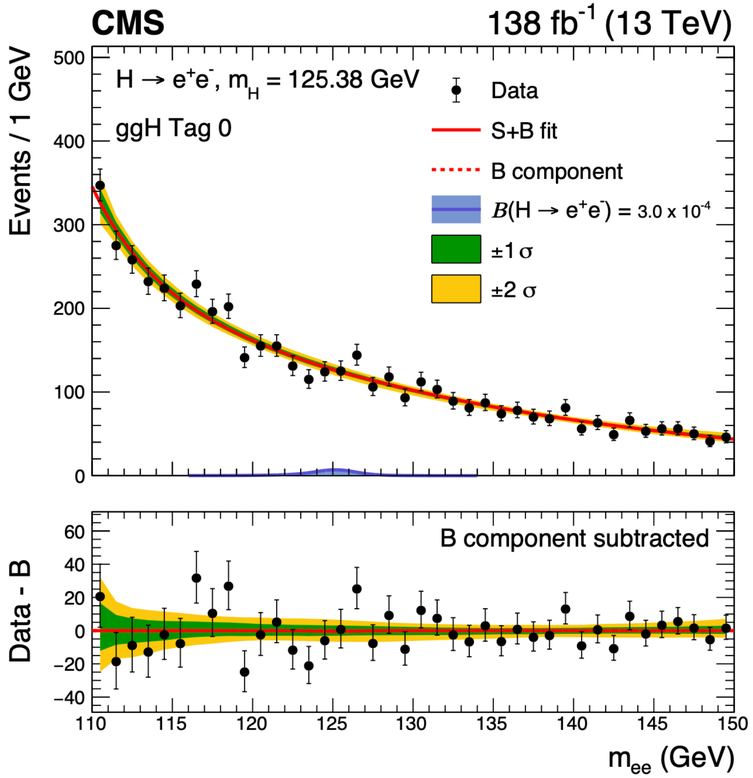
Search for $H \to e^+e^-$

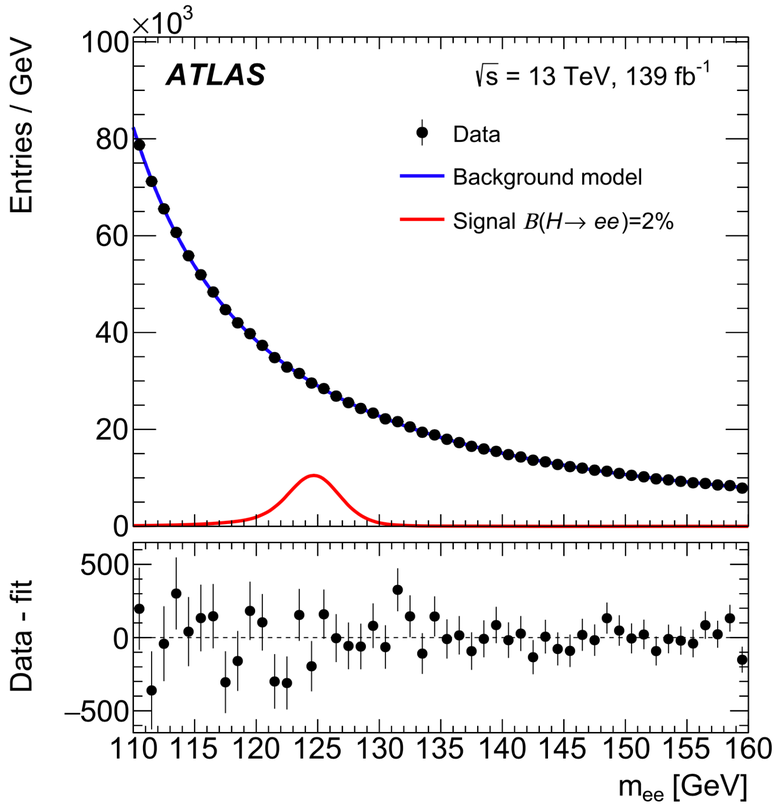
Search for $H \to e^+e^-$

- The SM predicted branching ratio (BR) of $H \to e^+e^-$ is around 5×10^{-9} while only ~8 million H were produced during Run II of the LHC
- A direct search for this decay remains important as BSM scenarios could enhance the BR
- Both the CMS (CERN-EP-2022-131) and ATLAS (Phys.Lett.B 801 (2020) 135148) searches focused on the ggH and VBF modes
- Backgrounds are dominated by DY events, followed by $t\bar{t}$ and diboson events

Search for $H \to e^+e^-$: Strategies

- Search strategies are similar to $H \to \mu^+\mu^-$
- CMS: categories defined with dedicated BDTs for a ggH and a VBF-enriched region
- ATLAS: categories defined to separate regions of different m_{ee} resolution





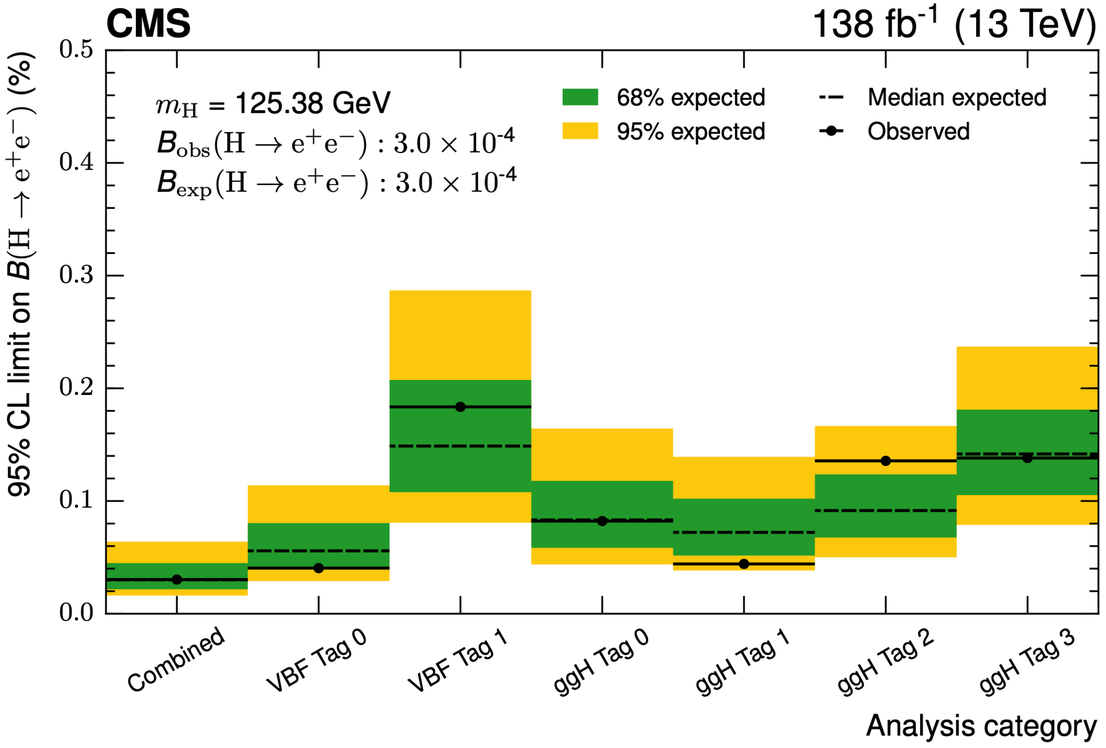
Search for $H \to e^+e^-$: Results

CMS (CERN-EP-2022-131)

- The observed (expected) 95% CL limit is set to be $B(H \to e^+e^-) < 3.0 \times 10^{-4}$ (3.0×10^{-4}), an order of magnitude improvement to the result from Run I at $\sqrt{s} = 8$ TeV with an integrated luminosity of 19.7 fb^{-1}

ATLAS (Phys.Lett.B 801 (2020) 135148)

- The observed (expected) 95% CL limit is set to be $B(H \to e^+e^-) < 3.6 \times 10^{-4}$ (3.5×10^{-4}), the first result ever from ATLAS



Search for $H \to c\bar{c}$

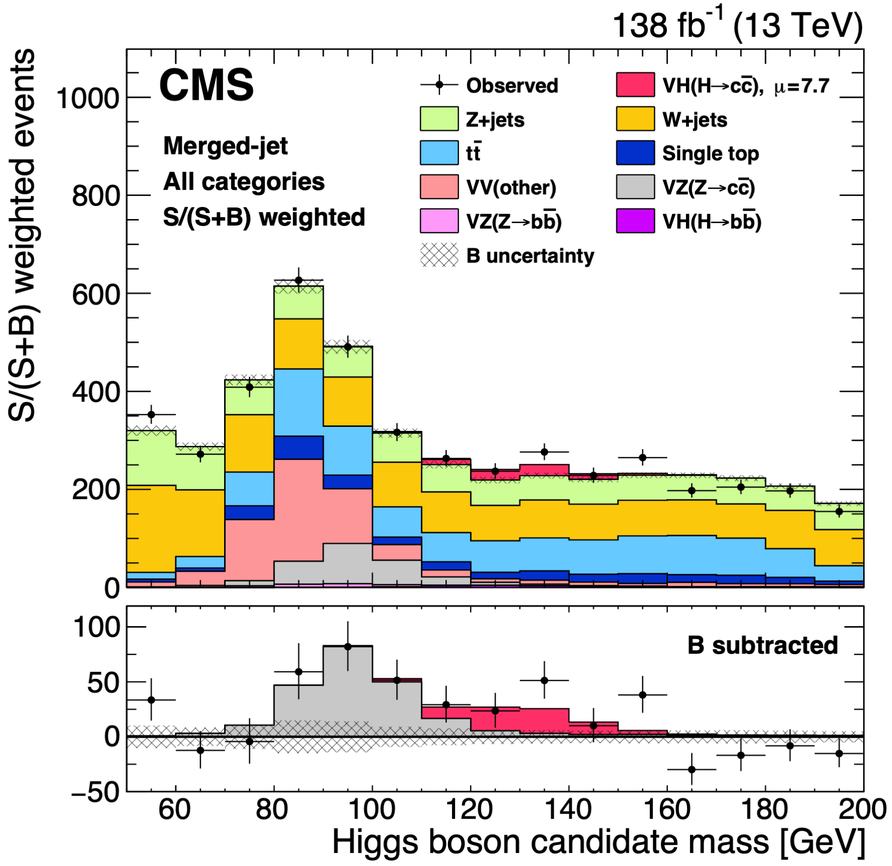
Search for $H \to c\bar{c}$

- A very challenging channel because of the small branching ratio (~2.89%) and the difficulty to distinguish charm jets in the hadronic environment at the LHC
- Both CMS (CERN-EP-2022-0811) and ATLAS (Eur.Phys.J.C (2022) 82:717) have published search for $VH(\to c\bar{c})$ targeting the $Z \to ll, Z \to \nu\nu, W \to lv$ channels, where $l = e, \mu$
- The dominated background are $t\bar{t}$ and $V+\text{jets}$ events

Search for $VH(\rightarrow c\bar{c})$: Strategies

CMS (CERN-EP-2022-0811)

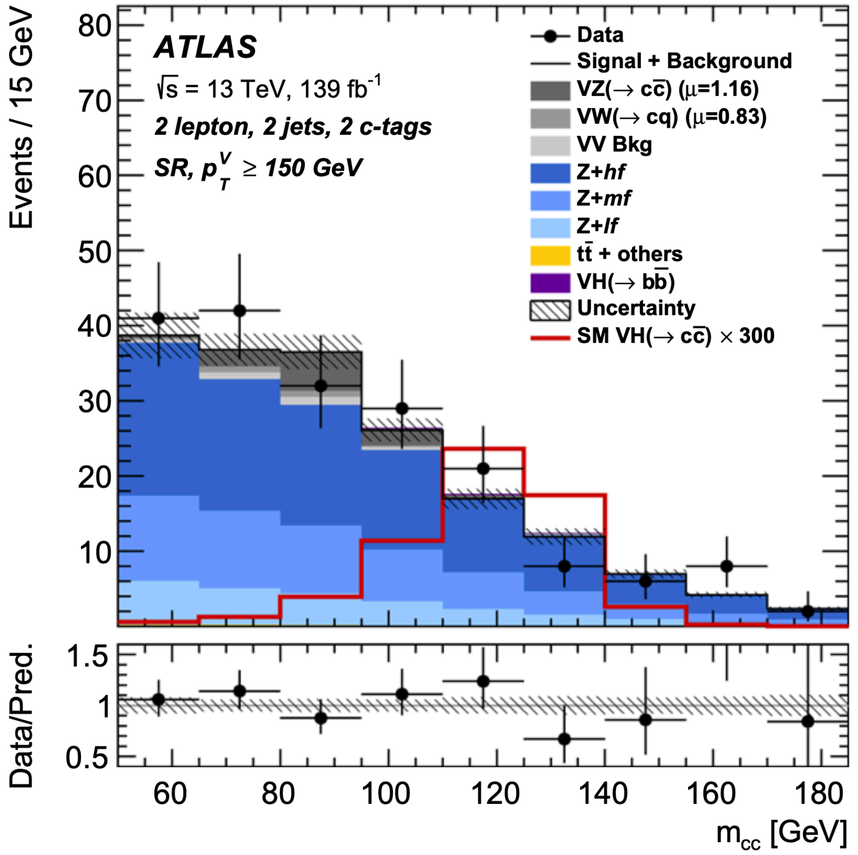
- Anti-k_T (AK) jet with $R = 1.5$ for $p_T^{H_{reco}} > 300$ GeV:
  - H is identified with a dedicated $c\bar{c}$ tagger
  - A ML fit of the signal strength is performed along the reconstructed Higgs mass
- 2 AK jets with $R = 0.4$ (AK4) with $p_T^{jet} > 25$ GeV:
  - H is reconstructed from two jets passing a c vs light and a c vs b tagger
  - A ML fit is performed along a dedicated BDT trained in each channel



Search for $VH(\rightarrow c\bar{c})$:

ATLAS (Eur.Phys.J.C (2022) 82:717)

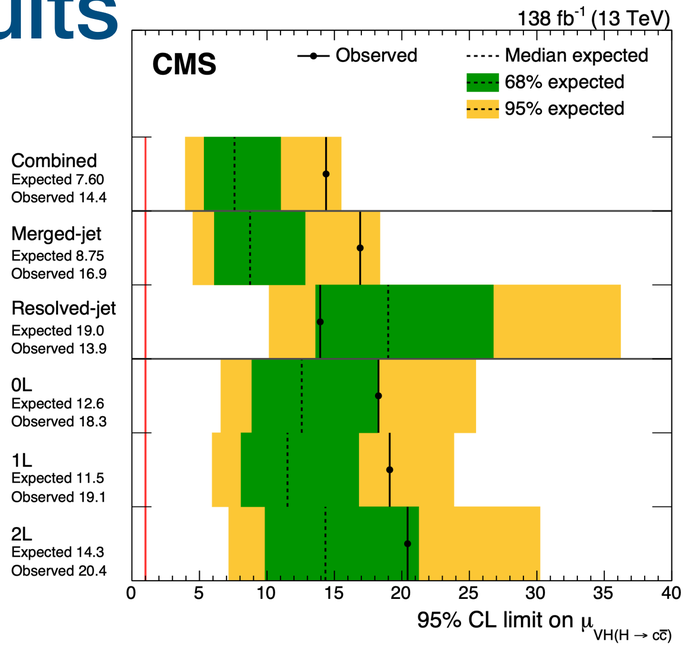
- The H candidate is reconstructed from 2 AK4 jets, with at least one passing a dedicated c tagger and not identified as a b-jet
- The reconstructed H candidate is required to have $p_T^H > 75$ GeV
- Events are categorized into 16 signal and 28 control regions (CRs) designed to constrain the V+jets, $t\bar{t}$, and single-top background
- A binned ML fit to the $m_{c\bar{c}}$ distribution is performed to extract the signal strength of $VH(\rightarrow c\bar{c})$, $VW(\rightarrow cq)$, and $VZ(\rightarrow c\bar{c})$ simultaneously



Search for $VH(\rightarrow c\bar{c})$: Results

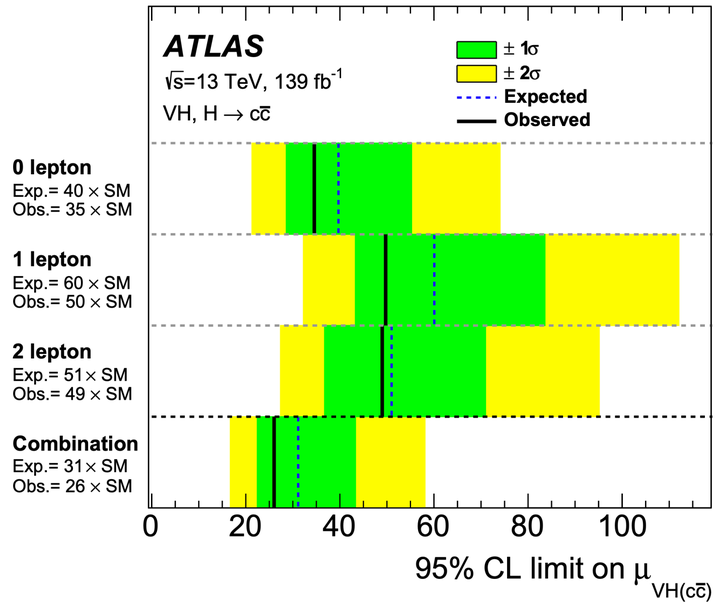
CMS (CERN-EP-2022-0811)

- A 95% CL observed (expected) upper limit on the signal strength of 14 (7.6) times the SM expectation is reported
- Analysis strategies are validated with a first observation of $VZ(\rightarrow c\bar{c})$ at a hadron collider in agreement with the SM with a significance of 5.7 σ



ATLAS (Eur.Phys.J.C (2022) 82:717)

- A 95% CL observed (expected) limit on the signal strength of 26 (31) times the SM expectation is reported
- A factor of 5 of improvement relative to the previous search at ATLAS with data from 2015 - 2016 of 36 fb^{-1}



Lepton Flavor Violation in Higgs

Lepton Flavor Violation in Higgs

- In the SM, H only couples to fermions of the same flavor through the diagonal Yukawa matrices
- In many BSM scenarios, such as
    1. the Type-III 2 Higgs Doublet model (2HDM) or
    2. effective field theory with dimension-6 operator

  tree-level lepton flavor violating (LFV) decays of $H \to \mu^{\pm}\tau^{\mp}/e^{\pm}\tau^{\mp}/e^{\pm}\mu^{\mp}$ could arise through non-diagonal Yukawa matrices
- The LHC provides opportunities to probe these exotic decays directly

Search for $H \rightarrow e^{\pm}\tau^{\mp}/\mu^{\pm}\tau^{\mp}$

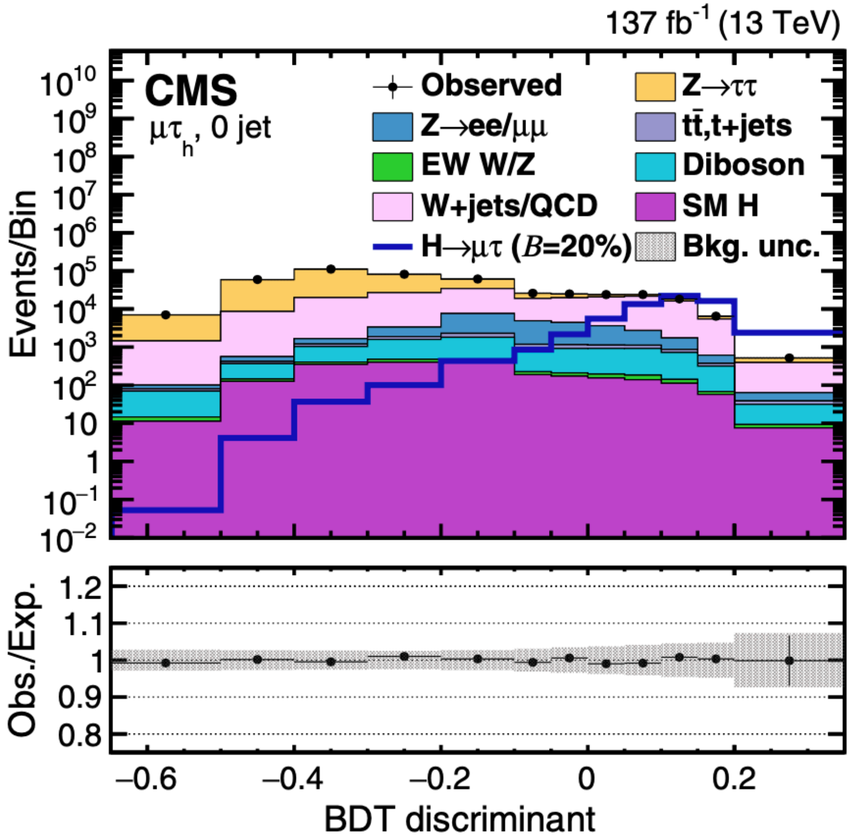
$H \to e^{\pm}\tau^{\mp}/\mu^{\pm}\tau^{\mp}$: Event Topology

- CMS focused on the ggH and VBF modes, while ATLAS considered also the contributions from VH
- Both CMS and ATLAS focused on four final states according to the τ decay mode:
  - Hadronic τ: $e\tau_h$, $\mu\tau_h$
  - Leptonic τ: $e\tau_\mu$, $\mu\tau_e$
- Dominated by $Z \to \tau\tau$, $W+$ jets, and QCD backgrounds

$H \to e^{\pm}\tau^{\mp}/\mu^{\pm}\tau^{\mp}$: Strategies

CMS (Phys. Rev. D 104, 032013 (2021))

- Backgrounds with a $\tau^{+}\tau^{-}$ pair are estimated by replacing the μ in $\mu^{+}\mu^{-}$ data events with simulated τ
- Background of jets misidentified (misID) as leptons are estimated from Z + jets (for τ_h) CRs or same charge CRs with loosen isolation requirements on the leptons (for τ_l)
- A ML fit is performed along BDT trained to extract a limit on $B(H \to e\tau)$ and $B(H \to \mu\tau)$ independently



$H \to e^{\pm}\tau^{\mp}/\mu^{\pm}\tau^{\mp}$: Strategies

ATLAS (CERN-EP-2022-279)

Leptonic Tau

- misID lepton backgrounds are estimated from same charge CRs with relaxed isolation requirement
- Three BDTs to target different backgrounds:
  1. misID leptons
  2. top-quark, diboson, and $H \to WW$
  3. Drell-Yan and $H \to \tau\tau$

Hadronic Tau

- misID lepton backgrounds are estimated from W + jets and QCD CRs with relaxed τ_h ID requirement
- Three BDTs to target different backgrounds:
  1. misID leptons (non-VBF $e\tau_h$ category only)
  2. $Z \to \tau\tau$
  3. others

- A ML fit is performed on $B(H \to e\tau)$ and $B(H \to \mu\tau)$ simultaneously along the combined BDT scores

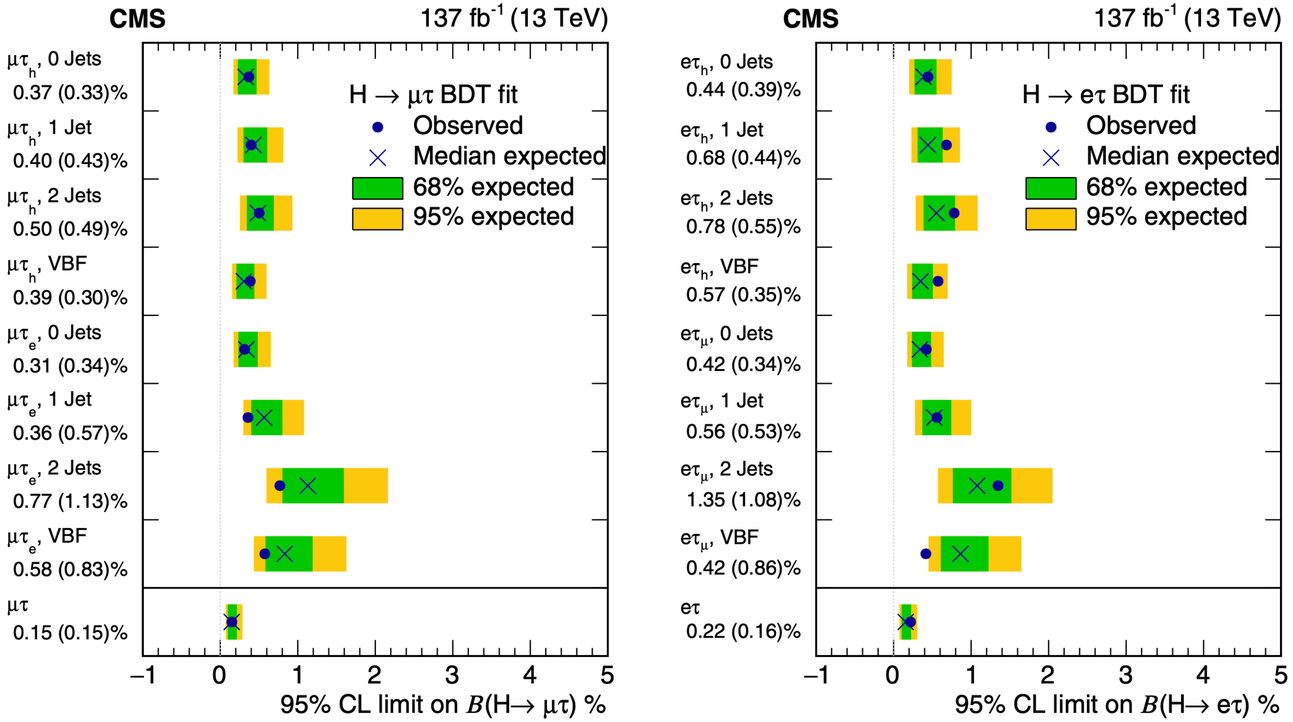
$H \to e^{\pm}\tau^{\mp}/\mu^{\pm}\tau^{\mp}$: Results

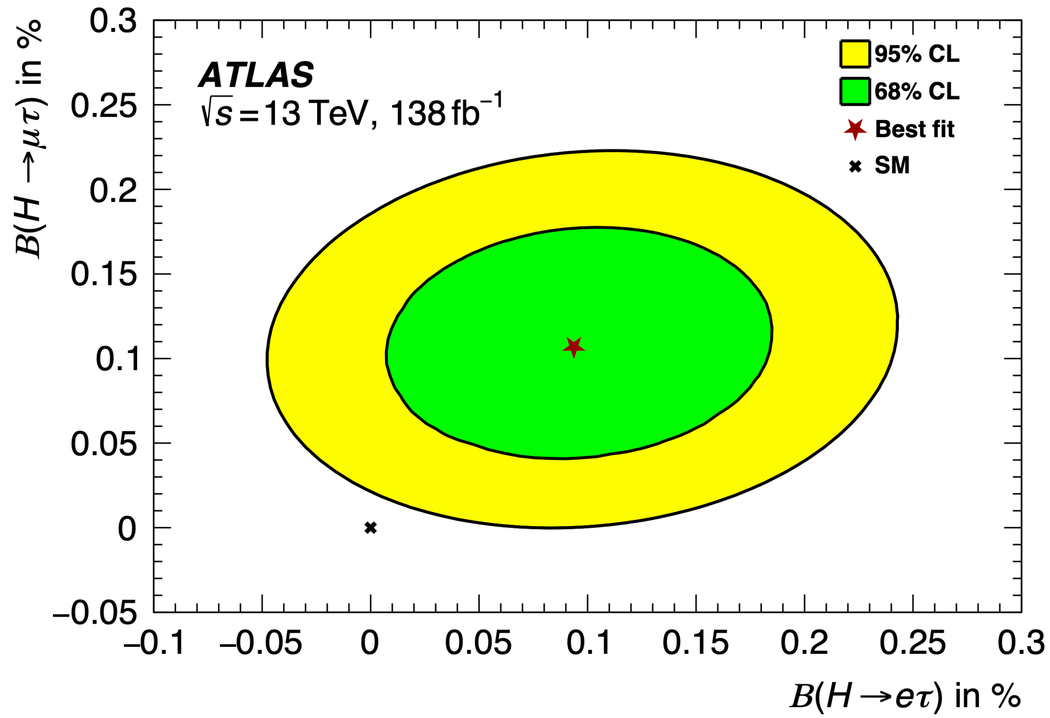
CMS (Phys. Rev. D 104, 032013 (2021))

- A 95% CL observed (expected) upper limits of
  - $B(H \to e\tau) < 0.22\ (0.16)\,\%$
  - $B(H \to \mu\tau) < 0.15\ (0.15)\,\%$ are reported

ATLAS (CERN-EP-2022-279)

- A 95% CL observed (expected) upper limits of
  - $B(H \to e\tau) < 0.20\ (0.12)\,\%$
  - $B(H \to \mu\tau) < 0.18\ (0.09)\,\%$ are reported





Search for $H \to e^{\pm}\mu^{\mp}$

$H \to e^{\pm}\mu^{\mp}$

- The most stringent limit on $\mathcal{B}(H \to e^{\pm}\mu^{\mp})$ is set indirectly from the null result of $\mu \to e\gamma$ to be $< 10^{-8}$, beyond the sensitivity of the Run II data

- The indirect limit, however, assumed SM values of Y_{ee} and $Y_{\mu\mu}$, and no cancellations of Higgs LFV from other sources => a direct probe remains important

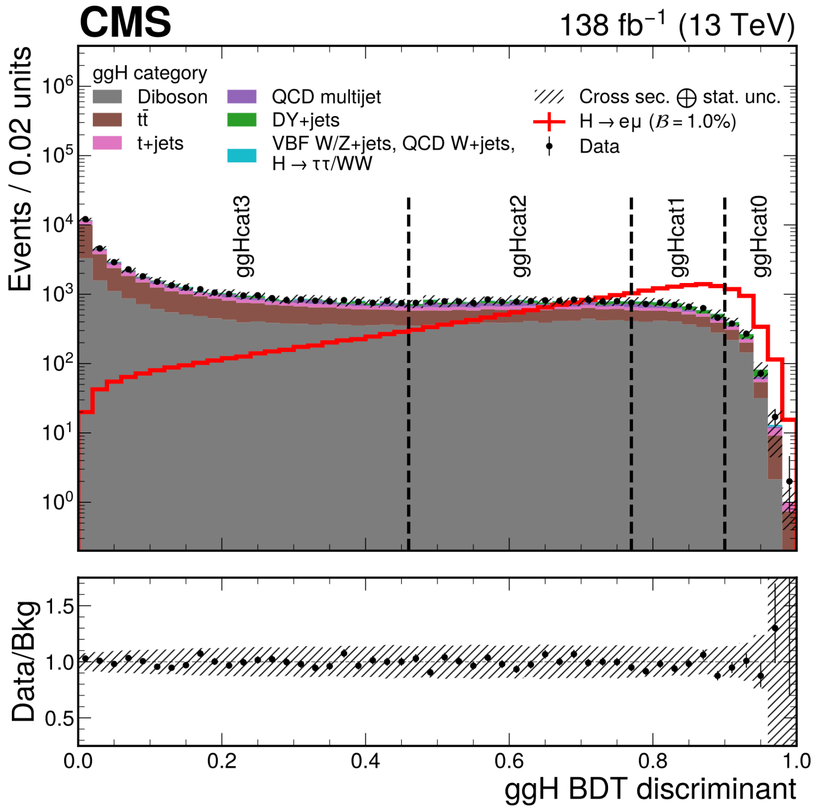
- Both CMS (CMS-PAS-HIG-22-002) and ATLAS (Phys.Lett.B 801 (2020) 135148) focused on the ggH and VBF modes, dominated by $t\bar{t}$ and WW backgrounds

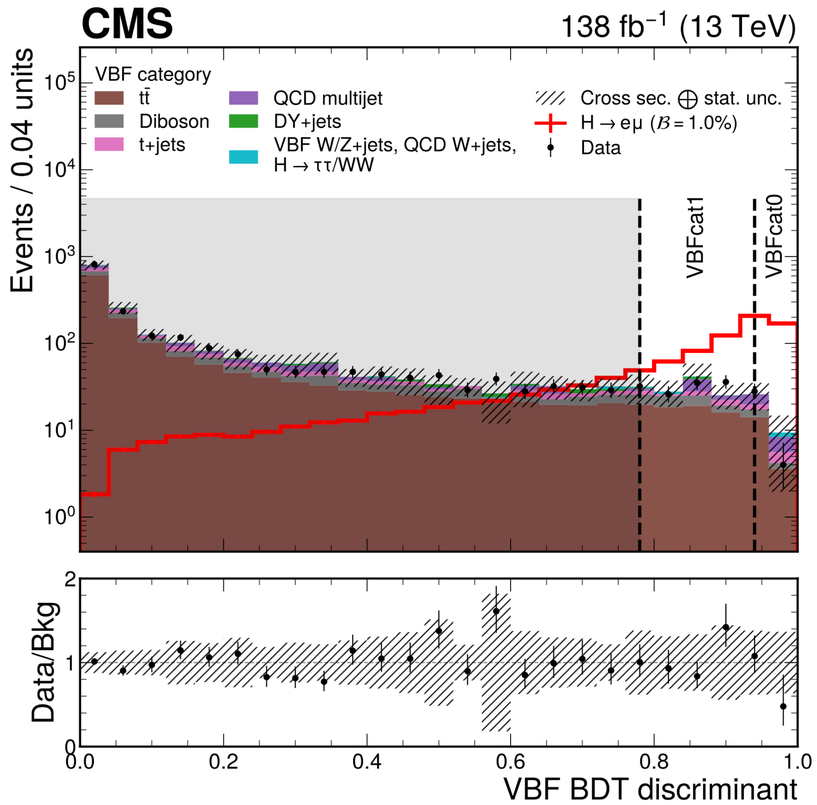
- CMS performed also a search for additional Higgs bosons ($X \to e^{\pm}\mu^{\mp}$) with a mass of 110-160 GeV in additional to H in this channel, while ATLAS focused on $H \to e^{\pm}\mu^{\mp}$ only

$H \to e^{\pm}\mu^{\mp}$: Strategies

CMS (CMS-PAS-HIG-22-002)

- A “bump-hunting” search along the $m_{e\mu}$ spectrum
- Events are separated into a ggH and a VBF-enriched region
- BDTs are trained for each region and categories are defined based on cuts on the BDTs that optimize the expected search sensitivity for $H \to e^{\pm}\mu^{\mp}$

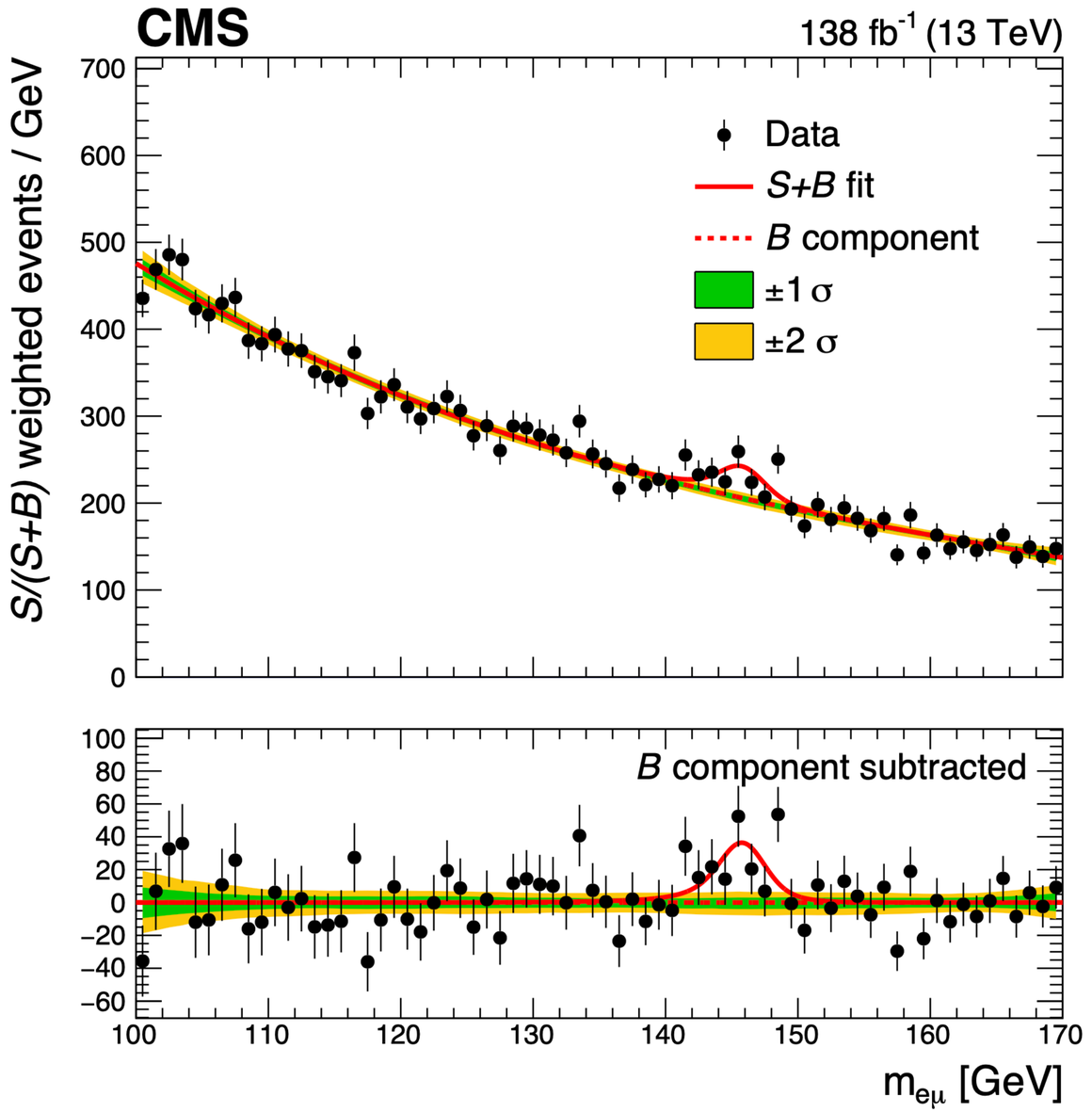




$H \to e^{\pm}\mu^{\mp}$: Strategies

CMS (CMS-PAS-HIG-22-002)

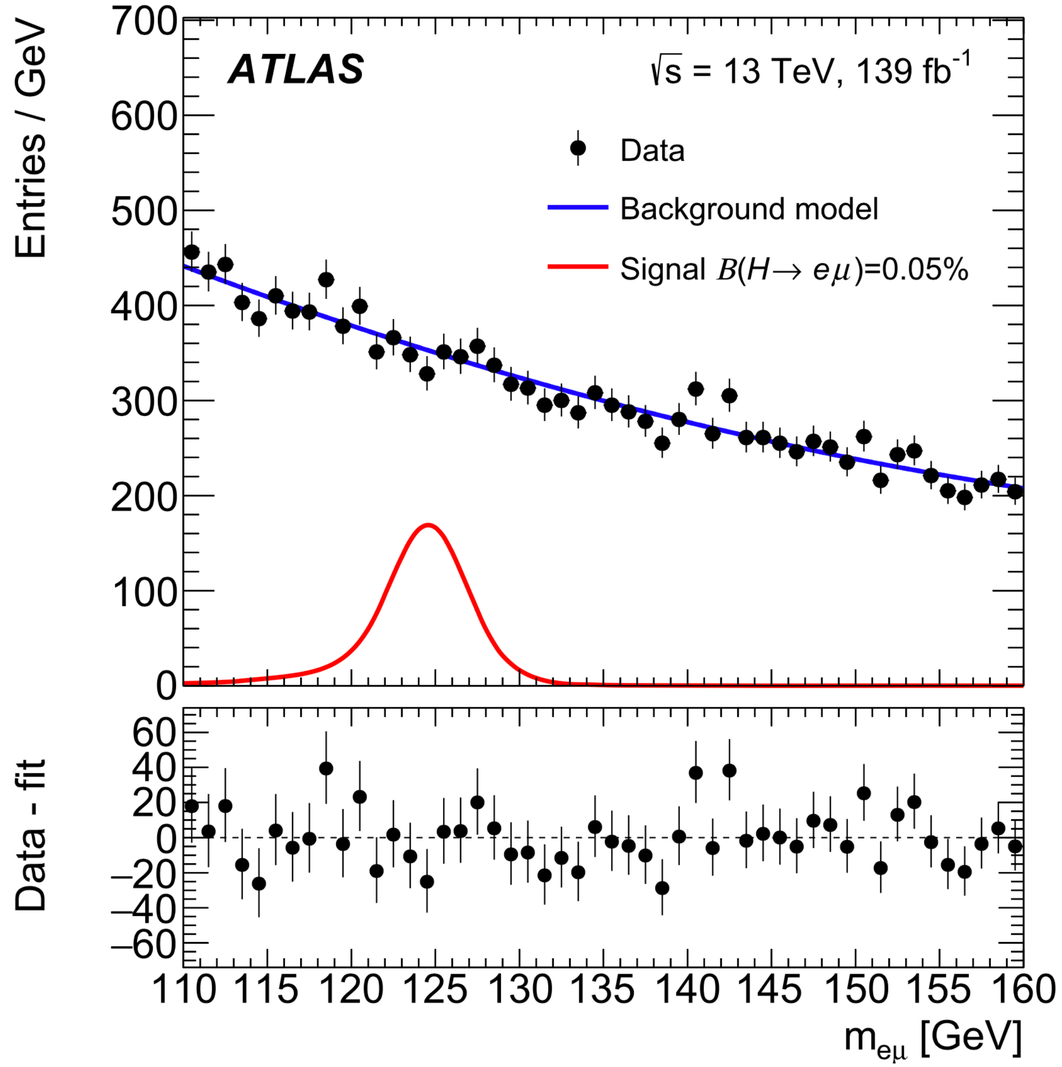
- Signals are simulated for both H and additional Higgs boson X with a mass from 110 to 160 GeV
- The fit of $m_{e\mu}$ is carried out from 100 to 170 GeV with background approximated from data directly
- Upper limits on $\mathcal{B}(H \to e^{\pm}\mu^{\mp})$ and $\sigma(pp \to X \to e^{\pm}\mu^{\mp})$ are reported



$H \to e^{\pm}\mu^{\mp}$: Strategies

ATLAS (Phys.Lett.B 801 (2020) 135148)

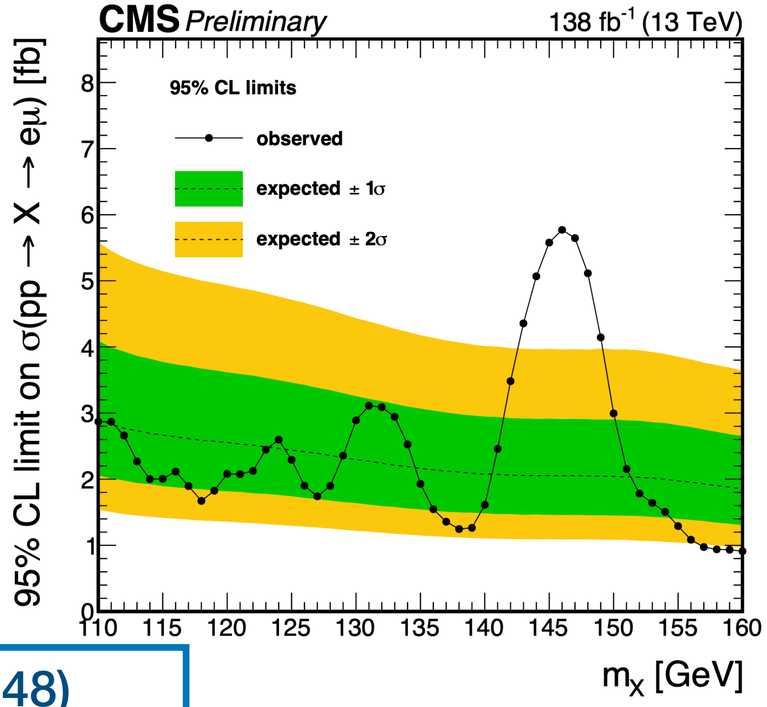
- A “bump-hunting” search along the $m_{e\mu}$ spectrum
- Categories defined based on detector region and p_T of the lepton pair to separate regions of different $m_{e\mu}$ resolution
- A category targeting VBF events is also defined



$H \to e^{\pm}\mu^{\mp}$: Results

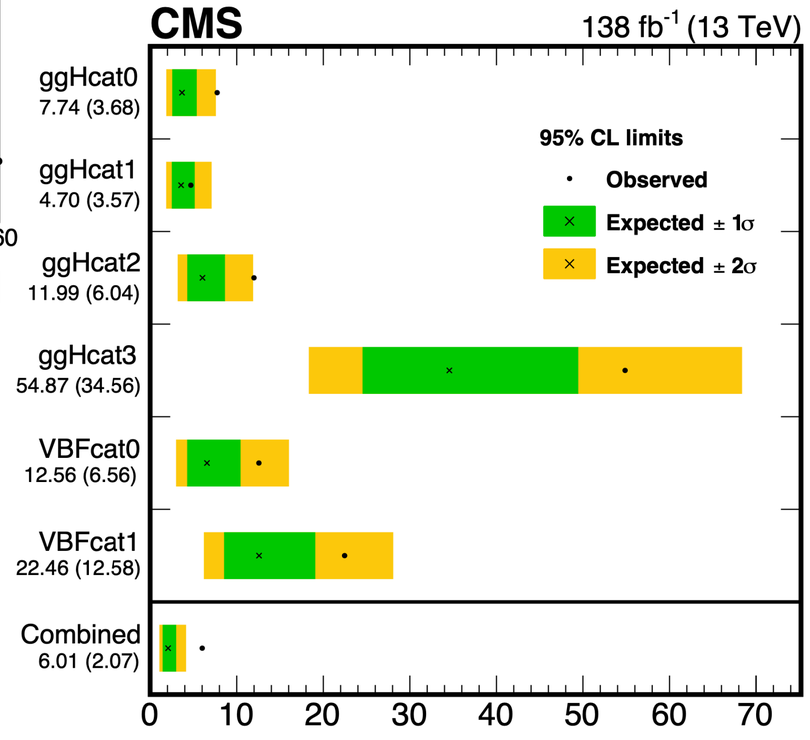
CMS (CMS-PAS-HIG-22-002)

- The observed (expected) 95% CL limit is set to be
  $B(H \to e^{\pm}\mu^{\mp}) < 4.4 \times 10^{-5}\ (4.7 \times 10^{-5})$
- An excess of 3 σ is reported at
  $m_X \approx 146$ GeV



ATLAS (Phys.Lett.B 801 (2020) 135148)

- The observed (expected) 95% CL limit is set to be
  $B(H \to e^{\pm}\mu^{\mp}) < 6.2 \times 10^{-5}\ (5.9 \times 10^{-5})$
- ATLAS data is in disfavor with the excess of CMS at 146 GeV

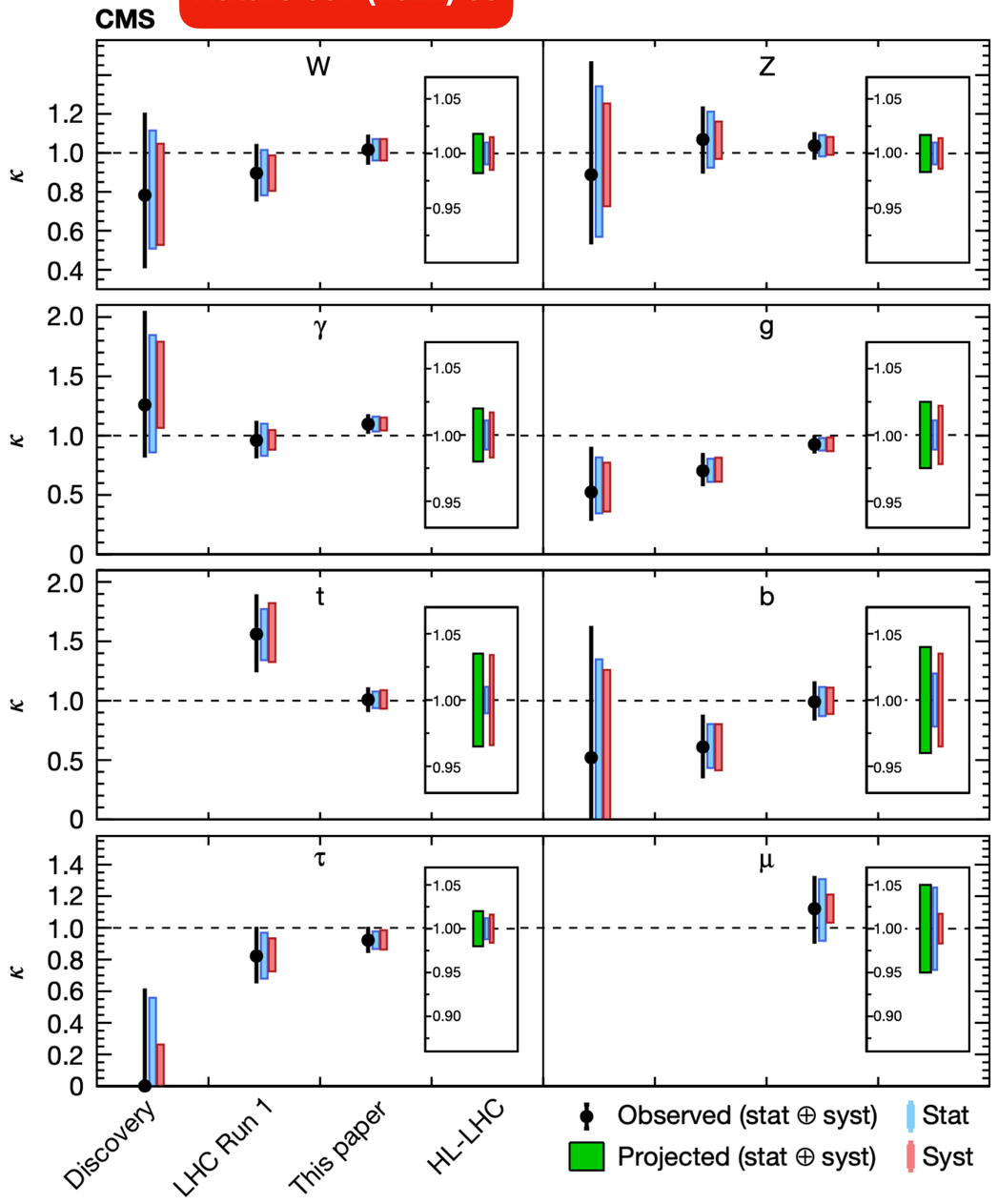


UNIVERSITY OF NOTRE DAME

Summary

- H couplings to μ, τ, b, W, Z, t are measured to be consistent with the Standard Model prediction
- Constraint on $H \to e^+e^-$ is improved and we are approaching the sensitivity to probe $H \to c\bar{c}$
- Direct constraints on LFV H decays have improved in all three channels ($\mu^{\pm}\tau^{\mp}/e^{\pm}\tau^{\mp}/e^{\pm}\mu^{\mp}$)
- An interesting excess of a Higgs-like resonance of $X \to e^{\pm}\mu^{\mp}$ at $m_X = 146$ GeV is observed by CMS
- Data will be ~2x in size for Run III (2022-2025), and up to 10x in size for the high-luminosity LHC (expected 2029), entering the era of precision Higgs physics

Nature 607 (2022) 60

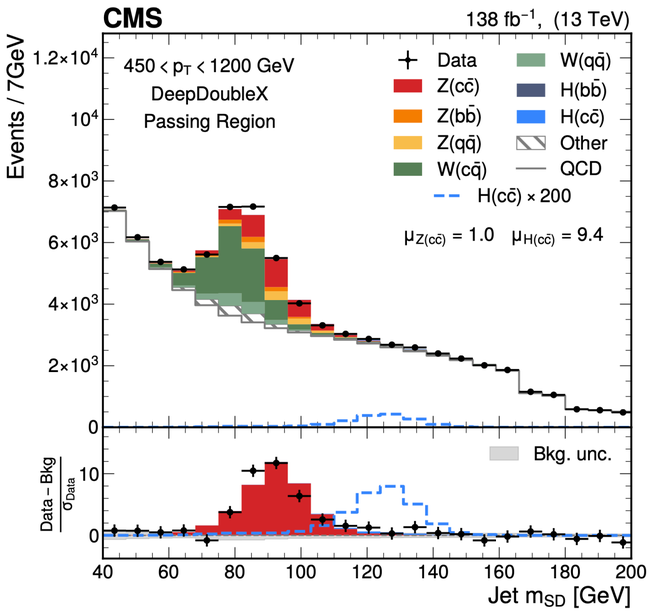


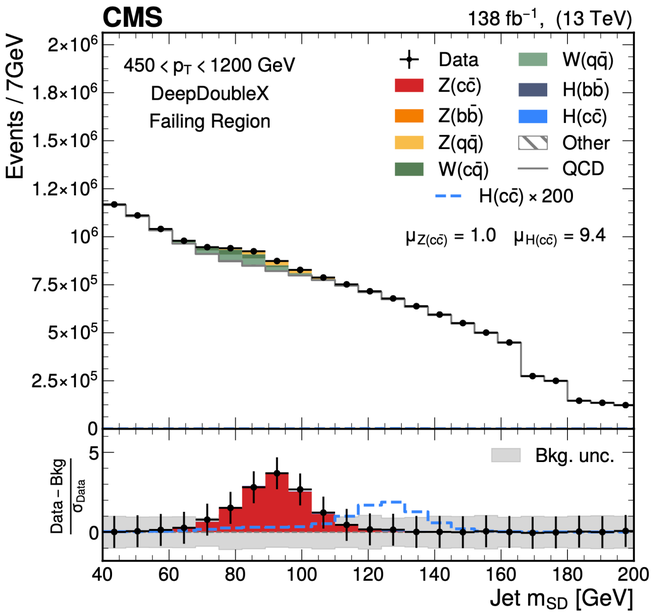
Backup

Boosted $ggH(\rightarrow c\bar{c})$

CMS (CERN-EP-2022-233)

- The H candidate is reconstructed as a AK jets with $R = 0.8$ and $p_T > 450$ GeV
- Soft-drop algorithm is applied to the jet mass to remove soft and wide-angle radiation from the dominant QCD backgrounds
- The signal (control) region is defined for events passing a c vs light and a c vs b tagger (passing the c vs light tagger but failing the c vs b tagger)
- A dedicated $t\bar{t}$ CR is defined to constrain the $t\bar{t}$ normalization
- Binned ML fit to the jet p_T and the soft-drop mass m_{SD} for the signal strength is performed across all regions





Search for boosted $ggH(\rightarrow c\bar{c})$: Results

CMS (CERN-EP-2022-233)

- An observed (expected) upper limit on the signal strength of 47 (39) times the SM expectation is reported
- Analysis is validated with an observation of $Z \rightarrow c\bar{c}$ in agreement with the SM with a significance of over 5 standard deviations