CMS HH results

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on behalf of CMS Collaboration

Higgs Hunting
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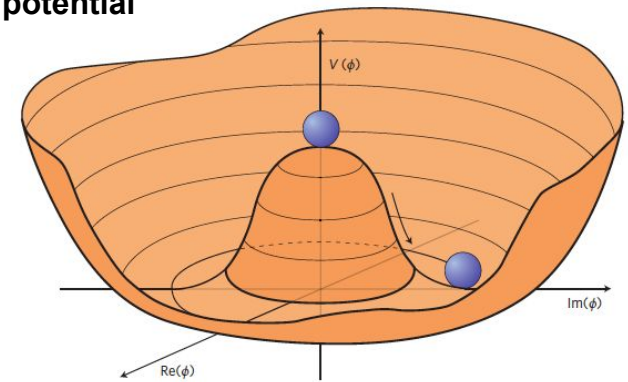
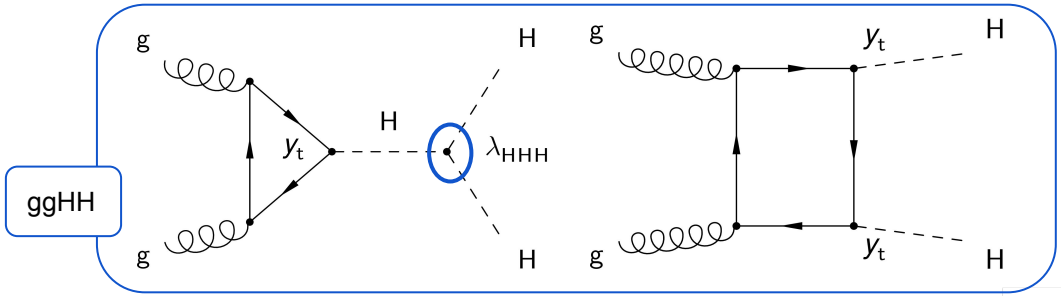
HH and the trilinear coupling

arXiv:1312.5672

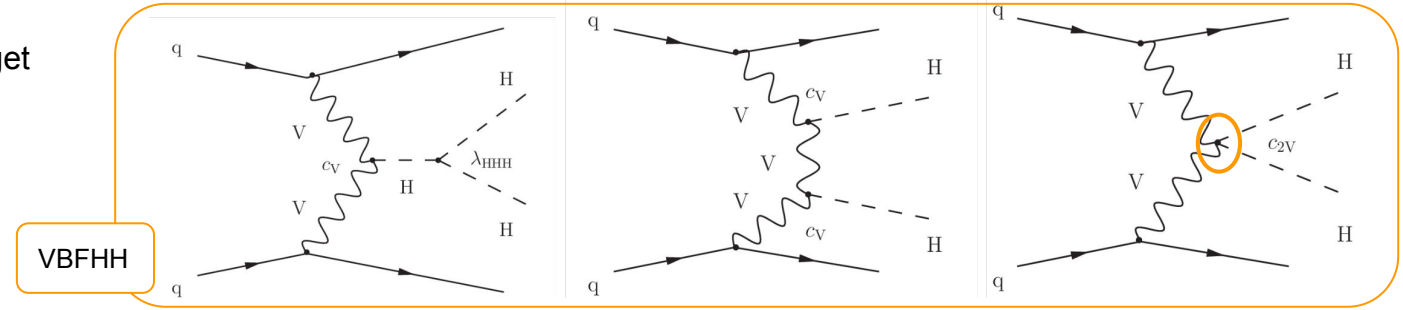
- HH production can be used to directly study **Higgs boson self-coupling** and **Higgs potential**
- At CERN LHC mainly produced through **gluon fusion** via fermion loop
- In SM destructive interference of triangle and box contributions
  → Tiny cross section (31.05 fb)
  → Experimentally very challenging



$$V\left(\phi^\dagger\phi\right) = \mu^2\phi^\dagger\phi + \lambda\left(\phi^\dagger\phi\right)^2$$



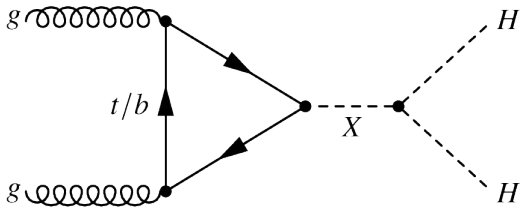
- With full Run2, possible to target also **vector boson fusion** production mode (1.72 fb)
  → sensitive to **VVHH** coupling



HH beyond the SM

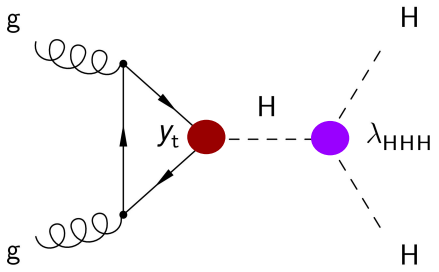
Resonant Production

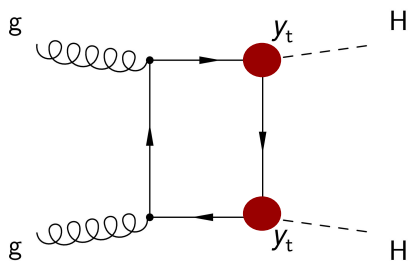
- New **resonance that decays into HH**
  →predicted by broad class of models
  →typically spin-0/2 resonances with
  $m_X > 250$ GeV
- Search for bump in m_{HH} distributions
- Wide mass range to explore

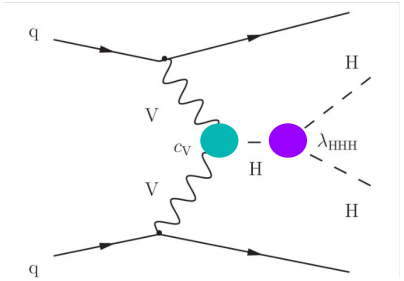


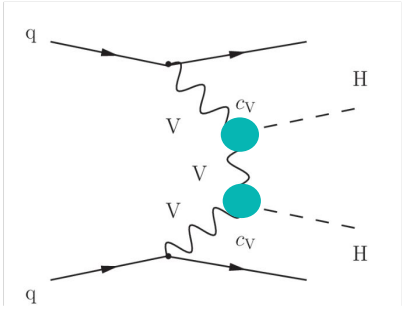
Nonresonant Production

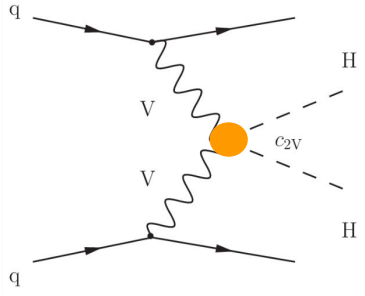
- BSM processes can **modify cross section** and **kinematic properties**
- EFT approach: leads to coupling modifications (k_λ, k_t, c_V, c_{2V})



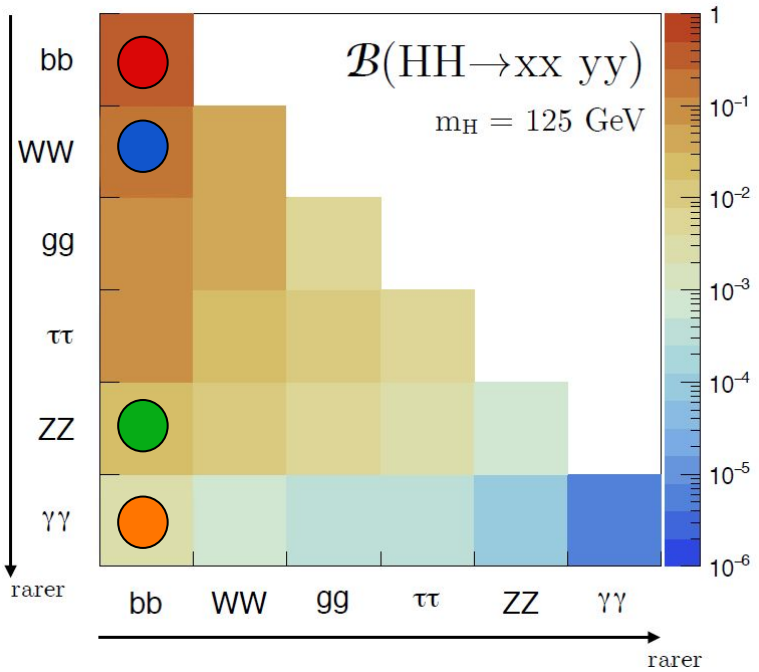








HH decay channels



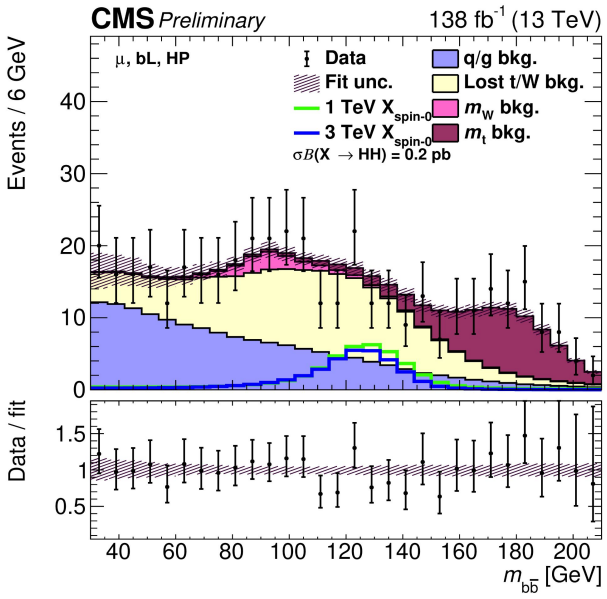
- Rich phenomenology with many final states accessible at LHC
- Many of them already studied in Run1 and Run2 2016 analyses
- This talk: focus on **full Run2 results**:
  - **HH→bbWW**, resonant (CMS-PAS-B2G-20-007)
  - **HH→4b** boosted, resonant (CMS-PAS-B2G-20-004)
  - **HH→4b** resolved, nonresonant (CMS-PAS-HIG-20-005)
  - **HH→bbγγ**, nonresonant (JHEP 03 (2021) 257)
  - **HH→bb4l**, nonresonant (CMS-PAS-HIG-20-004)

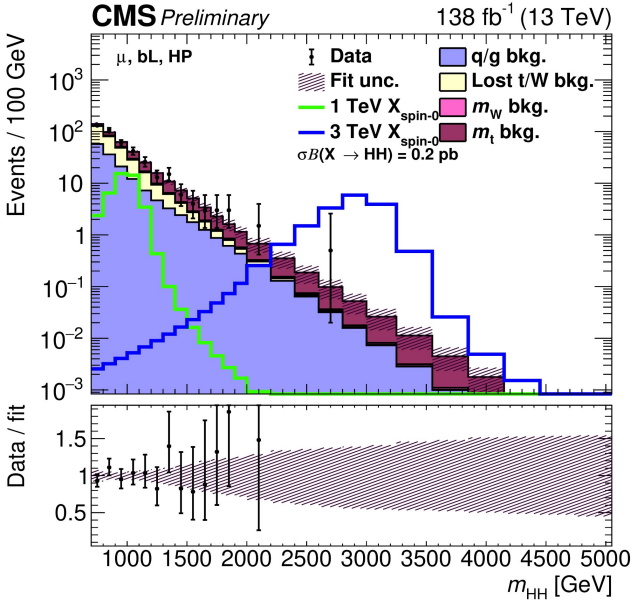
HH → bbWW - resonant

CMS-PAS-B2G-20-007

- **Single lepton** channel (HH→bbWW*->bblνqq) and **di-lepton** channel (HH→bbWW*→bblνlν and HH→bb$\tau\tau$→bbl$\nu\nu$l$\nu\nu$)

- bbZZ events included in the acceptance: 1-3% of total expected signal yield
- Main background: top pair production
- **Boosted topology: H→bb** and W→qq reconstructed as **single large jets** (R=0.8 anti-k$_T$ jets)
- Fine categorization based on flavour and jet substructure
- Results extracted by fitting 2D **(m_{bb},m_{HH})** distributions





HH → bbWW - resonant

CMS-PAS-B2G-20-007

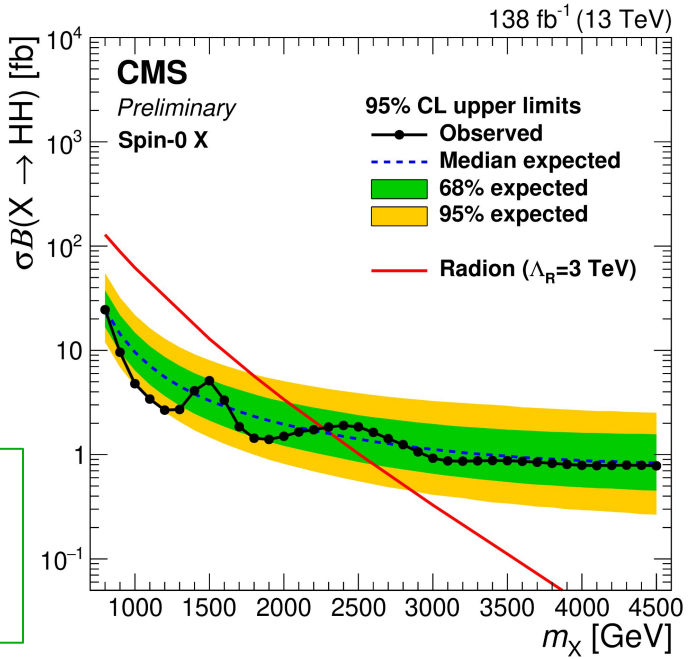
- Search in mass range **0.8 < m_X < 4.5 TeV**

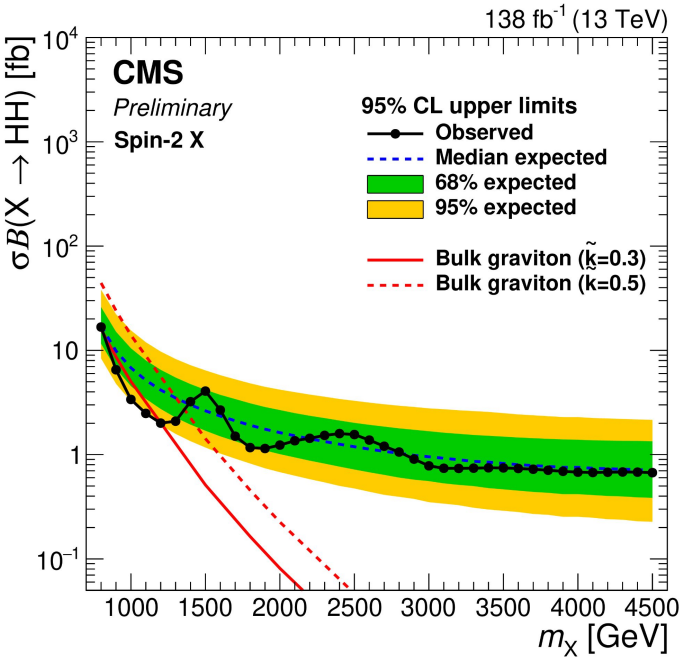
Radion (spin-0):
- UV cutoff Λ_R = 3 TeV
- BR to HH: 25%

Bulk graviton (spin-2):
- BR to HH: 10%
- 2 hp considered
  - $\tilde{k}$ = 0.3
  - $\tilde{k}$ = 0.5

$$\tilde{k} = \sqrt{8\pi} k / M_{Pl}$$

- ~1 order of magnitude gained w.r.t. 2016 analysis
- Scan range extended by 1 TeV



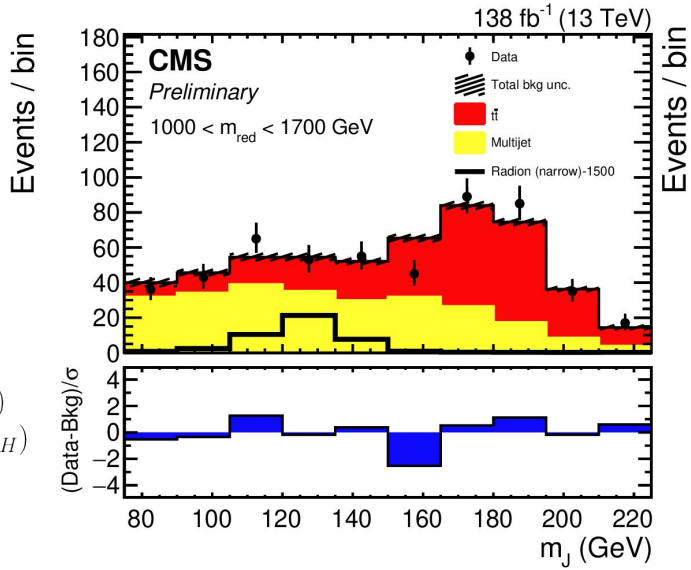


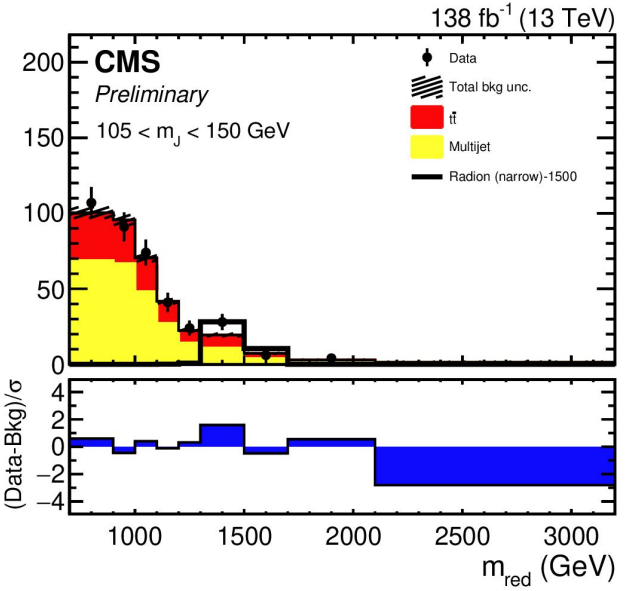
HH → 4b boosted - resonant

CMS-PAS-B2G-20-004

- (Semi) **boosted topology**: events with 2 R=0.8 anti-kT jets, or 1 R=0.8 anti-kT jet and 2 R=0.4 anti-kT jets)
- Main backgrounds: multijet production and tt+jets
- Identification and categorization based on NN (DeepAK8)
- Results extracted with fit on 2D **(m_J,m_{red})** distributions

$$m_{red} = m_{JJ} - (m_J - m_H) - (m_{J2} - m_H)$$
$$m_{red} = m_{Jjj} - (m_J - m_H) - (m_{jj}(j_1, j_2) - m_H)$$





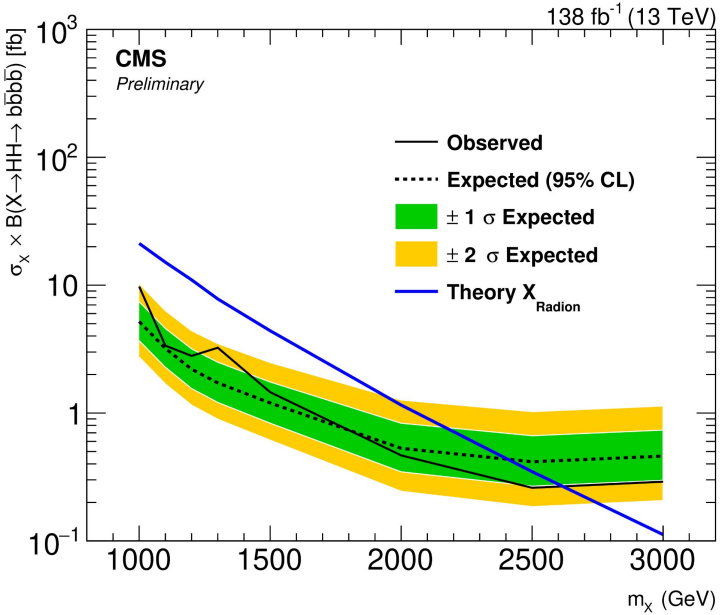
HH → 4b boosted - resonant

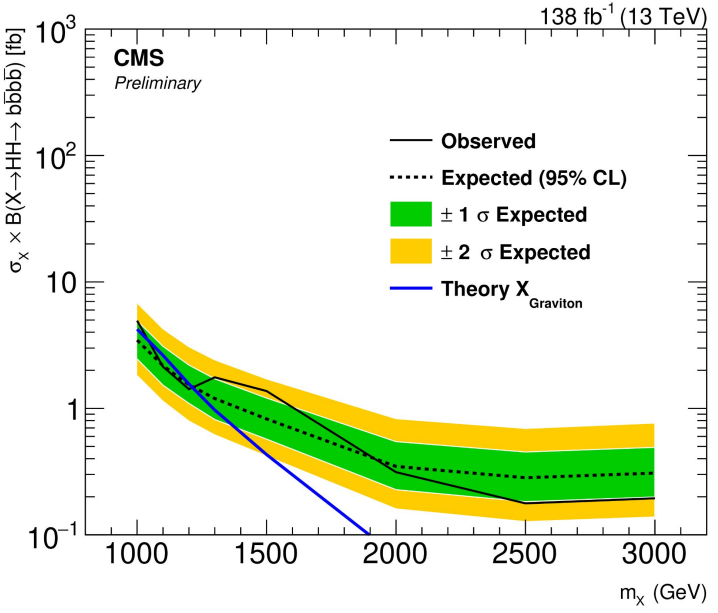
CMS-PAS-B2G-20-004

- Search in mass range **1 < m_X < 3 TeV**

Radion (spin-0):
- UV cutoff Λ_R = 3 TeV
- BR to HH: 23%
- excluded @95% CL in [1, 2.6] TeV

Bulk graviton (spin-2):
- BR to HH: 10%
- k/M_{Pl} = 0.5
- excluded @95% CL in [1, 1.2] TeV

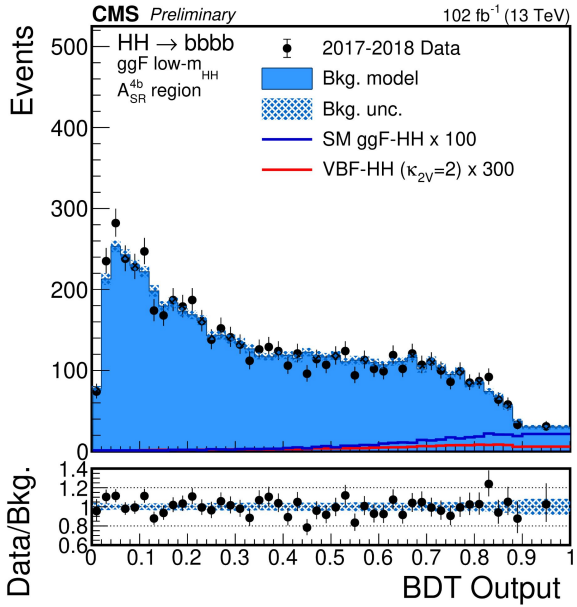


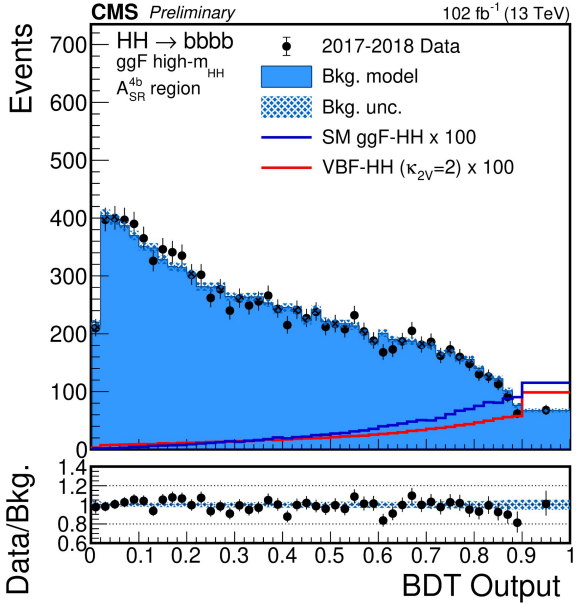


HH → 4b resolved - nonresonant

CMS-PAS-HIG-20-005

- Events with at least 4 identified b-jets
- Largest BR =34% @m_H=125 GeV
- Non-trivial **jet pairing** to build H candidates
- Large multijet background from QCD and tt hadronic processes: estimated from data
- Target also **VBFHH**:
  - ggHH/VBFHH categories
  - BDT to separate ggHH from VBFHH
  - subcategories based on mHH or BDT output
- Results extracted fitting the 4 categories simultaneously





HH → 4b resolved - nonresonant

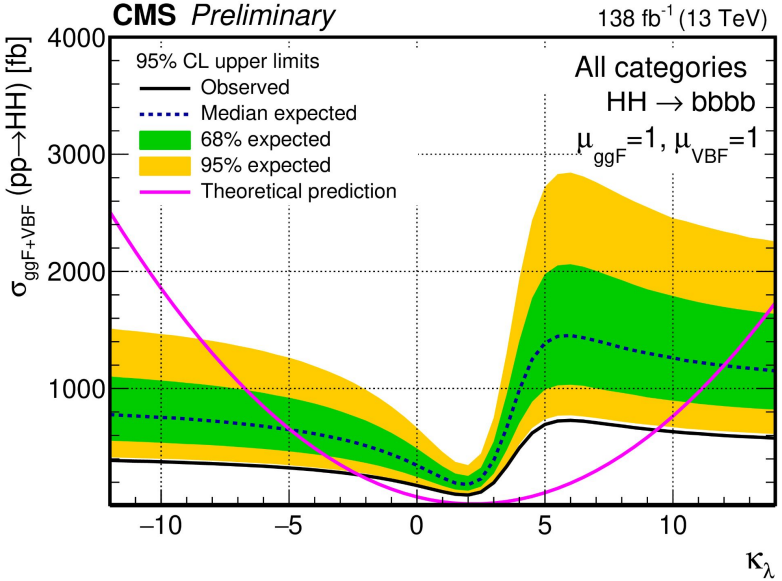
CMS-PAS-HIG-20-005

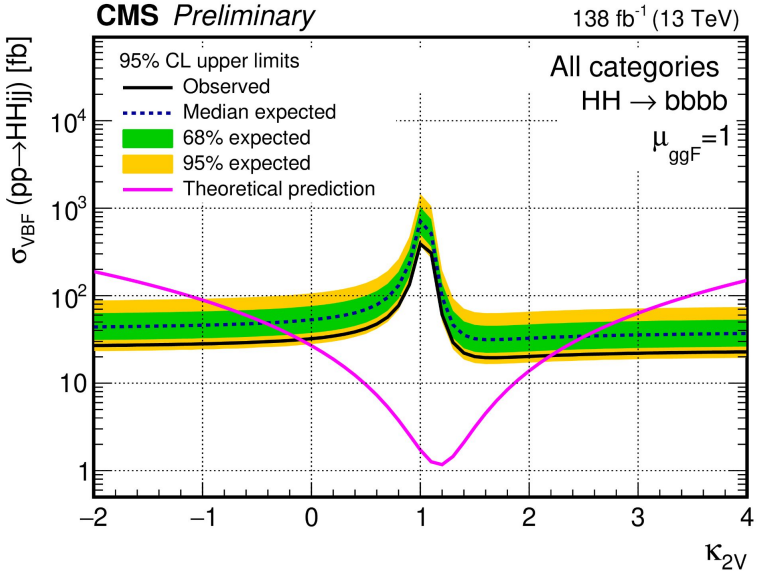
Observed (expected) limits @95% CL:
- σ(HH→bbbb) < 3.6 (7.3) σ_{SM}
- -2.3 < k_λ < 9.4 (-5.0 < k_λ < 12.0)
- -0.1 < k_{2V} < 2.2 (-0.4 < k_{2V} < 2.5)

Best limit value in CMS!

Large improvement w.r.t. 2016 analysis!

See also HH→4b boosted VBF, nonresonant search (CMS-PAS-B2G-21-001), in CMS joker talk!





HH → bbγγ - nonresonant

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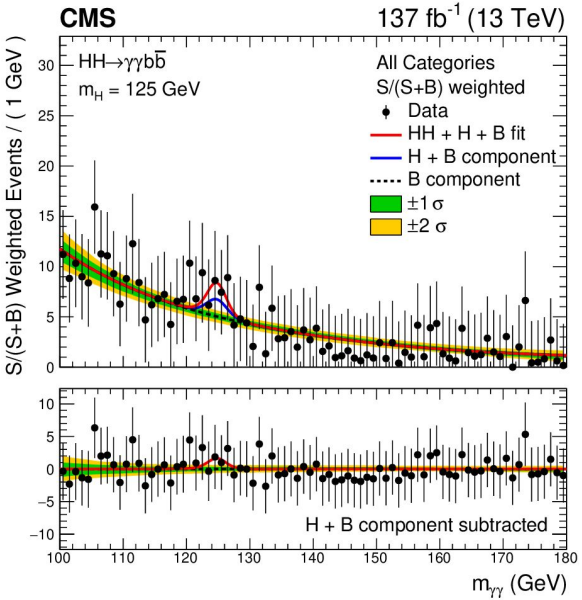
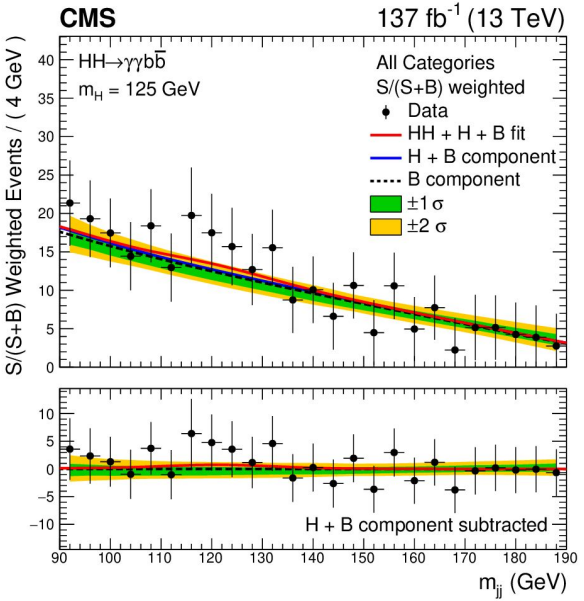
- Events with at least 2 identified photons + jet selection
- Tiny BR = 0.26% @m_H=125GeV
- Good $m_{\gamma\gamma}$ resolution
- Relatively low **background**: main source **nonresonant $\gamma(\gamma)$+jets** (data-driven estimate)
- MVA to separate signal from background
- Target also **VBFHH**: fine categorization based on MVA output and reduced mass
- Results extracted fitting 2D **($m_{\gamma\gamma}$, m_{jj})** simultaneously in all categories

$$\tilde{M}_x = m_{\gamma\gamma jj} - (m_{jj} - m_H) - (m_{\gamma\gamma} - m_H)$$





HH → bbγγ - nonresonant

Observed (expected) limits @95% CL:

- $\sigma(HH \to bb\gamma\gamma) < 7.7\ (5.2)\ \sigma_{SM}$
- $-3.3 < k_\lambda < 8.5\ (-2.5 < k_\lambda < 8.2)$
- $\sigma_{VBF}(HH \to bb\gamma\gamma) < 225\ (208)\ \sigma_{SM}$
- $-1.3 < k_{2V} < 3.5\ (-0.9 < k_{2V} < 3.1)$

Large improvement w.r.t. 2016 analysis!

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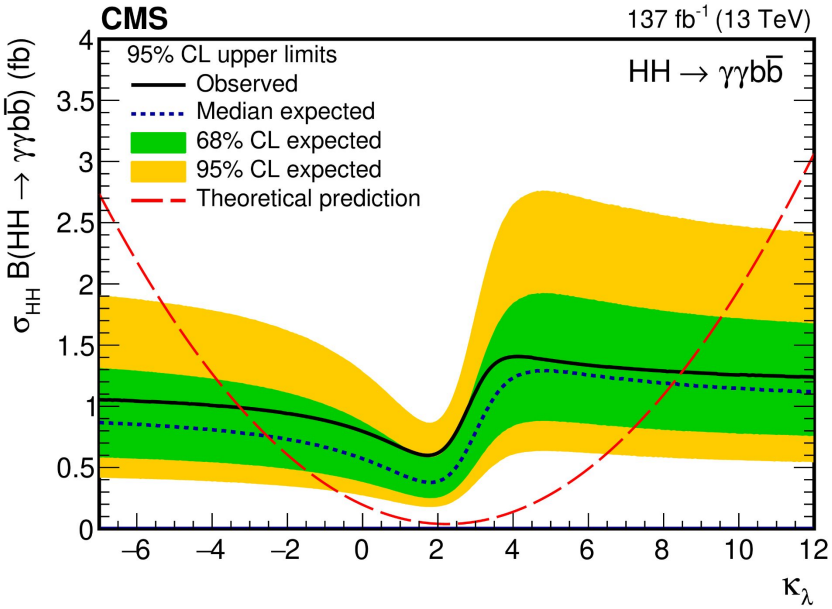

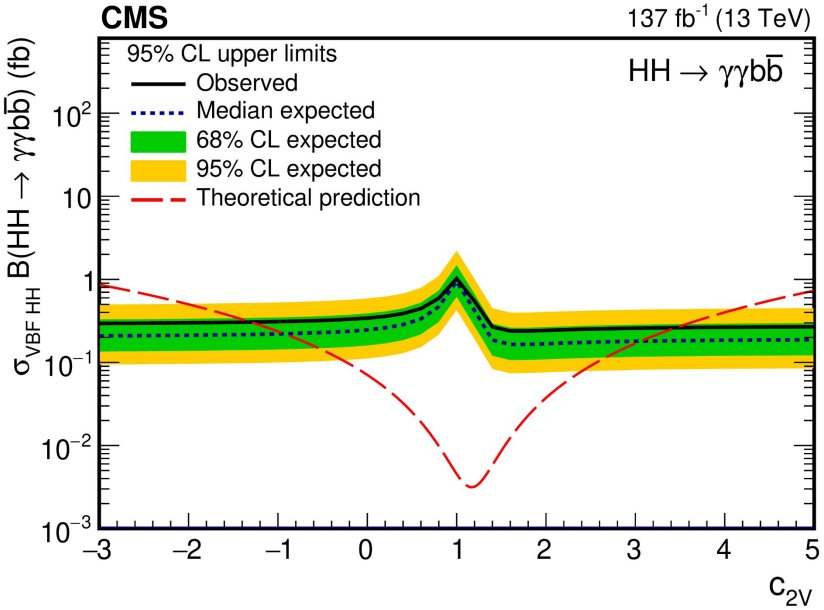

HH → bbγγ - nonresonant

- **Combination** with **ttH(→γγ)** to improve constrain k_λ and k_t

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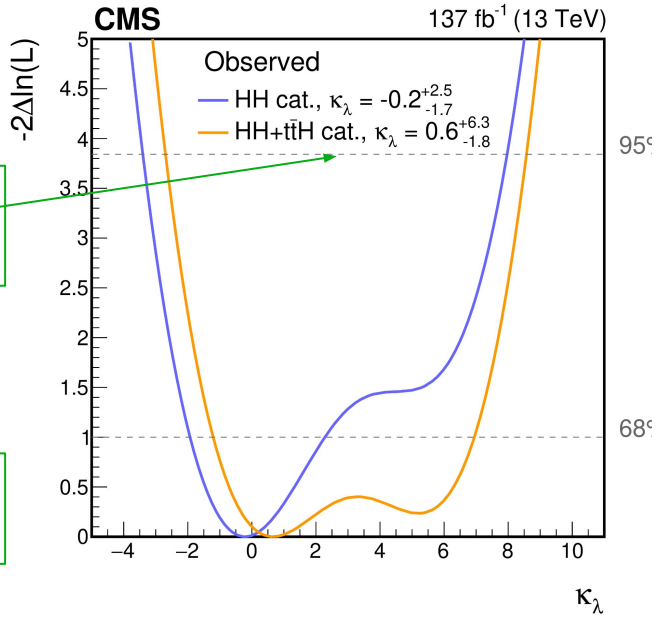
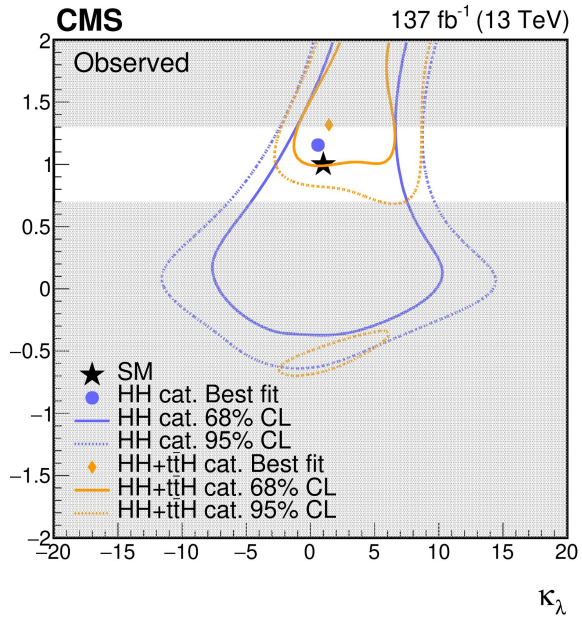
- **Additional** orthogonal **categories** for events not passing HH selection to **target ttH**

- fixing k_t=1, **k_λ= 0.6** obs. (1.0 exp.)
- k_λ values outside **[-2.7,8.6] excluded** @95% CL
- 2 minima likelihood due to cross section dependence on k_λ and different acceptance of categories

- 2D scan (k_λ,k_t) to better constrain k_λ and k_t (valid only when $|k_t|$~1)

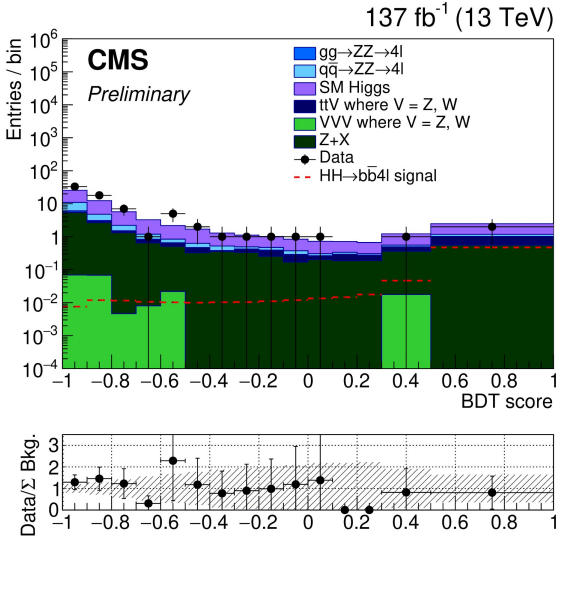


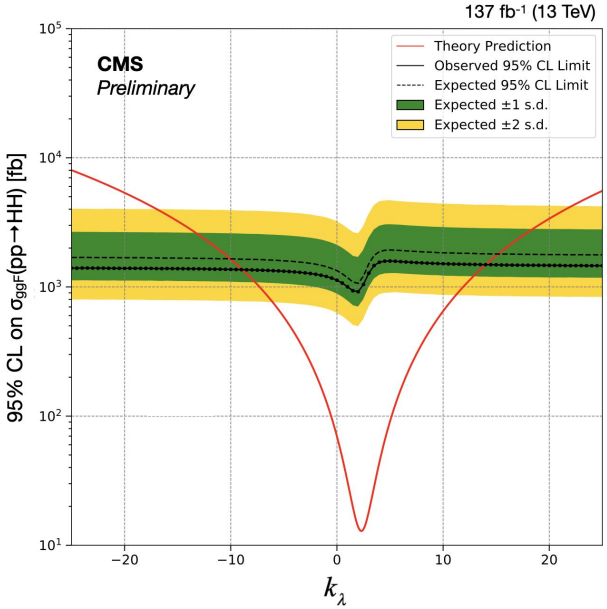


HH → bb4l - nonresonant

CMS-PAS-HIG-20-004

- Events with 4 identified leptons (e,μ) + jet selection
- **First result in this channel!**
- Tiny BR = 0.014% @m_H=125GeV
- Clear signature
- backgrounds: single H and ZZ production (from MC), reducible background (from data)
- BDT to separate signal from background
- Results extracted fitting BDT discriminant





Observed (expected) limits @95% CL:
- σ(HH→bb4l) < 30 (37) σ_{SM}
- -9 < k_λ < 14 (-11 < k_λ < 16)

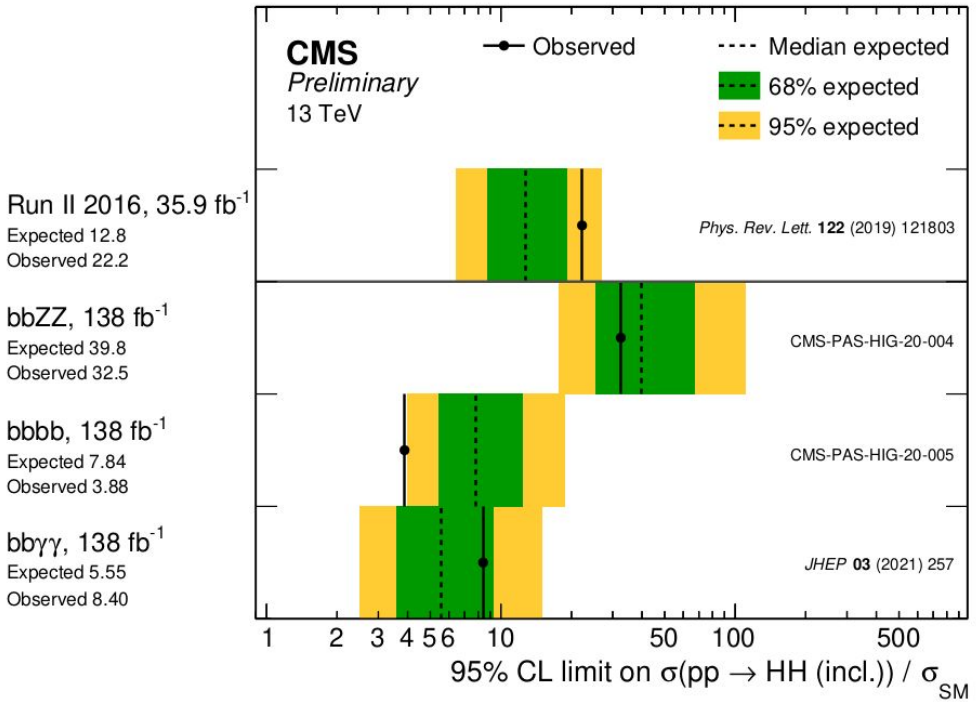
Conclusions and prospects

HL-LHC extrapolation (based on 2016 results): $\sigma(HH) < 0.77\ \sigma_{SM}$

arXiv:1902.00134

- **Full Run2 results very promising!** (even more than HL-LHC prospects!)
- Limits on SM and BSM HH production becoming increasingly stringent
- Lots of **progress w.r.t. 2016 analyses**
  - extended resonance mass scan range
  - Y→XH signatures
  - some rarer channels explored
  - combination with single H
  - target VBFHH
- **More to come in the future!**
  - More data in Run3 and beyond
  - Possibility for improvement both in techniques and analysis strategy

see Alexandros' and Ralf's talks

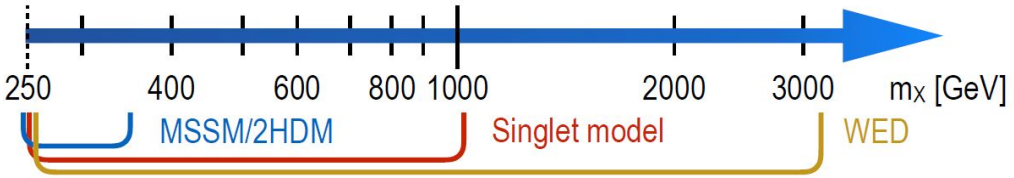


Backup

HH beyond the SM

Resonant Production

- New **resonance that decay into HH**
  →predicted by broad class of models
  →typically spin-0/2 resonances with
  $m_X > 250$ GeV
- Search for bump in m_{HH} distributions
- Wide mass range to explore



HH beyond the SM

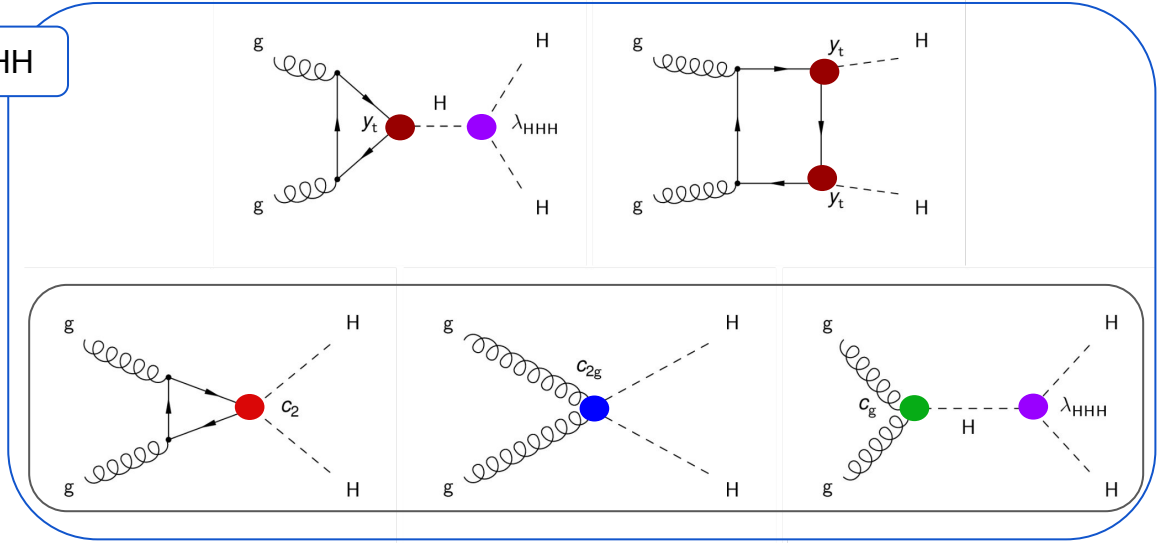
Nonresonant Production

- BSM processes can **modify cross section** and **kinematic properties**
- EFT approach:

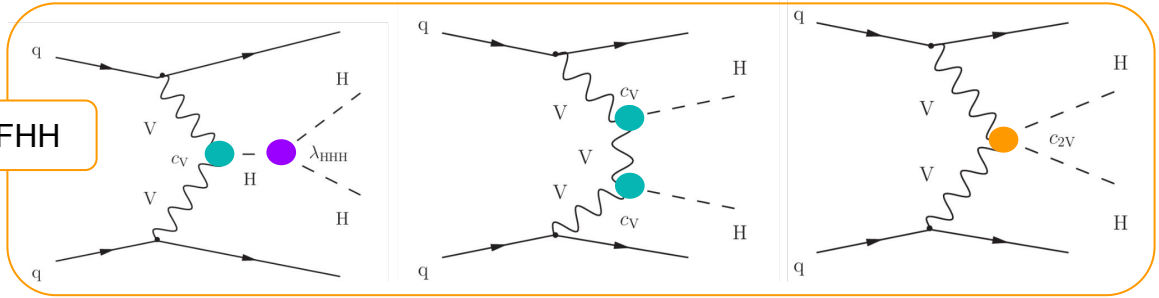
→ 5 parameters controlling tree-level interactions for ggHH (k_λ, k_t, c_2, c_{2g}, c_g)

→ with full run2 dataset, possible to study VBFHH: modification to VVHH and VVH couplings (c_V, c_{2V})

ggHH



VBFHH



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Benchmarks

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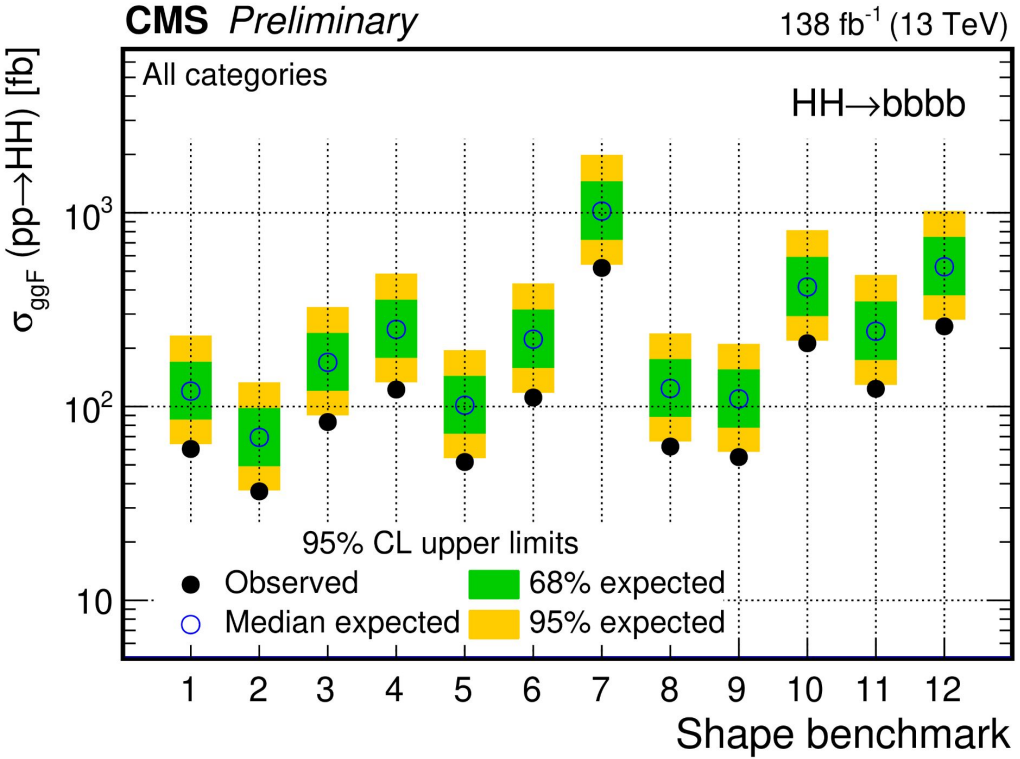
Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	−1.0	0.0	0.0
2	1.0	1.0	0.5	−0.8	0.6
3	1.0	1.0	−1.5	0.0	−0.8
4	−3.5	1.5	−3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	−1
6	2.4	1.0	0.0	0.2	−0.2
7	5.0	1.0	0.0	0.2	−0.2
8	15.0	1.0	0.0	−1	1
9	1.0	1.0	1.0	−0.6	0.6
10	10.0	1.5	−1.0	0.0	0.0
11	2.4	1.0	0.0	1	−1
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

HH → 4b resolved - nonresonant

CMS-PAS-HIG-20-005



HH → 4b resolved - nonresonant

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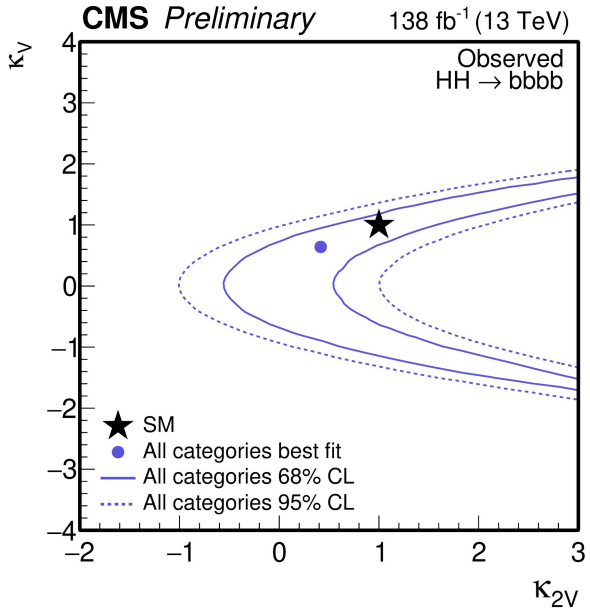
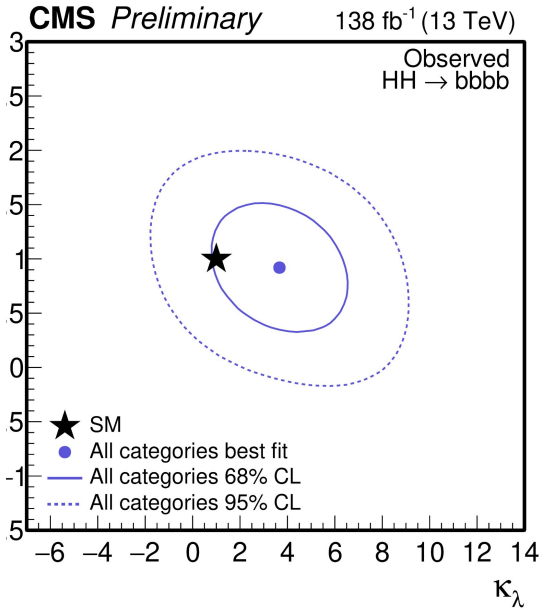
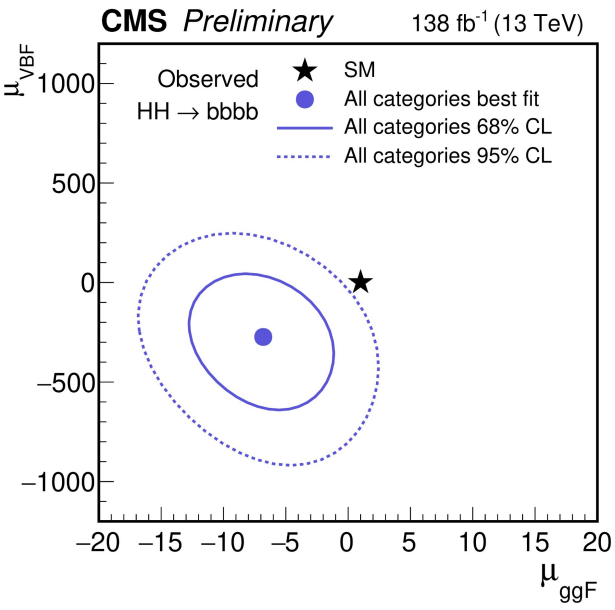
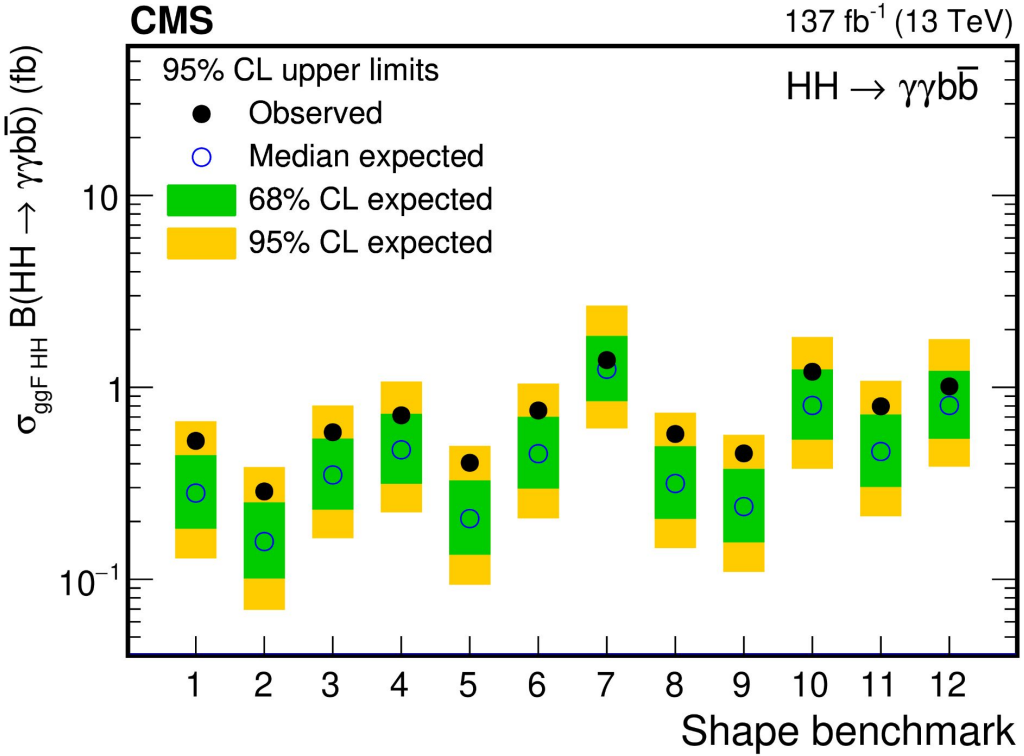






HH → bbγγ - nonresonant



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HH → bbγγ - nonresonant

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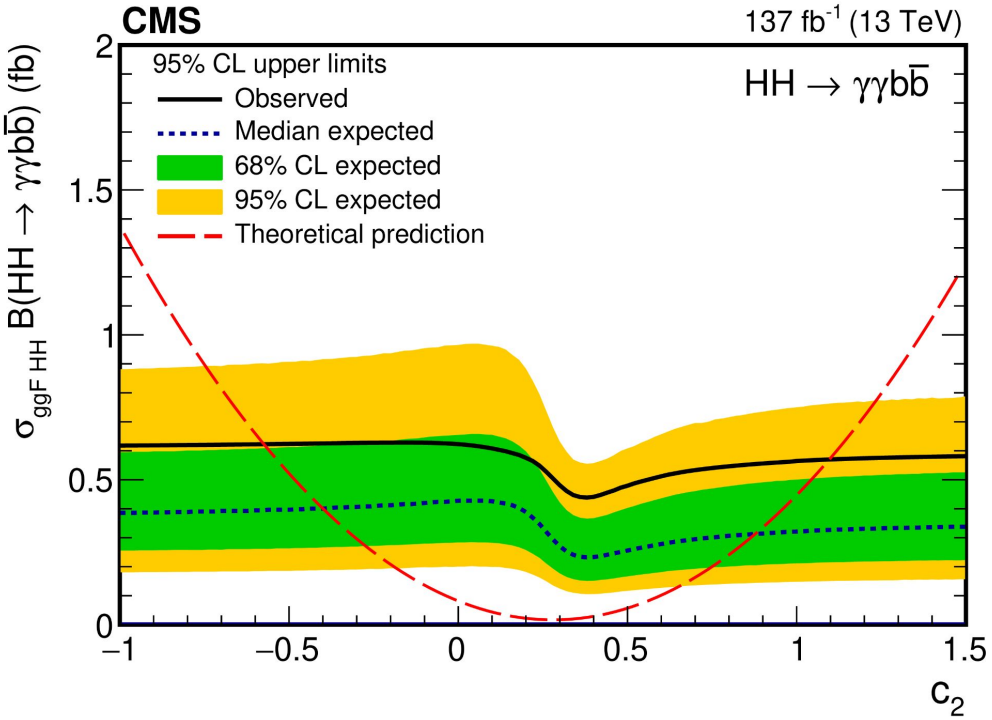

HH → bbγγ - nonresonant

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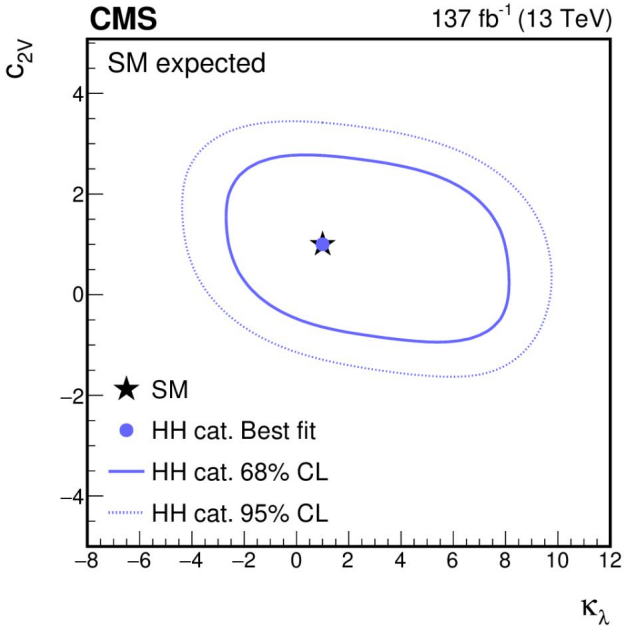

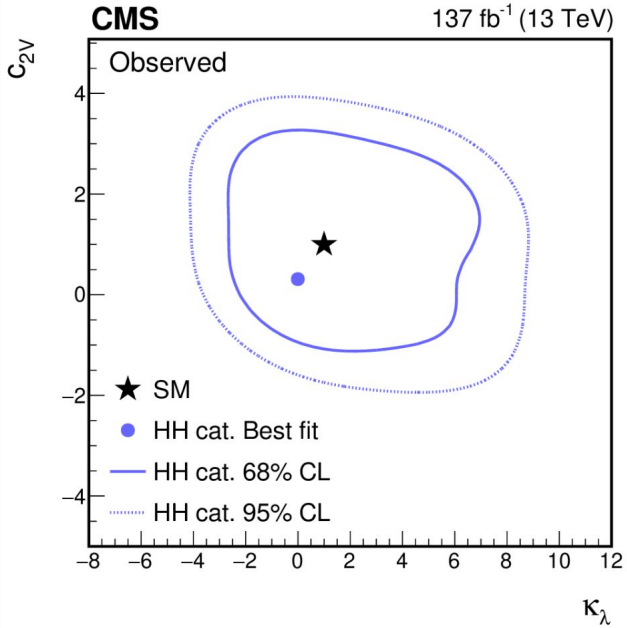

HH → bbγγ - nonresonant

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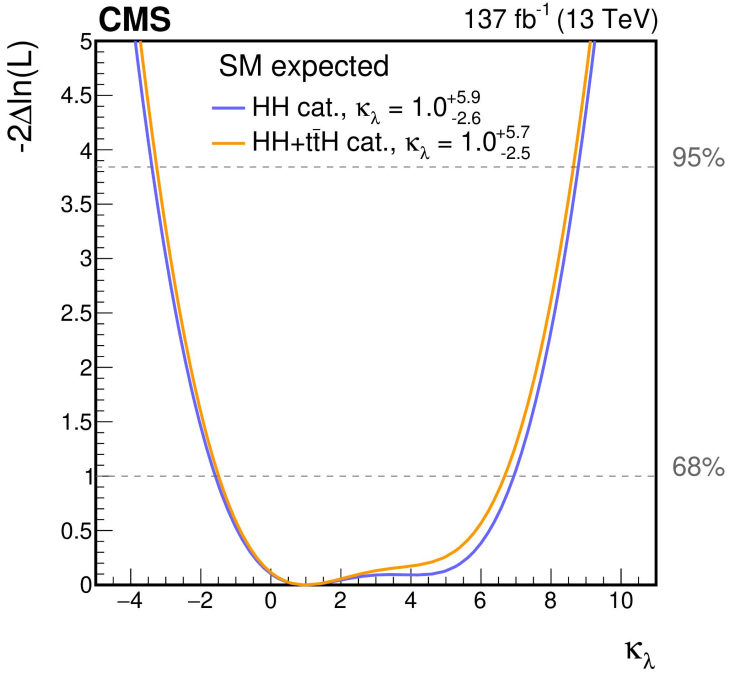

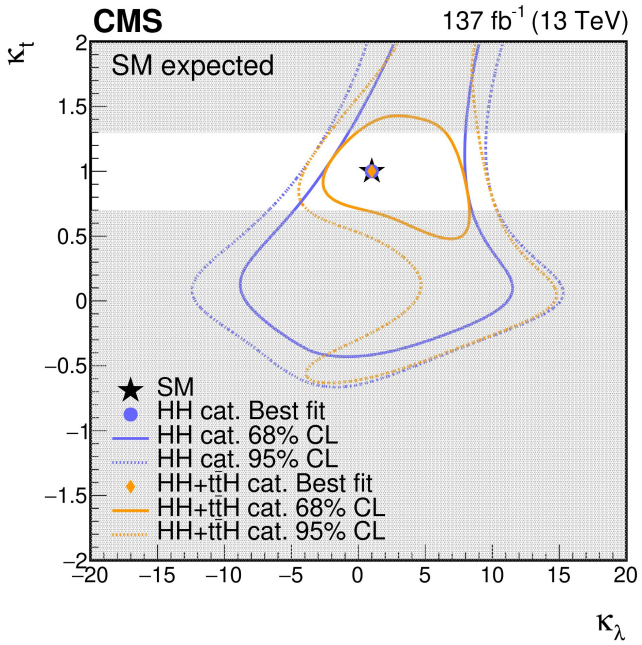

HH → bbγγ - nonresonant

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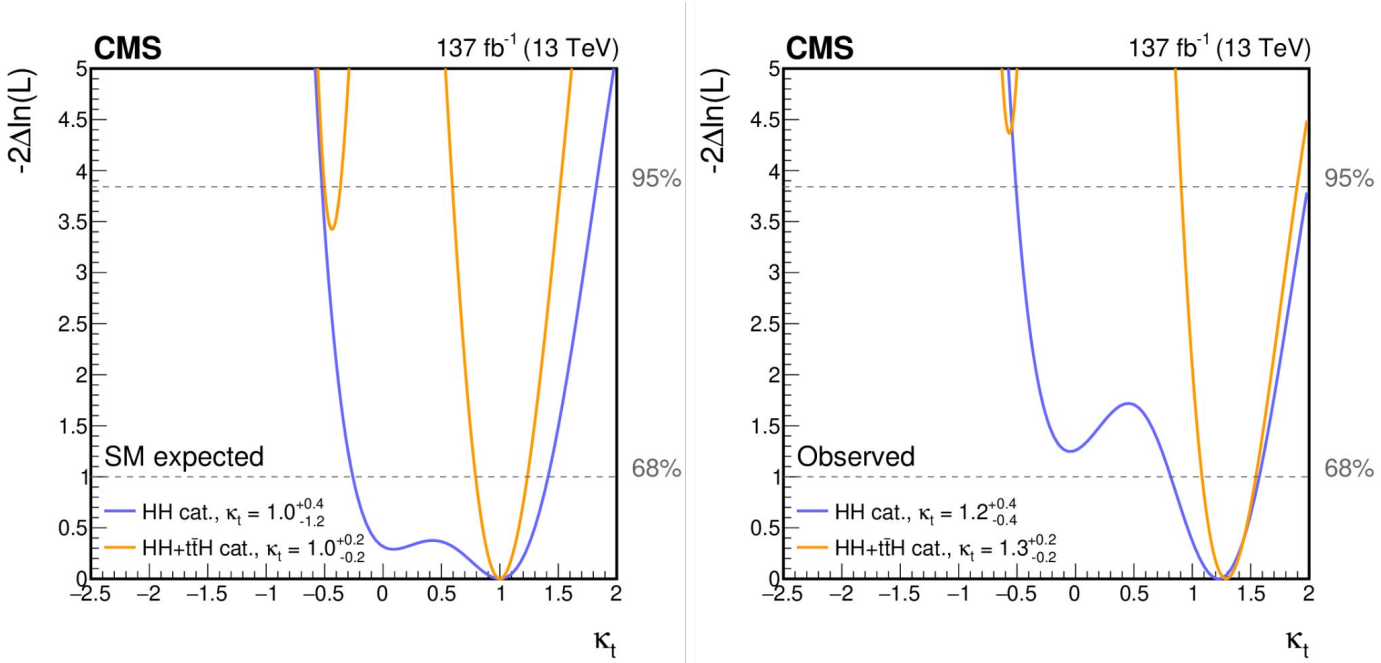

Combination

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