Higgs pair production at CMS

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On behalf of the CMS collaboration

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Outline

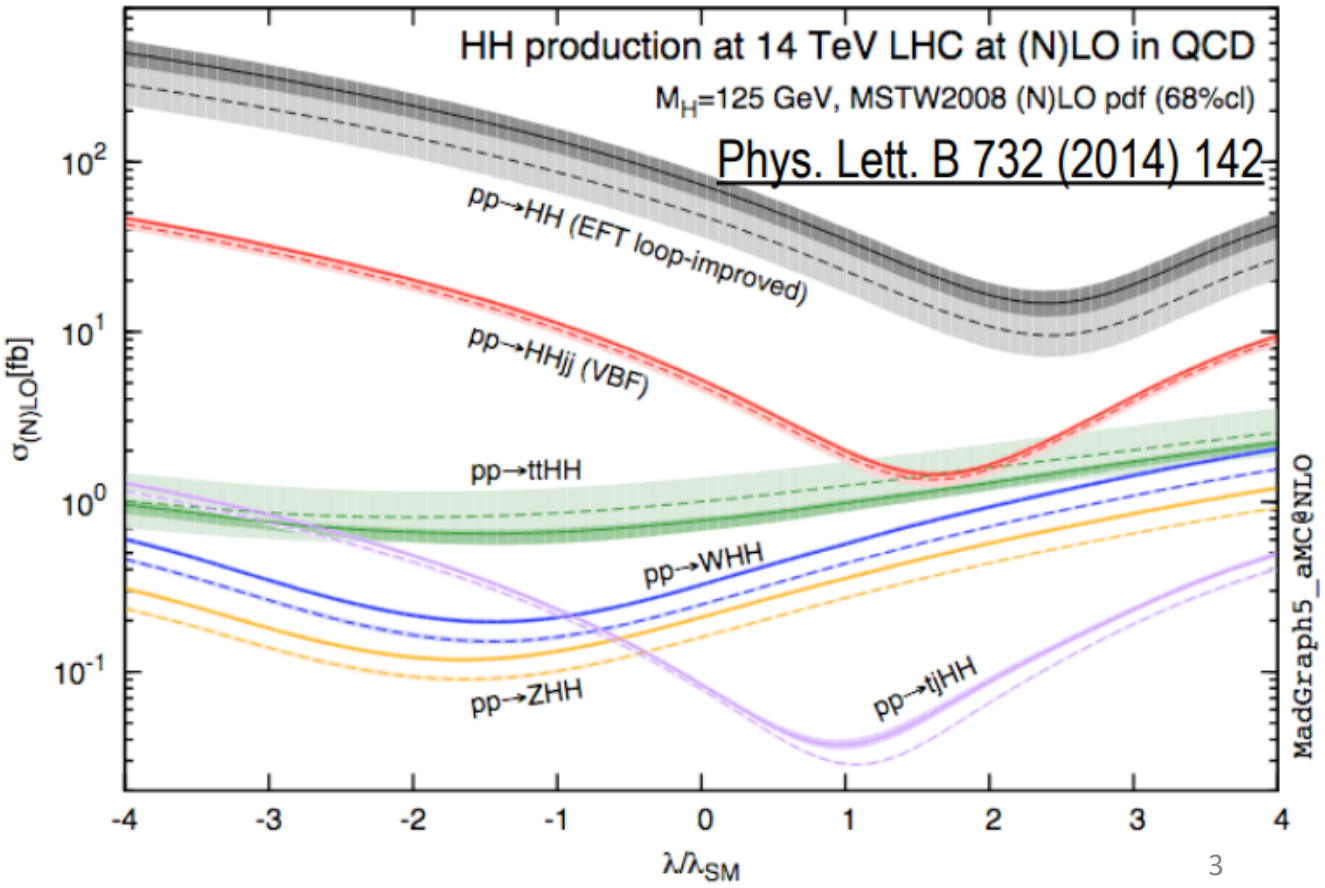
This presention is focussed on the non-resonant production of Higgs pairs

- **Motivation within the SM**
- **Motivation to go beyond SM**
- **What CMS has (analyses)**
- **Summaries of the analyses**
- **Summaries of the results**
- **Celebrating the 10 years anniversary of the Higgs boson looking at Higgs pairs**
- **Conclusions**

Motivation – SM-like searches

- At the LHC dominant production mechanism for SM double Higgs production is gluon fusion (GGF)

- Other productions modes, such as vector boson fusion (VBF), ttHH and VHH could also be accessible
  - Smaller rate

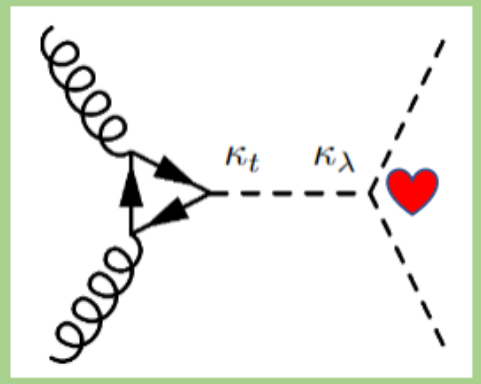


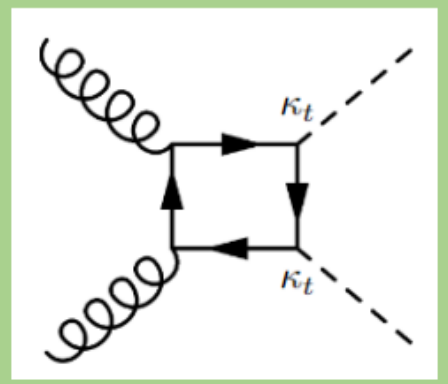
Testing the SM

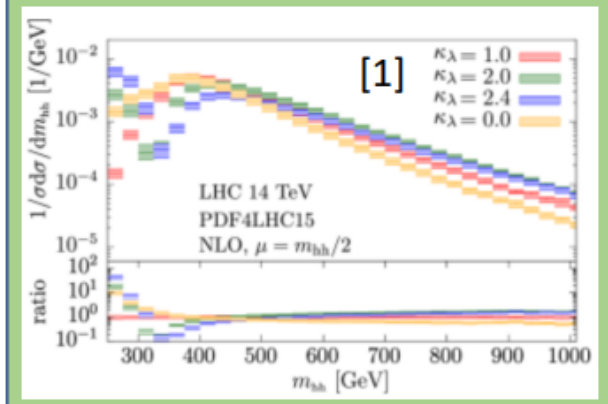
In the assumption of no extra BSM couplings the HH channel can offer a first view for two couplings

Gluon fusion mode

⇒ provides better direct contraints to kl





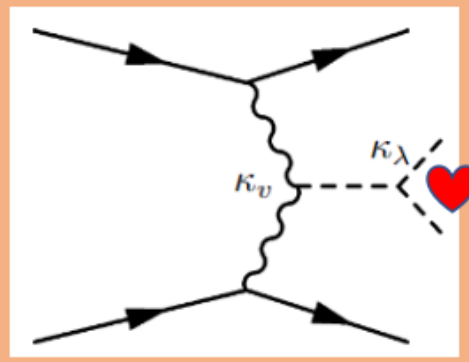


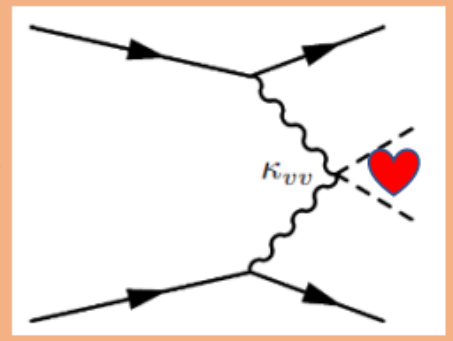
|kl| >> 1
➔ softer Higgs bosons

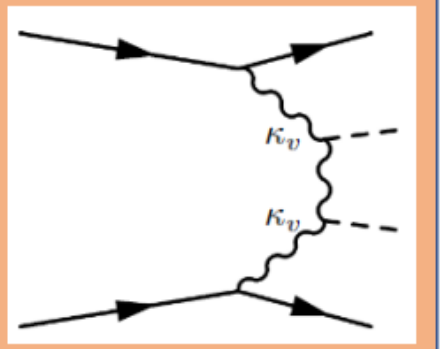
Around largest interference (kl = 2.45)
➔ harder Higgs bosons

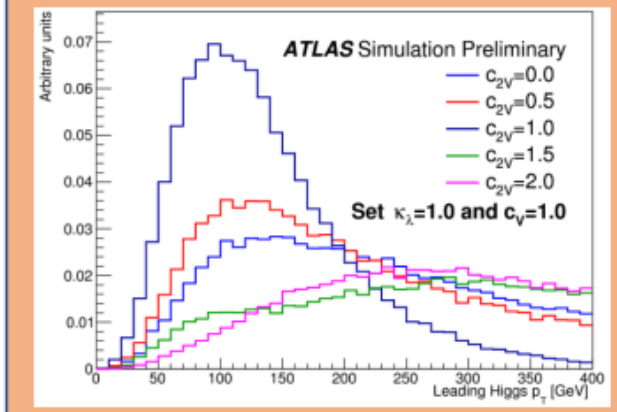
Vector boson fusion mode

Only process to approach the 4-linear HHVV coupling
=> A test of the doublet structure of the Higgs field









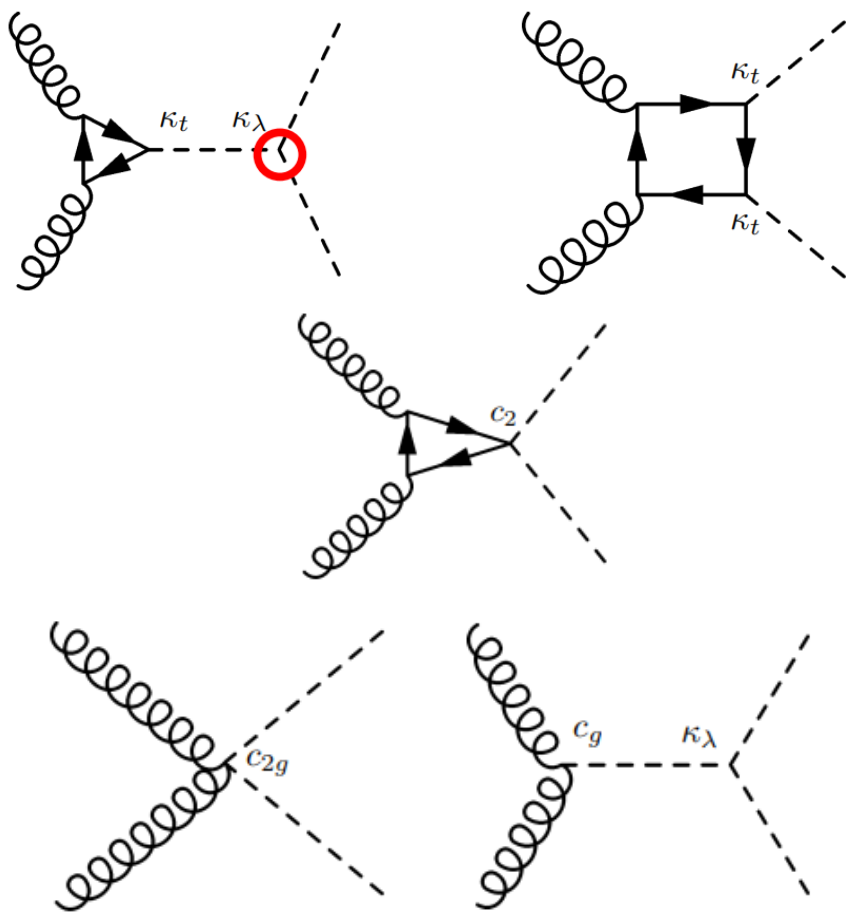
If kv/kvv deviates from the SM-value (=1)
➔ harder Higgs bosons

Modifications in H couplings do not only alther HH cross section, but also its kinematics

*κx refers to the coupling modifiers, defined wrt the SM value of that coupling. At the SM κx=1

Probing BSM hypotheses

- Deviations of Higgs couplings do not usually come alone
- Several BSM theories predict the possibility of three more coupling structures for the GGF production
  - Parametrized in the Higgs Effective Theory as coupling multipliers that are zero in the SM case*
- Variations on BSM-only generate more violent signal topology and XS modifications [1]
  - Too many parameters to deal with experimentally!
    - Two approaches at CMS:
      1. Parameter scans involving the c2 parameters
      2. Classification of signal types in terms of signal topology, namelly shape benchmarks [1,2]
         - A more complete exemplification of the effects of Higgs anomalous interactions in the results of experimental analyses



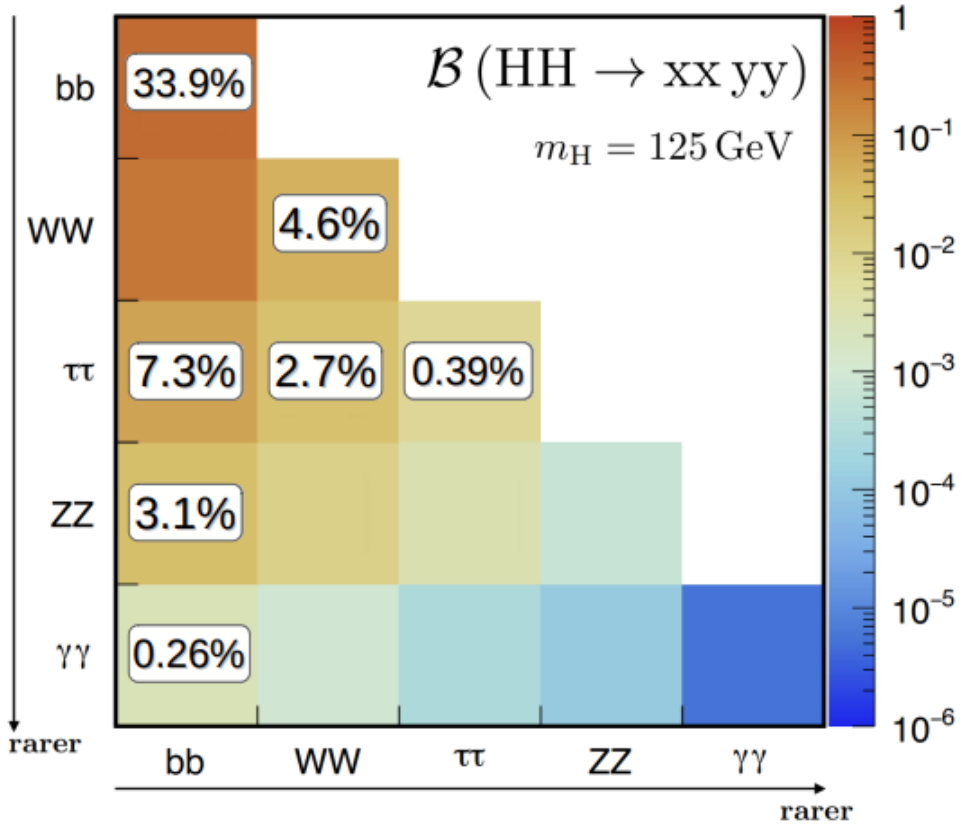
[1, JHEP04] A.C., M. Dall'Osso, T. Dorigo, F. Goertz, C. Gottardo, M. Tosi'2015

[2, JHEP03] Heinrich, G., Capozi, M. '2019

*In other EFT parametrizations those may be correlated in different ways

What CMS has

- Different final states for HH define different analyses, each one with its pros and cons



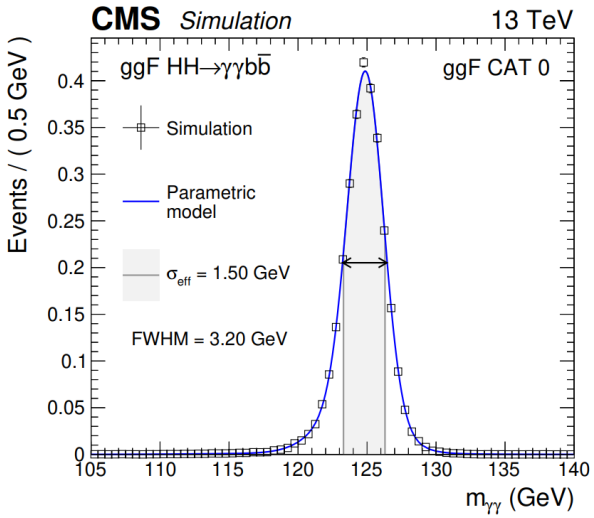
- HH → bbbb resolved (Phys. Rev. Lett. 129 (2022) 081802)
  - Large BR, large backgrounds
- HH → bbbb merged-jet (arXiv:2205.06667)
  - Merged jets topology
- HH → bbττ (arXiv:2206.09401)
  - Sizeable BR, small backgrounds
- HH → bbγγ (JHEP03(2021)257)
  - Small BR, very clean mass resolution
- HH → WWWW + WWττ + ττττ (arXiv:2206.10268)
  - Medium/small BR, multiple final states
- HH → bbZZ(4l) (arXiv:2206.10657)
  - Medium BR, moderate backgrounds

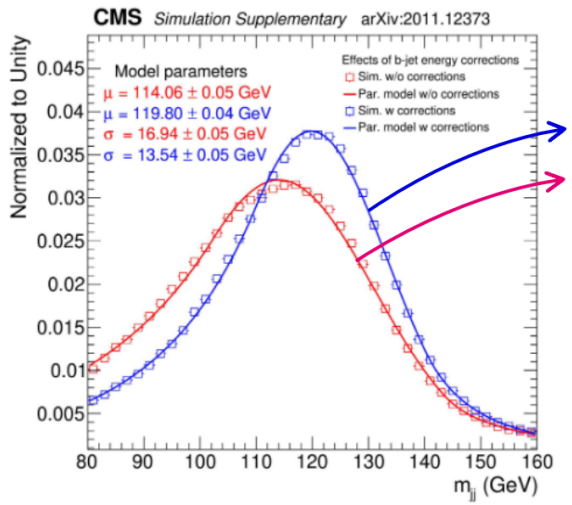
JHEP 03 (2021) 257

HH → bbγγ

Strategy:

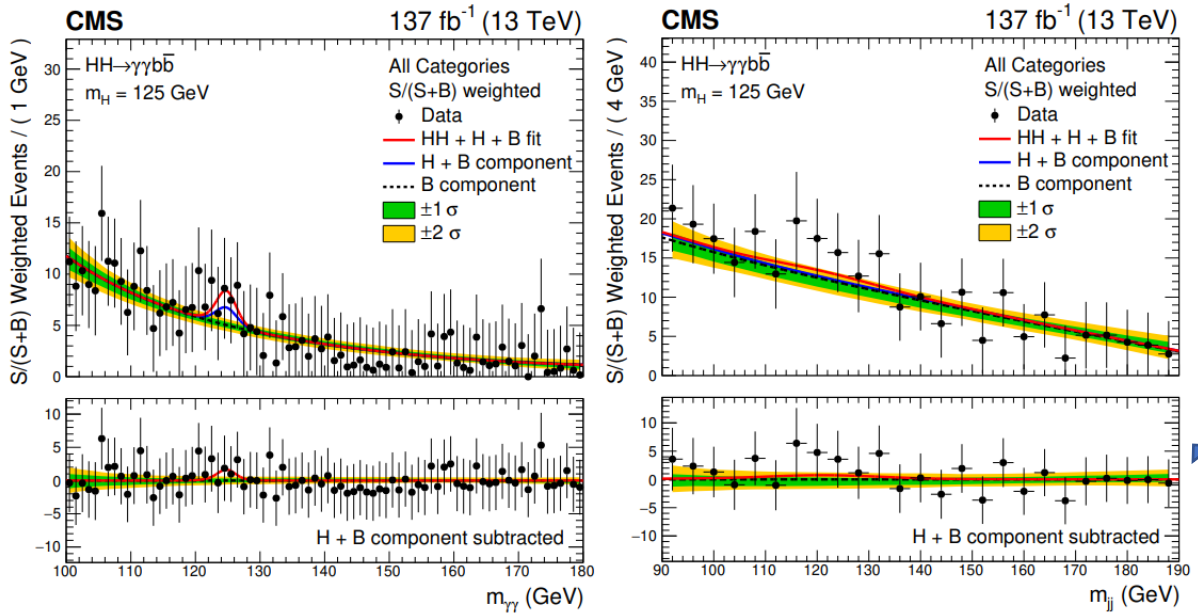
- **γγ selection**
  - pT1 (pT2) > 0.33 (0.25) · mγγ
  - 100 < mγγ < 180
    - mγγ resolution of 1.4 - 2.0 GeV
- **bb selection**
  - 2 jets with highest b-tag score (CMS DeepJet)
  - 70 < mbb < 190 GeV
  - b-jet energy regression improves mbb resolution in about 20 %
- 2D maximum likelihood fit on mjj and mγγ





After correction

Before correction



Optimization to the different physics scenarios:

- Events are categorized in GGF and VBF HH production and separate single H production* using different BDT classification scores

Fits in one of the categories

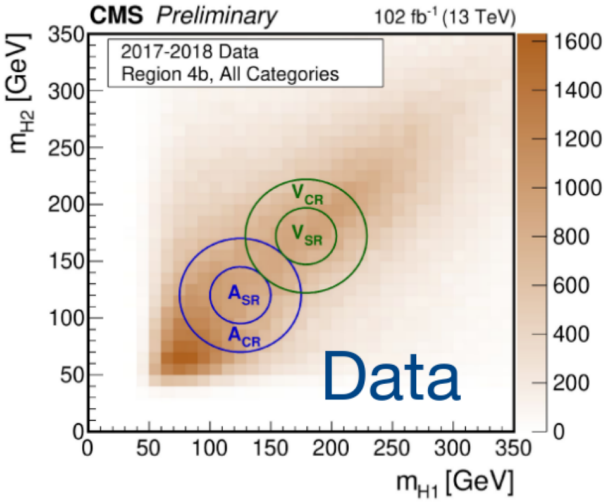
*ttH, H → γγ production, a resonant BKG in mγγ

HH → bbbb

[Phys. Rev. Lett. 129 (2022) 081802](#) (resolved)

Strategy:

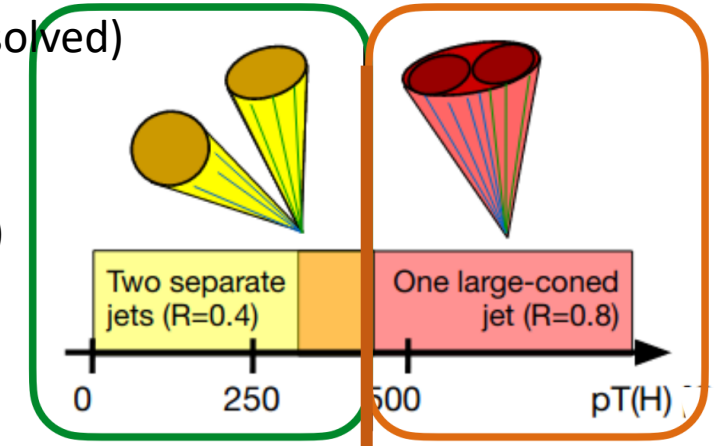
- Select events with 4 resolved b jets
  - Rely on CMS DeepJet efficiency (75%) and b-jet energy regression



- Events are selected around the masses of the jet pairs
- A control region is defined
  - Used to a data-driven estimation of the BKG

Optimization to the different physics scenarios:

- Events are categorized in GGF and VBF HH type
  - GGF events are classificated in high/low mHH
  - VBF events are classifyed as SM/BSM like (kvv >> 1)
- Results are derived fitting a BDT separating signal and BKG



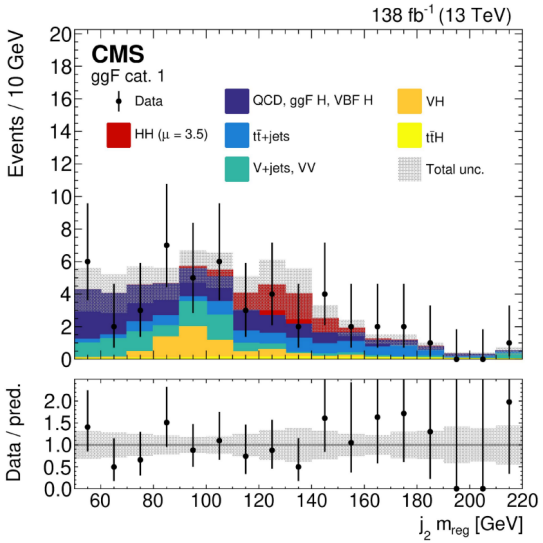
[arXiv:2205.06667](#) (merged-jet)

Strategy:

- Exploit boosted topology identifing B-hadrons in large-cone jets with [ParticleNet algorithm](#) (GNN-based)

Optimization to the different physics scenarios:

- Events are categorized in GGF and VBF HH type
  - For VBF-type of events are categorized wrt BDT targeting an anomalous VBF signal (kvv >> 1)
- Results are derived fitting the sub-leading reconstructed Higgs (GGF categories) and mHH (VBF categories)



arXiv:2206.09401

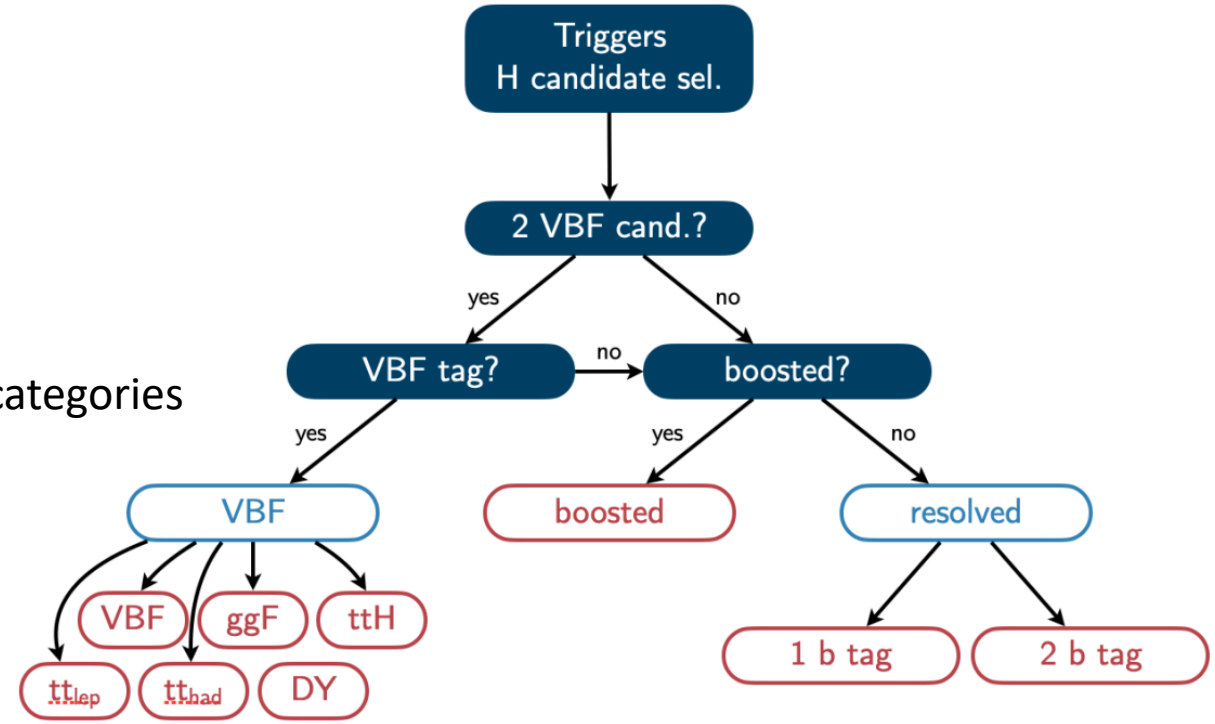
HH → bbττ

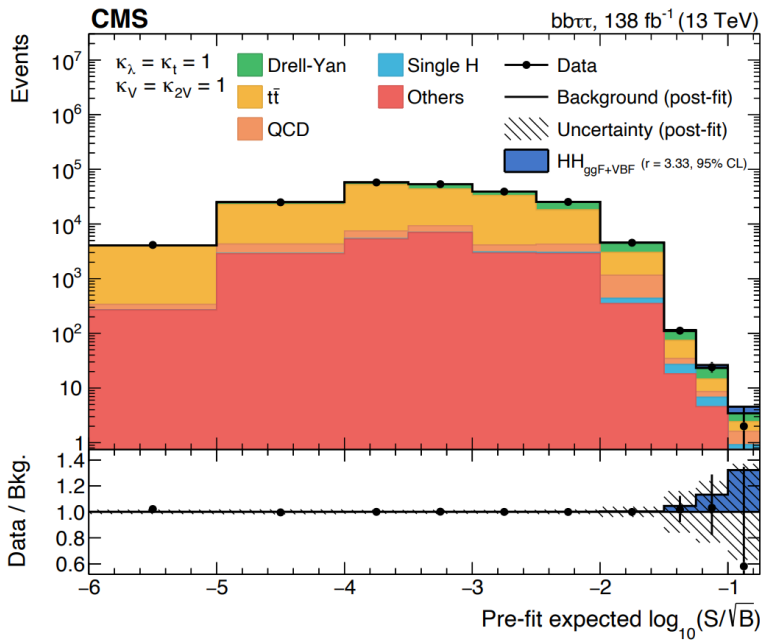
Strategy:

- Profit from CMS DeepFlavour and DeepTau object taggers to select events
- Split phase space into resolved, boosted and VBF

Optimization to the different physics scenarios:

- Events are categorized in GGF and VBF HH type
  - VBF events are classified using a multi-classification DNN
- Toguether with lepton flavour classification that results in 72 categories
  - Results are derived fitting a these DNN scores

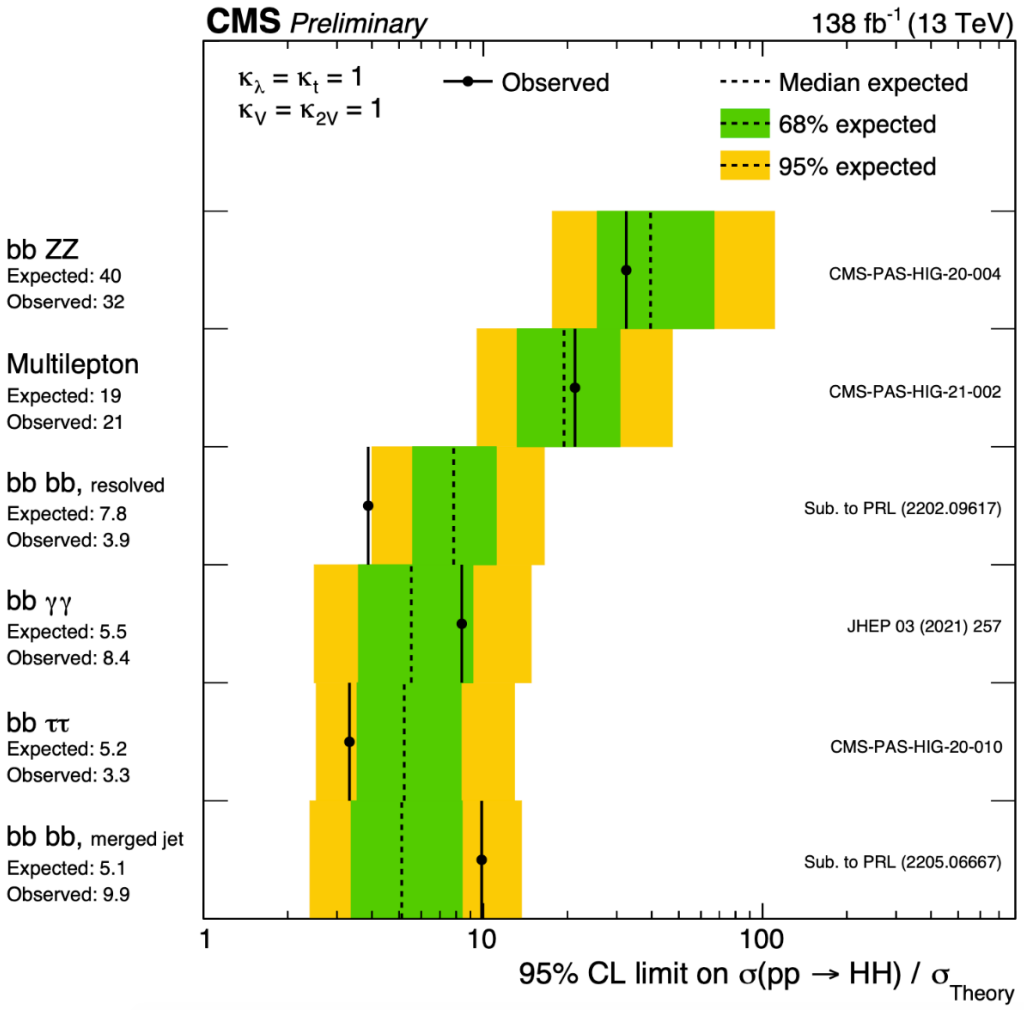




Cumulative Run 2 DNN score bins ordered by their pre-fit S/B ratio split into physics processes

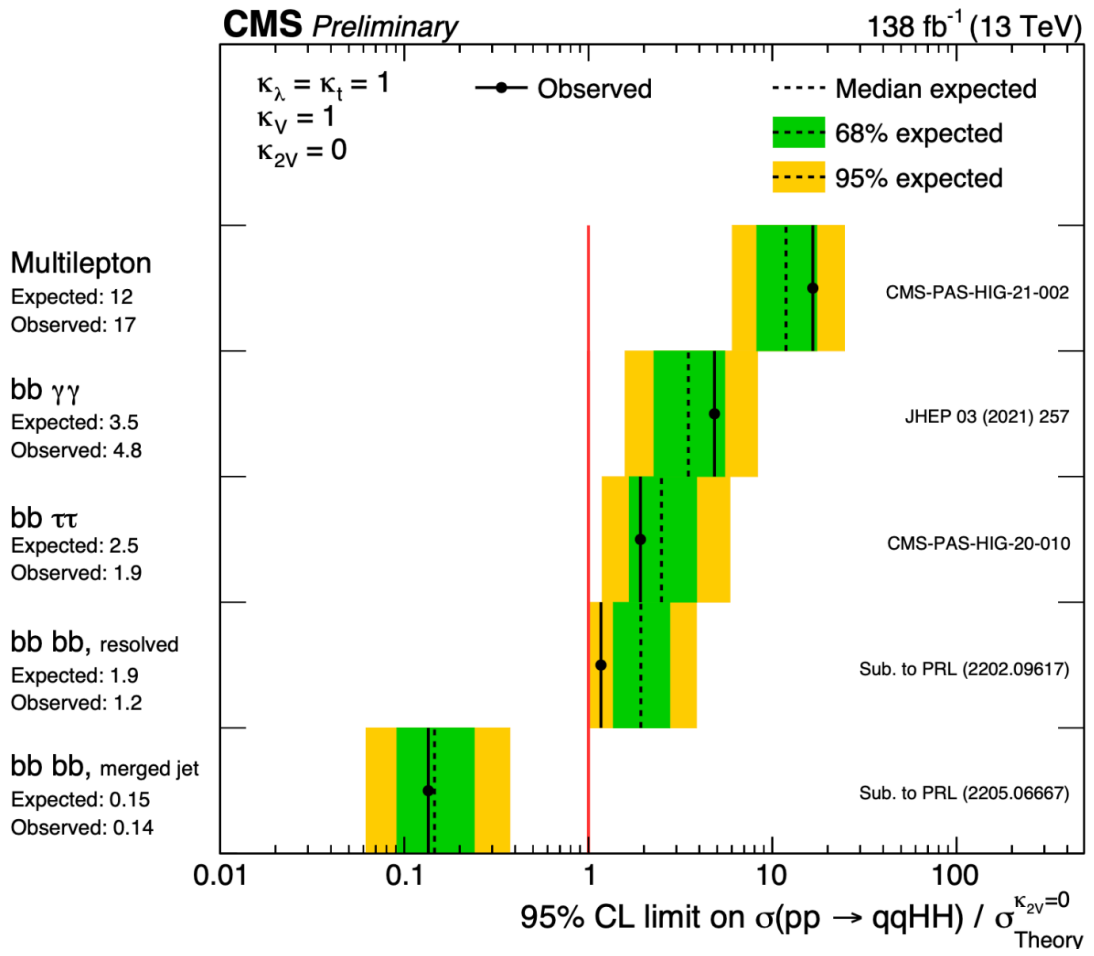
Summary of results – Upper limits in the HH signal

For the SM case



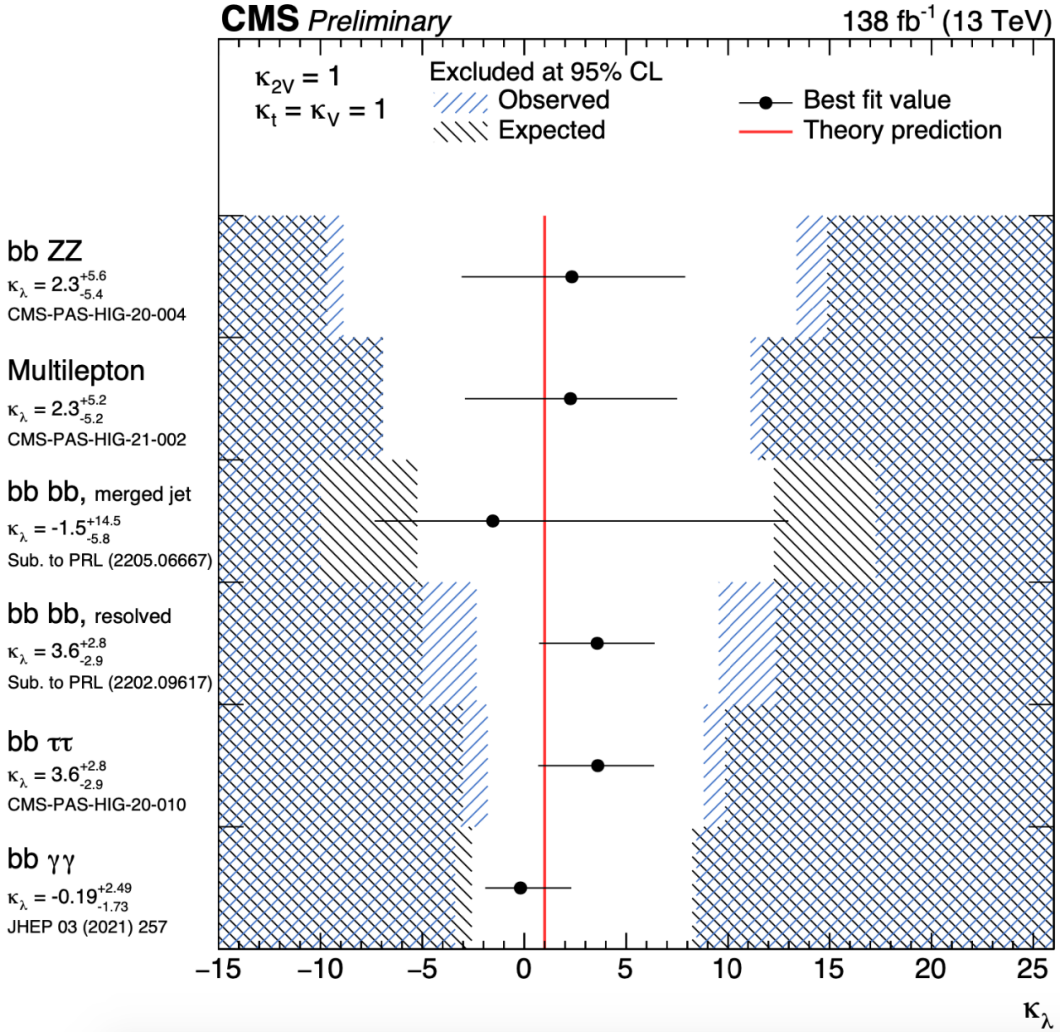
No distinctive golden channel

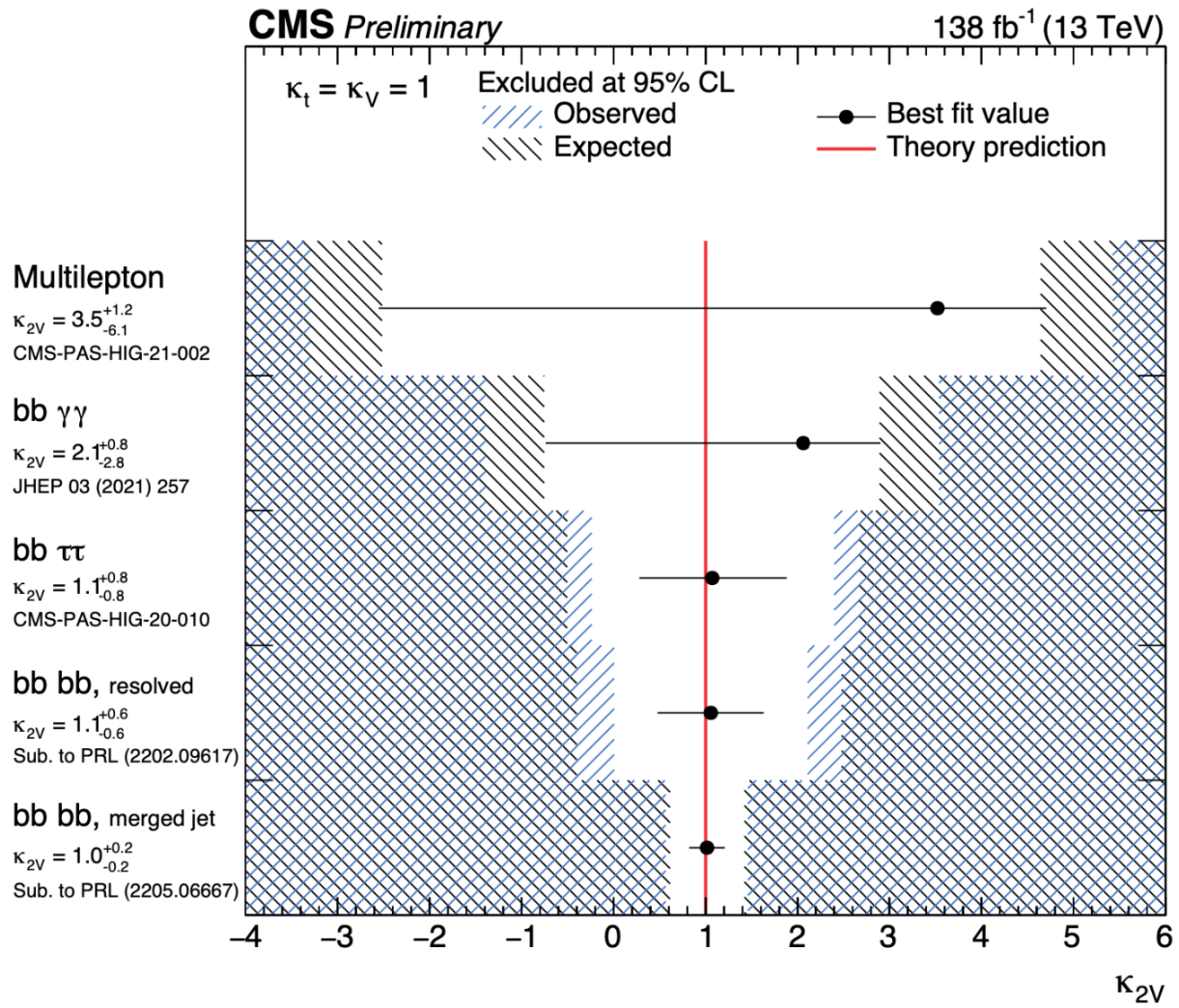
For the case of no κ2v coupling



The 4b merged-jet analysis is the first one to exclude the κ2v = 0 case

Summary of results – Scans on SM-like couplings



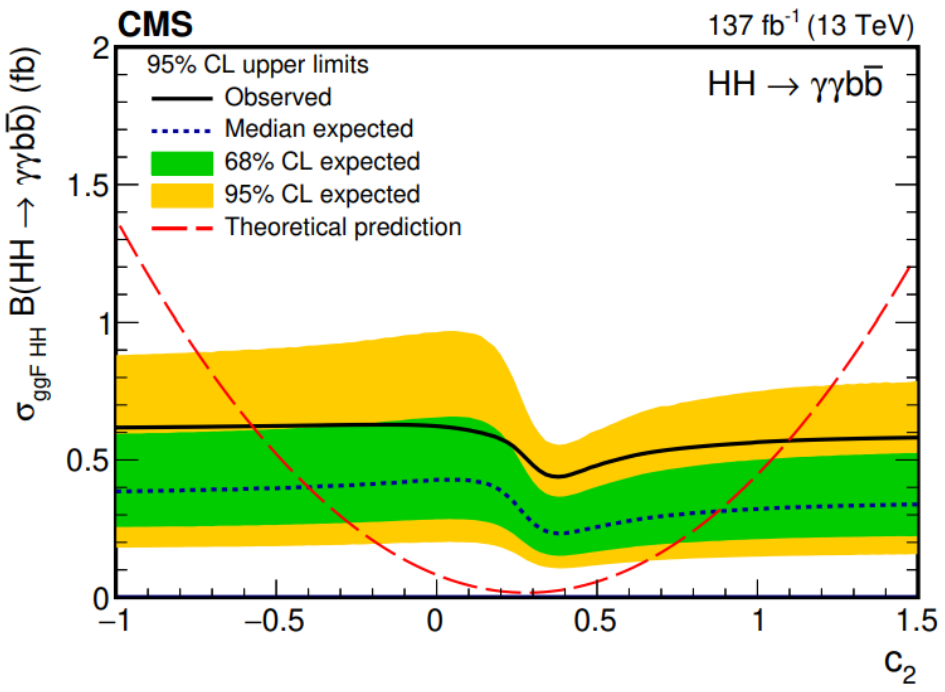


The order of the most sensitive channels is not the same of the UL

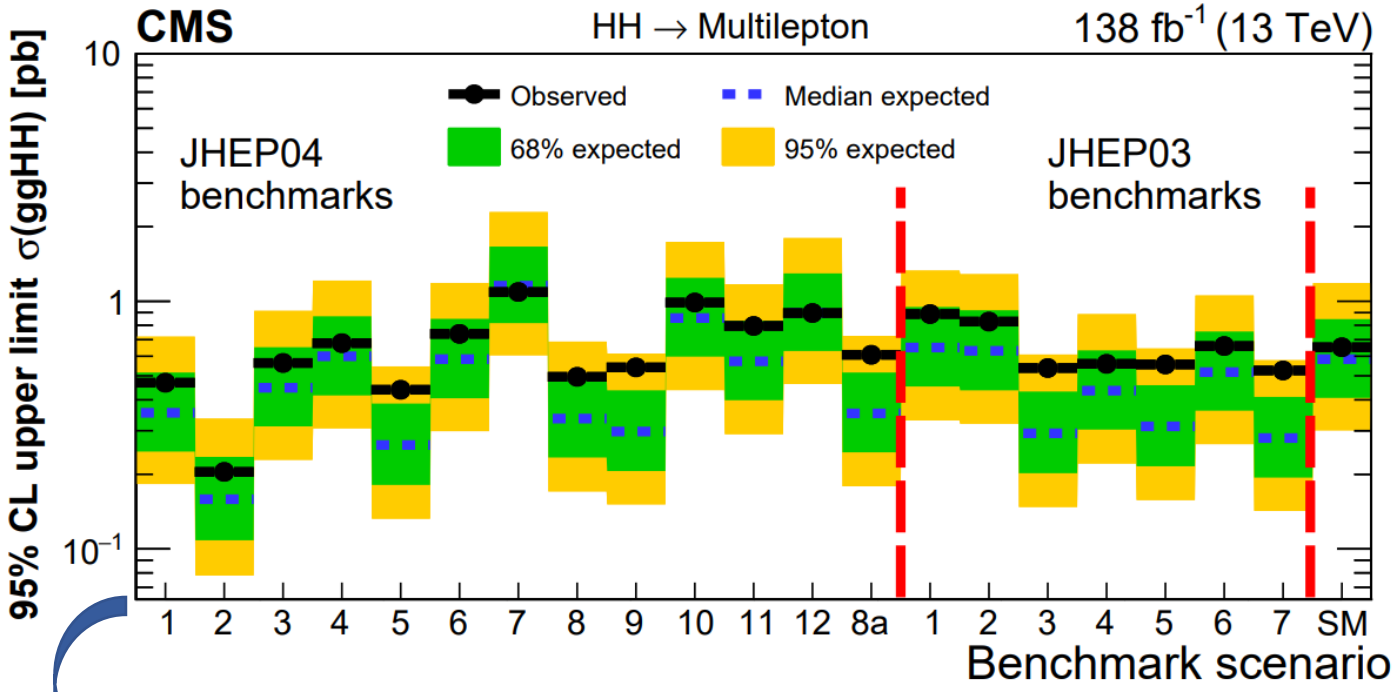
Effect of the change on signal kinematics with couplings

Summary of results – upper limits in BSM scenarios

Scans on ttHH contact interactions



Upper limits on shape benchmaks



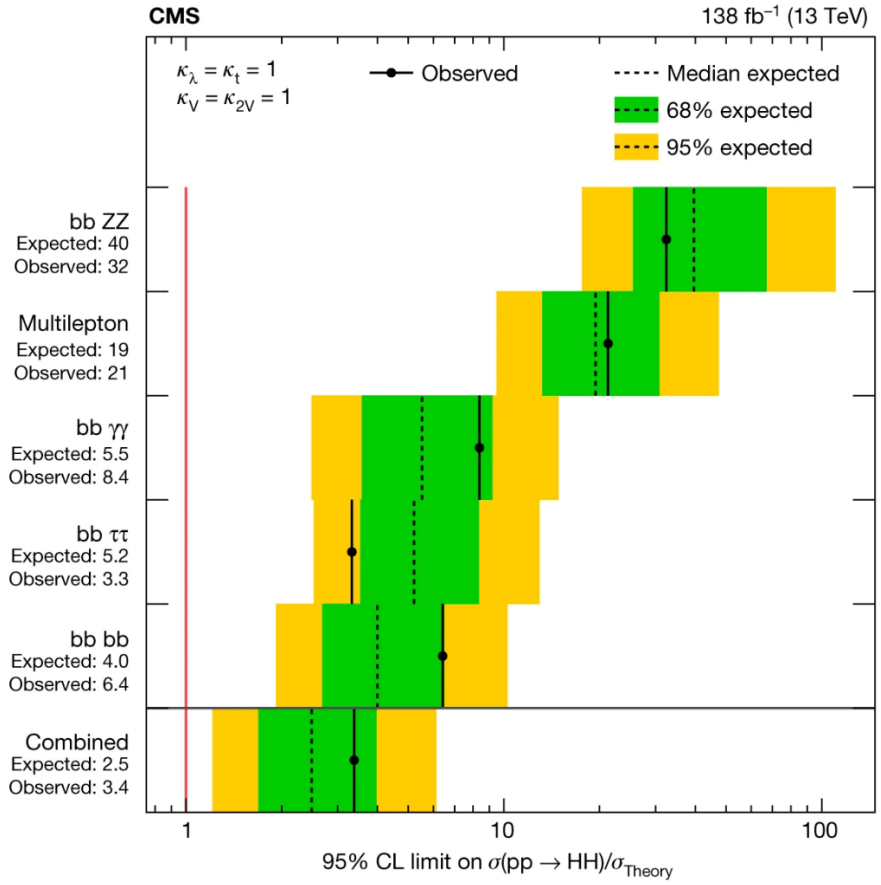
- Up to one order of magnitude modifications in UL
  - Can be used to estimate constraints in specific models and/or different coupling scans (eg *JHEP* 02 (2021) 049)

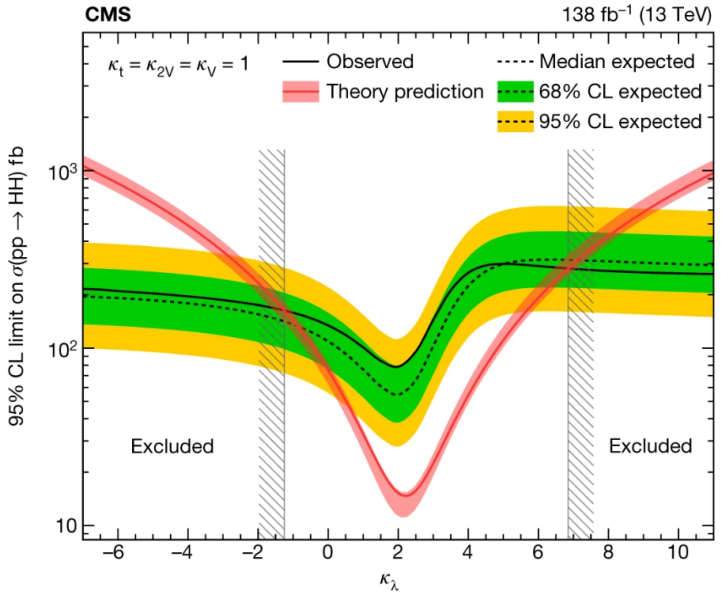
Celebrating the 10 years anniversary of the Higgs boson

A preliminary combination of the HH searches featuring the SM-like scenario was published

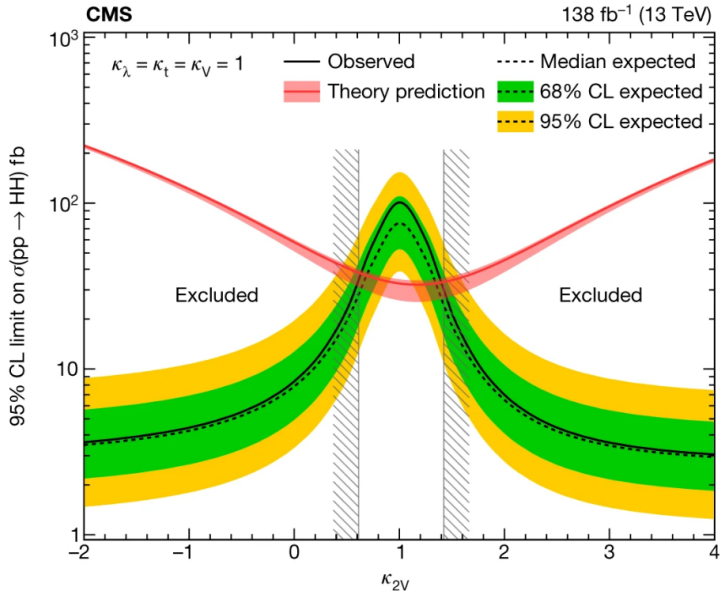
=> The state of the art from the CMS results on searches for Higgs pairs

Nature 607 (2022) 60





κλ [-1.25, +6.85] @95% CL



κ2v [0.67, 1.38] @95% CL

- Comparing with a previous combination (Phys. Rev. Lett. 122 (2019) 121803) with partial Run II luminosity we observed majour improvements in the results

Major improvements due to

- ➜ Detector upgrades & trigger development
- ➜ CMS reconstruction & object tagging
- ➜ Improved analysis techniques
- ➜ Additional decay channels

Summary

- Searches of non resonant HH production at CMS aim to investigate
  - both tri-H and quartic VVHH couplings when investigating SM-like parameters
  - But also, BSM-like Higgs couplings

- Five decay channels published and combined for the case of SM-like couplings
  - $k2V \leq 0$ excluded with 6.6σ assuming otherwise SM couplings
  - Combined upper limit on inclusive HH production observed as 3.4 x SM

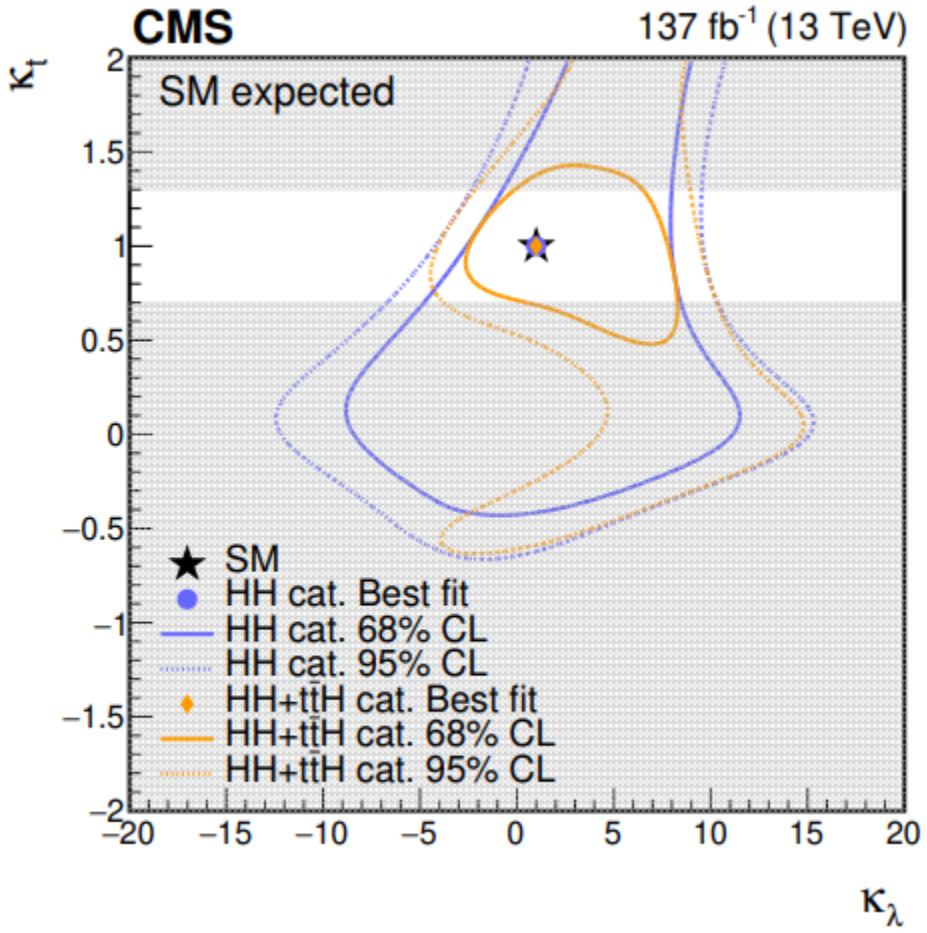
- Ongoing efforts to include more decay channels and production modes

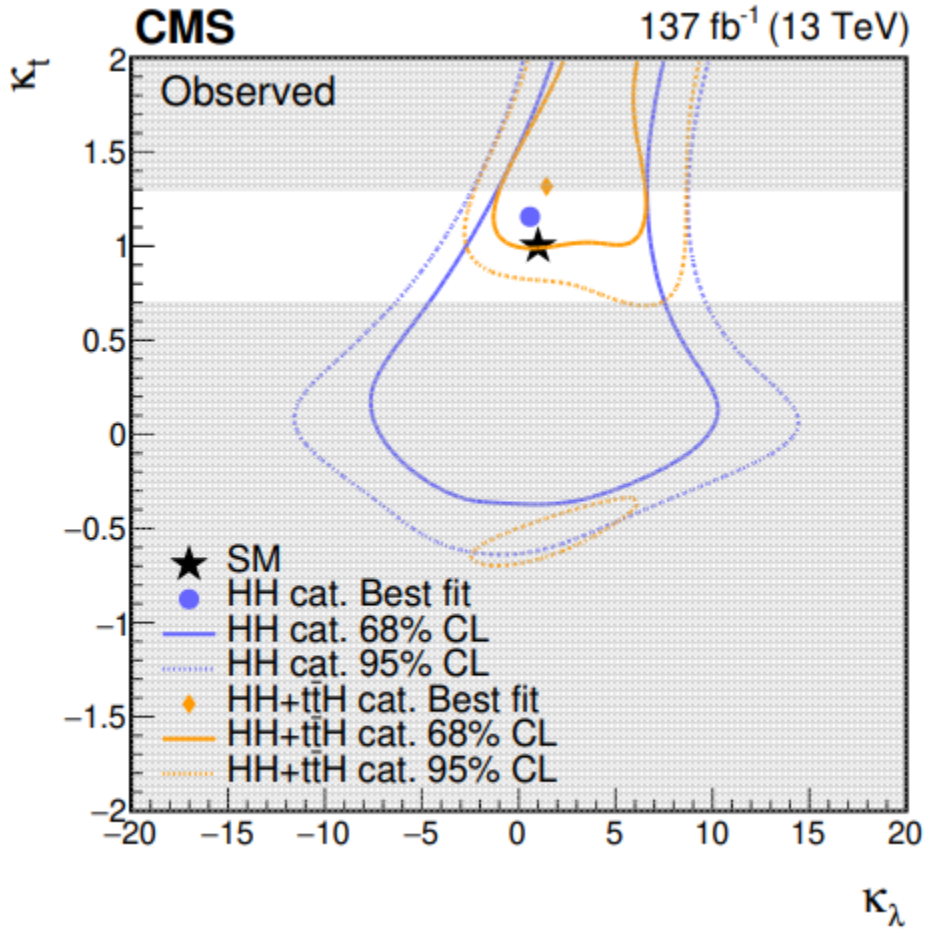
- We are closing up to measure Higgs pair production
  - Exciting years for the upcoming phases of the LHC !

Backup

Highlights on analyses: HH → bbγγ

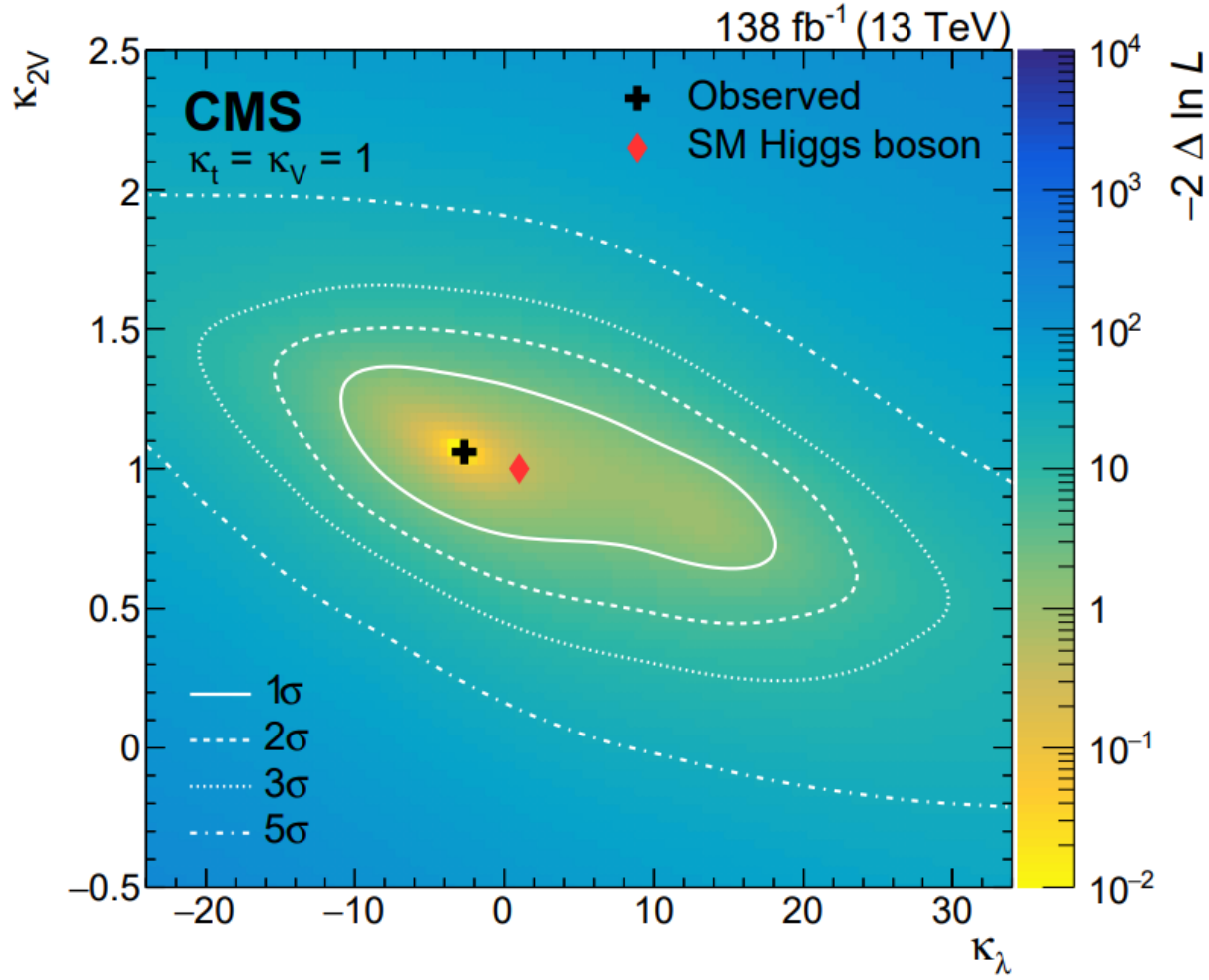
- Combination of results with single H categories





Highlights on analyses: HH → bbbb merged-jet

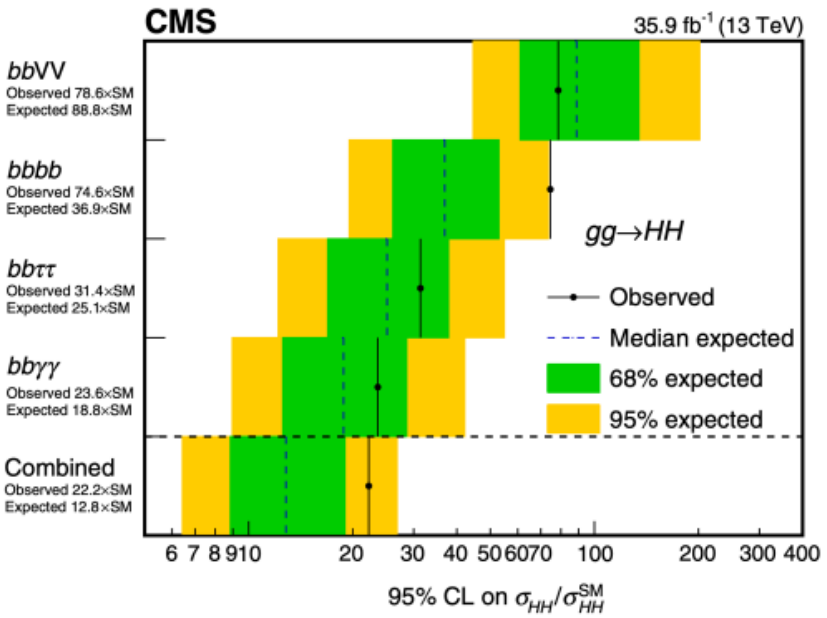
- More 2D scans of parameters



Comparisons between combinations

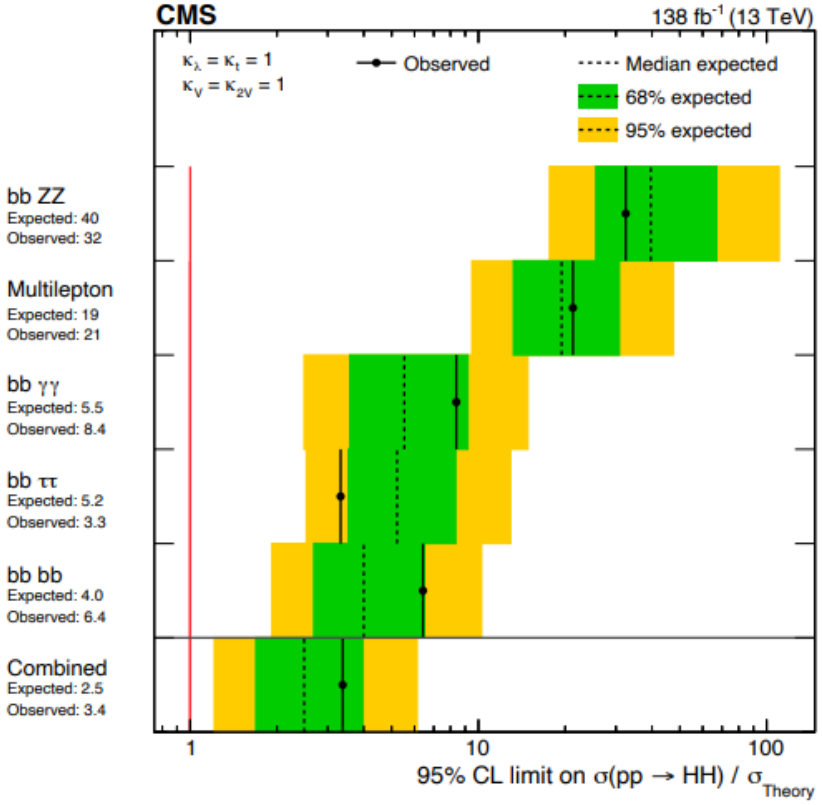
2016 data

Phys. Rev. Lett. 122 (2019) 121803



Run 2 combination

Nature 607 (2022) 60



new

new

x **3** improvement

x **5** improvement

x **5** improvement
(x **30** in boosted ch.)