Di-Higgs: searches at CMS

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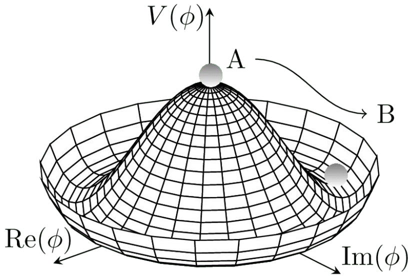
Outline

- Motivations
- Non-resonant searches at CMS
  - Key channels: the top 3
  - HH combinations
  - More challenging decay modes
- Run 3 improvements
- Conclusions

Probing the Higgs potential

- Higgs boson discovery revealed only a part of the Higgs potential
  - important property of the Higgs boson still weakly constrained by LHC data is the Higgs self-coupling (λ)
    - crucial component of our understanding!



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

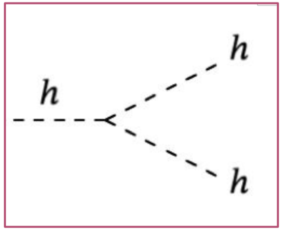
↓ EWSB

$$V_H = \lambda v^2 H^2 + \lambda v H^3 + \lambda H^4 \to \frac{1}{2} m_H^2 H^2 + \lambda_{HHH} v H^3 + \lambda_{HHHH} H^4$$

- *HH production*

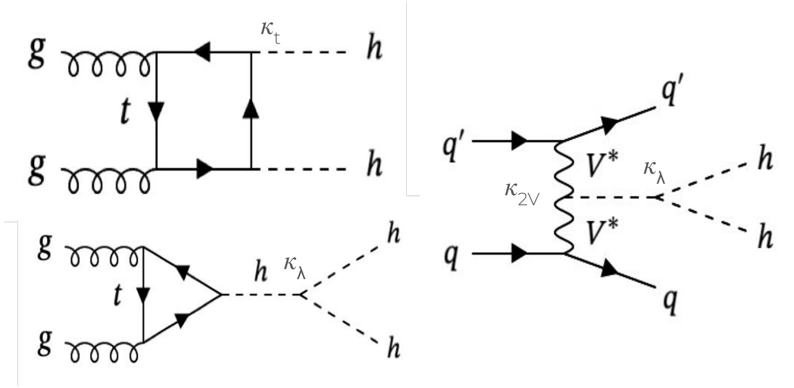
  → direct probe of Higgs self-interaction

  → the Higgs potential



- Any deviations from the SM predictions would indicate the presence of new physics
  - the modifier of λ_{HHH} wrt the SM prediction is denoted as $\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{SM}$

Hunting for HH at LHC



- At LHC, HH production through:
  - gluon fusion (ggF) : ~ 88% at 13 TeV
  - Vector Boson Fusion (VBF) : ~ 7% at 13 TeV
  - smaller contributions from VHH and ttHH

- Searches are both focused on:
  - resonant: new resonances decaying into HH
    - several models: search for a bump in the m_{HH} distributions
      → **more in [Rainer Mankel's talk]**
  - **non-resonant**: upper limits on the SM HH production XS & explore possible BSM processes (could modify XS or kinematics properties)
    - EFT approach → deviations from SM are defined by coupling modifiers (e.g. κ_λ)
      → **addressing these searches in this talk**

Non-resonant searches at CMS: main players

- Higgs boson decay branching ratios: *large variety of final states*

- Sensitivity is driven by 3 final states: good compromise between branching ratios and selection purity

  - bbbb
    - ggF and VBF production
      - resolved topologies [Phys. Rev. Lett. 129, 081802]
      - boosted topologies [Phys. Rev. Lett. 131, 041803]
    - VV production [arXiv:2404.08462]
  - bbγγ [JHEP03 (2021) 257]
  - bbττ [Phys. Lett. B 842 (2023) 137531]

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

Non-resonant searches at CMS: rarer decays

- Recently, searches have also directed towards rarer decays:
  - WWWW, WWττ, ττττ (multilepton) [JHEP 07 (2023) 095]
  - bbZZ (4ℓ) [JHEP 06 (2023) 130]
  - bbWW [arXiv:2403.09430]
  - WWγγ [CMS-HIG-PAS-21-014]
  - ττγγ [CMS-PAS-HIG-22-012]

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Phys. Rev. Lett. 129, 081802

HH → bbbb (resolved)

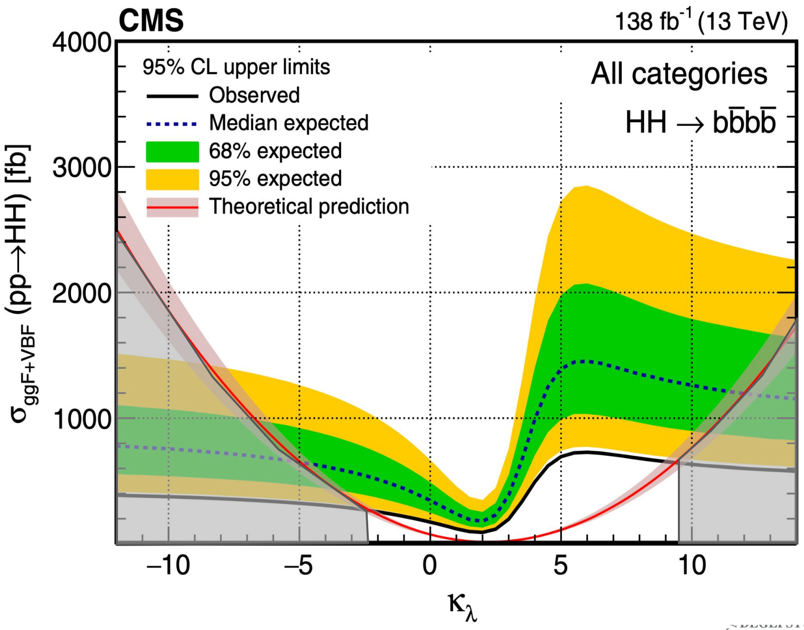
✅ Large branching ratio

❌ Multi-jet background

- Branching ratio: 33%
- Background: multi-jet QCD and tt processes
  - data-driven estimate

- Strategy insights:
  - DeepJet b-tag
  - Non-trivial jet pairing
  - Simultaneous fit of BDT for ggF and of m_{HH} for VBF

- Upper limits @ 95%
  - observed: $-2.3 < \kappa_\lambda < 9.4$
  - expected: $-5 < \kappa_\lambda < 12$



J. High Energ. Phys. 2021, 257

HH → bbγγ

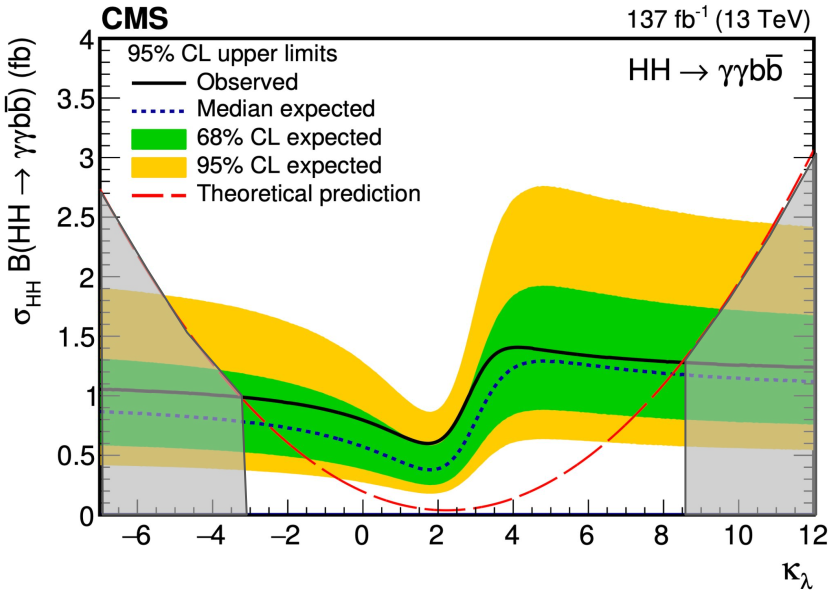
✅ Clean signature and precise resolution of $m_{\gamma\gamma}$

❌ Small BR

- Branching ratio: 0.26%
- Background: $\gamma(\gamma)$ + jets and single Higgs
  - data-driven estimate

- Strategy insights:
  - DeepJet b-tag + kinematical signal region
  - DNN to reduce ttH
  - 2 BDT to separate signal from background

- Upper limits @ 95%
  - observed: $-3.3 < \kappa_\lambda < 8.5$
  - expected: $-2.5 < \kappa_\lambda < 8.2$



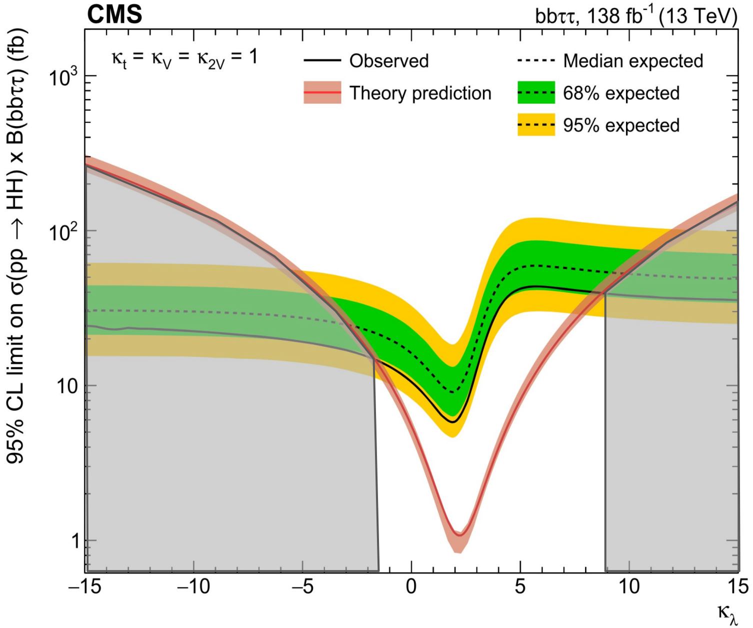
Phys. Lett. B 842.137531

HH → bbττ

✅ Good compromise between BR and clean signature

❌ EW and top background

- Branching ratio: 7.3%
- Background: DY, tt and QCD multi-jet
  - QCD estimated from data
- Strategy insights:
  - DeepJet b-tag and DeepTau
  - elliptical cut on m_{bb} and $m_{\tau\tau}$ to reduce bkg
  - DNN-based discriminant for signal extraction
- Upper limits @ 95%
  - observed: $-1.7 < \kappa_\lambda < 8.7$
  - expected: $-2.9 < \kappa_\lambda < 9.8$

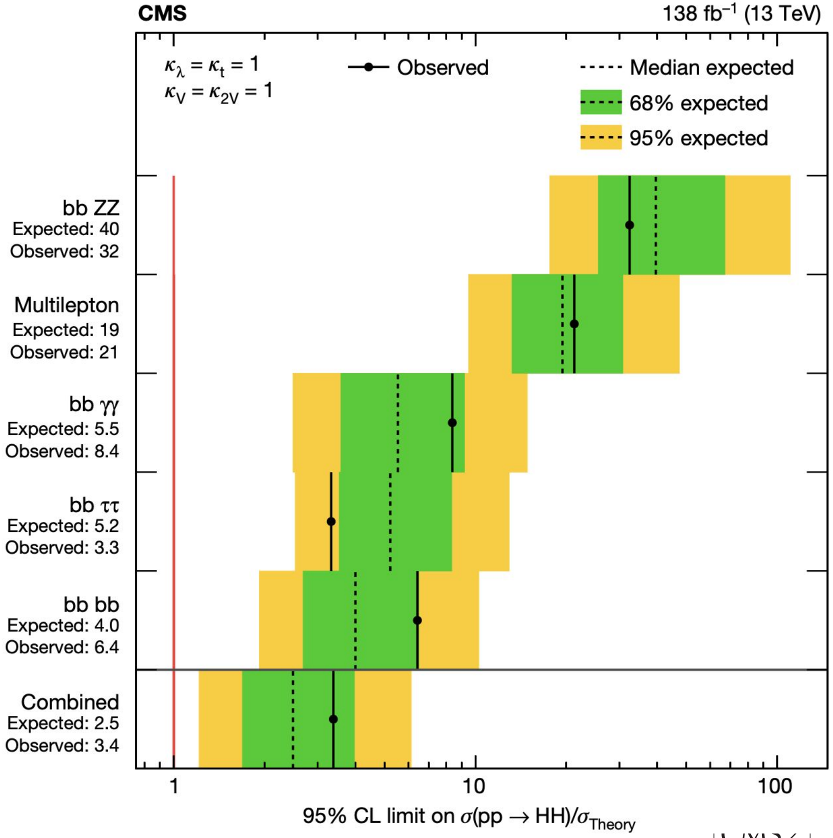


Nature 607 (2022) 60

Run 2 HH combination

- Combined full Run2 measurement : $2.5 \times \sigma_{HH}^{SM}$
    - based on the early Run2 results, we would have anticipated ~ $6.5 \times \sigma_{HH}^{SM}$ due to luminosity scaling

- Improvements principally thanks to:
    - New ML techniques for
        - jet tag
        - τ ID
        - signal extraction
    - Improved triggers (both L1 and HLT)



CMS-PAS-HIG-23-006

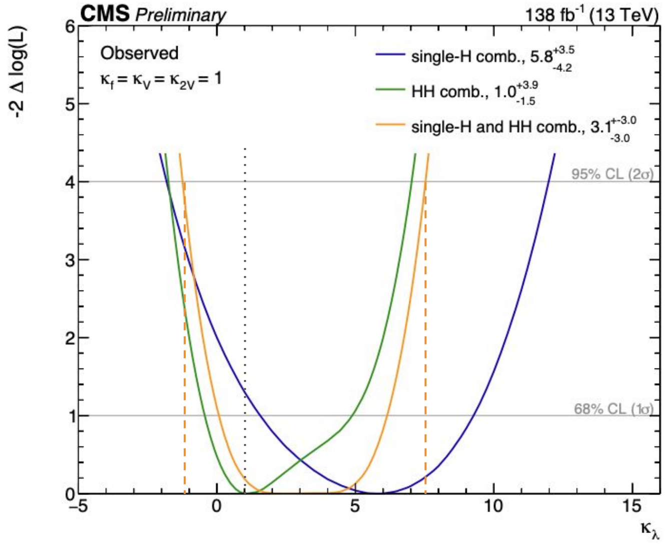
Run 2 HH+H combination new since LHCP24!

- H measurements are sensitive to κ_λ through NLO EW corrections
  - affect XS and decay widths, with significant impact on processes like ttH and VH

- Combination of H measurements and HH searches simultaneously constrain the Higgs self-coupling

- Challenge: managing overlaps between signal regions in different analyses to avoid double-counting and reduce uncertainties, ensuring precise and accurate constraints

- Constraints on κ_λ :
  - HH channel is close to 1 ($-1.7 < \kappa_\lambda < 7.0$), aligning with SM expectation of -2.3 to 8
  - H channel is slightly above 1 ($-1.2 < \kappa_\lambda < 7.5$), with expected κ_λ being from -4.5 to 11.
  - **Combining H and HH**: -1.2 to 7.5 (observed) and -2.0 to 7.7 (expected)



CMS-PAS-HIG-22-012

HH → ττγγ

new since LHCP24!

- Never studied before!

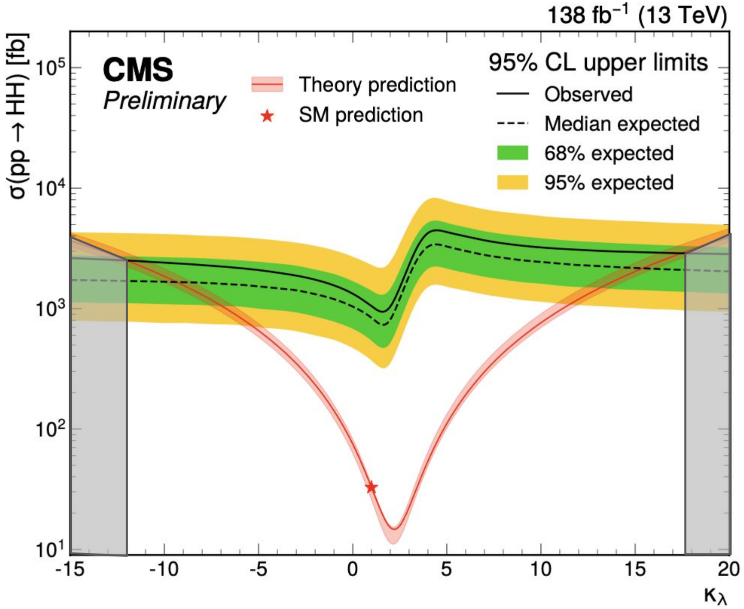
✅ γγ has a good mass resolution and ττ features a quite clean signature

❌ small BR (0.027%)

- **Background**: modeled through analytic functions by fitting $m_{\gamma\gamma}$ spectrum

- **Strategy insights**:
  - cut on $m_{\gamma\gamma}$
  - events categorized according to a discriminant designed to separate signal from background
  - double Crystal Ball fitted on simulation for signal

- **Upper limits** @ 95%
  - observed: $-13 < \kappa_\lambda < 18$
  - expected: $-11 < \kappa_\lambda < 16$



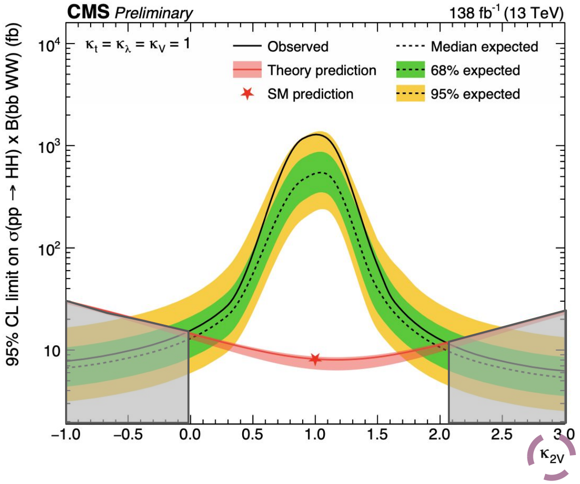
HH → bbVV new since ICHEP24!

- Never studied before!

✅ high branching ratio, sensitive to κ_{2V} deviations

❌ hadronic final state → high QCD background

- Branching ratio: 13%
- **Background**: data driven background: parametric transfer factor from QCD
- **Strategy insights**:
  - first use of Particle Transformer!
  - multi-variate event classification to improve sensitivity
  - fit to m_{bb} distribution
- **Upper limits** @ 95%:
  - observed: $-0.04 < \kappa_{2V} < 2.05$
  - expected: $0.05 < \kappa_{2V} < 1.98$

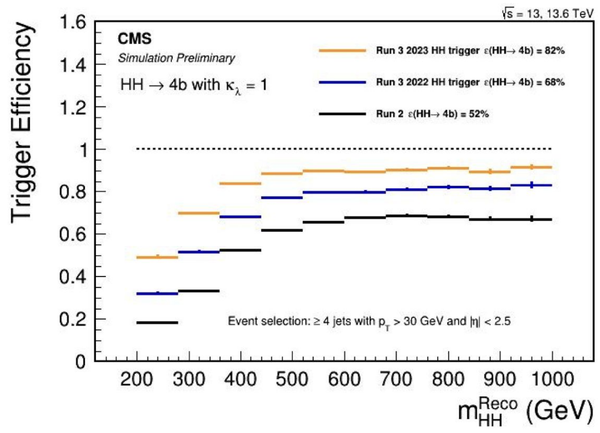


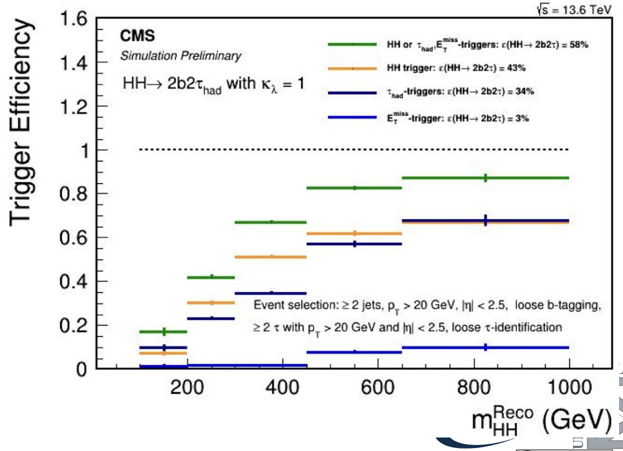
Run 3 improvements

CERN-CMS-DP-2023-050

- New trigger deployed at the HLT targeting HH and HHH production
  - exploiting recent improvements with ParticleNet tagger
  - data parking strategy for HH
  - subsequent investigations demonstrated effectiveness of this new trigger for HH → 4b and HH → bb$\tau\tau$

- Improved τ_{had} triggers, DeepTau based
- Particularly anticipating improvements in HH searches where one Higgs boson decays to bb or $\tau\tau$





Conclusions

- Measuring the Higgs boson self coupling is fundamental to probe the Higgs potential and test our Standard Model predictions

- Full Run-2 results have been highly promising, surpassing even our expectations thanks to new and improved analysis techniques

- We are getting closer to reaching sensitivity levels aligned with the SM value
  - we also explored new channels, with combined potential and strong κ_{2V} constraints
  - Run2 delivered great results, including new H+HH combination

- With more data available in Run-3 combined with more and more precise techniques, there are ample opportunities for advancements in analysis strategies

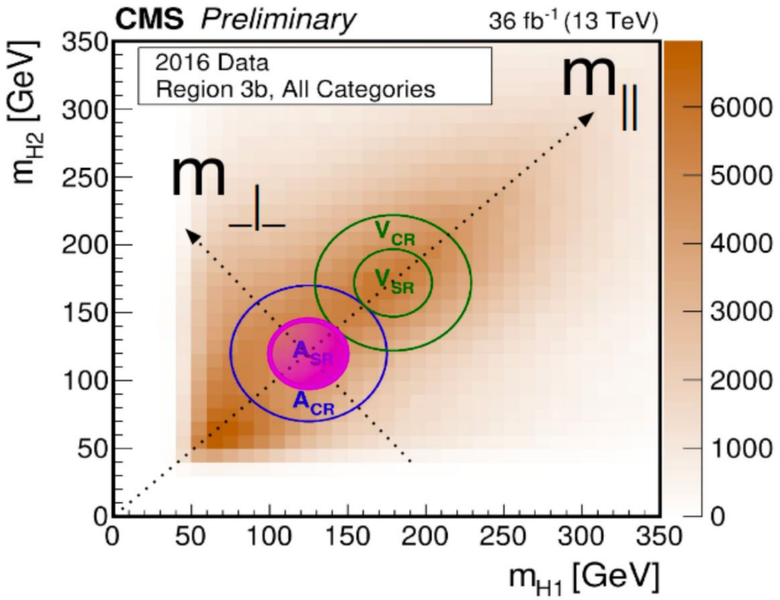
- In conclusion, the future looks bright as we move forward with our research, building on the successes of Run-2 and facing the challenges and opportunities presented by Run-3 and beyond
  - aiming for 5σ observation at HL-LHC!

Backup

Phys. Rev. Lett. 129, 081802

HH → bbbb (resolved) - strategy

- Triggers on jet p_T and H_T
- Background estimation :
  - SR (4b) QCD estimation using SR (3b) data
  - Scaling the number of events using the TF in the CR
  - TF dependence in the mass plane parameterised by $m_{//}$
  - BDT-reweighting used to model differences between 3b and 4b regions,
    - trained on CR, applied on SR
    - For each GGF and VBF categories
  - Validation :
  - Depleted signal region V
  - Same method applied
    - Found good agreement between estimate and V_{SR}^{4b}



Phys. Rev. Lett. 131, 041803

HH → bbbb (boosted)

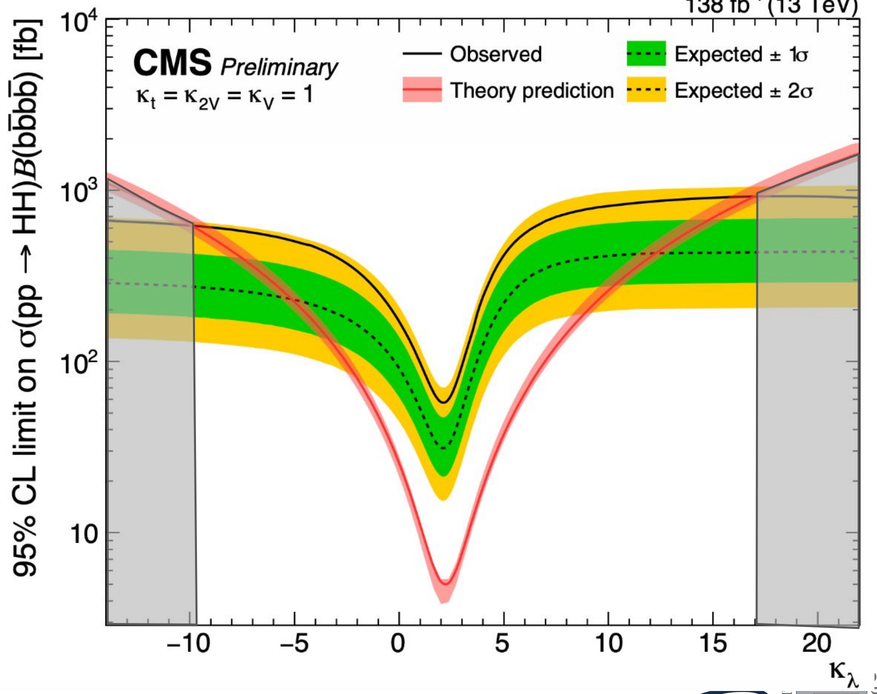
✅ Large branching ratio

❌ Multi-jet background

- Branching ratio: 33%
- Background: multi-jet QCD and tt processes
  - data-driven estimate

- Strategy insights:
  - first analysis using ParticleNet for b-tagging
  - BDT to separate signal from background

- Upper limits @ 95%
  - observed: $-9.9 < \kappa_\lambda < 16.9$
  - expected: $-5.1 < \kappa_\lambda < 12.2$

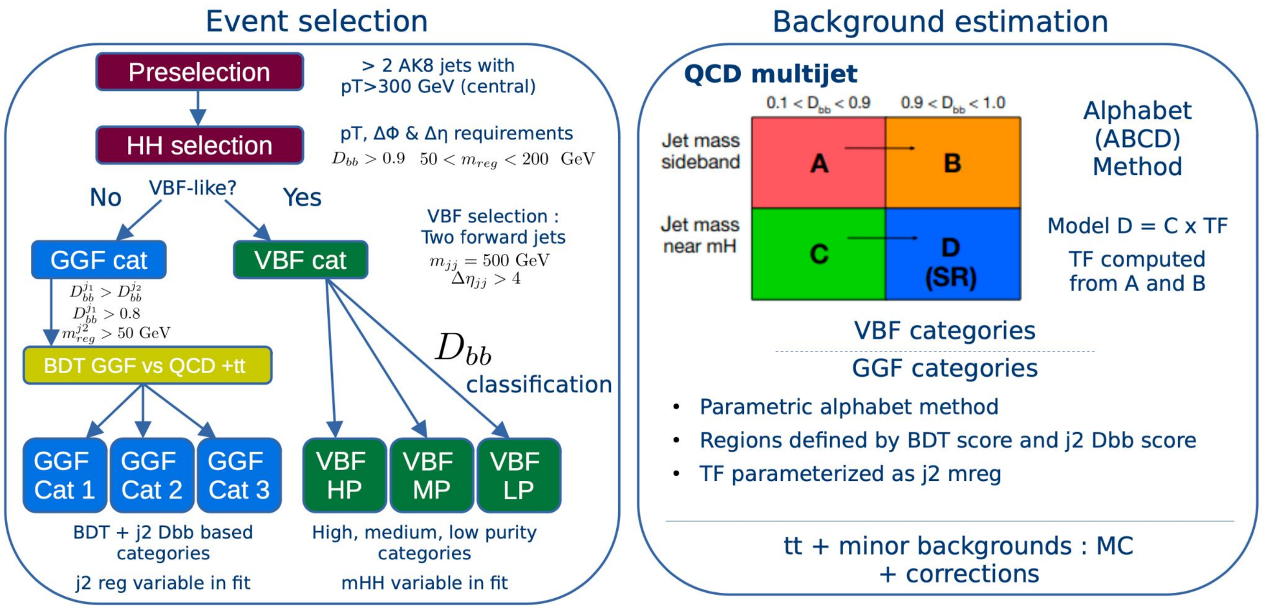


[Phys. Rev. Lett. 131, 041803](#)

HH → bbbb (boosted) - strategy

- Triggers
  - Several single-jet + H_T triggers :
  - Requirements in H_T, jet p_T, trimmed mass & double b-tagging
  - Fully efficient for jet p_T>500 GeV

- ParticleNet AK8 jet-tagger
  - discriminant score D_{bb}



[from ICHEP 2022 presentation](#)

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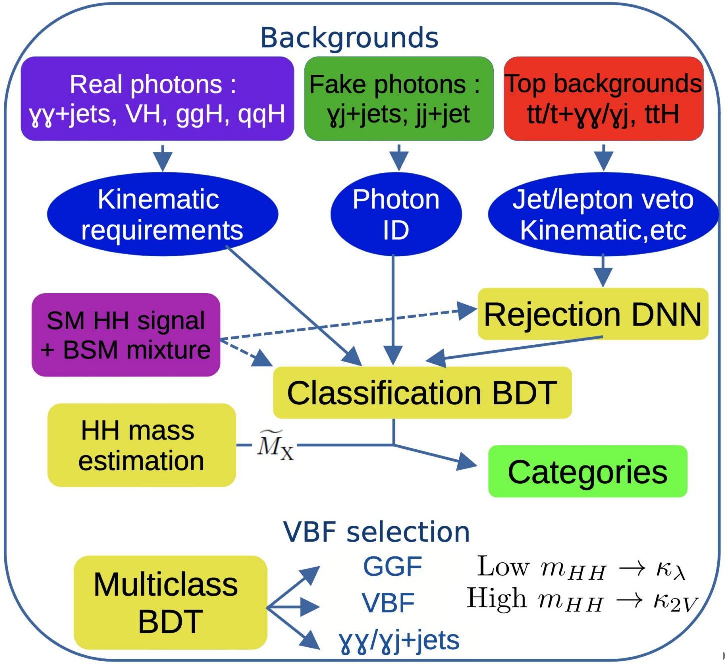
HH → bbγγ - strategy

- Di-photons triggers + photon requirements
  - excellent resolution (~1.4-2 GeV)
- b-jets: selected the first two with the highest score from DeepJet
- Background from:
  - real photons are mitigated through kinematic requirements
  - fake photons by requiring photon ID
  - top backgrounds are reduced with jet/lepton veto + kinematic
  - ttH rejection through a dedicated DNN (ttHScore)
- BDT for event categorization
- 2D maximum likelihood fit on (m_{bb}, $m_{\gamma\gamma}$)

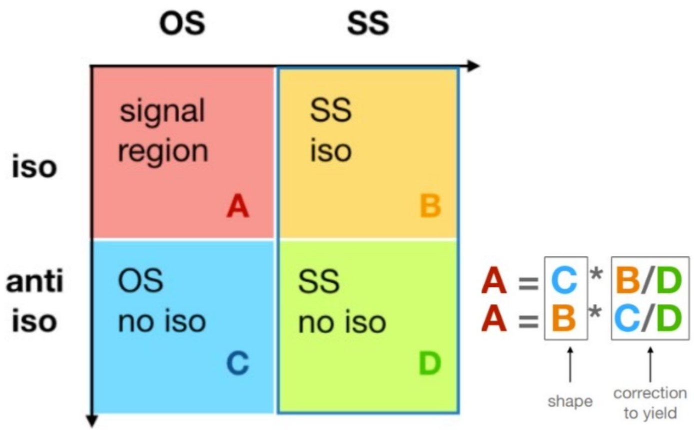


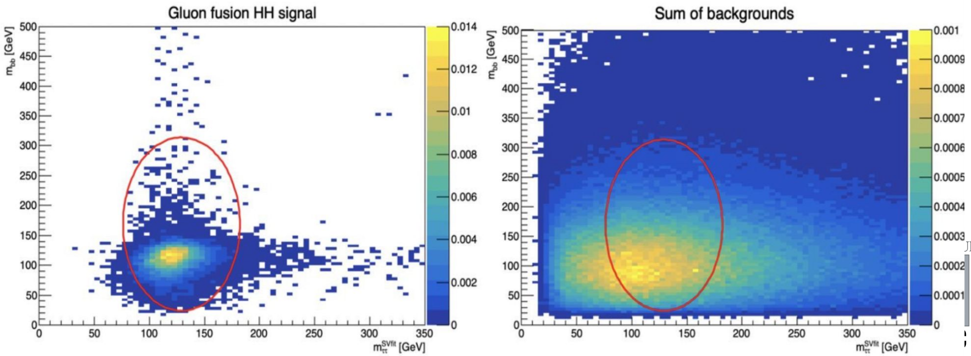
from ICHEP 2022 presentation

Phys. Lett. B 842.137531

HH → bbττ - strategy

- Triggers based on leptons and hadronic taus
- 3 channels considered: $\tau_{had}\tau_{had}$, $\tau_{had}e$, $\tau_{had}\mu$
- 2 jets with p_T > 20 GeV and $|\eta|<2.5$ + b-tagging using HH-btag
- Elliptical cut on m_{bb} and $m_{\tau\tau}$ to reduce background
- Background estimation:
  - tt, DY+jet from simulations (+normalization from CR)
  - Multijet QCD from data using ABCD method
  - Other processes from simulation





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HH → bbZZ

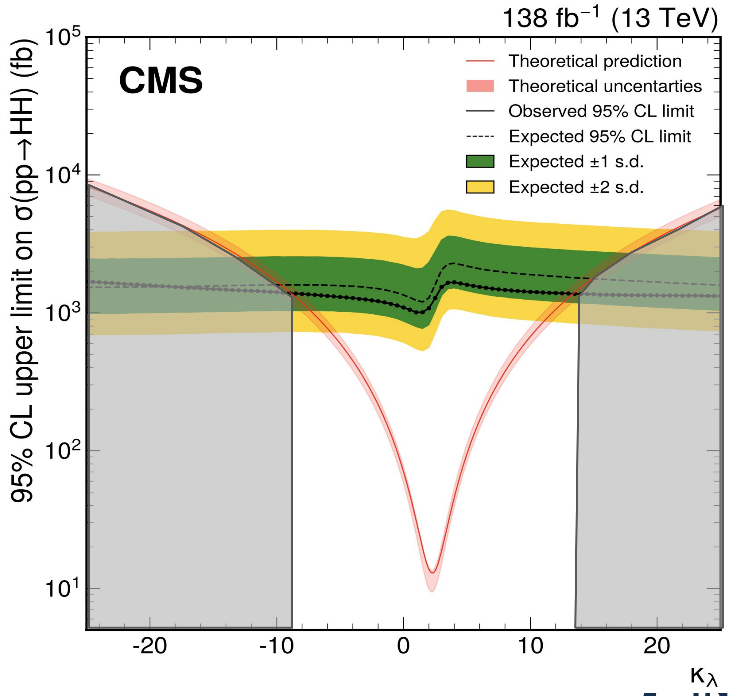
✅ Only result in this channel in LHC

❌ Small BR

- Branching ratio: 3.1%
- Background: ZZ and single Higgs

- Strategy insights:
  - DeepJet b-tag
  - BDT used for signal extraction

- Upper limits @ 95%
  - observed: $-8.8 < \kappa_\lambda < 13.4$
  - expected: $-9.8 < \kappa_\lambda < 15$



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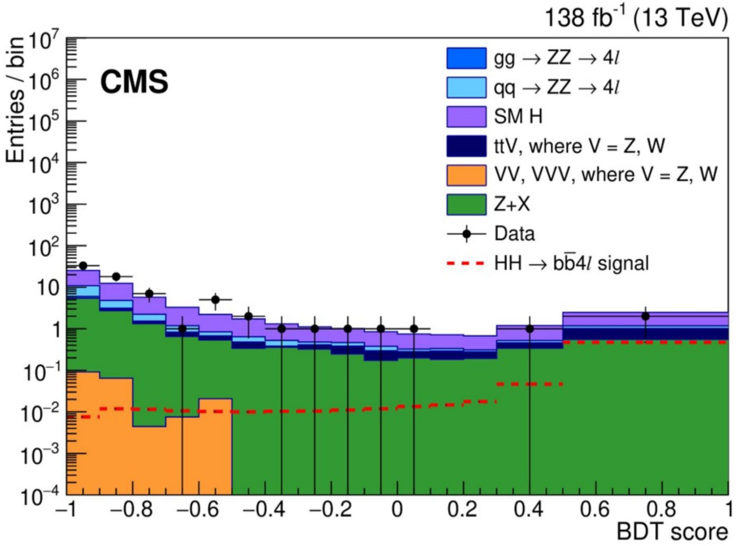
HH → bbZZ - strategy

- Events with 4 identified leptons (e, μ) + jet selection
  - b-jets selected as those with the highest score
- 3 categories: 4e, 4μ, 2e2μ
- Cut on 4leptons invariant mass (115, 135) GeV
- Background
  - Reducible b. (fake leptons) reduced with a data driven approach (fake factors in control regions)
  - Irreducible b. modeled from MC
- BDT for signal extraction



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HH → multilepton

✅ Small background

❌ Small BR

- Branching ratio: (4W)=4.6% (WW$\tau\tau$)=2.7% (4τ)=0.4%
- Background: QCD, V, VV, tt processes
- Strategy insights:
  - 7 categories of l-multiplicity
  - BDT used for signal extraction
- Upper limits @ 95%
  - observed: $-6.9 < \kappa_\lambda < 11.1$
  - expected: $-6.9 < \kappa_\lambda < 11.7$