Searches for Higgs boson pair production at CMS

Elvira Martín Viscasillas - CIEMAT

CMS

GOBIERNO
DE ESPAÑA

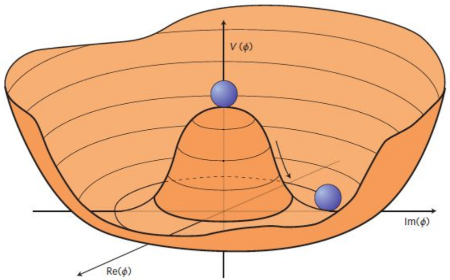
MINISTERIO
DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES

Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

13th June, 2024
SUSY2024, IFT (Madrid)

Exploring the Higgs Potential

- Precision measurement of the Higgs boson properties is one of the main goals of the LHC
- Higgs self-coupling is not measured yet in the SM → Direct access via Di-Higgs production and indirect access through Single-Higgs production

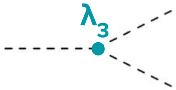


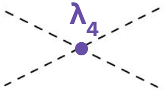
$$V(H) = \boxed{\frac{1}{2}m_H^2 H^2} + \boxed{\lambda_3 v H^3} + \boxed{\frac{1}{4}\lambda_4 H^4}$$

Mass term

Trilinear self-coupling λ_3: responsible for HH production

Quartic self-coupling λ_4: responsible for HHH production



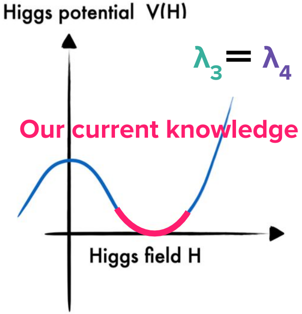


Standard Model

- **λ_3 fully determined given m_H and VEV v**

$$\lambda_3 = \frac{m_H^2}{2v^2} \approx 0.13$$

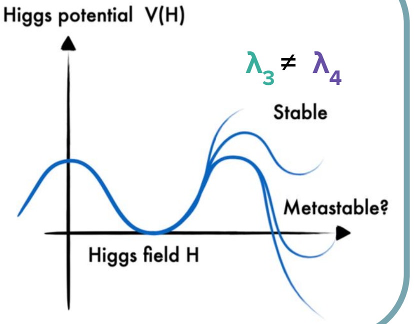
→ Needs to be measured



New physics

- **New physics can affect the shape of the Higgs potential**
- **Define deviation of the trilinear term (no quartic terms considered)**

$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$



Di-Higgs production

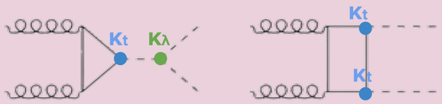
- The Di-Higgs cross section in the SM it's ~1000 times smaller than Single-Higgs
- New physics effects can modify HH production rates and kinematics

Non-Resonant HH production (SM & BSM)

- **SM HH production mechanisms:**
  - **→ ggF and VBF main production modes**
  - **→ First results on VHH and prospects for ttHH**
- **BSM physics effects parametrized by coupling modifiers: κ_λ , κ_t, κ_V, κ_{2V}**

Gluon-Gluon Fusion

σ_{ggF} = 31.05 fb @ NNLO

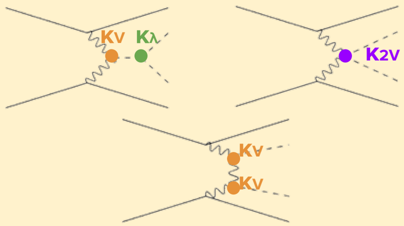


Destructive interference between box and triangle diagrams

→ Direct access to κ_λ (main sensitivity)

Vector Boson Fusion

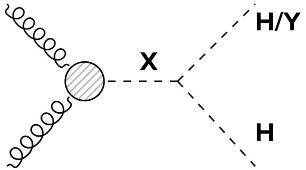
σ_{VBF} = 1.73 fb @ N3LO



→ Direct access to κ_λ, κ_V and κ_{2V}

Resonant HH production (BSM)

- **Higgs pair produced from heavy resonance X**



- **Resonant BSM models:**
  - **→ 2HDM two Higgs doublet models (including MSSM)**
  - **→ Generic resonances, e.g. Warped extra dimension models → spin-0 Radion / spin-2 Graviton**
- **BSM physics effects parametrized by heavy resonance mass m_X**

- Rare production rate and complex signal kinematics → Experimental challenges

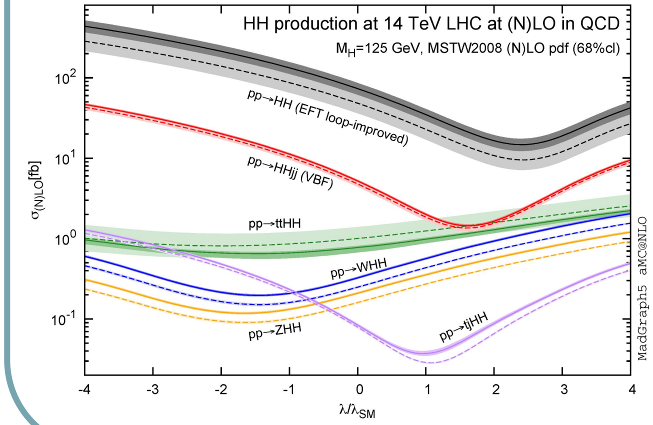
Measuring couplings modifiers

- Self-couplings can be constrained through total HH cross section and differential distributions

→ Experimental sensitivity to κ_λ and κ_{2V} depends on HH kinematics → directly related to the m_{HH} shape

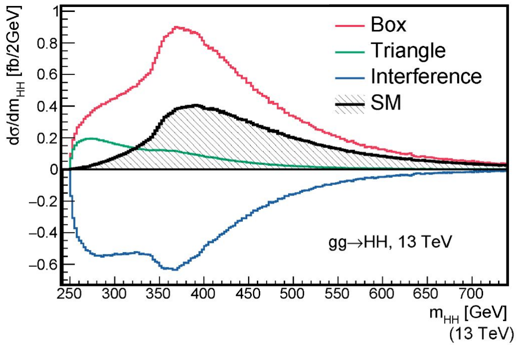
Total HH cross section

Dependence with κ_λ Phys. Lett. B 732

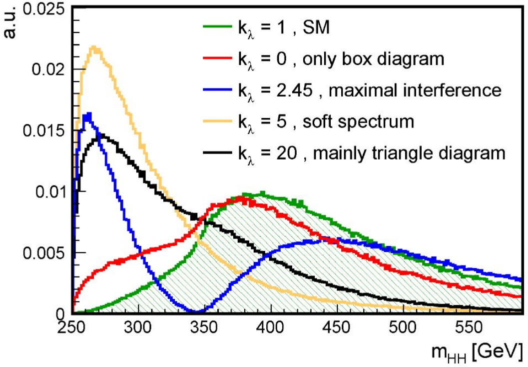


Differential cross section dσ/dmHH

Symmetry 2022, 14(7), 1467



Anomalous κ_λ values alter the shape of the m_{HH} → m_{HH} largely differs for various coupling hypotheses



Di-Higgs phenomenology

- Rich phenomenology with many final states accessible at LHC
  → **There is not a single golden channel**

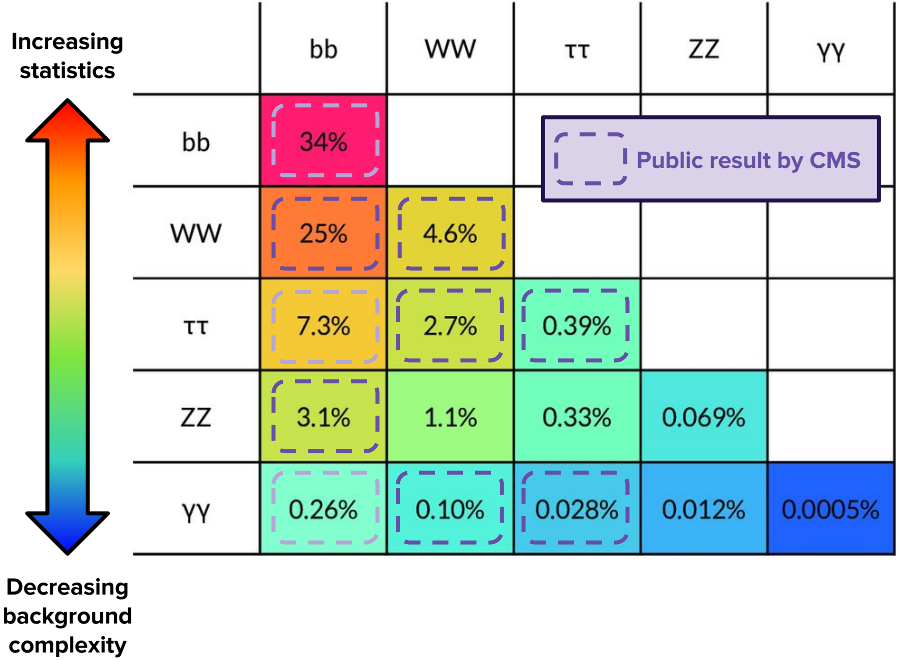
- Significant experimental challenges due to their rare production rate and complex final states
- To achieve good sensitivity → **compromise** between
  - **Branching Ratio (BR)**
  - **Final state signal purity**

→ Escaping gradually these two constraints thanks to improving reconstruction techniques and identification methods

"Big 3" HH analyses

HH→4b : Largest BR, challenging due to high b-jet multiplicity and QCD background
HH→2b2τ : sizeable branching ratio, lower QCD background
HH→2b2γ : rare process but clean signature due to photons

HH Branching Ratios



	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%

Analysis Landscape

☆ **The newcomers**
✩ **In this presentation**

- Final states covered by **CMS**

HH→4b
  - Phys. Rev. Lett. 129, 081802 (non-resonant, resolved)
  - Phys. Rev. Lett. 131.041803 (non-resonant, boosted)
  - CMS-PAS-B2G-21-001 (non-resonant, VBF boosted)
  - Submitted to JHEP (non-resonant, VHH production)
  - Phys. Lett. B 842. 137392 (resonant X→YH)
  - B2G-20-004 (resonant, boosted)

HH→2b2τ
  - Phys. Lett. B 842.137531 (non-resonant)
  - JHEP 11 (2021) 057 (resonant X→YH)

HH→2b2γ
  - JHEP 03 (2021) 257 (non-resonant)
  - CMS PAS HIG-21-011 (resonant) ✩

HH→2b2Z
  - JHEP 06 (2023) 130 (non-resonant)
  - Phys. Rev. D. 102.032003 (resonant)

HH→2b2W
  - CMS PAS HIG-21-005 (non-resonant + resonant)
  - JHEP 05 (2022) 005 (resonant)

HH→2W2γ
  - CMS-PAS-HIG-21-014 (non-resonant)

HH→4W+2W2τ+4τ
  - JHEP 07 (2023) 095 (non-resonant + resonant)

HH→2γ2τ
  - CMS-PAS-HIG-22-012 (non-resonant + resonant) ☆✩

- Searches across various decay channels complement each other ↔ complementary sensitivity to coupling variations

→ Combination is the key

- **HH combination** → Nature 607 (2022) 60 ✩
- **H+HH combination** → CMS-PAS-HIG-23-006 ☆✩

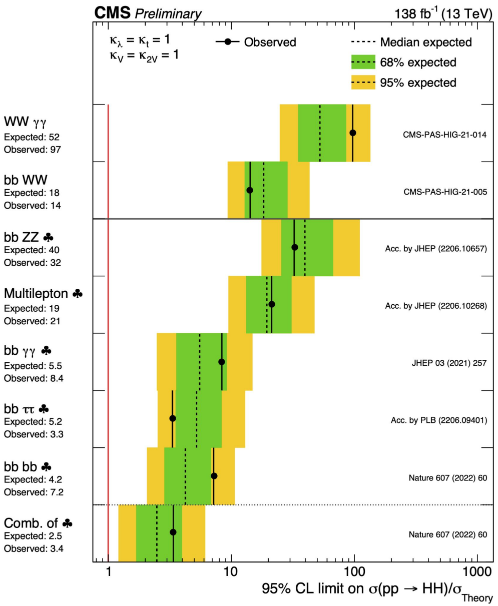
Non-resonant production

Non-resonant HH Run 2 combination

Nature 607 (2022) 60

- Similar sensitivity between **boosted HH→4b**, **HH→2b2τ** and **HH→2b2γ**
- Maximal sensitivity obtained through combination → **most restrictive upper limits** on the Di-Higgs cross section

Limits on signal strength

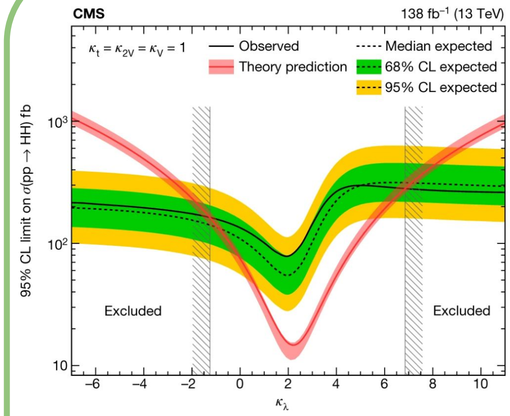


$\sigma^{HH} < 3.4\ (2.5) \times \sigma^{HH}(SM)$ Obs (Exp)

x5 better than $36 fb^{-1}$ combination

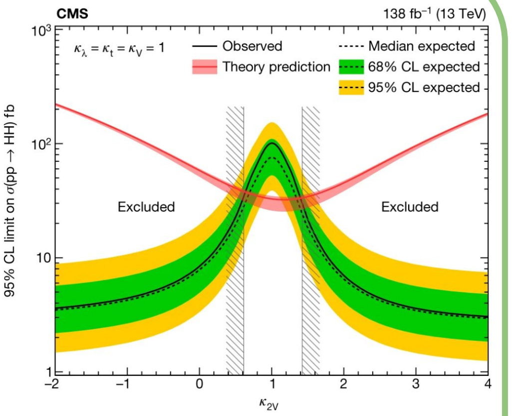
Much better than predicted by simple luminosity scaling thanks to improved reconstruction/ID techniques and analysis techniques → Crucial role of developing analysis strategies

Limits on couplings



$-1.24 < \kappa_\lambda < 6.49$

Approaching the exclusion of $\kappa_\lambda = 0$



$0.67 < \kappa_{2V} < 1.38$

$\kappa_{2V} = 0$ excluded at >5σ

The newcomers: H + HH combination

CMS-PAS-HIG-23-006

- Combine all recent CMS analyses targeting the most sensitive **Single-Higgs** and **Di-Higgs** production modes

Single-Higgs

- **Indirect κ_λ access via NLO contributions to Single-Higgs production and decay**
- **$\sigma_H > \sigma_{HH}$ → sensitivity to smaller variations**

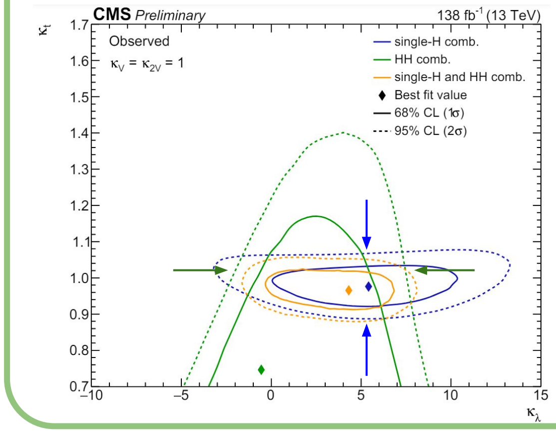
Di-Higgs

- **High sensitivity to κ_λ and κ_{2V}**
- **Weaker constraints on H coupling to fermions and vector bosons**

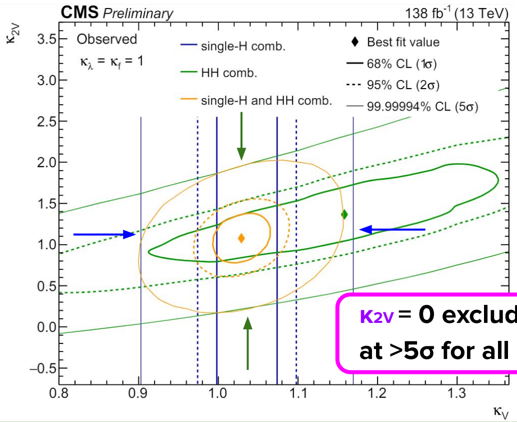
Constraints on Higgs couplings from both measurements are complementary:
→ Constraints on κ_t and κ_V are driven by Single-Higgs
→ Constraints on κ_λ and κ_{2V} are driven by Di-Higgs

→ Di-Higgs constraints ←
→ Single-Higgs constraints ←

2D Likelihood scan of (κ_λ, κ_t)

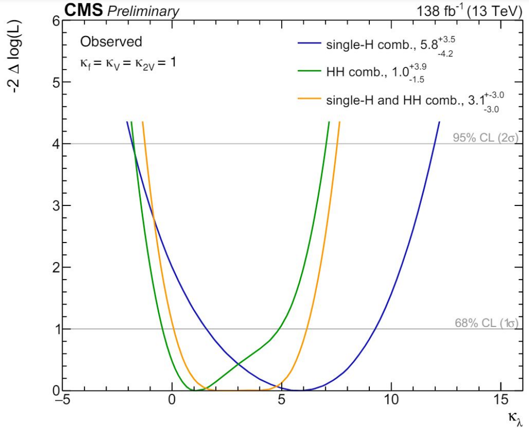


2D Likelihood scan of (κ_{2V}, κ_V)



κ_{2V} = 0 excluded at >5σ for all κ_V

1D Likelihood scan of κ_λ



CMS-PAS-HIG-22-012

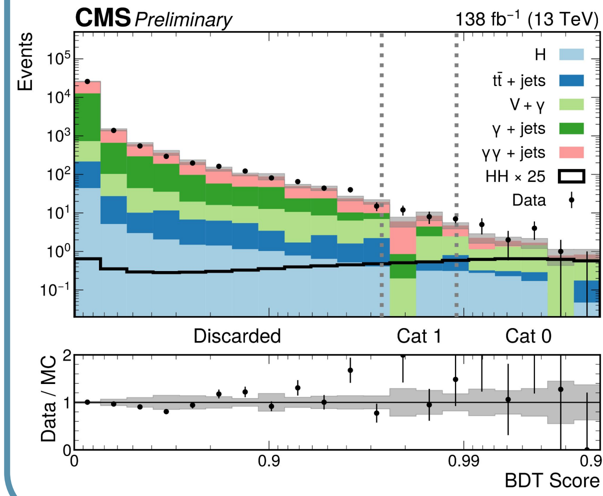
The newcomers: HH→$\gamma\gamma\tau\tau$

- HH production in the **2γ2τ** final state covered **for the first time**
  → Very tiny branching ratio (0.028%), but clean final state from good di-photon resolution

Analysis method

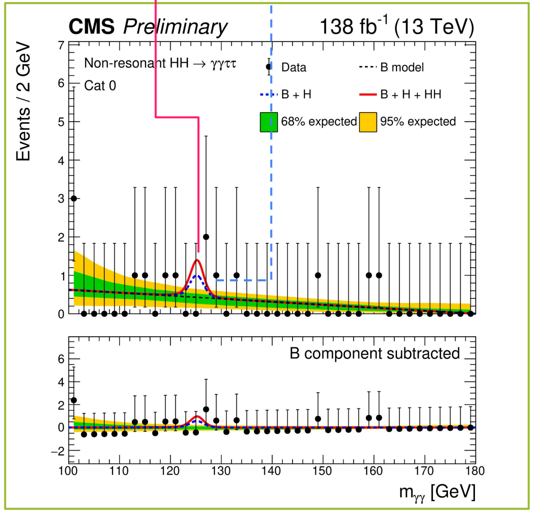
- **Search in all di-τ final states: hadronic + leptonic**
- **Fit performed using $m_{\gamma\gamma}$ → No significant excess found**
- **Various scenarios considered in the analysis: non-resonant and resonant**

BDT to define signal enriched categories



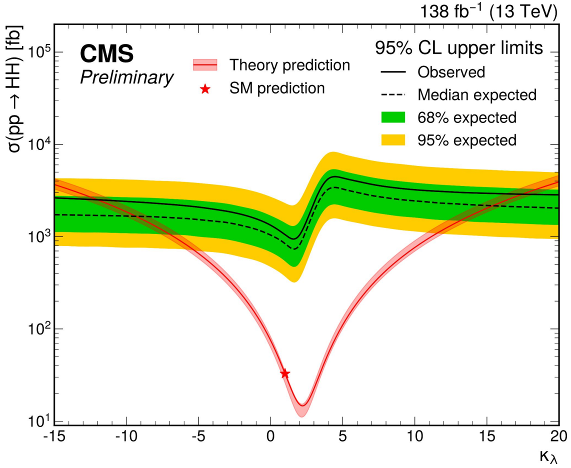
Di-Higgs

Single-Higgs



Non-resonant results

Upper limit on σ_{HH} : 33 (26) × SM Obs (Exp)



-13<κ_λ<18

Resonant production

CMS-PAS-HIG-22-012

The newcomers: X→HH/HY→$\gamma\gamma\tau\tau$

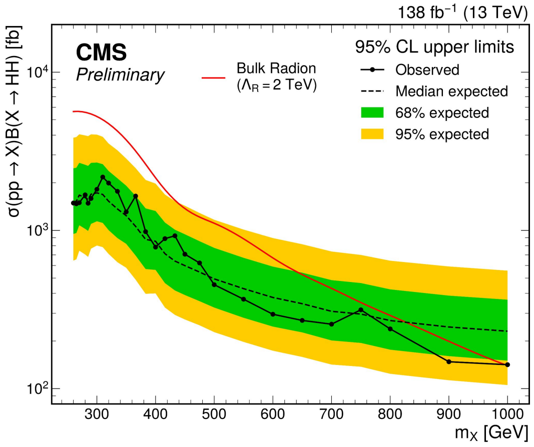
- **Resonant scenario**: **X→HH**, **X→H(2γ)Y(2τ)** and **X→H(2τ)Y(2γ)** (split into low-mass and high-mass channels) production
  - X mass range 260-1000 GeV, spin-0 and spin-2
  - Y mass range 50-800 GeV, spin 0

Resonant HH results

Limits on σHH × BR:

spin-0	spin-2
140 fb - 2200 fb	170 fb - 1800 fb

spin-0

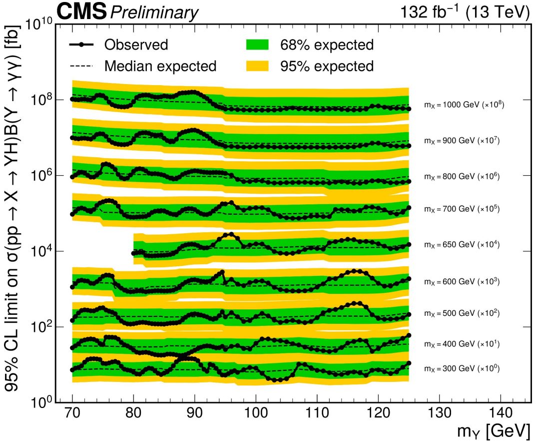


Resonant HY results

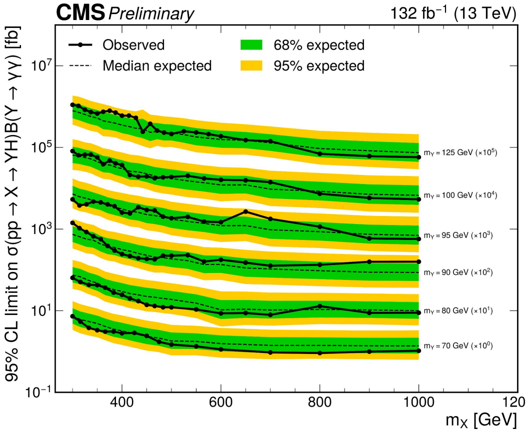
Limits on σHH × BR (over the range of mx and mY):

H(2γ)Y(2τ)	0.054 fb - 1.2 fb
H(2τ)Y(2γ)	Low-mass: 0.51 fb - 9.7 fb High-mass: 0.53 fb - 15 fb

X→H(2τ)Y(2γ) low-mass (mY)



X→H(2τ)Y(2γ) low-mass (mx)



No excess found, but → Local 2.3σ significance at mx=650 GeV, mY=95 GeV interesting when put into context of recent excesses in CMS

Resonant searches: X→HH/HY→bb$\gamma\gamma$

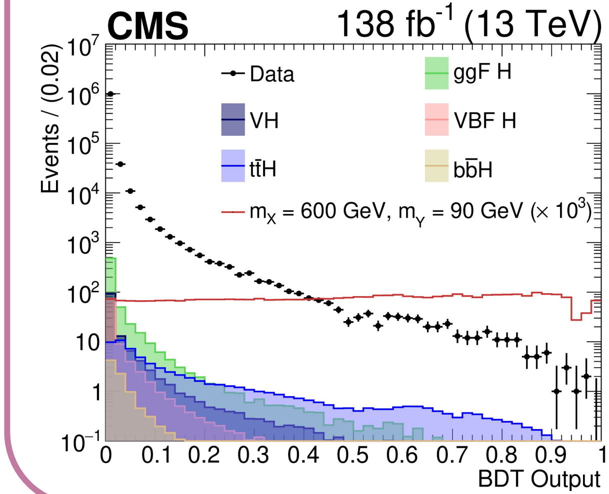
JHEP 05 (2024) 316

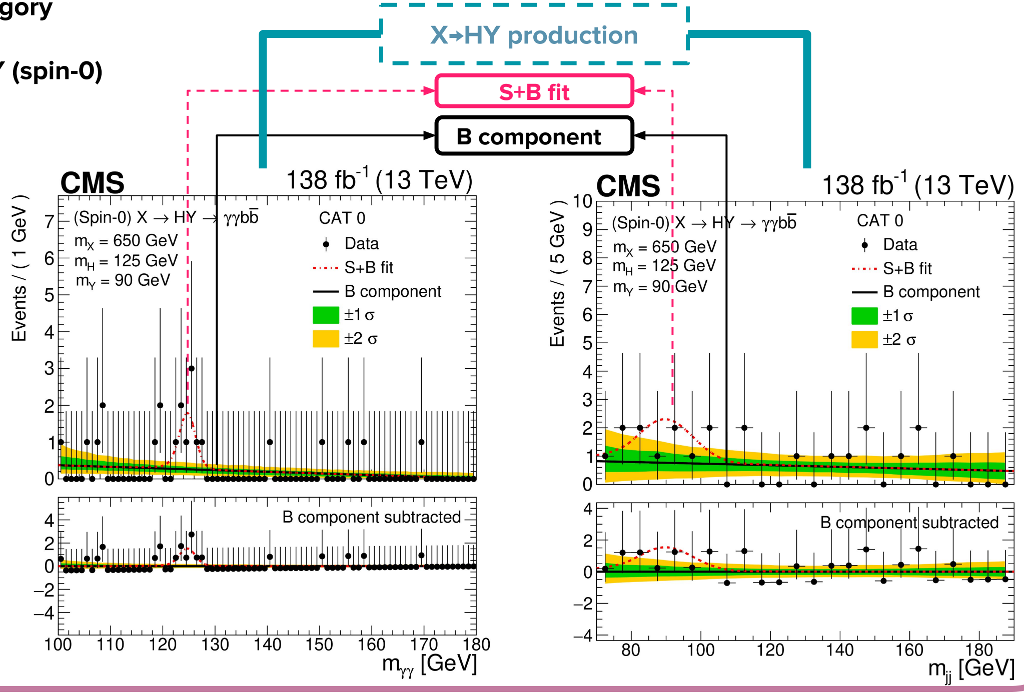
- Resonant HH and HY production decaying into **2b2γ** (**H→2γ, H/Y→2b**)
  - X mass range 260-1000 GeV, spin-0 and spin-2
  - Y mass range 90-800 GeV, spin-0

Analysis method

- **Categories based on m_X and m_Y → BDT per category**
- **Fit performed in $m_{\gamma\gamma}$ and mjj simultaneously**
- **X→HH (spin-0 and spin-2 hypothesis) and X→HY (spin-0)**

BDT to define categories




X→HY production

S+B fit

B component

Resonant searches: X→HH/HY→bb$\gamma\gamma$

JHEP 05 (2024) 316

- Resonant HH and HY production decaying into **2b2γ** (**H→2γ, H/Y→2b**)
  - X mass range 260-1000 GeV, spin-0 and spin-2
  - Y mass range 90-800 GeV, spin-0

Local 3.8σ excess at m_X=650 GeV, m_Y=90 GeV (global 2.8σ)

Resonant HH results

Limits on σ_{HH} × BR:

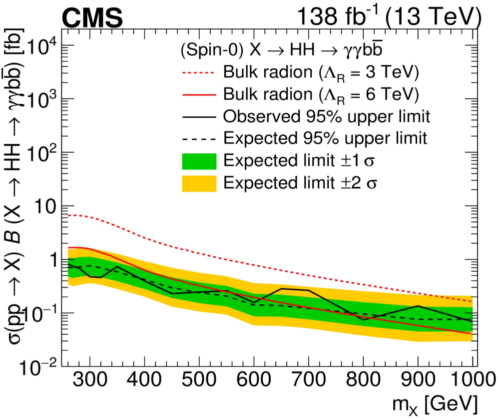
spin-0

0.82 fb - 0.07 fb

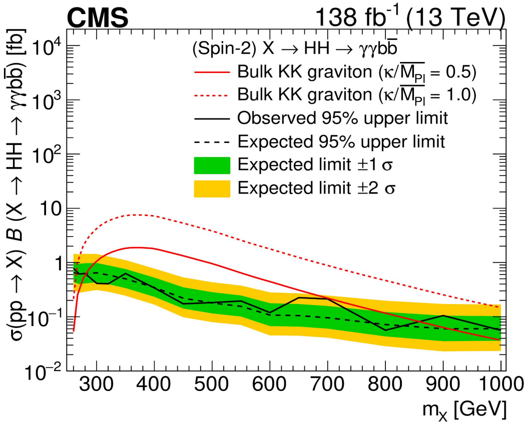
spin-2

0.78 fb - 0.06 fb

spin-0



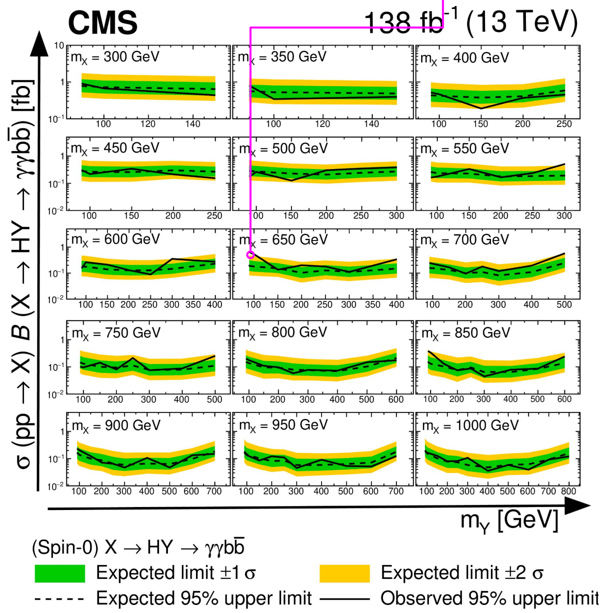
spin-2



Resonant HY results

Limits on σ_{HH} × BR:

0.79 fb - 0.05 fb over the range of m_X and m_Y



CMS-B2G-23-002

Resonant searches: HH/HY sensitivity

- Results and combinations of the latest full Run 2 resonant X→HH/HY searches performed by CMS

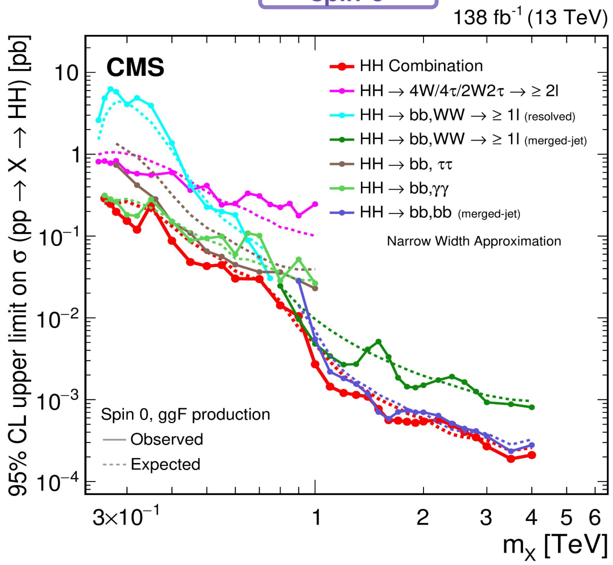
Relative HH sensitivity

→ **HH Combination: Combined likelihood analysis**

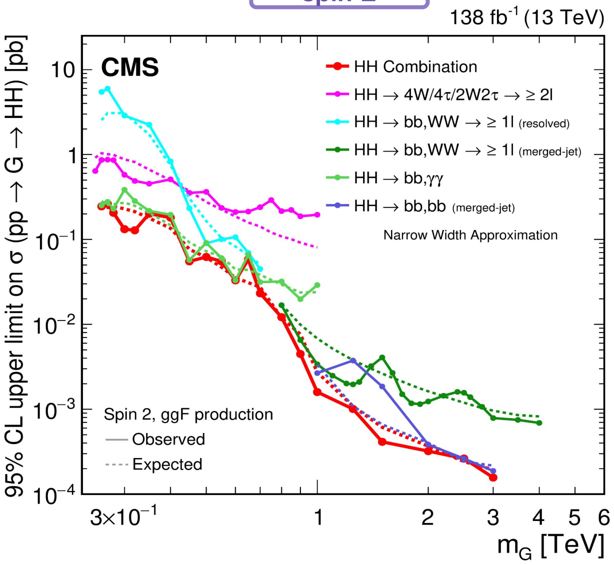
→ **2b2γ is strongest at low mass** → **4b dominates at the highest masses** → **2b2W helps in the intermediate mass range**

→ **More analysis targeting additional HH decay modes to come**

spin-0



spin-2



CMS-B2G-23-002

Resonant searches: HH/HY sensitivity

- Results and combinations of the latest full Run 2 resonant X→HH/HY searches performed by CMS

Relative HY sensitivity

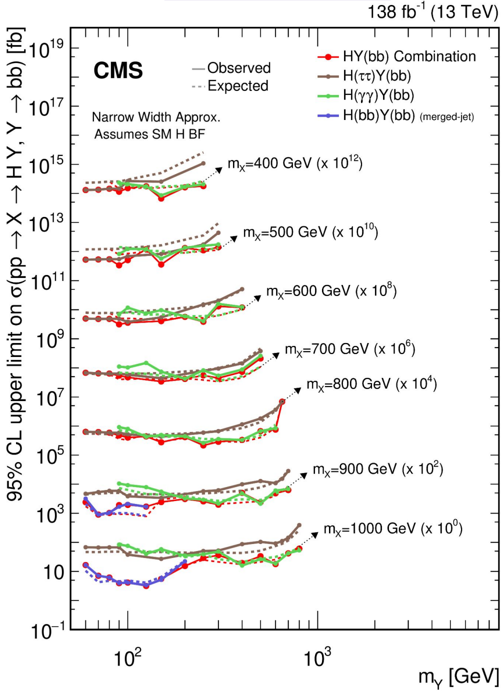
→ **HY(2b) Combination: Combined likelihood analysis**

→H(2γ)Y(2b)
→H(2τ)Y(2b)
→H(2b)Y(2b)

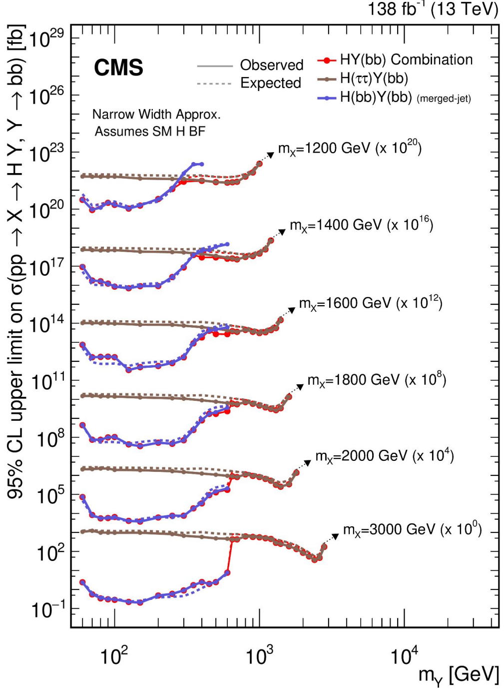
Generally are still the most important ones, but other final states can be most sensitive depending on mY and the model

Two masses to scan → large phase space to probe

mX [400-1000]



mX [1200-3000]



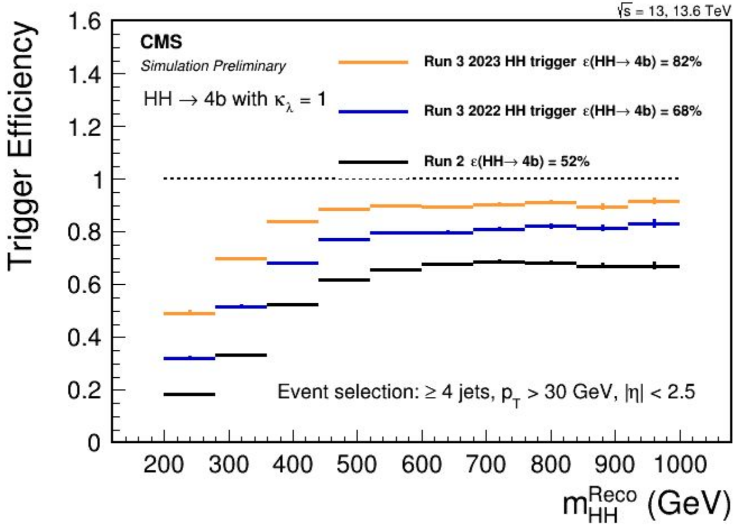
CMS-DP-2023-050

Run 3 improvements

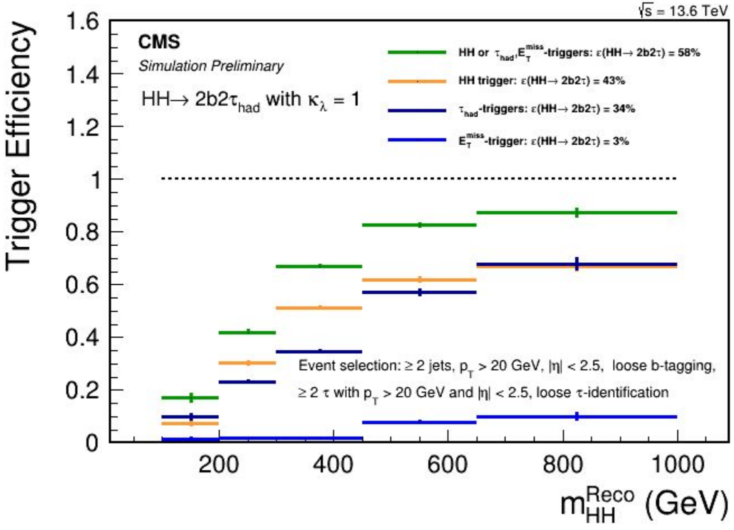
- Improved reconstruction and object identification techniques (eg. ParticleNet, extensive and improved use of Machine Learning)
- Improved trigger strategies for Run 3 based on improved object identification: new b-tagging and τ-tagging algorithms (ParticleNet and DeepTau)

  ➔ Improvements are expected for all HH searches targeting **bb** or **ττ** final states

HH➔4b trigger



HH➔2b2τ trigger

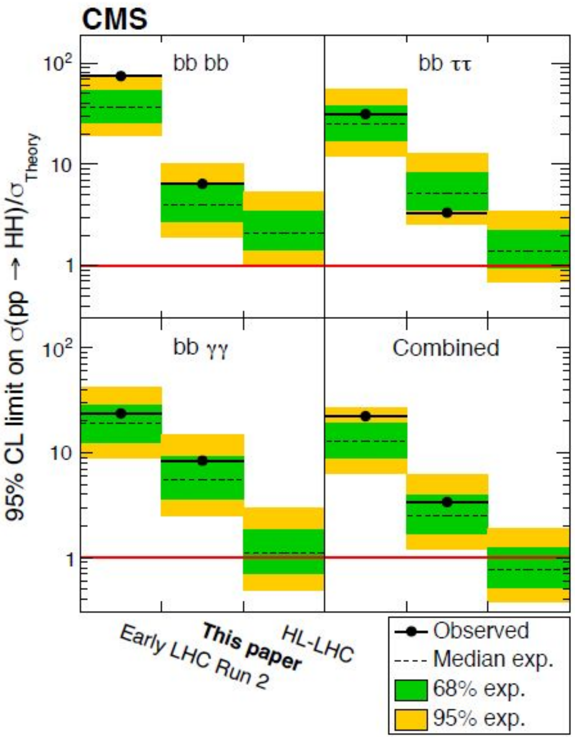


Nature 607 (2022) 60

YR2018 (ECFA) Snowmass ATLAS+CMS

Prospects for HH measurements

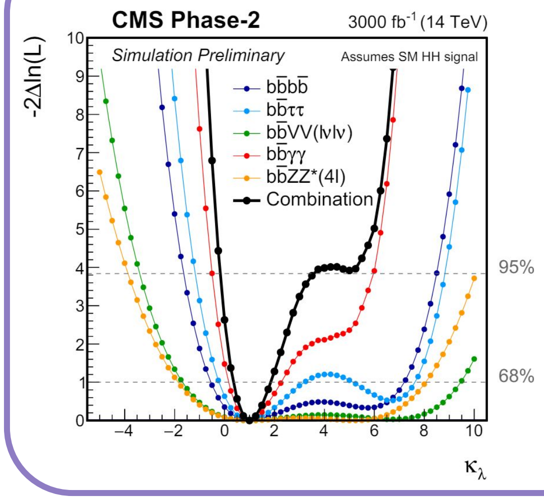
- Large impact of the high luminosity that allows to extend the Di-Higgs production and decays modes accessible at LHC
- Many new developments on reconstruction and identification methods (triggers, machine learning based taggers)

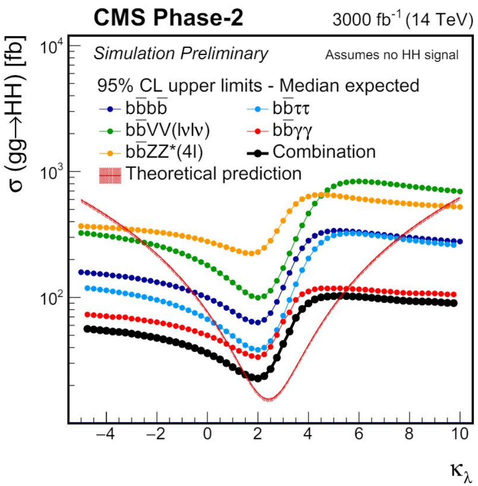


→ Potential to observe HH on HL-LHC (ATLAS+CMS)

Expected likelihood scan (assuming HH signal)

Prospects for λHHH (assuming no HH signal)





Conclusions

- Investigating the Di-Higgs process is fundamental for a complete understanding of the shape of the Higgs potential and one of the primary goals of Higgs Physics for the coming years
- Great results already accomplish in LHC **Run 2** thanks to:
  - **Innovative analysis techniques**
  - **Exploration of new HH decay channels**
  - **HH and H+HH combinations**

➜ Limits and constraints on non-resonant production

- Upper limit on Di-Higgs cross section: **$\sigma^{HH} < 3.4\times\sigma^{HH}$(SM) @ 95% CL**
- Self coupling constrained to: **$-1.24<\kappa_\lambda<6.49$ (assuming other couplings = 1) @ 95% CL**
- Excluded the absence of VVHH at >5σ: **$\kappa_{2V} \neq 0$ for all κ_V**

- **Run 3** is ongoing and represents a huge opportunity to improve sensitivity:
  - More data to analyze
  - Improved triggering strategy
  - Extended interpretations and exploration of models
  - Test-bench for new ideas and analysis strategies for HL-LHC

- So many improvements such as innovative detector technology, machine learning methods and activation strategies have the potential to lead us to observation at the **HL-LHC** … **Exciting results to come!**

Backup

Overcoming experimental challenges

- Improve statistics → Run 3 is underway, with higher energy and more data to analyze
- More advanced analysis techniques → Taking advantage of new tools and techniques becoming available
- Include new final states → Expand the available phase space
- Add more production modes → Bring access to other couplings
- Combination with Single-Higgs → Connection between H and HH to investigate the entire Higgs sector
- Exploration of extended interpretations → SMEFT, HEFT