CMS searches for new physics in the Higgs sector

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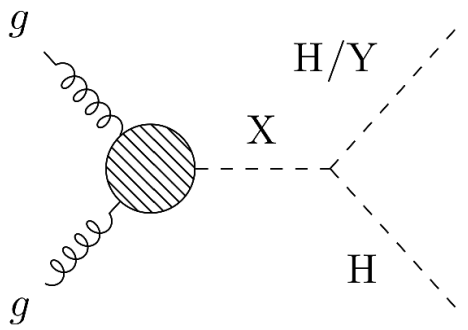
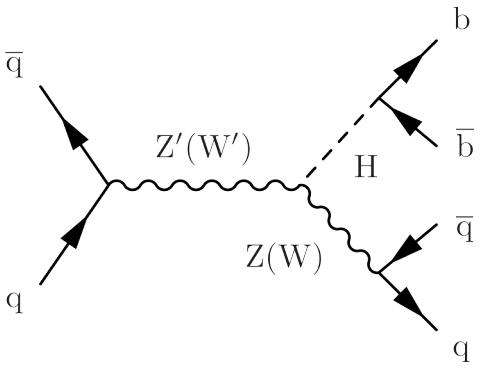
Only one Higgs boson found so far… could there be more out there?

- **Possible extensions of the SM Higgs sector:**
  - Additional Higgs singlets, e.g., **TRSM** – one extra scalar per singlet,
  - Additional Higgs doublets, e.g., **2HDM, MSSM** – 5 bosons: H, X, A, $H^{\pm}$,
  - Combination of doublets and singlets, e.g., **2HDM+S, NMSSM** – 7 bosons: H, Y, X, A, a, $H^{\pm}$,
- **Possible new scalars: X, Y** ($m_X > m_Y$), **and pseudoscalars: A, a** ($m_A > m_a$),
- **Possible decays: X → HH, X → YH, A → ZH, H → aa, X, A → ff,**
- Similar phenomenology:
  - models with **Warped Extra Dimensions**: spin-0 radion (R), spin-2 graviton excitations (G), **R, G → HH**,
  - models with W', Z', e.g. **Heavy Vector Triplet** model: spin-1 **V' → VH**,
- Many potentially interesting final states to explore.





CMS searches for A, V' → V H

Channel	Analysis / Paper	Dataset	Mass range covered
A → Z(ll,νν) H(bb resolved)	EPJC 79 (2019) 564	36 fb^{-1}	225-1000 GeV
A → Z(ll) H(ττ)	HIG-22-004 **Preliminary**	138 fb^{-1}	220-800 GeV
W' → W(lν) H(bb merged)	PRD 105 (2022) 032008	137 fb^{-1}	1000-4500 GeV
V' → V(jj merged) H(bb merged)	PLB 844 (2023) 137813	138 fb^{-1}	1300-6000 GeV
Z' → Z(ll,νν) H(bb merged)	EPJC 81 (2021) 688	137 fb^{-1}	800-4600 GeV
Z' → Z(ll,νν) H(jj merged)	2411.00202 **NEW!** (submitted to JHEP)	138 fb^{-1}	1400-5000 GeV

$A \to Z(ee,\mu\mu)\, H(\tau\tau)$

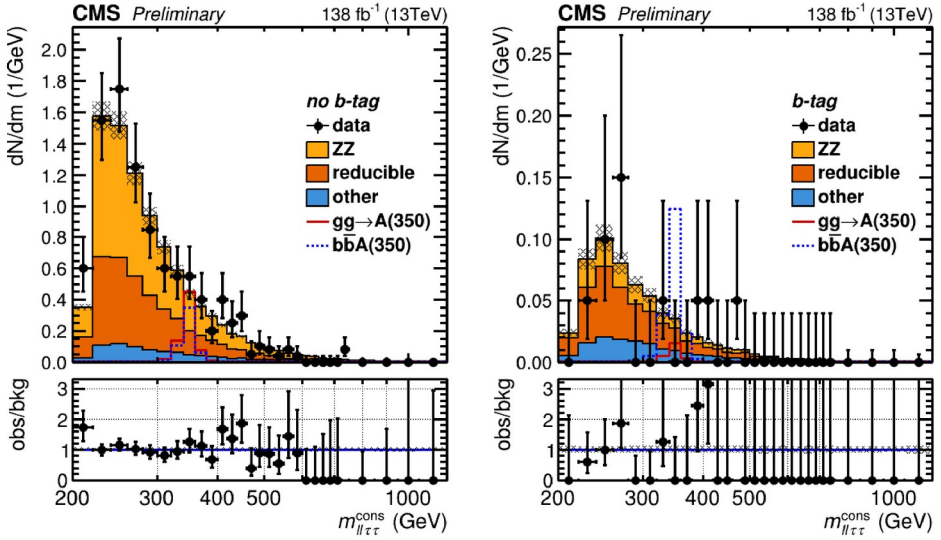
CMS PAS HIG-22-004

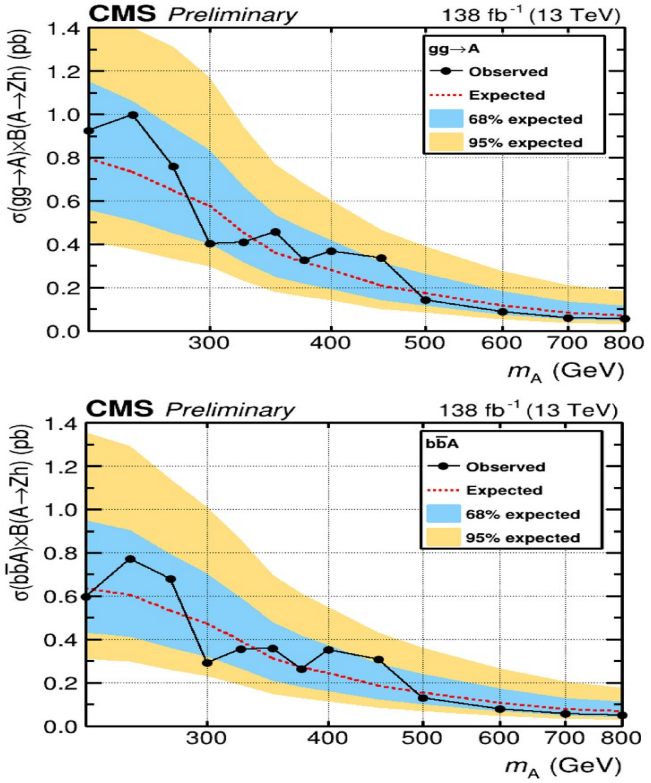
- **2 Z decay modes x 3 H decay modes ($e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) considered,**

- H 4-vector reconstructed with FastMTT algorithm (ME techniques) [1603.05910], using p_T^{miss} vector and putting m_H = 125 GeV as input
  → estimate of "constrained A mass" $m^c_{ll\tau\tau}$ with a 5-7% resolution,

- **Improvements wrt. 1910.11634 (36 fb^{-1}):**
  - inclusion of b associated production (2 event categories: ≥1 b-tag, no b-tag),
  - improved b jet identification – DeepJet algo [1712.07158, 2008.10519],
  - improved τ identification – DeepTau [2201.08458],

- Exclusions in the tanβ vs. m_A plane in MSSM benchmark scenarios.

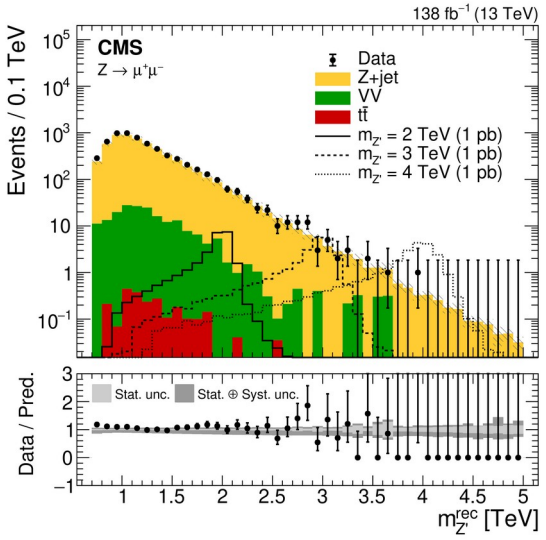


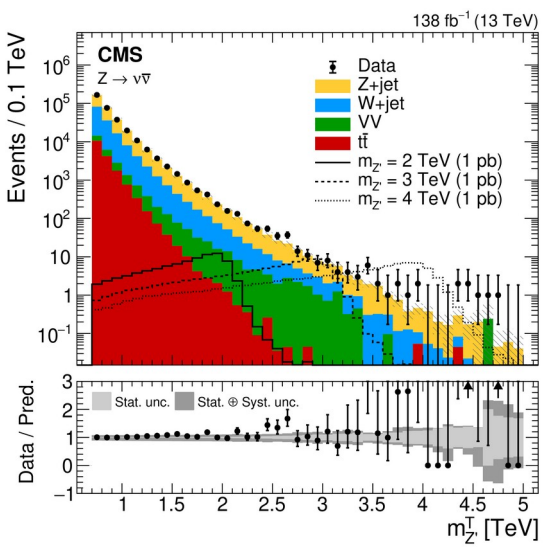


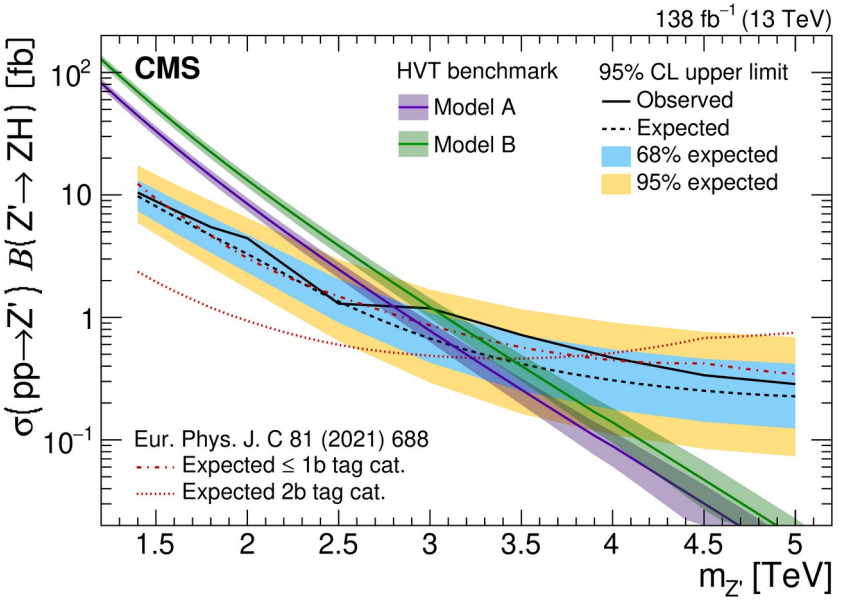
Z' → Z(ee,μμ,νν) H(jj merged)

CMS PAS B2G-23-008
2411.00202

- H candidate: AK8 jet with p_T > 200 GeV, Δφ(H,Z) > 2,
- For νν: p_T^{miss} > 250 GeV, for ll: p_T^Z > 200 GeV, ΔR(l,l) < 0.45,
- **Changes wrt. previous analysis 2102.08198** (137 fb^{-1}):
  - improved ML jet flavor tagging techniques to discriminate against QCD background, ParticleNetMD algo [1902.08570],
  - inclusion of H → cc and H → VV* → 4q, improved sensitivity to high resonance masses,
  - require ≤1 b-tag to minimize overlap with 2102.08198,
- Upper limits on Z' couplings to fermions and bosons in the HVT model.

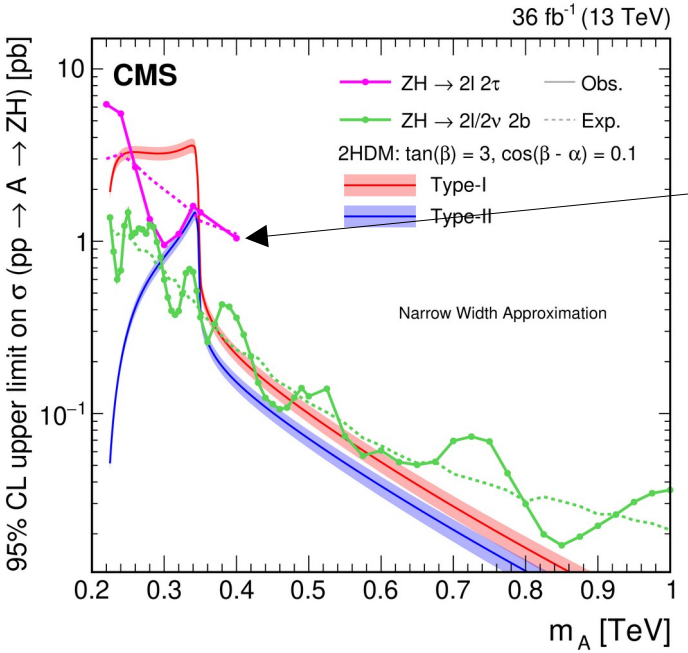






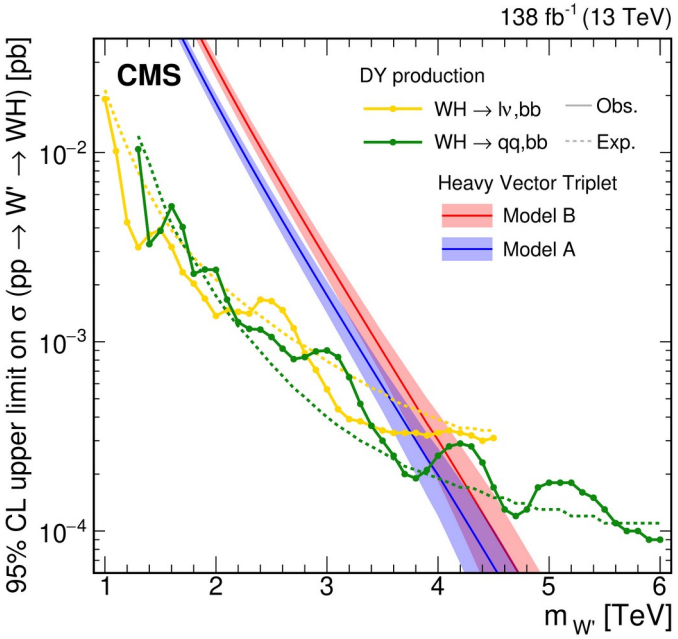
Combination of CMS resonant HV searches

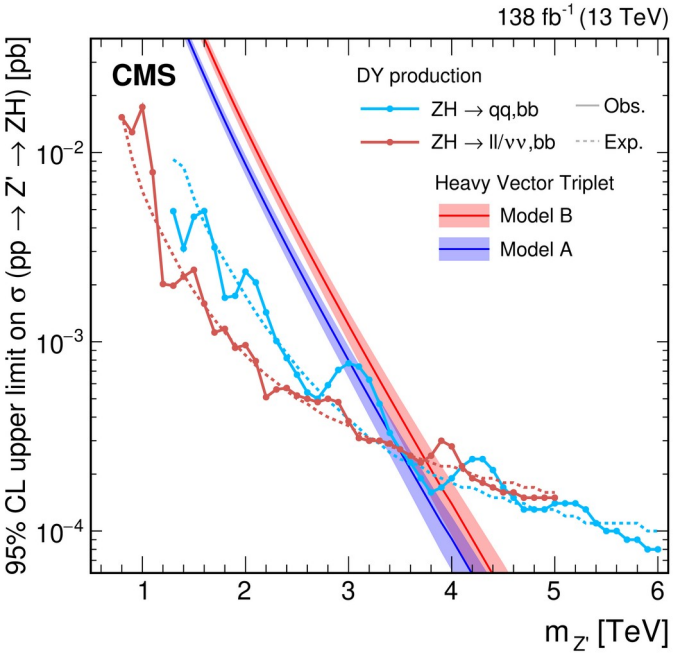
NEW! CMS PAS B2G-23-002
2403.16926
(submitted to PR)



With the updated 2l 2τ analysis HIG-22-004:
- Extension of m_A coverage up to 800 GeV,
- New limits significantly more stringent, comparable with 2l/2ν 2b

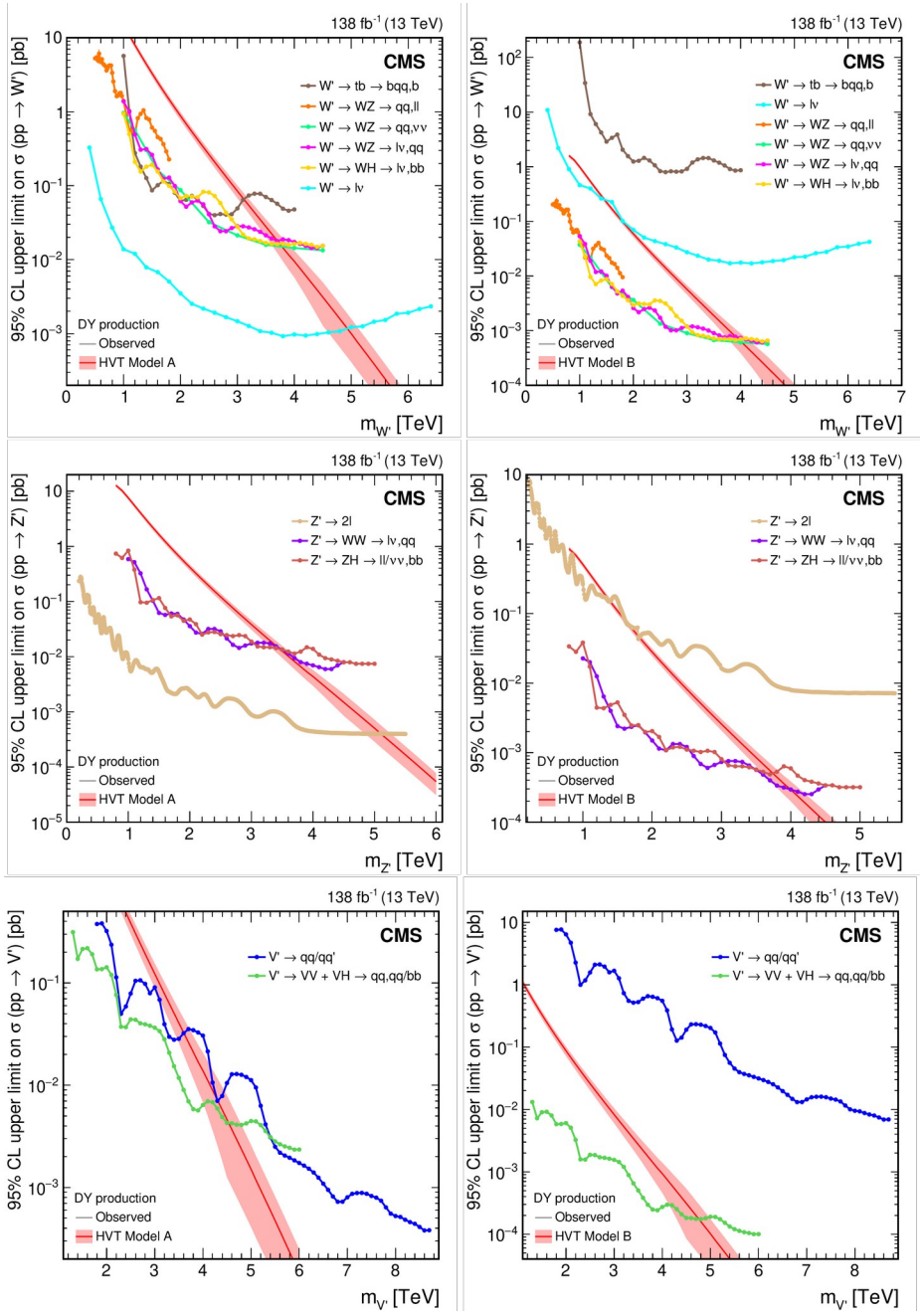
New ll/νν jj analysis 2411.00202:
- improved sensitivity at high mass, (events with less than 2 b-tagged subjets)





V’ → HV vs. other decay channels

CMS PAS B2G-23-002
2403.16926
(submitted to PR)



- Assuming branching fractions of **HVT models** A (left) and B (right) [1402.4431] :

  - **Model A** (weakly coupled extended gauge symmetry): fermionic final states dominate,

  - **Model B** (Minimal strongly coupled Composite Higgs Model): VV and HV are most sensitive,

- Interesting also in the context of models with 2 complex Higgs doublets:
  - hMSSM,
  - general 2HDM,
  for detailed interpretations see 2403.16926

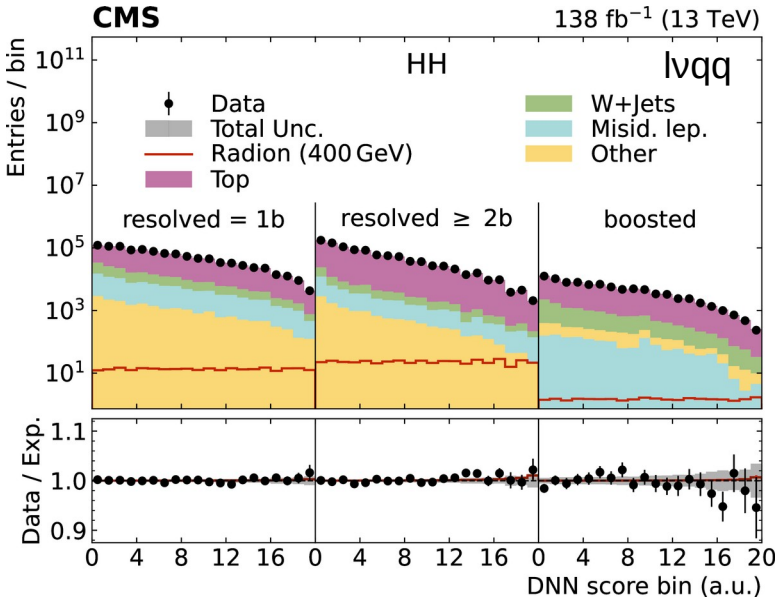
CMS searches for $X \rightarrow H\,H$

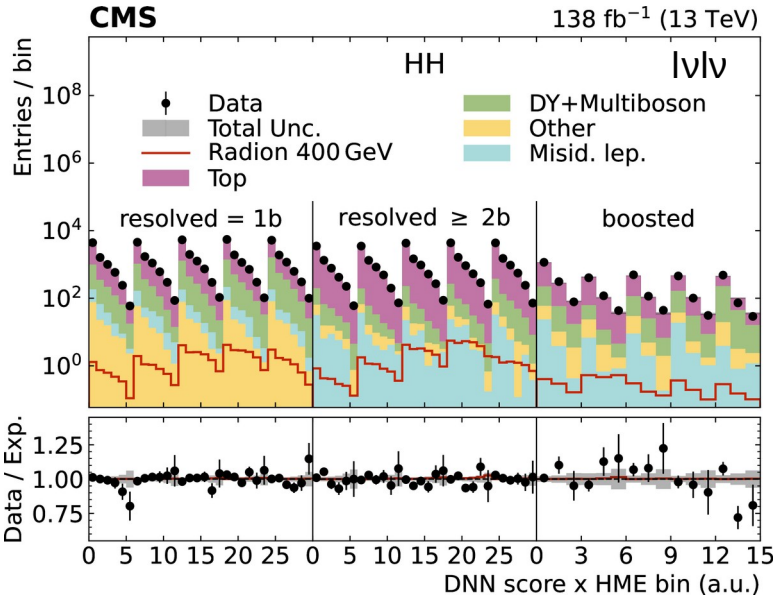
Channel	Analysis / Paper	Dataset	Mass range covered
$X \rightarrow H(WW \rightarrow l\nu l\nu, l\nu qq)\ H(bb$ merged$)$	JHEP 05 (2022) 005	138 fb^{-1}	800-4500 GeV
$X \rightarrow H(WW, \tau\tau)\ H(WW, \tau\tau)$	JHEP 07 (2023) 095	138 fb^{-1}	250-1000 GeV
$X \rightarrow H(\gamma\gamma)\ H(bb$ resolved$)$	JHEP 05 (2024)	138 fb^{-1}	260-1000 GeV
$X \rightarrow H(WW \rightarrow l\nu l\nu, l\nu qq)\ H(bb)$	2403.09430 **NEW!** (submitted to JHEP)	138 fb^{-1}	250-900 GeV
$X \rightarrow H(bb$ merged$)\ H(bb)$	2407.13872 **NEW!** (submitted to JHEP)	138 fb^{-1}	1000-3000 GeV
$X \rightarrow H(\gamma\gamma)\ H(\tau\tau)$	HIG-22-012 **Preliminary**	138 fb^{-1}	260-1000 GeV

X → H(WW → lνlν, lνqq) H(bb)

2403.09430
(submitted to JHEP)

- One AK8 jet (DeepCSV) or 2 AK4 jets (DeepJet), at least 1 b-tag, + 1 lepton and ≥1 AK4 jet not b-tagged (lνqq), or 2 leptons (lνlν),
- Targeted signal: WED with spin-0 radion or spin-2 graviton,
- Events classified based on multiclass DNN outputs, 1 signal (lνqq or lνlν) and 5 (lνqq) or 7 (lνlν) background nodes,
- Heavy Mass Estimator [1701.04442] to reconstruct HH mass in lνlν.

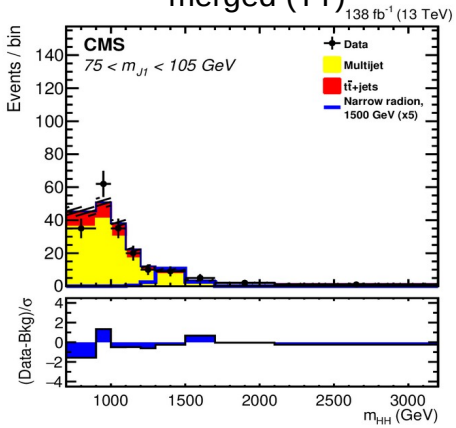


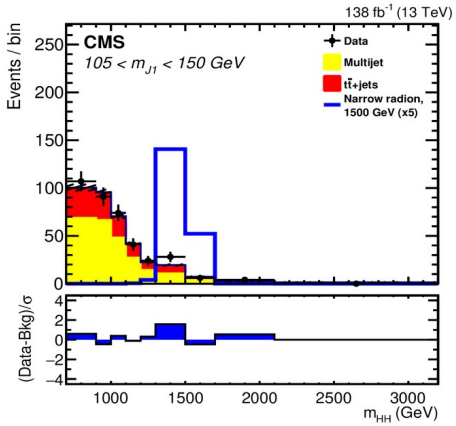


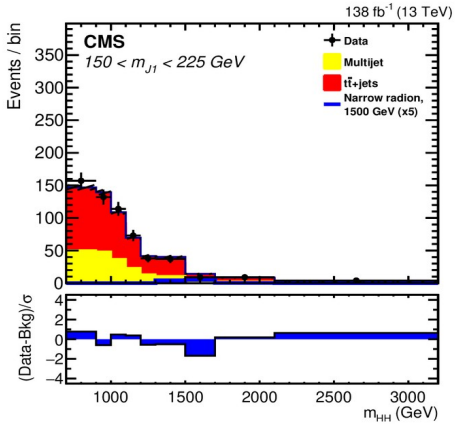
X→H(bb merged) H(bb)

2407.13872
(submitted to JHEP)

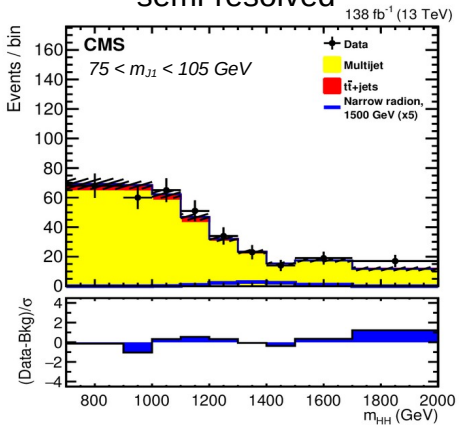
merged (TT)

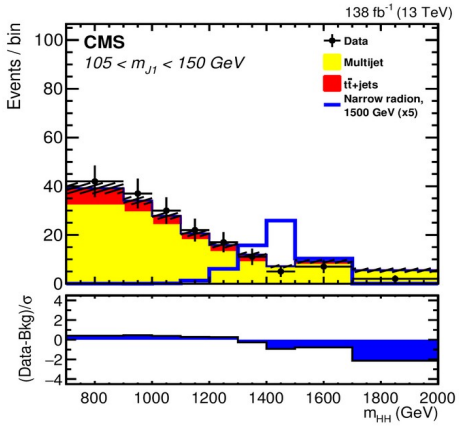


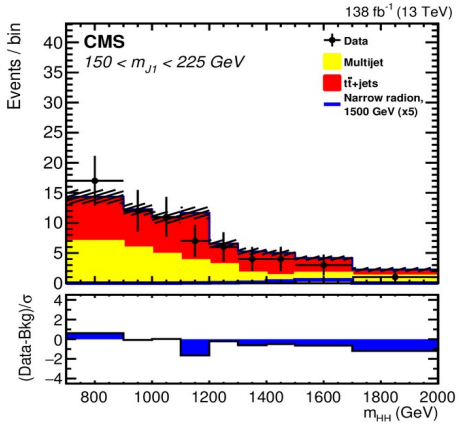




semi-resolved







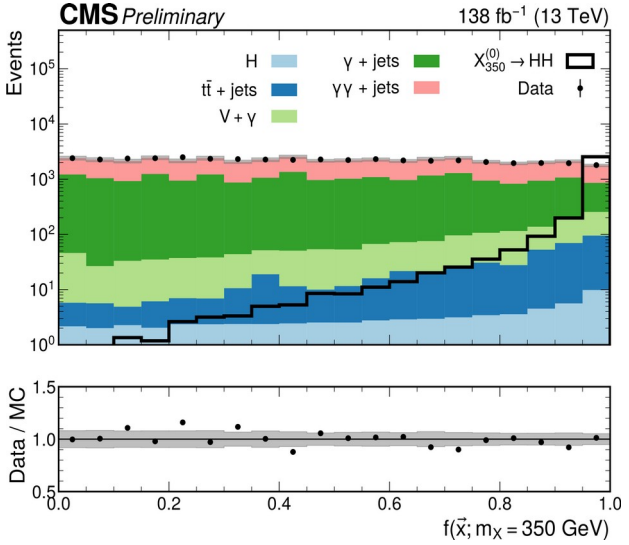
- Two AK8 jets (J_1,J_2) or one AK8 jet (J) and 2 AK4 b-tagged jets (j_1,j_2),
- Improved DeepAK8 b-tagging [2004.08262], required at least 1 tight b-tag, DeepAK8 score sidebands used for background CRs,
- Selections: $|\Delta\eta(HH)| > 1.3$, for semi-resolved: $\Delta R(J,jj) > 0.8$, $\Delta R(j_1,j_2) < 1.5$,
- **Corrected di-Higgs mass:** $m_{HH} = m_{JJ} + (m_H - m_{J1}) + (m_H - m_{J2})$ for merged, or $m_{HH} = m_{Jjj} + (m_H - m_J) + (m_H - m_{j1j2})$, for semi-resolved,
- Targeted signal: WED, spin-0 or spin-2, in bins of m_{HH} and m_{J1}.

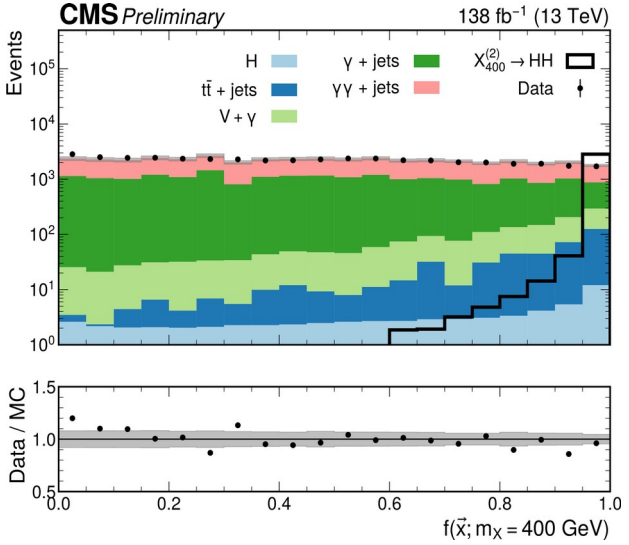
X → H(ττ) H(γγ)

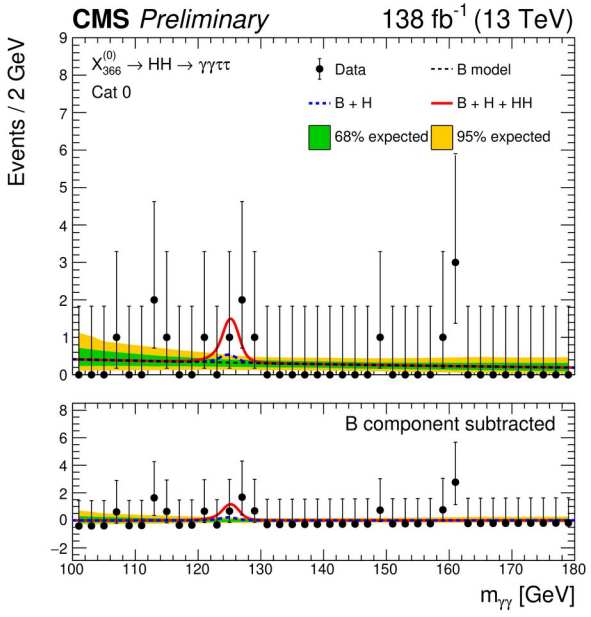
CMS PAS HIG-22-012

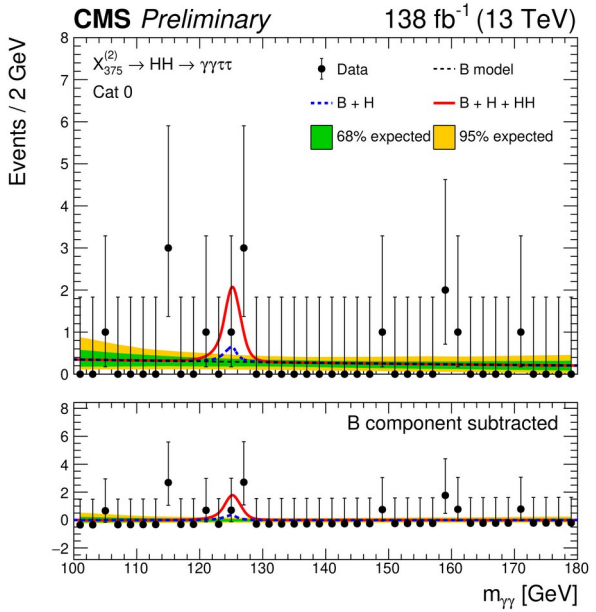
- Hadronic and leptonic τ decays considered,
- At least 2 high-p_T photons, $p_T^{\gamma 1}/m_{\gamma\gamma} > 1/3$, $p_T^{\gamma 2}/m_{\gamma\gamma} > 1/4$,
- Parametric Neural Network trained to identify signal for different m_X (and m_Y), spin 0 or spin 2, pNN output used for event categorization,
- Maximum likelihood fits to $m_{\gamma\gamma}$ separate for each mass hypothesis.

Examples of pNN scores





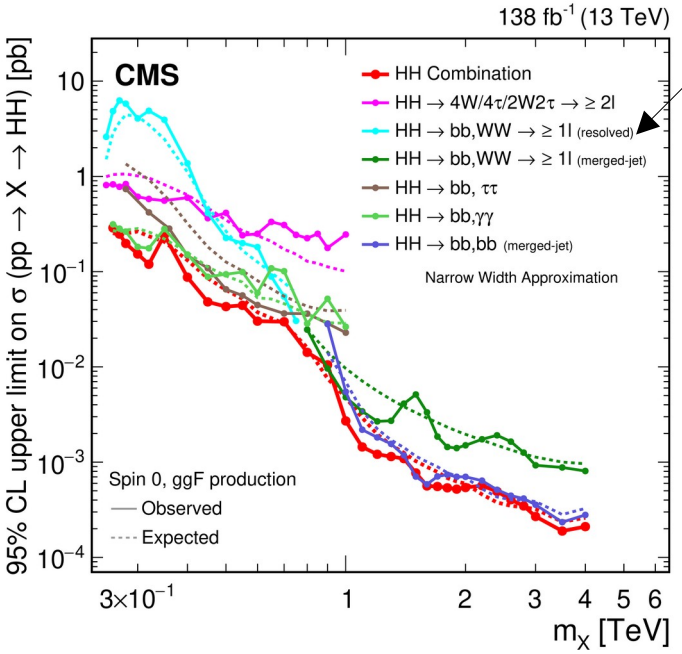


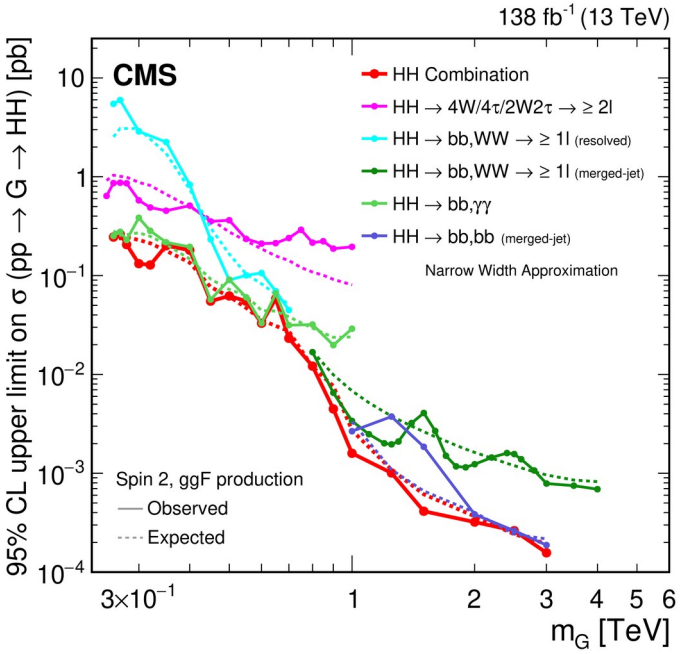


Combination of CMS resonant HH searches

2403.16926
(submitted to PR)

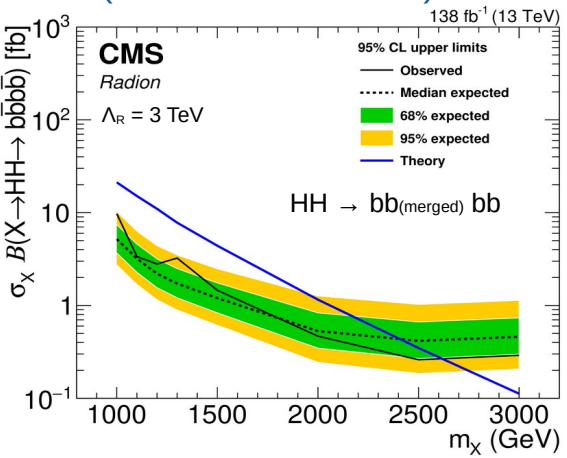
2403.09430

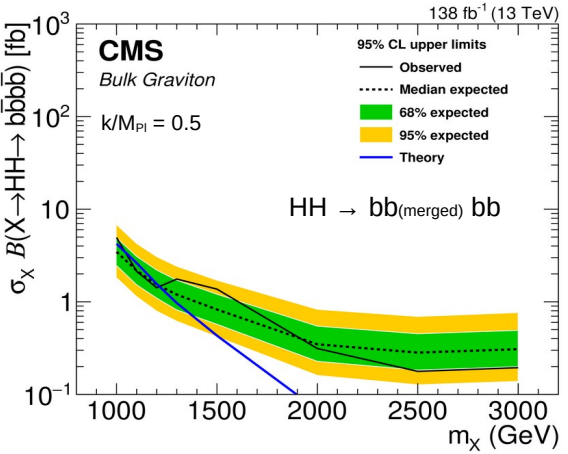




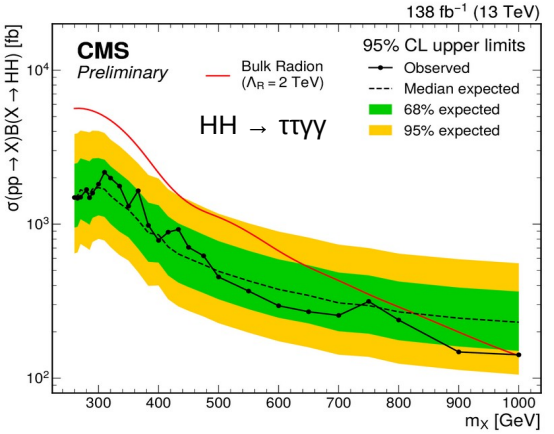
+ brand new results:

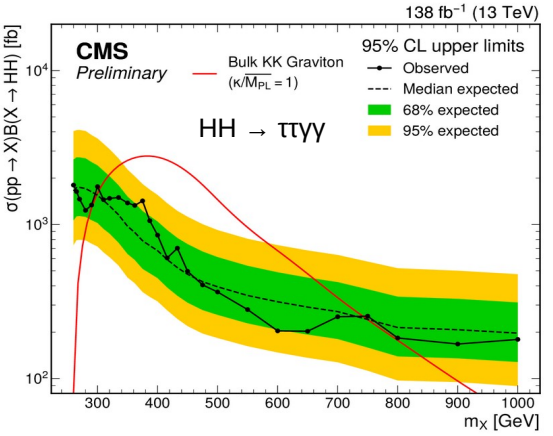
2407.13872
(submitted to JHEP)





CMS PAS HIG-22-012

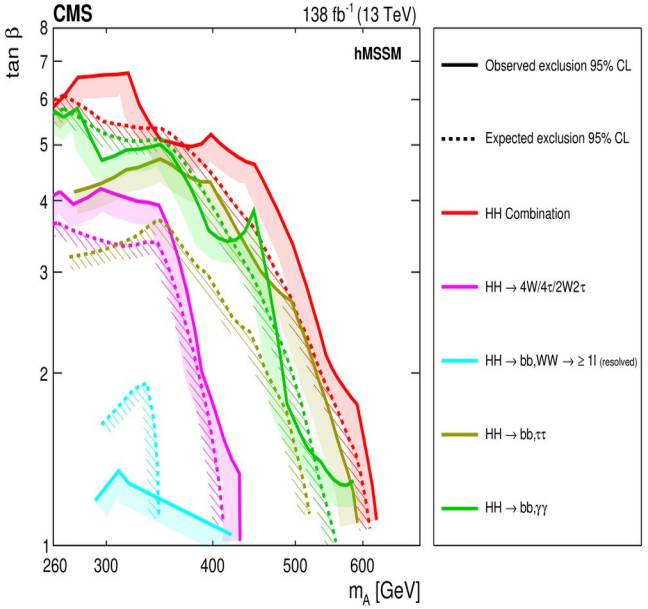


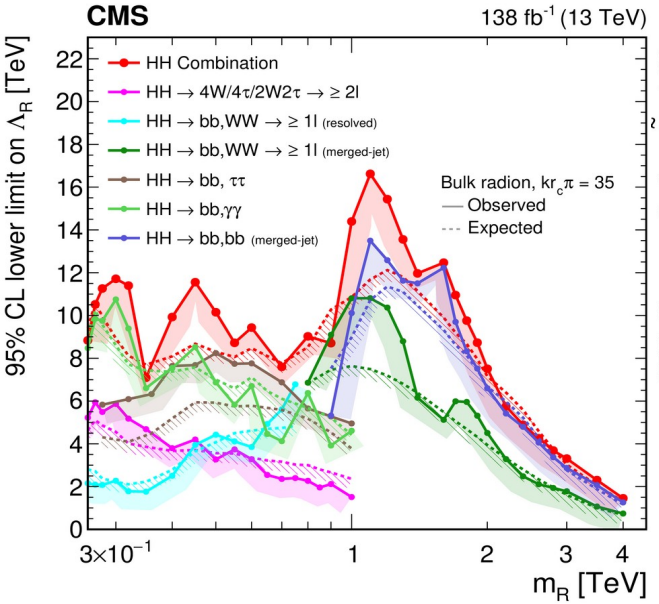


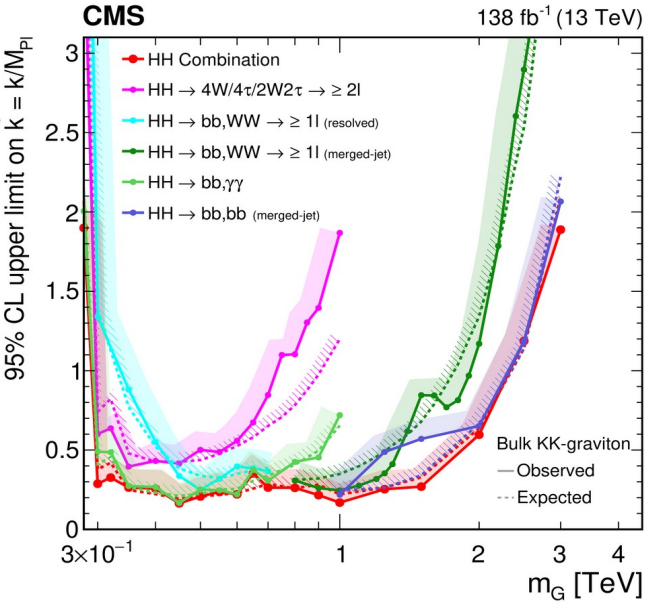
No deviation larger than 2 s.d. observed

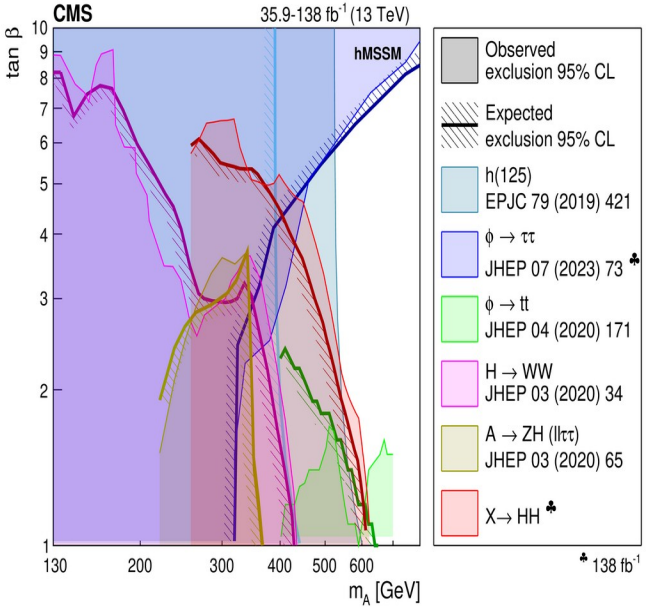
X → HH vs. other exclusions in BSM models

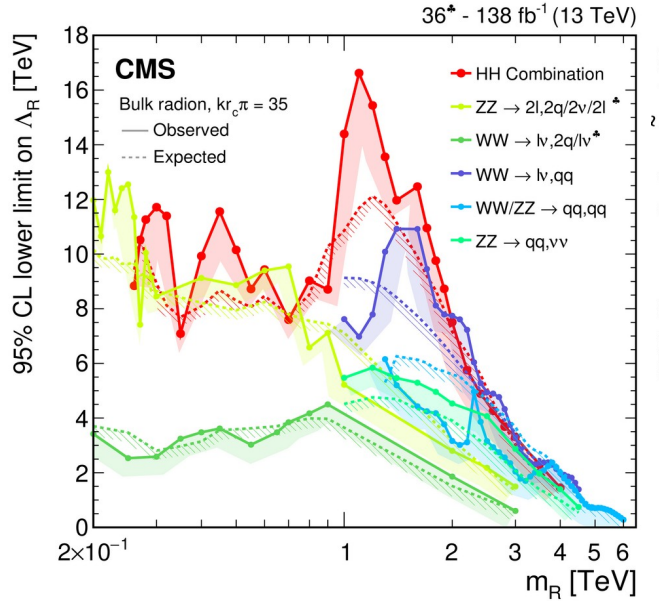
2403.16926
(submitted to PR)

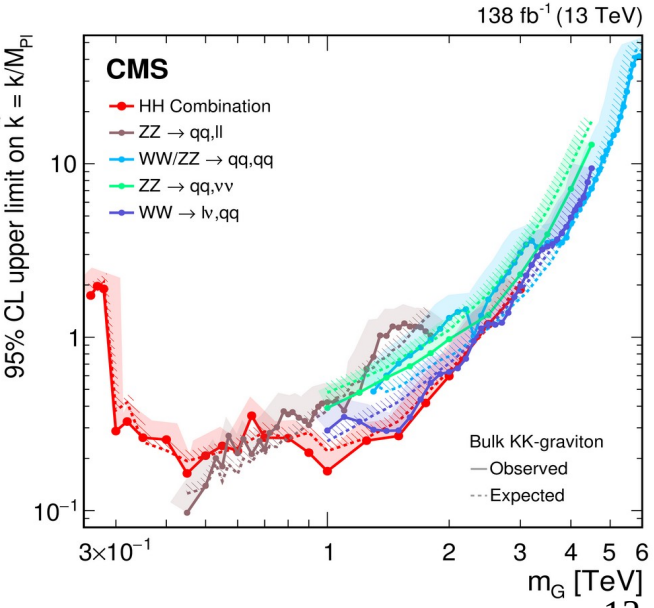












CMS searches for $X \rightarrow Y\,H$

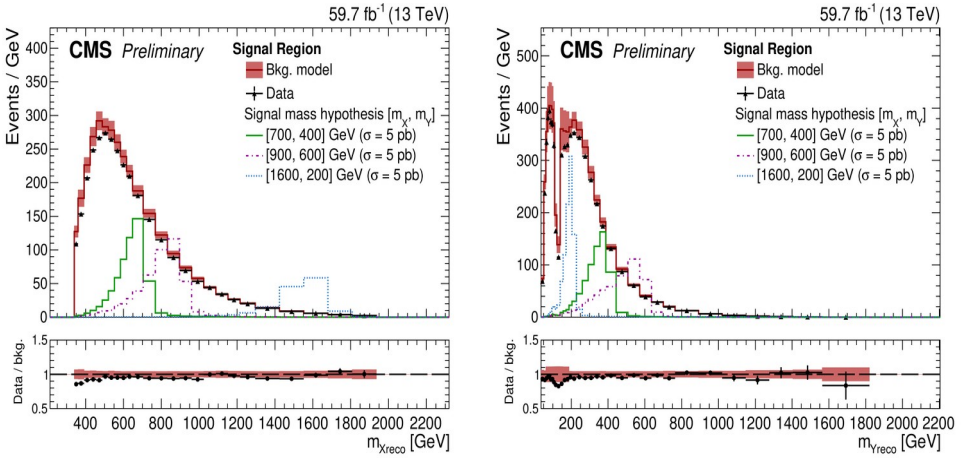
Channel	Analysis / Paper	Dataset	Mass range covered
$X \rightarrow Y(bb$ resolved$)\, H(\tau\tau)$	JHEP 11 (2021) 057	137 fb^{-1}	X: 240-3000 GeV Y: 60-2800 GeV
$X \rightarrow Y(bb$ merged$)\, H(bb$ merged$)$	PLB 842 (2023) 137372	138 fb^{-1}	X: 900-4000 GeV Y: 60-600 GeV
$X \rightarrow Y(bb$ resolved$)\, H(\gamma\gamma)$	JHEP 05 (2024) 316	138 fb^{-1}	X: 300-1000 GeV Y: 90-800 GeV
$X \rightarrow Y(bb$ resolved$)\, H(bb$ resolved$)$	HIG-20-012 **Preliminary**	138 fb^{-1}	X: 400-1600 GeV Y: 60-1400 GeV
$X \rightarrow Y(\tau\tau)\, H(\gamma\gamma),\, Y(\gamma\gamma)\, H(\tau\tau)$	HIG-22-012 **Preliminary**	138 fb^{-1}	X: 300-1000 GeV Y: 50/70-800 GeV

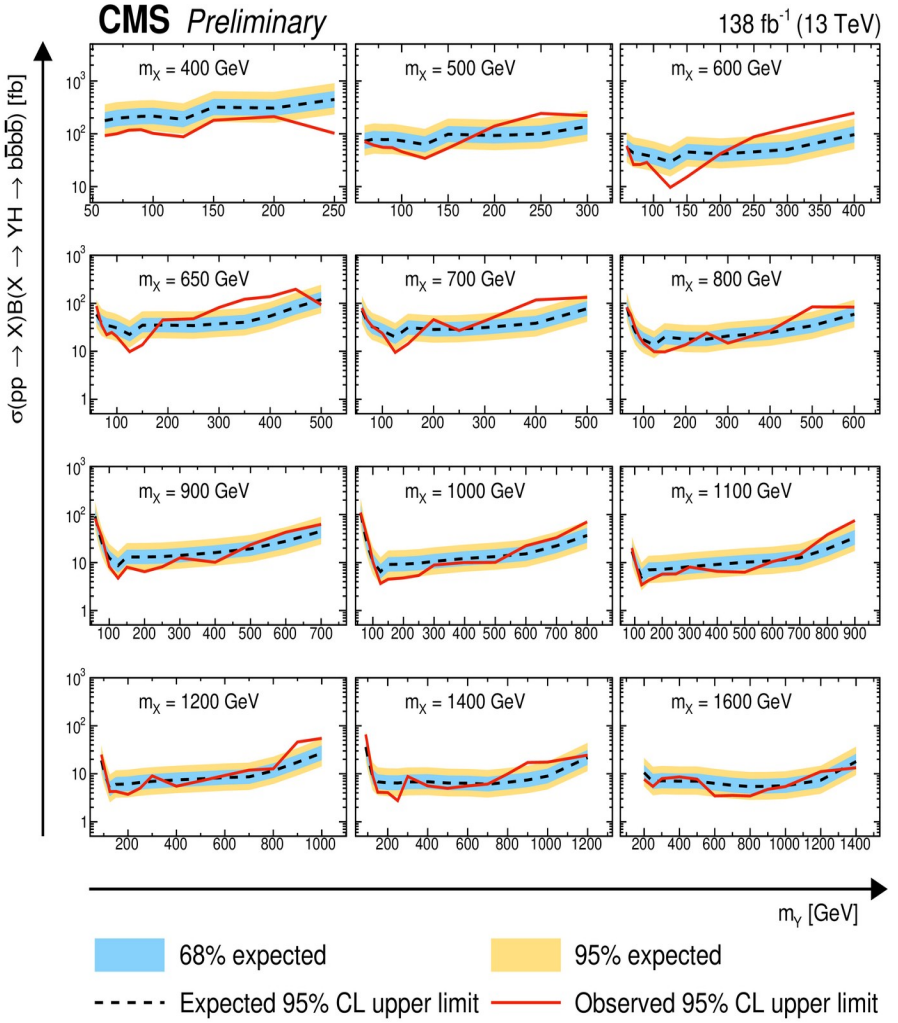
Note: All the above searches are also relevant to $X \rightarrow HH$

X → Y(bb resolved) H(bb resolved)

CMS PAS HIG-20-012

- Four AK4 b-tagged jets, 4b (signal) and 3b (background dominated),
- Validation Region and Control Region based on reconstructed m_H,
- SM background assessed from 3b sample, BDT-based weights calculated in CR to reproduce 4b sample, validated in VR,
- Generic spin-0 signal, 2-dim m_X vs. m_Y.



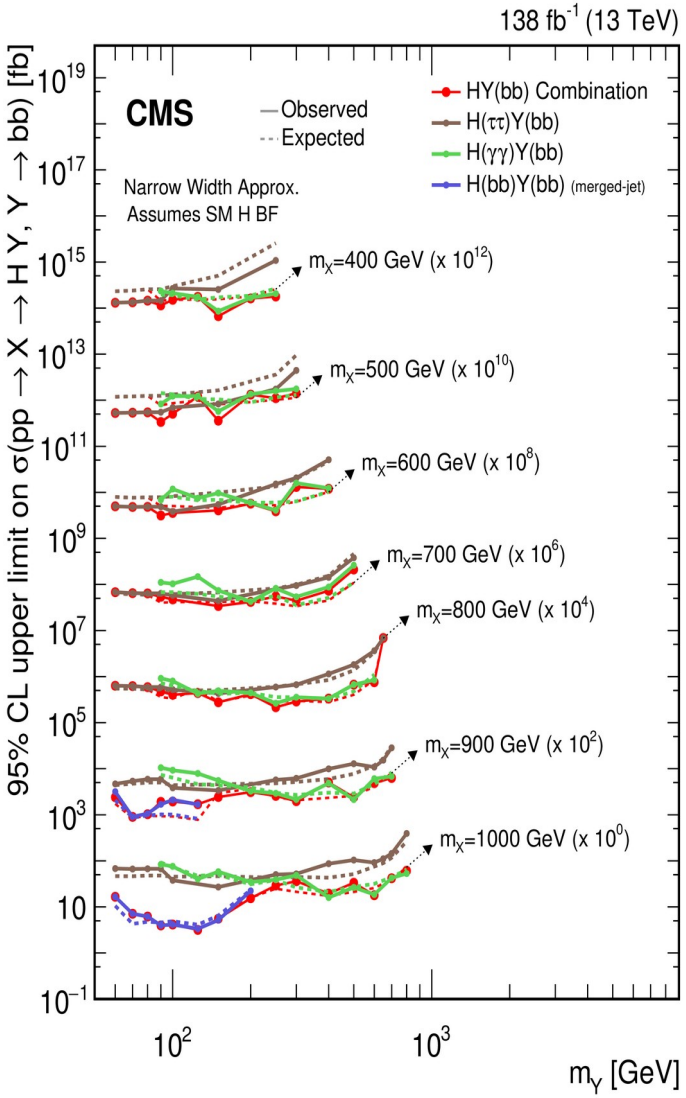


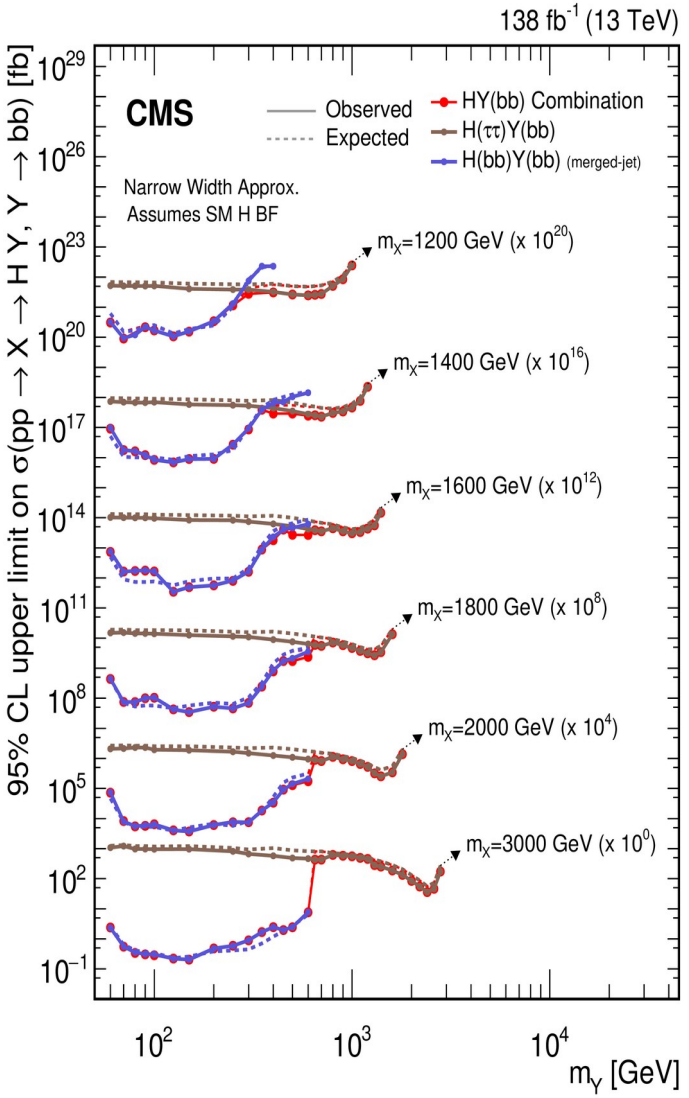
Largest excess observed at m_X = 700 GeV, m_Y = 400 GeV, with a local (global) significance of 4.1 (2.8) s.d.

Combination of CMS X → YH searches

2403.16926
(submitted to PR)

All Y(bb) channels





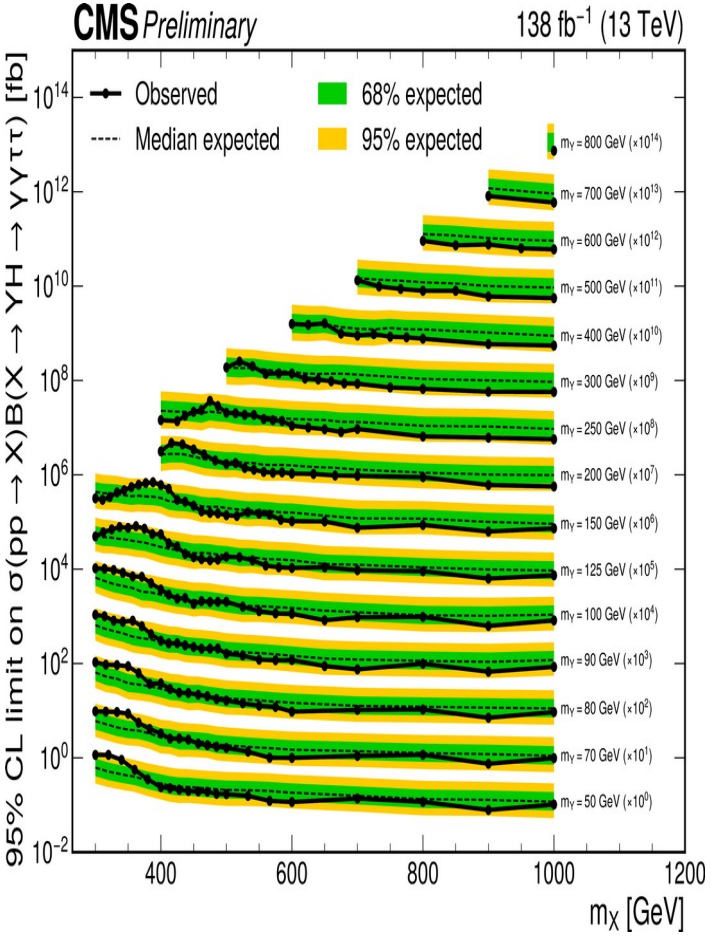
- New results from bbbb resolved HIG-20-012 fully competitive, with significant improvements for $m_X < 1000$ GeV,
- Interpretations within the NMSSM: only parameter dependent exclusions, but for $m_Y \leq 150$ GeV limits close to maximally allowed values.

X → Y(ττ) H(γγ), Y(γγ) H(ττ)

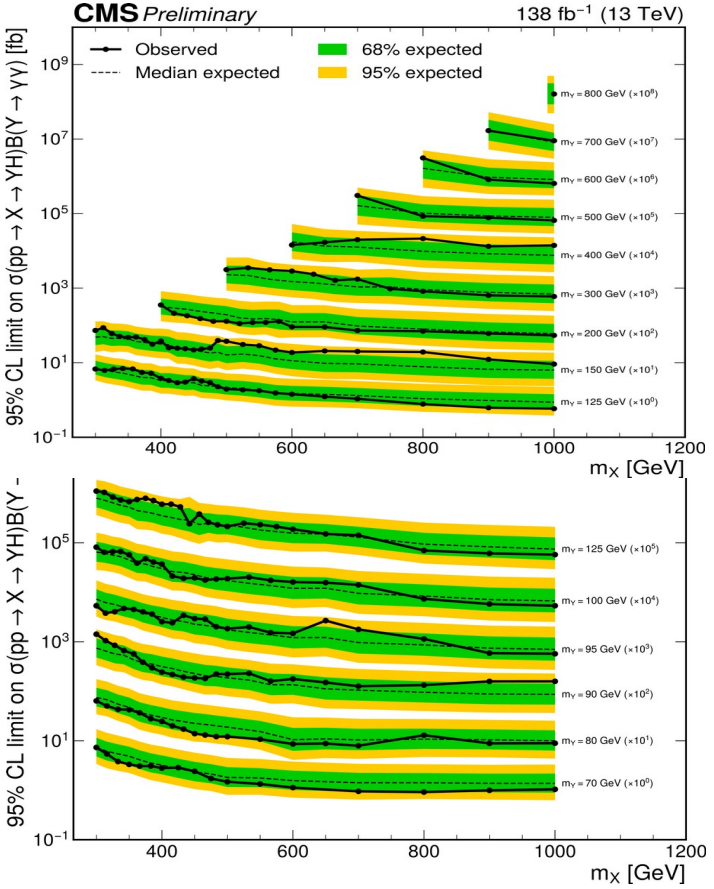
CMS PAS HIG-22-012

- Same analysis as X → H(ττ) H(γγ) (slide 11), extended to $m_Y \neq m_H$

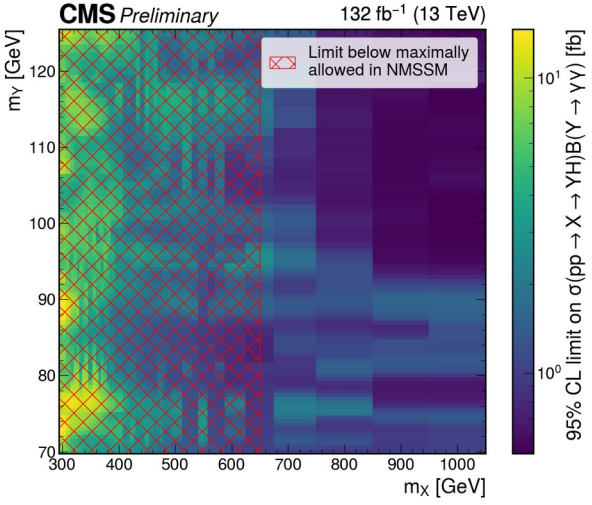
X → Y(ττ) H(γγ)



X → Y(γγ) H(ττ)



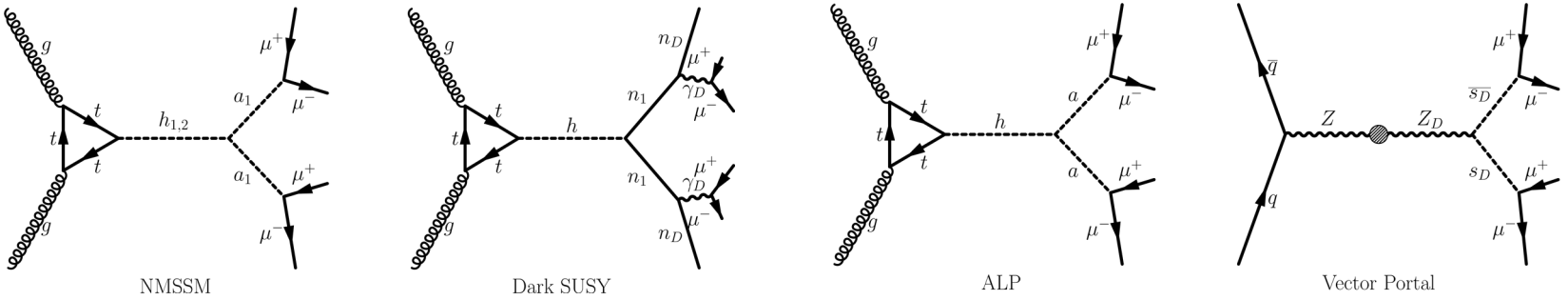
- NMSSM interpretation: for $m_X < 650$ GeV limits on σ(pp → X → YH) x Br(Y → γγ) lower than maximally allowed



Largest excess seen in Y(ττ)H(γγ) at m_X = 320 GeV, m_Y = 60 GeV, with a local (global) significance of 2.6 (2.2) s.d.

CMS searches for $H \rightarrow a\,a$

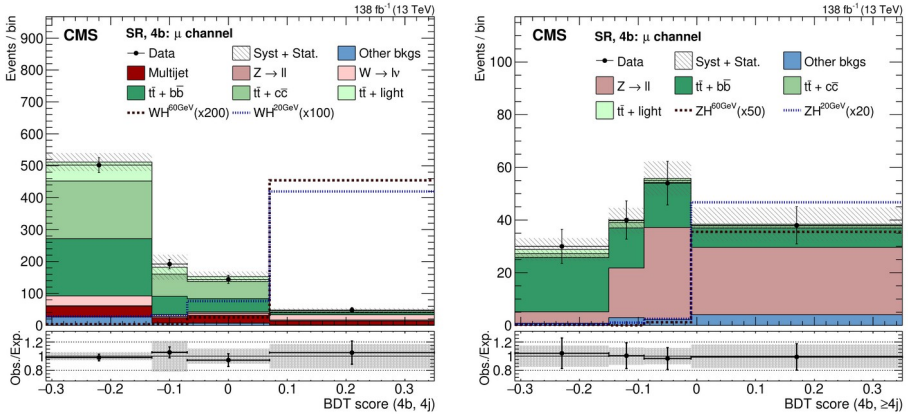
Channel	Analysis / Paper	Dataset	Mass range covered
$H \rightarrow aa \rightarrow bbbb$	JHEP 06 (2024) 097	138 fb^{-1}	15 – 60 GeV
$H \rightarrow aa \rightarrow \mu\mu bb, \tau\tau bb$	EPJC 84 (2024) 493	138 fb^{-1}	12 – 60 GeV
$X,H \rightarrow aa \rightarrow \mu\mu\mu\mu$	2407.20425 **NEW!** (submitted to JHEP)	137 fb^{-1}	0.21 – 60 GeV
$H \rightarrow aa \rightarrow \mu\mu\tau\tau, \tau\tau\tau\tau$	SUS-24-002 **Preliminary**	138 fb^{-1}	4 – 15 GeV

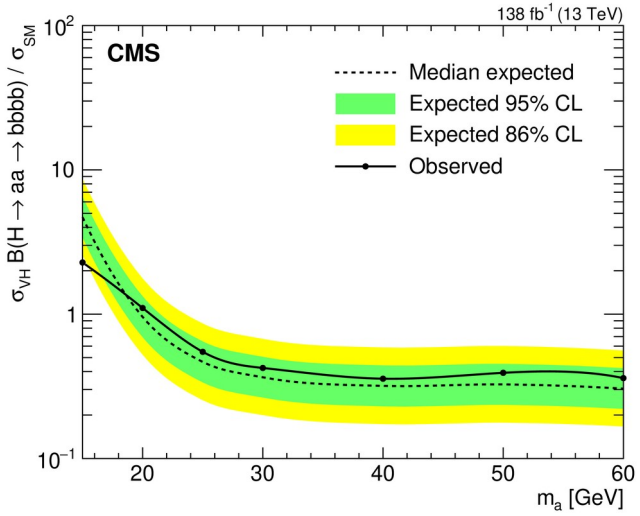


$H \to aa \to bbbb$ and $H \to aa \to \mu\mu bb, \tau\tau bb$

JHEP 06 (2024) 097

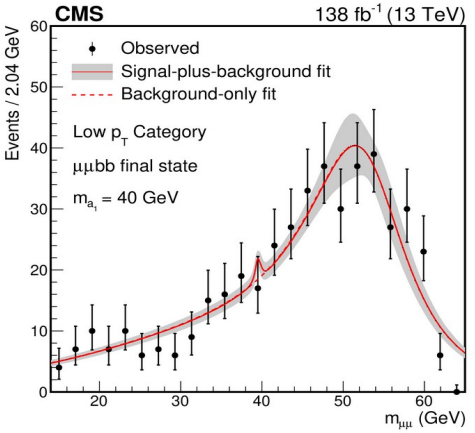
- **Associated WH or ZH production + leptonic W, Z decays,**
- Four AK4 jets, SR: at least 3 b tags.

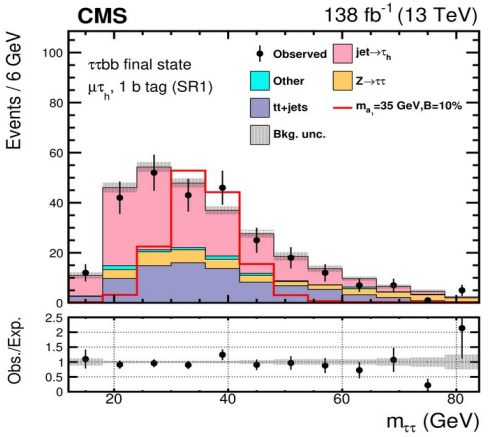




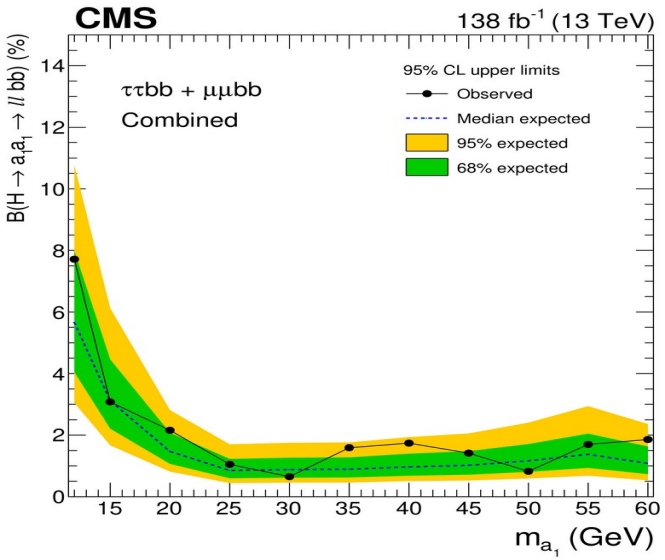
EPJC 84 (2024) 493

- **τ decays: eμ, eτ$_h$, μτ$_h$,**
- Two AK4 jets, at least 1 tight b tag





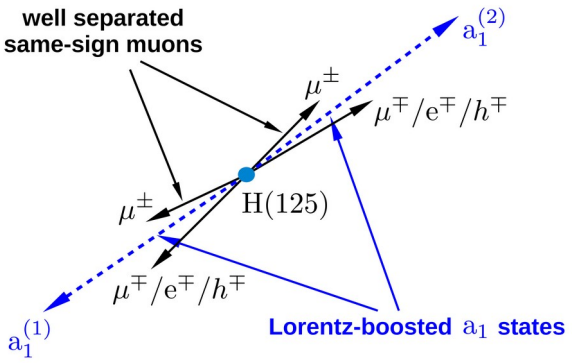
- Limits on B($H \to aa$) in 2HDM+S scenarios.

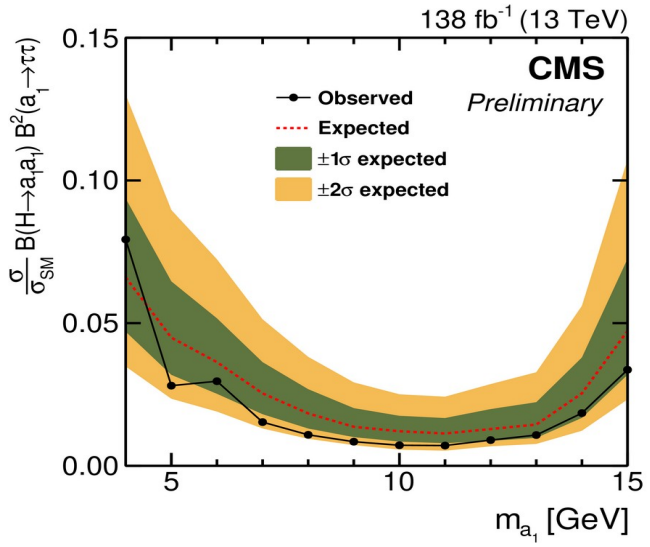


$H \to aa \to \mu\mu\tau\tau$, $\tau\tau\tau\tau$ and X, $H \to aa \to \mu\mu\mu\mu$

CMS PAS SUS-24-002

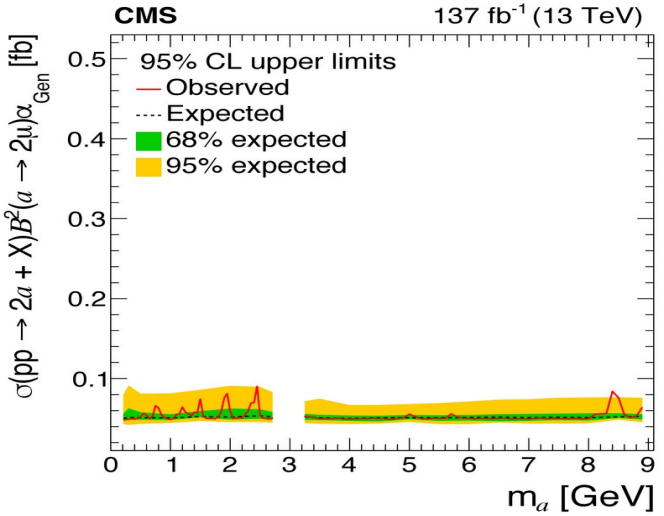
- **Pairs of $\tau_\mu\tau_{1prong}$ or $\mu\tau_{1prong}$ Lorentz boosted,**
- 2 same sign muons with $\Delta R > 1.5$ with 1 opposite sign particle within $\Delta R < 0.5$



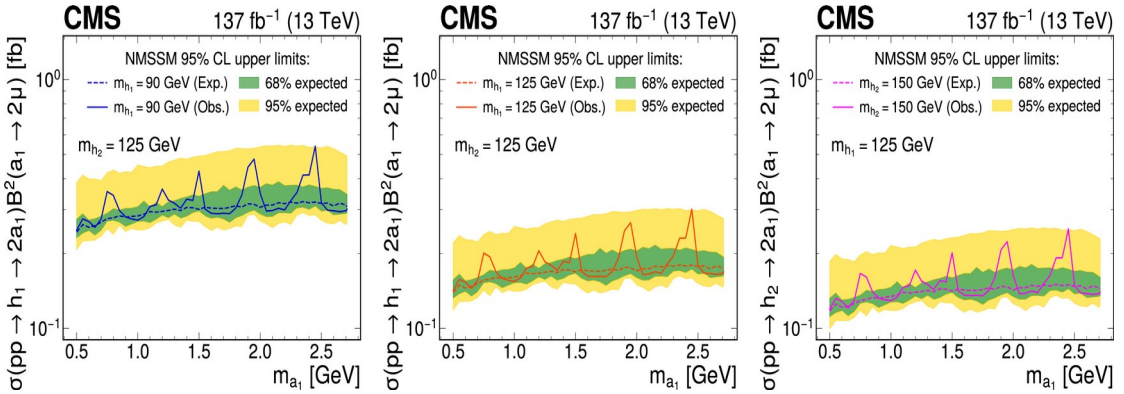


2407.20425

- **No Higgs constraint** (model independent), 2 dimuons with consistent masses 10-60 GeV,



- Model dependent interpretations



Hit of the season: A, X → tt

Search for A, X → tt

CMS PAS HIG-22-013 **Preliminary!**

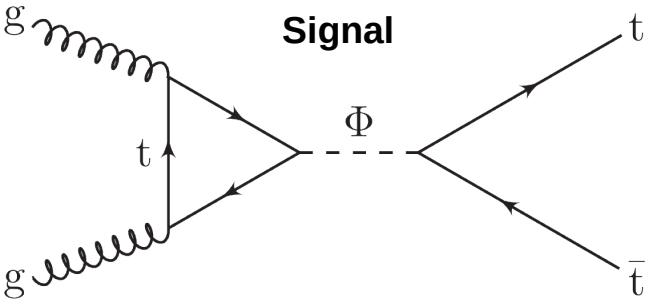
- Final states: **ljbb** - exactly one lepton + 3 jets or ≥4 jets, including 2 b-tags,
  llbb - exactly 2 leptons + at least 2 jets, including 1 b-tag,

- **tt reconstruction**:
  - p^{ν} from p_T^{miss}, using W and t mass constraints
    [ljbb: 1305.1878, llbb: hep-ph/0603011],
  - assignment of jets to final state quarks
    based on mass probability densities,

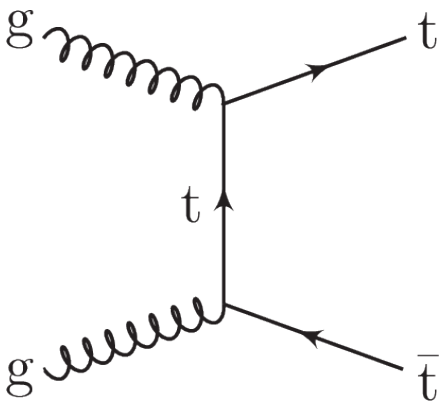
- Backgrounds: SM tt (**pQCD only**), single top – simulation,

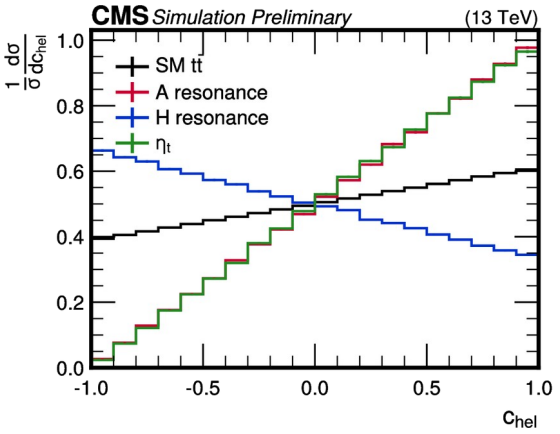
- **Signal: Φ = H, A, η_t** ($^1S_0^{[1]}$ tt bound state, simplified model [2102.11281]),
  B. Fuks, K. Hagiwara, K. Ma, Y.-J. Zheng
  signal extraction:
  - from 2D templates m_{tt} vs. $|\cos\theta^*_{tl}|$ (ljbb),
  - from 3D templates m_{tt} vs. spin correlation observables c_{hel}, c_{han} (llbb)

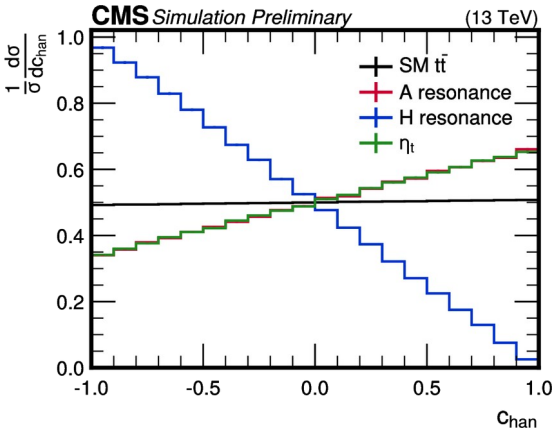
Signal



Background

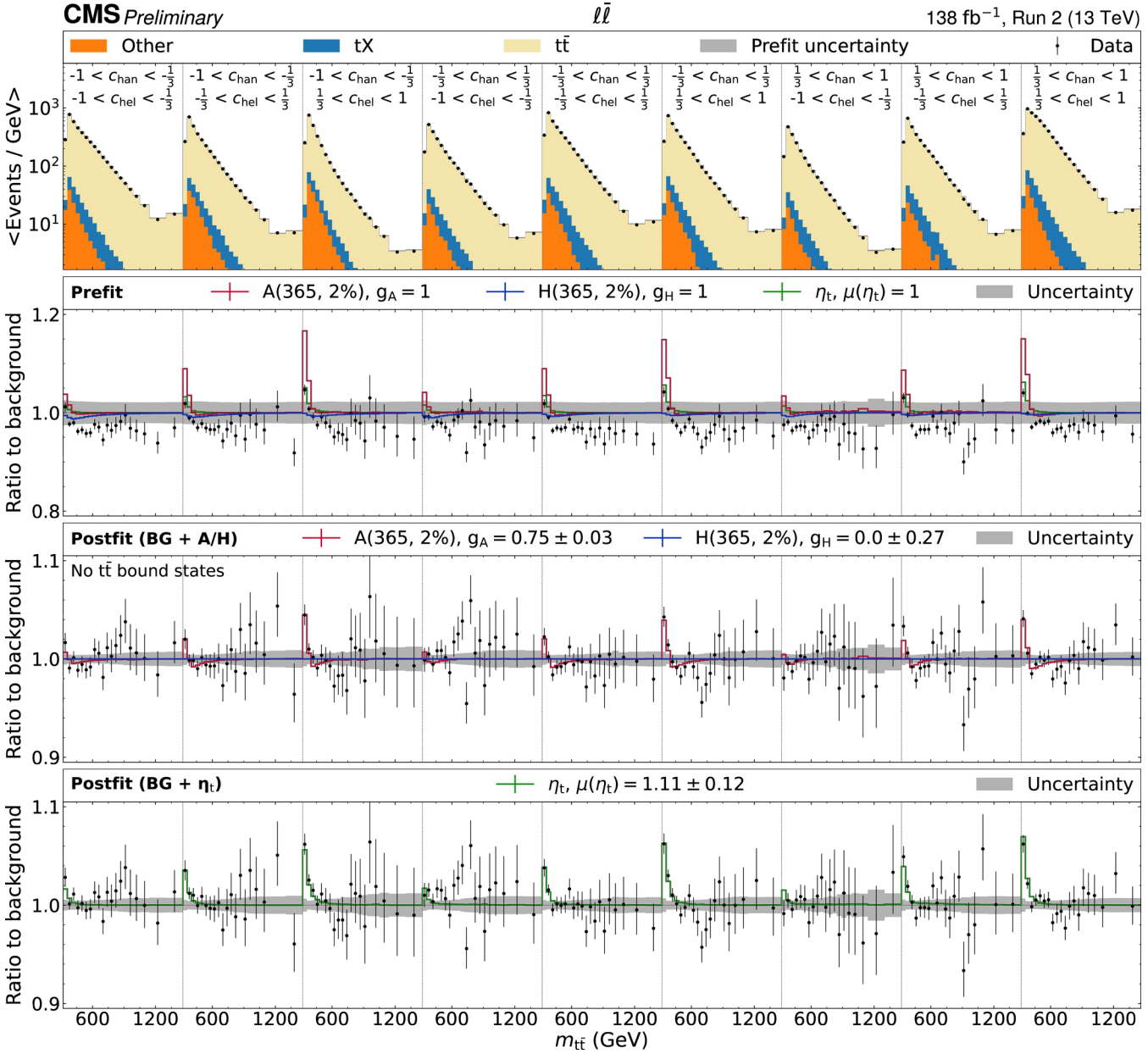


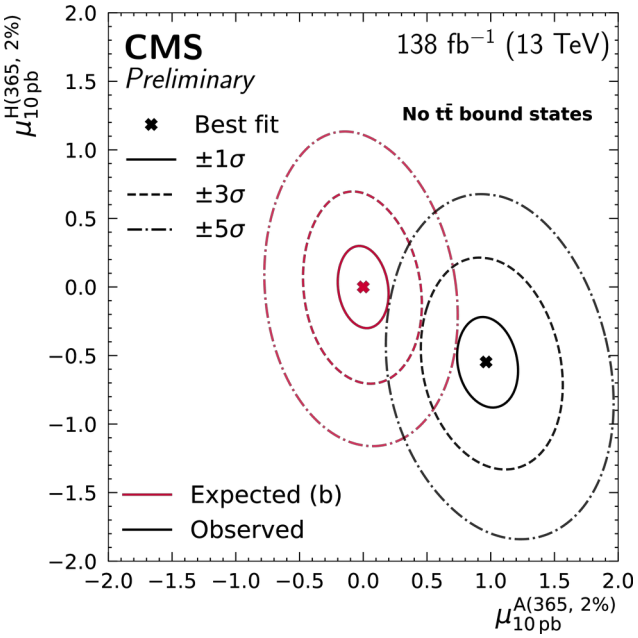




Search for A, X → tt (contd.)

- Clear excess of events **(>5 s.d. total)** at the tt threshold observed in all 3 categories





- Consistent with being $J^P = 0^-$ rather than $J^P = 0^+$, slightly favoring η_t hypothesis (no interference with background)

Search for A, X → tt (contd.)

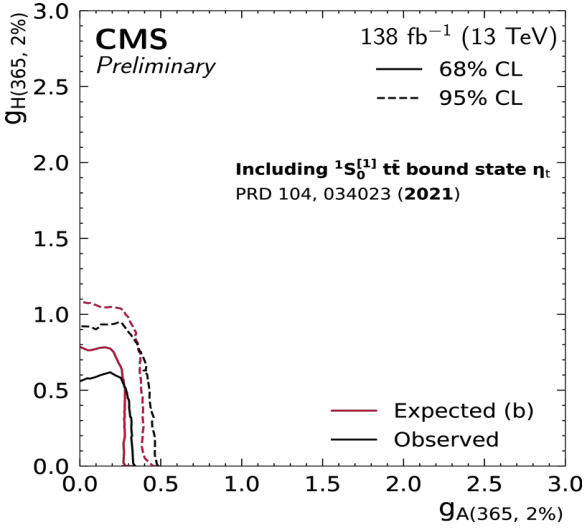
- Extracted cross section: **$\sigma(\eta_t)$ = 7.1 pb ± 11%** in agreement with non-relativistic QCD prediction

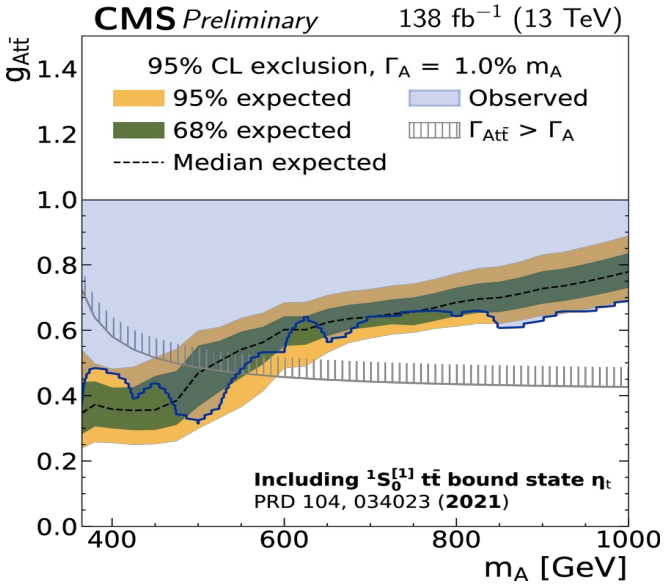
- Upper limits are set on

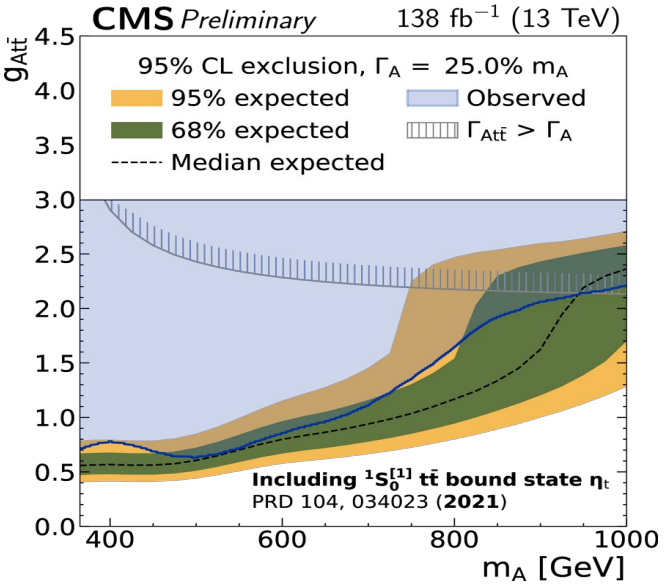
  g_{Att} vs. m_A →

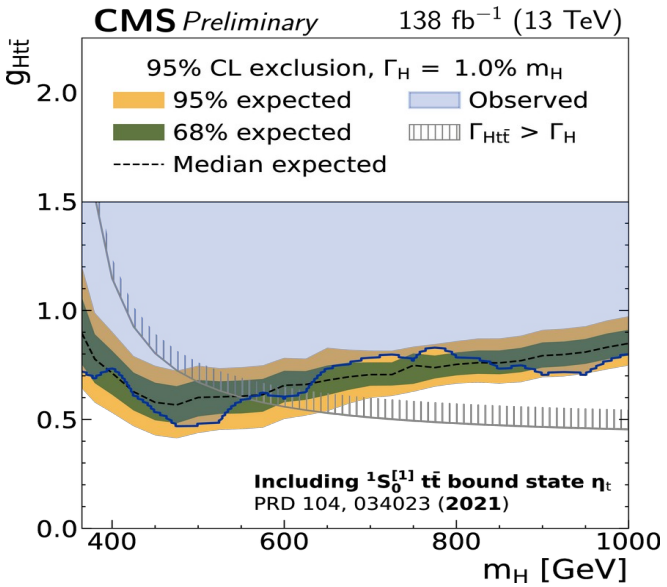
  g_{Htt} vs. m_H ↘

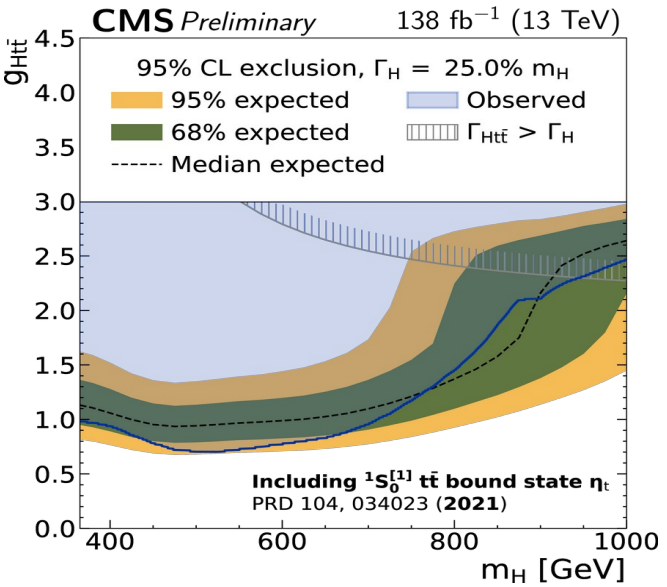
  g_{Htt} vs. g_{Att} ↓











Summary & outlook

- **Many new analyses** published over the course of last year, mostly continuations and extensions of previous analyses based on 2016 data alone,
- **Many improvements** in data analysis techniques,
- **Run 2 data almost fully analyzed**, with a few pending exceptions,
- A few interesting excesses over SM predictions observed, with global significances between 2-3 s.d., otherwise no sign of BSM,
- **Highlight:** first significant (> 5 s.d.) observation of a resonant pseudoscalar structure at the tt production threshold, consistent with a toponium bound state,
- **Now turning the focus to Run 3 data.**