Searches for Higgs boson production through decays of heavy resonances

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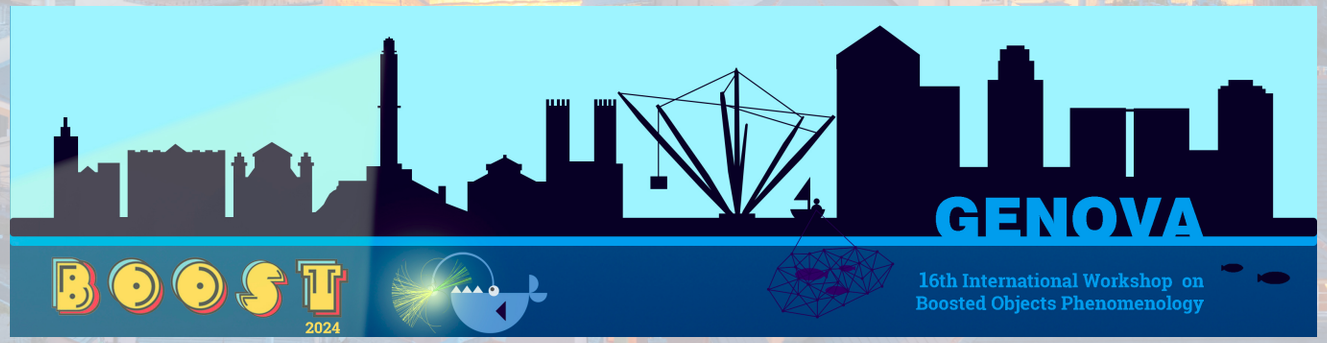


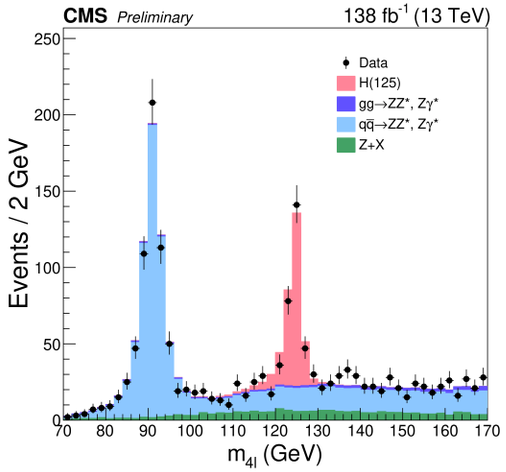
31/07/2024

Higgs boson as a window to new physics

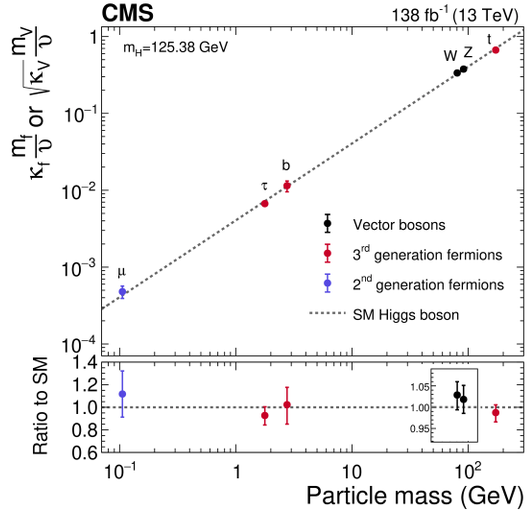
Newest fundamental particle discovered: Last missing piece in standard model (SM)

Many things unknown → could answer limitations of SM

Tremendous progress on understanding H



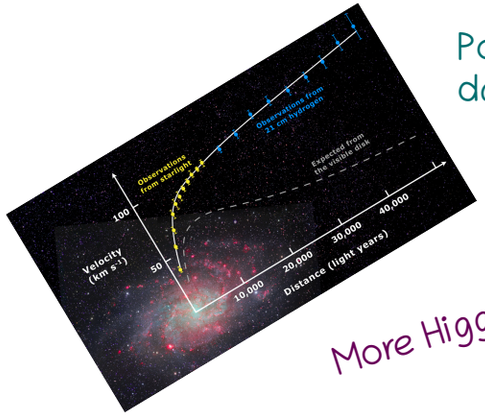
CMS-PAS-HIG-21-019



Nature 607 (2022) 60-68

Fundamental/Composite ?

Flavor violation?

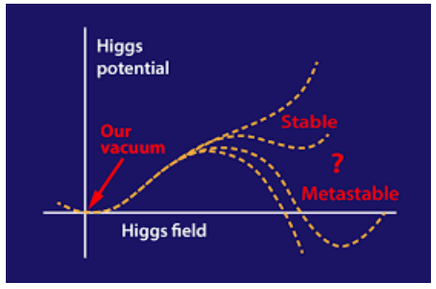


Portal to dark matter?

Anomalies in couplings & CP nature

Baryon asymmetry of universe

More Higgs bosons?

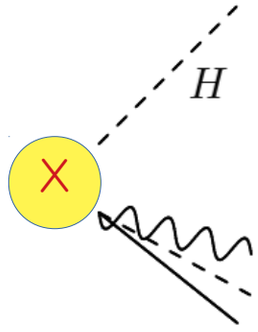


Higgs potential → SM-like?

+ ...

Many extensions of SM
→ predict signature with Higgs boson

E.g. new particles decaying to Higgs boson(s)



Outline of results to be discussed

Topics

- Search for VH resonances
  - Scalar resonance (A → ZH)
  - Vector resonances (W'/Z' → W/Z H)
- Search for di-Higgs (HH) resonances
- Search for X → YH resonances

Focus of this talk

Combination of multiple final states
+
Interpretation in benchmark models
+
HL-LHC projections

&
New results

Released in 2024

References

Review article by CMS on resonance searches with Higgs boson(s)

arXiv: 2403.16926

Under review in Physics Reports

CMS-PAS-HIG-22-004
CMS-PAS-B2G-23-006
CMS-PAS-B2G-23-008
CMS-PAS-HIG-22-012

Will not discuss analysis strategies for published results
Already shown in past BOOST conferences

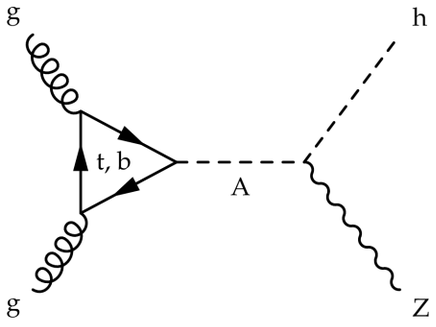
Searches for VH resonances

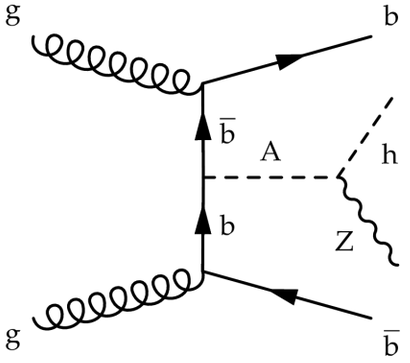
Scalar resonance

A → ZH → 2l 2τ JHEP 03 (2020) 065 [35.9 fb^{-1}]
CMS-PAS-HIG-22-004 [138 fb^{-1}] new

A → ZH → 2l/2v 2b EPJC 79 (2019) 564 [35.9 fb^{-1}]

A → ZH → 2l 2t CMS-PAS-B2G-23-006 [138 fb^{-1}]





Vector resonance

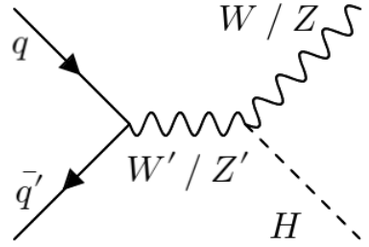
W' → WH → lν bb Phys. Rev. D 105 (2022) 032008

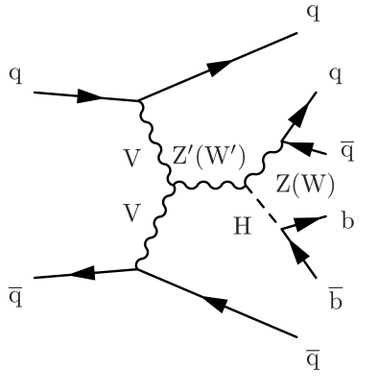
Z' → ZH → ll bb EPJC 81 (2021) 688

Z' → VH → qq bb/qq Phys. Lett. B 844 (2023) 137813

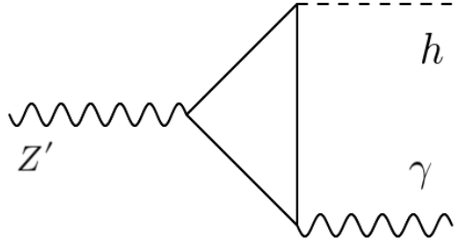
Z' → VH → ll/νν cc/4q CMS-PAS-B2G-23-008

[138 fb^{-1}]



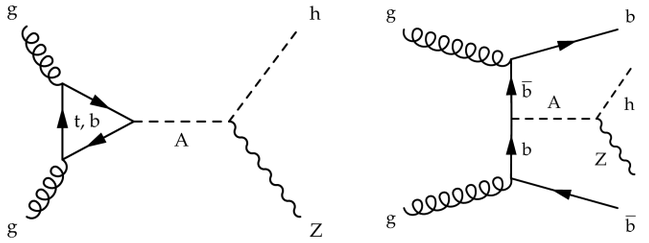


Z' → H(→ bb) γ Phys.Rev.Lett. 122 (2019) 8, 081804 [35.9 fb^{-1}]



Scalar for scalar resonances: A→ZH (2016-only)

arXiv: 2403.16926



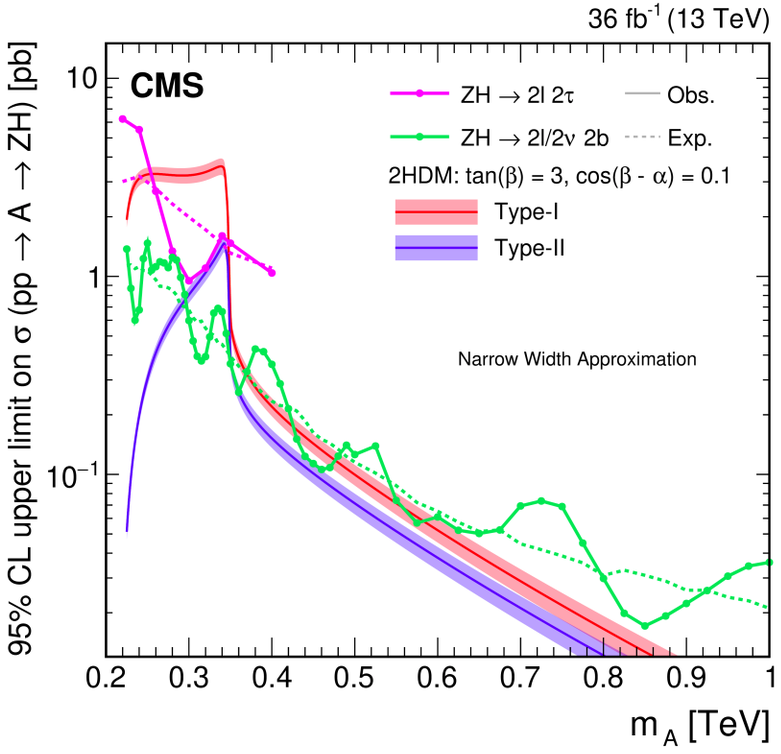
- Topology realized in models with an extended Higgs sector

Results interpreted in 2HDM

2HDM = SM + a complex Higgs doublet → H X A H^+ H^-

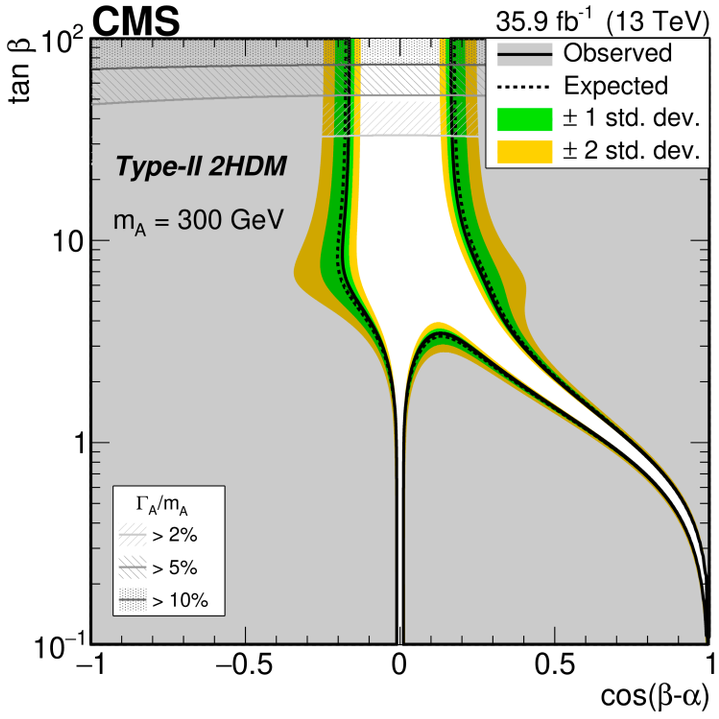
Recent review by Wang, Yang, Zhang (2023)

Analyses using 2016 data



Probing high m_A with H→ $b\bar{b}$ and Z→ νν decay modes

Type 2 2HDM → Higgs sector of MSSM



Interpretation using A→ ZH(bb) search

Strong constraints at low tanβ

except at alignment limit β-α = π/2 & diagonal (α=0)

A→ZH→ llττ: Full Run 2

new

CMS-PAS-HIG-22-004

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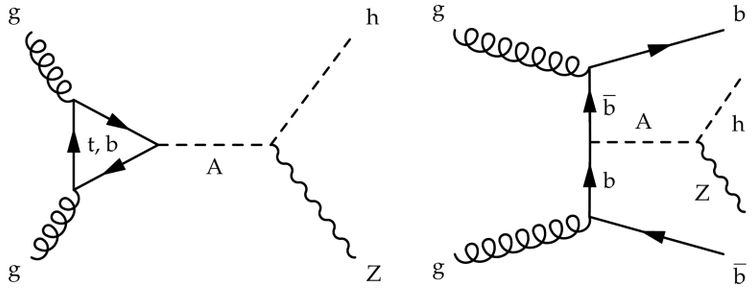


- Irreducible background
  ZZ, ttZ, ZH/ttH, triboson

← from simulation

- Reducible background
  jet faking as τ_h / lepton

← estimated from data

Decay mode:

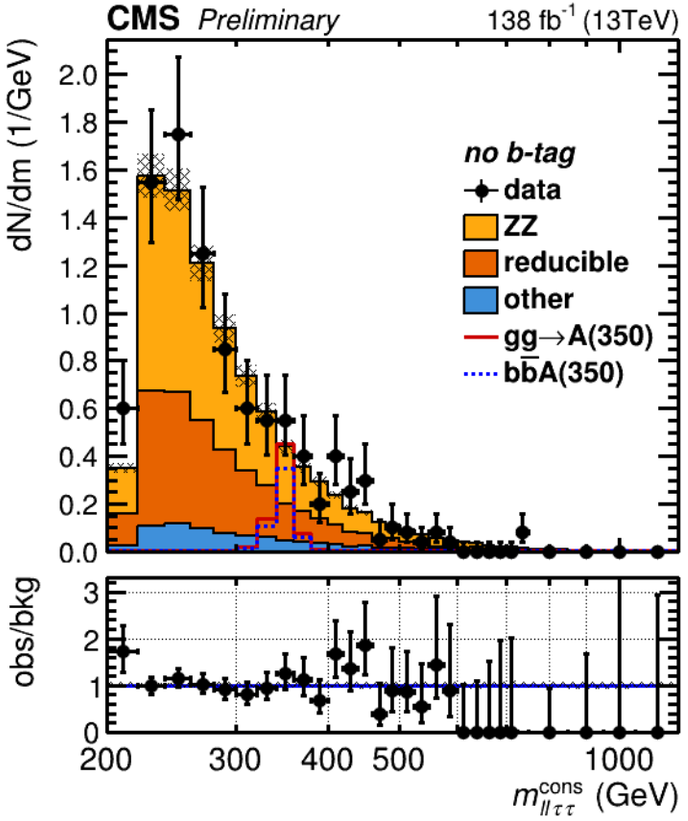
$Z \rightarrow l\,l + h \rightarrow \tau\,\tau$

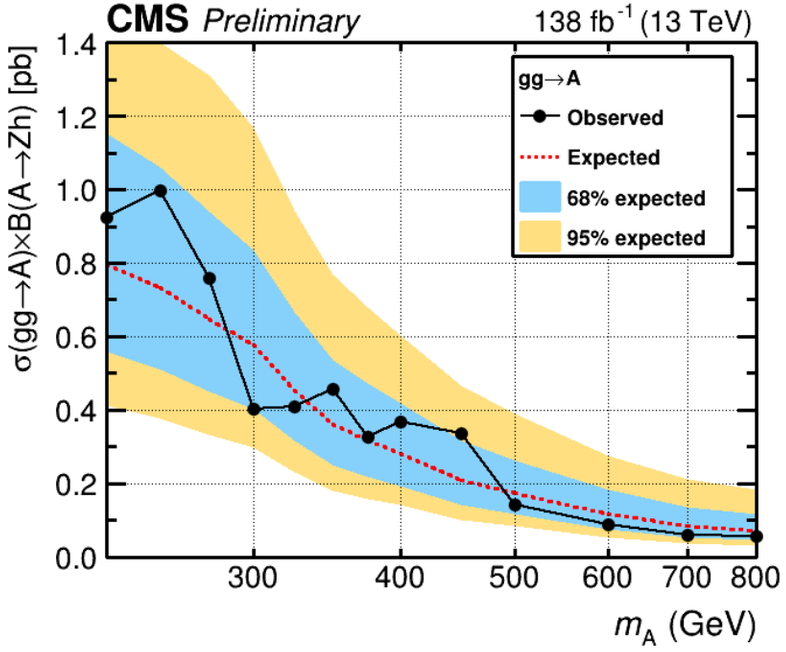
Final states considered:

- ee/μμ + eτ_h
- ee/μμ + μτ_h
- ee/μμ + $\tau_h\,\tau_h$

Event categorization:

Using # of b-tagged jets: =0, >=1
targeting two production modes





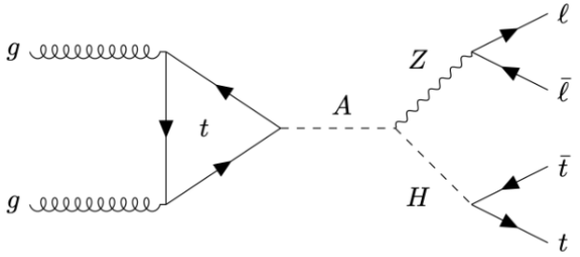
x2 extension of mass range w.r.t. 2016 analysis

Search variable:

4-object invariant mass using lepton momenta, missing energy (+covariance matrix), H mass constraint → *mass resolution: 5-7%*

$A \to ZH_{BSM} \to lltt$: Full Run 2

CMS-PAS-B2G-23-006

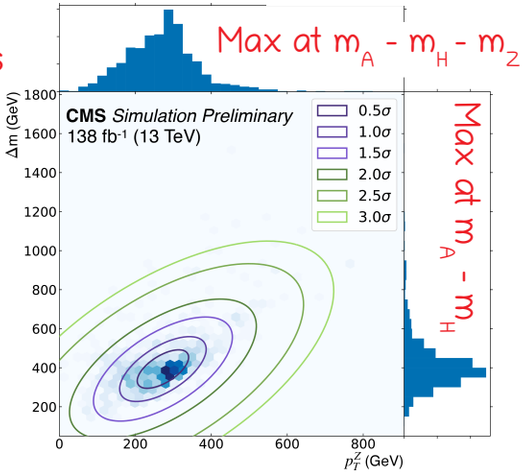


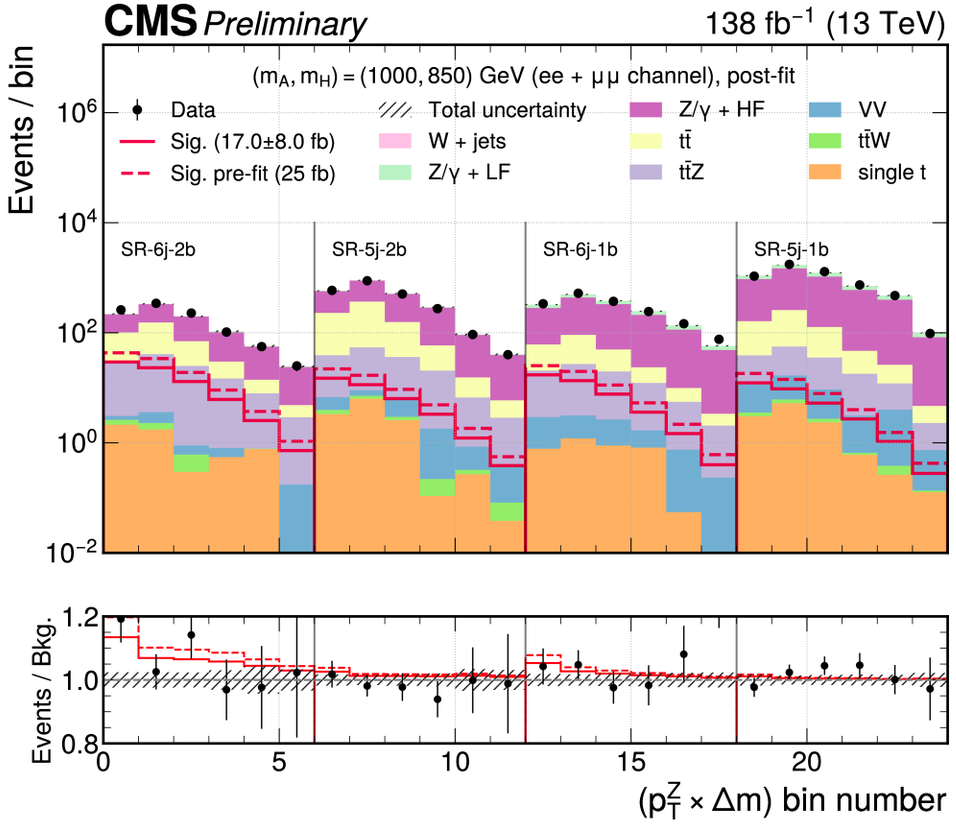
Probing alignment region in 2HDM → complementary to A→ ZH searches

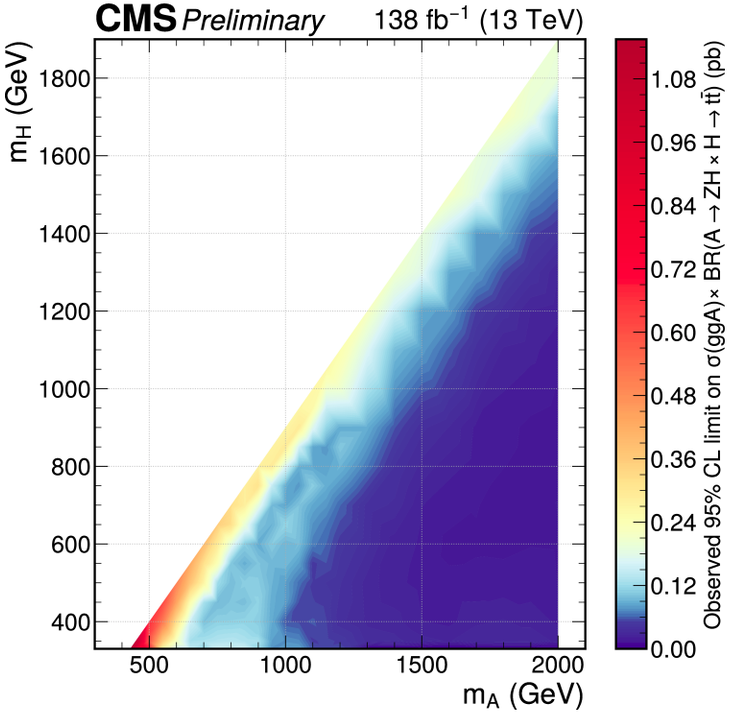
Reconstruction of hadronic tt system with small-radius (AK4) jets

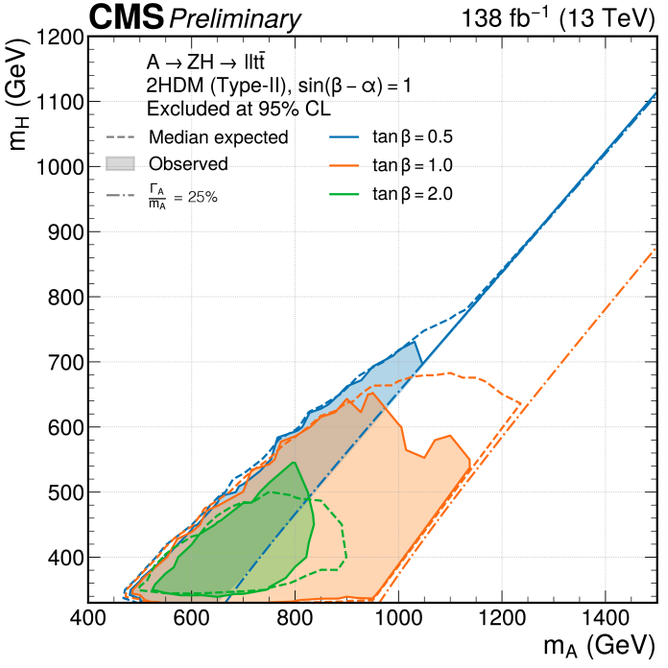
Sensitive variable: p_T of dilepton system & $\Delta m = m_{ttZ} - m_{tt}$

Binning using elliptical regions around mean for targeted (m_A, m_H) signal







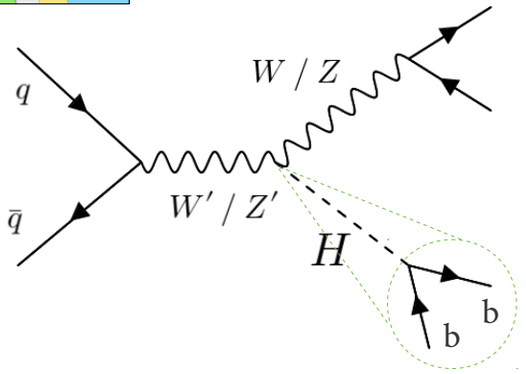


Excess [2.8σ local] seen by ATLAS at (600, 450) GeV is not confirmed

ATLAS-CONF-2023-034

Search for vector resonances decaying to V+H

arXiv: 2403.16926

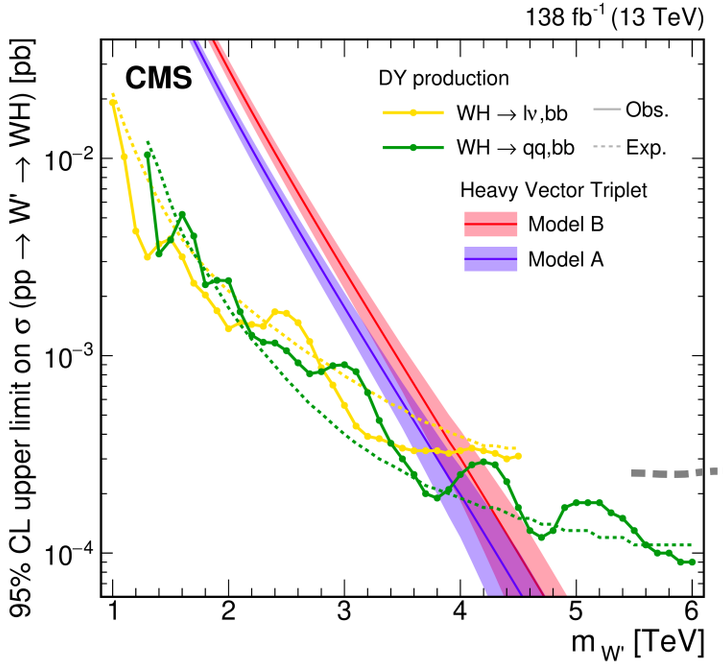


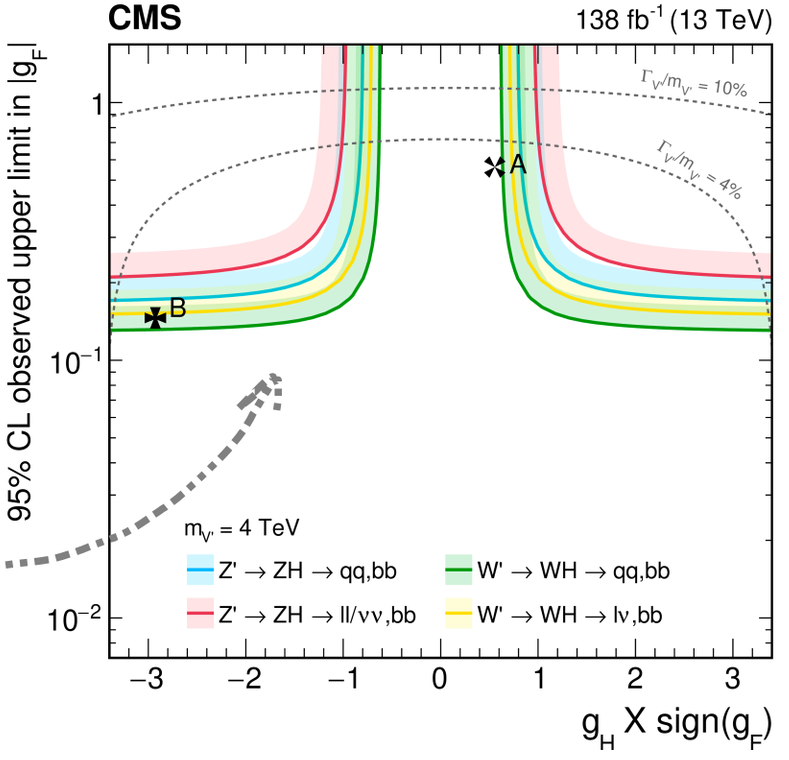
Vector resonances in generalized extensions of SM: heavy-vector triplet (HVT) models

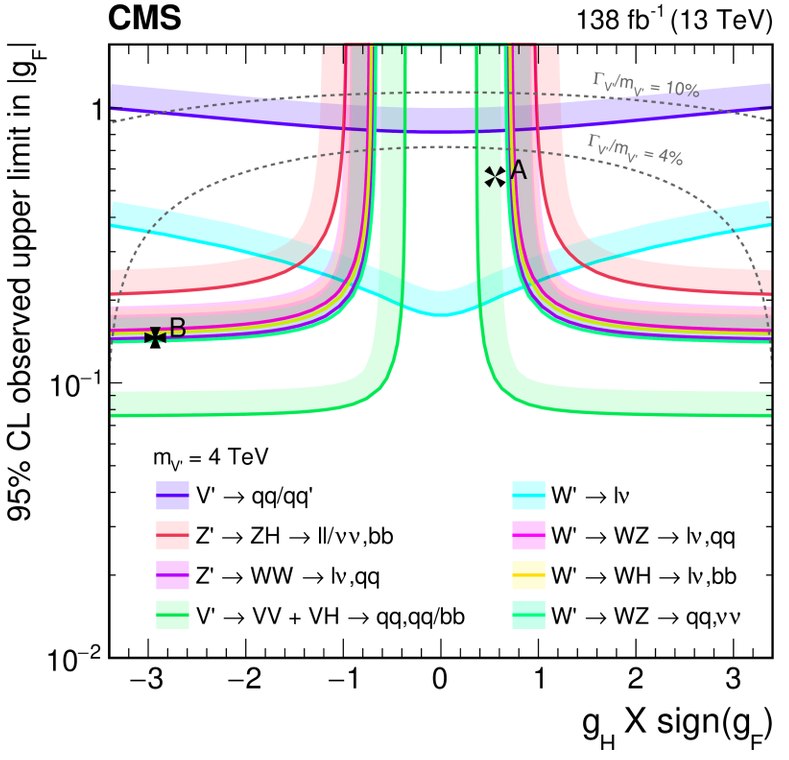
HVT model A → Similar coupling to fermions & bosons → larger branching ratio to fermions

HVT model B → Enhanced coupling to bosons ← exclusively probed with VH resonance searches

Leveraging on jet substructure techniques





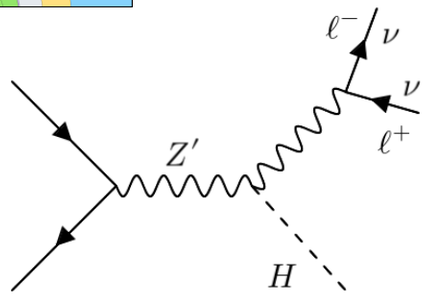


Bosonic decay modes →

Most stringent constraints
If coupling is not too small

Search for Z'→ Z(→ll/νν)H(→cc/4q)

CMS-PAS-B2G-23-008

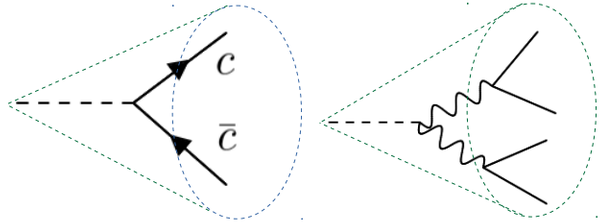


Complementary to Z'→ZH searches targeting H→ bb decay

H→ cc/(VV→)4q tagging using mass-decorrelated ParticleNet tagger

Details in D. Troiano's talk

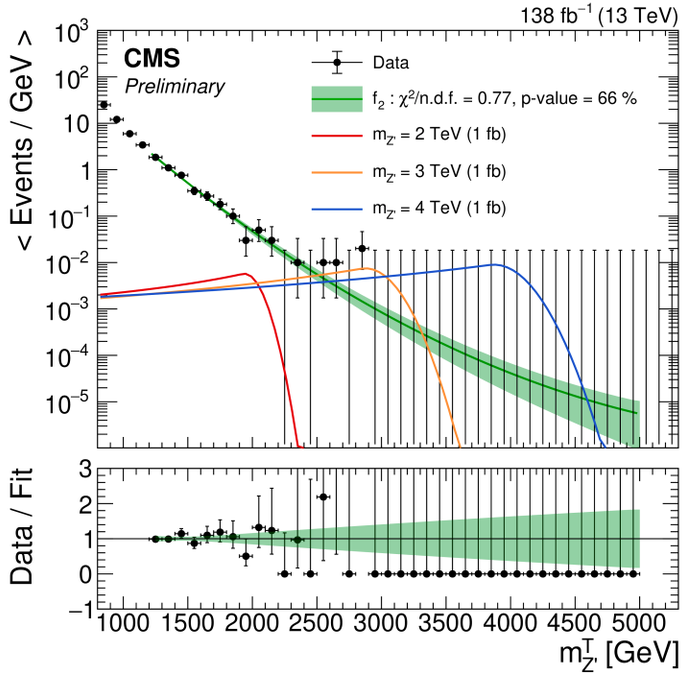
Veto H candidates with 2 b-tagged subjets

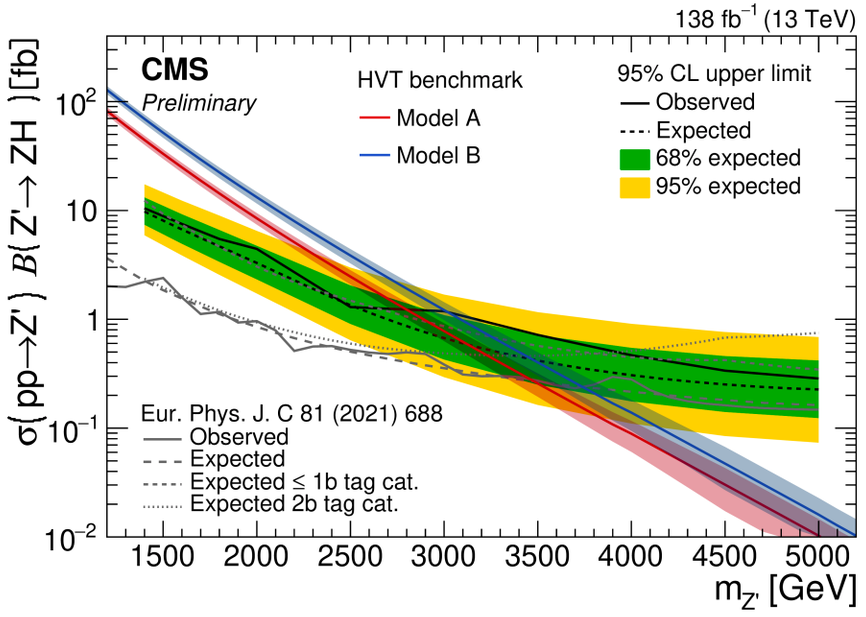


H reconstruction with a large-radius jet

Search variable: Invariant mass of dilepton + H system (in μμ/ee channels)
Transverse mass of MET + H system (in νν channel)

Background modeling using functional parameterization (→ validated in control regions)

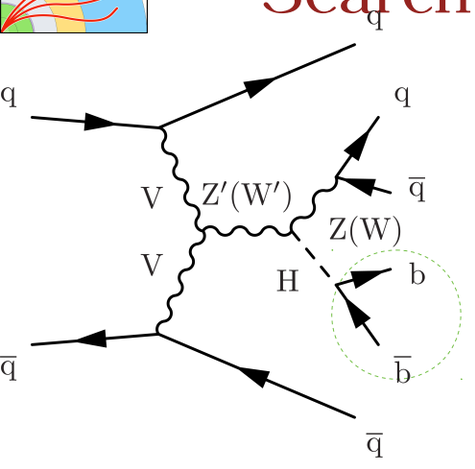




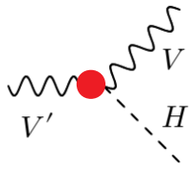
Improvement over <= 1 b tag category
(H with <=1 b-tagged subjets)
in Z(→ll/νν)H(→bb) search

Search for vector resonances decaying to V+H: VBF production

arXiv: 2403.16926

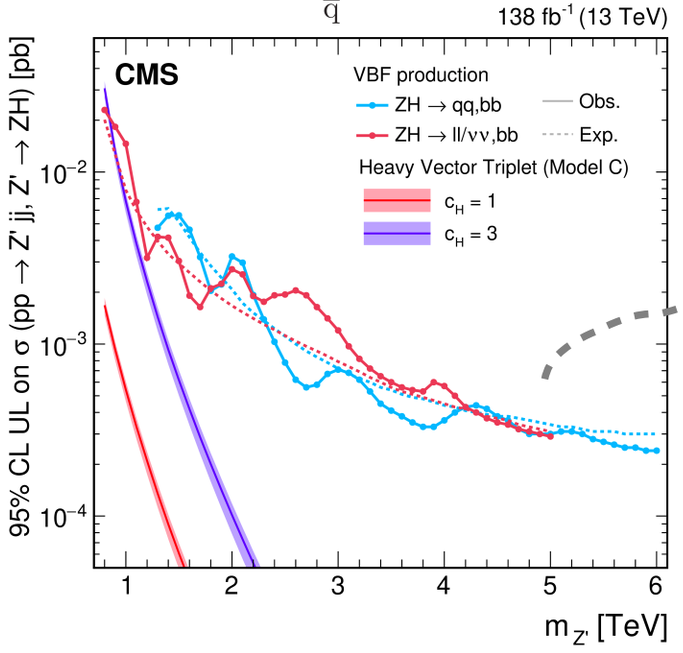


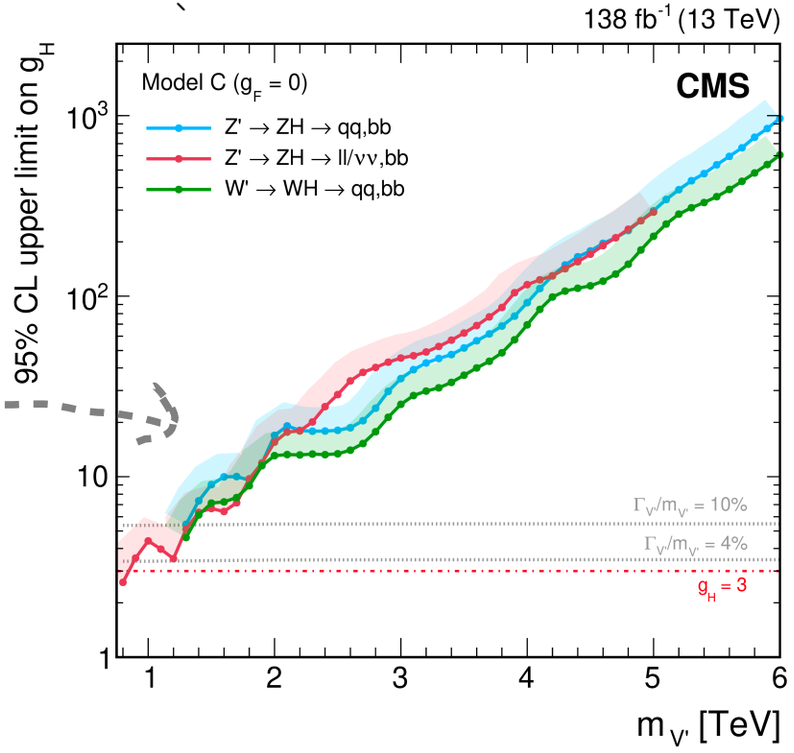
HVT model C → No coupling to fermions

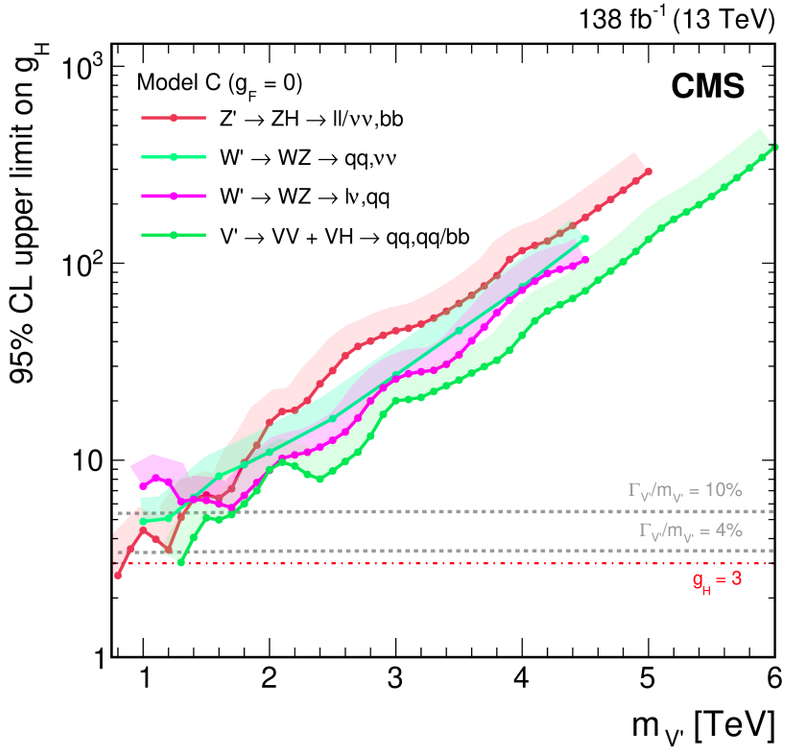


← exclusively probed in V' production via vector boson fusion

Combination of hadronic VH & VV channels



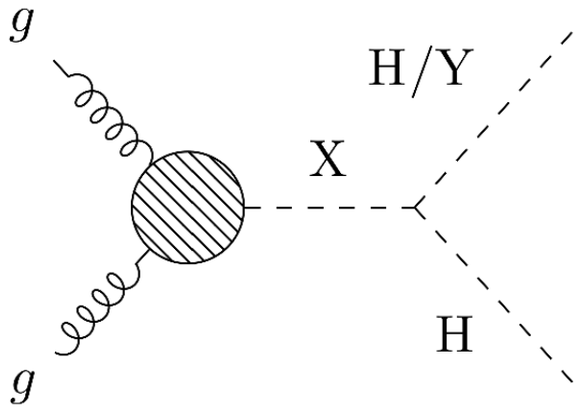




- Starting to become sensitive to VBF production for g_H=3 at ~800 GeV

- Hadronic final states dominate sensitivity a high masses

Searches for di-Higgs resonances



X→HH searches

X → HH → WWWW / WWττ/ ττττ (multilepton) JHEP 07 (2023) 095

X → HH → 2b 2W (resolved) arXiv: 2403.09430 (accepted for publication in JHEP)

X → HH → 2b 2W/2τ (boosted) JHEP 05 (2022) 005

X→YH searches

X → HH/YH → 2b 2b Phys. Lett. B 842 (2023) 137392

X → HH/YH → 2b 2τ JHEP 11 (2021) 057

X → HH/YH → 2b 2γ JHEP 05 (2024) 316

X → HH/YH → 2τ 2γ CMS-PAS-HIG-22-012 new

[138 fb^{-1}]

Non-resonant HH searches also heavily using jet substructure

e.g., HH → bb WW (hadronic) CMS-PAS-HIG-22-013

Not a topic of this talk

new

Covered in C. Zhou's talk

Combination performed using
→ different final states
→ targeting resolved/boosted topologies

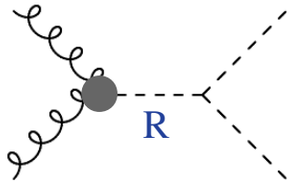
arXiv: 2403.16926

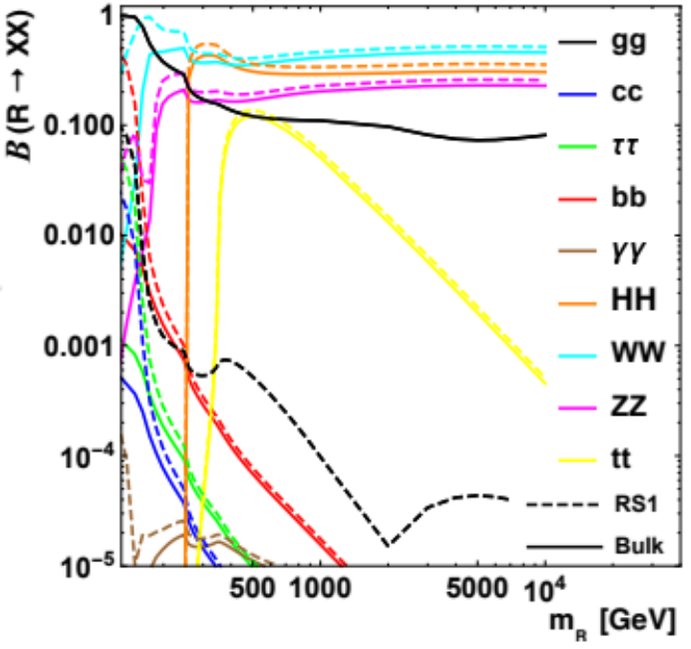
Combination of X→HH searches

arXiv: 2403.16926

Probing models with extra spatial dimensions predicting new resonances at high mass scale

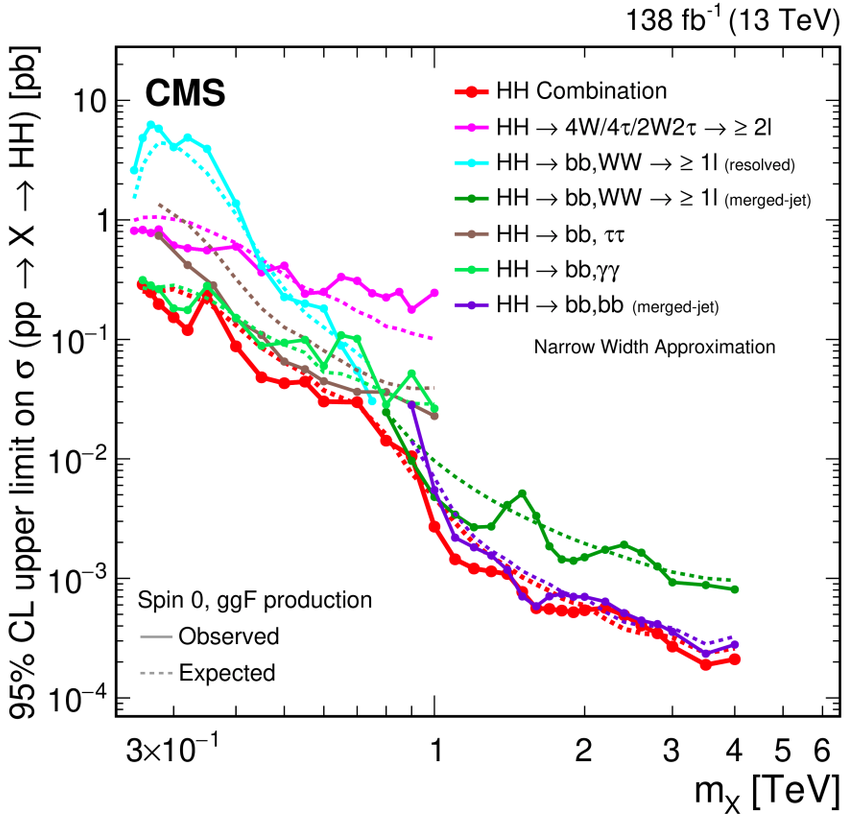
Spin-0: Radion
Spin-2: Kaluza-Klein graviton → H+H





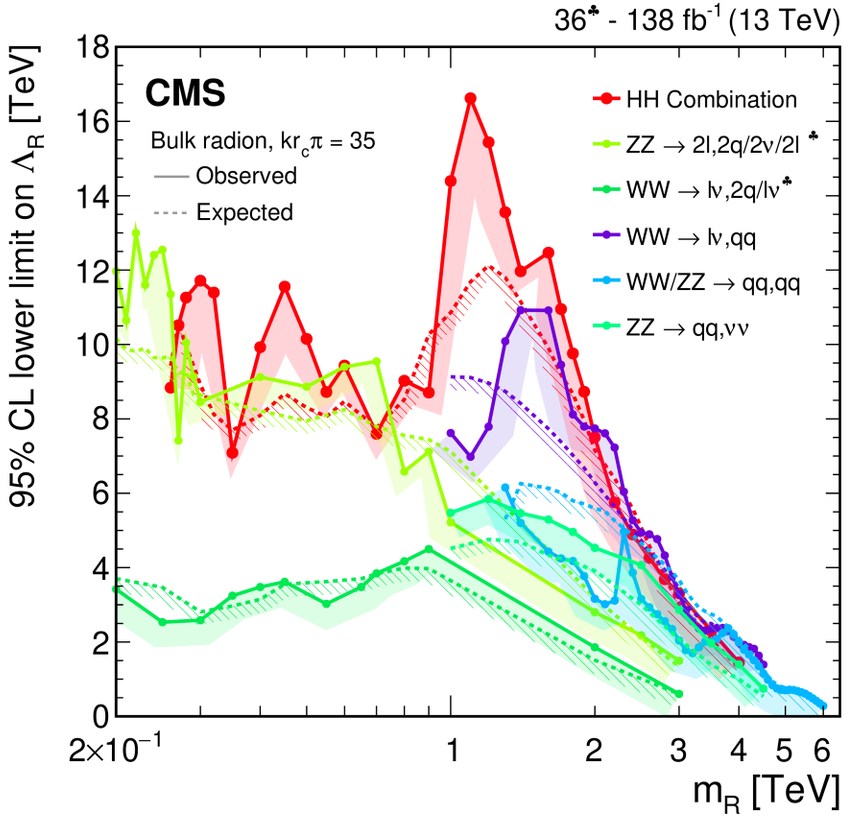
Sensitivity dominated by →

Combination of various channels



bbγγ @ small m_X
bbbb (merged) @ large m_X
multiple final states @ intermediate m_X

$\Lambda_R = \sqrt{6}\, e^{-kl}\overline{M}_{Pl}$ → UV cut-off

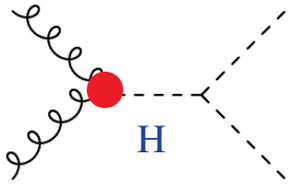


Strongest constraints from di-Higgs searches for radion mass > 300 GeV

Combination of X→HH searches (2)

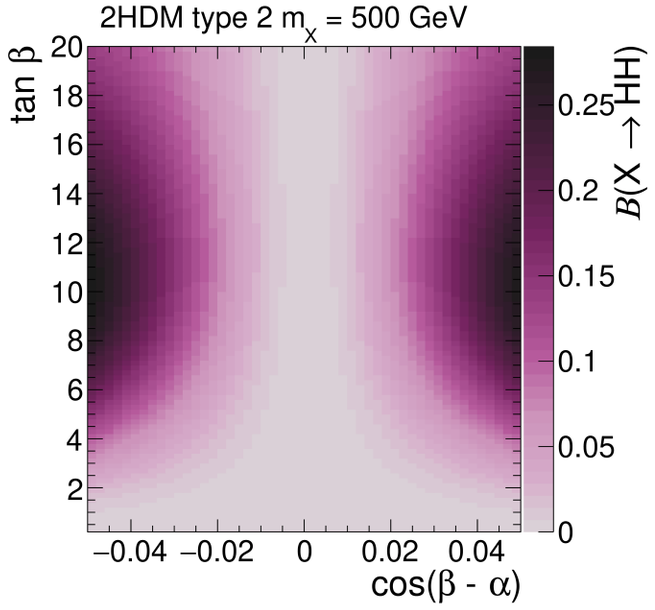
arXiv: 2403.16926

Probing models with extended Higgs sectors using di-Higgs resonance searches

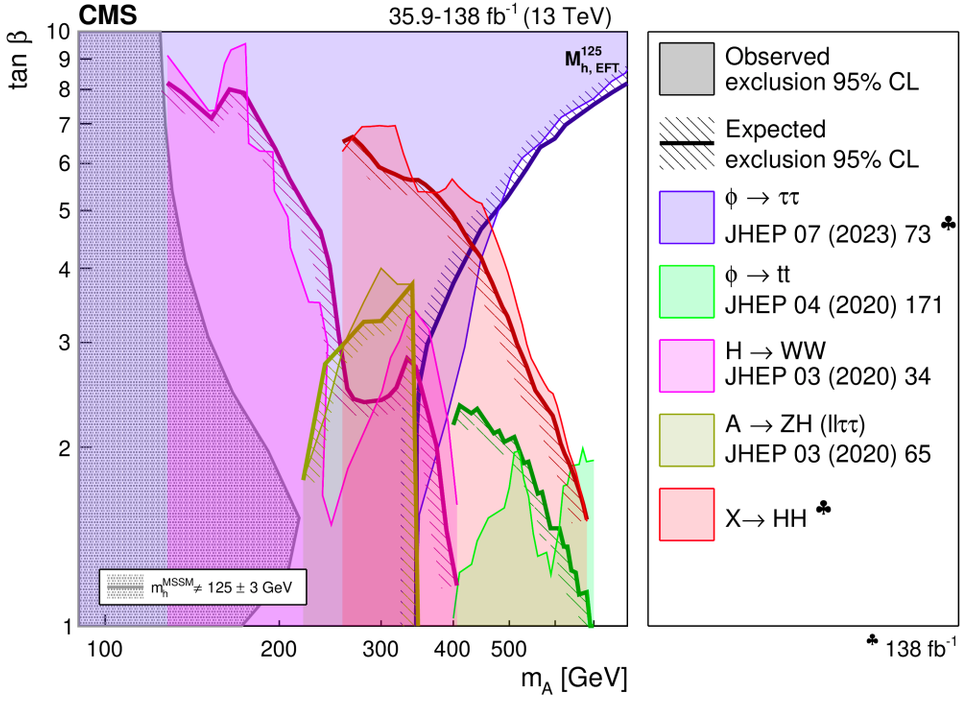


Higgs-to-Higgs decays

Additional Higgs bosons decaying to SM-like H pairs



Interpretation in $M_{h,EFT}^{125}$ scenario



Exclusive sensitivity from di-Higgs searches at high m_A and intermediate tanβ

→ Complementary to searches with fermionic decays

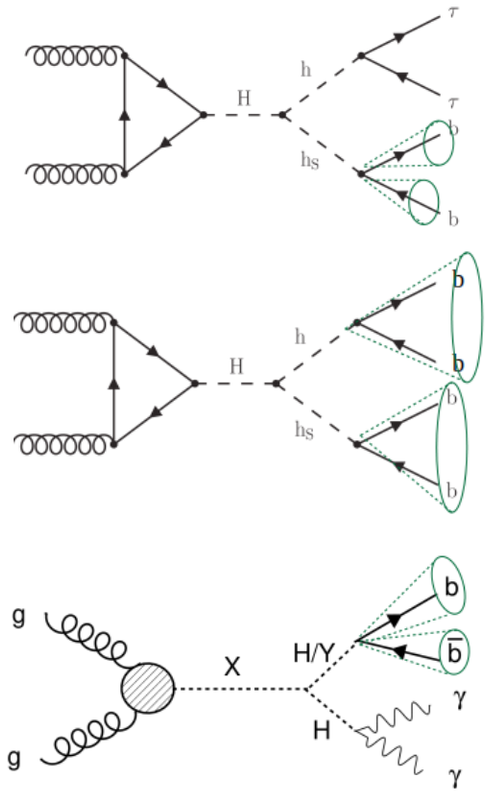
Combination of X→YH searches

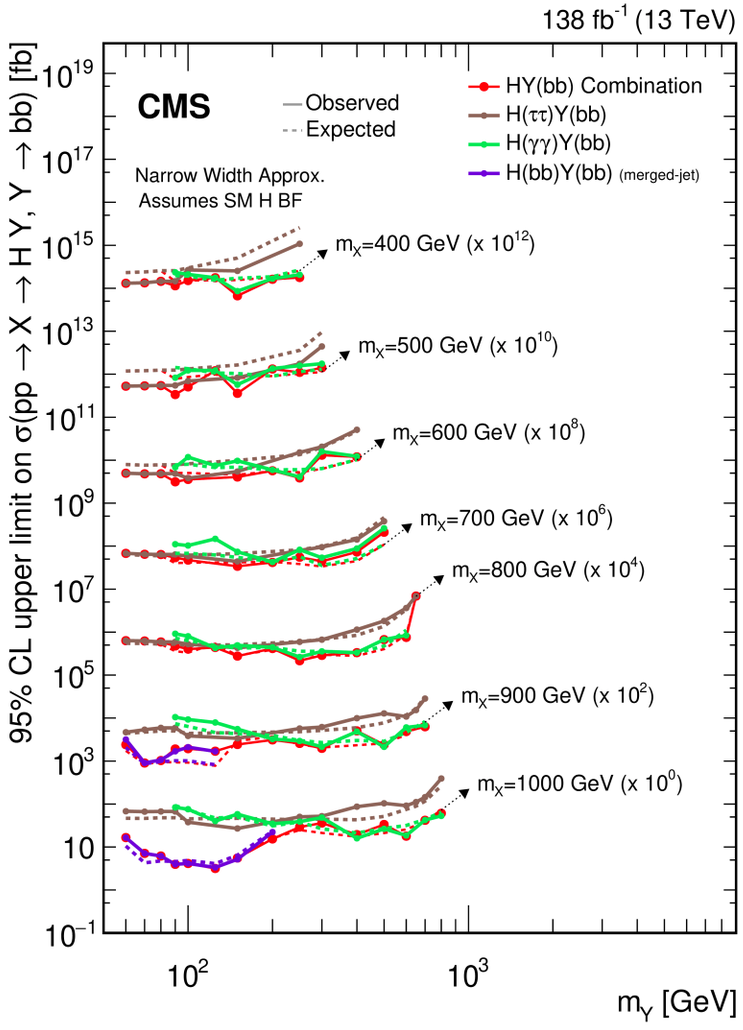
arXiv: 2403.16926

Probing models predicting 3 CP-even Higgs bosons

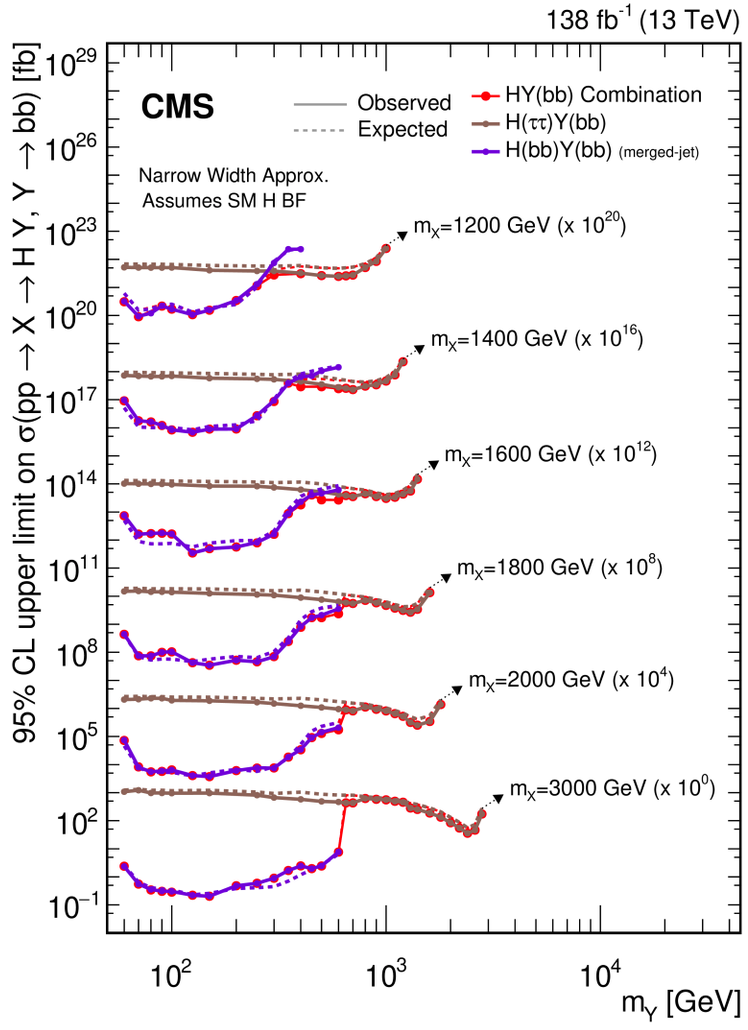
e.g., SM + 1 Higgs doublet + 1 complex singlet (NMSSM)
SM + 2 real singlets (TRSM)

'Big 3' channels *





Small m_X ↔ High m_X



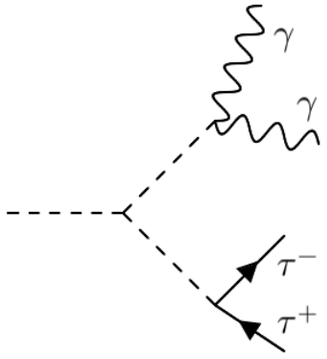
* phrase taken from J. Alison

Complementary sensitivity in analyses targeting different final states & kinematic topologies

Search for X→ HH/YH → ττγγ

CMS-PAS-HIG-22-012

HEPHY
INSTITUT FÜR HOCHENERGIEPHYSIK



Many searches in one final state

X (spin-0) → HH → γγττ
X (spin-2) → HH → γγττ
X → Y→ (ττ)H(→ γγ)
X → Y(→ γγ)H(→ ττ) [low & high m_Y]

low m_Y = [70, 125] GeV
high m_Y = [125, 800] GeV

Complementary to previous X→ YH searches: Including bosonic decay of Y

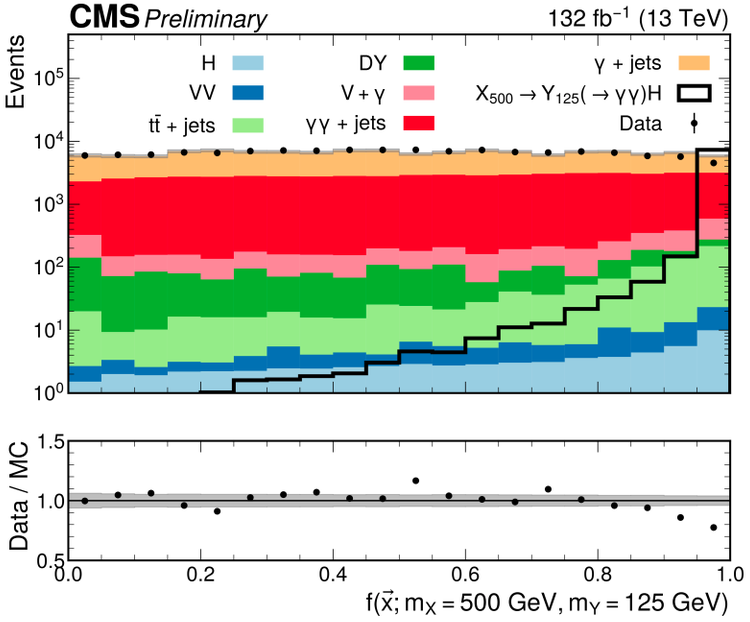
Signal extraction using $m_{\gamma\gamma}$

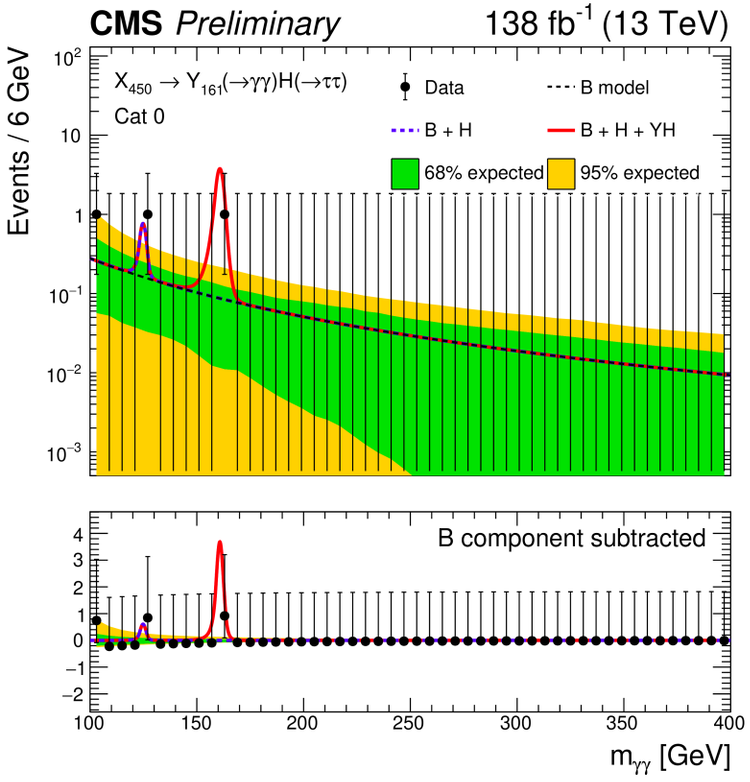
- Non-resonant γγ+jets background from data
- DY+jets background estimated from data
- H(→γγ) + jets background from simulation

Signal separation using neural networks

parametric in m_X (& m_Y)

→ PNN scores used for event categorization



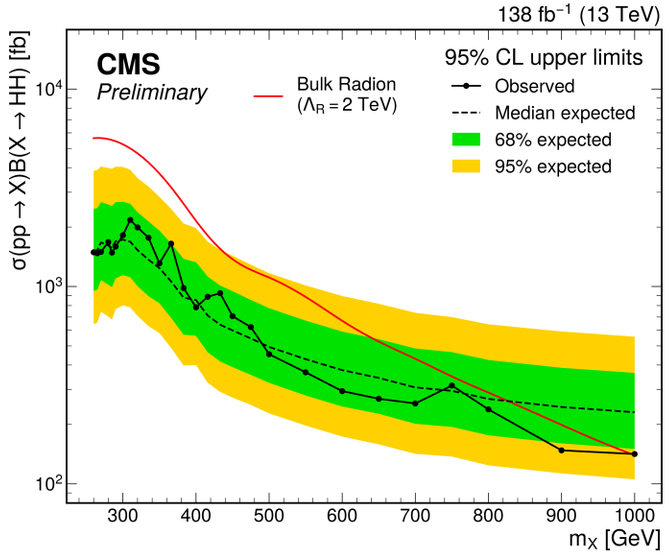


Search for X→ HH/YH → ττγγ

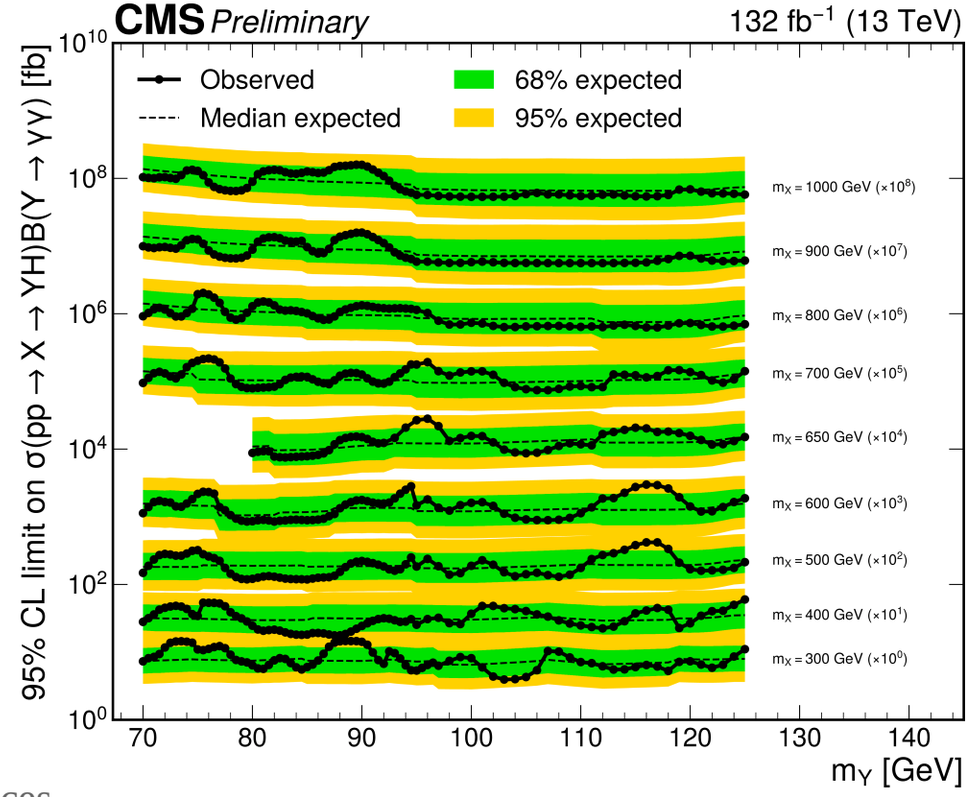
CMS-PAS-HIG-22-012

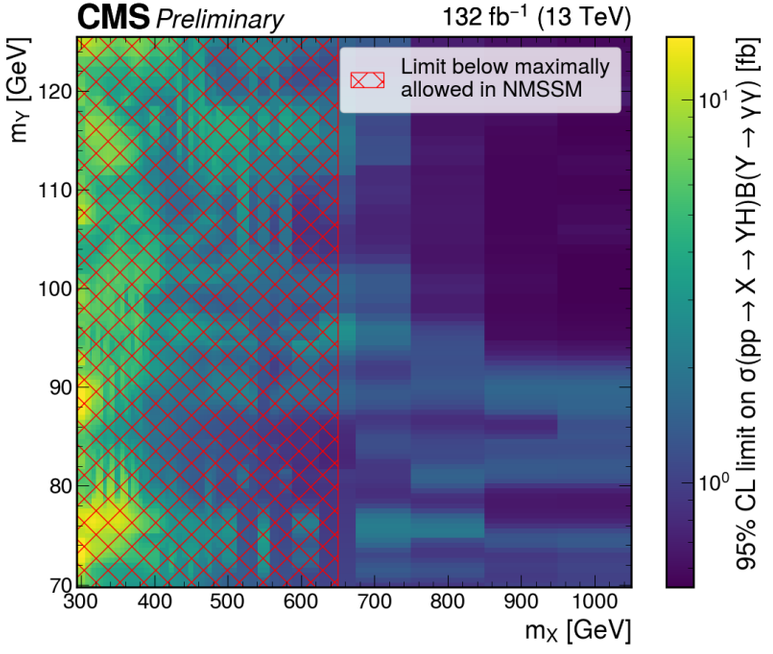
No excess observed in X→HH search

Highest local significance ~ 1.7 σ



Results of new X→ YH →γγττ search useful to constrain NMSSM parameter space





Also reported constraints for spin-2 resonances

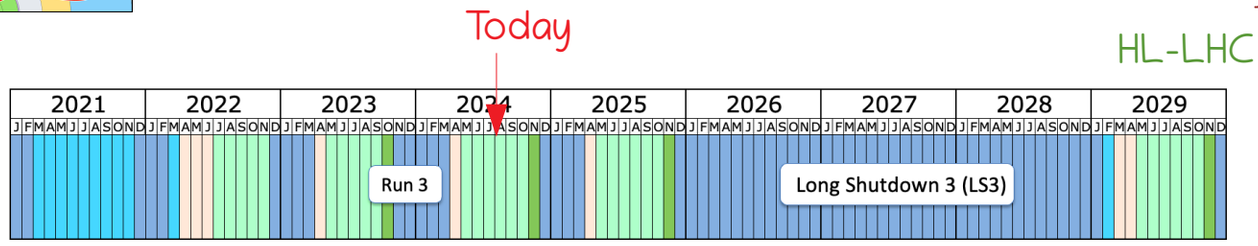
Maximum deviations observed:

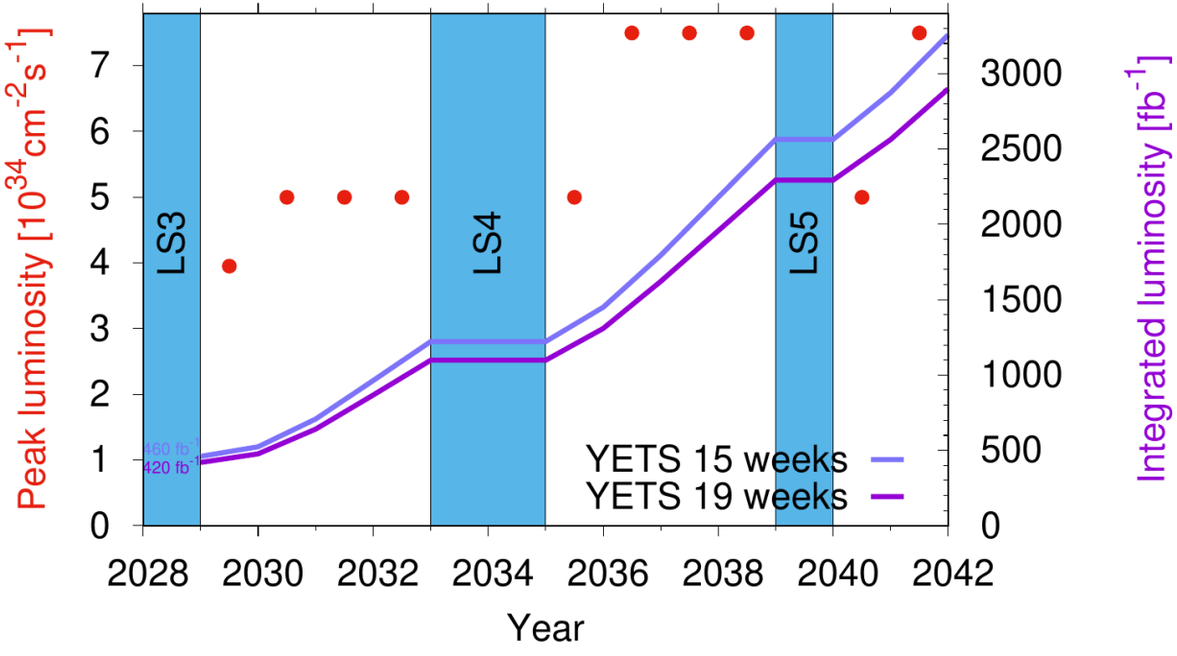
$X \to Y(\to \tau\tau)\, H(\to \gamma\gamma)$: 2.6 (2.2) σ significance at m_X = 320, m_Y = 60 GeV

$X \to Y(\to \gamma\gamma)\, H(\to \tau\tau)$: 3.4 (0.1) σ significance at m_X = 525, m_Y = 115 GeV

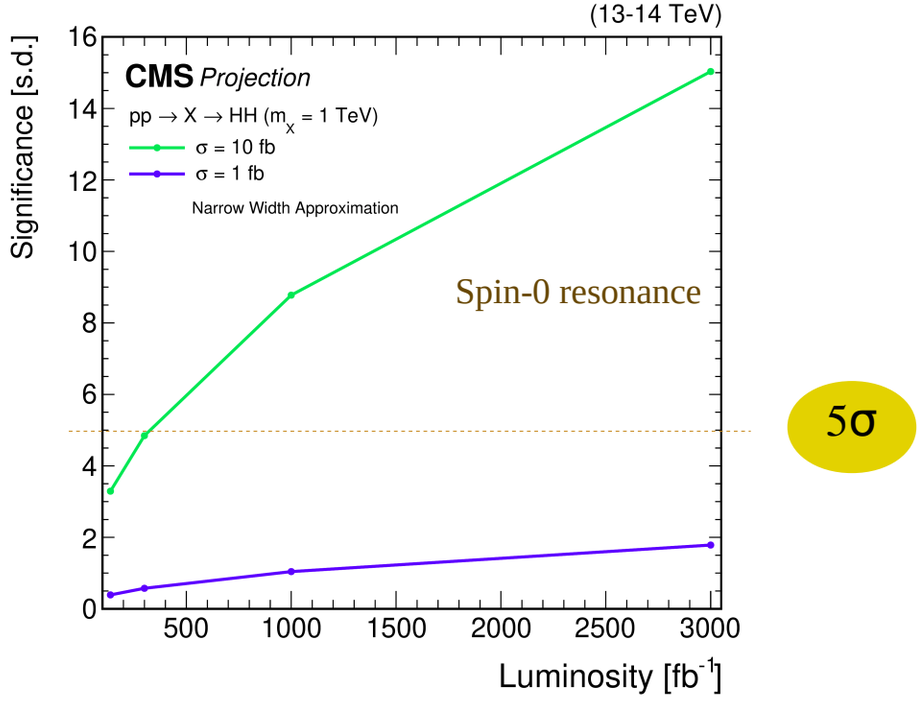
$X \to Y(\to \gamma\gamma)\, H(\to \tau\tau)$: 3.2 (0.3) σ significance at m_X = 462, m_Y = 161 GeV

Road towards future: projections for HL-LHC





arXiv: 2403.16926



5σ

Projection to HL-LHC:

Extrapolation of Run-2 results

Signal cross section @ √s = 14 TeV

- Potential for discovery in Run 3 if $\sigma_{pp->HH}$ >= 10 fb

- 5σ significance possible with HL-LHC data if $\sigma_{pp->HH}$ >= 3 fb

Strategy similar to 2018 Yellow Report & Snowmass 2021 Report

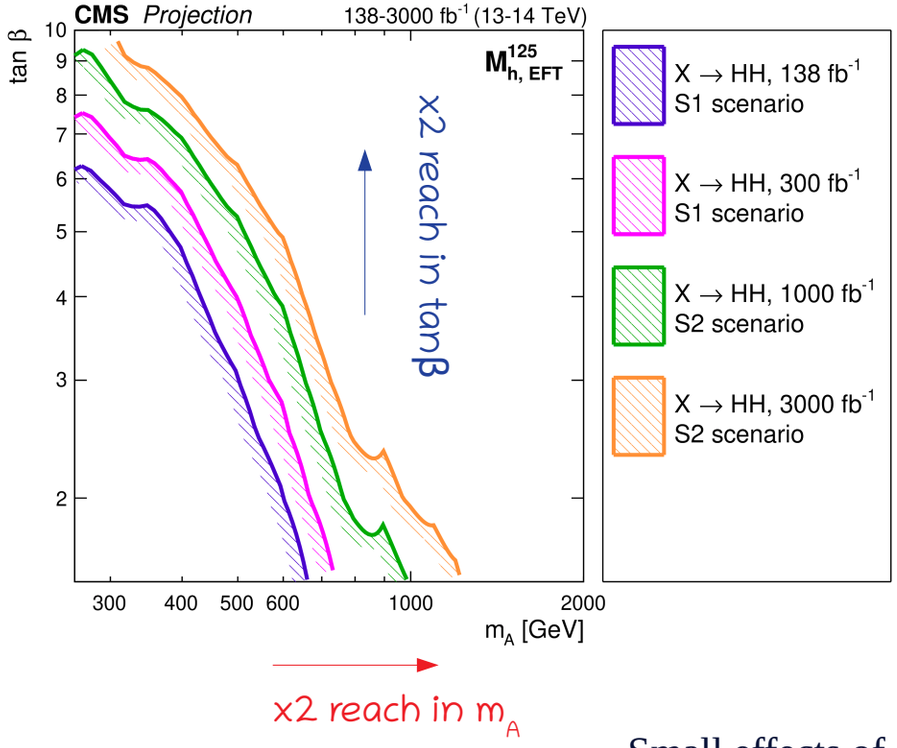
HL-LHC projection for X→HH searches

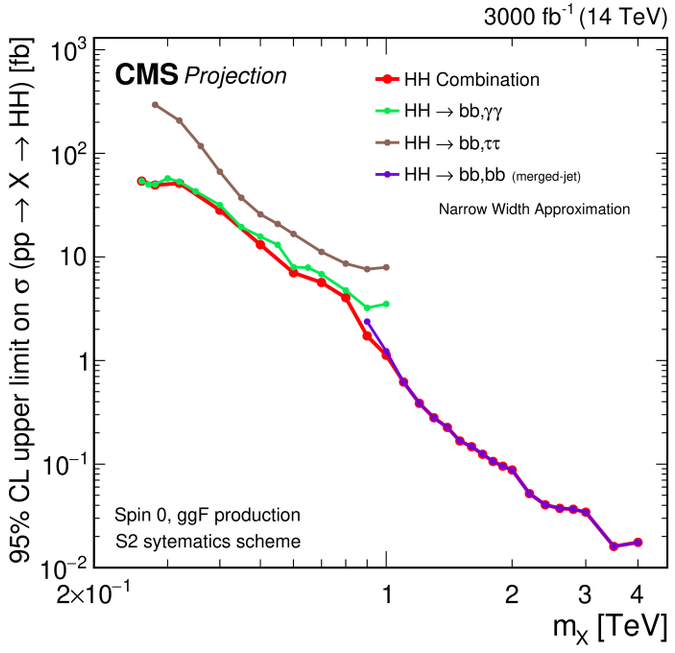
arXiv: 2403.16926

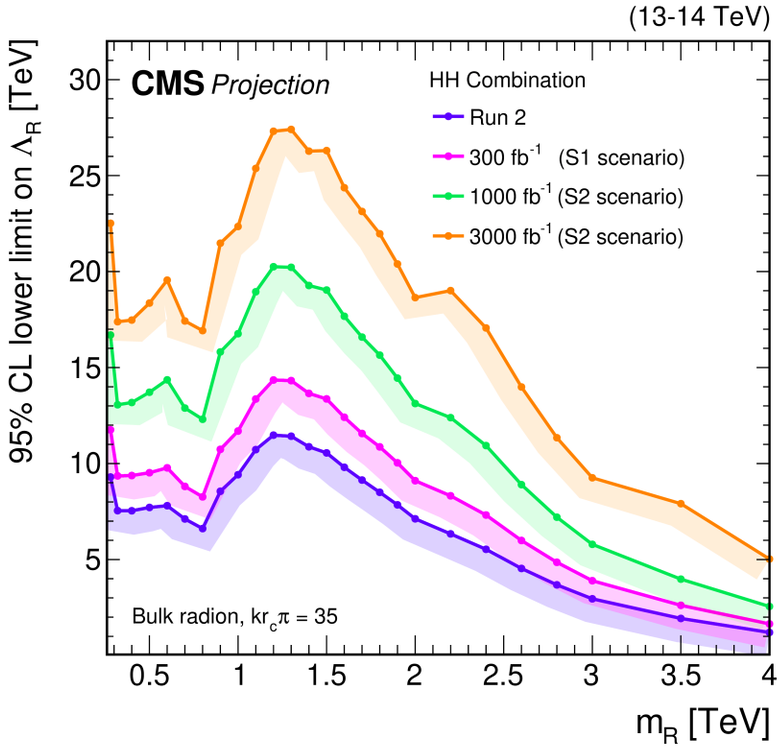
S1: Systematic uncertainties assumed to be same as Run 2 [over-conservative]

S2: Theory uncertainties halved, experimental ones ~ scaled down by √L details in CMS-PAS-FTR-18-011

Final states use for projection: bbγγ, bbττ, 4b (merged)







- Small effects of systematic uncertainties in most sensitive channels

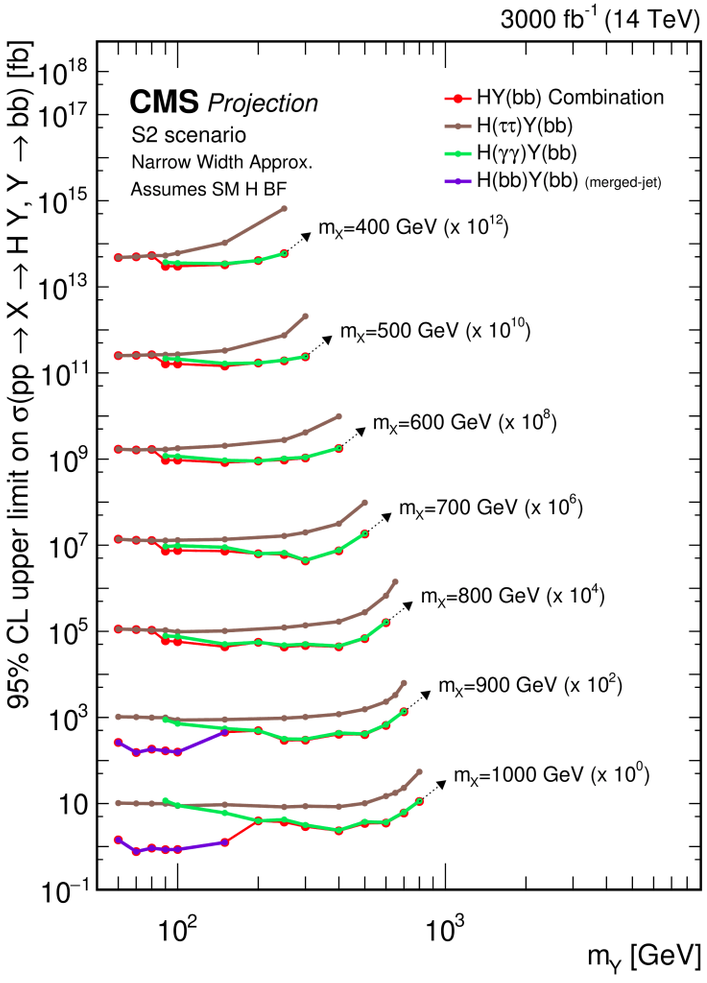
- Sensitivity controlled by bbγγ at low mass & 4b (merged) at high mass

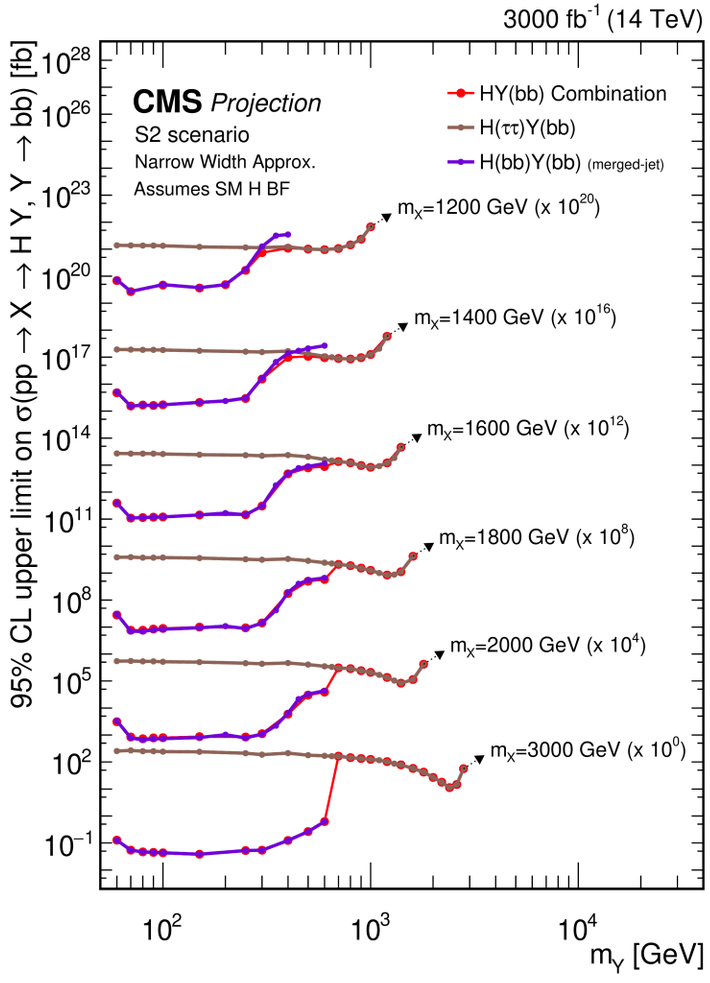
x2 improvement in limits on cut-off scale

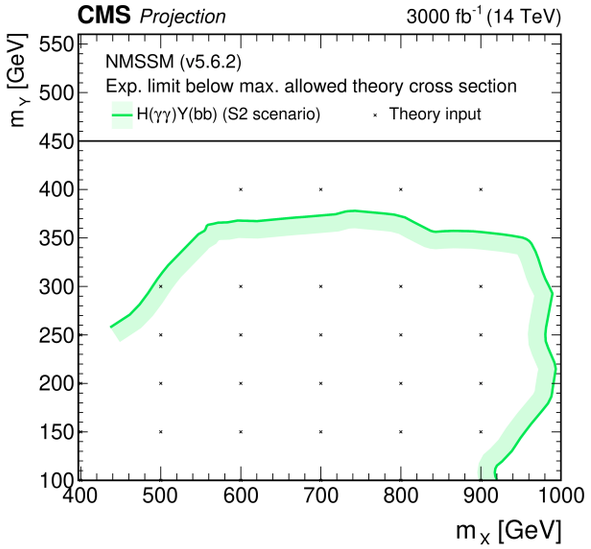
HL-LHC projection for X→YH searches

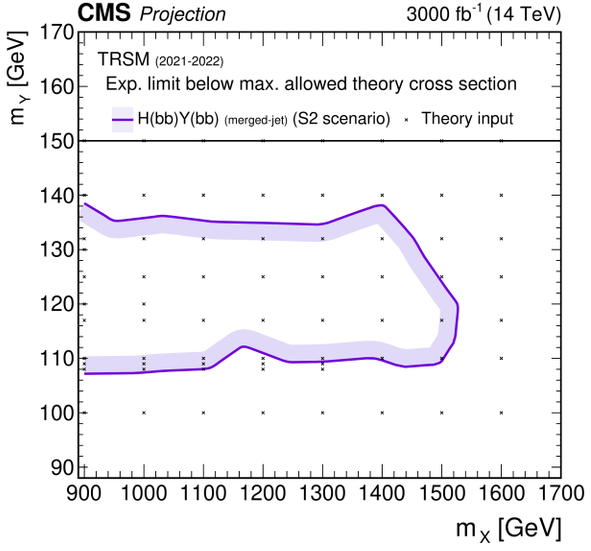
arXiv: 2403.16926

Small m_X ◄ ► High m_X









Combination results dominated by bbγγ except for large mass splittings

Contribution of 4b (merged) topology remains dominant at high m_X

Future measurements sensitive to a large portion of model parameter space

Summary & Outlook

- Presented summary of searches by CMS experiment for resonances decaying to at least one Higgs boson

  A → ZH V' → VH X → HH X → YH

- Combination of analyses + new results targeting different topologies and final states

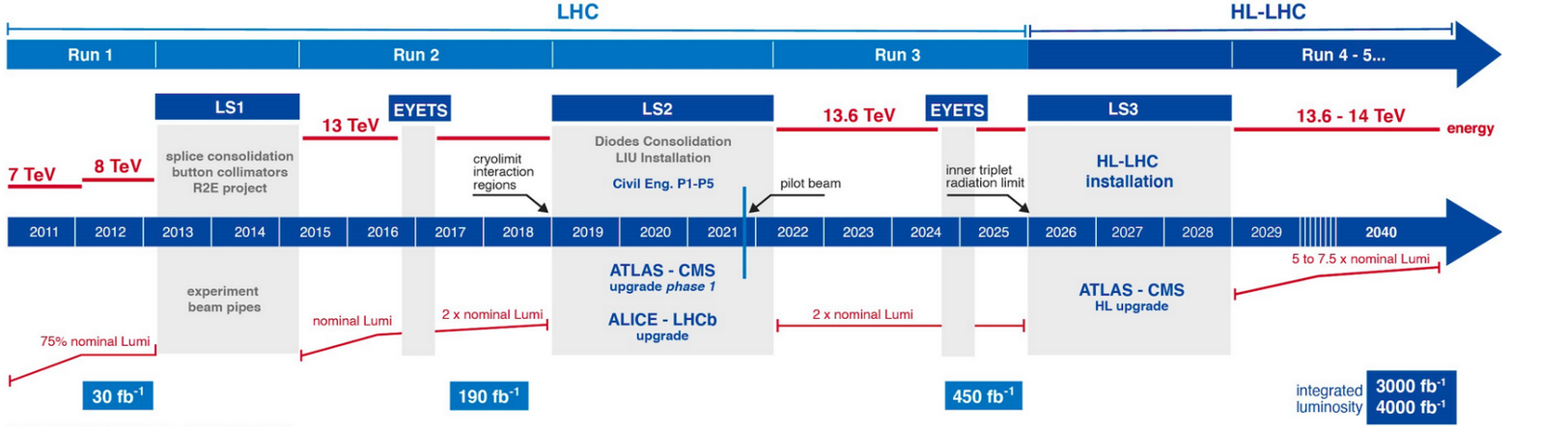
  - resolved vs boosted

  - final states with: electrons, muons, taus, photons, small-radius / large-radius jets

- Interpretation of results in benchmark BSM models & projections for high-luminosity phase of LHC

  → Guide to develop new ideas

Looking forward to share more Run-2 results & fresh ones with Run-3 data + beyond !!

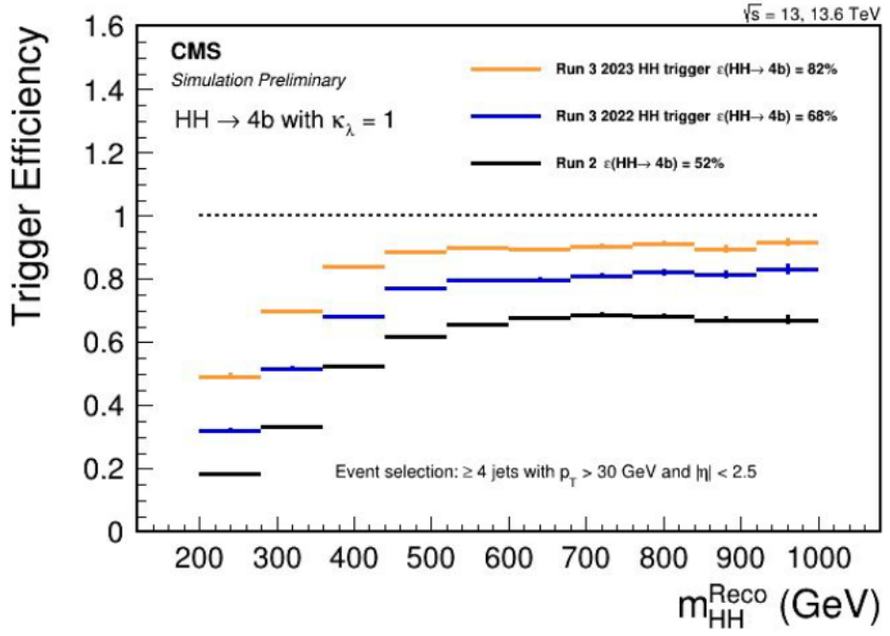


Extra Material

Run3 prospects: X→HH

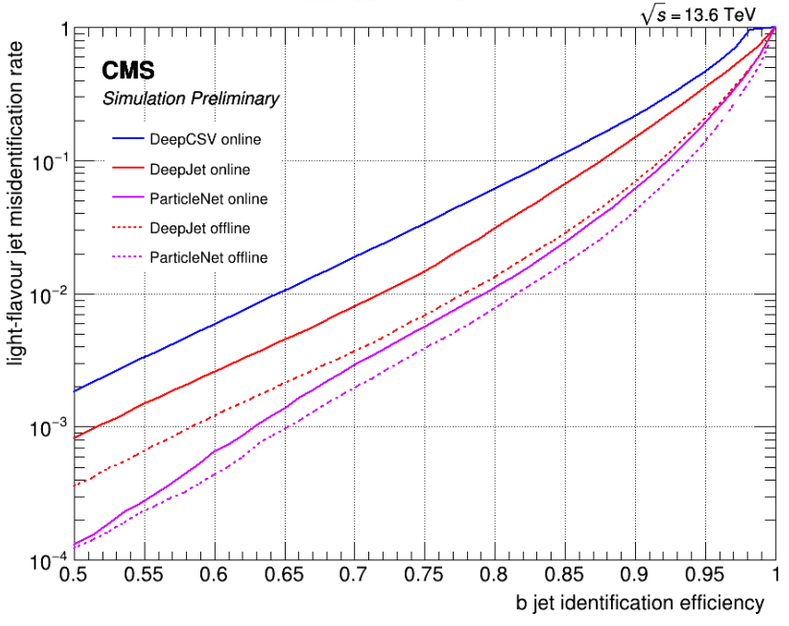
Parking triggers

CMS-DP-2023-050



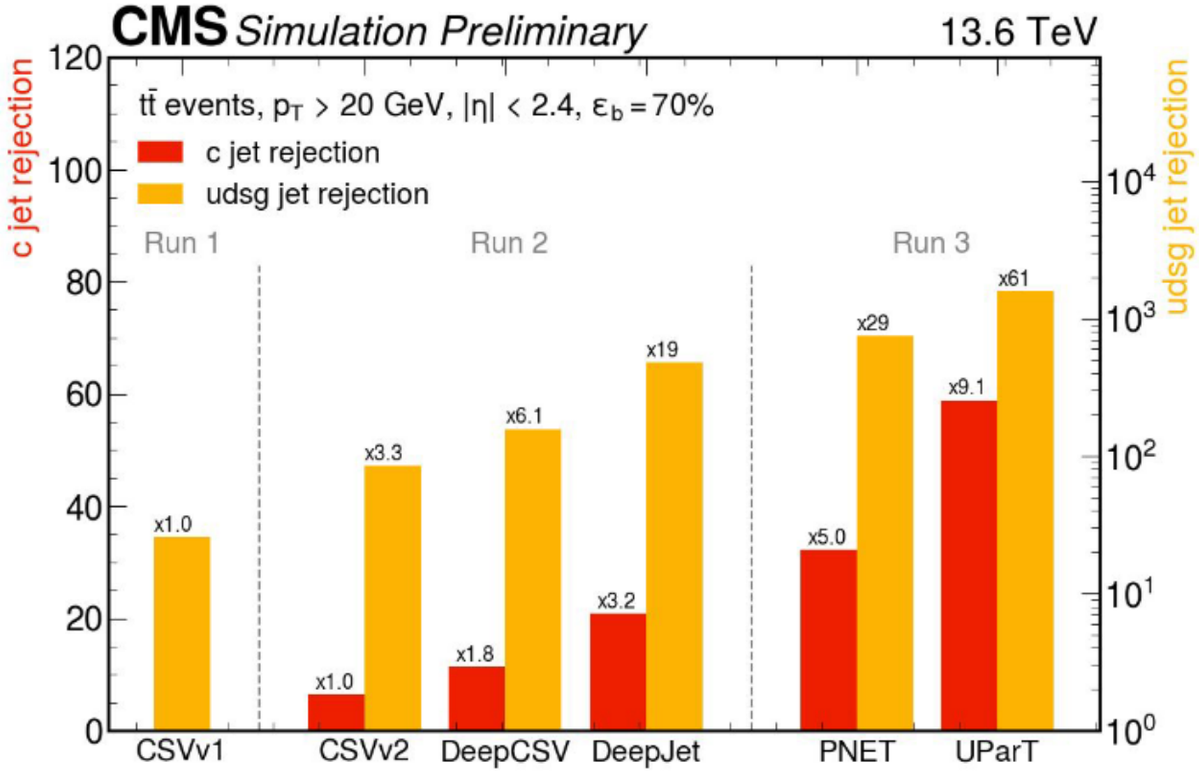
ParticleNet @ HLT

CMS-DP-2023-021



Offline b tagging

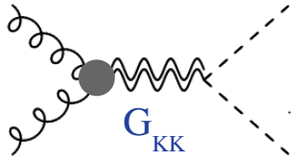
CMS-DP-2024-066

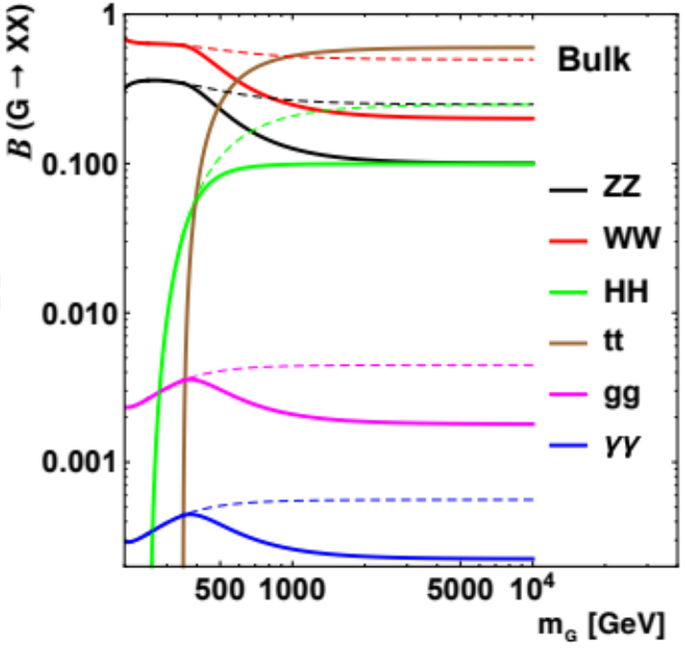


Combination: X→HH

arXiv: 2403.16926

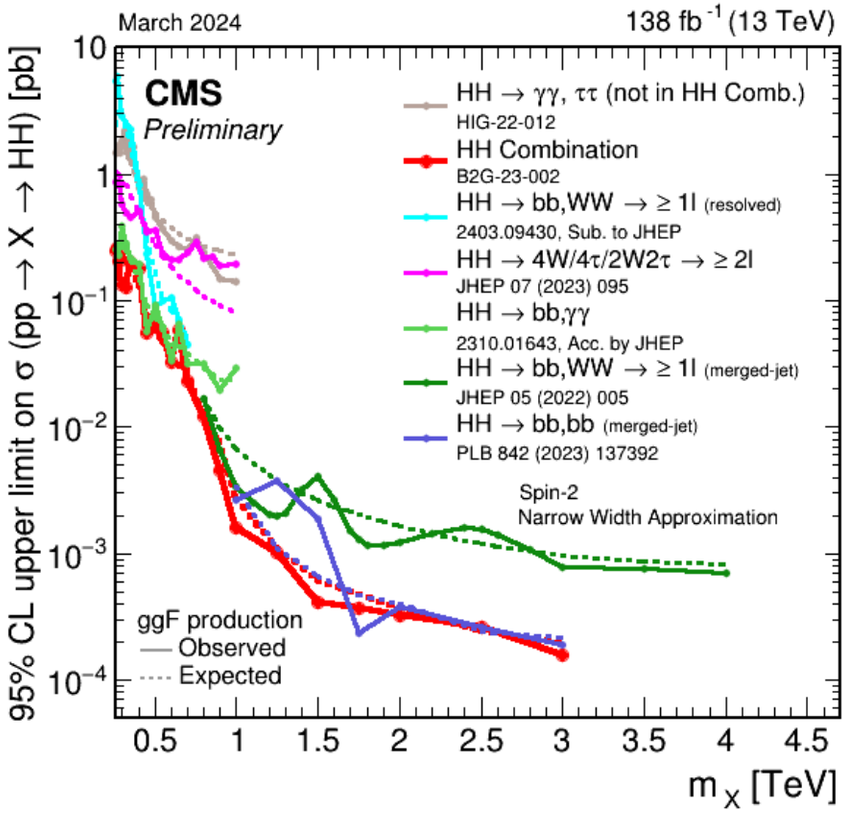
Probing models with extra spacial dimensions predicting new resonances at high mass scale





Sensitivity dominated by →

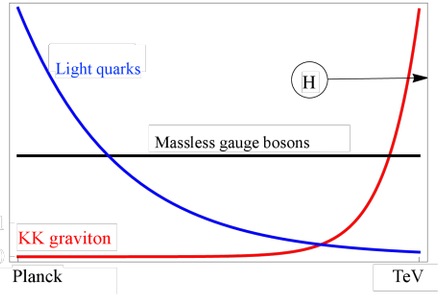
Combination of various channels

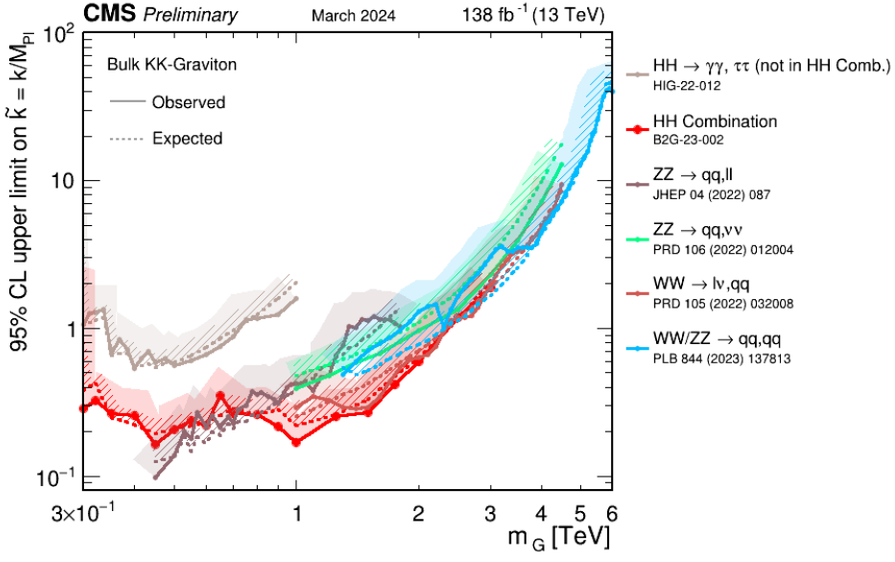


bbγγ @ small m_X

bbbb (merged) @ large m_X

multiple final states @ intermediate m_X



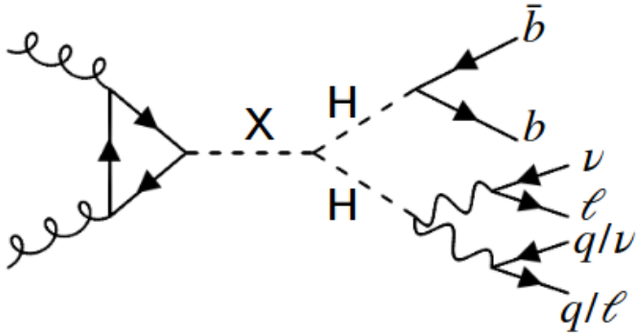


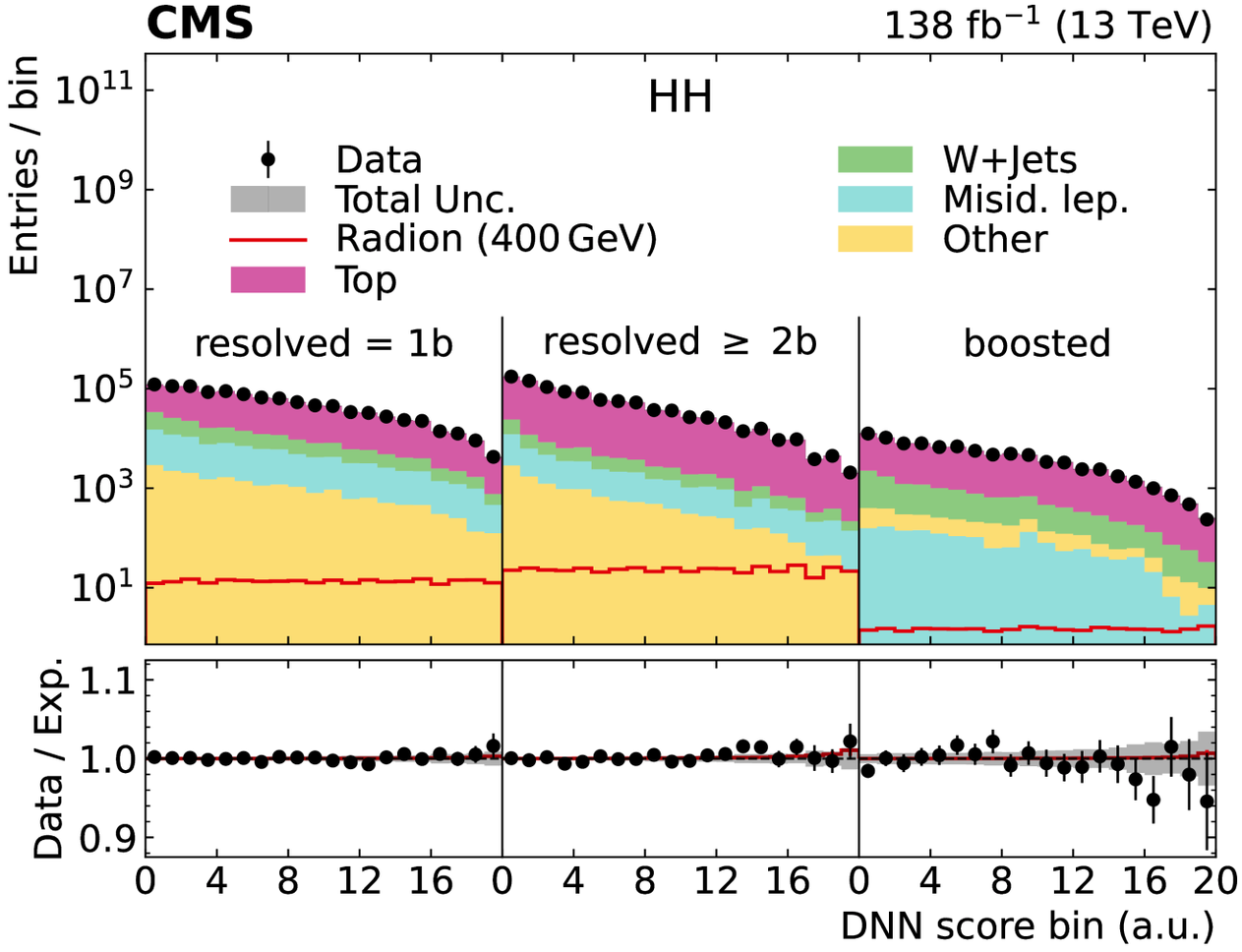
CMS B2G Diboson Summary plots

Strongest constraints from di-Higgs searches for small and large graviton masses

arXiv: 2403.09430
(accepted for publication in JHEP)

X→HH → bbWW (resolved + semi-boosted)





Final states considered:

H→ WW* → 2 leptons + MET / 1 lepton + jets + MET

H→ bb → 2 small-radius jets / 1 large-radius jet

Background estimation:

Data-driven approach for particular backgrounds:
- 1 lepton channel: fake lepton background
- 2 lepton channel: Drell-Yan + jets background

All other background processes estimated using simulation

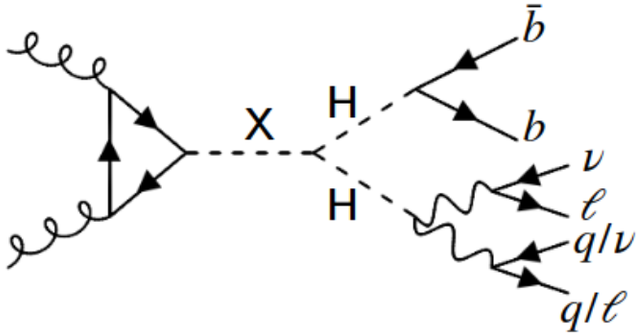
Deep neural network training:

- separate signal & background
- score used to extract signal

Training performed separately for single- and di-lepton final states

arXiv: 2403.09430
(accepted for publication in JHEP)

X→HH → bbWW (resolved + semi-boosted)



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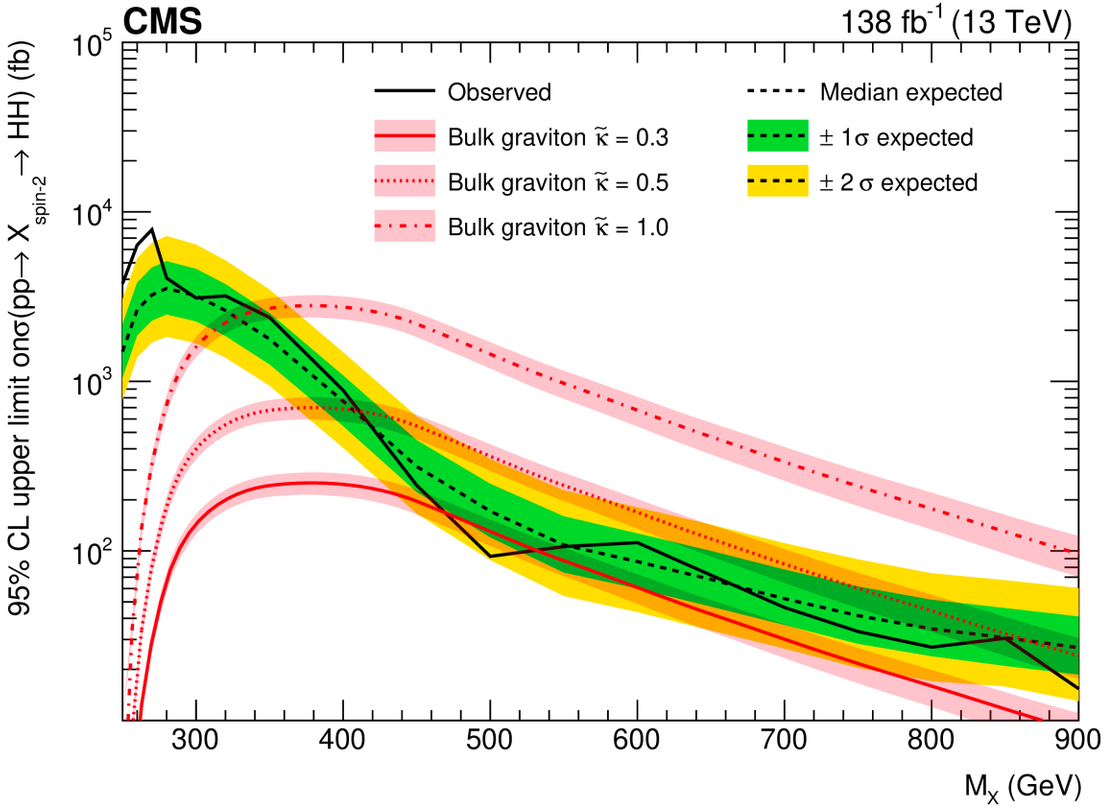
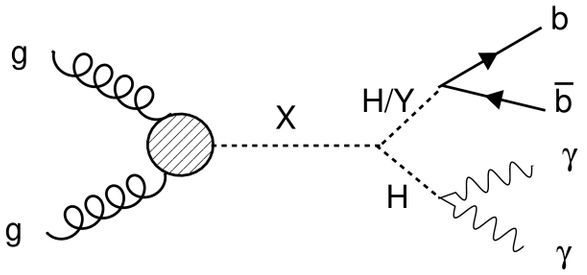


Model-independent constraints placed on spin-0 CP-even resonance
(also on spin-2 resonances)

X→HH/YH → bb γγ

JHEP 05 (2024) 316



Final states considered:

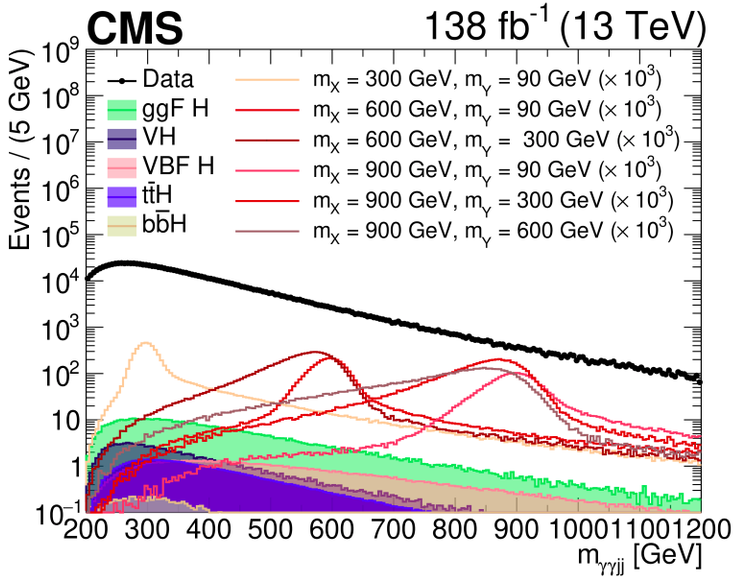
2 isolated photons + 2 (b-tagged) AK4 jets

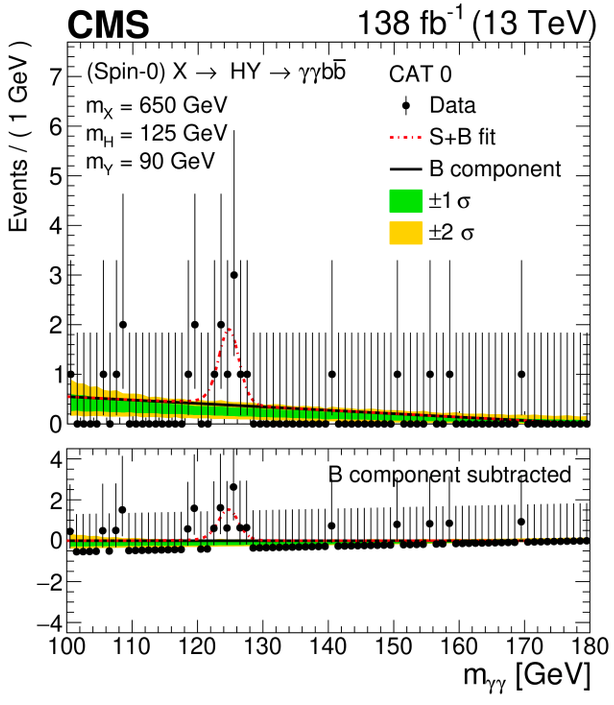
Dominant backgrounds:

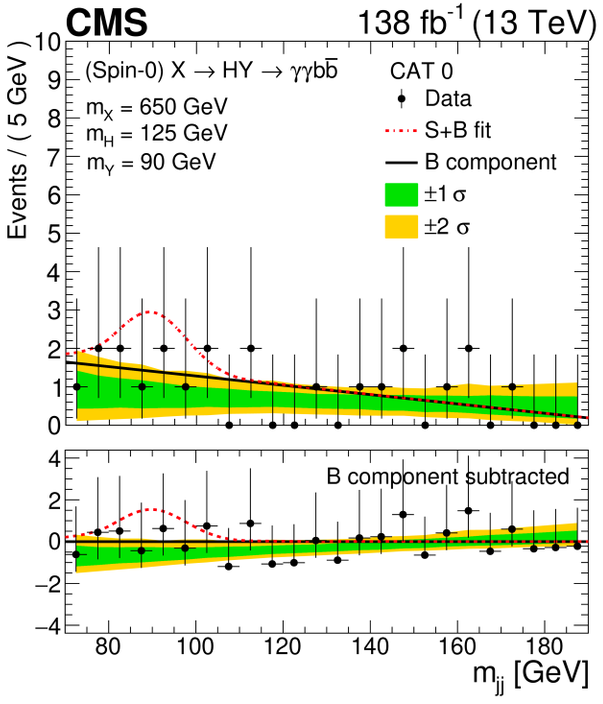
- γ+jets, γγ+jets, production in QCD
  ← reduced using BDT *trained in multiple exclusive regions targeting different m_X-m_Y ranges*
  + estimated with functional forms fitted using data
- Resonant ttH(→γγ) background reduced using neural network

* X candidate mass reconstruction using $\tilde{m}_X = m_{\gamma\gamma jj} - (m_{\gamma\gamma} - m_H) - (m_{jj} - m_Y)$

Signal extraction using 2D mass distributions (m_{jj} – $m_{\gamma\gamma}$) in regions defined by BDT scores







X→HH/YH → bb γγ (contd ...)

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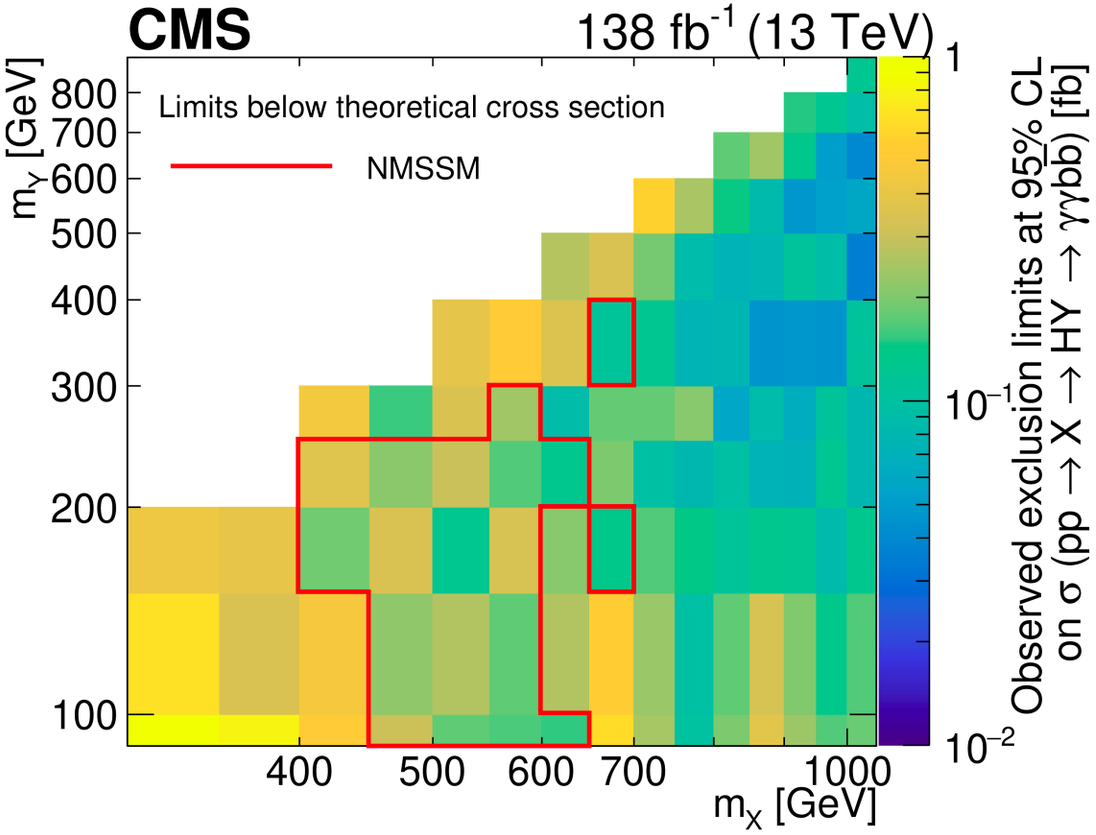
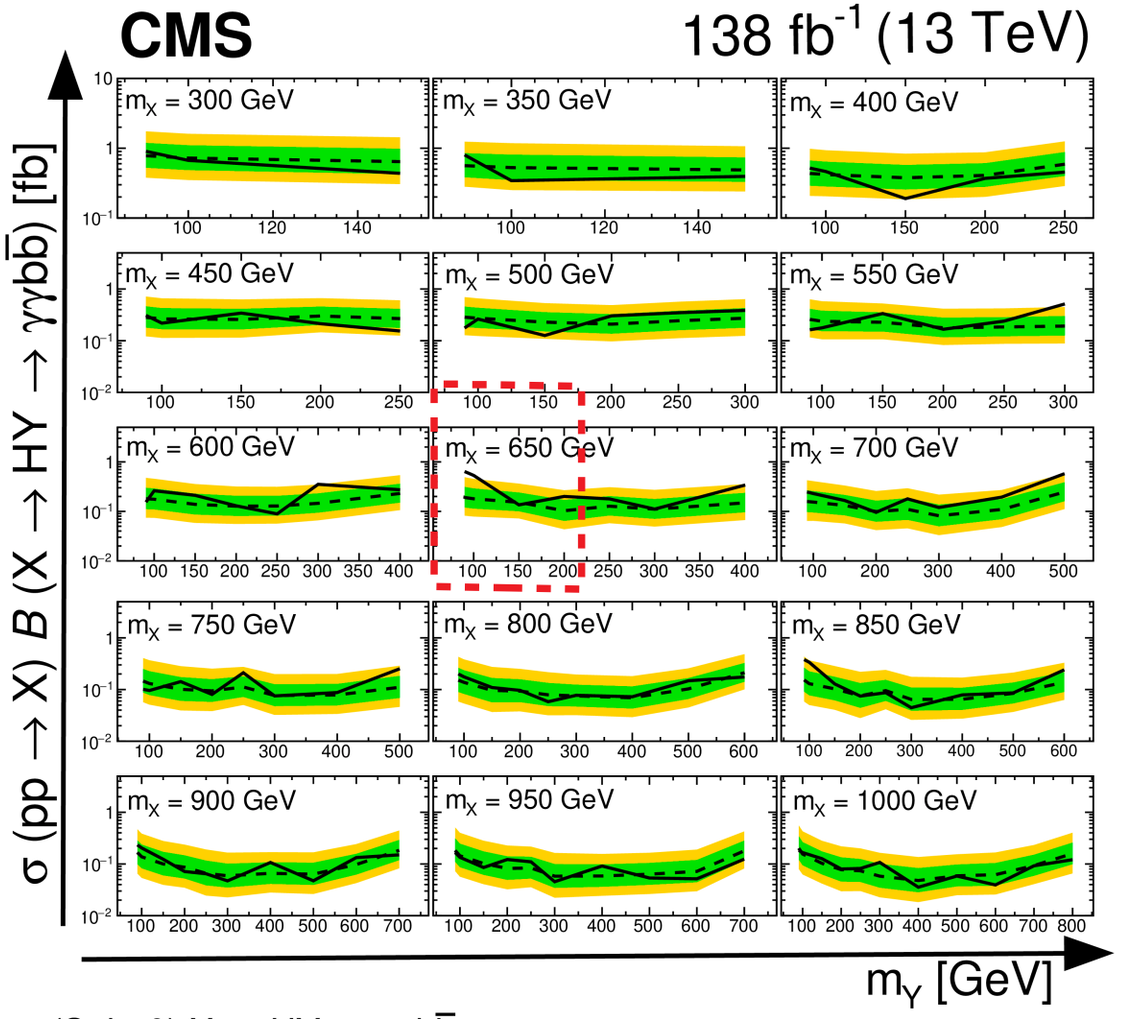


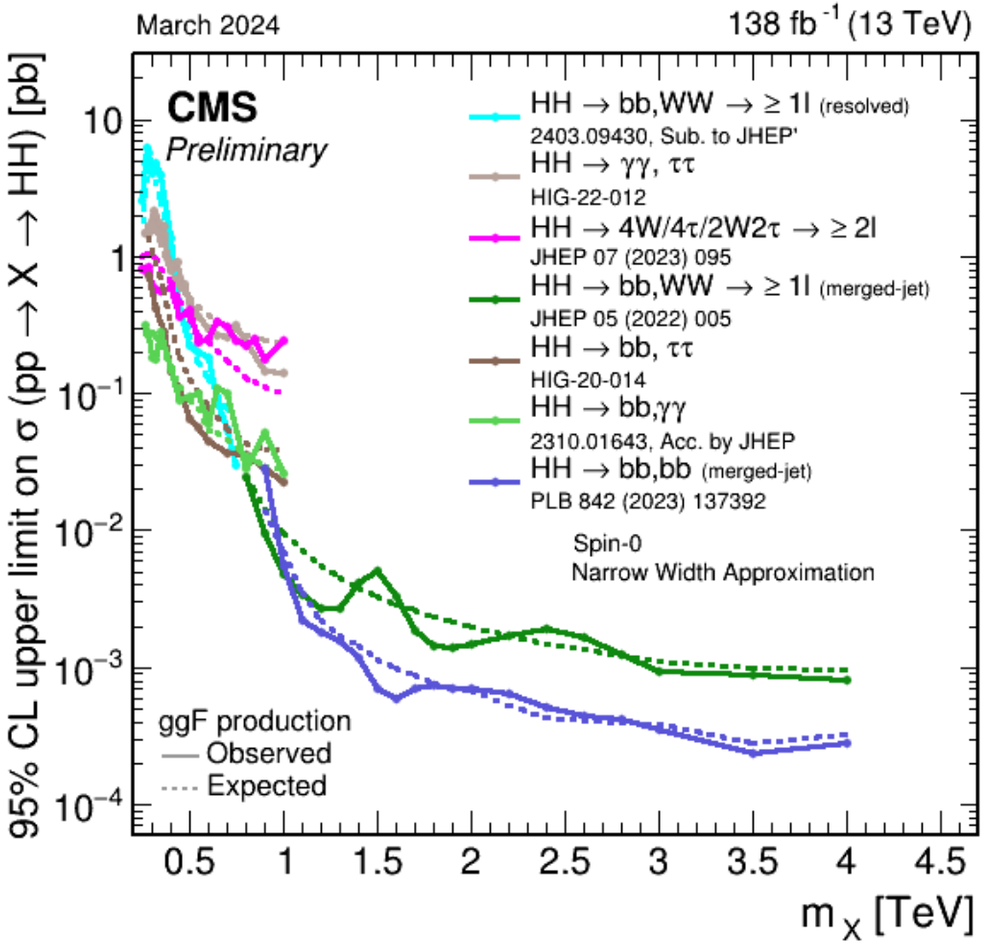


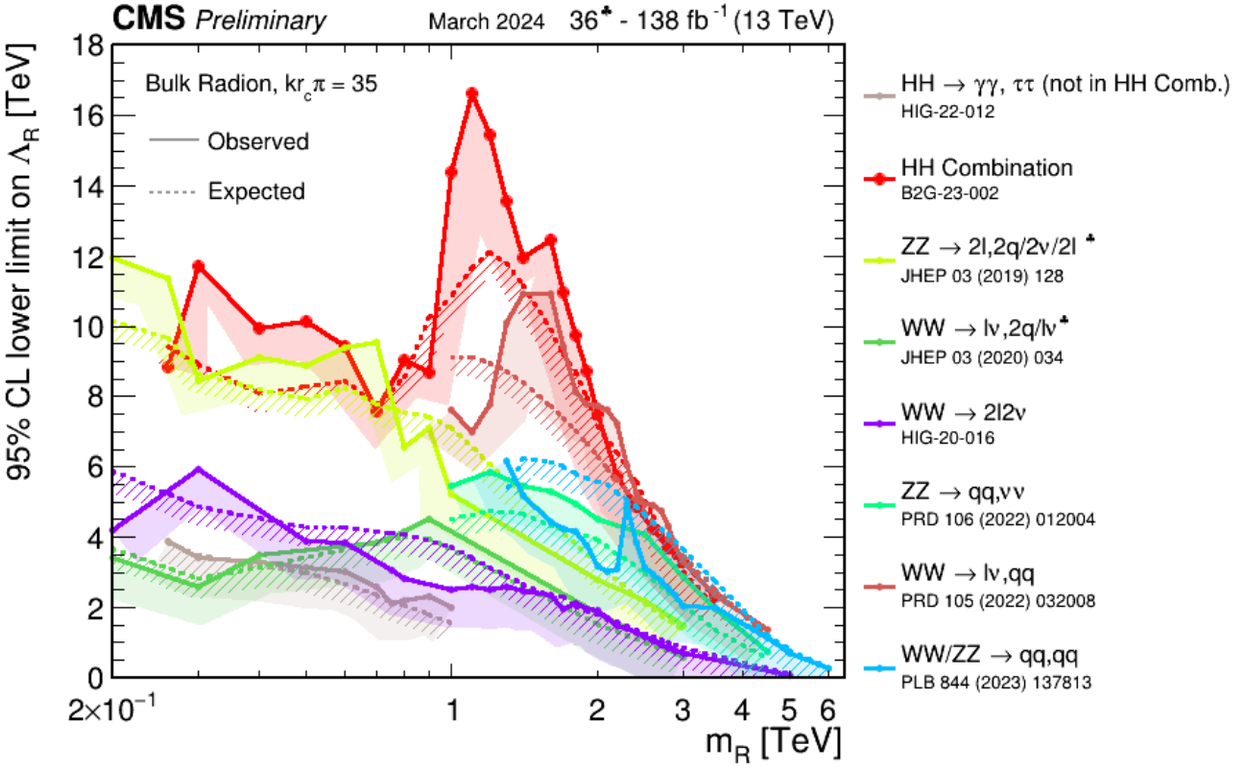
Excess observed at m_X, m_Y = 650, 100 GeV

← 3.8 (2.8) local (global) significance

Summary plots (X→HH)

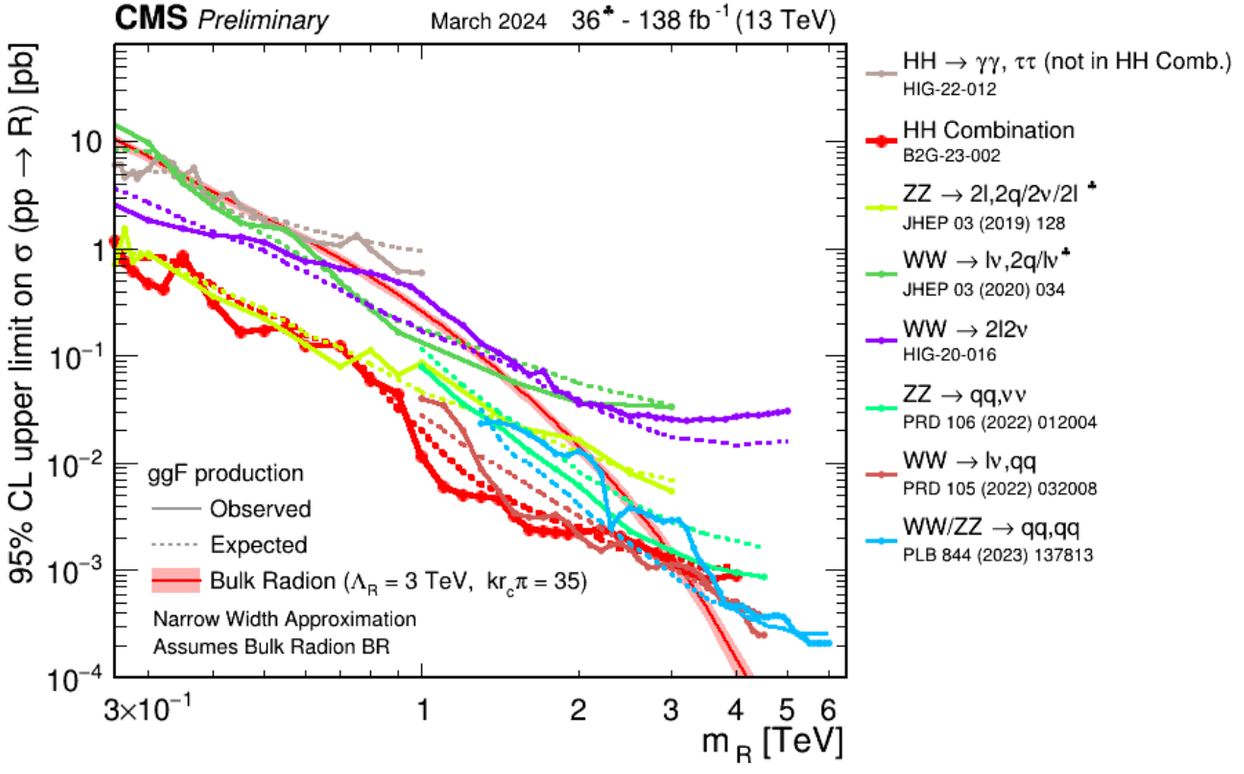
Constraints on spin-0 Radion



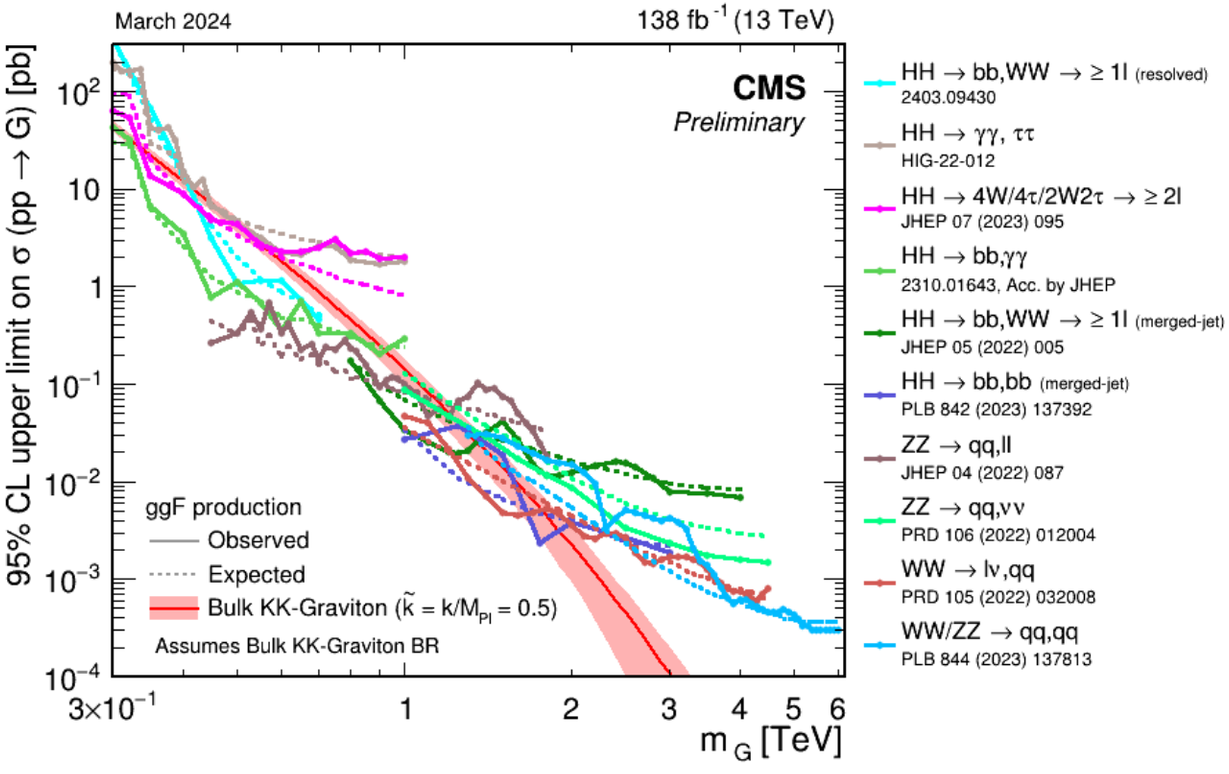


Summary plots (X→HH/VV)

Constraints on spin-0 Radion



Constraints on spin-2 Graviton



Interference effects in X→HH production

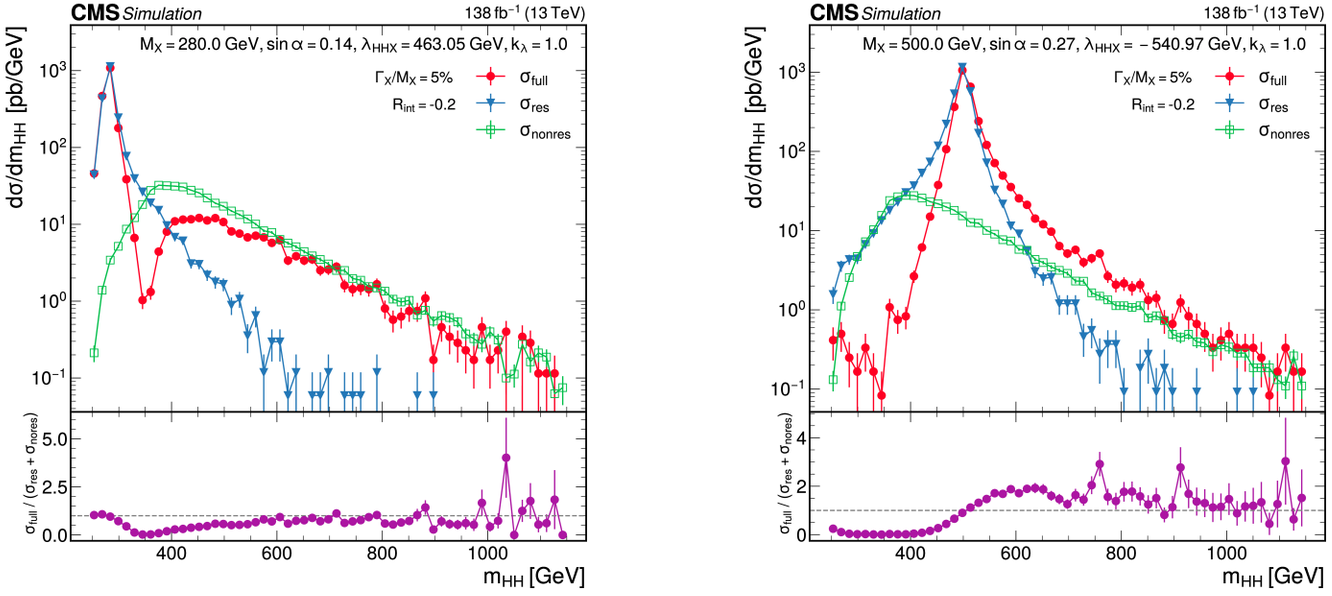
arXiv: 2403.16926

Interference between resonant BSM and non-resonant SM HH productions explored in a model with one real singlet

$$g_{Xkk} = -g^{SM}_{Hkk}\sin\alpha \qquad g_{Hkk} = g^{SM}_{Hkk}\cos\alpha$$

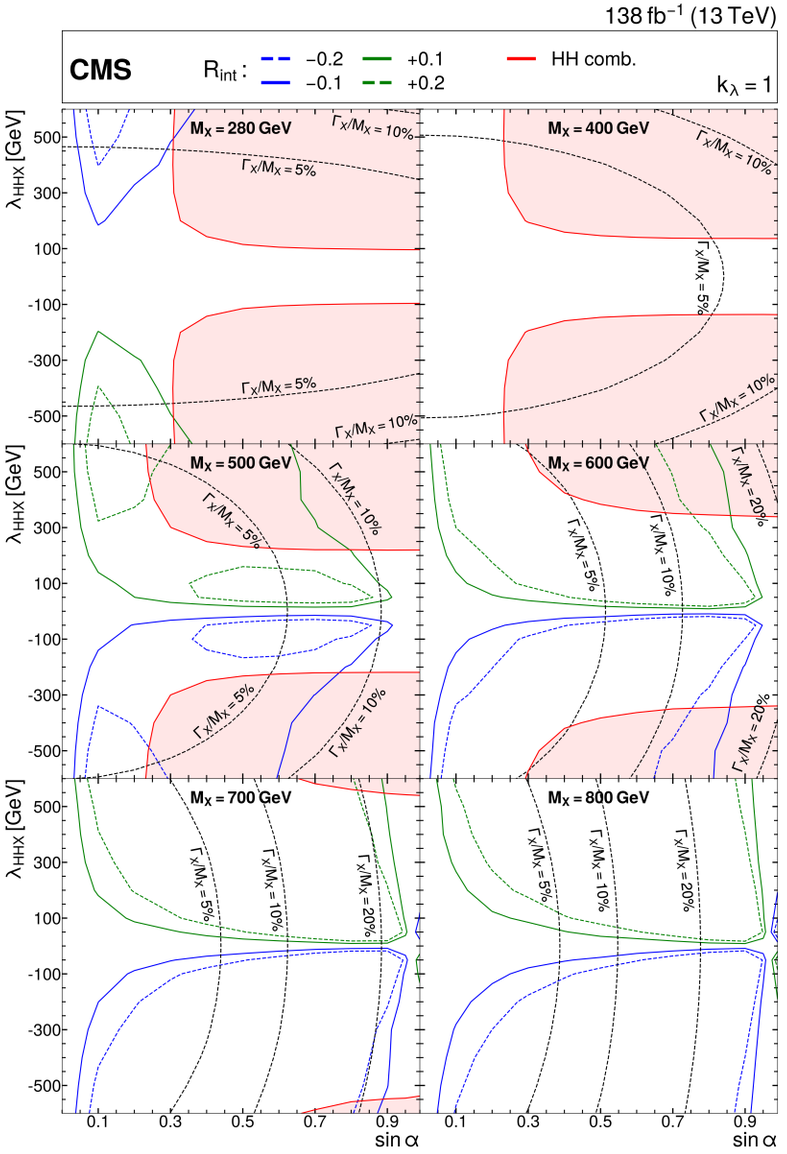
$$\Gamma_X = \sin^2\alpha\,\Gamma^{SM}(m_X) + \frac{\lambda^2_{HHX}\sqrt{1-4m_H^2/m_X^2}}{8\pi m_X}$$

$$R_{int} = \frac{\sigma^{full} - \left(\sigma^{resonant\text{-}only} + \sigma^{nonresonant}\right)}{\sigma^{resonant\text{-}only} + \sigma^{nonresonant}}$$



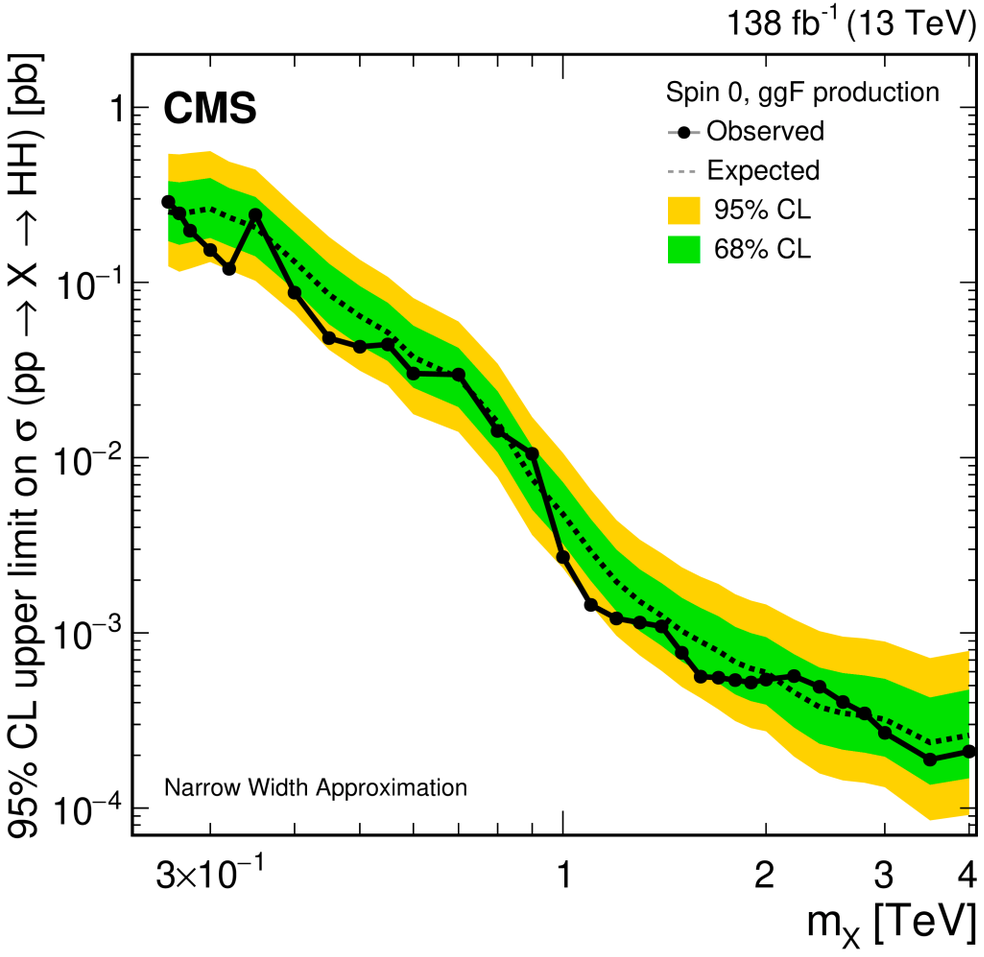
Different effects on mass spectrum for small and large m_X values

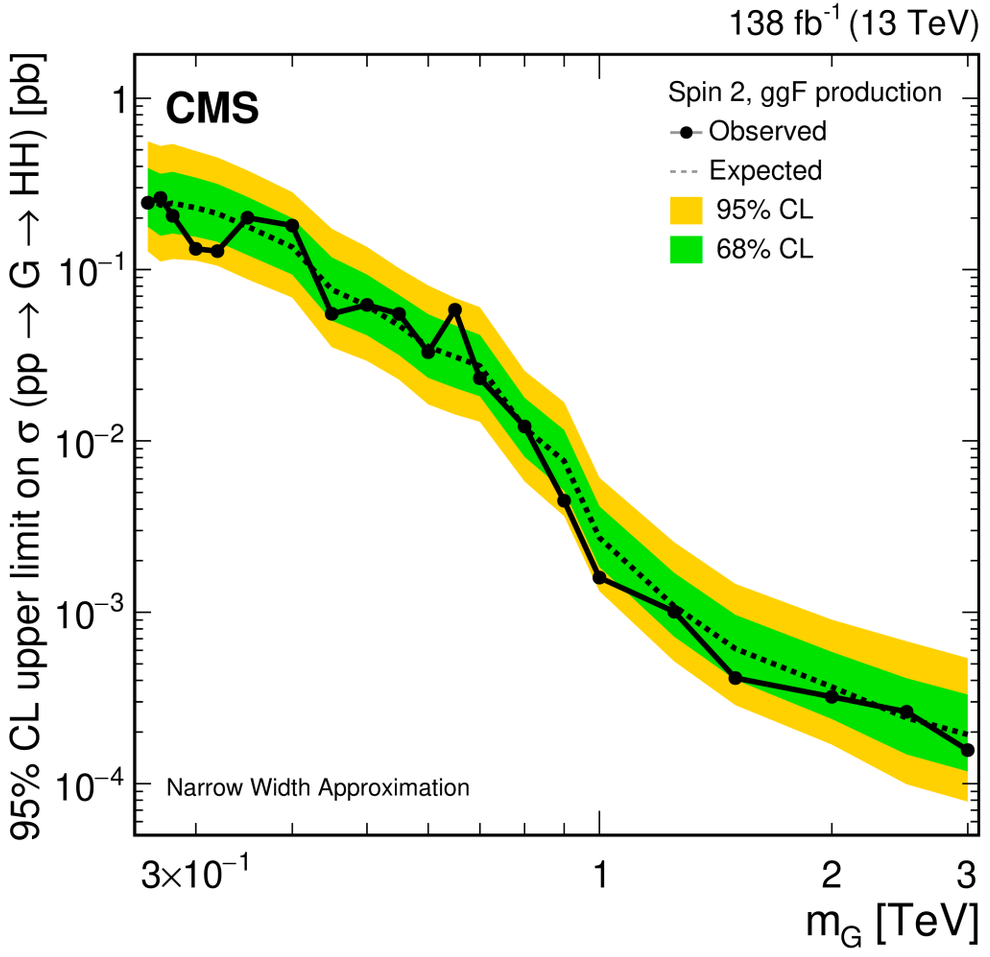
Interference effects
- can be important at intermediate masses
- are small compared at high mass



Combination: X→HH

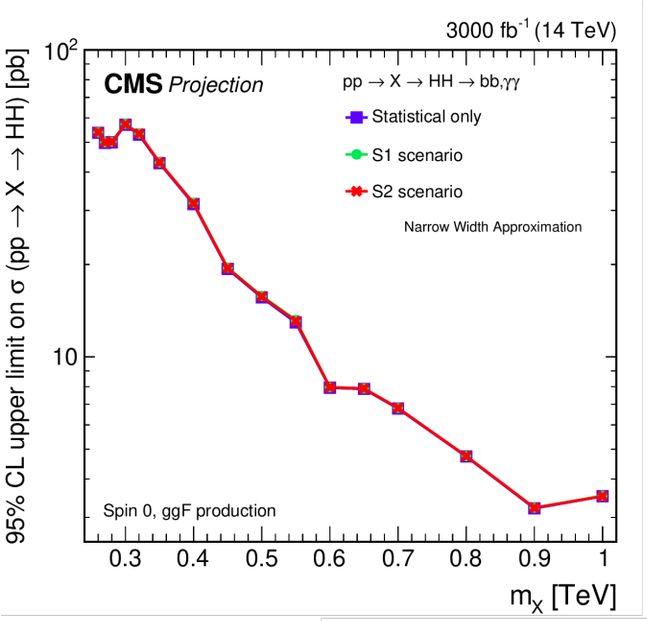
arXiv: 2403.16926

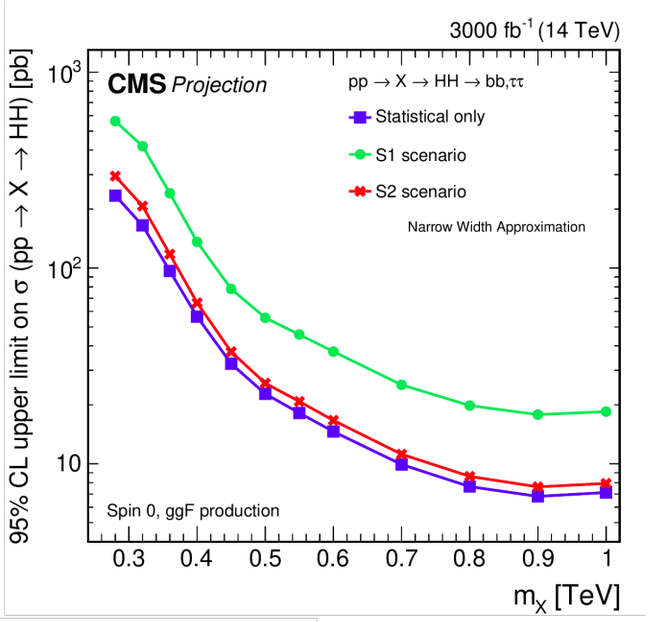


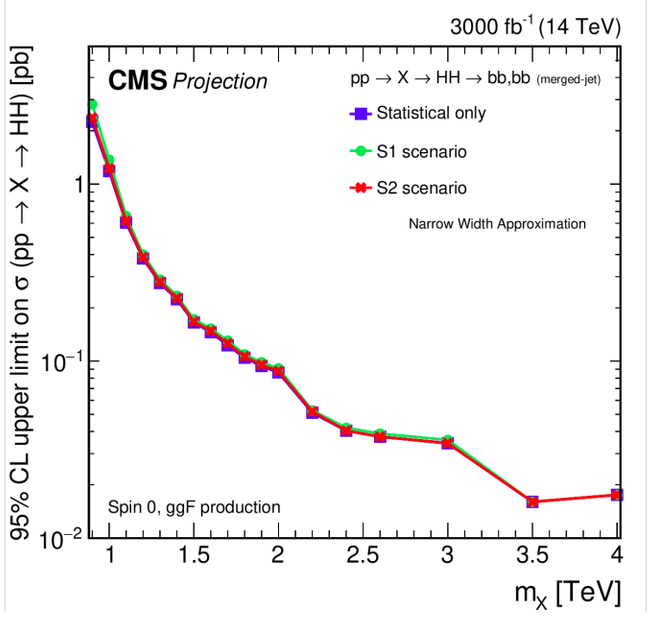


HL-LHC projection for X→HH searches

arXiv: 2403.16926







Interpretation: V'→VH

arXiv: 2403.16926