Searches for heavy particles decaying to Higgs bosons in CMS experiment

Suman Chatterjee

HEPHY, Austrian Academy of Sciences, Vienna

12/12/2023

International Conference on High Energy Particle & Astroparticle Physics (ICHEPAP 2023)

SINP, Kolkata

Triumph of Standard Model

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

Triumph of Standard Model

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

CMS summary plots

EW

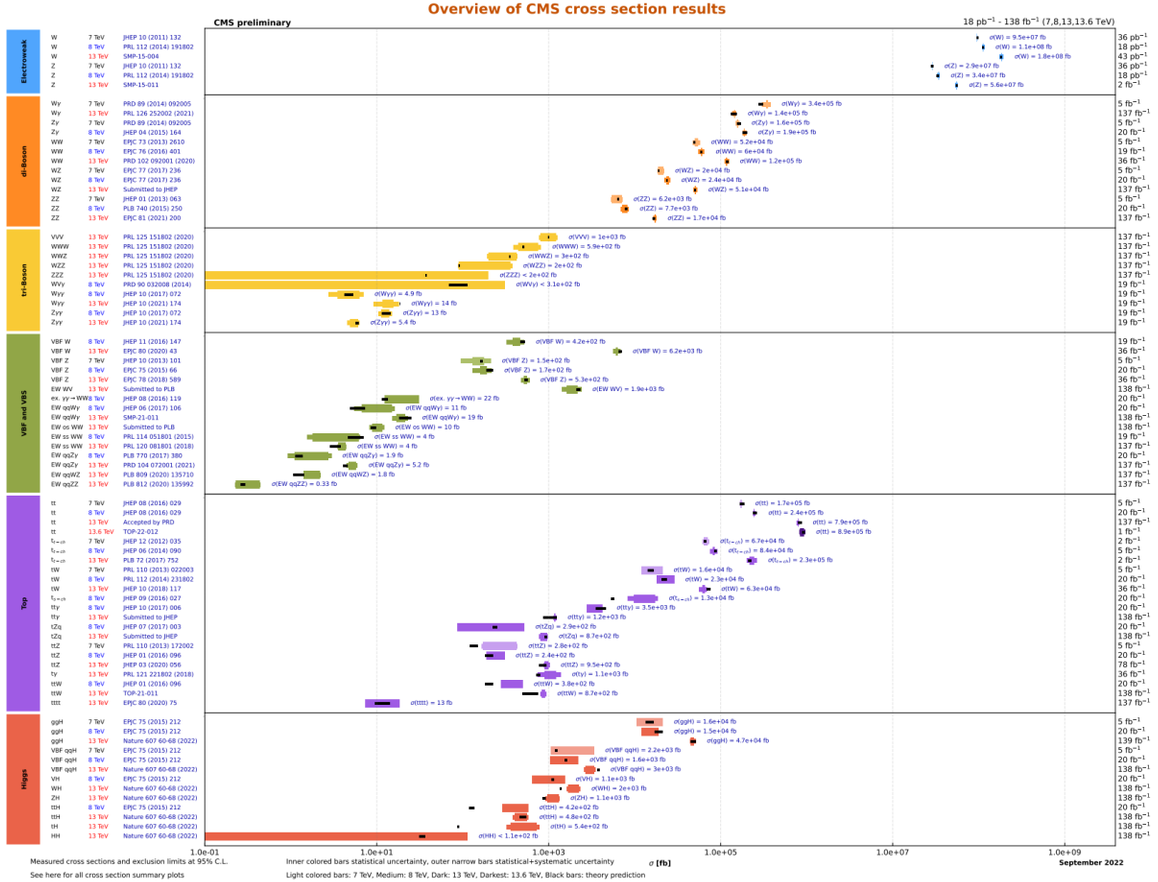
VV

VVV

VBF
VBS

top

Higgs

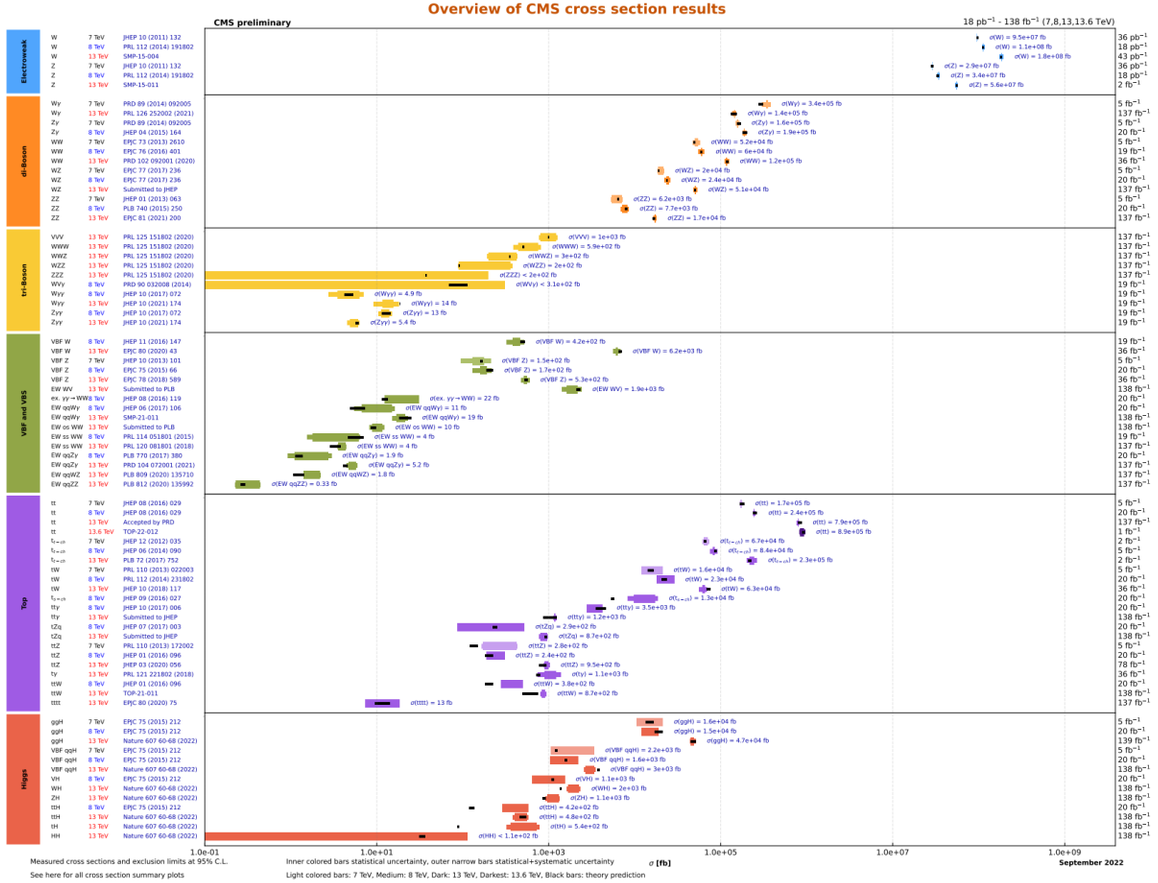


Precision measurement of plethora of processes
→ In general, good agreement with SM prediction

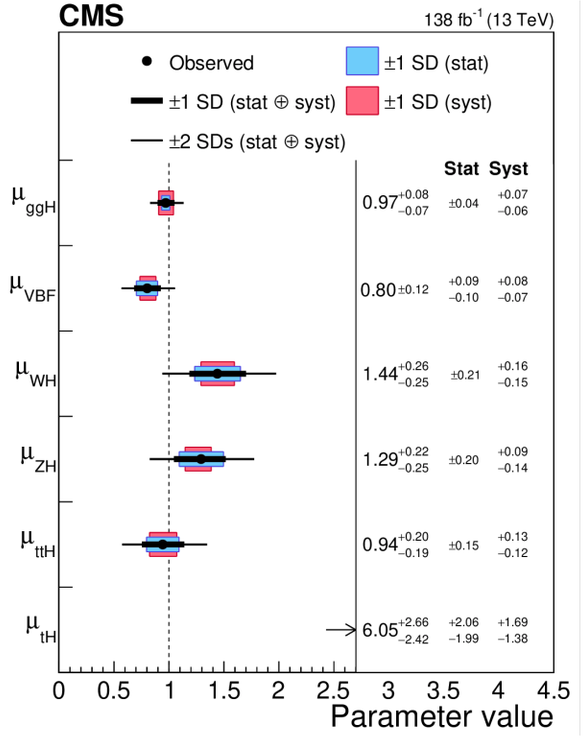
Triumph of Standard Model

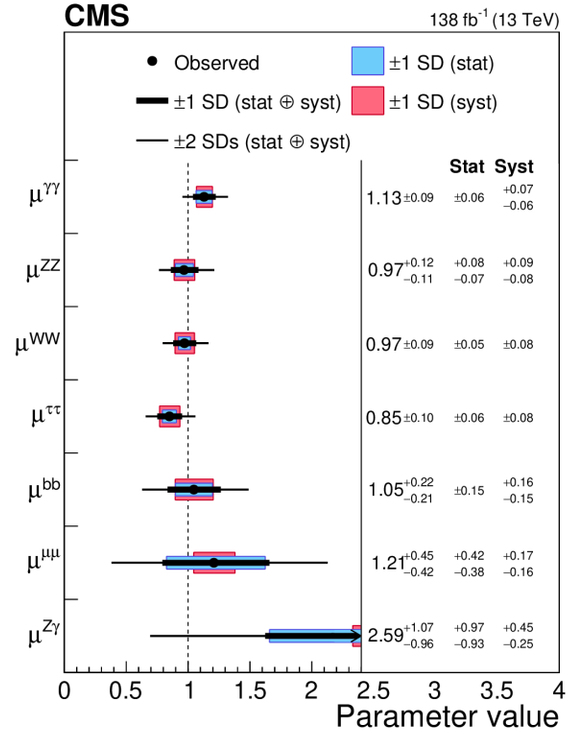
Newest fundamental particle discovered: Last missing piece in standard model (SM)

CMS summary plots



Nature 607 (2022) 60-68





Precision measurement of plethora of processes
→ In general, good agreement with SM prediction

Standard model predictions match data very well for Higgs production & decay also

Limitations of Standard Model

Baryon asymmetry of universe

Observation:

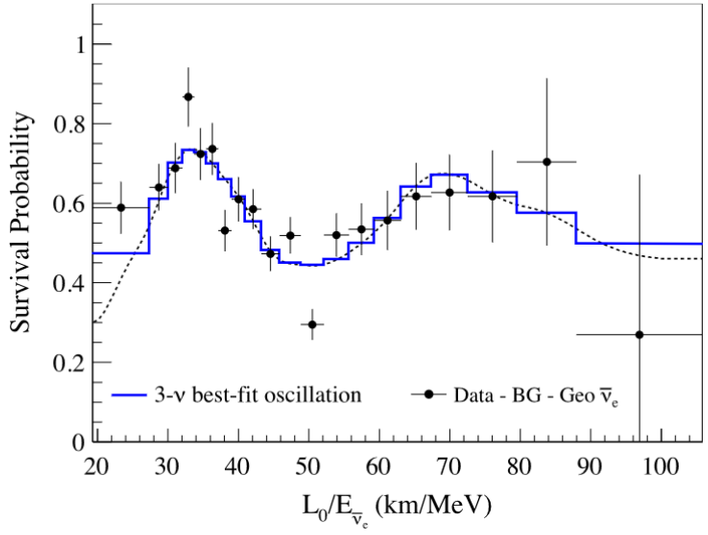
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6.1 \times 10^{-10}$$

$$\eta = \frac{n_B - n_{\bar{B}}}{s} \sim 8.6 \times 10^{-11}$$

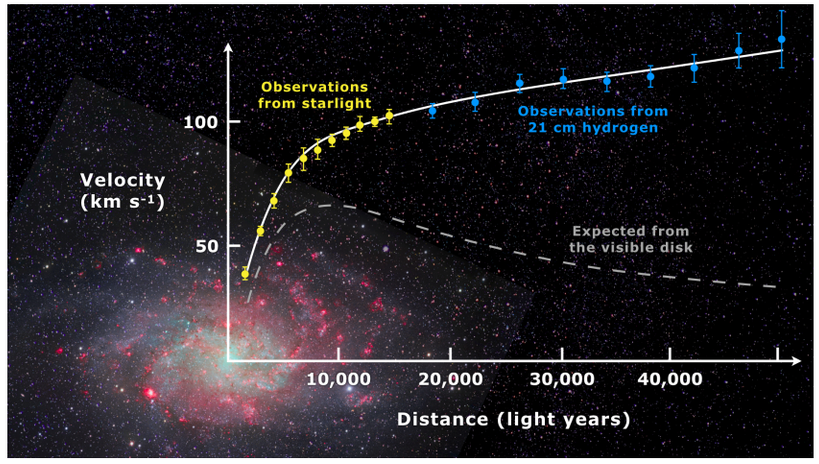
SM prediction:

$$|\eta| = |\frac{n_b - \bar{n}_b}{s}| \leq 6 \times 10^{-27}$$

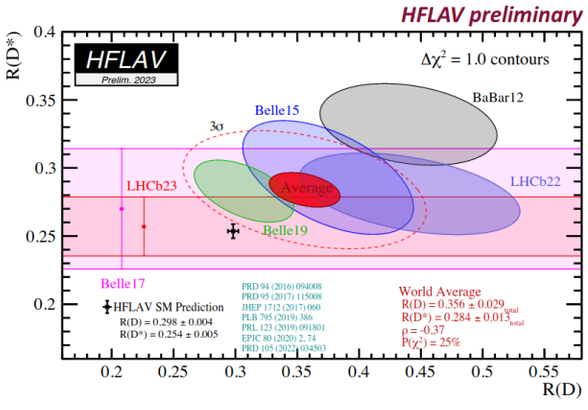
Neutrino oscillation

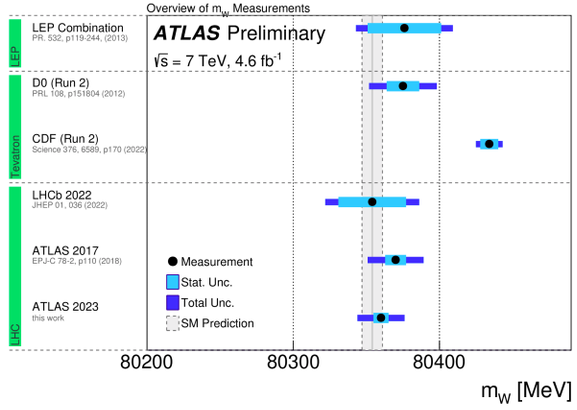


Dark matter

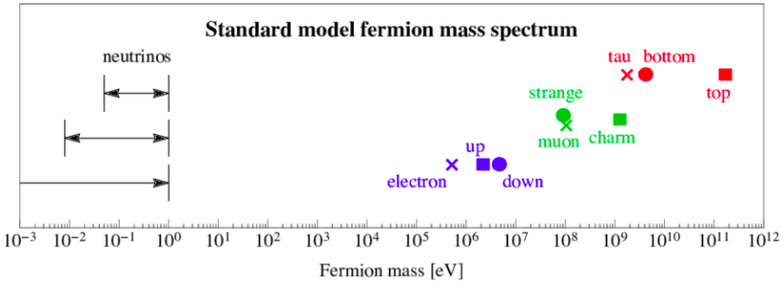


Flavor anomalies, W mass, $(g-2)_\mu$ ...





Pattern of fermion masses



'Naturalness' of Higgs mass

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

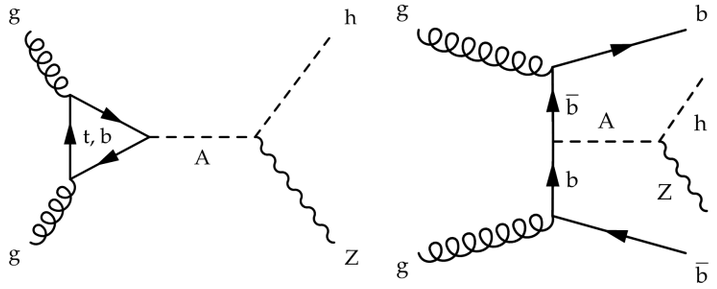
$$V = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

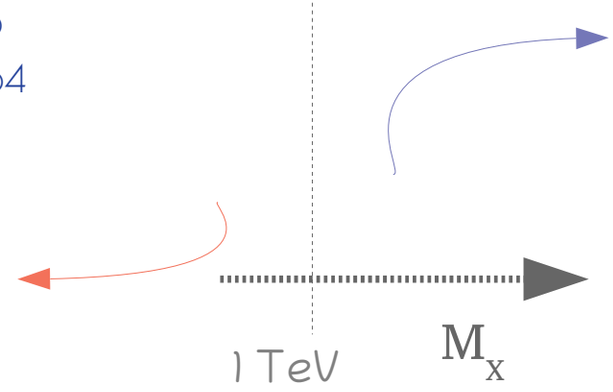
Searches for resonances decaying to Higgs boson(s)

VH final state:

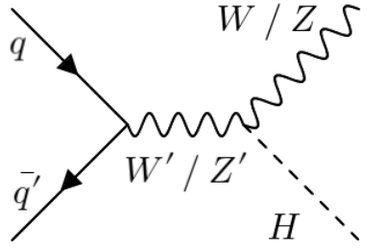
X→VH

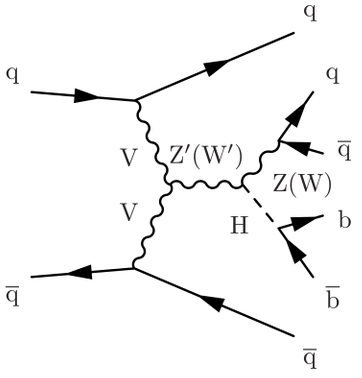
A→ ZH → 2l 2τ JHEP 03 (2020) 065
A→ ZH → 2l/2v 2b EPJC 79 (2019) 564





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

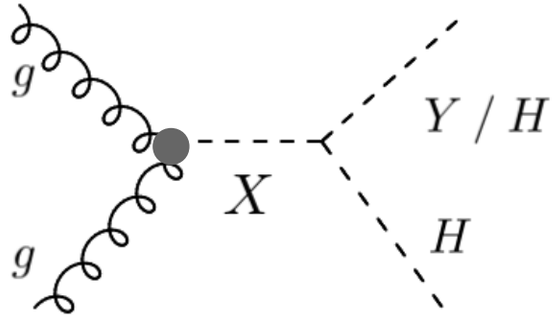




HH/YH final state:

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 arXiv:2310.01643

X→ HH →WWWW / WWττ/ ττττ (multilepton) JHEP 07 (2023) 095
X→ HH → 2b 2W (resolved) CMS-PAS-HIG-21-005
X→ HH → 2b 2W/2τ (boosted) JHEP 05 (2022) 005

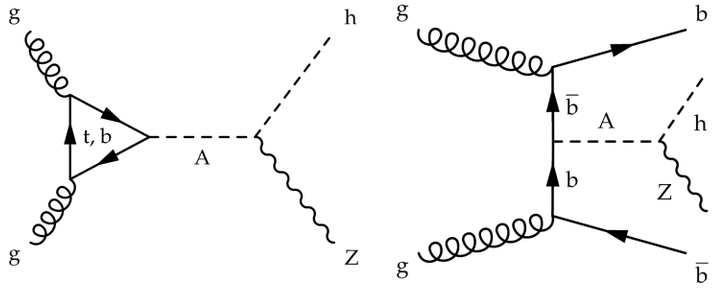


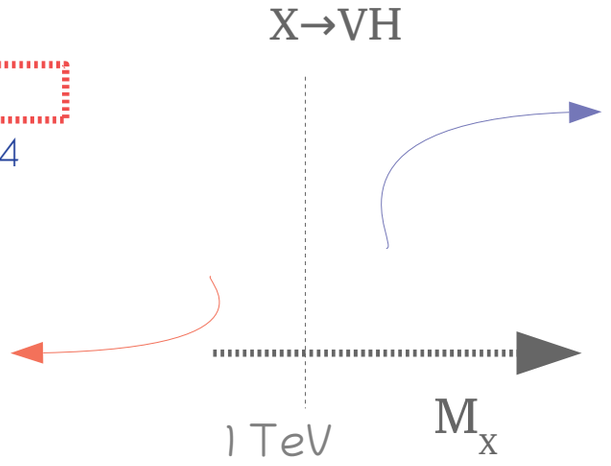
Searches for resonances decaying to Higgs boson(s)

VH final state:

A → ZH → 2l 2τ JHEP 03 (2020) 065

A → ZH → 2l/2v 2b EPJC 79 (2019) 564

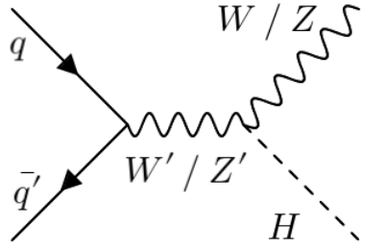


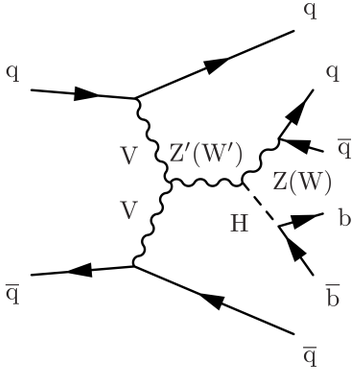


W' → WH → lν bb Phys. Rev. D 105 (2022) 032008

Z' → ZH → ll bb EPJC 81 (2021) 688

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





Covered in this talk!

HH/YH final state:

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

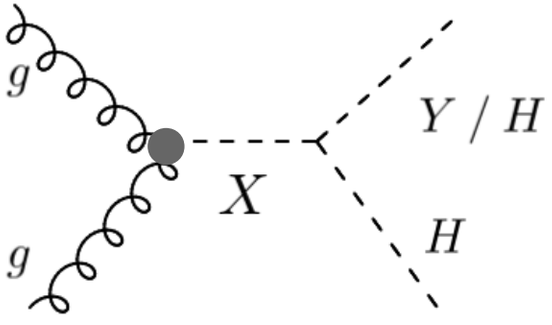
X → HH/YH → 2b 2τ JHEP 11 (2021) 057

X → HH/YH → 2b 2γ arXiv:2310.01643

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

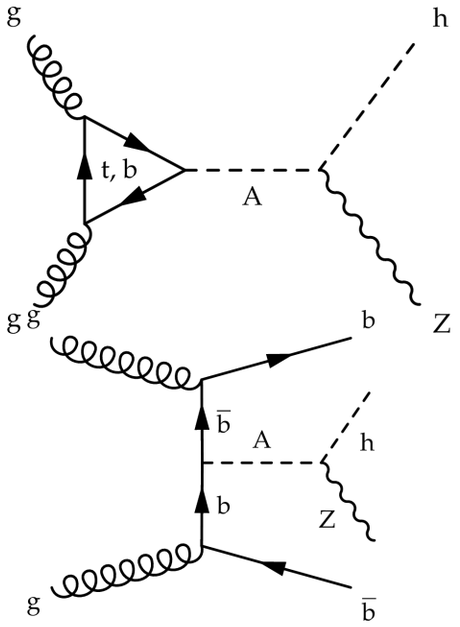
X → HH → 2b 2W (resolved) CMS-PAS-HIG-21-005

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

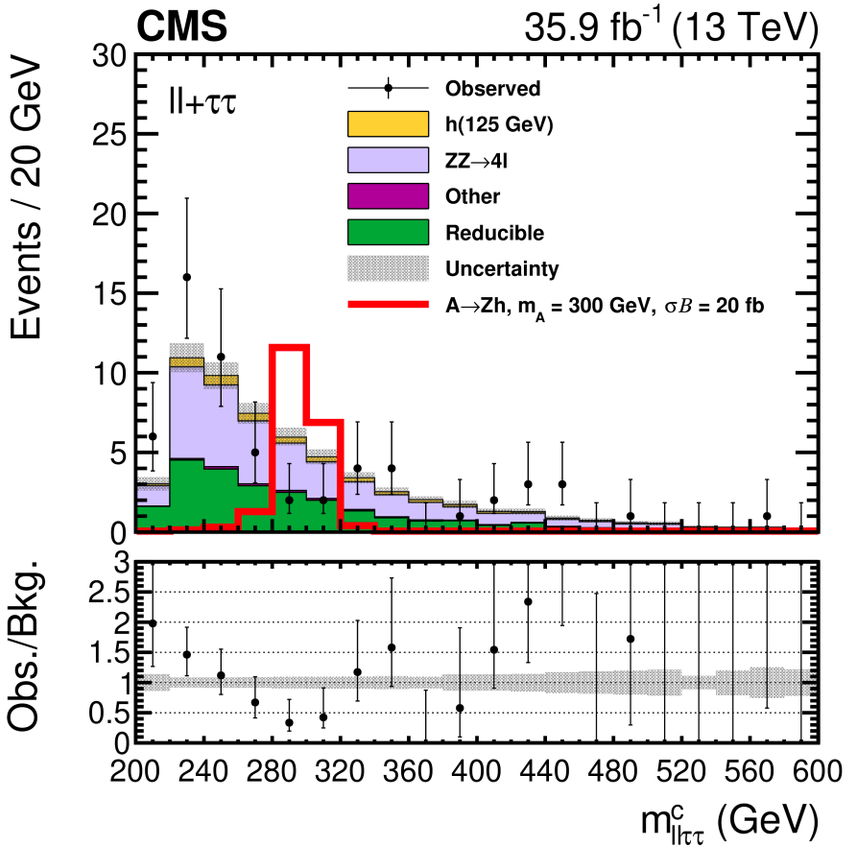


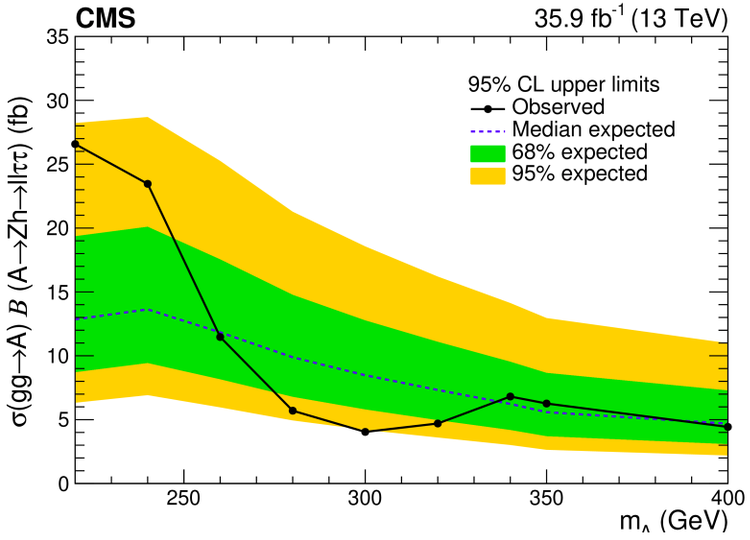
JHEP 03 (2020) 065

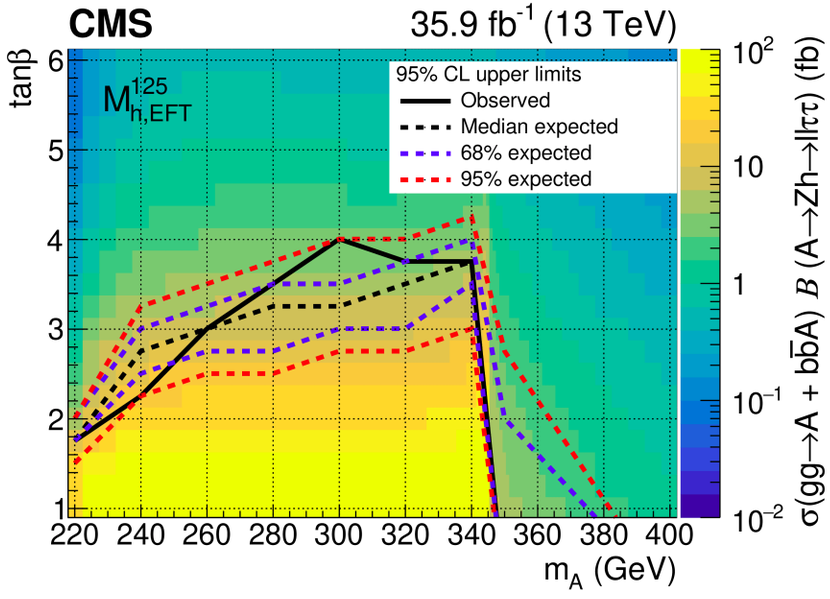
A→ ZH → llττ



- Irreducible background (ZZ → 4l, ttZ, WWZ, WZZ, ZZZ) ← from simulation
- Reducible background (jet faking as lepton) ← estimated from data







Decay mode:

Z → l l + h → τ τ

Final states considered:

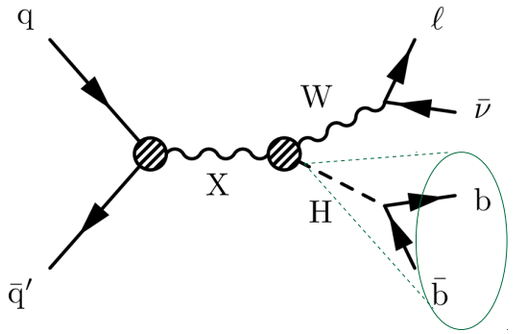
ee + eτ$_h$	μμ + eτ$_h$
ee + μτ$_h$	μμ + μτ$_h$
ee + τ$_h$τ$_h$	μμ + τ$_h$τ$_h$
ee + eμ	μμ + eμ

No significant deviation over predicted background

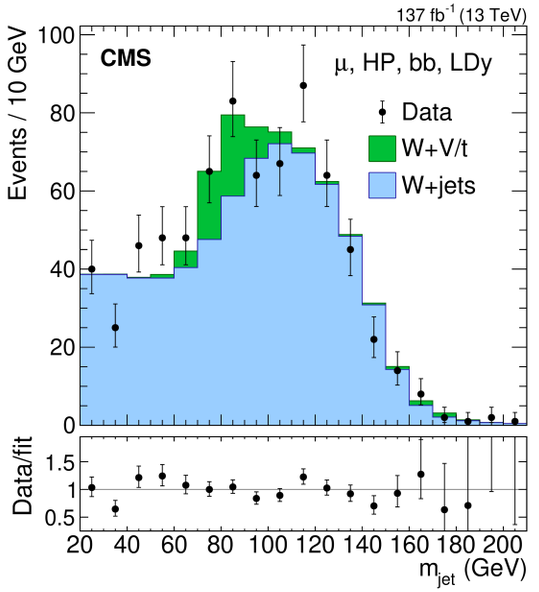
Strong constraints at low tanβ in minimal supersymmetric extension of SM (MSSM)

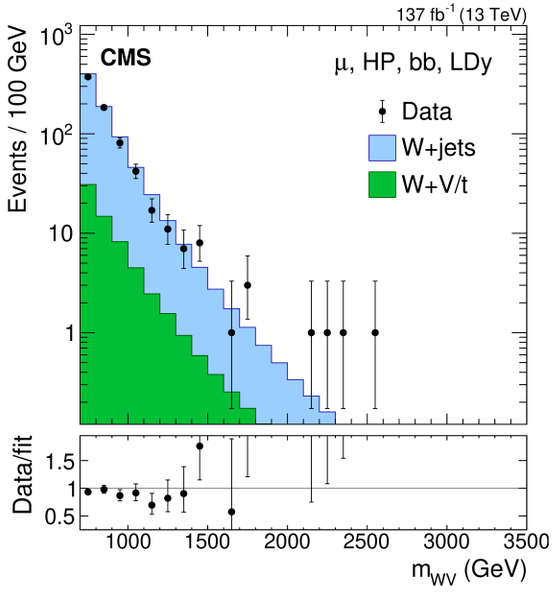
Phys. Rev. D 105 (2022) 032008

W'→ WH → lvbb

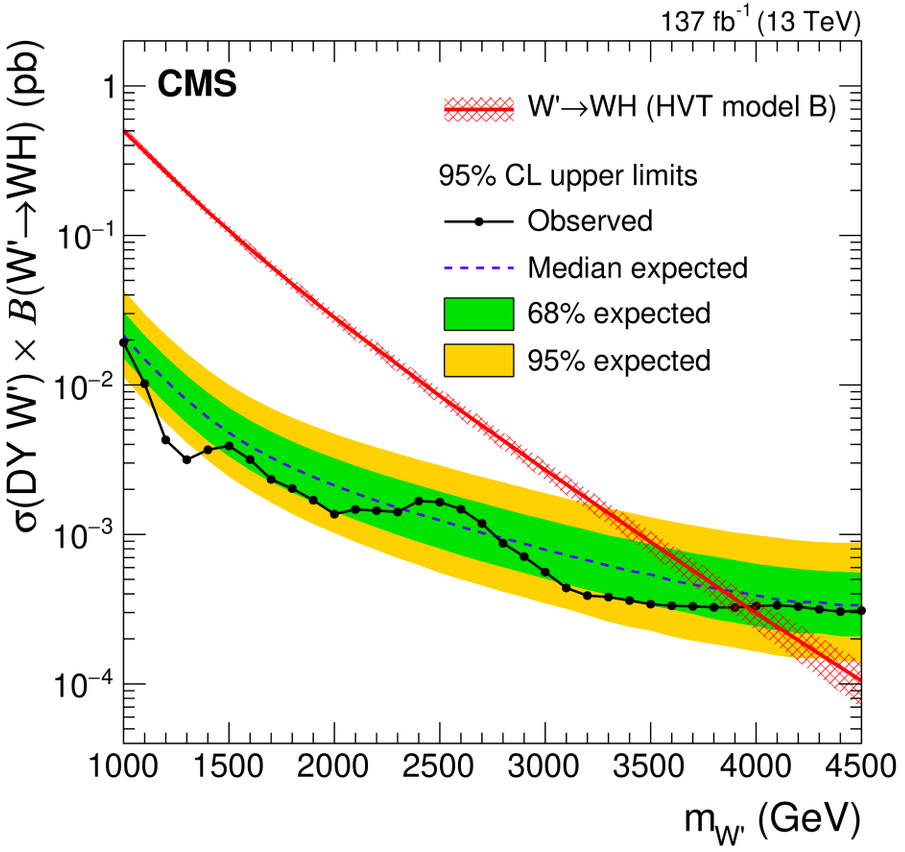


- Background processes primarily from simulation → smoothened / modeled with functional forms





Signal extraction using 2D mass distributions (m_J – m_{VV})
- fitted in all categories simultaneously



<u>Decay mode:</u>

$W \rightarrow l\,\nu + H \rightarrow b\,b$

<u>Final states considered:</u>

1 muon/electron + 1 large (AK8) jet + p_T^{miss}

- bb tagging of AK8 jet (H candidate) using BDT

JINST 13 (2018) P05011

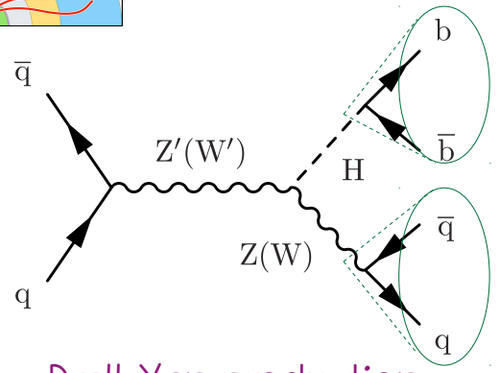
<u>Multiple event categories used:</u>

- Δy (W,H) <=1 (LDy) or > 1 (HDy)
- 2-prongness of H candidate jet:
  Mass-decorrelated τ_{21} <0.5 (high-purity)
  >= 0.5 (low-purity)

Analysis also explored WW, WZ final states

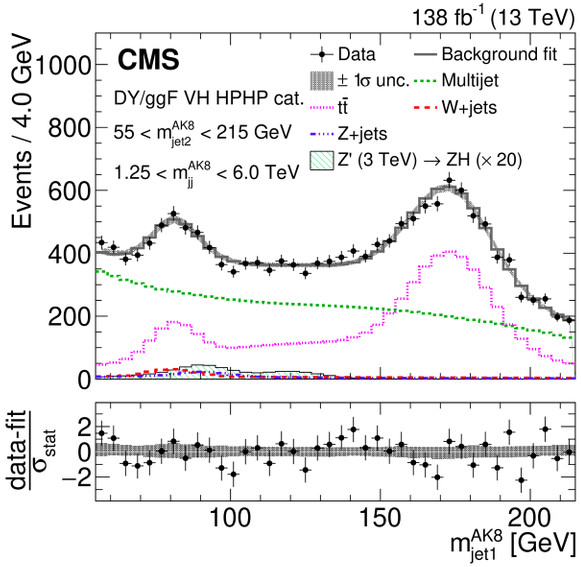
Phys. Lett. B 844 (2023) 137813

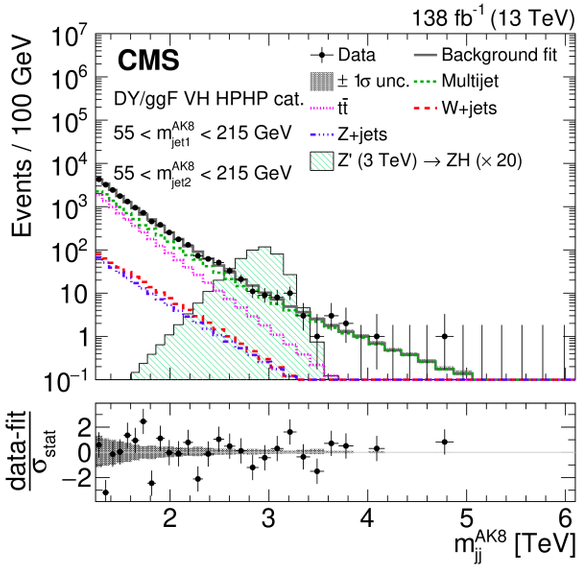
Z'→ (W/Z)H → qqbb



Drell-Yan production

- Background estimated from data by fitting nonresonant (QCD) & resonant (W/Z+jets) in 3 dimensions: m^{SD}_{J1}, m^{SD}_{J2}, m_{VV} → Constrained using jet mass sidebands





Decay mode:

W/Z → q q + H → b b

Final states considered:

- 2 large (AK8) jets

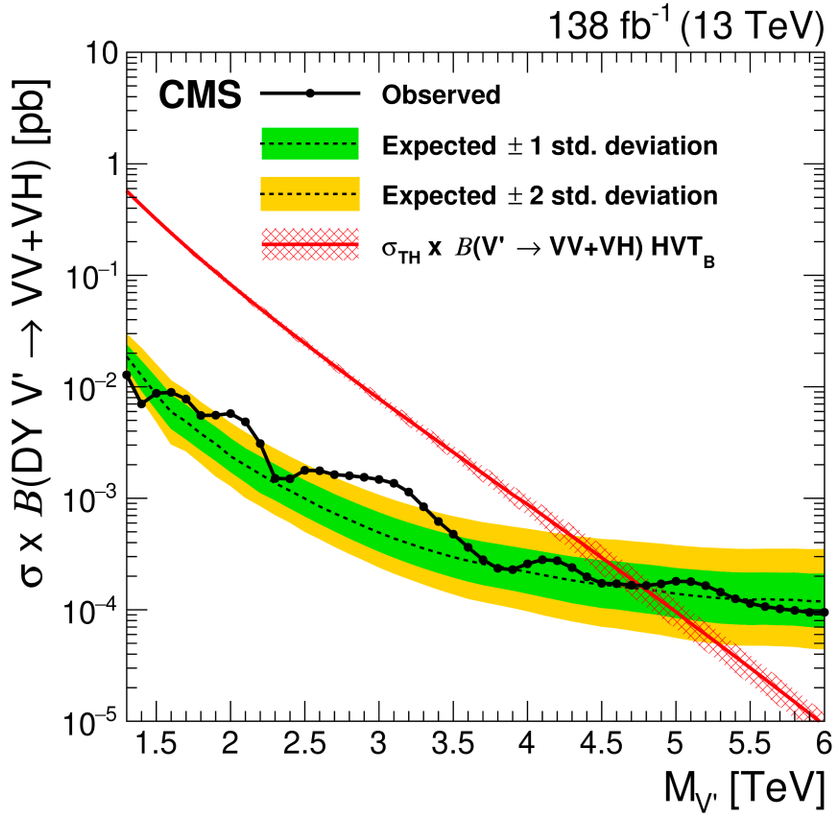
→ bb- & qq-tagging of AK8 jets using deep neural networks (DeepAK8) w/ mass decorrelation

JINST 15 (2020) P06005

Multiple event categories used:

- Δy (W/Z,H) <=1 or > 1

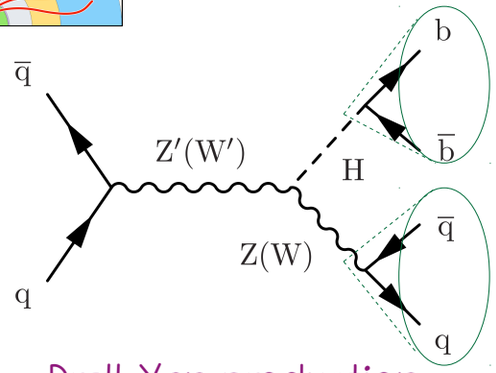
- Using DeepAK8 scores



Analysis also explored WW, WZ final states

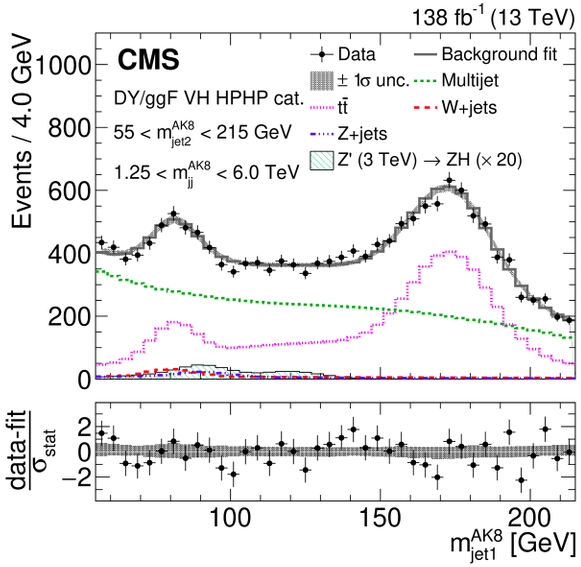
Phys. Lett. B 844 (2023) 137813

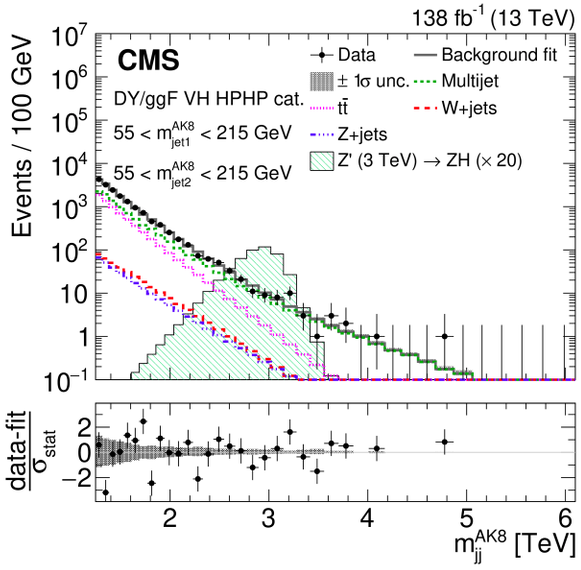
Z'→ (W/Z)H → qqbb

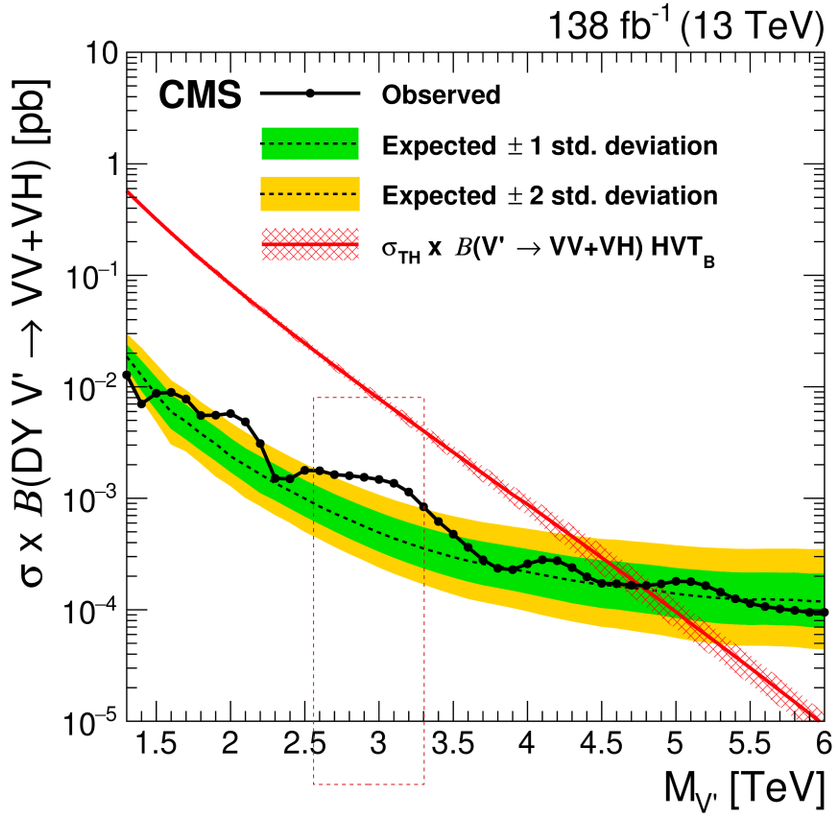


Drell-Yan production

- Background estimated from data by fitting nonresonant (QCD) & resonant (W/Z+jets) in 3 dimensions: m^{SD}_{J1}, m^{SD}_{J2}, m_{VV} → Constrained using jet mass sidebands







Local excess: ~ 3.6 (2.3) σ

Decay mode:

W/Z → q q + H → b b

Final states considered:

- 2 large (AK8) jets

→ bb- & qq-tagging of AK8 jets using deep neural networks (DeepAK8) w/ mass decorrelation

JINST 15 (2020) P06005

Multiple event categories used:

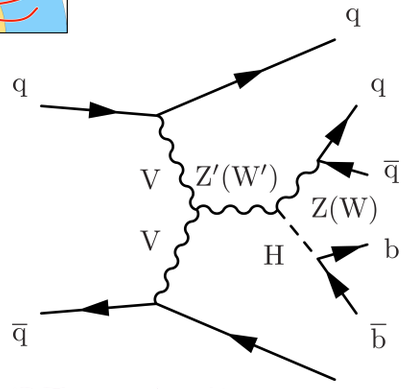
- Δy (W/Z,H) <=1 or > 1

- Using DeepAK8 scores

Analysis also explored WW, WZ final states

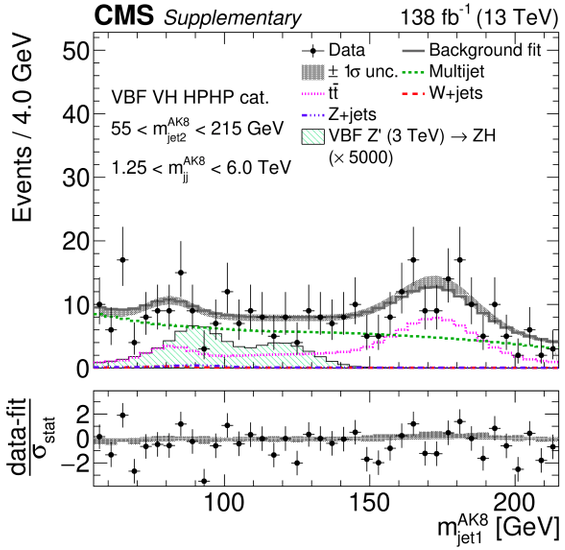
Phys. Lett. B 844 (2023) 137813

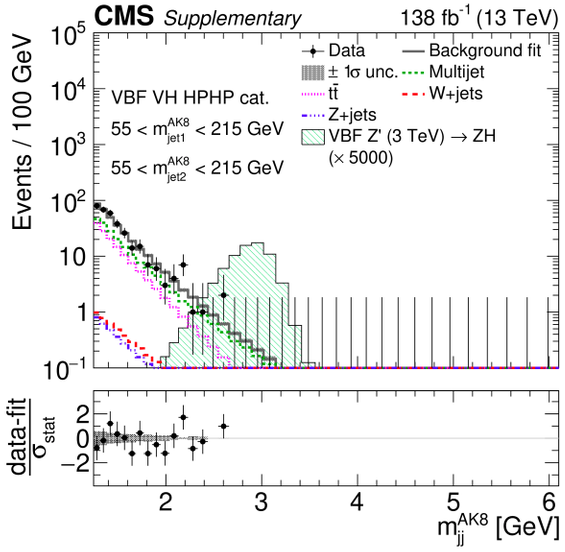
Z'→ (W/Z)H → qqbb (contd ...)

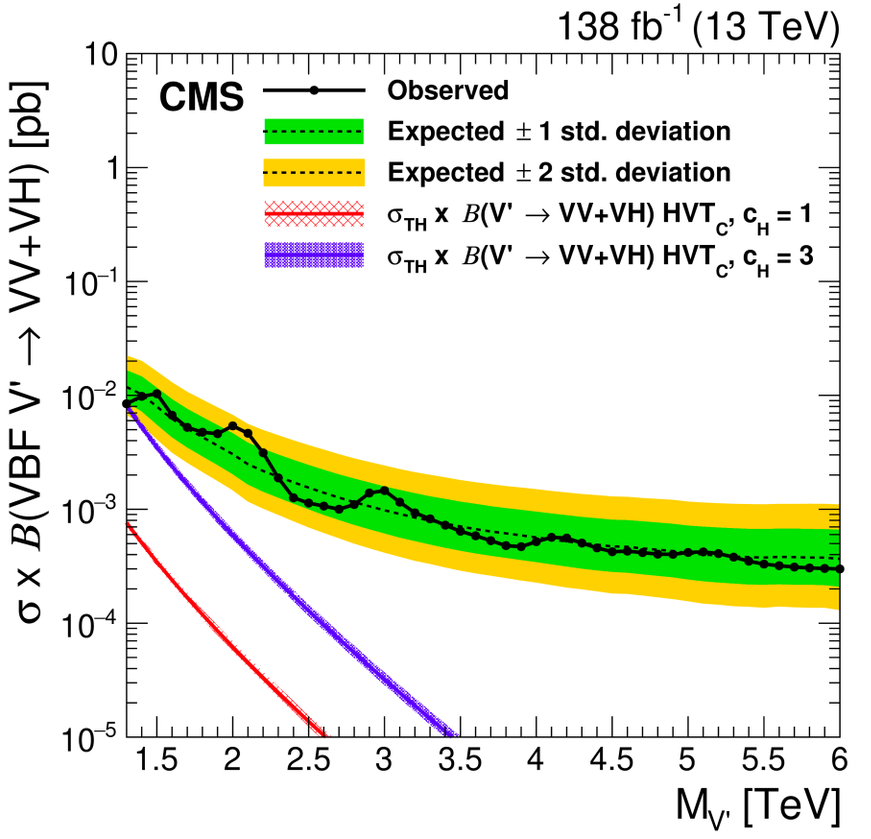


VBF production

- Background estimated from data by modeling w/ parametric functions in 3 dimensions: m^{SD}_{J1}, m^{SD}_{J2}, m_{VV} → Constrained using jet mass sidebands







Decay mode:

W/Z → q q + H → b b

Targeting VBF production w/ additional conditions:

- $\Delta\eta$ (j,j) > 4.5

- m_{jj} > 800 GeV

j ← AK4 jet (not overlapping w/ V & H candidates)

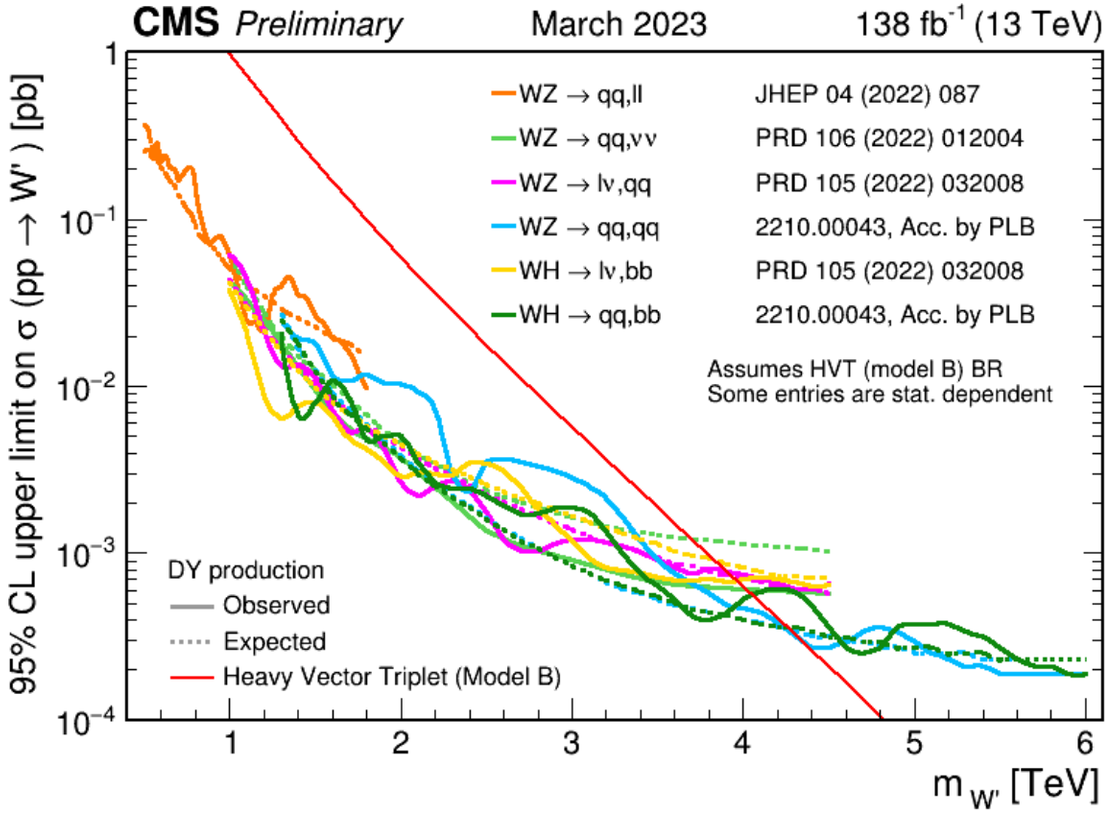
Analysis is not sensitive to VBF production yet

Summary plots (W'→VV/VH)

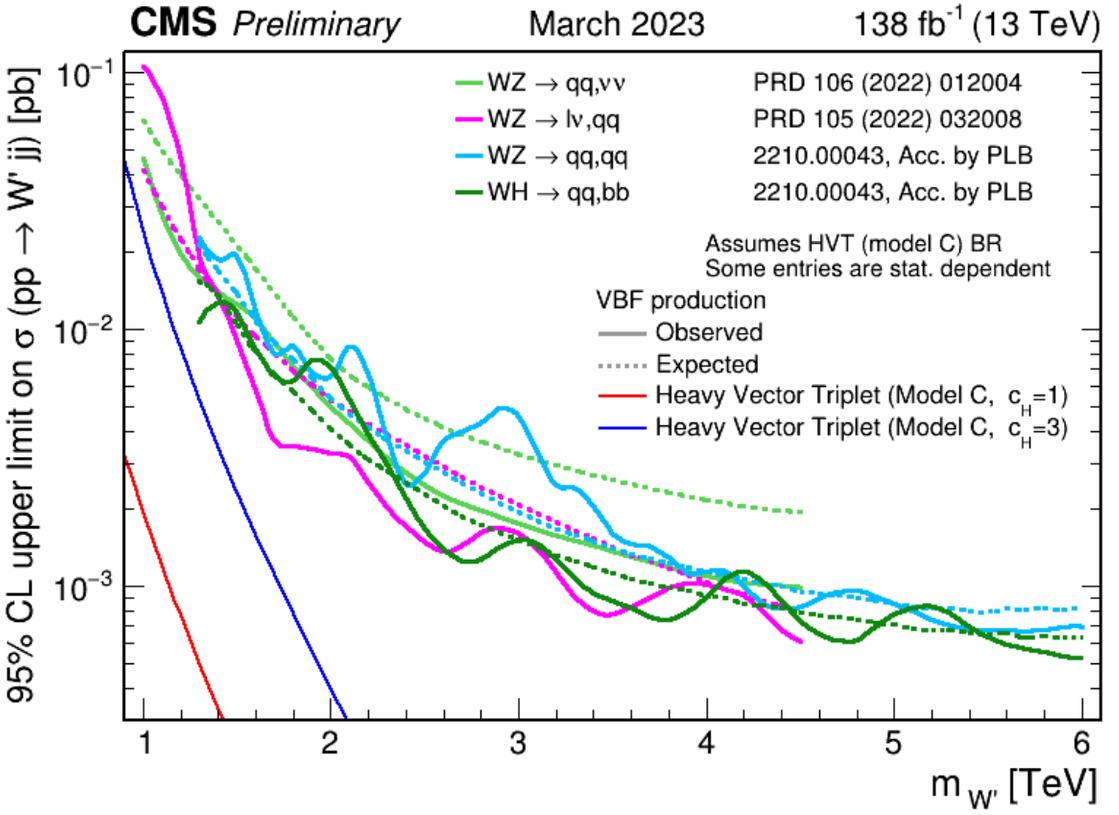
Interpretation performed in heavy-vector triplet models for scenarios with suppressed V'→ fermion couplings

Pappadopulo, Thamm, Torre, Wulzer (2014)

Drell-Yan production



VBF production



- Comparable sensitivity between W' → WZ & W' → WH searches

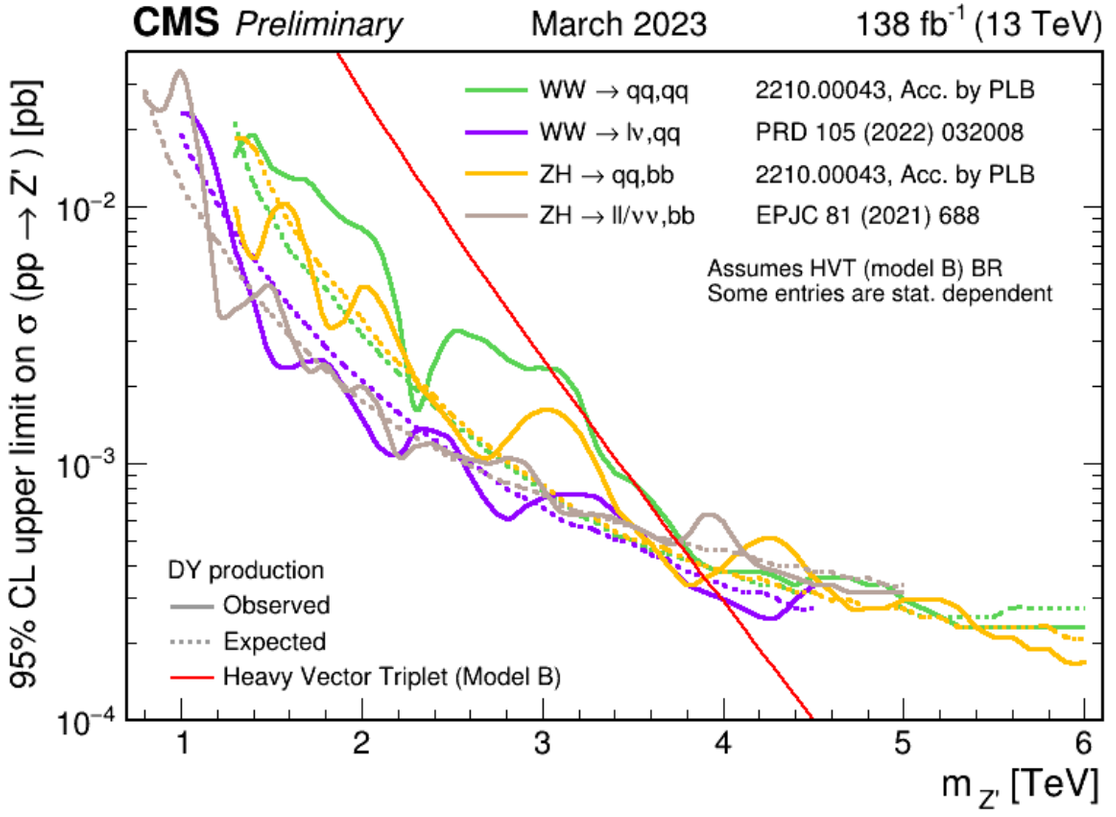
- WH search offers best senstivity for W' production via VBF at very high mass

Summary plots (Z'→VV/VH)

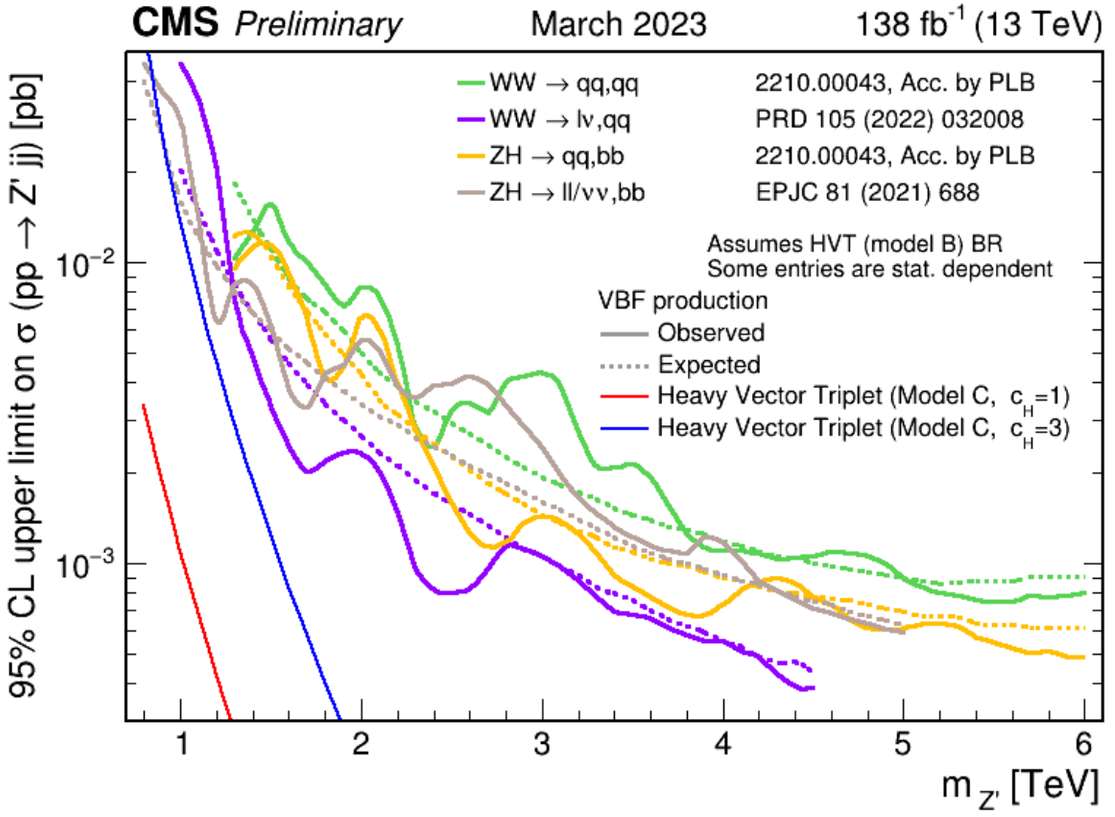
Interpretation performed in heavy-vector triplet models for scenarios with suppressed V'→ fermion couplings

Pappadopulo, Thamm, Torre, Wulzer (2014)

Drell-Yan production



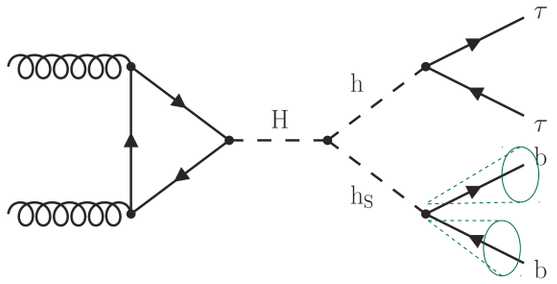
VBF production



- Comparable sensitivity between Z' → WW & Z' → ZH searches

- ZH search offers best senstivity for Z' production via VBF at very high mass

X→YH → bbττ



Final states considered:

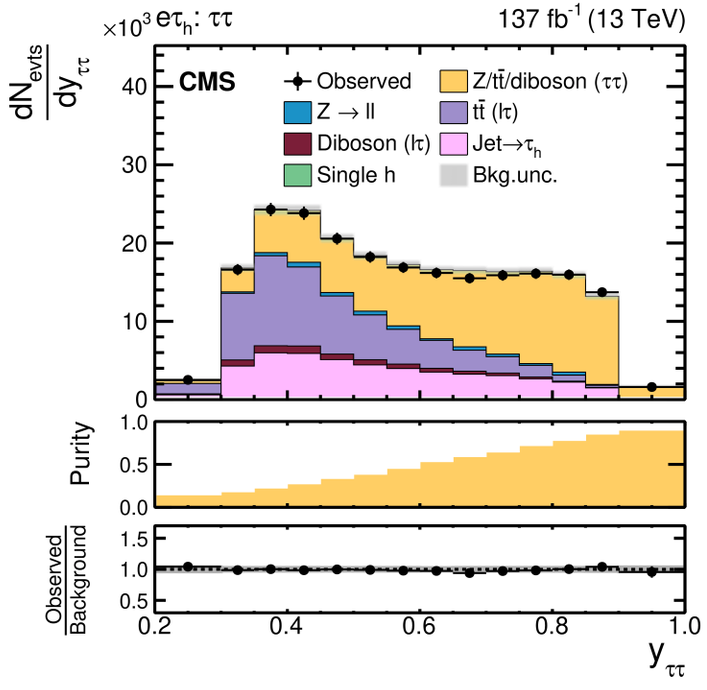
$e\tau_h$ + bb, $\mu\tau_h$ + bb, $\tau_h\tau_h$ + bb

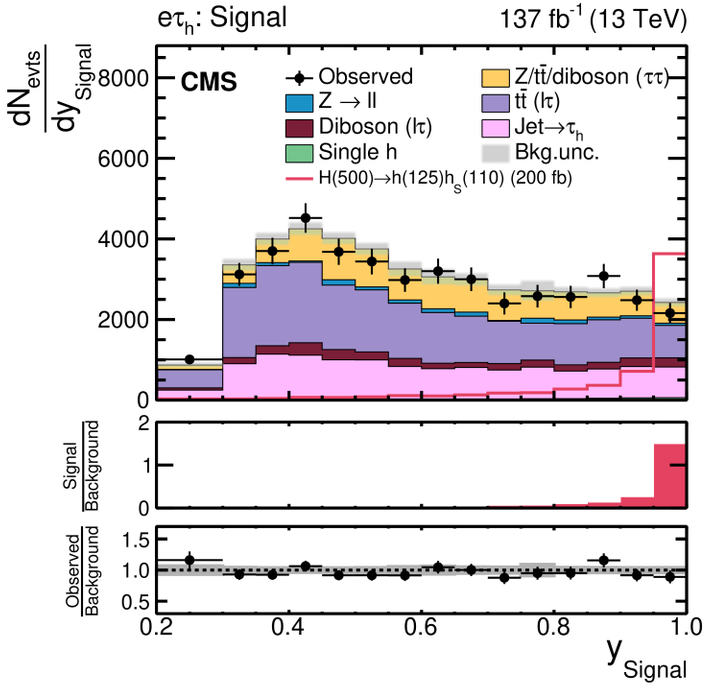
Dominant backgrounds:

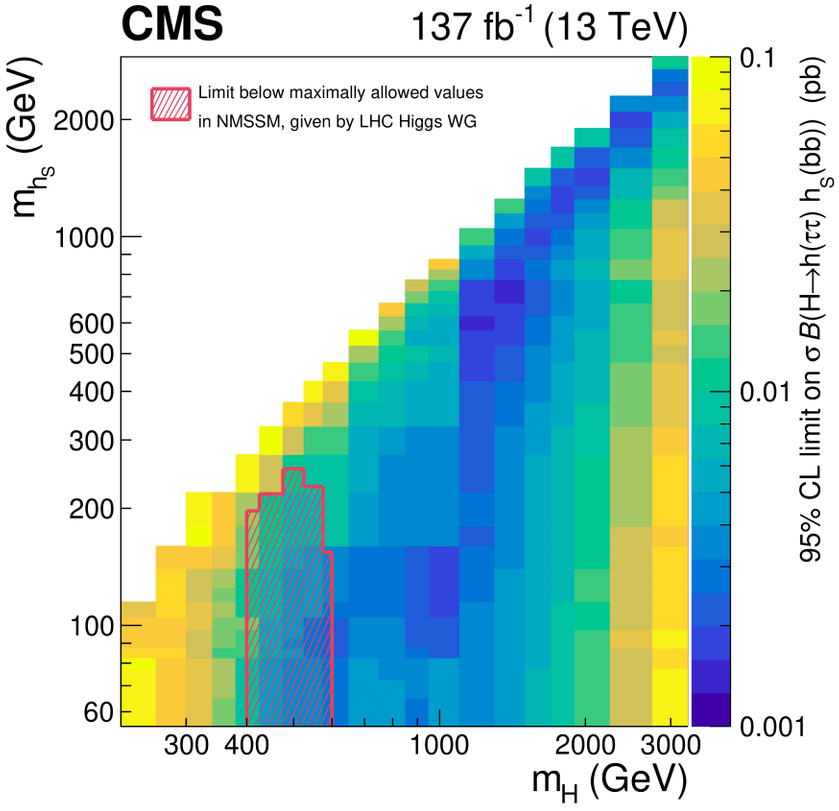
Real τ: DY / VV/ tt → ττ ← estimated from data

Jet faking as τ_h

- Separate multiclass neural network (NN) trainings with multiple (clusters of) signals + background processes
- NN discriminators used to extract signal & control background shapes



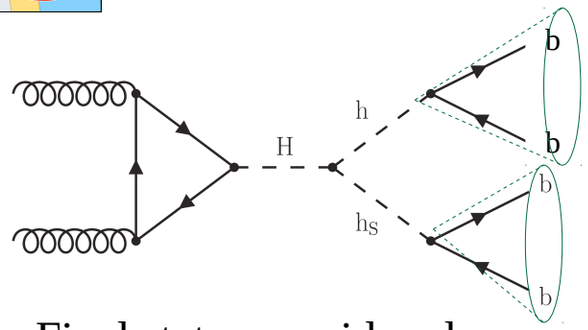




No significant excess observed on 2-D mass plane

Phys. Lett. B 842 (2023) 137392

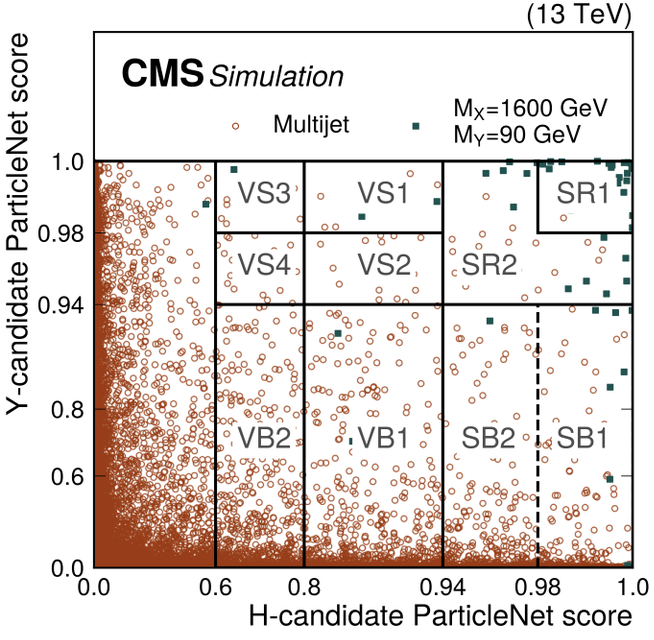
X→YH → bbbb (boosted)



Final states considered:

2 AK8 jets

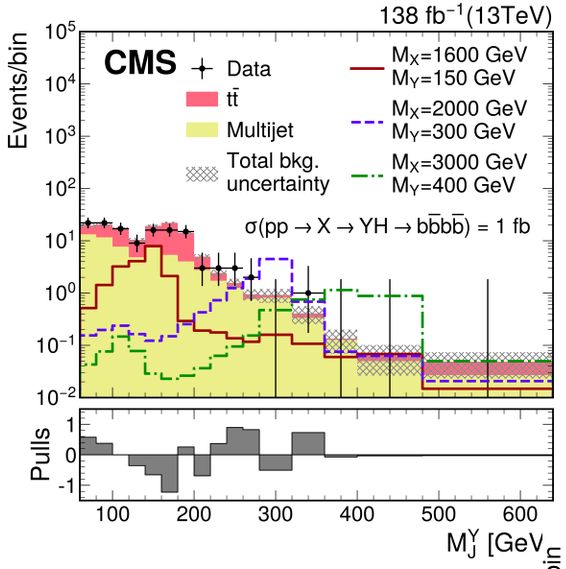
- Graph-neural network based jet tagging boost signal sensitivity

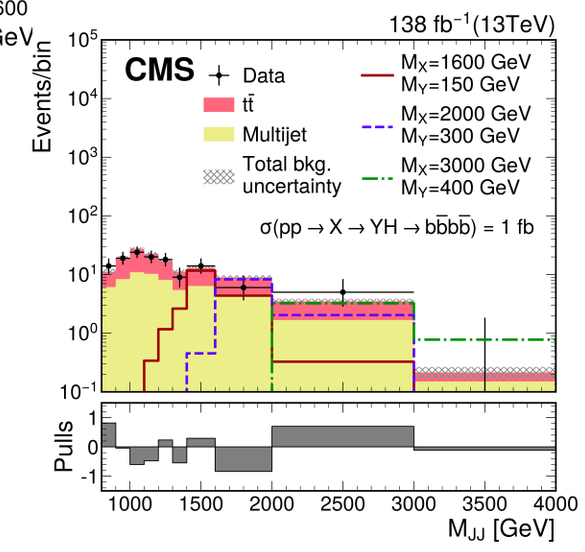


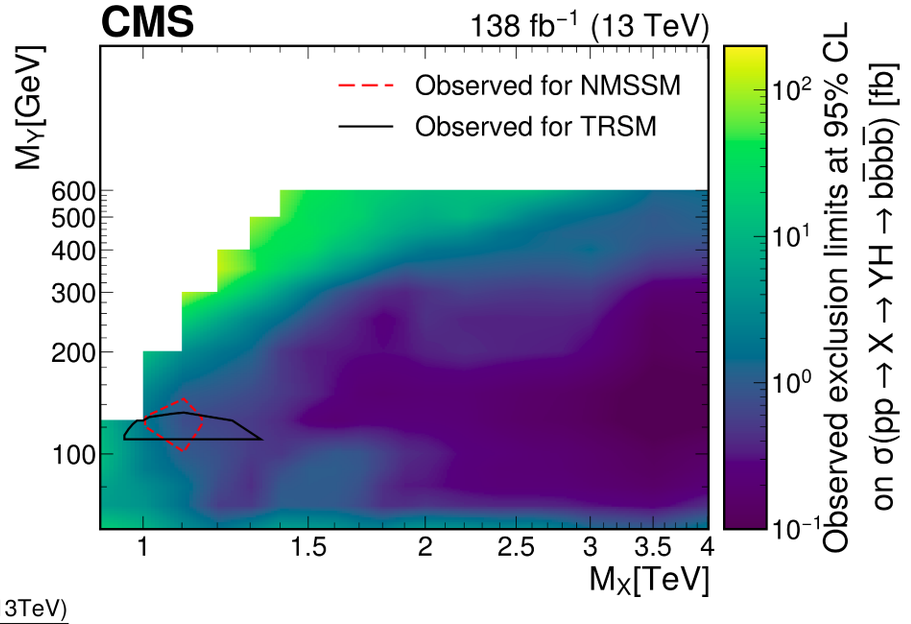
Dominant backgrounds:

Multijet production in QCD ← estimated from data

tt ← estimated from simulation + data-based correction





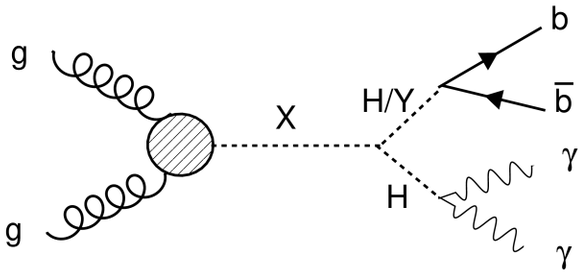


Search is sensitive to allowed parameter spaces in multiple models :)

Multiple signal regions to cover wide range X & Y masses

arXiv:2310.01643

X→HH/YH → bb γγ



Final states considered:

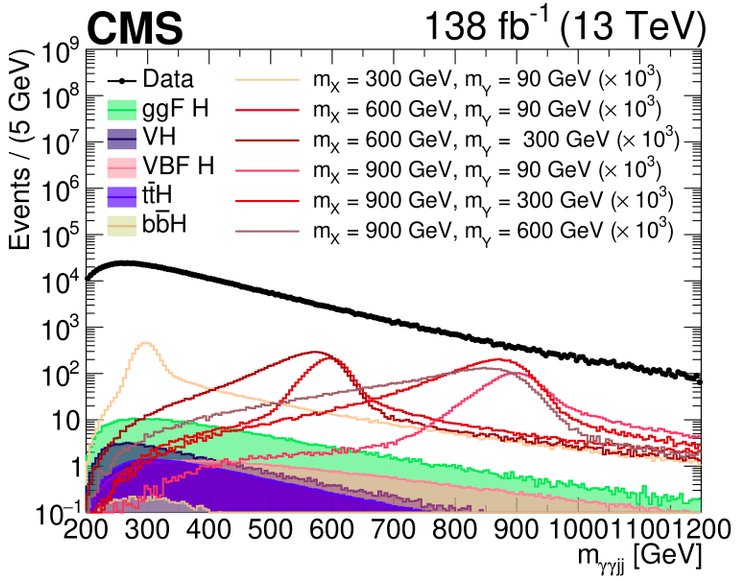
2 isolated photons + 2 (b-tagged) AK4 jets

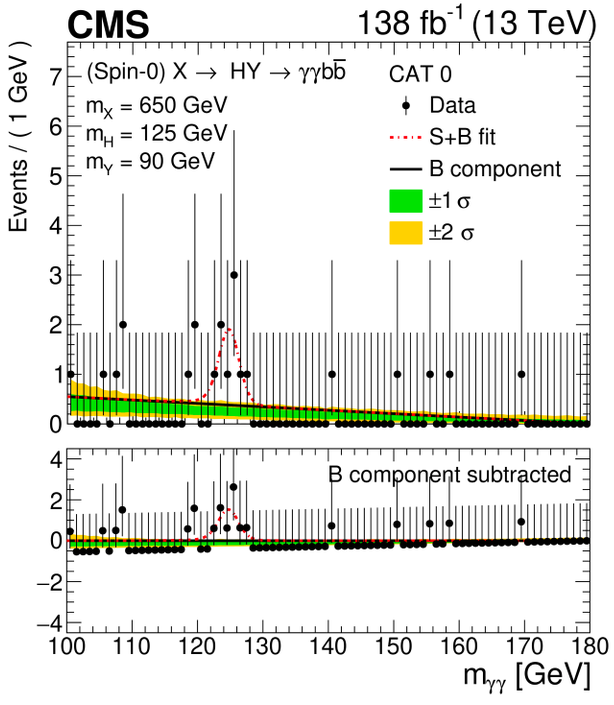
Dominant backgrounds:

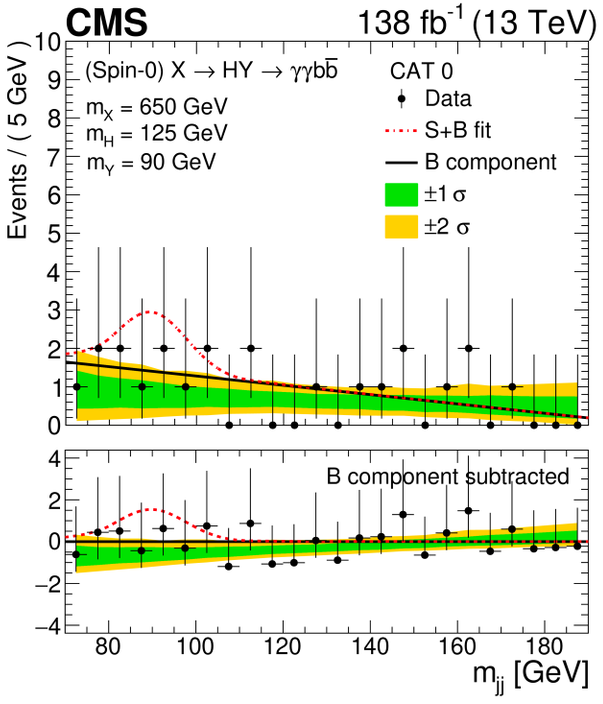
- γ+jets, γγ+jets, production in QCD
  ← reduced using BDT *trained in multiple exclusive regions targeting different m_X-m_Y ranges*
  + estimated with functional forms fitted using data
- Resonant ttH(→γγ) background reduced using neural network

* 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

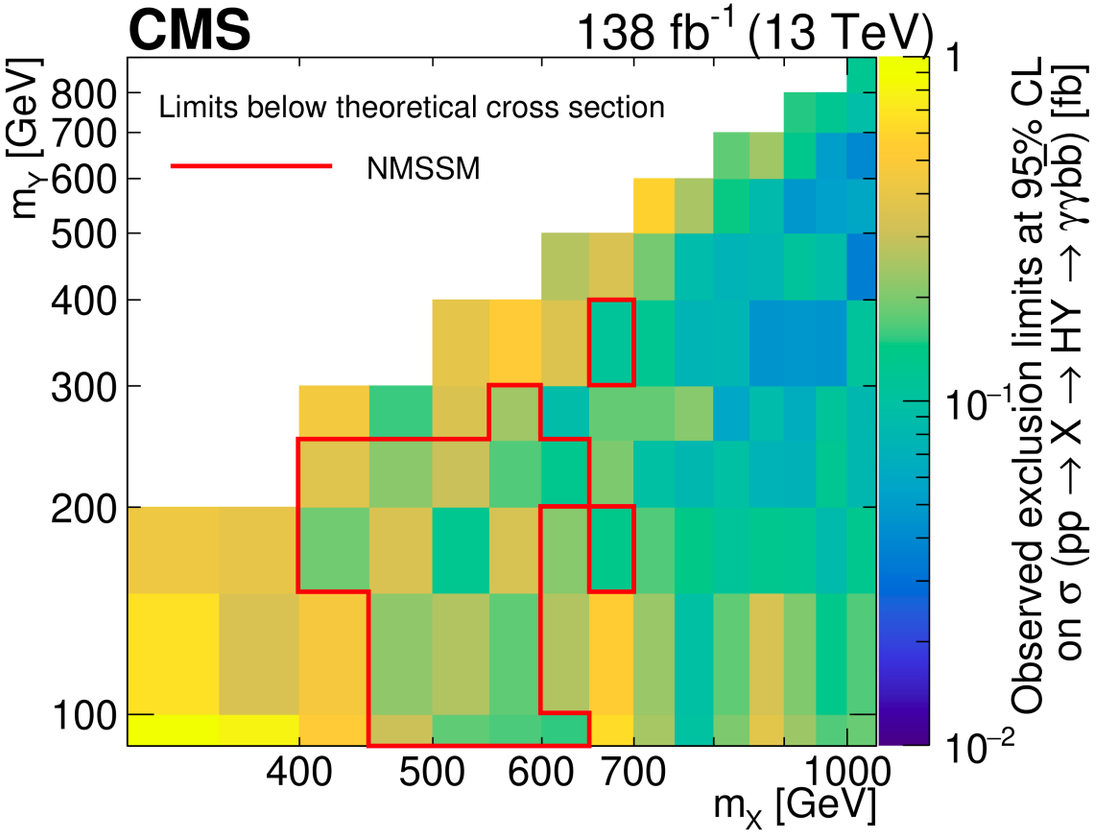


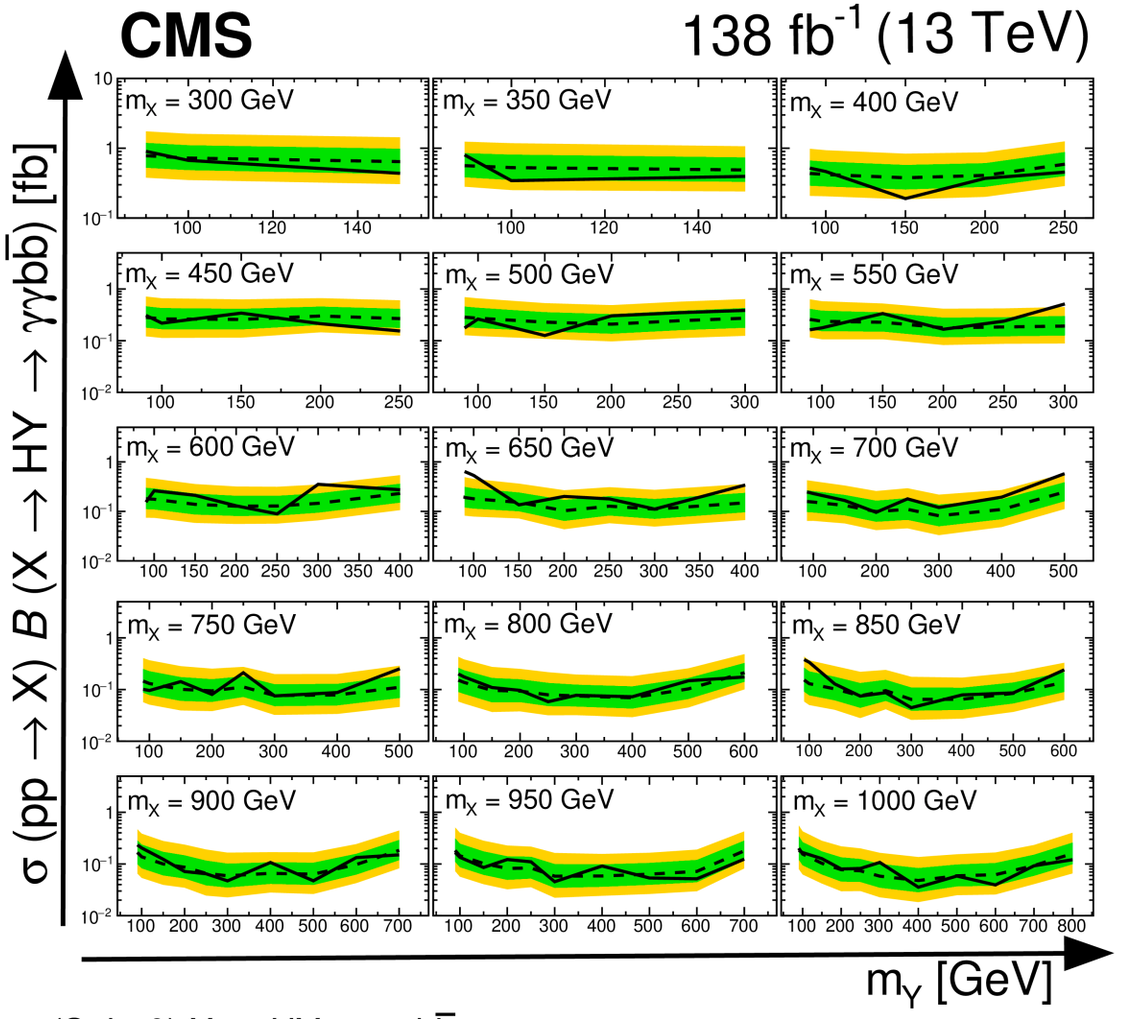




arXiv:2310.01643

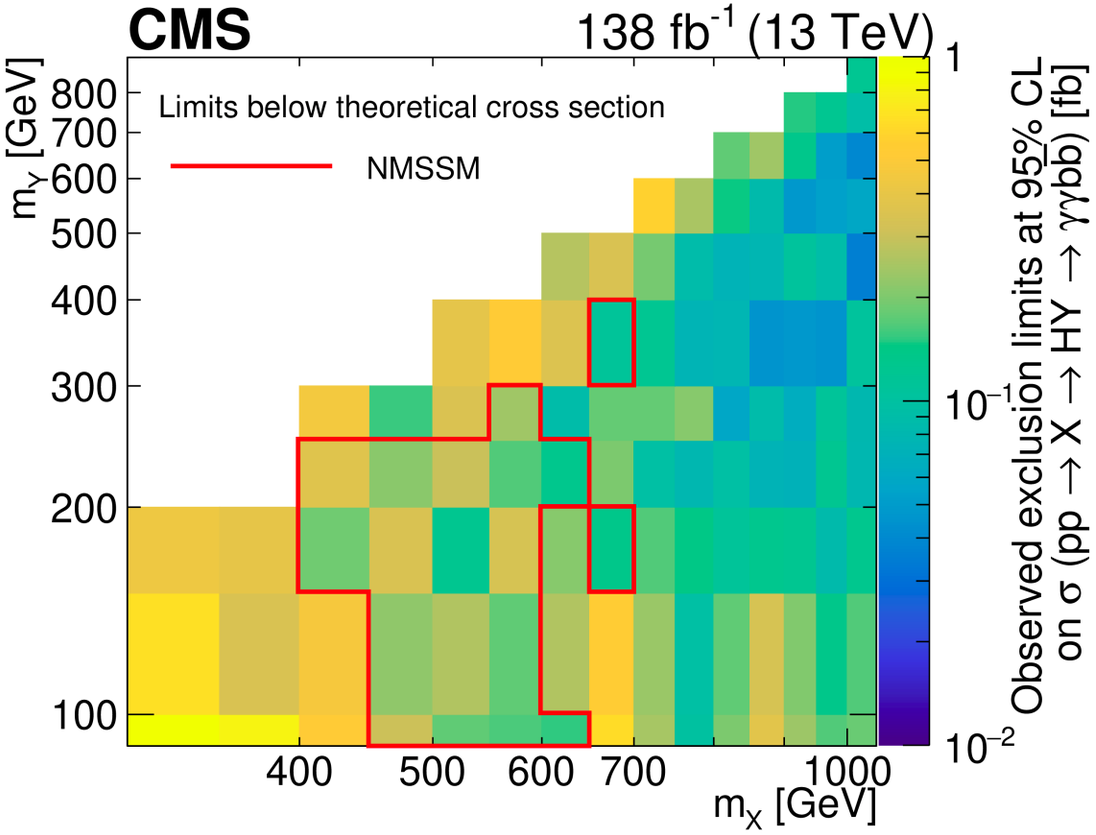
X→HH/YH → bb γγ (contd ...)

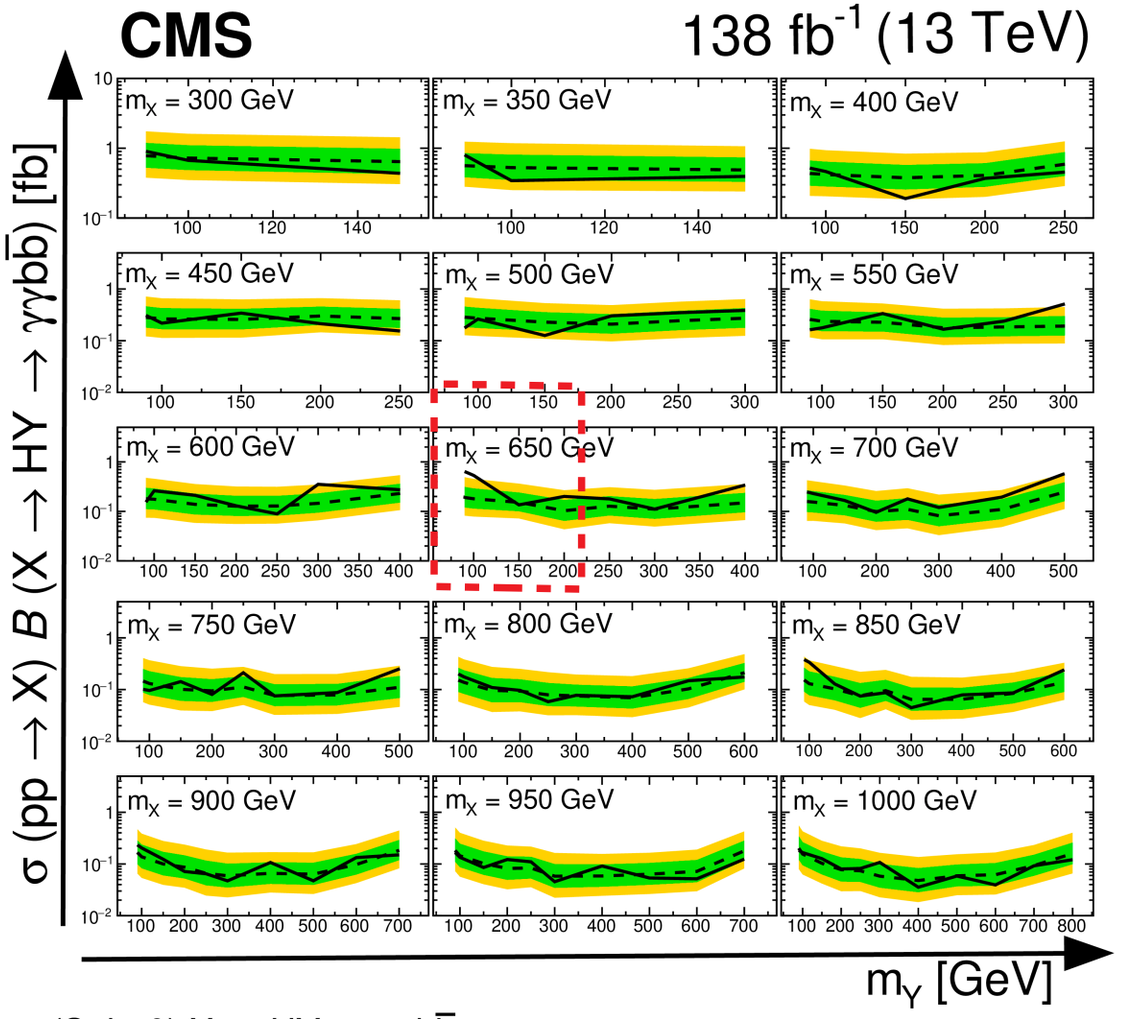




arXiv:2310.01643

X→HH/YH → bb γγ (contd ...)



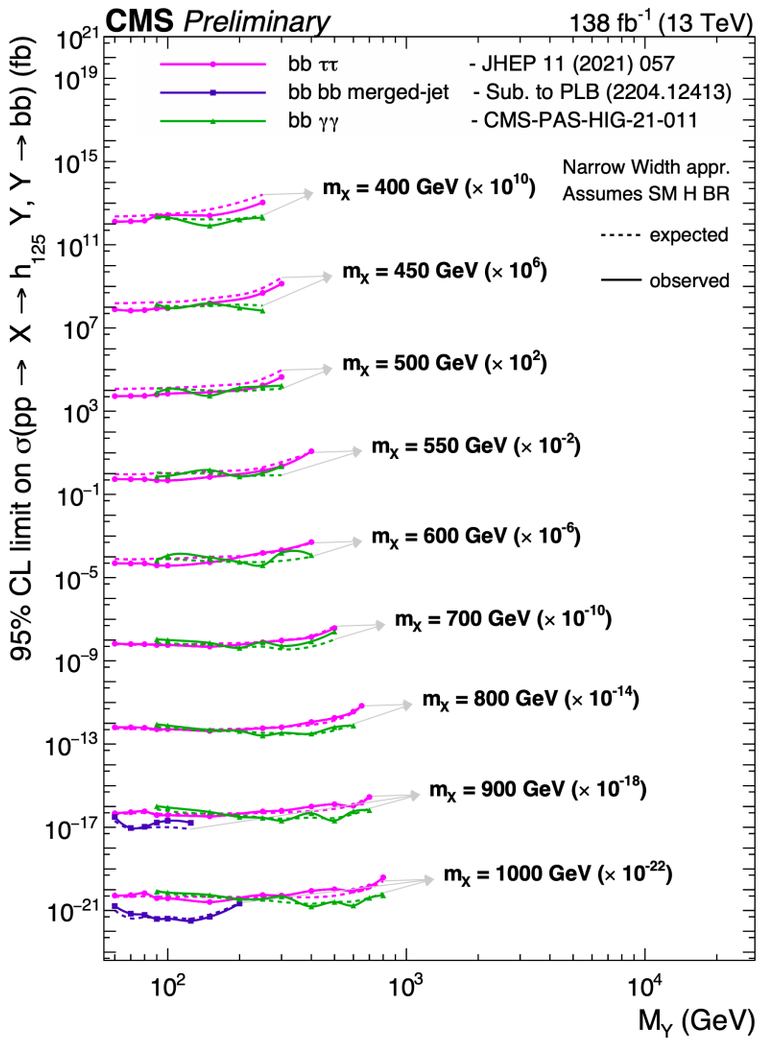


Excess observed at m_X, m_Y = 650, 100 GeV

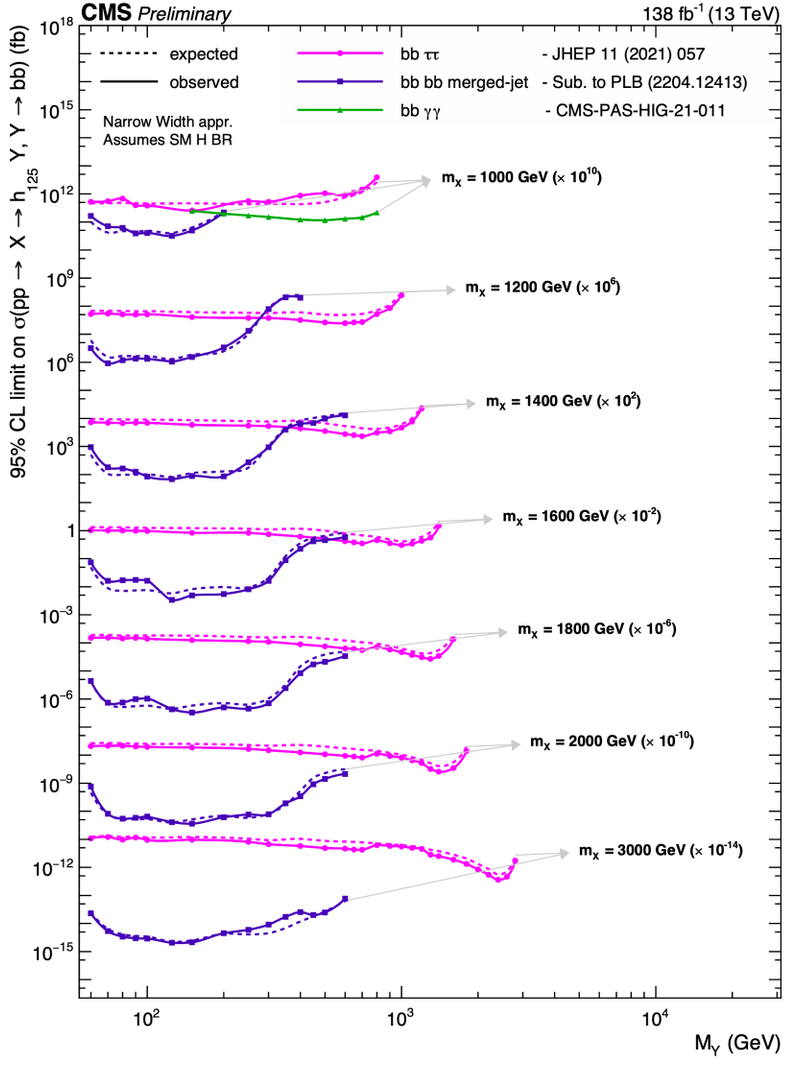
← 3.8 (2.8) local (global) significance

Summary plots (X→YH)

X mass: < 1 TeV

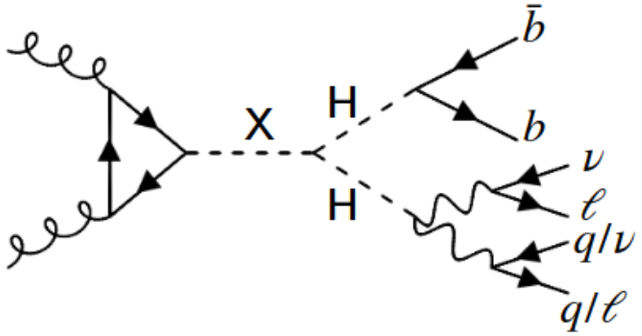


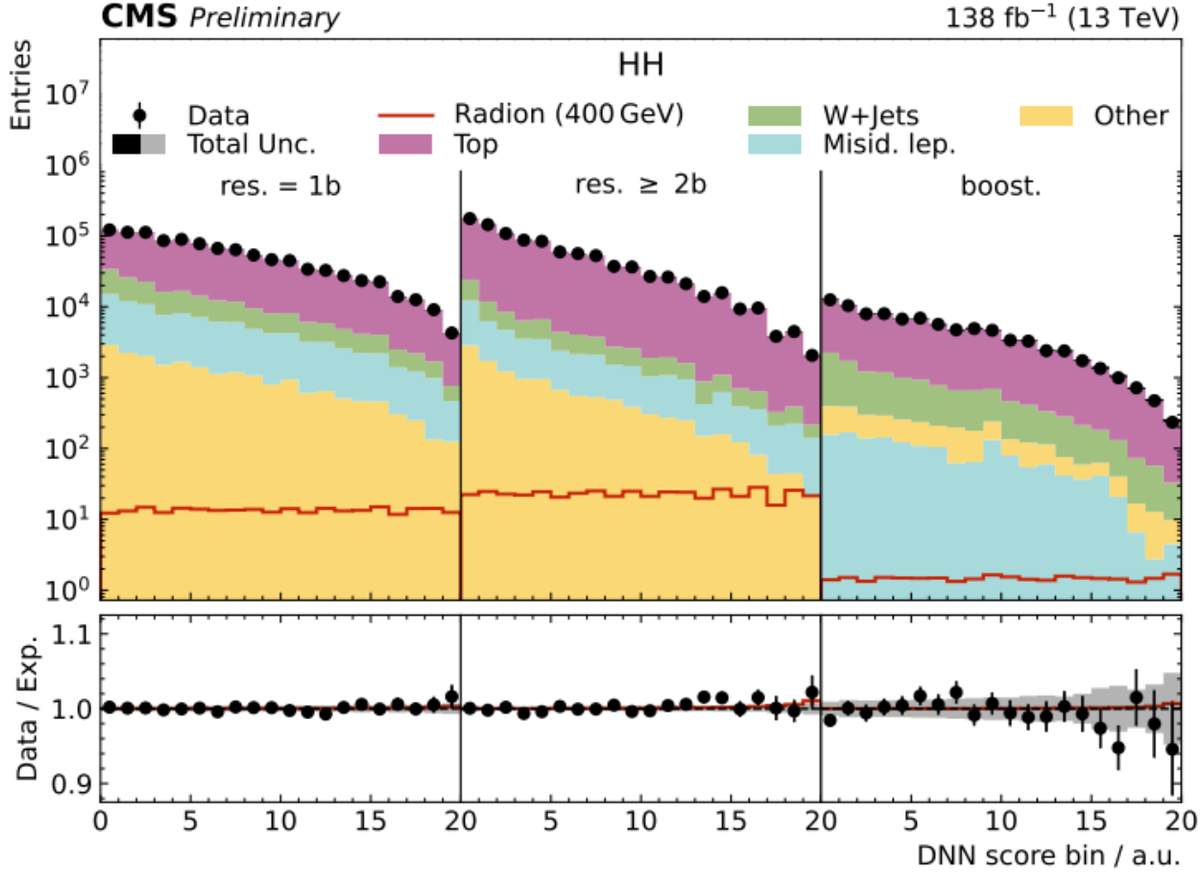
X mass: >= 1 TeV



Complementary sensitivity in analyses targeting different final states

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

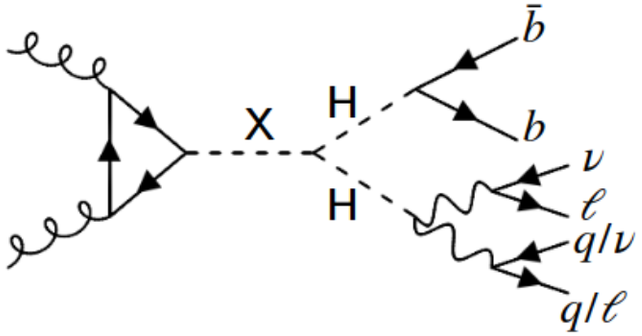
All other background processes estimated using simulation

Deep neural network training:

- separate signal & background
- score used to extract signal

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

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:

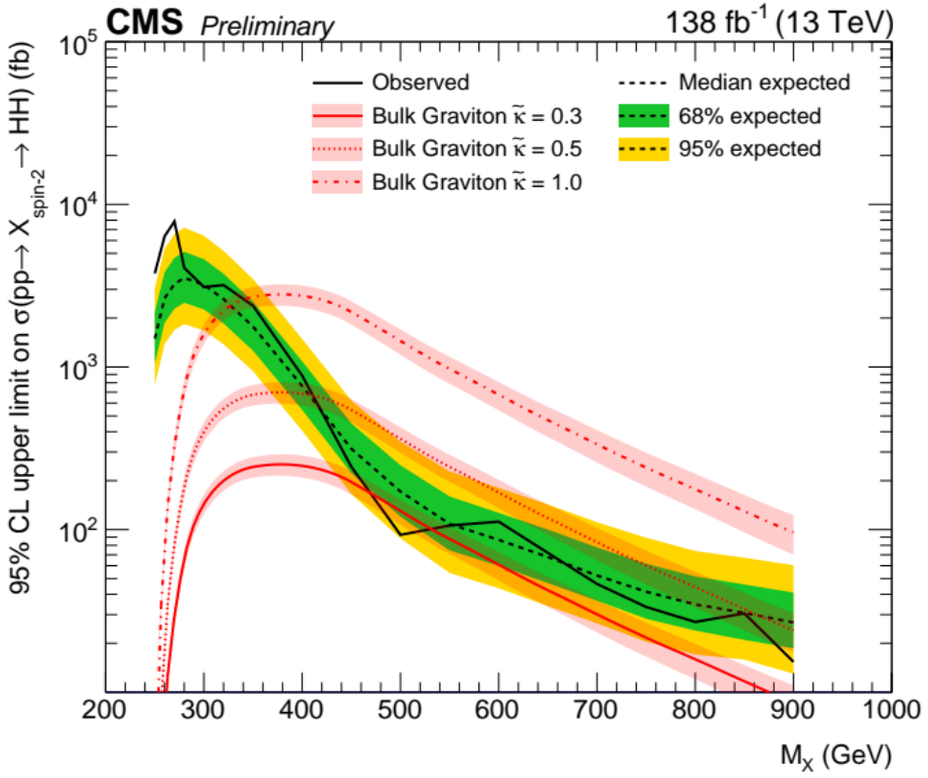
Data-driven approach for particular backgrounds:
- 1 lepton channel: fake lepton background
- 2 lepton channel: Drell-Yan + jets background

All other background processes estimated using simulation

Deep neural network training:

- separate signal & background
- score used to extract signal

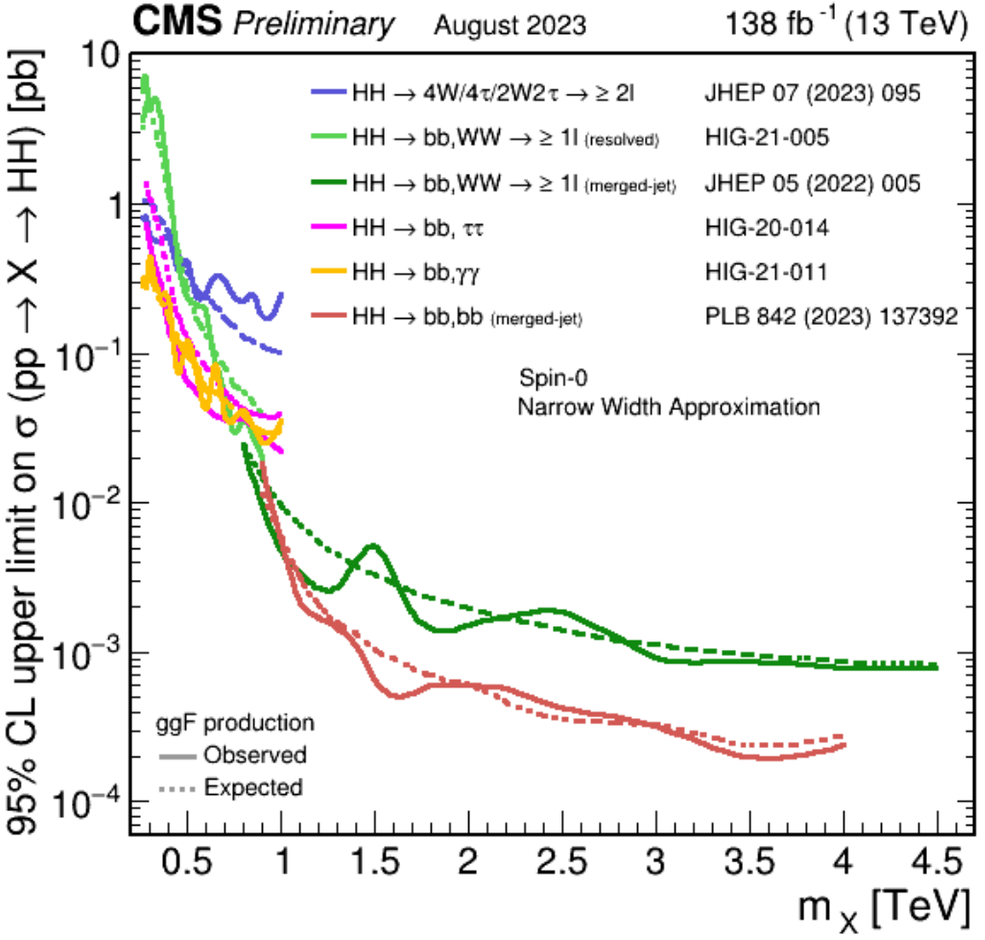
Training performed separately for single- and di-lepton final states



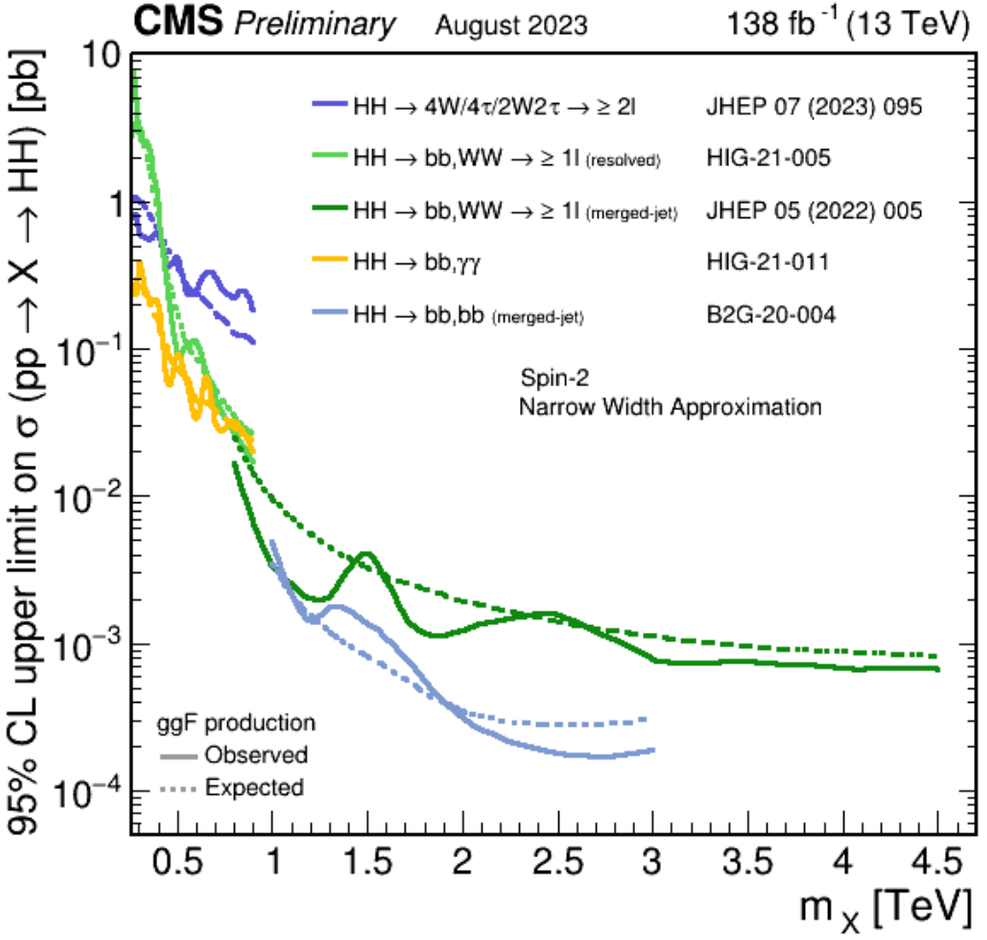
Model-independent constraints placed on spin-0 CP-even resonance (also on spin-2 resonances)

Summary plots (X→HH)

Constraints on spin-0 Radion



Constraints on spin-2 Graviton

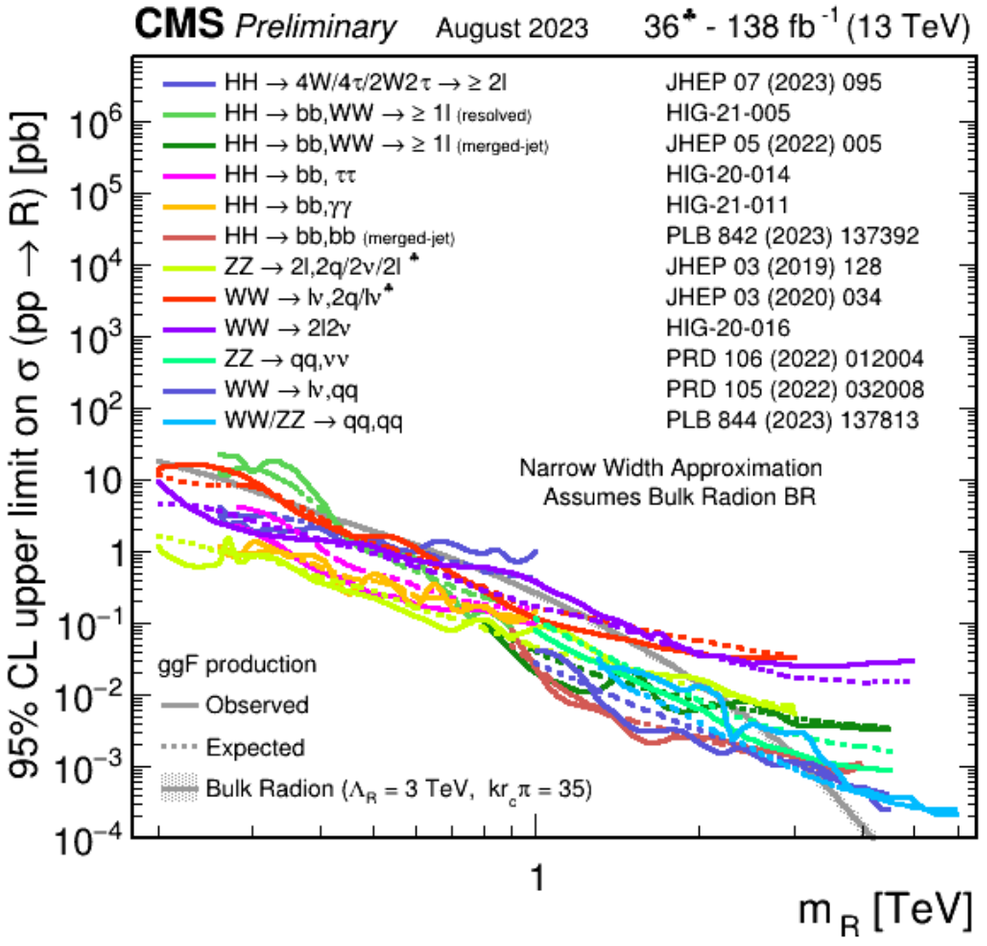


Nice complementarity between analyses targeting

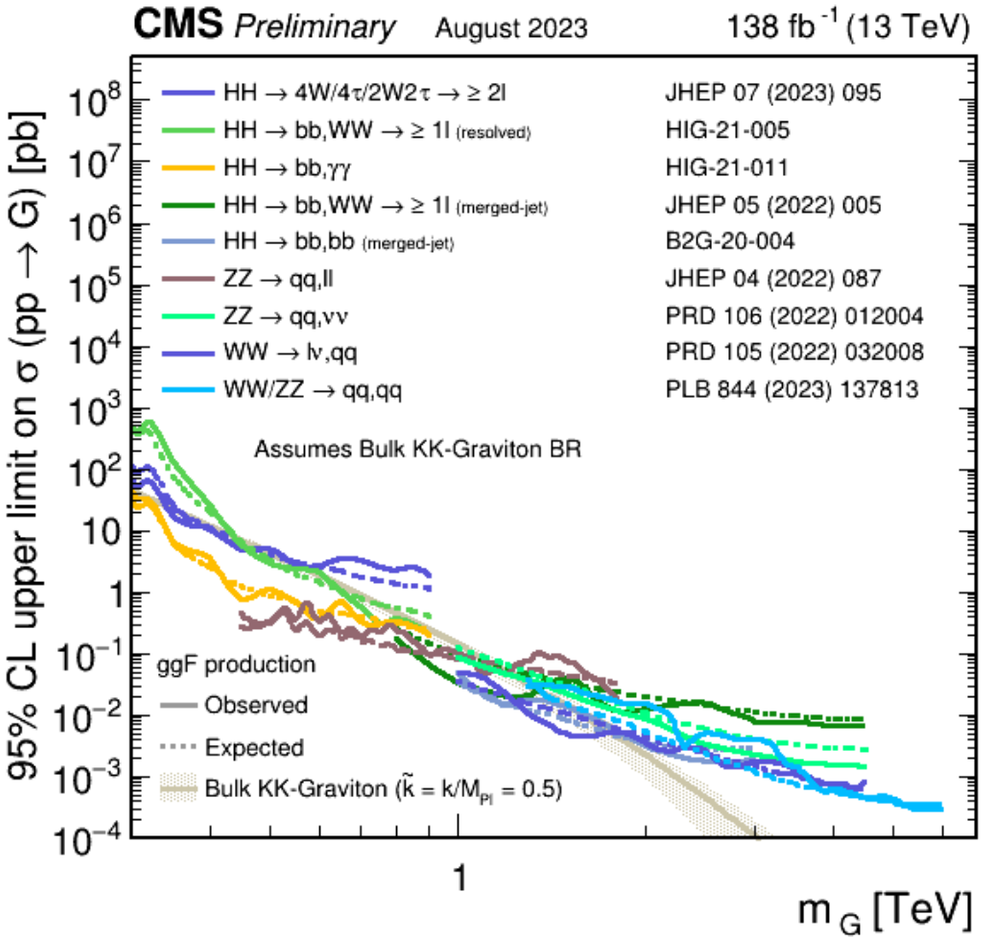
- resolved and boosted topologies
- different final states

Summary plots (X→HH/VV)

Constraints on spin-0 Radion



Constraints on spin-2 Graviton



Comparable sensitivity in analyses targeting X → HH & X → VV decays

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

- Multiple analyses discussed targeting different topologies and final states

  - Resolved vs boosted

  - Final states with: Electrons, Muon, Taus, Photons, Small-radius / Large-radius jets

- Some local excesses are observed

- Looking forward to share new results w/ Run-3 data 'soon' !!

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

All these results are being summarized in a review article!

- Multiple analyses discussed targeting different topologies and final states

  - Resolved vs boosted

  - Final states with: Electrons, Muon, Taus, Photons, Small-radius / Large-radius jets

- Some local excesses are observed

- Looking forward to share new results w/ Run-3 data 'soon' !!

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

All these results are being summarized in a review article!

- Multiple analyses discussed targeting different topologies and final states

  - Resolved vs boosted

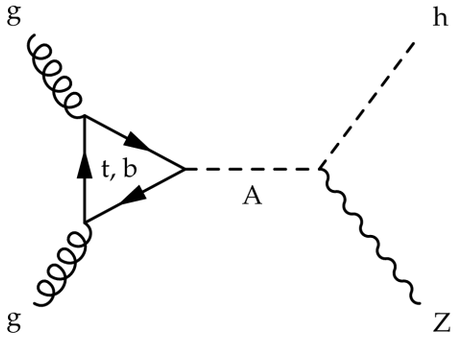
  - Final states with: Electrons, Muon, Taus, Photons, Small-radius / Large-radius jets

- Some local excesses are observed

- Looking forward to share new results w/ Run-3 data 'soon' !!

Extra Material

A→ ZH → ll/vvbb



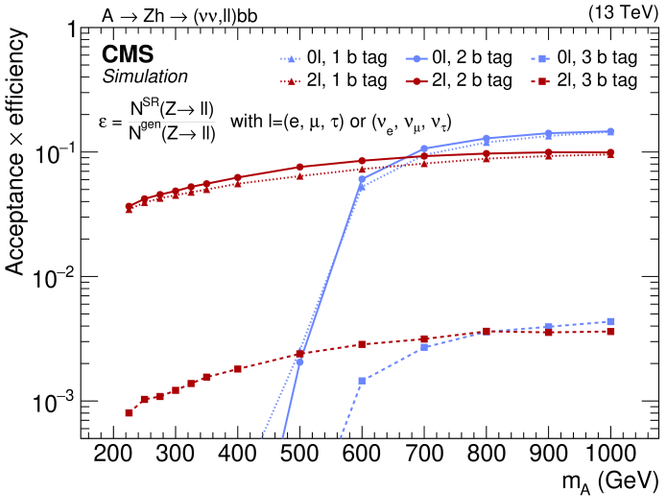
- Use of kinematic and angular information to reduce bkg
- Background primarily from simulation
  + normalization extracted from multiple control regions

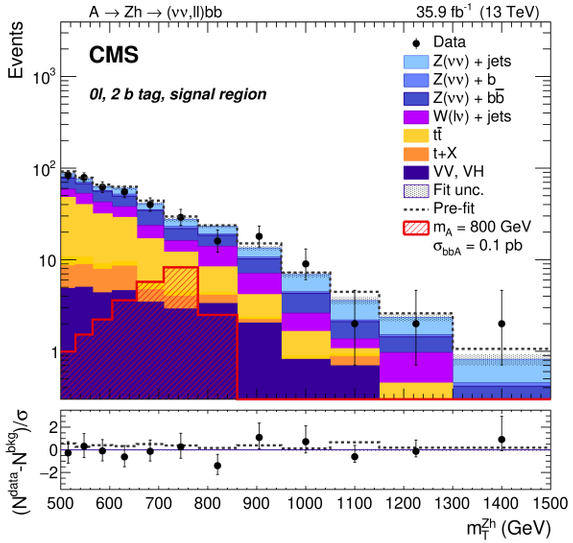
<u>Decay mode:</u>

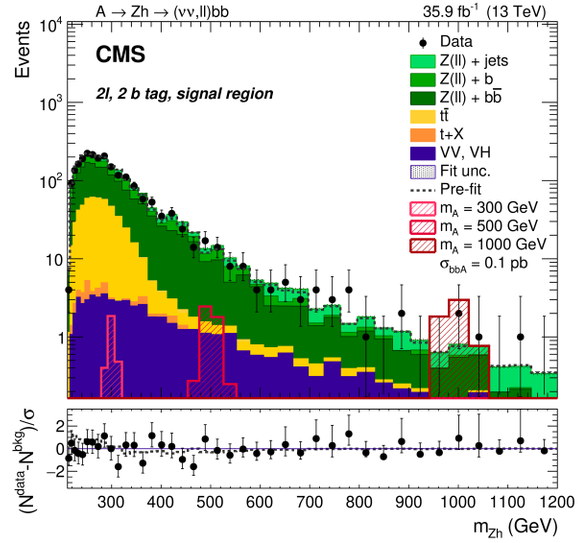
$Z \rightarrow l\,l$ / $\nu\nu + H \rightarrow b\,b$

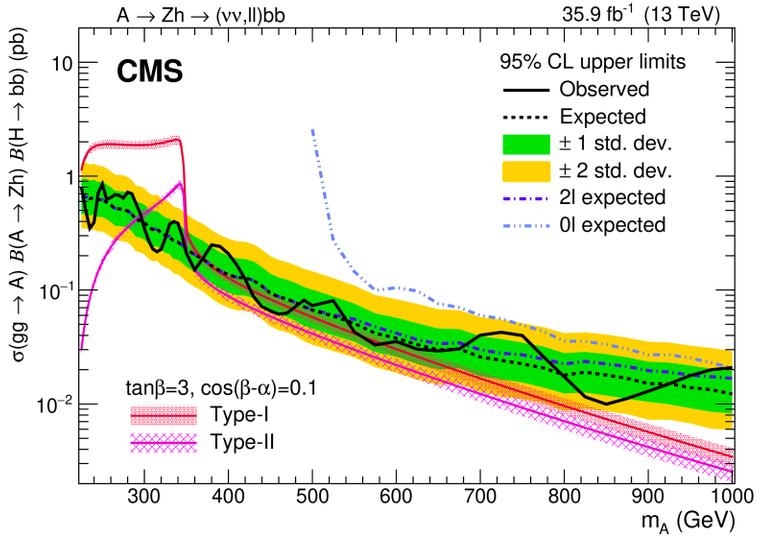
<u>Final states considered:</u>

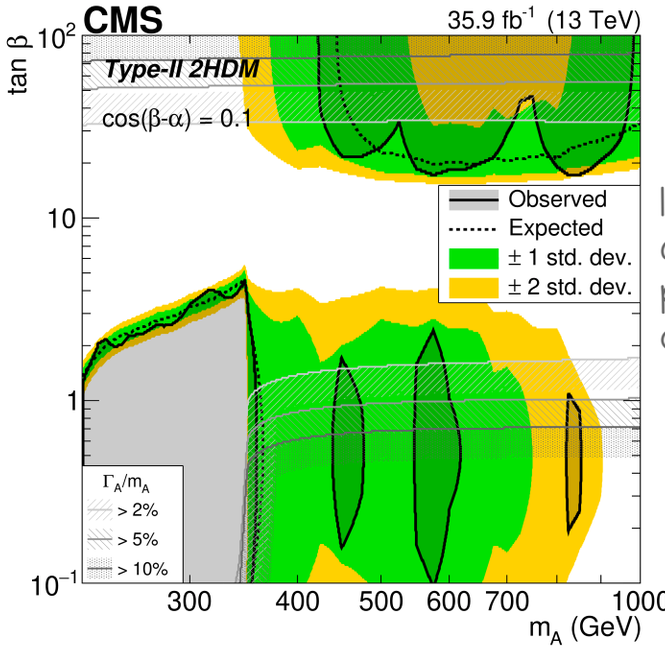
0/2 leptons + 1/2/3 b-tags









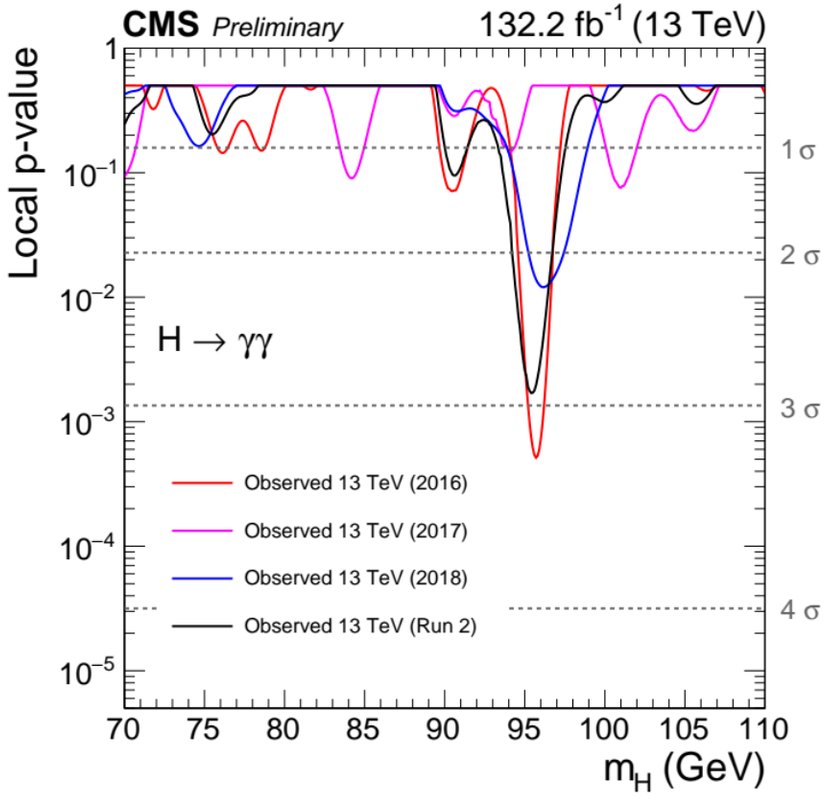


Interpretation also performed in other 2HDMs

Strong constraints at low tanβ + $m_A < 2m_t$

Some excesses in recent times seen by CMS

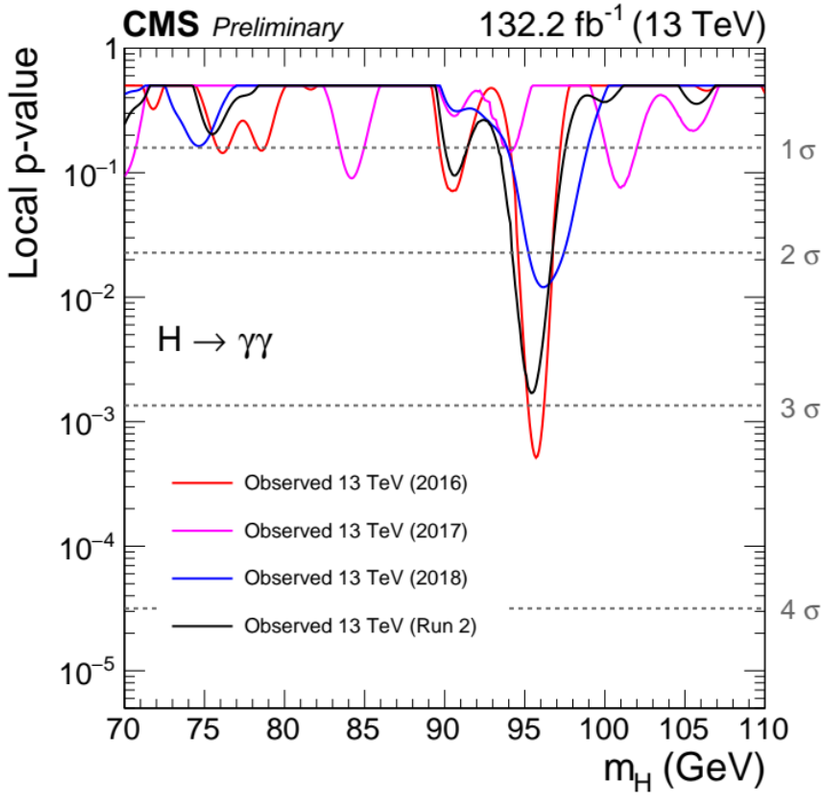
Low-mass di-photon search ($\varphi \rightarrow \gamma\gamma$)



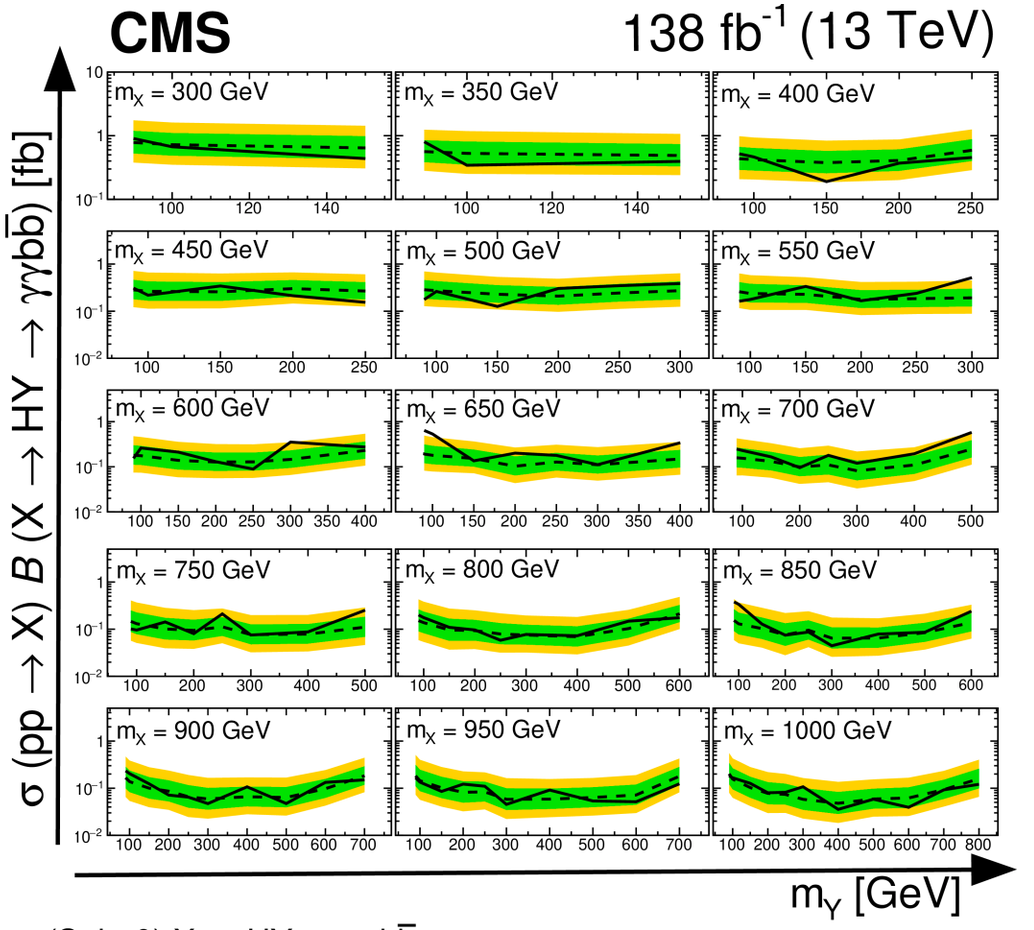
CMS-PAG-HIG-20-002

Some excesses in recent times seen by CMS

Low-mass di-photon search ($\varphi \rightarrow \gamma\gamma$)



X→ H(→ γγ) Y(→ bb) resonance search



(Spin-0) X → HY → γγbb̄

Expected limit ±1 σ Expected limit ±2 σ

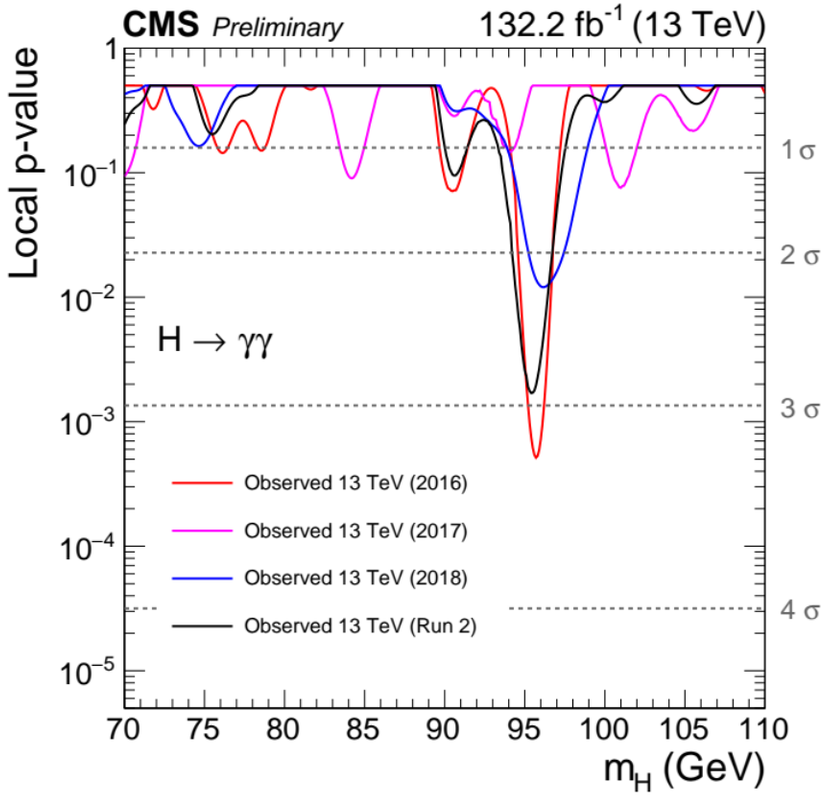
Expected 95% upper limit Observed 95% upper limit

CMS-PAG-HIG-20-002

arXiv: 2310.01643

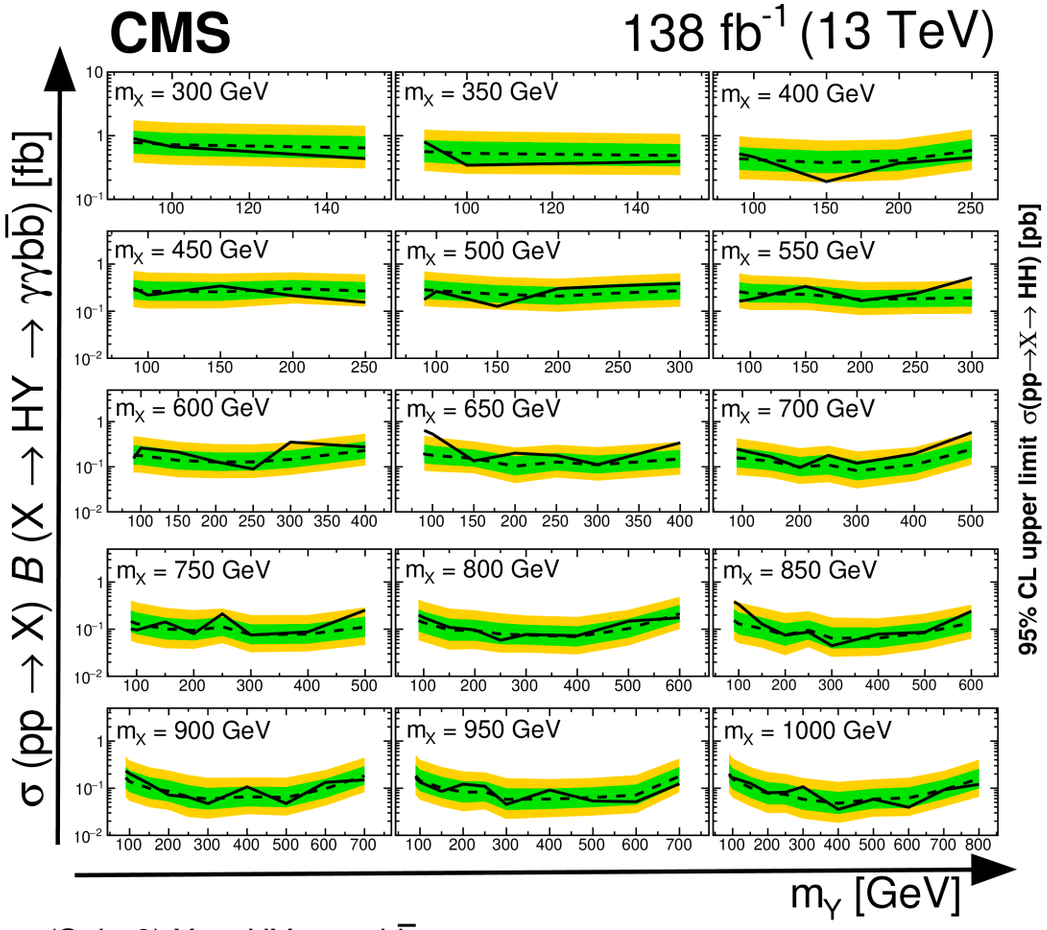
Some excesses in recent times seen by CMS

Low-mass di-photon search ($\varphi \rightarrow \gamma\gamma$)



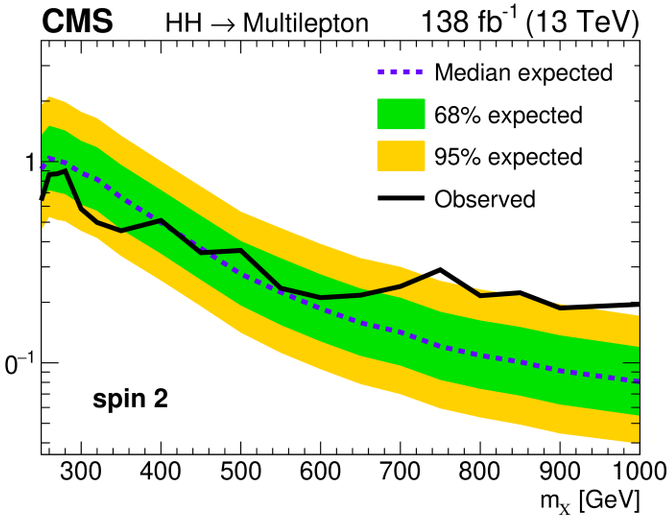
CMS-PAG-HIG-20-002

X→ H(→ γγ) Y(→ bb) resonance search



arXiv: 2310.01643

X→ HH → WWWW/WWττ/ττττ resonance search



JHEP07(2023)095