Search for HH/HY resonances with $\gamma\gamma$ in the final state at CMS

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on behalf of CMS collaboration

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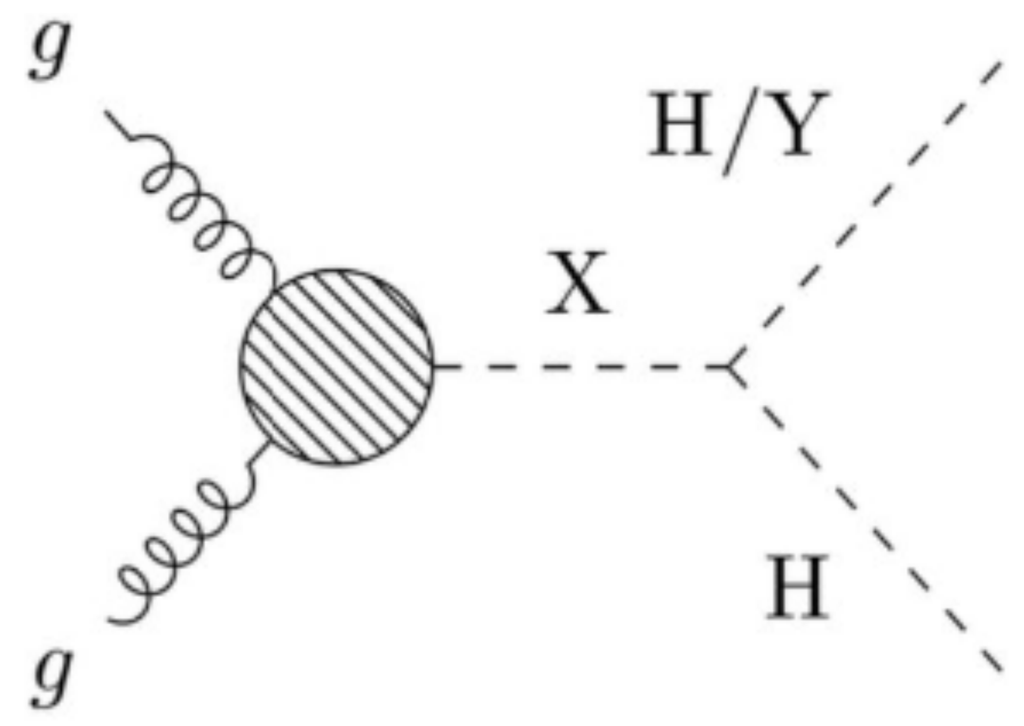
Introduction

- The standard model: the most successful so far, but not complete.
  - Open questions: the hierarchy problem, origin of dark matter etc
- Higgs boson could be a probe to explore new physics
- Many BSM theories predict new massive resonances that could interact with the SM Higgs boson.
  - New heavy resonance could decay to two SM Higgs bosons
    - Extended Higgs Sectors, Warped Extra Dimensions…
  - New heavy resonance could decay to one SM Higgs boson + one scalar (Y)
    - NMSSM, TRSM…

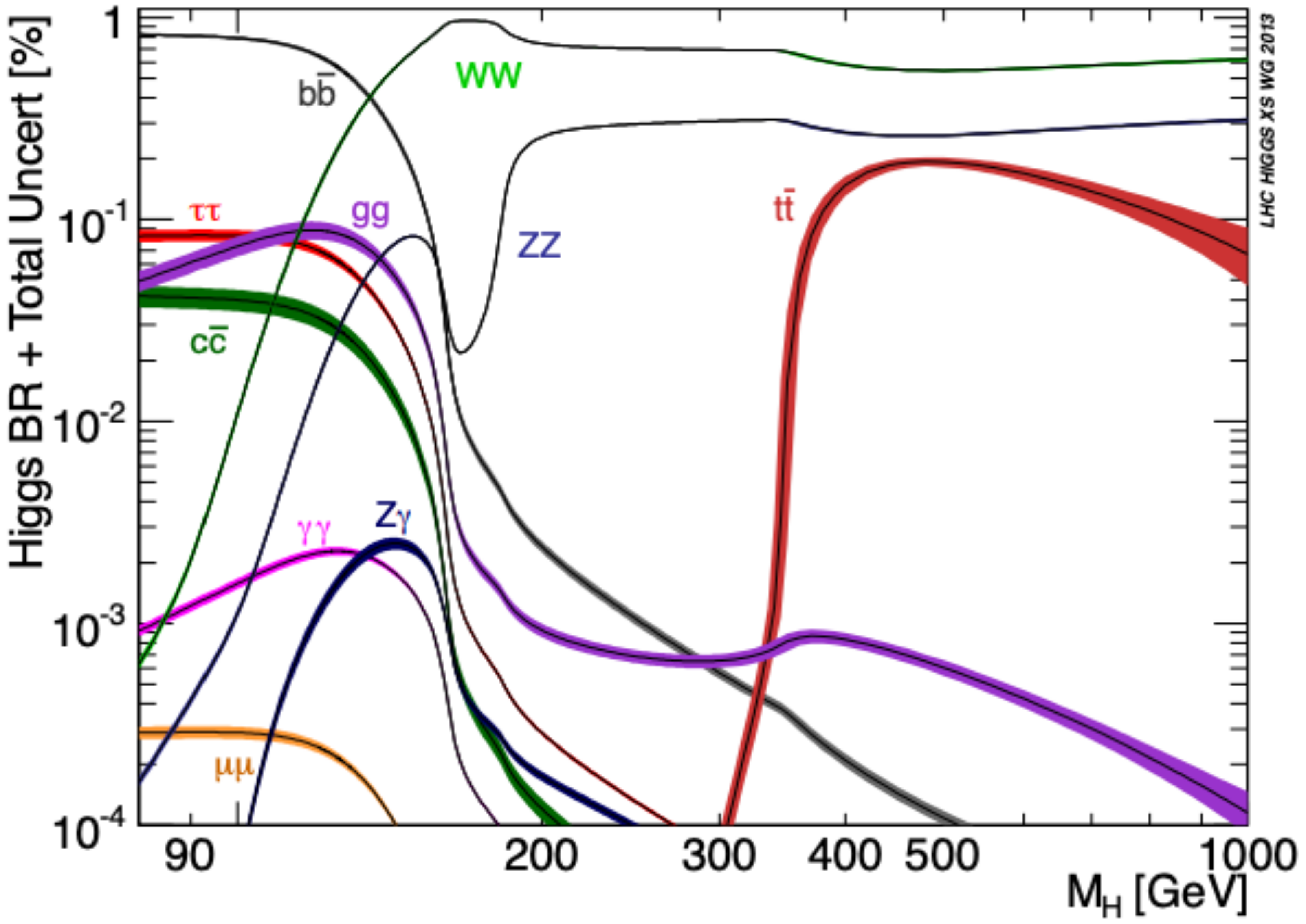


Search for X→HH/YH at CMS with full Run2 data

- 40 possible combinations of YH decay modes
- Large available parameter space (m_X, m_Y)
- Many YH channels have been explored in CMS with full Run2 data
- All X → YH(125) cover X → H(125)H(125)
- 3 YH analysis will be discussed in more detail :
  - Y(bb)H(γγ) [JHEP05(2024)316]
  - Y(γγ)H(ττ)/Y(ττ)H(γγ) [CMS-PAS-HIG-22-012]
  - Y(γγ)H(bb) [CMS-PAS-B2G-24-001]
- H → γγ handle with good resolution and high selection efficiency
- H → bb have the largest H(125) branch ratio
- H → ττ are relatively clean, compared to multijet and ttbar background.

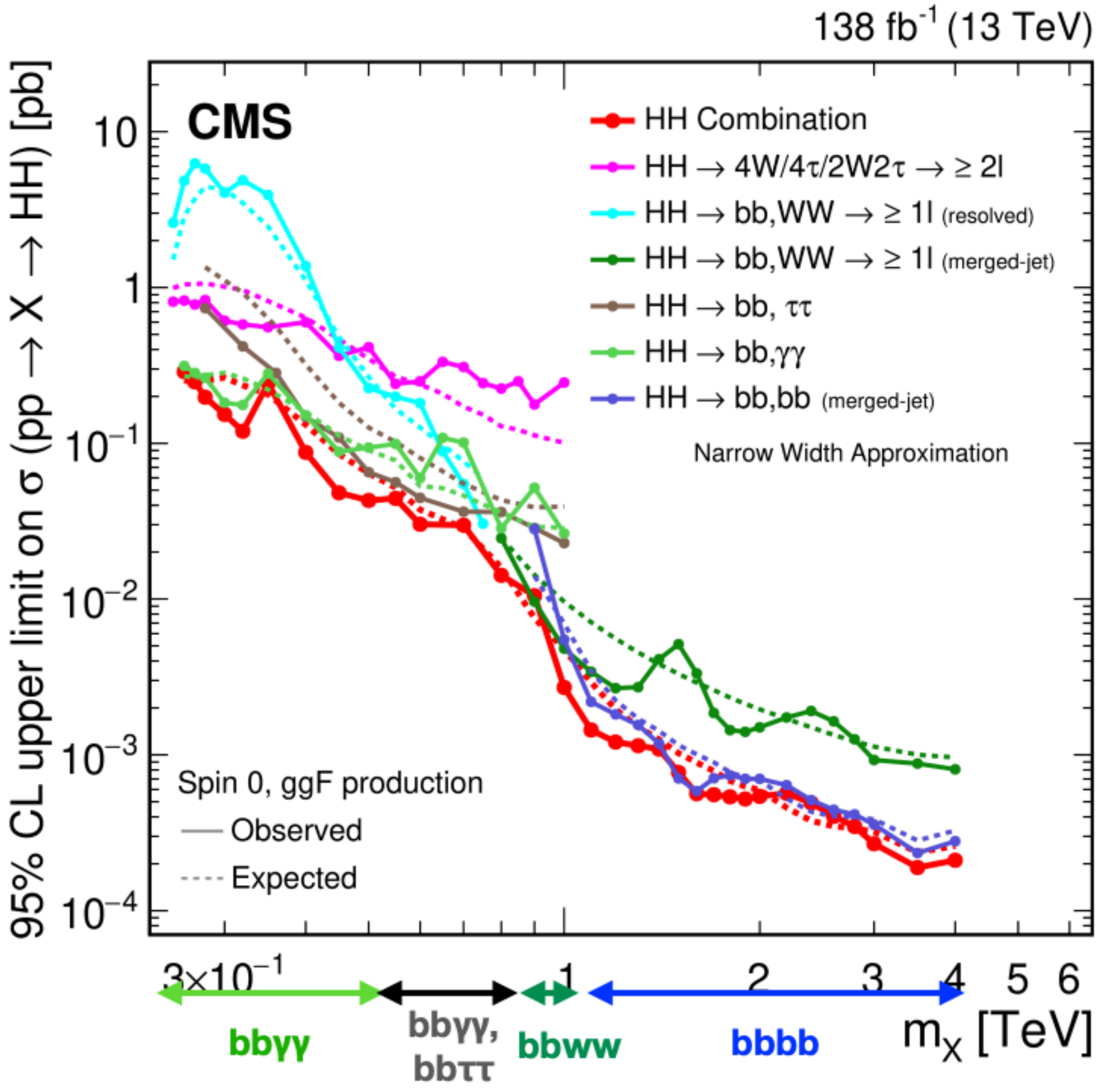
Talk from Shin-Shan in LP2025

X→YH	h→bb	h→WW	h→ττ	h→ZZ	h→γγ
BR(h→X)	58.24%	21.37%	6.272%	2.619%	0.227%
Y→bb	✔		✔		✔
Y→WW	✔		✔		✔
Y→ττ					✔
Y→ZZ	✔		✔		✔
Y→γγ	✔		✔		
Y→HH	✔				
Y→tt	✔				
Y→qq	✔				
Y→anomaly	✔				



Search for X→HH/YH at CMS with full Run2 data

- $X \to H(125)H(125)$
- HH combination
  - Limits on $\sigma_{X \to HH}$: 0.19 - 288 fb
- 3 HH analysis will be discussed in more detail :
  - $H(bb)H(\gamma\gamma)$ [JHEP05(2024)316]
  - $H(\tau\tau)H(\gamma\gamma)^{*}$ [CMS-PAS-HIG-22-012]
  - $H(WW)H(\gamma\gamma)^{*}$ [CMS-PAS-B2G-24-010]
- $H \to \gamma\gamma$ handle with good resolution and high selection efficiency
- $H \to bb$ have the largest $H(125)$ branch ratio
- $H \to \tau\tau$ are relatively clean, compared to multijet and ttbar background.
- $H \to WW$ have the second largest $H(125)$ branch ratio



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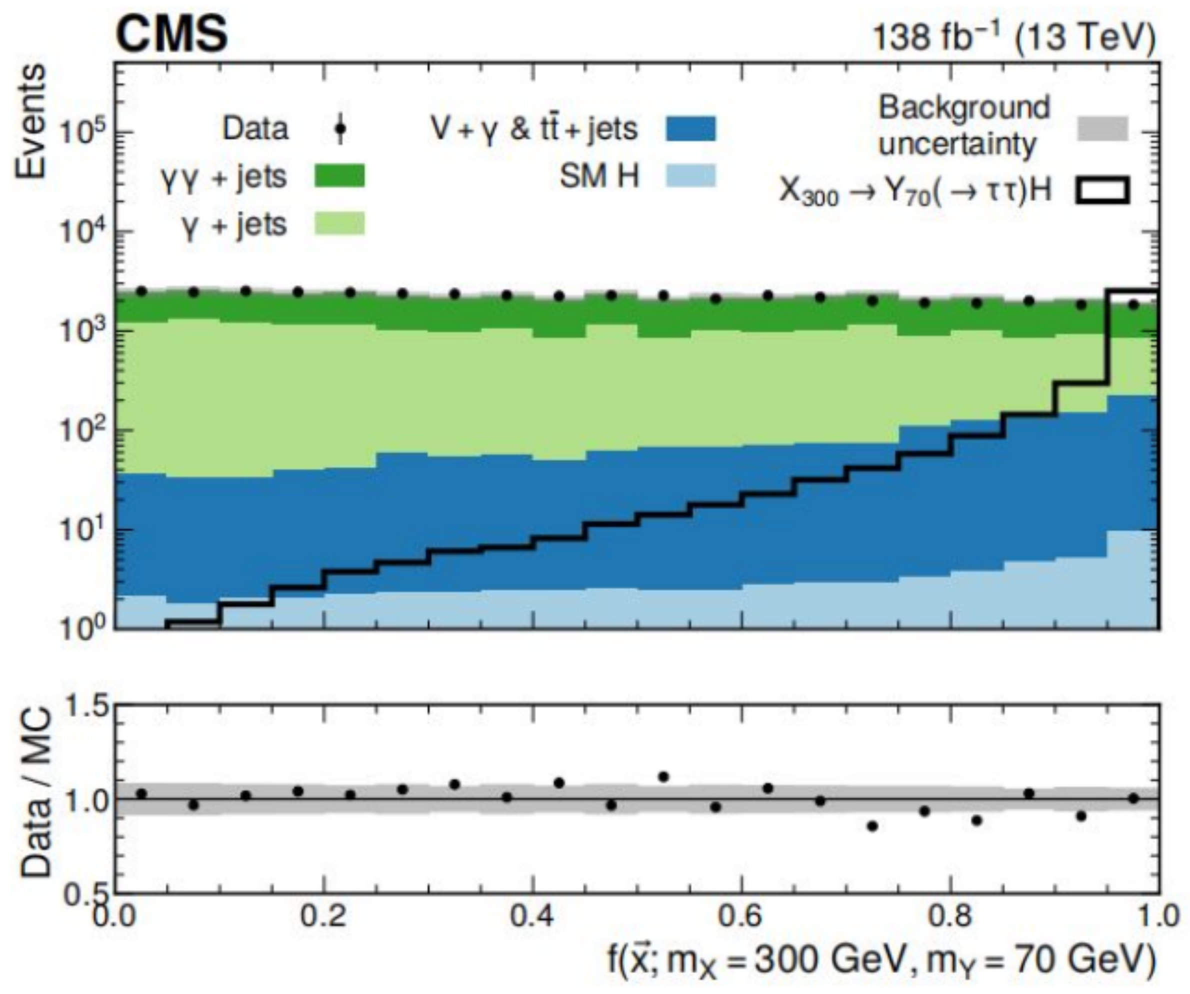
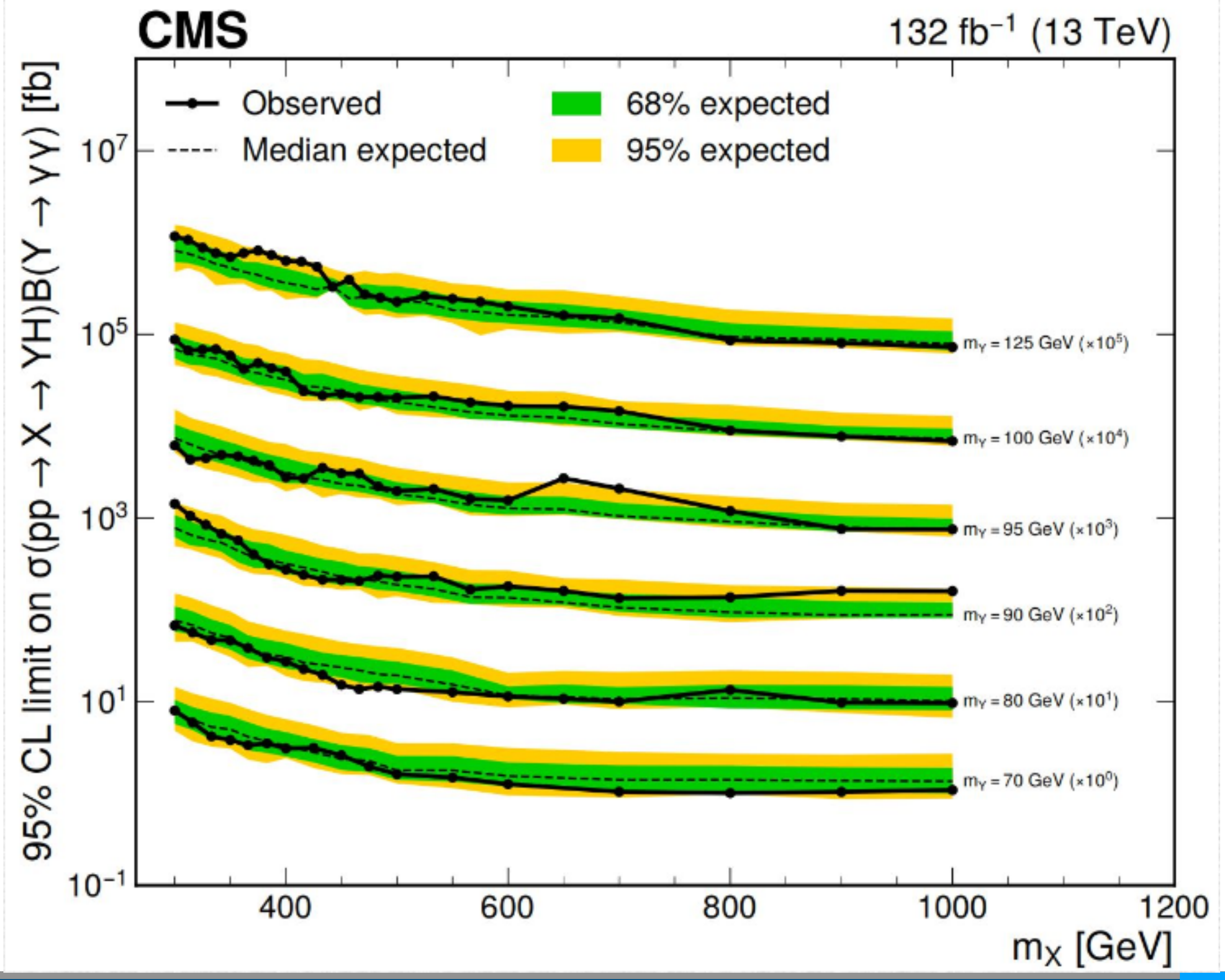
*not in HH combination

General strategy

- Pre-selection
  - Apply loose **online** (trigger) and **offline** object/event criteria
- Event-level ML Classification
  - Use BDTs or Parametric Neural Networks (PNNs) for signal–background separation. For PNNs, treat m_X and m_Y as continuous parameters of the network
  - Define a phase space with high signal efficiency and strong background rejection.
- Signal and background modelling
  - Extract **line shapes** (mass distributions) of all processes in the signal region
  - Use data-driven techniques for non-resonant background estimation
- Statistical Interpretation
  - Perform a **maximum-likelihood fit** of the signal and background models to data
  - Derive expected and observed upper limits on the signal cross-section



CMS-PAS-HIG-22-012



Outline

- $H(bb)H(\gamma\gamma)/Y(bb)H(\gamma\gamma)$ [JHEP05(2024)316]
- $H(\tau\tau)H(\gamma\gamma)/Y(\gamma\gamma)H(\tau\tau)/Y(\tau\tau)H(\gamma\gamma)$ [CMS-PAS-HIG-22-012]
- $Y(\gamma\gamma)H(bb)$ [CMS-PAS-B2G-24-001]
- $H(WW)H(\gamma\gamma)$ [CMS-PAS-B2G-24-010] New

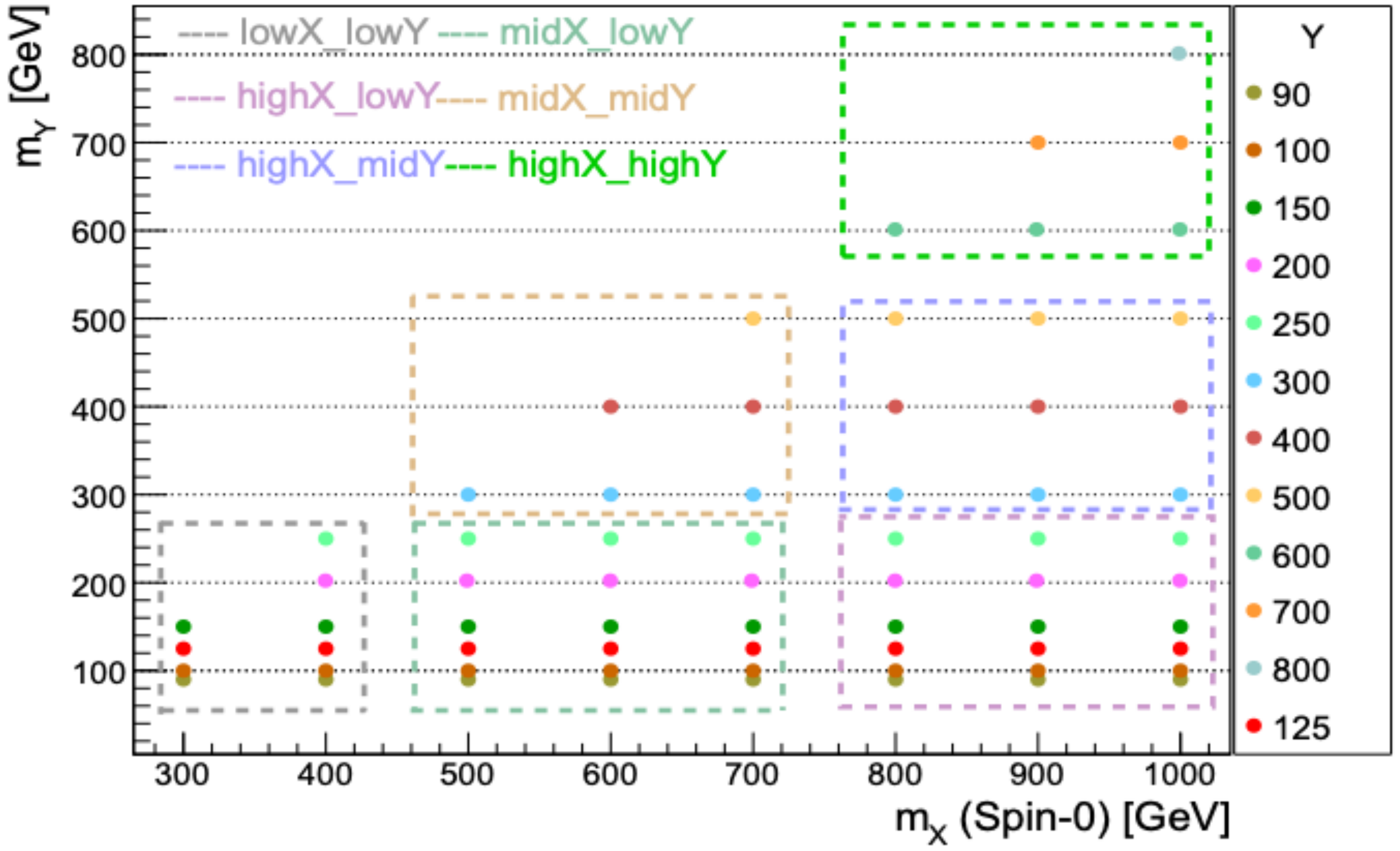
$X \to H(bb)H(\gamma\gamma)/Y(bb)H(\gamma\gamma)$ [JHEP05(2024)316]

- Model independent analysis
  - Performed under the narrow-width approximation (NWA)
  - HH search: 260 GeV $\leq m_X \leq$ 1 TeV; YH search: 300 GeV $\leq m_X \leq$ 1 TeV, 90 GeV $\leq m_Y \leq$ 800 GeV
- Pre-selection
  - 100 GeV < $m_{\gamma\gamma}$ < 180 GeV
  - HH: 70 GeV < m_{bb} < 190 GeV; HY: 70 GeV < m_{bb} < 1200 GeV
- Background components
  - Non-resonant $\gamma\gamma$+jets, γ+jets
  - Resonant SM single Higgs(**mainly ttH**)
    - events where both top quarks decay to b quarks, yielding m_{jj} near the Higgs boson mass.
- Background rejection
  - A NN-based ttH-killer classifier is applied to suppress ttH background
  - BDT classifier is applied to suppress non-resonant background.

up to **10% improvement** in the final sensitivity

Non-resonant background MCs are only used in the BDT training

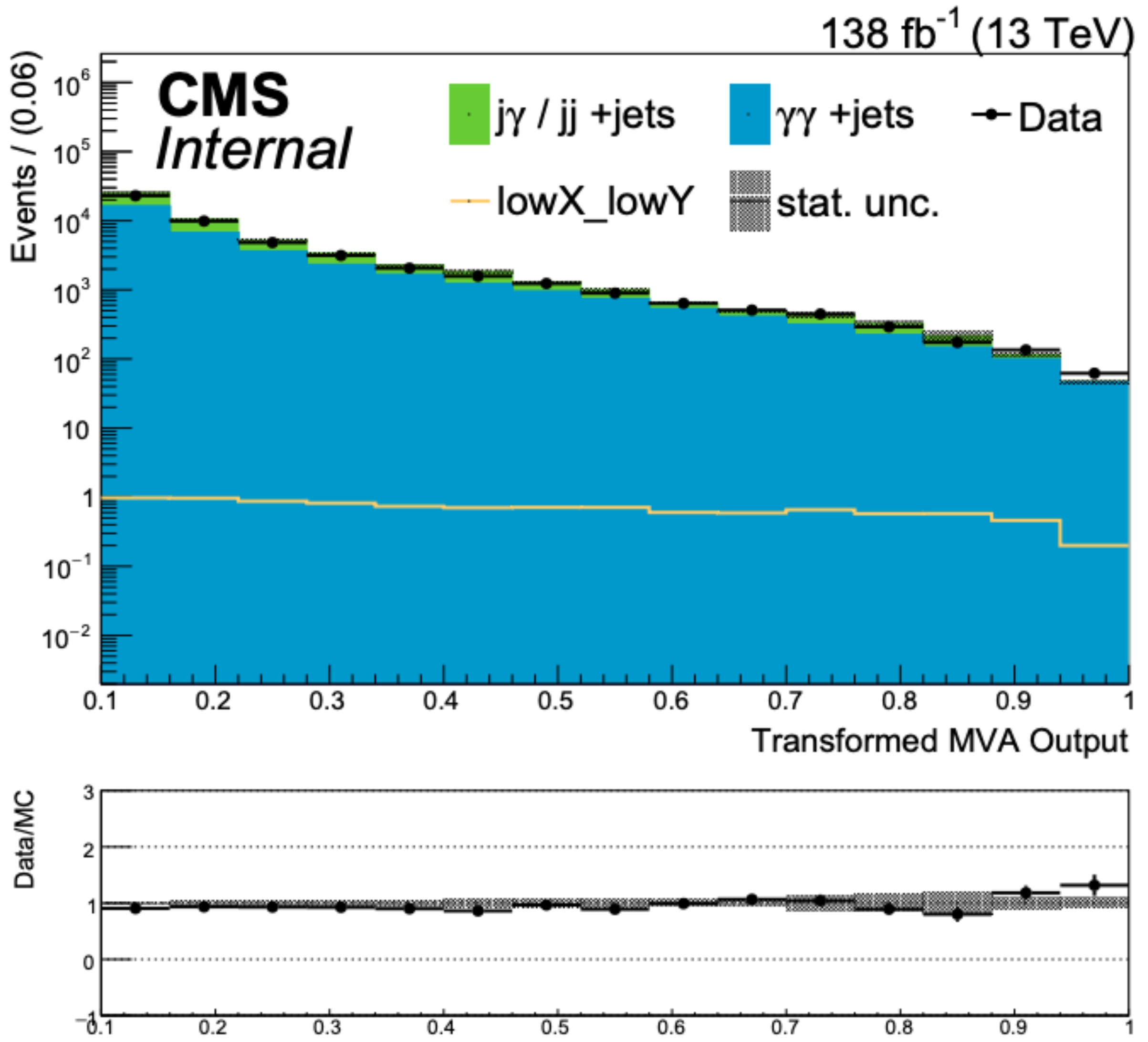
- In order to make analysis strategy optimal for each (m_X, m_Y) point, BDTs are trained separately for 6 different mass ranges



m_X-m_Y bins for MVA training

Mass Range	γγ+jets (AUC)	γ+jets(AUC)
lowX_lowY	0.9602	0.9744
midX_lowY	0.9896	0.9934
highX_lowY	0.9971	0.9981
midX_midY	0.9849	0.9930
highX_midY	0.9958	0.9978
highX_highY	0.9871	0.9956

At higher resonance masses, the training performance shows improvement within the same m_Y range, as the event kinematics become more discriminative.

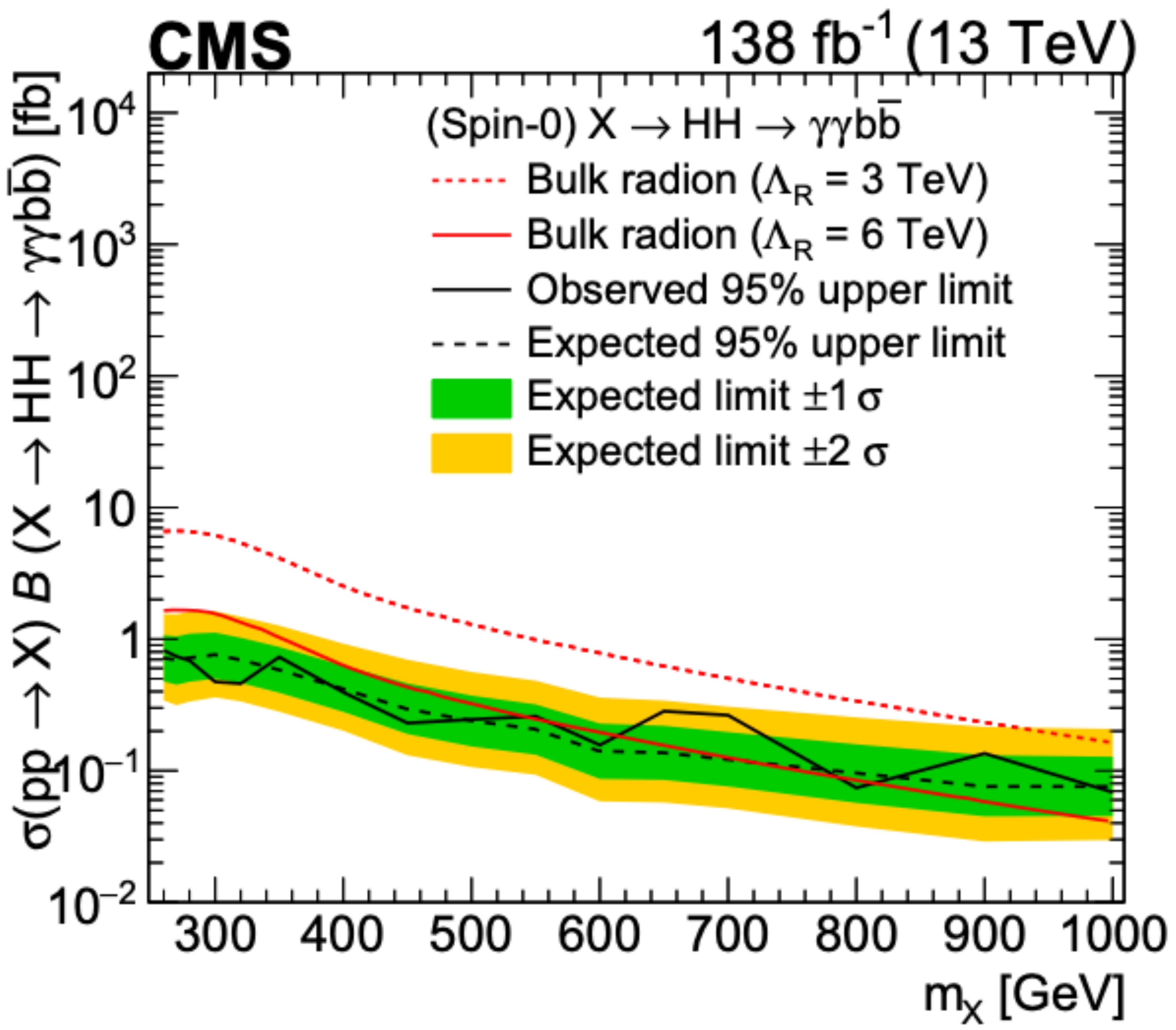


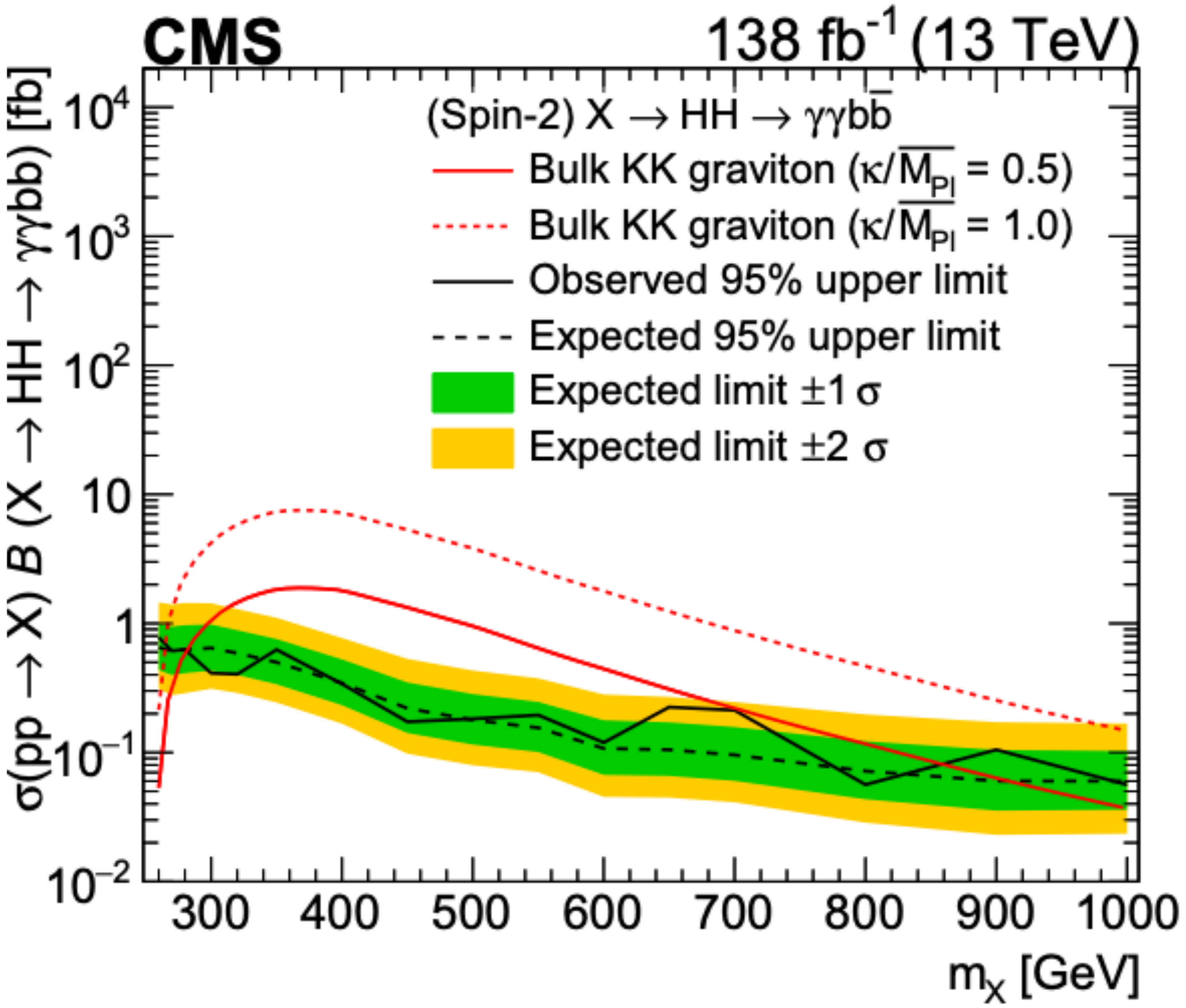
MVA score Data/MC comparison

- 3 signal categories are provided for each mass range, category boundaries are optimized according to best significance

$X \to H(bb)H(\gamma\gamma)/Y(bb)H(\gamma\gamma)$ [JHEP05(2024)316]

- Limit extraction:
  - Signal: fit $m_{\gamma\gamma}$ using up to five Gaussians functions; fit m_{jj} using DCB function or Sum of CB and Gaussian
  - Background: Data-driven background model using functional (Exp., Bern. polynomial, Power Law) fits and 2D envelope method.



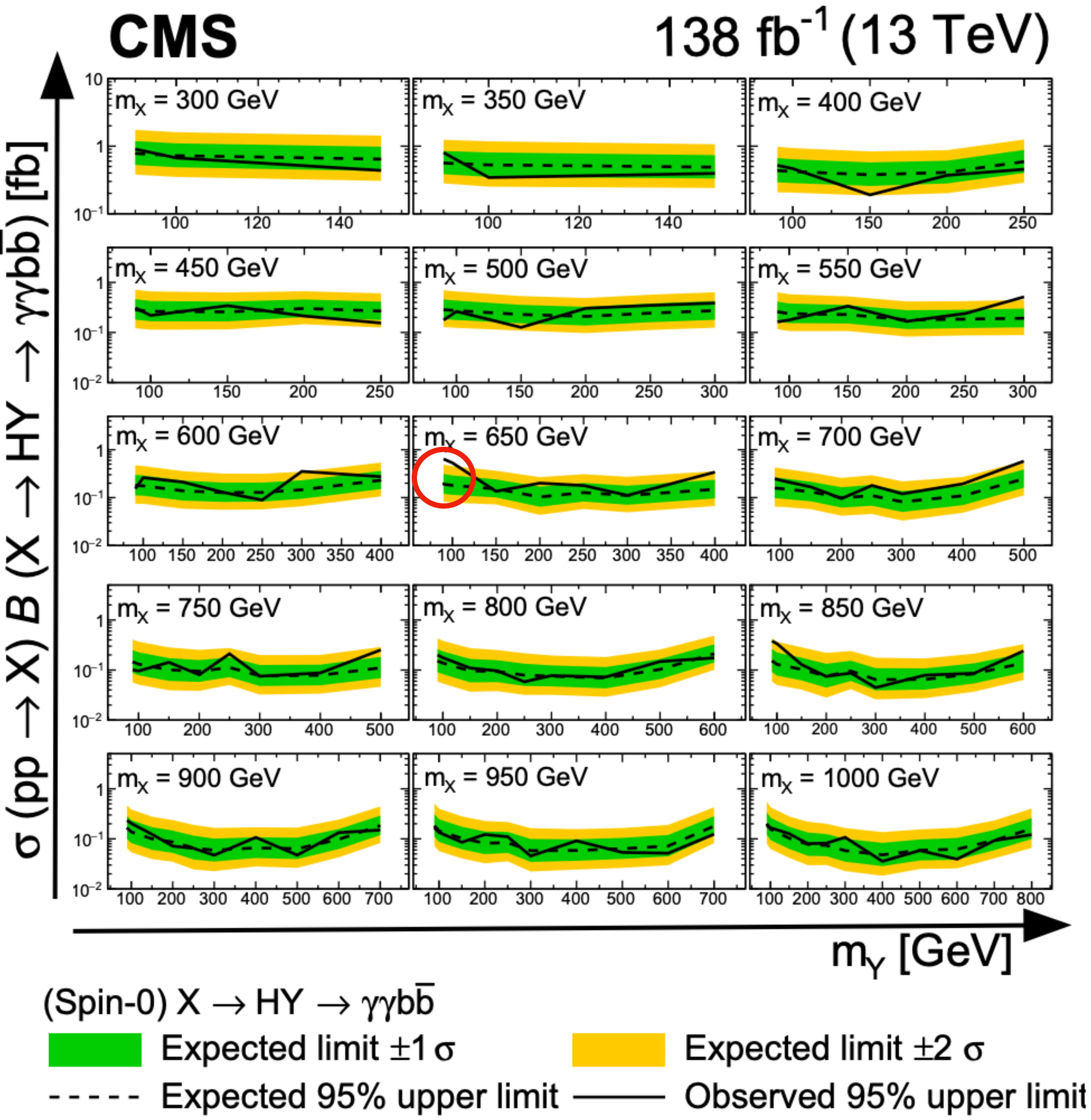


Expected limits decrease with increasing m_X, and observed limits agree within 2σ.

The 95% CL observed upper limits range from 0.82–0.07 fb (spin-0), 0.78–0.06 fb (spin-2), excluding several theoretical models.

X → H(bb)H(γγ)/Y(bb)H(γγ) [JHEP05(2024)316]

- In most of the cases, observed limits consistent with expectations within 2σ
- The largest excess is observed for mX = 650 GeV and mY = 90 GeV with a local significance of 3.8σ.
- After accounting for the look-elsewhere effect (LLE), a global significance of 2.8σ is obtained in the partial phase space defined by 300 < m_X < 1000 GeV and 90 < m_Y < 150 GeV.
- Although not globally significant, this excess motivates further searches for the X → YH



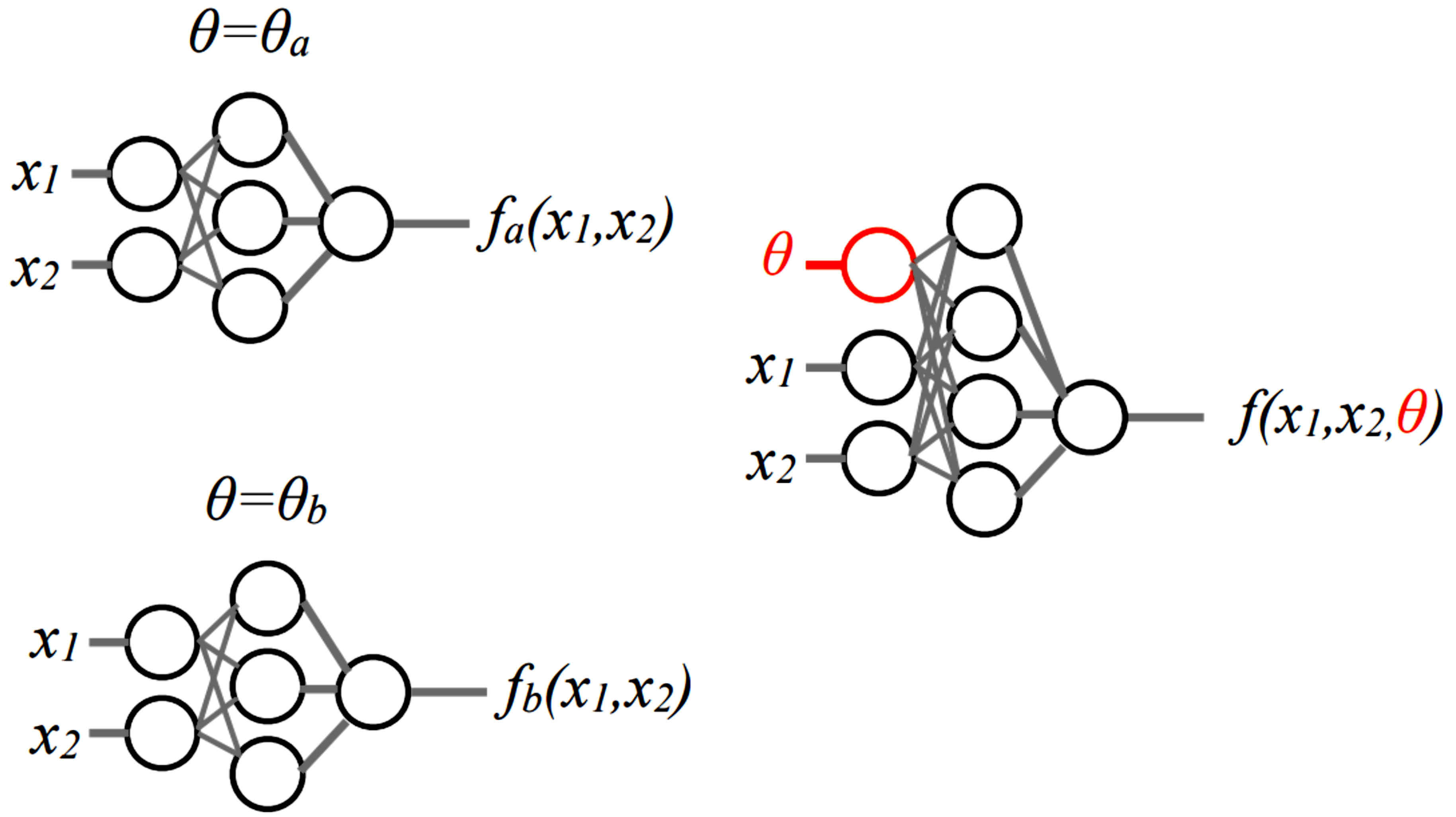
$X \rightarrow H(\tau\tau)H(\gamma\gamma)/Y(\gamma\gamma)H(\tau\tau)/Y(\tau\tau)H(\gamma\gamma)$ [CMS-PAS-HIG-22-012]

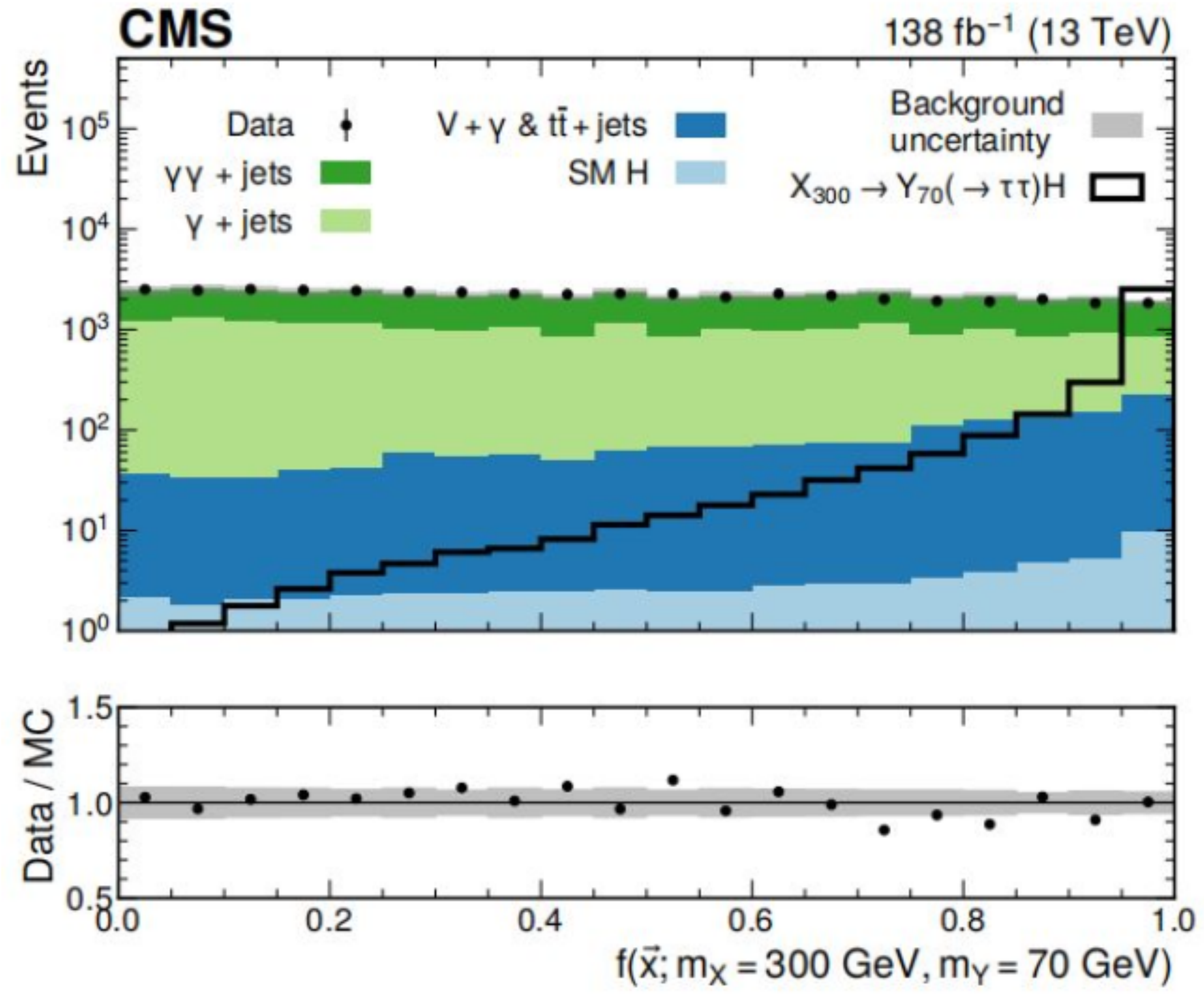
- Model independent analysis
  - Performed under the narrow-width approximation (NWA)
  - HH search: 260 GeV $\leq m_X \leq$ 1 TeV
  - $Y(\tau\tau)H(\gamma\gamma)$ search: 300 GeV $\leq m_X \leq$ 1 TeV, 50 GeV $\leq m_Y \leq$ 800 GeV
  - $Y(\gamma\gamma)H(\tau\tau)$ search: 300 GeV $\leq m_X \leq$ 1 TeV, 70 GeV $\leq m_Y \leq$ 800 GeV
- Pre-selection
  - Event must have a valid $\tau\tau$ candidate or a single τ_h candidate, and both hadronic and leptonic decay mode of the τ leptons are considered.
- Background components
  - Non-resonant $\gamma\gamma$+jets, γ+jets, $V + \gamma$, $t\bar{t} + \gamma(s)$, where jets can be misidentified as photons or tau leptons.
  - Resonant SM single Higgs
  - Additional low-mass $Y(\gamma\gamma)H(\tau\tau)$ background: Drell–Yan ($Z\rightarrow ee$) events can mimic a diphoton signature when both electrons are misidentified as photons, producing a peak in the $m_{\gamma\gamma}$ spectrum near m_Z A Data-driven ABCD method has been performed specifically to model the Drell–Yan background.

$X \rightarrow H(\tau\tau)H(\gamma\gamma)/Y(\gamma\gamma)H(\tau\tau)$[CMS-PAS-HIG-22-012]

1. The signal hypothesis depends on the resonance masses m_X, m_Y
2. Training a single NN for all mass points reduces sensitivity, while training separate NNs for each mass point is computationally expensive.

- Parametric Neural Network(pNN): adapts predictions smoothly across different mass points. Eur. Phys. J. C 76 (2016) 235
  - The parameters m_X and m_Y are included as inputs to the network.
  - Background events assigned random m_X, m_Y to match signal masses
  - Ensures m_X, m_Y have no discriminant power but improve per-mass optimization
  - Enables interpolation for intermediate mass points



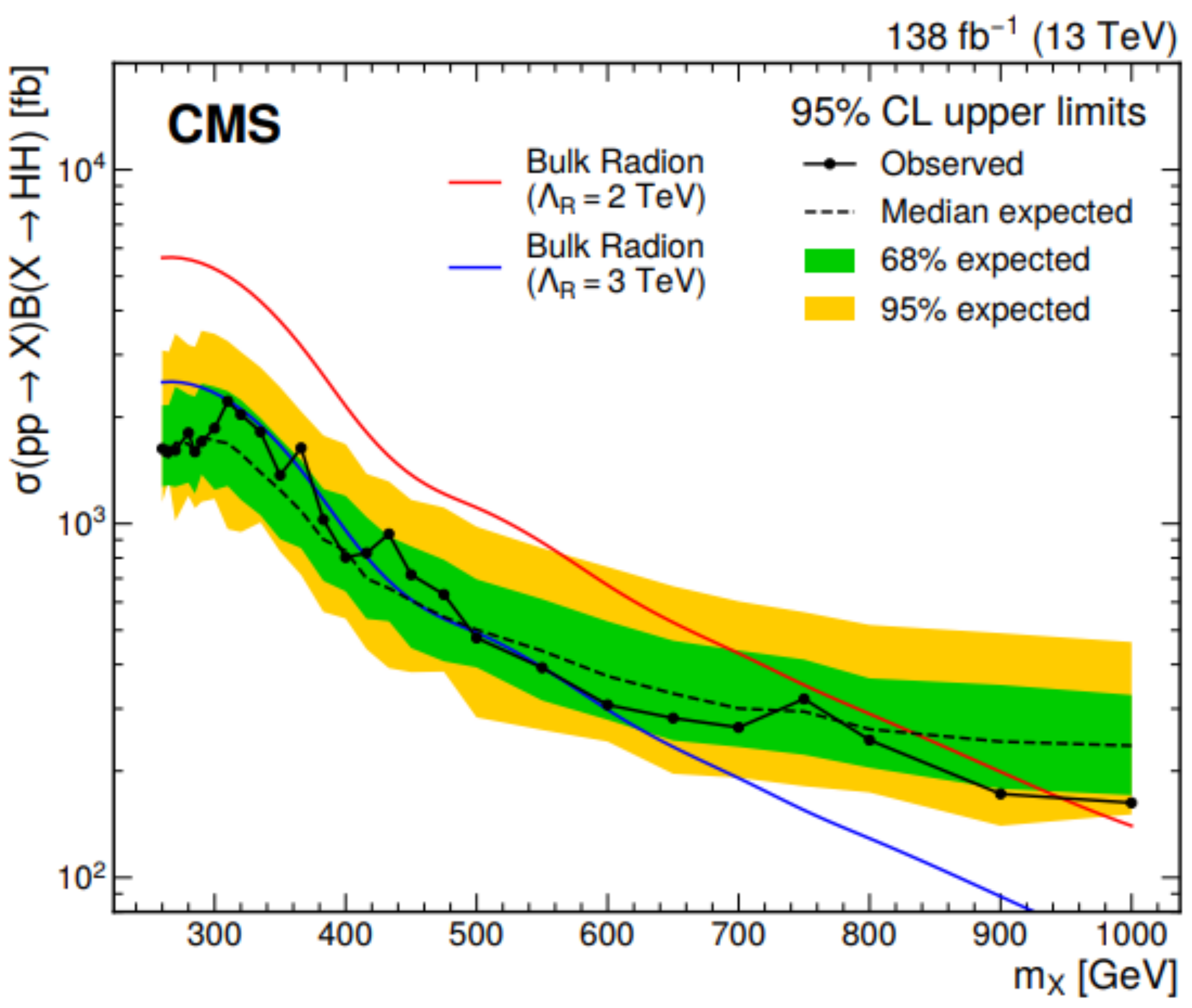


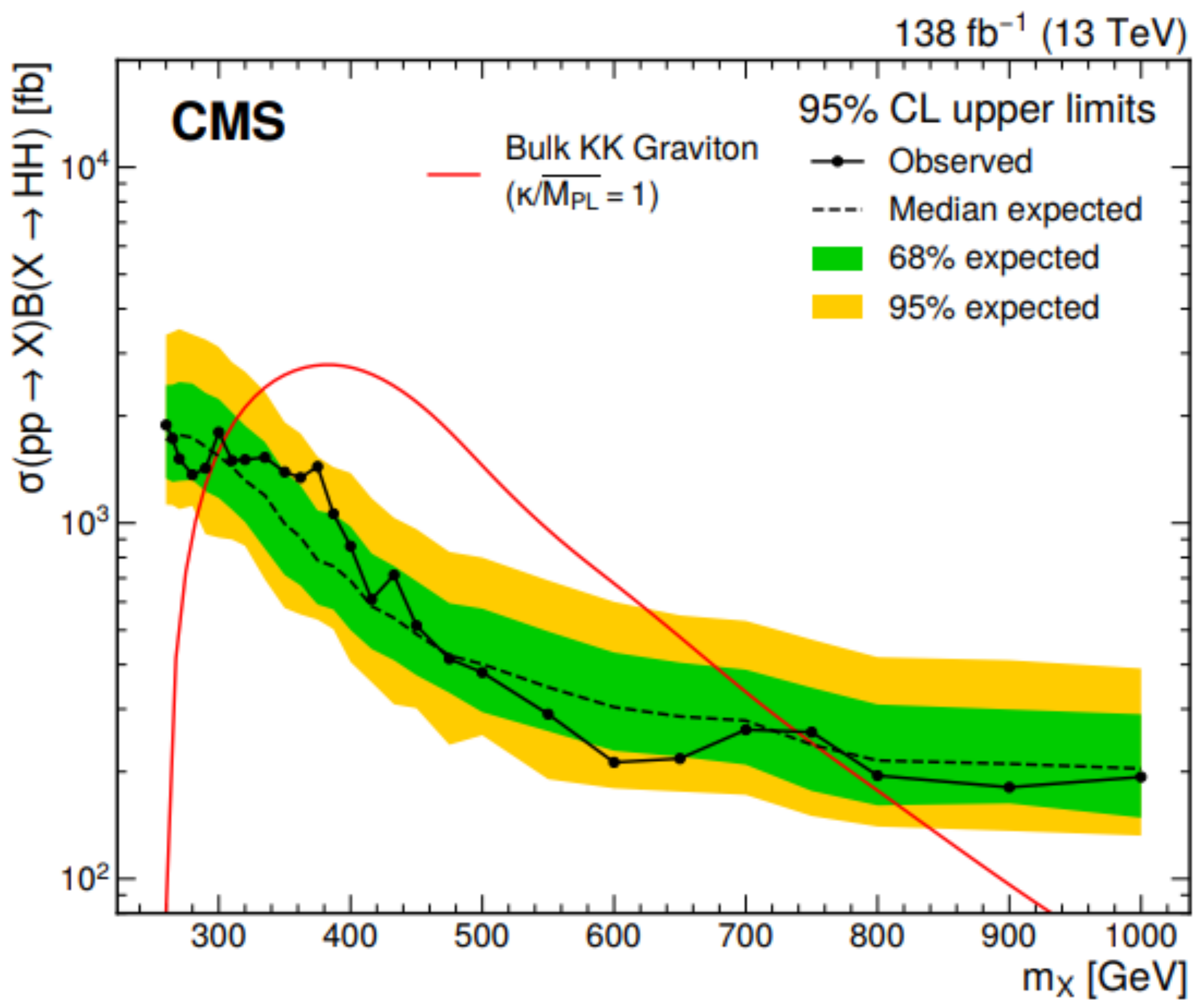
pNN Data/MC comparison *

* pNN outputs are transformed to flatten the background, so score thresholds correspond to consistent background efficiency across all m_X and m_Y, enabling smooth, predictable signal efficiency and interpolation.

$X \to H(\tau\tau)H(\gamma\gamma)/Y(\gamma\gamma)H(\tau\tau)$ [CMS-PAS-HIG-22-012]

Expected limits decrease with increasing m_X, and observed limits agree within 2σ. Exclude m_X up to 900 GeV at ΛR = 2 TeV, Exclude m_X between 310 and 700 GeV at $\kappa/\bar{M}_{PL} = 1$

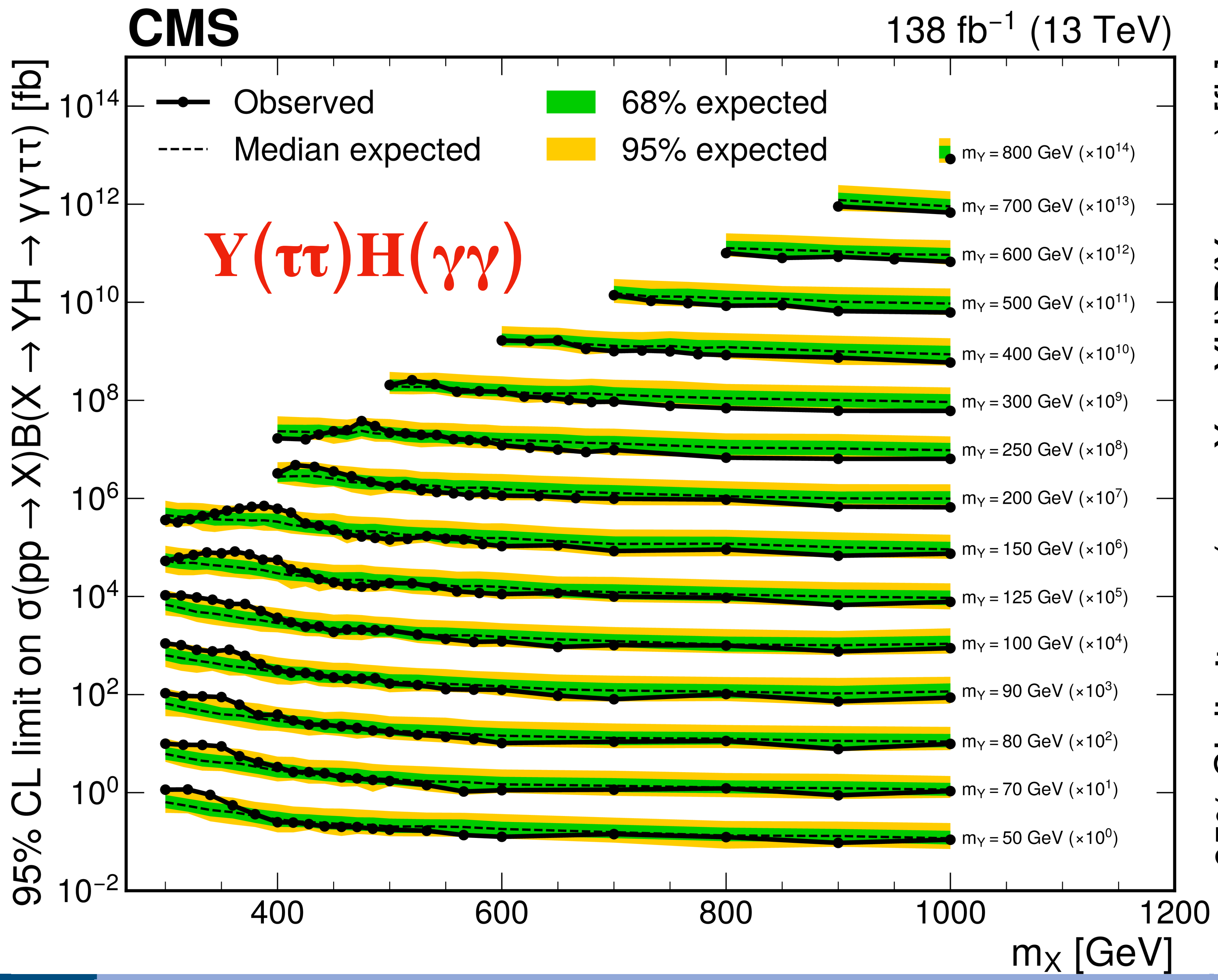


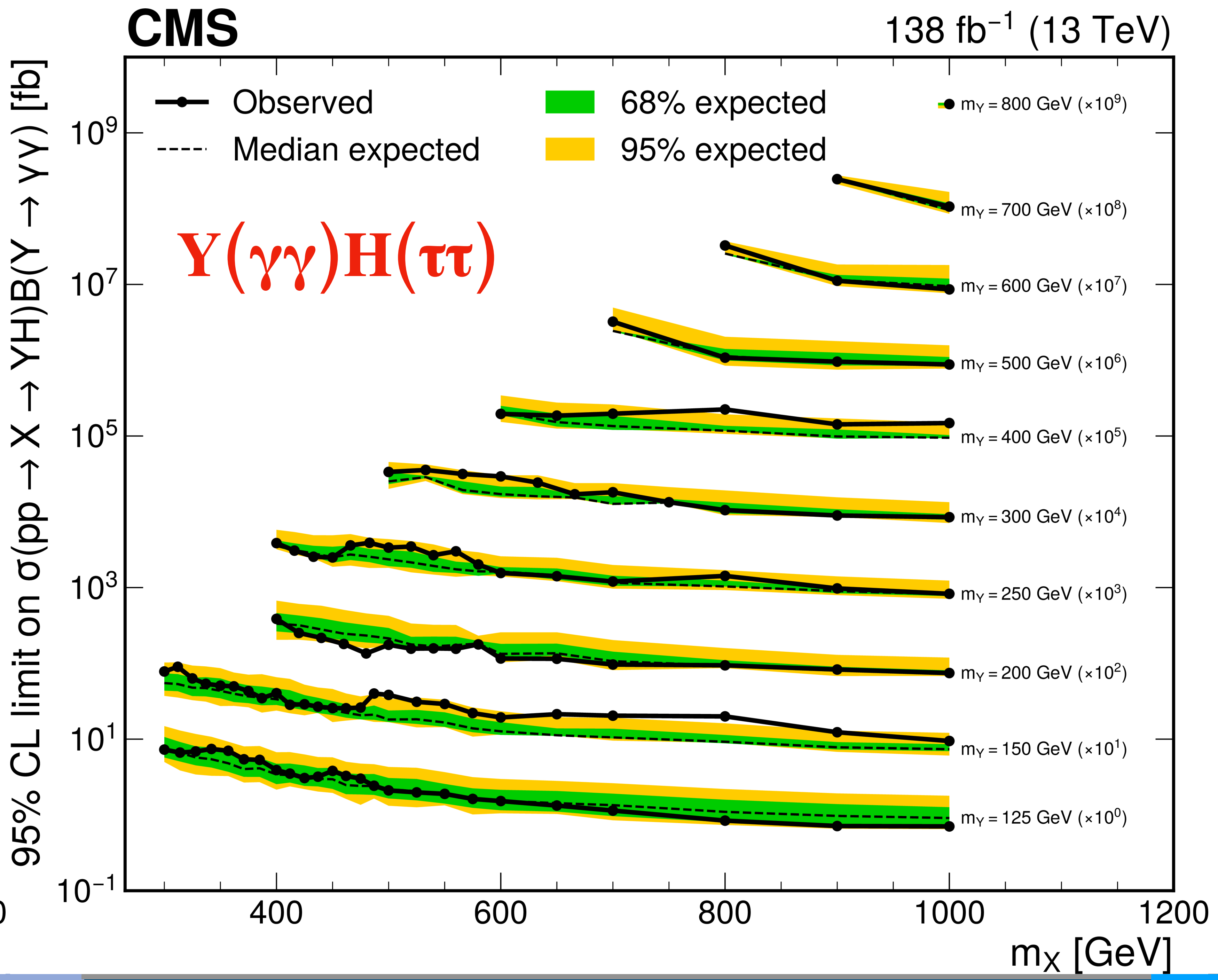


Higher (lower) limits for mass points with lower (higher) m_X-m_Y difference

Due to the large range in mass hypothesis considered, there is a LLE.

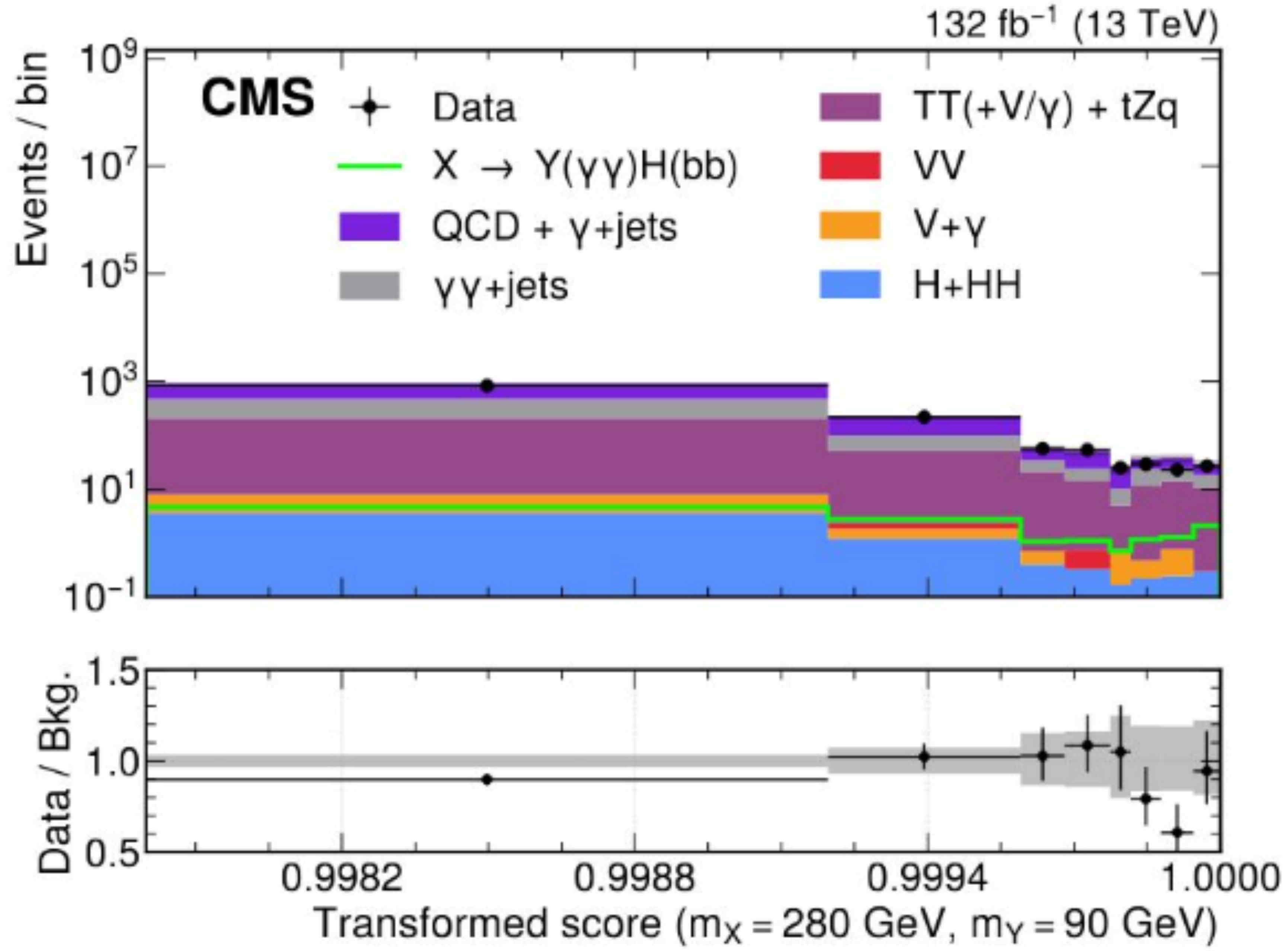
No significant excess observed.





$X \to Y(\gamma\gamma)H(bb)$ [CMS-PAS-B2G-24-001]

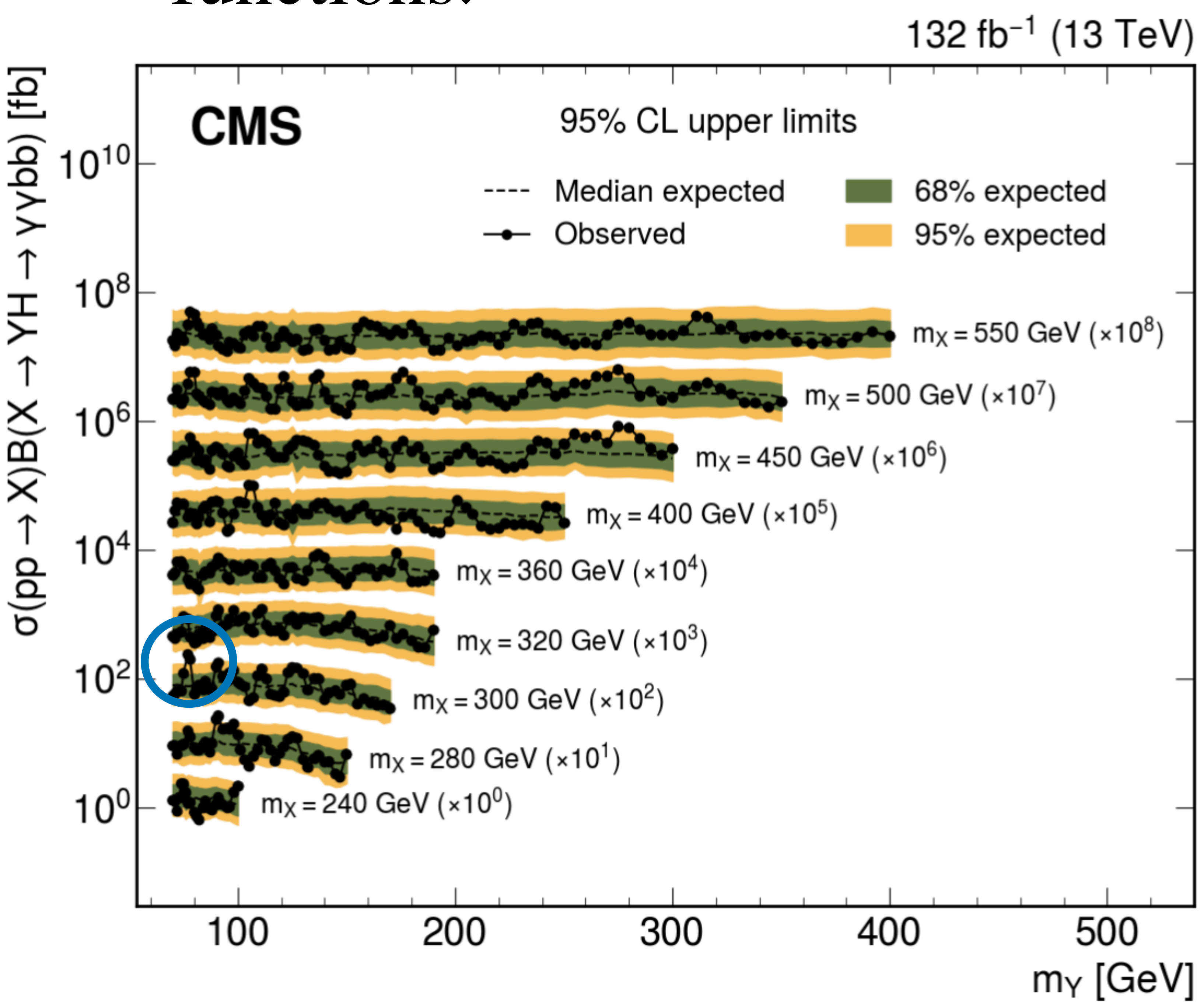
- Model independent analysis
  - Performed under the narrow-width approximation (NWA)
  - 240 GeV $\leq m_X \leq$ 1 TeV, 70 GeV $\leq m_Y \leq$ 800 GeV
- Preselection:
  - Events pass loose diphoton and dijet preselections.
  - No restriction on $m_{\gamma\gamma}$ or m_{bb}
- Background:
  - Non-resonant $\gamma\gamma$+jets, γ+jets
  - Resonant SM single Higgs, Drell-Yan, VV
- Background rejection
  - pNN is trained and applied.
  - Signal region boundaries and number of signal regions are optimized with a cut-and-count expected upper limit. i.e. adding a signal region if seeing significant improvement in cut-and-count limit

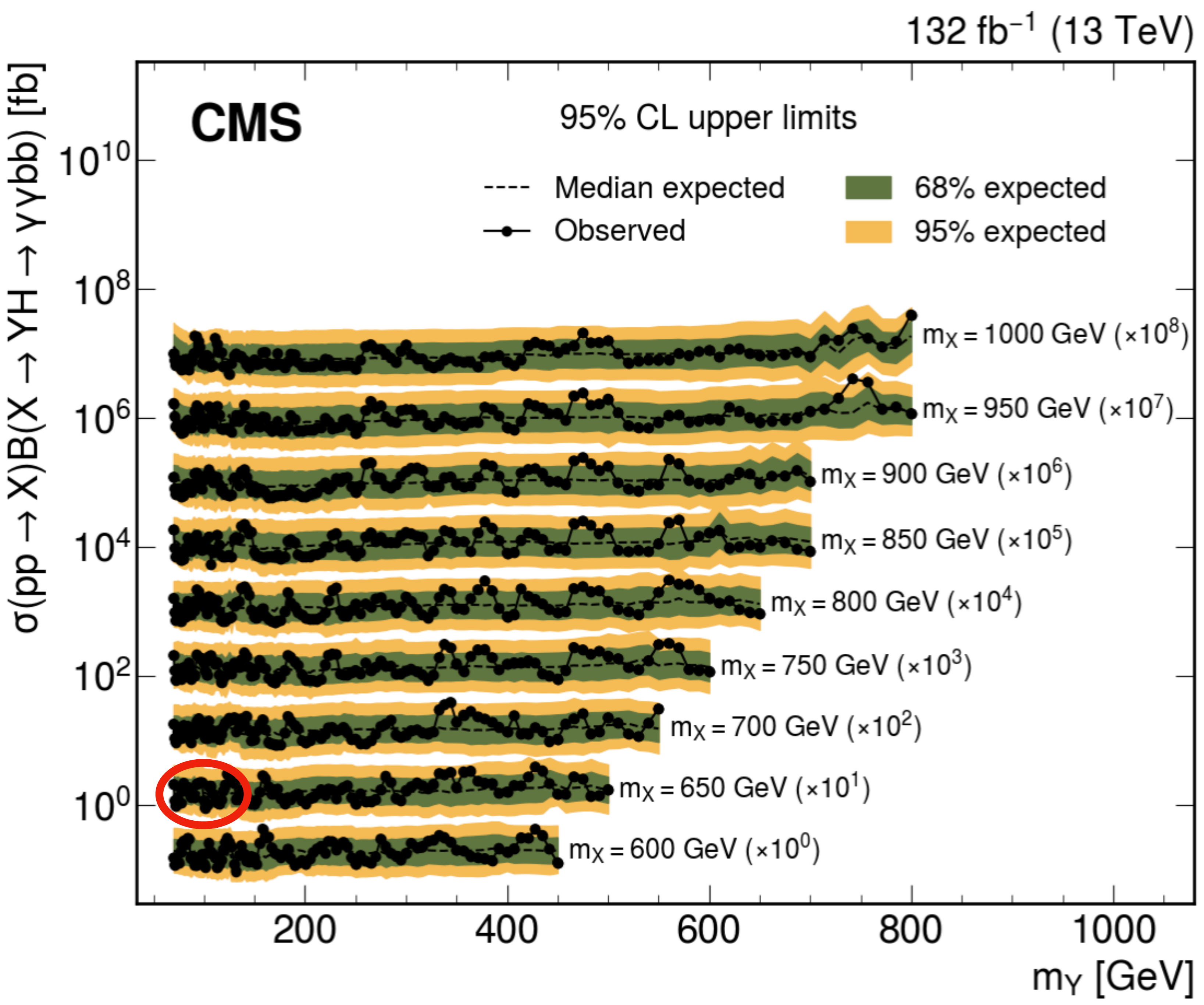


pNN score Data/MC comparison*

* pNN outputs are transformed to flatten the background

- Limit extraction
  - $m_{\gamma\gamma}$ is used for signal extraction
  - Signal: Double Crystal-Ball (DCB) function
  - Resonant background: DY derived using a data-driven ABCD method; SM Higgs, HH modeled by DCB
  - Non-resonant background: Discrete profiling method by fitting each signal region with multiple falling functions.

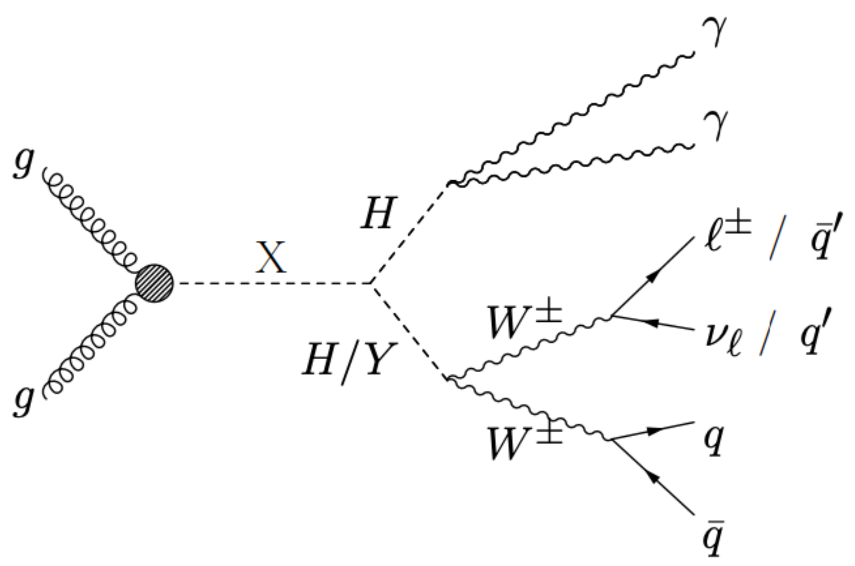




- A local (global) significance of 3.33σ (0.65σ) is observed at m_X=300GeV, m_Y=77GeV
- The previously reported local (global) excess of 3.8σ (2.6σ) at m_X = 650GeV, m_Y = 90GeV in $Y(bb)H(\gamma\gamma)$ is not confirmed by this analysis.

$X \rightarrow H(WW)H(\gamma\gamma)$ [CMS-PAS-B2G-24-010]

- Model independent analysis
  - Performed under the narrow-width approximation (NWA)
  - HH search: 250 GeV ≤ m_X ≤ 3 TeV
  - Both fully hadronic (FH) and semi-leptonic (SL) WW decay channels are included, covering all possible WW topologies.
  - First CMS search for a resonance X→HH→WWγγ
  - First LHC search for a resonance X→HH→WWγγ in the boosted topology.
  - First LHC search for a resonance X→HH→WWγγ with fully hadronic decay modes.

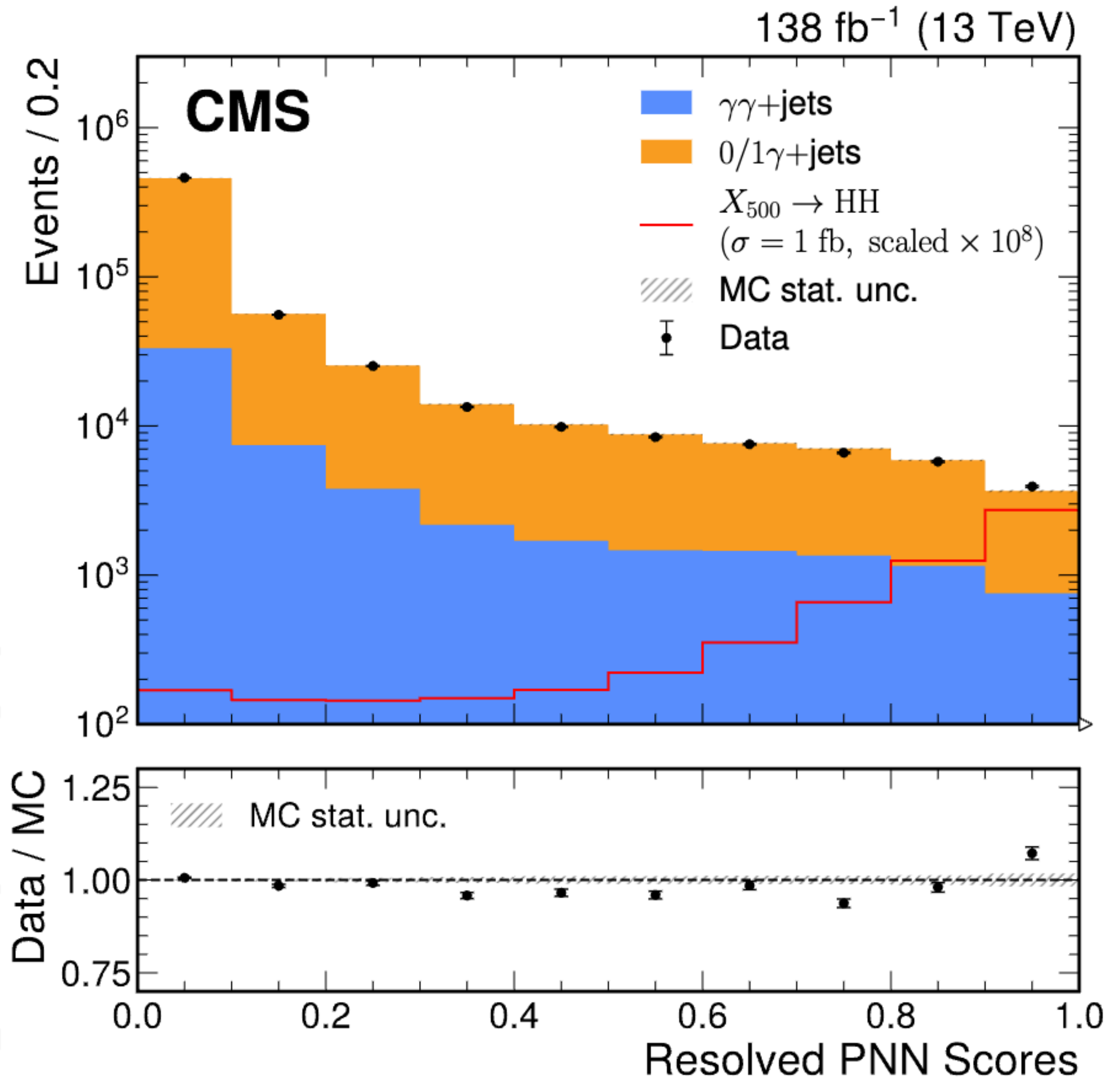


New

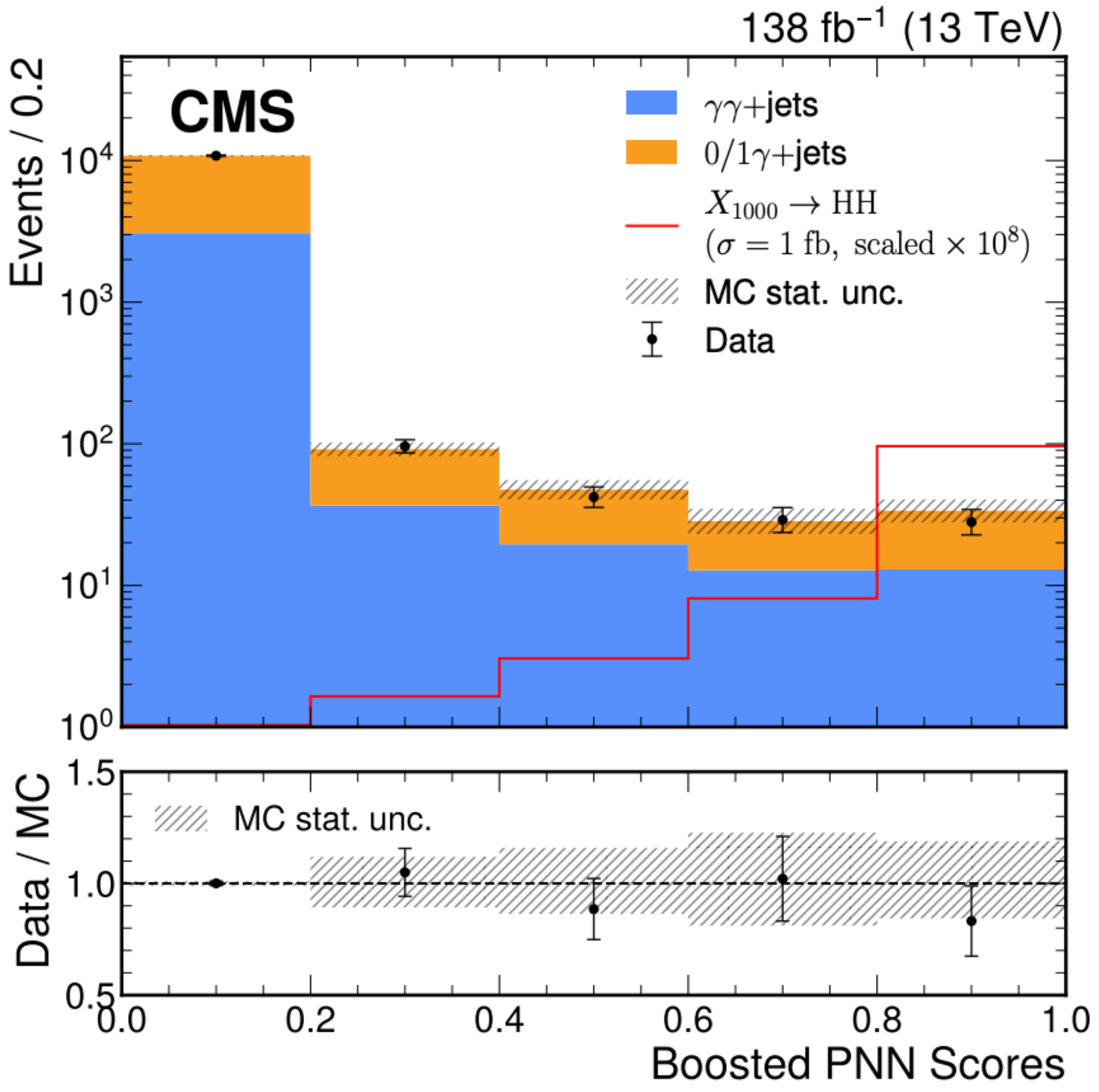
- Preselection
  - 100GeV < $m_{\gamma\gamma}$ < 180GeV, one diphoton pair
  - ParticleNet and Particle Transformer taggers are used to identify boosted H → WW and W → qq fatjets.
  - FH resolved events require at least two jets and no leptons
  - SL resolved events require at least 1 jet with 1 lepton.

$X \to H(WW)H(\gamma\gamma)$ [CMS-PAS-B2G-24-010]

- Background components
  - Non-resonant $\gamma\gamma$+jets, γ+jets
  - Resonant SM single Higgs
- Background rejection
  - Two separate pNNs are trained and applied for the boosted and resolved event categories.
  - The pNN score categorizations are optimized to maximize the significance using a Bayesian algorithm.
- Limit extraction
  - $m_{\gamma\gamma}$ is used for signal extraction
  - Signal and resonant background: fit $m_{\gamma\gamma}$ using up to five Gaussians functions
  - Continuum background: fit data sideband $m_{\gamma\gamma}$ using discrete profiling method.



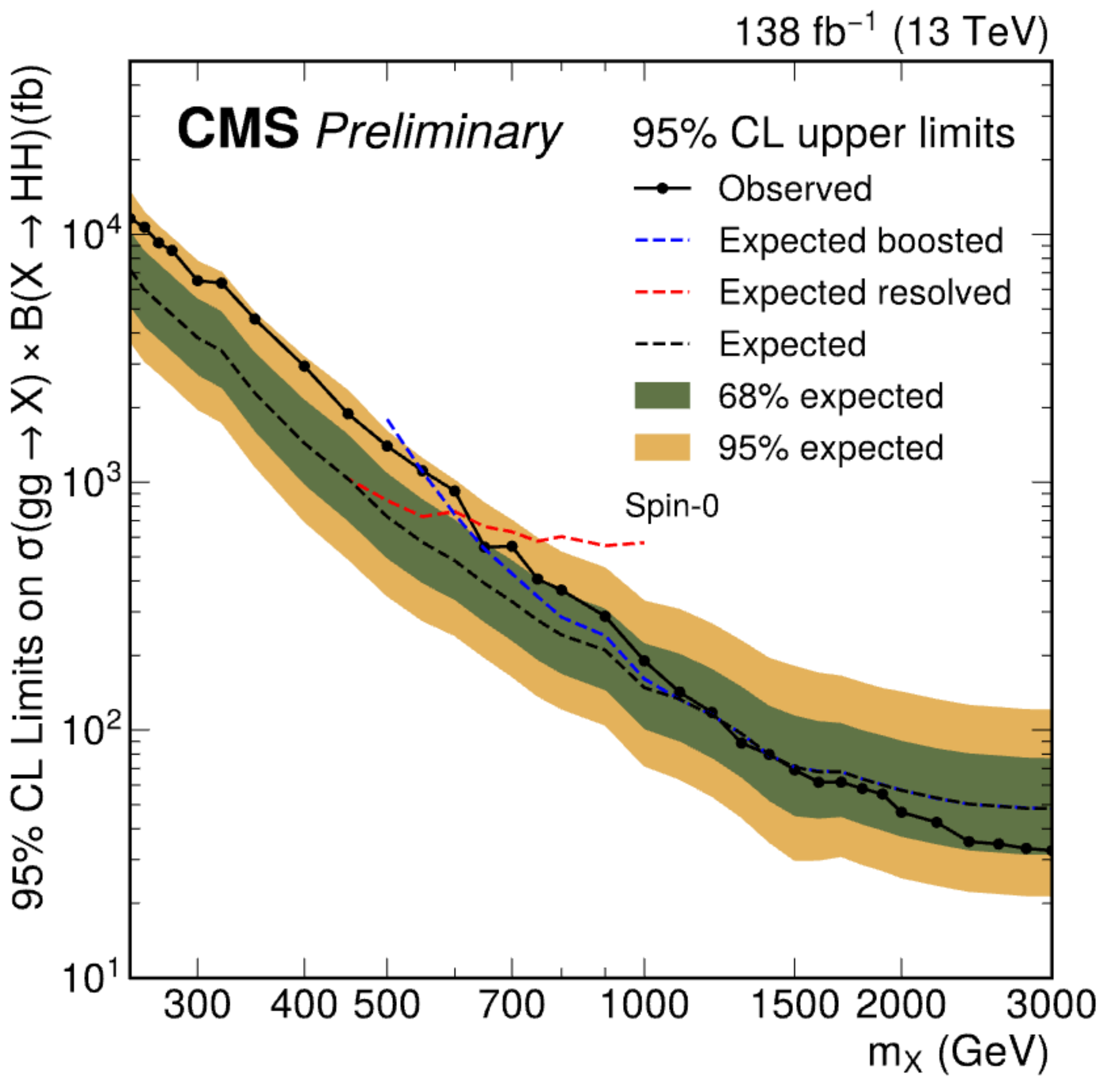
Resolved pNN score Data/MC comparison

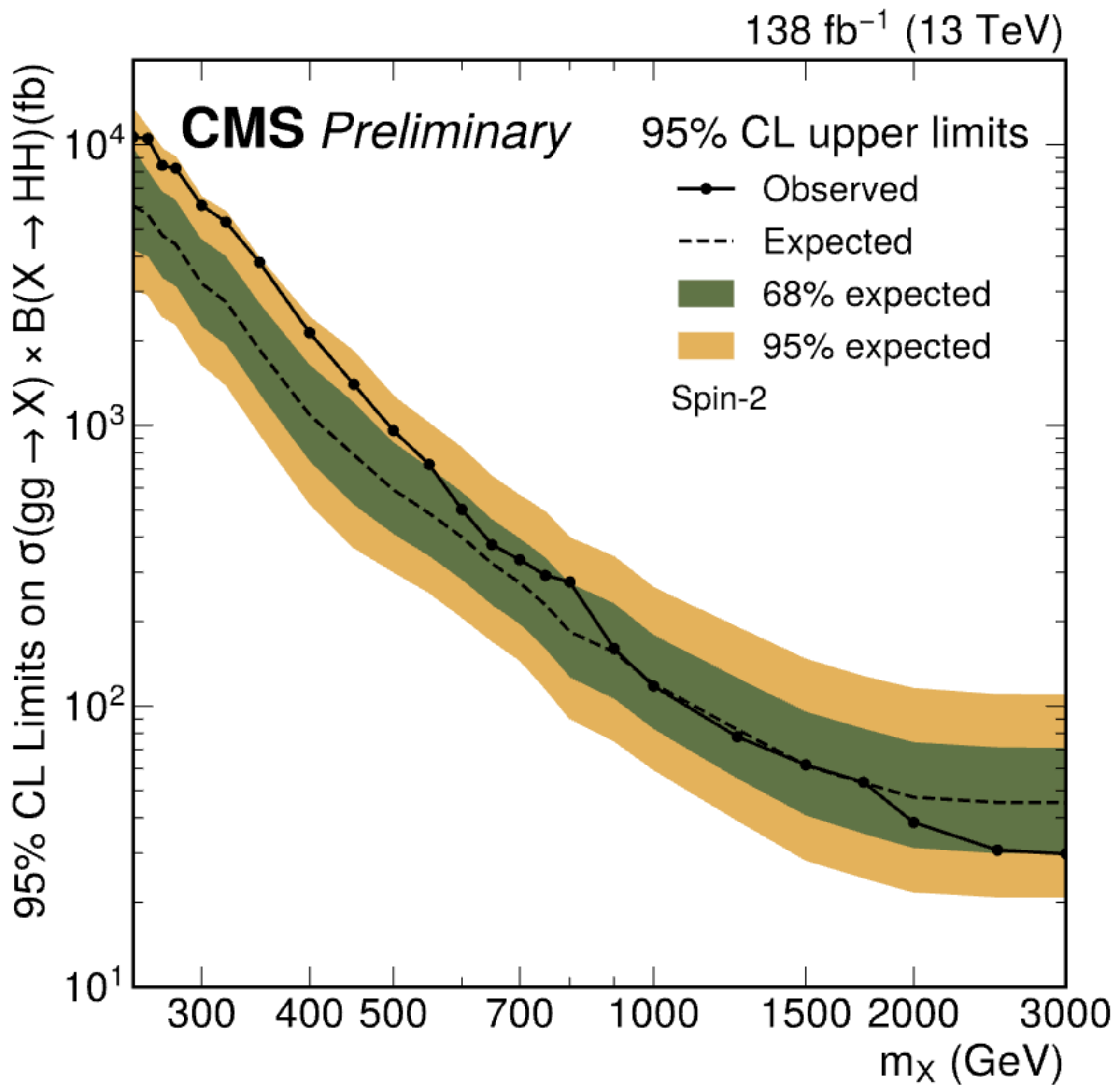


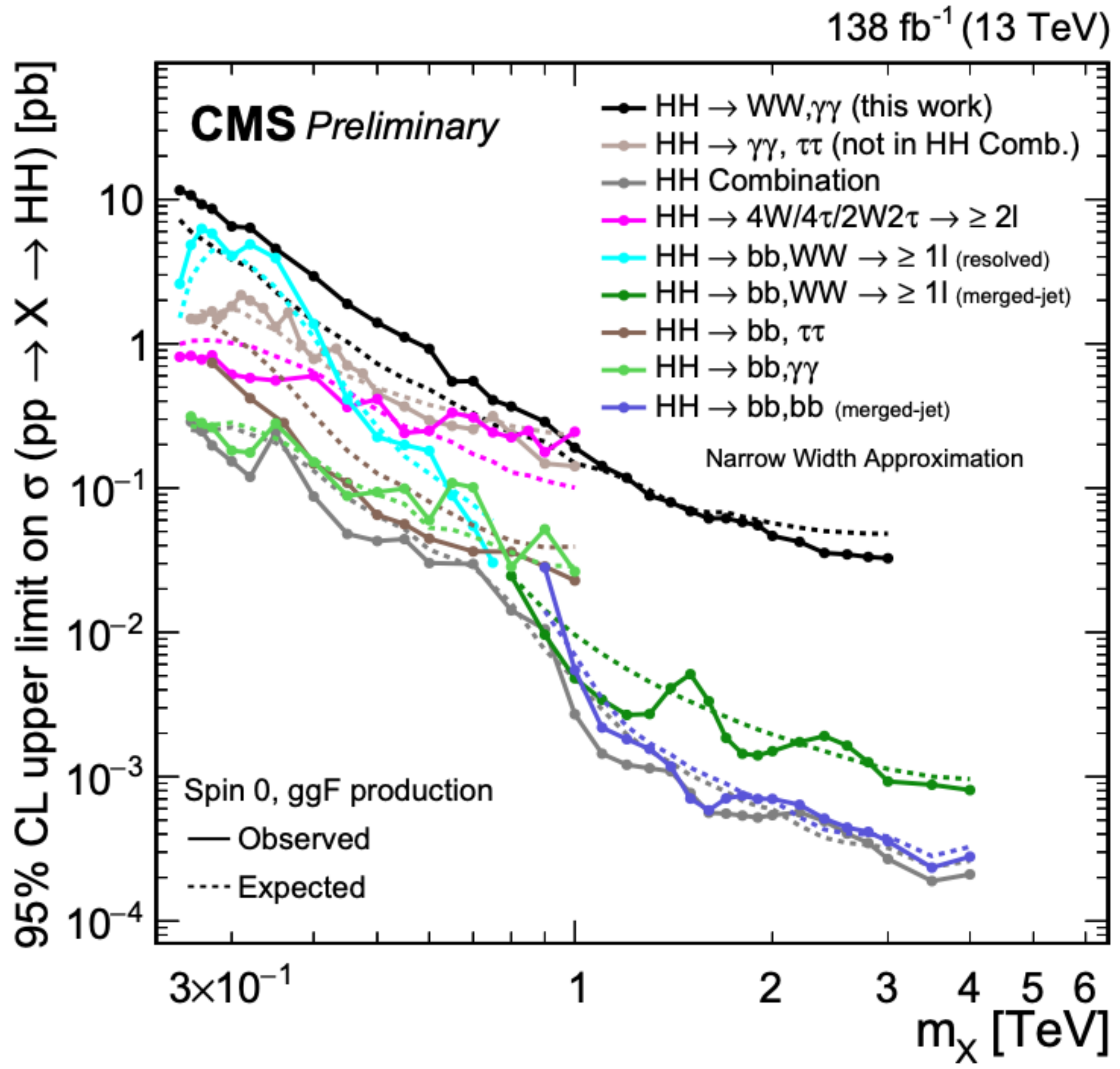
Boosted pNN score Data/MC comparison

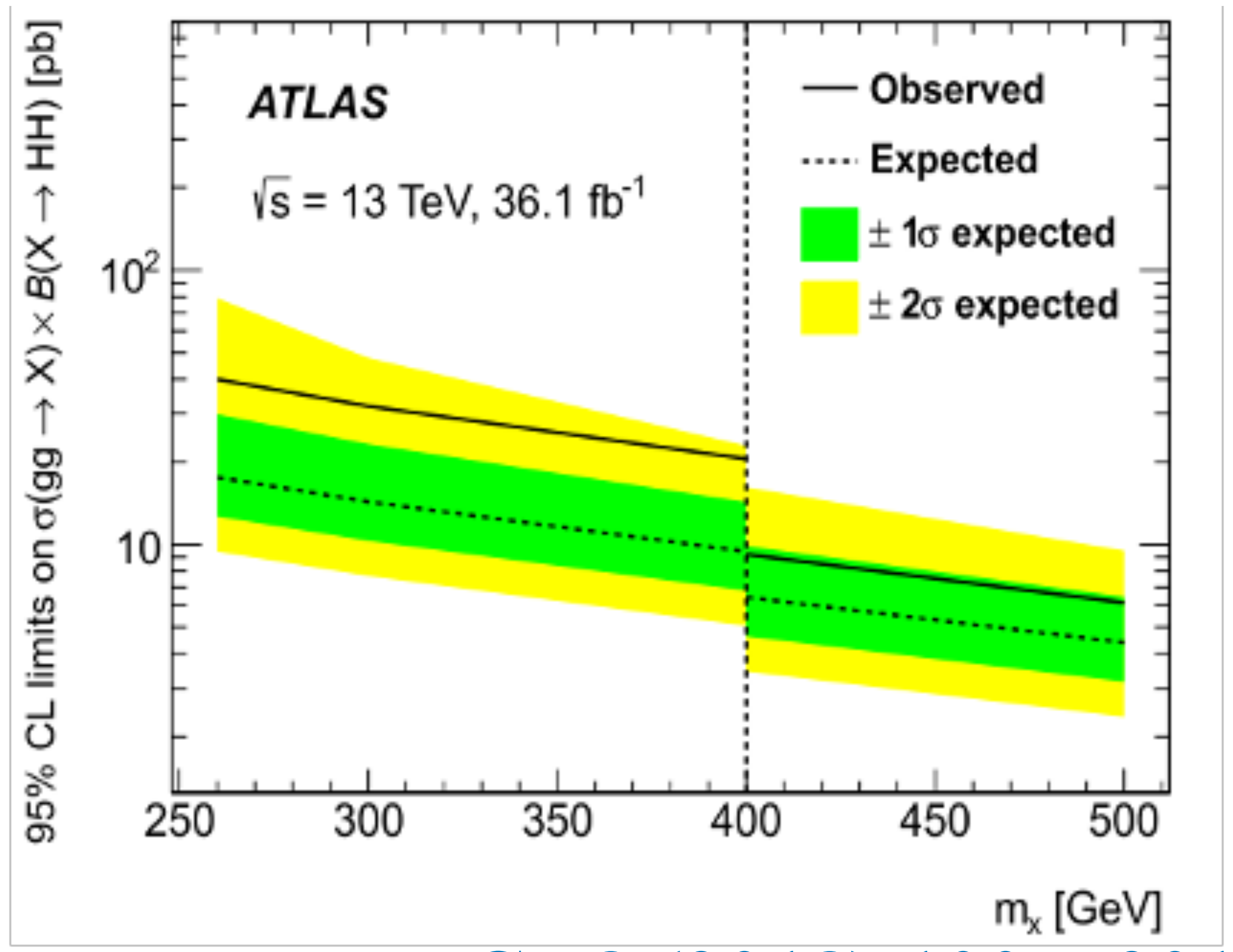
$X \rightarrow H(WW)H(\gamma\gamma)$ [CMS-PAS-B2G-24-010]

- Expected limits decrease with increasing m_X, and observed limits agree within 2σ.
- Exclude m_X from 400 GeV to 1300 GeV at ΛR = 3 TeV.
- The upper limits in this analysis are comparable with the $\tau\tau\gamma\gamma$[CMS-PAS-HIG-22-012]in the intermediate resonance mass region.
- With a comparable integrated luminosity and focusing on the same final state (SL resolved only), this analysis achieves a **30−60% improvement** in sensitivity over the ATLAS Run-2 $WW\gamma\gamma$ results[Eur.Phys.J.C 78 (2018) 1007].









Eur.Phys.J.C 78 (2018) 1007, 2018.

Summary

- Searches for X → HH and X → YH provide powerful probes of various BSM scenarios.
- The X→HH/YH searches in CMS with γγ final states benefit from the clean γγ signature and excellent mass resolution:
  - H(bb)H(γγ)/Y(bb)H(γγ) [JHEP05(2024)316]
  - H(ττ)H(γγ)/Y(γγ)H(ττ)/Y(ττ)H(γγ) [CMS-PAS-HIG-22-012]
  - Y(γγ)H(bb) [CMS-PAS-B2G-24-001]
  - H(WW)H(γγ) [CMS-PAS-B2G-24-010]
- Excesses in X → HH/YH channels reported by CMS and ATLAS are not mutually confirmed.
- Enhanced jet tagging and machine learning methods further refine background rejection and signal extraction.
- Higher luminosity and upgraded reconstruction performance will extend the reach for new resonances.
- Run 3 results are expected to provide more stringent constraints and possibly reveal new hints of BSM physics.

Thank you for your attention!

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