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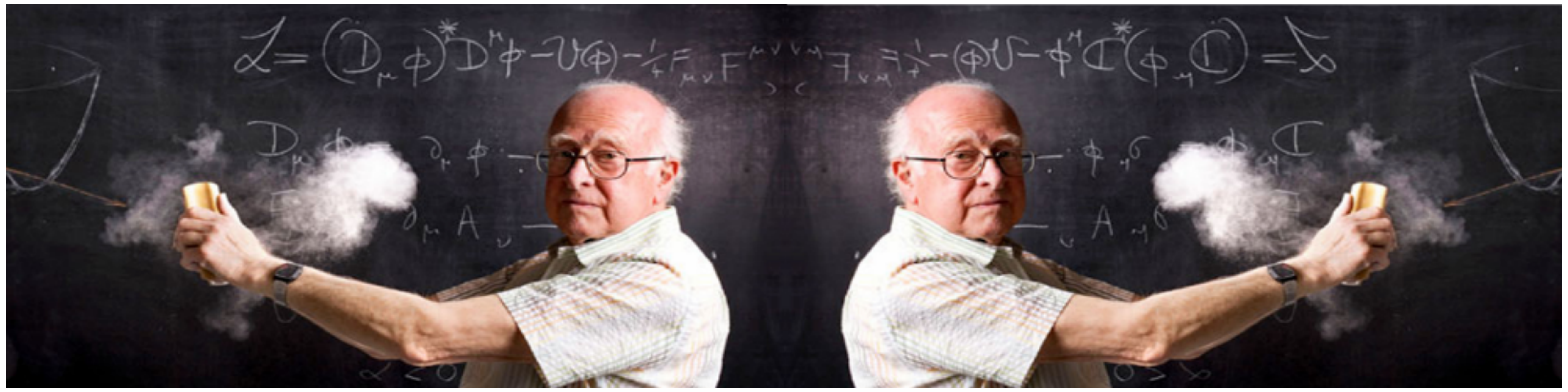

Search for double Higgs resonances with gamma gamma in the final state at CMS

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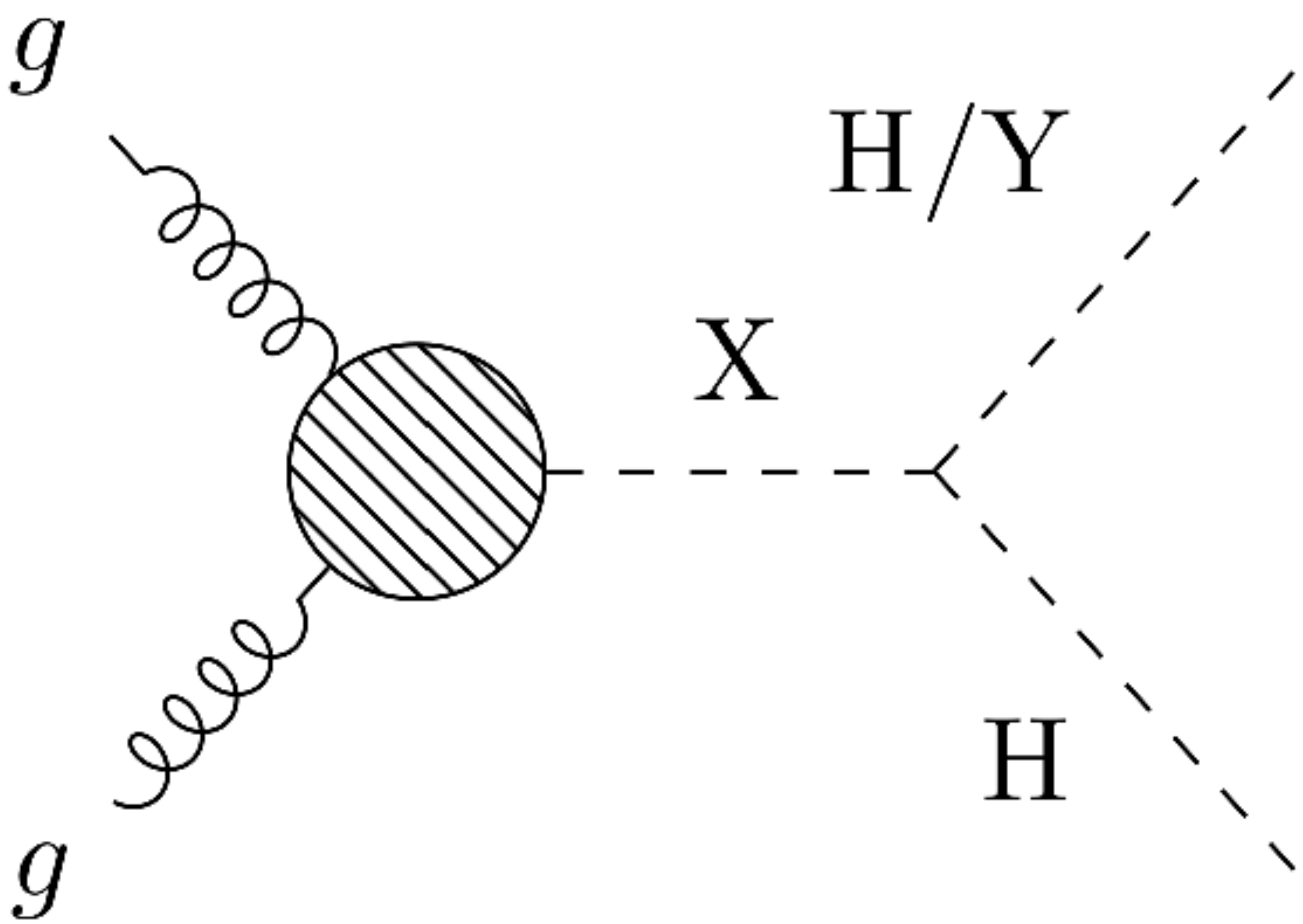
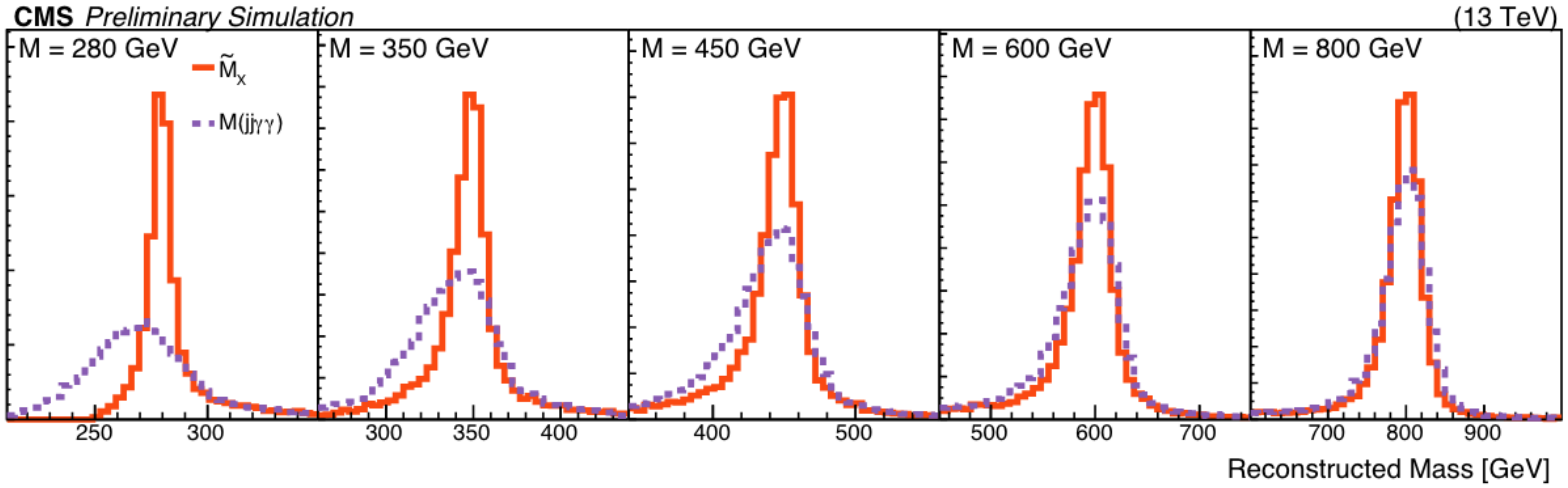
IHEP of Chinese Academy of Sciences (CN)

Introduction

- Many BSM models predict new resonances:
  - 2HDM
  - composite-Higgs
  - Warped extra dimensions
    - Radio (spin 0) / Graviton (spin 2)
  - SUSY (NMSSM)
  - Two-real-scalar-singlet extension of the SM (TRSM)
- Main production mode:
  - Gluon-gluon fusion of heavy resonance X
  - X decays to either HH or HY
- Analyses:
  - H/Y decays to different final states
    - Today focus on HH/YH in $\gamma\gamma$ final state
  - Target different spin and mass hypotheses



Introduction



	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

- Why HH/YH in $\gamma\gamma$ final states:
  - Small branching fraction (0.2%), but clean final state with two highly energetic and isolated photons, so final state can be fully reconstructed with excellent mass resolution (1-2%)
  - Relatively less backgrounds than hadronic decay
    - Continuum $\gamma\gamma$ (irreducible)
    - Fakes from γj and jj (reducible)

- $X \to HH/YH \to bb\gamma\gamma$ (https://doi.org/10.1007/JHEP05(2024)316)
- $X \to HH/YH \to \tau\tau\gamma\gamma$ (PAS)
- $X \to HH/YH \to WW/ZZ\ \gamma\gamma$ in progress with CADI B2G-24-010
- $X \to HH/YH \to bb\ \gamma\gamma$ high mass in progress with CADI B2G-24-017

$X \to HH/YH \to bb\gamma\gamma$ (https://doi.org/10.1007/JHEP05(2024)316)

- $X \to HH/YH \to bb\gamma\gamma$ (X is spin-0 and spin-2 particle) at center-of-mass energy of 13 TeV with CMS Run 2 data with 138 fb^{-1} luminosity

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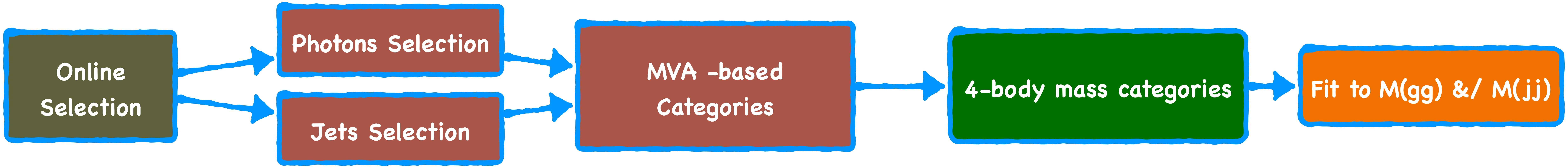
Analysis Strategy

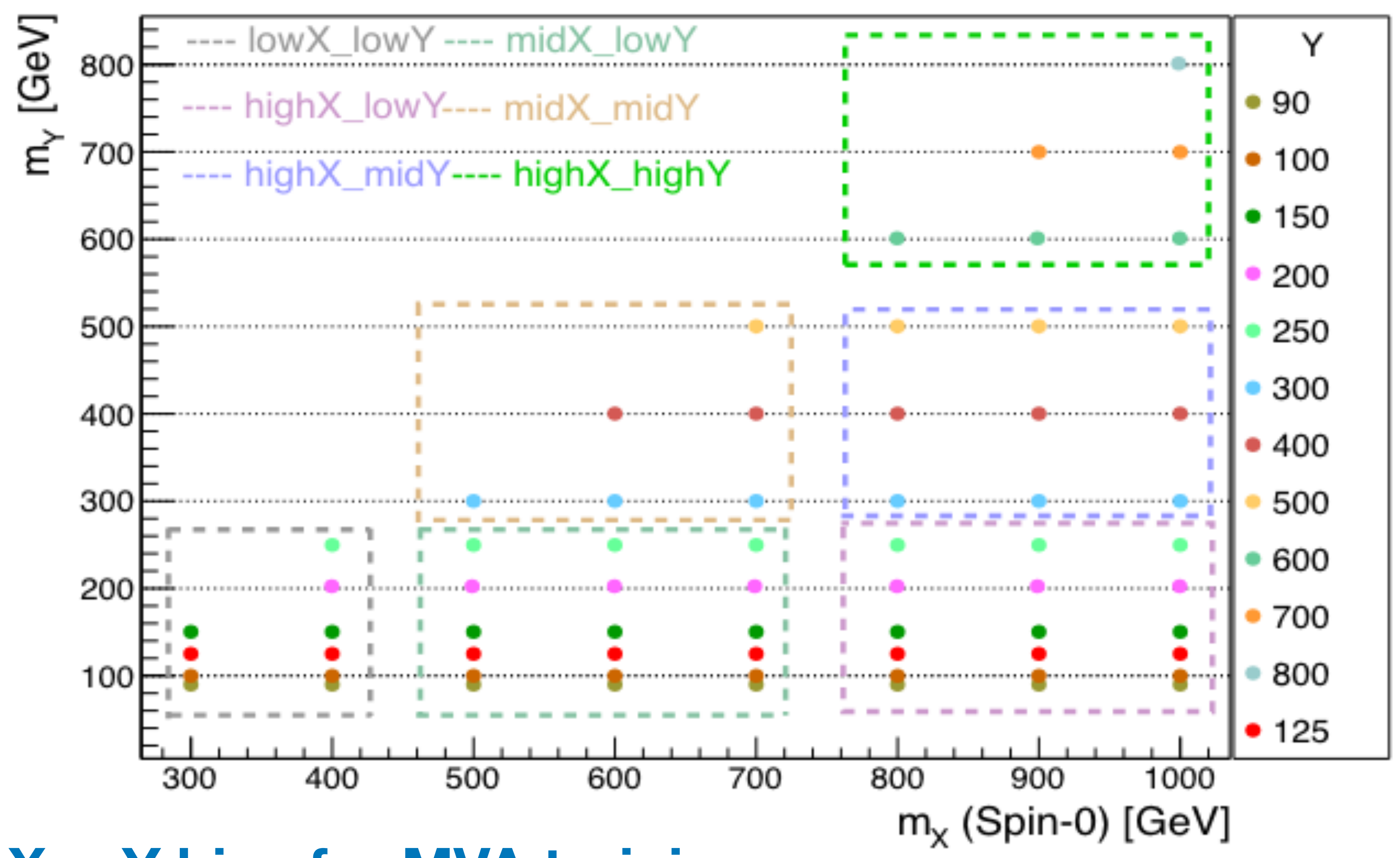


- **Trigger:**
  - 2016 : HLT_Diphoton30_18_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90_v*
  - 2017 : HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90_v*
  - 2018 :HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90/95_v*

- **Photons**
  - Hgg MVA photon ID > -0.9
  - Pixel-safe electron veto is applied
  - $p_T(\gamma_1)/M(\gamma\gamma) > 1/3$, $p_T(\gamma_2)/M(\gamma\gamma) > 1/4$, $100 < M(\gamma\gamma) < 180$ GeV
- **Jets:**
  - B jets are chosen with the highest sum of b-tag score: DeepJet
  - B jet are corrected with b-jet energy regression: DNN based
  - p_T(jets) > 25 GeV, $|\eta(jets)| < 2.4$ (2016) & $|\eta(jets)| < 2.5$ (2017/2018)
  - Jet ID: 2016 - Loose, 2017 - Tight, 2018 - Tight
  - ΔR (jet, γ's) > 0.4
  - Mass window: 70 < M(jj) < 190 GeV

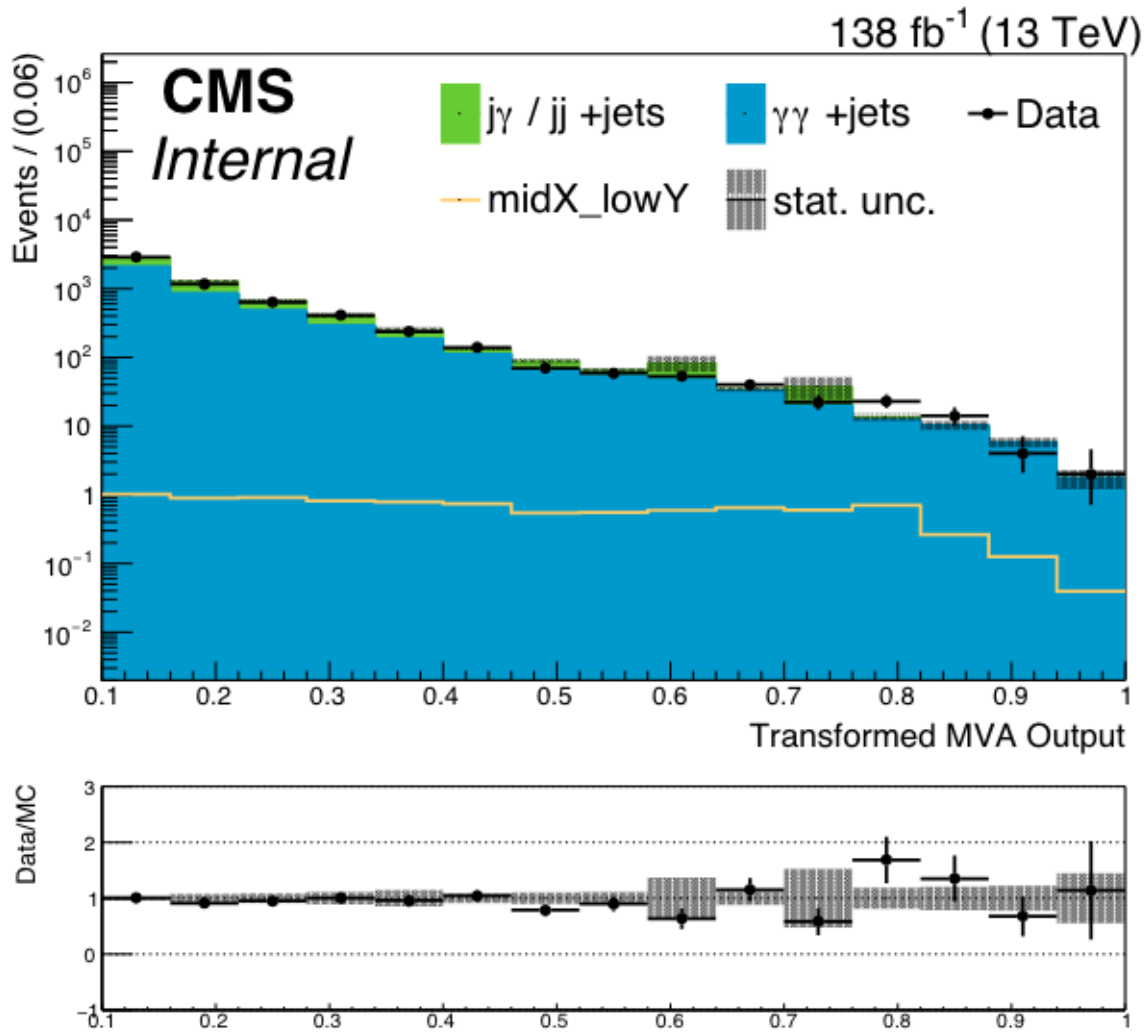
BDT Classifier and Categorization

- **Multi-class Boosted Decision Trees (BDT) for background discrimination:**
  - Signal = signal MC (YH)
  - Background-1 = $\gamma\gamma$ + jets
  - Background-2 = jγ / jj+jets
- **Training input variables**
  - ~25 discriminant features
  - Boost factors for different mass region
- **Validation in control region for Data/MC**
- **MVA categorization**
  - Based on significance
  - High, medium, low categories



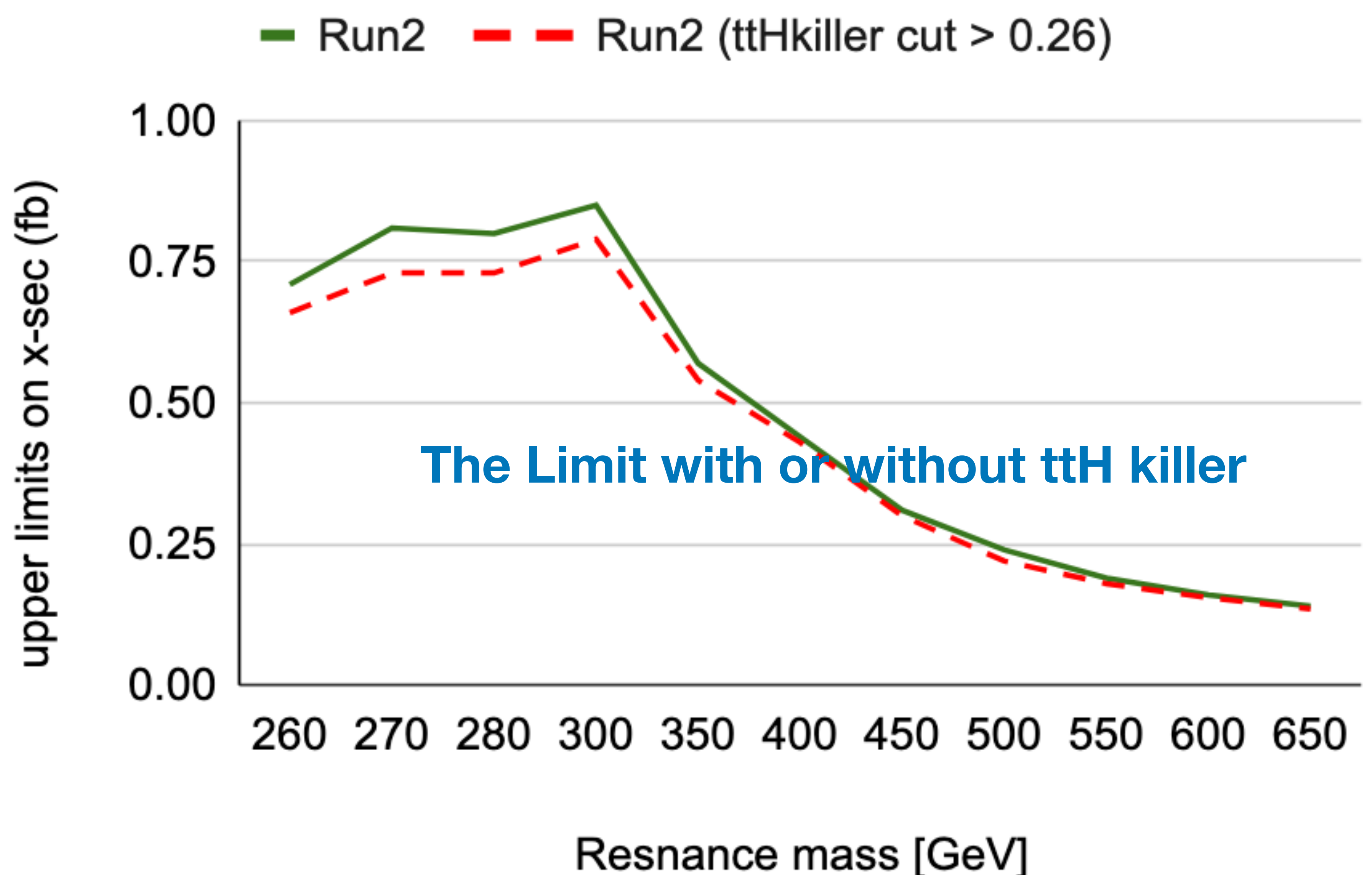
mX-mY bins for MVA training

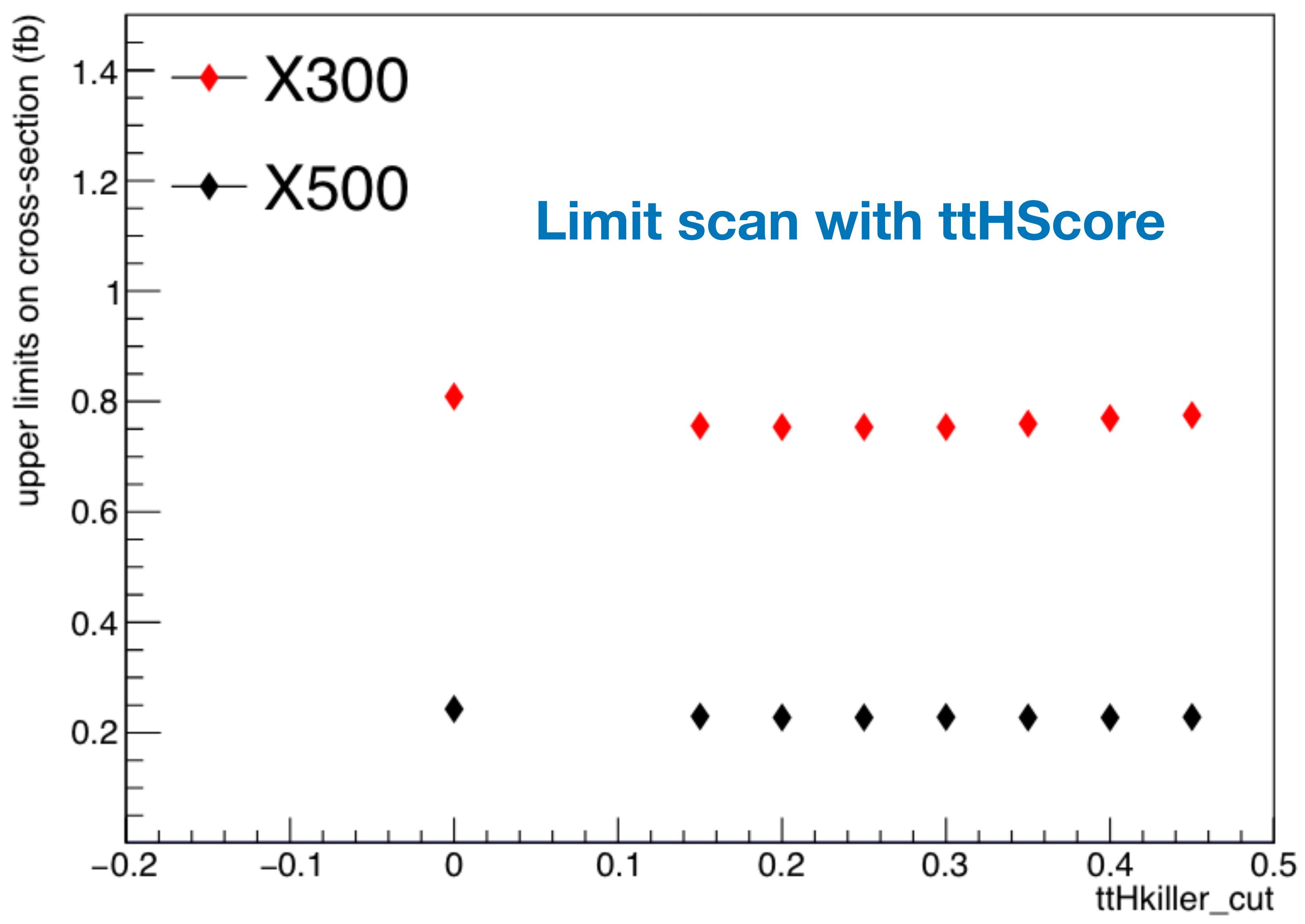
Score distribution



Single Higgs background rejection

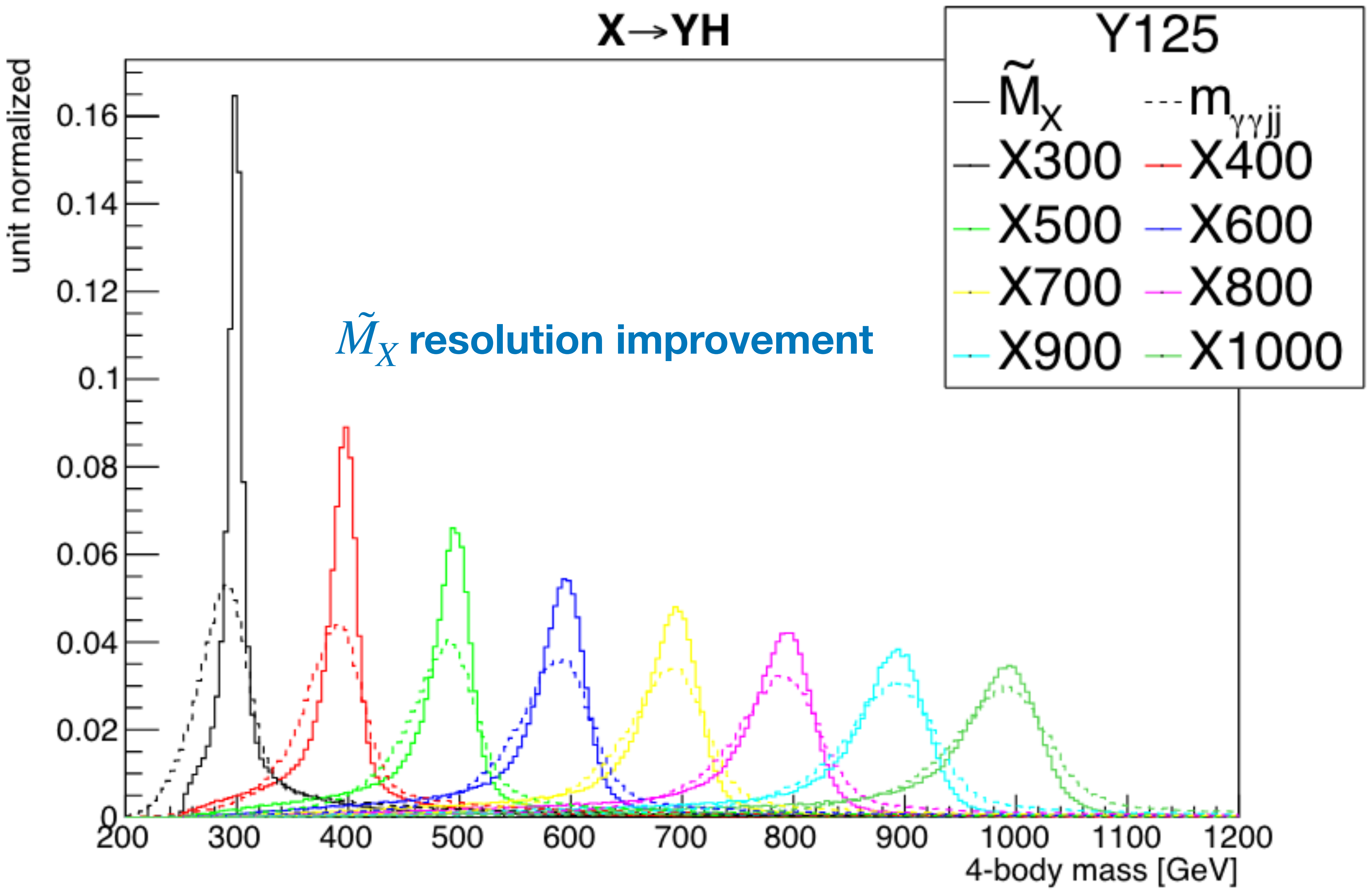
- Resonant background are single Higgs process which have similar diphoton mass distribution peaking around m_H
- The most dominant background is ttH for this analysis
- Contamination have only been considered for $m_X < 600$ GeV;
- Develop MVA based ttHkiller for removing ttH
  - Based on neural network training
  - Order of magnitude for sensitivity improvement with m X < 600 GeV is up to 10%.

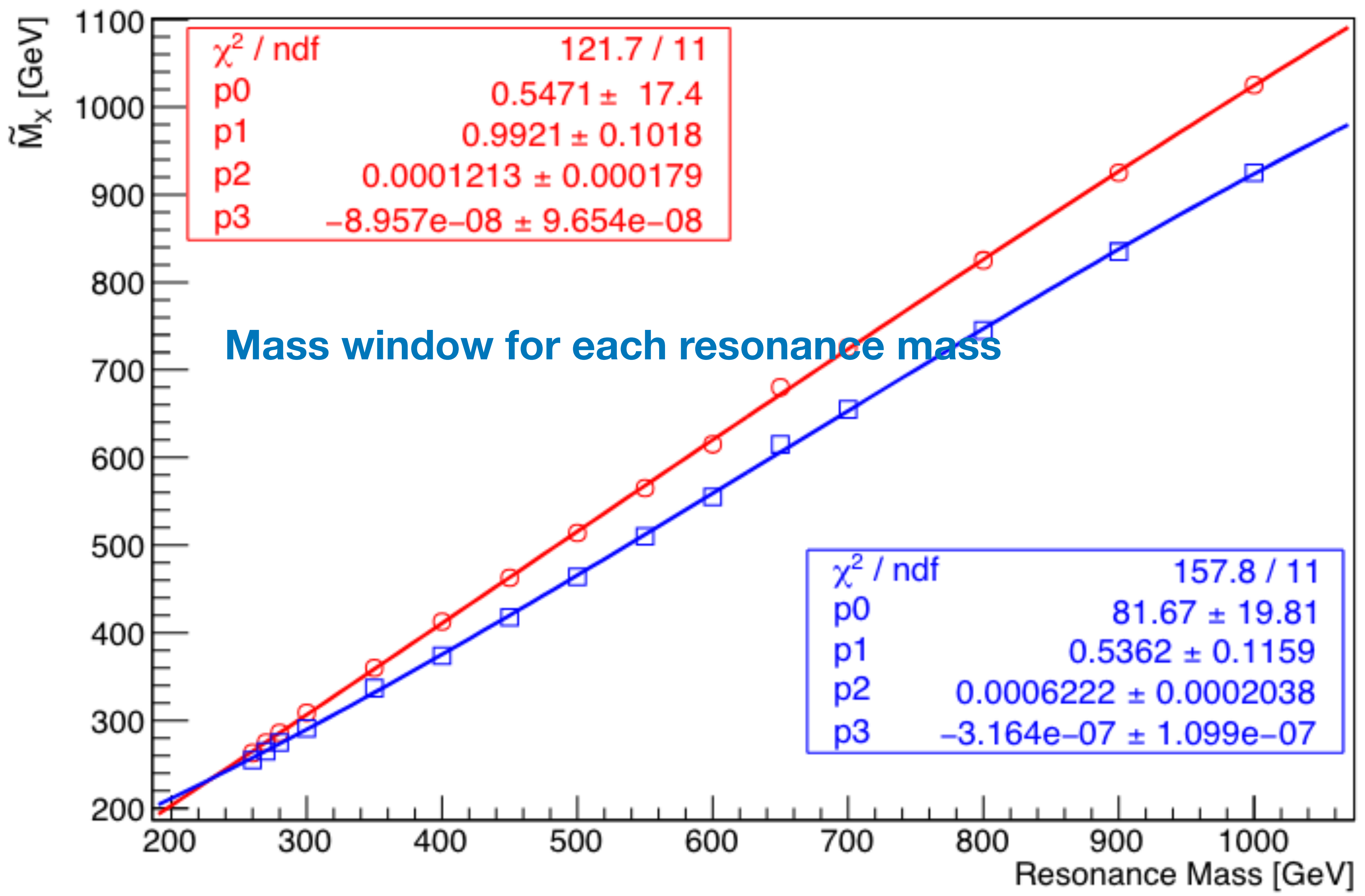




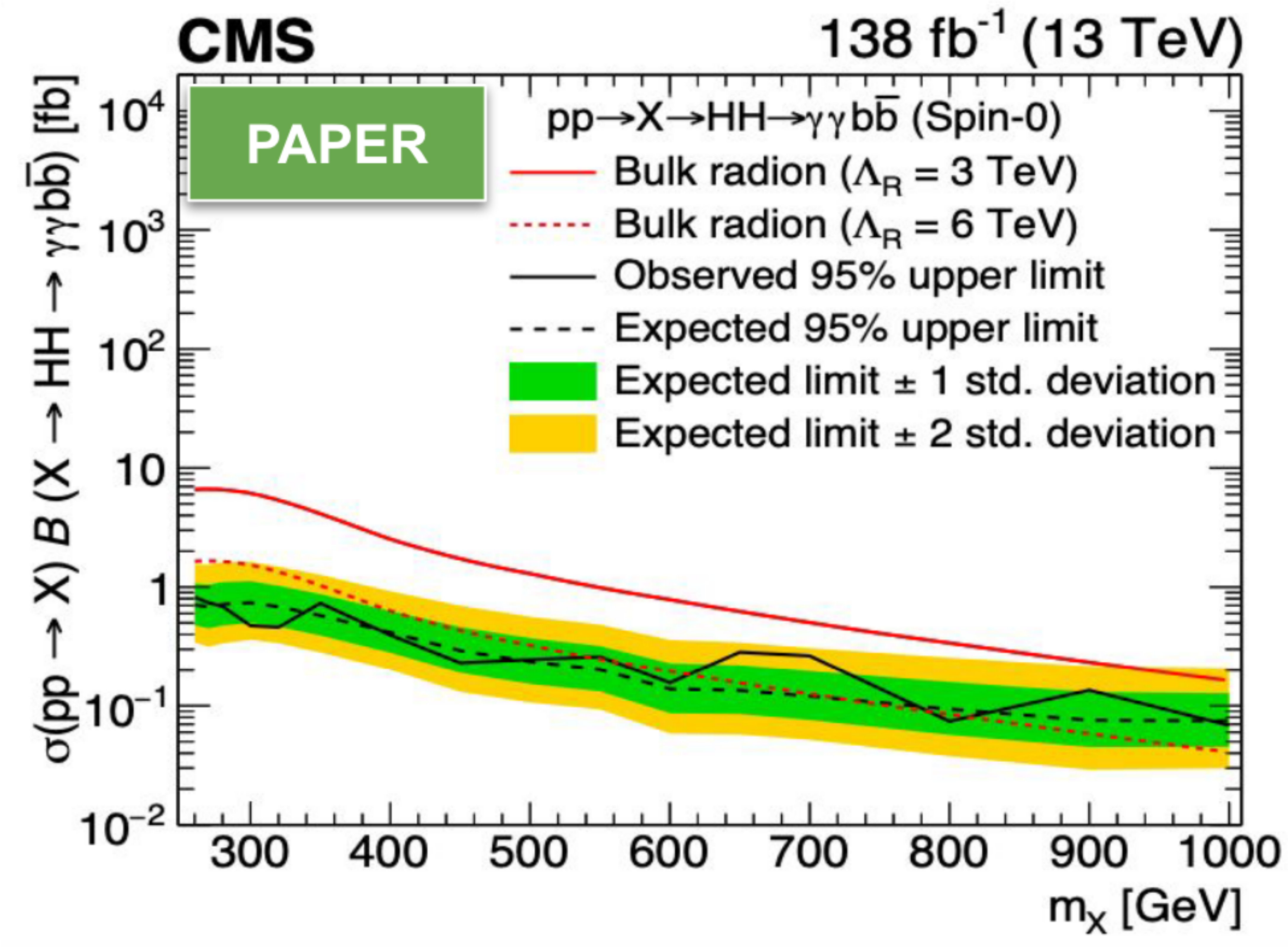
MX window selection

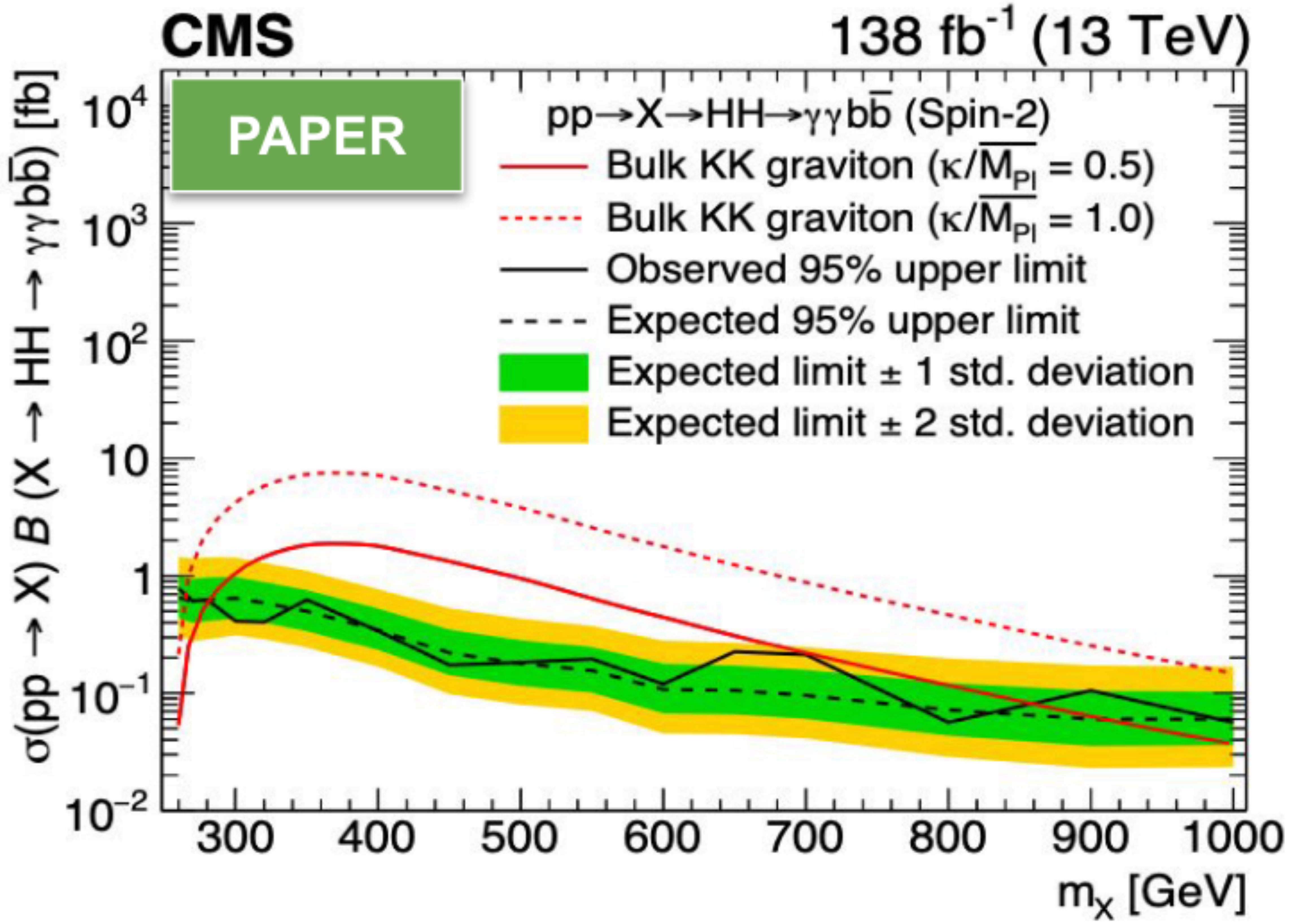
- **Selection on four-body mass** $\tilde{M}_X = (m_{jj\gamma\gamma} - mjj - m\gamma\gamma + m_H + m_Y)$
- Mx performs a kinematic fit on four-body mass and results better resolution (30%-90%) w.r.t $m_{jj\gamma\gamma}$
- Mx windows are optimized keeping more than **60% signal efficiency**
- It also helps to suppress single Higgs contribution (<1%)





Results $X \rightarrow HH$

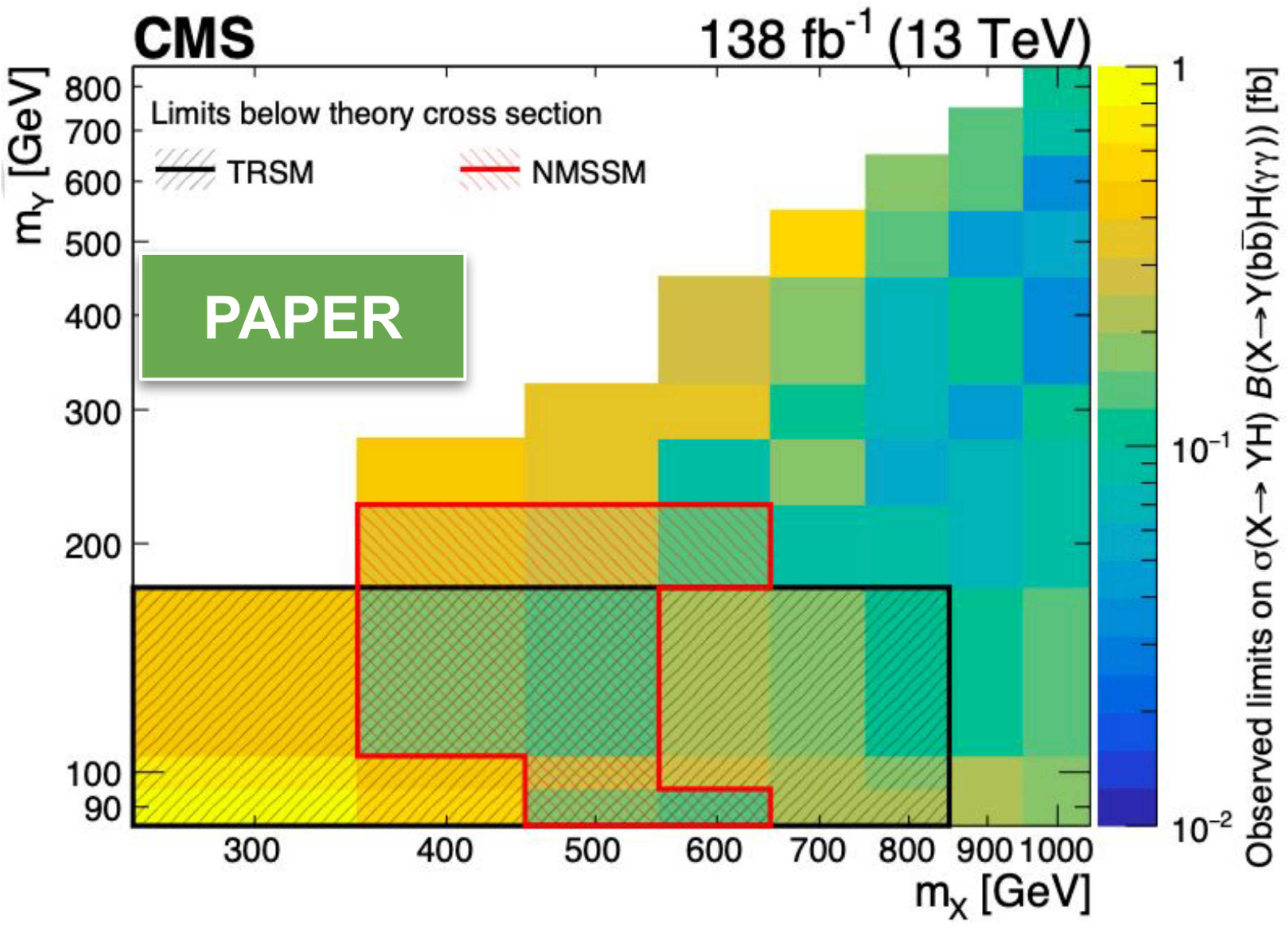


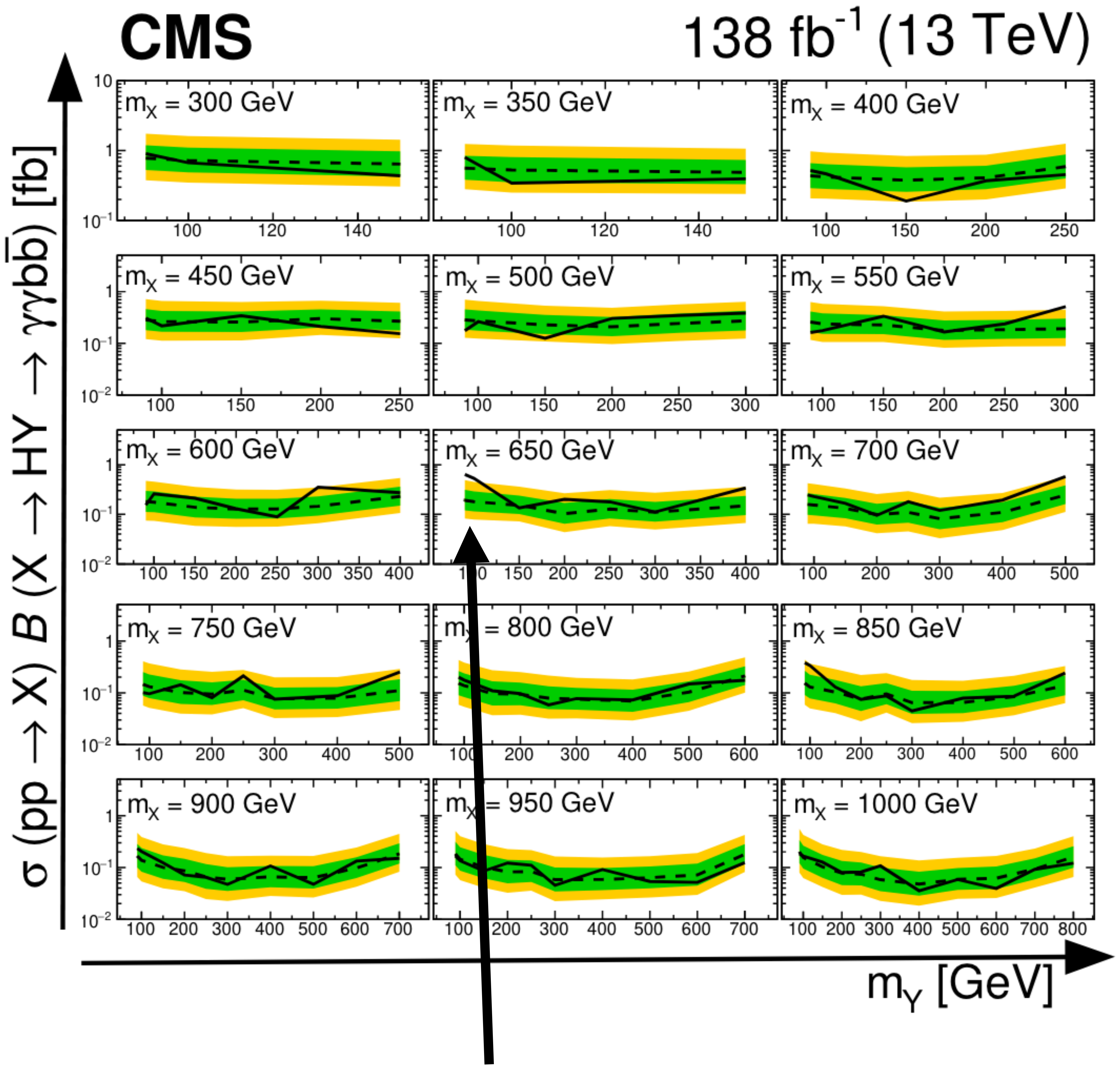


- Left plot (spin-0): For **Λ**R = 3 TeV, excludes masses up to 1 TeV; for **Λ**R = 6 TeV, excludes masses up to 600 GeV.
- Right plot (spin-2): With κ/Mpl = 0.5, excludes resonance masses up to 850 GeV.

Results $X \to YH$

- NMSSM and TRSM interpretations
  - Exclude region mX =[400-600] GeV and mY = [90–250] GeV for NMSSM
  - Exclude region mX =[300-800] GeV and mY = [90–150] GeV for TRSM
- Excess in mX = 650 GeV and mY = 90GeV





3.8σ local (2.8σ global) for mX = 650 GeV and mY = 90 GeV

CMS

$X \rightarrow HH/YH \rightarrow \tau\tau\gamma\gamma$ (CMS-PAS-HIG-22-012)

- $X \rightarrow HH/YH \rightarrow \tau\tau\gamma\gamma$ (X is spin-0 and spin-2 particle) at center-of-mass energy of 13 TeV with CMS Run 2 data with 138 fb^{-1} luminosity

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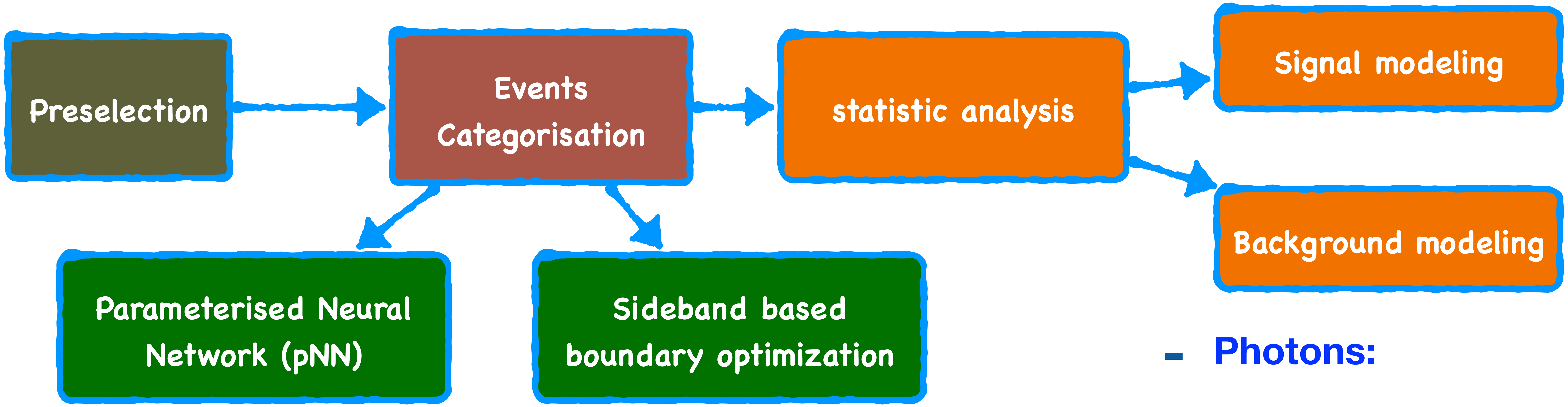

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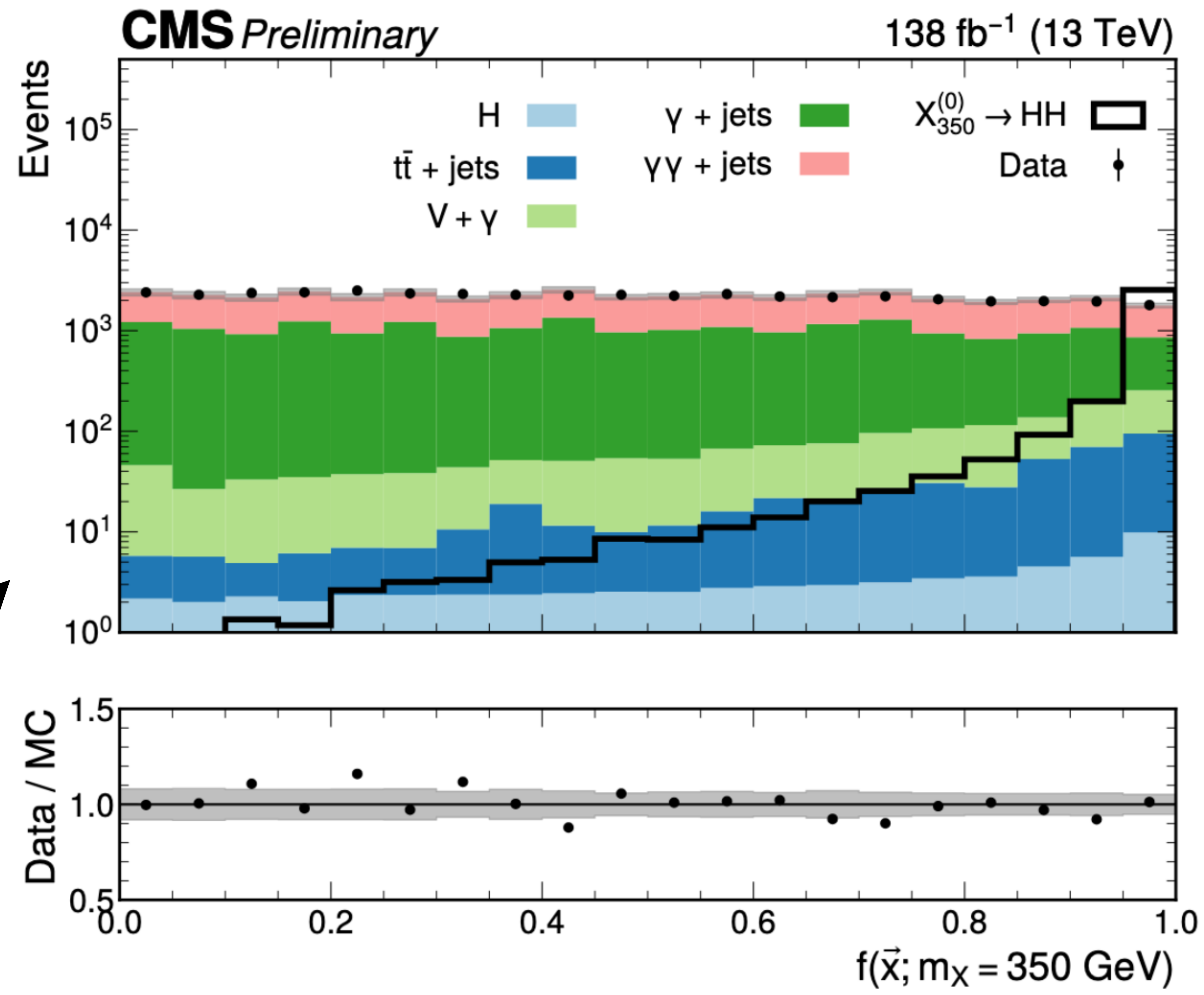
  - 2018 :HLT_Diphoton30_22_R9Id_OR_IsoCaloId_AND_HE_R9Id_Mass90/95_v*

- **Photons:**
  - $p_T >$ 25(30) GeV
  - Isolation cuts
  - EG Photon ID WP90
- **taus:**
  - $p_T >$ 20 GeV
  - $|d_Z| <$ 0.2 cm
  - deepTau ID (vs jet, μ and e)

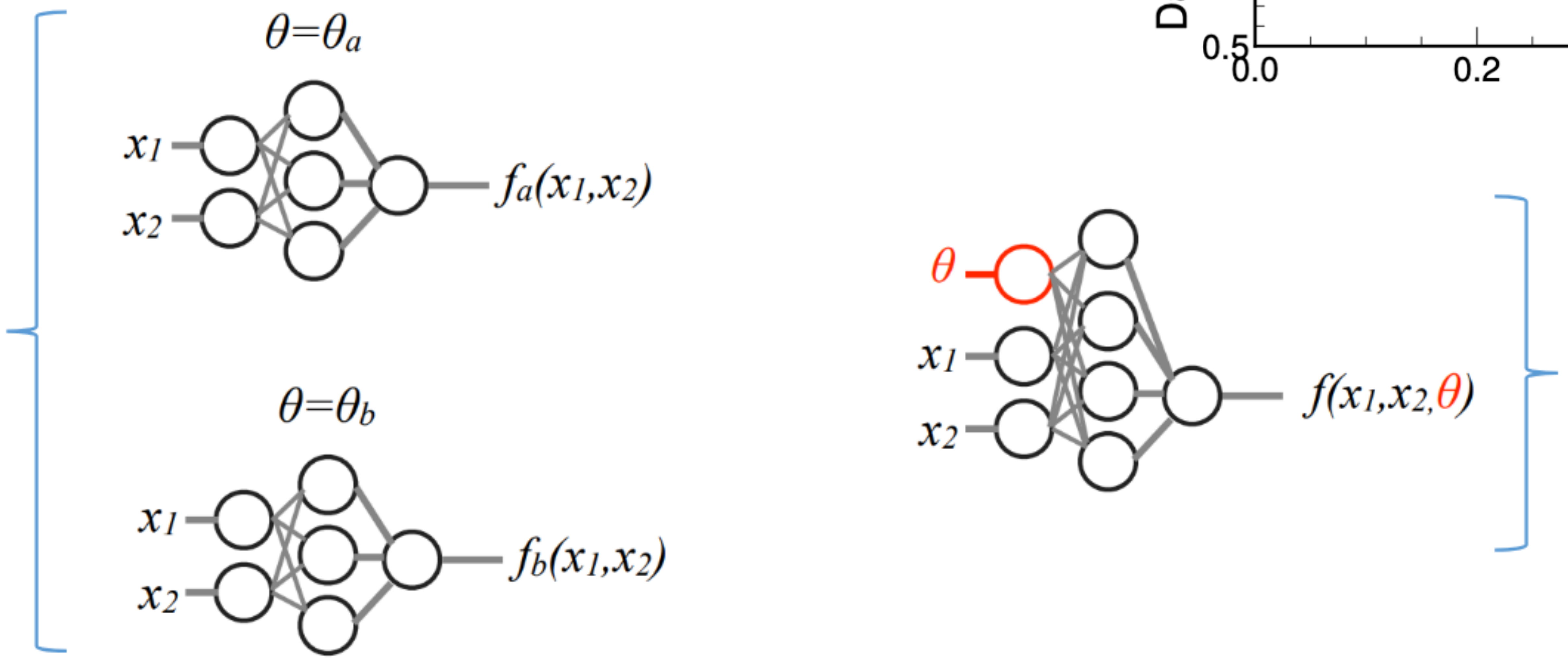
- **Muons:**
  - $p_T >$ 10 GeV
  - $|d_{xy}| < 0.045cm$
  - $|dz| < 0.2$ cm
  - Isolation cuts
- **Electrons:**
  - $p_T >$ 15 GeV
  - $|d_{xy}| < 0.045cm$
  - $|dz| < 0.2$ cm
  - Isolation cuts

Parameterised Neural Network (pNN)

- **Task: develop an MVA that discriminates well at nominal and intermediate mass points (too many X and Y mass points)**
- **Solution: a Parameterised Neural Network(PNN) whose target function is** $f(\vec{x}; mx, mY)$
  - Add m_X, m_Y as additional training features
  - Train on all signal MC, $\{m^1, m^2 \dots\}$, simultaneously
  - Give background MC random values of m_X from $\{m^1, m^2 \dots\}$
  - Output scores have good discriminant power and good Data/MC agreement



Networks trained on single mass points



Parameterised NN with mass an input

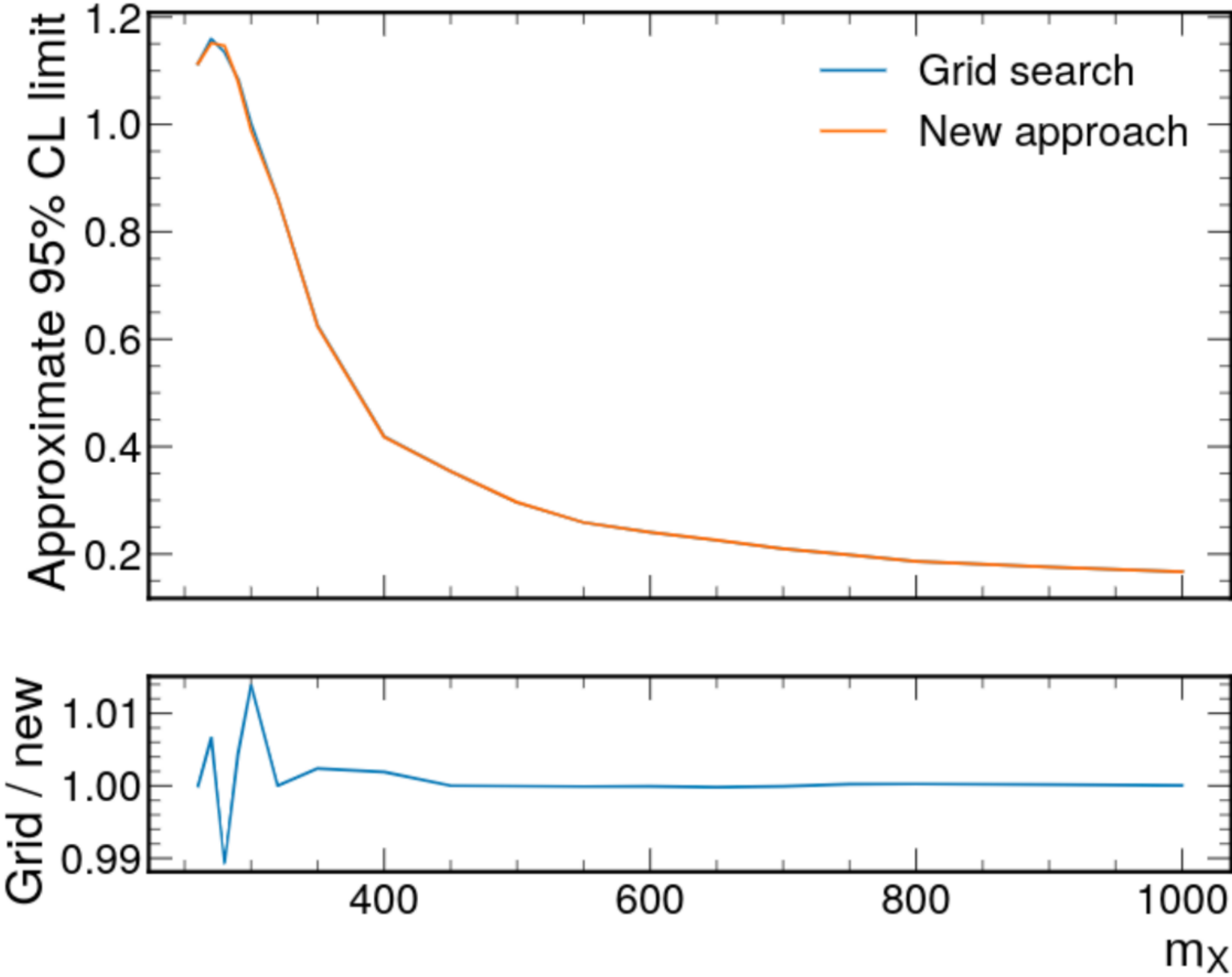
Categorisation

- **Task: derive optimal boundaries in PNN output score to form categories with expected limit at all mass points**

- Without signal MC, we cannot individually optimise for intermediate mass points → **create a common category definition** using nominal mass point MC

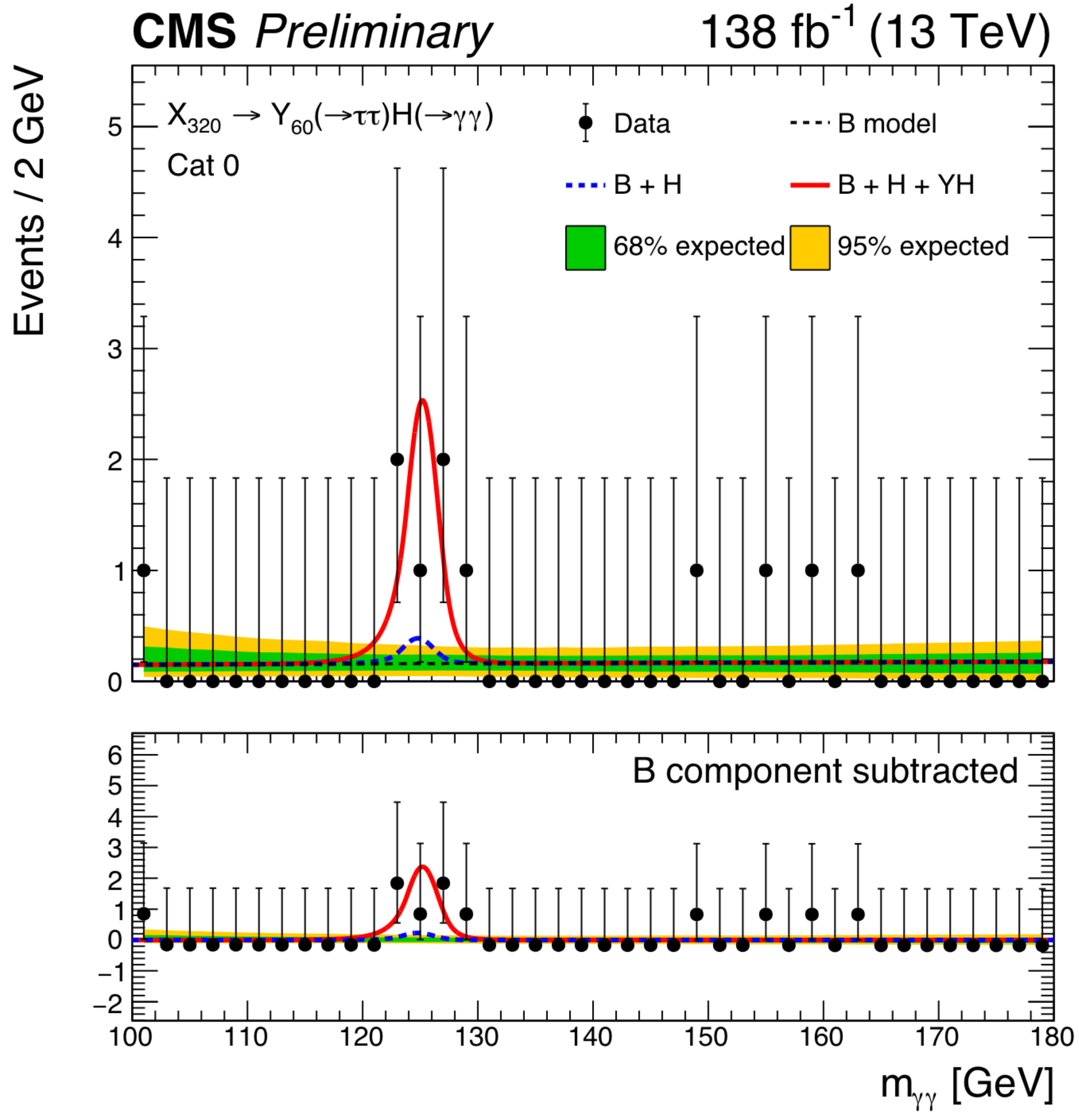
- Choose to define categories based on N data events in the sidebands

- Similar performance compare with grid search

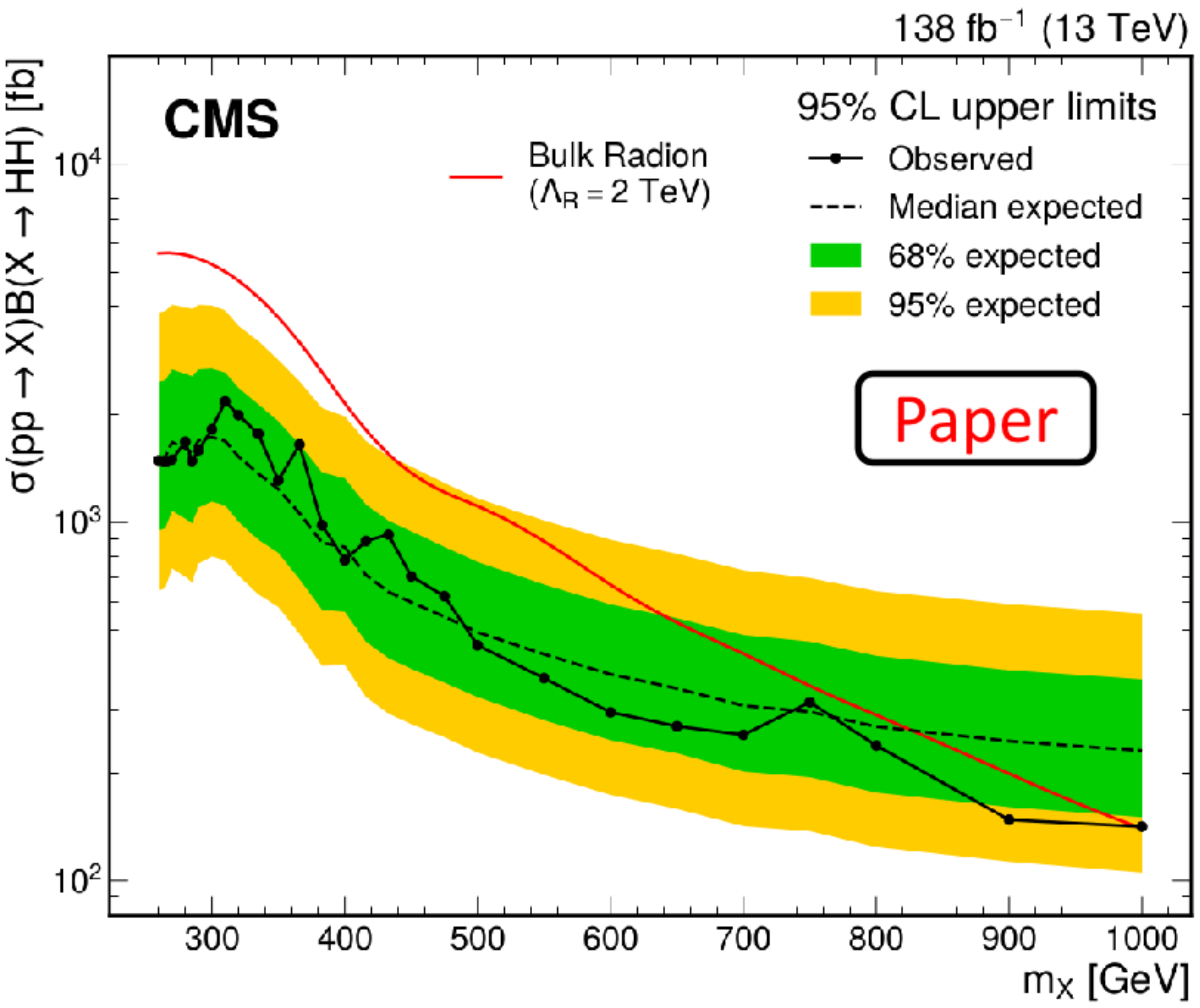


Signal & Background Modeling

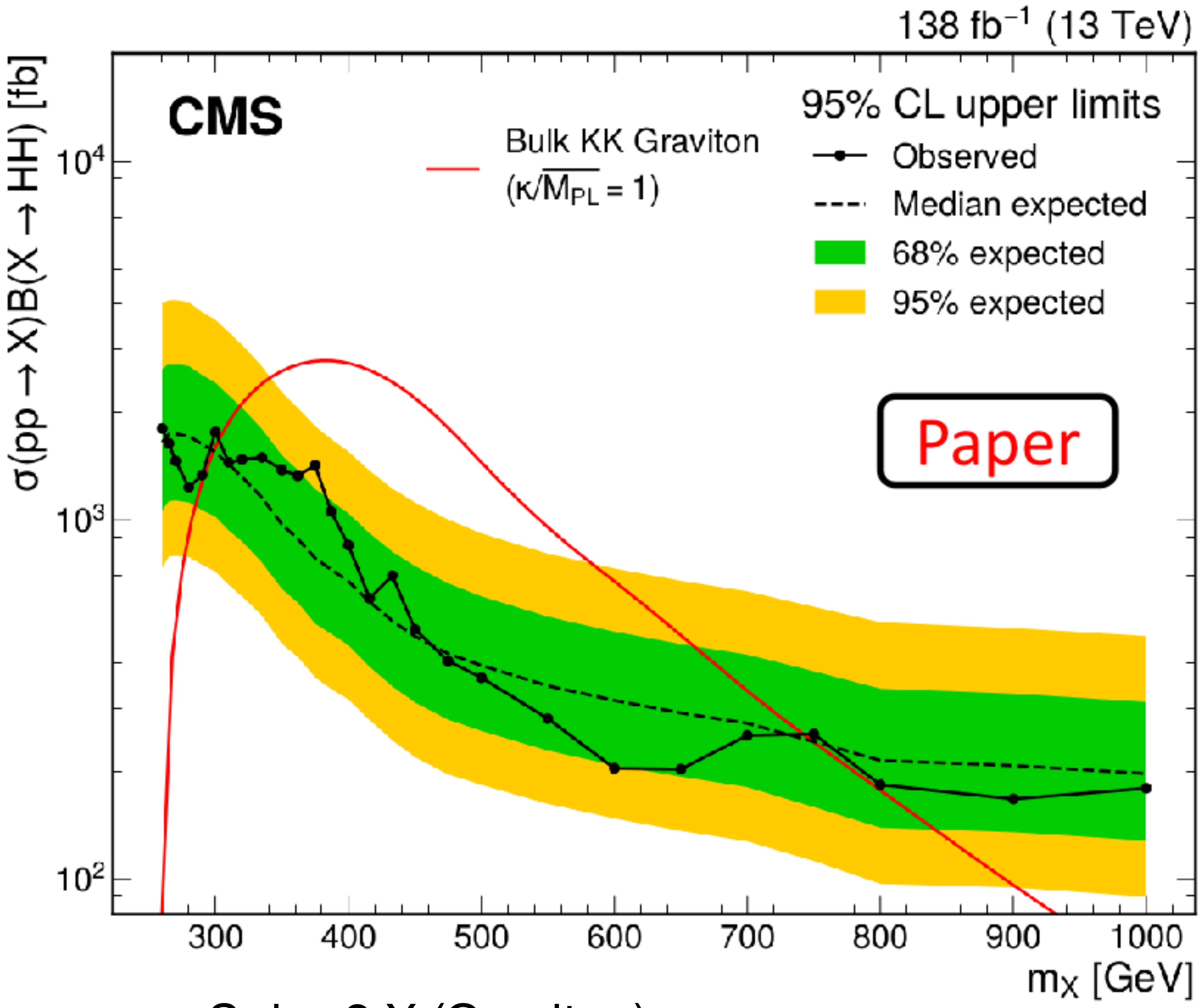
- Signal modelling:
  - Derived from fits to the MC with a Double Cystal Ball (DCB) for better interpolation with PNN results
- Background modeling:
  - Same as $bb\gamma\gamma$,falling component modelled by an envelope of smoothly falling functions using the discrete profiling method
- Single H background modeling same as signal



Results $X \to HH$



Spin -0 X (Radion)



Spin -2 X (Graviton)

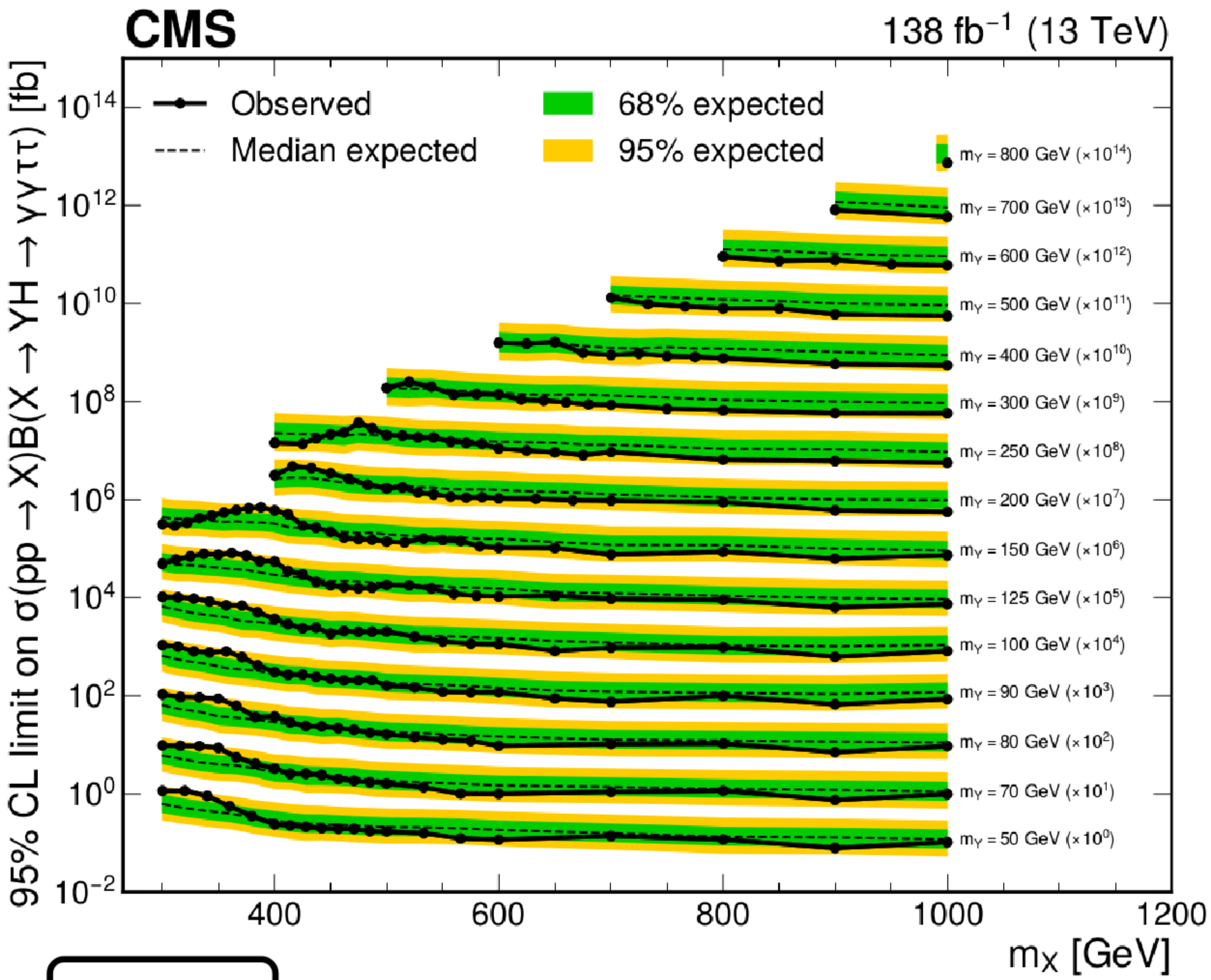
Exclude m_X up to 900 GeV at ΛR = 2 TeV

Exclude m_X between 310 and 700 GeV at k/MPL = 1

Results $X \to YH$

$Y \to \tau\tau$

- No excess seen at X650 or Y90 GeV
- Maximum local significance of 2.6σ at mX, mY = (320, 60) GeV with global 2.2σ significance



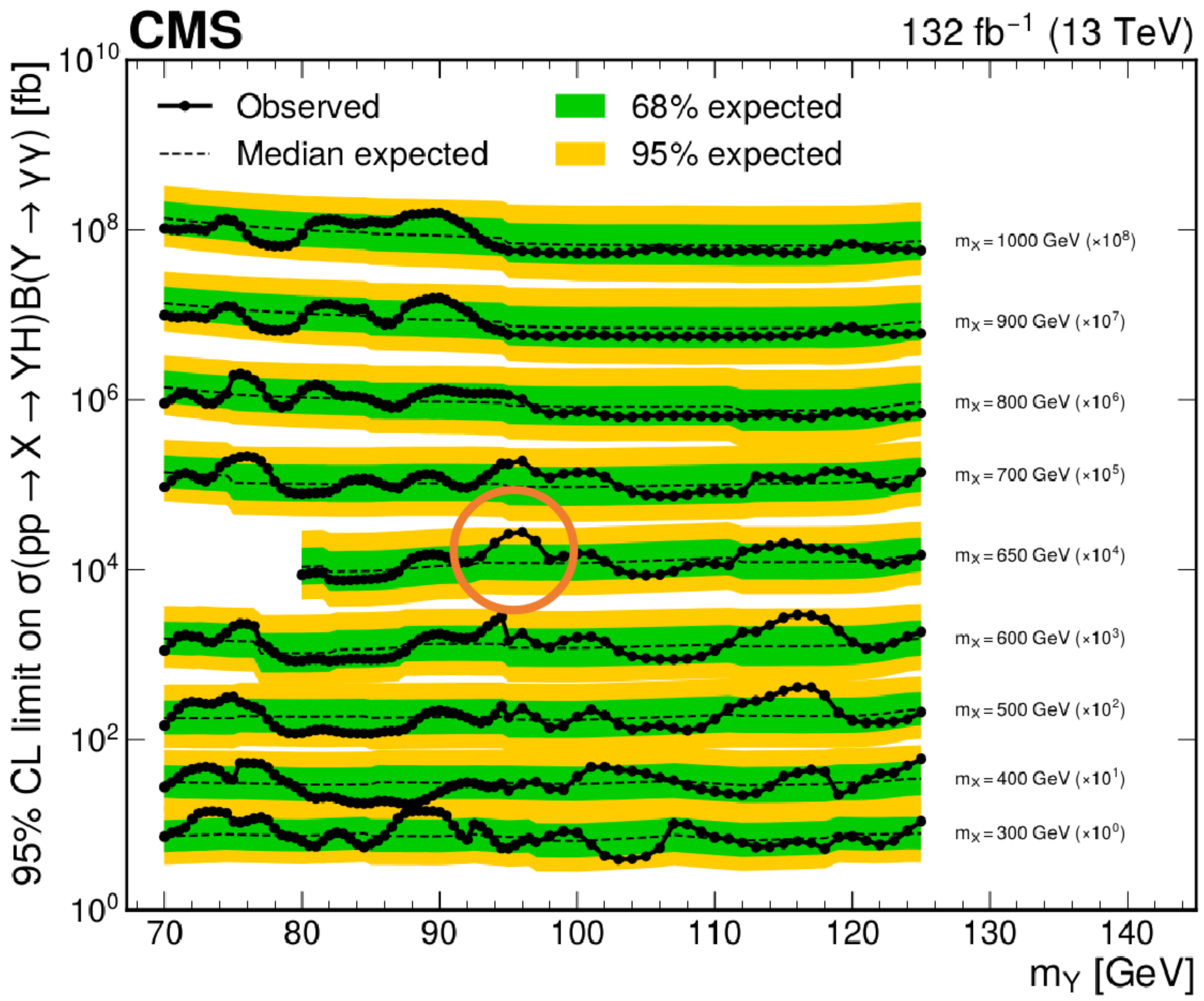
Paper

Results $X \to YH$

$Y \to \gamma\gamma$

- excess at mX, mY = (650,95) GeV in low $Y \to \gamma\gamma$ analysis: 2.5σ local significance

Paper



Summary

- $X \to HH/YH \to bb\gamma\gamma$:
  - New **BDT training** method with boost factor
  - New **ttHKiller** for ttH single Higgs background
  - Better categorisation from **boundary optimization and mass window** selection
  - **Results for $X \to HH$**
    - ✳ Spin-0 Radion: Up to 1 TeV (Λ_R = 3 TeV), up to 600 GeV (Λ_R = 6 TeV)
    - ✳ Spin-2 Graviton: Up to 850 GeV (κ/M_Pl = 0.5)
  - **Results for $X \to YH$**
    - ✳ **Excess in mX = 650 GeV and mY = 90GeV**

- $X \to HH/YH \to \tau\tau\gamma\gamma$
  - New **PNN training** method
  - New Categorisation from **sideband boundary optimization**
  - **Results for $X \to HH$**
    - ✳ Spin-0 Radion: Up to 900 GeV (Λ_R = 2 TeV)
    - ✳ Spin-2 Graviton: Between 310 and 700 GeV (κ/M_Pl = 1)
  - **Results for $X \to YH$**
    - ✳ **Excess in mX = 320 GeV and mY = 90GeV for $Y \to \tau\tau$**
    - ✳ **Excess in mX = 650 GeV and mY = 95 GeV for $Y \to \gamma\gamma$**

Thank you for listening