Search for a new resonance $X \rightarrow HY \rightarrow \gamma\gamma bb$ in proton-proton collisions at $\sqrt{s} = 13$ TeV

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On behalf on the CMS collaboration

NOTE:

- *Approved and public by the CMS collaboration: CMS-PAS-HIG-21-011 (presented during ICHEP 2022)*

Outline

- Physics Motivation
- Analysis Strategy
- Results with theoretical interpretations
- Summary

Physics Motivation

- Many BSM theories predict direct or indirect production of new resonances with enhanced cross-section ; direct coupling with SM-like or/and BSM Higgs boson
- **Analysis features:**
  - Model-independent approach with narrow-width approximation
  - Searches are motivated from:
    Next-to-minimal supersymmetric model (**NMSSM**) and Two-real-scalar-singlet model (**TRSM** [Ref.])
- **First time looking at NMSSM and TRSM motivated searches**

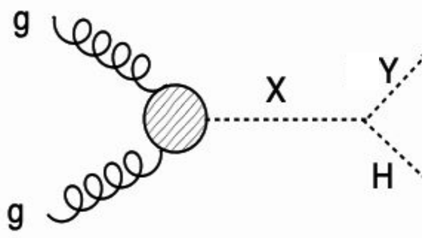
Physics Motivation

Next-to-minimal supersymmetric model

- Enriches Higgs sector with 7 Higgs bosons (lets label three NMSSM Higgs boson scalars as X, Y and SM-like H)
- dominant singlet component of Y suppresses its direct production at LHC; production via a heavy Higgs boson X → YH becomes important

Two-real-scalar-singlet model

- Extension of SM with two scalar singlet fields
- Three scalars⇒ one is identified as SM-like Higgs boson
- Gives same topology for X→YH



Physics Motivation

Next-to-minimal supersymmetric model

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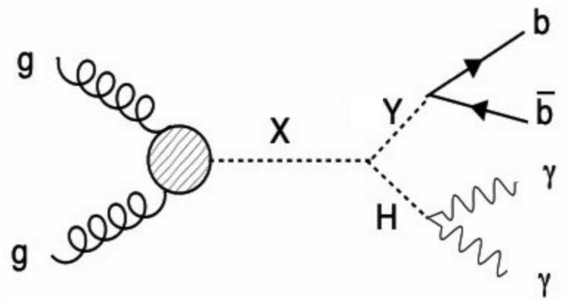
γγbb final state

- H→γγ handle with high purity and selection efficiency due to excellent ECAL response
- For Y→ bb handle b tagging rejects high multijet background contamination

Two-real-scalar-singlet model

- Extension of SM with two scalar singlet fields
- Three scalars⇒ one is identified as SM-like Higgs boson
- Gives same topology for X→YH

X mass upto 1 TeV
Y mass upto 800 GeV
$m_Y < m_X - m_H$



Analysis Strategy

Event selections → Background rejection methods → Statistical Analysis

Event Selections

Trigger Selection (Standard H→ γγ triggers)

Photon selections

(Same as H→ γγ analysis)

- photon MVA ID > -0.9 (99% eff.)
- Electron veto (suppress Z→ ee)
- $p_T(\gamma 1)/M(\gamma\gamma) > 1/3$
- $p_T(\gamma 2)/M(\gamma\gamma) > 1/4$
- $100 < M(\gamma\gamma) < 180$ GeV

Jets selection

(similar to non-resonant HH→γγbb *JHEP 03 (2021)***)**

- p_T (jets) > 25 GeV, $|\eta(\text{jets})| < 2.4(2.5)$ (2016(2017/18))
- Jet corrected with b jet energy regression (Ref.)
- Jet Id selection with efficiency > 99%
- $\Delta R(\text{jet},\gamma\text{'s}) > 0.4$
- $70 < M(jj) < 1200$ GeV
- Jet pair with highest sum of DeepJet score

Background rejection

Non-resonant background

- Includes SM multijet backgrounds with up to two prompt photon contribution
- BDT training is used to reject the dominant $\gamma\gamma$+jets and γ+jets backgrounds
- Events are classified into three BDT categories after discarding the background pure region

Resonant background

- Includes SM single H processes where $H \rightarrow \gamma\gamma$ (giving the signal-like $m_{\gamma\gamma}$ shape)
- NN-based discriminant is used to reject dominating ttH background
- Along with Event classification, a tight selection on $\tilde{M}_X$ ($= m_{\gamma\gamma jj} - m_{\gamma\gamma} - m_{jj} + m_H + m_Y$) variable is applied which make resonant contribution < 1%

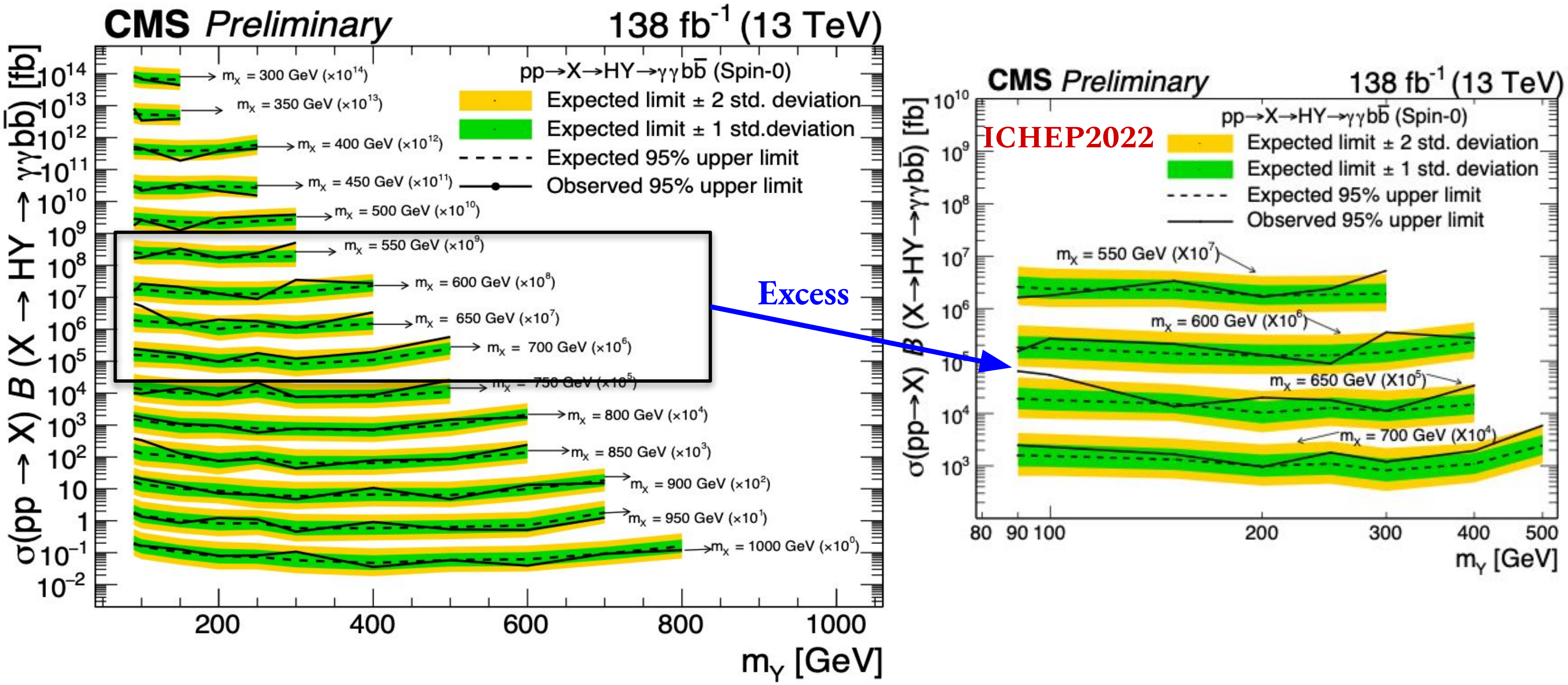
Signal and Background Model

- **Signal is extracted by 2D fit in uncorrelated $m_{\gamma\gamma}$:m_{jj} plane**
- **Signal**
  - $m_{\gamma\gamma}$: sum of gaussian functions is used (upto 5)
  - m_{jj}: DoubleCrystalBall (DCB) function or Sum of CB and Gaussian
- **Non-resonant background:**
  - Determine from data-driven method
  - 2D envelope method (1Dx1D)
- **Resonant background:**
  - $m_{\gamma\gamma}$: Same as signal modeling
  - m_{jj}: differs depending upon the process

Results

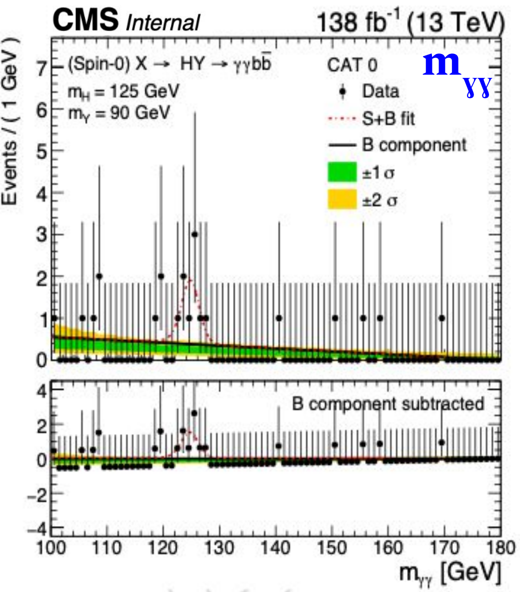
- We find no deviation from SM background predictions except m_X = 650 GeV and m_Y <= 100 GeV
- 95% upper limits are set on product of cross section and branching fraction to γγbb final state
- Results are also interpreted for NMSSM and TRSM scenario

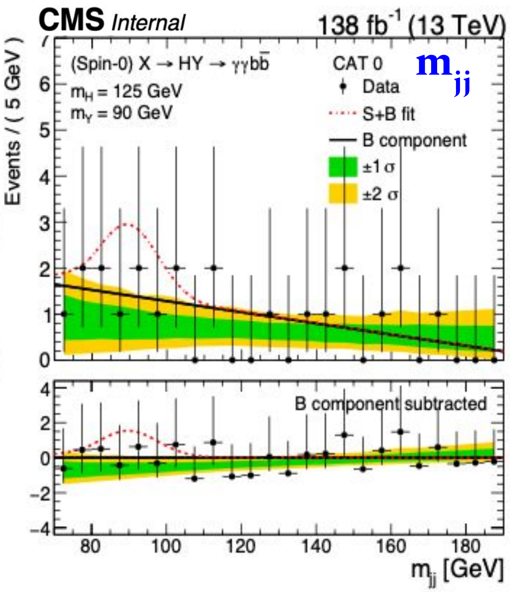
Results: X→HY

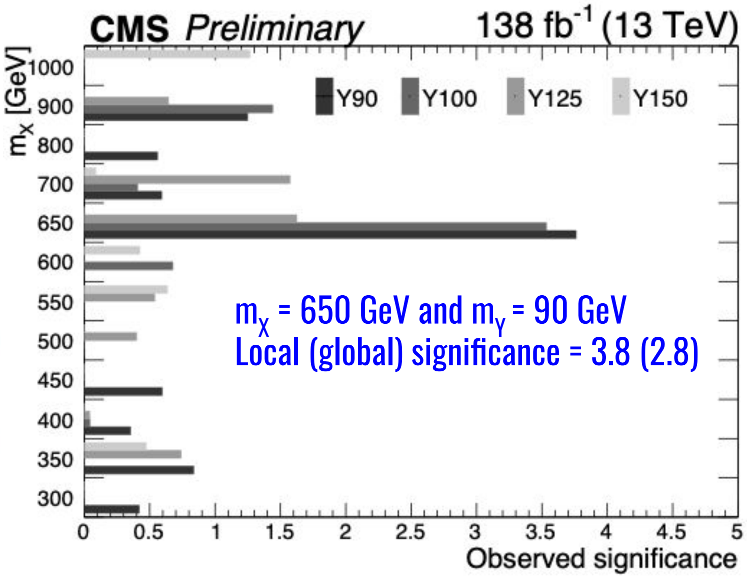

CMS Preliminary
138 fb^{-1} (13 TeV)
pp→X→HY→γγbb̄ (Spin-0)
Expected limit ± 2 std. deviation
Expected limit ± 1 std.deviation
Expected 95% upper limit
Observed 95% upper limit
m_X = 300 GeV (×10^{14})
m_X = 350 GeV (×10^{13})
m_X = 400 GeV (×10^{12})
m_X = 450 GeV (×10^{11})
m_X = 500 GeV (×10^{10})
m_X = 550 GeV (×10^{9})
m_X = 600 GeV (×10^{8})
m_X = 650 GeV (×10^{7})
m_X = 700 GeV (×10^{6})
m_X = 750 GeV (×10^{5})
m_X = 800 GeV (×10^{4})
m_X = 850 GeV (×10^{3})
m_X = 900 GeV (×10^{2})
m_X = 950 GeV (×10^{1})
m_X = 1000 GeV (×10^{0})
σ(pp → X) B (X → HY → γγbb̄) [fb]
m_Y [GeV]
Excess
CMS Preliminary
138 fb^{-1} (13 TeV)
ICHEP2022
pp→X→HY→γγbb̄ (Spin-0)
Expected limit ± 2 std. deviation
Expected limit ± 1 std. deviation
Expected 95% upper limit
Observed 95% upper limit
m_X = 550 GeV (X10^{7})
m_X = 600 GeV (X10^{6})
m_X = 650 GeV (X10^{5})
m_X = 700 GeV (X10^{4})
σ(pp→X) B (X→HY→γγbb̄) [fb]
m_Y [GeV]

S + B fit and significance

Distribution of the observables for the highest excess





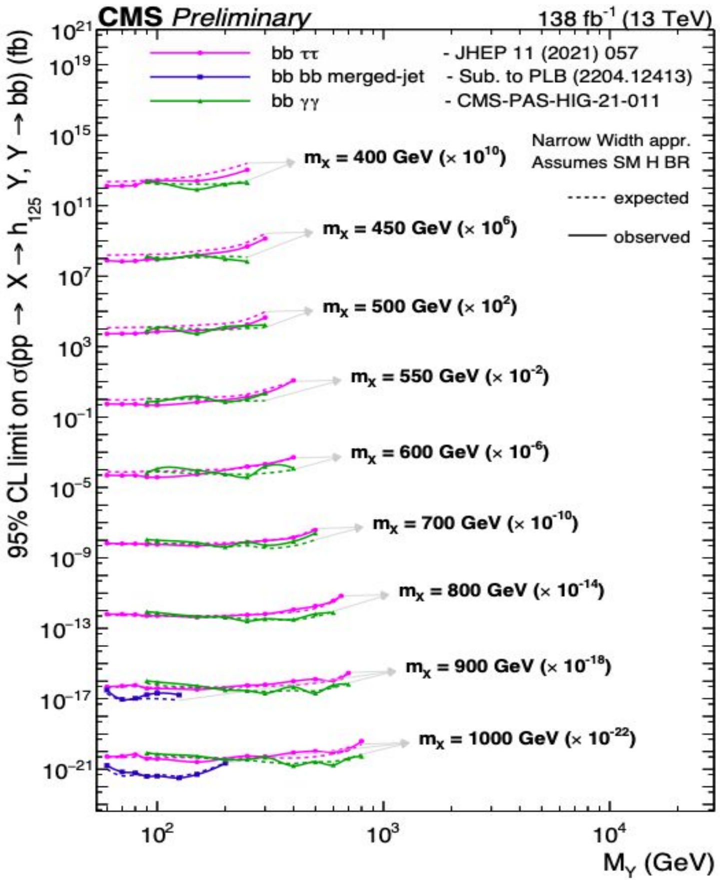


m_X = 650 GeV and m_Y = 90 GeV

Local (global) significance = 3.8 (2.8)

TWiki

More about “Excess”



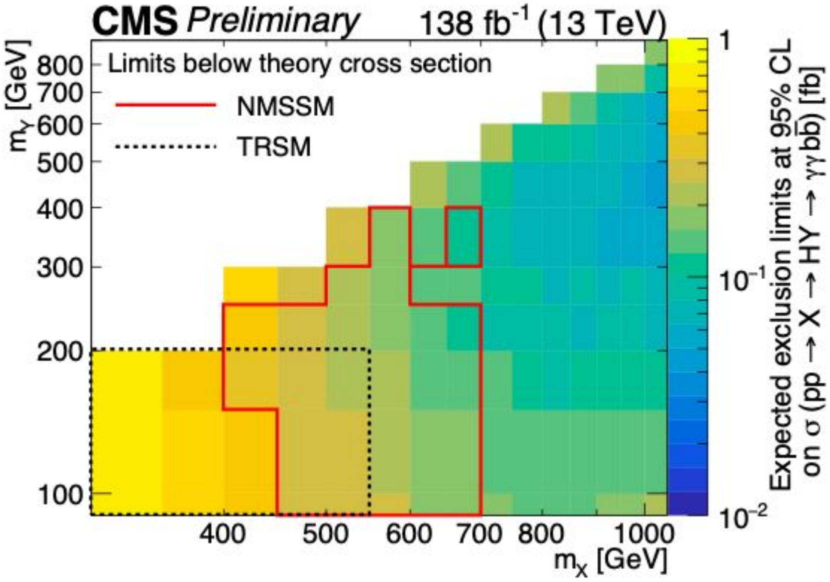
Other reported excess by CMS:

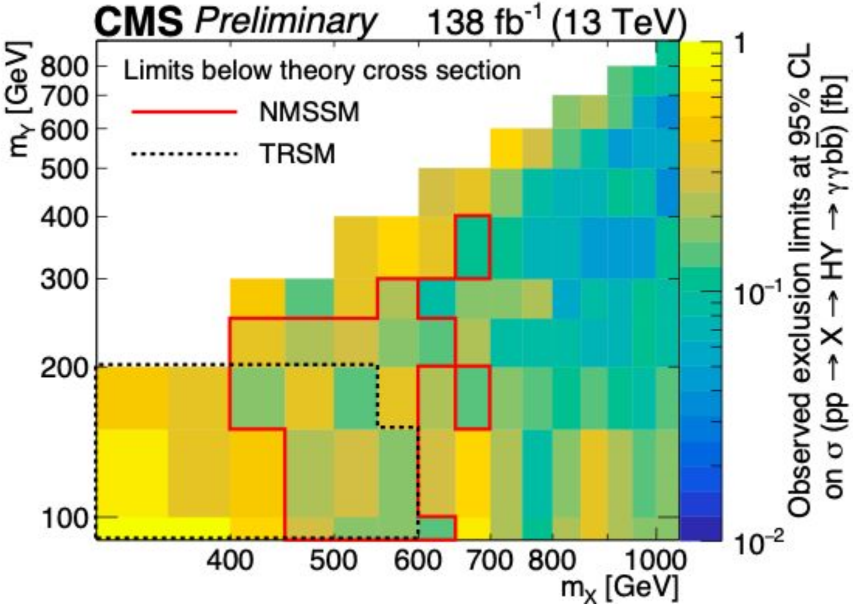
- Resonant WW searches (in fully leptonic final state) by CMS
  - Local (global) significance resonance mass 650 GeV = 3.8 (2.6)
- Additional BSM Higgs searches in ττ final states by CMS
  - Local (global) significance BSM Higgs mass 95 GeV = 2.6 (2.3)
- Low mass SM-like Higgs searches with γγ final state around 95 GeV by CMS
  - Local (global) significance 2.8 (1.3)
  - Full Run-2 results are ongoing

For X→YH, CMS compares ττbb, bbbb and γγbb:

- The excess reported in this analysis at m_X = 650 GeV, was only checked for γγbb
- Other channels still need to study this region

Theoretical interpretations





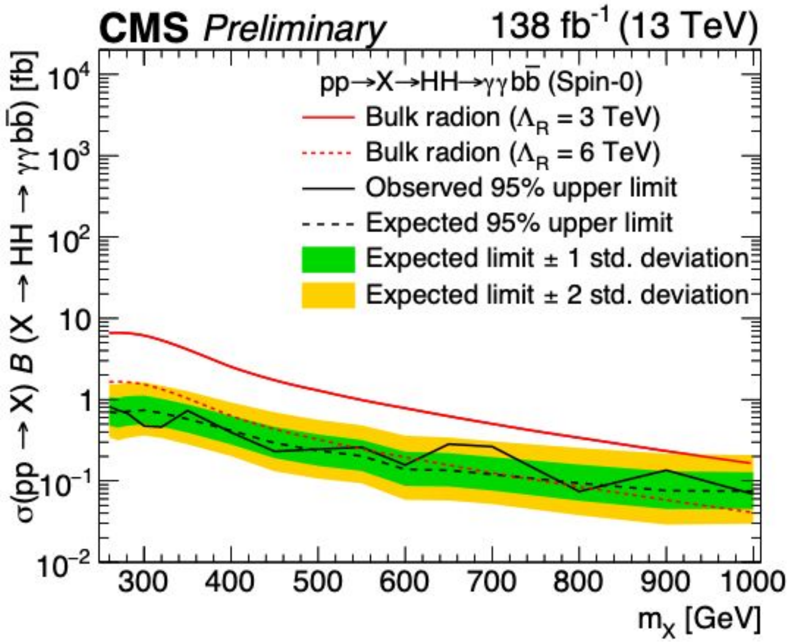
- **We make NMSSM and TRSM interpretations with given maximum allowed theoretical cross sections**
  - exclude region m_X=[400-600] GeV and m_Y = [90–300] GeV for NMSSM (TWiki)
  - exclude region m_X=[300-500] GeV and m_Y = [90–150] GeV for TRSM (TWiki)

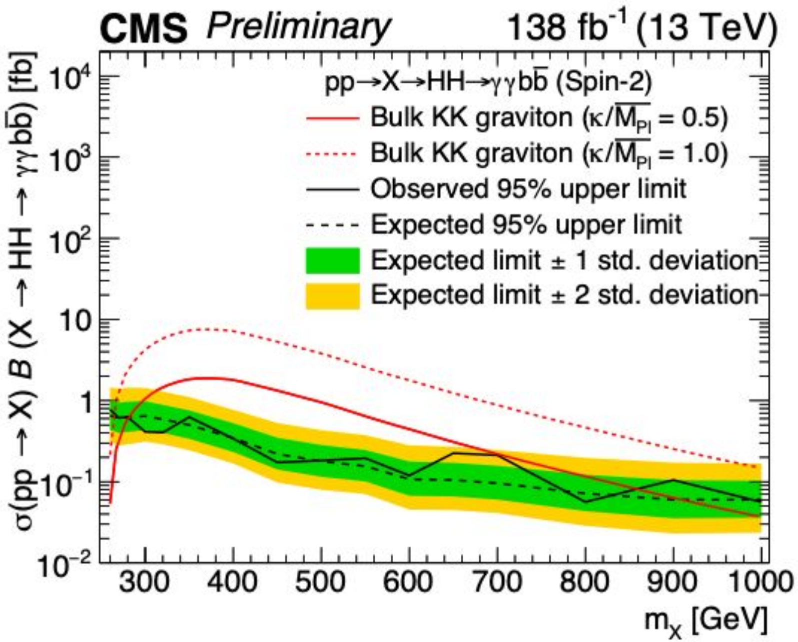
Summary

- Search for resonance X, decaying to two spin-0 bosons, in $\gamma\gamma bb$ final state is presented using CMS Run-2 data with $m_X <= 1$ TeV
- Explore asymmetric X→ HY (first time) decay modes with $m_Y <= 800$ GeV
- **Model independent results** are shown; **1-2% systematic impact**
    - Observe highest excess at $m_X = 650$ GeV and $m_Y = 90$ GeV
    - NMSSM and TRSM interpretations are made which partially exclude allowed mass regions

Backup

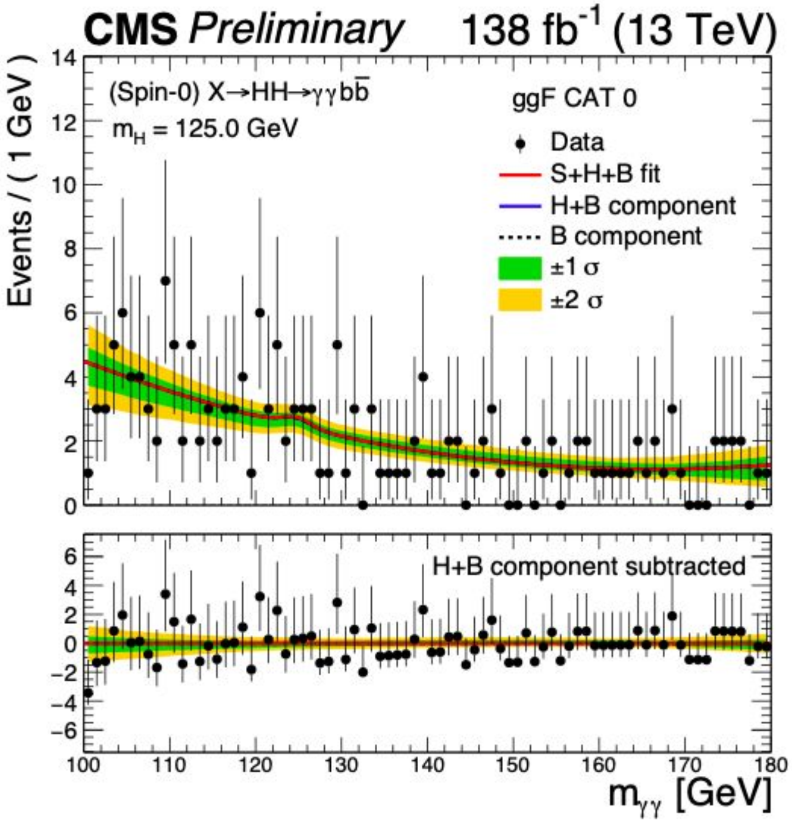
Results: X→HH

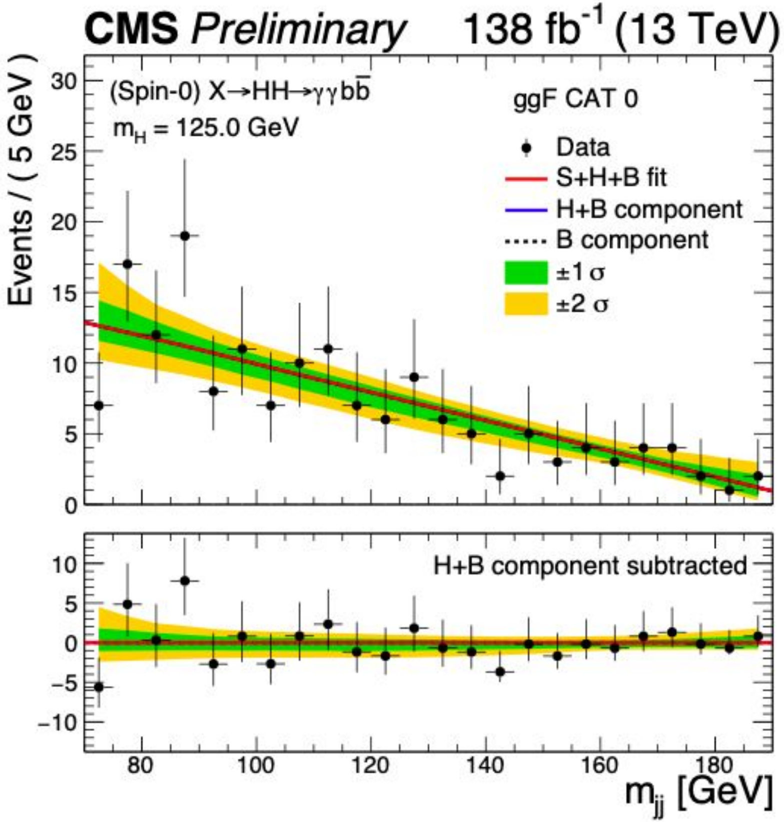




- **Left plot (spin-0):** For $\mathbf{\Lambda_R}$= 3 TeV, excludes mass up to 1 TeV;
  For $\mathbf{\Lambda_R}$= 6 TeV, excludes mass up to 600 GeV
- **Right plot (spin-2):** $\kappa/\overline{M}_{pl}$ = 0.5, excludes resonance mass upto 850 GeV

S + B fit for X→HH





Analysis Strategy

Online:
Event passing diphoton triggers

Non-resonant backgrounds:
MVA training
MVA categorization

Data driven Backgrounds:
2D envelope method
($m_{\gamma\gamma}$ X m_{jj}) fit in $\tilde{M}_X$ window

Event selections → **Analysis optimization methods** → **Statistical Analysis**

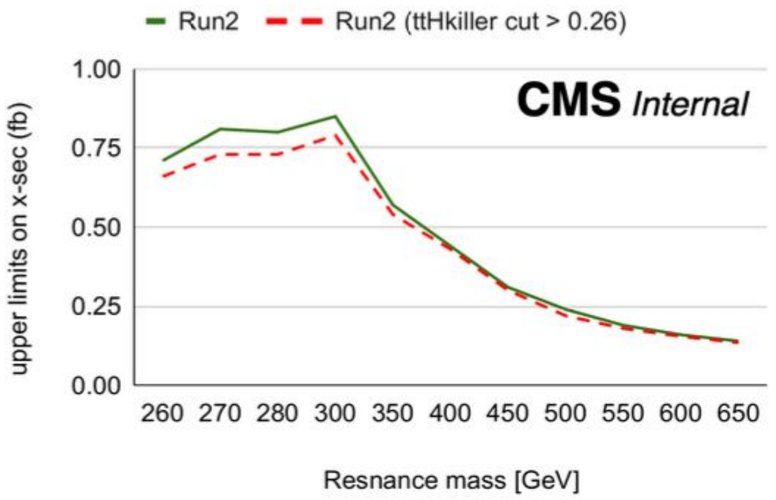
Offline:
selections on photons and jets from [JHEP 03 (2021)]

Resonant backgrounds:
NN based ttHkiller

Signal:
$m_{\gamma\gamma}$:Sum of Gaussians
m_{jj}: Double Sided Crystal ball / Crystal ball + Gaussian

Selection on ttHKiller discriminant

- Resonant background are single Higgs process which have similar diphoton distribution peaking around m_H
- Contamination is higher only for m_X < 600 GeV; ttH contribution dominates
    - Simply neglect for higher masses
- Apply a selection on **NN-based ttHkiller variable**
- Order of magnitude for sensitivity improvement with m_X < 600 GeV is up to 10%.



BDT Classifier

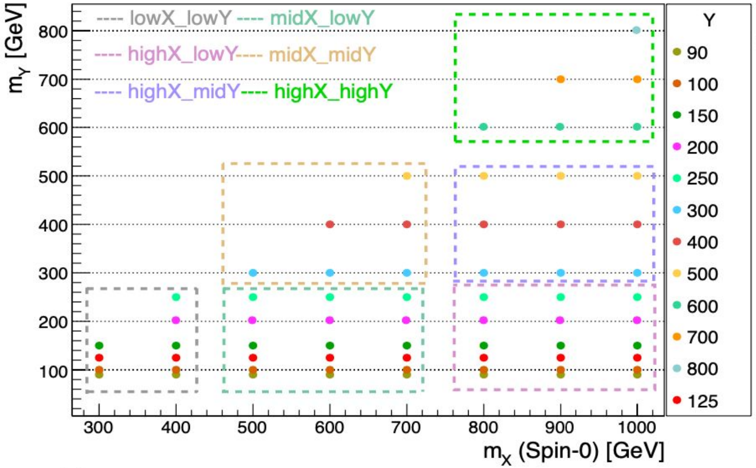
- Using XGBoost + Scikit-learn to train multiclass BDT classifier to discriminate signal from non-resonant backgrounds (in 6 different X-Y mass ranges in m_X:m_Y 2D plane)

  Signal: Resonant X → YH → bbγγ (Spin0)

  Non-resonant Background: SM multijet process with prompt photons⇒ γγ+Jets and γ+Jets

- Use three set of input variables

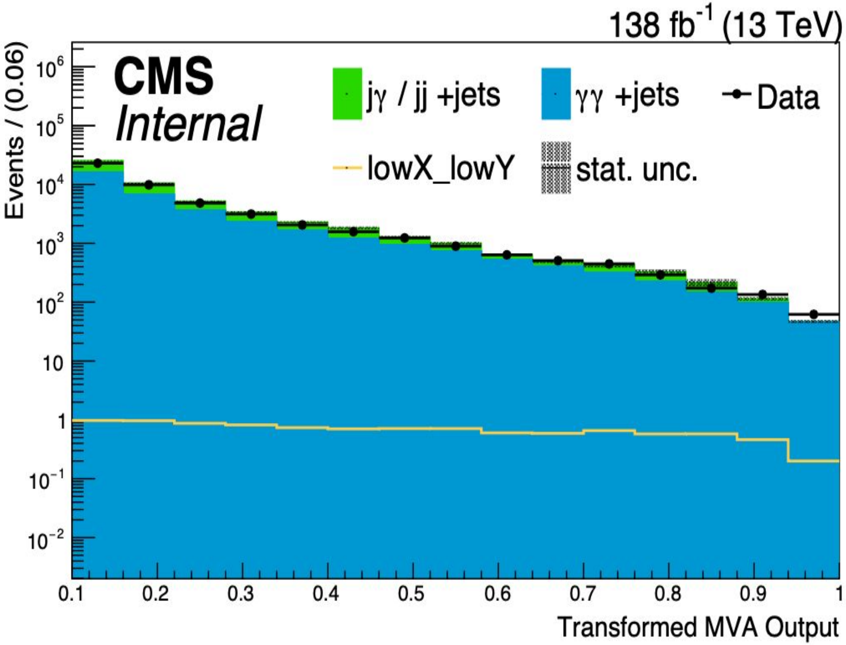
1) **Kinematic distributions which discriminate signal from background**
2) **Object identification variables to reject fake contribution**
3) **Energy resolution variables**



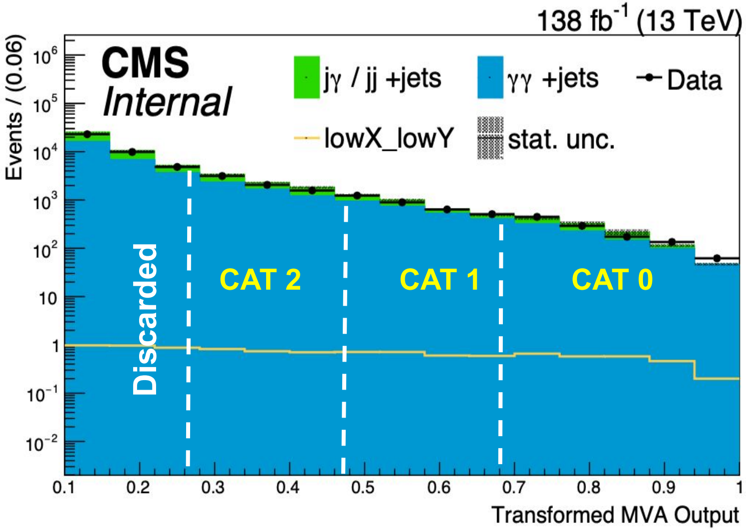
BDT performance

- Table shows the AUC from ROC
- As we tend to higher masses, training performance improves within same m_Y range$\Rightarrow$ performance gets improved as kinematics gets more discriminative

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



MVA Categorization



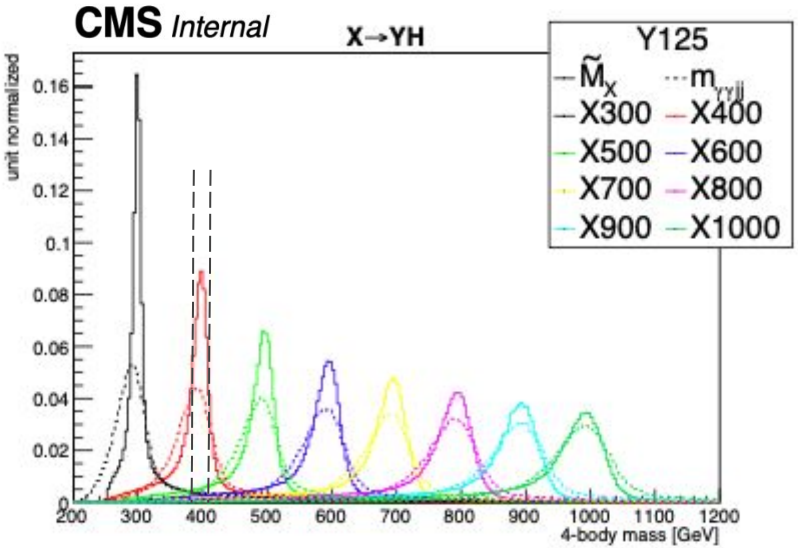
- Categorization using MC simulations samples
- For boundary optimization ROOT Minuit package is used with MIGRAD minimizer
  a. uses Punzi FOM ($S_{eff}/(1+\sqrt{B})$) as input function
- Constrain background statistics have robust background modeling

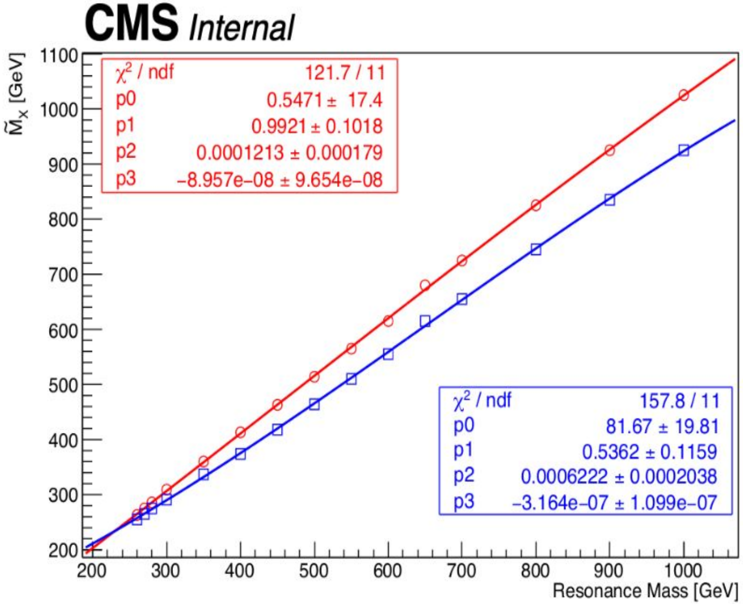
Optimized MVA categories

mass range & category	lowX_lowY	midX_lowY	highX_lowY	midX_midY	highX_midY	highX_highY
CAT2	[0.174, 0.329]	[0.213, 0.401]	[0.215, 0.304]	[0.180, 0.352]	[0.177, 0.239]	[0.129, 0.286]
CAT1	[0.329, 0.627]	[0.401, 0.550]	[0.304, 0.500]	[0.352, 0.600]	[0.239, 0.350]	[0.286, 0.400]
CAT0	[0.627, 1.000]	[0.550, 1.000]	[0.500, 1.000]	[0.600, 1.000]	[0.350, 1.000]	[0.400, 1.000]

$\tilde{M}_X$ Window Selection

- Selection on four-body mass $\tilde{\mathbf{M}}_X = (\mathbf{m}_{jj\gamma\gamma} - \mathbf{m}_{jj} - \mathbf{m}_{\gamma\gamma} + \mathbf{m}_H + \mathbf{m}_{Y,H})$
  - $\tilde{M}_X$ results better resolution (30-90%) w.r.t $m_{jj\gamma\gamma}$
- A Tight $\tilde{M}_X$ helps to enhance signal to background ratio
- It also helps to suppress single Higgs contribution (<1%)





Systematic Uncertainty

Mostly standard $H \rightarrow \gamma\gamma$ systematics with jet systematics and theoretical systematics

- Preselection SF
- Triggers
- BR
- Luminosity
- PS / UE
- PDF and QCDscale
- Photons
- photon σ_E/E
- electron veto SF
- JEC and JER
- b-tagging SF
- HEM
- L1-prefiring

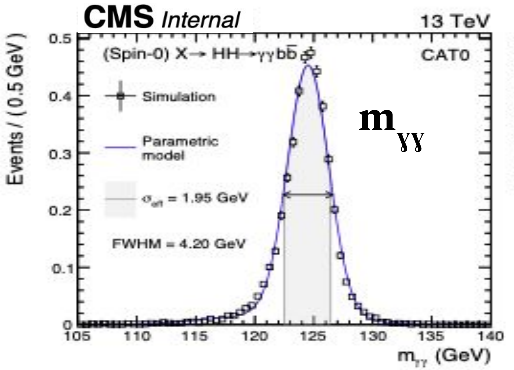
We check impact in all six mass ranges which modify limits 1-2%

Highest impact from QCD scale and b tagging systematics for all masses

- Other systematics contribution < 1%

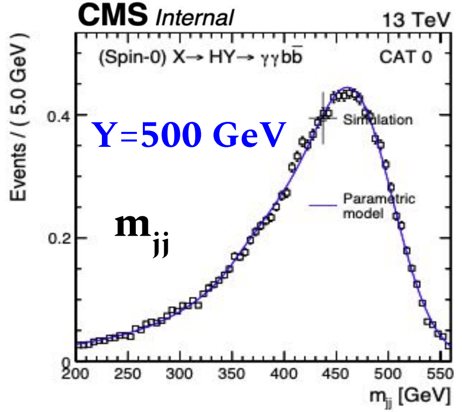
Signal Model

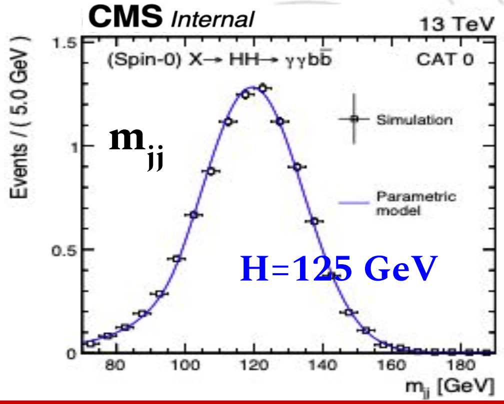
- $m_{\gamma\gamma}$:
  - sum of gaussian functions is used (upto 5)
  - number of gaussian function is decided from F-test
- m_{jj}:
  - DoubleCrystalBall (DCB) function or Sum of CB and Gaussian
  - Choose the best fit with best chi2
-

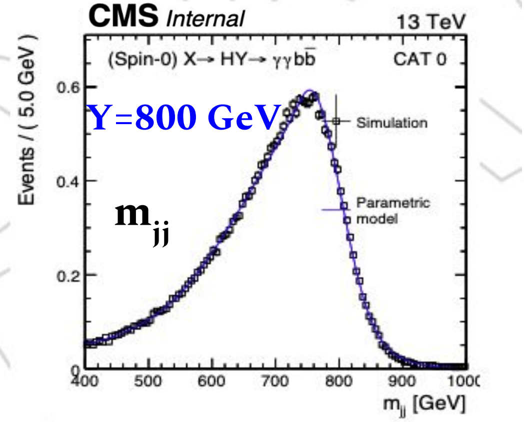


(a) Radion300

Figure 25: $M(\gamma\gamma)$ mod







NOTE: m_{jj} plots are shown for all three bins

Comparison of the resonant analyses ATLAS vs CMS

- Similar performance of γ reco+ID and b jet ID
- Similar analyses preselections

	ATLAS	CMS
Interpretations	• Spin-0 X→ HH→ bbγγ	• Spin0/2 X→ HH→ bbγγ • NMSSM X→ YH → bbγγ
ttH rejections	• ele and muon veto and < 6 jets	• ttH vs HH→ bbγγ DNN
MVA approach	• BDT to reject ttγγ & γ(γ)+jets • BDT to reject single H	• BDT to reject γ(γ)+jets
BDT training	• Inclusive to all m_X points • Signal m_X reweighted to match continuum bkg shape	• Separate in six mass region defined by boost factor $m_X/(m_X + m_Y)$
Categories	• 1 BDT-based category	• 3 BDT-based category
Signal extraction	• 1D $m_{\gamma\gamma}$ fit	• 2D $m_{\gamma\gamma}$:m_{jj} fit