Searches for new physics in CMS in events with photons in the final state

Jyoti Babbar

On behalf of the CMS collaboration

18-24 July, 2024

CMS

INFN TRIESTE

ICSC Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

ICHEP 2024

PRAGUE

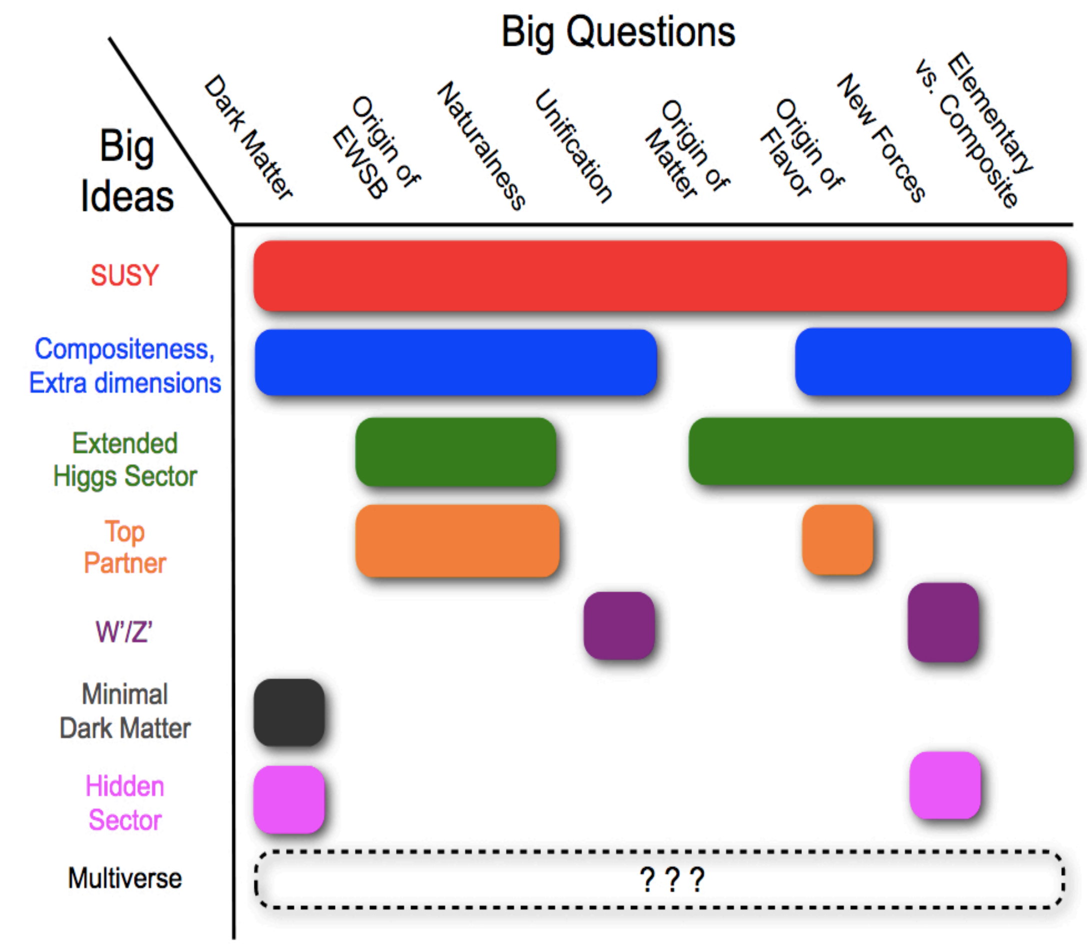
42nd International Conference on High Energy Physics

18-24 July 2024 Prague Czech Republic

Introduction

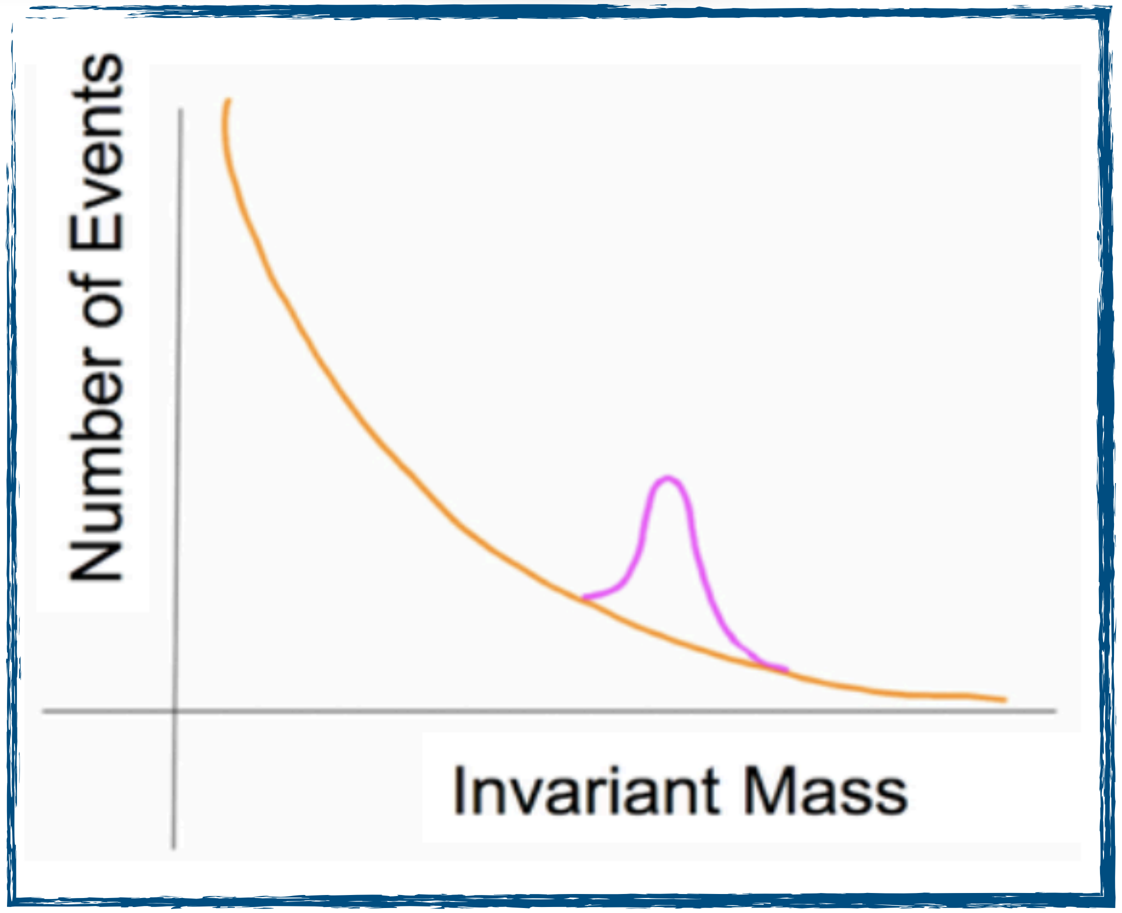
We are all aware of how successful the SM is

- But we also know there has to be something more
- The SM alone can't explain many things
  - Hierarchy/naturalness/fine-tuning?
  - Why more matter than antimatter in the universe?
  - What are "dark matter" and "dark energy"?
  - Do quarks and leptons have substructure?



Hunt for new physics

- **Direct searches for BSM physics remains a key part of the CMS physics program**
- Directly for example w. "**bump**" hunting
  - reconstruct sensitive variables like invariant Mass
  - look for a "bump" on a smooth falling background
  - experimentally robust, small systematics
  - difficult to model different backgrounds



- **This talk will cover the latest searches with photons in the final state**
  - $X \to W\gamma$
  - $X \to \phi\phi \to \gamma\gamma\gamma\gamma$
  - $X \to \gamma\gamma$
  - $\tau^* \to \tau\tau\gamma$

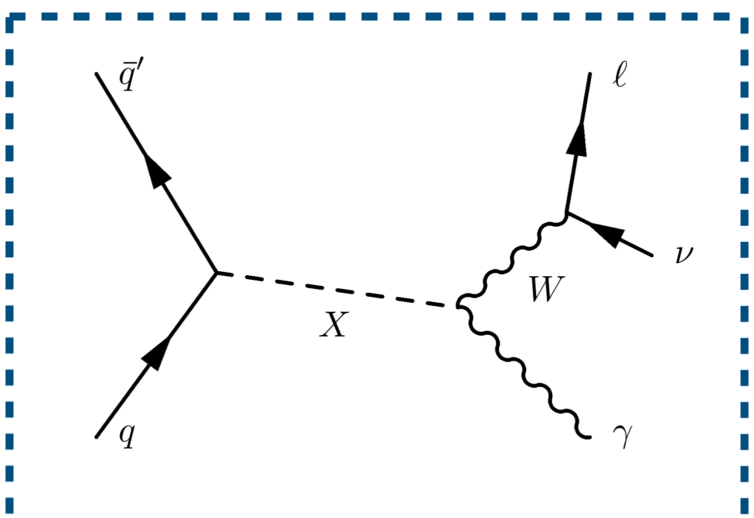
Search for a resonance decaying to Wγ

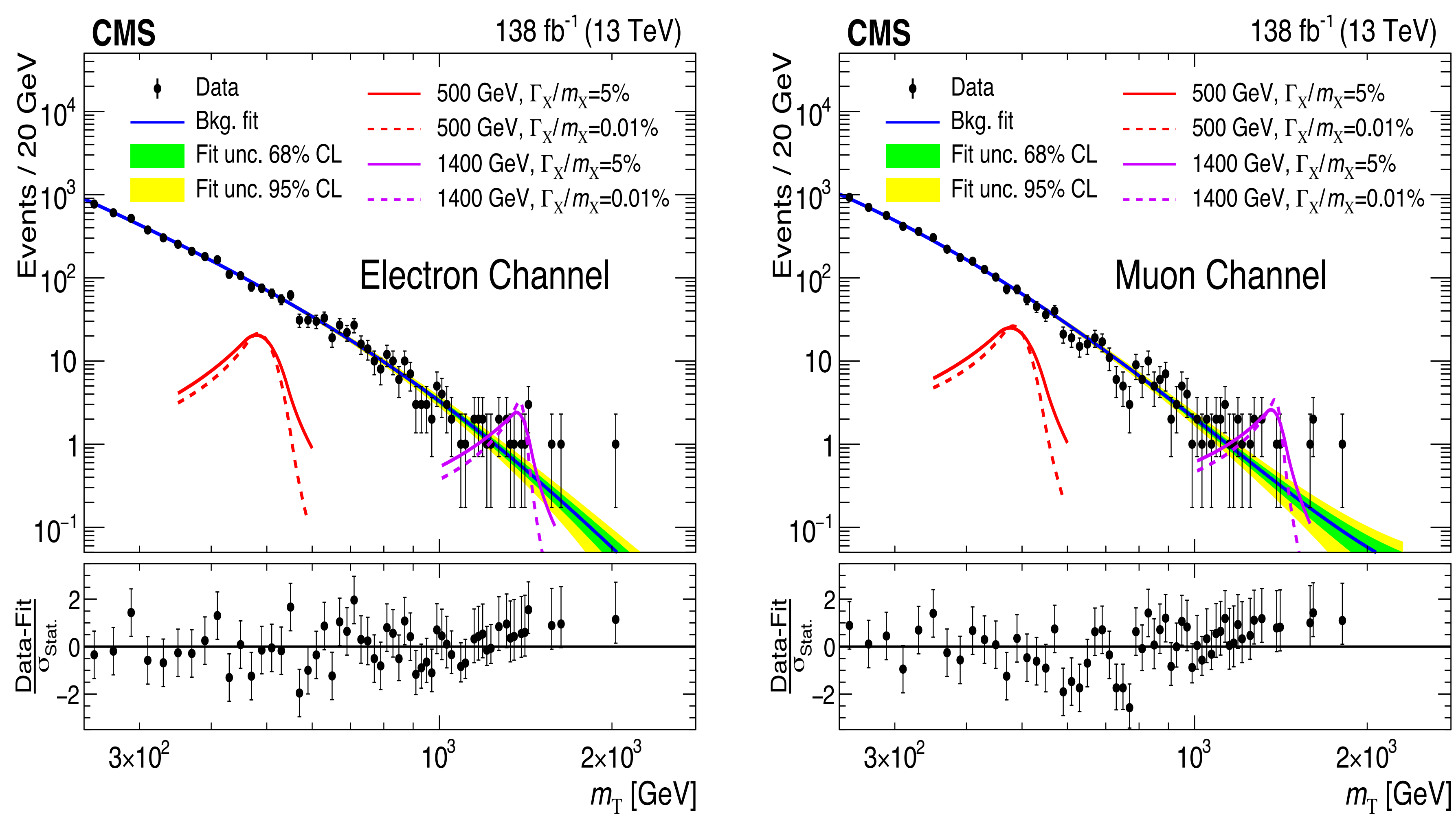
Search for heavy charged and spinless resonance decaying into Wγ

CMS-EXO-21-017

arXiv:2406.05737

- W boson decays leptonically (e or μ)
- Bump hunt in the transverse mass mT spectrum
  - narrow (0.01%) and broad (5%) resonances
- Parametric fit to the data using signal shape templates
- **No significant deviation from the background-only expectation is observed**

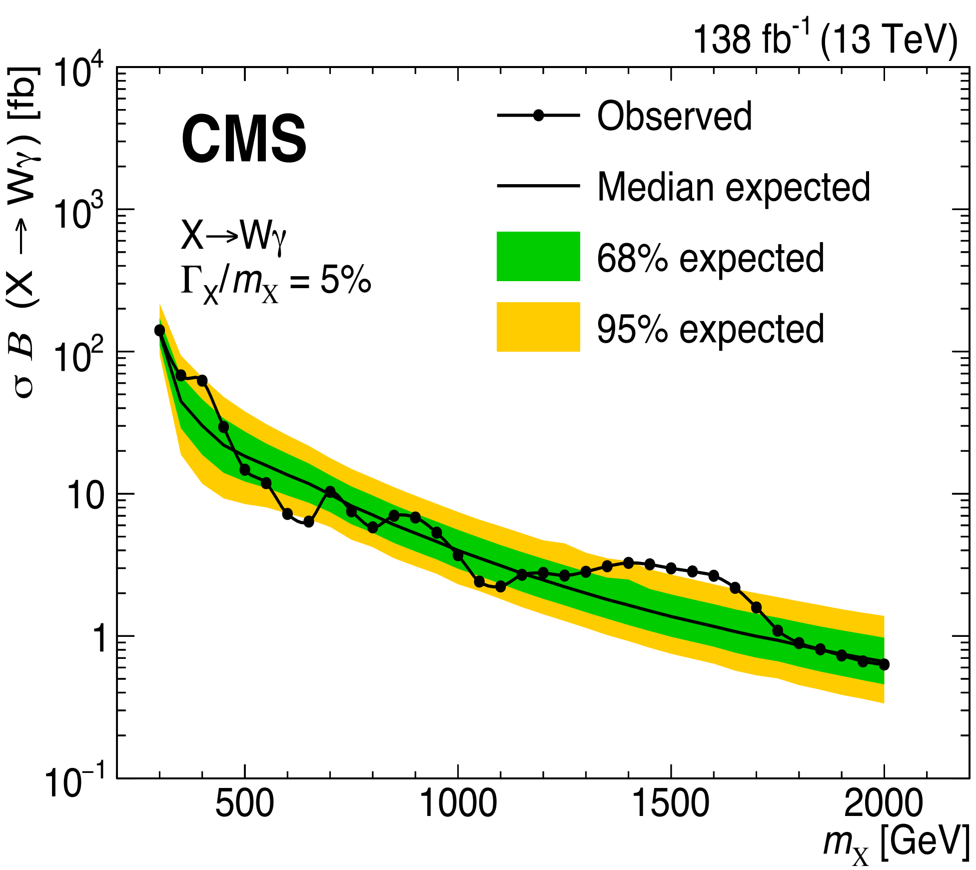




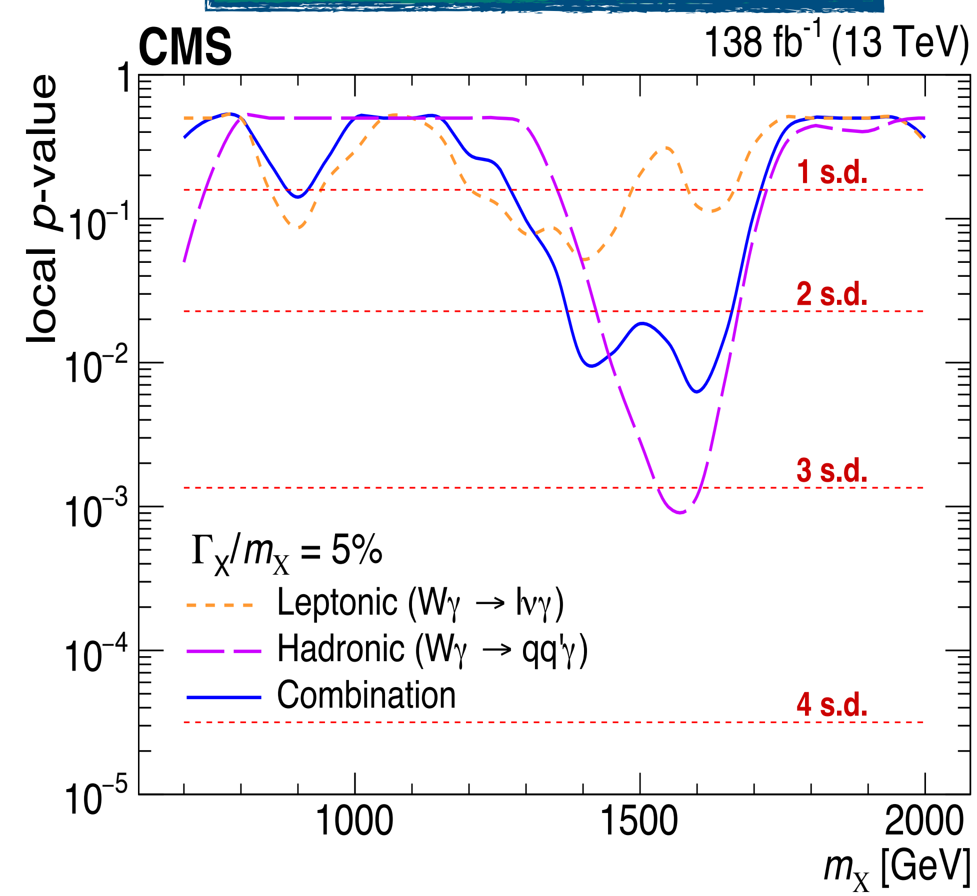
Search for a resonance decaying to Wγ

- Results combined with hadronic channel doi:10.1016/j.physletb.2022.136888
- **Local excess of 3.1σ in the hadronic analysis reduced to 2.5σ with the two channels combined**
- **Most stringent limits to date in the 0.3-2 TeV mass range**

Limit hadronic+ leptonic



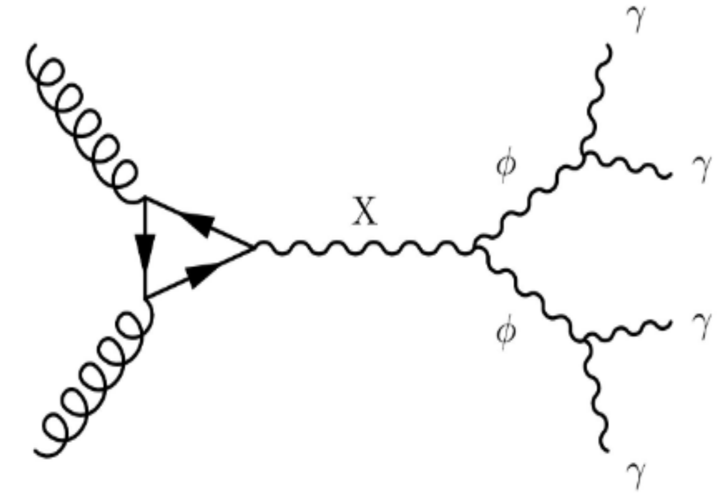
Signal Significance



Search for boosted multi-photon $X \to \phi\phi \to \gamma\gamma\gamma\gamma$

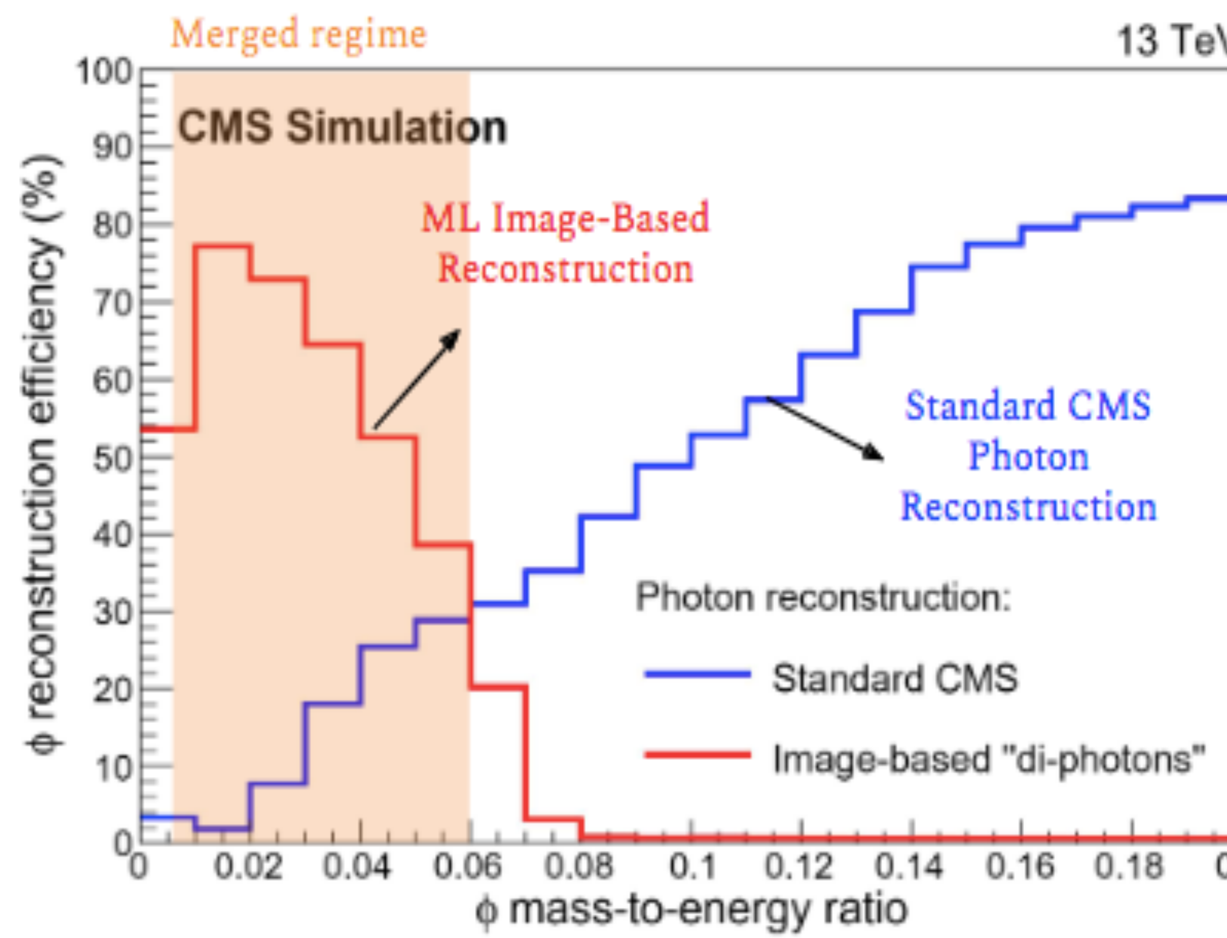
CMS-EXO-22-022
arXiv:2405.00834

- Extended Higgs sector with two new spin-0 particles (X and ϕ)
- Looking at topologies with highly merged photons
- **Two deposits in the ECAL, each of which looks like two photons overlapping**
  - Could not rely on standard photon reconstruction
- Merged Regime (i.e heavier M_X) requires new analysis tools (ML)
- Define $\alpha = M_\phi / M_X$



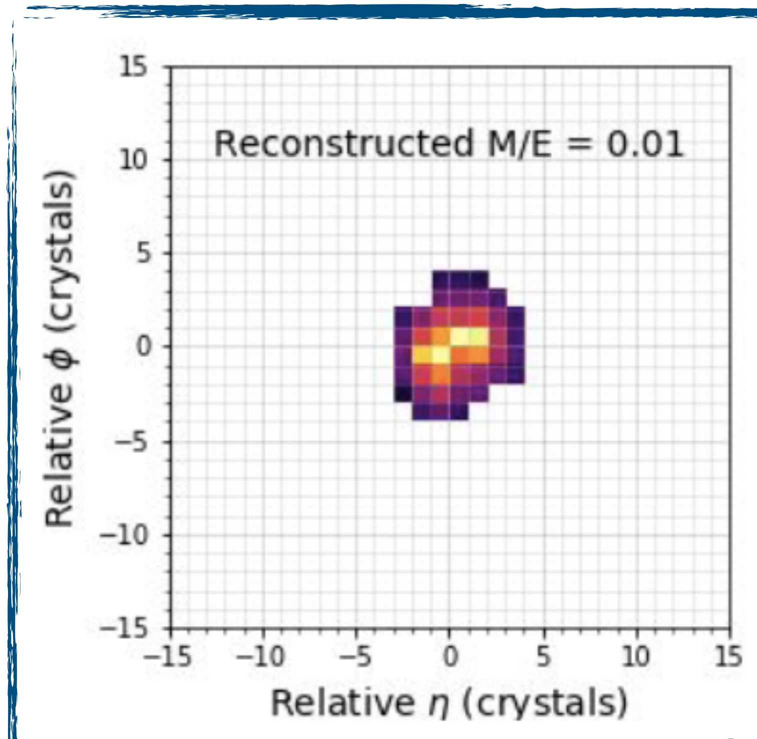
Analysis Regime:

- 300 GeV < M_X < 3000 GeV
- 0.005 < α < 0.025
- Barrel Only

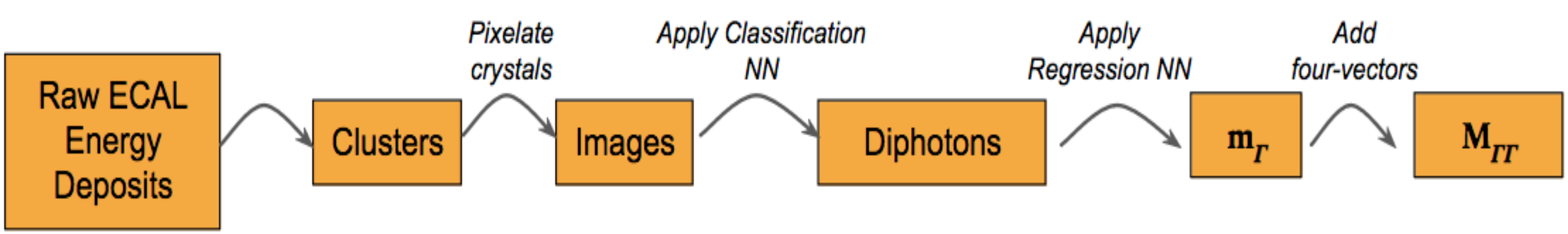


Search for boosted multi-photon

- Analysis utilizes custom 'diphoton clusters'
  - Images made from ECAL detector information
- **Cluster images are then fed into two Convolutional Neural Networks:**
  - **Classification NN_1**: selects diphotons from monophoton and hadronic background
  - **Regression NN_2** : predicts mass of the diphoton (by giving an unit-less output : Mass / Energy ratio)
  - $m_{\Gamma} \equiv$ diphoton cluster mass
- Combine clusters to get the Di-Cluster mass, $M_{\Gamma\Gamma}$, i.e. reconstructed X or four-photon mass
- **Final search is a bump hunt in $M_{\Gamma\Gamma}$**

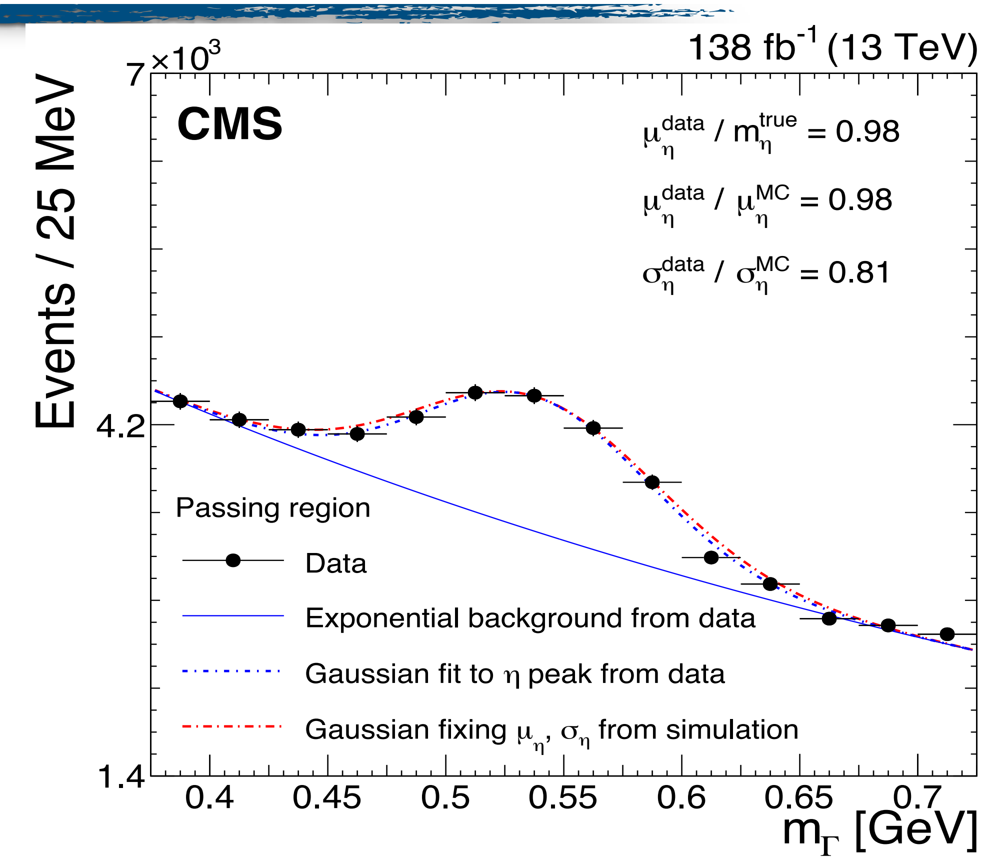


Diphoton cluster image

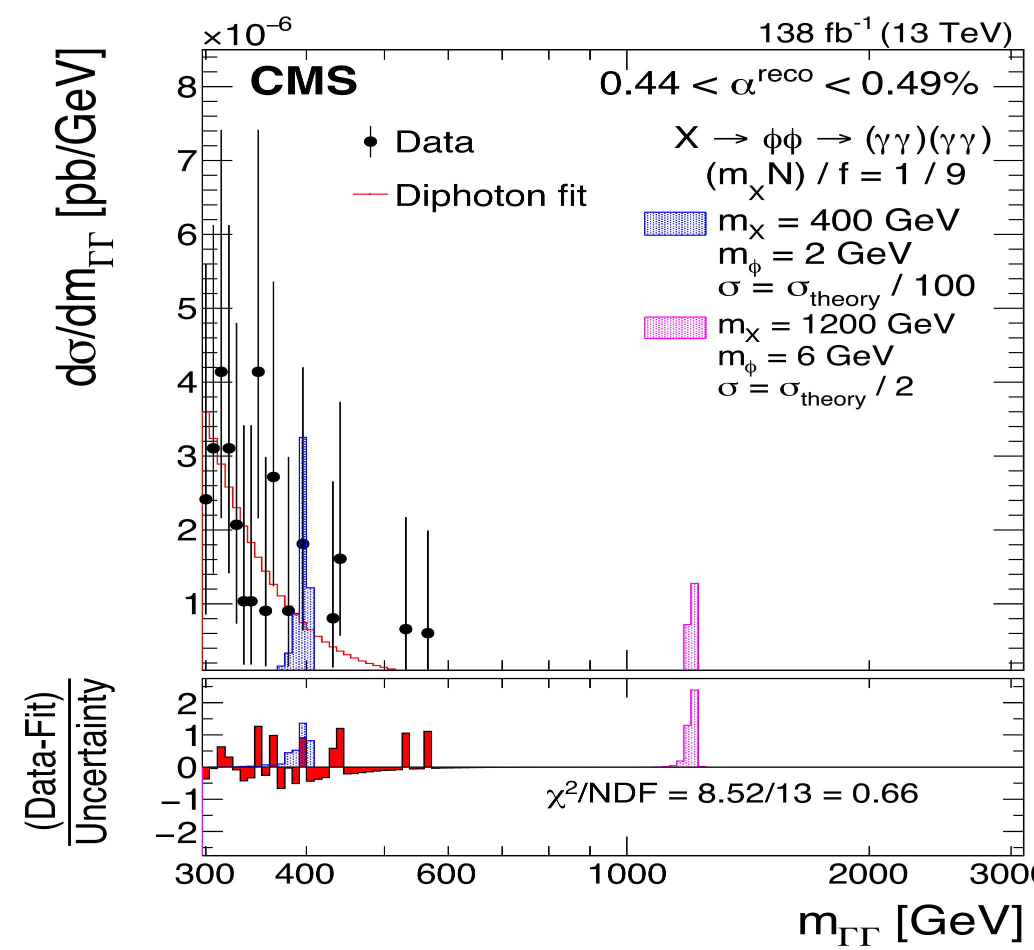


Search for boosted multi-photon

- **To validate the performance of CNN, $\eta \to \gamma\gamma$ control sample is used.**
  - **Simultaneous fits of pass/fail η peaks allows for Data/MC comparison**
  - η fit with Double Sided Crystal Ball Function

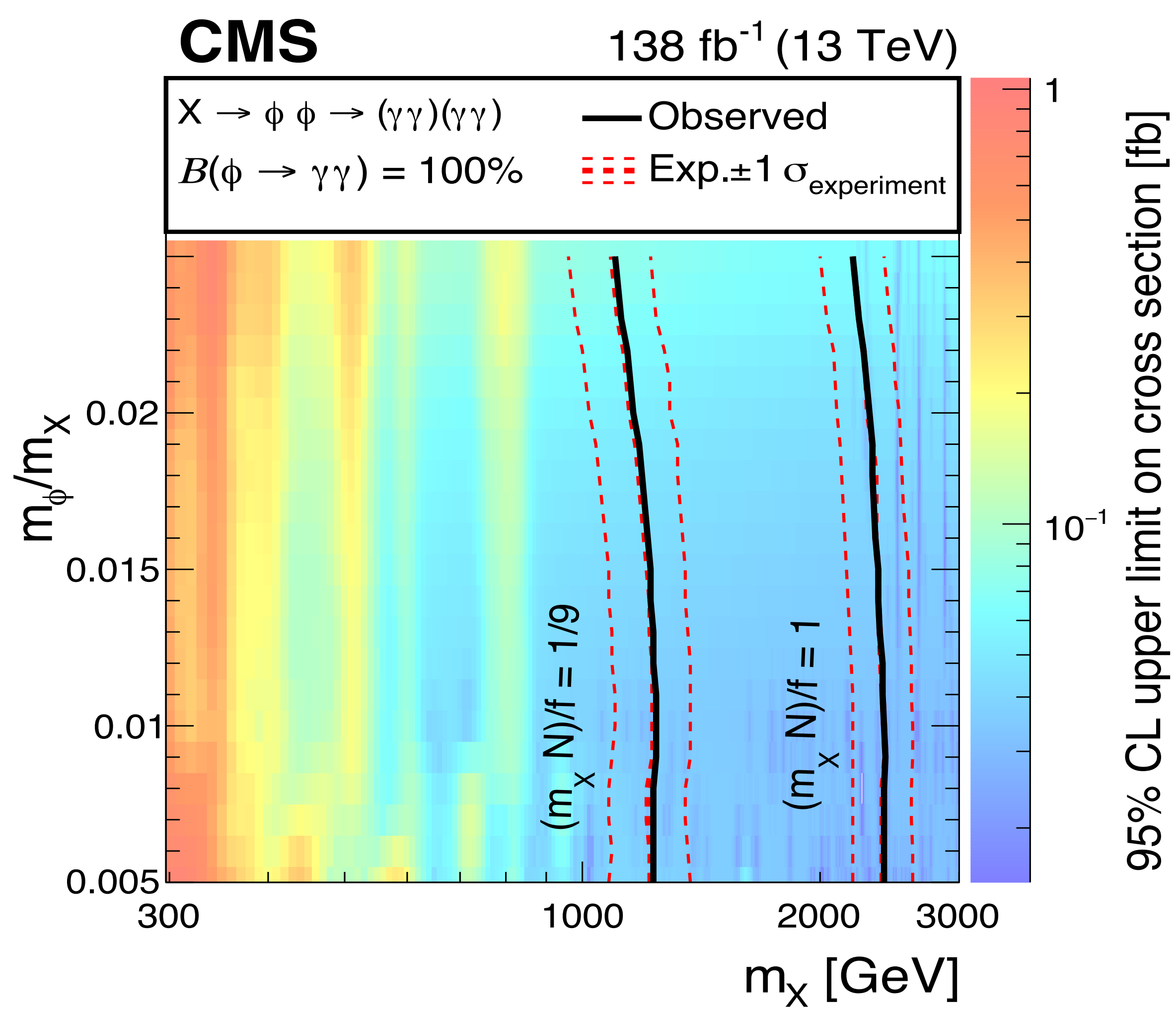


- **Data is binned in fixed slices of α_{reco}**
  - $\alpha_{reco} = m_\Gamma / M_{\Gamma\Gamma}$
- **Fit falling data spectrum in each α_{reco} slice**
  - **Series of 1D searches to scan full 2D spectrum**
  - Fit uses envelope method with 5 different functional forms



Search for boosted multi-photon

- Deriving model independent limits
- Extended Higgs sector limits at 95% CL set on cross section times BR vs. mass of X and ratio $\alpha = M_\phi / M_X$
- **Limits range between 0.03-1.6 fb for X masses between 0.3-3 TeV and α between 0.5%-2.5%**
- **The largest observed excess corresponds to about m_X = 720 GeV and α = 0.7% (m_ϕ = 5.04 GeV), with a local (global) significance of 3.57 (1.07) standard deviations.**

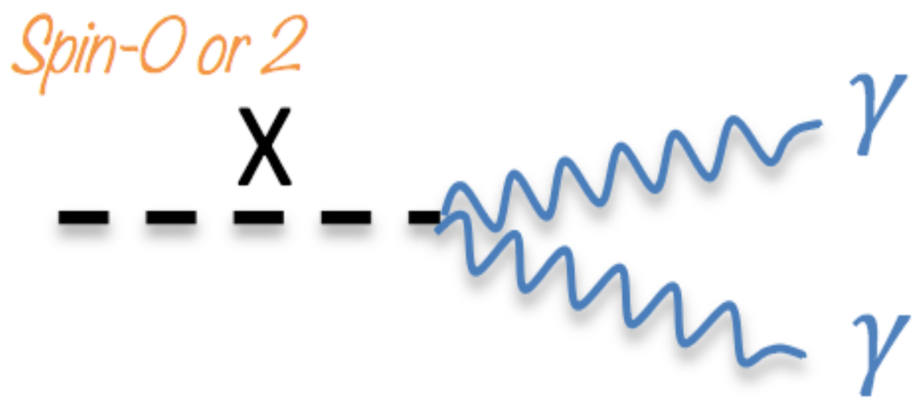


Search for resonant & non-resonant diphoton

CMS-EXO-22-024

arXiv:2405.09320

- **Resonant - Heavy Higgs and Randall-Sundrum Graviton (RSG) and**
  - spin0 (heavy Higgs) and spin-2 (RS graviton)
  - scan resonance width (10^{-2}, 1%, 5.6%)



- **Non-resonant enhancements - Large Extra Dimensions (ADD) and Continuous Clockwork Model (CW)**
  - Model Parameters - Ms: ultraviolet cutoff parameter for the virtual graviton exchange process , k sets the inverse size of the extra dimension, M5 : 5D Planck Scale

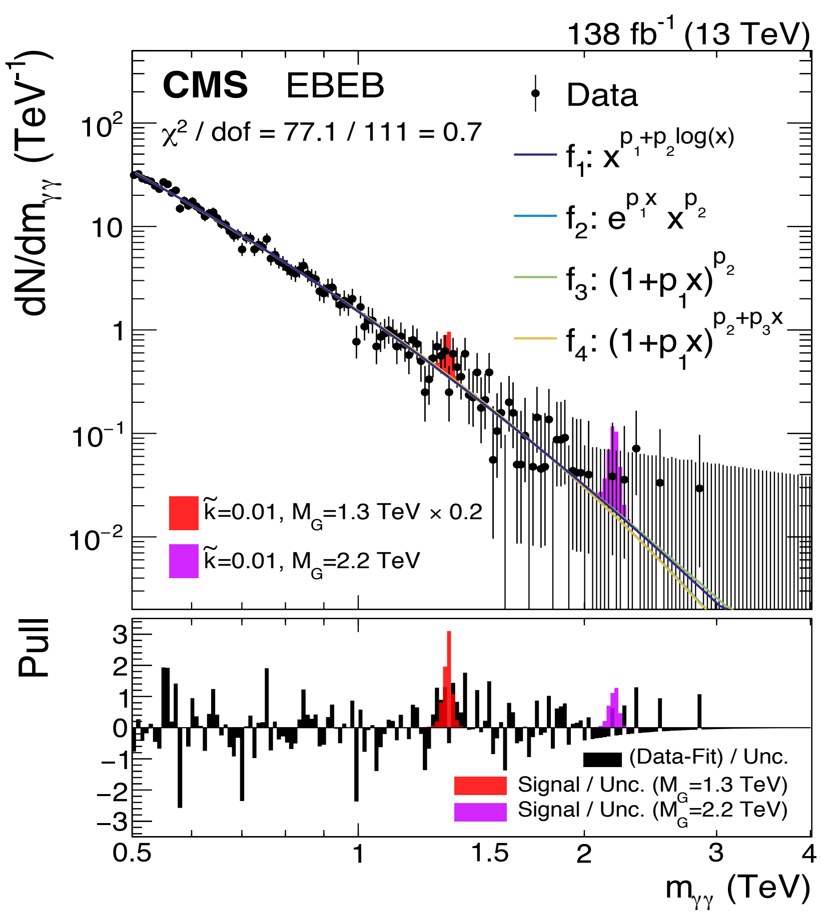
- **Both non-resonant models address the Hierarchy Problem through the possibility of extra dimensions**

- Two channels: both central photons (EBEB), or one central and one forward (EBEE).

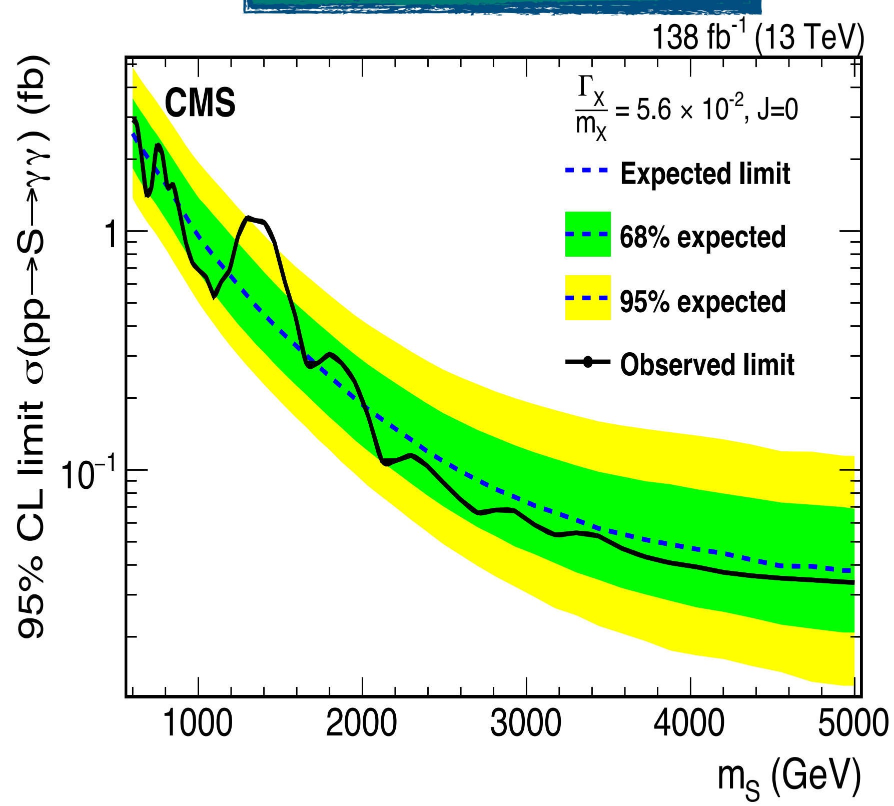
Resonant diphoton

Bump search in the diphoton mass spectrum

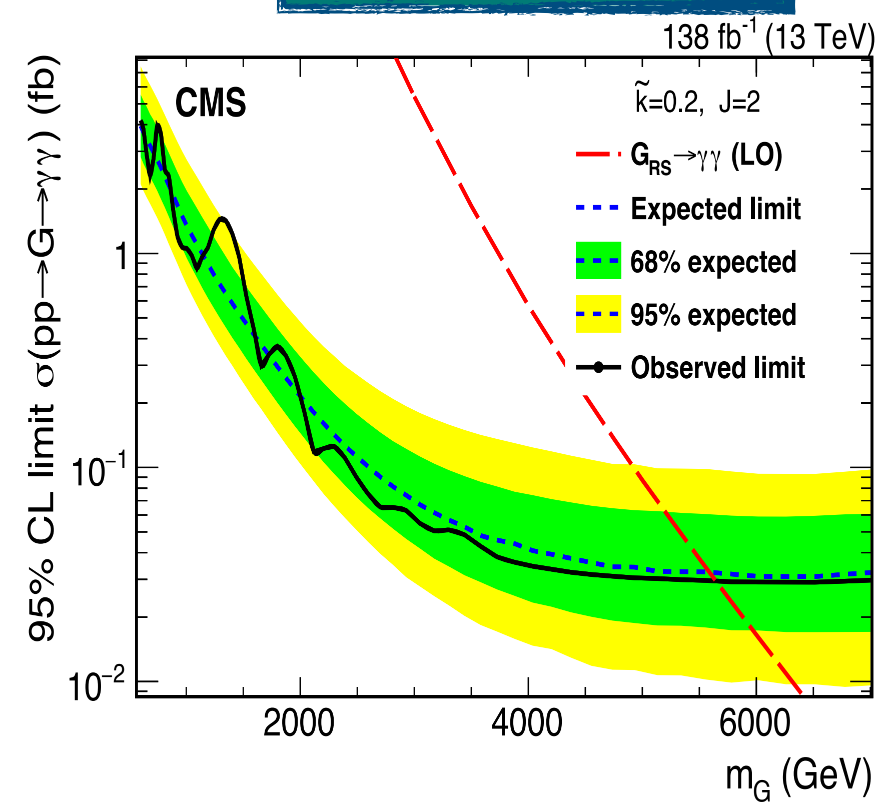
- $M_{\gamma\gamma}$ described by functional forms fit to data with best-fit function chosen in discrete profiling scan
- **Largest local excess of 2.6σ at ~1.3 TeV for the broad resonance model**
  - global significance 0.8σ
  - no excess observed by ATLAS analysis (arXiv:2102.13405)



Heavy Higgs

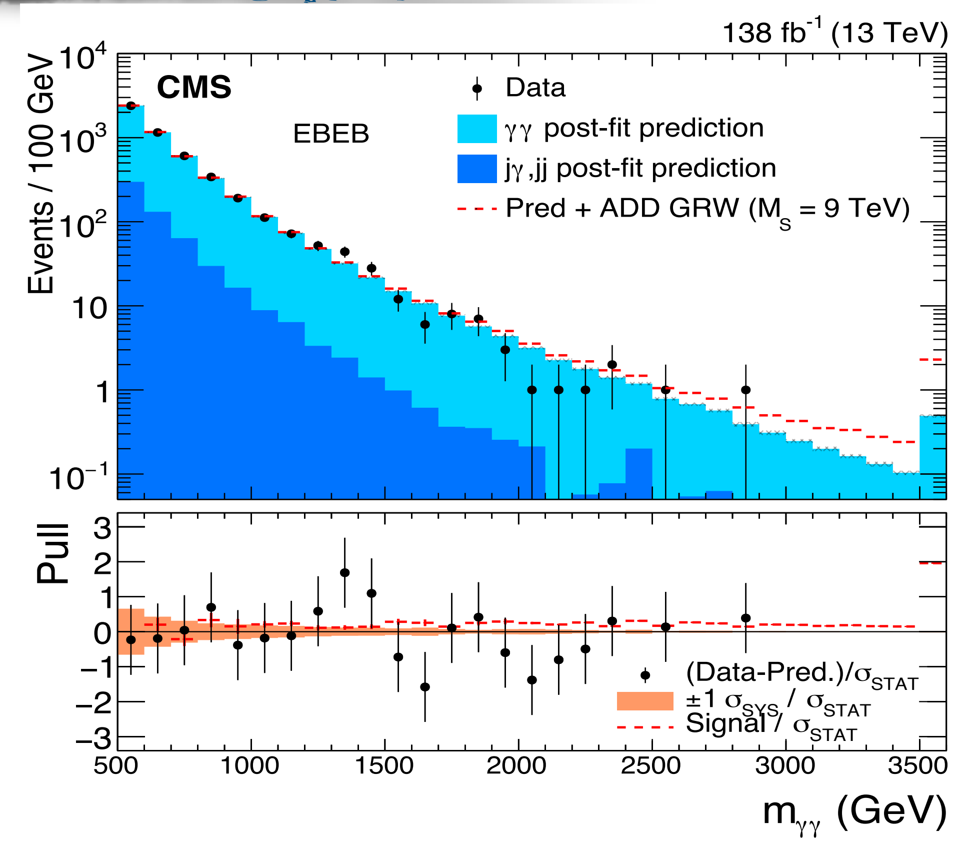


RS Graviton



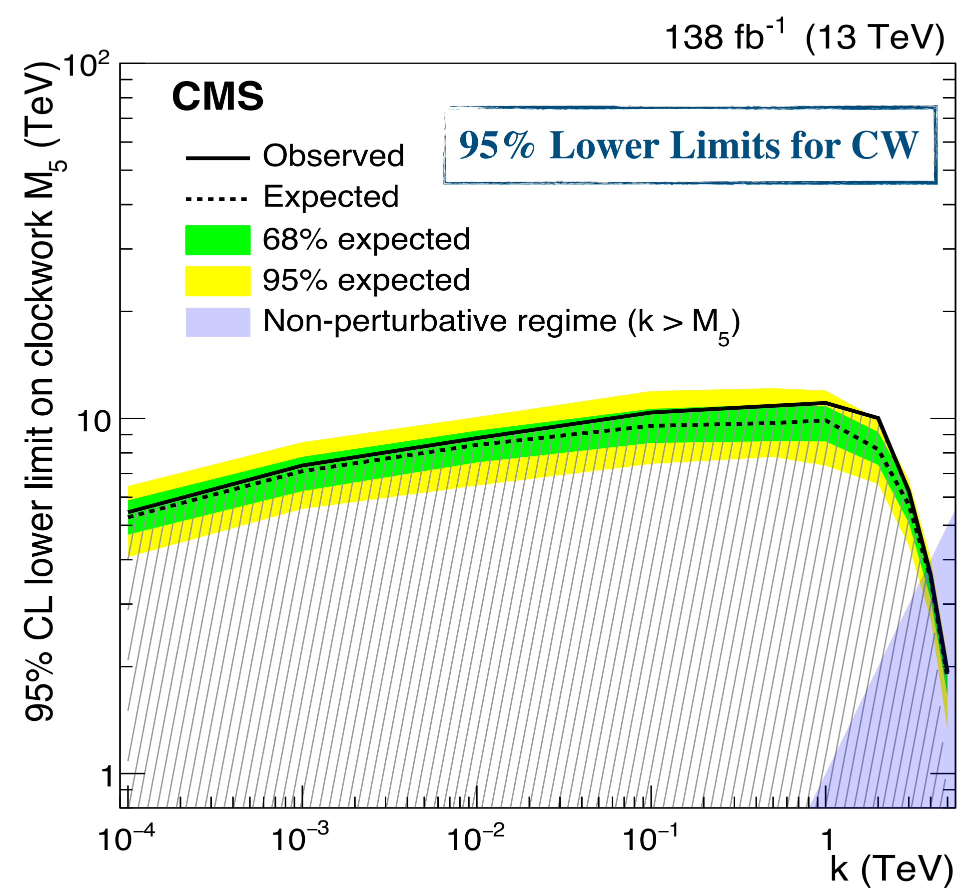
Non-resonant diphoton

- Look for excess at high mass in $\gamma\gamma$ spectrum
- Background estimation :
  - $\gamma\gamma$ SM background from SHERPA + NNLO k factor from MCFM
  - Background from jets misidentified as photons estimated using control samples in data (5% in EBEB and 10% EBEE) using fake rate method.
- No event observed with $M\gamma\gamma > 3$ TeV
  - in the most sensitive ECAL barrel category
- Set limits in ADD and clockwork model
  - comparable sensitivity with ATLAS (arXiv: 2305.10894) for CW model 4



ADD lower limits on Ms [TeV]

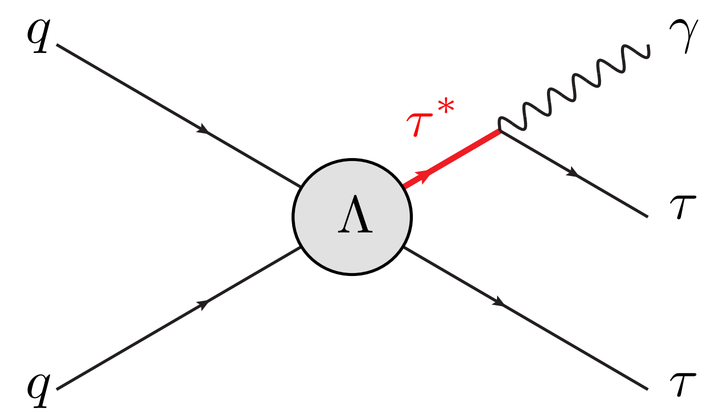
Signal:	GRW	Hewett		HLZ				
		negative	positive	n_{ED}=3	n_{ED}=4	n_{ED}=5	n_{ED}=6	n_{ED}=7
Expected:	$8.7^{+0.7}_{-0.6}$	$7.3^{+0.3}_{-0.3}$	$7.8^{+0.6}_{-0.5}$	$10.3^{+0.8}_{-0.7}$	$8.7^{+0.7}_{-0.6}$	$7.9^{+0.6}_{-0.5}$	$7.3^{+0.6}_{-0.5}$	$6.9^{+0.6}_{-0.5}$
Observed:	9.3	7.1	8.3	11.1	9.3	8.4	7.8	7.4



Search for excited taus

CMS-EXO-22-007

Search for an excited tau in the $\tau\tau\gamma$ final state

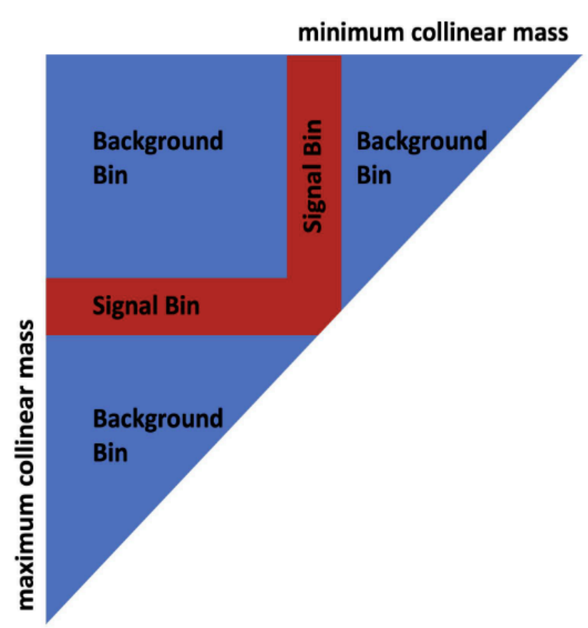


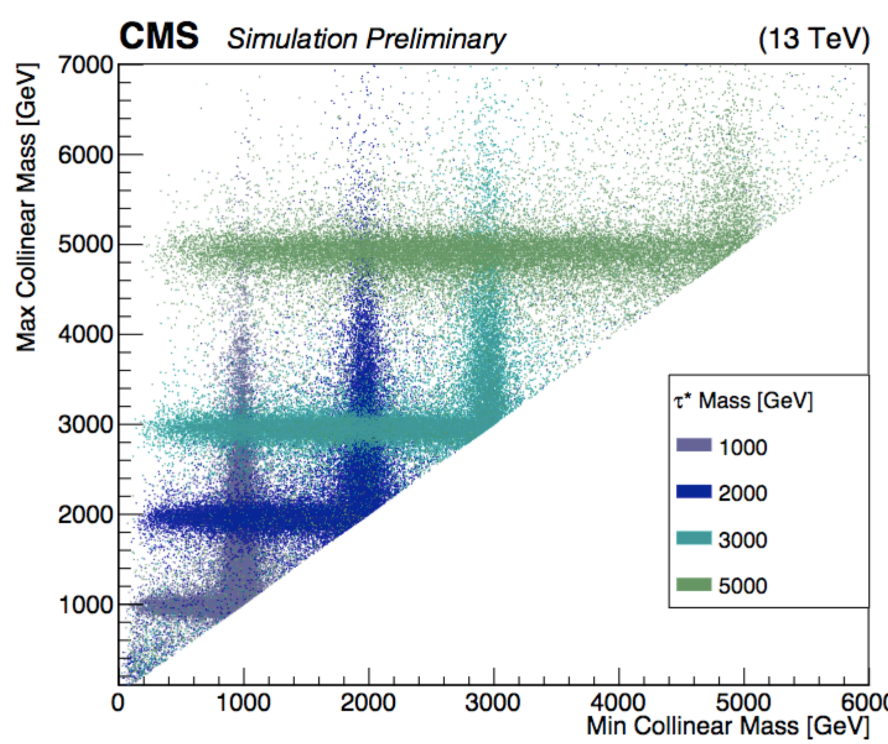
- First LHC result in $\tau\tau\gamma$ state
  - Previously done by LEP
  - τ^* produced in conjunction with SM τ via contact interactions
- **The existence of τ^* would give evidence of compositeness scale Λ**

Analysis Regime:
m_{τ^*}: [175-5000] GeV
through channel $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$

- **Reconstruct full τ decays by assuming ν's are collinear with visible components to form "collinear mass": 2 pairs → min-max value on 2D plane**

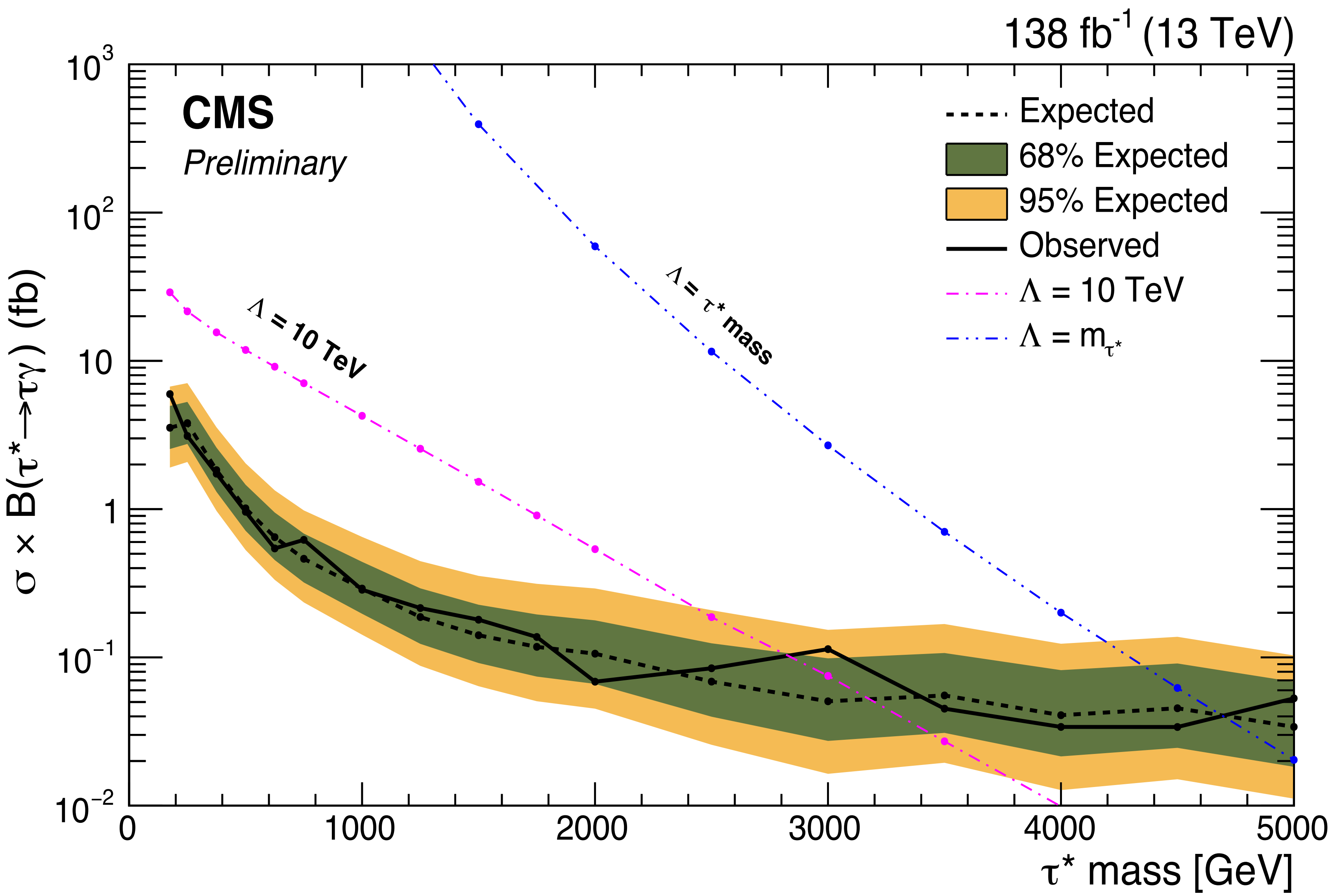
Signal bin is L-band centered on mass hypothesis with width chosen to contain 90% of signal





Search for excited taus

- Main background:
  - Real τ → estimated by MC
  - Fake τ (mis-reconstructed jets) →estimated by ABCD method (charge of 2 τ's vs. isolation
- **No excess above the expected background is observed → derive limits.**
  - ☑ **m_{τ^*} > 4700 GeV for Λ = m_{τ^*} TeV**



Summary

- CMS has a very rich BSM physics program!
- New physics is being hunted in every possible corner!
- **No significant excess is seen so far in any of these searches. A few of the searches show hints of excess which will be further investigated using Run 3 data.**
- **Experimental techniques evolves to more sensitive to low masses objects and more sophisticated approaches using ML tools**
- *Many interesting results, more yet to come!*

Stay tuned !!!!!

Thanks for your attention

Backup

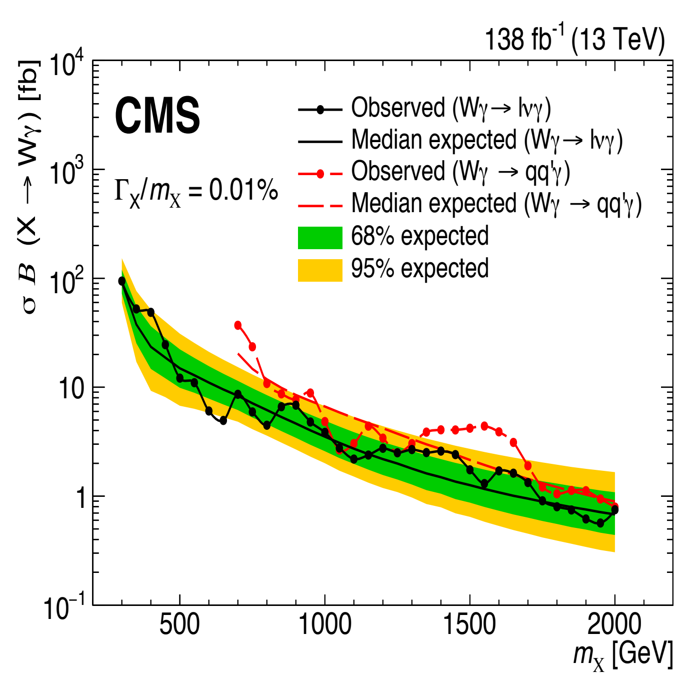
- The longitudinal component of the neutrino momentum cannot be measured or inferred directly, the variable used for the resonance search is the transverse mass m_T

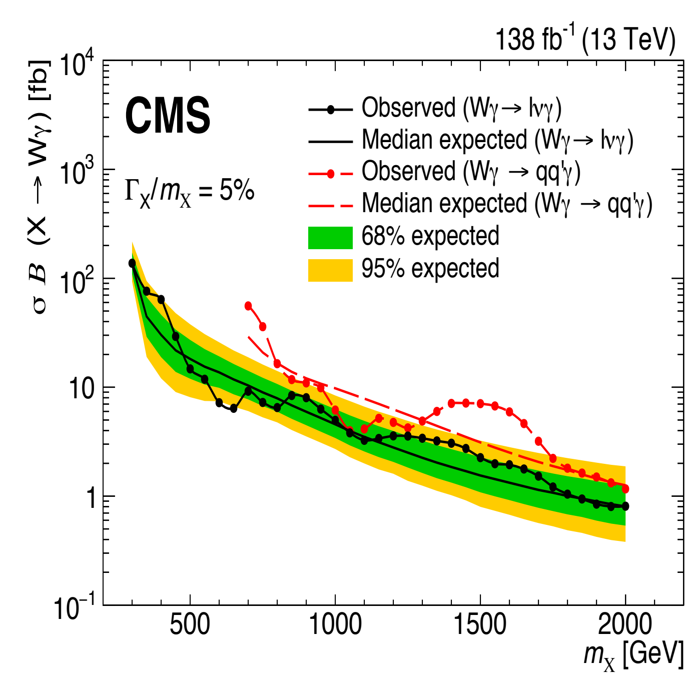
$$(m_{\rm T})^2 = \left(E_{\rm T}(\gamma) + E_{\rm T}(\ell) + p_{\rm T}^{\rm miss}\right)^2 - |\vec{p}_{\rm T}(\gamma) + \vec{p}_{\rm T}(\ell) + \vec{p}_{\rm T}^{\rm miss}|^2,$$

where E_T is defined as √m2 + p2,

- To reduce backgrounds from tt and multi-boson processes, events with more than one lepton or photon passing the basic requirements are rejected

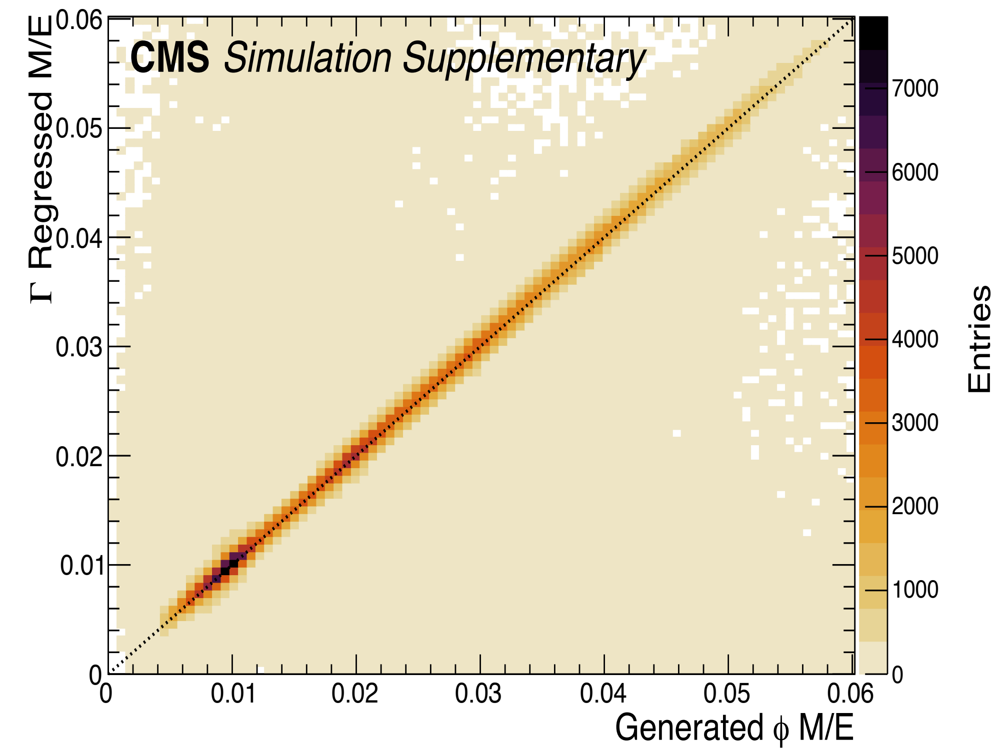
Selection	Electron channel	Muon channel
e/μ sel.	$p_T(e) > 35$ GeV and tight ID	$p_T(\mu) > 30$ GeV and tight ID
p_T^{miss}	>40 GeV	
γ sel.	$0.4\, m_T < p_T(\gamma) < 0.55\, m_T$ and $\lvert\eta\rvert < 1.44$	
Z veto	$\lvert m_{e\gamma} - 91.0\rvert > 20$ GeV and PSV	—
b veto	No medium b-tagged jets	

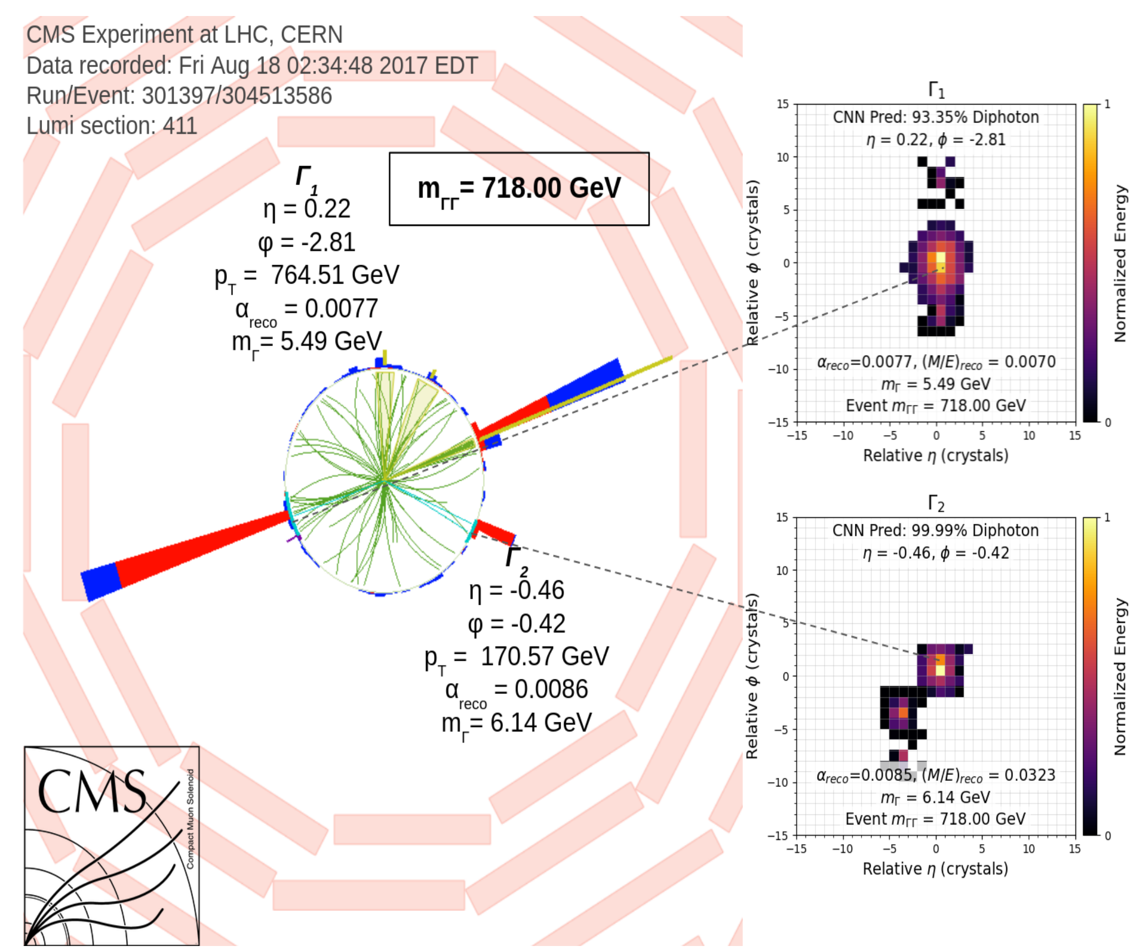




Search for boosted multi-photon

- The clustered energy deposits are converted to a 30×30 image, centered on the most energetic deposit, where the brightness of a pixel corresponds to the energy deposited in a single crystal.
- The architectures of both CNNs are based on the DEEPTOP CNN
- For the classification, this is followed by one fully-connected (FC) linear layer with three outputs corresponding to the output classes.
  - A logarithmic softmax function is used to convert these to probabilities that the cluster belongs to each category: diphoton ($P_{\gamma\gamma}$), photon (P_{γ}), or hadron (P_{had}).
- To suppress the dominant background from misidentified jets, a relative isolation r_{iso} is defined and applied to each Γ candidate in the analysis. Jets reconstructed with the anti-kT algorithm [41] and a distance parameter of 0.4, using the FASTJET package [42], are used.
  - If a Γ candidate overlaps with such a jet within $\Delta R < 0.15$, its r_{iso} is defined as the ratio of its energy to that of the jet. Otherwise, it is set to unity.
- Both Γ candidates must also fulfill the following requirements: $r_{iso} > 0.8$ and $P_{\gamma\gamma} > 0.9$. This $P_{\gamma\gamma}$ requirement retains ≥80% of simulated signal across all masses and rejects approximately 99% of the background.





Jyoti Babbar

Search for resonance in diphoton

- In ADD extra dimensions, the KK modes are closely spaced and result in a continuum excess of diphoton events over the expected SM background.
- In the RS graviton model, the KK modes are on-shell and appear as resolvable resonances in the diphoton mass spectrum.
- In the continuum limit of the clockwork, the massless graviton is accompanied by an infinite tower of massive spin-2 graviton KK modes with a characteristic pattern of masses and couplings.
- The minimum reconstructed invariant mass of the diphoton system is required to be $m_{\gamma\gamma} > 500$ GeV.
- Photon pairs must additionally satisfy $\Delta R_{\gamma\gamma} > 0.4$

ADD conventions

Total ADD cross-section

$$\sigma_{\text{total}} = \sigma_{\text{SM}} + \frac{\mathcal{F}}{M_S^4}\sigma_{\text{int}} + \frac{\mathcal{F}^2}{M_S^8}\sigma_{\text{ADD}}, \quad (1)$$

where σ_{SM}, σ_{int}, and σ_{ADD} are the cross sections for the SM-only, the interference term, and the direct term, respectively. The variable $\mathcal{F}$ transforms the predictions into the different conventions,

$$\mathcal{F} = \begin{cases} 1 & \text{(GRW)}, \\ \log\left(\frac{M_S^2}{\hat{s}}\right), & \text{if } n_{\text{ED}} = 2 \\ \frac{2}{n_{\text{ED}}-2}, & \text{if } n_{\text{ED}} > 2 \end{cases} \text{(HLZ)} \\ \pm\frac{2}{\pi} \quad \text{(Hewett)} \quad (2)$$

where $\sqrt{\hat{s}}$ is the center-of-mass energy of the colliding partons.

Excited taus

Signal Selection

- visible mass > 100 GeV to suppress Z→ττ events
- b-jet veto to suppress top events : e+τh, μ+τh channels only
- Z→ee, μμ veto : loosened id/iso for e,μ
- γ pT: >100, 100, 75 GeV (e+τh, μ+τh, τh+τh)
- Veto additional leptons : 1e 0μ in e+τh, 0e 1μ in μ+τh, 0e 0μ in τh+τ e

Jet → hadronic tau

- The background arising from jet faking τh is estimate during a data-driven ABCD approach.
- Control regions and sidebands are defined by inverting the isolation criteria of the τh and/or the relative charge between the reconstructed particle pairs.
- In the B,C,D regions, yields are corrected by first subtracting e,μ,τh→ τh events taken from MC.
- In the τh+τh channel at least 1 τh is required to be anti isolated.

Signal Region A opposite-sign isolated τ_h	**Control Region B** opposite-sign anti-isolated τ_h
Sideband Region C same-sign isolated τ_h	**Sideband Region D** same-sign anti-isolated τ_h

$$\frac{A}{B} =? \frac{C}{D} \quad \rightarrow \quad A_{pred} = B * \frac{C}{D}$$