CMS-PAS-HIG-24-014

Search for a narrow resonance with mass between 10 and 70 GeV decaying to a pair of photons

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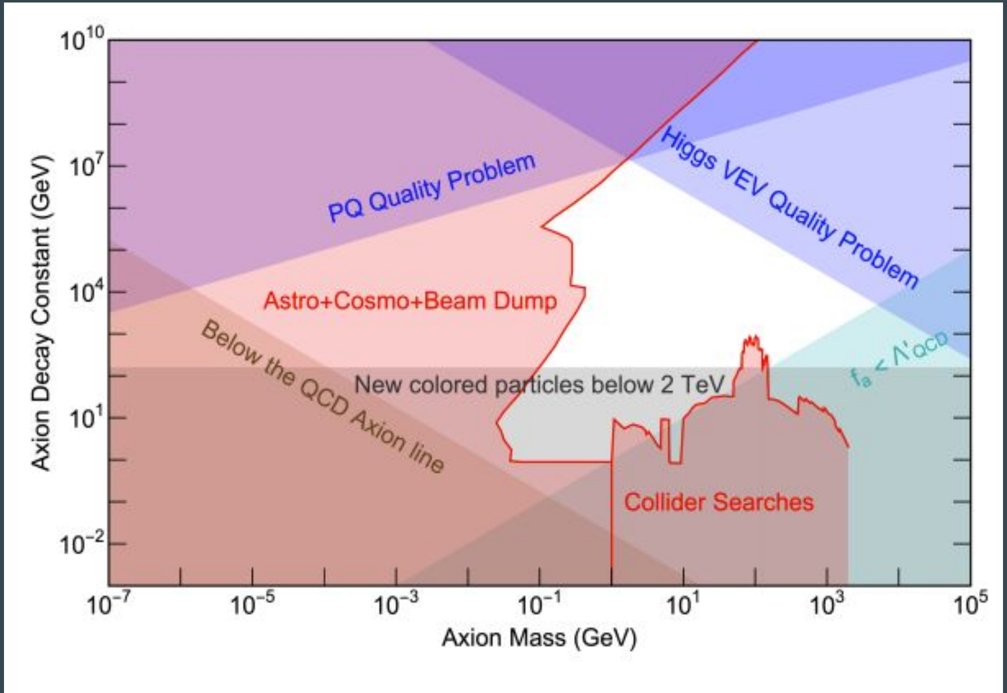
Motivation

Physics case: Search for a spin-zero diphoton resonance between 10-70 GeV.

Many generalizations of the Standard Model (SM) predict the existence of additional spin-zero states, including potential dark matter candidacy and axions.

Axion: a theoretical particle that solves the strong charge-parity problem[1] of the SM.

GeV-scale axions and axion-like particles (ALPs) theoretically motivate collider searches below SM Higgs mass.



[arXiv 1911.12364]

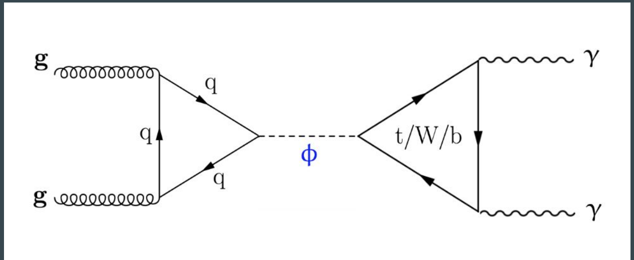
1: [doi:10.1103/PhysRevLett.38.1440]

Analysis Strategy

Objective: Obtain first limits with CMS data on production cross section of Higgs-like narrow resonance ϕ via gluon-gluon fusion (ggϕ) times branching ratio of ϕ decaying into two photons

$$(\sigma_{gg\rightarrow\phi} \times BR(\phi\rightarrow\gamma\gamma))$$

- Minimal model dependencies in ggϕ allow for inclusive sensitivity estimations and ALP recasting
- Diphoton resonance searches performed in CMS[2] for 70-110 GeV and in ATLAS[3,4] for 10-110 GeV
- Utilization of bump hunt strategy on data-driven background using data taken in 2018
    - Search enabled by new trigger in 2018 which removed 55 GeV diphoton mass cut
    - Signal: Higgs-like particle produced via gluon-gluon fusion and decaying to two photons
    - Simulates narrow width resonance which would peak above background shape



2: [doi:10.1016/j.physletb.2024.139067]
3: [doi:10.1007/JHEP07(2023)155]
4: [doi:10.1007/JHEP01(2025)053]

Event Selection

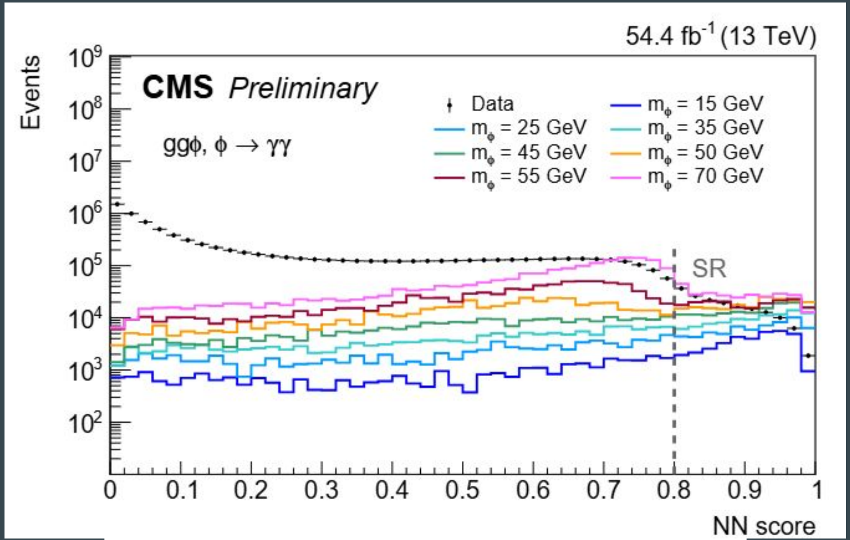
Online trigger: Thresholds applied to photon kinematics and identification variables.

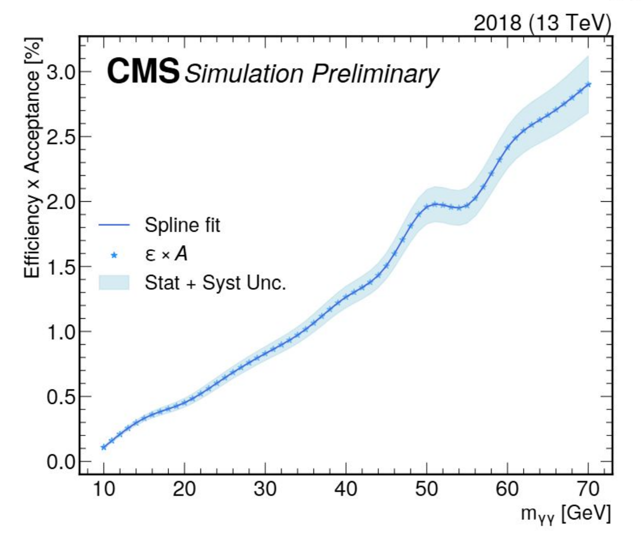
- $p_{T,\gamma 1} > 30$ GeV and $p_{T,\gamma 2} > 18$ GeV
- $|\eta_{\gamma 1}|$ and $|\eta_{\gamma 2}| < 2.5$

Offline preselection: tightens online selections, then adds photon object classification and diphoton vertex identification.

Diphoton event classifier: Neural network (NN) based method using signal simulation as signal input and simulated diphoton events + data-driven representation of processes with misidentified photons as background input.

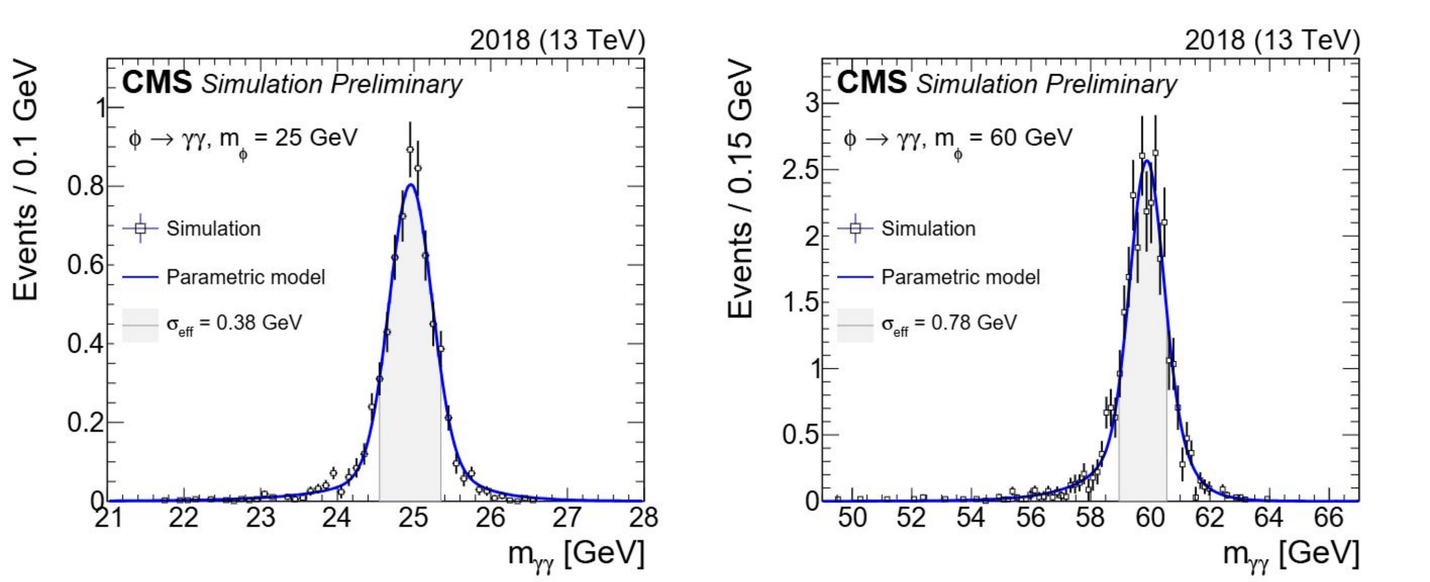
- Input variables include photon kinematics and diphoton features along with discrete mass hypothesis
- Using figures of merit throughout mass range, signal region (SR) is created with highest sensitivity





Signal Modeling

Signal model: Double Crystal Ball + Gaussian used as parametric model, and fit parameters linearized with respect to mass. The experimental resolution (σ_{eff}) varies linearly at 1.5% of $m_{\gamma\gamma}$ and is used to define granularity of limit estimations.



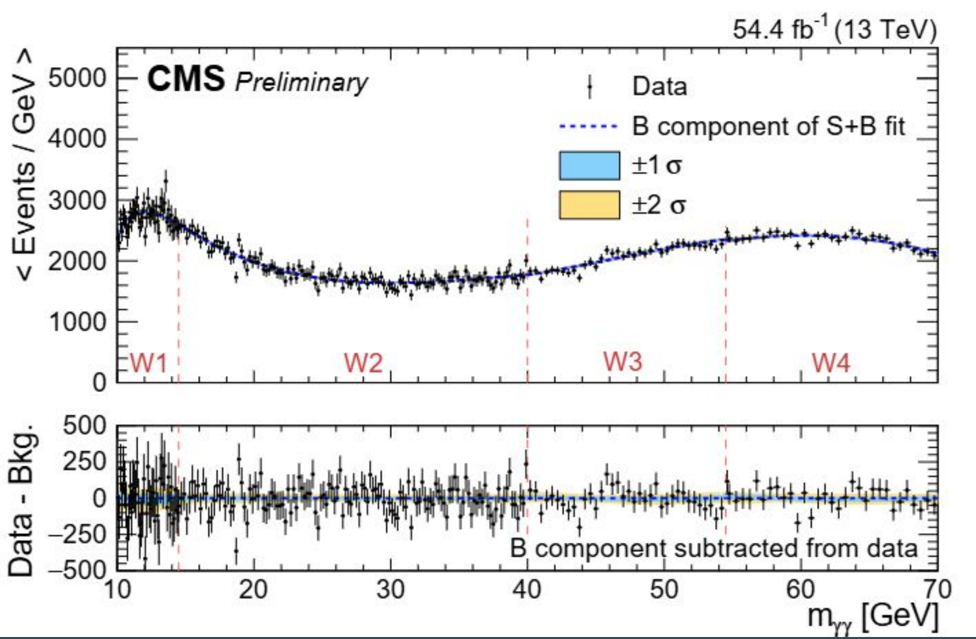
Background Modeling

Background shape due to trigger selections at around 50 GeV and photon isolation criteria at around 12 GeV.

Background model: Mass spectrum divided into four sub ranges, with the discrete profiling method[5] applied in each one.

Envelope of functions includes:

- 2^{nd}-4^{th} order Bernstein
  3^{rd} order Exponential
  3^{rd} order Power Law



5: [arXiv 1408.6865]

Results

Background modeling and statistical uncertainties are largest uncertainties in this analysis. Limits estimated using maximum likelihood fit made from signal and background models, applying uncertainties as nuisance parameters.

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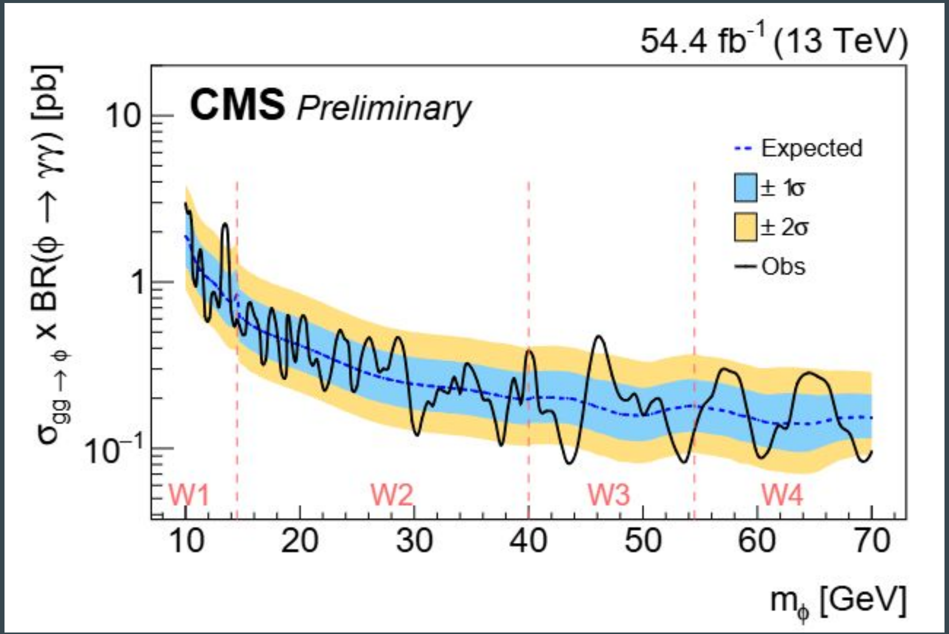
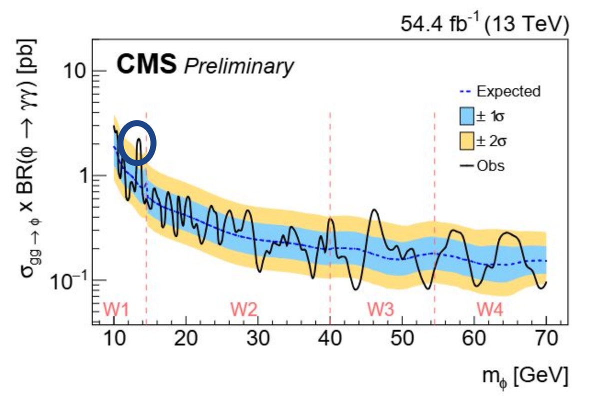
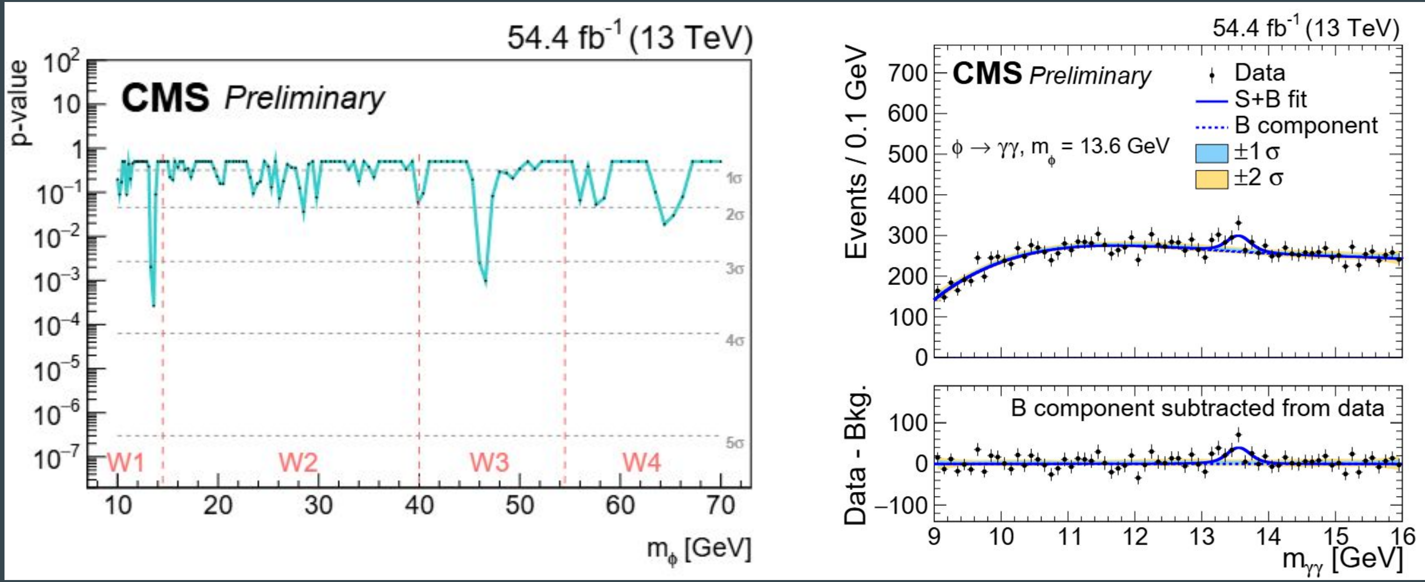


Checking 13.6 GeV



Most significant excess at 13.6 GeV with local significance of 3.47σ.
Global significance calculated using toy datasets: (1.9±0.1)σ.



Special thanks to Ilaria Brivio for her input in the understanding of the ALP model!

Reinterpretation to ALP

ALP production via gluon-gluon fusion (gg→a) is simulated at leading order (LO) using MadGraph:

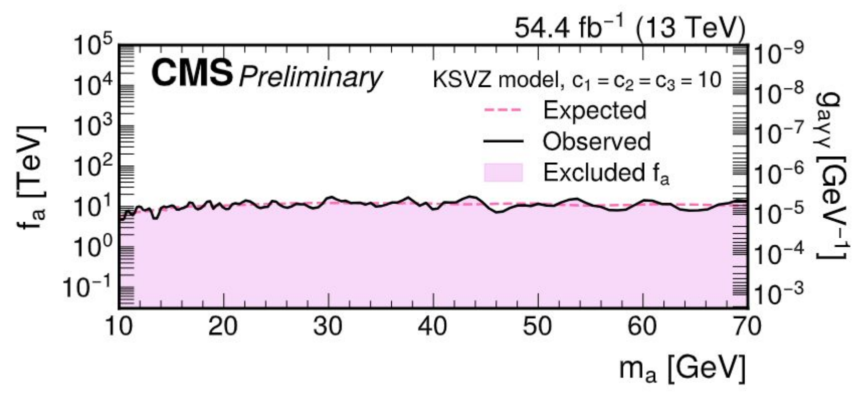
- Coupling parameters $c_1=c_2=c_3=10$ in KSVZ ALP model[6,7]
- Assumption that acceptance is the same at NLO for ALP production as for SM-like boson with the same mass

$$f_a = \sqrt{(\sigma^{TH}[f_a = 1\ \mathrm{TeV}] * \text{K-factor}/\sigma^{CMS})}$$

Upper bound limits are recast as lower bounds in ALP phase space on ALP decay constant f_a, with K-factor of 2 to account for NLO corrections in the ALP model.

$$\mathcal{L}_{\mathrm{int}} = \frac{a}{4\pi f_a}\left[\alpha_s c_3 G\tilde{G} + \alpha_2 c_2 W\tilde{W} + \alpha_1 c_1 B\tilde{B}\right]$$

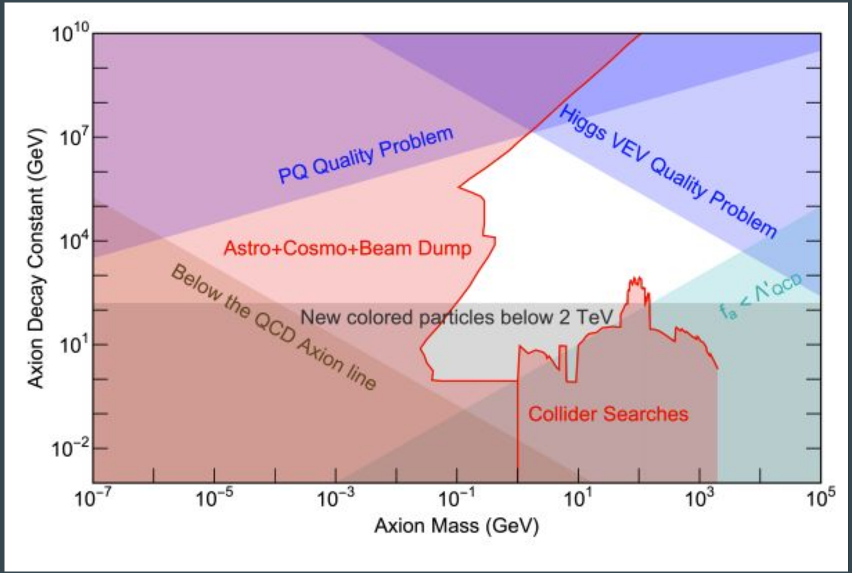
[arXiv 1710.01743]



$$g_{a\gamma\gamma} \equiv \alpha_{\mathrm{EM}} \cdot E/(\pi \cdot f_a) \text{ with } E = (c_2 + 5/3 \cdot c_1)$$

6: [doi:10.1103/PhysRevLett.43.103]
7: [doi:10.1016/0550-3213(79)90022-1]

Reinterpretation to ALP



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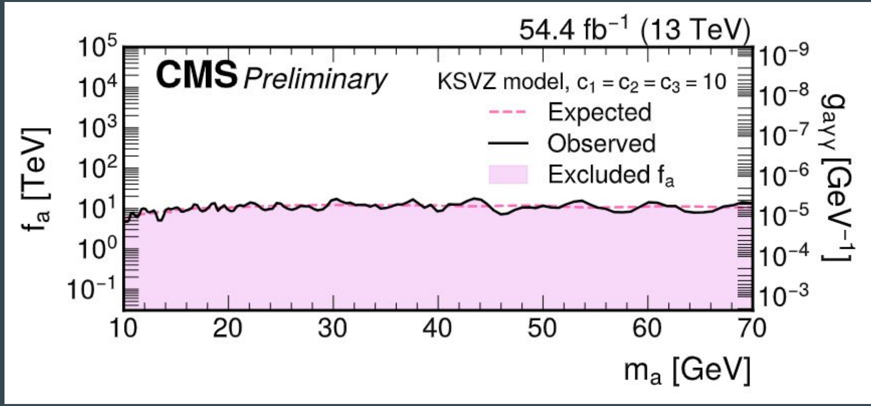

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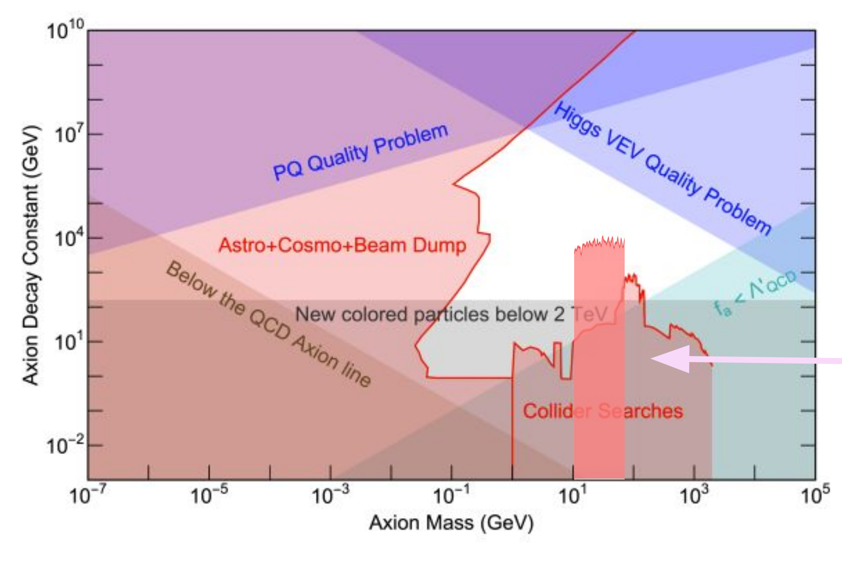

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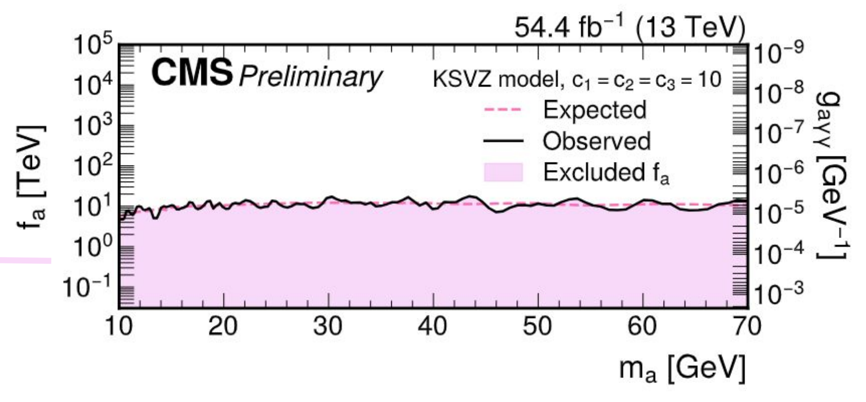

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Summary and Prospects

The first limits from CMS of $\sigma_{gg\to\phi}$ x BR ($\phi\to\gamma\gamma$) at 10-70 GeV were presented using data collected in 2018.

- A trigger introduced in 2018 enables CMS to access a new phase space below the SM Higgs mass, going down to 10 GeV.
- To optimize the sensitivity of the search in this challenging region, a dedicated NN is used for event selection, and signal and background modeling strategies are developed for the resultant SR.
- No significant excess is found, so upper bounds on the σ * BR of a diphoton resonance production are shown and recasted in the ALP model as lower limits on the ALP decay constant.
- An optimized trigger to increase signal acceptance in the lower part of the diphoton mass spectrum is running online since the start of Run 3 data-taking.

We look forward to continuing this analysis with Run 3 data!

Thank you for listening!

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Backup

Online and Offline Event Selection

Online trigger:

- $p_{T,\gamma1} > 30$ GeV and $p_{T,\gamma2} > 18$ GeV
- $|\eta_{\gamma1}|$ and $|\eta_{\gamma2}| < 2.5$
- $H/E_{EB} < 0.12$, $H/E_{EE} < 0.1$
- $R_{9,EB} > 0.5$, $R_{9,EE} > 0.9$
- $\sigma_{i\eta i\eta,EB} < 0.015$, $\sigma_{i\eta i\eta,EE} < 0.035$
- ECAL cluster isolation < $6.0+0.012E_T$ GeV
- γ_2 track isolation < $6.0+0.002E_T$ GeV

Offline preselection:

- $p_{T,\gamma1} > 30$ GeV and $p_{T,\gamma2} > 18$ GeV
- $p_{T,\gamma1}/m_{\gamma\gamma} > 0.47$ and $p_{T,\gamma2}/m_{\gamma\gamma} > 0.28$
- $|\eta_{\gamma1}|$ and $|\eta_{\gamma2}| < 2.5$
- $H/E < 0.08$
- $R_{9,EB} > 0.5$, $R_{9,EE} > 0.9$
- $\sigma_{i\eta i\eta,EB} < 0.015$, $\sigma_{i\eta i\eta,EE} < 0.035$
- ECAL cluster isolation < 4.0 GeV
- Track isolation < 6.0 GeV
- γ ID score > -0.7

Run 3 Prospects

New supplemental trigger introduced for Run 3 data-taking with lowered p_T thresholds and tightened identification variables:

- $p_{T,\gamma1} > 22$ GeV and $p_{T,\gamma2} > 14$ GeV
- $|\eta_{\gamma1}|$ and $|\eta_{\gamma2}| < 1.5$ (Barrel only)

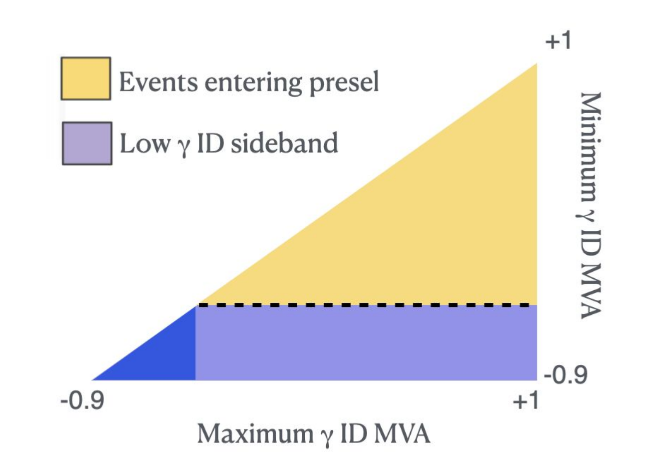
Consideration: Merged diphoton analysis (EXO-22-022) for $X \rightarrow \phi\phi \rightarrow (\gamma\gamma)(\gamma\gamma)$ employs a convolutional neural network to classify events containing merged diphotons and regress the cluster mass.

- Methodology can be applied to extract more boosted diphoton events and probe further into lower mass

Building Data-driven Input

Simulated diphoton events + data-driven representation of processes with misidentified photons as background input.

- Events enter preselection region with minimum γ ID score > -0.7
- Events enter sideband region if minimum γ ID score $\in$ [-0.9, -0.7] (orthogonal to preselection)
  - Sideband region used as data-driven representation in background input
  - Minimum γ ID score regenerated for each event
  - Further reweighting on background input using fitting templates
  - Additional reweighting using photon σ_E/E, scaled p_T, and η is applied to sideband events to provide a better description for background input to NN



NN Input Variables and Architecture

Standardized input variables:

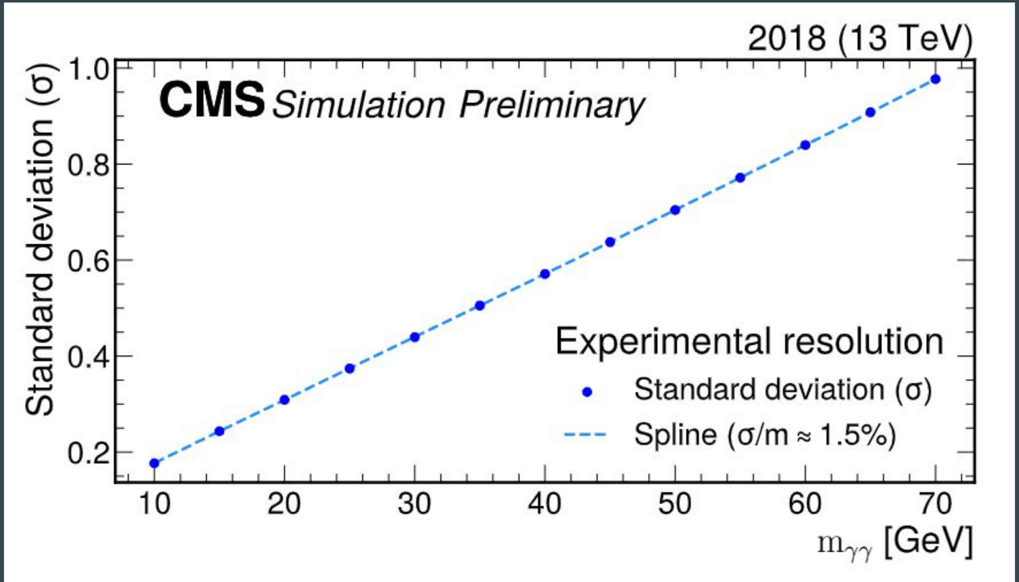
- Scaled transverse momenta, $p_T^{1,2}/m_{\gamma\gamma}$, and pseudorapidity, $\eta^{1,2}$, of each photon
- Photon ID score of each photon
- Cosine of angle between the two photons, $\cos(\Delta\varphi)$
- Per-event estimate of mass resolution assuming the use of the right (wrong) primary vertex, $\sigma_{rv(wv)}$
- Per-event estimate of probability that the correct primary vertex was selected, p_{vtx}
- Discretized mass hypothesis m_{hyp}
    - Signal - invariant mass point of the sample; Background - closest mass hypothesis point to reconstructed diphoton mass

NN trained using TensorFlow:

- Loss: Weighted cross entropy
- Architecture: 11, 50, 50, 50, 1 w/ ReLU activation function
- Epochs: Early stop

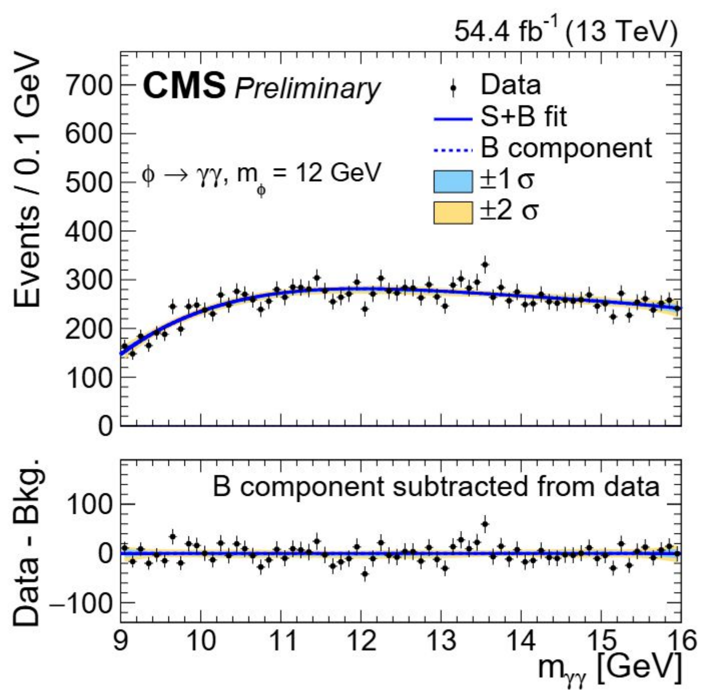
Signal Widths

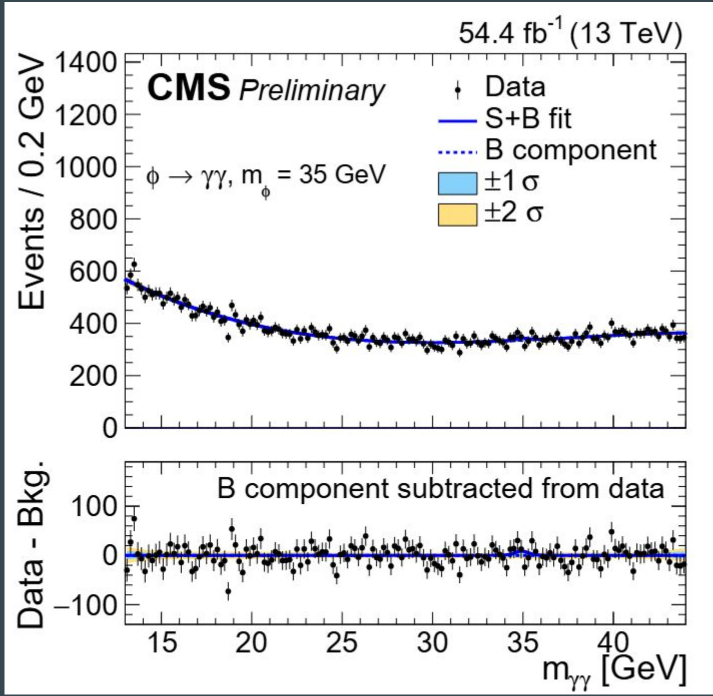
Experimental resolution (σ) varies linearly and is used to define granularity of limit estimations.



S+B Fit on Sub Ranges (1)

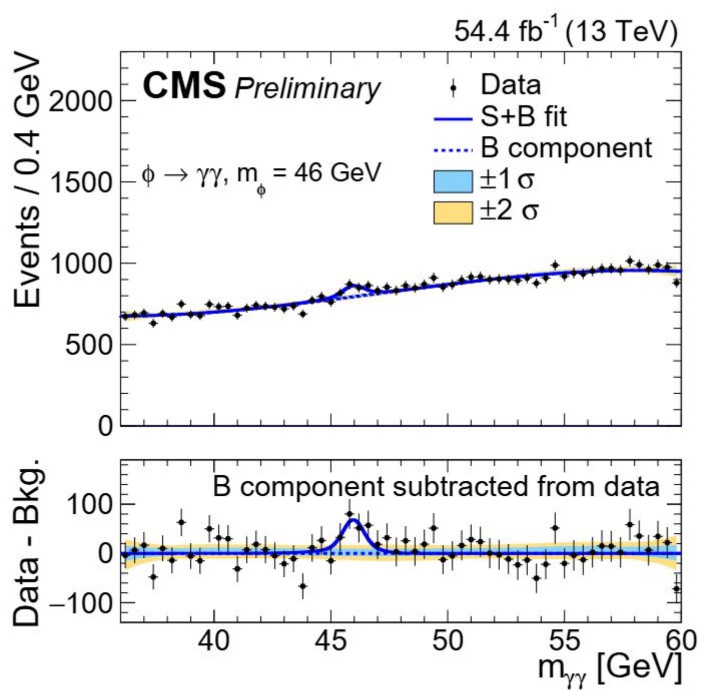
Example mass points used for signal in each sub range.

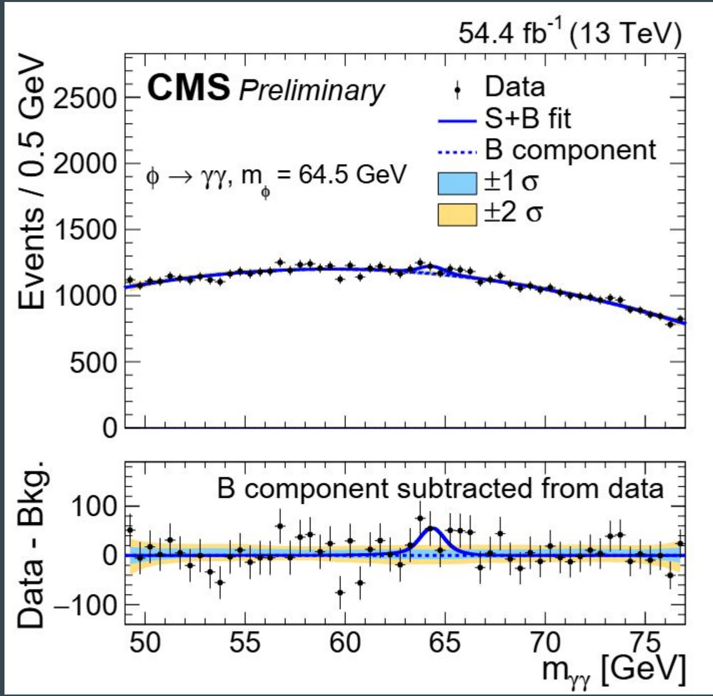




S+B Fit on Sub Ranges (2)

Example mass points used for signal in each sub range.





Systematics

The largest uncertainties are due to statistics and background modeling.

Theoretical uncertainties:

- PDF weights (60 variations) → negligible
- AlphaS (α_S) weights → around 3%
- Scale weights → maximum value of 3%

Lumi uncertainty (2018): 1.5%

Dedicated NVtx reweighting uncertainty: < 1%

NN SR migration: negligible

Experimental uncertainties: (Log normal)

- (Loose MVA, Preselection, e-veto) SFs uncertainty
  - 0.5%, 5%, 0.2% respectively
- Trigger weights uncertainty: < 0.5%

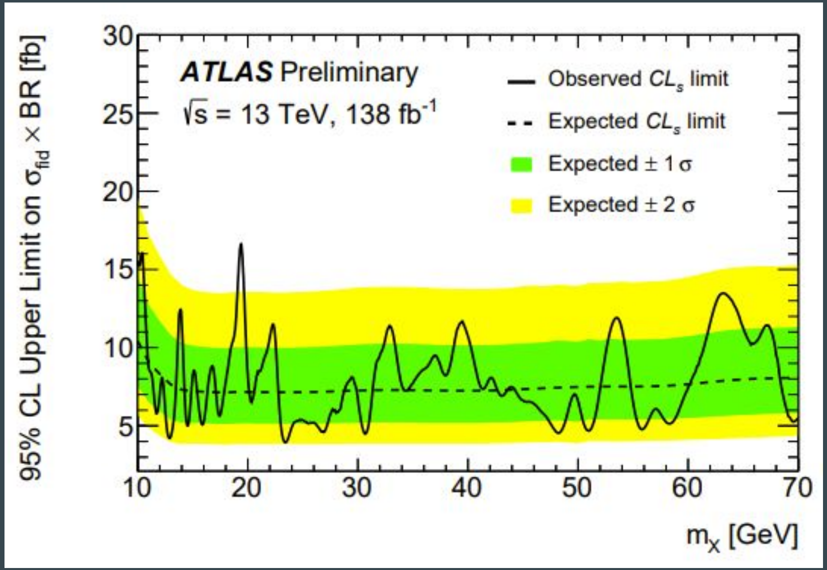
Experimental uncertainties: (Trees with up/down variations)

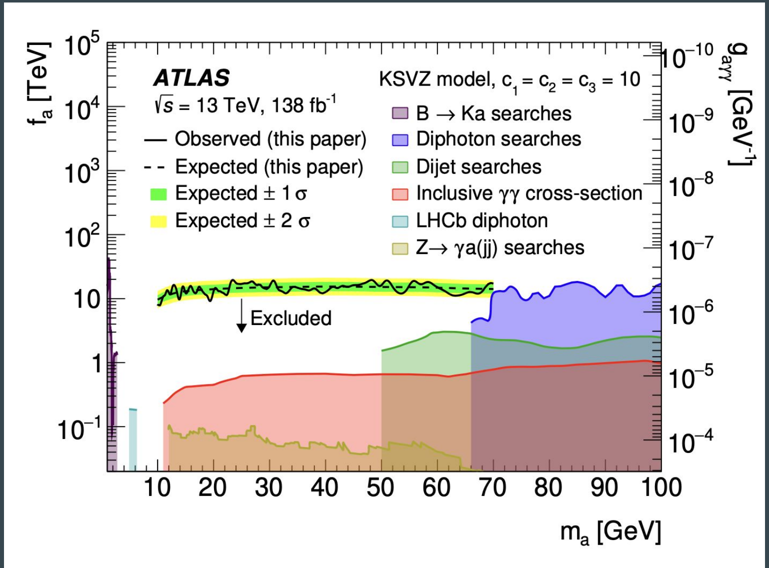
- Scales corrections:
  - Shower shape
  - Material (central barrel, outer barrel, forward)
  - FNUFEB/FNUFEE
- MC scale and smearing (|η| and R9 bins)
- Photon ID MVA shift: < 3-4% in average
- SigmaEOverE shift: < 3-4% in average

Systematic uncertainties applied as nuisances to likelihood fit.

ATLAS Results

Fiducial cross section includes $p_{T,\gamma1}$ and $p_{T,\gamma2} > 22$ GeV, $|\eta_{\gamma1}|$ and $|\eta_{\gamma2}| < 2.37$, $p_{T,\gamma\gamma} > 50$ GeV, and photon isolation in a cone with $\Delta R = 0.2$ $E_T^{iso} < 0.065\ E_T$





Paper: [doi:10.1007/JHEP07(2023)155]
HEPData: [ins2178061]