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

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Introduction

- Photons and leptons offer clean, high-resolution final states
  → Ideal for probing rare decays and deviations from SM.

- Many BSM models predict light intermediate states decaying to $\gamma\gamma$, $\ell\ell$, or $\ell\ell\gamma$
  → Often highly boosted and collimated - **challenging standard reconstruction.**

- New strategies at CMS are pushing the frontier
  → Machine learning for reconstruction and classification
  → New dedicated data streams

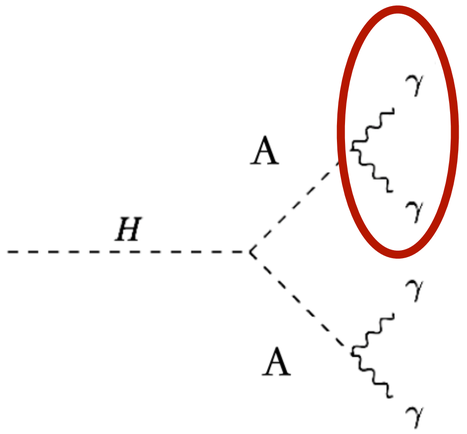
- This talk highlights recent CMS Run 2 searches targeting complex γ+ℓ final states using innovative techniques.

Search for H→AA→4γ in partially-merged topology

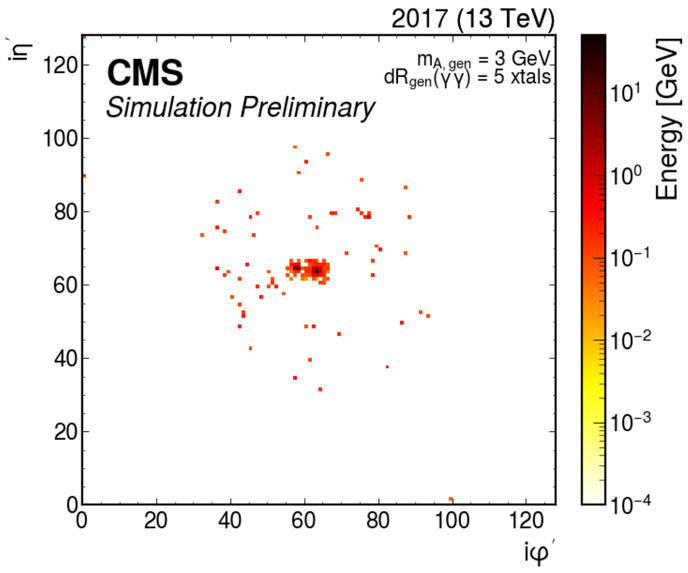
✨New!✨ CMS-PAS-EXO-24-025

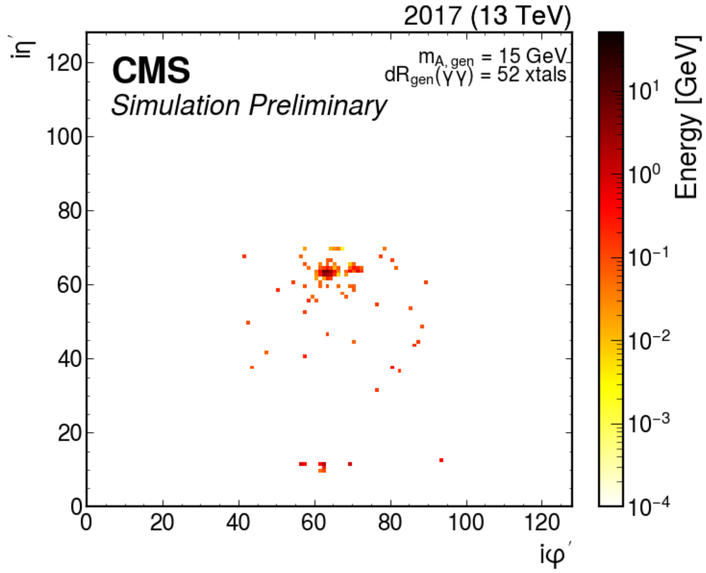
Model and signatures

- Exotic decay of Higgs to identical light pseudoscalars:
  H→ A+A → 2γ+ 2γ
  in 3 photon final state.
- One pair of resolved photons and the other pair:
  - Truly merged photons (dR < 0.14) - single photon in reconstruction
  - One photon reconstructed and the other is not due to detector / reconstruction thresholds.
- M_A =[1, 15] GeV - intermediate range between fully-merged (2 photons, M_A = [0.1, 1.2] GeV, **PhysRevLett.131.101801** and fully-resolved (4 photons, M_A = [15, 60] GeV, **JHEP07(2023)148**) CMS searches



→ 1 photon in reconstruction



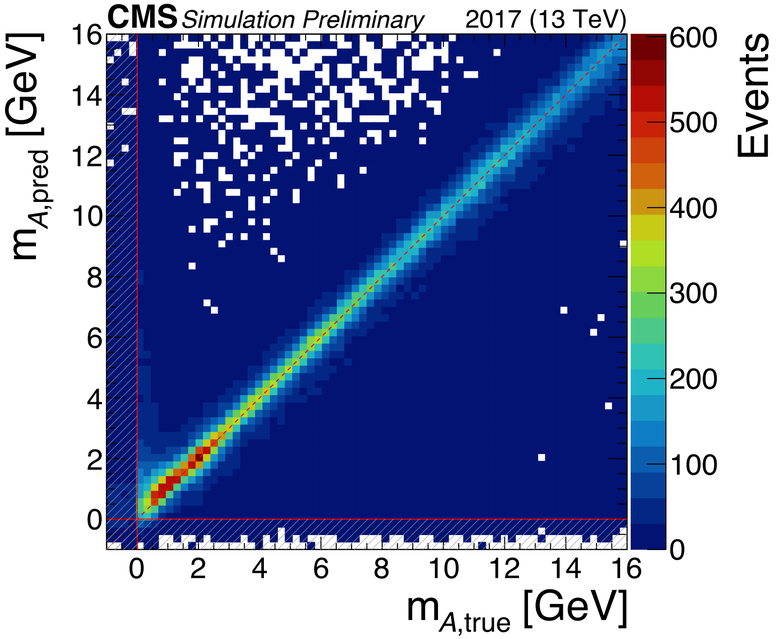


Search for H→AA→4γ in partially-merged topology

Challenge!

How to reconstruct the mass of A without the second photon?

—-> A state-of-the-art GNN-based mass regressor network to reconstruct the mass of A using energy deposits in the ECAL.

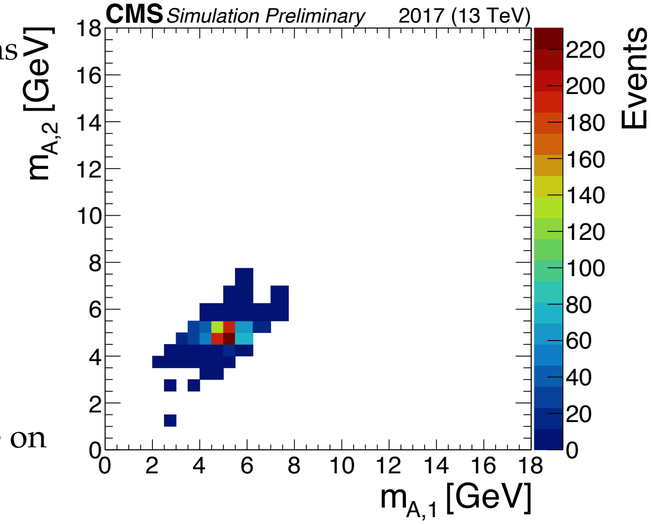


Predicted vs True mass
A-particle samples in training

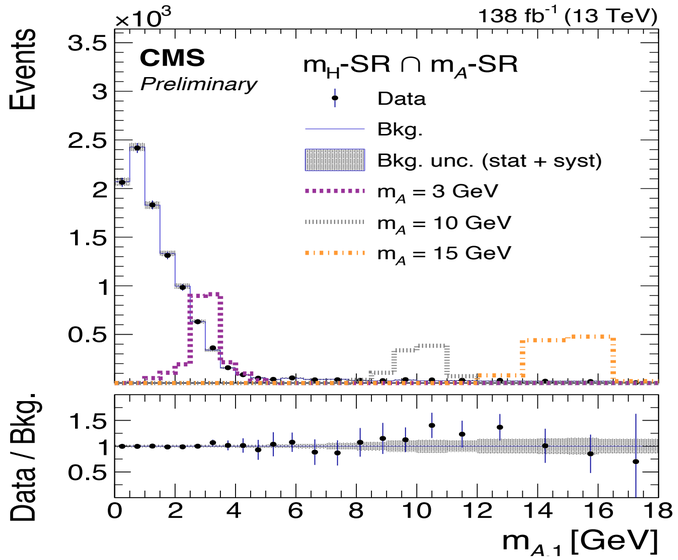
Analysis strategy:

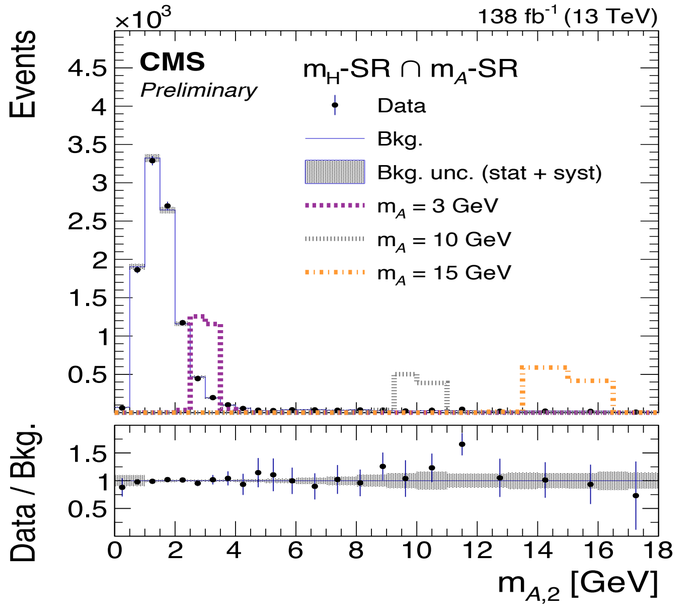
✨New!✨ CMS-PAS-EXO-24-025

- Reconstruct the A-mass:
  - **Merged leg (m_{A1}):** from the ML regressor.
  - **Resolved leg (m_{A2}):** from the momenta of the two photons
- Fill a 2D-m_A (m_{A1} vs m_{A2}) template.
- Signal and sideband regions defined along two axes:
  - Triphoton mass $m_{\gamma\gamma\gamma}$ axis, defined by the Higgs mass window, m_H-SR = (100 - 135) GeV
  - 2D-m_A template axis:
    —-> Under the identical mass hypothesis, signal will lie on the diagonal of the 2D-m_A plane
    (m_A-SR)
- The unrolled distribution of the 2D-m_A template diagonal of the m_H-window => the final discriminant for the maximum likelihood estimate fit.
- Data-driven background modeling using the sidebands.
- Signal model from MC.



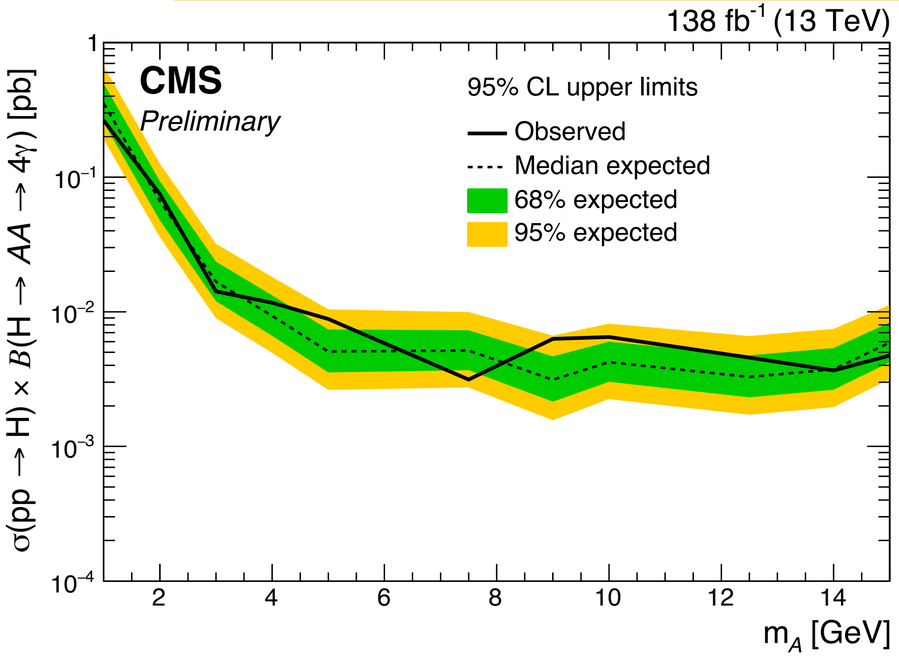
Search for H→AA→4γ in partially-merged topology

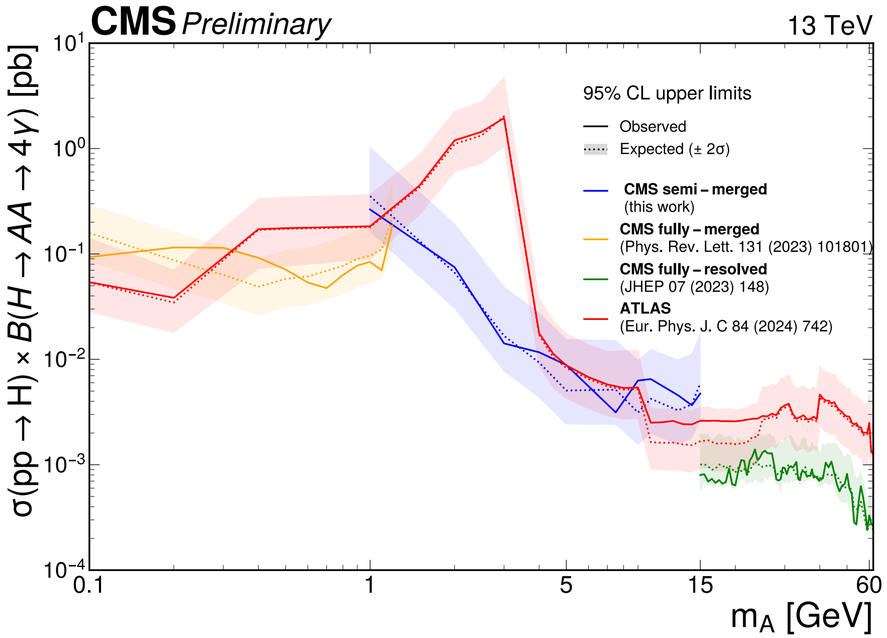




Results ✨New!✨ CMS-PAS-EXO-24-025

- No significant excess observed.
- Most stringent limits yet in the majority of the mass range explored.
- Connects well to the previous CMS fully-merged and fully-resolved results.
- ML-based mass regression enables direct mass reconstruction of the partially-merged photon systems.





Search for H→AA→4e with merged electron pairs

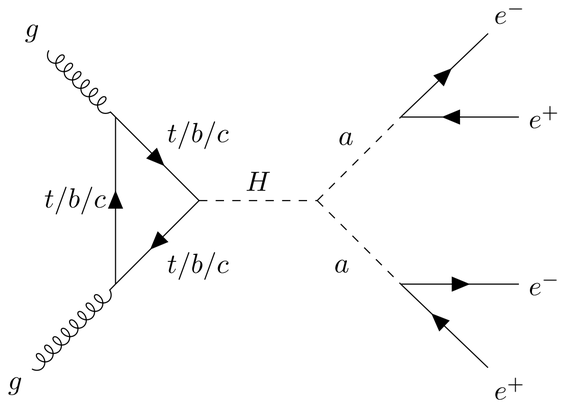
CMS-PAS-EXO-24-031

Model and signatures

- Search for **H→ A+A → e⁺ e⁻ + e⁺ e⁻**

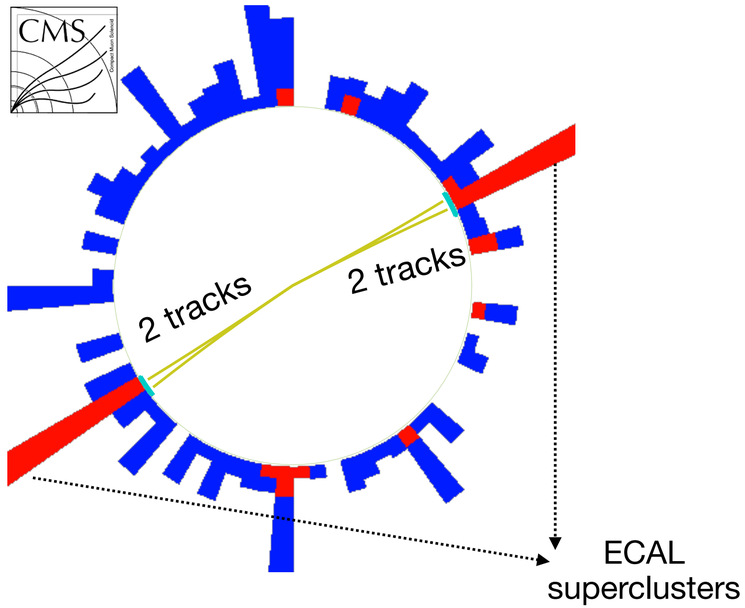
  probing sub-GeV mass M_A = [10, 100] MeV, $c\tau$ = 1, 10, 100 μm predicted by ALP models.

- Highly challenging to reconstruct!
  - Merged electron pairs (MEP) forming single superclusters in ECAL, but with resolved tracks.



Analysis Strategy

- Reconstruct MEP by matching the two tracks within $\Delta R < 0.015$ to the single ECAL supercluster.
- Custom BDT model and isolation cuts developed for MEP ID.
- Reconstruct the Higgs candidate mass for the final fit.

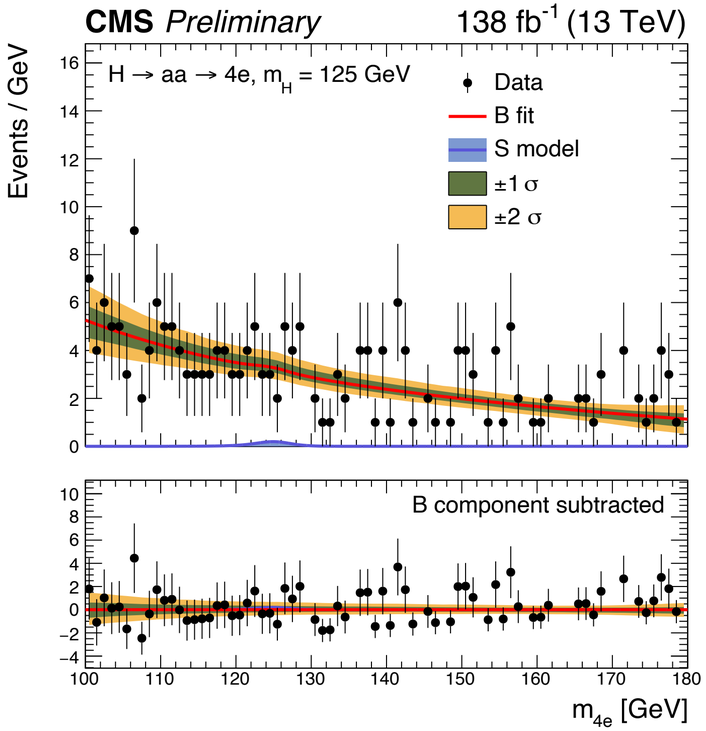


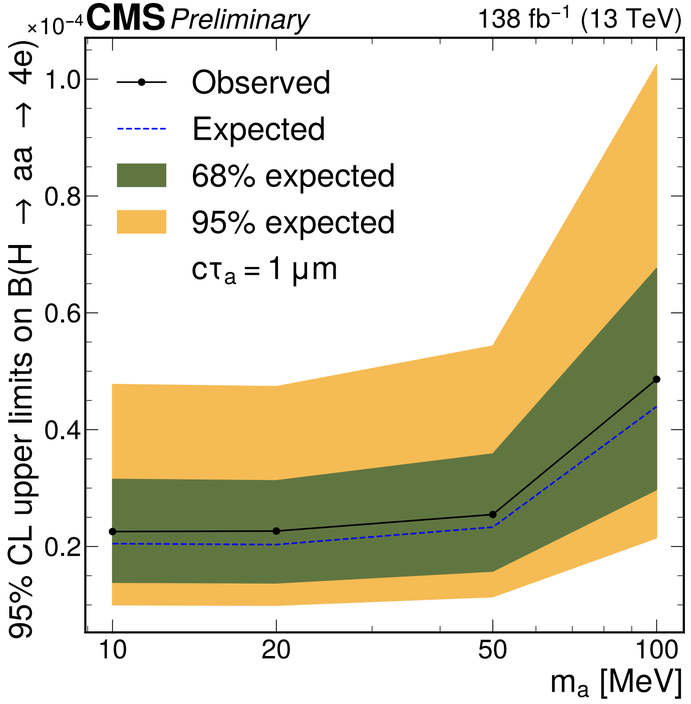
Search for H→AA→4e with merged electron pairs

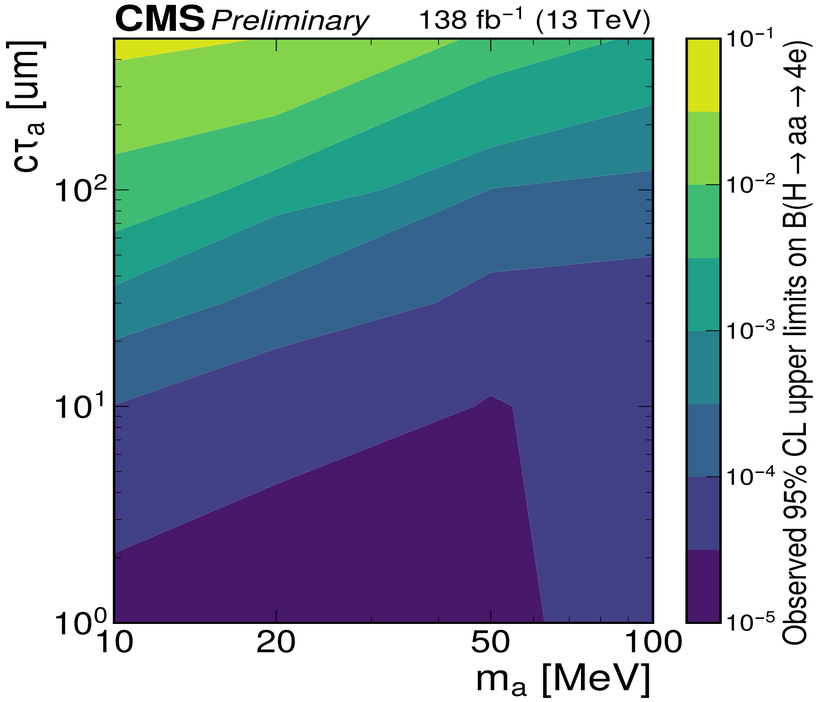
Results

CMS-PAS-EXO-24-031

- No significant excess observed over SM.
- First CMS limits on tens-of-MeV ALPs and for different lifetimes!
- Strong exclusion limits on the BR (H—>AA—>4e) up to < 10^{-5}





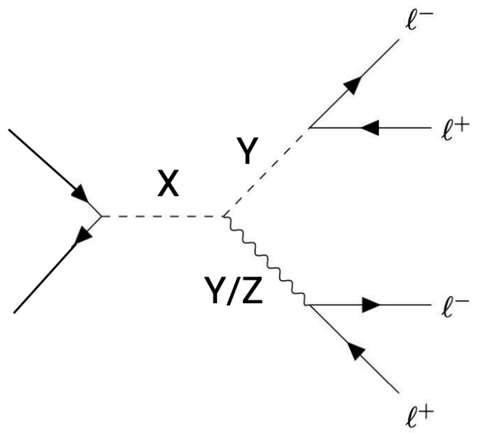


Search for a high mass resonance: X —> YY/ZY —> 4l

CMS-PAS-EXO-24-006

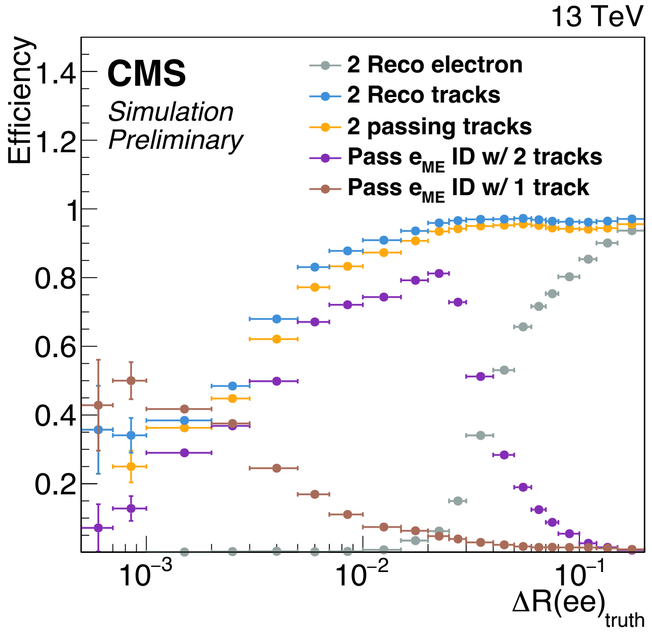
Model and signatures

- Search for a heavy resonance X decaying to two light bosons Y or Z (SM), with each Y / Z —> $l^+ l^-$, where l = e, μ
  - M_X = [250, 2000] GeV, M_Y > 0.4 GeV



Analysis Strategy

- 4 lepton final state - 9 signal regions with various boosts explored.
- New techniques developed for boosted lepton final states:
  - Merged electrons (e_{ME}) ID using an MVA classifier.
  - Collimated / cleaned muons ID utilizing missing transverse momentum p_T^{miss}



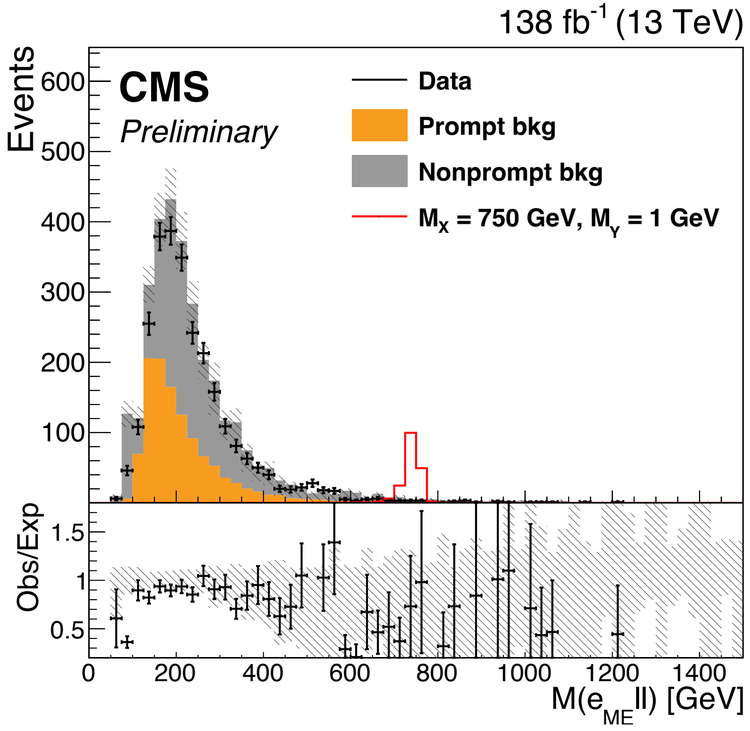
Search for a high mass resonance: X —> YY/ZY —> 4l

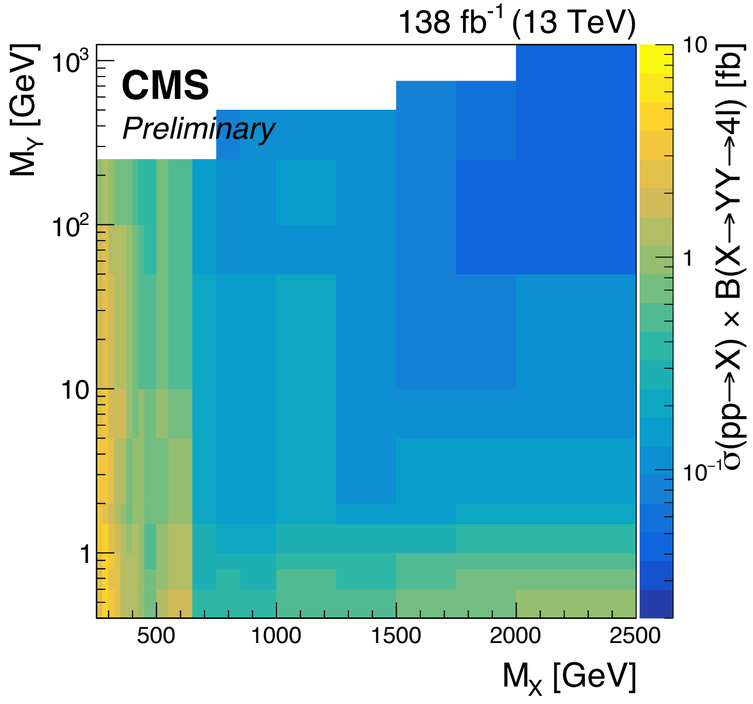
Results

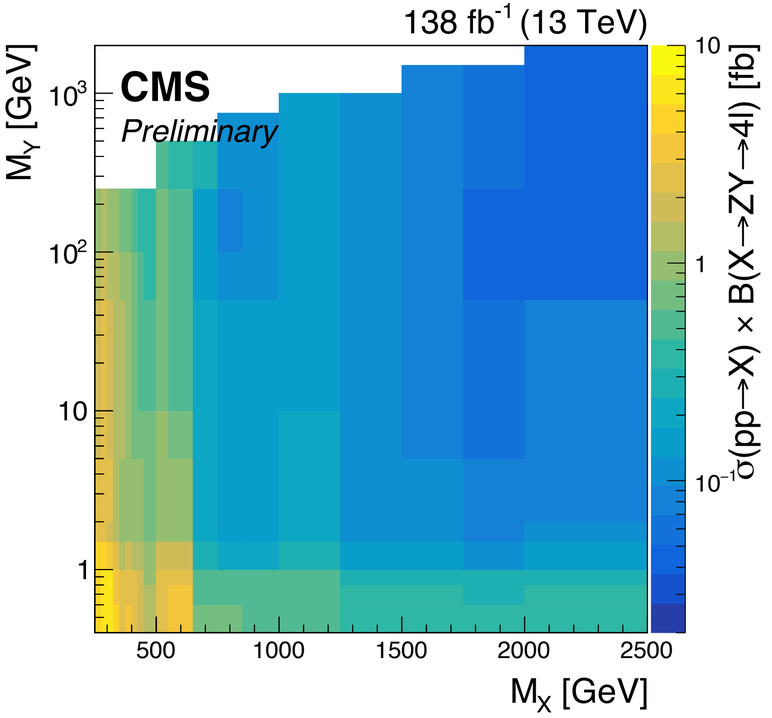
CMS-PAS-EXO-24-006

- No significant excess found.
- Upper limits are set on
  $\sigma(pp \to X) \times B(Y \to \ell\ell)$ for various X, Y masses.
- The first of its kind of LHC search for X→YY / ZY→4l resonance covering wide ranges of Lorentz boosts O(1) – O(10^3)

ll + e_{ME} SR





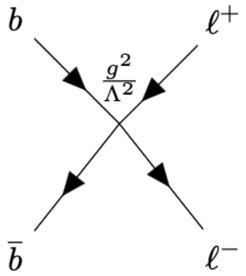


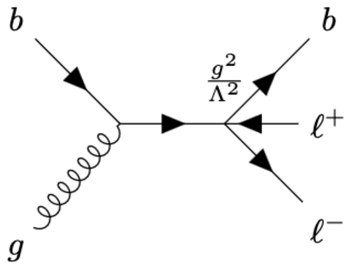
Nonresonant search in high mass ll +b

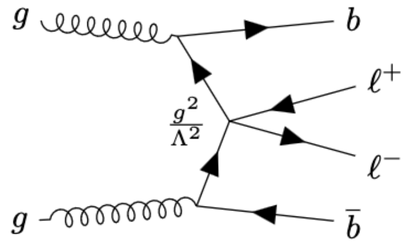
CMS-PAS-EXO-23-010

Model and signatures

- Search for non-resonant production of dilepton pairs and b-jets in the final state.
- Probes new physics via contact interactions between lepton pair and b and s quarks, motivated by EFT models: *bbll* and *bsll*.

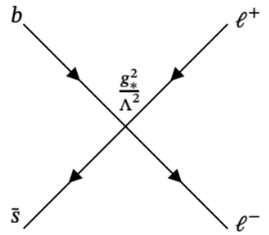


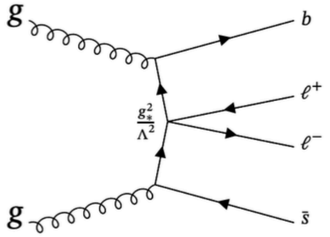




Analysis Strategy

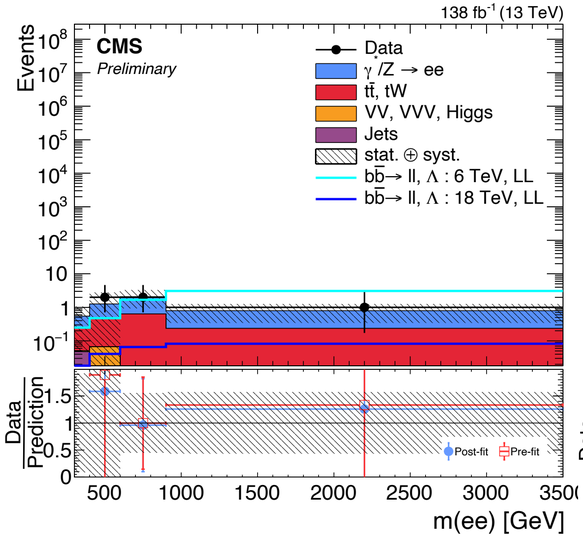
- Events categorized according to b-jet multiplicity into 0b, 1b, >=2b categories.
- DNN-based discriminator used for $t\bar{t}$ background suppression in >1b categories.
- Final fit variable: dilepton invariant mass (m_{ll})
- **Lepton flavor universality** tested by comparing the dielectron and dimuon mass spectra ratio for different b-jet multiplicities



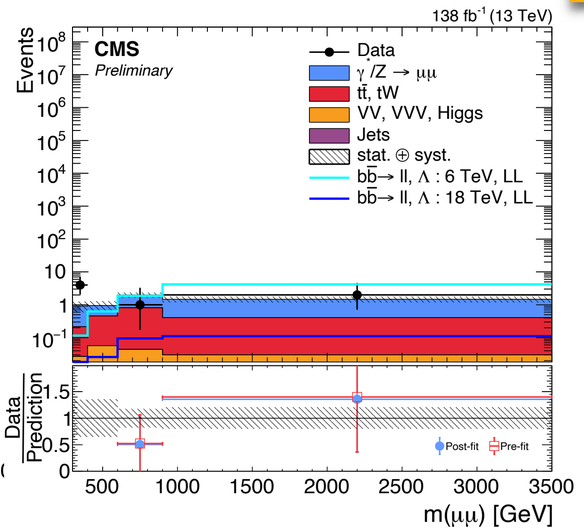


Nonresonant search in high mass ll +b

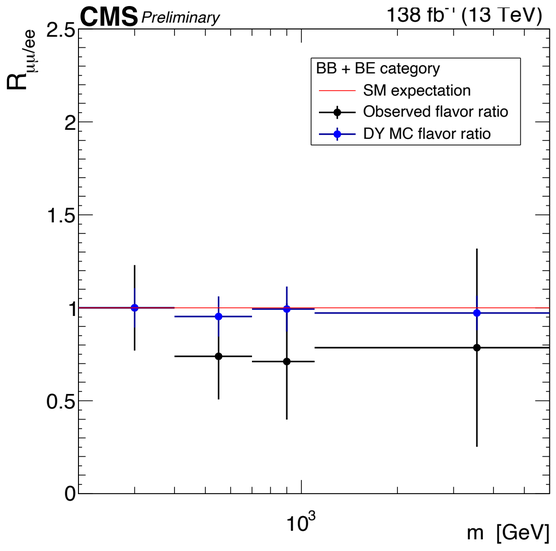
1b + ee



1b + $\mu\mu$



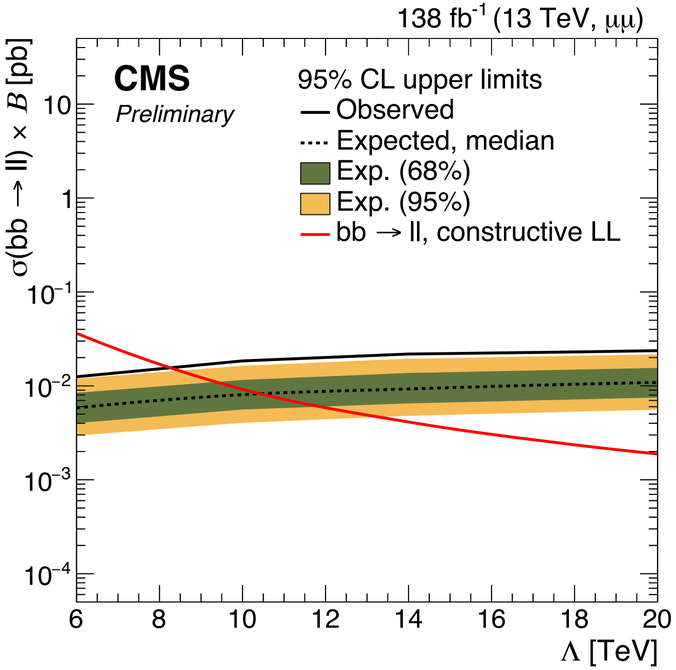
R$\mu\mu$/ee in 1b+2b

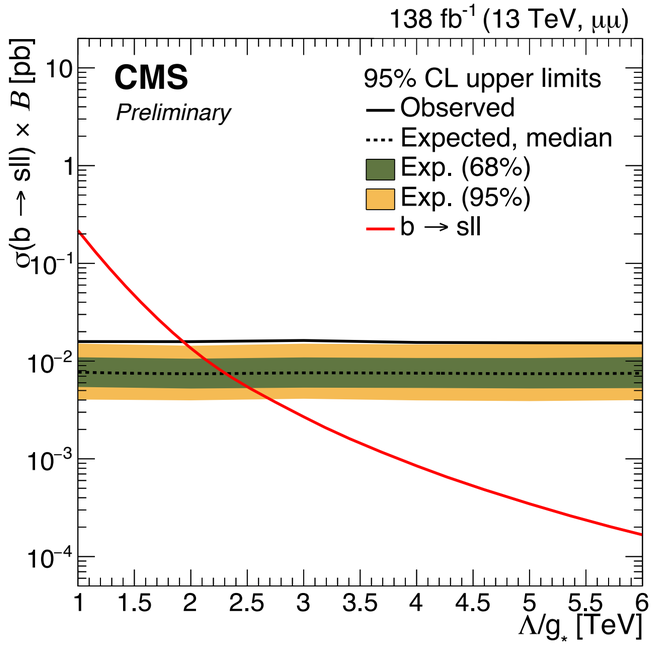


Results

CMS-PAS-EXO-23-010

- No excess observed.
- Limits set on σ × B interpreted as a function of scale of new physics, Λ.
  - *bbll*: lower limit on Λ, ranging from (8.3 -9.0) TeV depending on chirality
  - *bsll*: lower limits set on the ratio of scale and coupling: Λ / g* > 2.4 TeV —-> **best limit to-date!**





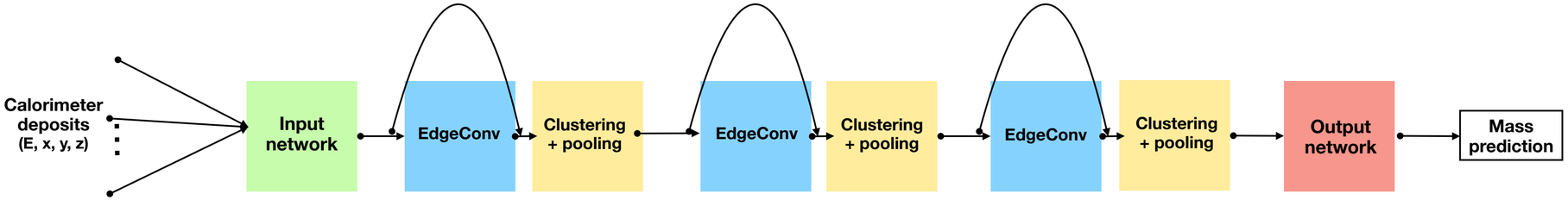
Summary

- A diverse set of searches for new physics in the photon/lepton final states being performed at CMS.
- No sign of new physics yet, but stringent exclusion limits set.
- Use of dedicated machine learning-based reconstruction and ID techniques crucial in exploring less-accessible phase-spaces.
- **Run 3 brings renewed discovery potential:** thanks to enhanced luminosity, innovative triggers, and powerful ML-driven analysis techniques.

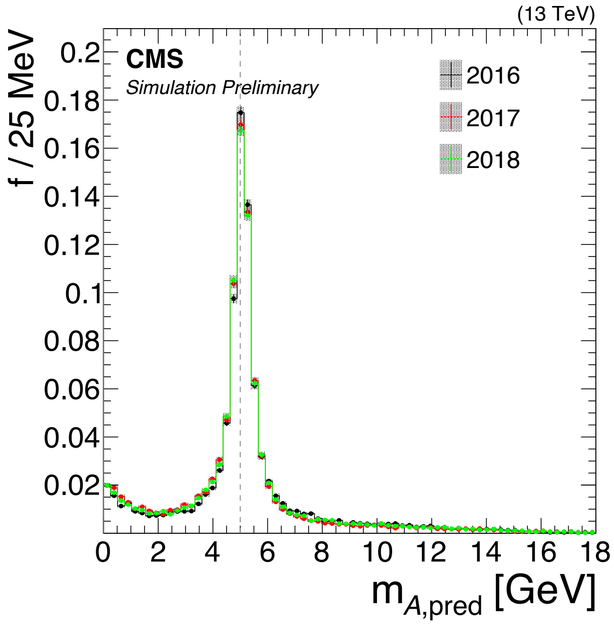
BACKUP

Search for H→AA→4γ in partially-merged topology| ML Network

- Network: **Graph neural network** (GNN): Dynamic Reduction Network with residual connections.
  - GNN makes use of the rotational symmetries in the shower deposits.
  - Input data is dynamic with different number of rechits for different photon clusters.

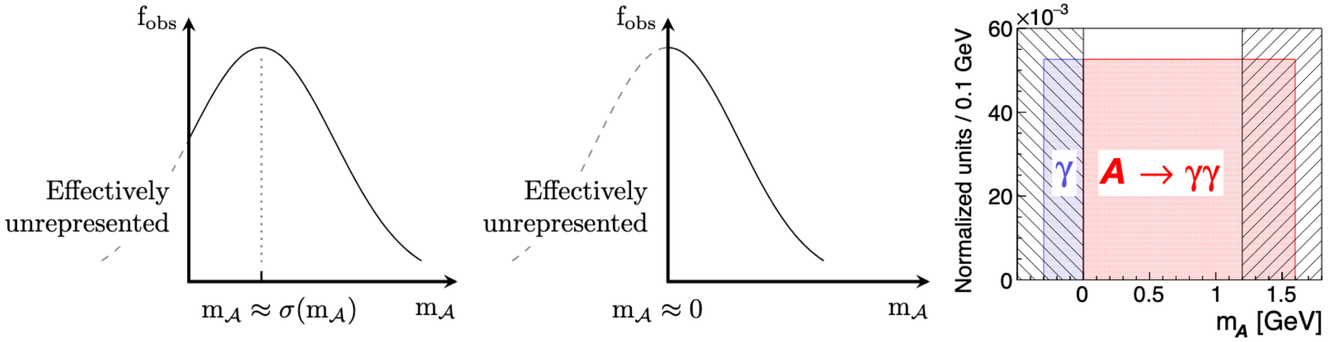


  - Trained using privately produced pythia8 **A**-particle guns with a flat distribution in (m_A, $p_{T,A}$) with PU, following RunIISummerUL17 AOD MC campaign.
  - Single photon gun samples are also added to the training set, but with a random negative mass value assigned for domain continuation. [Ref: EGM-20-001]
    - Cropped Ecal Rechit (AOD) energy map dR~2.22 around the seed, separated into E_T and E_Z components.
    - Rechit position x, y, z



Search for H→AA→4γ in partially-merged topology| ML Network domain continuation

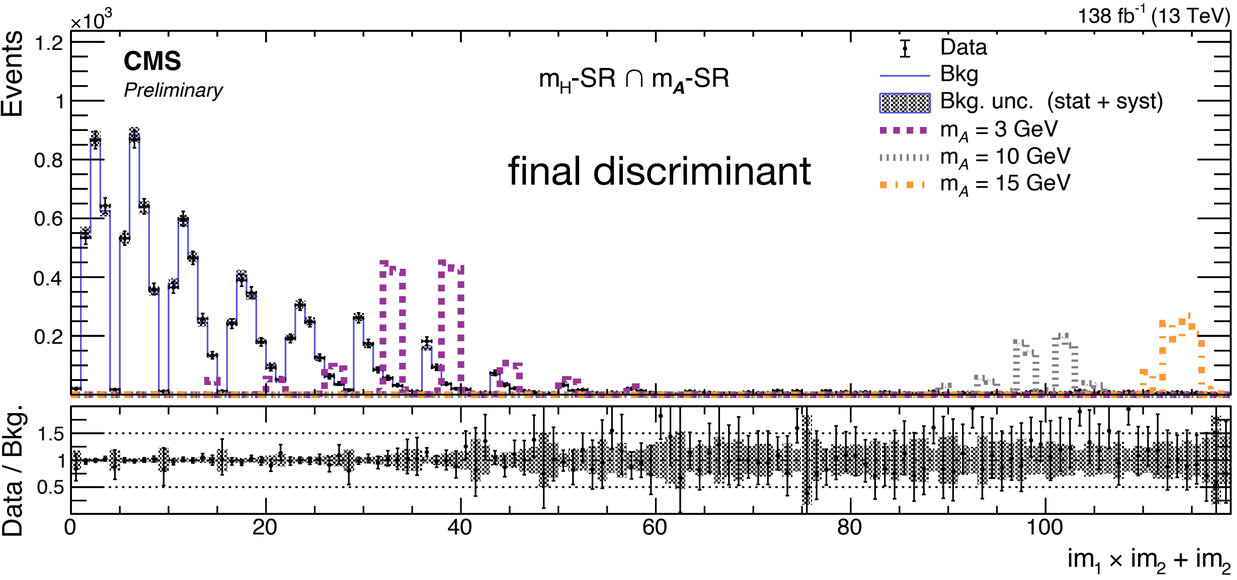
CMS-EGM-20-001

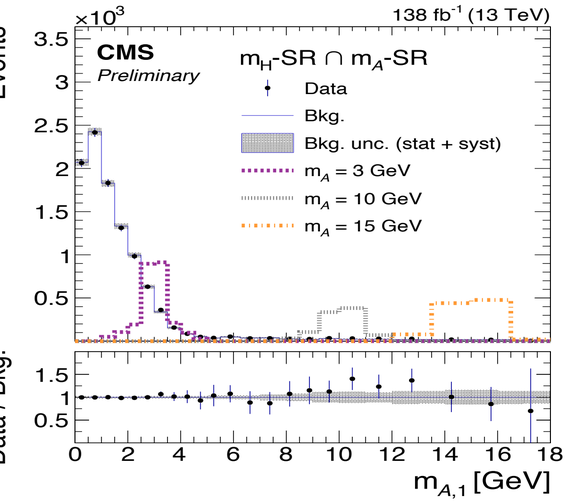


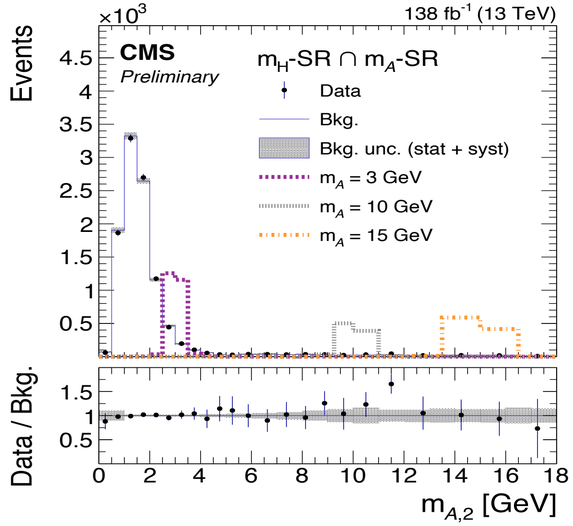
- For m_a ~ detector resolution $\sigma(m_a)$, the observable mass width (f_{obs}) becomes under represented in the training set. As m_a —> 0, almost half of the mass width is not seen by the regressor.
- So we augment the training set (A → $\gamma\gamma$, red) with randomly assigned nonphysical "negative" masses with topologically reasonable samples: single γ (blue), keeping constant mass density on positive and negative sides.
- During inference we omit the negative mass predictions.
- Advantage: Natural photon veto: photons mostly reconstructed with m_pred < 0, mitigating photon contamination of m(a→$\gamma\gamma$) spectrum, without biasing the position of a→$\gamma\gamma$ mass peaks.

Search for H→AA→4γ in partially-merged topology

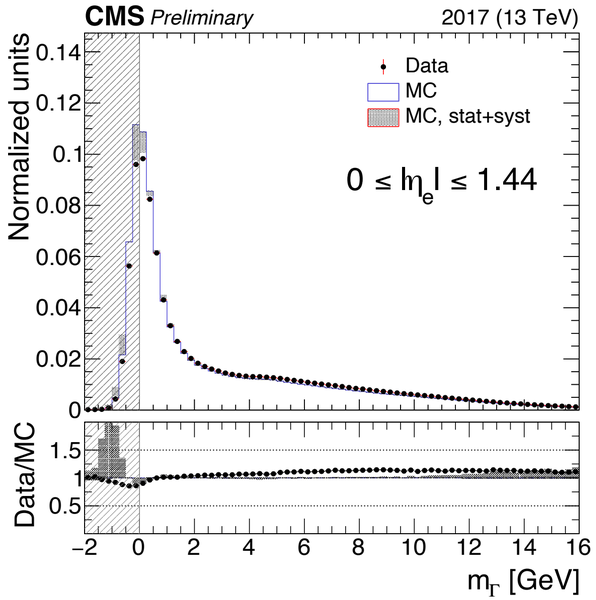
CMS-PAS-EXO-24-025

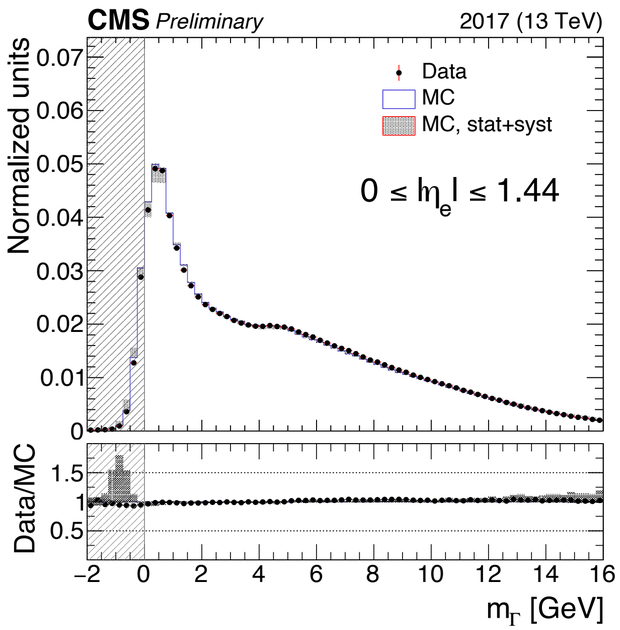






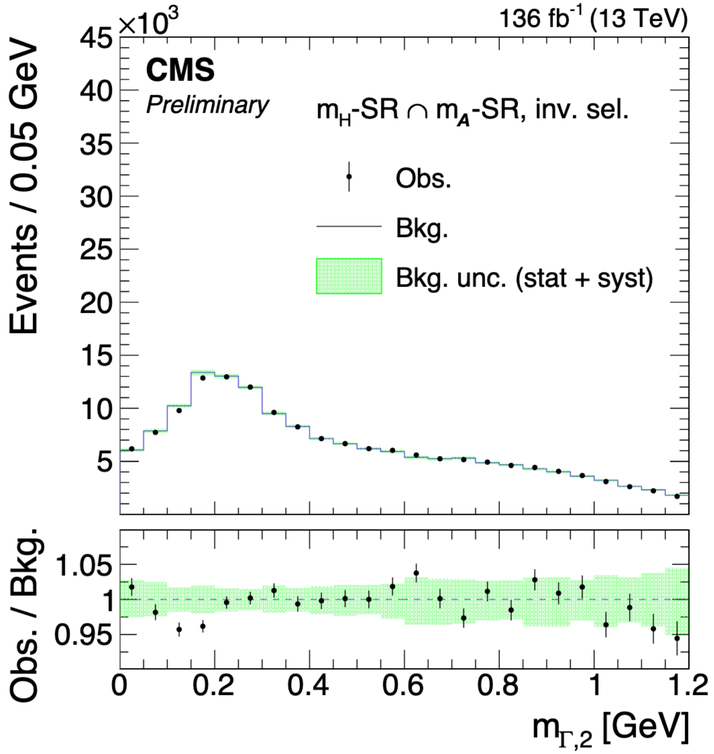
Mass Regressor systematics| Data vs MC

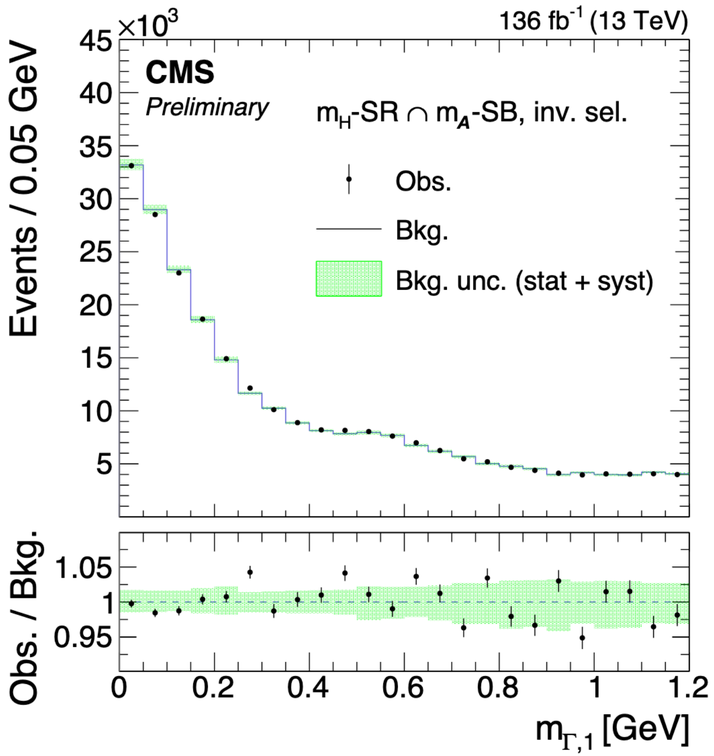




CMS fully-merged analysis

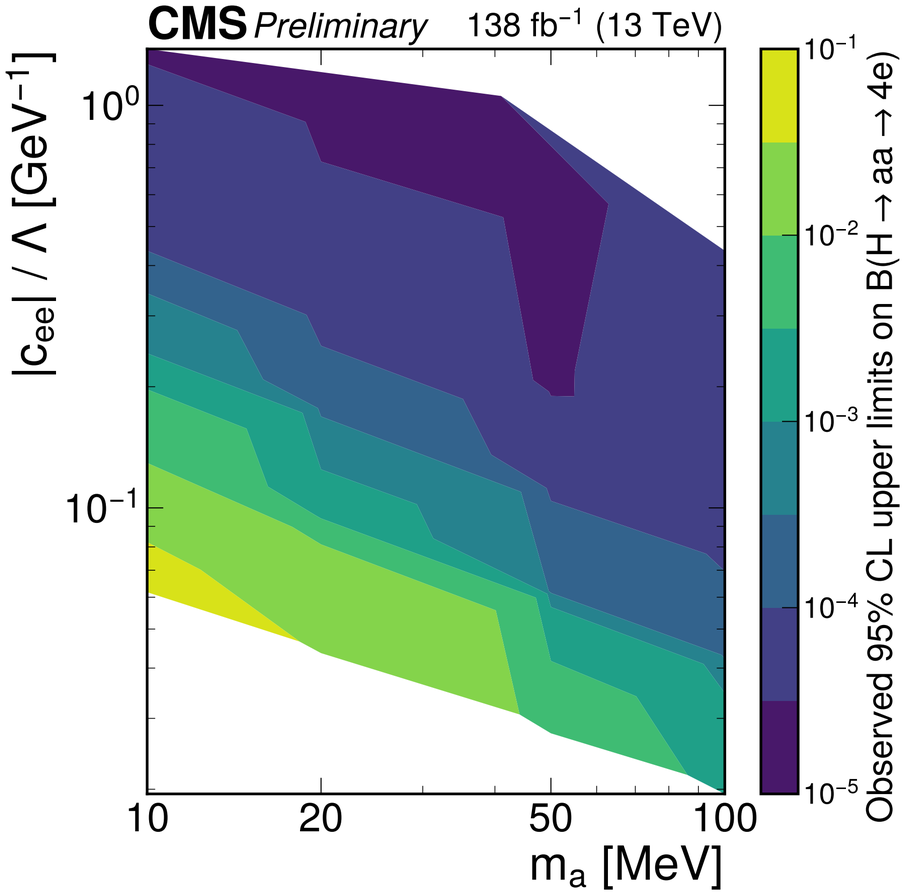
CMS-PAS-HIG-21-016





- Observed vs. predicted mass in a jet-enriched background selection shows reconstruction of pi0 (left) and a hint of eta (right) mass peaks.

EXO-24-031

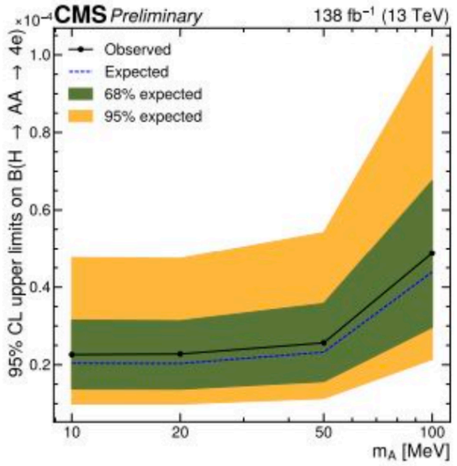


The observed upper limits at 95% CL on the Higgs boson branching fraction for H → aa → 4e, as a function of the ALP mass and the ratio of the ALP coupling to electrons and the energy scale of the ALP effective interaction.

Compare Results with H→AA→4photon

H→AA→4e(This Analysis)

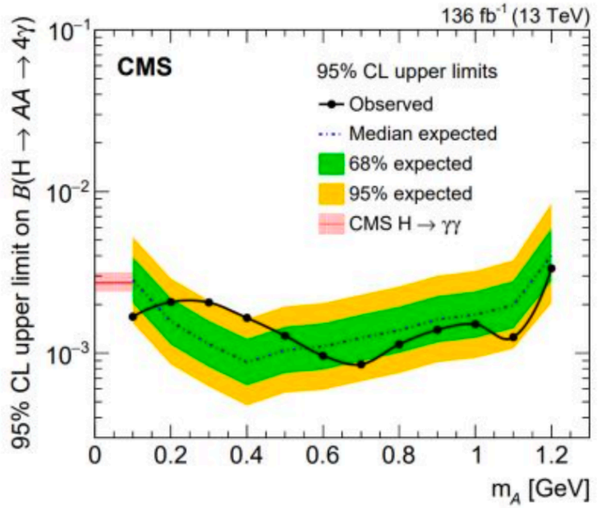
- ALPs mass: 10MeV-100MeV
- Limits: BR($H \to AA \to 4e$) at 10^{-5} scale



Limit of 1um ALPs

H→AA→ 4γ(Phys.Rev.Lett.131,101801)

- ALPs mass: 100MeV-1200MeV
- Limits: BR($H \to AA \to 4\gamma$) at 10^{-3} scale



Limit of prompt ALPs

Search for a high mass resonance: X —> YY/ZY —> 4l