Searches for BSM Higgs with CMS

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Experimental signatures

- Almost any extension of the SM contains additional Higgs bosons
- Other new scalars (e.g. axion-like particles) also in play

  $\rightarrow$ Searches for additional scalars easy to motivate
- Either heavier or lighter than H(125)
  - H(125) could decay to them, e.g., $H \rightarrow aa$
  - They could decay to H(125), e.g., $X \rightarrow HY$
  - Both kinds could be involved, e.g., $X \rightarrow aa$
- A *huge* number of possible final states!
- Depending on the mass ratios, decay products could be boosted

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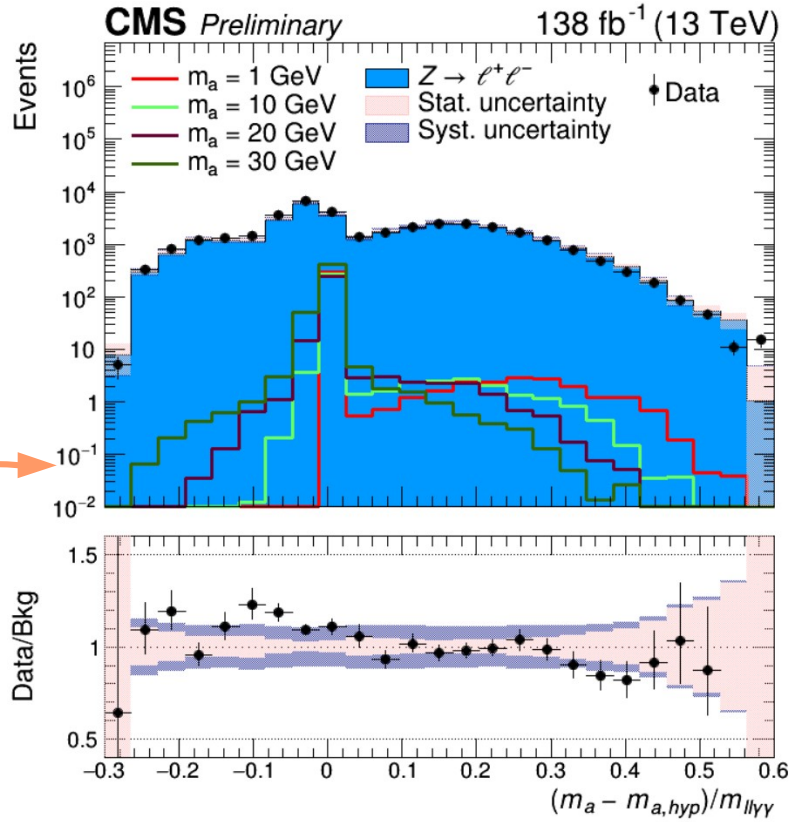
Both boosted, but not covered today.

$H(125) \to Za \to (\ell\ell)(\gamma\gamma)$

- $Z \to \ell\ell$ assumed to be on-shell $\implies m_a < m_{\mathrm{H}} - m_{\mathrm{Z}} \approx 35\,\mathrm{GeV}$
  - Focus on $1 < m_a < 30$ GeV
- Below $m_a \sim 1$ GeV, photons merge; not feasible in this analysis, but wait a few slides...
- Even above 1 GeV, photons are separated but highly collimated
  - Variables related to isolation are removed from cut-based selection, and put into BDT



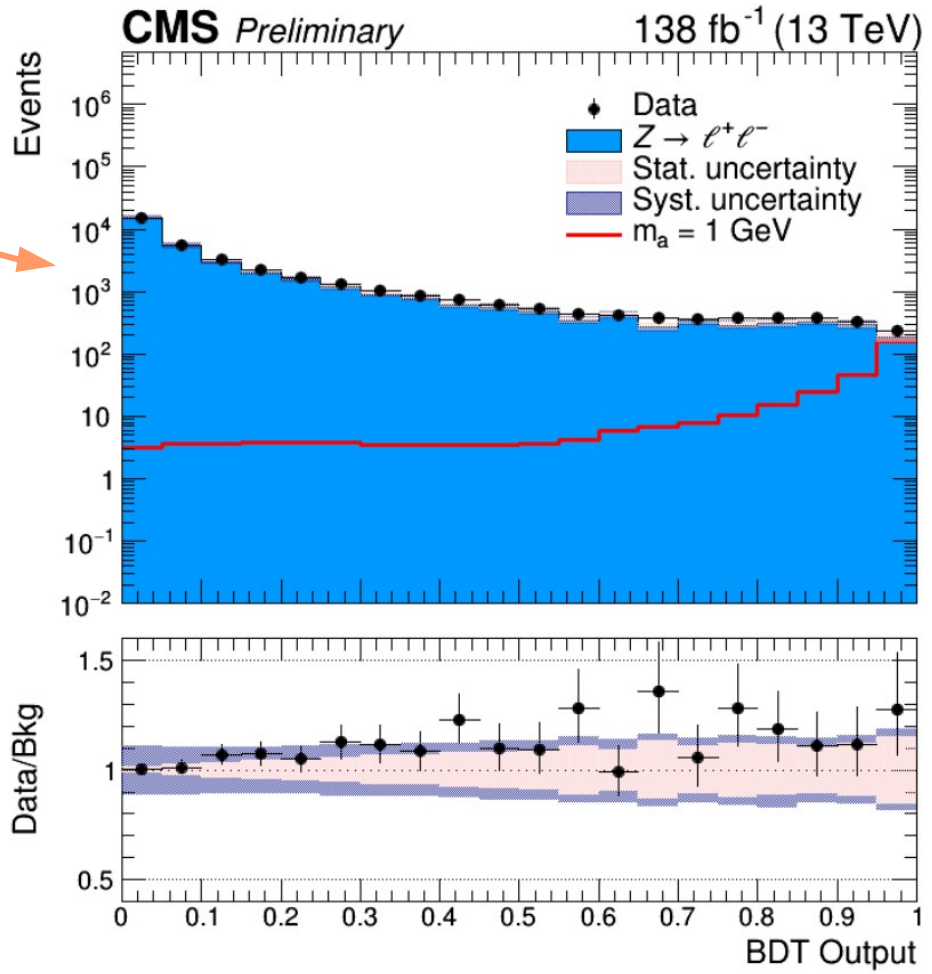
How close is m_a to its hypothesized mass

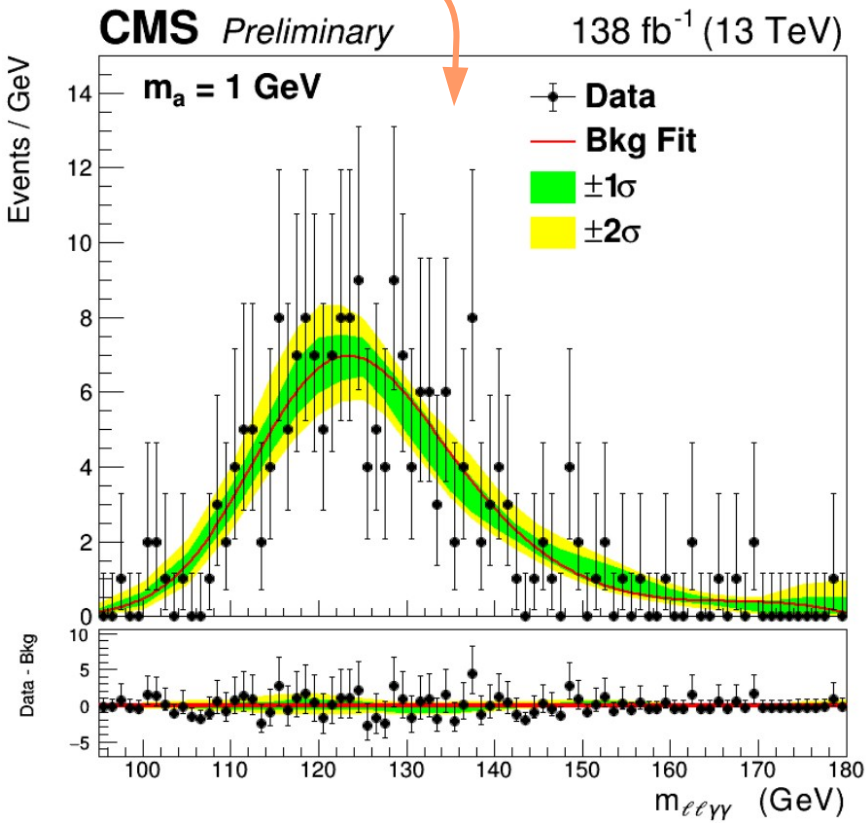
$$\frac{m_a - m_{a,\mathrm{hyp}}}{m_{\ell\ell\gamma\gamma}}$$

$H(125) \to Za \to (\ell\ell)(\gamma\gamma)$

HIG-22-003

- BDT is trained for each value of m_a
- Fit $m_{\ell\ell\gamma\gamma}$ for each m_a

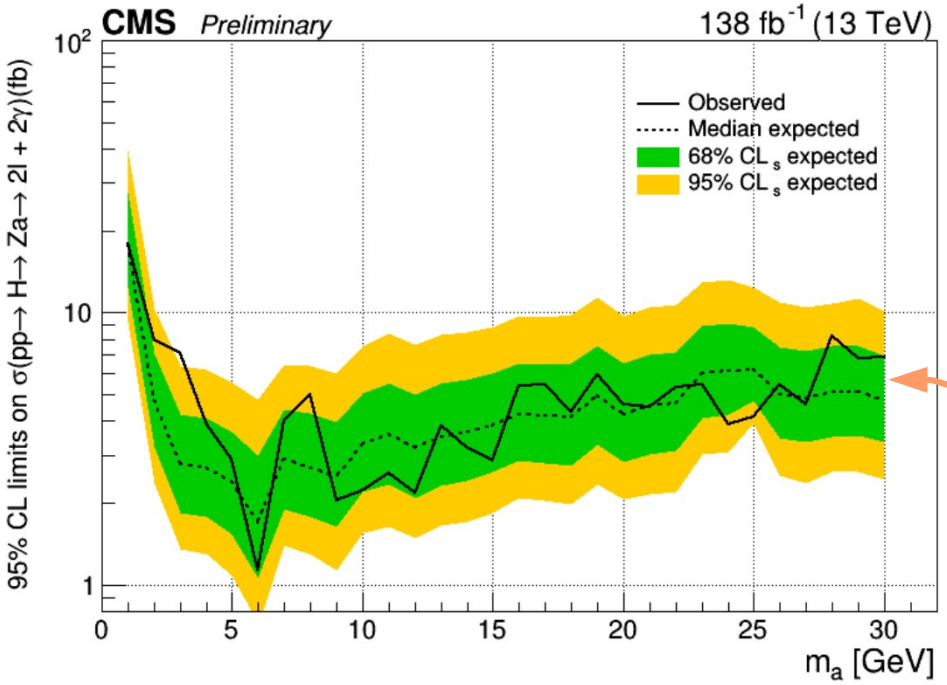




Fit is a bump hunt on parametric bkg shape

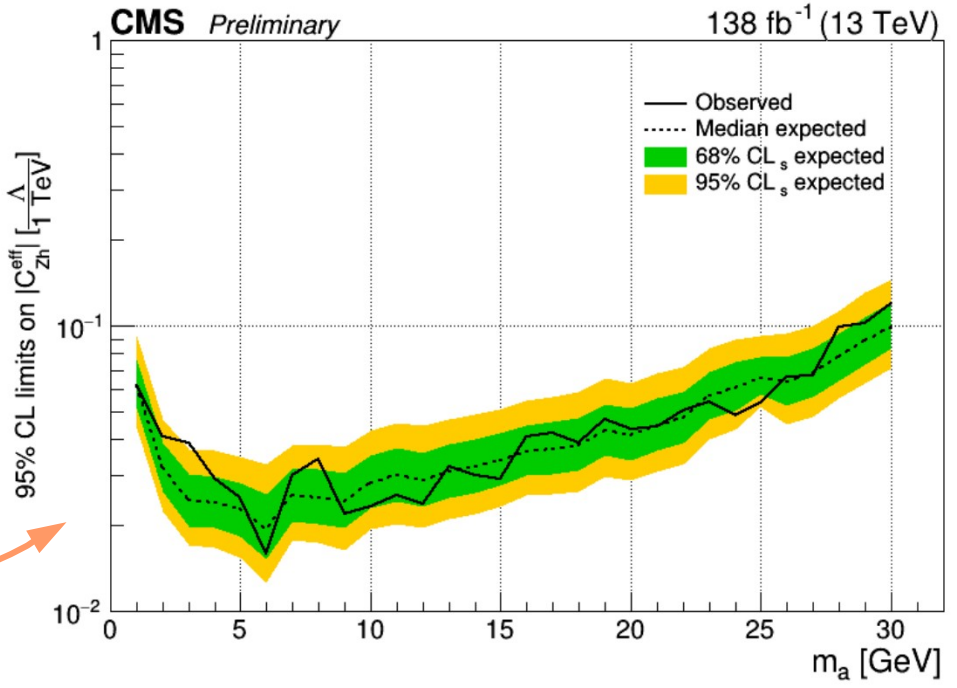
$H(125) \to Za \to (\ell\ell)(\gamma\gamma)$

HIG-22-003



Exclusion limits on $\sigma \times \mathrm{BR}$

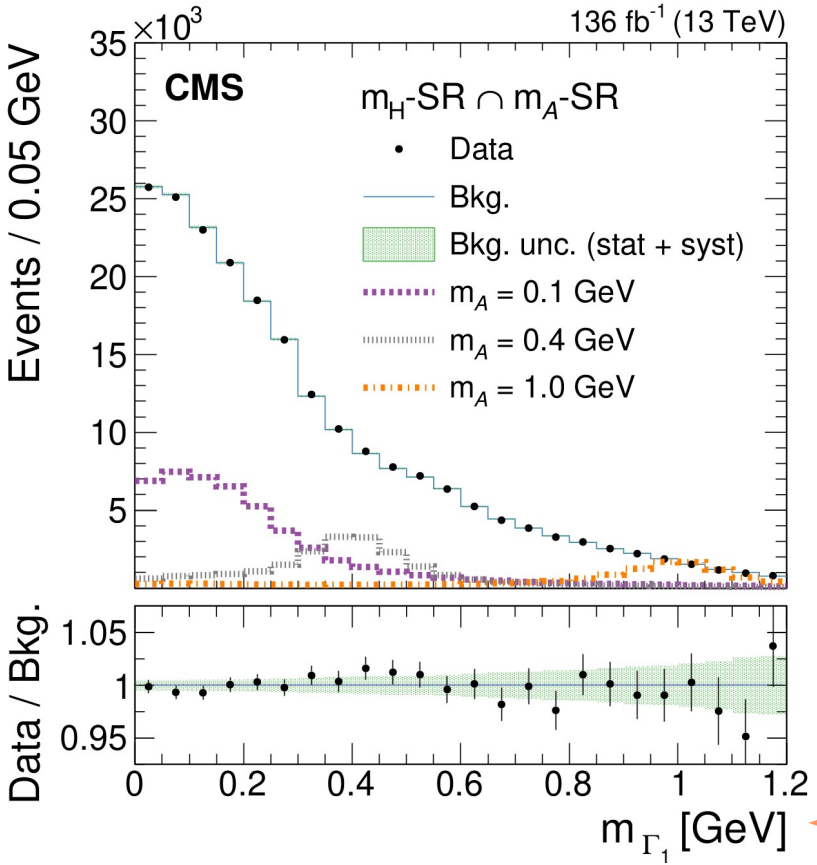
Limits on $\sigma \times \mathrm{BR}$ are now converted Into limits on the coupling $\dfrac{C_{ZH}^{\mathrm{eff}}}{\Lambda}$



H → AA → two merged diphotons (Γ)

HIG-21-016

- New scalar $\mathcal{A}$ is very light. Decays to $\mathcal{A} \to \gamma\gamma$
- Even from decay of H(125), $\mathcal{A}$ is highly boosted
  - Photons from $\mathcal{A} \to \gamma\gamma$ decay merge

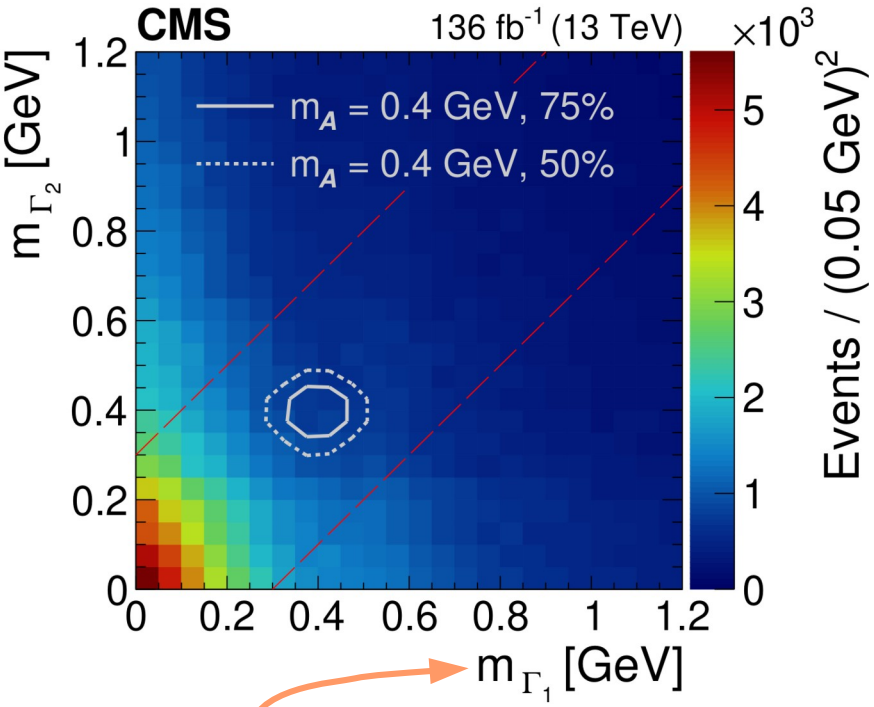


- Special reconstruction technique
  - deep learning algorithm
  - "end-to-end" reconstruction
  - trained directly on ECAL energy deposits to estimate $m_{\mathcal{A}}$
  - Problem: back to RECO data

Mass of a diphoton pair

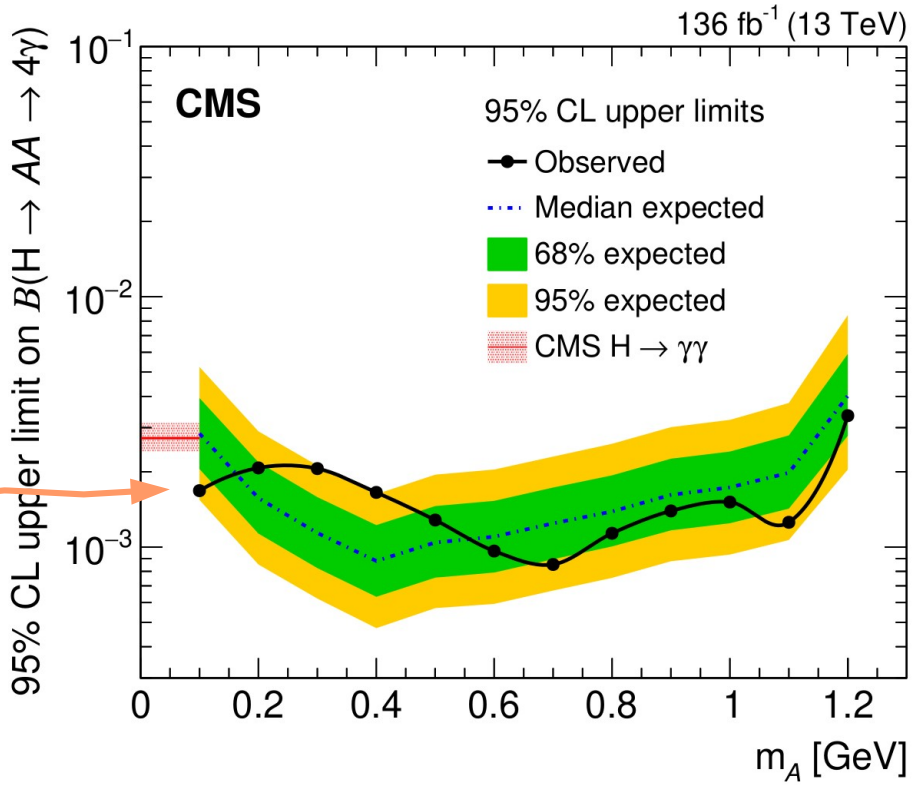
H → AA → two merged diphotons (Γ)

HIG-21-016



Masses of diphoton pairs

- Signal Region:
  - Between red lines ($m_{\Gamma_1} \approx m_{\Gamma_2}$)
  - $m_{\Gamma\Gamma}$ is in Higgs mass window



Currently the best constraints on $H \to \mathcal{A}\mathcal{A} \to 4\gamma$

$H(125) \to aa \to (\ell\ell)(b\bar{b})$

HIG-22-007

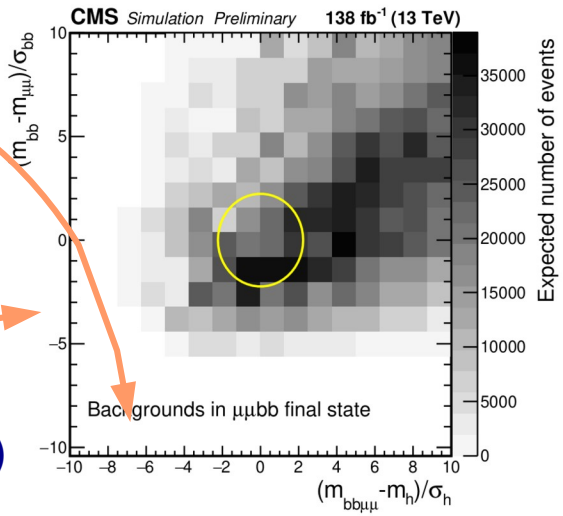
- Using $\mu^+\mu^- b\bar{b}$ and $\tau^+\tau^- b\bar{b}$ final states
  - In 2HDM+scalar model, BR's to both can vary
- Triggers and event reconstruction:
  - $\mu^+\mu^- b\bar{b}$: lower BR, but clean; use dimuon trigger
  - $\tau^+\tau^- b\bar{b}$: two leptonic taus, or $\ell\tau_h$ (leptonic trigger)
  - Hadronic τ_h reconstructed using DeepTau
- Cut on $(\chi_{\mathrm{bb}} + \chi_{\mathrm{H}})^2$:

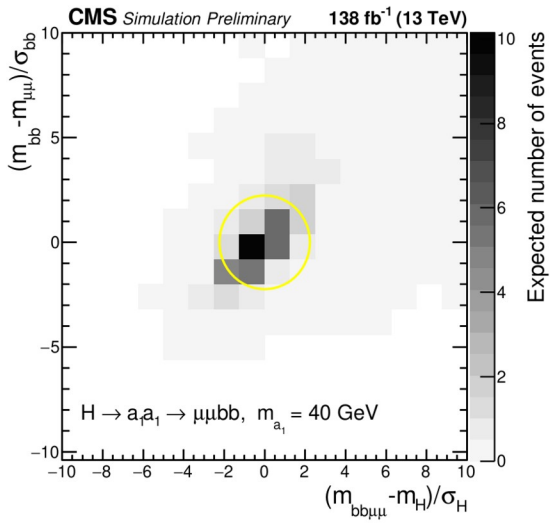
$$\chi_{\mathrm{H}} = \frac{(m_{\mu\mu\mathrm{bb}} - 125)}{\sigma_{\mathrm{H}}}$$

(constant)

$$\chi_{\mathrm{bb}} = \frac{(m_{\mathrm{bb}} - m_{\mu\mu})}{\sigma_{\mathrm{bb}}}$$

(varies with $m_{\mu\mu}$)



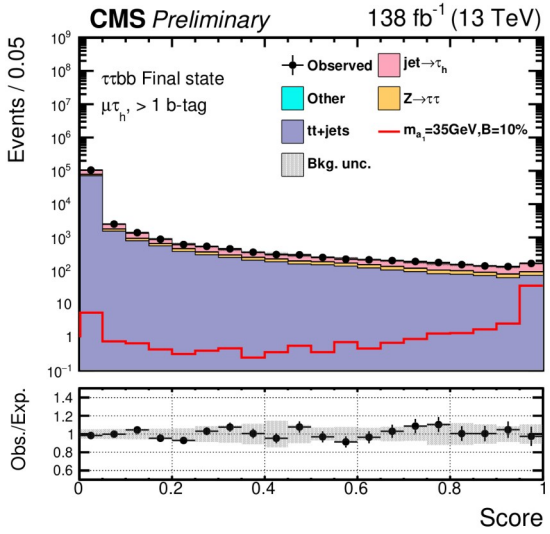


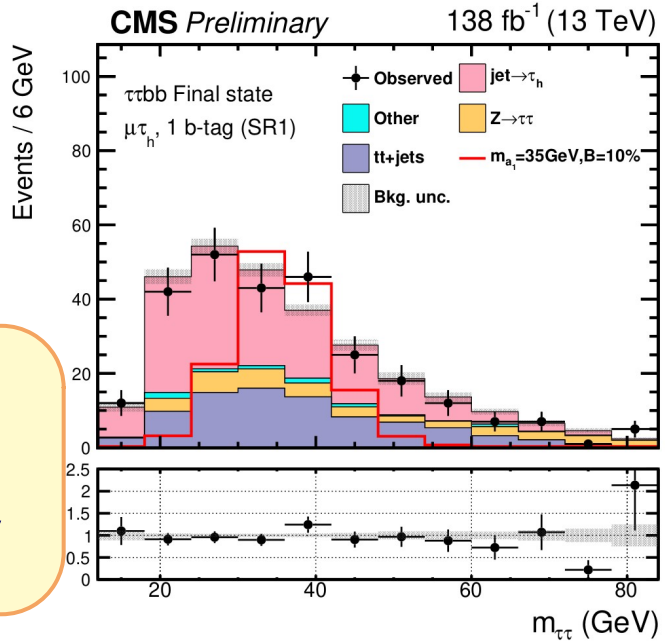
$H(125) \to aa \to (\ell\ell)(b\bar{b})$

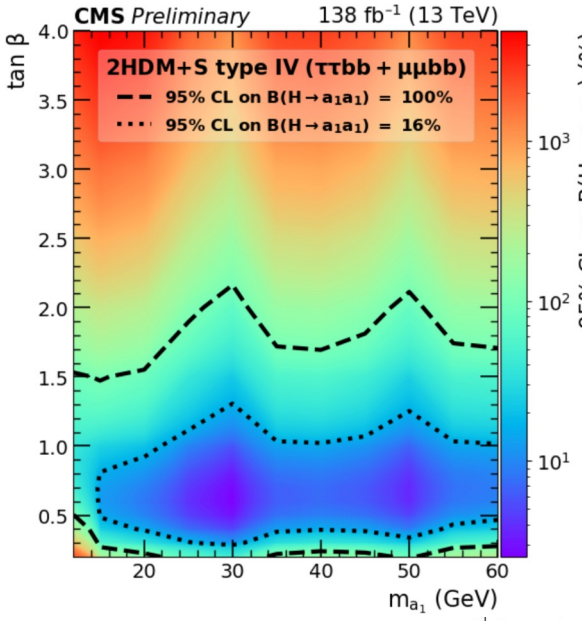
HIG-22-007

- Further categorization based on b tagging and VBF:
  - DNN trained for each category
  - Bkgs estimated from data

Low p_T	at least one b-jet with $p_T < 20$ GeV
VBF	two add. jets with $p_T > 30$ GeV, $\lvert\eta\rvert < 4.7$, and $m_{jj} > 250$ GeV
TL	looser b jet passes L but fails M
TM	looser b jet passes M but fails T
TT	looser b jet passes T





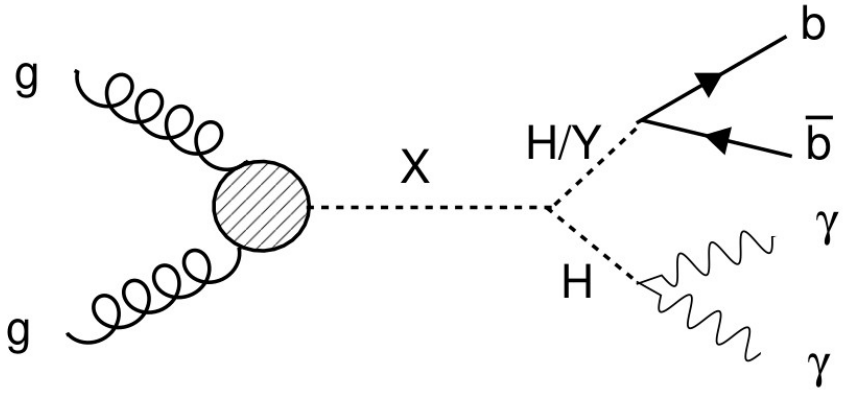


Many model-dependent limits from 15 to 60 GeV

$X \to H + H/Y \to (\gamma\gamma)(b\bar{b})$

HIG-21-011

- Now looking for a heavier Higgs, or two at the same time



- NN is trained to reject $t\bar{t}H$
- BDT for event selection
- Further categorize using

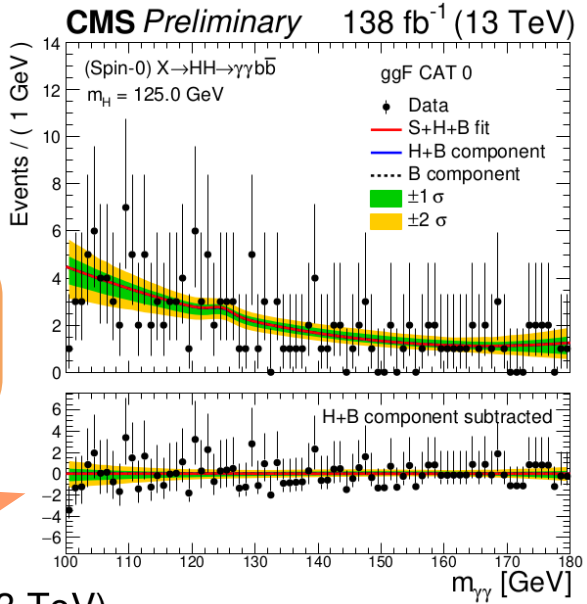
$$\tilde{M}_{\mathrm{X}} \equiv m_{\gamma\gamma\mathrm{jj}} - m_{\gamma\gamma} - m_{\mathrm{jj}} + m_{\mathrm{H}} + m_{\mathrm{H,Y}}$$

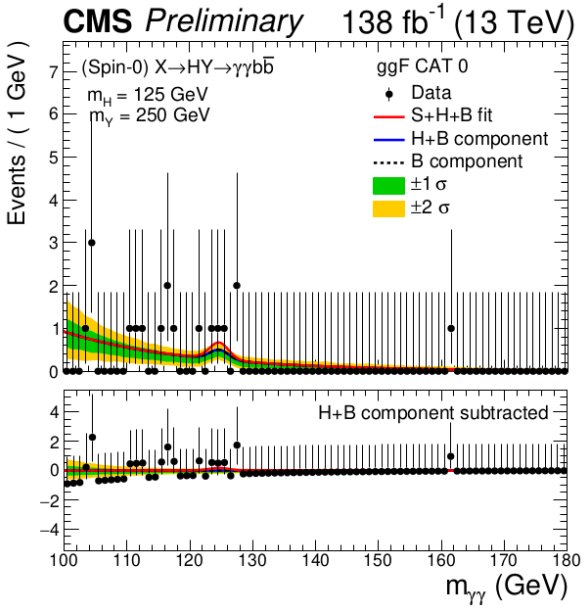
- Here, event kinematics greatly affected by masses
- Define "boost factor" = $\dfrac{m_X}{m_H + m_Y}$
- Train BDT in slices of m_X and m_Y

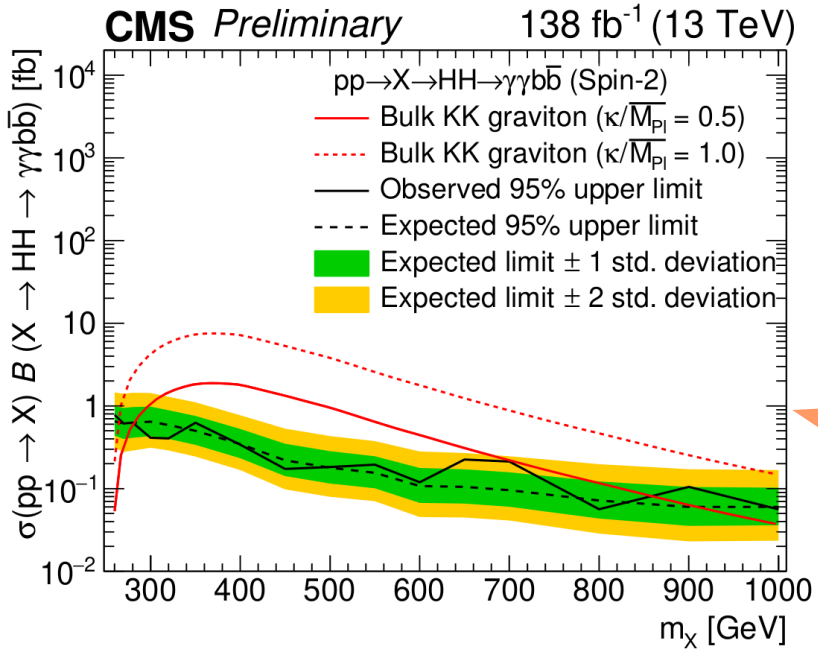
$X \to H + H/Y \to (\gamma\gamma)(b\bar{b})$

- Fit 2D distribution of $m_{\gamma\gamma}$ vs. m_{jj}

2D bkg analytically parameterized







Limits on $X \to HH$

$X \to H + H/Y \to (\gamma\gamma)(b\bar{b})$

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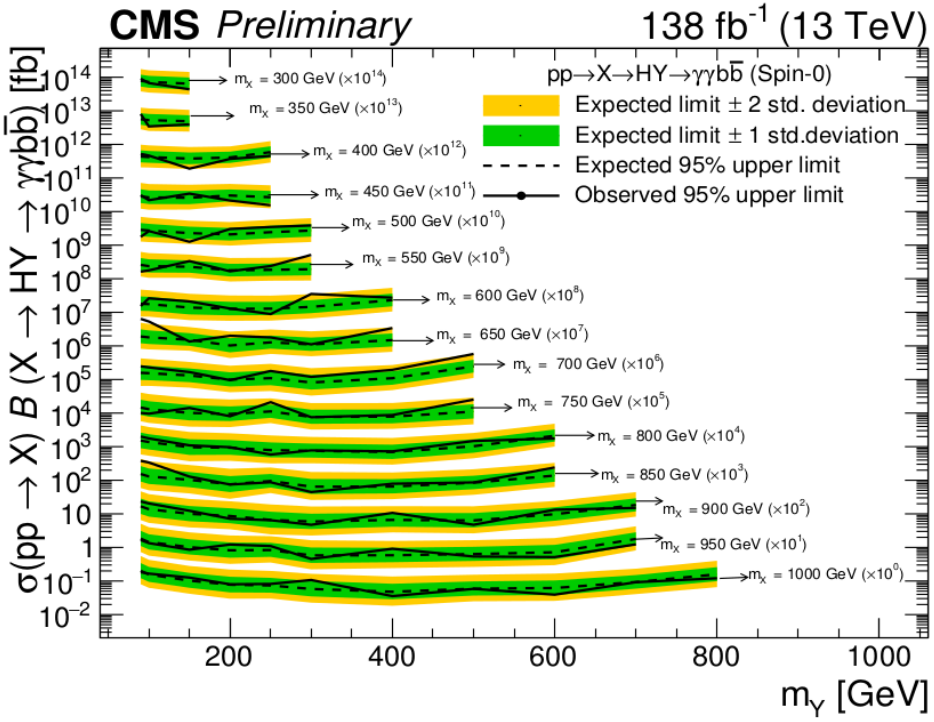
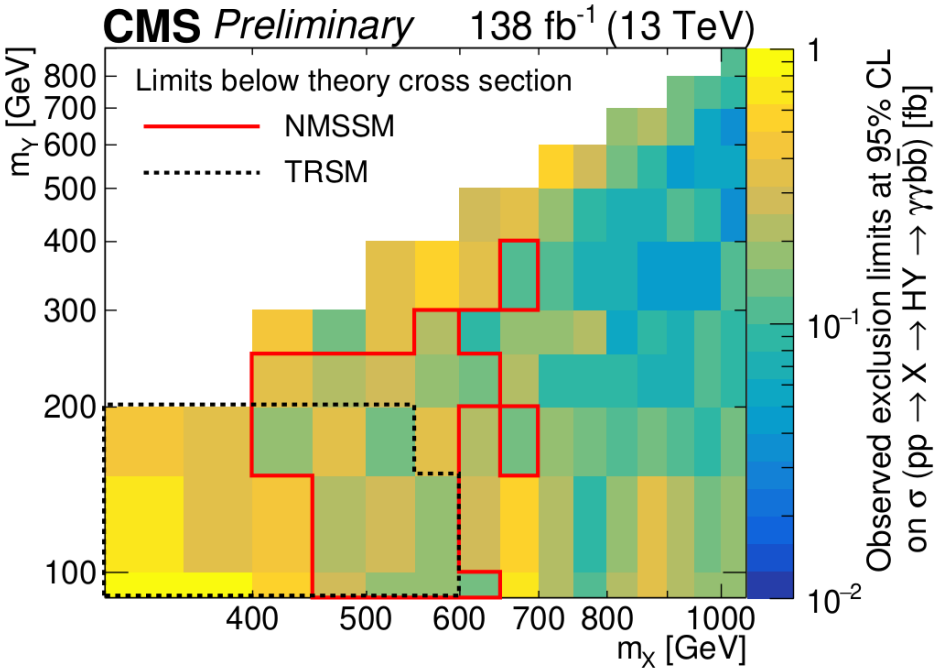
- Limits on $X \to HY$ are necessarily 2D:





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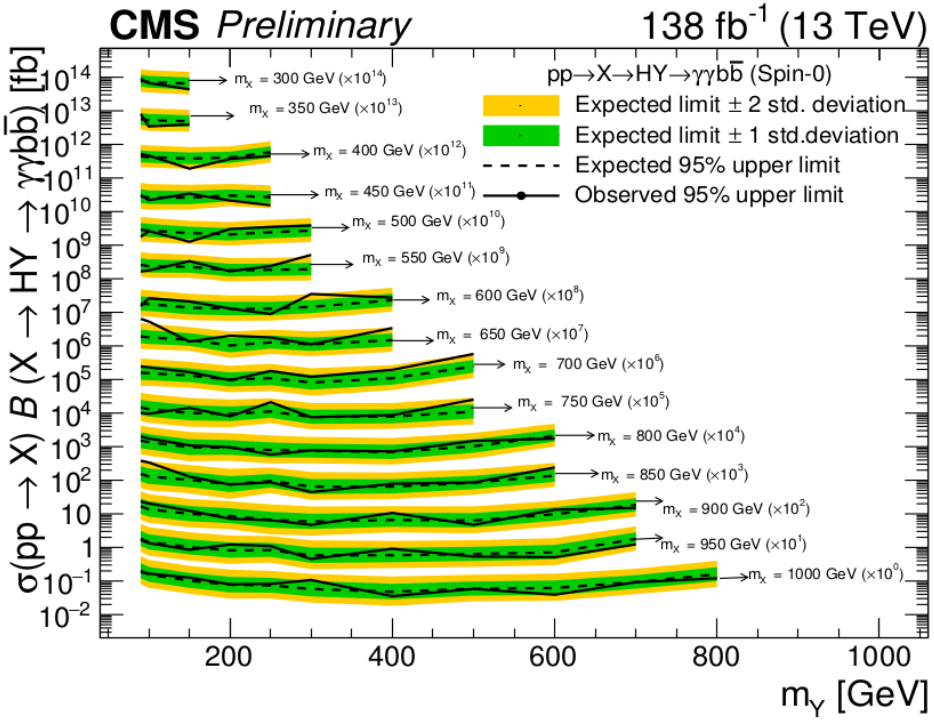

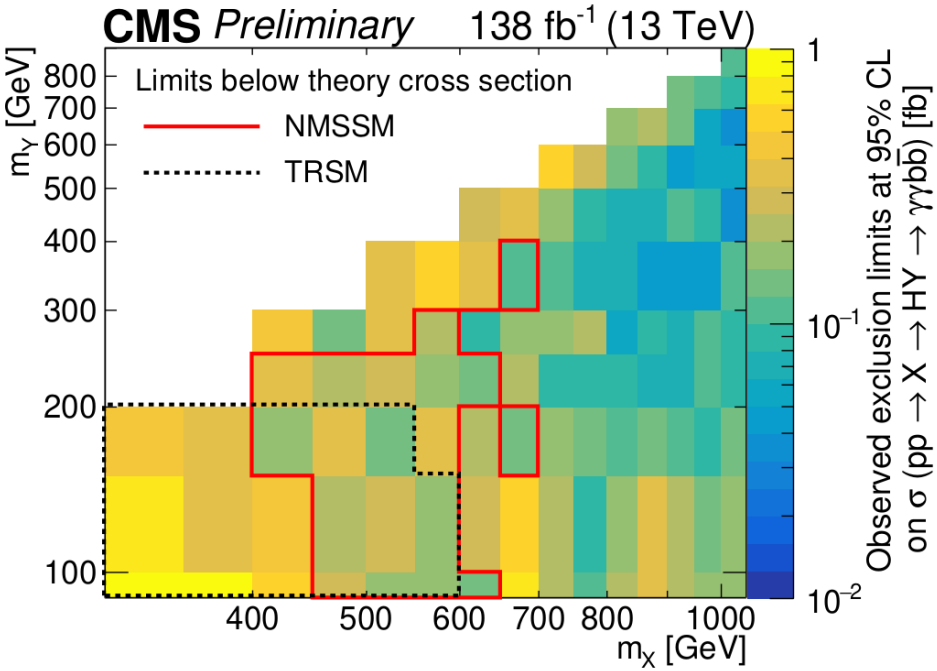

Analyses like these are just the tip of an iceberg! Many more to come!

Takeaways from this talk

- Extra scalars are well-motivated in most BSM scenarios
- Depending on the mass ratios, searches involve boosted objects
- CMS has a vibrant program of searching for both
  - Heavy Higgs bosons that produce boosted objects
    - Have been covered at BOOST for years
  - Light scalars that are themselves often boosted
    - Relatively recent, but now a hot topic
  - Special reconstruction (e.g. with ML) often needed and used
- Seeking input from model-builders about new decays and new signatures