YSF: Search for a pair of (pseudo)scalars in decays of the Higgs boson at CMS

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on behalf of the CMS Collaboration

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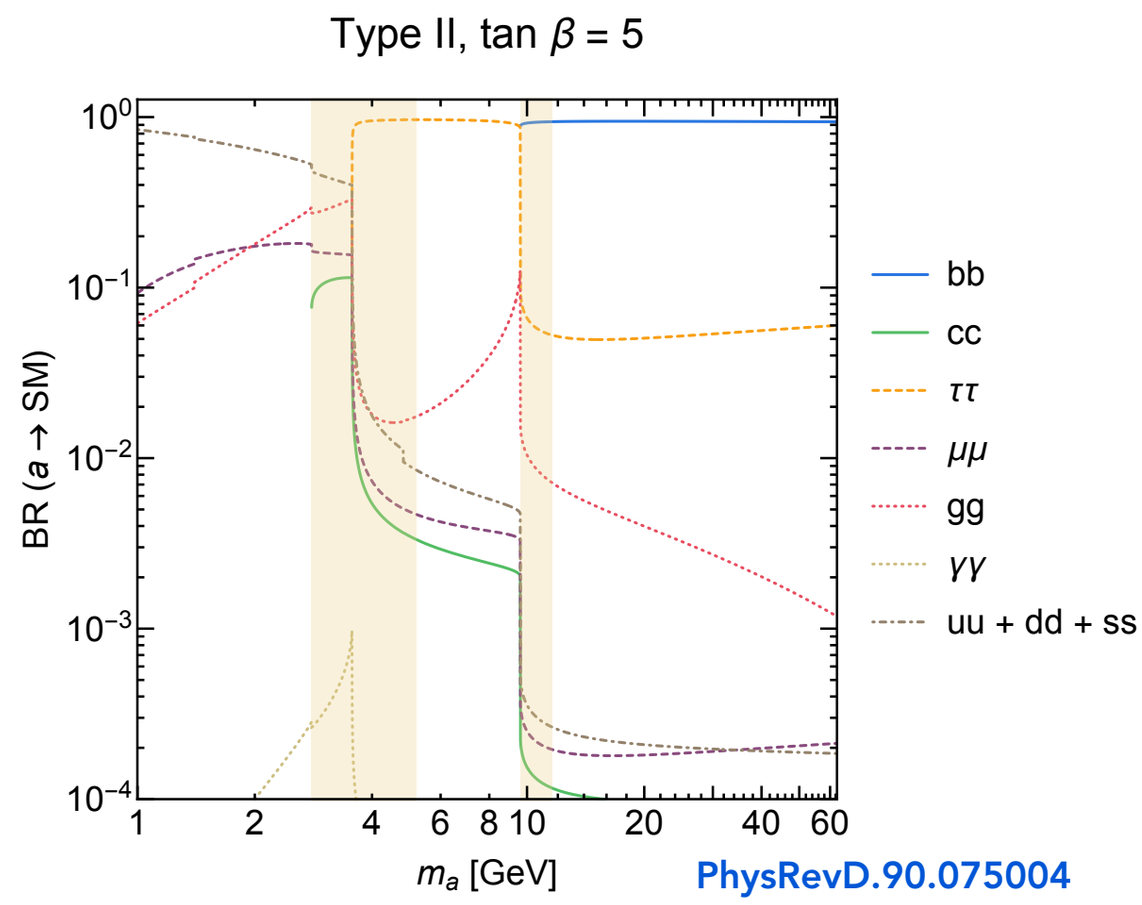
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Introduction

- Assuming the SM production for the Higgs boson, **$\mathcal{B}$(H→BSM) < 16%** at 95% CL [1]

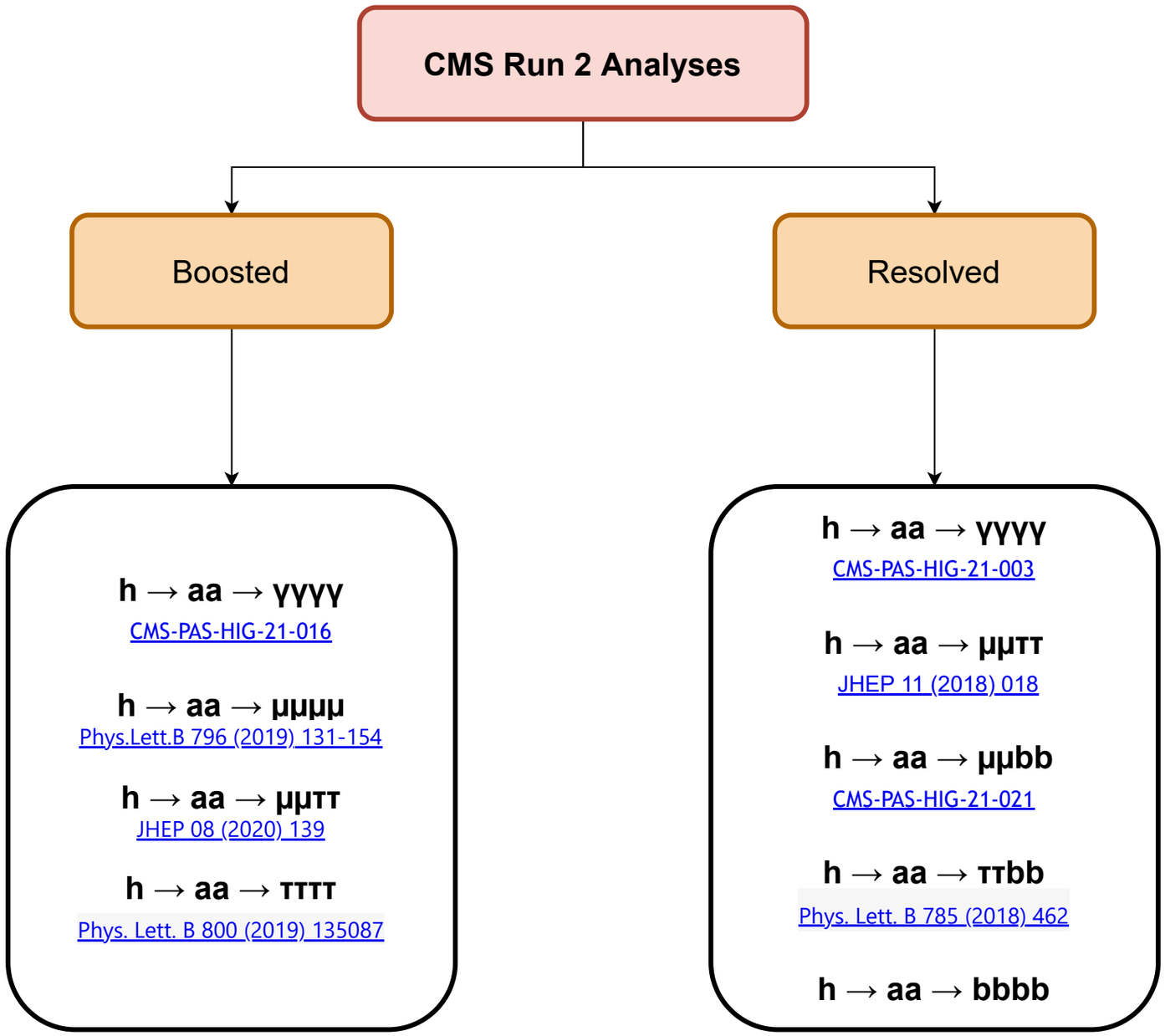
- Possibility of light (pseudo)scalar states in several well-motivated models
  - 2HDM+S
    - Extension of 2HDM by addition of a complex singlet, $S_R + iS_I$
    - Higgs sector composed of 7 physical states:

      2 charged bosons ($H^{\pm}$), 3 scalars ($h_{1,2,3}$), 2 pseudoscalars ($a_{1,2}$)

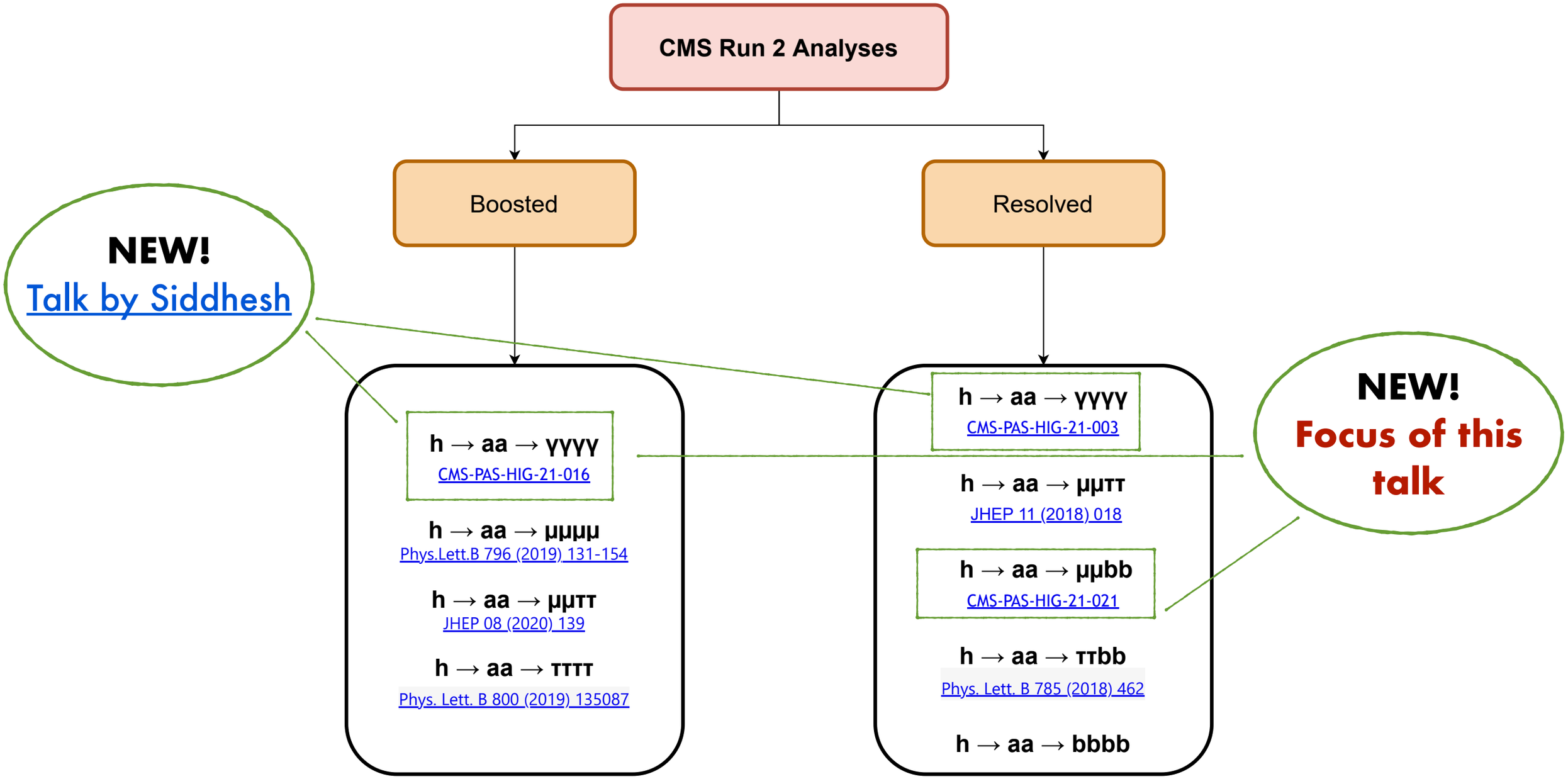


[1] *Nature* **607**, 60-68 (2022)

H→aa searches within CMS



H→aa searches within CMS



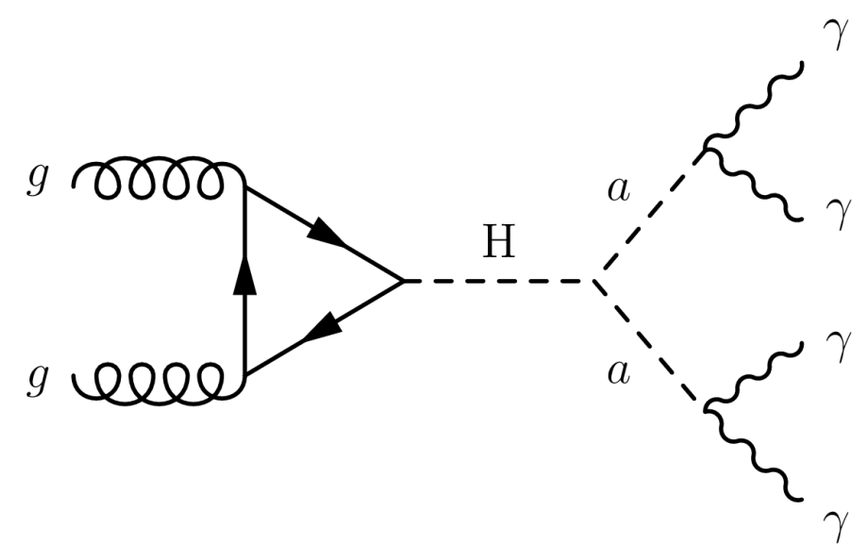
$H \to aa \to 4\gamma$ (boosted)

CMS-PAS-HIG-21-016

H→aa→4γ (boosted)

CMS-PAS-HIG-21-016

- $\mathcal{B}(a\to\gamma\gamma)$ enhanced below $m_a < 2m_\mu$
- However diphoton invariant mass measurement extremely challenging in this a mass regime
  - Smaller m_a → larger Lorentz boost $\gamma_L = E_a/m_a$
  - $\gamma\gamma$ part of the same super-cluster



- First CMS analysis of H→aa→4γ for merged photons ($0.1 < m_a < 1.2$ GeV)
  - Complements parallel CMS search in resolved regime
  - First direct probe of mass spectrum of merged photons thanks to novel end-to-end m_Γ regression technique

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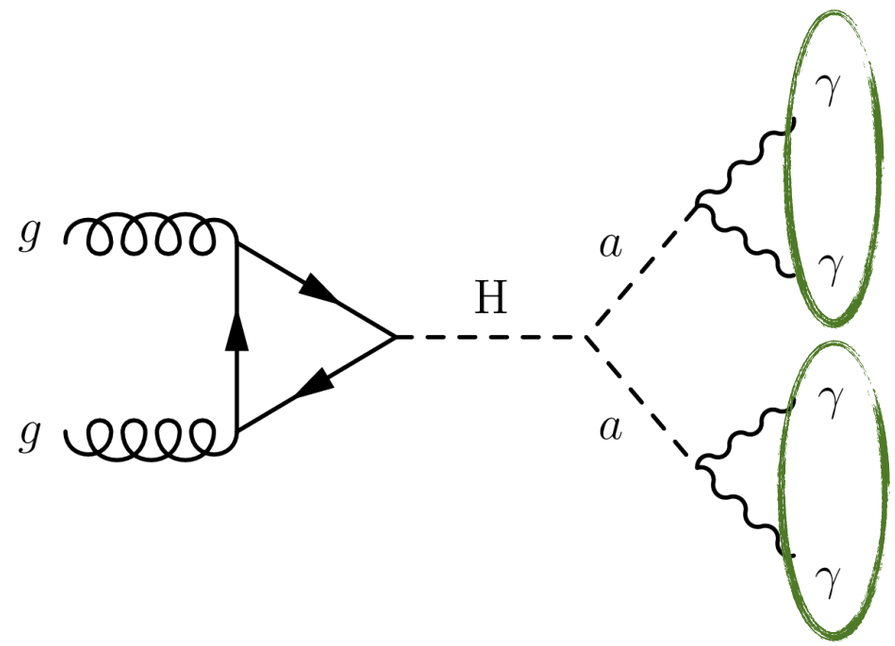

Merged reco Γs

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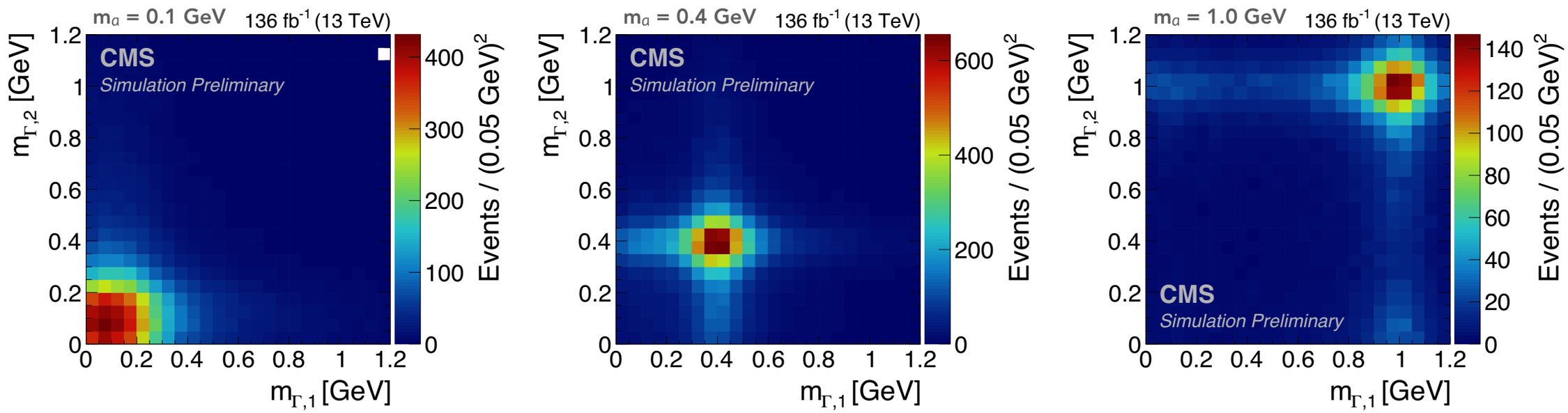
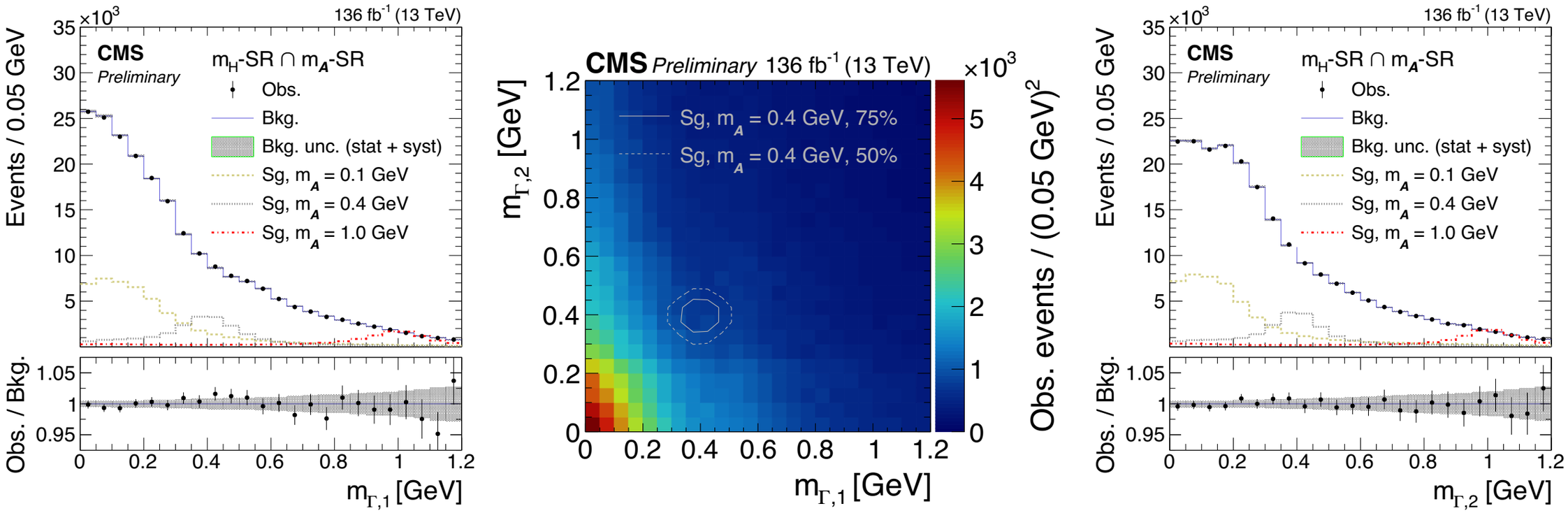
H→aa→4γ (boosted)



- Photons selected using a diphoton trigger, selection requirements imposed
  - Only barrel photons used to reduce tracker material effects
  - Cluster shape constraints relaxed, isolation constraints increased to compensate
  - CNN technique used to reconstruct and measure the mass of merged photon system in CMS ECAL arXiv:2204.12313, Talk by Shilpi

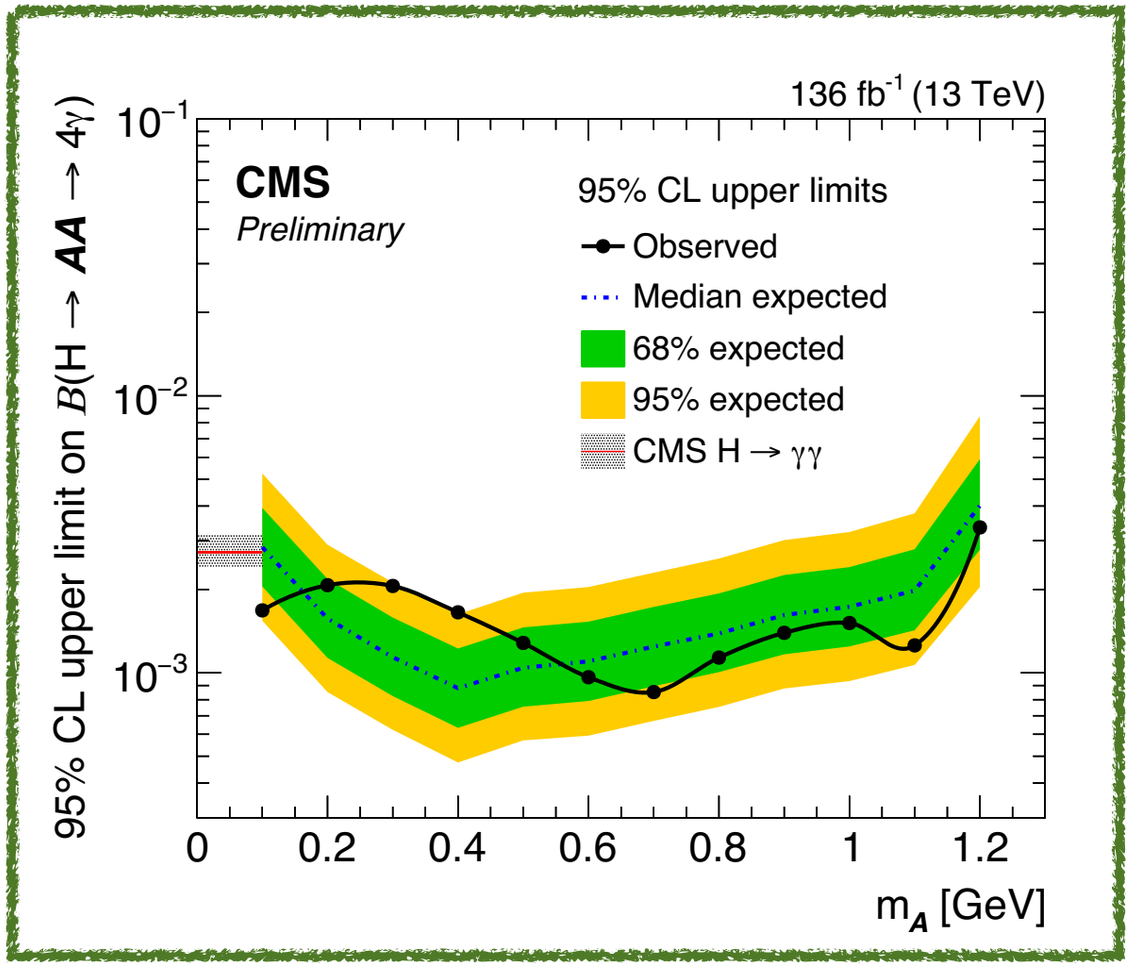
H→aa→4γ (boosted)



- Background: H→γγ, non-resonant QCD dijet and γ+jet production
- Using MC simulation for H→γγ and data-driven templates for non-resonant background

H→aa→4γ (boosted)

- Results
  - No excess of events above expected background
  - Upper limits on $\mathcal{B}$(H→aa→4γ) set at 95% CL
    - Observed limits: (0.9 - 3.3) × 10^{-3}
  - First direct probe of the invariant mass of merged a→γγ candidates



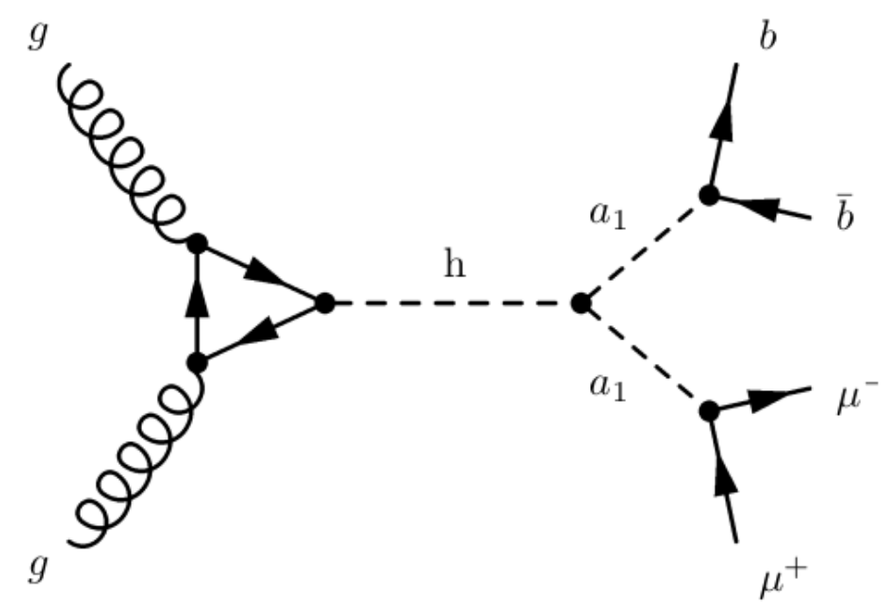
$H \to aa \to \mu\mu bb$

CMS-PAS-HIG-21-021

H→aa→$\mu\mu$bb

CMS-PAS-HIG-21-021

- Very attractive channel for discovering H→aa decays
  - a→$\mu\mu$: two muons are easily detectable and have a very precise mass resolution
  - a→bb: large BR in many parts of the parameter space



- Analysis performed using full CMS Run 2 data
- m_a ranges from 15 to 62.5 GeV - lower bound set in order to ignore intermediate states with quarkonia
- Gluon-gluon fusion and vector boson fusion mechanisms considered for Higgs boson production

H→aa→$\mu\mu$bb

- Two muons (di-muon trigger) and two b-jets selected
- To further suppress background, χ^2_{tot} defined

$$\chi^2_{tot} = \chi^2_{bb} + \chi^2_H$$

$$\chi_{bb} = \frac{m_{bb} - m_{\mu\mu}}{\sigma_{bb}} \qquad \chi_H = \frac{m_{\mu\mu bb} - 125}{\sigma_H}$$

- χ_{bb} and χ_H correlated → Decorrelated and new variable χ^2_d defined

$$\chi^2_d = \chi^2_{H,d} + \chi^2_{bb,d}$$

- Events with χ^2_d < 1.5 selected

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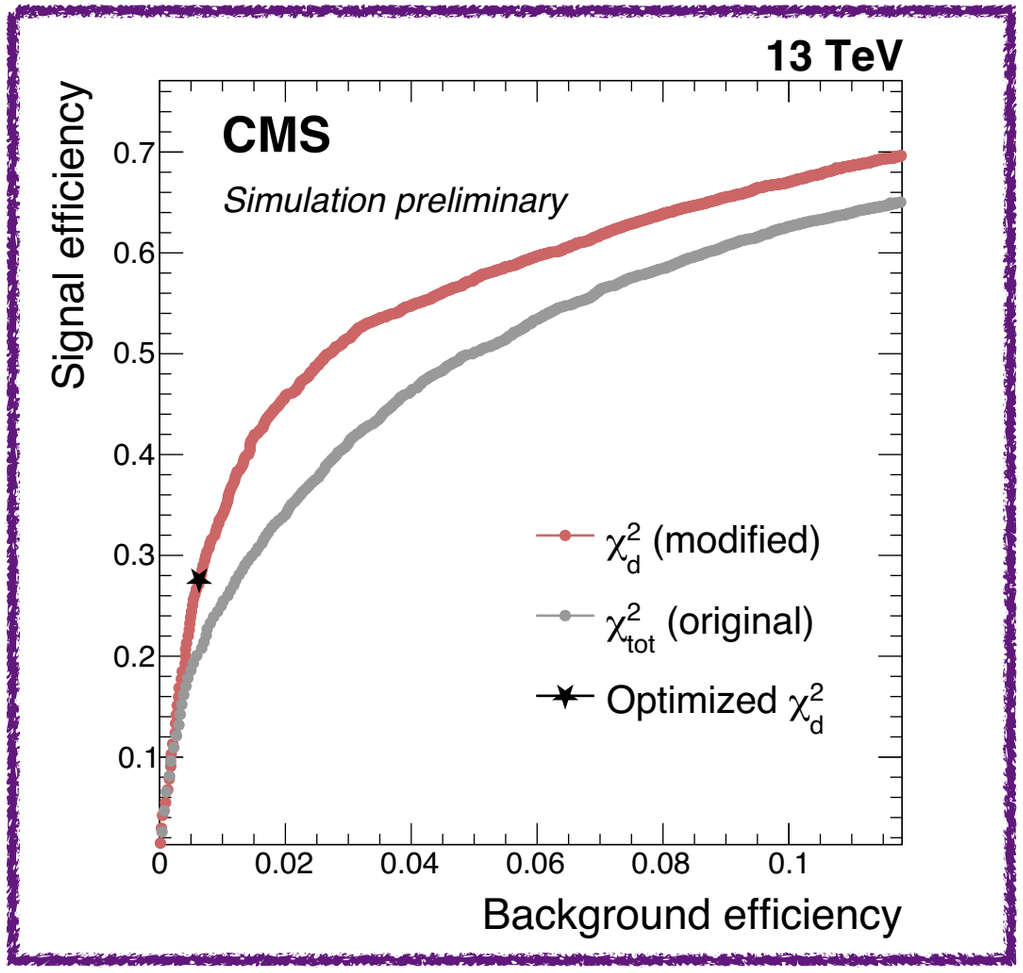

$H \to aa \to \mu\mu bb$

- **Signal model**
  - Constructed from simulation
  - Modeled as Voigt Profile + Crystal Ball function
  - All parameters, except resolutions, found independent of m_a
- **Background model**
  - Fully data driven method
  - Background modeling and estimation with the envelope method
  - Different types of polynomials checked on data in SR for different categories

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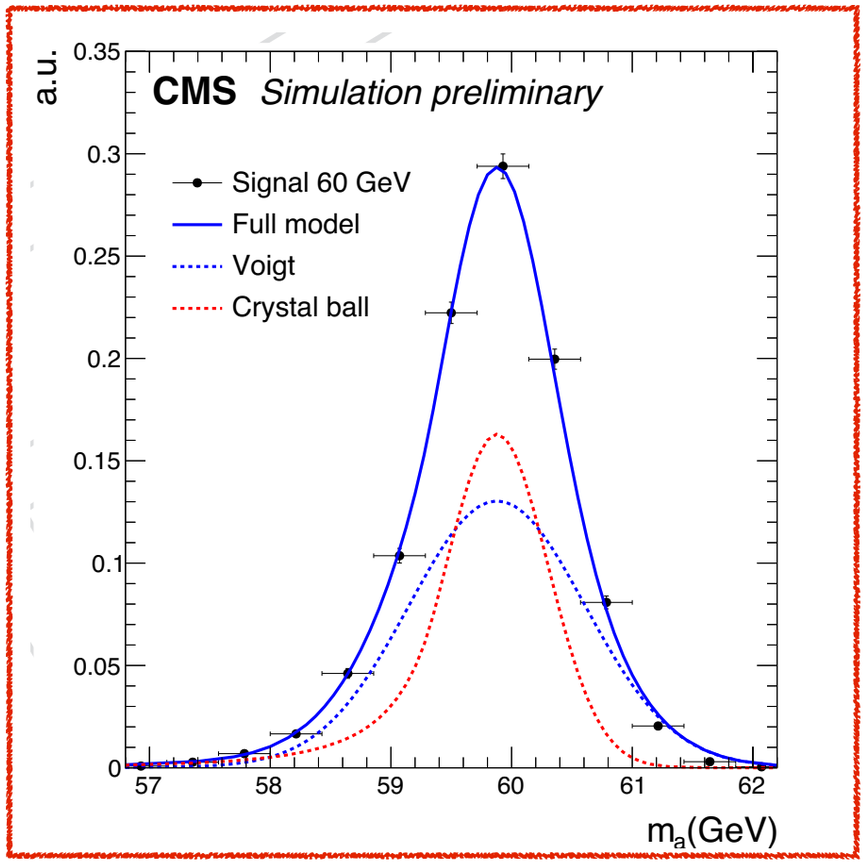

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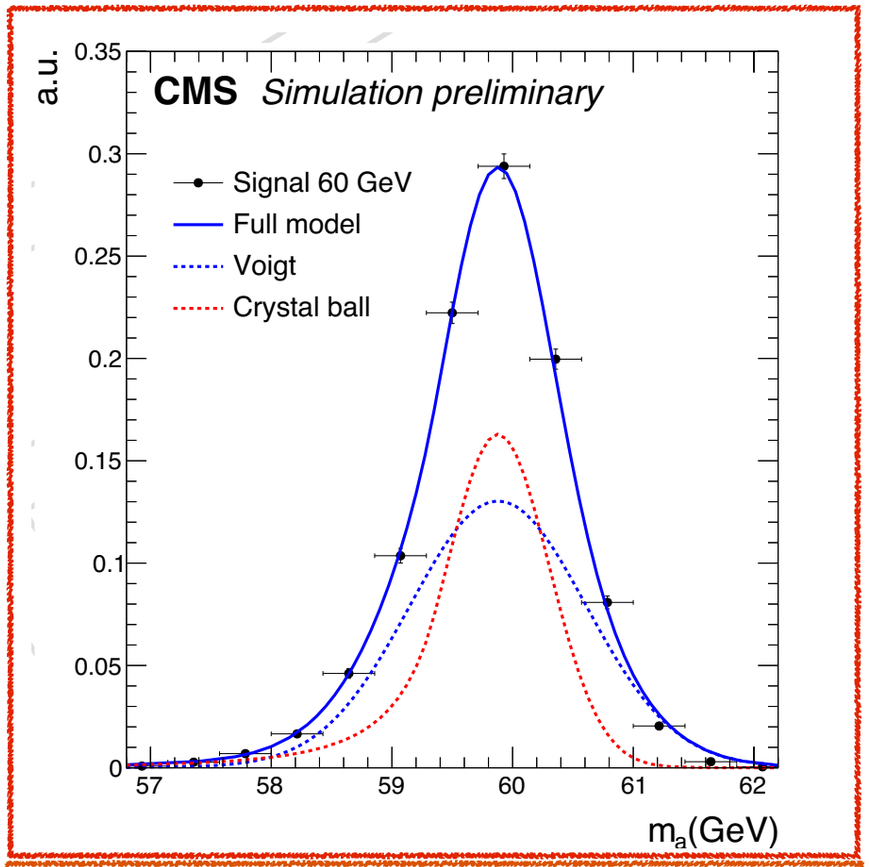
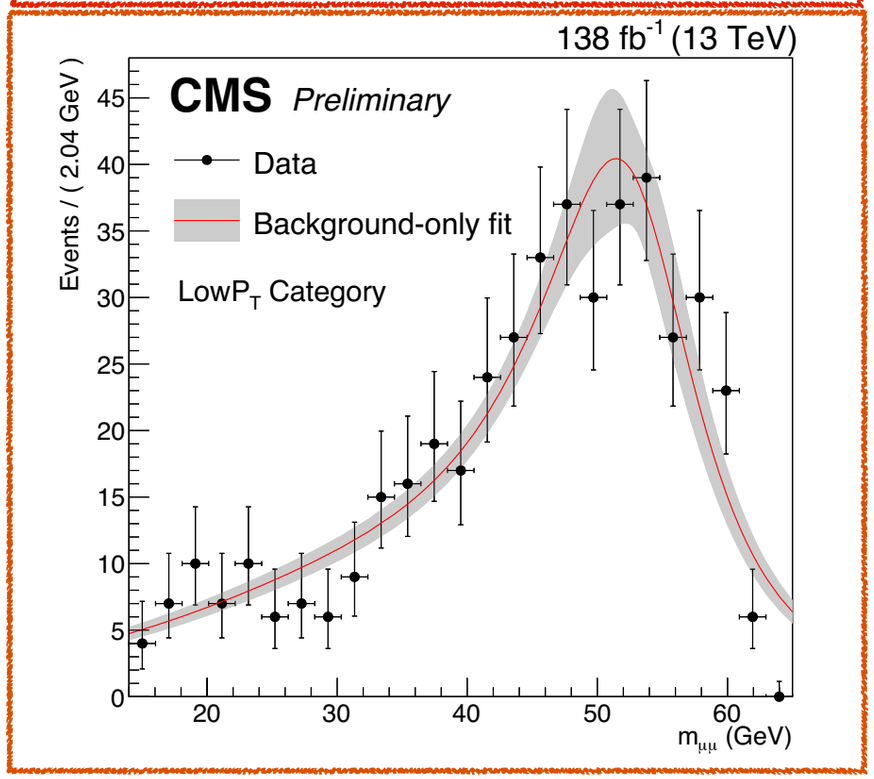
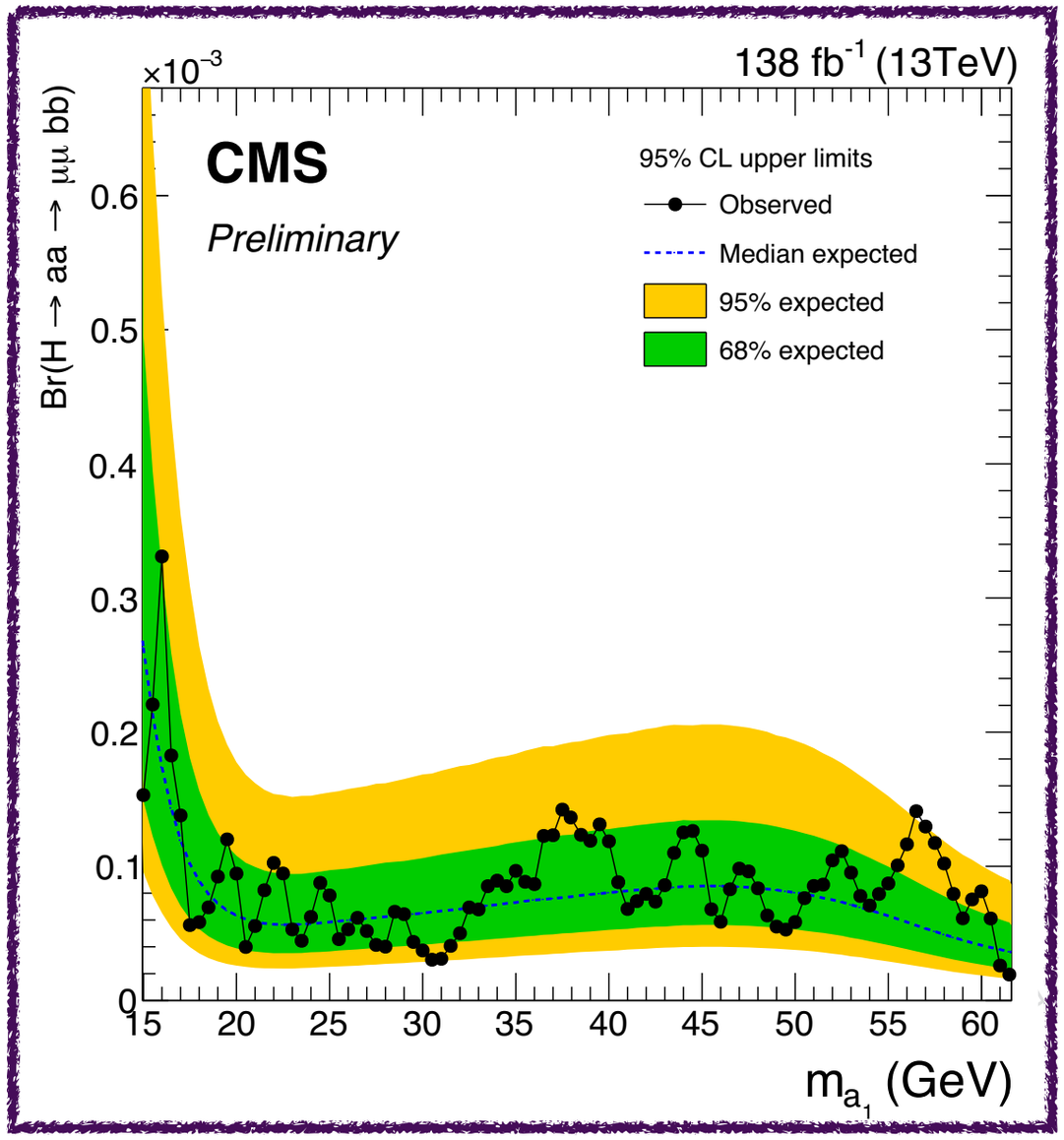




H→aa→$\mu\mu$bb

- Results
  - Upper limits on $\mathcal{B}$(H→aa→μμbb) set at 95% CLs, for mass range 15 to 62.5 GeV,
    - Observed: (0.17 - 3.3) × 10^{-4}
  - Significant improvement as compared to previous published CMS result with partial Run 2 data
- Latest ATLAS measurement:
  - Observed: (0.22 - 4) × 10^{-4}

    PhysRevD.105.012006

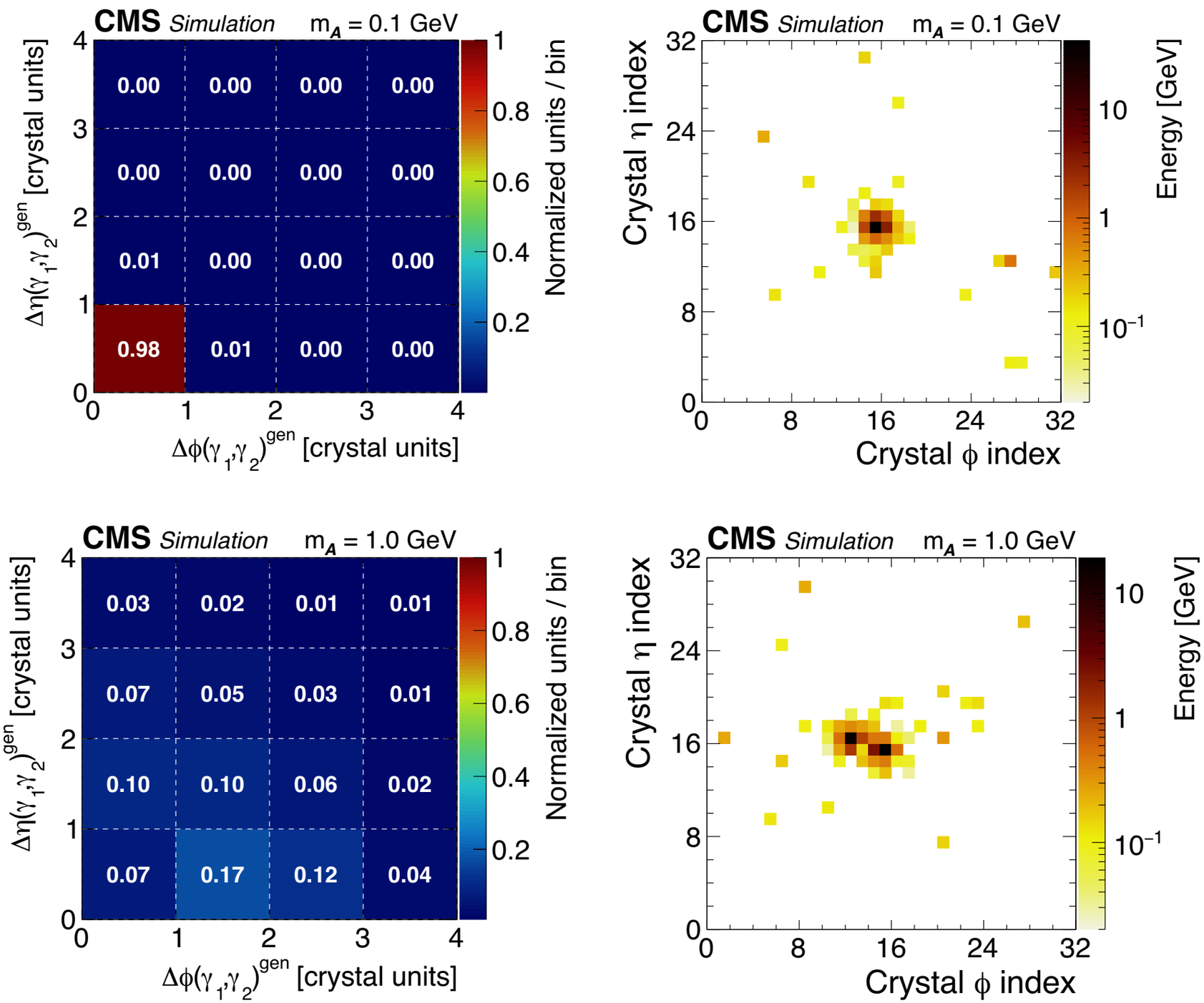


Summary

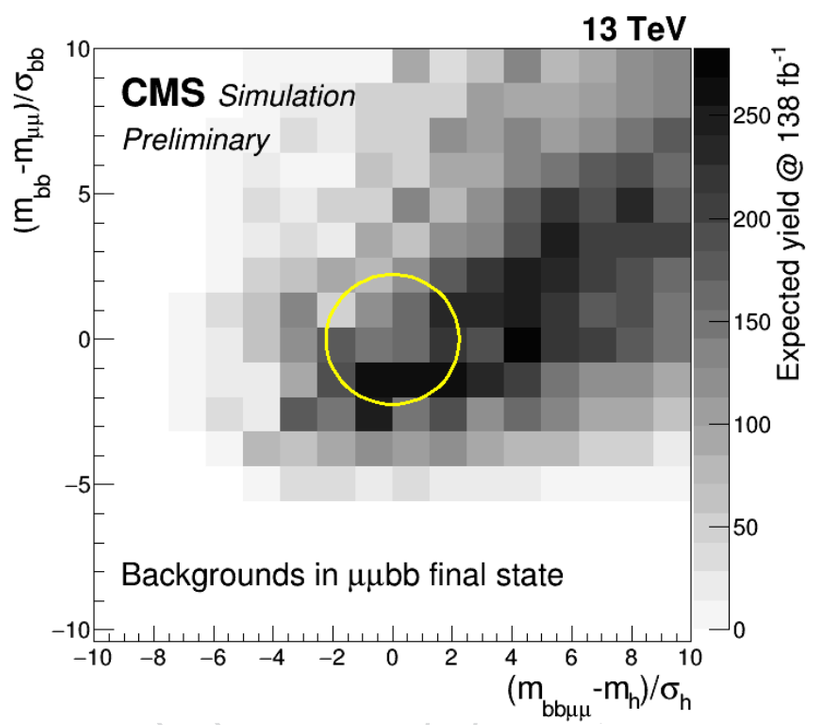
- Rich set of H→aa searches being pursued by CMS
  - Extensive range of masses of the (pseudo)scalar boson covered, from very boosted to non-boosted topologies
  - Many channels investigated using 2016 data and a few full Run 2 results already completed. Several more results in the pipeline!
  - First CMS results for H→aa→4γ with merged photons now available!
  - Improved sensitivities achieved for H→aa→$\mu\mu$bb
- No significant excess or deviation yet
- Vast parameter phase-space still to be probed

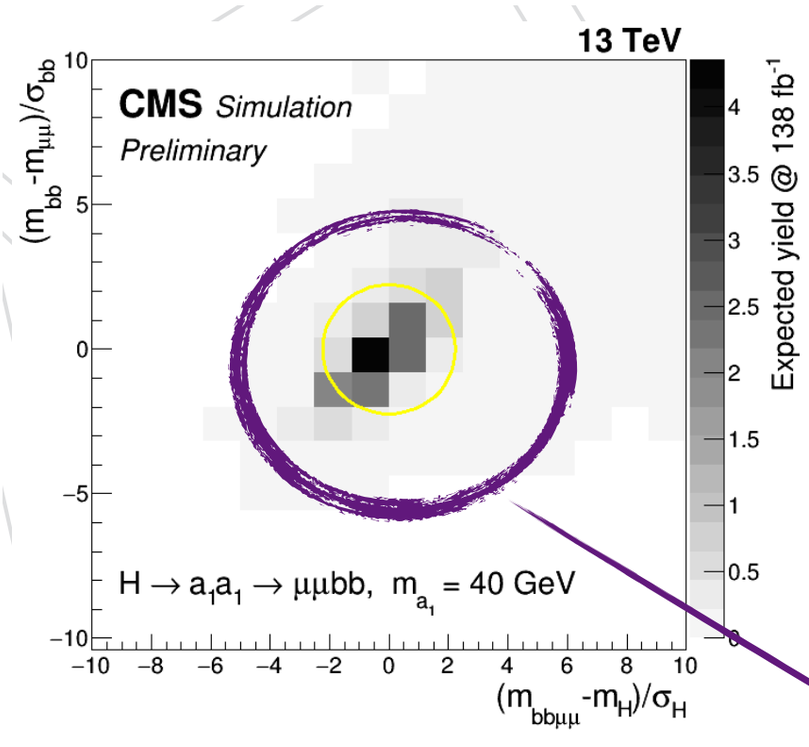
Backup

H→aa→4γ (boosted)



H→aa→$\mu\mu$bb





Two variables correlated

- To decorrelate χ_{bb} and χ_H, the two quantities evaluated in a new basis

$$\begin{pmatrix} \chi_H \\ \chi_{bb} \end{pmatrix}_d = \begin{pmatrix} \frac{a}{\sqrt{\lambda_1}} & \frac{b}{\sqrt{\lambda_1}} \\ \frac{-b}{\sqrt{\lambda_2}} & \frac{a}{\sqrt{\lambda_2}} \end{pmatrix} \begin{pmatrix} \chi_H \\ \chi_{bb} \end{pmatrix}_c$$

$\lambda_1, \lambda_2 \rightarrow$ eigen values

$\begin{pmatrix} a \\ b \end{pmatrix} \rightarrow$ eigen vector of the correlation matrix

$$\chi_d^2 = \chi_{H,d}^2 + \chi_{bb,d}^2$$

H→aa→$\mu\mu$bb

- Events further classified on the basis of properties of the b-jets

Categories for selected events	Criteria
Low p_T	at least one b-jet with p_T < 20 GeV
VBF	two additional 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

T: Tight M: Medium L: Loose