Unlocking the 2HDM Phase Space:
Recent Experimental Insights and Discovery Potential

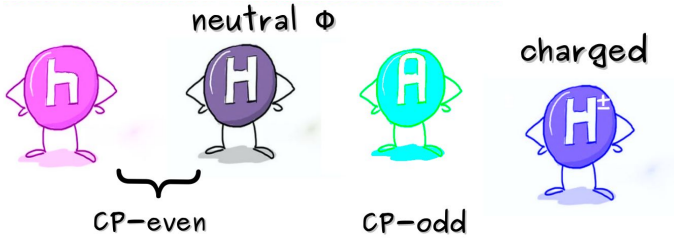
Extended Scalar Sectors From All Angles

21–25 Oct 2024

Khawla JAFFEL on behalf of the CMS collaboration

USTC

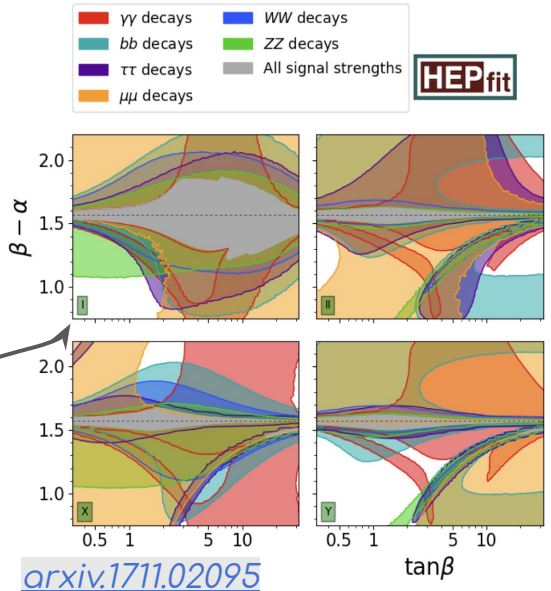
Why Explore the 2HDM ?



The SM is highly successful but leaves unanswered questions, such as the origin of electroweak symmetry breaking and the nature of dark matter, etc...

2HDM introduces two Higgs doublets, leading to five physical Higgs bosons (h, H, A, H^+, H^-), allowing for richer scalar sectors and diverse experimental signatures

- Addressing SM limitations
  - Provides a natural mechanism for **generating CP violation**, important for explaining the matter-antimatter asymmetry in the universe.
  - Can explain deviations from SM predictions, such as **anomalies in fermionic couplings and electroweak precision tests**.
- New Physics Potential
  - Some 2HDM variants naturally incorporate a stable particle, providing a **possible dark matter candidate**.



arxiv.1711.02095

The landscape at the start of LHC full Run 2

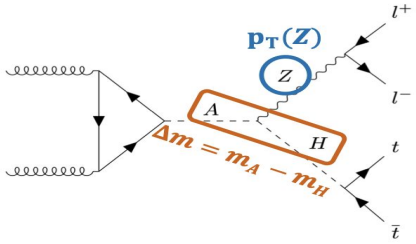
- Connection to Supersymmetry and Other BSM Theories
  - 2HDM appears in many BSM scenarios, including supersymmetry, offering a framework that can unify with broader new physics models.
- Experimental Relevance
  - 2HDM predicts observable signatures at the LHC, such as heavy Higgs bosons with distinctive decay patterns, making it highly testable with current and future data.
  - **Exploring Uncharted Territory:** Many regions of the 2HDM parameter space remain unexplored, providing an opportunity to discover new physics beyond the SM.

Selected recent CMS searches

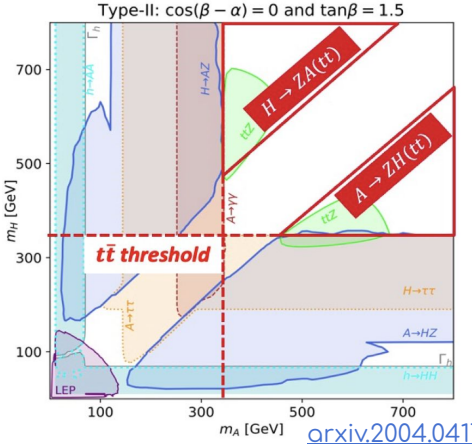
- ❏ $A \rightarrow ZH \rightarrow (\ell\ell)(t\bar{t})$
- ❏ A/H with FCNC based on g2HDM
- ❏ $A/H \rightarrow t\bar{t}$
- ❏ $A \rightarrow Zh125 \rightarrow (\ell\ell)(\tau\tau)$

⇒ The results are not all necessarily interpreted within the 2HDM, but the searches target H and A bosons, which are part of the 2HDM framework.

$A \to ZH \to (\ell\ell)(t\bar{t})$



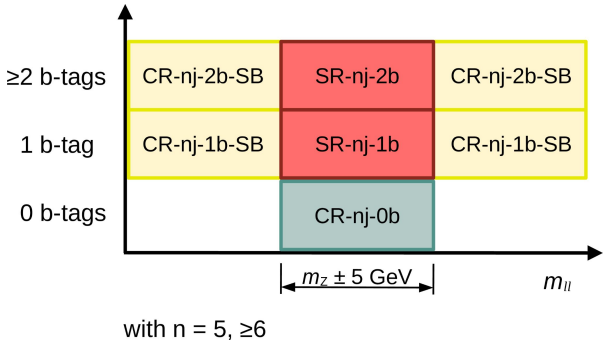
CMS-PAS-B2G-23-006



JHEP06(2020)163

arxiv.2004.04172

- This is the first time CMS has explored this signature, with recent efforts by ATLAS as reported in ATLAS-CONF-2023-034.
- The two-dimensional distribution of Δm and ρT(Z) is used as final observable to extract the signal.
- Simultaneous fit over 10 regions defined as a function of mZ(|mZ|> (or <) 5 GeV), number of jets (5, ≥6), and number of bjets (1, 2)

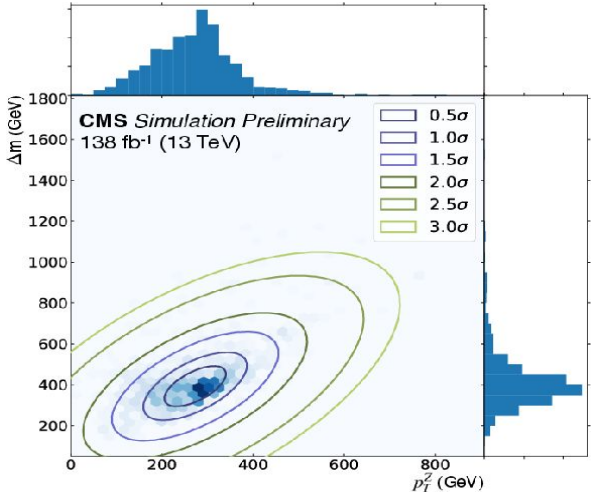


with n = 5, ≥6

Targeted process

- **SR**: *AZH*
- **SB**: *tt*
- **0b**: *DY+Jets*

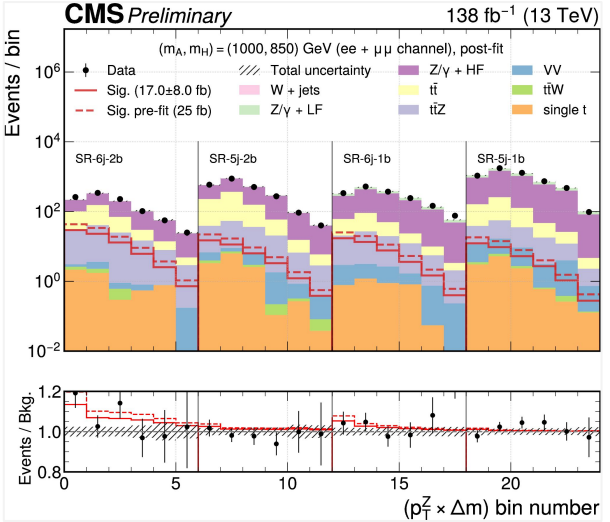
Normalization floating in the fit!

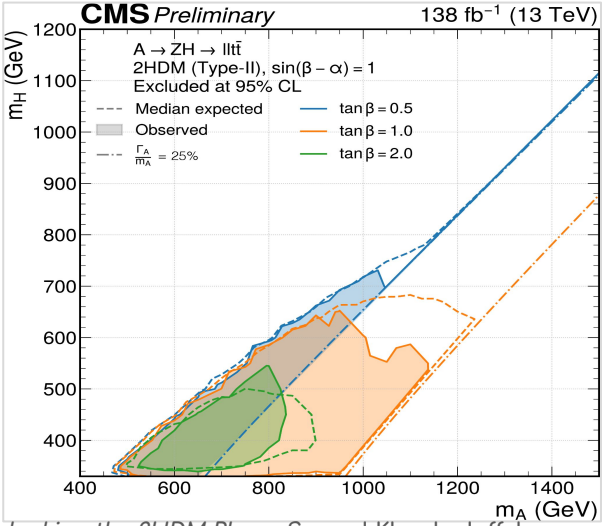


$A \rightarrow ZH \rightarrow (\ell\ell)(t\bar{t})$

- The explored channel is considered a smoking gun for a FOEWPT with parameter region targeted in this search following Thomas Biekötter et al JCAP03(2023)031.
- Model-independent upper limits for narrow resonances up to 2.1 TeV were derived at 95% CL.
- The results were interpreted in the context of the type II 2HDM.
- CMS results do not confirm the excess reported by ATLAS (ATLAS-CONF-2023-034) in the region around (*m*A,*m*H) = (650,450) GeV with a local significance of 2.85 SD .

CMS-PAS-B2G-23-006





- The largest fluctuation compared to the background-only hypothesis is observed for mA = 1000 GeV and mH = 850 GeV, corresponding to a local significance of 2.1 SD.

A/H with FCNC based on g2HDM

- The 2HDM without Z2 symmetry can facilitate electroweak baryogenesis through sub-TeV extra Higgs bosons (Hou & Kikuchi, EPL 123 (2018) 11001).
- In the g2HDM framework, alignment occurs when additional Yukawa couplings are present.
  - This model does not allow for HVV or AVV interactions.
  - The light Higgs h does not permit FCNC, while heavier Higgs bosons H and A can.
- Production Mechanism: The production process includes

$$qg \to tH \to tt\bar{q} \to (\ell^+ b\nu)(\ell^+ b\nu)\bar{q}$$

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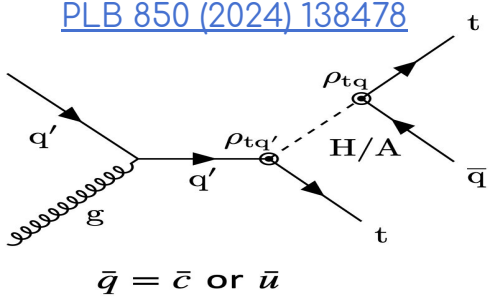

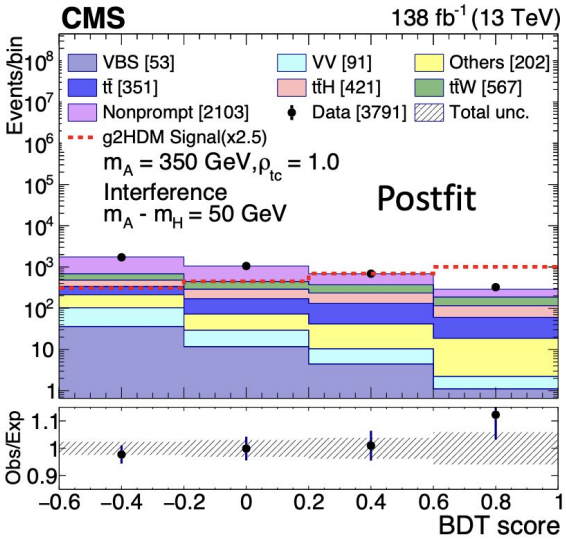

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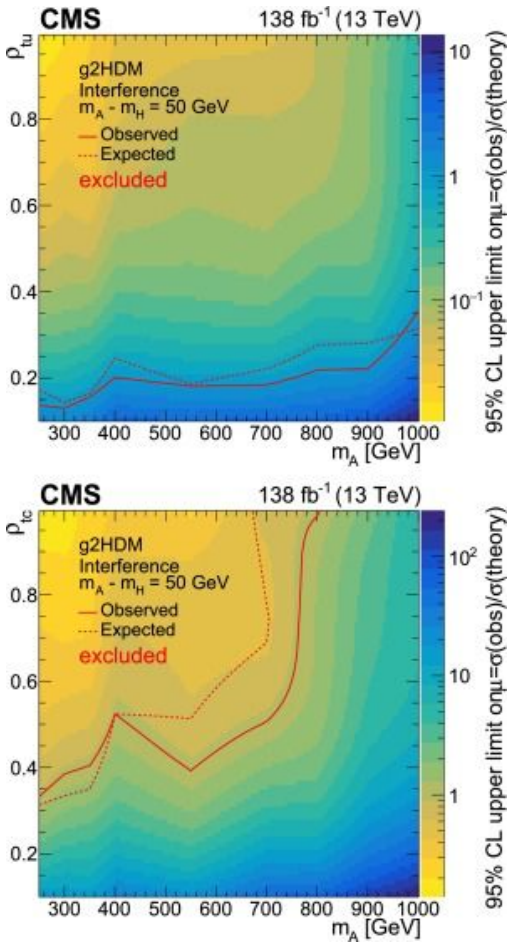
A/H with FCNC based on g2HDM

⇒ The first search based on the g2HDM framework, incorporating A-H interference effects.

- 4 bins of BDT score in each decay mode simultaneously fit to extract limits for each signal mass-coupling hypothesis.

Observed (expected) mass limit [GeV]			
	without interference	with interference	with interference
	m_A or m_H	m_A	m_H
ρ_{tu}			
0.4	920 (920)	1000 (1000)	950 (950)
1.0	1000 (1000)	1000 (1000)	950 (950)
ρ_{tc}			
0.4	no limit	340 (370)	290 (320)
1.0	770 (680)	810 (670)	760 (620)



- ptu largely excluded, yet significant portions of the phase space remain unconstrained for certain parameters.
- Stricter limits are observed for specific scenarios due to the increased signal cross section, which arises from PDF effects.

- With interference effects, the signal cross section increases further due to the simultaneous presence of A and H .

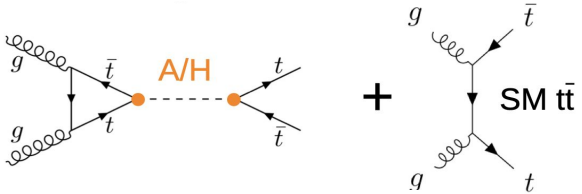
CMS-PAS-HIG-22-013

A /H → tt̄

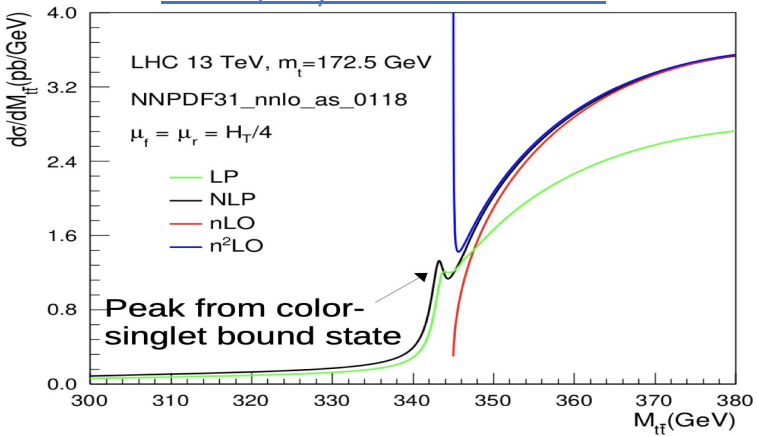
- Search for new spin-0 (pseudo)scalars in tt final states with full Run 2 UL
- Two analysis channels: dilepton (ℓℓ) and lepton+jets (ℓj)
- Interpretations as...
  - Generic pseudoscalar (A) or scalar (H) state,

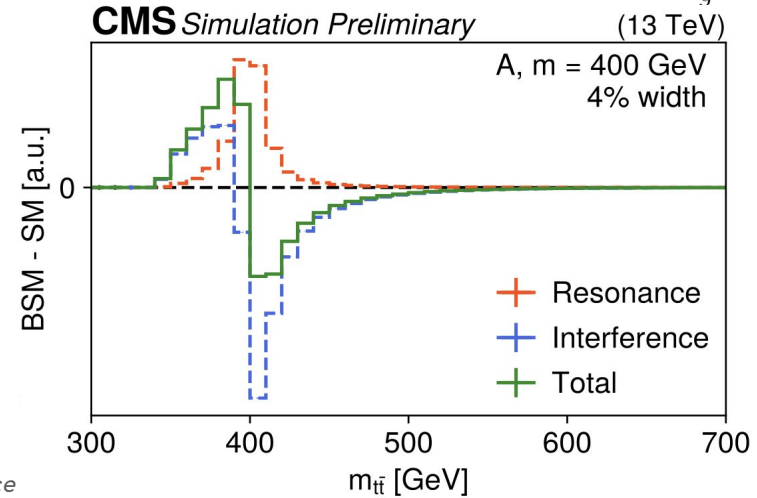
includes interference with SM → peak-dip structure in tt spectrum

  - Pseudoscalar color-singlet tt bound state (ηt)



10.1103/PhysRevD.104.034023



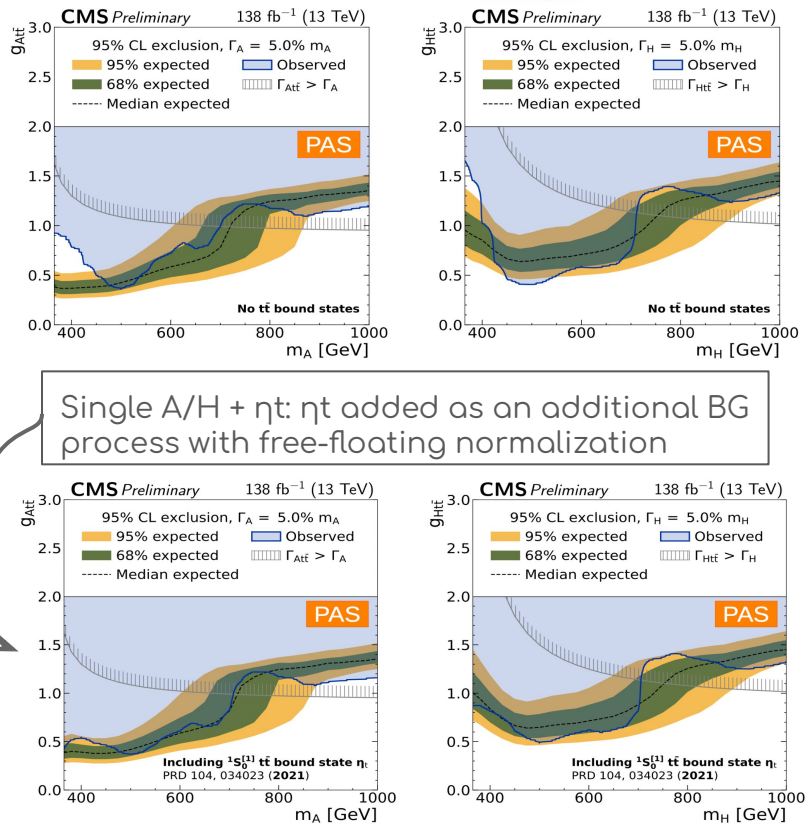


CMS-PAS-HIG-22-013

A /H → tt̄ model-independent constraints

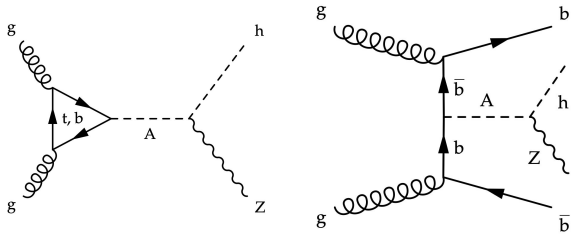
- A local excess, at low mtt, has been observed in data with >5σ significance,
  which fits better to pseudoscalar than scalar hypothesis
- Fuks et al. (PRD 104 (2021) 3, 034023):
  Color-singlet pseudoscalar particle ηt coupling to gluons and top quarks $m_{\eta t}$ = 343 GeV, $\sigma_{\eta t}$ = 6.43 pb
  ⇒ Generated in MadGraph, filtering out events outside $m_{\eta t}$ = 343 ± 6 GeV
- Excess also fits best to a model of the tt̄ bound state ηt, a cross section

$$\sigma(\eta_t) = 7.14 \pm 0.77\,\text{pb}$$



A → Zh125 → (ℓℓ)(ττ)

CMS-PAS-HIG-22-004



- Previous Results from CMS (HIG-18-023, JHEP03 (2020) 065)
- Production modes targeted : gg→A and bbA
- Final states studied : *Zh*(125)→(*ee*, *μμ*)(*τeτh*, *τμτh*, *τhτh*)

Single e/μ triggers
One or both of Z decay leptons must fire the HLT

Z→ee/μμ candidates
- loose e/μ ID
- 60 < m_{ll} < 120 GeV

H→ eτ_h, μτ_h, $\tau_h\tau_h$
- deepTau MediumVSJet

Veto additional leptons (e/μ)

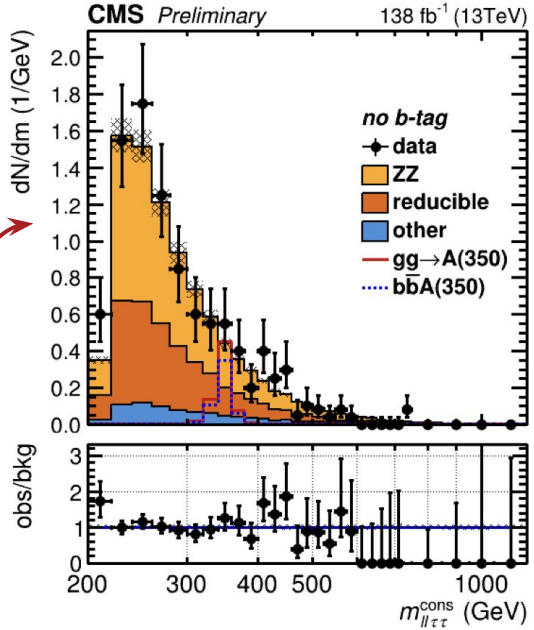
FastMTT algorithm
- mass estimator
- inputs : 4-vectors of leptons, MET, MET covariance matrix
- collinear approximation

Fit w/o m(125) constraint
90 < $m_{\tau\tau}$ < 160 GeV

Fit with m(125) constraint
m_{4l} : final discriminant

 # b jets categorization
- deepJet tagger medium WP
- bbA → Nbtag ≥ 1
- ggA → Nbtag = 0

Statistical inference with m(4l) as final discriminant
- 2 POIs : r_{ggA} and r_{bbA}
- model independent results : constraints on r_{bbA} and r_{ggA}
- Interpretation within theoretical models (2HDM)



CMS-PAS-HIG-22-004

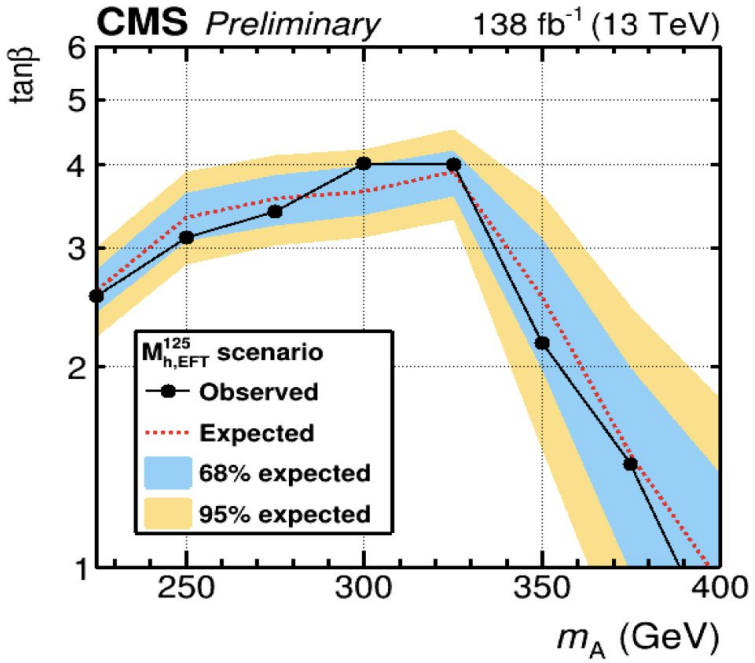
A → Zh125 → (ℓℓ)(ττ)

W.r.t. 2016 CMS analysis, increased integrated luminosity, better hadronic lepton ID and b jet tagger, added bbA production, and the range extended by ~2x.

- Model independent interpretation
  - Observed limit ranges from 0.041 (0.040) pb at mA= 1 TeV to 1.00 (0.77) pb at mA= 250 GeV for gg→A (bbA) process

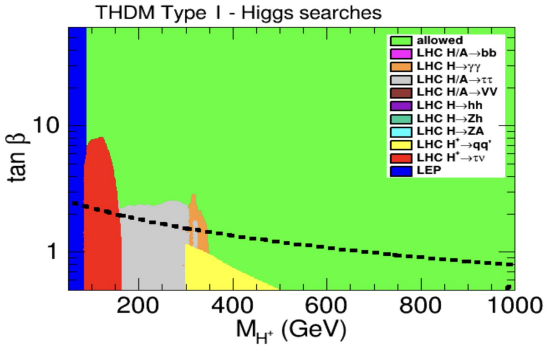
Model dependent interpretation

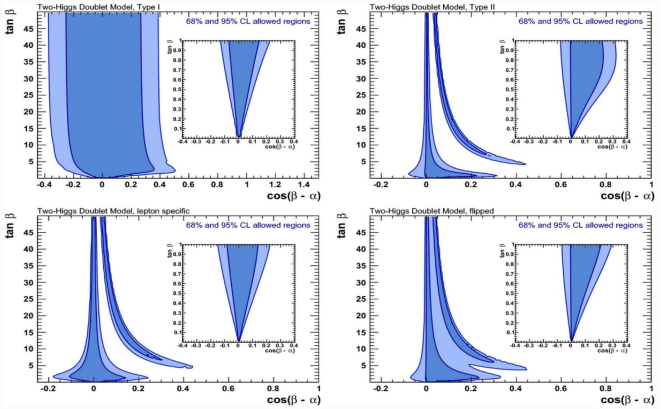
- Lower 95% CL limits are set on tanβ as a function of mA in the mh(125, EFT) MSSM benchmark
- Values of tanβ below 2.2 are excluded at 95% CL for 225 ≤ mA ≤ 350 GeV



Future directions of heavy Higgs searches

- Explore less constrained regions of the 2HDM parameter space, including higher masses and different tan(β) and alignment limits, which may reveal new signals.
- Broaden search efforts to include non-resonant final states or scenarios with small mass differences between Higgs bosons, which might have been missed in earlier searches.
- Consider the effects of interference between A and H to refine predictions and improve sensitivity to overlapping signals.
- Combining direct and indirect constraints from precision electroweak and flavor physics measurements to complement direct searches, as these provide powerful limits on the 2HDM parameter space.
- and more...



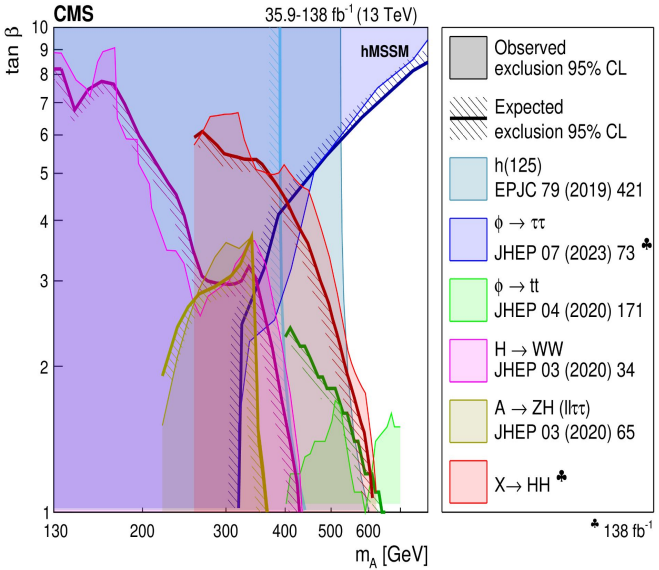


Summary

- CMS has carried out extensive searches for additional heavy Higgs bosons, with numerous results already published and many ongoing analyses;
    - targeting both **neutral** and **charged Higgs bosons** across different models.
- Besides the standard 2HDM framework, there are model extensions, e.g, that include an additional electroweak scalar singlet 2HDM+S, etc... been probed with LHC data, contributing to a broader exploration of potential BSM physics.
- Significant efforts, including advancements in search strategies, object reconstruction, and ML techniques, have led to the exclusion of large portions of the 2HDM parameter space.

⇒ With continued analysis, we look forward to new findings and, hopefully, groundbreaking discoveries in the near future!

cms-public-results/CMS-B2G-23



Thanks for listening!

Backup

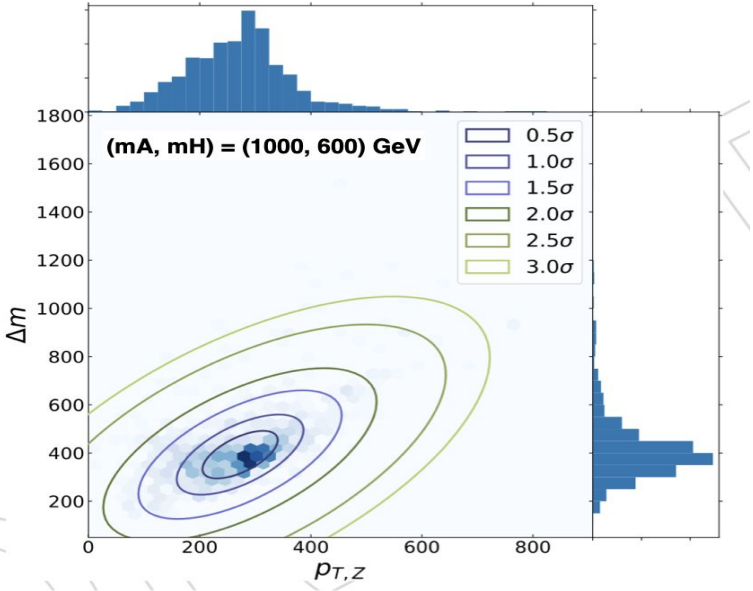
$A \rightarrow ZH \rightarrow (\ell\ell)(t\bar{t})$

Sensitive observable

The two-dimensional distribution of Δm and pT(Z) is used as final observable to extract the signal. (Variables inspired from arXiv:1807.07734)

Concentric elliptical bins are built in the $(\Delta m, p_T(Z))$ plane as follows:

- **Multivariate gaussian fit of $(\Delta m, p_T(Z))$ and get angles and axes from diagonalisation of the covariance matrix**
- **In SR:** ellipses centred around the mean of the signal distribution, **i.e. one per signal HP**
- **In CR: same ellipses centred around the mean of the total expected background**



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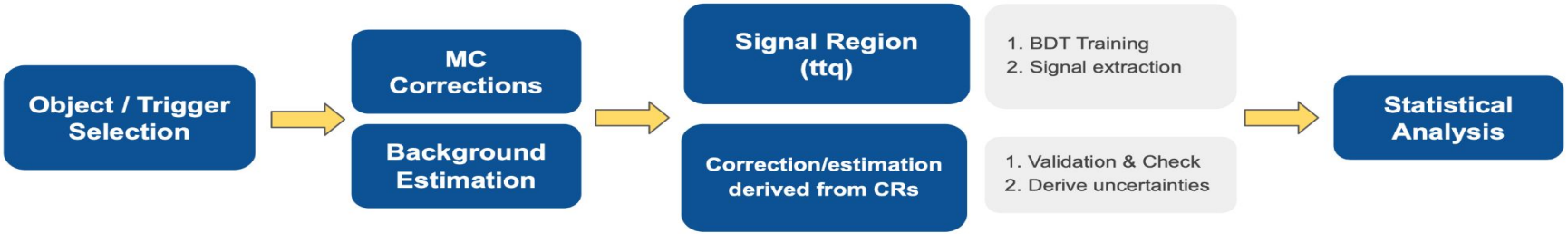
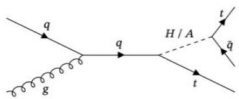
A/H with FCNC based on g2HDM

Analysis Strategy



Signal Extraction Strategy



Coupling
1. ρtc (ρtu = 0)
2. ρtu (ρtc = 0)

Non-interference
only consider A (H)

Interference
$m_A - m_H = 50$ GeV

Signal Extraction with BDT

Probe ttc/u via DeepJet CvL, CvB + other sensitive variables

ttu
- different A mass
- H-A interference

ttc
- different A mass
- H-A interference

Train BDT in each setting to maximize discriminant power

Same sign dilepton condition suppresses most of SM bkg

Dominant backgrounds
1. Nonprompt lepton
2. ttX process
3. Charge misID event

Slides from Gouranga Kole Talk: here

A /H → tt̄

Color-singlet toy model

- No full calculation available → use toy model proposed by Fuks et al (arXiv:2102.11281)
  - Generic color-singlet pseudoscalar particle η_t coupling to gluons and tops
  - Fit peak position, width and cross section to pNRQCD prediction (from arXiv:1007.0075)
  - ➔ $m_{\eta t}$ = 343 GeV, $\Gamma_{\eta t}$ = 7 GeV, $\sigma_{\eta t}$ = 6.43 pb
  - Generate in MadGraph, allowing for off-shell tops
  - Keep only events close to peak ($m_{t\bar{t}}$ = 343 ± 6 GeV)
- Result: similar signature as low-mass pseudoscalar A