Searches for Extended Higgs Sectors with the CMS Experiment

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on behalf of the CMS Collaboration

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Higgs 2024

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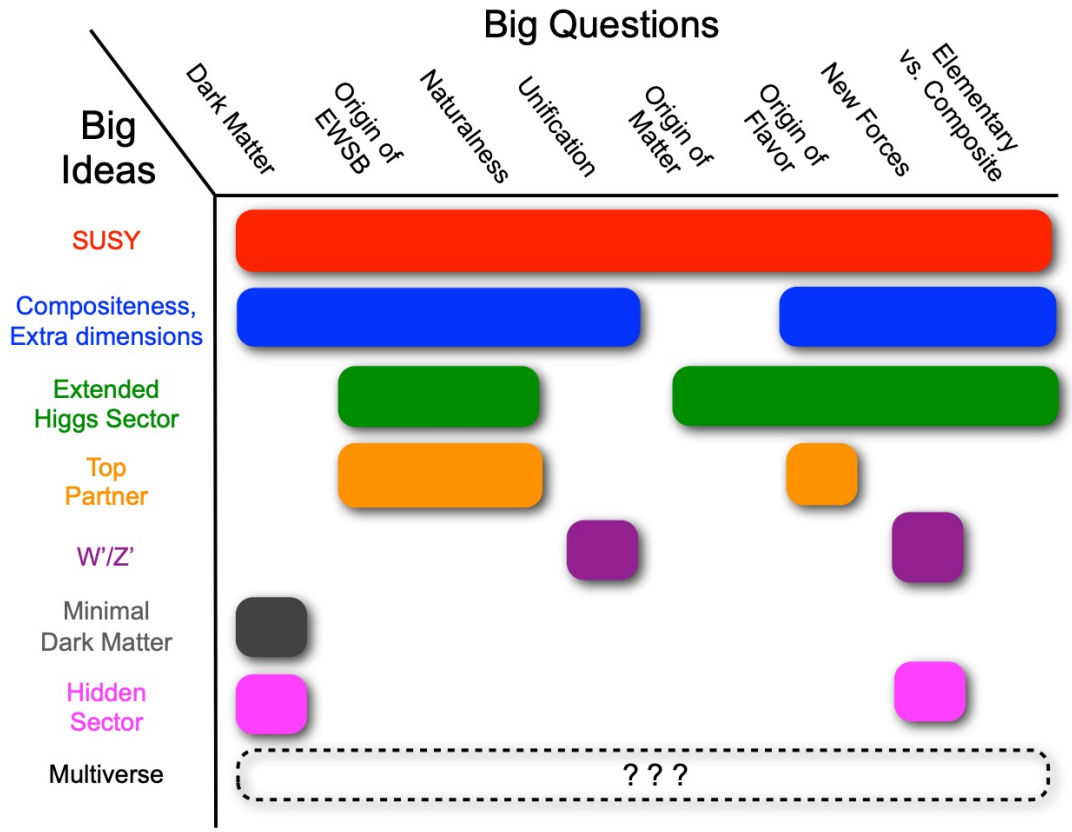
Physics Motivation

- Despite striking Standard Model (SM) success, many reasons to believe it is incomplete
- Several big questions unexplained in the SM framework
  - What is Dark Matter?
  - **Is the Higgs boson solely responsible for Electroweak Symmetry Breaking (EWSB) and the origin of mass?**
  - Are fundamental parameters finely tuned?
  - What is the origin of the matter-antimatter asymmetry?
  - Do quarks and leptons have substructure?
- Several big ideas → Many Beyond SM (BSM) theories



arXiv:1311.0299

Extended Higgs Sector Models

arXiv:2209.07510

Additional Singlet

- Simplest extension: $\mathcal{L} \supset \lambda_{\phi S}\phi^2 S^2$, S: real singlet scalar
- **Higgs portal** → connection to dark sector
- With Z_2 symmetry**, 3 new free parameters:** mass of the scalar, mixing angle α, ratio of two VEVs $\tan\beta$
- Couplings inherited from SM h_{125} suppressed by $\sin\alpha$

Additional Singlet + Doublet

- 2HDM+S: 2HDM extended with a complex singlet
- Additional CP-odd/even scalars wrt pure 2HDM
- Required by next-to-minimal supersymmetric SM (**NMSSM**)

Additional Doublet

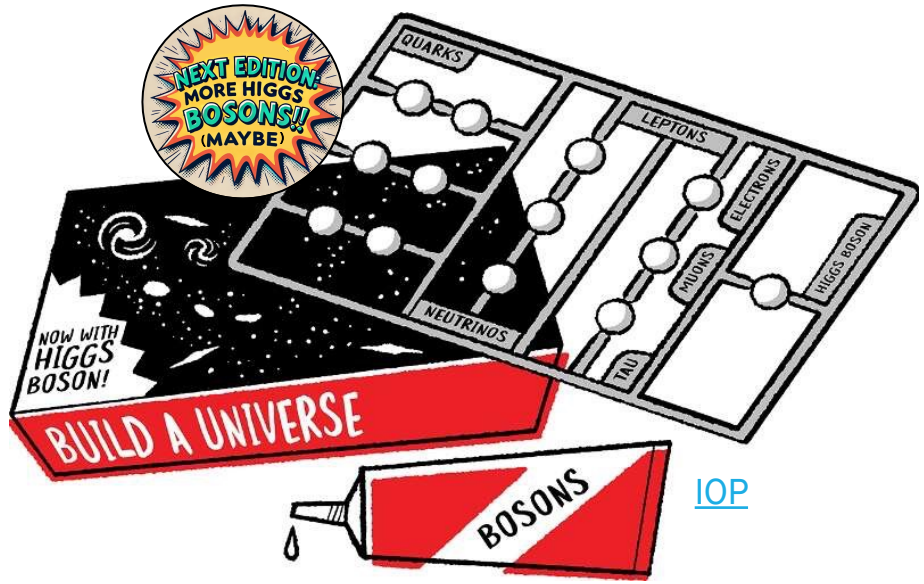
- Two Higgs Doublet Models (**2HDMs**): additional SU(2) doublet → Richer phenomenology
- **Required by SUSY** → received a lot of attention over time
- Standard parametrization: $\tan\beta$, α, masses
- **5 physical scalar states**: two neutral CP-even (H, h), one neutral CP-odd (A) and two charged ($H^{\pm}$)
- In the *alignment limit* $(\cos(\beta-\alpha)\to 0)$: h≡ h_{125}
- Yukawa couplings: $\lambda_f^{SM} = \frac{\sqrt{2}}{v} m_f$, $\lambda_f^{BSM} = \frac{\eta_f}{\tan\beta}\lambda_f^{SM}$

	Type-I	Type-II	Type-L	Type-F
η_u	1	1	1	1
η_d	1	$-\tan^2\beta$	1	$-\tan^2\beta$
η_l	1	$-\tan^2\beta$	$-\tan^2\beta$	1

Selected Recent CMS Searches

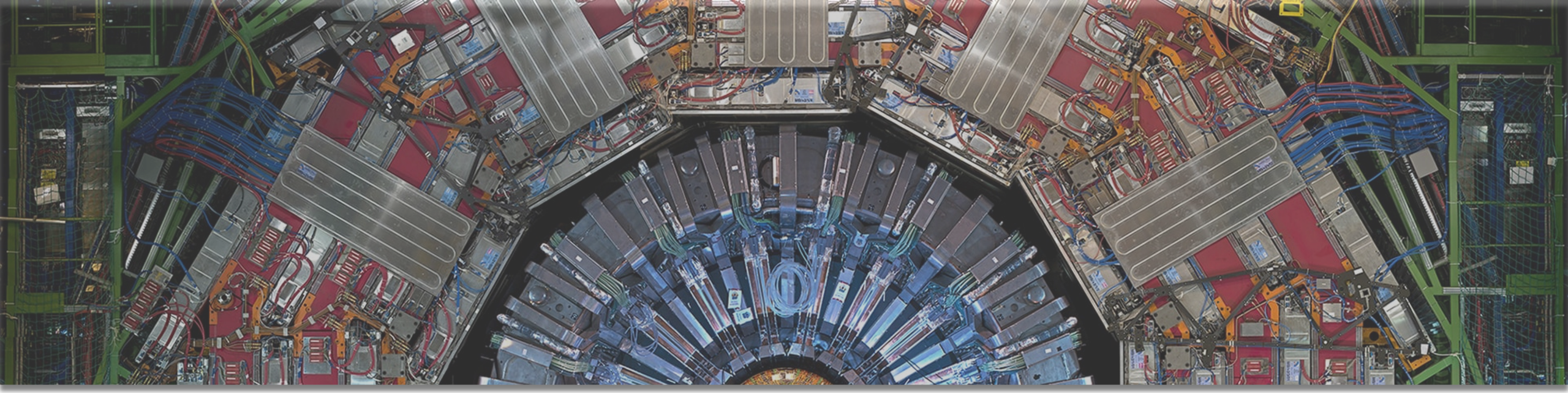
- Many searches for additional scalar bosons performed at CMS with full Run 2 data, complemented by model-depended interpretations

- A selection of 2023/2024 results is presented in this talk:
  - $\mathbf{A \rightarrow ZH \rightarrow \ell\ell t\bar{t}}$, 2HDM interpretation [CMS-PAS-B2G-23-006]
  - $\mathbf{A/H \rightarrow t\bar{t}}$, 2HDM /toponium interpretation [CMS-PAS-HIG-22-013]
  - $\mathbf{tH \rightarrow tc\bar{c}, tu\bar{u}}$, g2HDM interpretation [PLB850(2024)138478]
  - $\mathbf{h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu}$, NMSSM interpretation [arXiv:2407.20425]



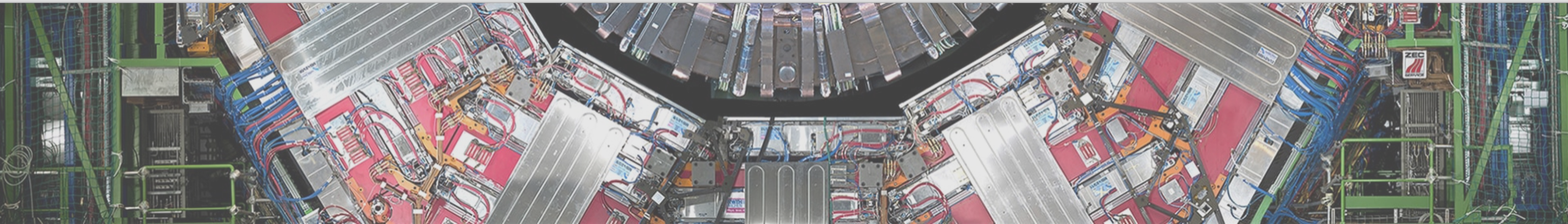
IOP

- $X \rightarrow V/Y/h_{125}$ h_{125} covered by Plenary Talk on Friday
- New scalars from h_{125} decay and low-mass searches in previous talks



Search for heavy neutral Higgs bosons A and H in the $t\bar{t}Z$ channel

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



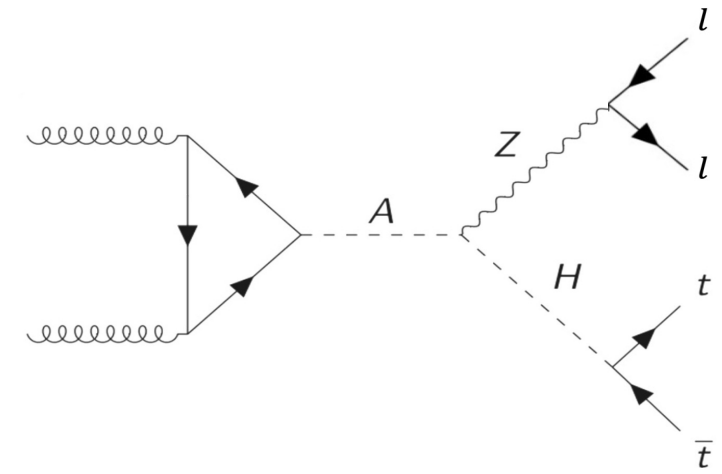
CMS-PAS-B2G-23-006

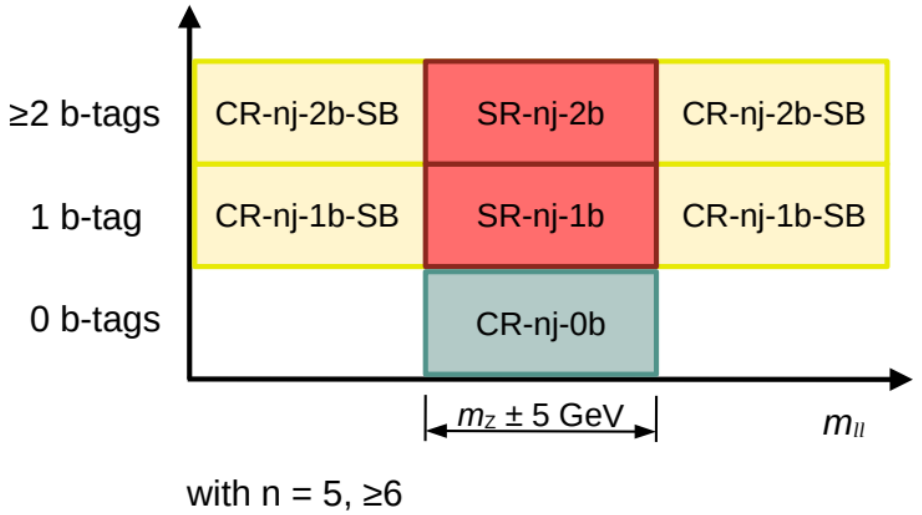
$A \rightarrow ZH \rightarrow \ell\ell t\bar{t}$: Analysis Strategy

- Search previously performed in $H \rightarrow \tau\tau/b\bar{b}/WW$ → good sensitivity until decays into top pairs becomes possible at m_H~350 GeV

- **Mostly unexplored region of 2HDM parameter space** favoured in models of electroweak baryogenesis

- Event selection: exactly 2 OS leptons + at least 5 jets → 10 categories per lepton flavour



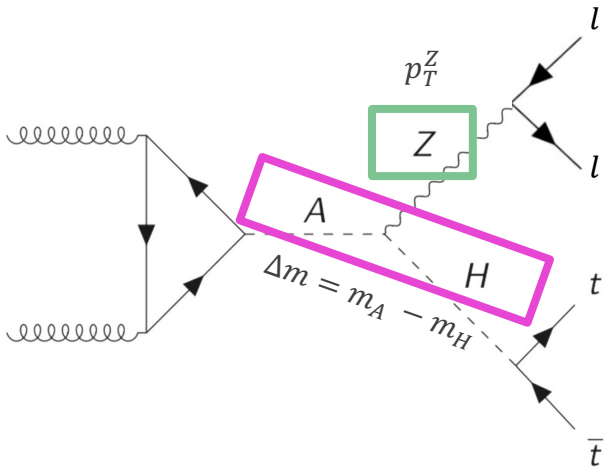


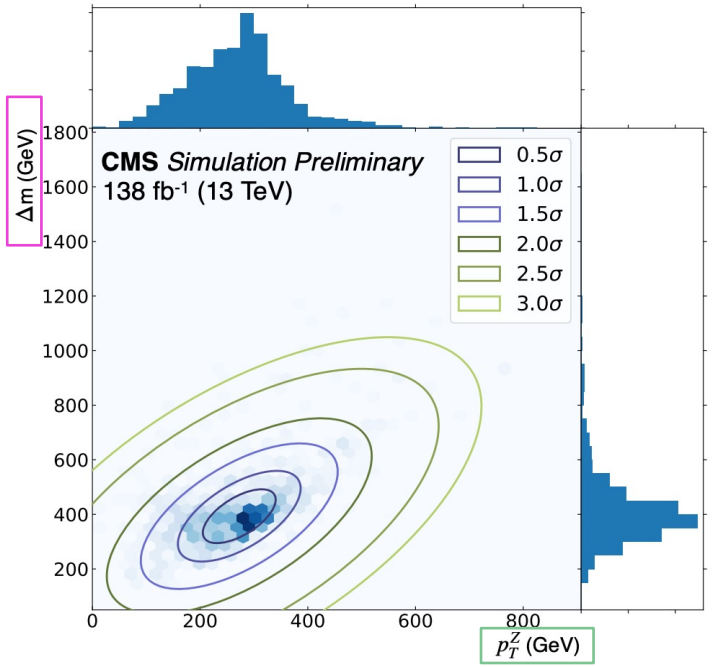
with n = 5, ≥6

CMS-PAS-B2G-23-006

$A \rightarrow ZH \rightarrow \ell\ell t\bar{t}$: Observables

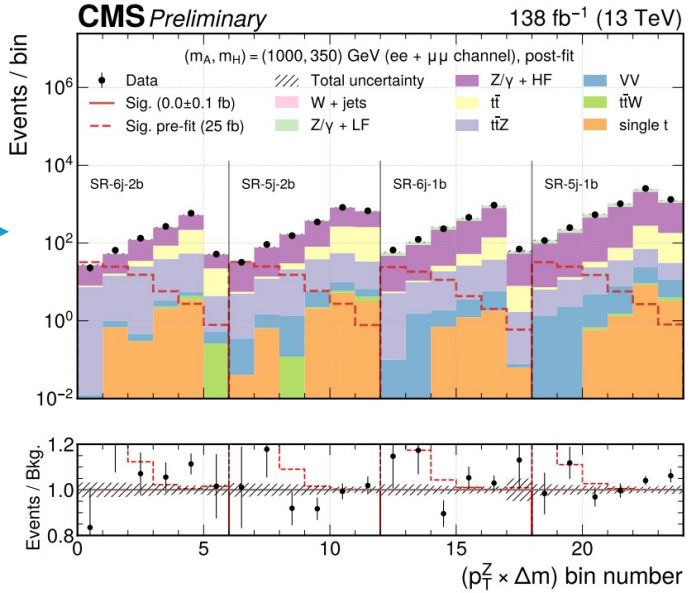
- Final fitted observable: 2-D distribution of Δm and p_T^Z
- Reduce to 1-D $p_T^Z \times \Delta m$





e.g. m_A=1 TeV m_H = 350 GeV

Unroll elliptical bins

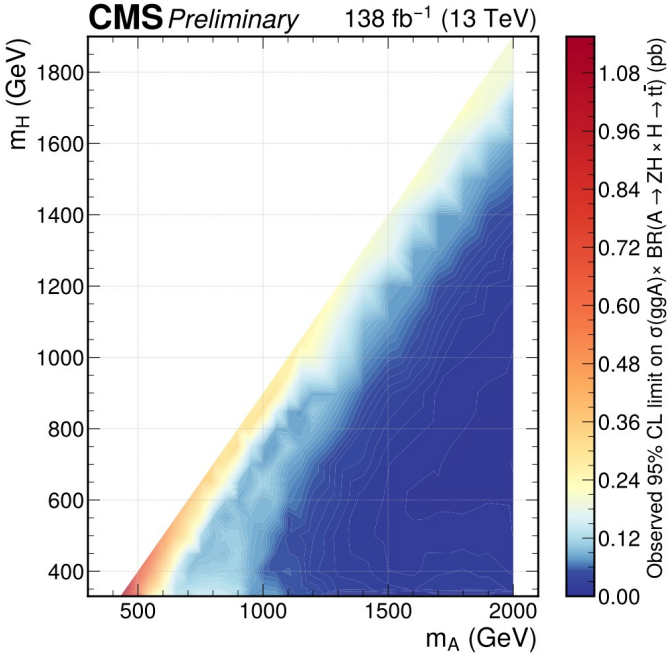


CMS-PAS-B2G-23-006

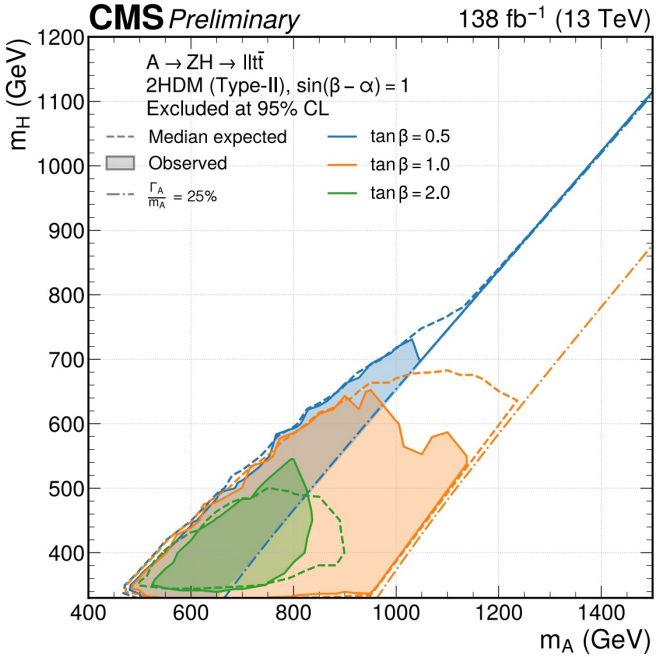
$A \rightarrow ZH \rightarrow \ell\ell t\bar{t}$: Results and Interpretation

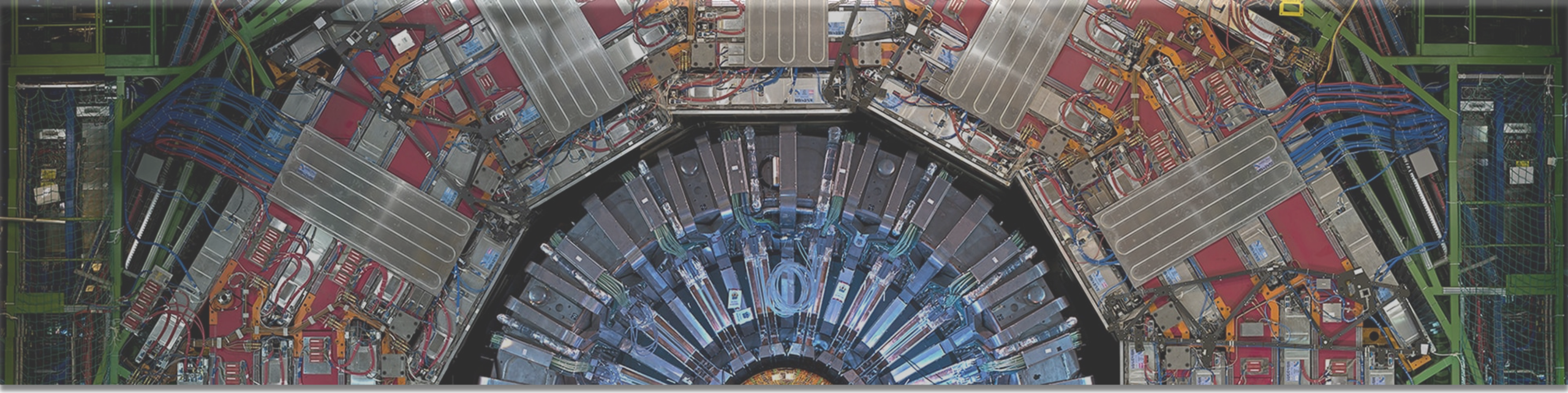
- Largest flactuation: local 2.1σ for (m_A , m_H) = (1000,850) GeV

Upper limits for generic Higgs-like narrow resonances



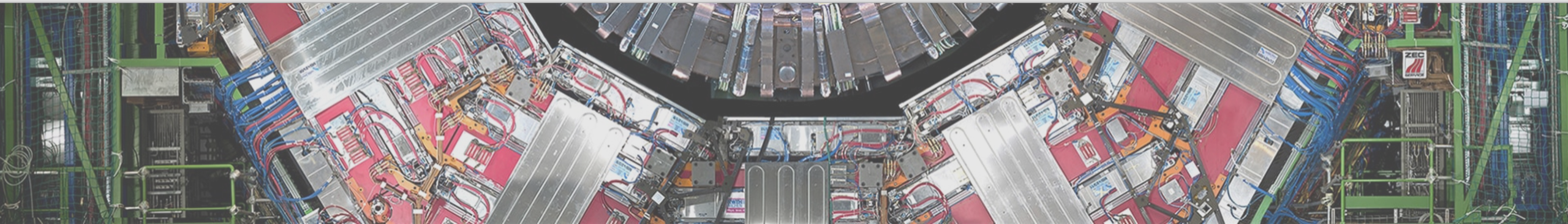
Type-II 2HDM interpretation





Search for heavy pseudoscalar and scalar bosons decaying to top quark pairs

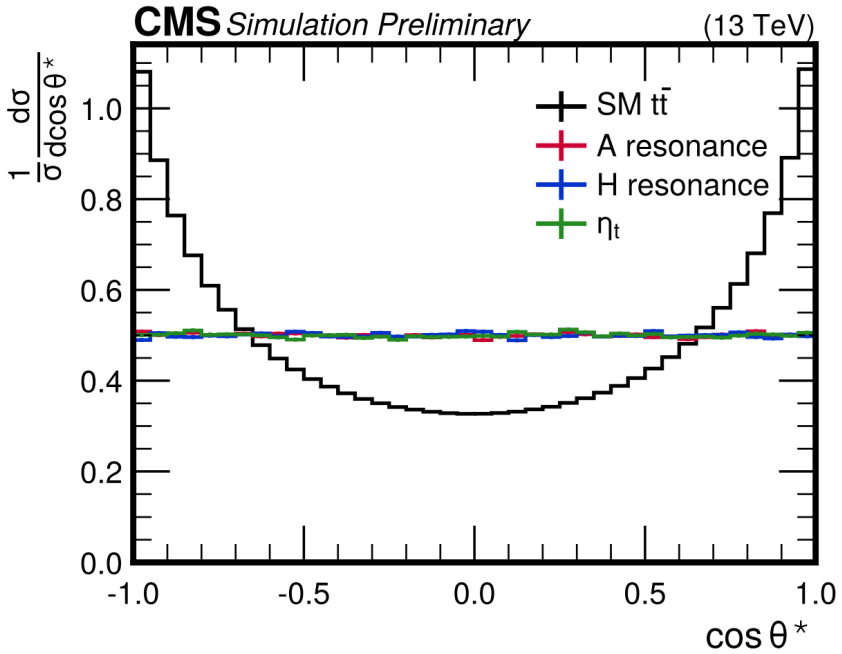
$A/H \rightarrow t\bar{t}$



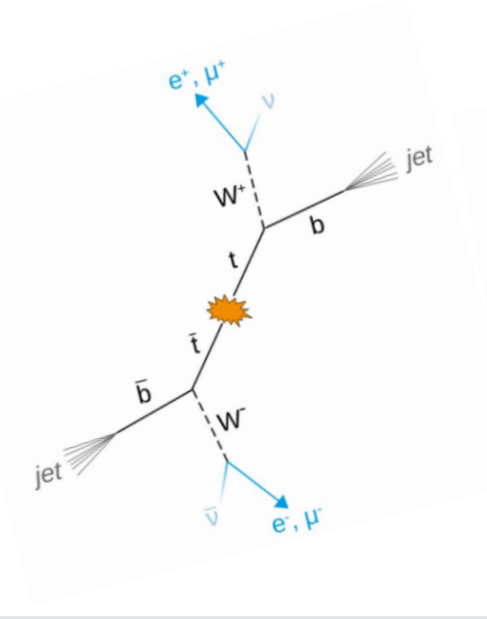
CMS-PAS-HIG-22-013

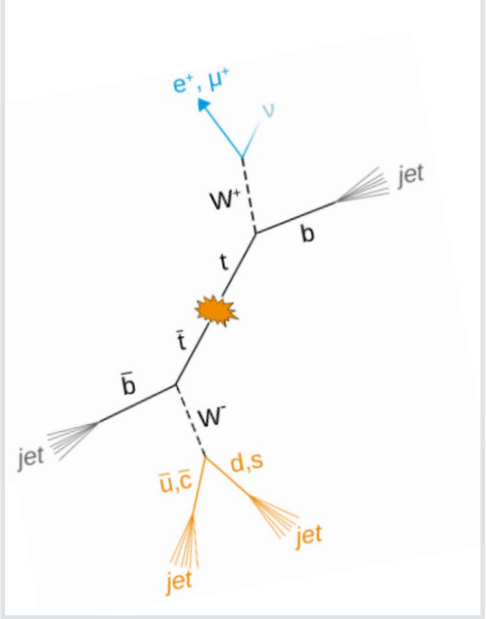
$A/H \rightarrow t\bar{t}$: Analysis Strategy

- Signal extraction using $m_{t\bar{t}}$ and spin correlation observables in final states with one or two leptons



Dileptonic channel	Semileptonic channel
2 OS ℓ (ee/eμ/$\mu\mu$) $\geq$ 2 jets $\geq$ 1 jets tagged b	1 ℓ (e/μ) $\geq$ 3 jets $\geq$ 2 jets tagged b





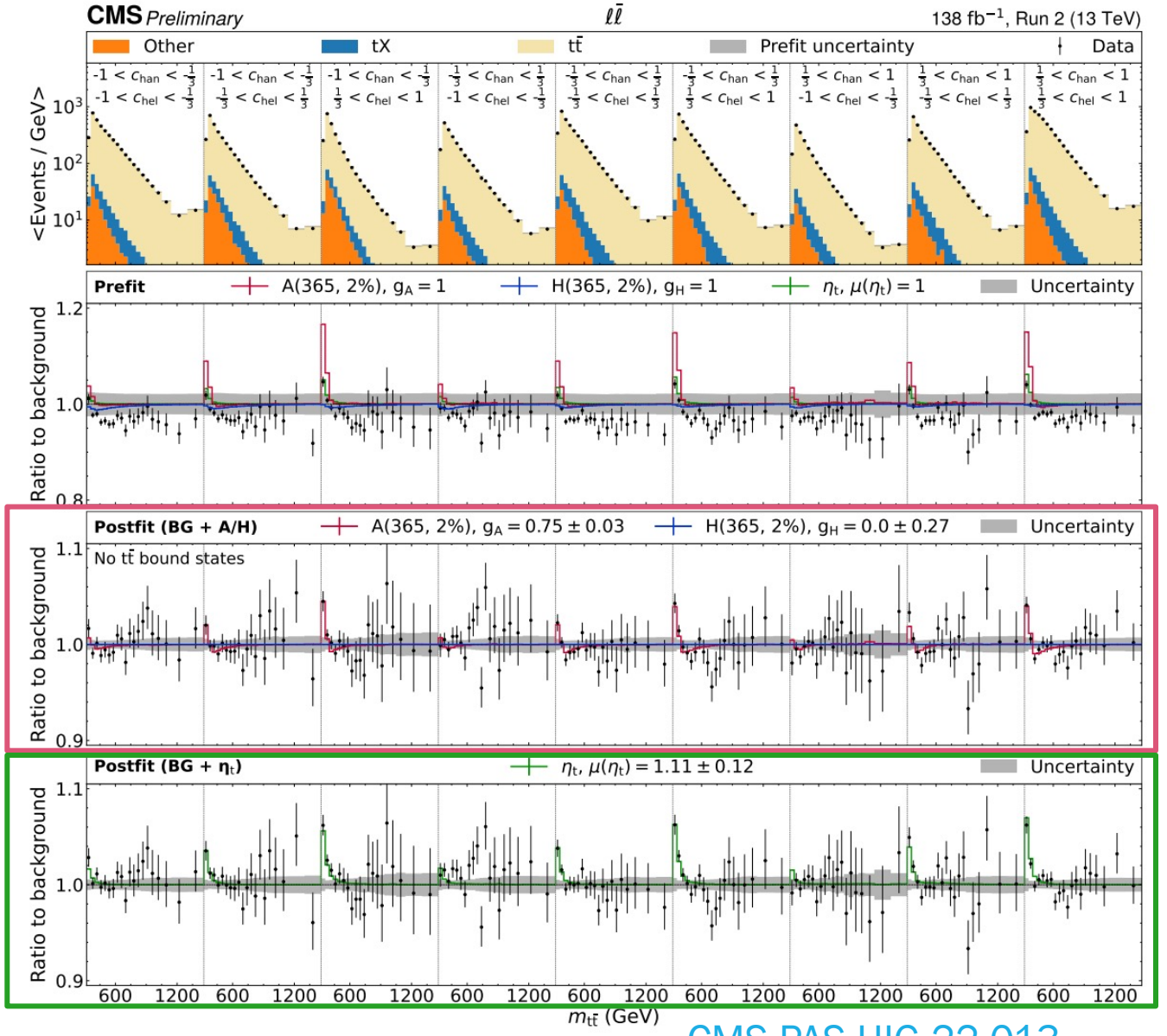
$A/H \rightarrow t\bar{t}$: Results

- Data is compared with **pQCD** predictions alone and including **A/H boson** and/or a pseudoscalar color-singlet $t\bar{t}$ **bound state** (η_t) from a simplified model of non-relativistic QCD (Fuks et al. arXiv:2102.11281)
- **> 5σ deviation** with respect to bkg-only

A/H interpretation: data are better described by A signal hypothesis

η_t interpretation:

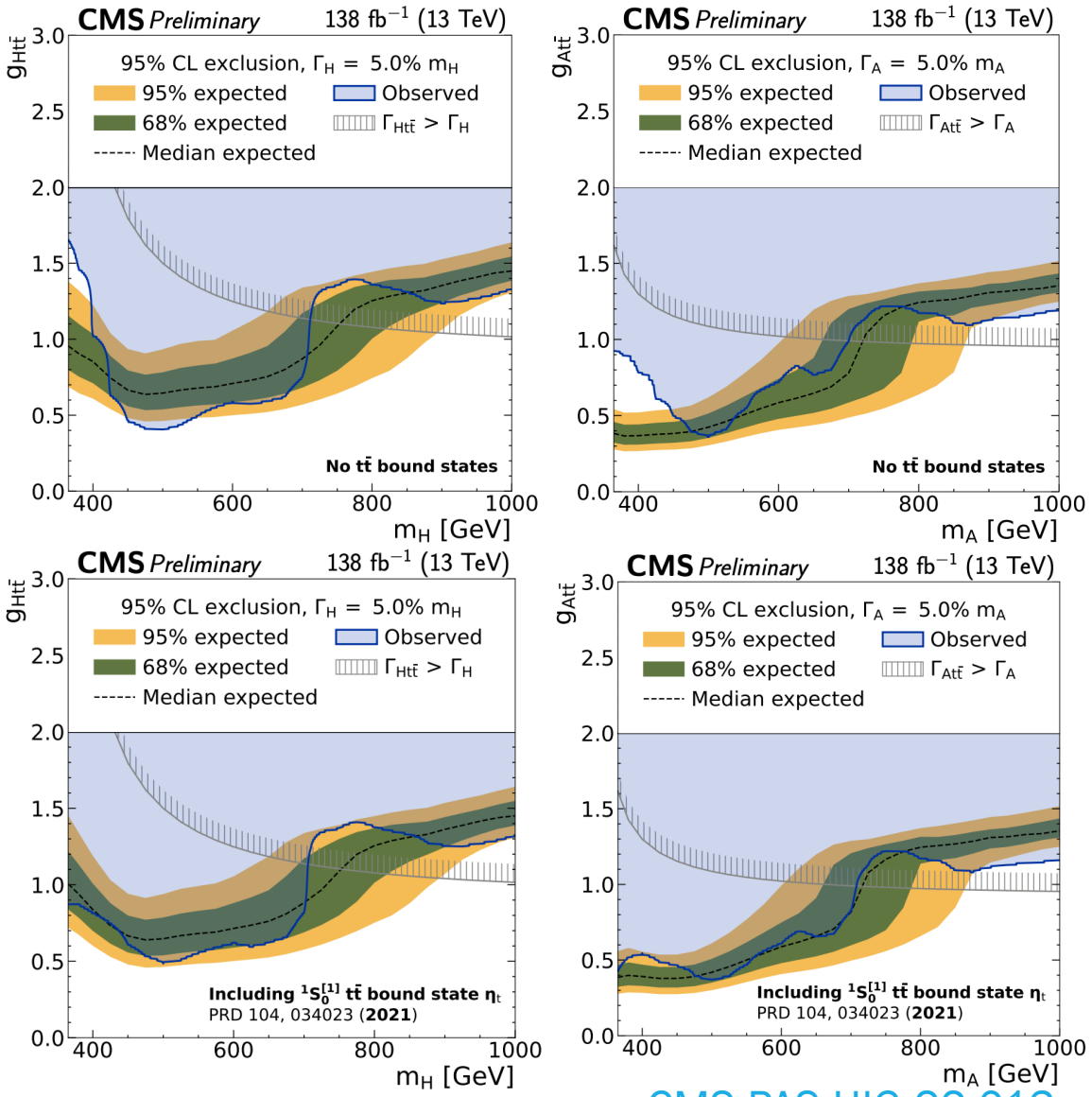
$\sigma(\eta_t) = 7.14 \pm 0.77$pb (th. 6.42 pb)



CMS-PAS-HIG-22-013

$A/H \rightarrow t\bar{t}$: Results

- Top row: pQCD SM background
  Bottom row: pQCD + η_t
- Including η_t production in bkg prediction leads to good description of observed data, **no hint for new A/H**
- → *Excluded coupling values as low as 0.4 (0.6) for A (H) for masses in 365-1000 GeV and widths 0.5-25%*



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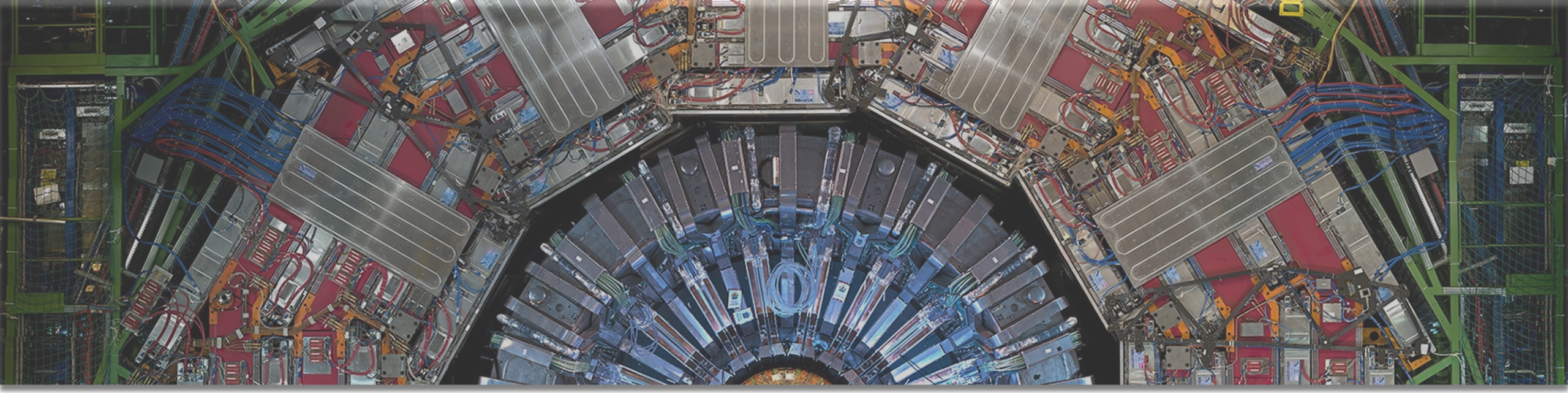
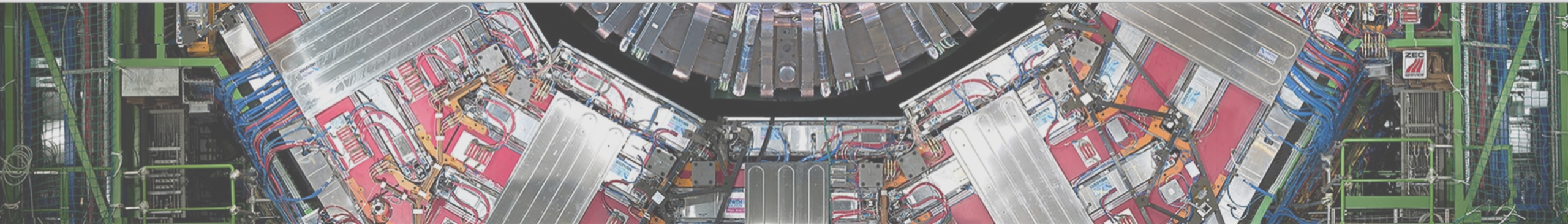


Search for new Higgs bosons via same-sign top quark pair production in association with a jet

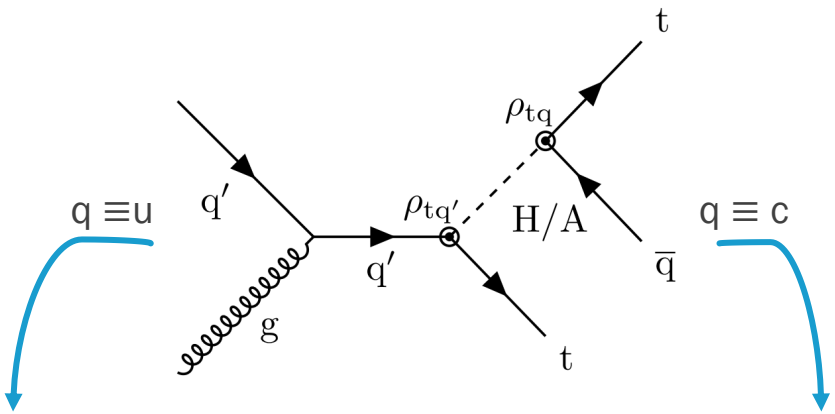
$\mathrm{tH} \rightarrow \mathrm{tt\bar{c}}, \mathrm{tt\bar{u}}$

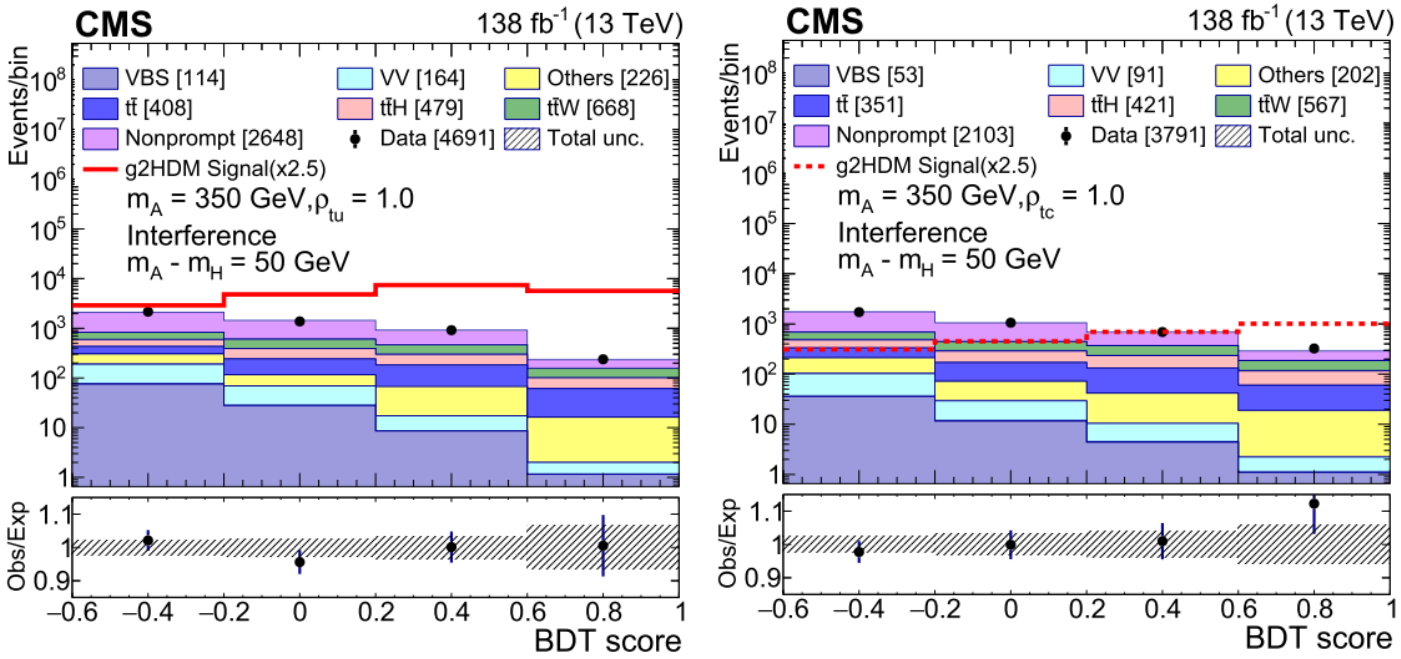


PLB850(2024)138478

$tH \rightarrow tt\bar{c}, tt\bar{u}$: Analysis Strategy

- Scenario of generalized 2HDM (**g2HDM**) with **flavour changing neutral higgs couplings** (with A/H bosons)
- New Yukawa couplings: ρ_{tu} , ρ_{tc}
- Boosted Decision Tree (BDT) score is used to extract the results

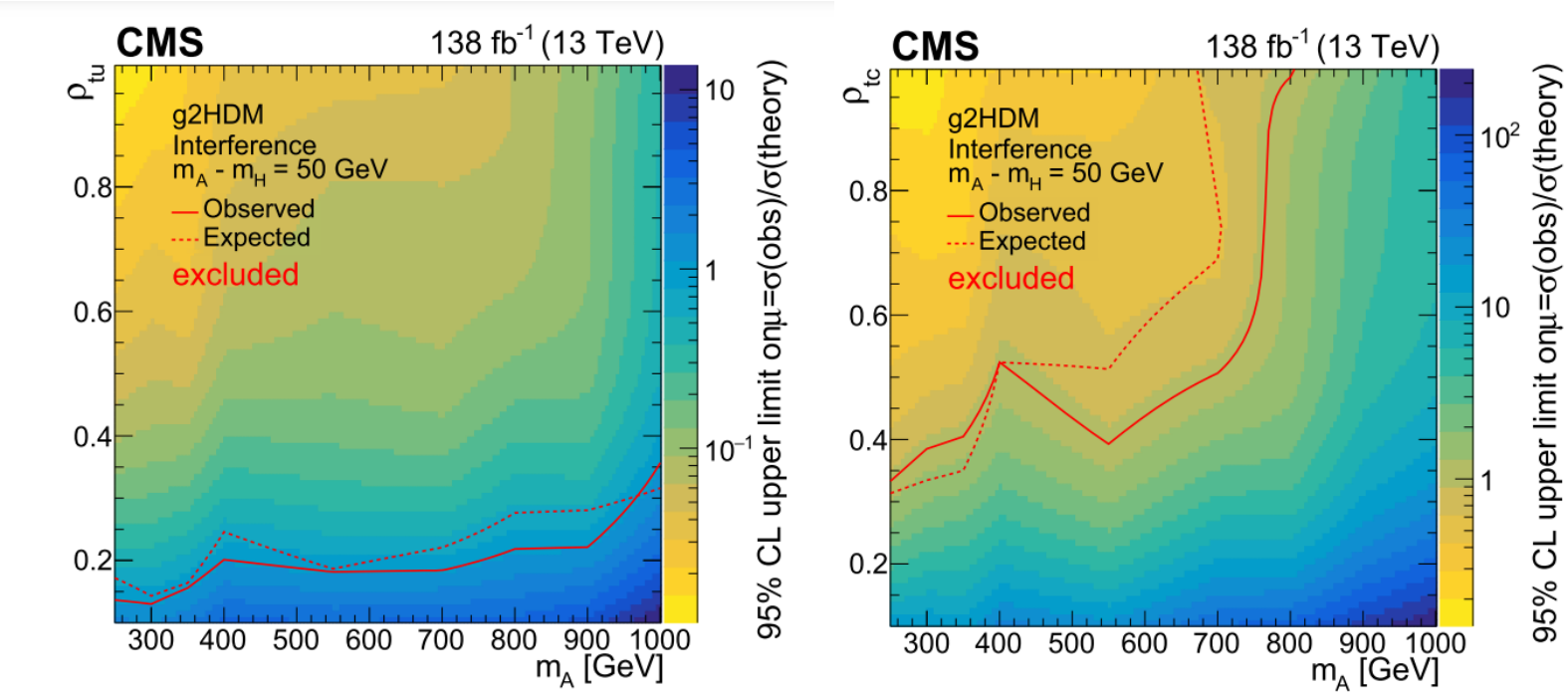


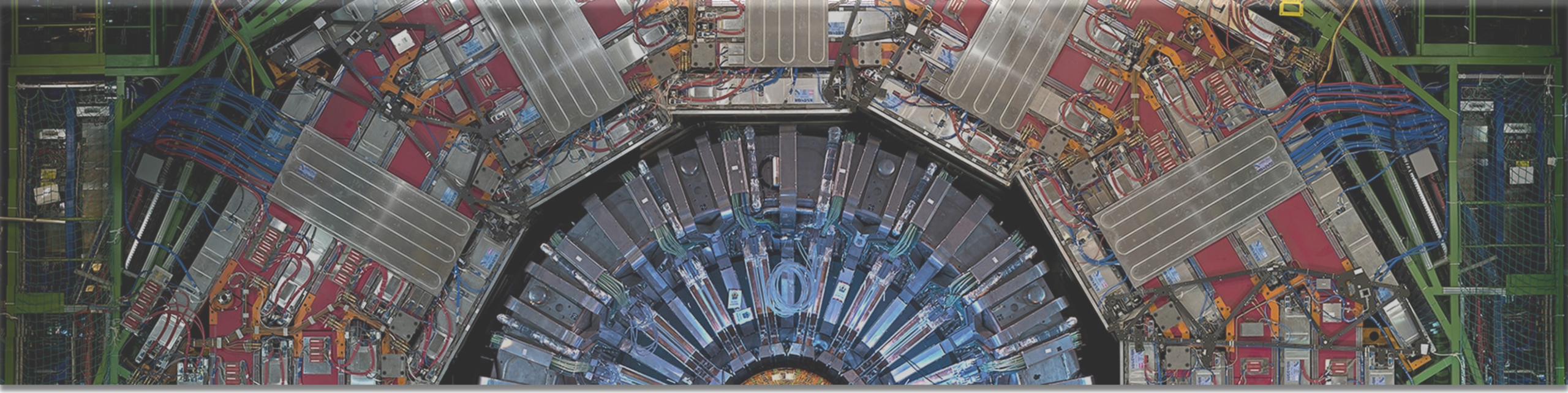


PLB850(2024)138478

$tH \rightarrow t\bar{t}c, t\bar{t}\bar{u}$: Results and Interpretation

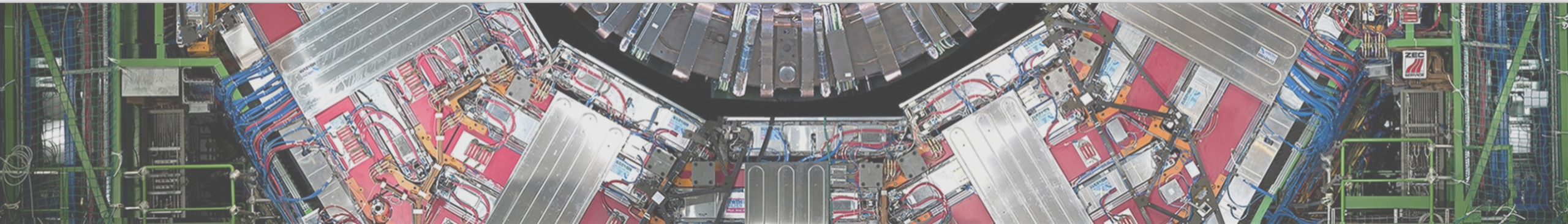
- A-H interference is included, with $m_A - m_H = 50$ GeV
- ρ_{tu} largely excluded, while for ρ_{tc} large region still allowed
- First search based on g2HDM considering A-H interference





Model independent search for pair production of new bosons decaying into muons

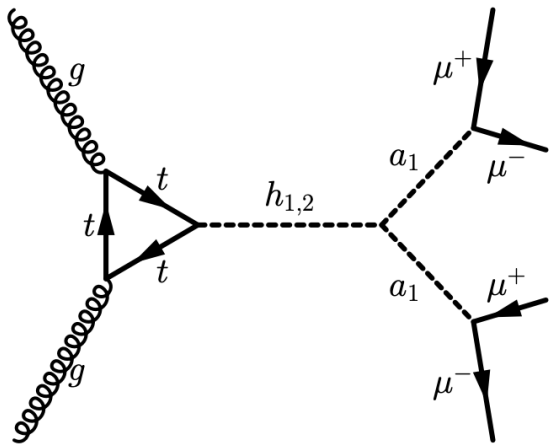
$h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$



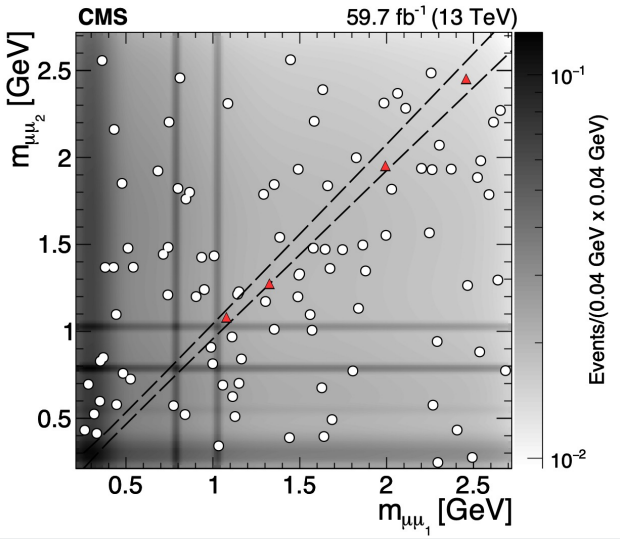
$\mathbf{h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu}$

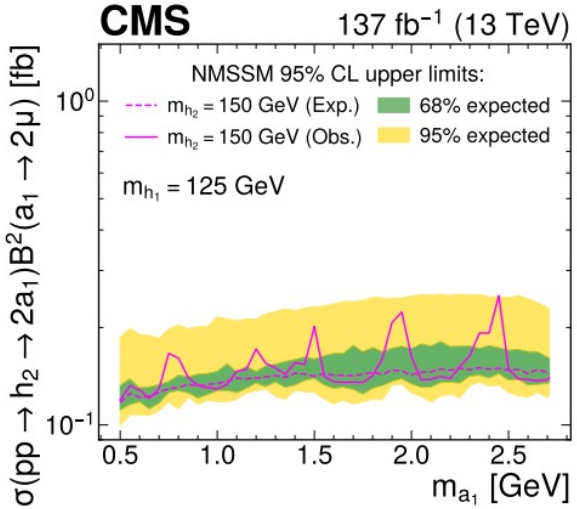
arXiv:2407.20425

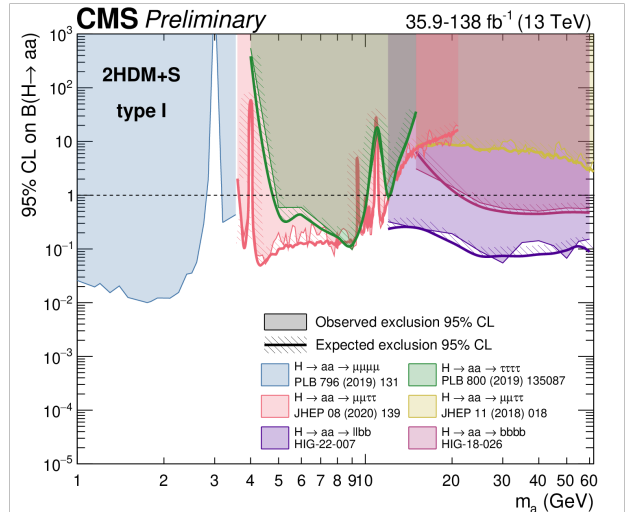
- **Model-independent analysis** with various BSM interpretation: here **NMSSM**
- 2D $(m_{\mu\mu_1}, m_{\mu\mu_2})$ window is defined for SR
- Event distribution is consistent with SM expectation



NMSSM





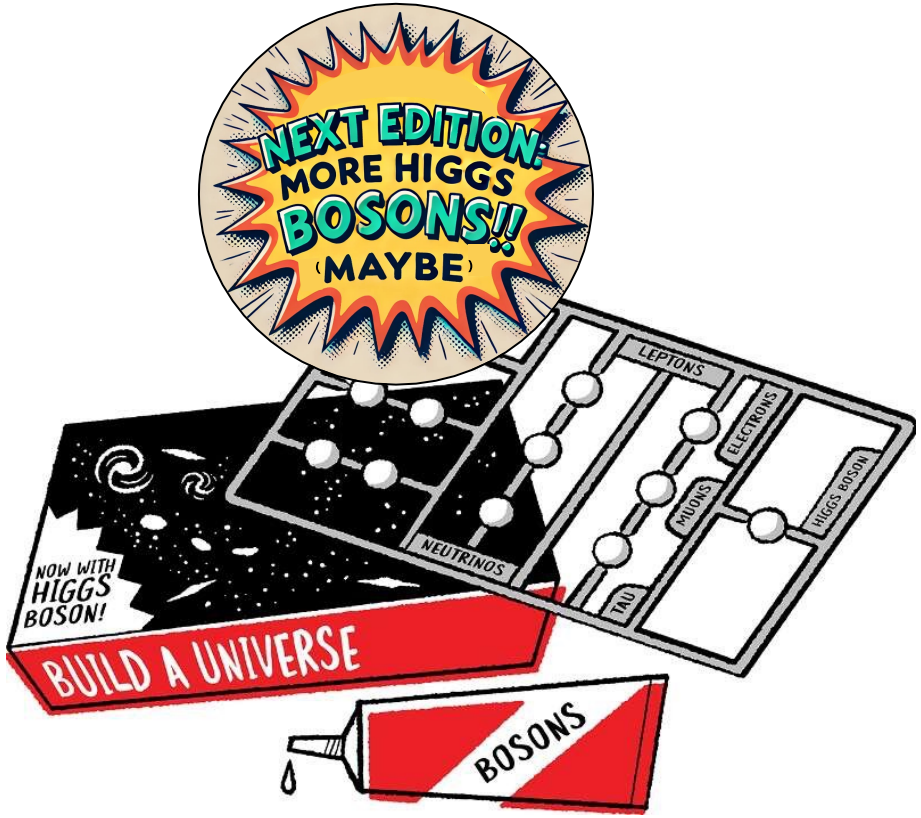


Summary plot of 2HDM+S searches

Summary

- Searches for Extended Higgs Sectors are an essential part of the CMS program at LHC
- Several benchmark models very well physics motivated are tested
- Tighter experimental constraints on model parameters are derived
- *Many interesting results, more yet to come (Run3 in the working)!*

Thanks for the attention!



BACKUP

$A/H \rightarrow t\bar{t}$: spin correlation variables in the dileptonic channel

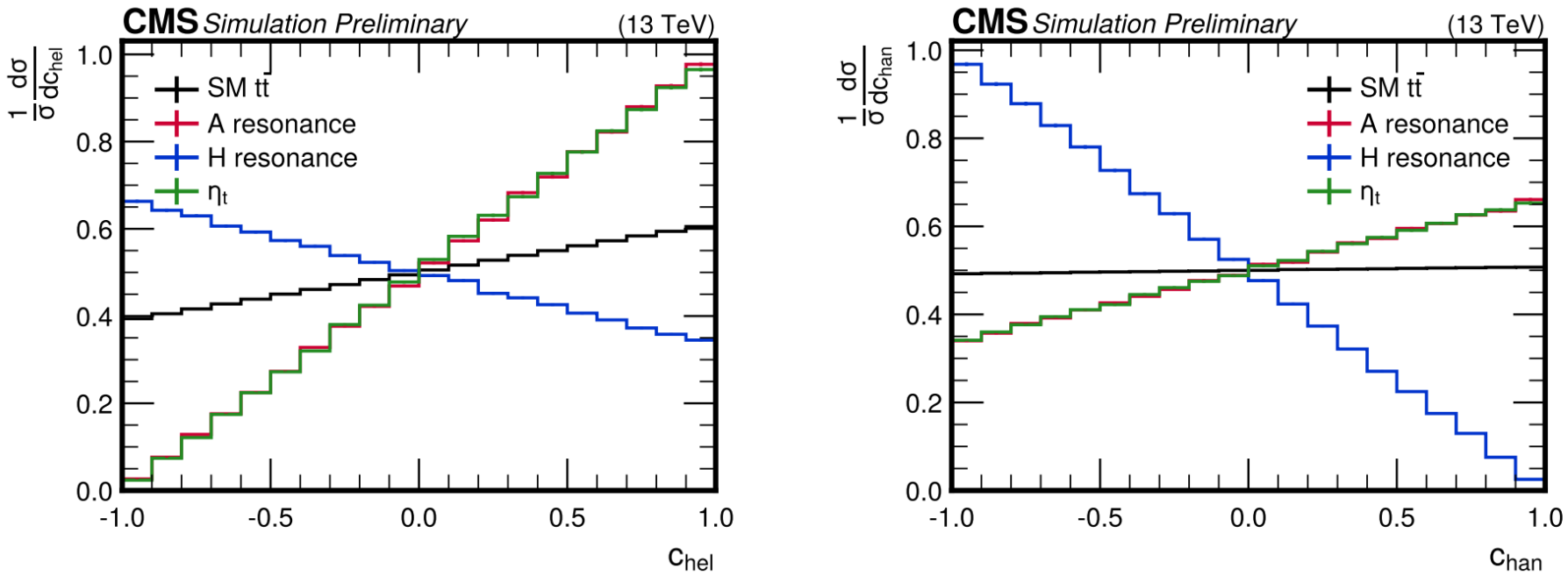
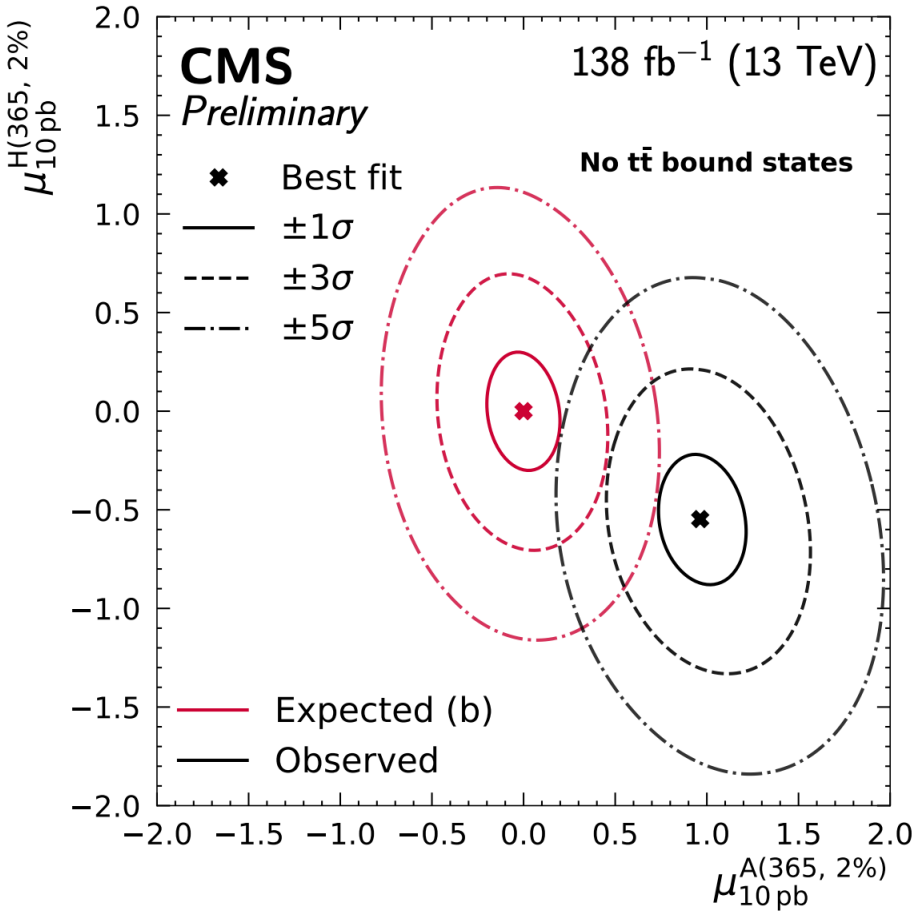


Figure 2: Normalized differential cross sections in the spin correlation observables c_{hel} (left) and c_{han} (right) at the parton level in the $\ell\bar{\ell}$ channel, with no requirements on acceptance, for SM $t\bar{t}$ (black), resonant A (red), resonant H (blue), η_t (green) production.

$A/H \rightarrow t\bar{t}$: characterization of the deviation in the $t\bar{t}$ threshold region

- A modified A+H interpretation is performed, assuming the pQCD-only background model and using the A/H(365, 2%) signal configuration.
- Only the resonant component of the signal model is used, and both the A and H contributions are independently normalized to an arbitrary nominal cross section of 10 pb



$A/H \rightarrow t\bar{t}$: checks

- c_{hel} and c_{han} in the low m_{tt} slice
- Compatible results