Searches in the BSM Higgs Sector with Run 2 Data

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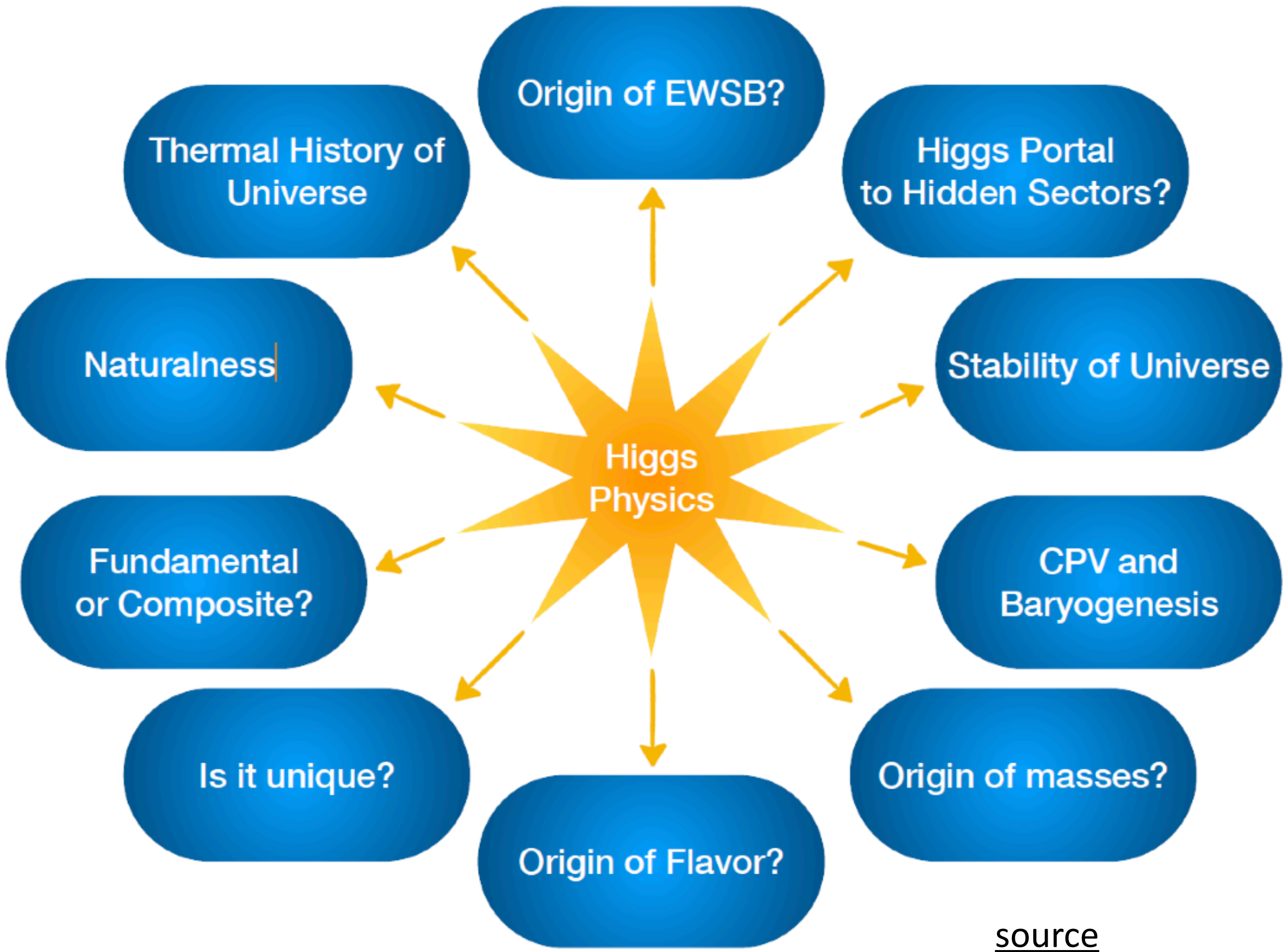
on behalf of the ATLAS and CMS Collaborations
23 - 30 March 2025

59th Rencontres de Moriond, Electroweak Interactions & Unified Theories

Motivation

- **SM** fails to explain phenomena like
  - Dark matter and dark energy
  - Matter-antimatter asymmetry
  - Strong CP problem and some other phenomena
- **Extended Higgs sector** provides some answers
  - Dark matter candidate
  - Additional sources of CP violation
- Some **popular extensions**
  - Extra scalar singlets
  - Extra doublets
  - Triplets, …
- Large portion of parameter space can be **tested at LHC**



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Extended Higgs Sector Models

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Additional Singlet

- Simplest extension, S: real singlet scalar
- Higgs portal → connection to dark sector
- Free parameters: mass of S, mixing angle α
- Couplings inherited from SM Higgs suppressed by $\sin\alpha$

Additional Singlet + Doublet

- 2HDM extended with a complex singlet
- Additional CP-odd/even scalars wrt 2HDM
- Example: next-to-minimal supersymmetric SM (NMSSM)

Additional Doublet

- Two Higgs Doublet Models (2HDM): additional SU(2) doublet
- Required by SUSY
- Free parameters: masses of additional states, mixing angle α, ratio of two VEVs $\tan\beta$
- 5 physical scalar states: two neutral CP-even (H, h), one neutral CP-odd (A) and two charged ($H^{\pm}$)
- Alignment limit $\cos(\beta-\alpha)\to 0$: $h \equiv h_{125}$
- Yukawa couplings:

$$\lambda_f^{SM} = \frac{\sqrt{2}}{v} m_f, \quad \lambda_f^{BSM} = \frac{n_f}{\tan\beta}\lambda_f^{SM}$$

	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

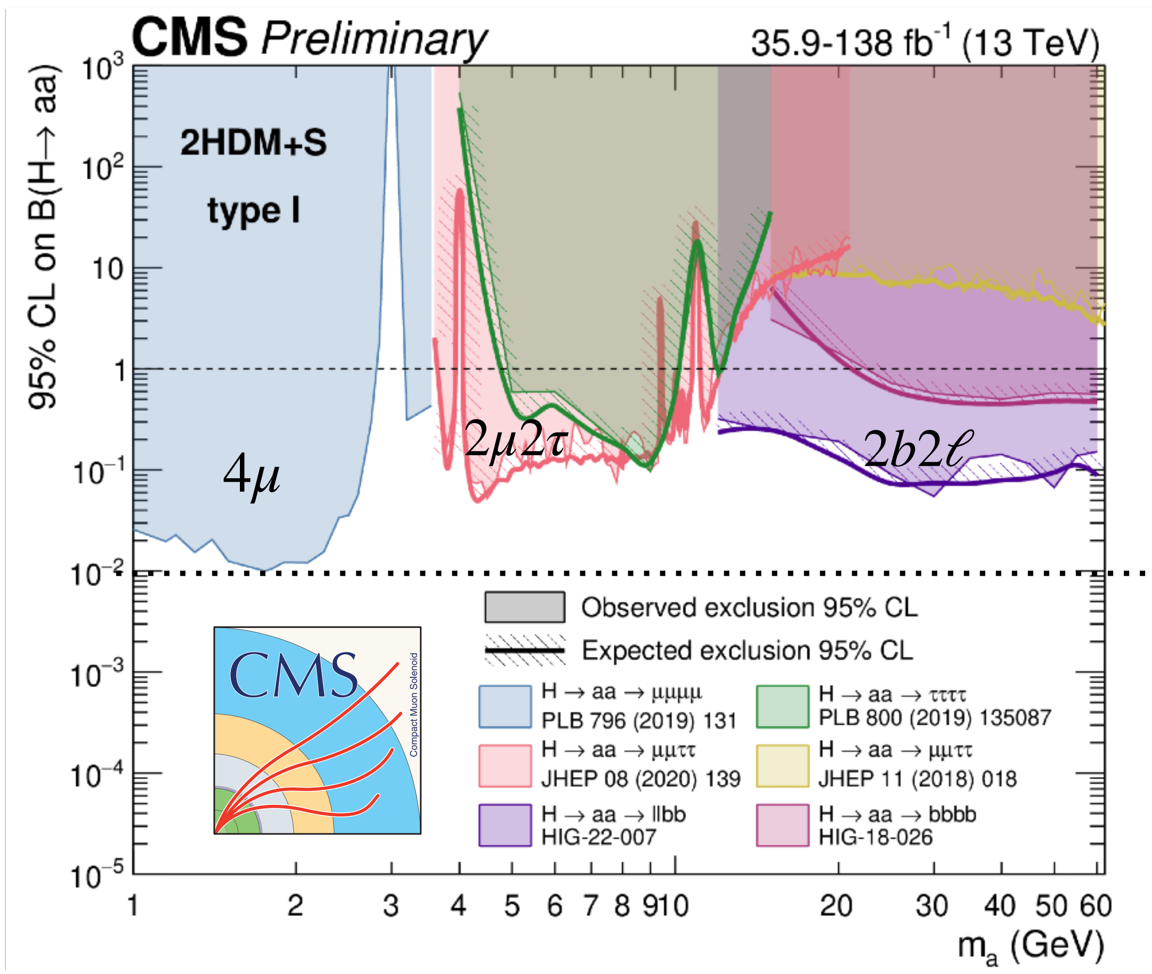
2HDM+S State of the Art

2HDM+S CMS Summary Plots

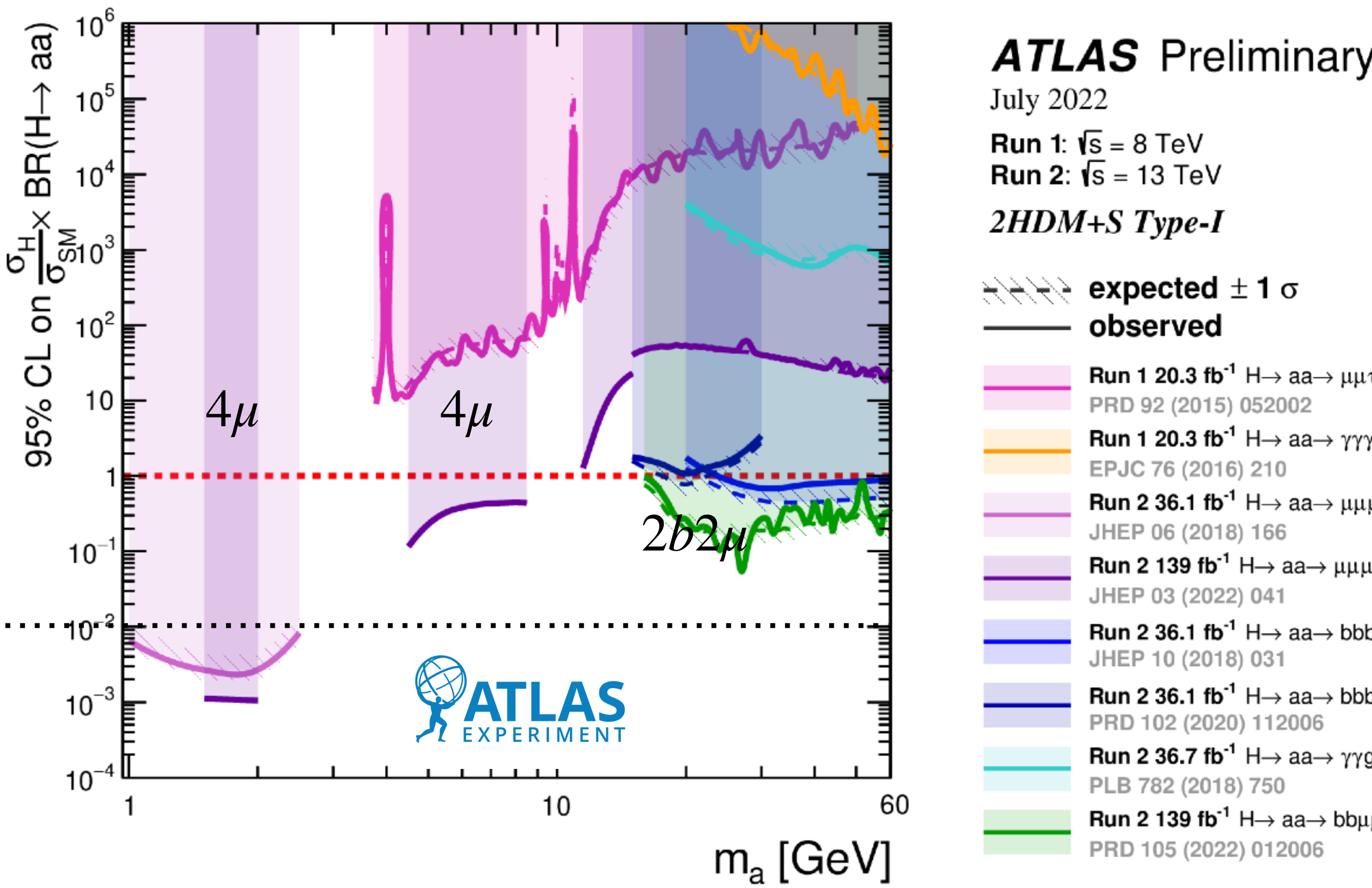
ATL-PHYS-PUB-2025-011

$$95\% \text{ CL on } \frac{\sigma(H)}{\sigma_{SM}} \times \mathscr{B}(H \to aa)$$

BR to SM particles calculated following arxiv:1312.4992



2HDM+S Type I

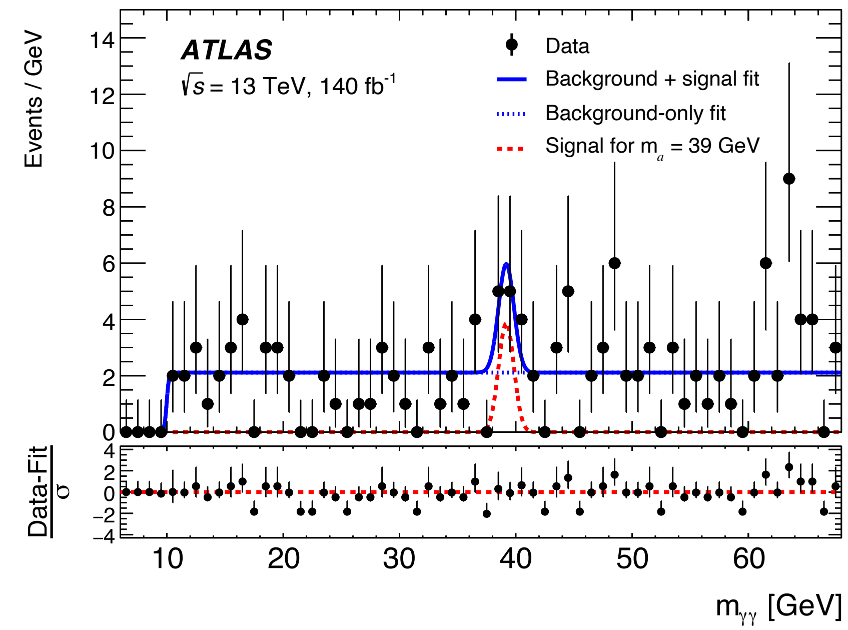


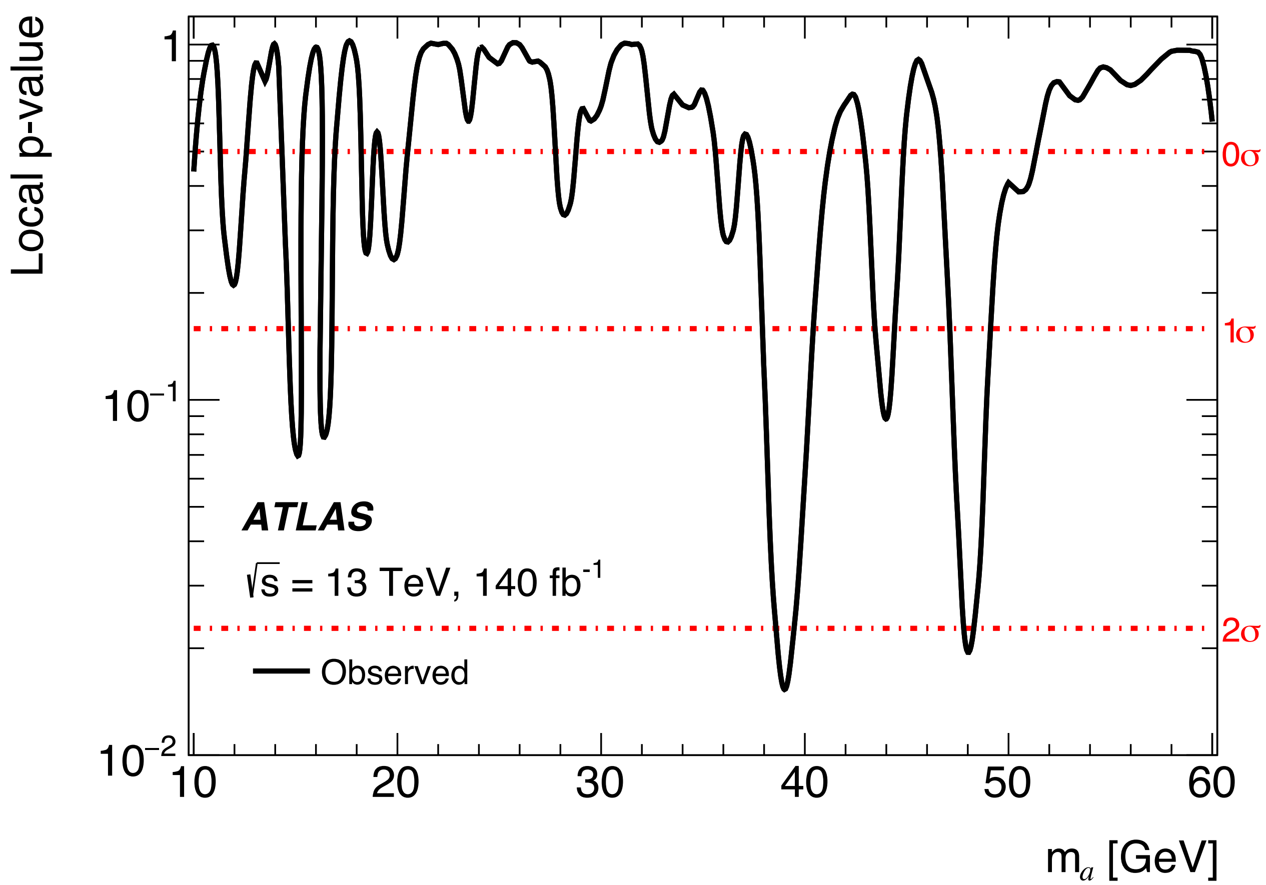
Light Higgs Searches

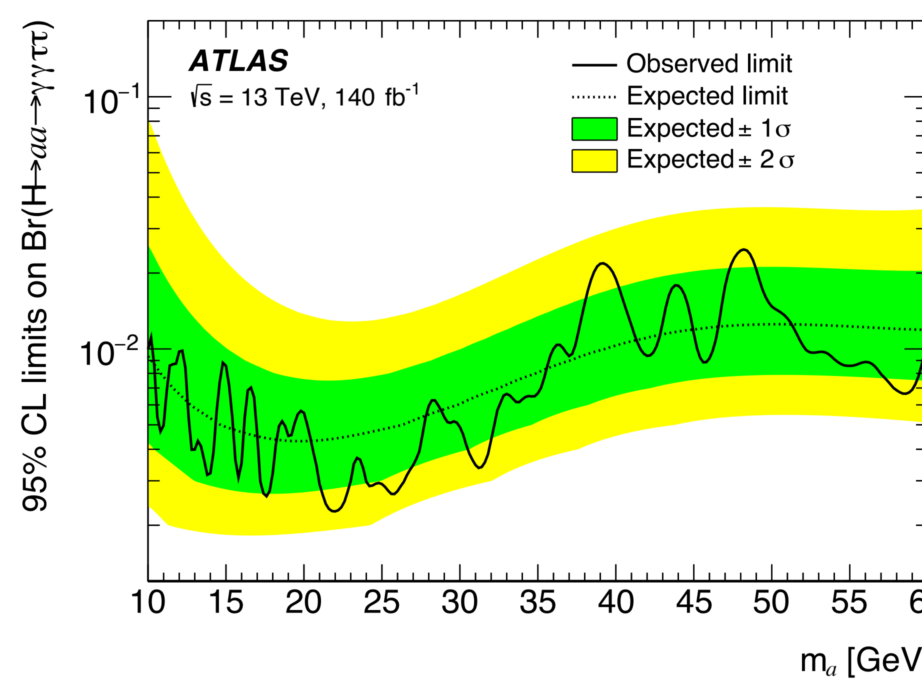
$\mathbf{H \to aa \to 2\gamma 2\tau}$

arXiv:2412.14046 (submitted to JHEP)

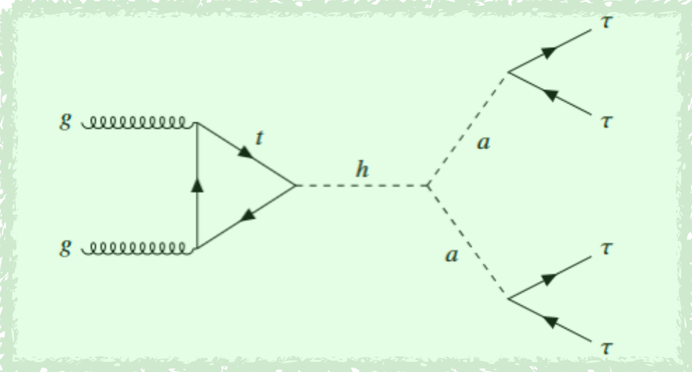
- **First search** in $\gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$ final state at LHC
- Light pseudoscalar a pair-produced in 125 GeV Higgs decay
  - $10 < m_a < 60$ GeV, best sensitivity < 35 GeV
- BDT to identify di-τ system at high p_{T}
- Largest excess at 39 and 48 GeV around 2σ







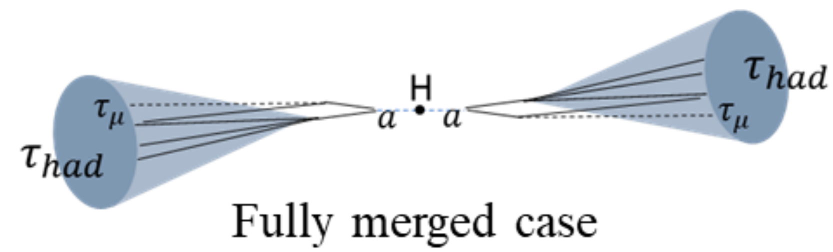
Limits on $\mathscr{B}(H \to aa \to \gamma\gamma\tau\tau)$ range from 0.2% to 2%

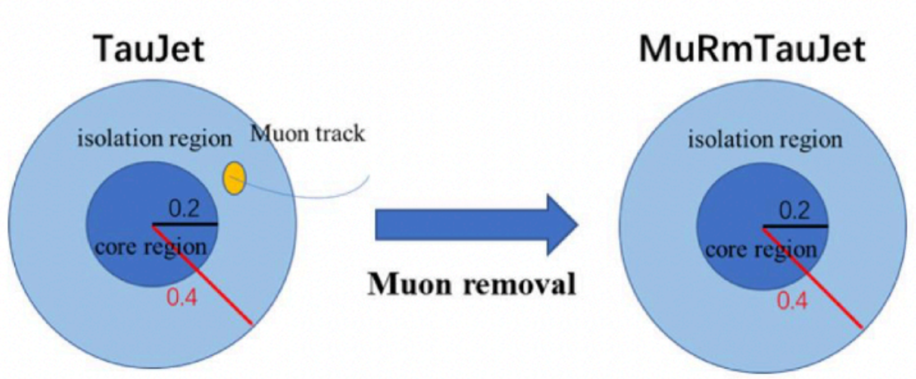


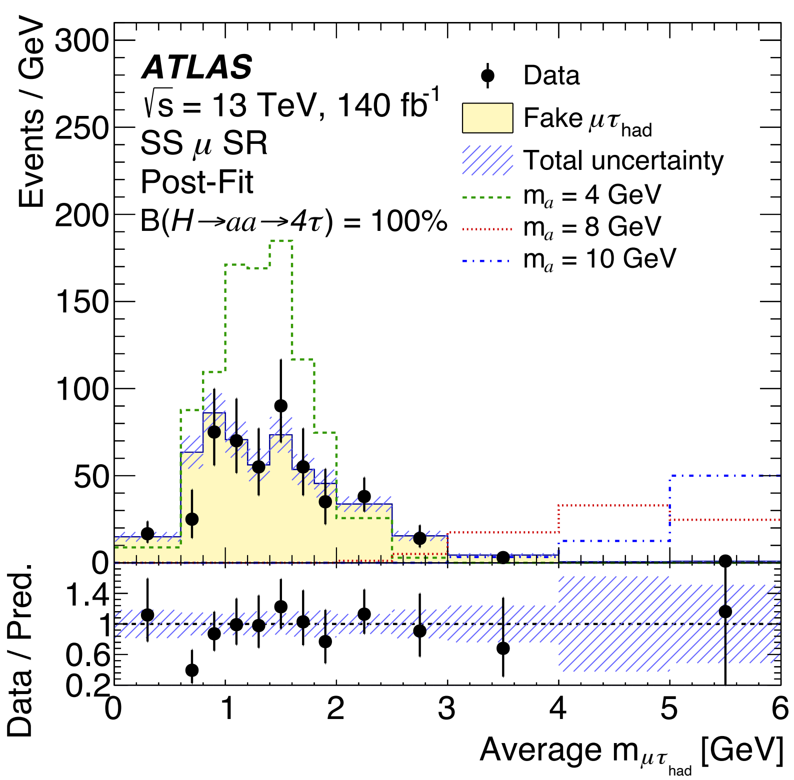
$H \to aa \to 4\tau$

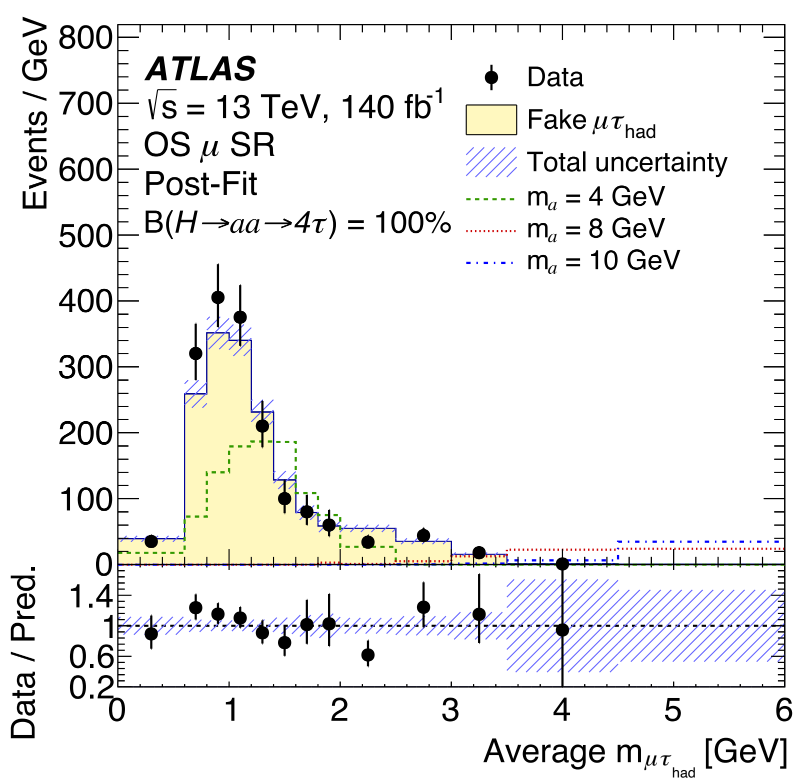
arXiv:2503.05463 (submitted to PLB)
Briefing: Learning From Tau

- Focus on the **low mass** $4 < m_a < 15$ GeV and $a \to \tau_\mu \tau_{had}$ decay
  - Dedicated μ-removal technique
- Non-prompt/fake bkg from data
  - Prompt bkg from MC, negligible
- No excess found
  - Fake bkg prediction agrees well with data

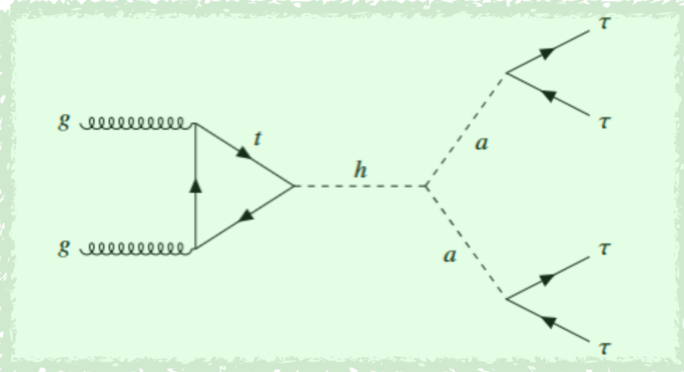








Process	SSμ region	OSμ region
Data	121	380
Fake-τ_{had} background	129 ± 12	350 ± 31
$q\bar{q} \to ZZ$ and $gg \to ZZ$	< 0.01	< 0.01
$H \to ZZ^*$	< 0.01	0.09 ± 0.04
Total background	129 ± 12	350 ± 31
$H \to aa \to 4\tau$ (m_a = 4 GeV)	20.2 ± 3.2	21.4 ± 3.3
$H \to aa \to 4\tau$ (m_a = 6 GeV)	9.7 ± 1.5	10.7 ± 1.7
$H \to aa \to 4\tau$ (m_a = 8 GeV)	7.8 ± 1.3	6.9 ± 1.1
$H \to aa \to 4\tau$ (m_a = 10 GeV)	6.6 ± 1.1	6.0 ± 1.0
$H \to aa \to 4\tau$ (m_a = 12 GeV)	3.7 ± 0.6	3.9 ± 0.6
$H \to aa \to 4\tau$ (m_a = 14 GeV)	3.1 ± 0.5	2.7 ± 0.5
$H \to aa \to 4\tau$ (m_a = 15 GeV)	2.4 ± 0.4	2.4 ± 0.4



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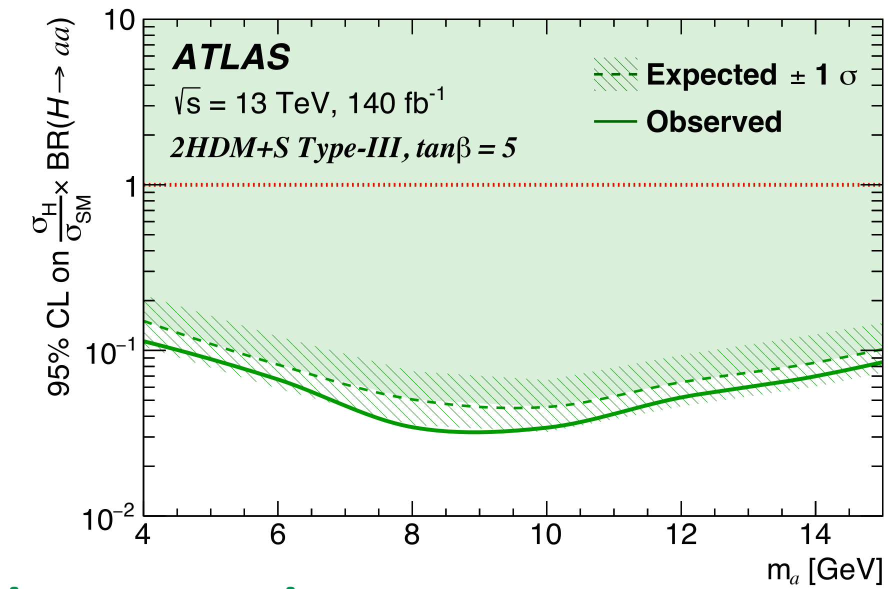
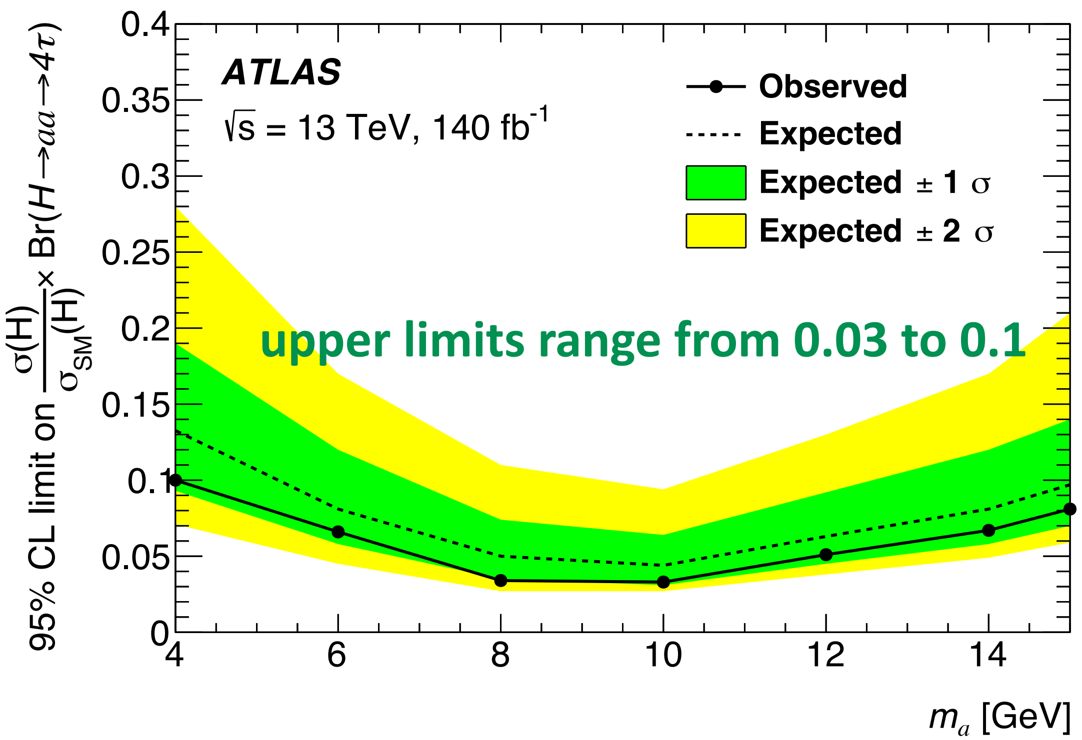
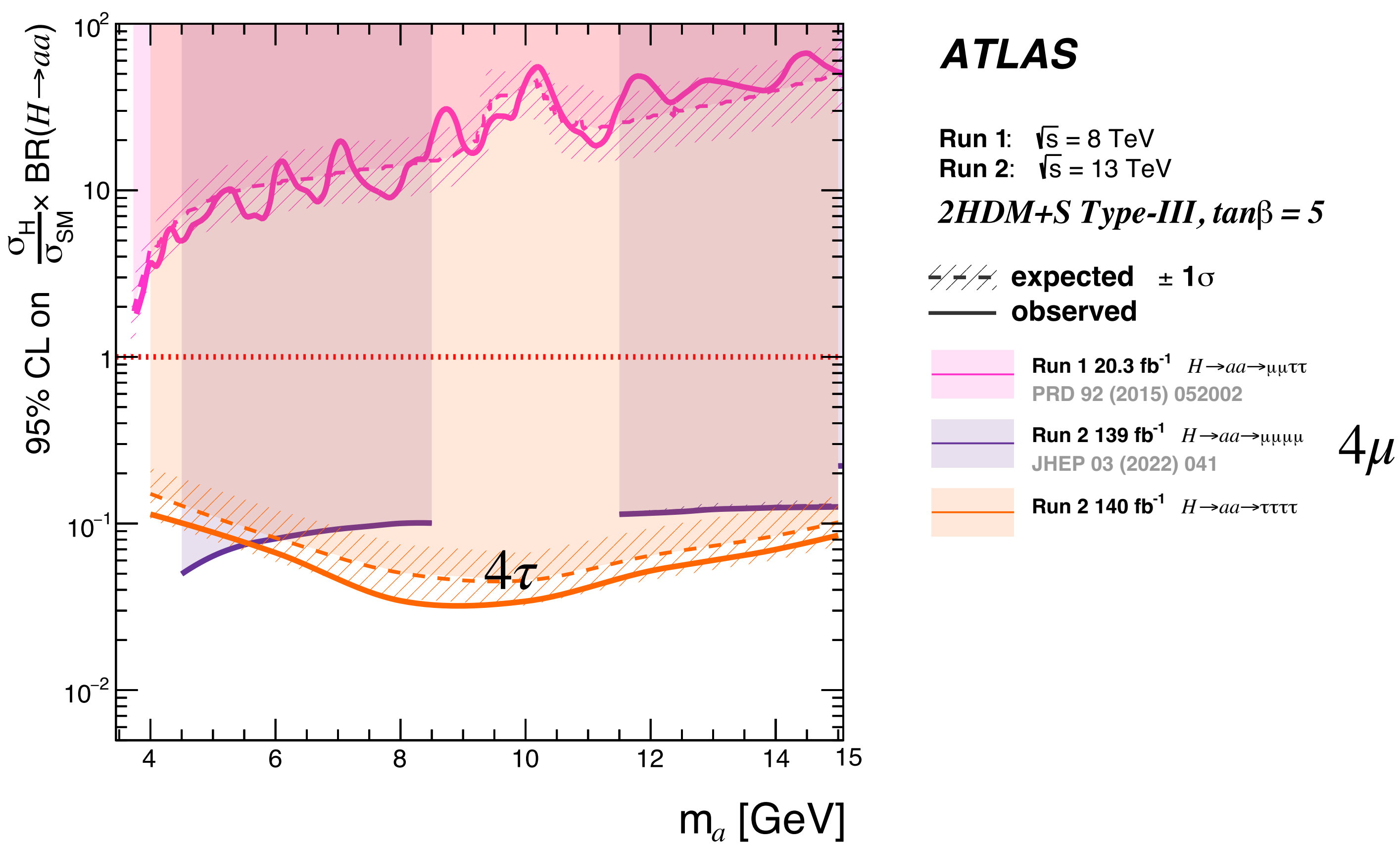
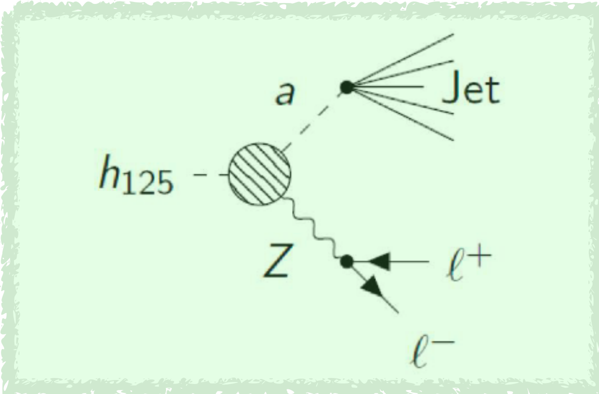


2HDM+S interpretations



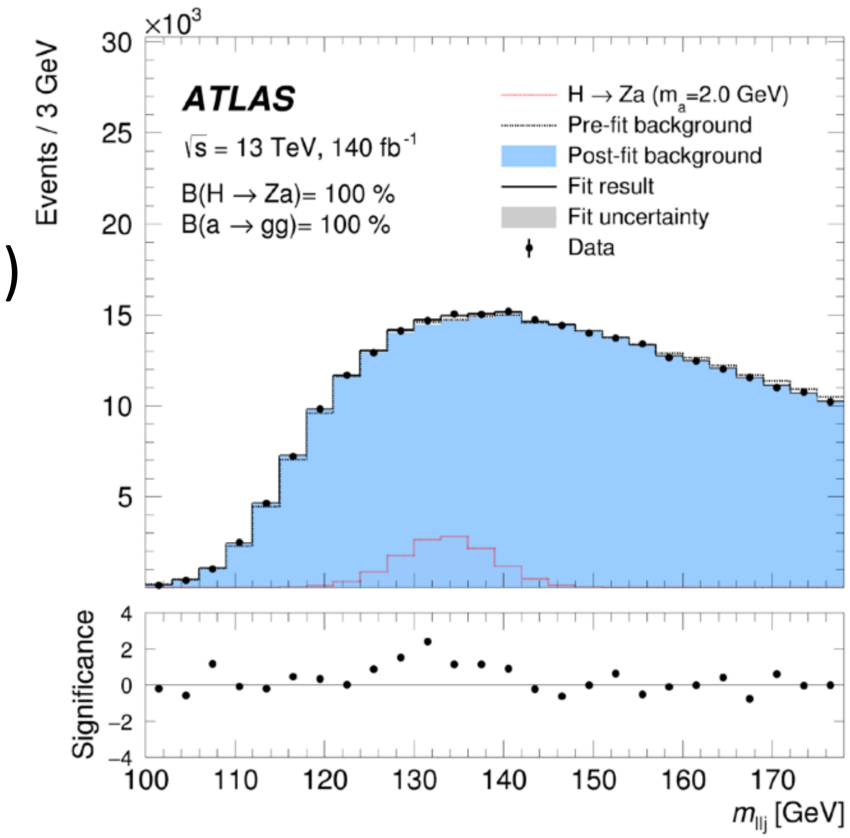


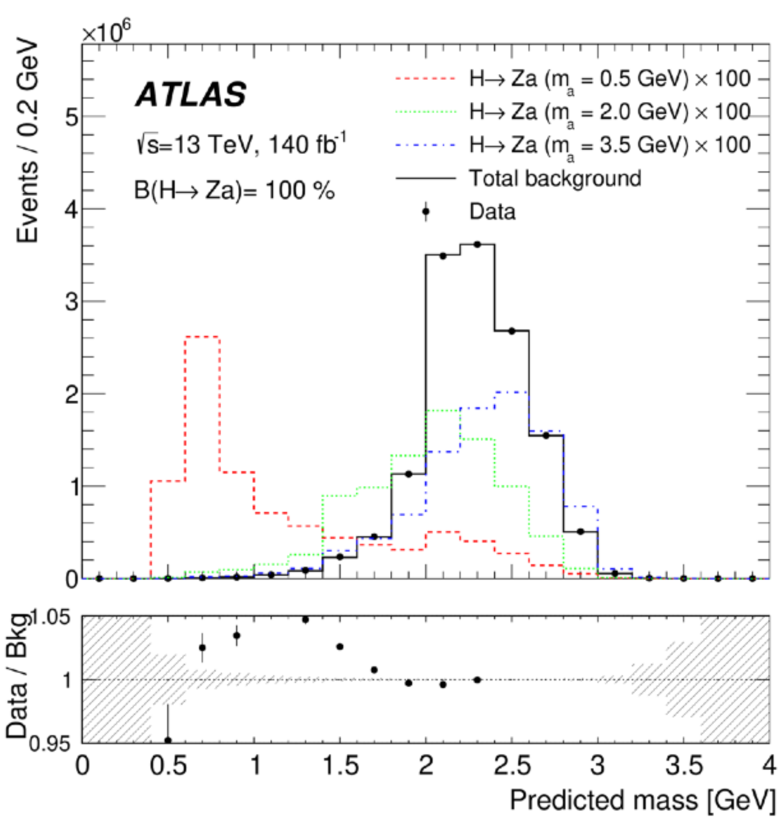


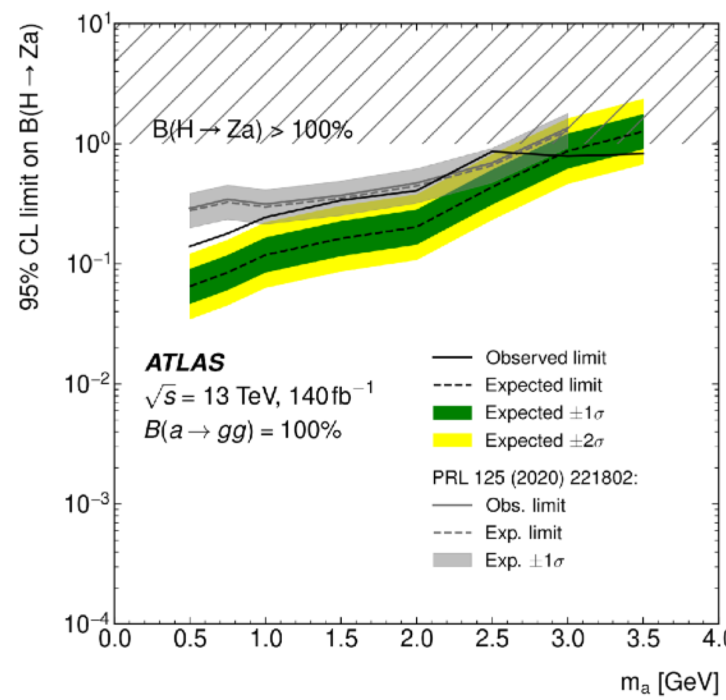
$H \to Za \to \ell\ell + \text{jet}$

arxiv:2411.16361 (submitted to PLB)

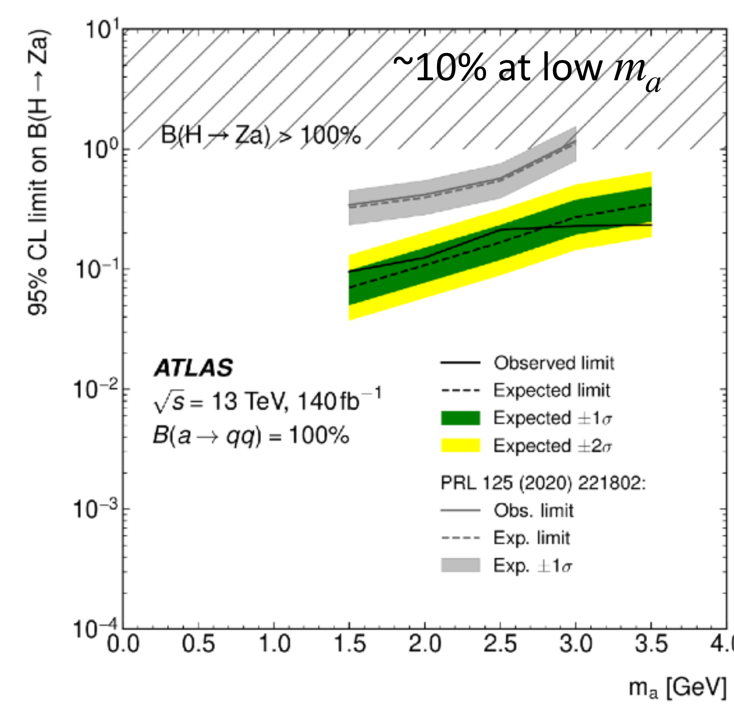
- Search for a light scalar a in the mass range 0.5 - 4 GeV
  - 2HDM + S and axion-like models (DM candidate)
- Hadronic a decays, reconstructed as a single jet (large boost)
- Main bkg: Z+jets, NN to suppress the bkg
- NN-based m_a: jet substructure to improve the jet mass resolution

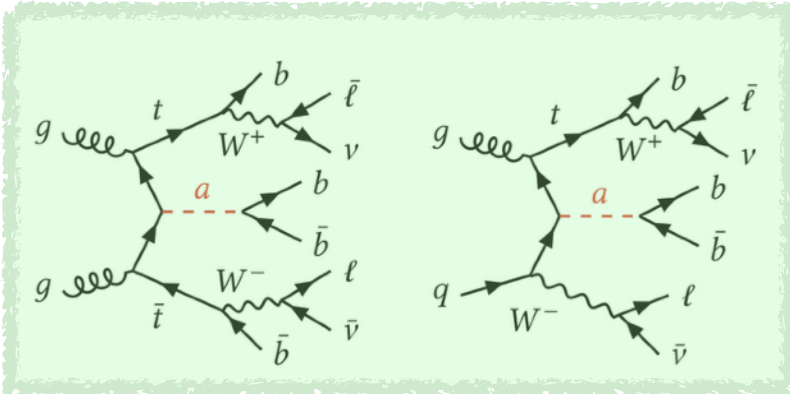






Upper limits on effective coupling $C_{ZH}^{\text{eff}}/\Lambda$ range from 0.9 to 2 TeV^{-1}





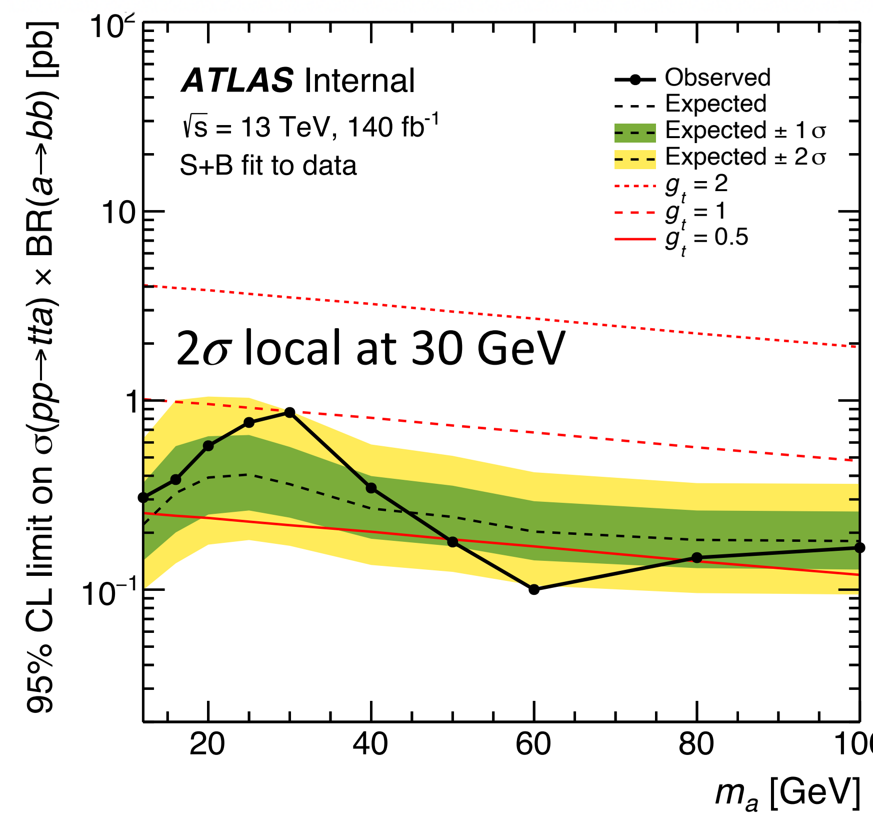
$t\bar{t}a,\, a \to b\bar{b}$ Search

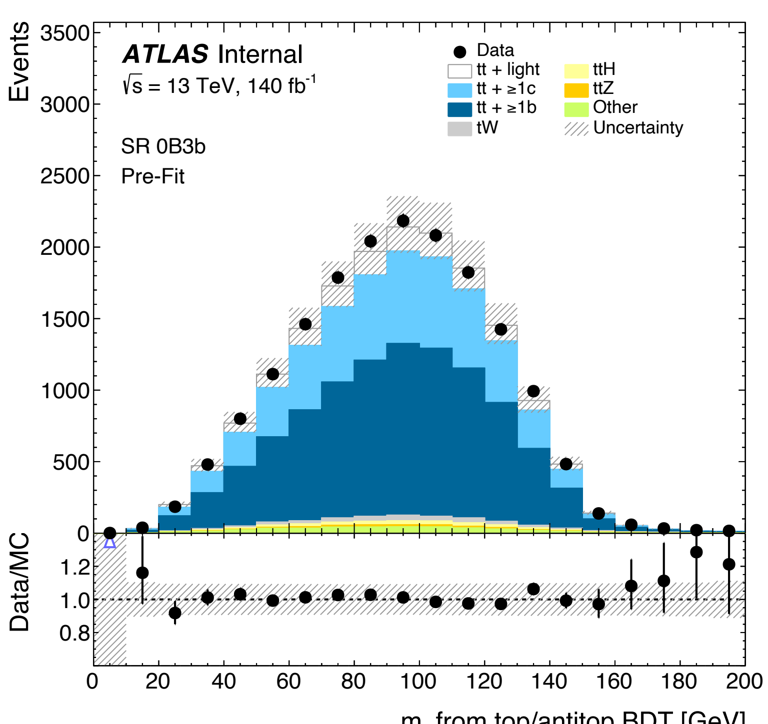
arXiv:2503.17254 (submitted to EPJC)

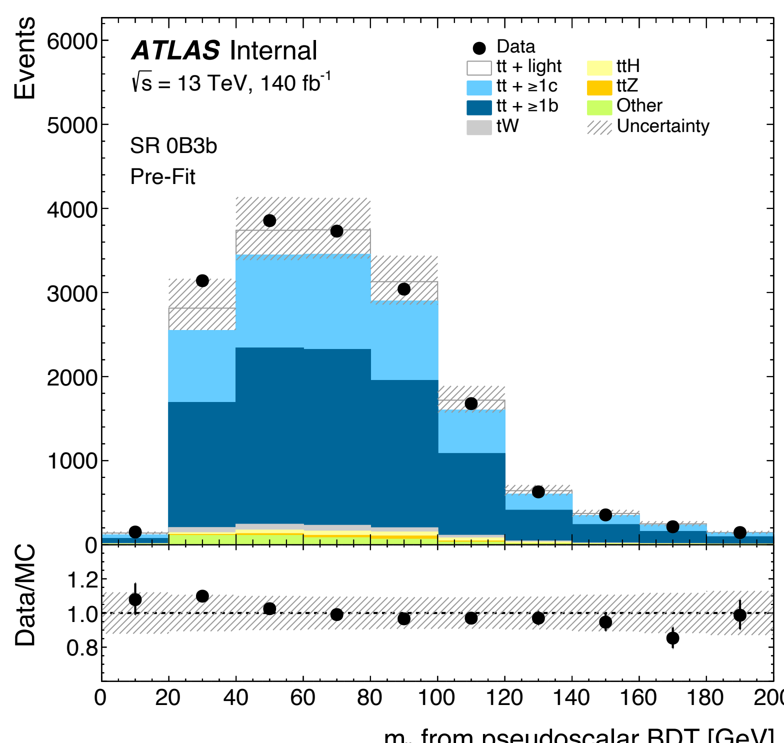
- **First $t\bar{t}a,\, a \to b\bar{b}$ search** at LHC
  - $t\bar{t}a$ and tWa production modes, 2ℓ final state
  - Targets $12 < m_a < 100$ GeV
- MVAs for event reconstruction and signal vs bkg discrimination
  - BDTs for $t \to \ell j$ and $a \to jj$ reconstruction
  - Mass-parametrised NN for signal classification
- Data-driven correction of main $t\bar{t}$+jets bkg

Simplified model

$$\mathcal{L} \ni \frac{g_t y_t}{\sqrt{2}}\bar{t}(i\gamma^5)at + \frac{g_b y_b}{\sqrt{2}}\bar{b}(i\gamma^5)ab$$



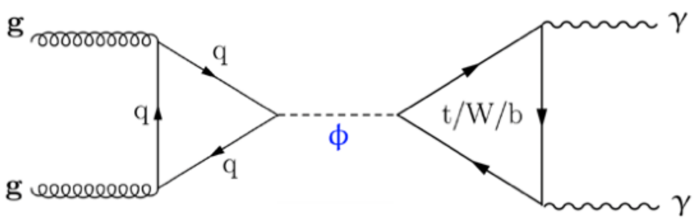




No significant excess over SM bkg

Upper limits at 95% CL

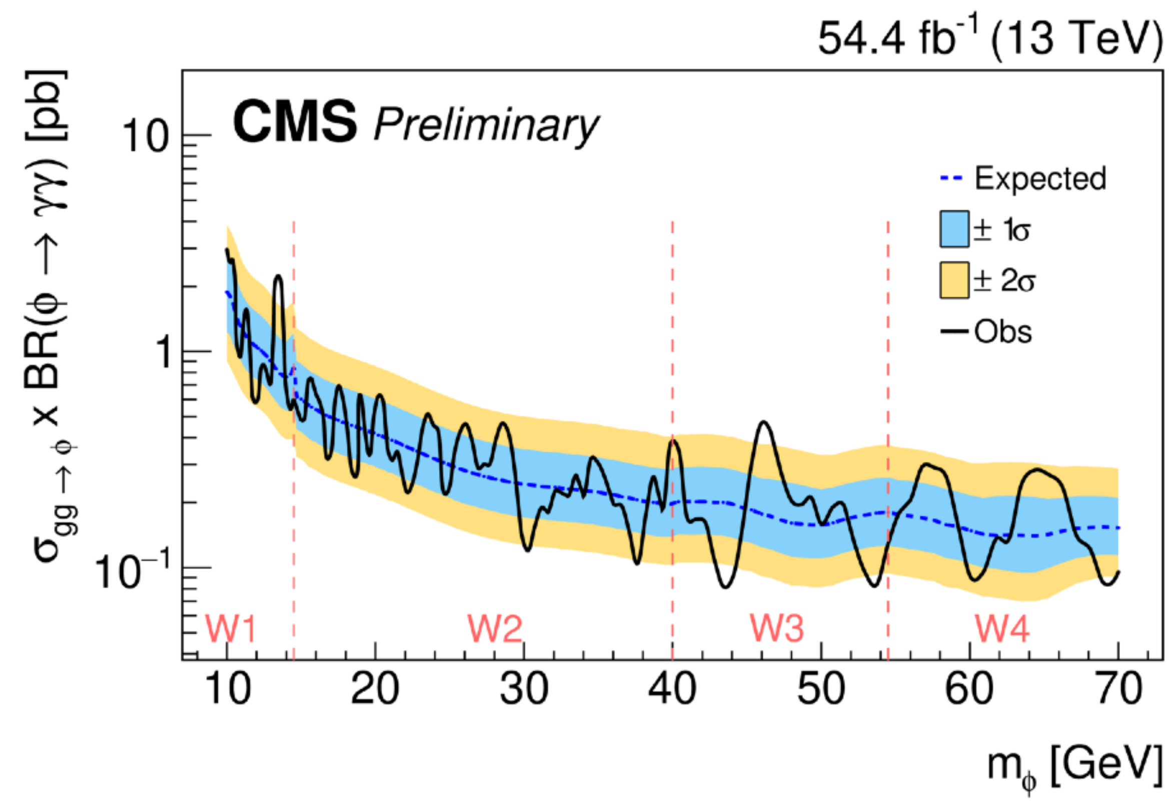
$\sigma(pp \to tta) \times \mathscr{B}(a \to bb)$ range from 0.1 to 0.9 pb

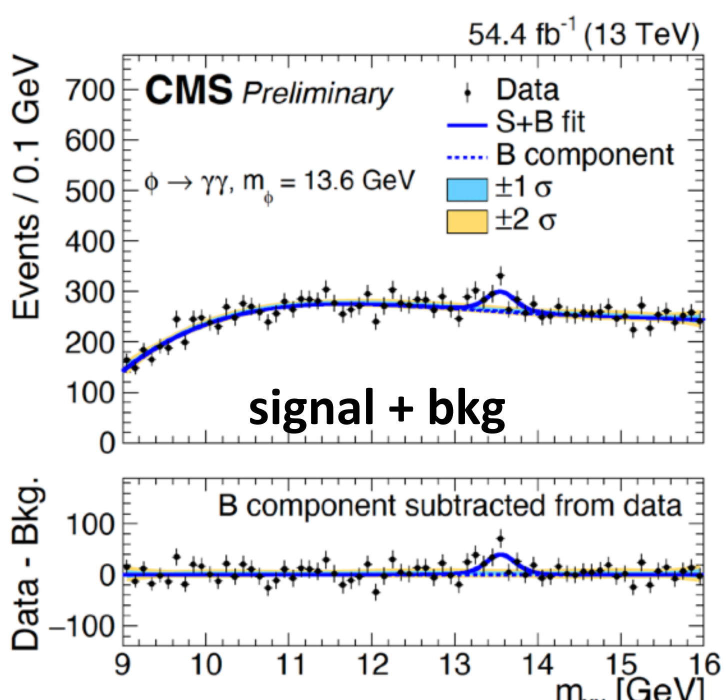


$H \rightarrow \gamma\gamma$ Low Mass Search

CMS-PAS-HIG-24-014

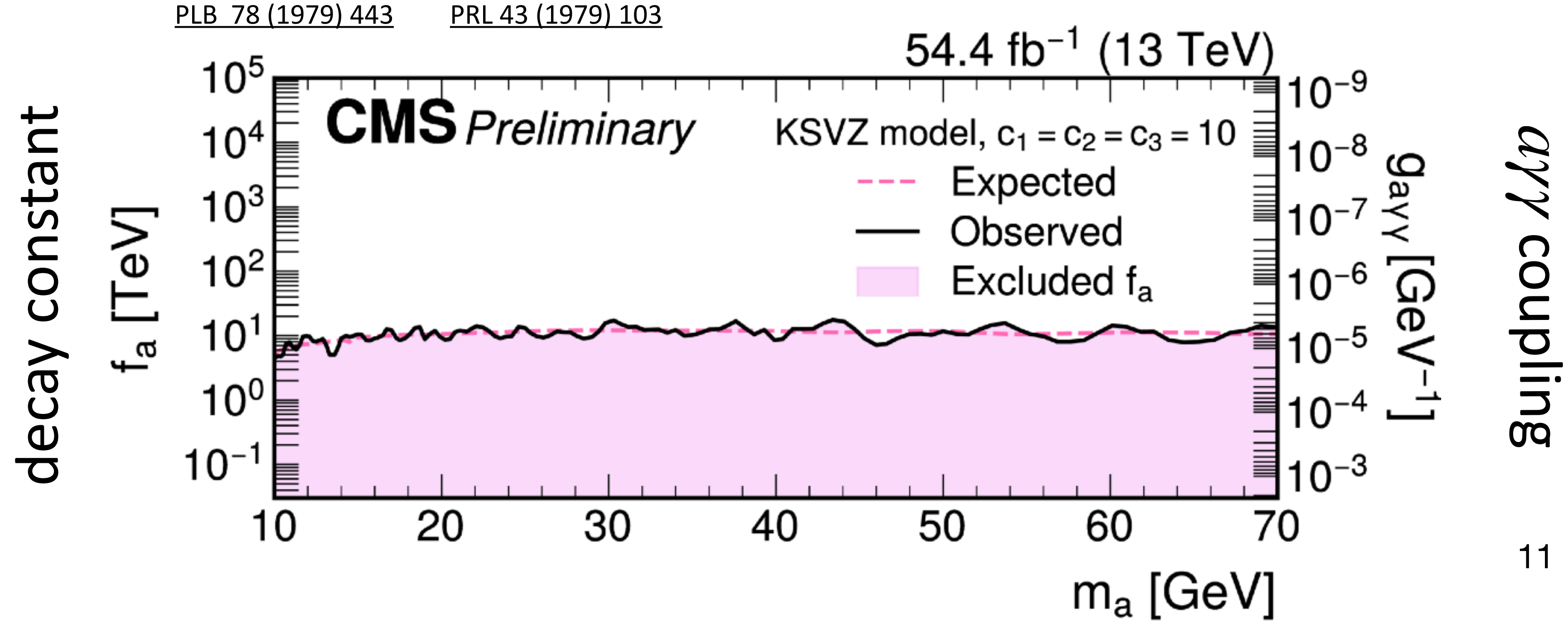
- Focus on $10 < m_{\gamma\gamma} < 70\,\mathrm{GeV}$
  - New di-photon trigger in 2018 with asymmetric p_{T} thresholds (30/18 GeV) and no $m_{\gamma\gamma}$ requirement
- Data-driven γ+jets and multijet bkg, di-photon bkg modelled with MC
- NN to classify events as signal or bkg
- Largest excess at 13.6 GeV $3.5(1.9)\sigma$ local (global)
- Results interpreted in a specific **ALP model**



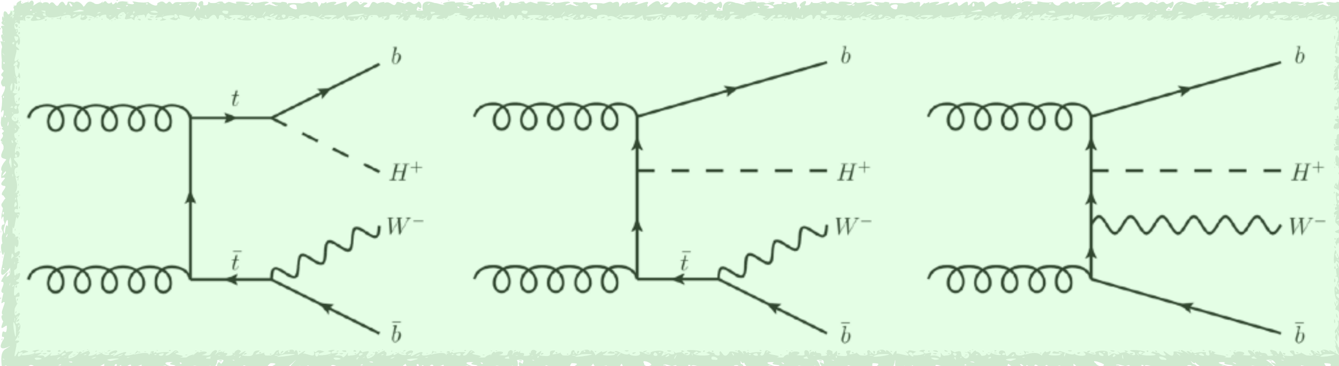


Kim-Shifman-Vainshtein-Zakharov ALP model

PLB 78 (1979) 443 PRL 43 (1979) 103



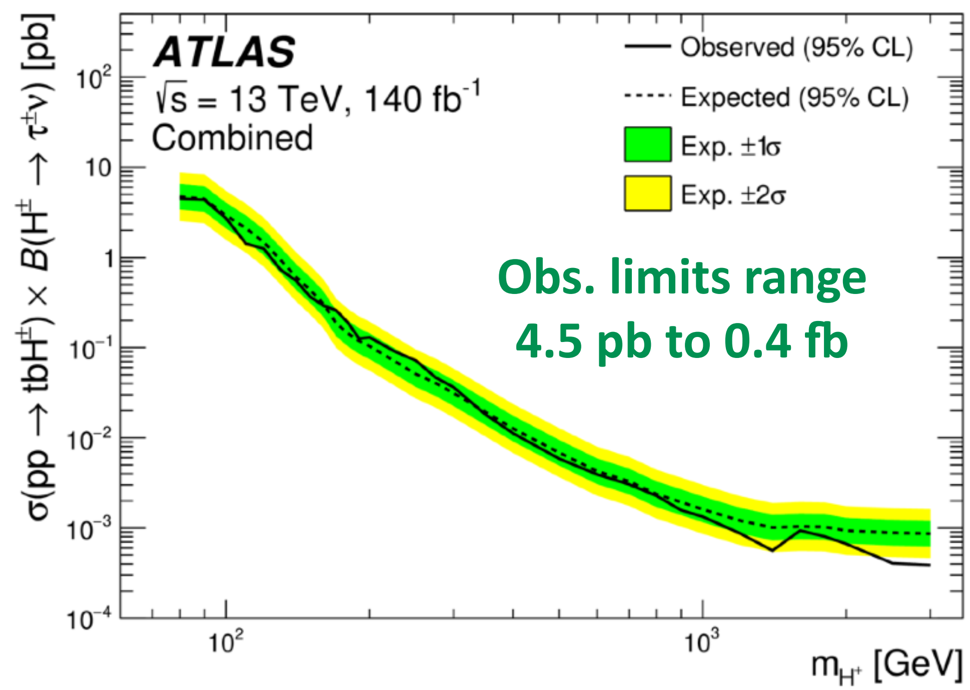
Heavy Higgs Searches

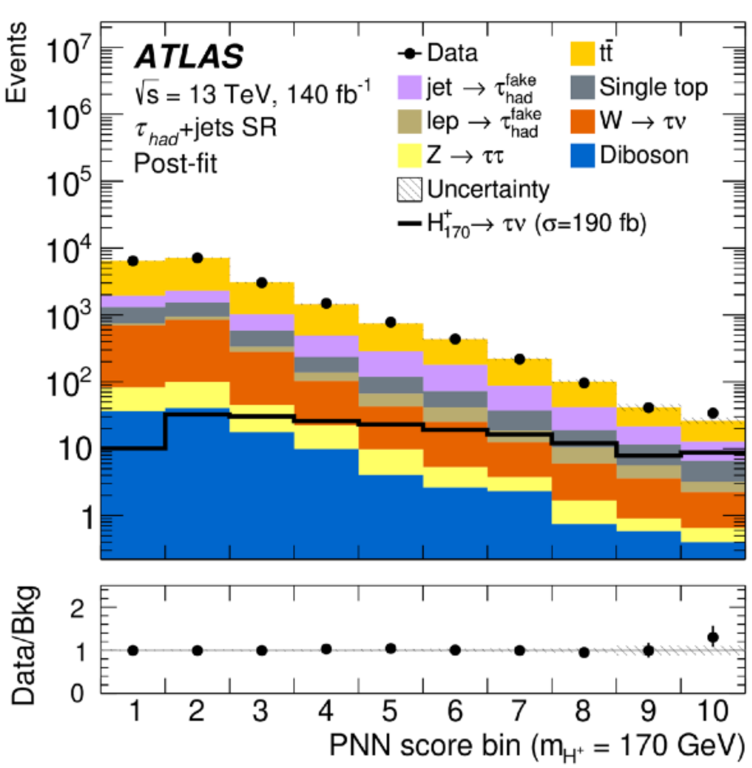


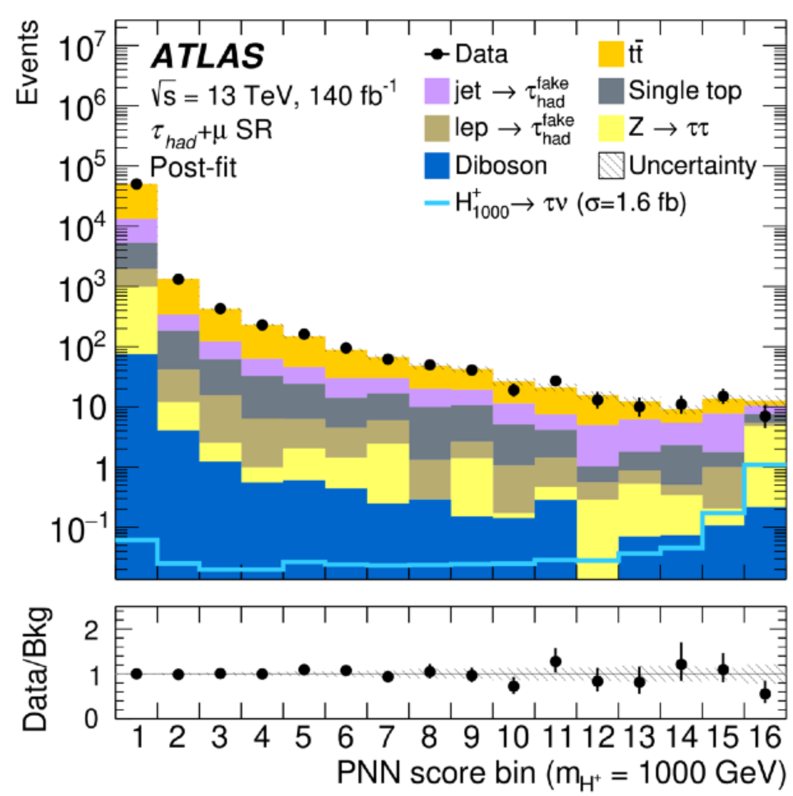
$H^{\pm} \rightarrow \tau^{\pm}\nu$

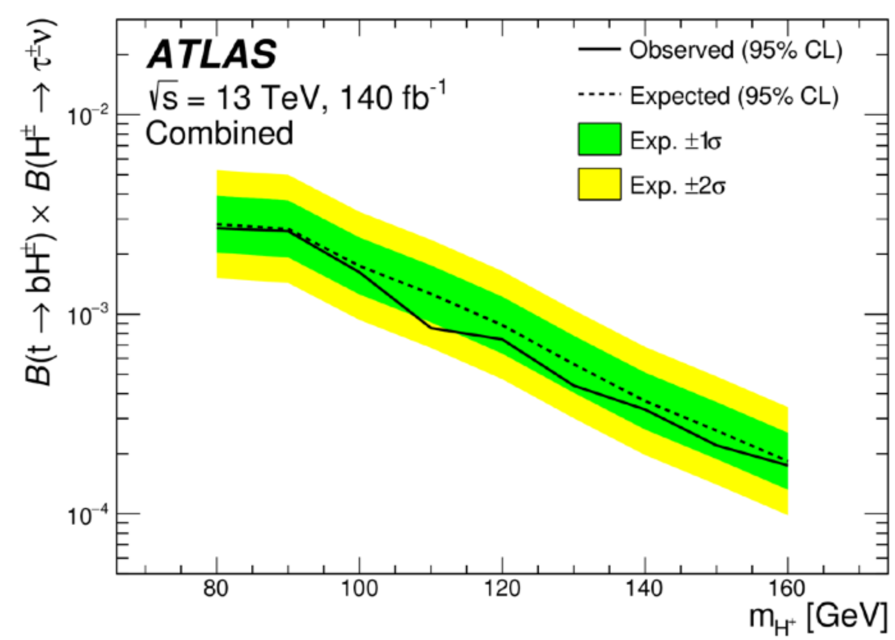
arxiv:2412.17584 (submitted to PRD)

- Search for $80 < m_{H^{\pm}} < 3000$ GeV in τ+jets and τ+lepton final states
- **Sizeable BR** over a **wide range** of **parameter** space
  - sensitive at high tan β, dominant at $m_{H^{\pm}} < 175$ GeV
- Main bkgs $t\bar{t}$ and W+jets from MC with data-driven corrections
- Mass-parametrised NN to classify signal and bkg events

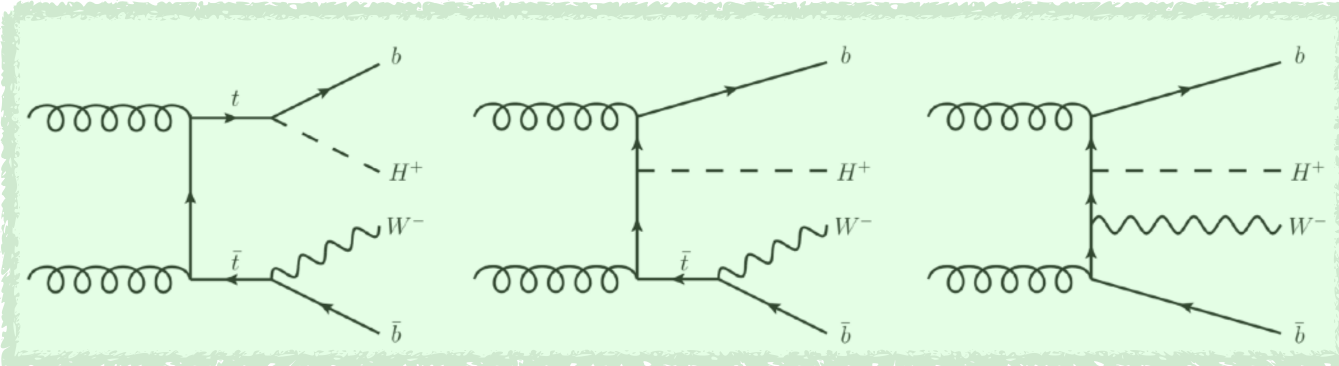








Limits on $\mathscr{B}(t \rightarrow bH^{+}) \times \mathscr{B}(H^{+} \rightarrow \tau\nu)$ between 0.27% and 0.02% at 80-160 GeV



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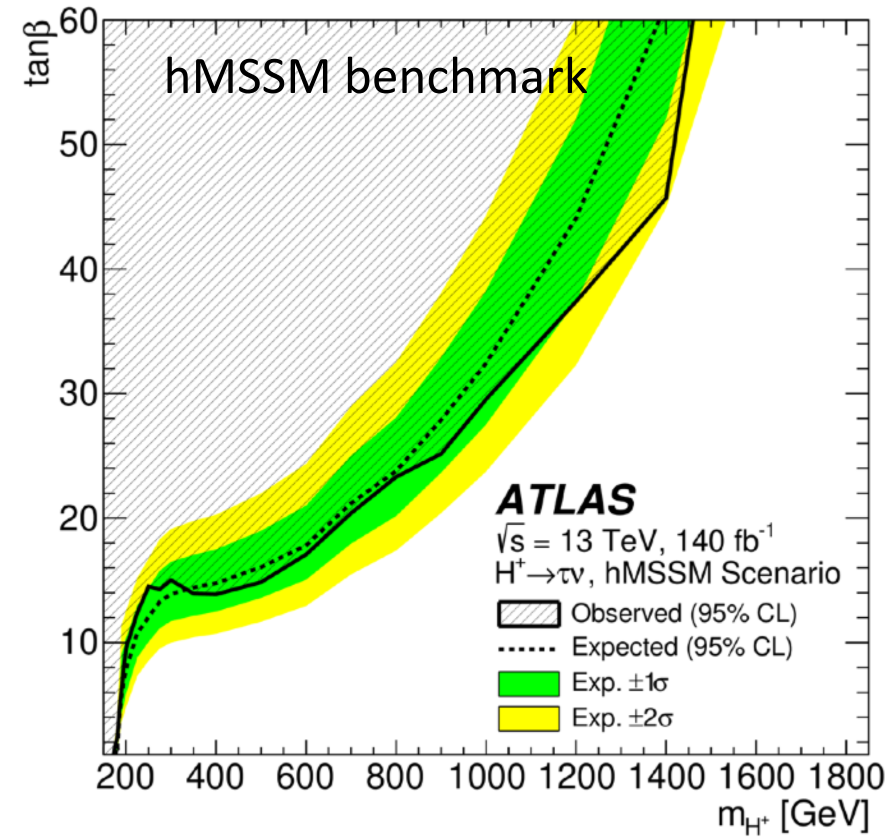
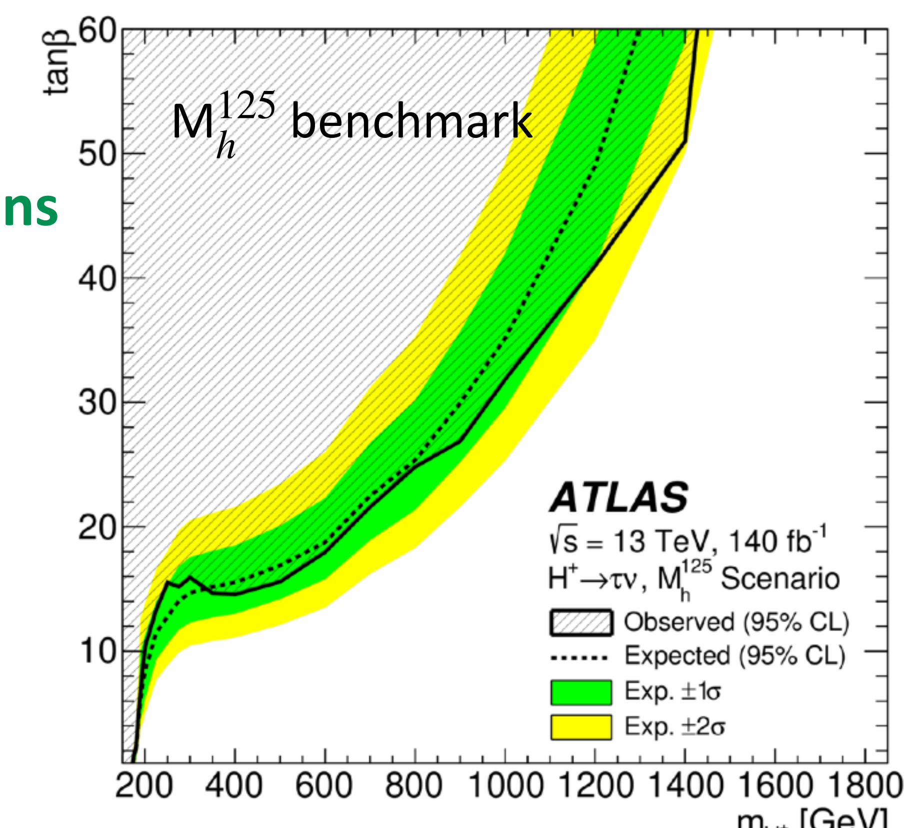
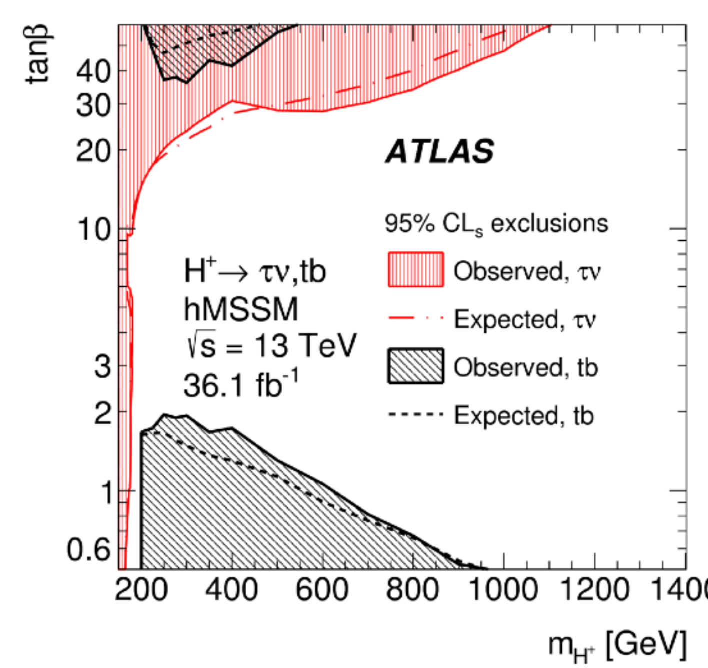
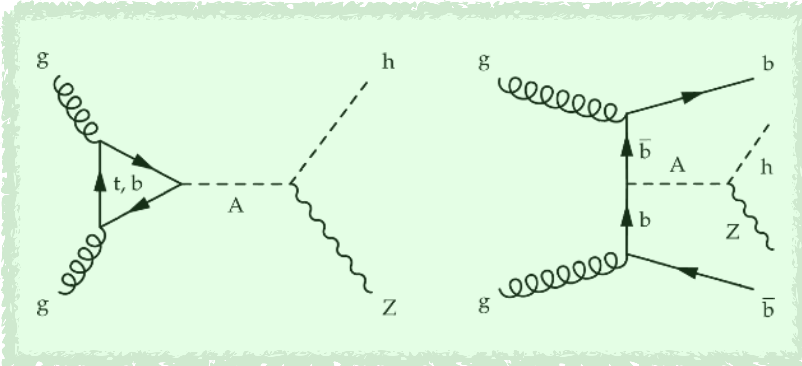


2HDM interpretations





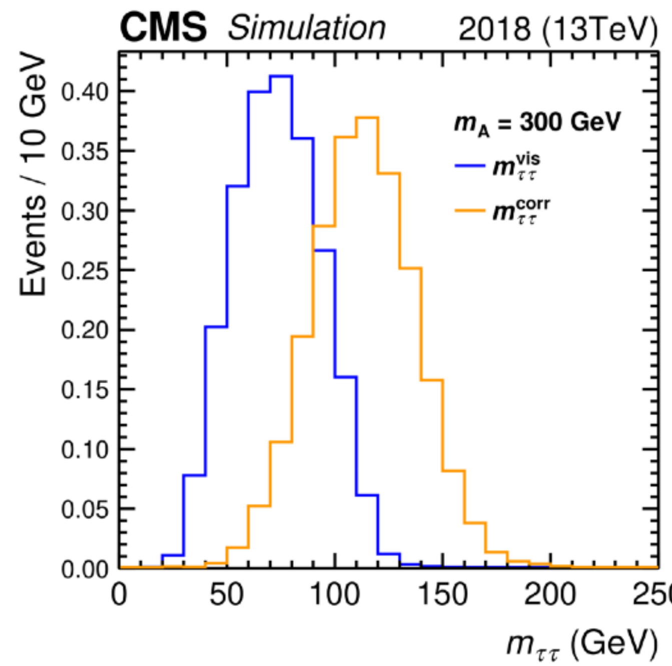
$36\,\mathrm{fb}^{-1}$ result

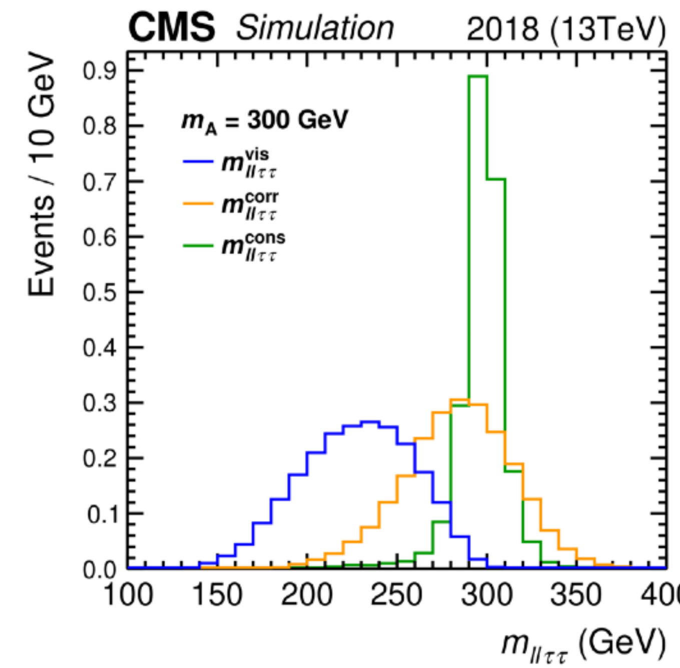


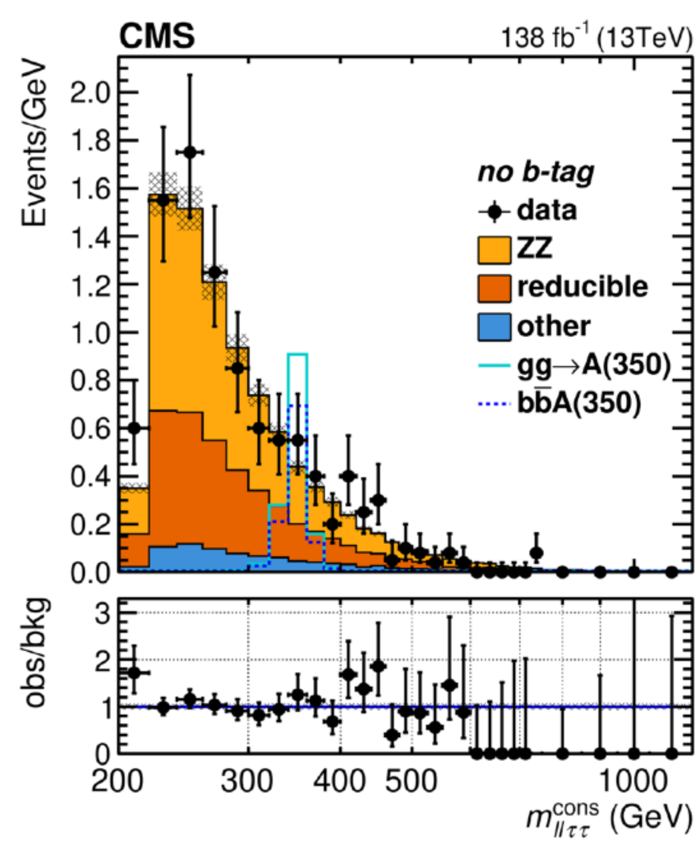
$A \to Zh_{125} \to \ell\ell\tau\tau$

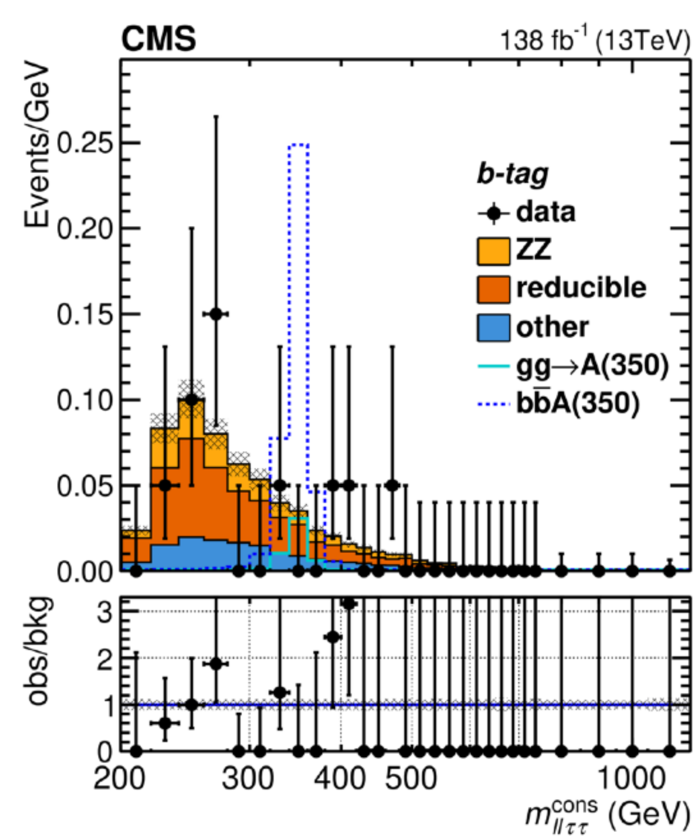
arxiv:2501.14825 (submitted to JHEP)

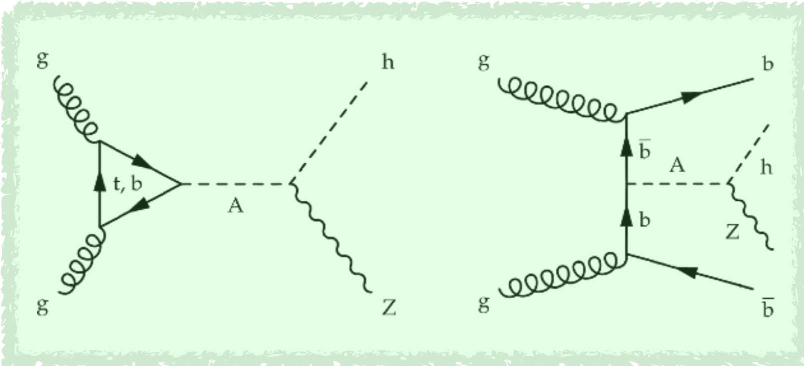
- Target $gg \to A$ and bbA production modes
  - Considered $e\tau$, $\mu\tau$ and $\tau_{had}\tau_{had}$ channels
  - Number of b-jets to categorise events
- Dedicated algorithm to reconstruct $h_{125} \to \tau\tau$
  - Consider missing energy from neutrinos
- 125 GeV Higgs mass constraint to improve the A-boson mass resolution











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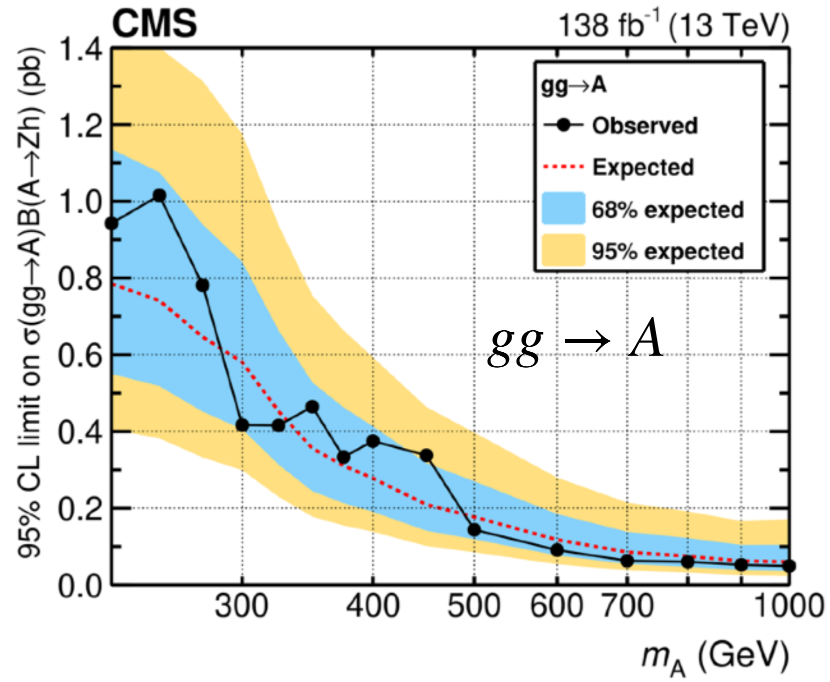
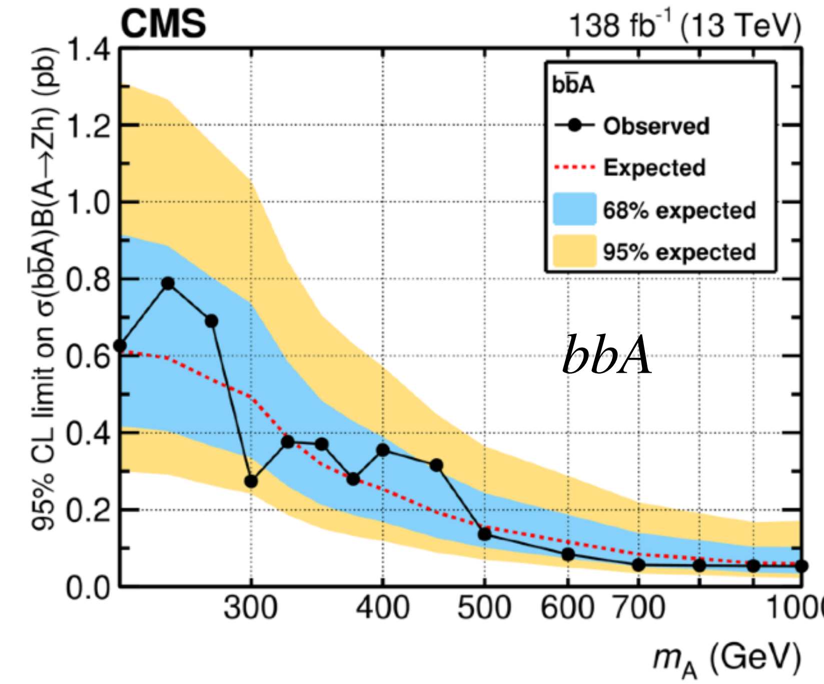
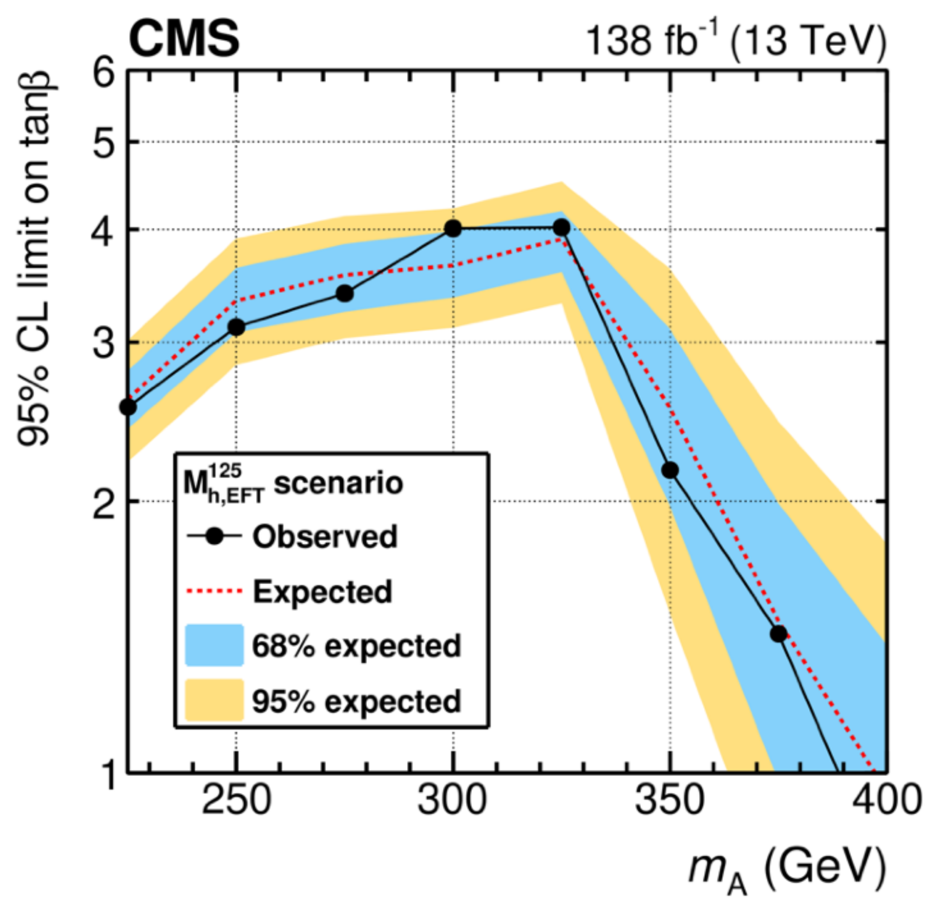
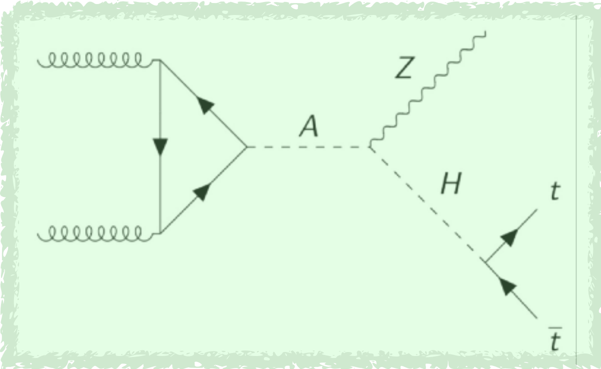






Observed limits range from 0.049 (0.053) pb at 1 TeV to 1.02 (0.79) pb at 250 GeV for $gg \rightarrow A$ ($b\bar{b}A$)

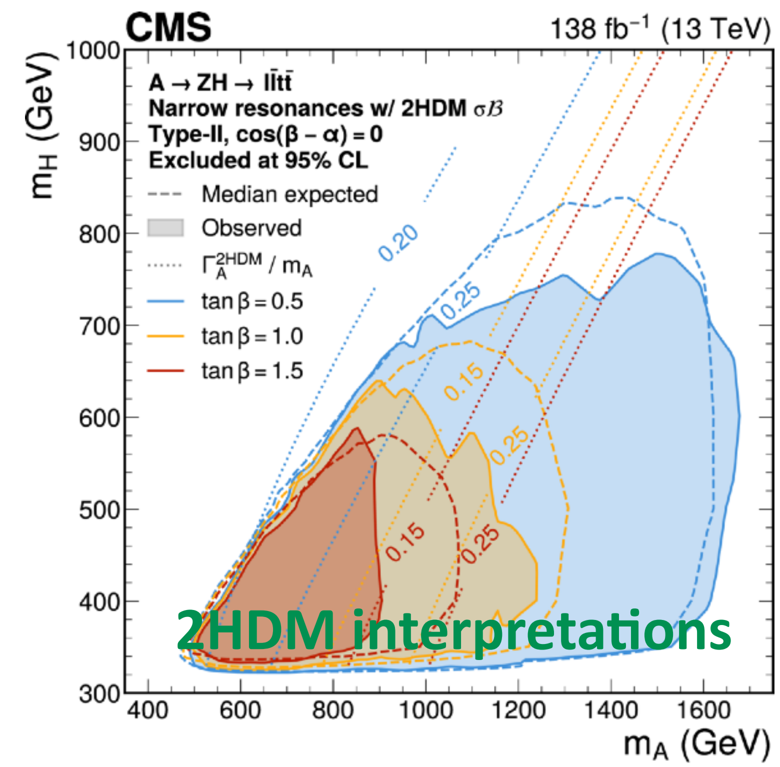
$\tan\beta < 2.2$ excluded from 225 to 350 GeV in M_h^{125} MSSM benchmark

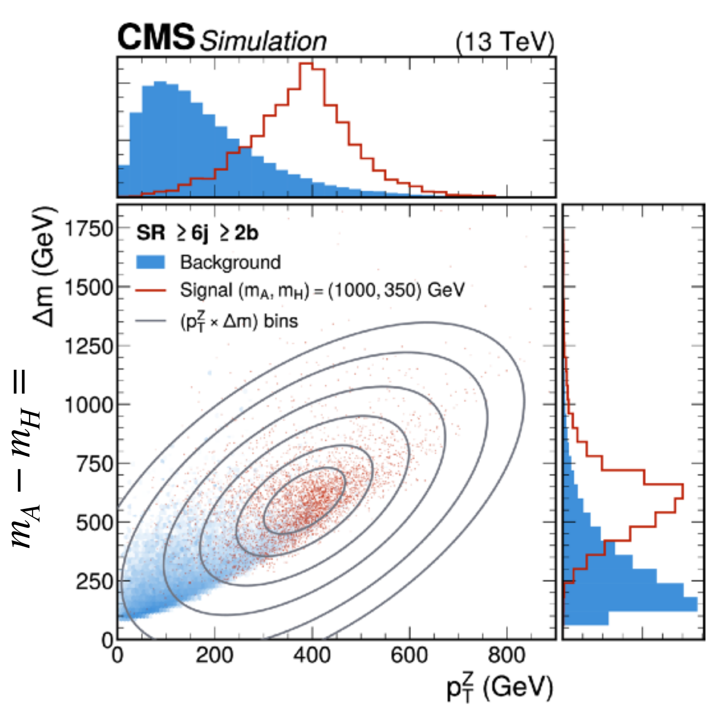


$A \to ZH \to Zt\bar{t}$

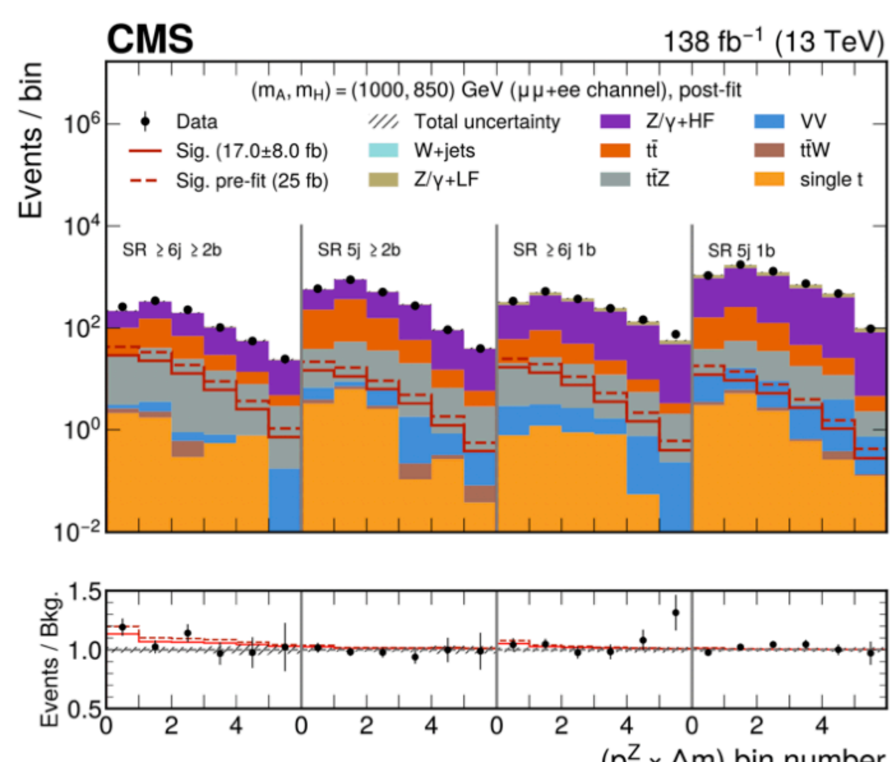
arXiv:2412.00570 (submitted to PLB)

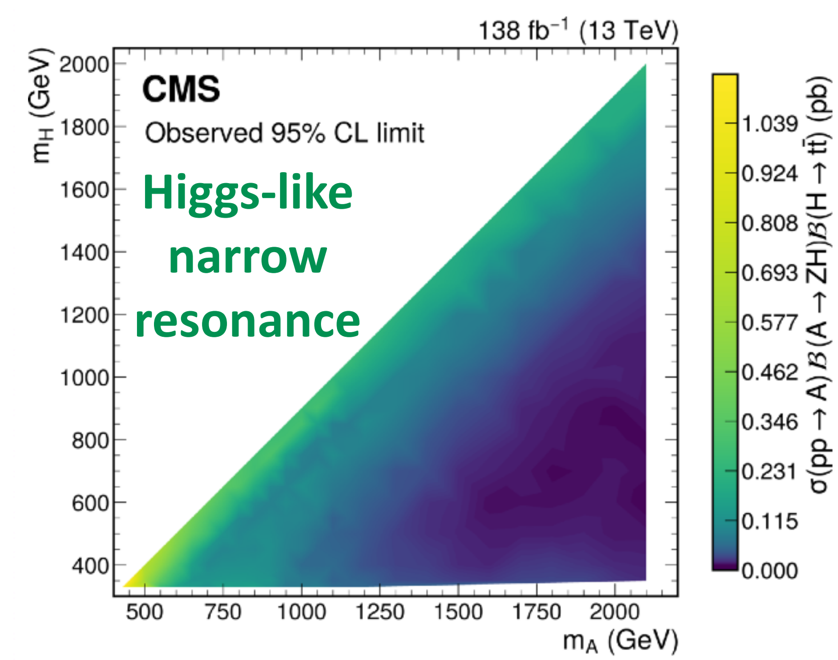
- Previous searches in $H \to \tau\tau, bb, WW$ final states
  - the sensitivity usually drops for $m_h > 350$ GeV
- $H \to t\bar{t}$ allows to study **mostly unconstrained 2HDM parameter space** → e.g. relevant for models explaining baryogenesis
- ATLAS 2.85σ excess at $(m_A, m_H) = (650, 450)$ GeV is not confirmed
- Largest fluctuation 2.1σ local @ $(1000, 850)$ GeV





unroll
elliptical bins





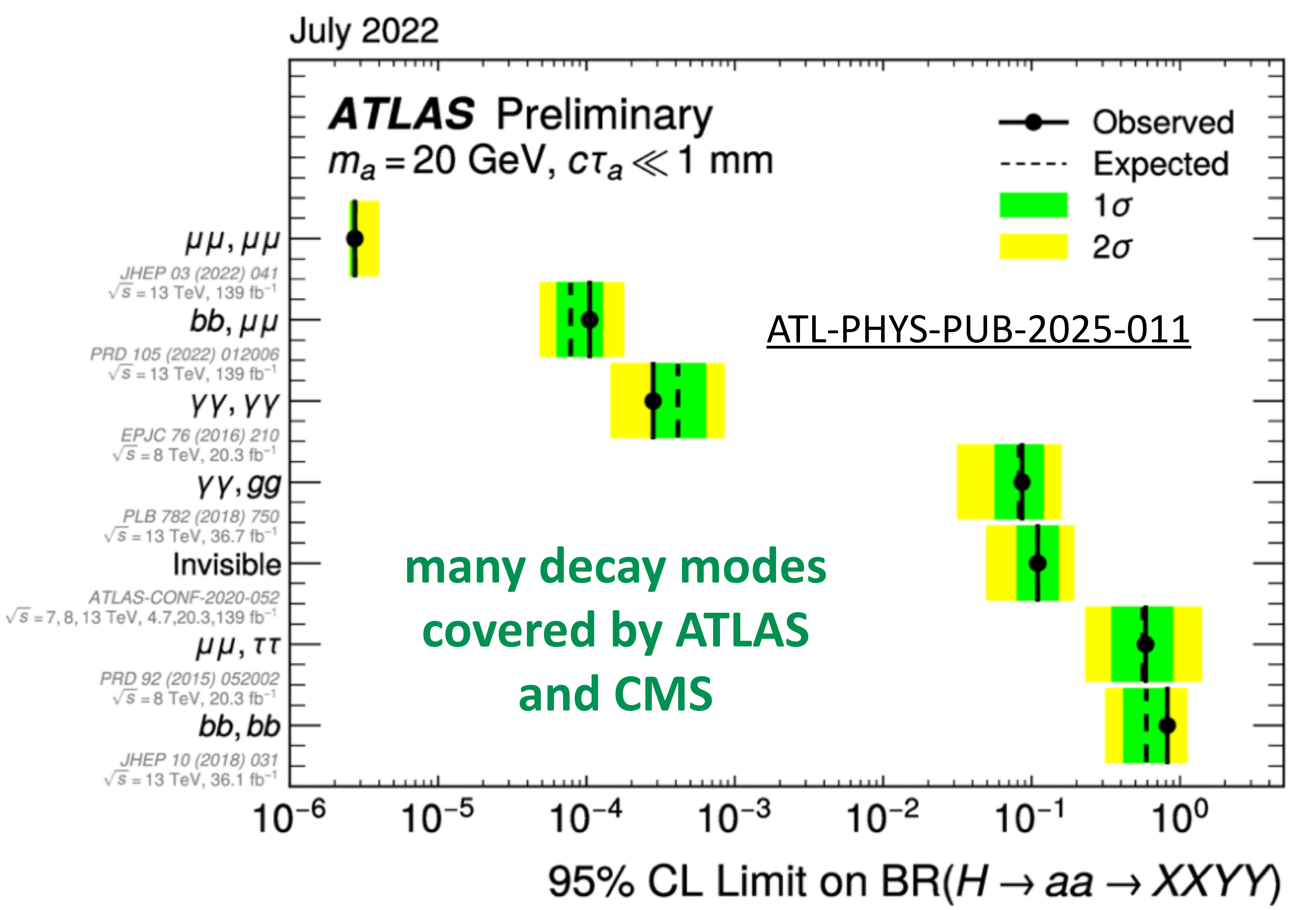
Conclusions

- **BSM Higgs searches** are **essential** for the ATLAS and CMS physics program at the LHC
- Several **benchmark models** tested in many channels
  - No significant excesses found so far and tighter constraints on model parameters are set
  - Covered a small subset of results here, see ATLAS and CMS webpages for everything else
- **Run 3** data (2022 - 2026) will allow to check the interesting Run -2 excesses
  - Higher centre-of-mass energy (**13.6 TeV**) beneficial for many signals
  - Might **triple the dataset** available for analysis

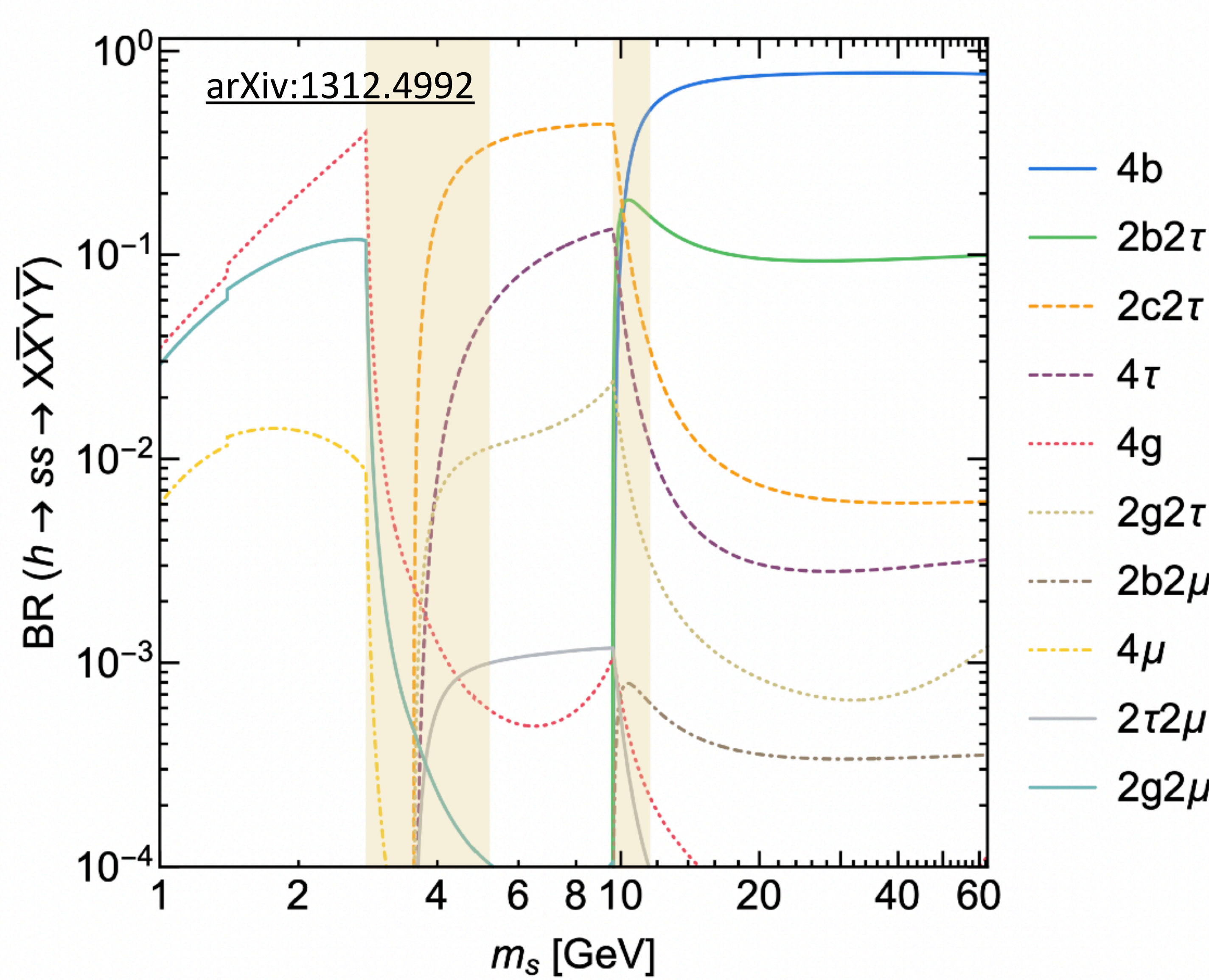
ADDITIONAL MATERIAL

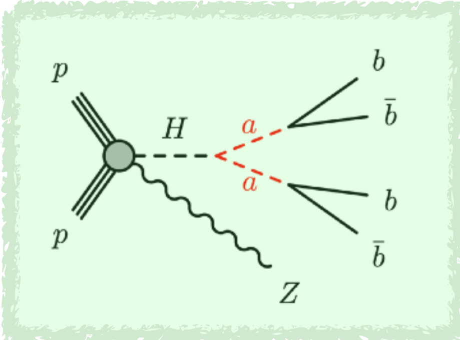
Exotic Higgs Decays

- SM Higgs decay width is 4.1 MeV
  - Limited precision of indirect measurements
  - Significant BSM contributions possible
- Small coupling to non-SM particle results in large branching fraction



Predicted decay BRs of 125 GeV Higgs to a pair of decoupled singlet state (s)





H → aa → 4b

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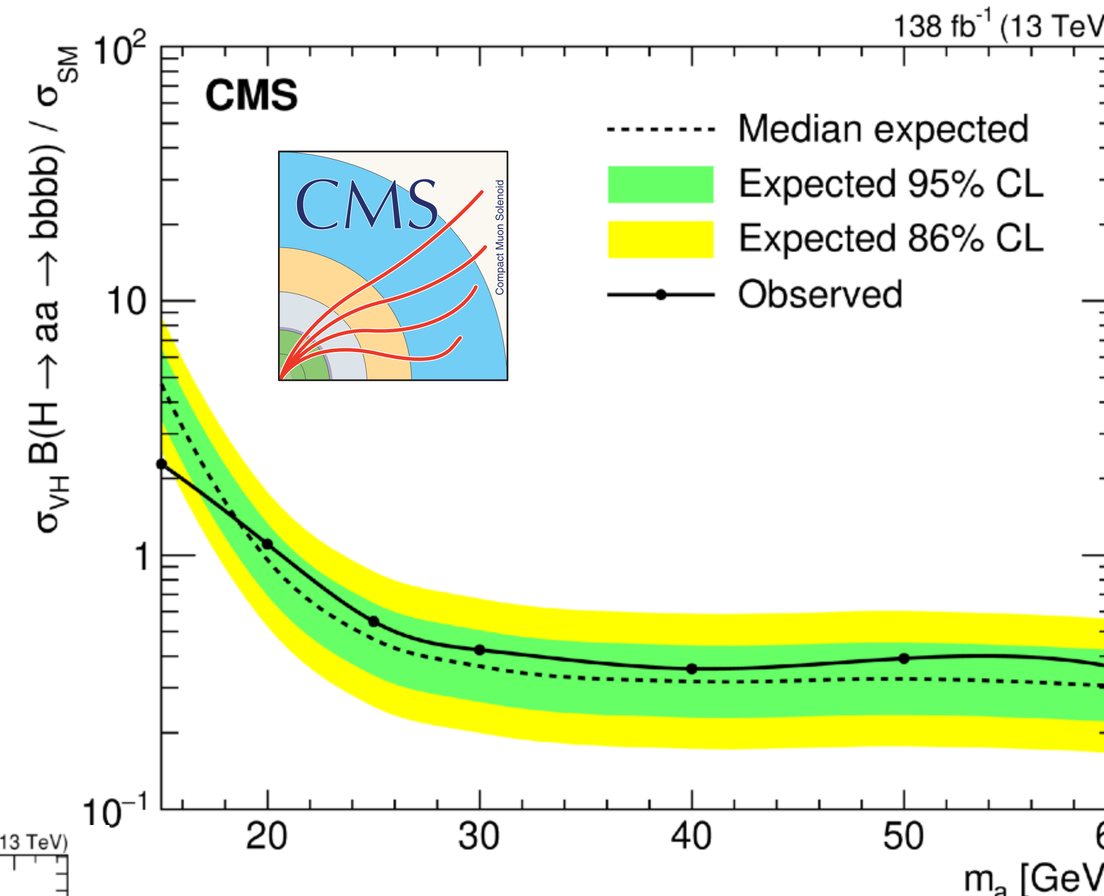
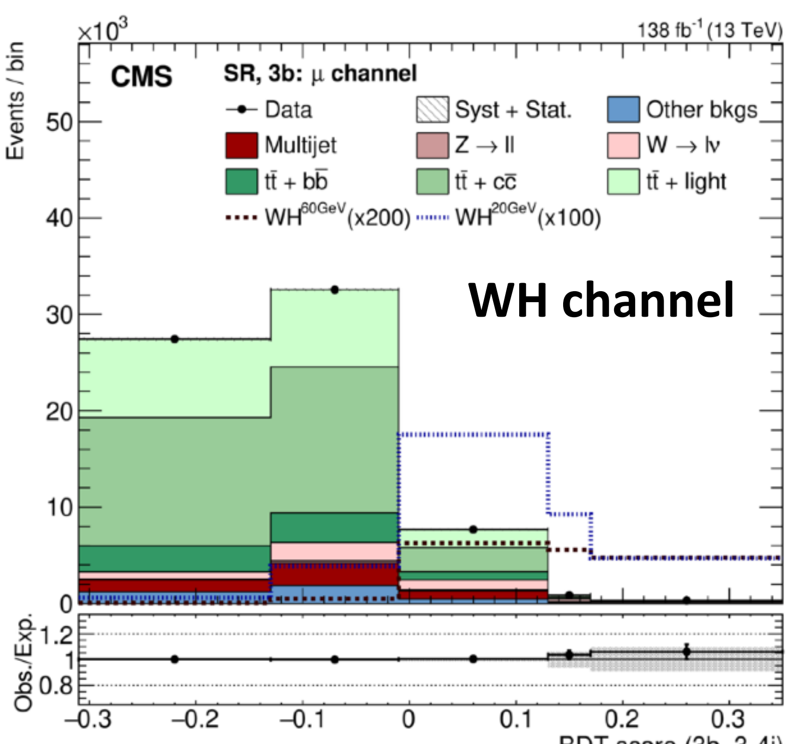
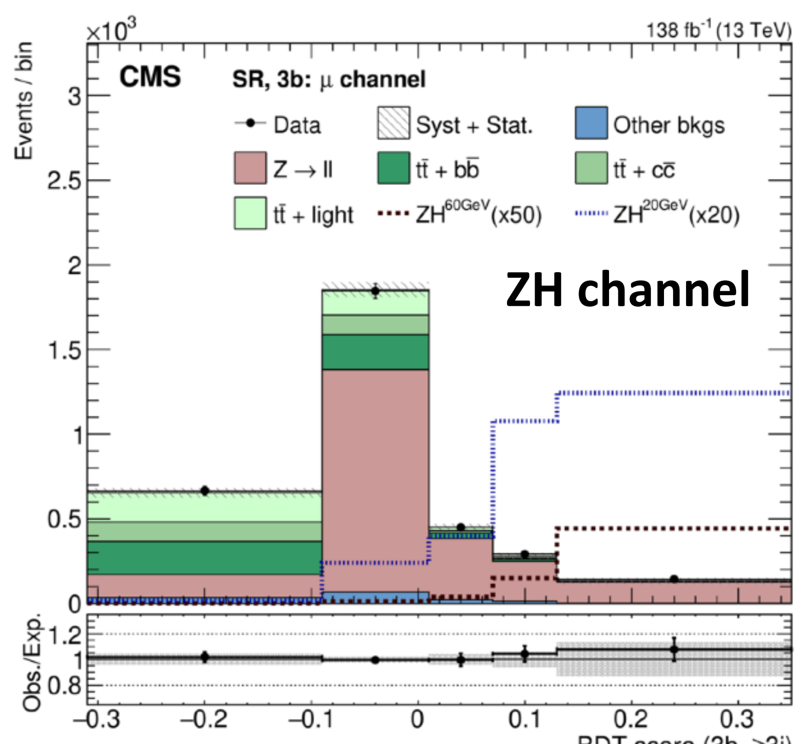
- Search in VH production mode with leptonically decaying V boson
- Dominant bkgs: $t\bar{t}$+jets, V+jets - dedicated control regions to constrain bkg norm
- Event categorisation based on number of jets and b-jets
- BDT to classify signal and bkg events







95% CL upper limit on $\mathscr{B}(H \to aa \to 4b)$ ranges from 1.10 at $m_a = 20$ GeV to 0.36 at $m_a = 60$ GeV

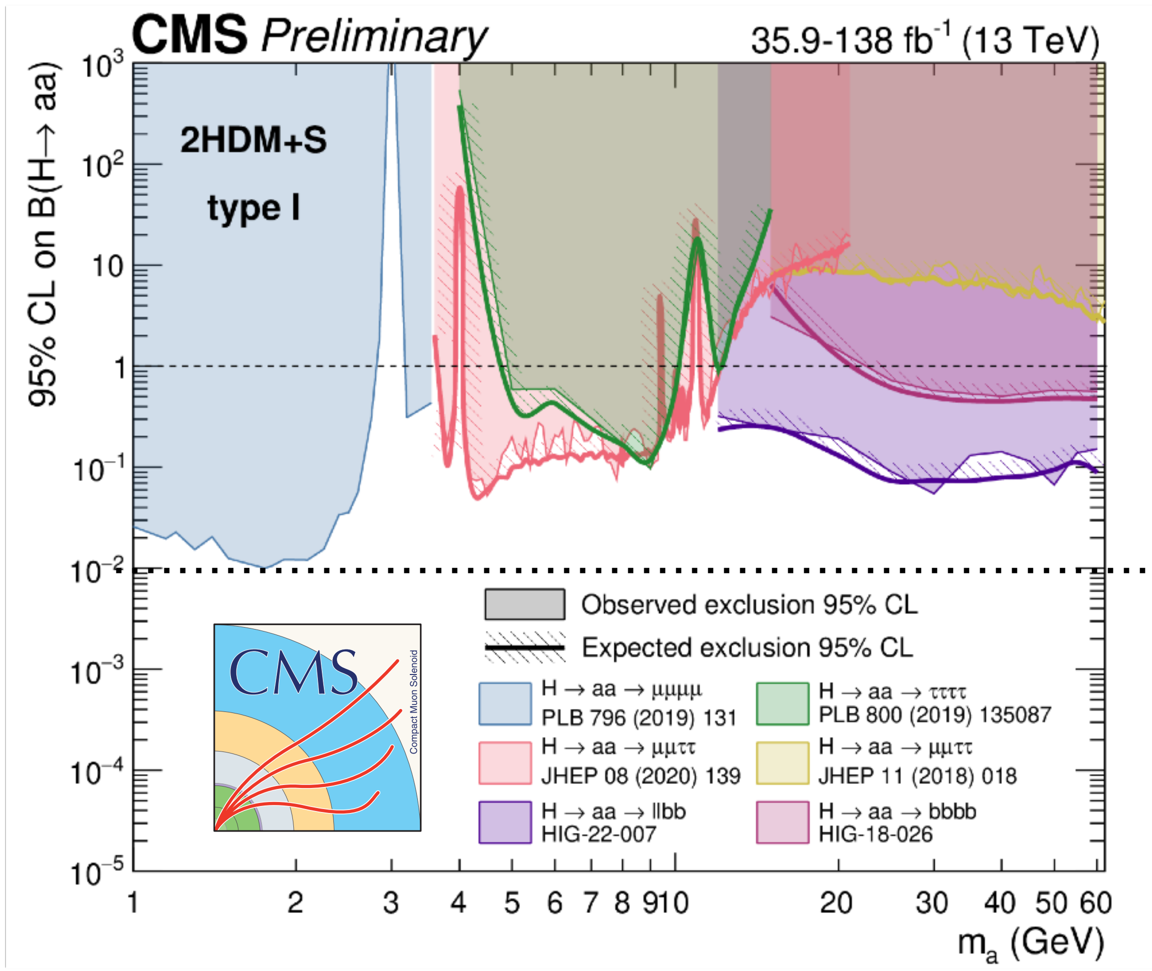
2HDM+S Summary Plots

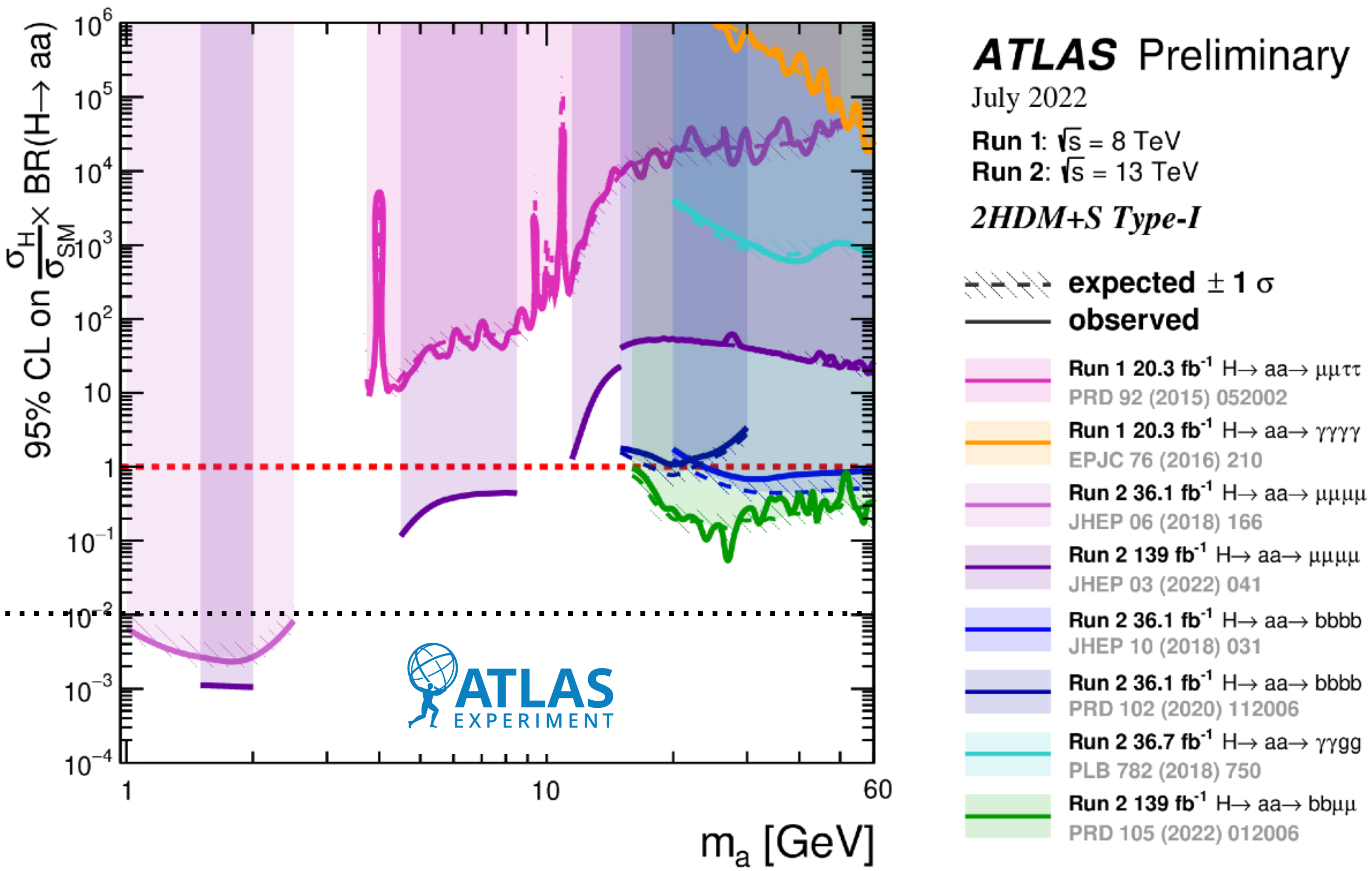
2HDM+S CMS Summary Plots

ATL-PHYS-PUB-2025-011

$$95\% \text{ CL on } \frac{\sigma(H)}{\sigma_{SM}} \times \mathscr{B}(H \to aa)$$

BR to SM particles calculated following arxiv:1312.4992





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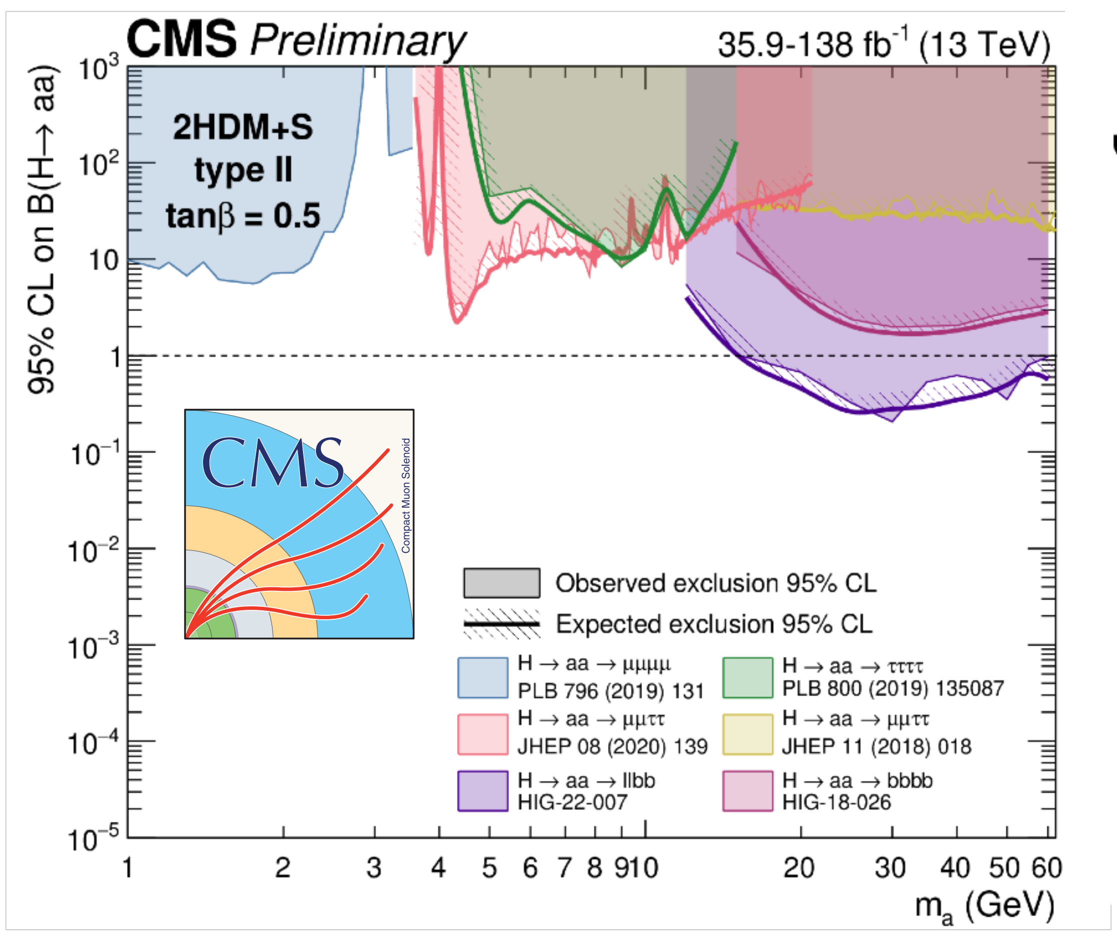

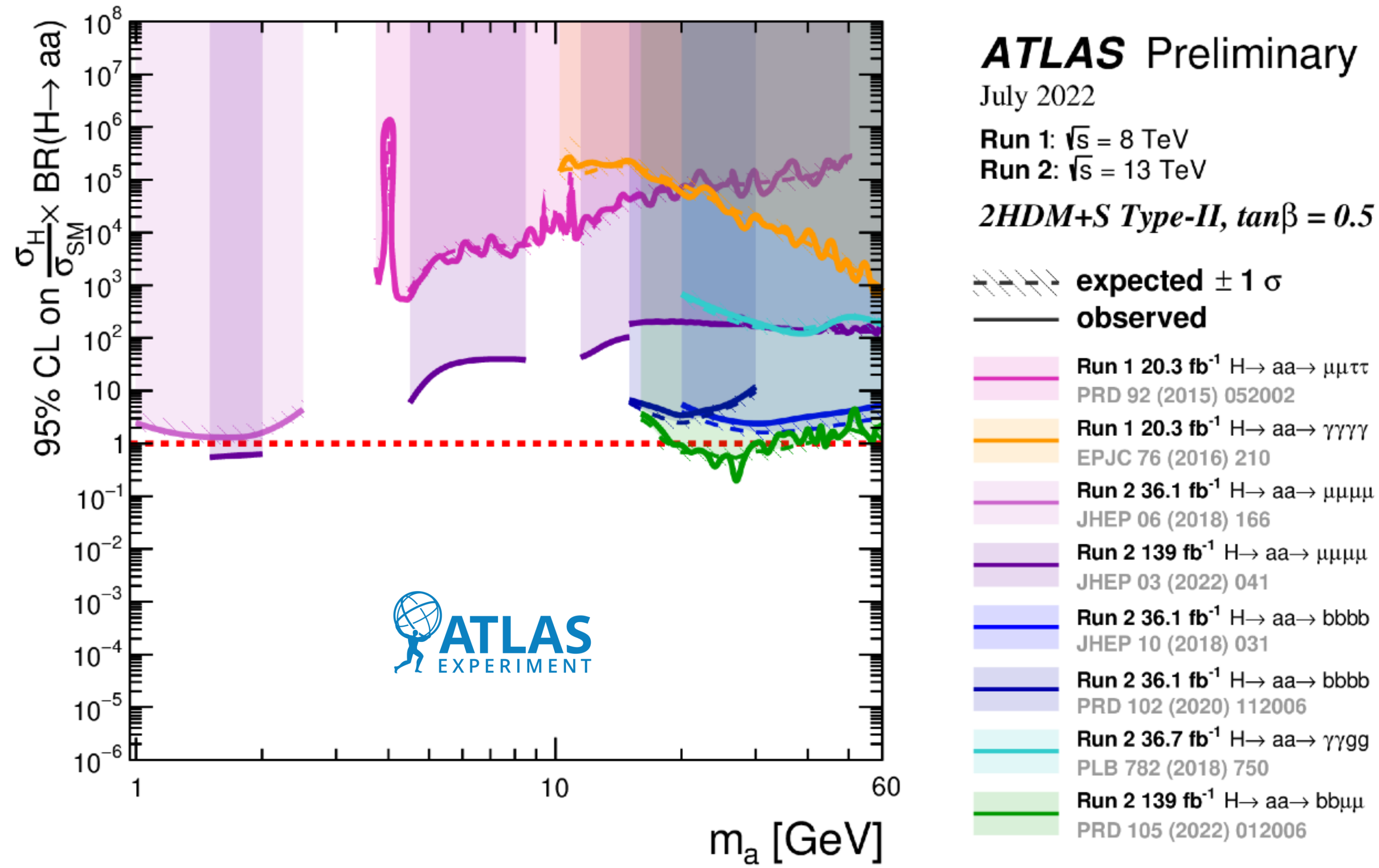

2HDM+S Summary Plots

2HDM+S CMS Summary Plots

ATL-PHYS-PUB-2025-011

95% CL on $\dfrac{\sigma(H)}{\sigma_{SM}} \times \mathscr{B}(H \rightarrow aa)$

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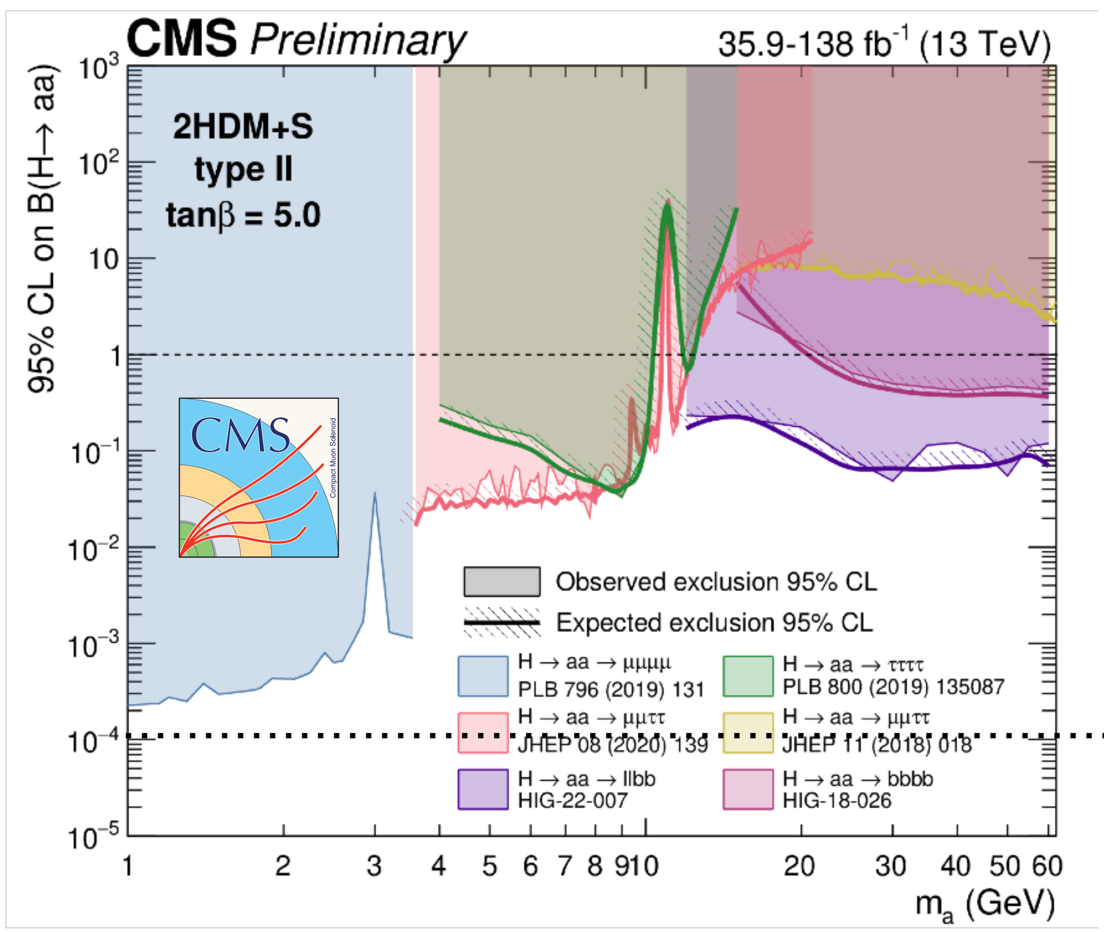
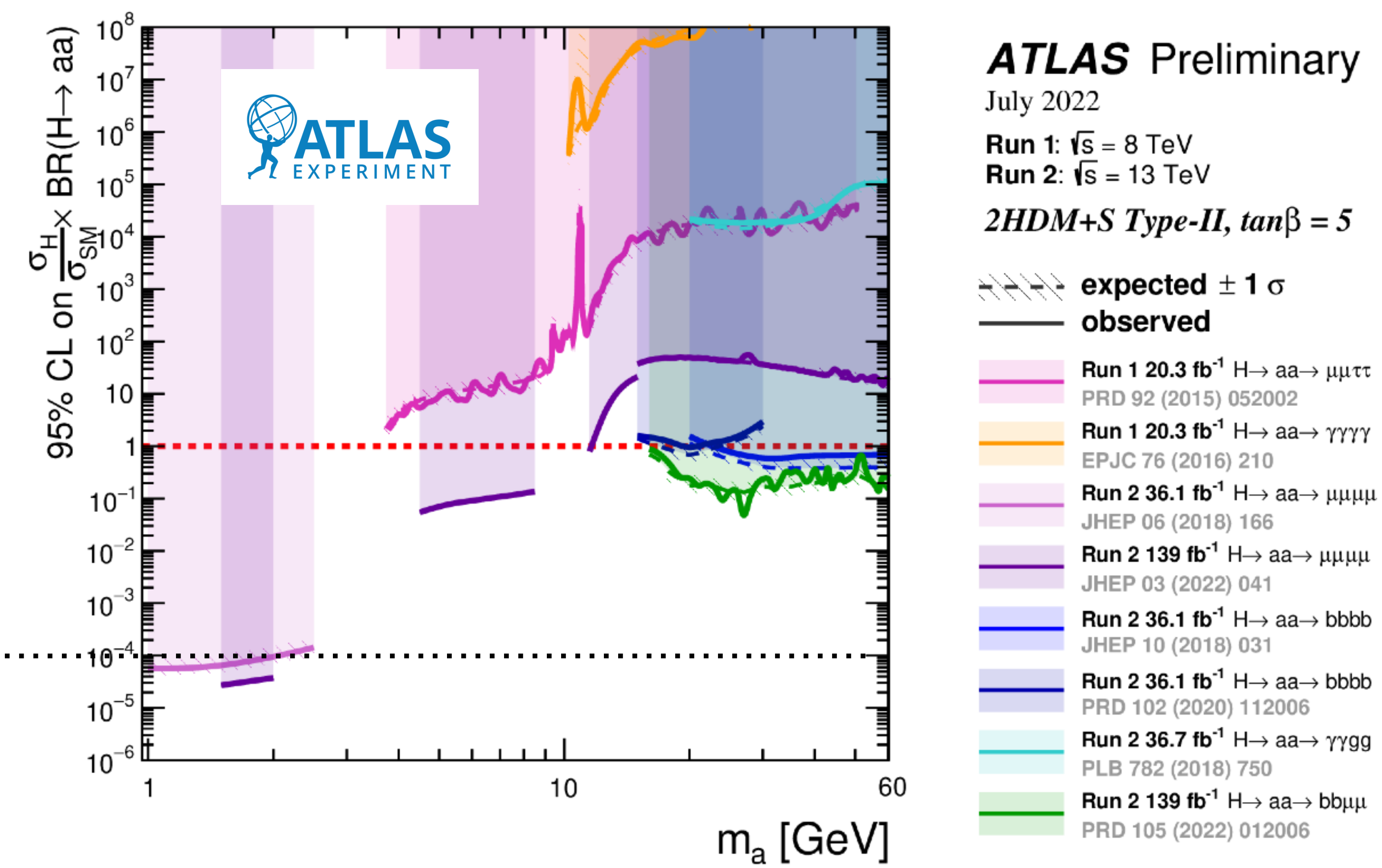
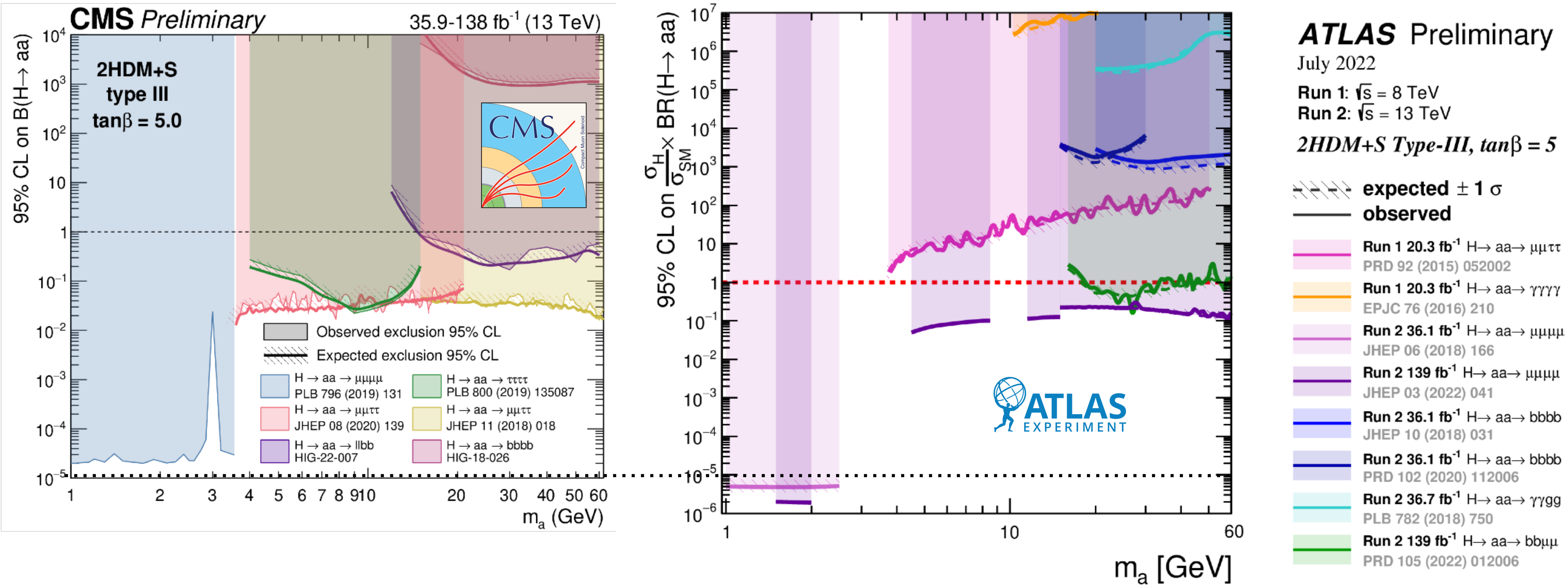




2HDM+S Summary Plots

2HDM+S CMS Summary Plots

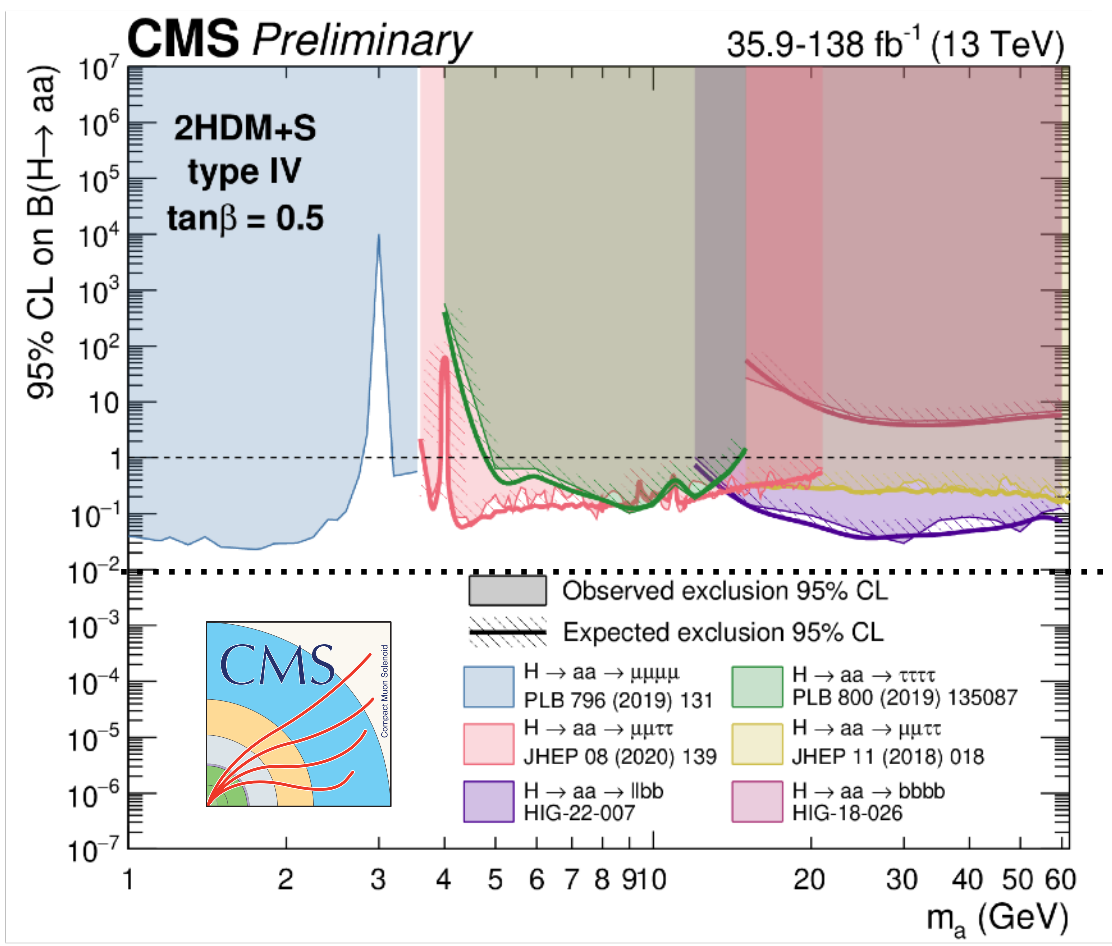
ATL-PHYS-PUB-2025-011

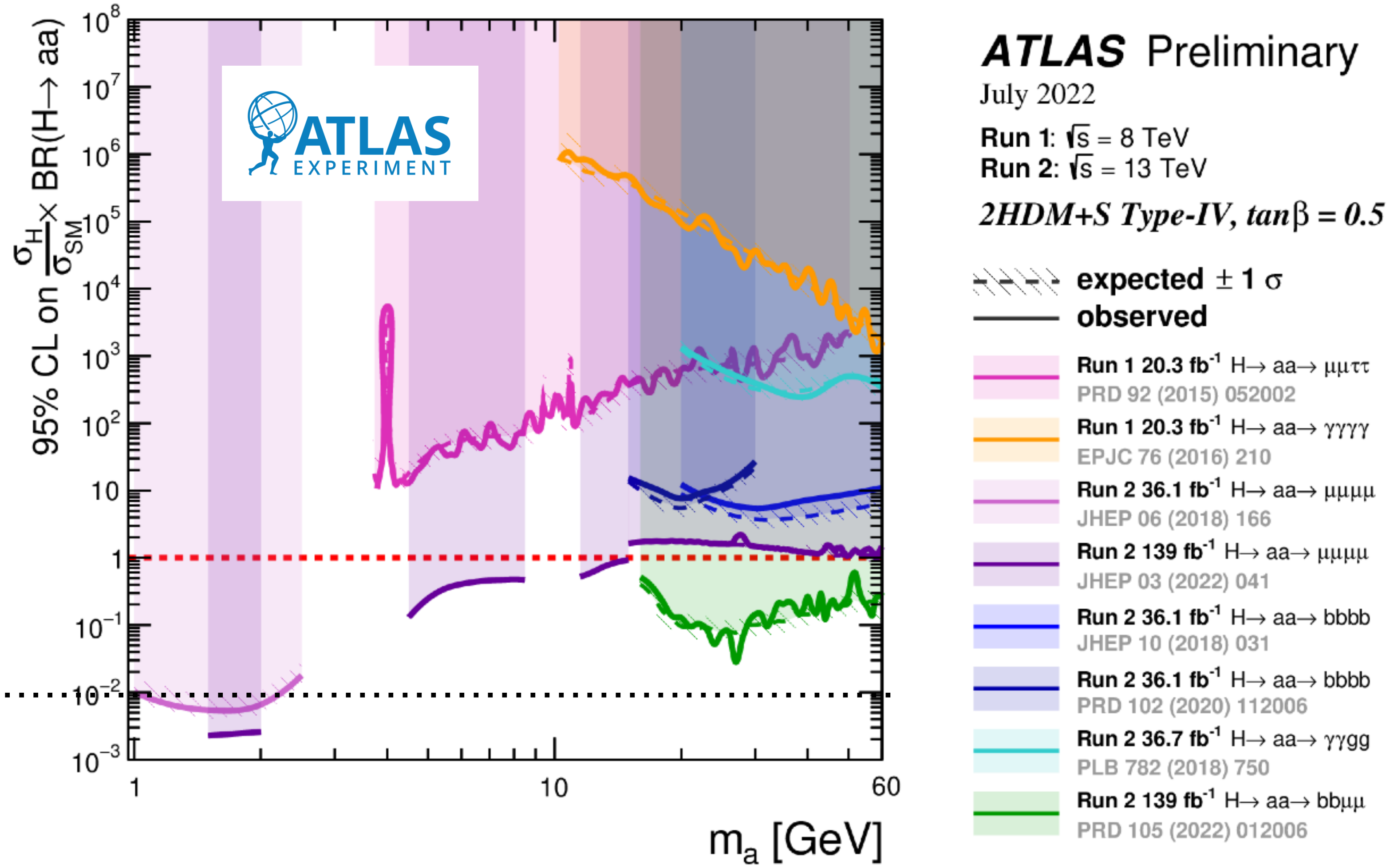


2HDM+S Summary Plots

2HDM+S CMS Summary Plots

ATL-PHYS-PUB-2025-011





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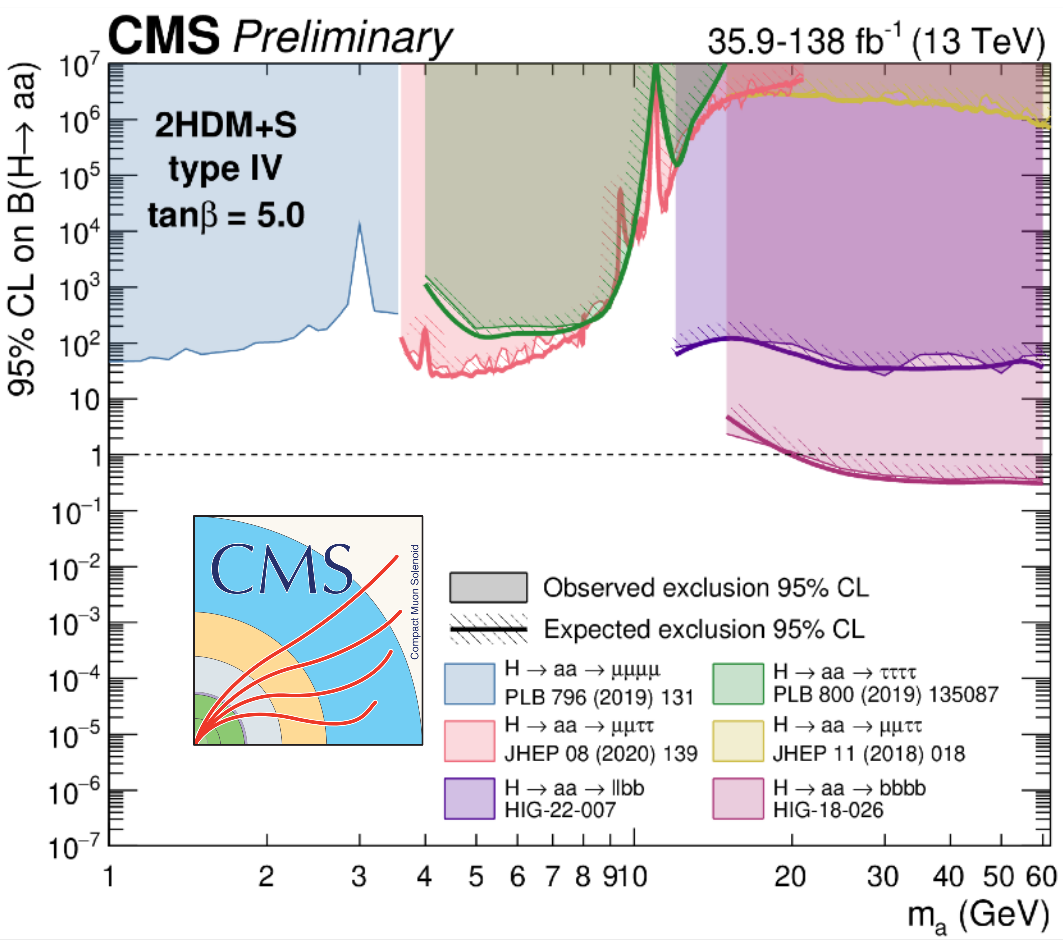
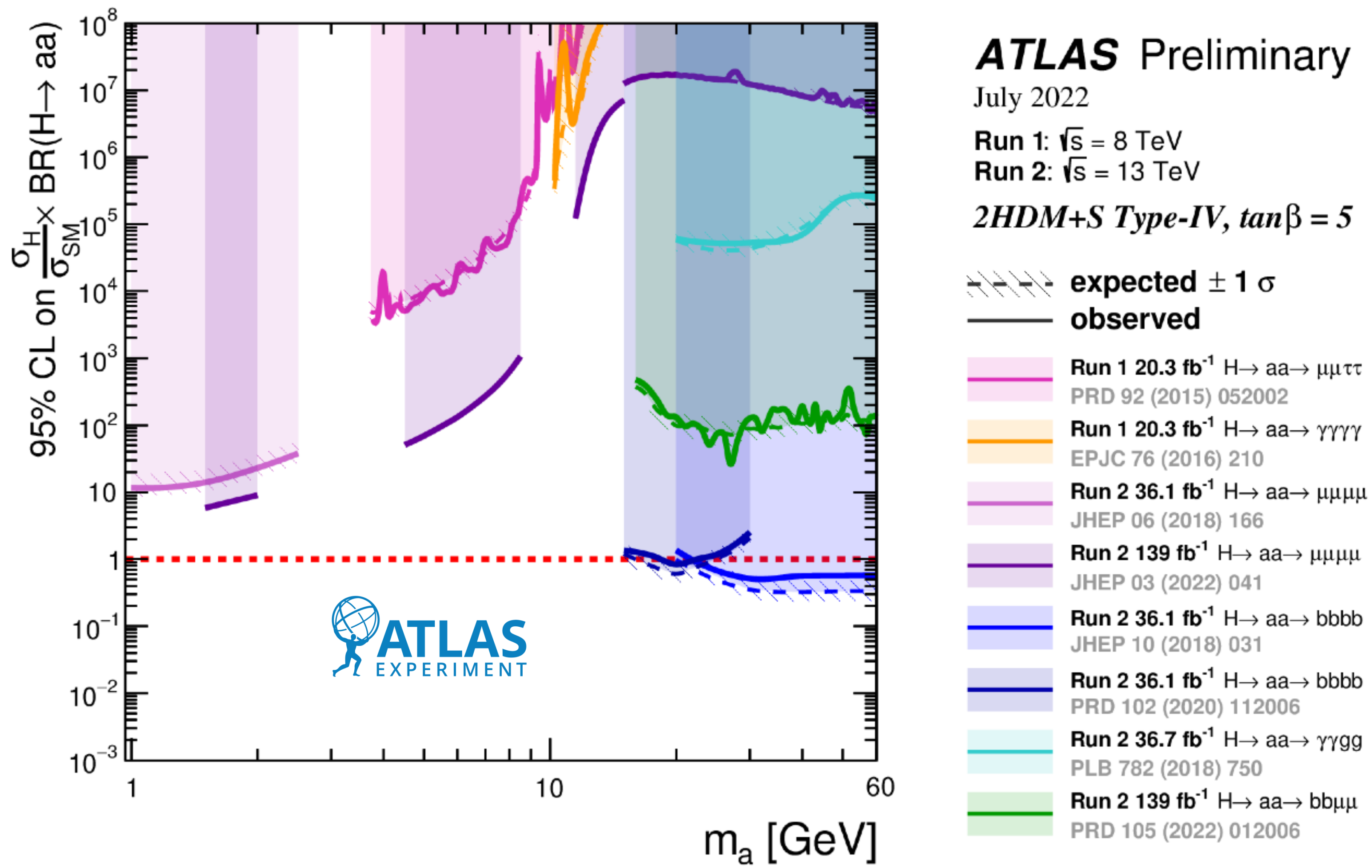
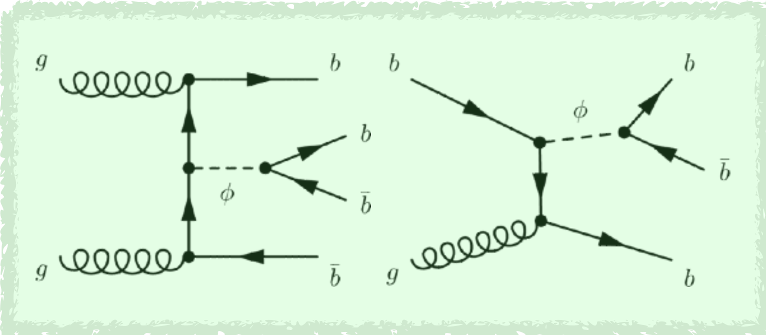


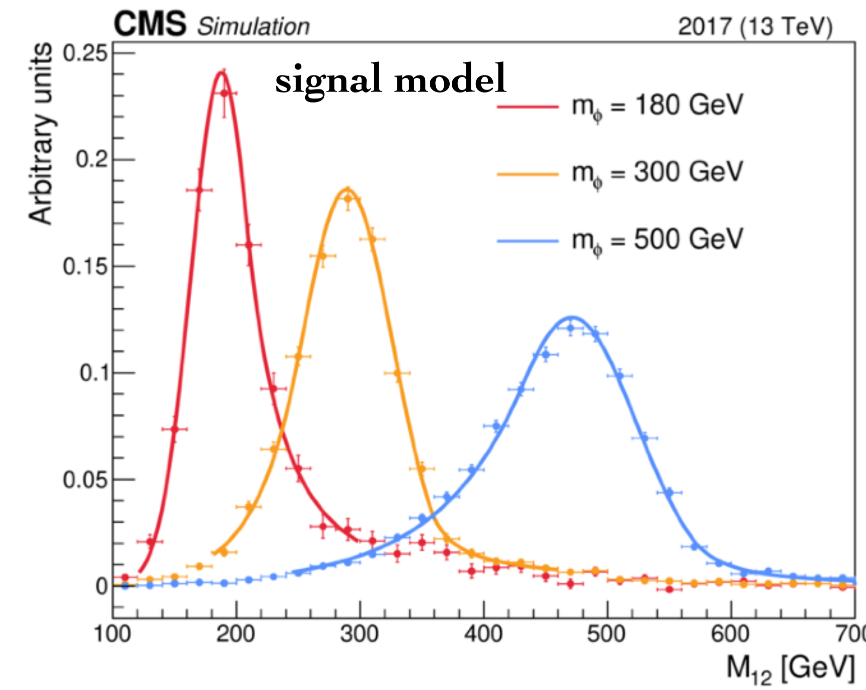




b(b)H/A, H/A → b$\bar{\text{b}}$

arxiv:2502.06568 (submitted to JHEP)

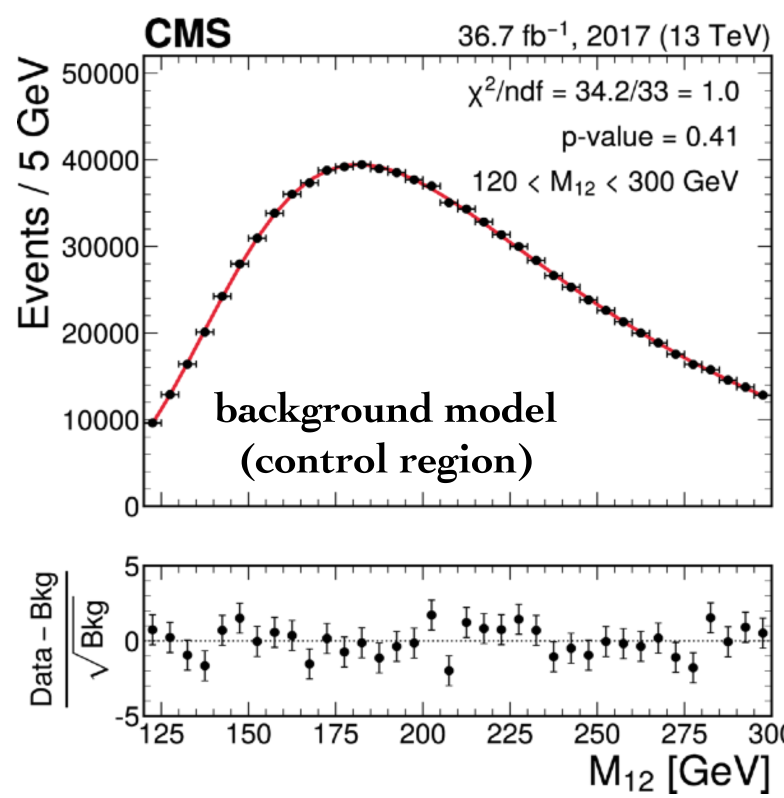
- Best channel in flipped and type-II 2HDM, enhanced production at high tan β
- Overwhelming multijet bkg, difficult to model
  - Use 2 b-tag control region to model 3+ b-tag signal region
  - Analytic function fitted to data, MC used to evaluate shape differences
- Largest excess in 2017 SL channel with local(global) significance of 3.2(2.4)σ at 250 GeV and 2.7(1.9)σ at 300 GeV
- Results interpreted in MSSM and 2HDM scenarios

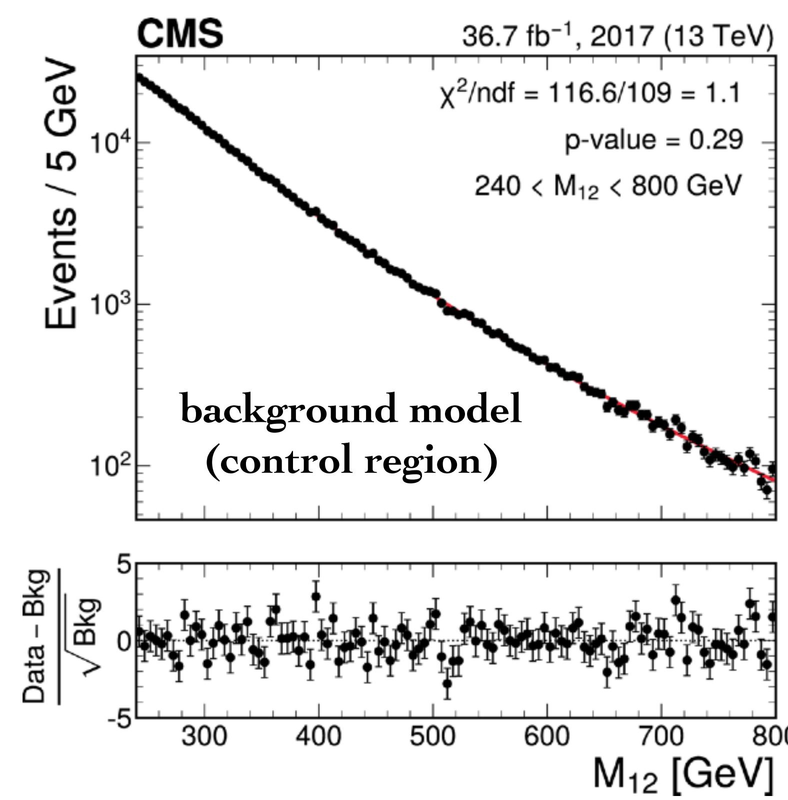


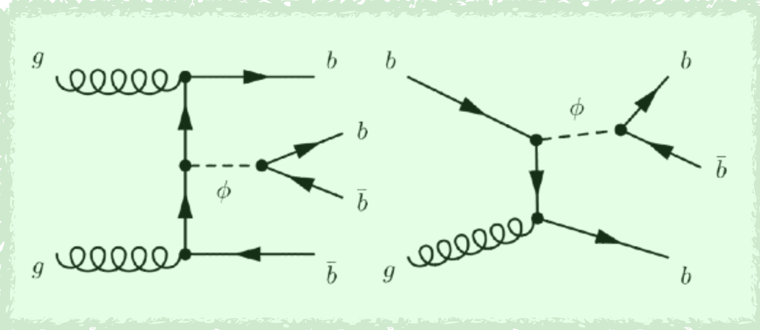
Signal regions

- 2016/2017/2018 FH: fully hadronic selection targets $m_H > 300$ GeV
- 2017 SL: semileptonic selection $125 < m_H < 700$ GeV

M_{12} inv. mass of 2 leading jets







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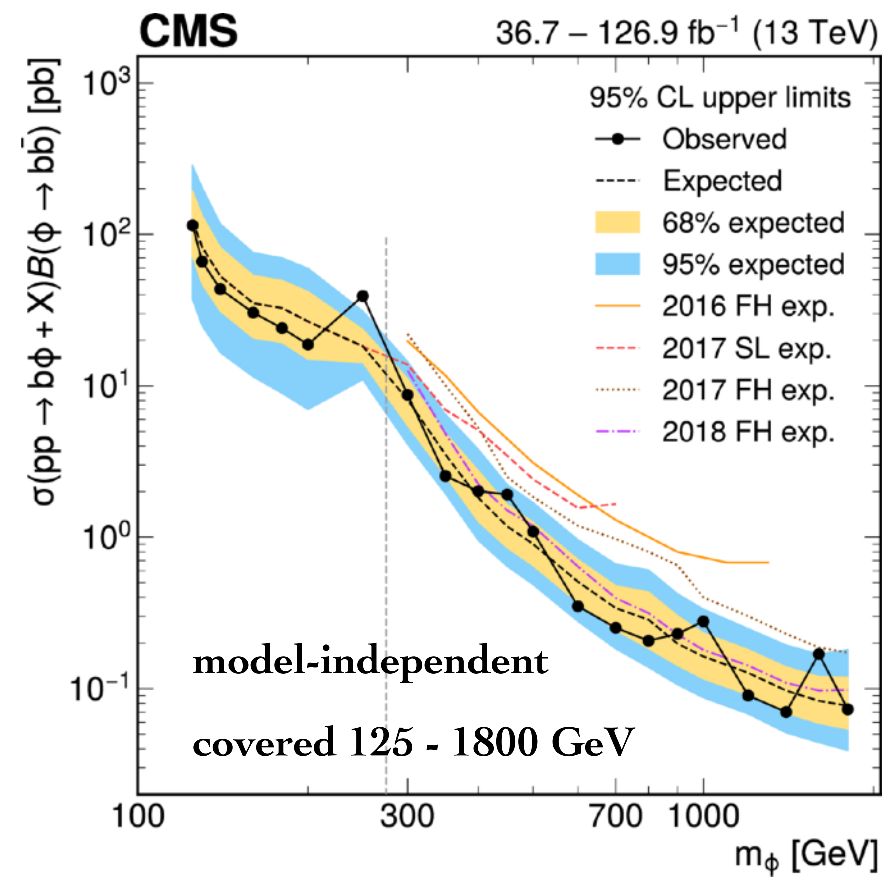
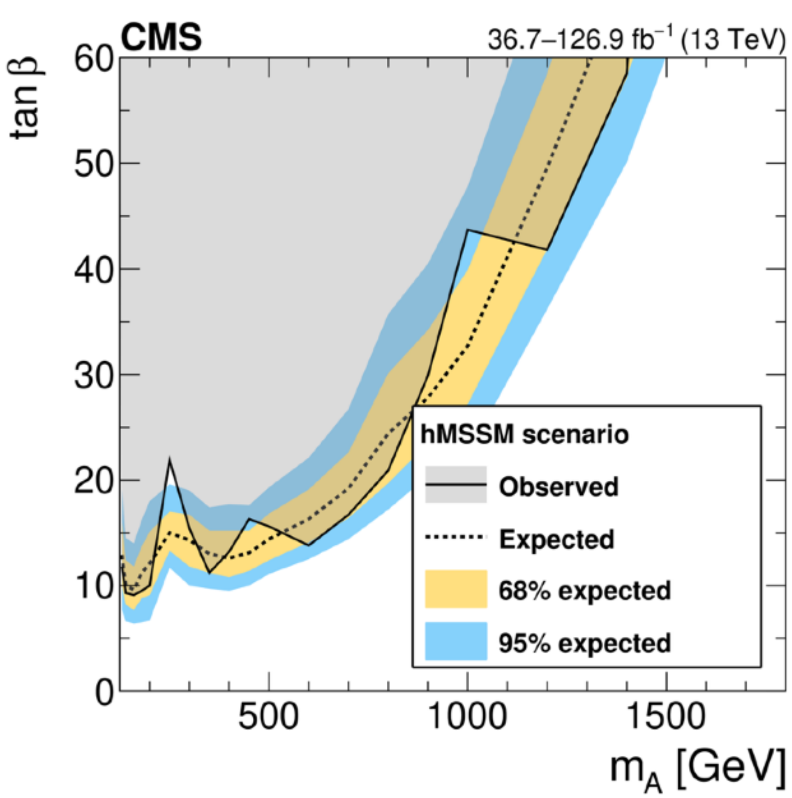
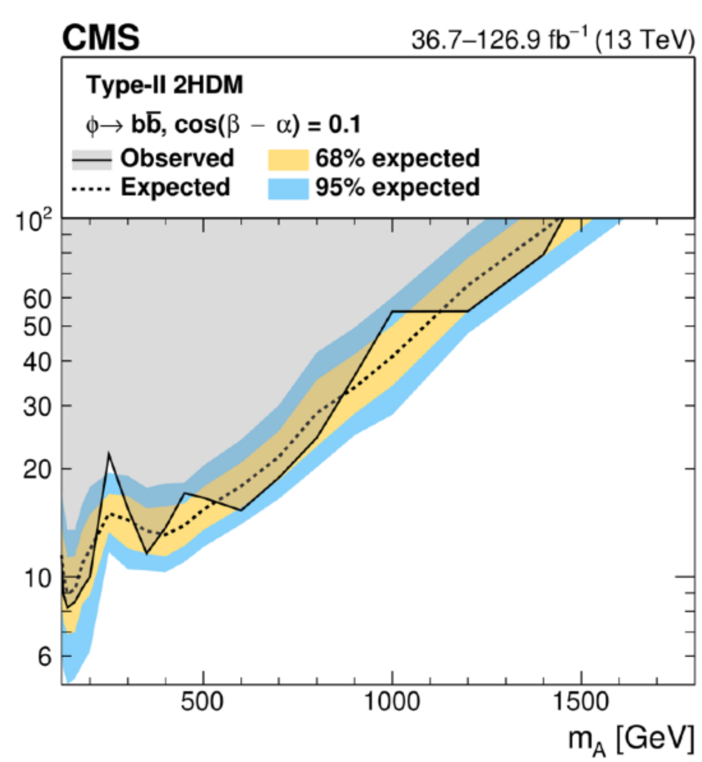
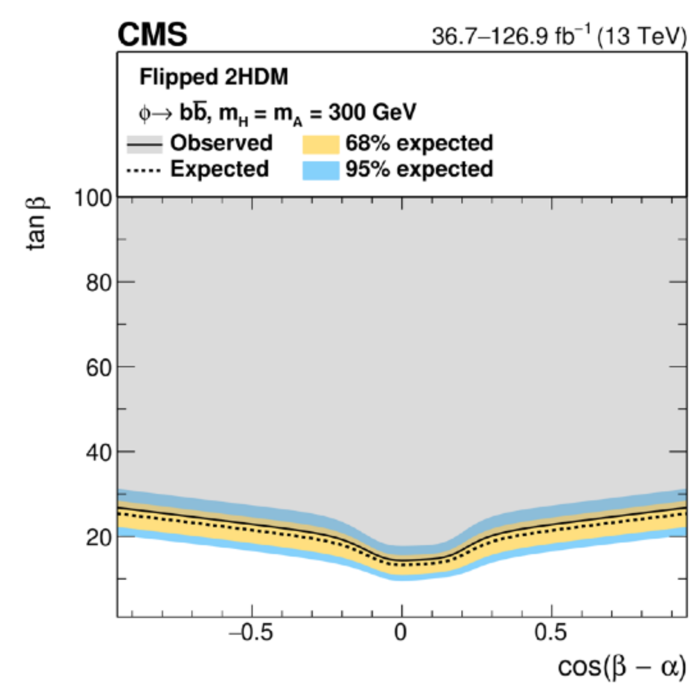




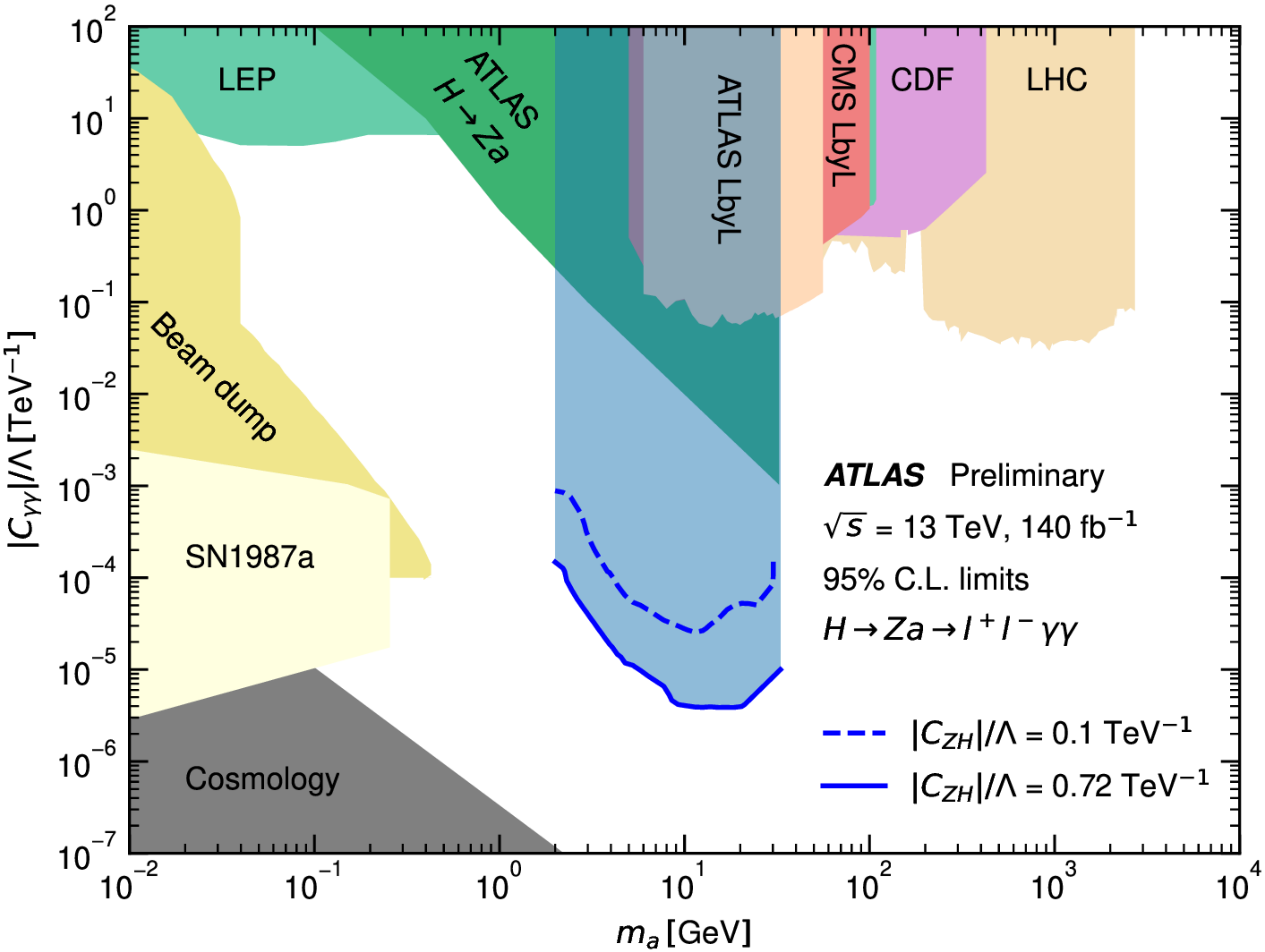


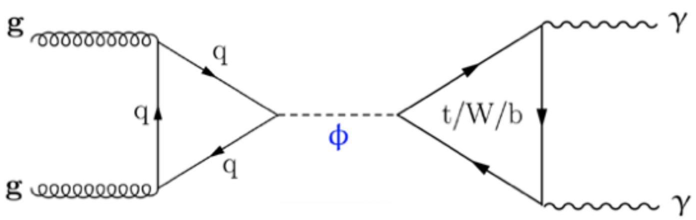


Most stringent limits at high mass in $A/H \rightarrow bb$ channel

Constraints on ALPs from $a \to \gamma\gamma$

ATL-PHYS-PUB-2025-007





$\mathbf{H} \rightarrow \gamma\gamma$ Low Mass Search

CMS-PAS-HIG-24-014

- Focus on $10 < m_{\gamma\gamma} < 70\,\text{GeV}$
  - New di-photon trigger in 2018 with asymmetric p_T thresholds (30/18 GeV) and no $m_{\gamma\gamma}$ requirement
- Data-driven γ+jets and multijet bkg, di-photon bkg modelled with MC
- NN to classify events as signal or bkg
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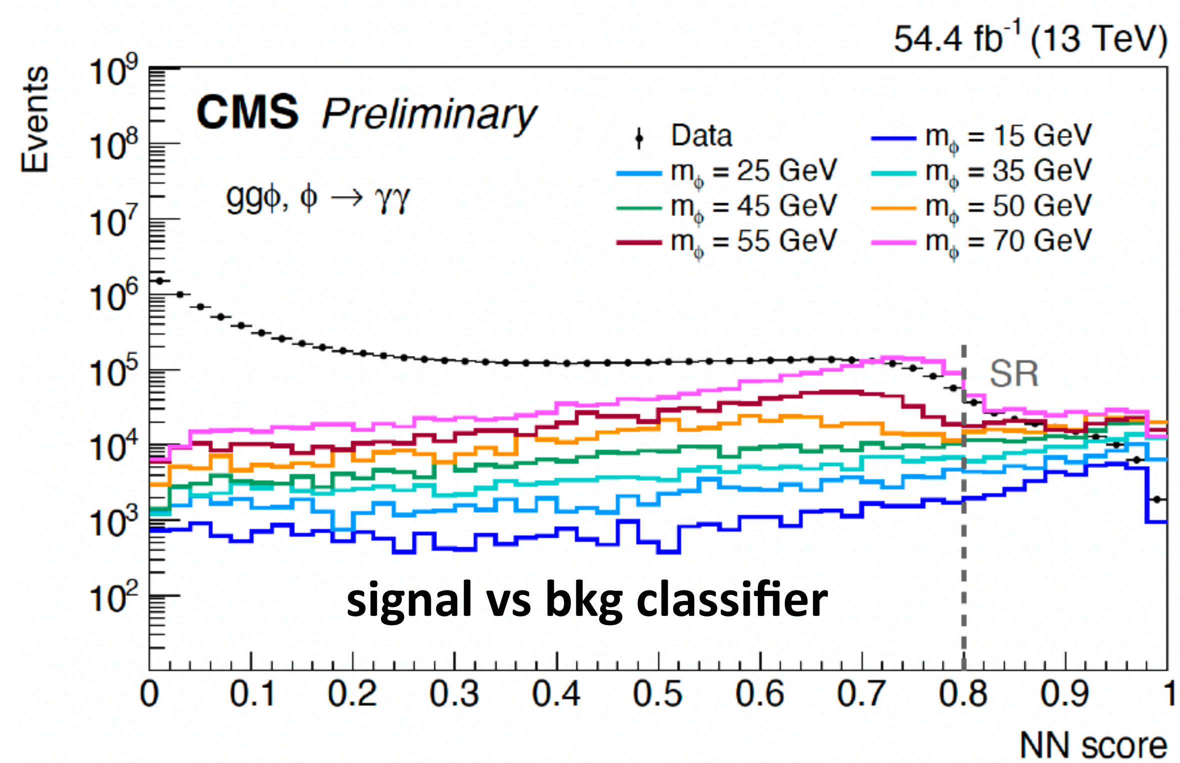
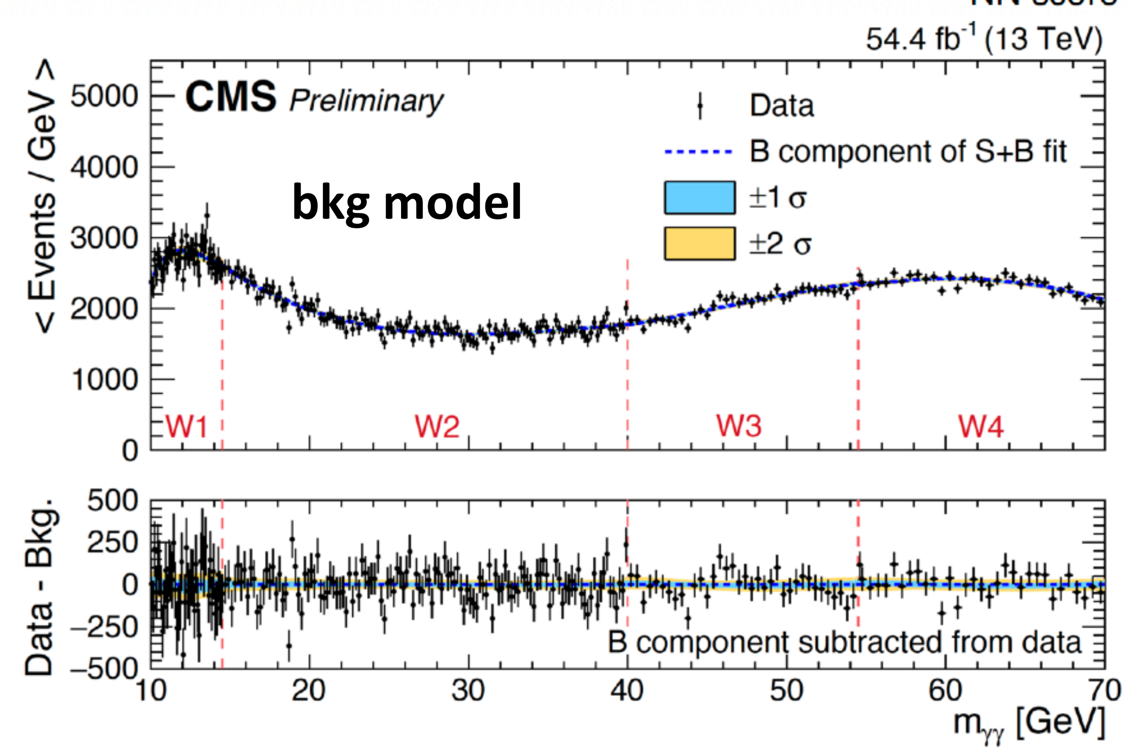
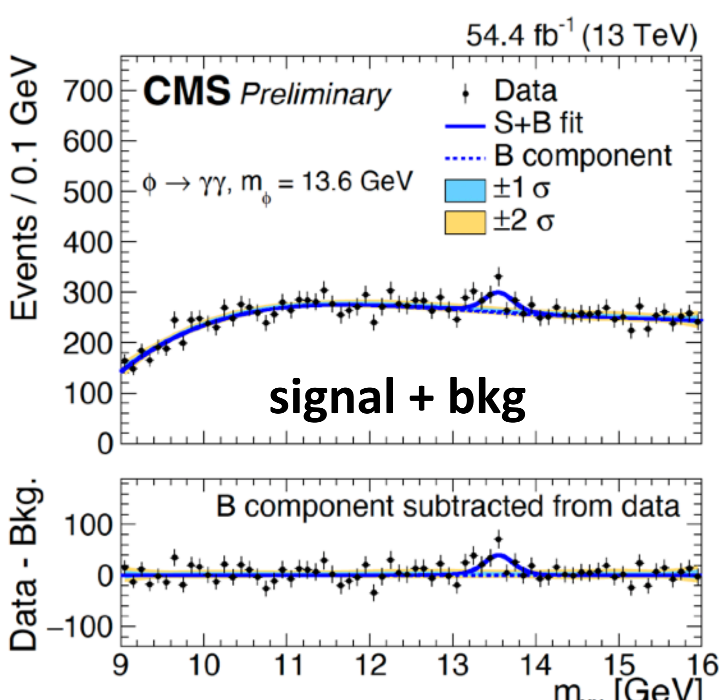
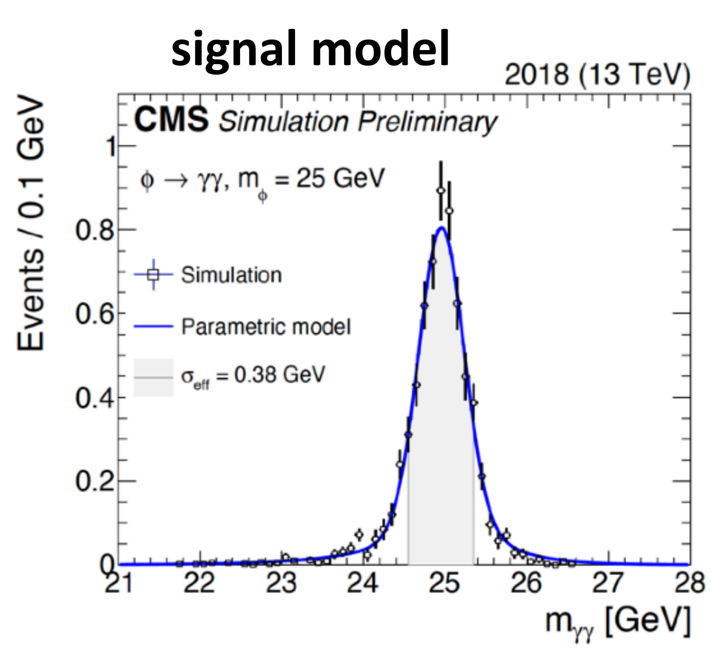
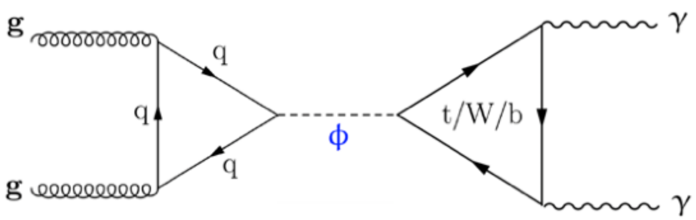
- Results interpreted in a specific **ALP model**











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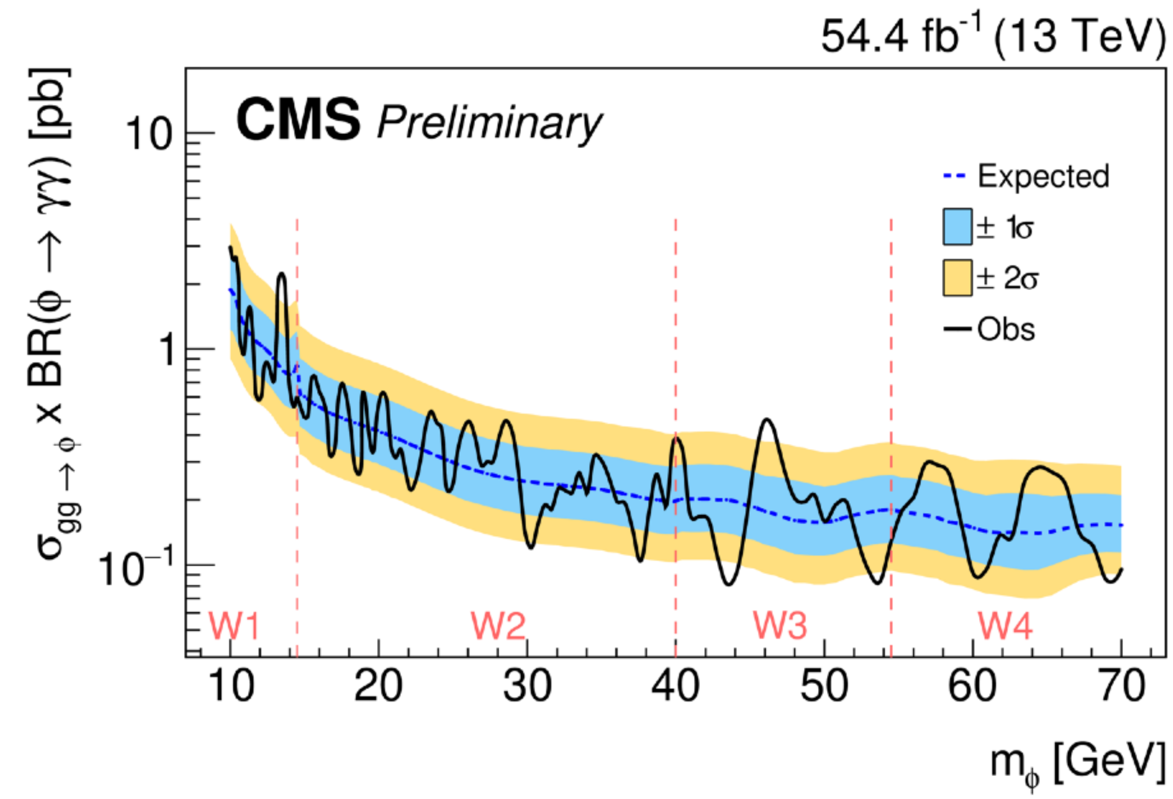

Kim-Shifman-Vainshtein-Zakharov ALP model

PLB 78 (1979) 443

PRL 43 (1979) 103