ATLAS Search for Charged Higgs in context of the GM Model

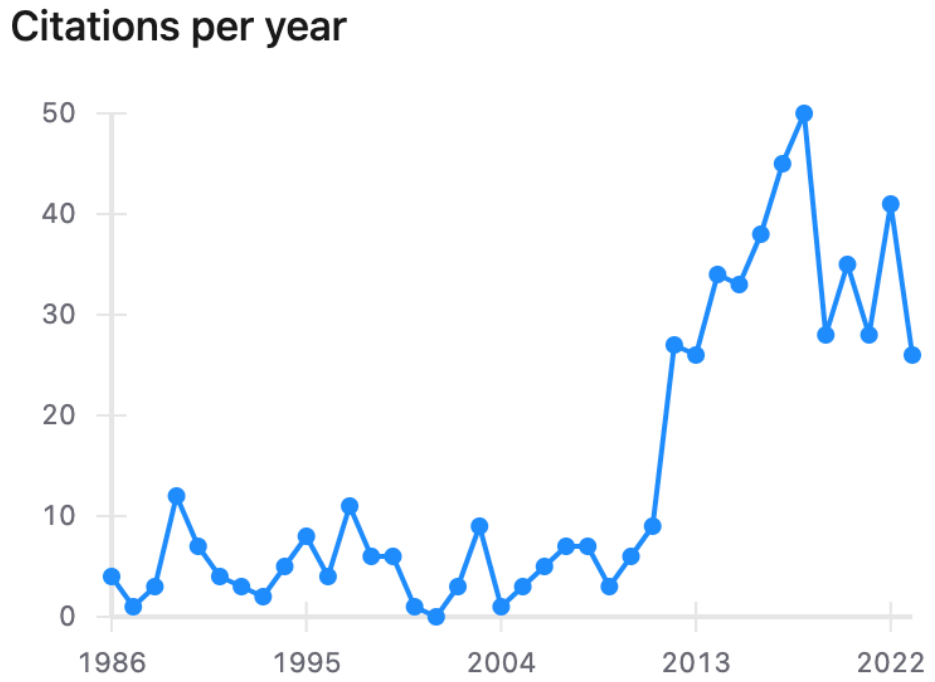
Thomas Gosart

DPF - PHENO

May 14, 2024

Introduction

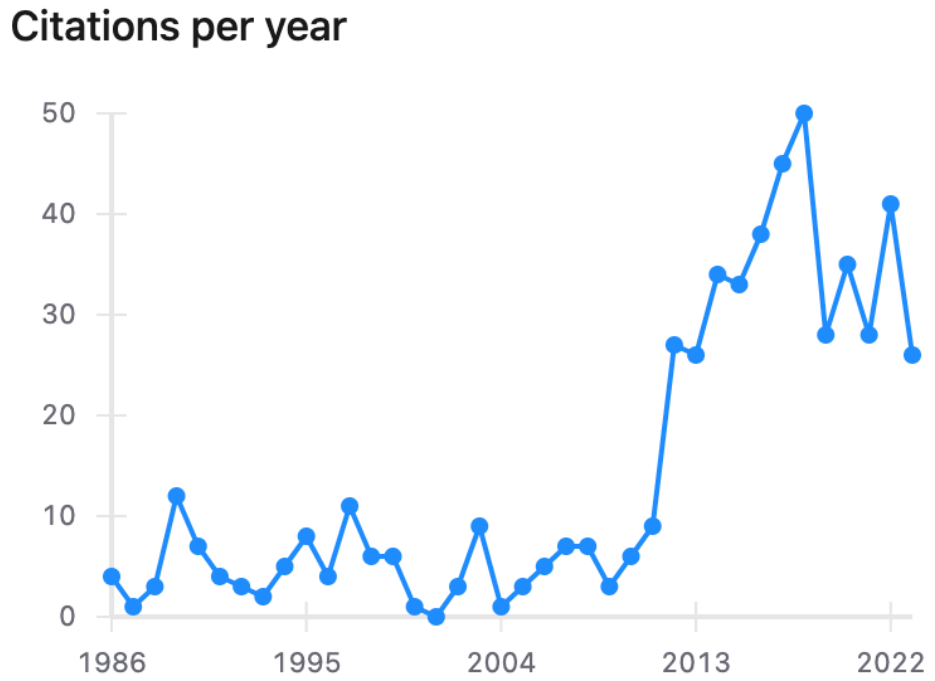
- The Georgi-Machacek (GM) model:[1] one of many BSM theories with expanded Higgs sector
- Originally from 1985; more significant work done since Higgs discovery



1: https://www.sciencedirect.com/science/article/pii/0550321385903256

Introduction

- The Georgi-Machacek (GM) model:[1] one of many BSM theories with expanded Higgs sector
- Originally from 1985; more significant work done since Higgs discovery



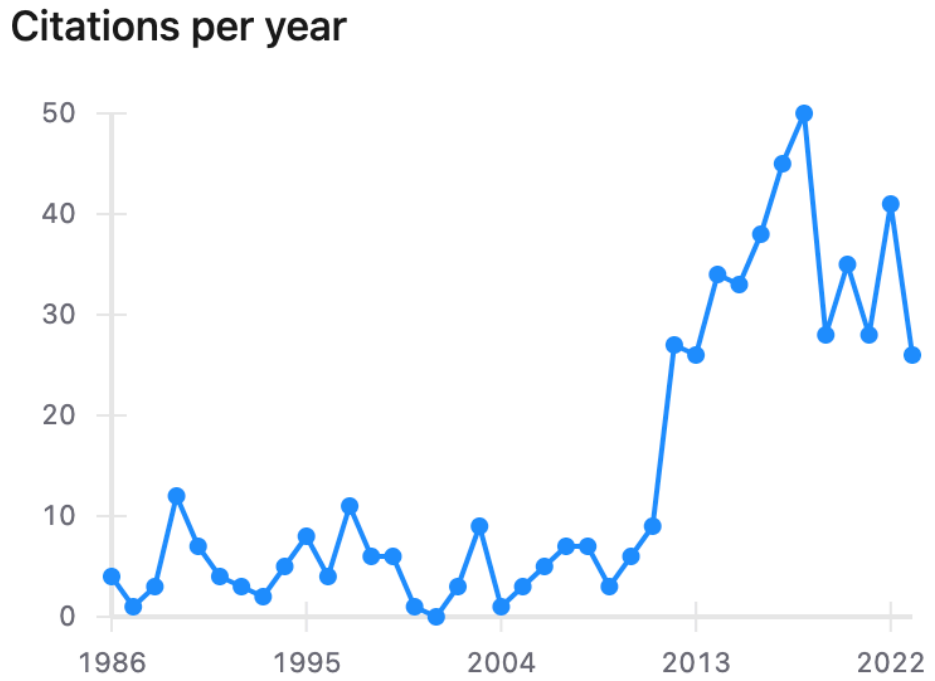
Original motivation:
EWK symmetry breaking

Now: neutrino mass, muon $g-2$, baryon asymmetry, more

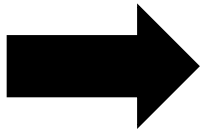
1: https://www.sciencedirect.com/science/article/pii/0550321385903256

Introduction

- The Georgi-Machacek (GM) model:[1] one of many BSM theories with expanded Higgs sector
- Originally from 1985; more significant work done since Higgs discovery



Original motivation:
EWK symmetry breaking



Now: neutrino mass, muon $g-2$, baryon asymmetry, more

- ATLAS and CMS conducted recent searches in context of the model

1: https://www.sciencedirect.com/science/article/pii/0550321385903256

New Triplets

- In addition to the SM doublet (ϕ), the GM model introduces real (ξ) and complex (χ) triplets:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

New Triplets

- In addition to the SM doublet (ϕ), the GM model introduces real (ξ) and complex (χ) triplets:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

- Triplets are used to predict 10 physical fields: *5-plet, 3-plet,* 2 singlets

$$H_5^{++} = \chi^{++}, \qquad H_5^{+} = \frac{(\chi^+ - \xi^+)}{\sqrt{2}}, \qquad H_5^0 = \sqrt{\frac{2}{3}}\xi^0 - \sqrt{\frac{1}{3}}\chi^{0,r},$$

$$H_3^{+} = -s_H\phi^+ + c_H\frac{(\chi^+ + \xi^+)}{\sqrt{2}}, \qquad H_3^0 = -s_H\phi^{0,i} + c_H\chi^{0,i},$$

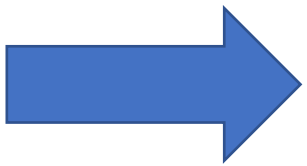
New Triplets

- In addition to the SM doublet (ϕ), the GM model introduces real (ξ) and complex (χ) triplets:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

- Triplets are used to predict 10 physical fields: 5-plet, 3-plet, *2 singlets*

$$H_1^0 = \phi^{0,r},$$
$$H_1^{0\prime} = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0,r}$$



$$h = \cos\alpha\, H_1^0 - \sin\alpha\, H_1^{0\prime},$$
$$H = \sin\alpha\, H_1^0 + \cos\alpha\, H_1^{0\prime}.$$

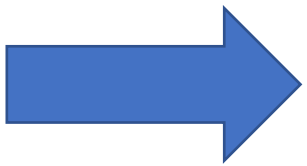
New Triplets

- In addition to the SM doublet (ϕ), the GM model introduces real (ξ) and complex (χ) triplets:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix}, \qquad \chi = \begin{pmatrix} \chi_{++} \\ \chi_+ \\ \chi_0 \end{pmatrix}, \qquad \xi = \begin{pmatrix} \xi_+ \\ \xi_0 \\ -\xi_- \end{pmatrix}$$

- Triplets are used to predict 10 physical fields: 5-plet, 3-plet, *2 singlets*

$$H_1^0 = \phi^{0,r},$$
$$H_1^{0\prime} = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0,r}$$



$$h = \cos\alpha\, H_1^0 - \sin\alpha\, H_1^{0\prime},$$
$$H = \sin\alpha\, H_1^0 + \cos\alpha\, H_1^{0\prime}.$$

SM Higgs

GM Model Features

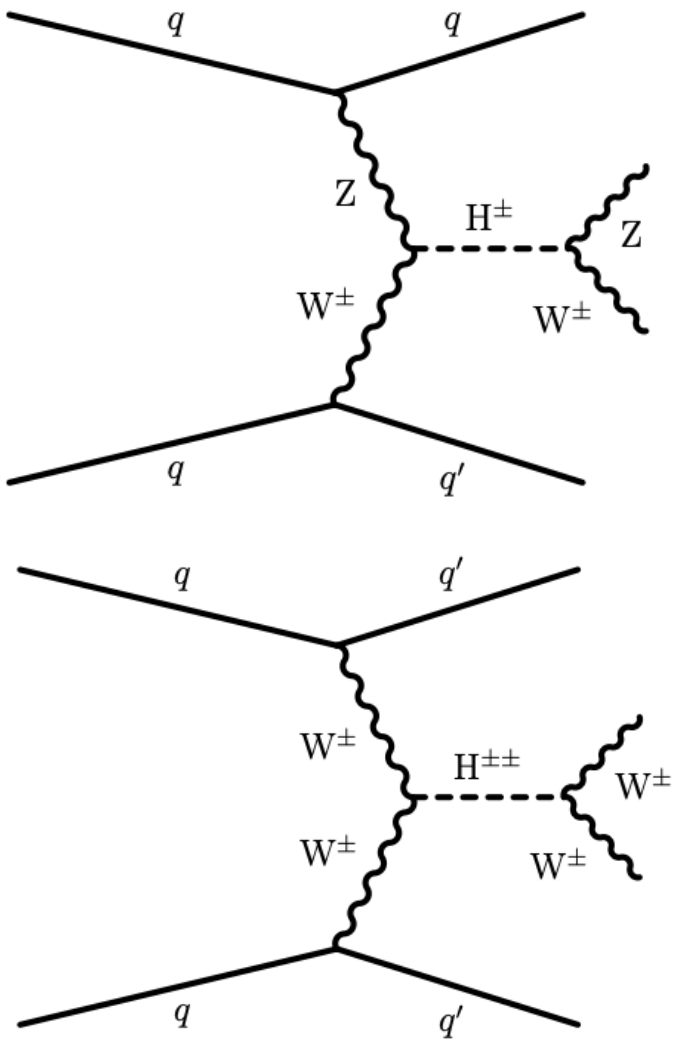
- New triplet VEVs are the same: $v_\chi = v_\xi$; theory has 2 VEVs:

$$v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246\ \text{GeV})^2 \qquad s_H \equiv \sin\theta_H = \frac{2\sqrt{2}\,v_\chi}{v}$$

- The 5-plet states ($H_5^{\pm\pm}$, $H_5^{\pm}$, H_5^0) are fermiophobic
  - Do not contain doublet field content ➔ no fermion couplings
- Primarily decay to vector bosons – can set $\text{BR}(H_5 \to VV) = 1$
  - Couplings H_5VV are function of the new VEV and SM constants
  - H_5 searches thus only depend on s_H and m_{H_5} – easy to search phase space!

$H^{\pm\pm}$ and $H^{\pm}$ Production

- At the LHC, the charged Higgs bosons can be produced via *vector-boson fusion (VBF)*
- BR($H_5 \rightarrow VV$) = 1 covers most of the model phase space[1]

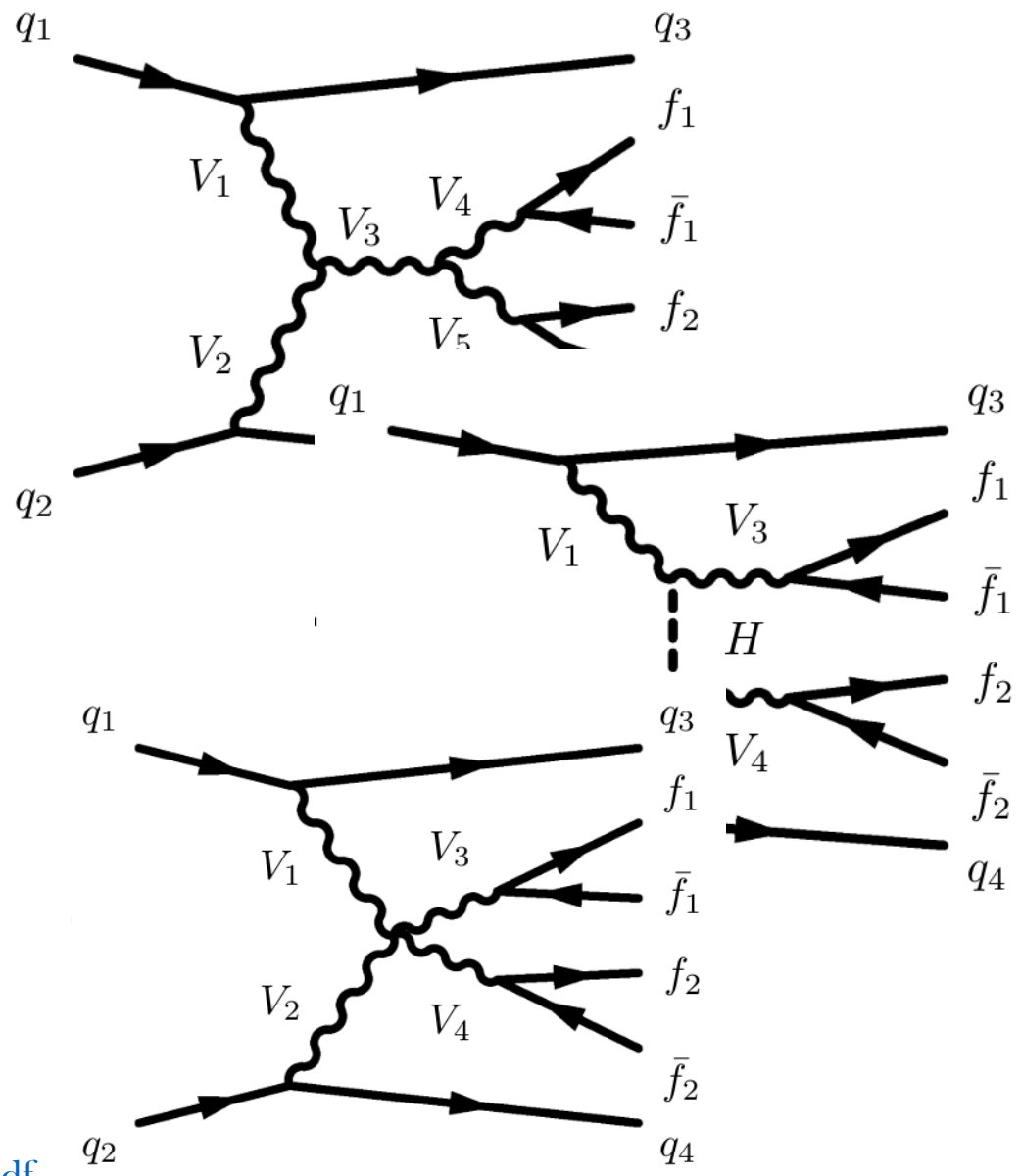


1: https://cds.cern.ch/record/2002500/files/LHCHXSWG-2015-001_2.pdf

$H^{\pm\pm}$ and $H^{\pm}$ Production

- At the LHC, the charged Higgs bosons can be produced via *vector-boson fusion (VBF)*
- BR($H_5 \to VV$) = 1 covers most of the model phase space[1]

Significant background from vector boson scattering (VBS) processes



1: https://cds.cern.ch/record/2002500/files/LHCHXSWG-2015-001_2.pdf

Previous Search Results

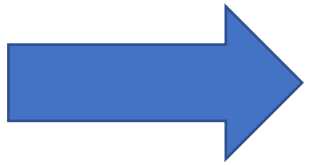
- $H^{\pm}$ and $H^{\pm\pm}$ searched for previously with LHC Run 2
  - ATLAS: $H^{\pm}$ resonance search[1] and $W^{\pm}W^{\pm}jj$ measurement[2]
- ATLAS observed 2 - 3σ local excesses!
- Combined GM Model interpretation underway with ATLAS
  - Note: a CMS search did not set more stringent limits

1: https://arxiv.org/abs/2207.03925
2: https://arxiv.org/abs/2312.00420
3: https://arxiv.org/abs/2104.04762

Previous Search Results

- $H^{\pm}$ and $H^{\pm\pm}$ searched for previously with LHC Run 2
  - ATLAS: $H^{\pm}$ resonance search[1] and $W^{\pm}W^{\pm}jj$ measurement[2]
- ATLAS observed 2 - 3σ local excesses!
- Combined GM Model interpretation underway with ATLAS
  - Note: a CMS search did not set more stringent limits

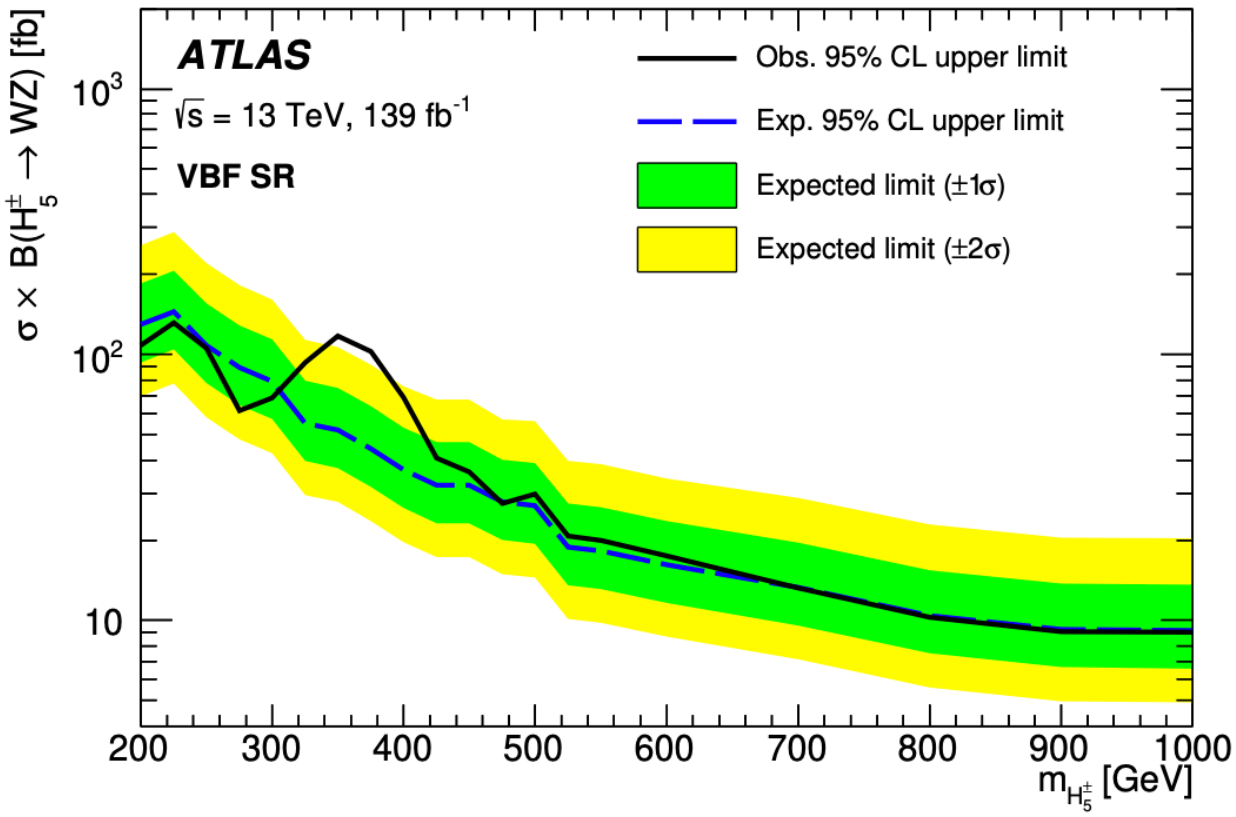
No search optimized specifically for GM model scalar production

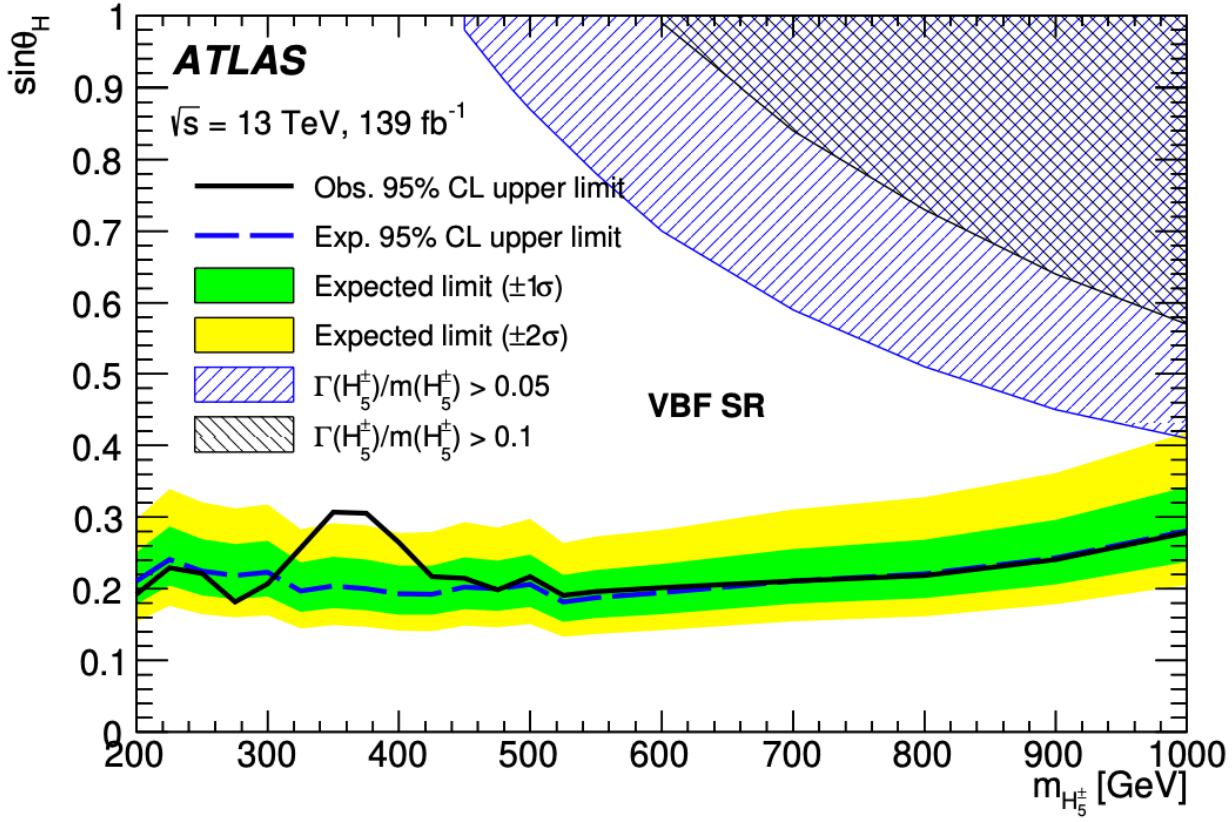


New search has great chance for optimization

1: https://arxiv.org/abs/2207.03925
2: https://arxiv.org/abs/2312.00420
3: https://arxiv.org/abs/2104.04762

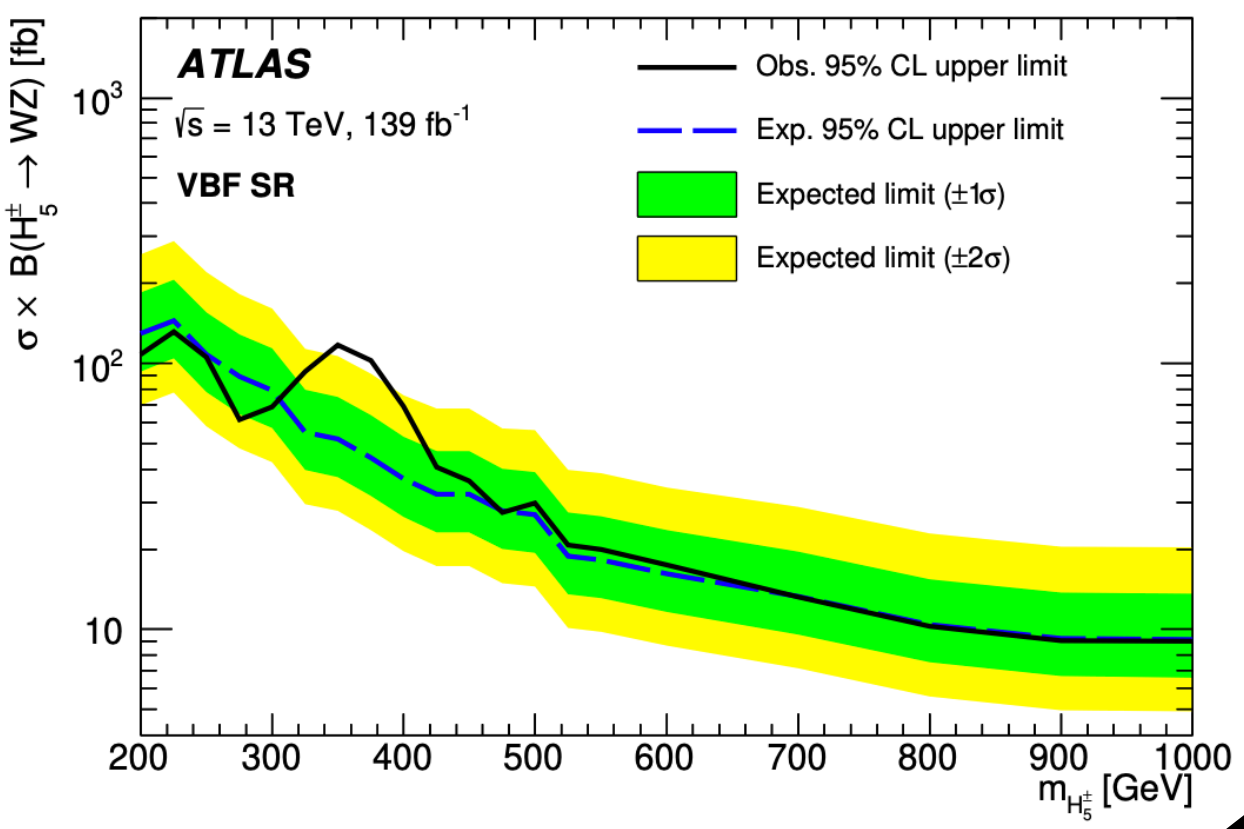
ATLAS VBF $H^{\pm}$ Search Limit Plots

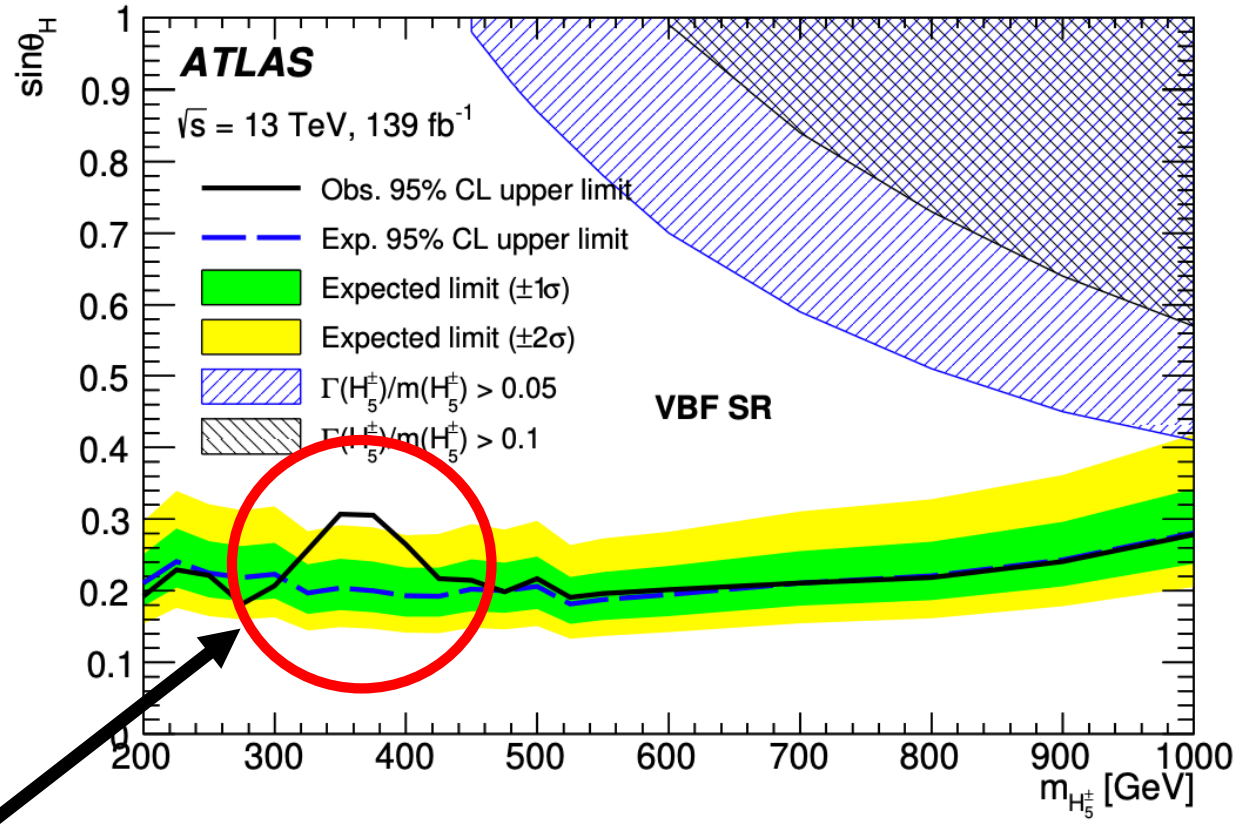




Source: https://arxiv.org/pdf/2207.03925.pdf

ATLAS VBF $H^{\pm}$ Search Limit Plots

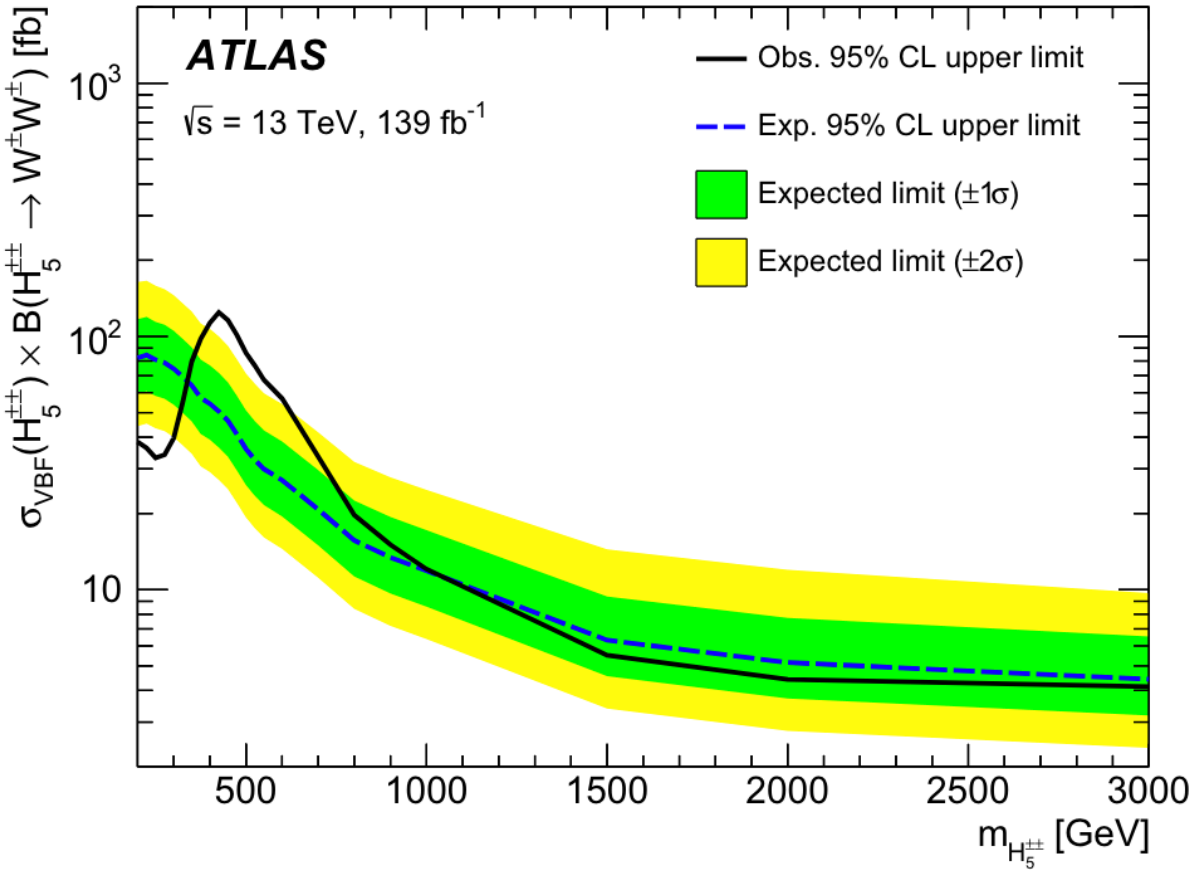


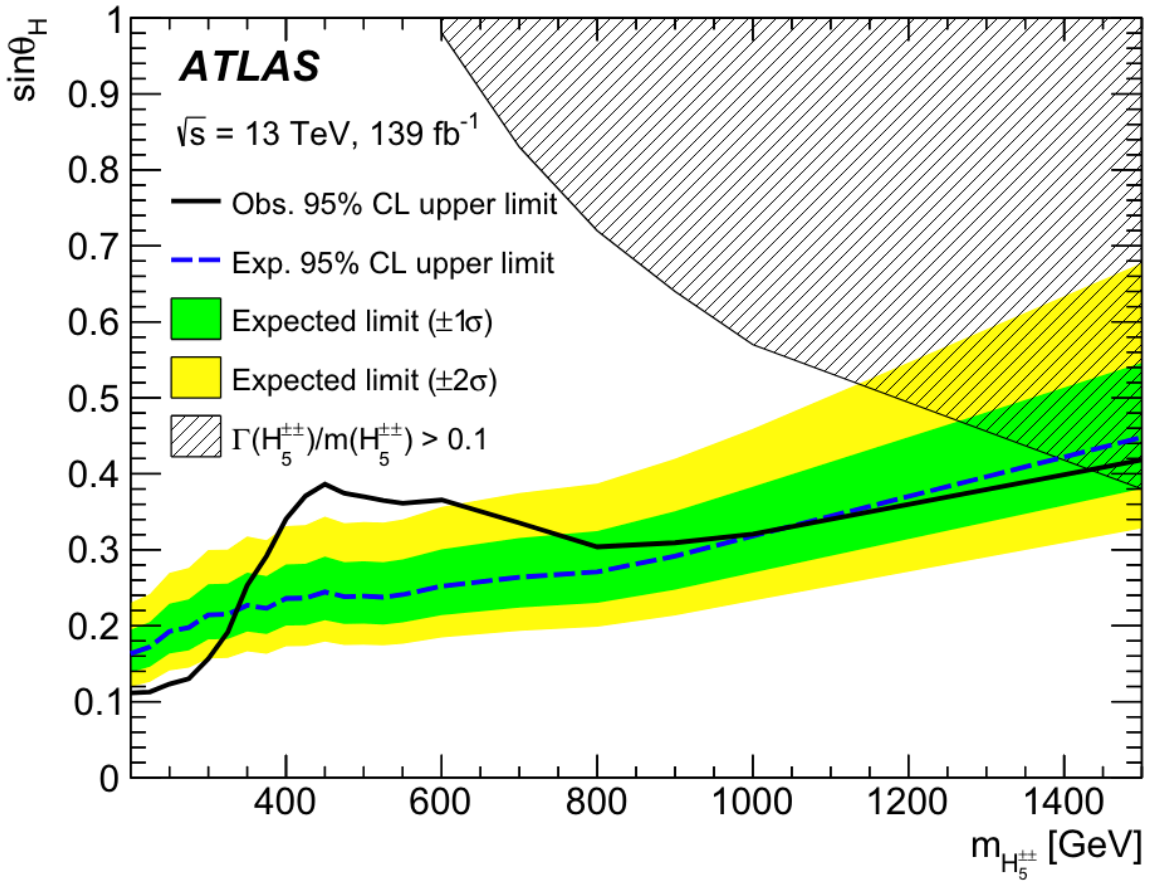


Excess of events between 300-400 GeV;
GM model less constrained in this region

Source: https://arxiv.org/pdf/2207.03925.pdf

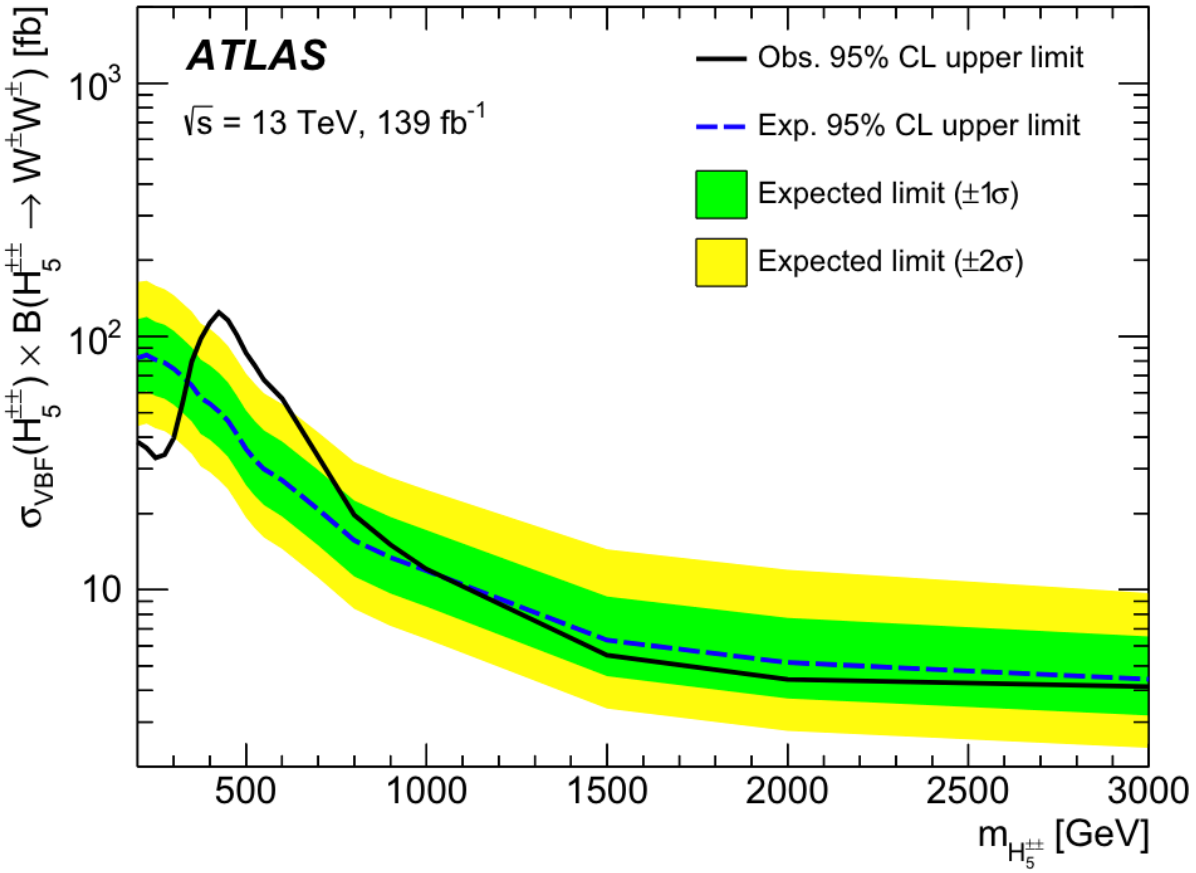
ATLAS $W^{\pm}W^{\pm}jj\ H^{\pm\pm}$ Search Limit Plots

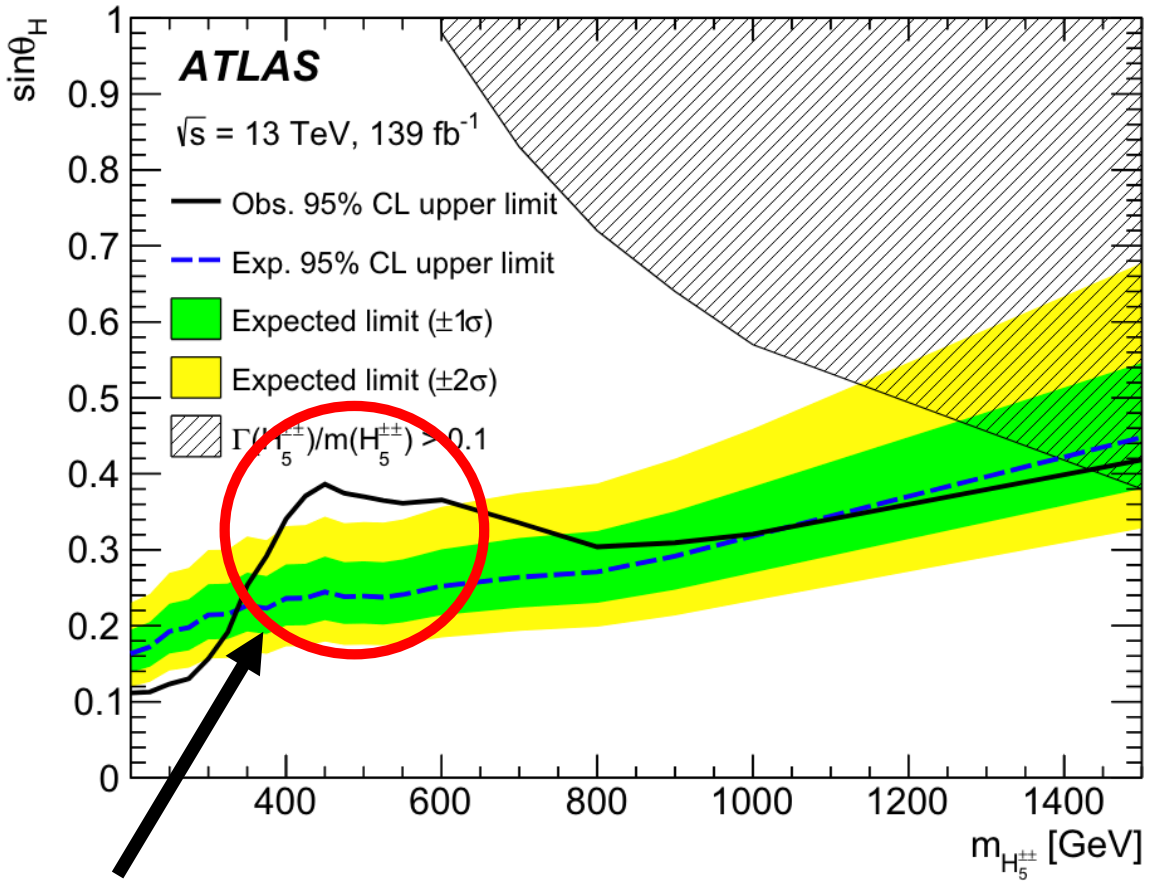




Source: https://arxiv.org/abs/2312.00420

ATLAS $W^{\pm}W^{\pm}jj\ H^{\pm\pm}$ Search Limit Plots

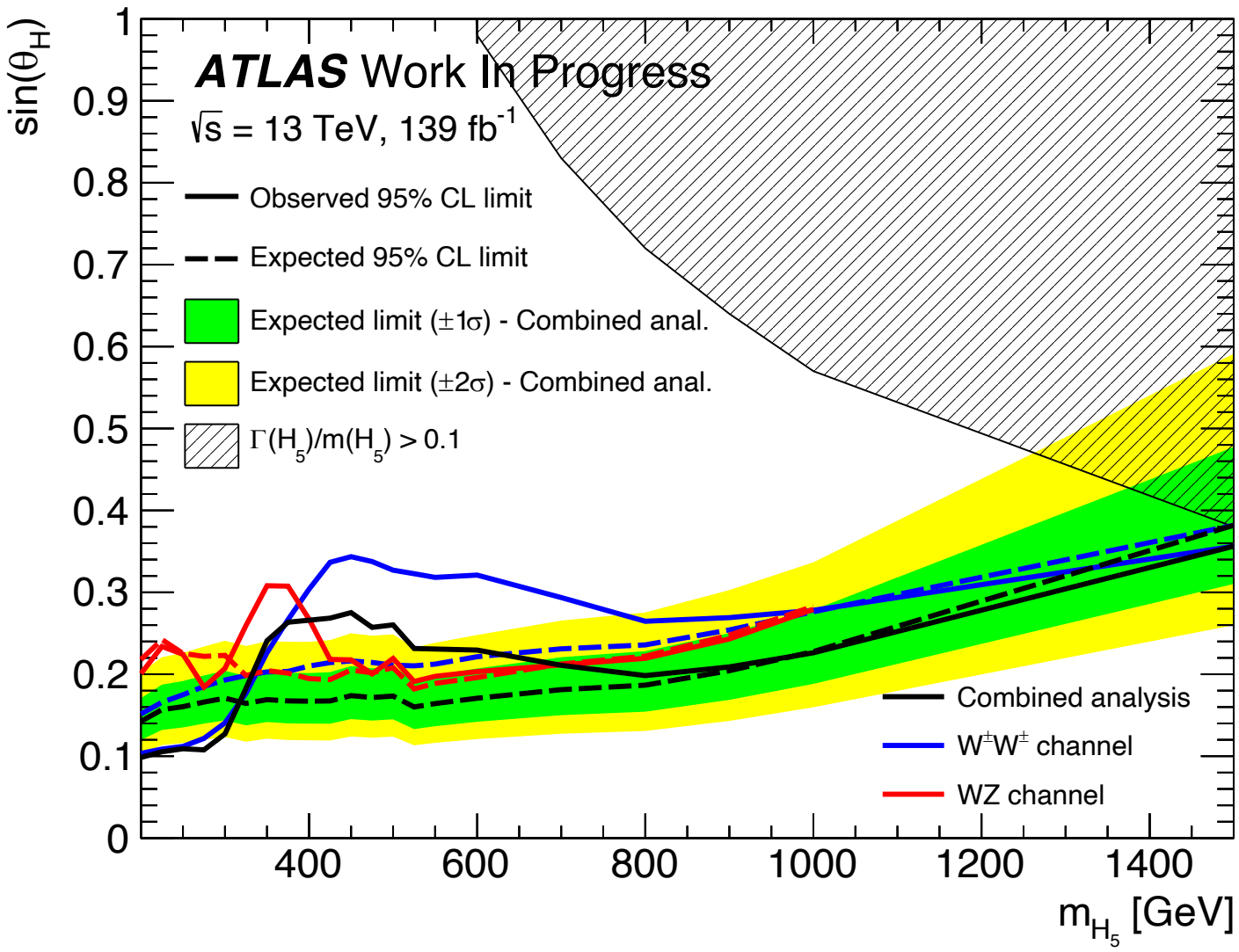




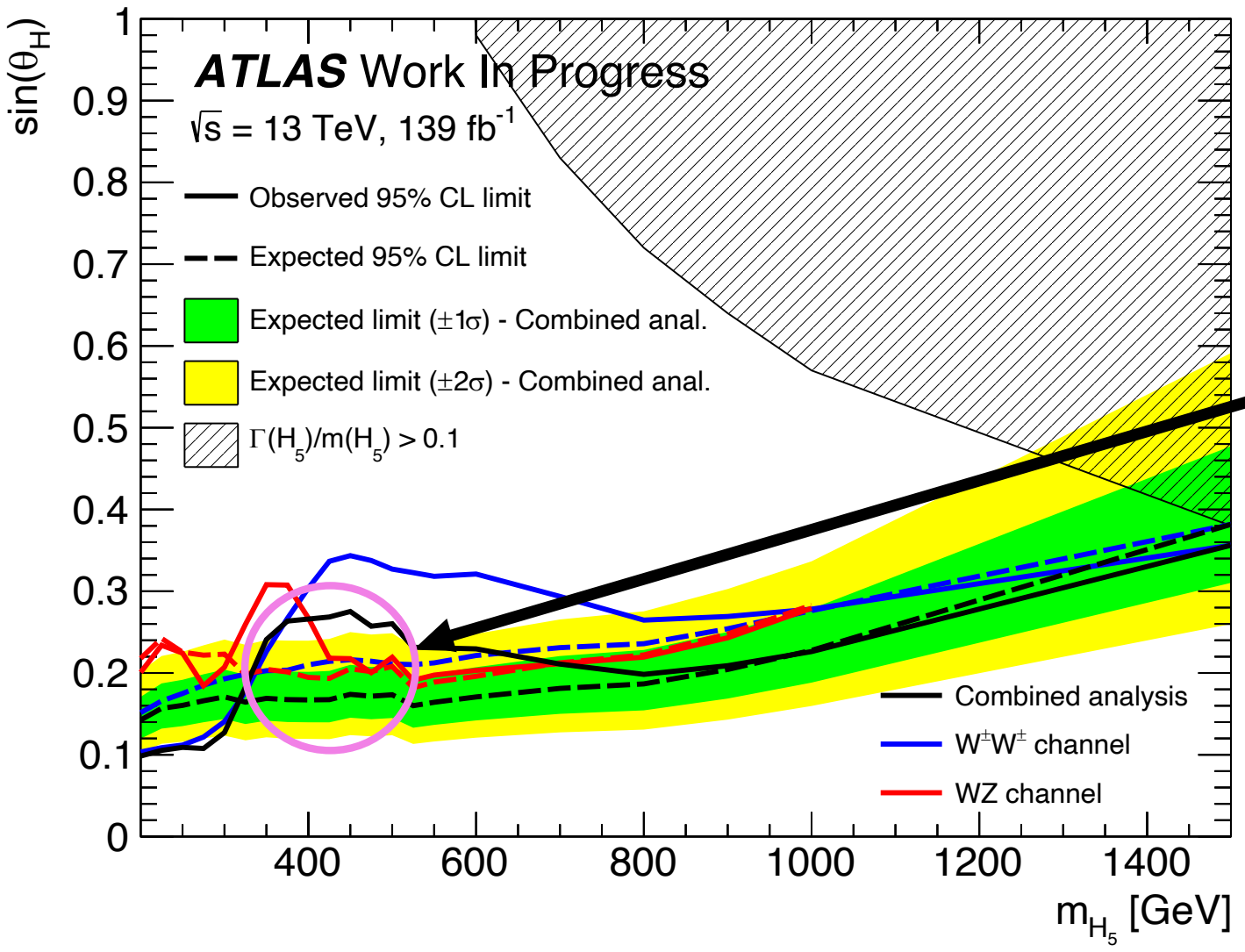
Excess of events between 350-600 GeV;
GM model less constrained in this region

Source: https://arxiv.org/abs/2312.00420

ATLAS Combined GM Model Limits



ATLAS Combined GM Model Limits



Combined fit of both searches further constrains GM model

Run 2 + Partial Run 3 Search

- LHC began new run (Run 3) at 13.6 TeV in 2022

Run 2 + Partial Run 3 Search

- LHC began new run (Run 3) at 13.6 TeV in 2022

Additional data + model optimization + existing excess
➔ exciting new analysis!

Run 2 + Partial Run 3 Search

- LHC began new run (Run 3) at 13.6 TeV in 2022

Additional data + model optimization + existing excess
➔ exciting new analysis!

  - New search (fully leptonic) began in 2023: Run 2 and partial Run 3 data
  - Using ATLAS's state-of-the-art analysis tools

- Potential improvements: implement boosted $Z \rightarrow ee$ tagger, machine learning, utilize Higgs' scalar nature as in $h \rightarrow WW$ search[1]

1: https://arxiv.org/abs/1412.2641

Run 2 + Partial Run 3 Search

- LHC began new run (Run 3) at 13.6 TeV in 2022

Additional data + model optimization + existing excess
➔ exciting new analysis!

  - New search (fully leptonic) began in 2023: Run 2 and partial Run 3 data
  - Using ATLAS's state-of-the-art analysis tools

- Potential improvements: implement boosted $Z \rightarrow ee$ tagger, machine learning, utilize Higgs' scalar nature as in $h \rightarrow WW$ search[1]

- Next steps: reproduce Run 2 results, develop new signal region

1: https://arxiv.org/abs/1412.2641

Thank you!

Email: tgosart3@sas.upenn.edu

Back Up

The VEVs

- To preserve custodial symmetry, the triplet VEVs are equal:

$$v_\chi = v_\xi \equiv v_\Delta$$

v_Δ and v_χ are used interchangeably

- The W and Z masses constrain:

$$v_\phi^2 + 8v_\chi^2 \equiv v^2 = \frac{1}{\sqrt{2}G_F} \approx (246\ \text{GeV})^2$$

  - v_ϕ is the SM Higgs doublet VEV

- EW symmetry is broken in the same way ➔ W and Z mass terms unchanged from SM ➔ $\rho = 1$ preserved at tree level

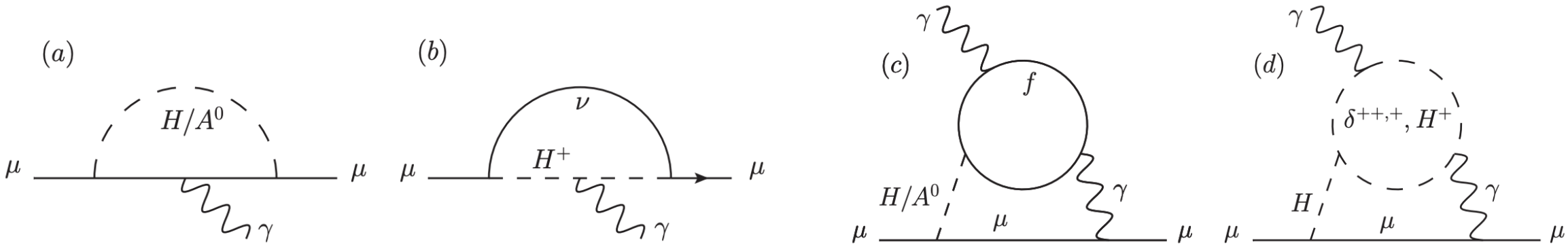
$$m_W^2 = g^2v^2/4 \text{ and } m_Z^2 = g^2v^2/(4\cos^2\theta_W)$$

Motivation

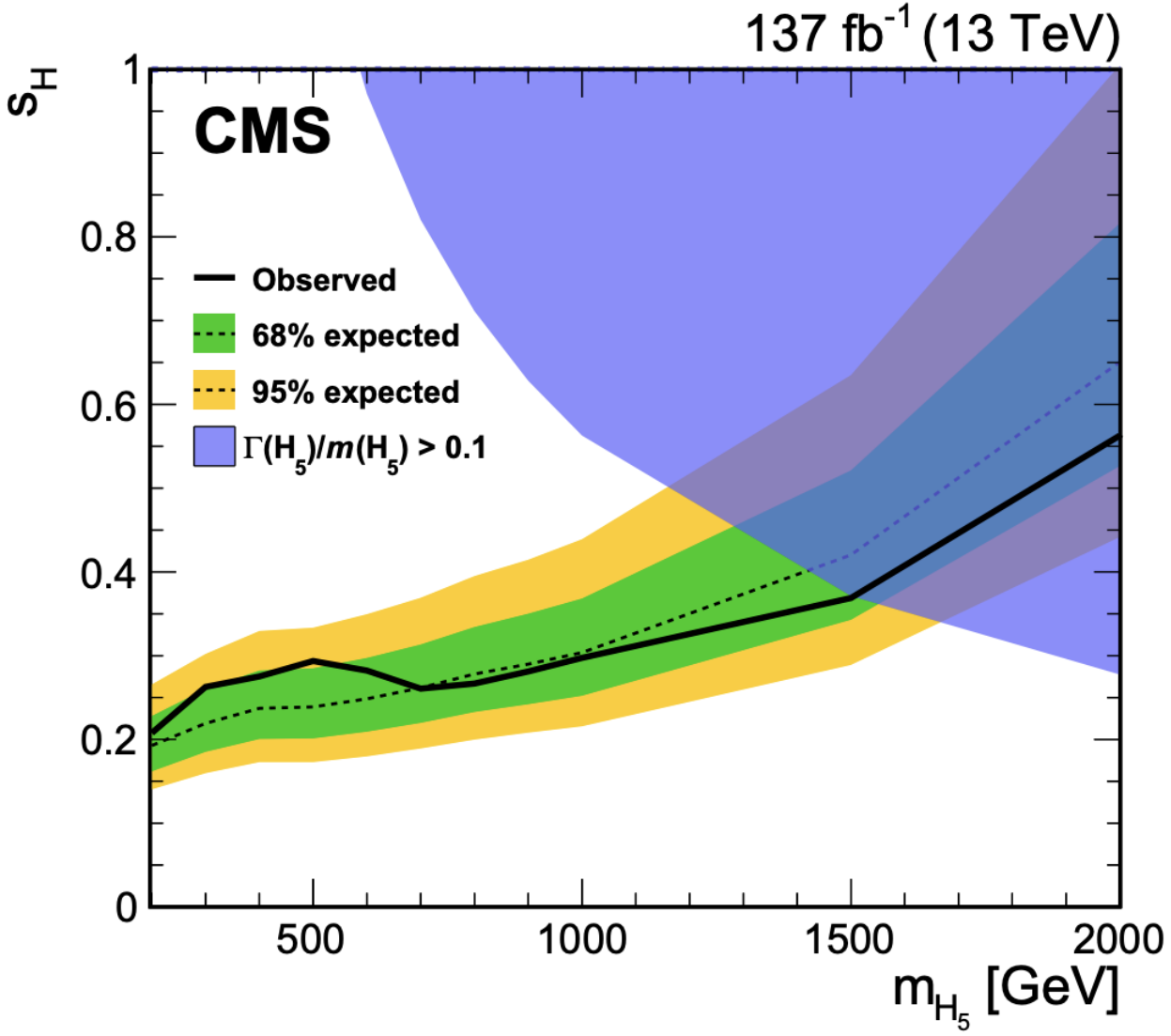
- GM model is used to explain a number of open questions
- SUSY: possible to supersymmetrize GM model
- Neutrino mass: can provide small masses via Seesaw mechanism
- Dark matter: all GM particles can decay, but an inert doublet can be added to the model which creates a DM candidate
- Baryon asymmetry: electroweak baryogenesis via large triplet VEV
- Muon $g-2$: extended GM with an additional doublet can create corrections to explain $g-2$ value
- W mass shift: extended GM with custodial symmetry breaking terms

GM Model Implication Examples

- Dark matter: adds inert doublet Φ_2 with VEV = 0
  - Custodial symmetry preserved in the same way
  - Potentially detectable at the LHC
- Muon $g-2$: additional Barr-Zee type Feynman diagrams
  - Both singly and doubly charged Higgs contribute
  - Not unique to GM model; also possible in 2HDMs and HTMs



CMS $H^{\pm\pm}/H^{\pm}$ Search



Source: https://arxiv.org/abs/2104.04762