Search for a $H^{\pm\pm}$ produced via VBF using the ATLAS detector

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On behalf of the ATLAS Collaboration

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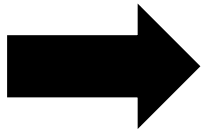
Let's make some charged scalars

- Standard model (SM) has some remaining open questions
- 1985 Georgi-Machacek (GM) model – expands Higgs sector

Original motivation:
EWK symmetry breaking



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

  - More significant work done since 2012 Higgs discovery

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

New Triplets

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

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

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

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

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

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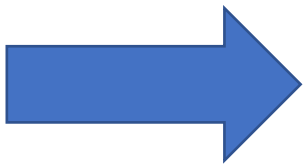
$$H_1^0 = \phi^{0,r},$$
$$H_1^{0\prime} = \sqrt{\frac{1}{3}}\xi^0 + \sqrt{\frac{2}{3}}\chi^{0,r}$$



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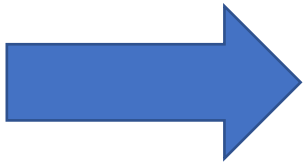

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SM Higgs

GM Model Features

- New triplet vacuum expectation values (VEVs) are the same: $v_\chi = v_\xi$

Overall theory has two 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!

Charged scalars at the LHC

- At the LHC, $H^{\pm\pm}$ can be produced via *vector-boson fusion (VBF)*
- 2022 ATLAS EWK $W^{\pm}W^{\pm}jj$ cross-section measurement (VBS/VBF)

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GM Model $H^{\pm\pm}$ has same final state

$H^{\pm\pm}$ search added to measurement

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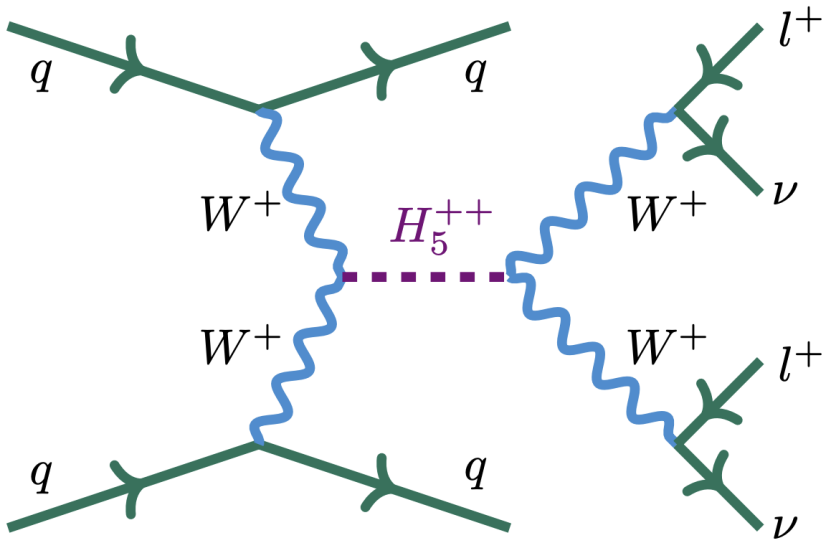

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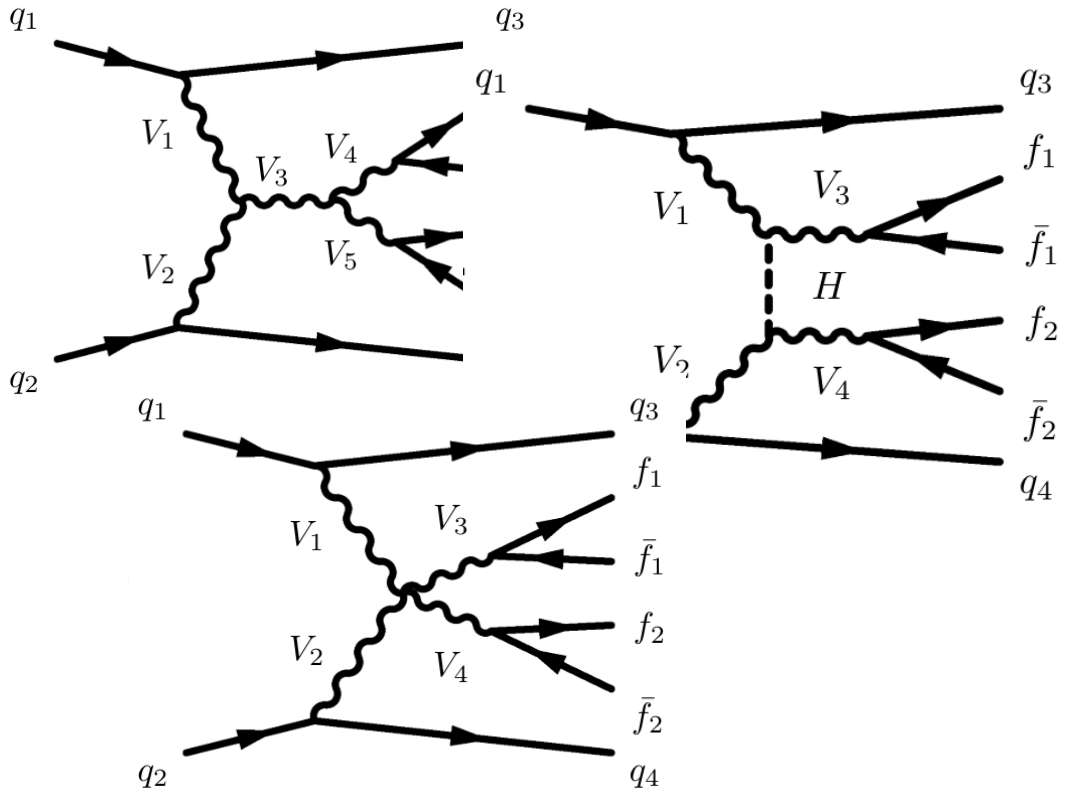
Significant background from vector boson scattering (VBS) processes



Event Selections

https://arxiv.org/abs/2312.00420

Requirement	SR	Low-m_{jj} CR	WZ CR
Leading and subleading lepton p_T		> 27 GeV	
Electron $\|\eta\|$		< 2.47 (1.37 in ee), excluding $1.37 \leq \|\eta\| \leq 1.52$	
Muon $\|\eta\|$		< 2.5	
Leading (subleading) jet p_T		> 65 (35) GeV	
Additional jet p_T		> 25 GeV	
Jet $\|\eta\|$		< 4.5	
$m_{\ell\ell}$		> 20 GeV	
E_T^{miss}		> 30 GeV	
Charge misid. $Z \to ee$ veto		$\|m_{ee} - m_Z\| > 15$ GeV	–
b-jet veto		$N_{b\text{-jet}} = 0$, $p_T^{b\text{-jet}} > 20$ GeV, $\|\eta^{b\text{-jet}}\| < 2.5$	
$N_{\text{veto leptons}}$	$= 0$	$= 0$	$= 1$, $p_T > 15$ GeV
$m_{\ell\ell\ell}$	–	–	> 106 GeV
m_{jj}	> 500 GeV	$200 < m_{jj} < 500$ GeV	> 200 GeV
$\|\Delta y_{jj}\|$		> 2	

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VBF event selection

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Improve modeling of WZ background

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Control background uncertainties

CR Distributions

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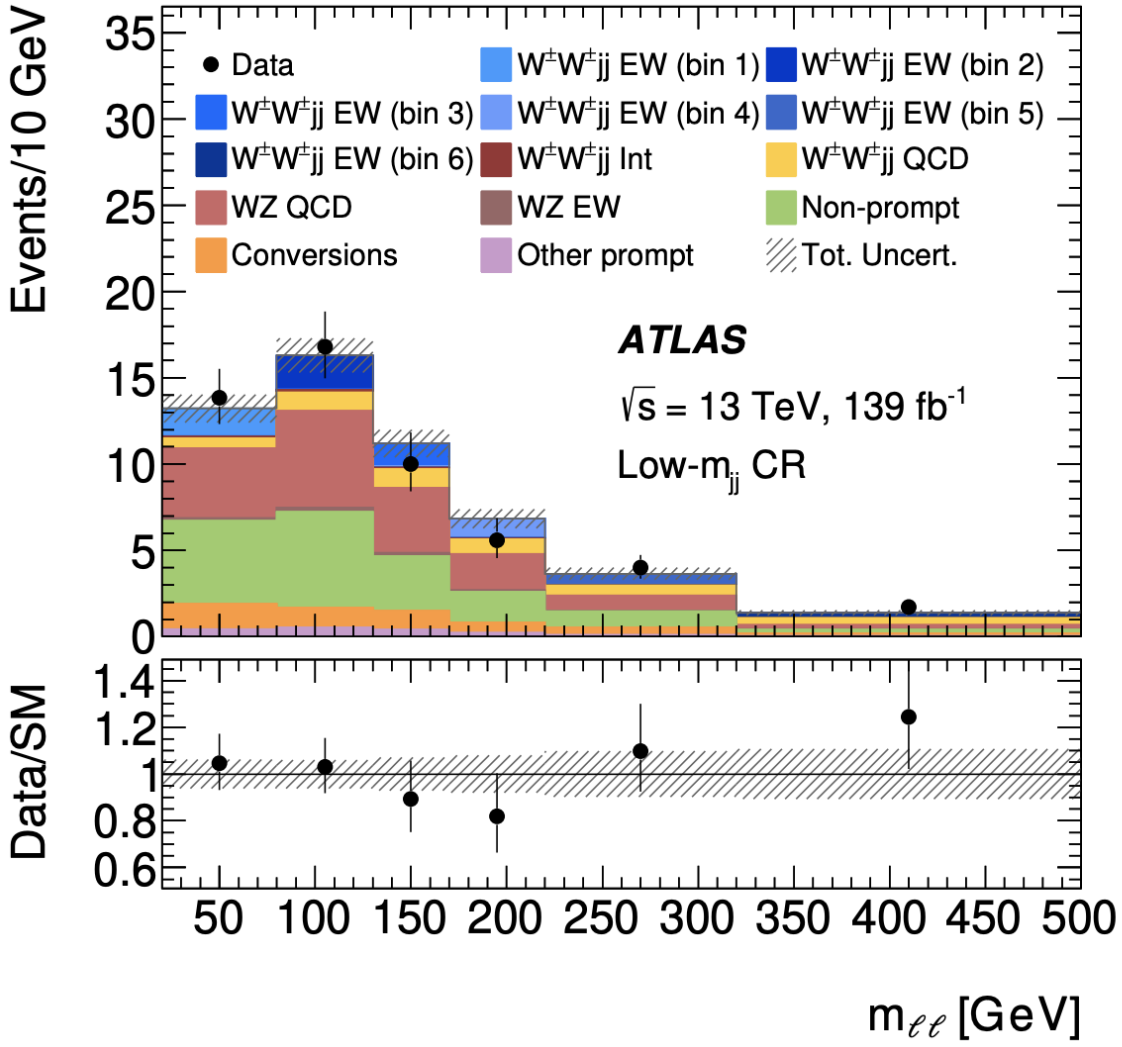

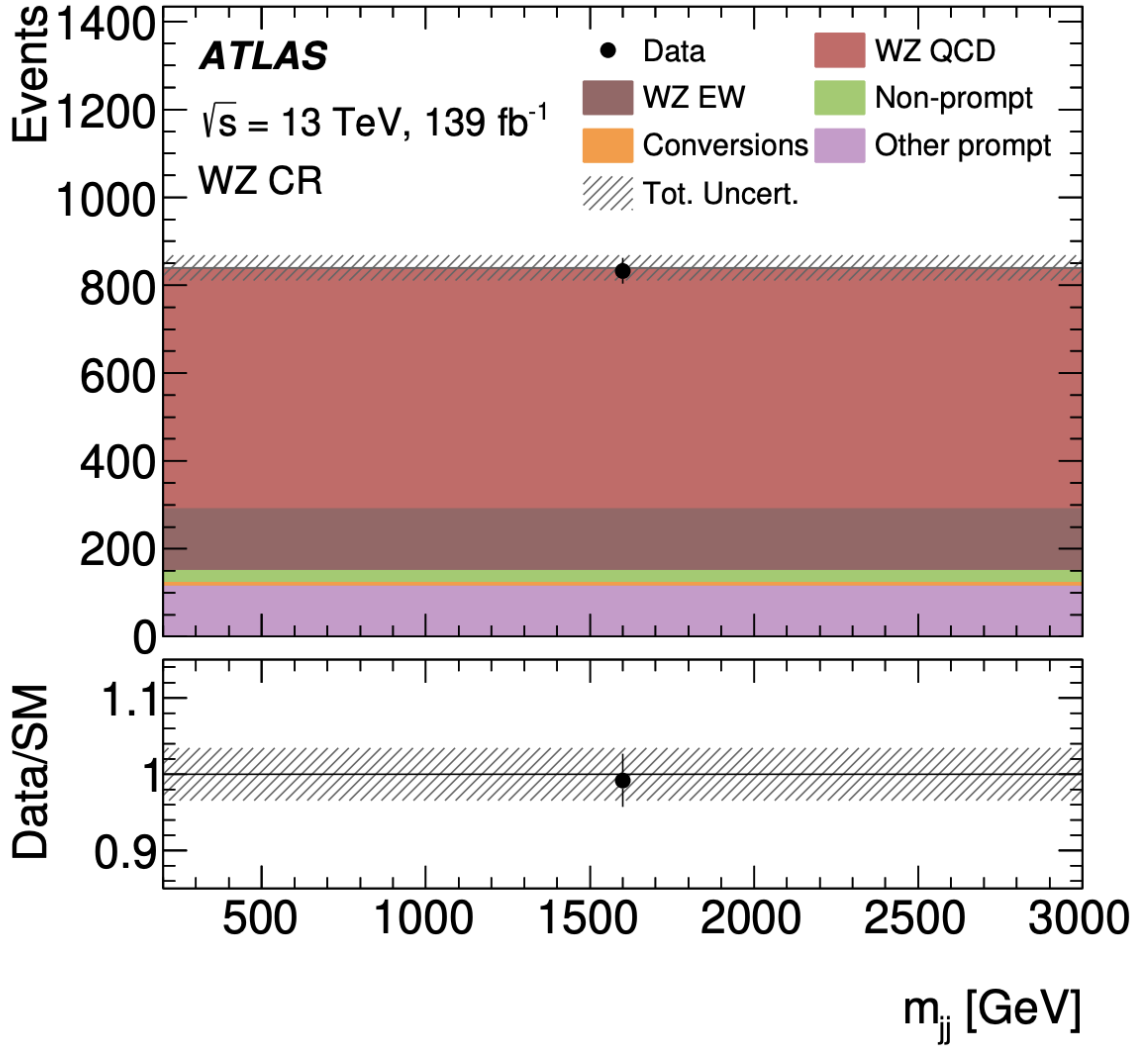

Excess in Run 2!

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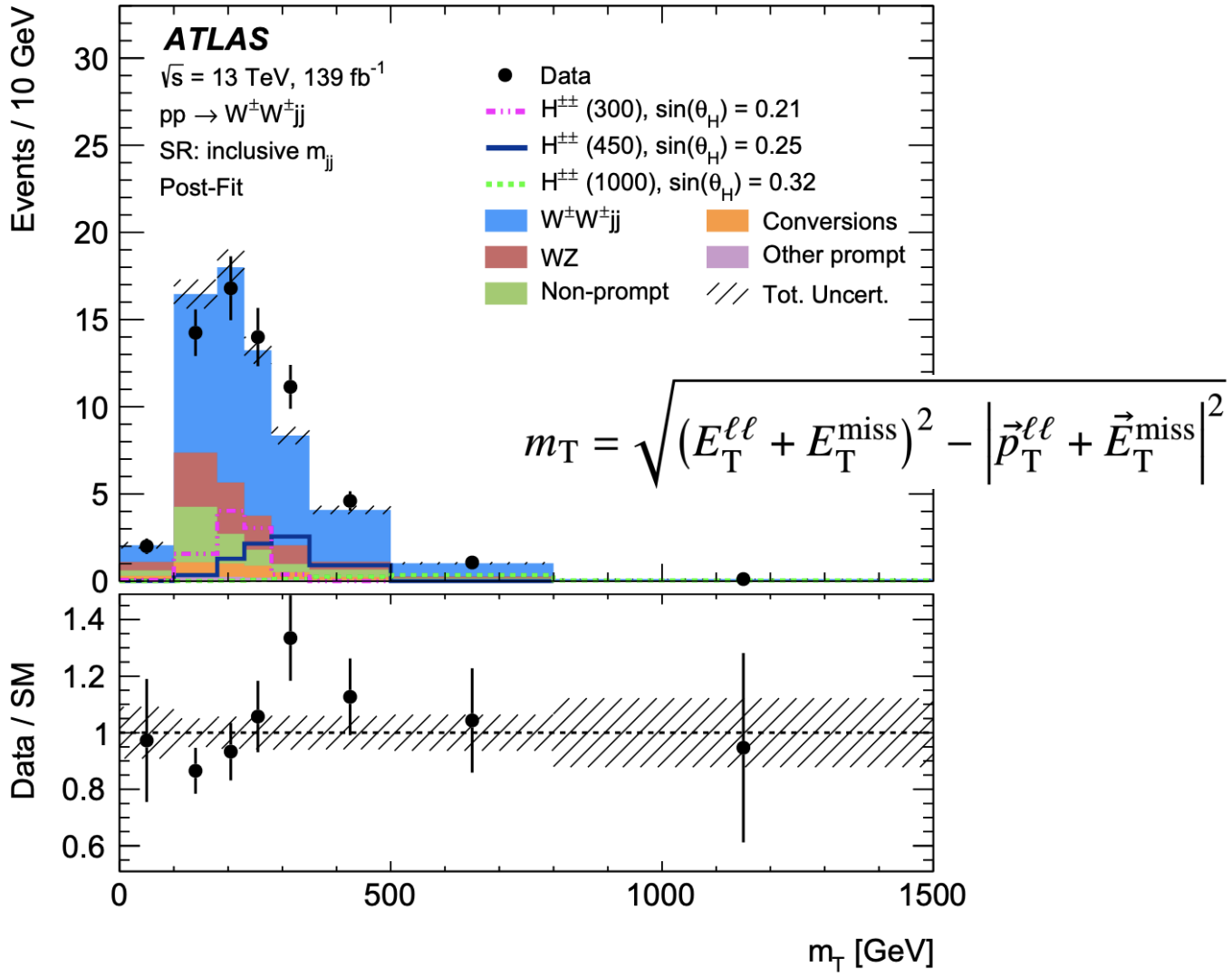

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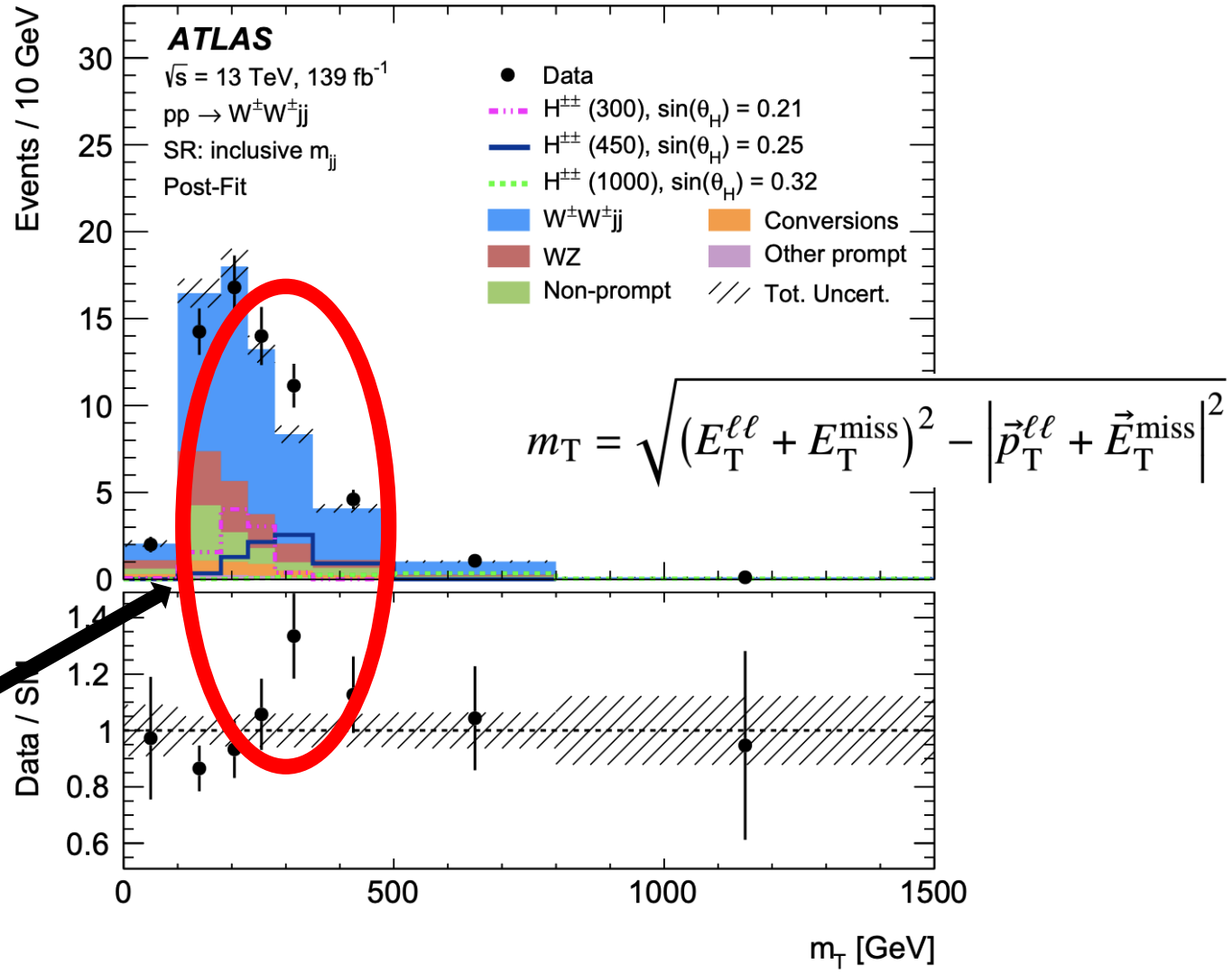

Excess around 450 GeV $H^{\pm\pm}$ resonance mass

ATLAS $H^{\pm\pm}$ Search Limits

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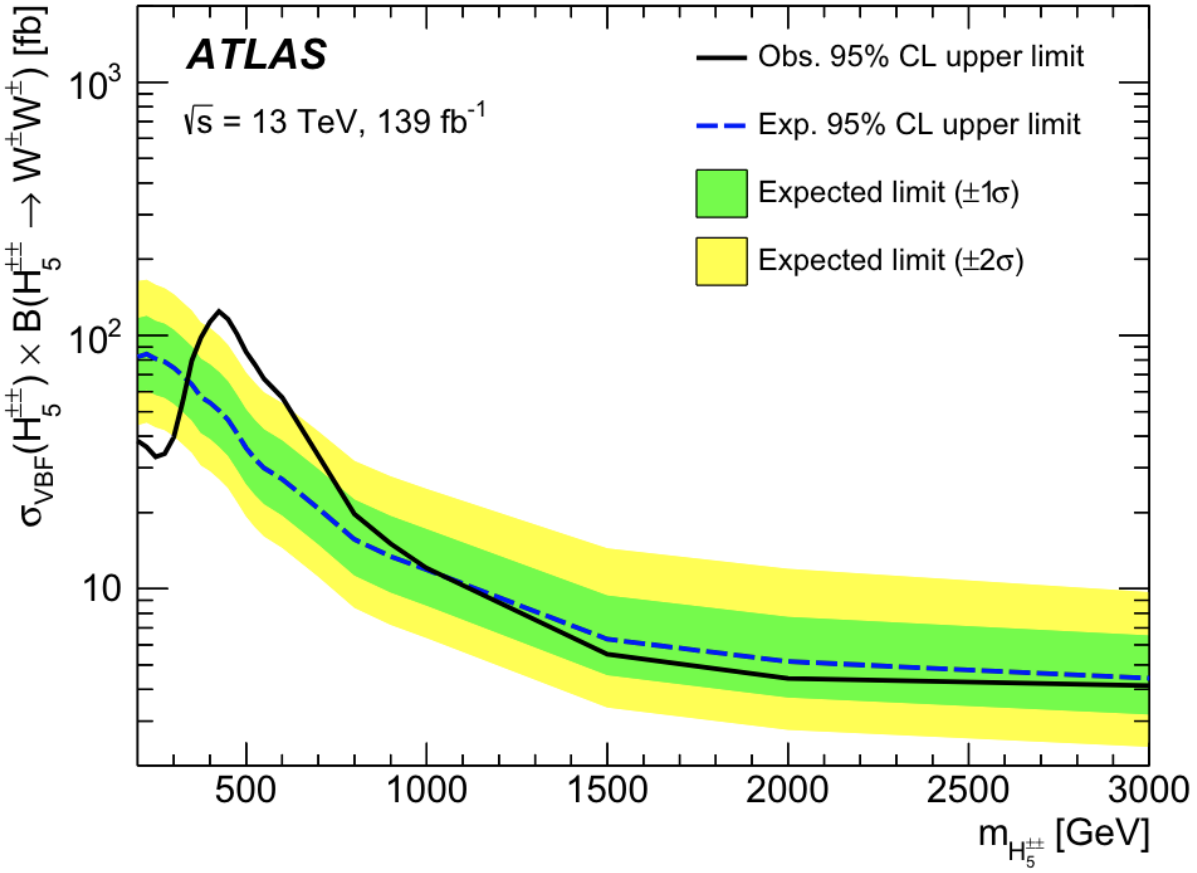

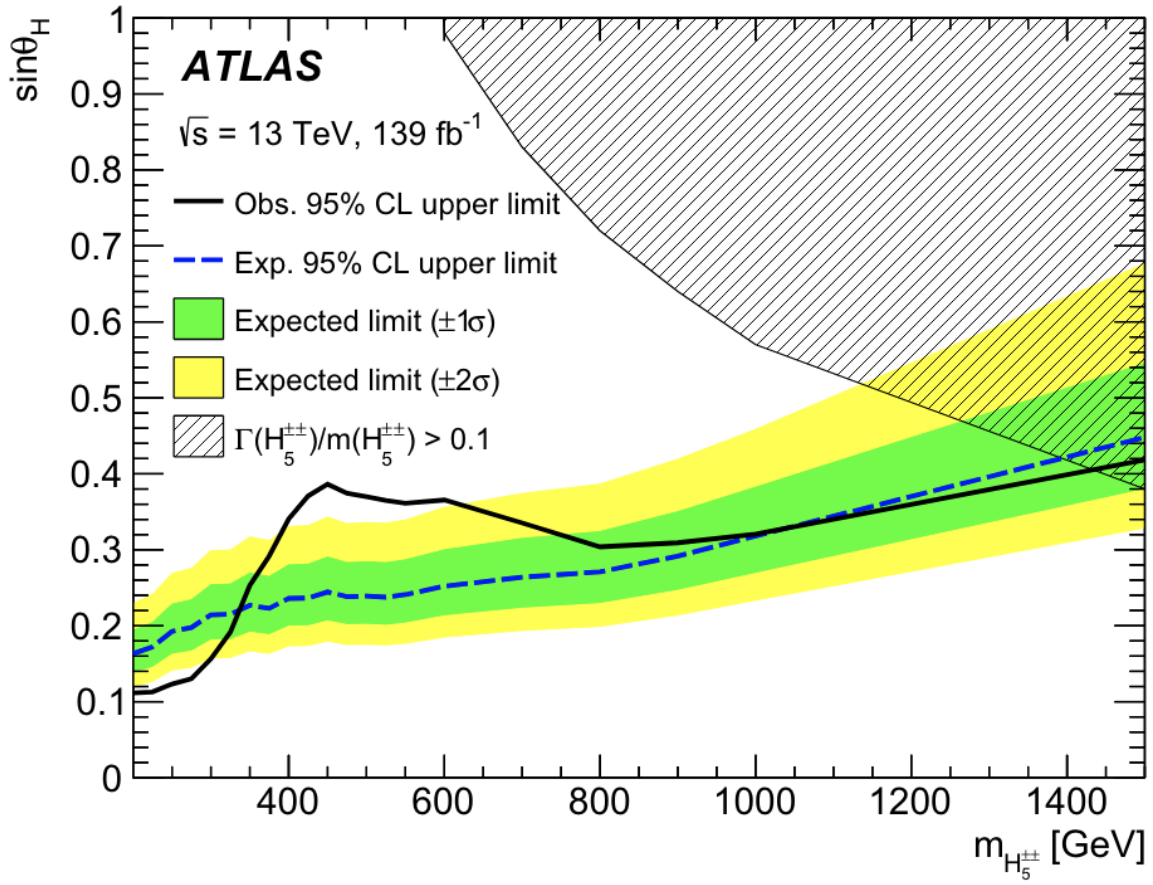

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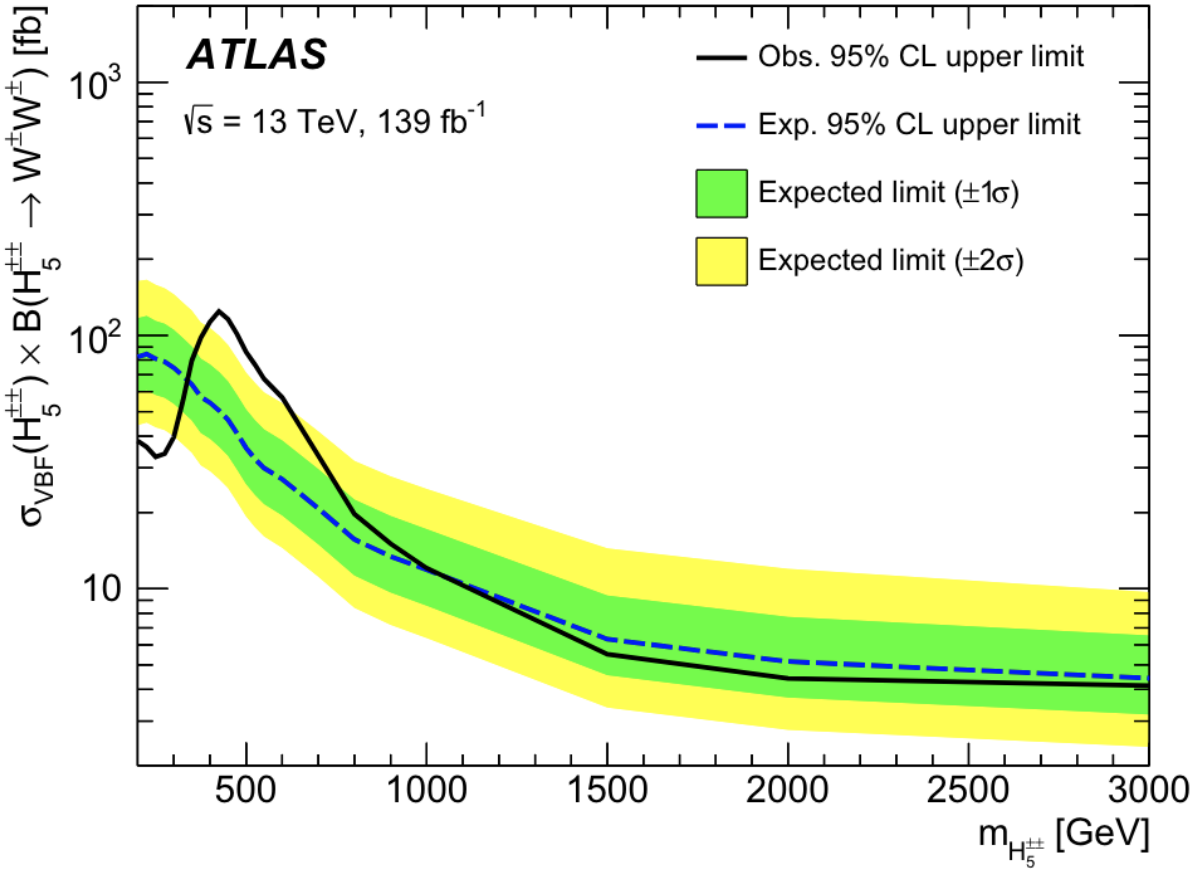

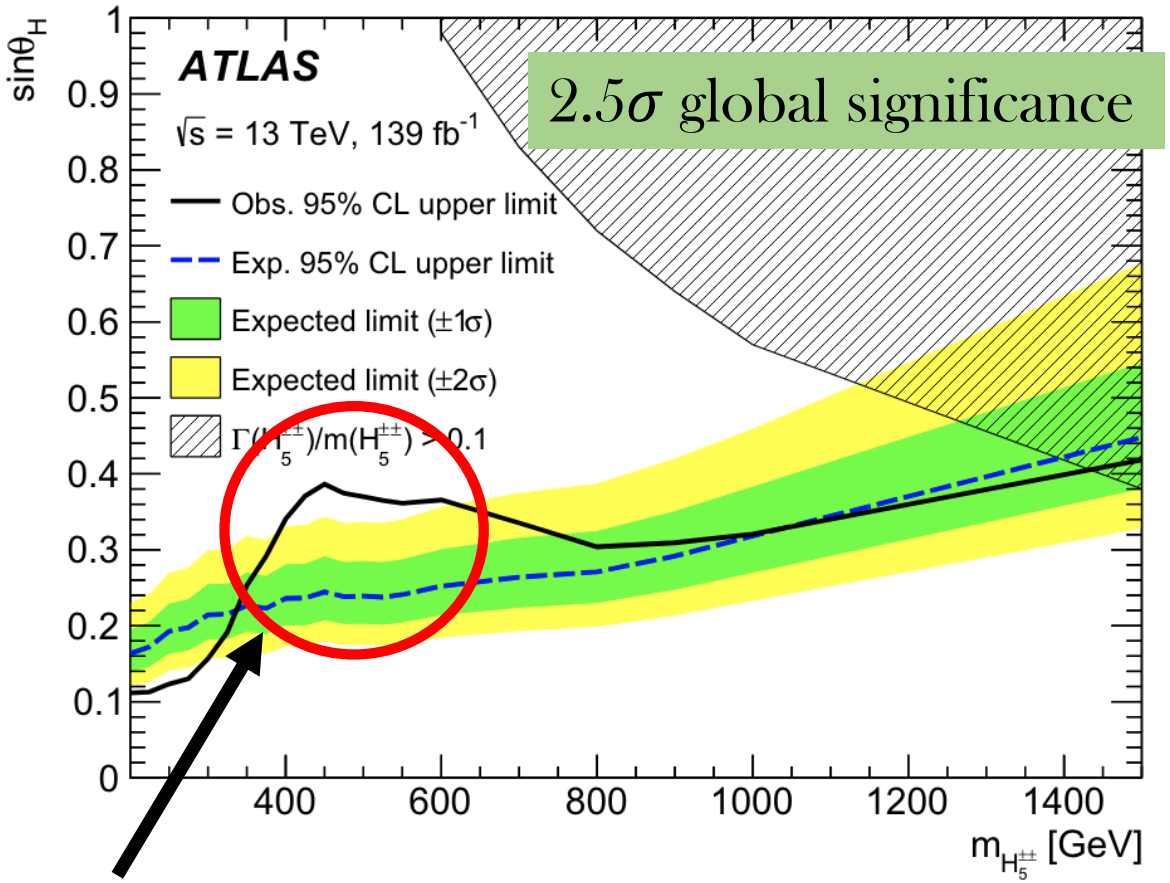

2.5σ global significance

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

Another GM Model Search – With an Excess!

Can also produce GM model 5-plet $H^{\pm}$ via VBF at the LHC

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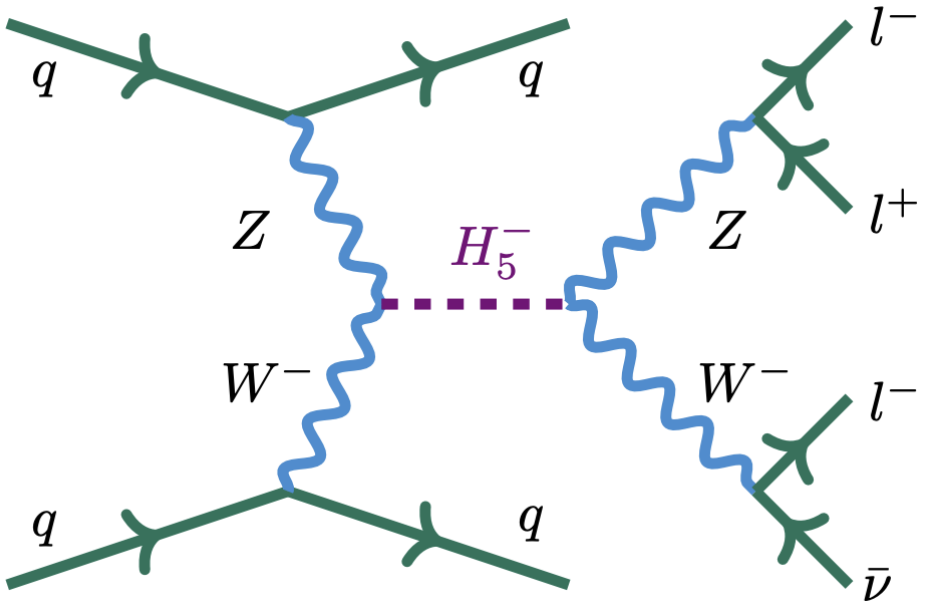

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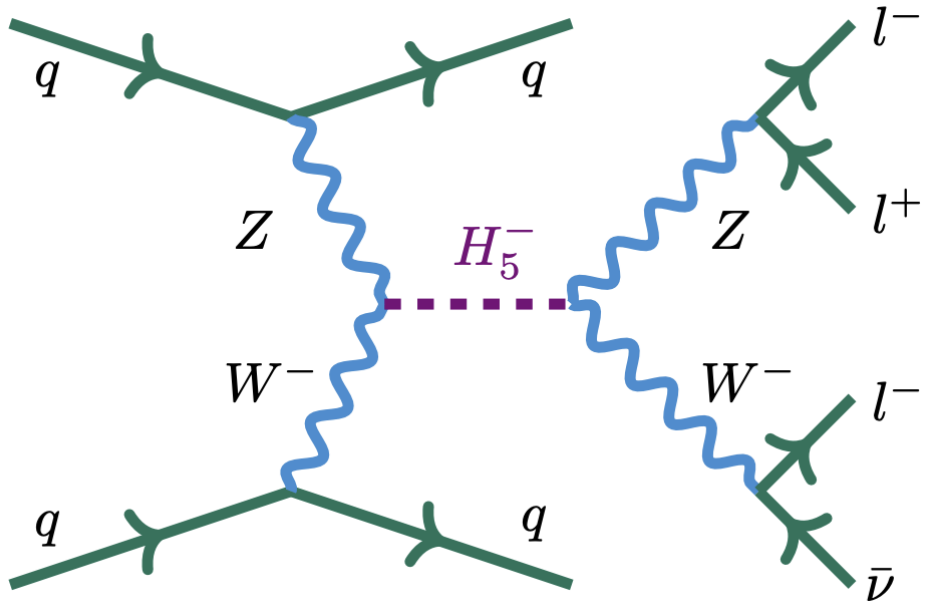

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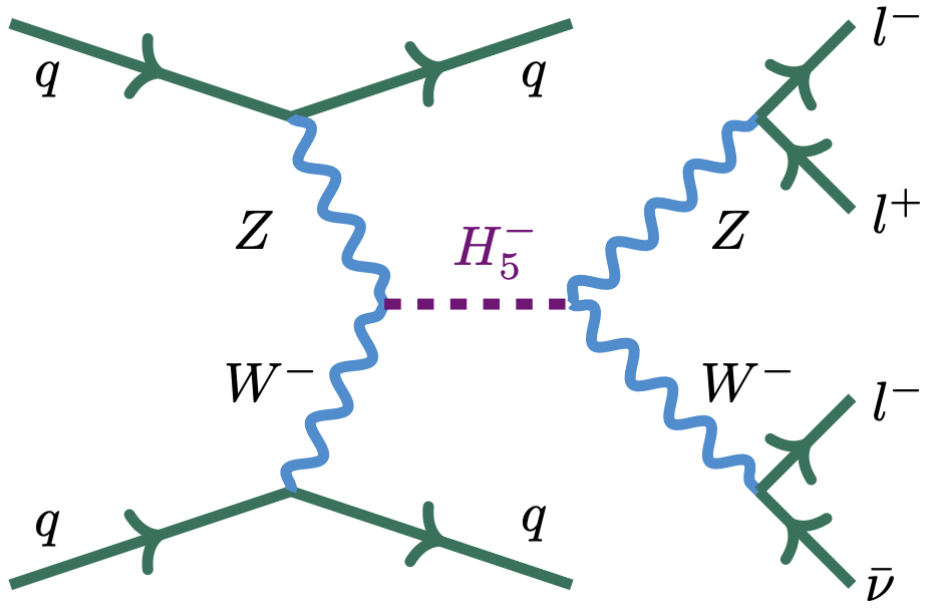

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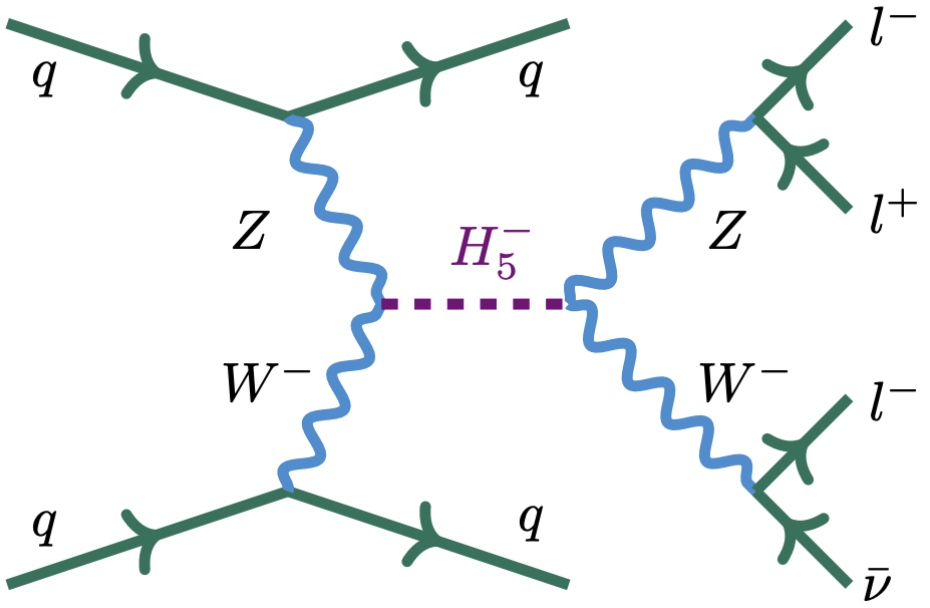
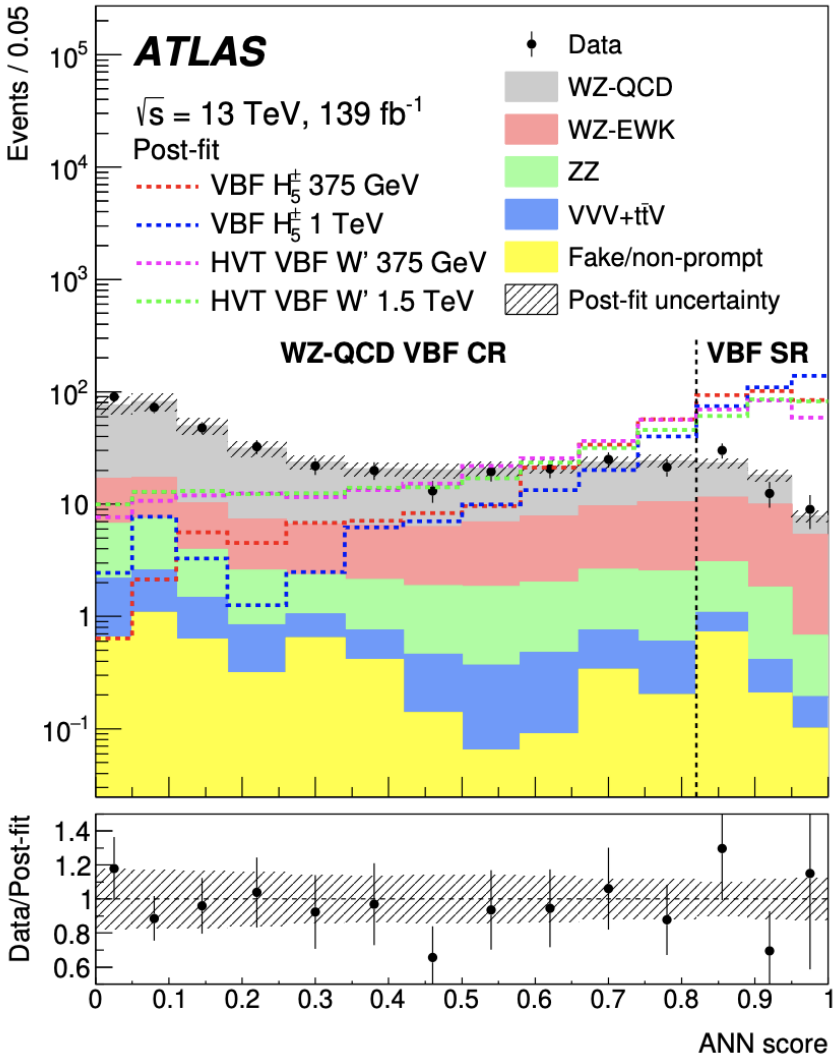
$H^{\pm\pm}$ and $H^{\pm}$ results can be *jointly* interpreted in context of GM model



ANN For S/B Classification

https://arxiv.org/pdf/2207.03925

See backup for details



(Another) Excess in Run 2!

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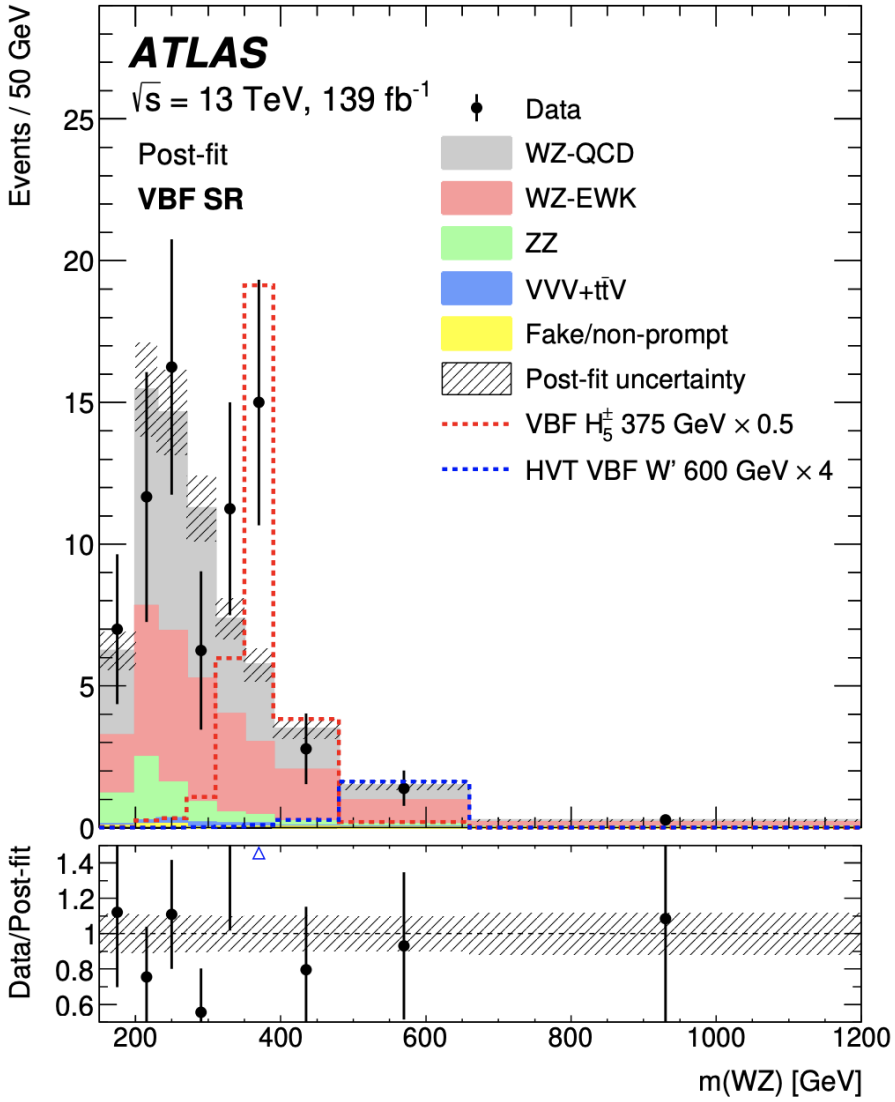

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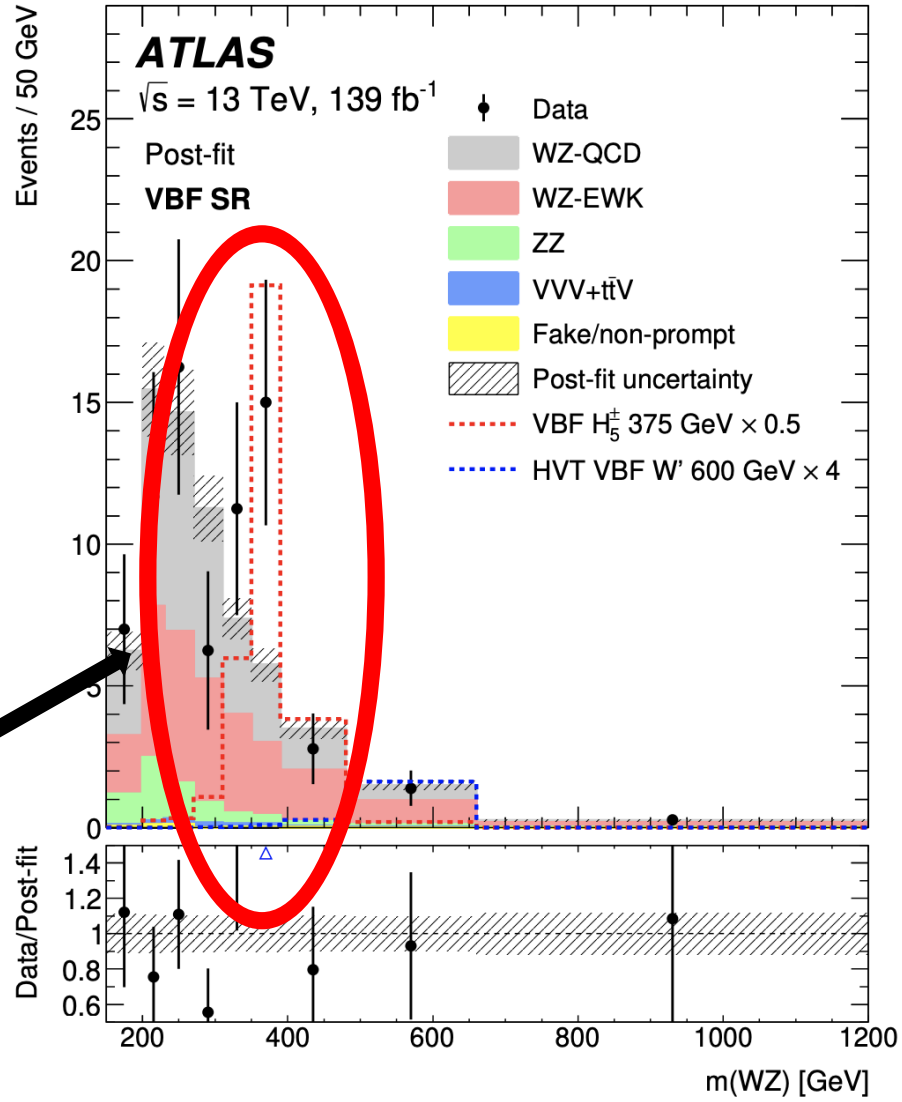
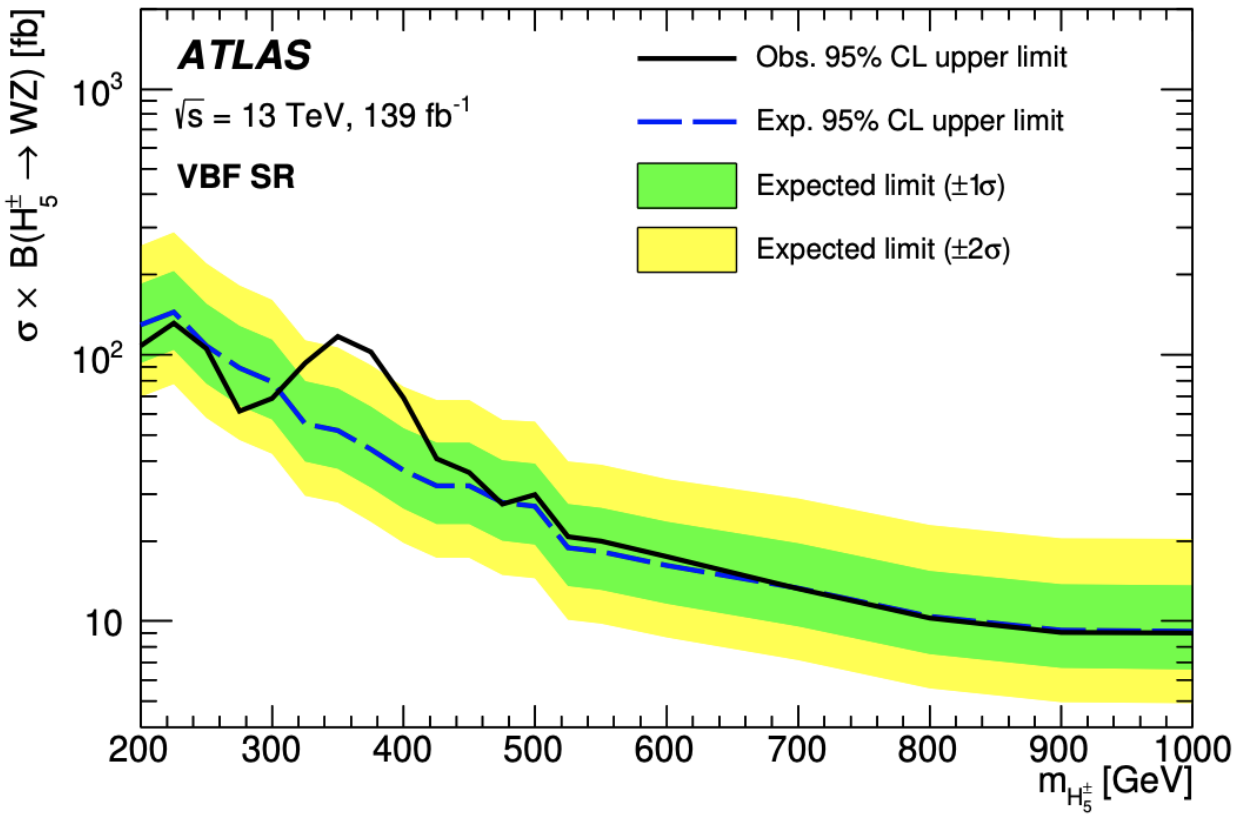
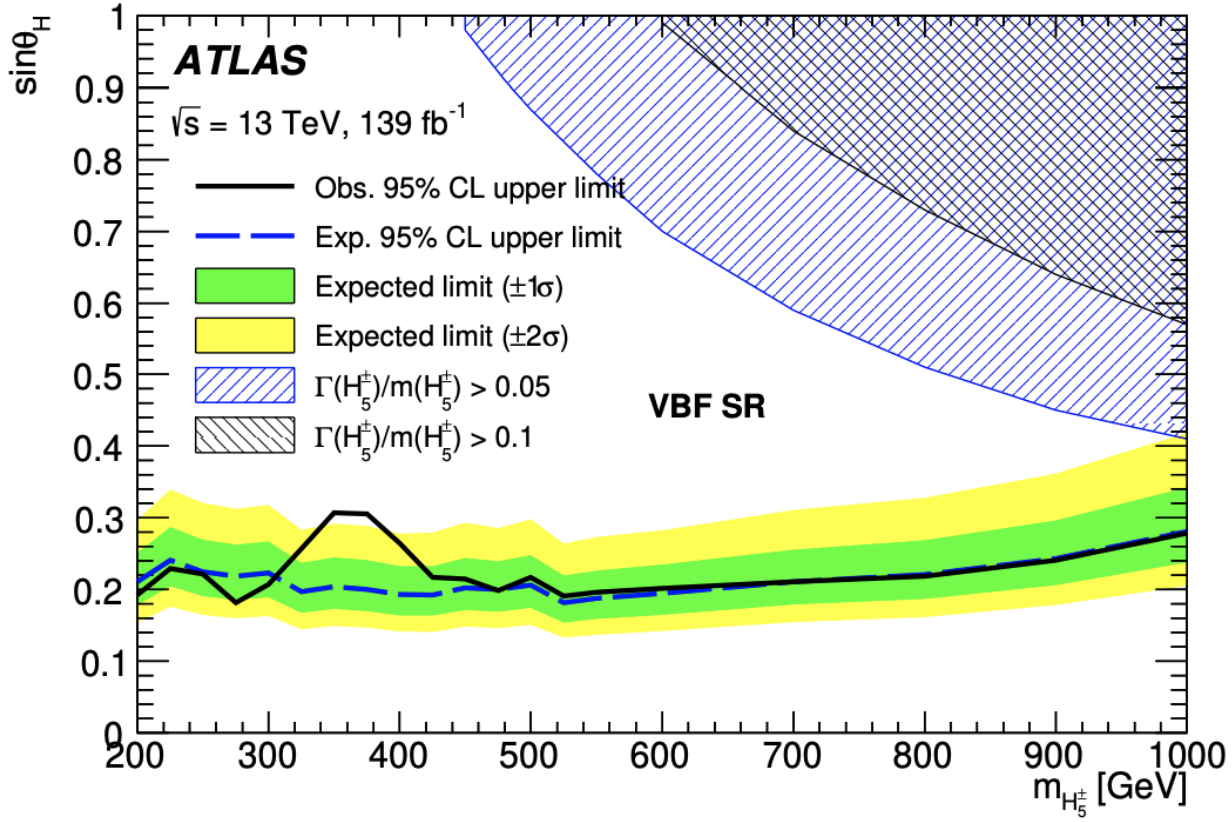


Excess around 375 GeV $H^{\pm}$ resonance mass

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





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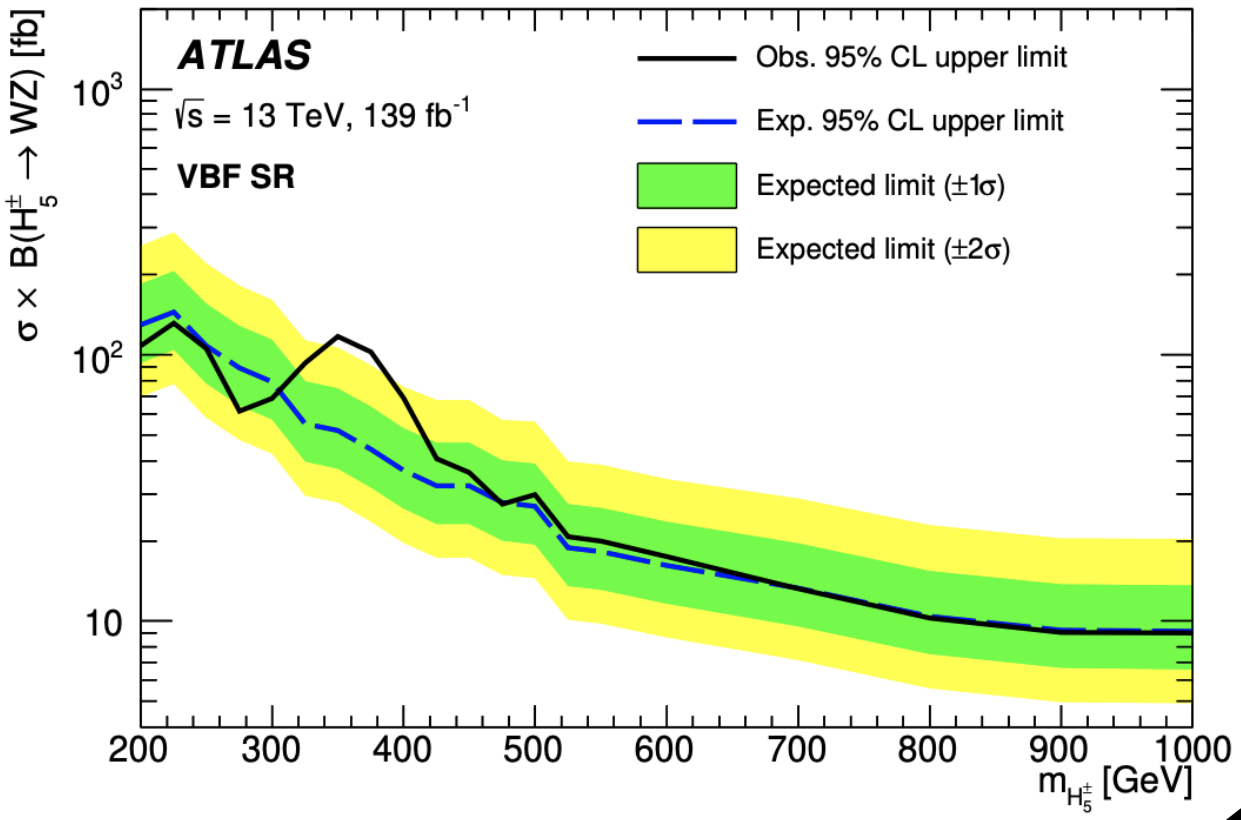

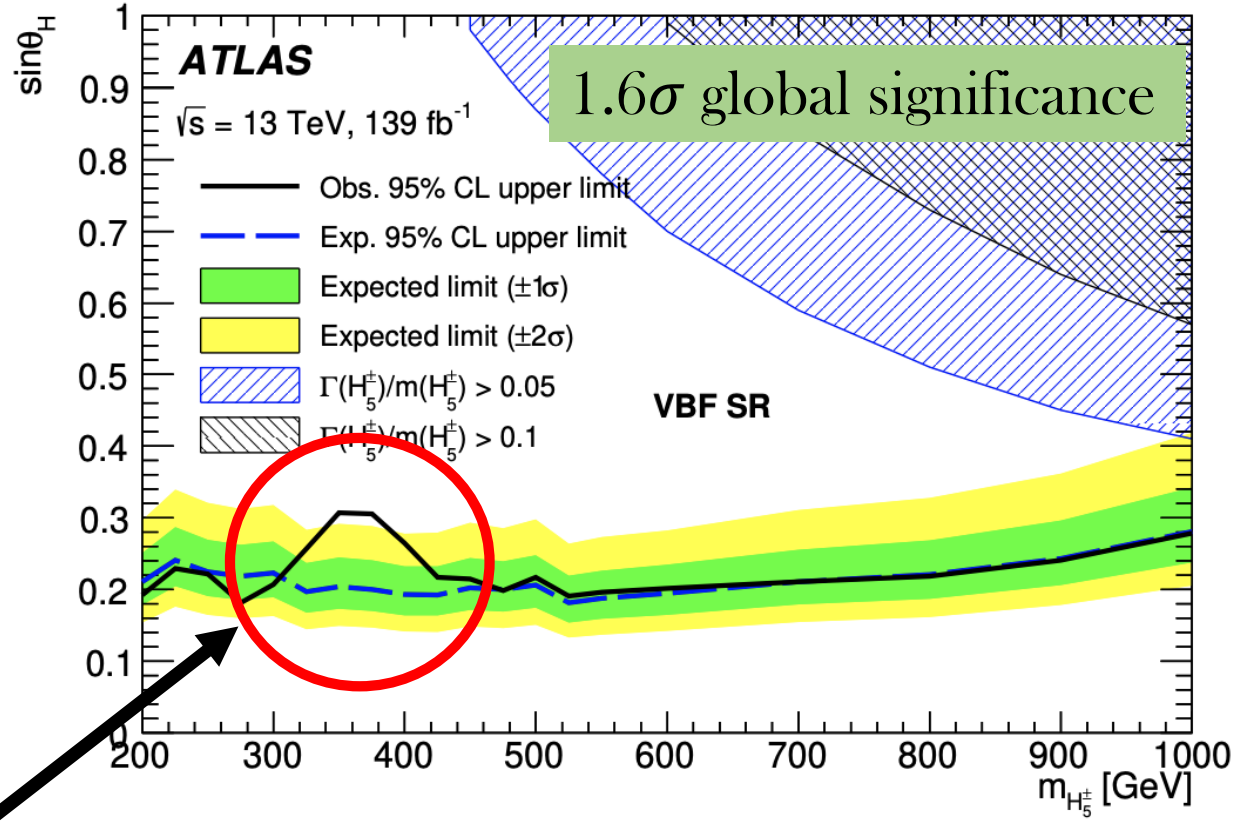

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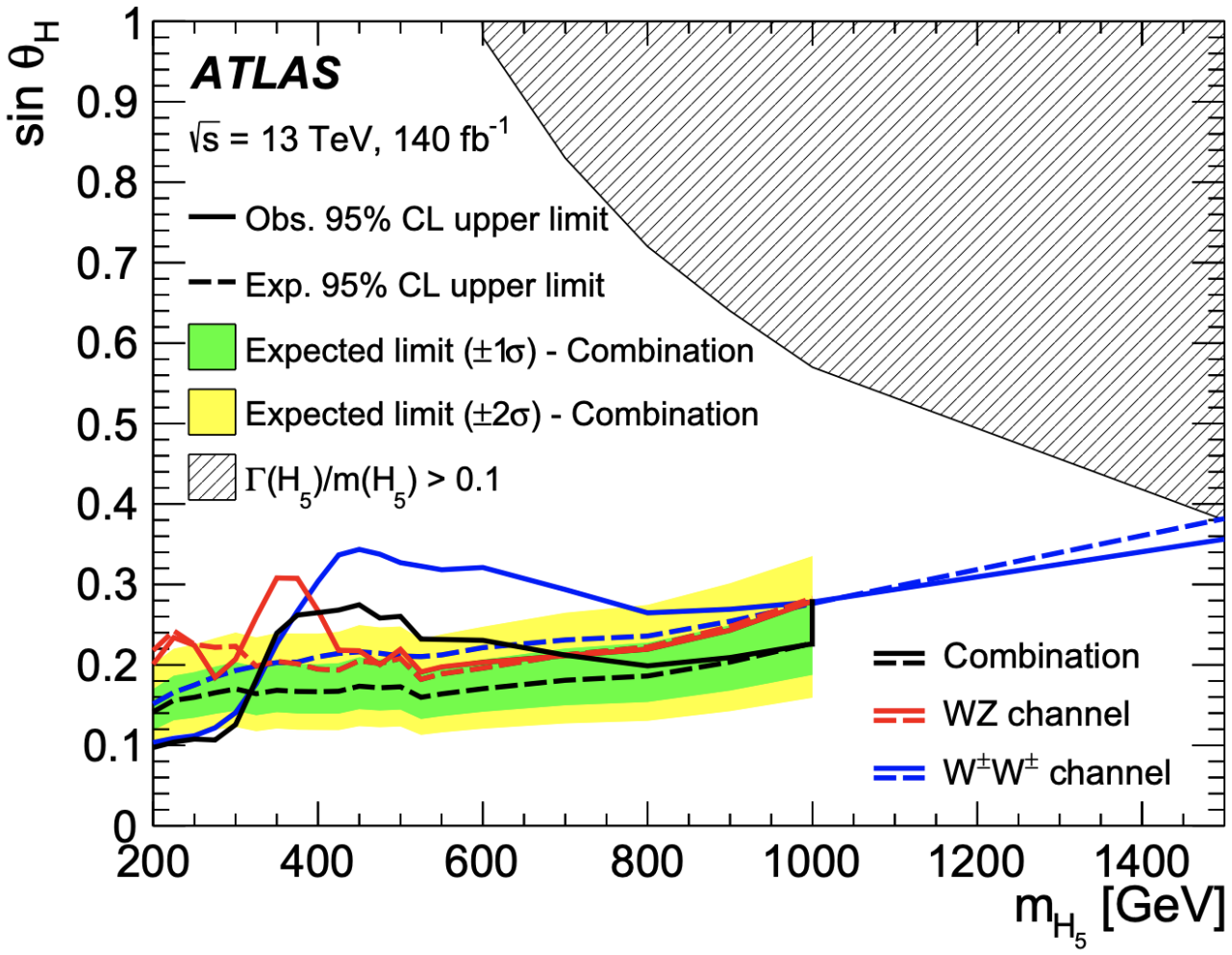
ATLAS GM Model Combined Limit



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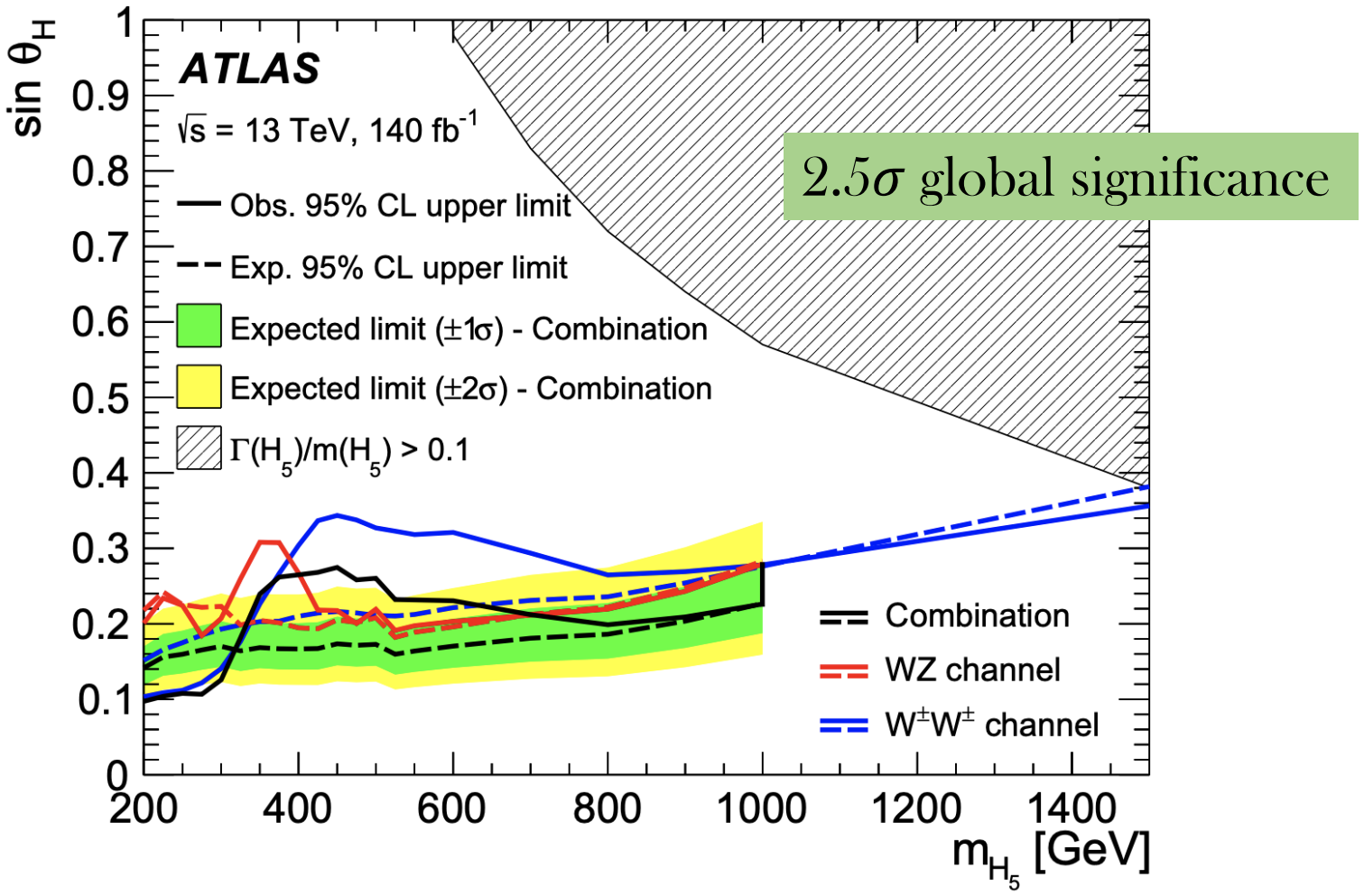

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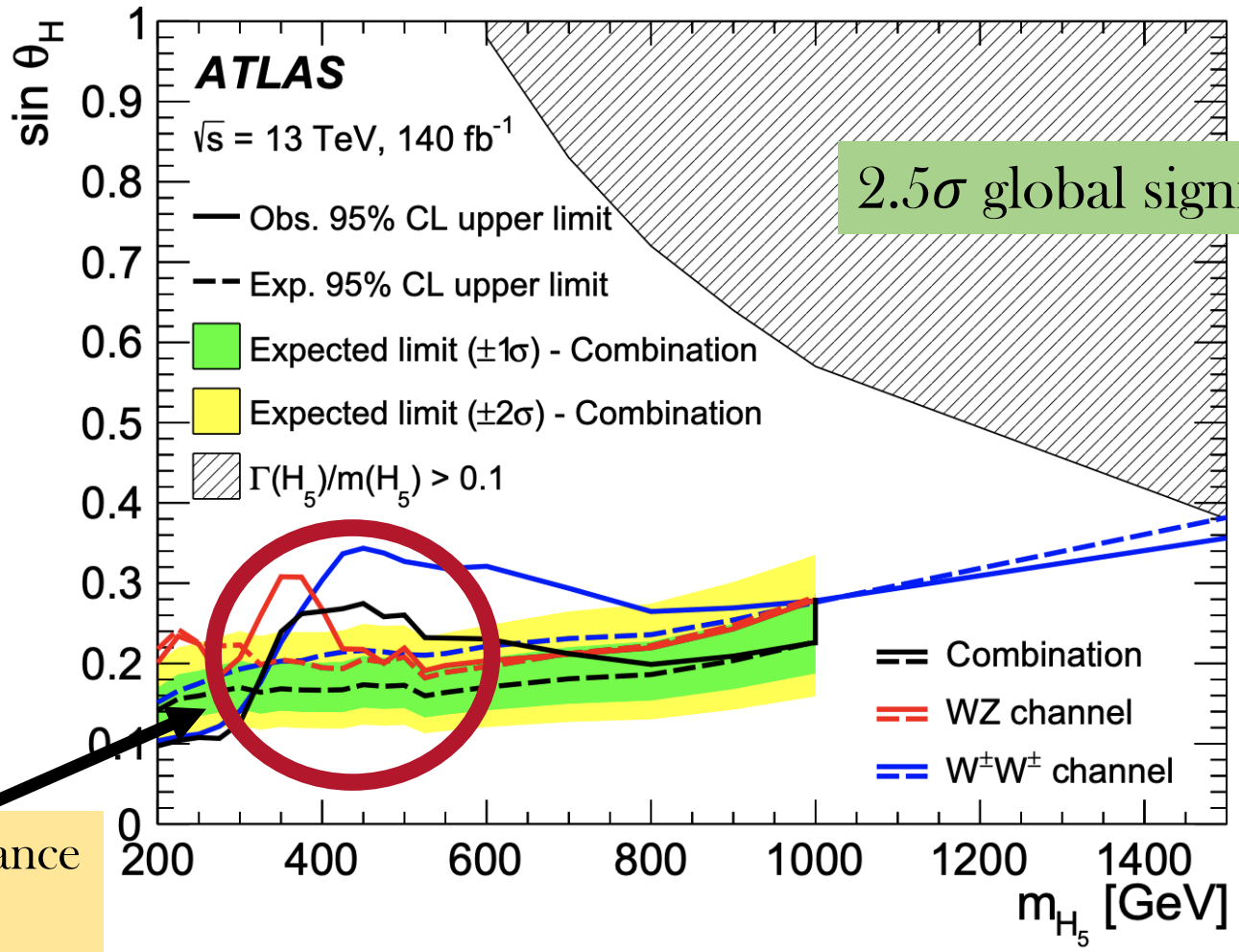
Source: https://arxiv.org/pdf/2407.10798

ATLAS GM Model Combined Limit



2.5σ global significance

3.3σ highest local significance at m_{H_5} = 375 GeV

Source: https://arxiv.org/pdf/2407.10798

Where to go from here

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

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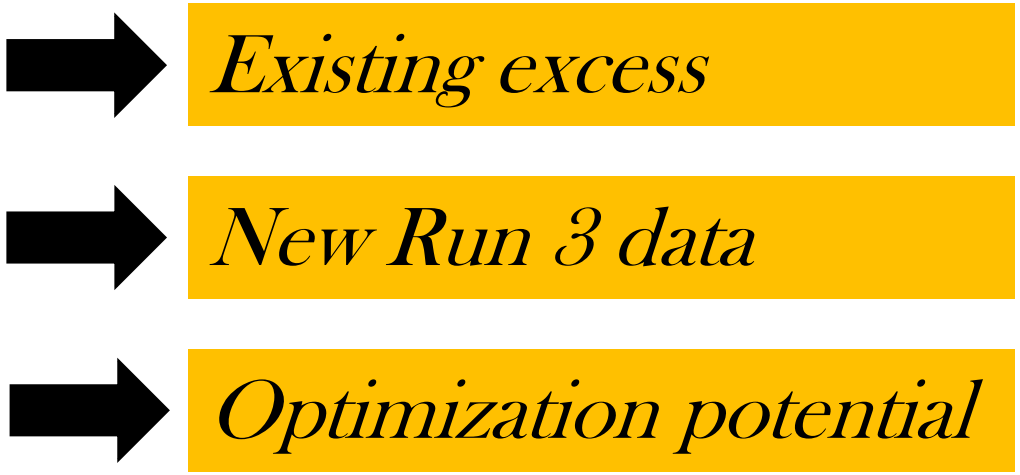

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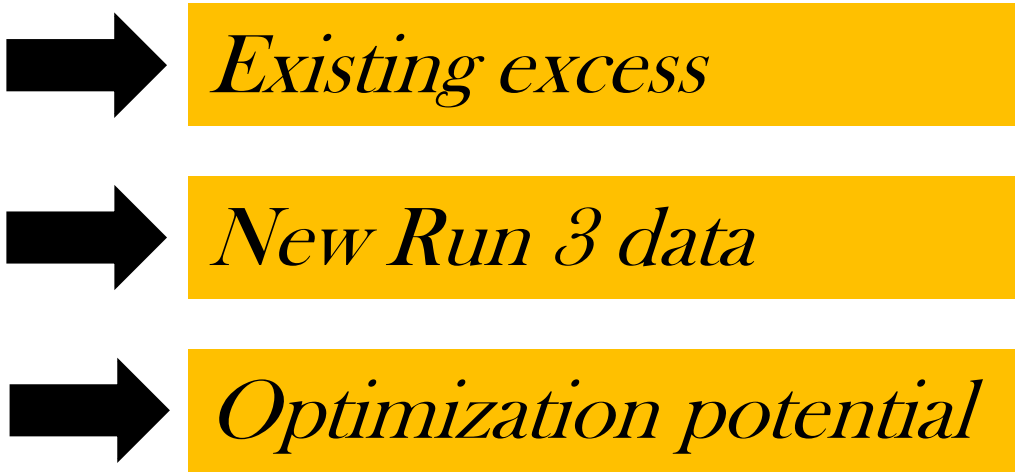
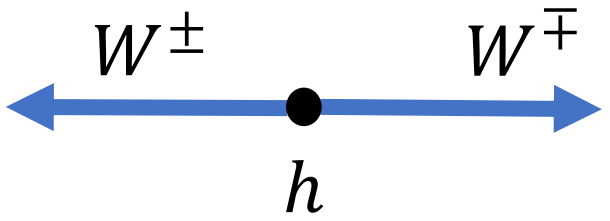


- Inspiration – $h \rightarrow WW$ search: https://arxiv.org/abs/1412.2641
- Also: machine learning, tagger algorithms

The scalar nature of the Higgs

- The Higgs is scalar

Decay products must have opposite spin



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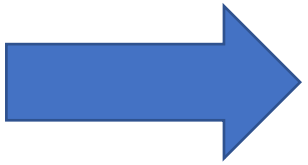

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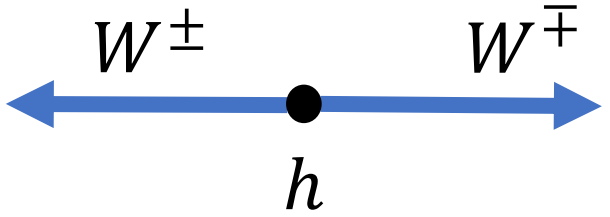

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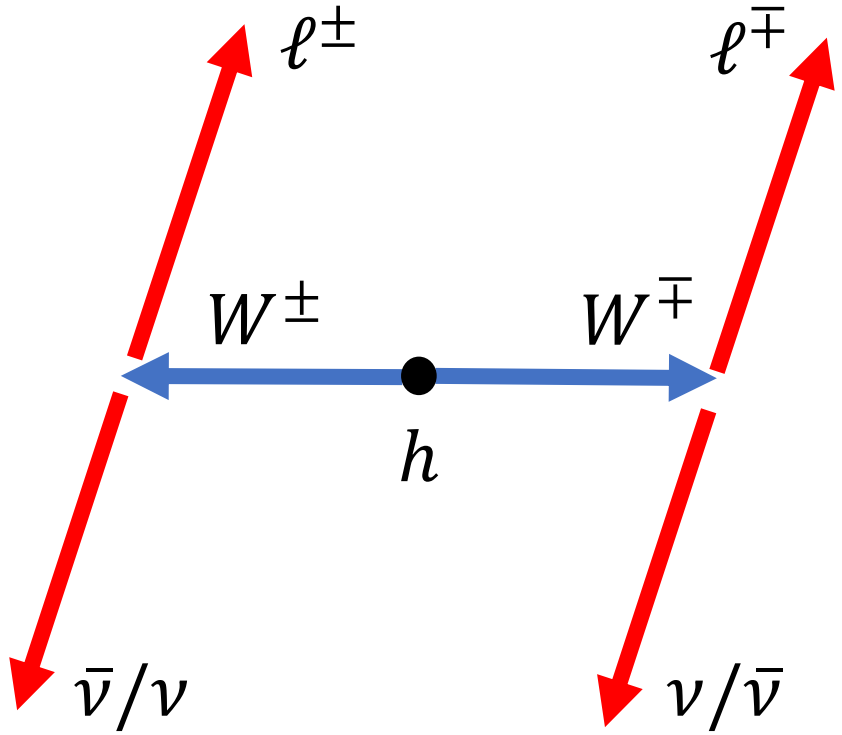

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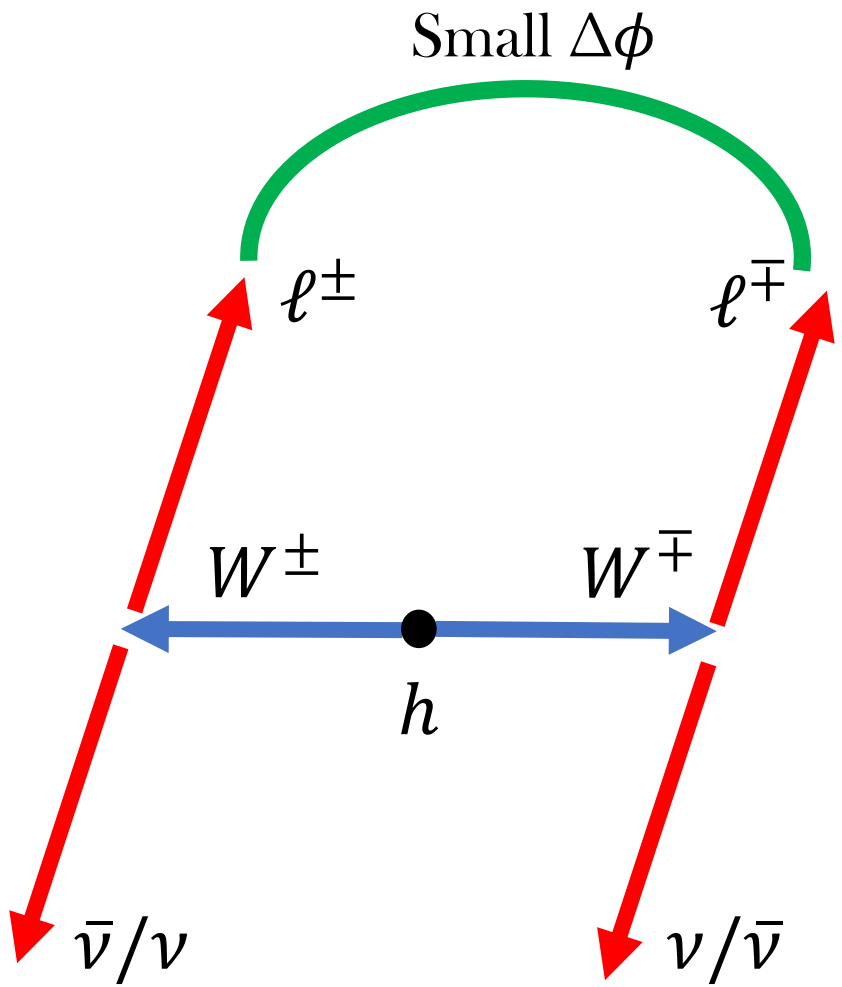
Small opening angle/$\Delta\phi$



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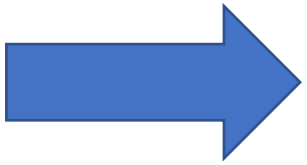

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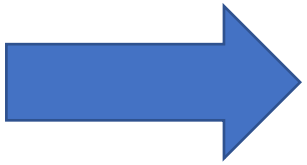

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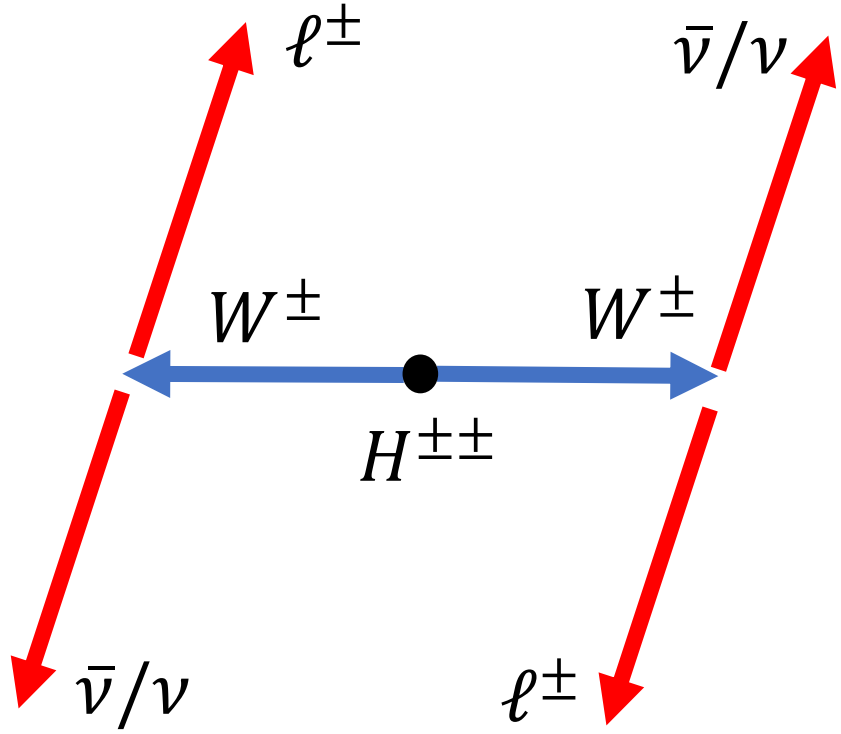

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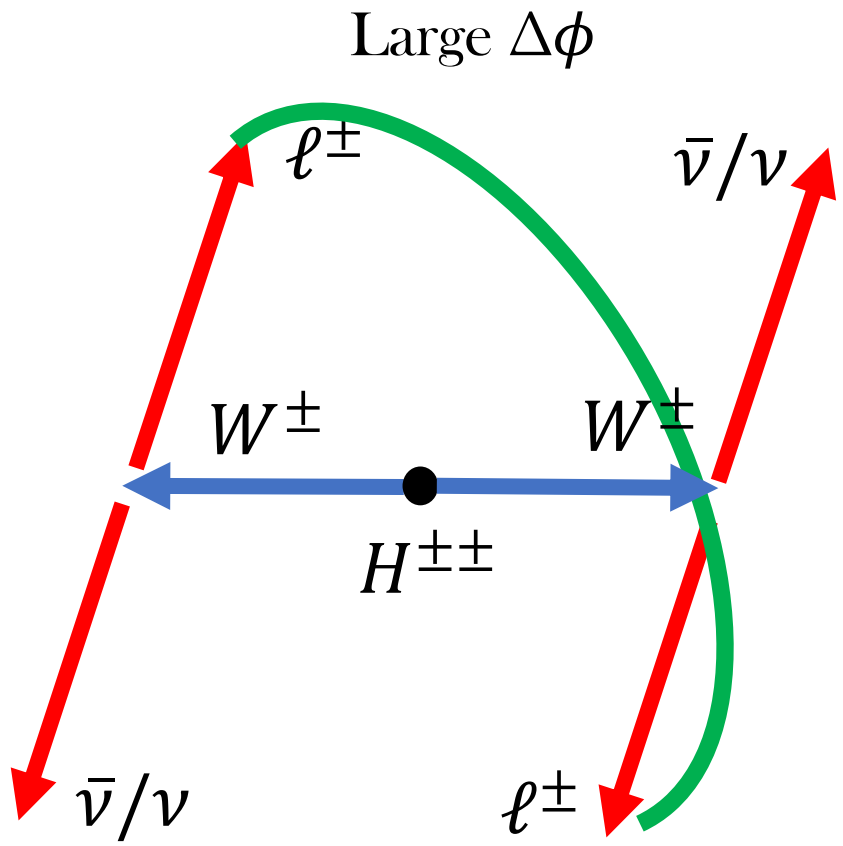

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Summary and Discussion

- The GM model extends the Higgs sector of the SM with additional scalar particles, including a singly and doubly charged Higgs ($H^{\pm}/H^{\pm\pm}$)

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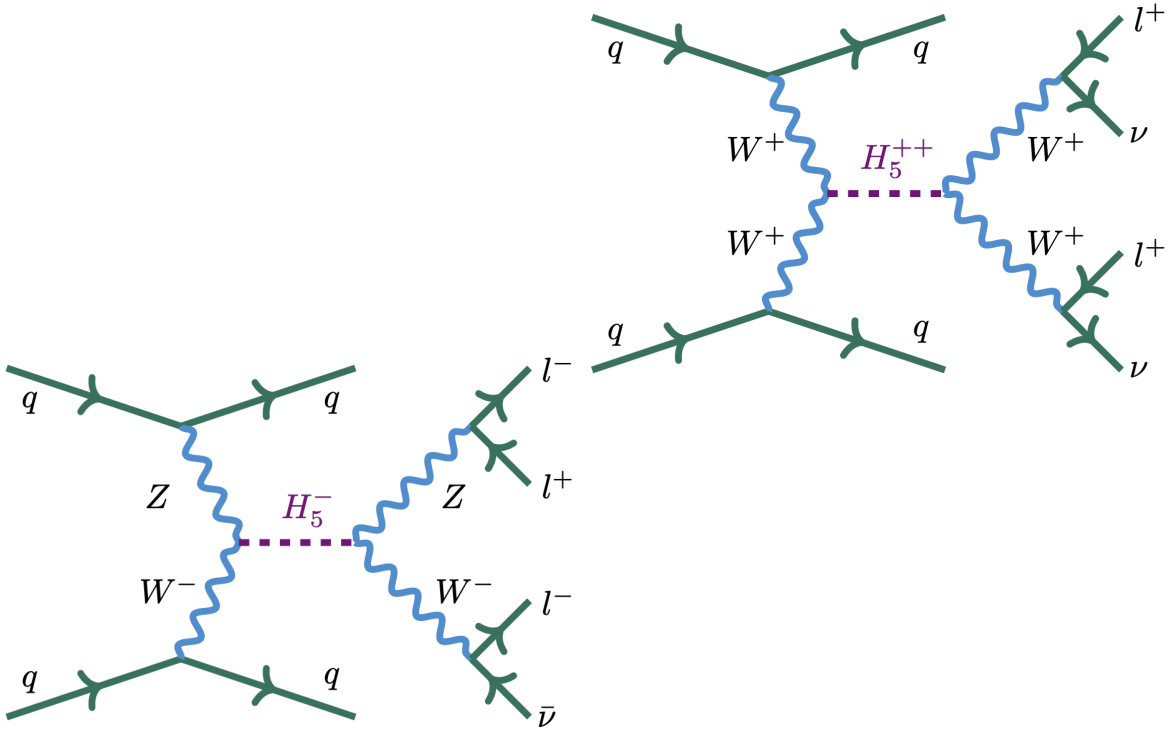
Run 2 ATLAS searches for $H^{\pm}$ and $H^{\pm\pm}$ saw slight excesses



Summary and Discussion

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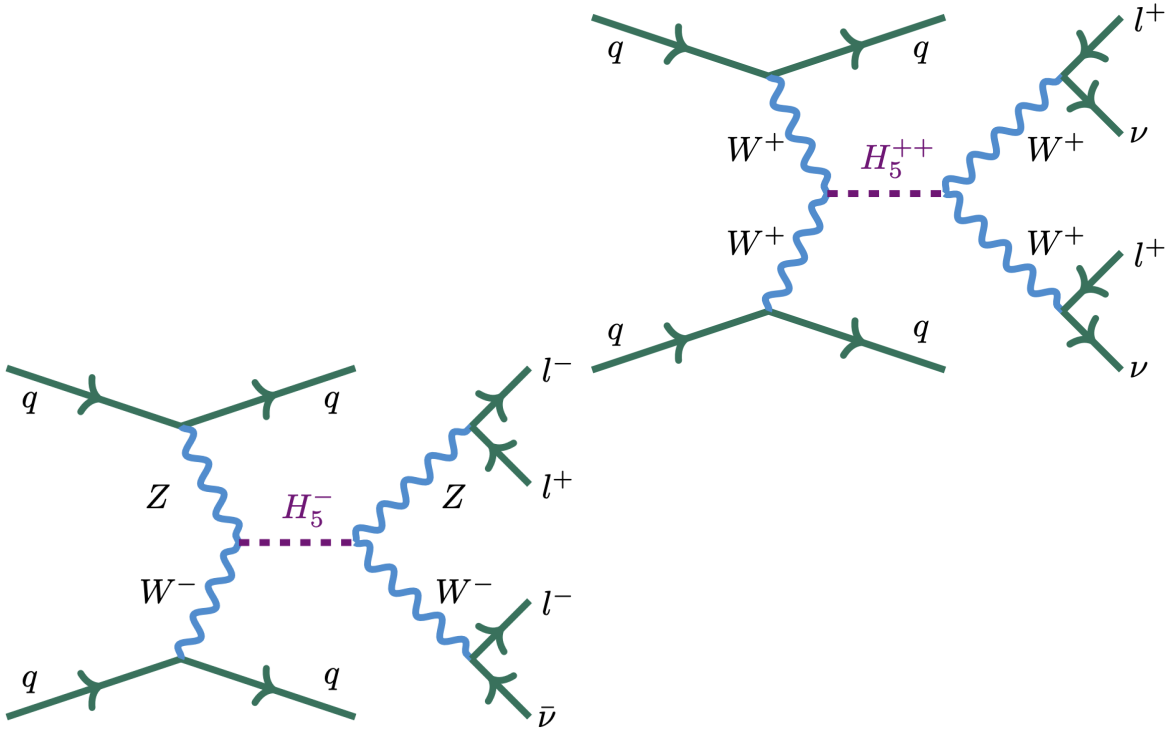
Run 3 data, scalar nature of particles offer a promising avenue for future study

What else can be improved?



Thank You!

email: tgosart3@sas.upenn.edu

Backup

GM Model 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

$H^{\pm}$ Search Event Selections

https://arxiv.org/pdf/2207.03925

Baseline *WZ* selection
Event cleaning and primary vertex
Single-electron or single-muon trigger
Exactly 3 *Loose* leptons (e or μ) with p_{T} >25 GeV (p_{T} >27 GeV for the trigger-matched lepton)
ZZ veto: veto events with additional *Baseline* leptons
Z candidate: A *Tight Z* same-flavour-opposite-sign lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 20$ GeV
W candidate: *Tight W* lepton requirements on 'non-*Z* leptons' and $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV

$H^{\pm}$ Search Event Selections

https://arxiv.org/pdf/2207.03925

Selection	**VBF**
Signal region	At least 2 *VBF jets* m_{jj} > 100 GeV Veto events with *b*-tagged jets ANN Output > 0.82
WZ-QCD control region	At least 2 *VBF jets* m_{jj} > 500 GeV Veto events with *b*-tagged jets ANN Output < 0.82
ZZ control region	Additional *Baseline* lepton No $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement At least 2 *VBF jets*

$H^{\pm}$ ANN Training

https://arxiv.org/pdf/2207.03925

Training variable	Definition
m_{jj}	Invariant mass of the two leading-p_{T} jets
$\Delta\phi_{jj}$	Difference in ϕ of the two leading-p_{T} jets
η_W, η_Z	Pseudorapidities of the reconstructed gauge bosons
η_{j1}	Leading-p_{T} jet pseudorapidity
ζ_{Lep}	Event centrality
$E_{\mathrm{T}}^{\mathrm{miss}}$	Missing transverse momentum
H_{T}	Scalar p_{T} sum of the *VBF jets* and the leptons from the *WZ* decay

Binary classification: training done with Keras on top of TensorFlow

Training region requires 2 VBF jets with $m_{jj} > 100$ GeV
Trained against *WZ* backgrounds only

$H^{\pm}$ CR Distributions

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