Direct Searches for New Physics in Multiboson final states in ATLAS & CMS

Multi-Boson Interactions 2023, San Diego

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On behalf of ATLAS and CMS collaborations

# BSM searches with multibosons

- Resonant and nonresonant new physics searches with multi bosons
  - Example BSM theories: composite Higgs, extended Higgs sectors, technicolor, warped extra dimensions, Majorana nuetrinos

- Mainly focus on the latest diboson VV searches by ATLAS and CMS
  - For VVV see next talk
  - $V\gamma$ and $\gamma\gamma$ searches are not covered in this talk
- Full Run-2 results are shown
  - First Run-3 results yet to come
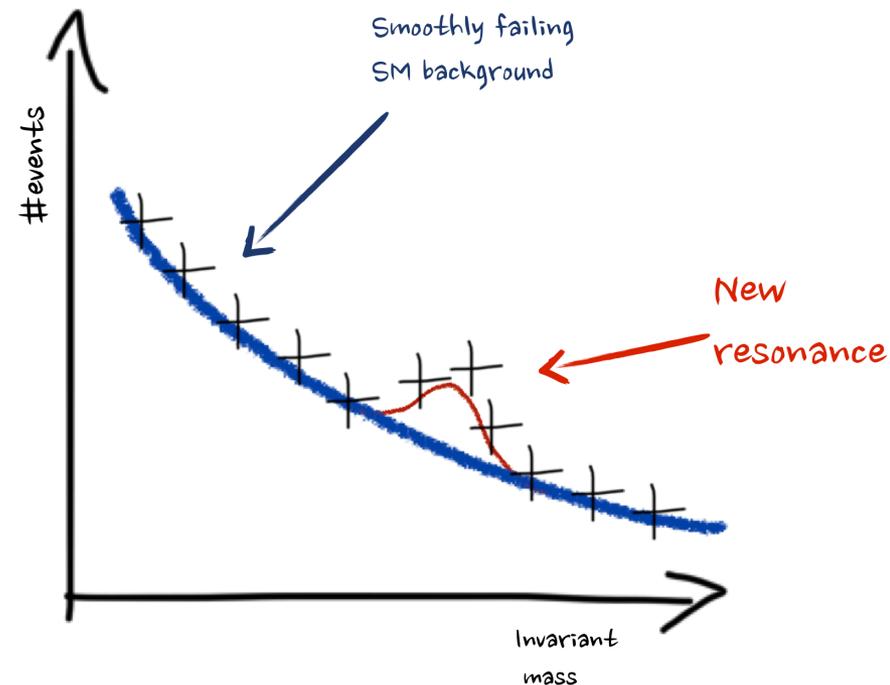
V = W or Z boson

Production modes

- Searches are often interpreted in the context of the Heavy Vector Triplet (HVT) simplified models
  - Spin-1 HVT W'/Z', narrow width
- Other benchmark scenarios include spin-0 radion and spin-2 Kaluza-Klein excitation (KK) in the context of the Randall-Sundrum (RS) models
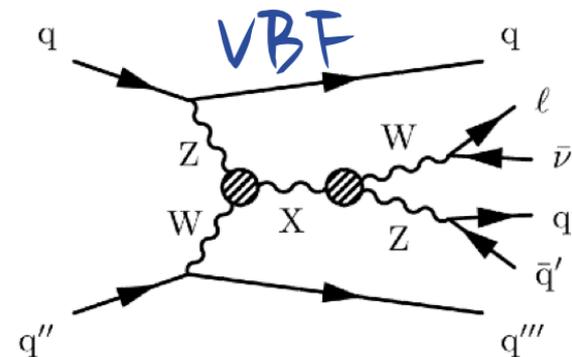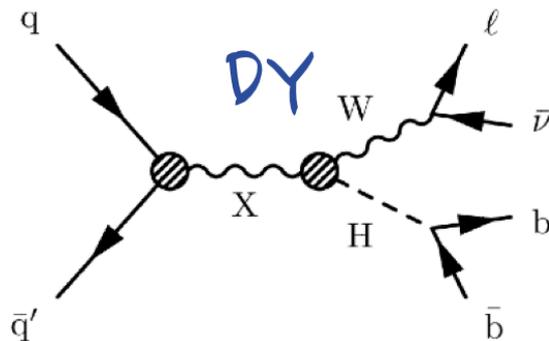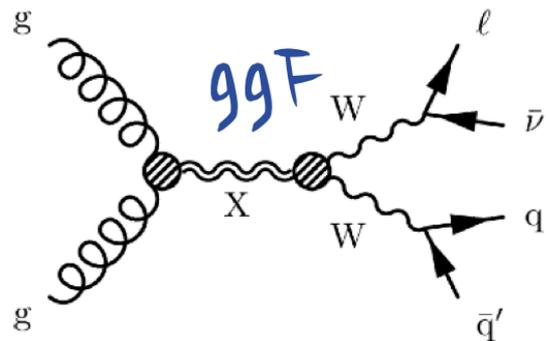
- Gluon fusion (ggF), Drell—Yan (qqA), and VBF production modes are considered

Production modes 2

- Vector boson fusion/scattering production

- Higgs triplet extensions

- Inclusion of one or more triplet (real or/and complex)

  - Two hallmark signatures of T=1

    - Tree level H^+ WZ coupling

    - Doubly charged higgs: H^{++}

- Non-resonant search for heavy Majorana neutrinos in the same-sign lepton final states
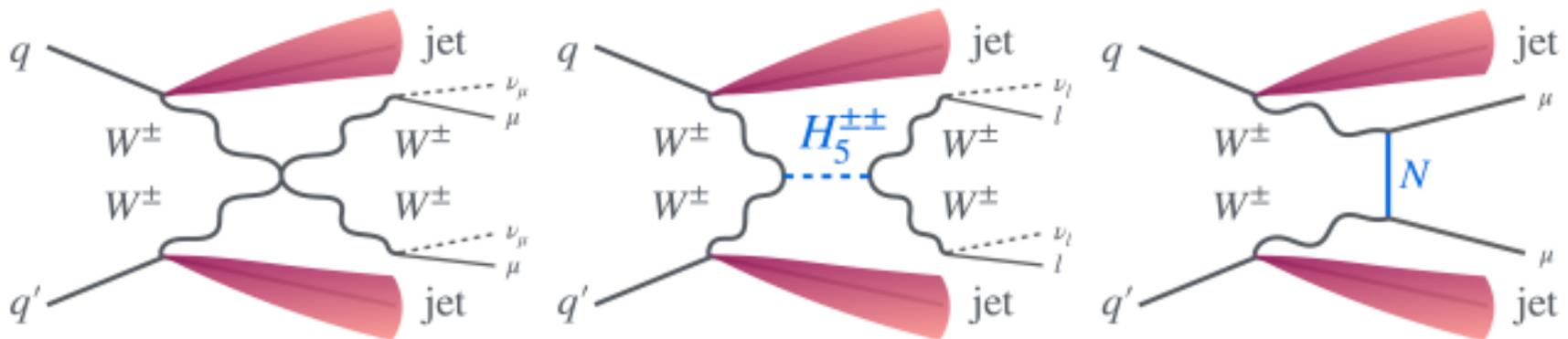
Georgi-Machacek model as benchmark

- We want to preserve the custodial symmetry
- Georgi-Machacek model: Doublet (T=1/2,Y=1), one triplet with (T=1,Y=0), and one triplet with (T=1,Y=2)
  - Tree level custodial symmetry even with large contribution of vev carried by triplet sector!
  - Fiveplet (H5) and triplet (H3) under custodial symmetry
  - Fermiophobic H++, H+, and H scalars from the fiveplet

$$\Phi = \begin{pmatrix} \phi_2^* & \phi_1 \\ -\phi_1^* & \phi_2 \end{pmatrix}, \qquad \Xi = \begin{pmatrix} \chi_3^* & \xi_1 & \chi_1 \\ -\chi_2^* & \xi_2 & \chi_2 \\ \chi_1^* & -\xi_1^* & \chi_3 \end{pmatrix}. \longrightarrow \quad \sin\theta_H =: s_H = \frac{2\sqrt{2}\,v_\Xi}{v_{SM}}$$

- For higher mass values and higher triplet vev vector boson fusion production dominates
  - H5plane benchmark (essentially ensures that H3 is heavier than H5 with BR(H5->VV) = 1)
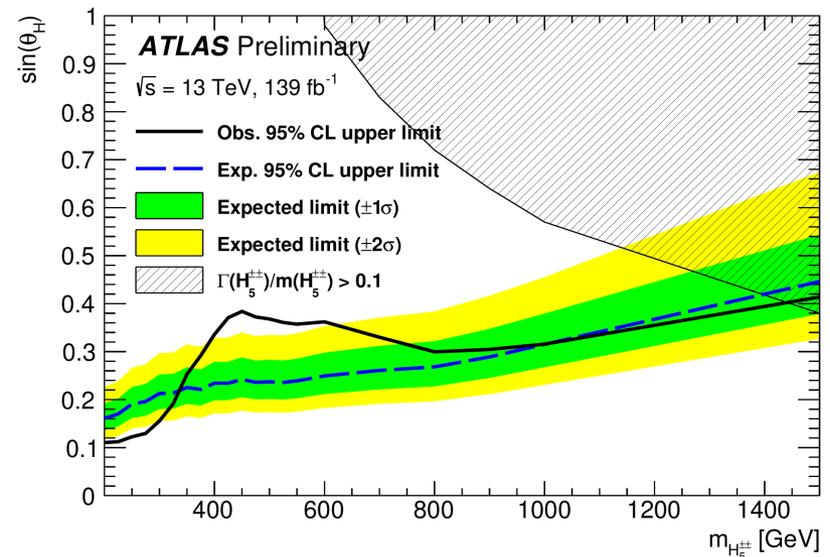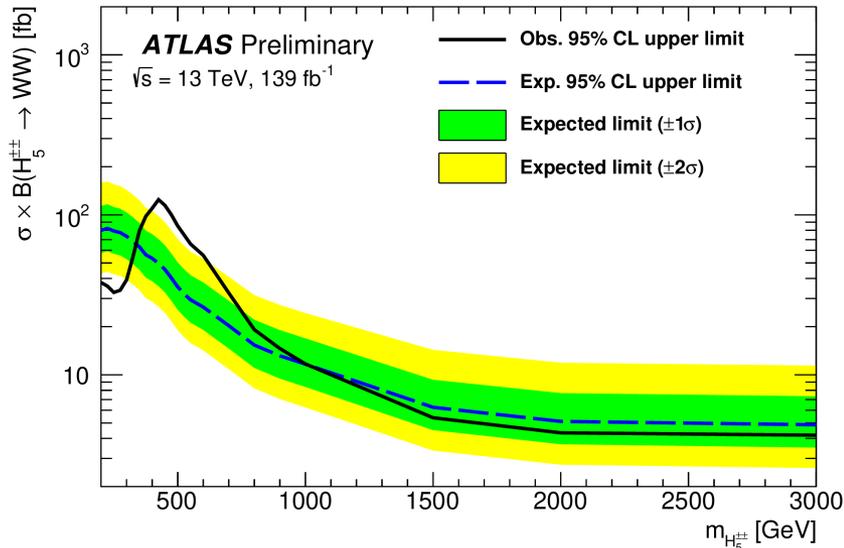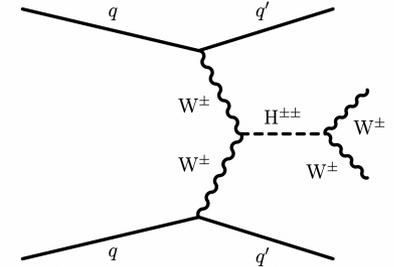
ATLAS Run 2 results: H++->W+W+

- Fully leptonic same-sign WW final state
- WZ is an important background
- Dedicated WZ control regions
  - Low mjj for WZ QCD production
- Signal extraction with 2D fit (m_{jj} x m_T)
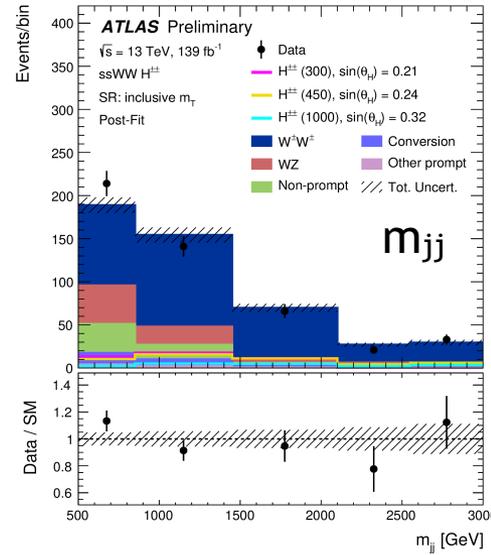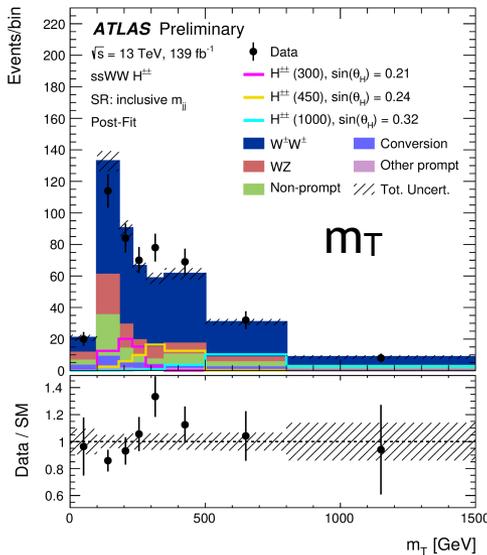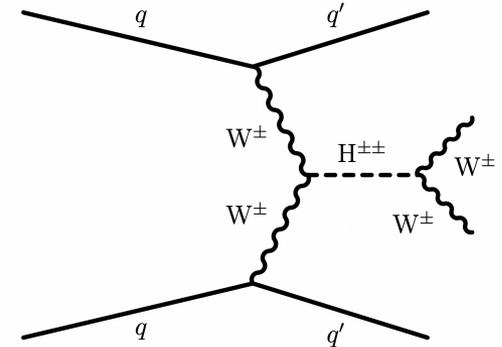
- Local excess of events at H^{++} mass of 450 GeV
  - Local sig.: 3.2 std.
  - Global sig.: 2.5 std.

ATLAS-CONF-2023-023
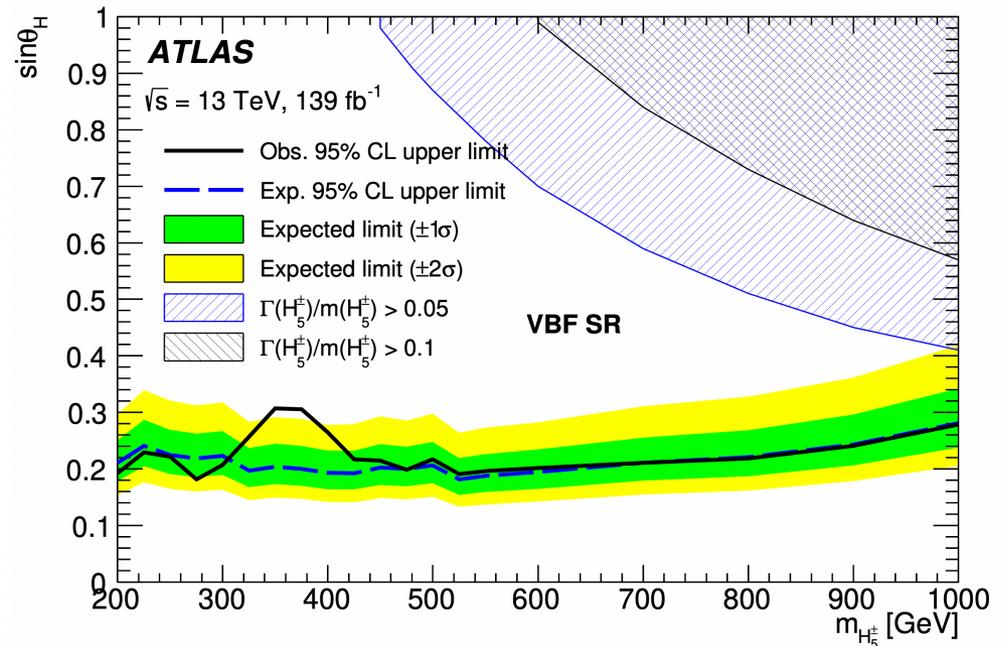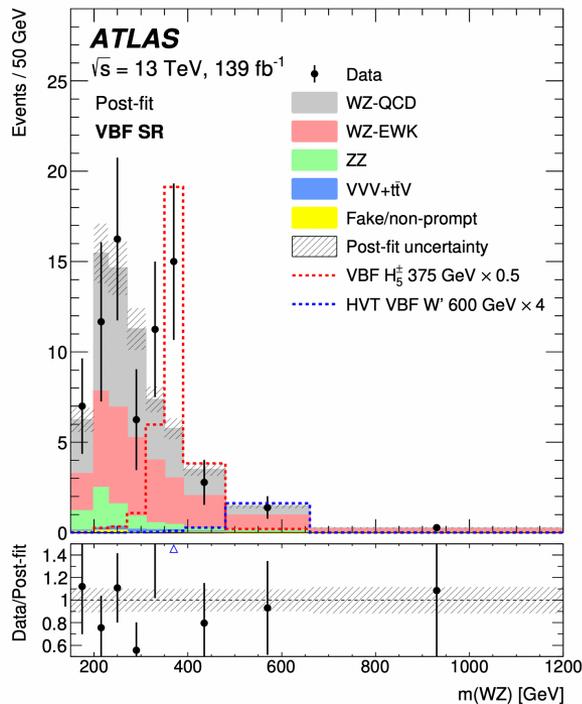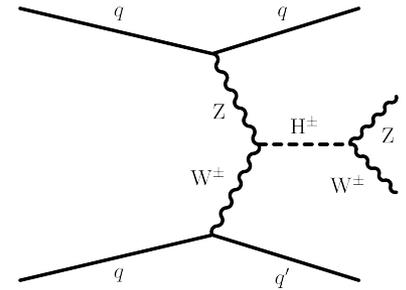
ATLAS Run 2 results: $H^{++} \rightarrow W^+ W^+$

- Fully leptonic same-sign WW final state
  - Part of *same-sign WW VBS* SM analysis
  - Exclusion limits on $\sigma \times Br(H^{++} \rightarrow W^+ W^+)$
  - Stringent exclusion limits on the s_H paramter

$$\sin \theta_H =: s_H = \frac{2\sqrt{2}\,v_\Xi}{v_{SM}}$$

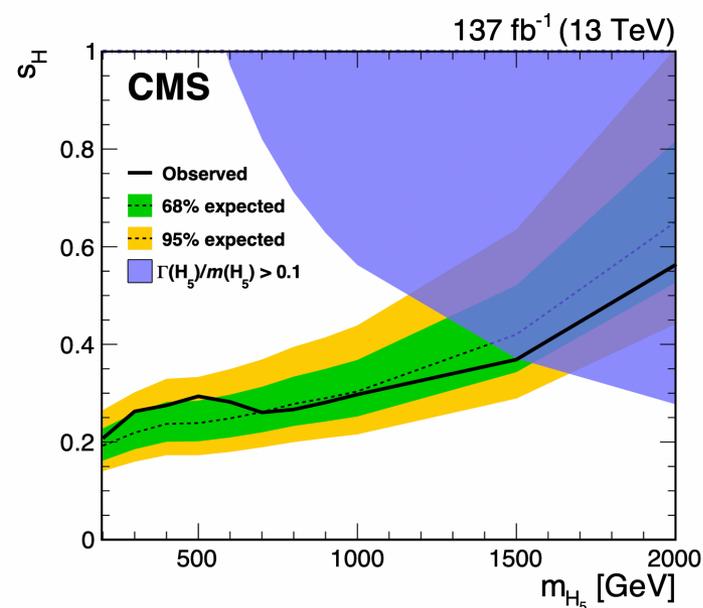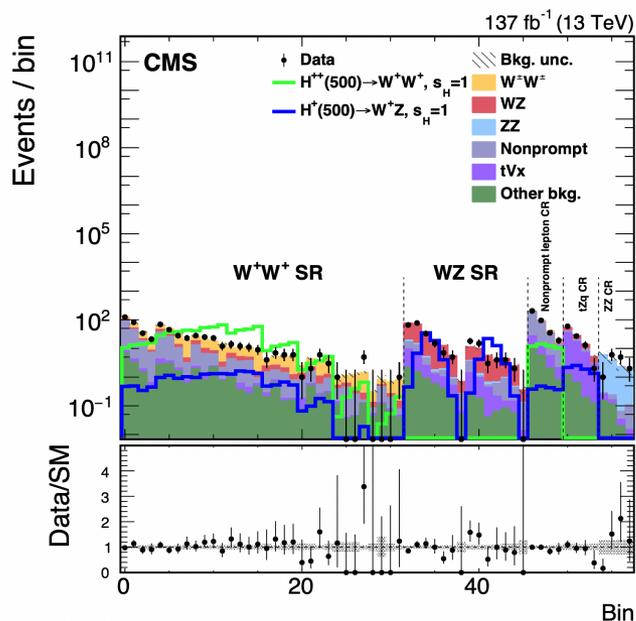# ATLAS Run 2 results: H$^+$->WZ

- Fully leptonic final states with 3 leptons + MET
  - Dedicated WZ QCD control region
  - ANN for VBF signal selection
  - s_H > ~0.3 excluded for m_{H5} of 200 to 1000 GeV

Arxiv:2207.03925

CMS Run 2 results

- Simultaneous analysis of $H^{++} \to W^+W^+$ and $H^+ \to WZ$ channels
  - WZ is an important background for same-sign WW
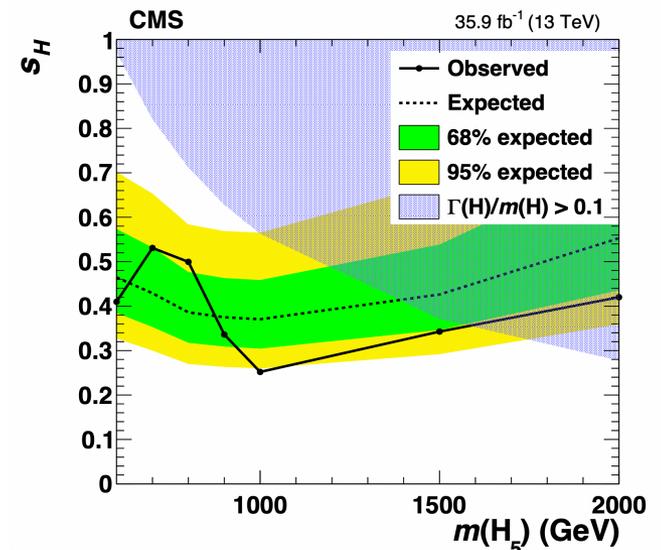 - Signal extraction with 2D fit (m_{jj} x m_T)

- Similar sensitivity by ATLAS and CMS

Arxiv:2104.04762

Semileptonic final states

- Semileptonic WV and ZV process where one boson decays to quarks
  - H$^+$ -> WV with W->lnu or H^{++} -> WW with one of the Ws decaying to lnu
  - H$^+$ -> ZV with Z->ll
- Dedicated study by CMS with merged V-jets
  - Using only 2016 data set
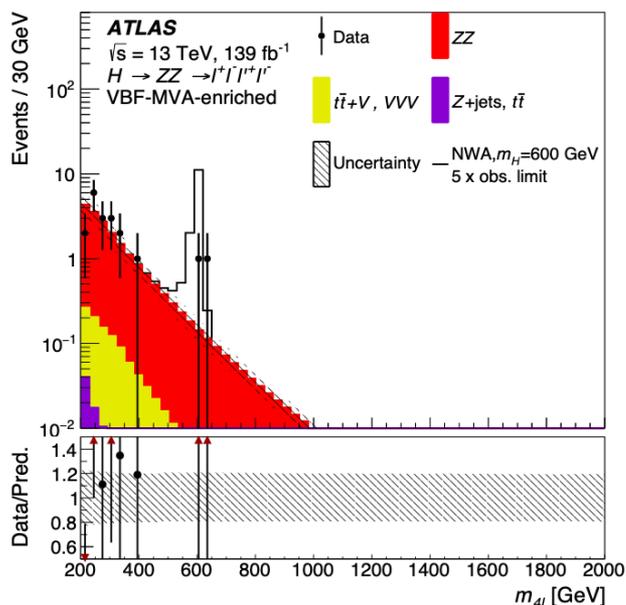 - Within a "SM" paper

Z→ | ll | nn | qq

W→ | ln | qq
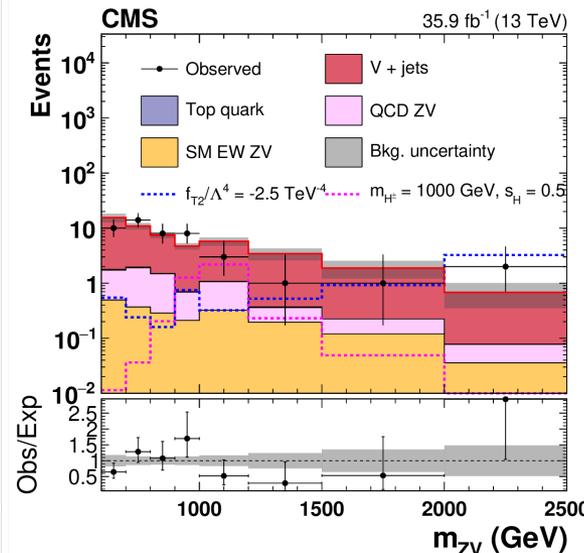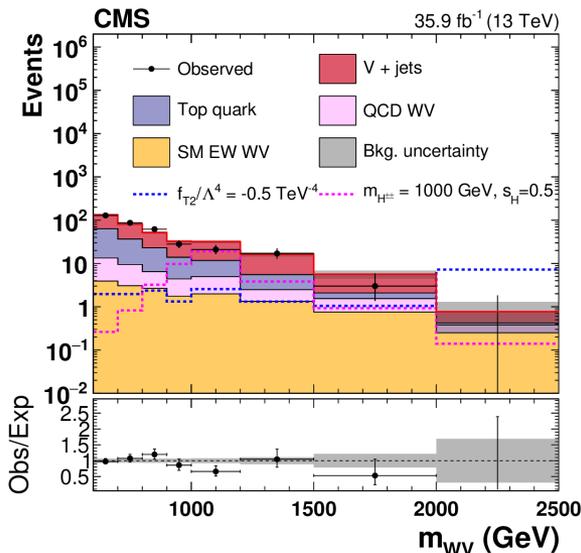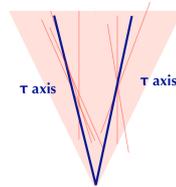
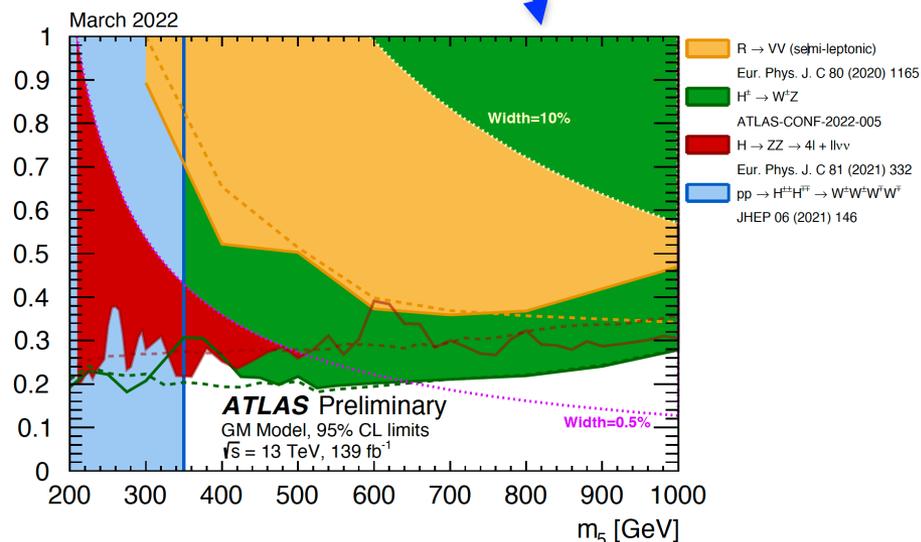Good sensitivity to higher masses!   Arxiv:1905.07445

Georgi-Machacek combination

- Can interpret other VBF heavy diboson searches in ATLAS
  - Interpret in terms of a narrow-width Higgs boson of the Georgi-Machacek mode
  - Would be good to perform a combination

Arxiv:2009.14791

ATLAS PUB note

Majorana neutrinos with same-sign WW scattering

- T-channel exchange of a heavy Majorana neutrino
  - No neutrinos in the final state
- ATLAS and CMS studied same-sign μμjj final state
  - Results are interpreted in a benchmark scenario of the Phenomenological Type-I Seesaw model
  - Sensitivity to dim-5 Weinberg operator is also investigated
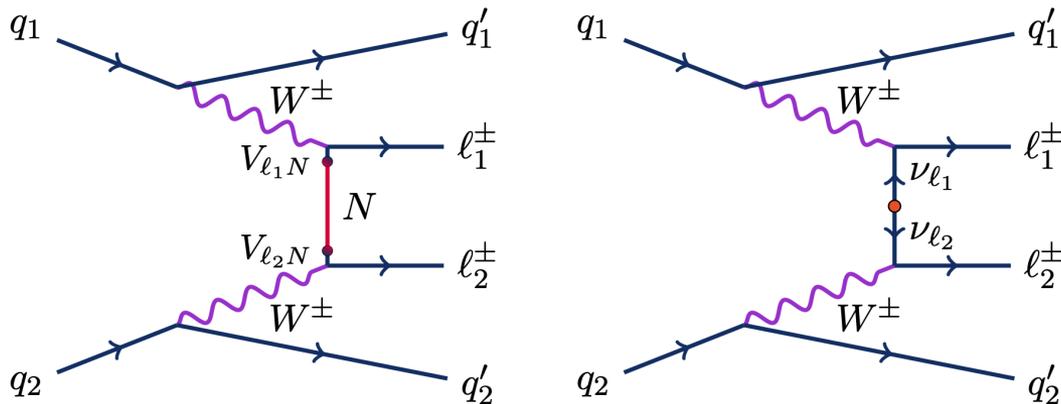
$$\mathcal{L}_5 = \frac{C_5^{\ell\ell'}}{\Lambda} [\Phi \cdot \overline{L}_\ell^c][L_{\ell'} \cdot \Phi]$$

$$m_{\ell\ell'} = C_5^{\ell\ell'} \upsilon^2 / \Lambda$$

$$\sigma(pp \to \mu^\pm \mu^\pm + X) \equiv |V_{\mu N}|^4 \times \sigma_0(pp \to \mu^\pm \mu^\pm + X)$$

Majorana neutrinos with same-sign WW scattering

- CMS search uses $H_T/p_T(\mu_1)$ as discriminating variable
  - H_T is the scalar sum of all the jets with $p_T > 30$ GeV
  - μ_1 is the leading muon in pT
- Simultaneous fit of signal and control regions

Arxiv:2206.08956
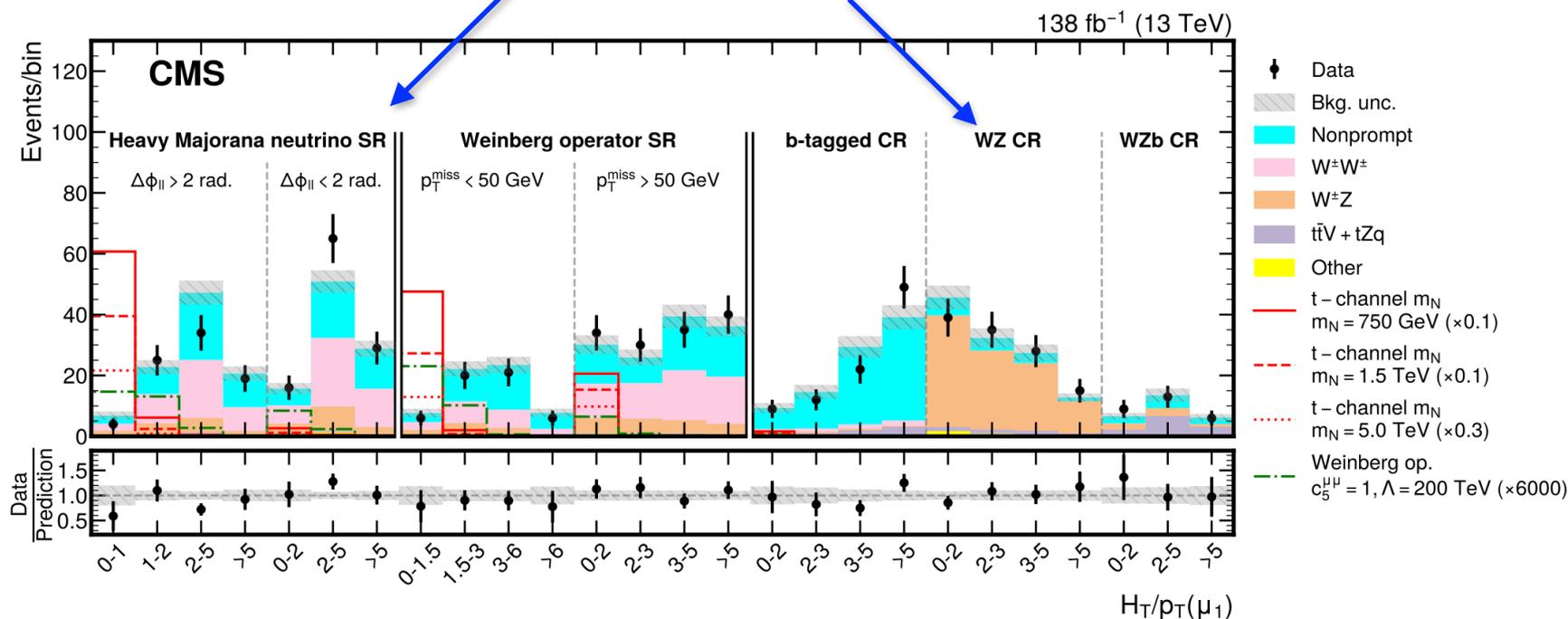
Majorana neutrinos with same-sign WW scattering

- ATLAS search uses $p_T(\mu_2)$ as discriminating variable
  - μ_2 is the sub-leading muon in pT
- Simultaneous fit of signal and control regions

Arxiv:2305.14931
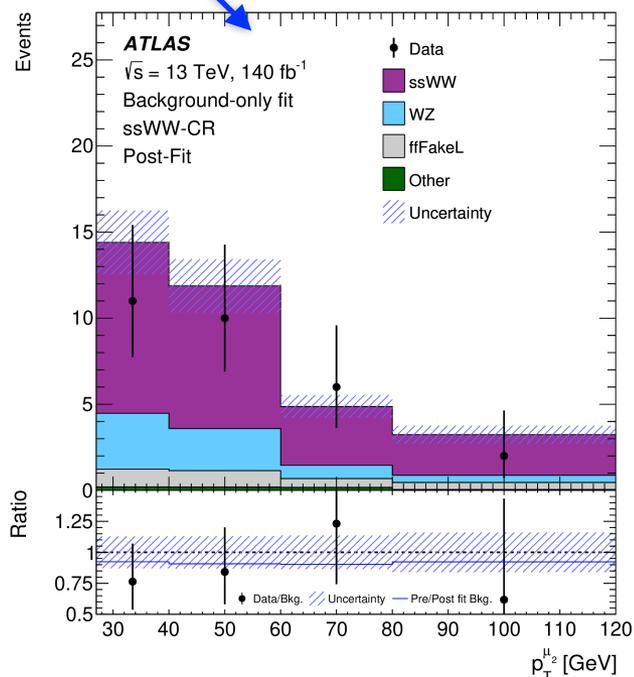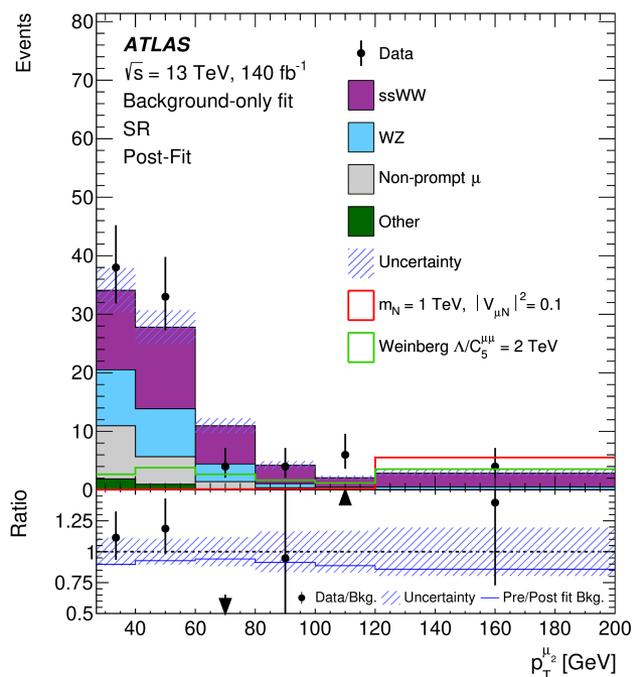
Majorana neutrinos with same-sign WW scattering

- The ATLAS and CMS t-channel results extend the sensitivity to Type 1 Seesaw heavy Majorana neutrino masses of up to 20 TeV
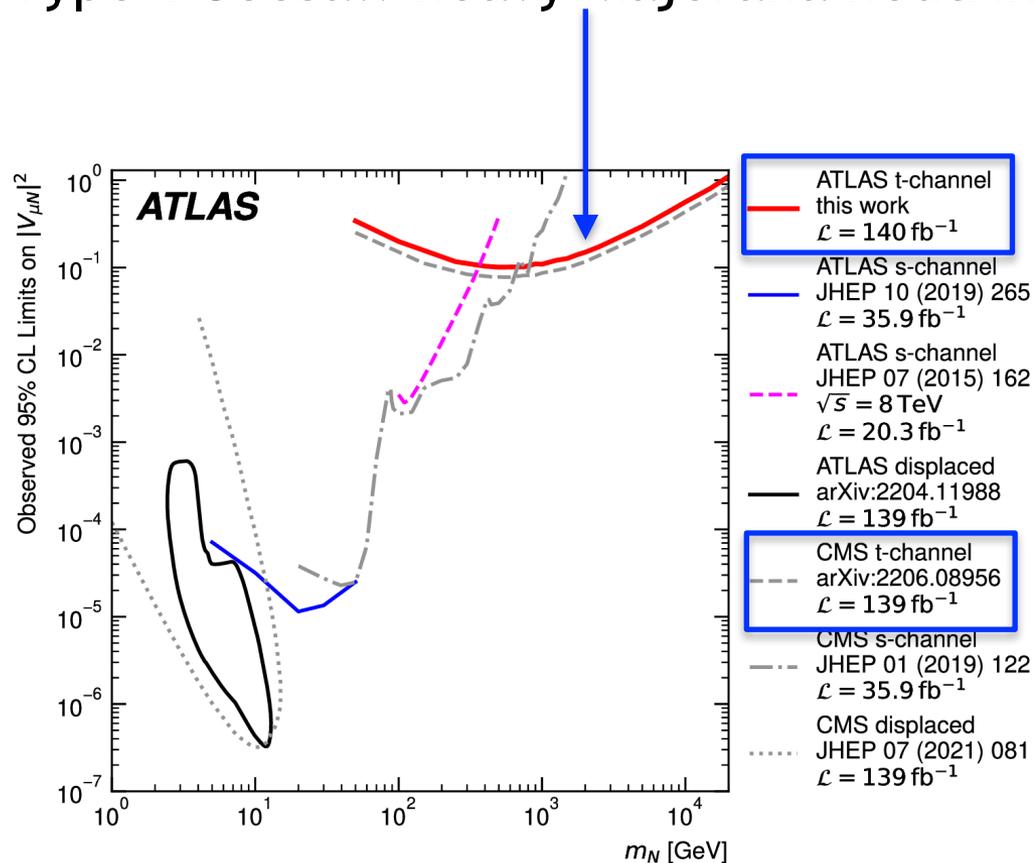
- Upper limits on effective Majorana mass
  - ATLAS: 16.7 GeV
  - CMS: 10.8 GeV

$$m_{\ell\ell'} = C_5^{\ell\ell'} v^2 / \Lambda$$

Arxiv:2305.14931

ATLAS R->WW search

- Search for heavy neutral resonances decaying to WW
  - Electron+Muon decay channel
  - ggF, VBF (1jet) and VBF (2jet) signal regions

R: narrow width resonant signal

ATLAS-CONF-2022-066

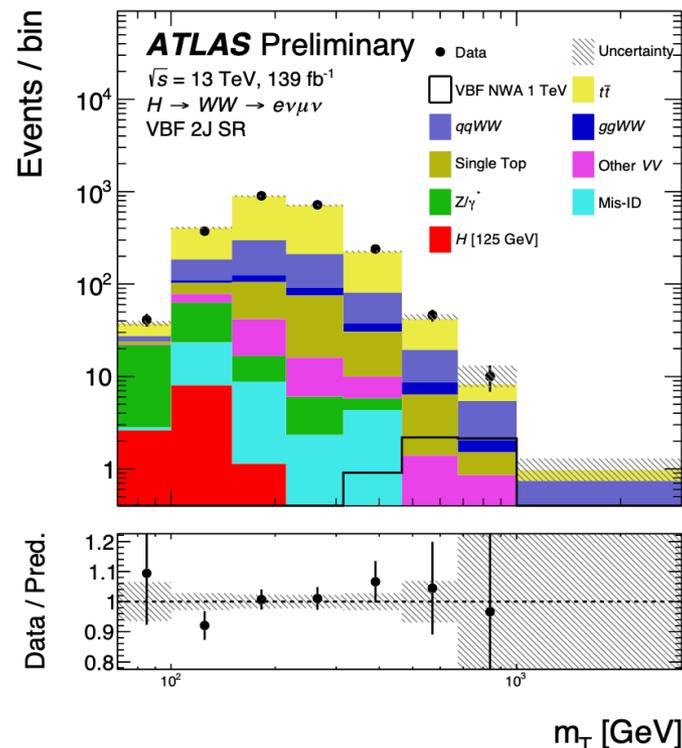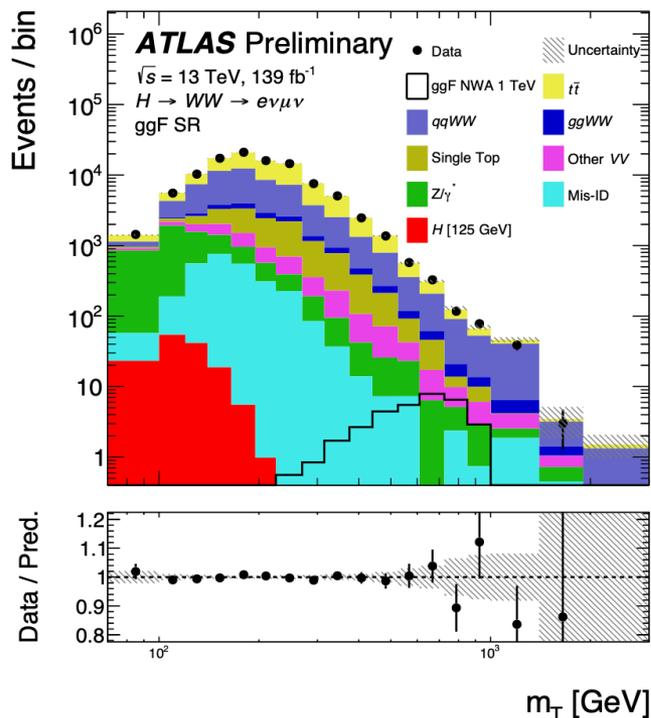# ATLAS R->WW search

- Search for heavy neutral resonances decaying to WW
  - Systematic uncertainties (impact on limits)

| ggF Production		VBF Production	
Systematic Source	Impact (%)	Systematic Source	Impact (%)
m_H = 300 GeV			
Flavour tagging: b-jets	11	WW QCD Scale	14
WW QCD Scale	10	Wt Shower	12
JES: b-jets	9	Wt Matrix Element	10
Floating Normalizations: WW	8.77	JES: Pile-up μ Offset	7.97
Data stat. uncertainty	9	Data stat. uncertainty	16
Total Syst. uncertainty	33	Total Syst. uncertainty	40
m_H = 1000 GeV			
WW Shower: Recoil	6	WW Scale	4
e fake factor stat. uncertainty	5	Wt Shower	3.4
Wt Interference	5	WW Shower: CKKW	3.4
WW QCD Scale	4	$t\bar{t}$ Final-state Rad.	2.9
Data stat. uncertainty	17	Data stat. uncertainty	25
Total Syst. uncertainty	20	Total Syst. uncertainty	10
m_H = 3000 GeV			
WW Shower: Recoil	20	WW Scale: QSF	7
WW Scale: QSF	19	WW Shower: Recoil	6
WW Shower: CKKW	16	WW Shower: CKKW	5
Wt Interference	7	Floating Normalizations: WW	1
Data stat. uncertainty	22	Data stat. uncertainty	18
Total Syst. uncertainty	21	Total Syst. uncertainty	15

ATLAS-CONF-2022-066

ATLAS R->WW search

- Upper limits on $\sigma \times$BR for resonances from 300 GeV to 4 TeV

| Model	Resonance spin	Production mode		
		ggF	qqA	VBF
NWA	Spin-0	x		x
GM				x
Radion		x		x
HVT	Spin-1		x	x
RS G^*_{KK}	Spin-2	x		x

ATLAS-CONF-2022-066
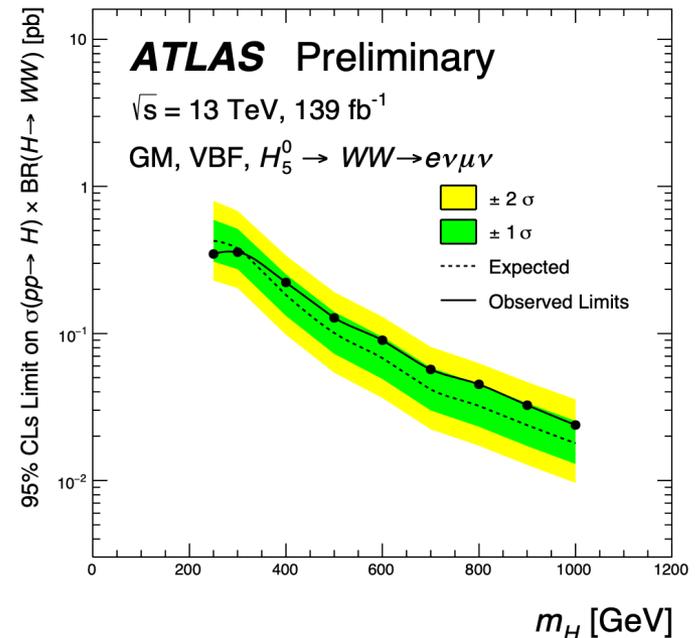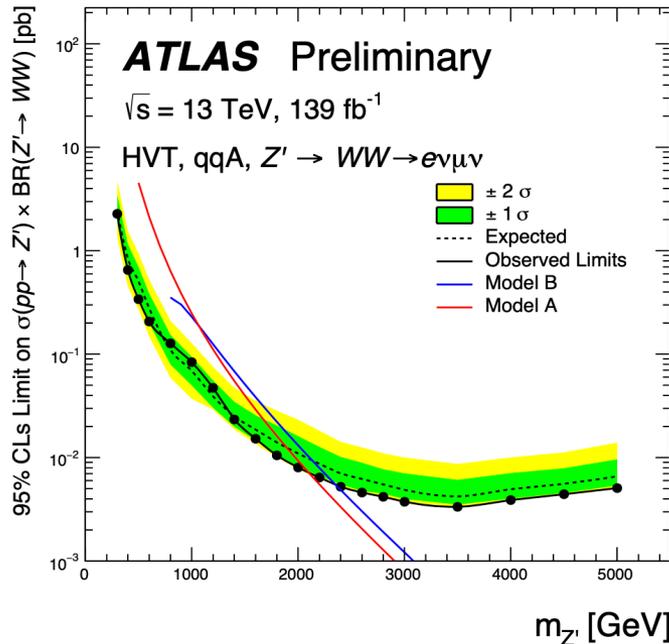
ATLAS W'->WZ search

- WZ production in fully leptonic final state
- DY process production
  - HVT used as benchmark model
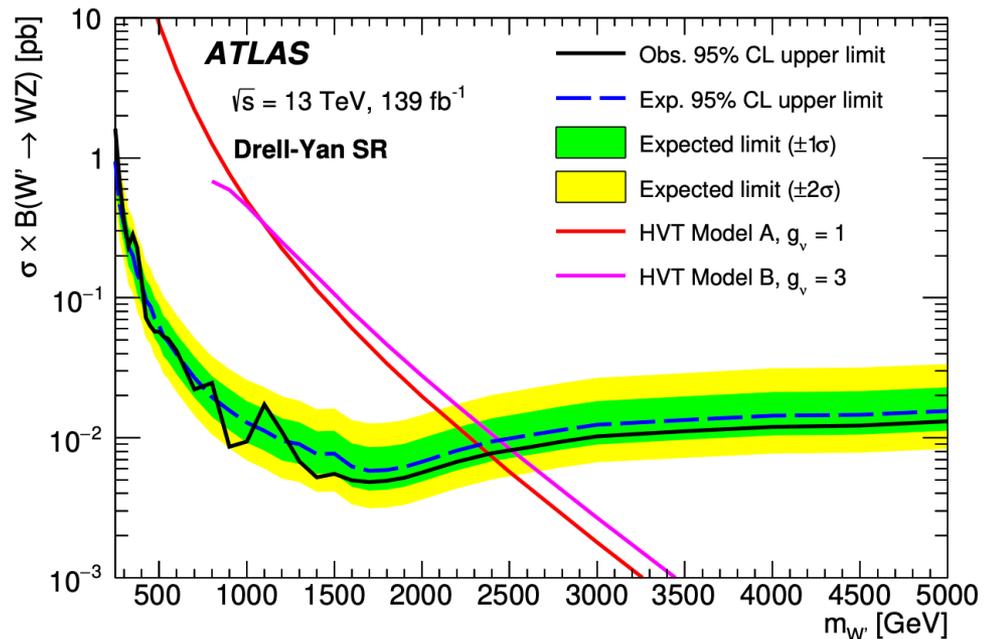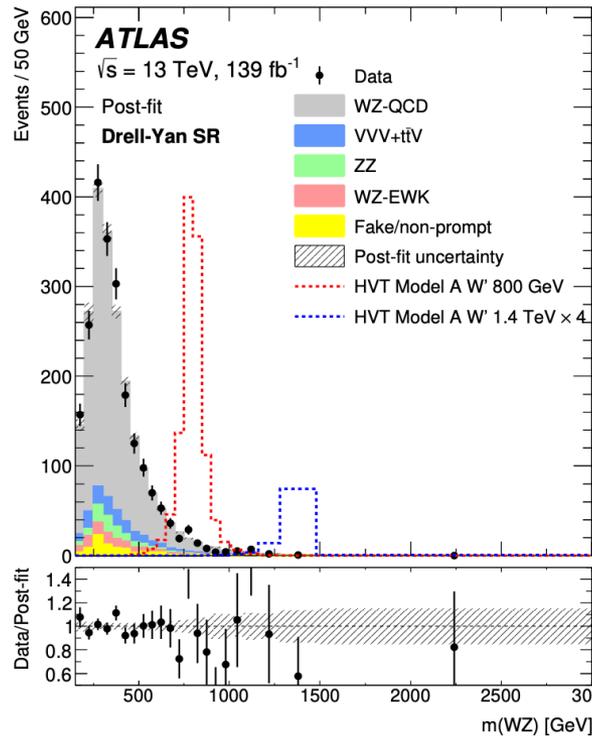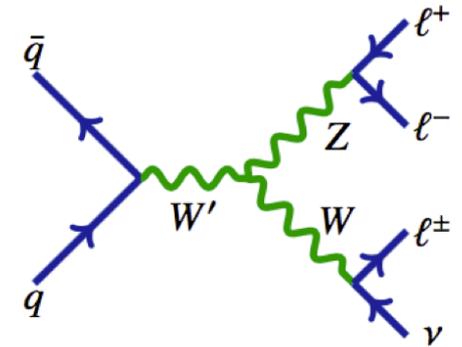
Arxiv:2207.03925

CMS search in fully hadronic final state

- Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state

  - Highly boosted bosons -> large-radius jets

- DeepAK8 tagger categorization used (Arxiv:2004.08262)

  - W/Z -> qq discrimination against single quark and gluon background

  - bb tagger: H/Z -> bb discrimination against single quark and gluon background

- VBF topology selected by requiring at least 2 AK4 jets
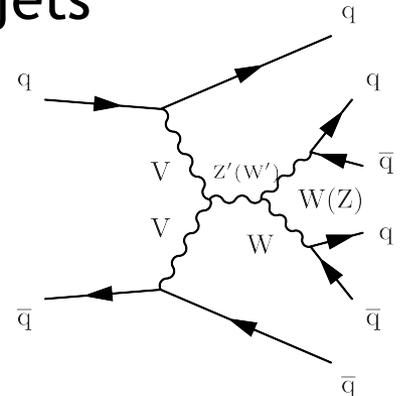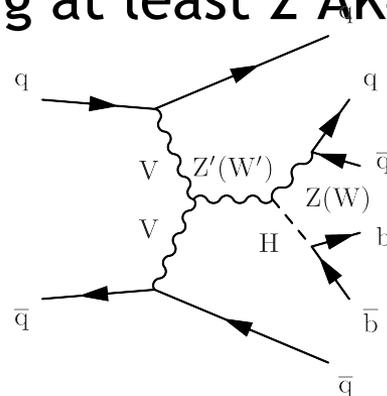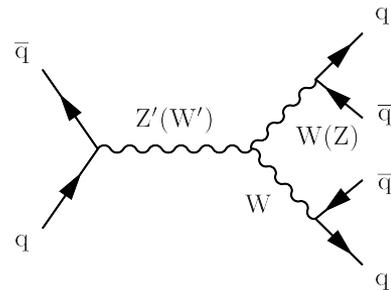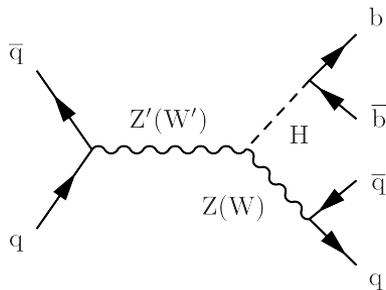
Arxiv:2210.00043

CMS search in fully hadronic final state

- Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state
  - Highly boosted bosons -> large-radius jets (p_T > 200 GeV)
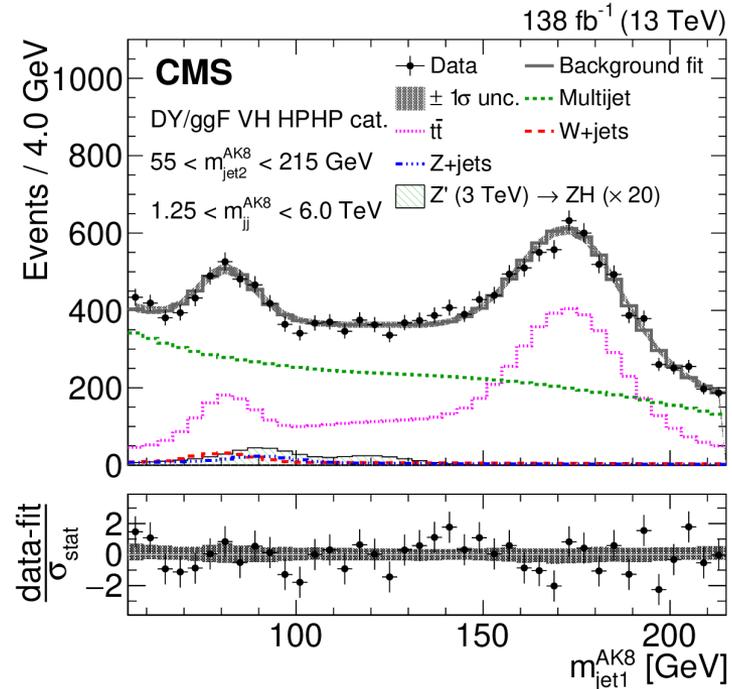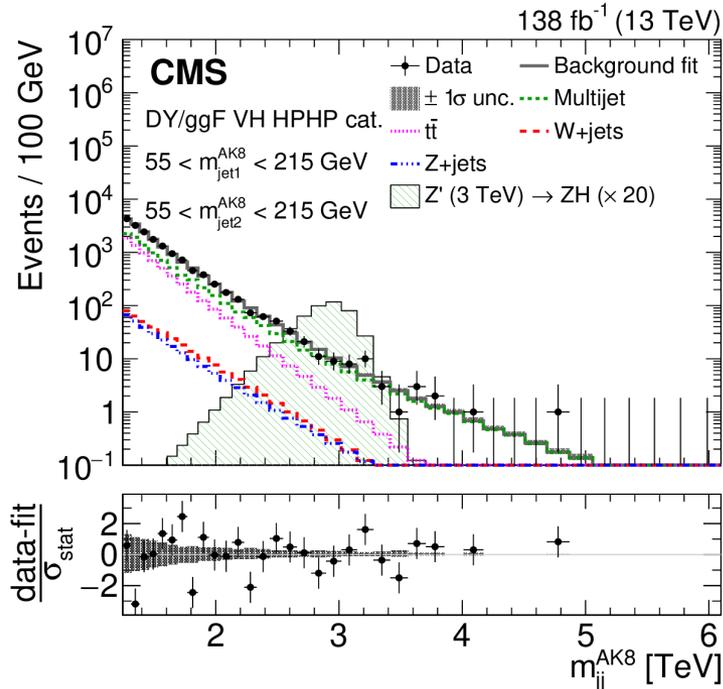 - 3D fit in m_{jj}, m_{jet1}, and m_{jet2}

CMS search in fully hadronic final state

- Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state
  - Categories most sensitive to DY/ggF (High Purity)
  - Excess of data events in some mass regions
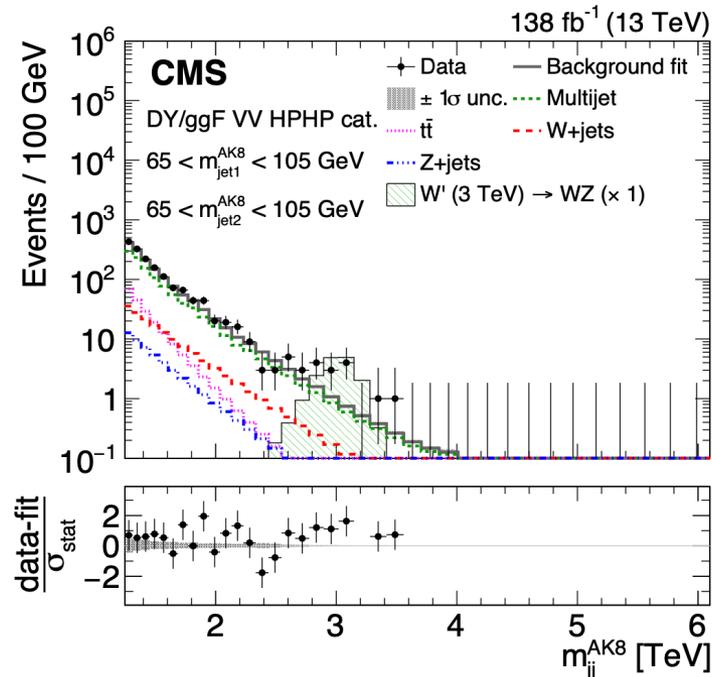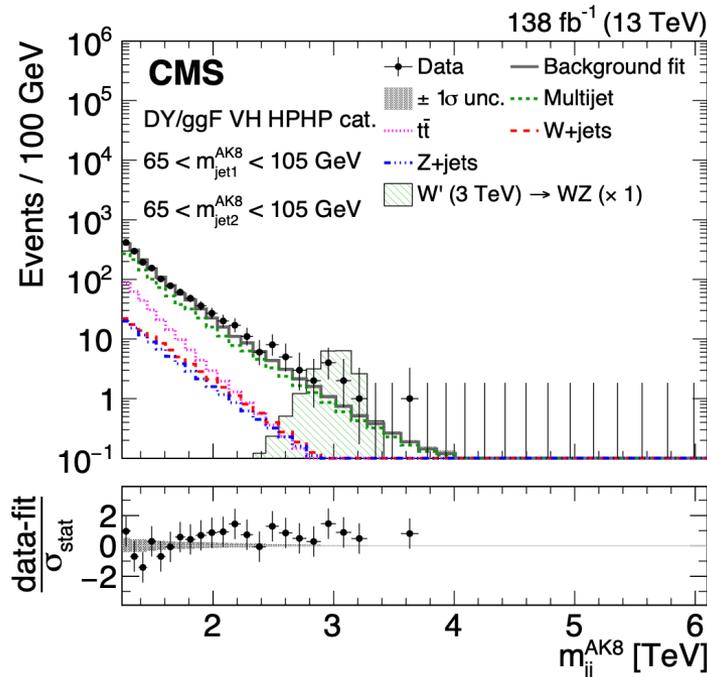
Arxiv:2210.00043

CMS search in fully hadronic final state

- Search for new heavy resonances decaying to WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state
  - Expected limits for resonant masses of 1.3 and 6 TeV
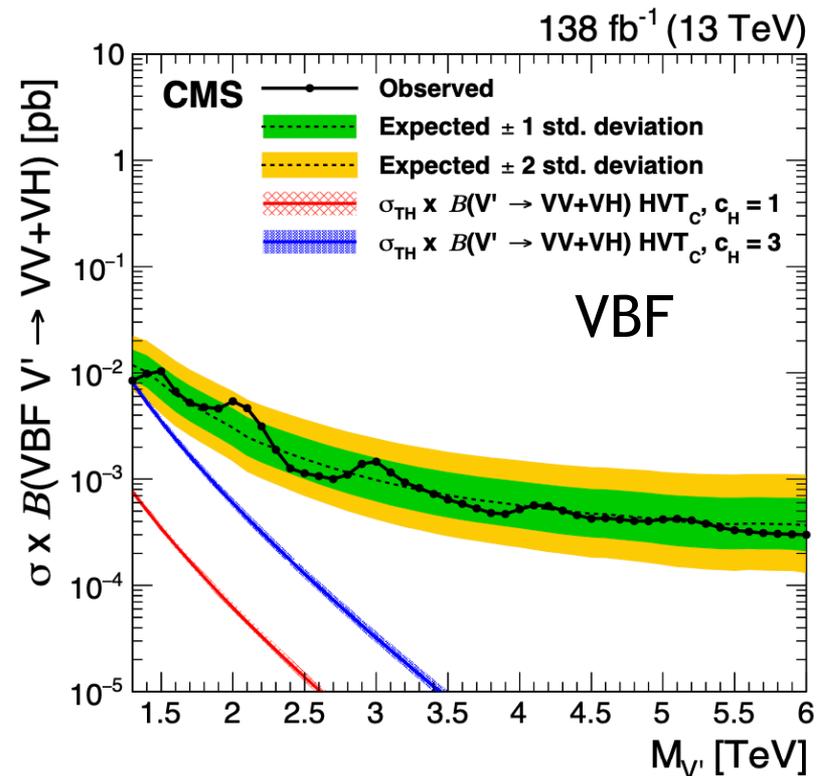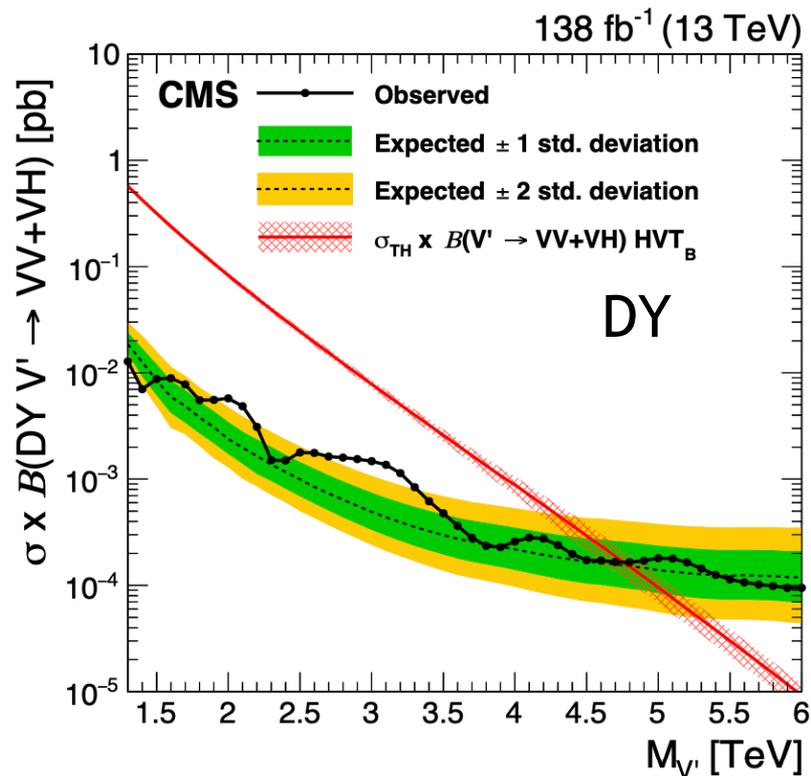
A maximum local (global) significance of 3.6 (2.3) standard deviations

ATLAS Summary of HVT W' -> WZ

- Comparison of exclusion limits of fully leptonic, semileptonic, and fully hadronic final states
  - W' -> WZ
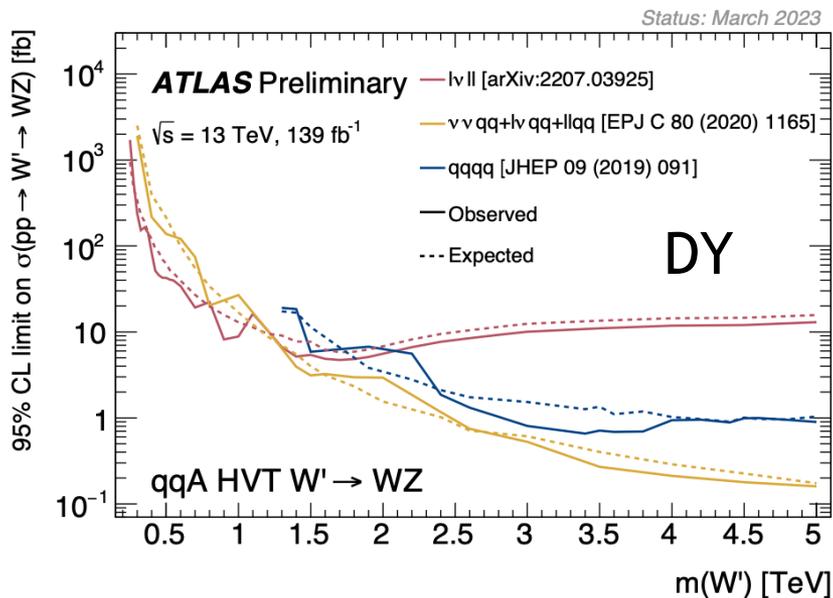
(a) *qqA*
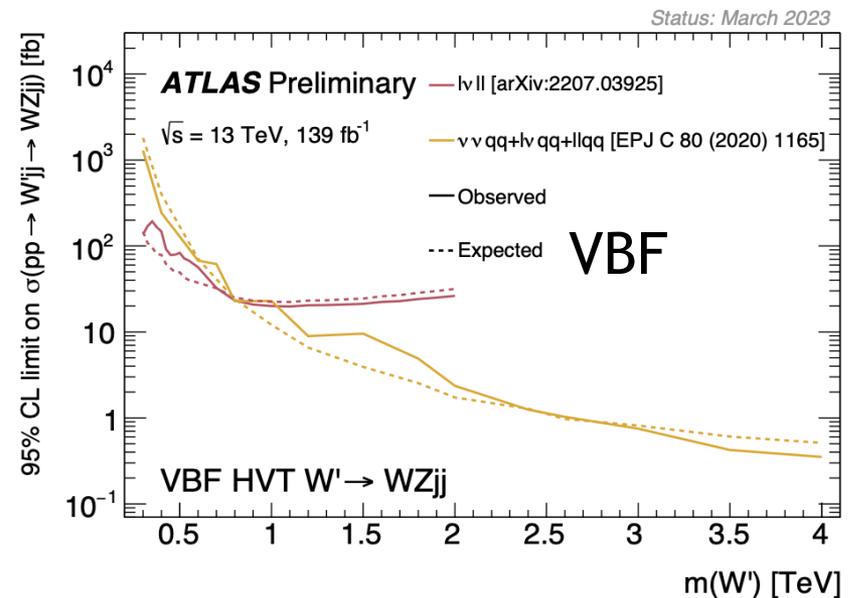
(b) *VBF*

Summary of HVT Z' -> WW

- Comparison of exclusion limits of fully leptonic, semileptonic, and fully hadronic final states
  - Z' -> WW

CMS Summary of HVT W' -> WZ

- Comparison of exclusion limits of fully leptonic, semileptonic, and fully hadronic final states
  - W' -> WZ

CMS Summary

Summary of various diboson searches

ATLAS Diboson Searches - 95% CL Exclusion Limits
Status: March 2023

ATLAS Preliminary
$\mathcal{L} = 139$ fb^{-1} $\sqrt{s} = 13$ TeV

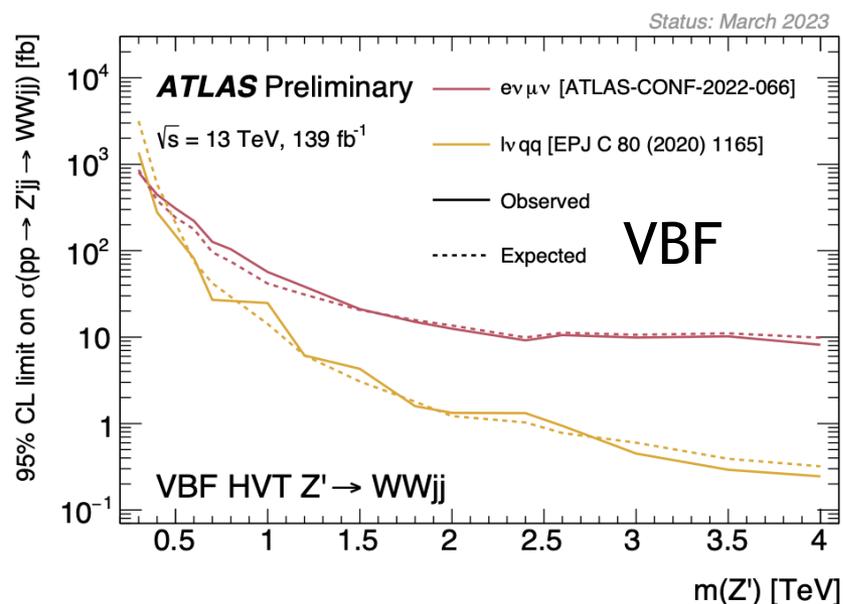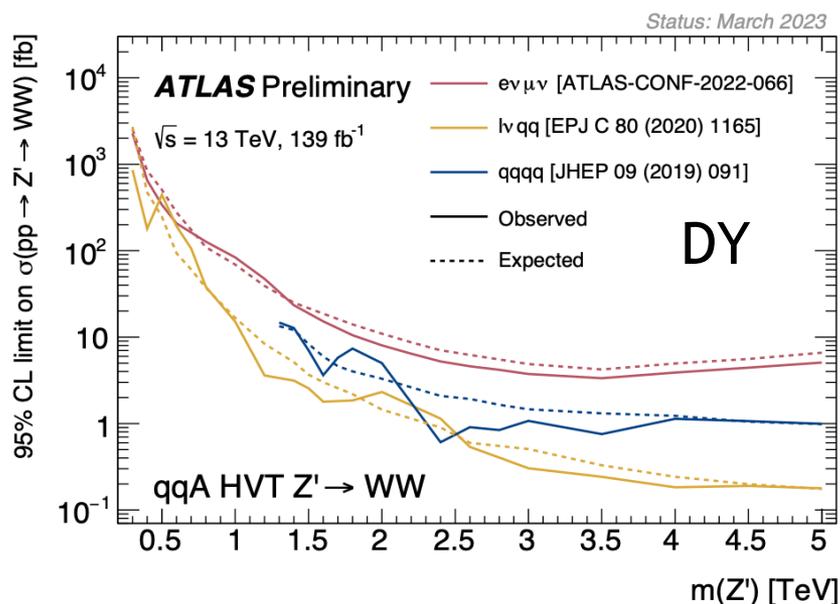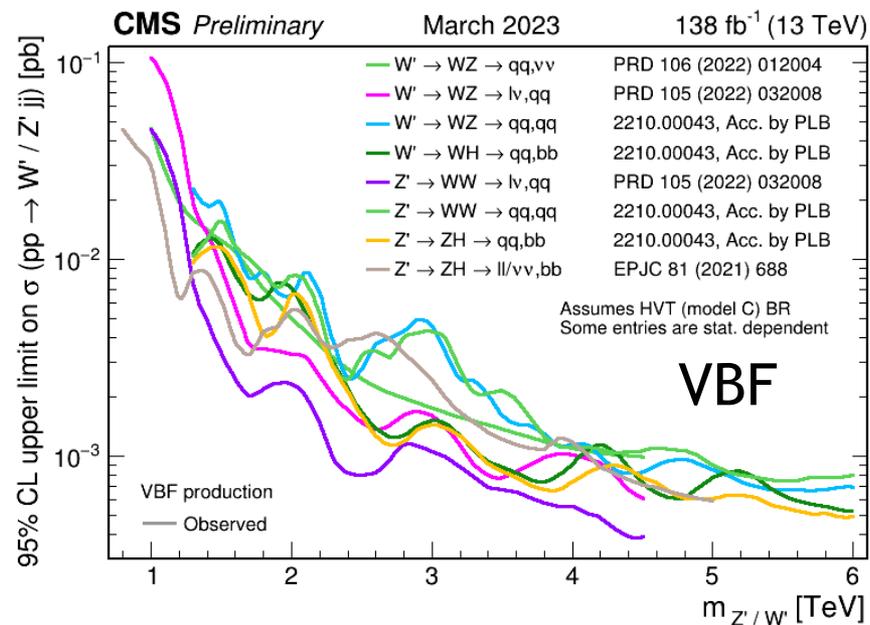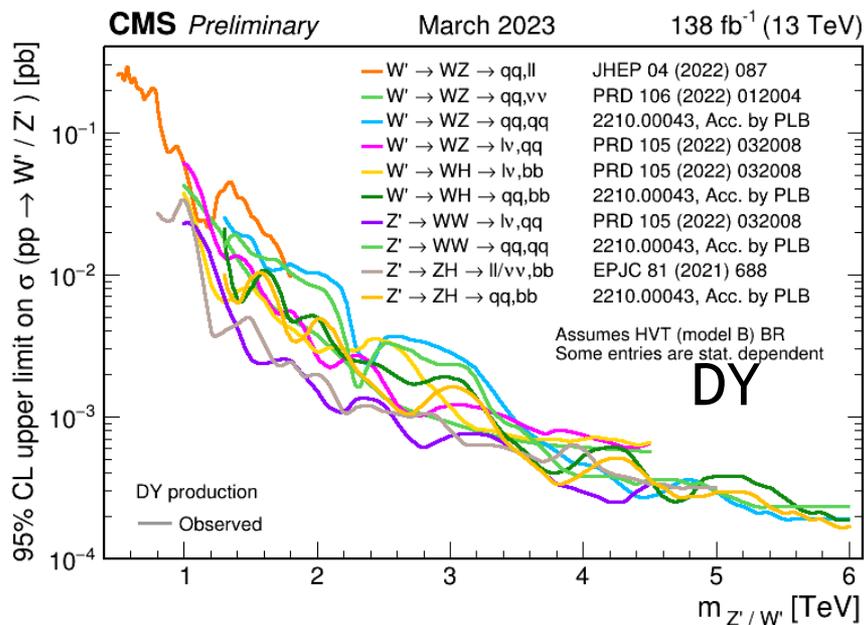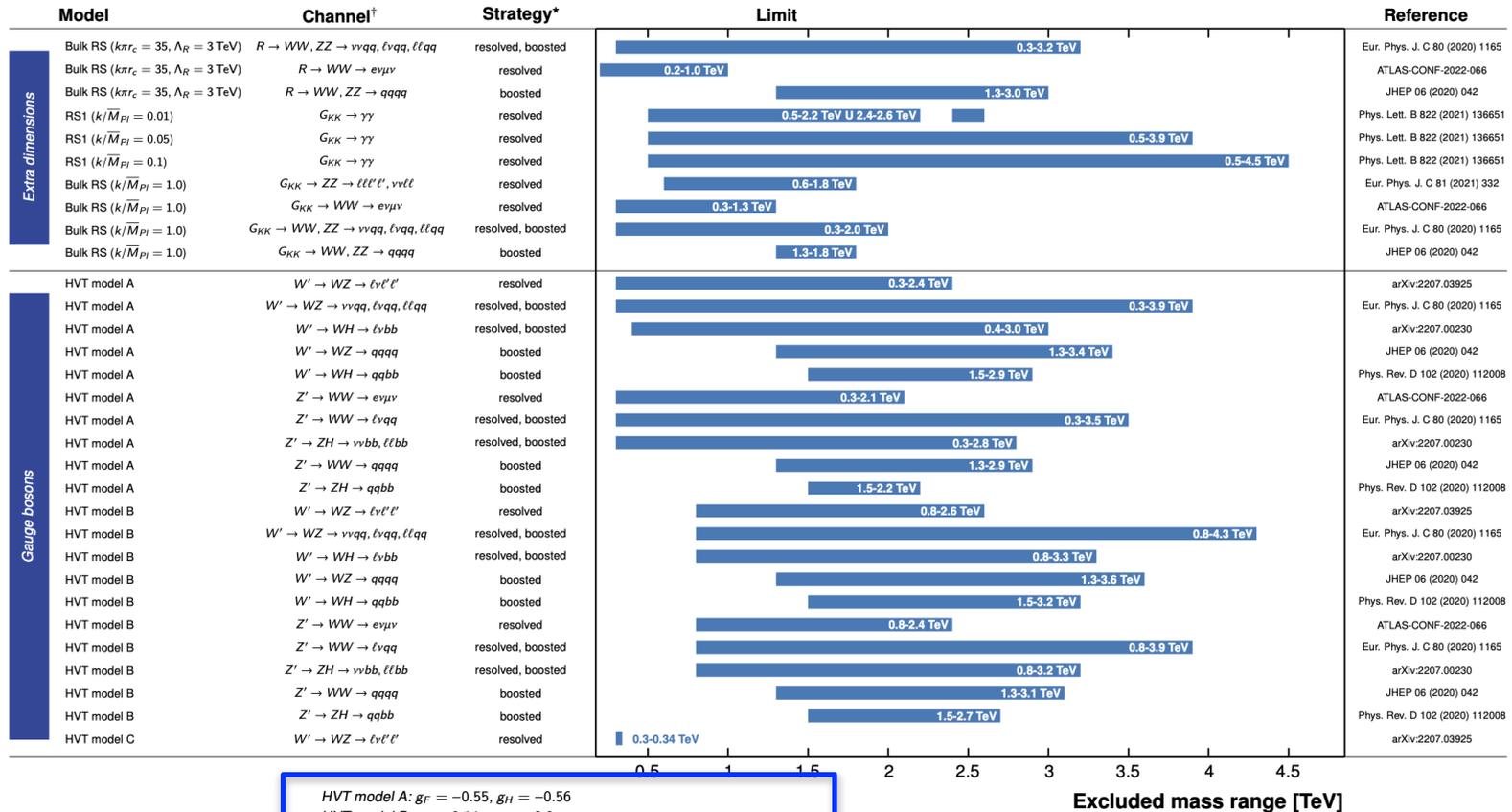|	Model	Channel†	Strategy*	Limit	Reference
Extra dimensions	Bulk RS ($k\pi r_c = 35, \Lambda_R = 3$ TeV)	$R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.2 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k\pi r_c = 35, \Lambda_R = 3$ TeV)	$R \to WW \to e\nu\mu\nu$	resolved	0.2-1.0 TeV	ATLAS-CONF-2022-066
	Bulk RS ($k\pi r_c = 35, \Lambda_R = 3$ TeV)	$R \to WW, ZZ \to qqqq$	boosted	1.3-3.0 TeV	JHEP 06 (2020) 042
	RS1 ($k/\overline{M}_{Pl} = 0.01$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-2.2 TeV U 2.4-2.6 TeV	Phys. Lett. B 822 (2021) 136651
	RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-3.9 TeV	Phys. Lett. B 822 (2021) 136651
	RS1 ($k/\overline{M}_{Pl} = 0.1$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-4.5 TeV	Phys. Lett. B 822 (2021) 136651
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$	resolved	0.6-1.8 TeV	Eur. Phys. J. C 81 (2021) 332
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.3-1.3 TeV	ATLAS-CONF-2022-066
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-2.0 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to qqqq$	boosted	1.3-1.8 TeV	JHEP 06 (2020) 042
Gauge bosons	HVT model A	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-2.4 TeV	arXiv:2207.03925
	HVT model A	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model A	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.4-3.0 TeV	arXiv:2207.00230
	HVT model A	$W' \to WZ \to qqqq$	boosted	1.3-3.4 TeV	JHEP 06 (2020) 042
	HVT model A	$W' \to WH \to qqbb$	boosted	1.5-2.9 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model A	$Z' \to WW \to e\nu\mu\nu$	resolved	0.3-2.1 TeV	ATLAS-CONF-2022-066
	HVT model A	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.3-3.5 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model A	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.3-2.8 TeV	arXiv:2207.00230
	HVT model A	$Z' \to WW \to qqqq$	boosted	1.3-2.9 TeV	JHEP 06 (2020) 042
	HVT model A	$Z' \to ZH \to qqbb$	boosted	1.5-2.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model B	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.8-2.6 TeV	arXiv:2207.03925
	HVT model B	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.8-4.3 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model B	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.8-3.3 TeV	arXiv:2207.00230
	HVT model B	$W' \to WZ \to qqqq$	boosted	1.3-3.6 TeV	JHEP 06 (2020) 042
	HVT model B	$W' \to WH \to qqbb$	boosted	1.5-3.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model B	$Z' \to WW \to e\nu\mu\nu$	resolved	0.8-2.4 TeV	ATLAS-CONF-2022-066
	HVT model B	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.8-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT model B	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.8-3.2 TeV	arXiv:2207.00230
	HVT model B	$Z' \to WW \to qqqq$	boosted	1.3-3.1 TeV	JHEP 06 (2020) 042
	HVT model B	$Z' \to ZH \to qqbb$	boosted	1.5-2.7 TeV	Phys. Rev. D 102 (2020) 112008
	HVT model C	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.3-0.34 TeV	arXiv:2207.03925

Excluded mass range [TeV]

HVT model A: $g_F = -0.55, g_H = -0.56$
HVT model B: $g_F = 0.14, g_H = -2.9$
HVT model C: $g_F = 0, g_H = 1$
*small-radius (large-radius) jets are used in resolved (boosted) events
†with $\ell = \mu, e$

Model A: weekly coupled scenario
Model B: strongly coupled scenario
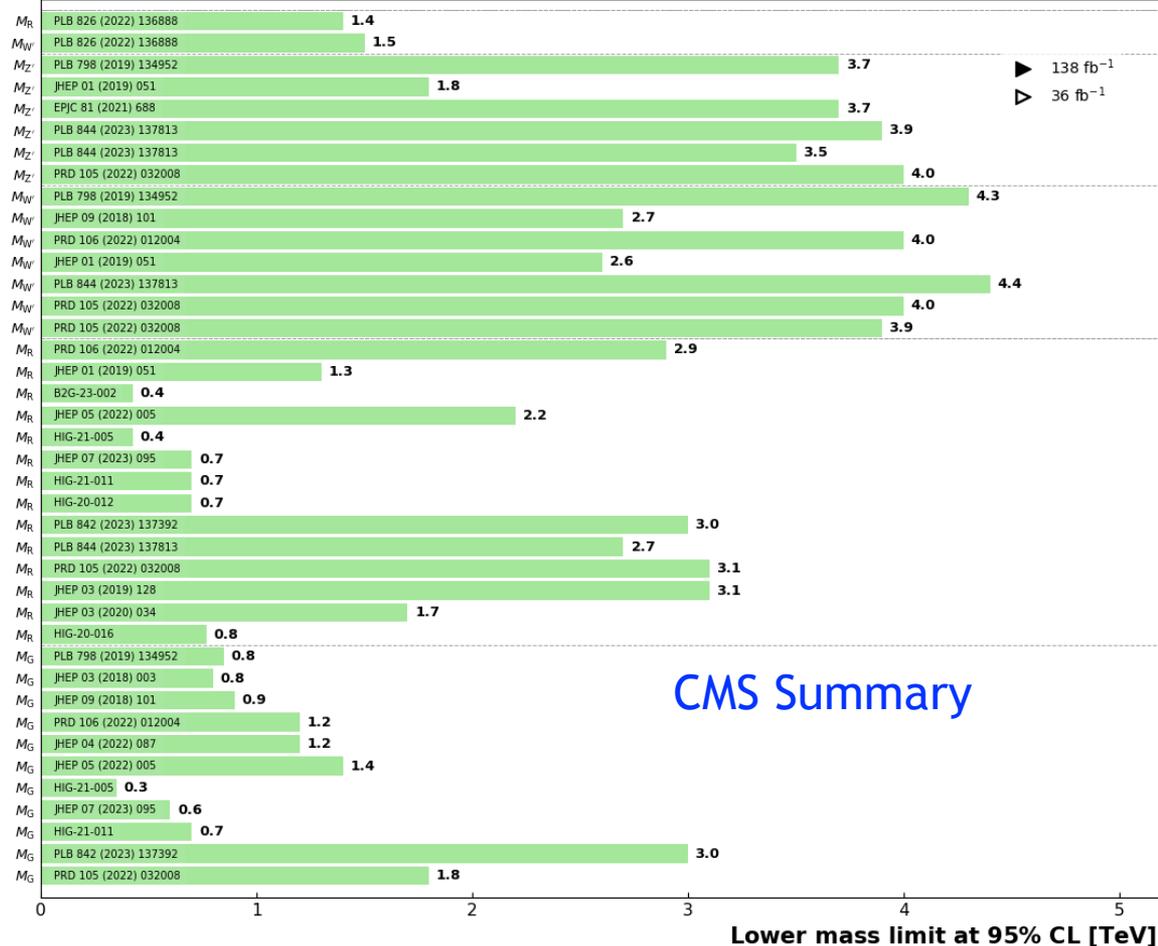Model C: no fermion couplings

Summary of various diboson searches

Overview of CMS B2G Results — August 2023

CMS Preliminary — $36 - 138\,fb^{-1}$ (13 TeV)

CMS Summary

Summary

- Wealth of ATLAS/CMS diboson BSM searches using Run 2 data
  - Complimentary searches with different V decay final states
  - Selected recent results were covered in this talk
- No clear signs of new physics yet
  - Couple of excesses with significance of ~3 standard deviations
- VBF/VBS searches for charged Higgs bosons and Heavy Majorana neutrinos
- Many more results still to come -> Run 3 is here!
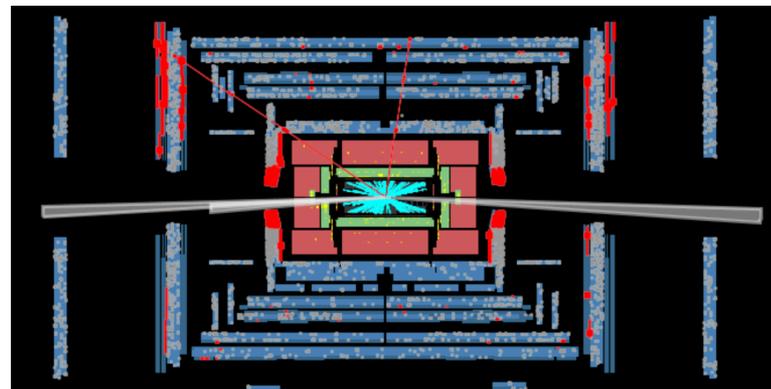
ADDITIONAL MATERIAL

VBF vs DY production

- Important to consider the Drell-Yan production
  - Production cross section independent of s_H
    - Valuable for low sH (VBF depends on s_H^2)
  - Large for low masses compared to VBF!
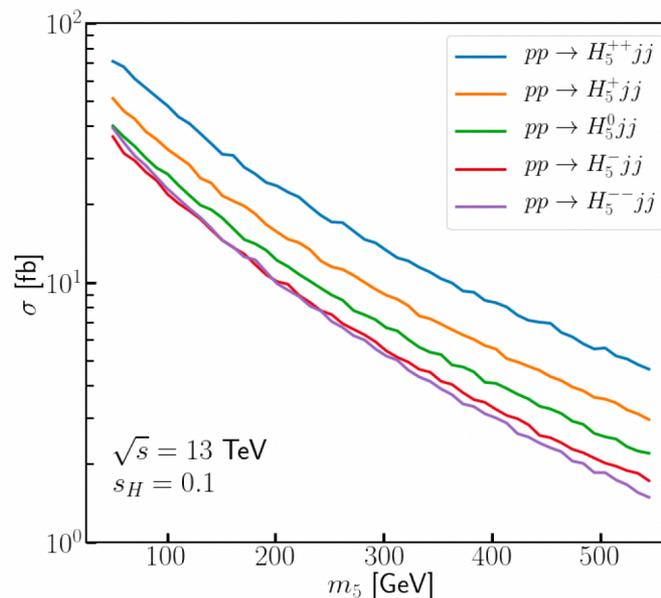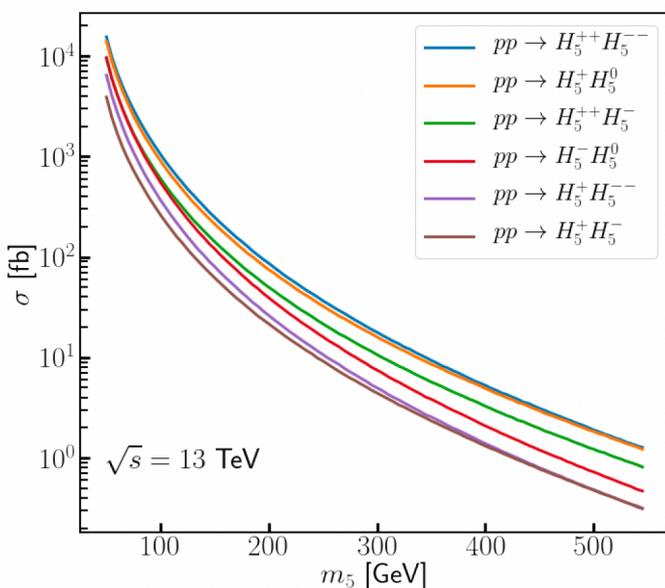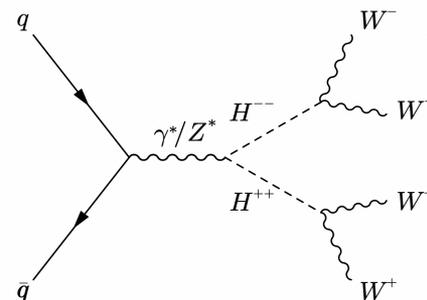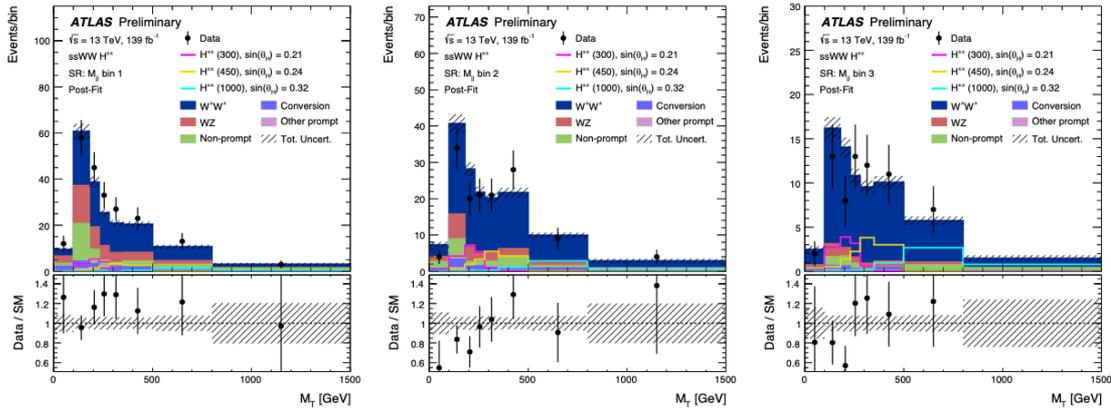

Arxiv:2003.05536
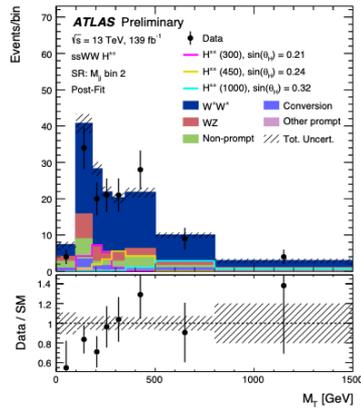
ATLAS search for doubly and singly charged Higgs

- Fully leptonic final state
  - Charged Higgs boson masses above 200 GeV is considered to keep W and Z bosons on-shell
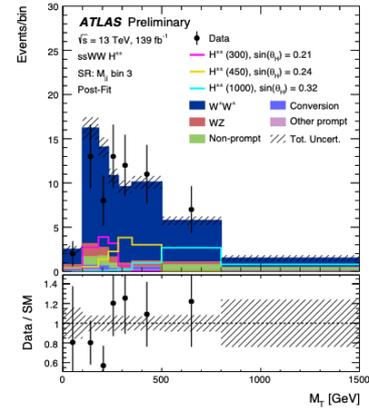 - Excluded H++ bosons for masses from 200 GeV to 350 GeV
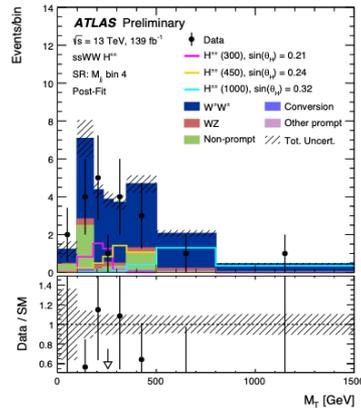

Arxiv:2101.11961
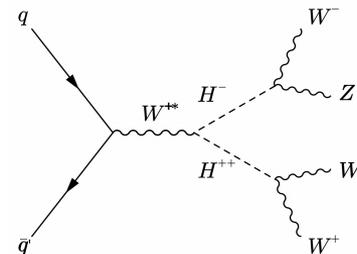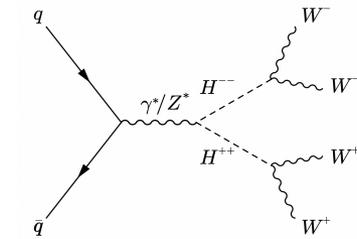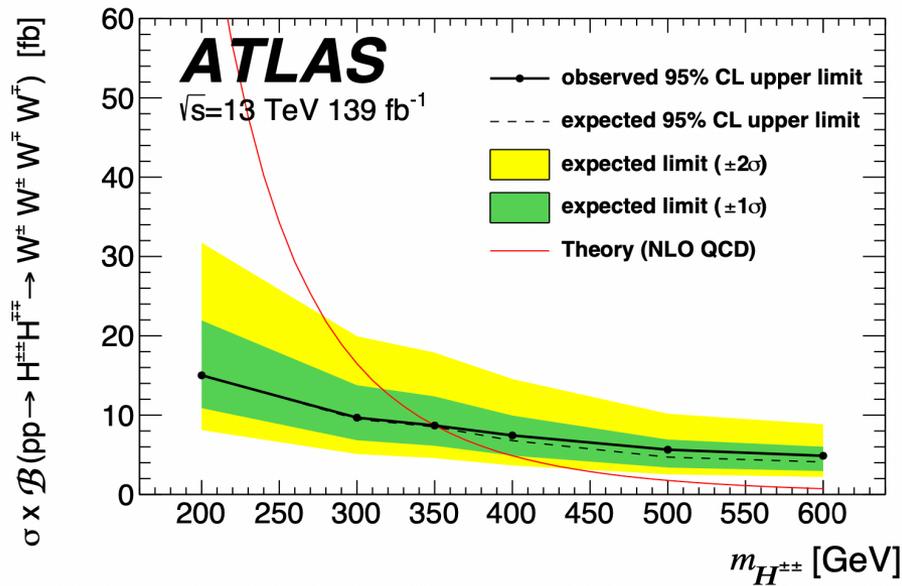
ATLAS Run 2 results: H++->W+W+

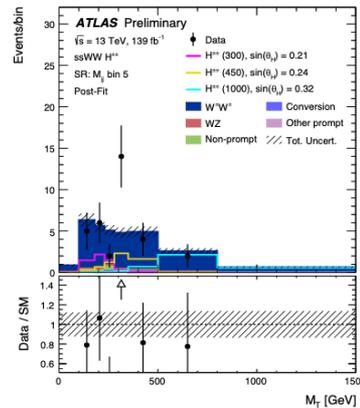(a) $500 \leq m_{jj} < 850$ GeV

(b) $850 \leq m_{jj} < 1450$ GeV

(c) $1450 \leq m_{jj} < 2100$ GeV
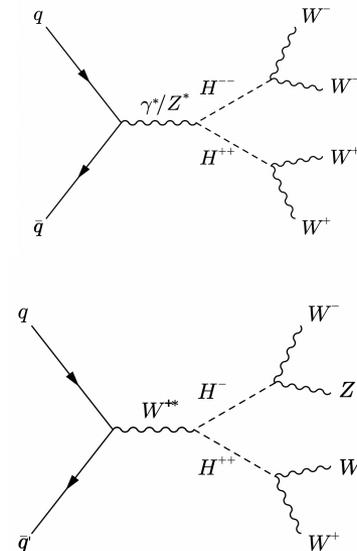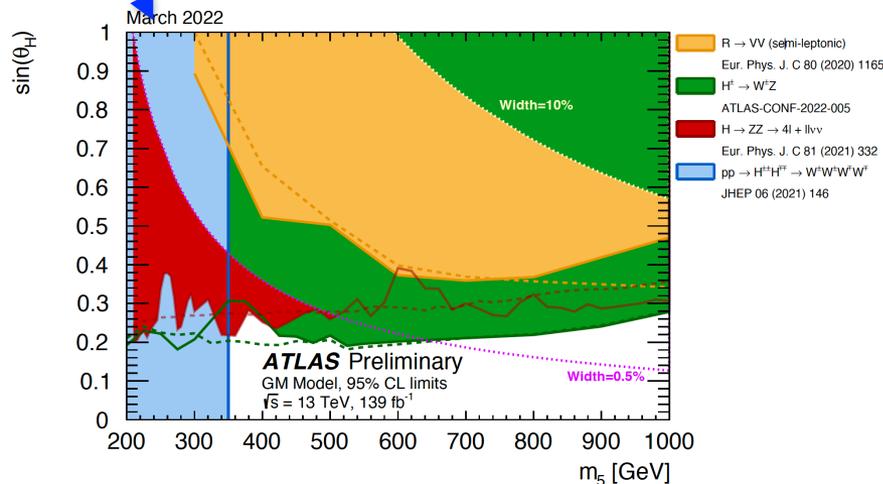
(d) $2100 \leq m_{jj} < 2550$ GeV

(e) $m_{jj} \geq 2550$ GeV

ATLAS search for doubly and singly charged Higgs

- Fully leptonic final state
  - Charged Higgs boson masses above 200 GeV is considered to keep W and Z bosons on-shell
  - Excluded H++ bosons for masses from 200 GeV to 350 GeV
  - Can be interpreted in the GM model as well
    - Would be really interesting to extend this analysis to lower masses!

Summary of HVT Z' -> WW

- Comparison of qqbb and leptons (MET) + bb final states
  - W' -> WH and Z' -> ZH

ATL-PHYS-PUB-2023-00