SEARCHES FOR NEW HEAVY PARTICLES USING THE ATLAS DETECTOR

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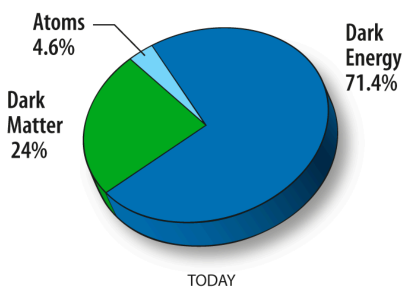
on behalf of the ATLAS Collaboration

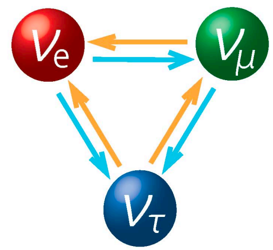
Kruger 2022

Beyond the Standard Model (BSM) physics

- The Standard Model (SM) has been experimentally validated and proven to be impressively precise. However, it cannot explain some of the important questions in physics:
  - Dark Matter (DM)?

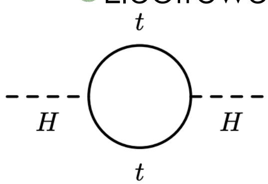


  - Neutrino masses?



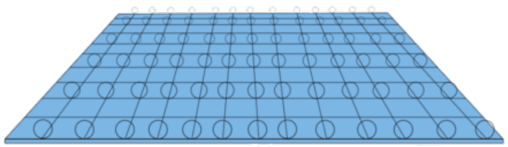
  - Matter/antimatter asymmetry?

  - Electroweak hierarchy problem?



$$\approx \int_0^{\Lambda} dE \approx m_{\text{Planck}}$$

  - Gravity?



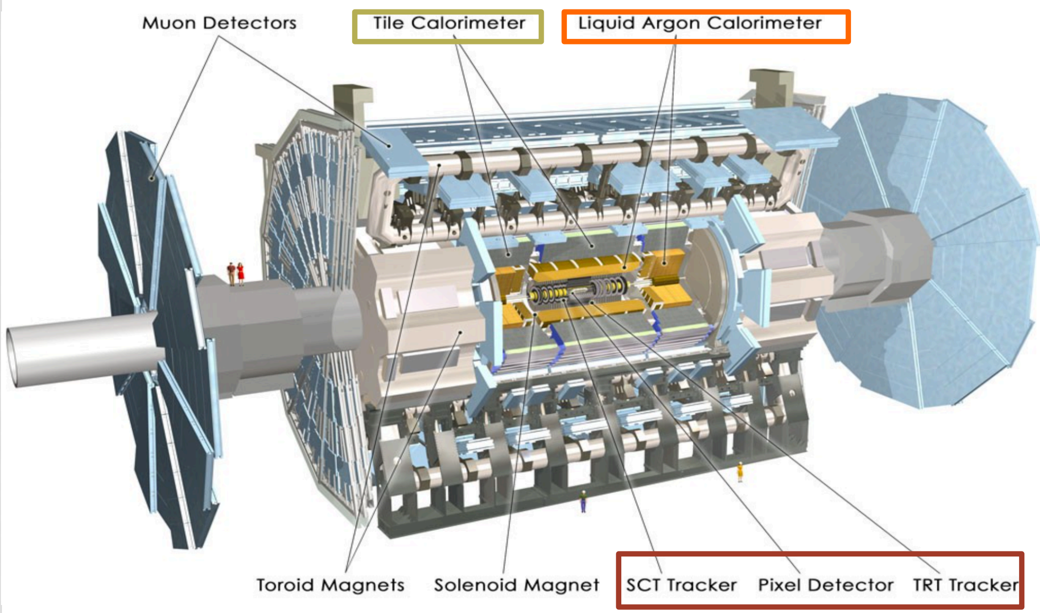
Several BSM models extends the SM by introducing new symmetries and particles/fields.

Some of the most popular in BSM searches at LHC:

- **Minimal Supersymmetric Standard Model (MSSM)** solution to "hierarchy problem" and has DM candidate
- Two Higgs Doublet Models (2HDM) extend beyond the SM Higgs sector to include two complex Higgs Doublets (subset of MSSM, could introduce baryon asymmetry or a DM candidate or neutrino masses)
- Heavy Vector Triplet model: Simplified model used to capture the phenomenology of a new resonance
- **Radion** model that includes Kaluza-Klein gauge bosons
- **Effective Field Theory (EFT):** Contact interactions for a more model-independent description
- **Simplified Models for DM:** Usually adding a massive mediator (e.g. Z')

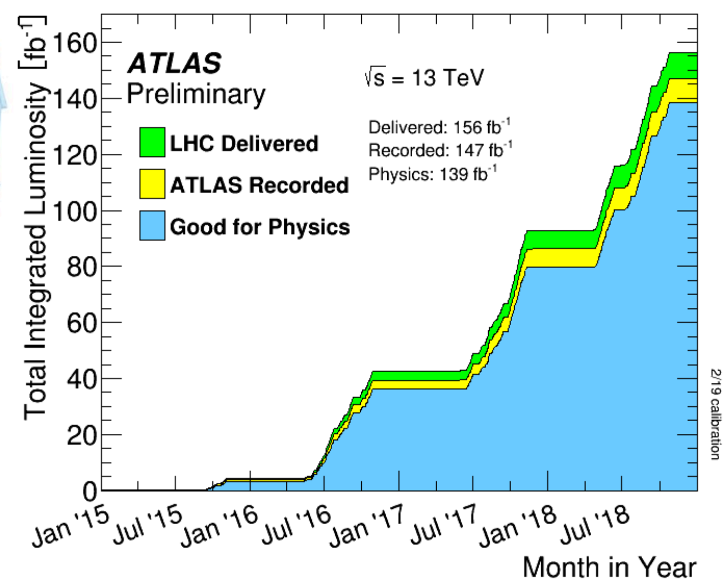
LHC operation and ATLAS detector

- General purpose detector with 4π coverage at LHC



- Run2 pp collision data-set, $\sqrt{s}$= 13 TeV.
- ~140 fb-1 used for this talk

Link to plot

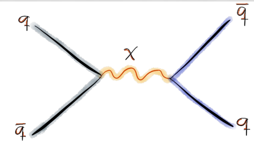


- SM is successful for particle collisions
- Discrepancies may indicate new physics ≡ new particles/fields

How to search for new particle at LHC?

Theory Models

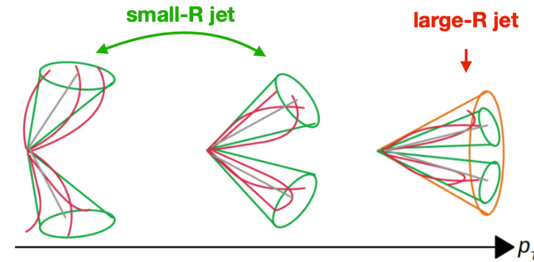
Signal Interpretation



Selection

Reconstruct Objects

E.g. Jets have different reconstruction techniques!



Signal Region definition

Select events with “X”
Veto other activity

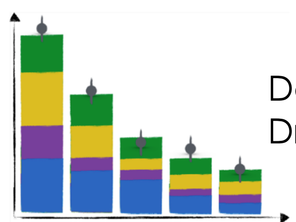
- W/Z/H and b-jets use tagging techniques
- Define discriminating variable:
  - Invariant Mass
  - Neural Network

Strategy

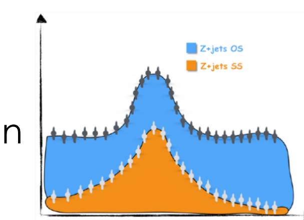
Background Estimation

Useful to define other regions (CR)

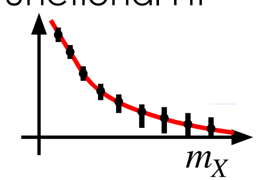
Monte Carlo



Data Driven



Functional Fit

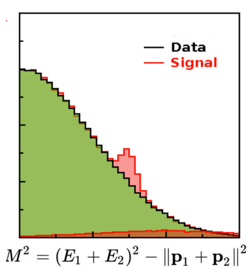


Results

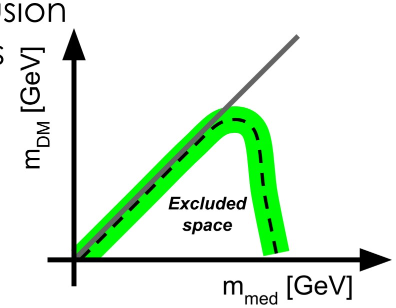
Data in Signal Regions

compare with theory expectations

Discovery

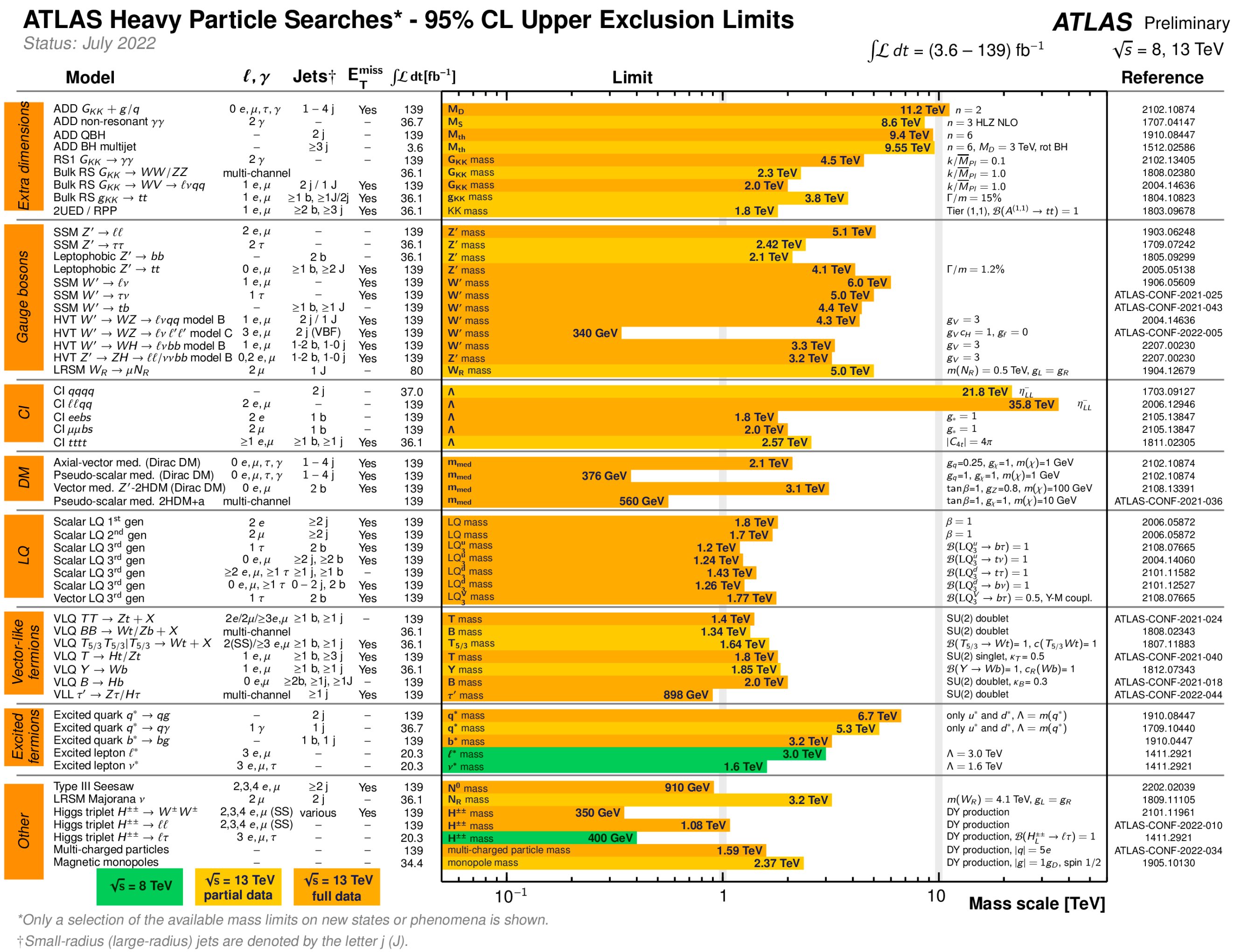


Exclusion Limits



Limits for BSM searches

[ATL-PHYS-PUB-2022-034]



- **~100 decay channels** studied for various models that predict certain production rate (extra dimensions, gauge bosons, contact interactions, dark matter, heavy quarks, excited fermions, leptoquarks, etc.)
- Commonly excluded masses **~ 0.4 – 12 TeV**
- Limits for SUSY searches here: [ATL-PHYS-PUB-2022-013] (and in bonus slides)

Some of the latest results

Using full Run 2 date-set!

Search for heavy resonances decaying into a Z or W and a Higgs boson in final states with leptons	ArXiv 2207.00230	July 2022
Combination of searches for heavy resonances	ATLAS-CONF-2022-028	May, 2022
Summary for beyond Standard Model Higgs boson benchmarks	ATL-PHYS-PUB-2022-043	Sep. 2022
Search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states	ArXiv 2211.02617	Nov. 2022 NEW
Search for new phenomena in multi-body invariant masses in events with at least one lepton and two jets	ArXiv. 2211.08945	Nov. 2022 NEW
Search for SUSY in final states with missing transverse momentum and three or more b-jets	ArXiv 2211.08028	Nov. 2022 NEW

In the bonus slides:

Search for heavy resonances in the decay channel WW→eνμν	ATLAS-CONF-2022-066	Nov. 2022 NEW
Search for resonant WZ→ℓνℓ'ℓ' production	ArXiv 2207.03925	Sep 2022
Search for Higgs boson pair production in association with a vector boson	ArXiv 2210.05415	July, 2022
Search for heavy flavour-violating Higgs bosons in multilepton plus b-jets final state	ATLAS-CONF-2022-039	June, 2022
Search for type-III seesaw heavy leptons in leptonic final states	ArXiv 2202.02039	June, 2022

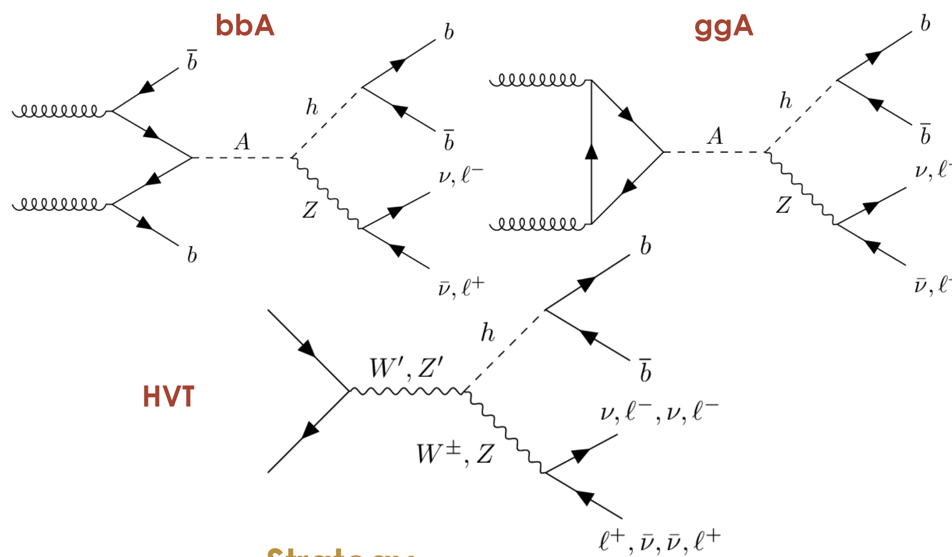
More papers and conference notes to be found in ATLAS publications page for Exotics: EXOT, Higgs/Diboson searches: HDBS, and Supersymmetry: SUSY

$A/V' \to Zh(\to bb)$: Search for heavy resonances decaying into a Z or W and a Higgs boson in final states with leptons ArXiv 2207.00230

- Search for new resonances decaying into Z or W and a SM Higgs boson
- $\nu\nu b\bar{b}$, $\ell\ell b\bar{b}$, $\ell\nu b\bar{b}$ final states

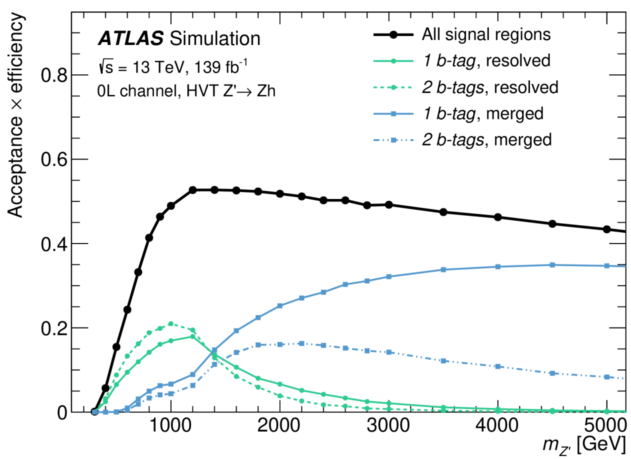
Theory Models

- Heavy CP-odd scalar boson ***A*** from a generic two Higgs Doublet Model (2HDM)
- ***Z'*** or ***W'*** from Heavy Vector Triplet (HVT)



Selection

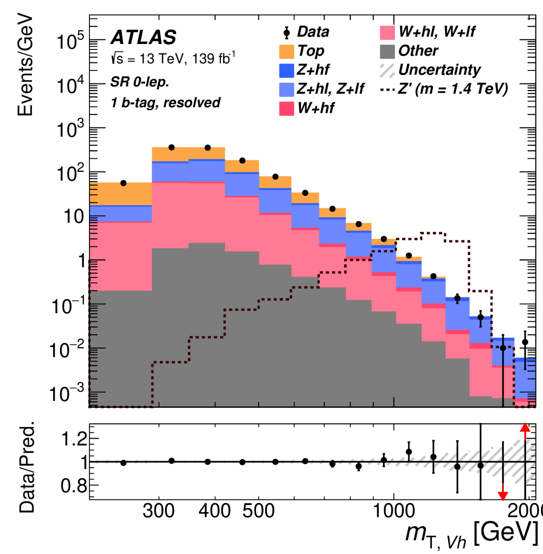
- Events with exactly 0, 1 or 2 charged leptons are selected with $E_{\mathrm{T}}^{\mathrm{miss}}$ or a combination of single-lepton triggers



- Higgs (bb) is reconstructed either as two small-R jets (resolved category) or as a single large-R jet (merged category)

Strategy

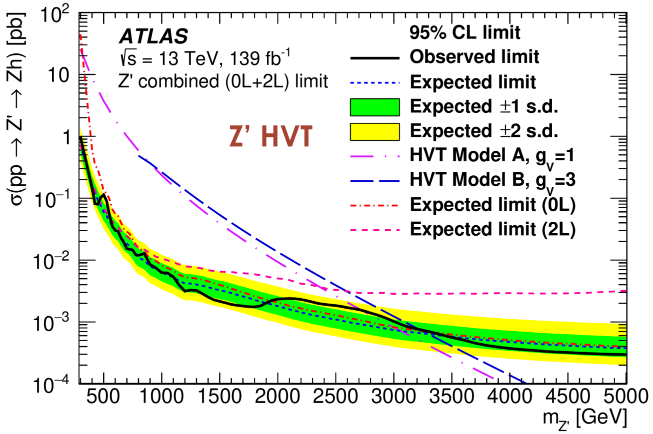
- Main discriminant: invariant or transverse mass distributions of Zh or Wh candidates

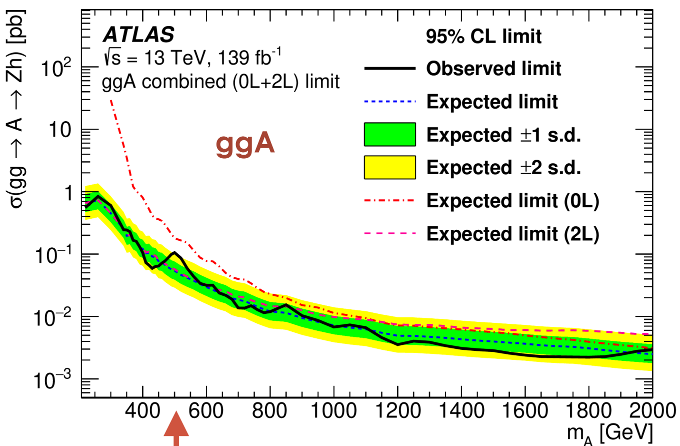


$A/V' \to Zh(\to bb)$: Search for heavy resonances decaying into a Z or W and a Higgs boson in final states with leptons

ArXiv 2207.00230

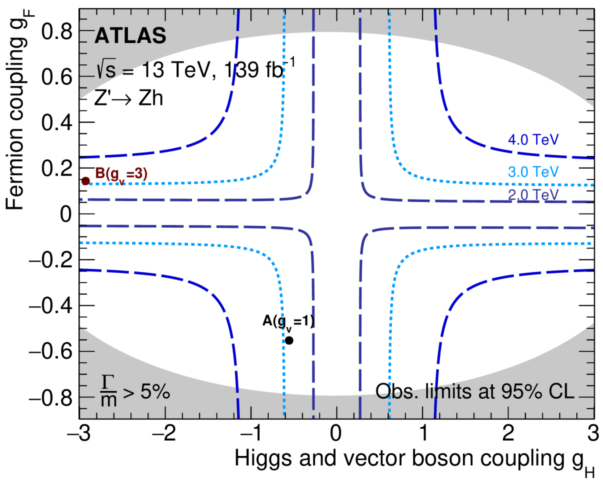
Results: Upper limit in cross-section





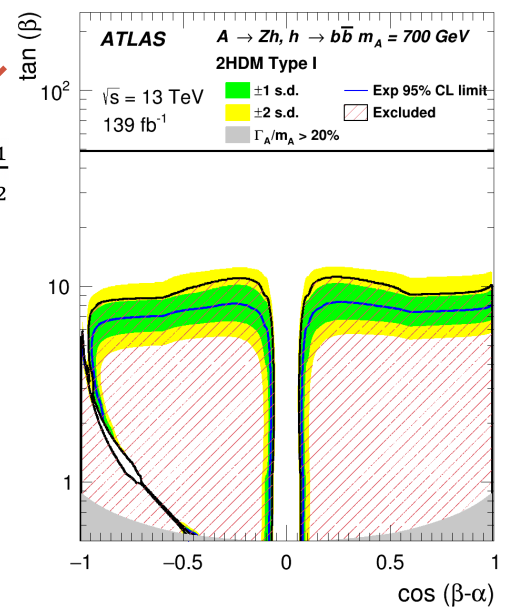
- Largest deviation is found in the **Z'** and **ggA** searches for a mass of **500 GeV** with a **local (global)** significance of **2.1 σ (1.1 σ)**

Results: Exclusion in HVT parameter space



Results: Exclusion in 2HDM parameter space

$$tan\beta \equiv \frac{v_1}{v_2}$$



Combination of searches for heavy resonances

ATLAS-CONF-2022-028

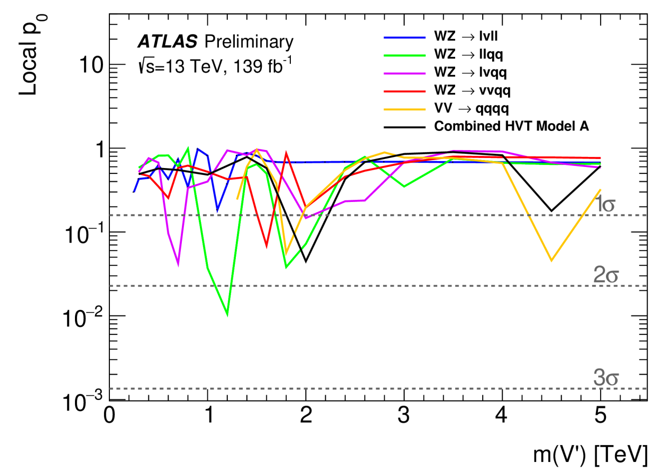
- Direct searches for new heavy resonances are a staple of the LHC physics program
- Combine 13 ATLAS publications during 2018 - 2022!
- **Final states:**
  - VV: $WZ \to qqqq$, $\nu\nu qq$, $\ell\nu qq$, $\ell\ell qq$, $\ell\nu\ell\ell$, $WW \to qqqq$,
  - VH: $WH \to qqbb$, $\ell\nu bb$, $ZH \to \nu\nu bb$, $\ell\ell bb$
  - Leptonic $\ell\ell$, $\ell\nu$, $\tau\nu$
- Analyses generally search for narrow-width resonances in the final-state mass distribution

Theory Models

- Spin-1 mass-degenerate Heavy Vector Triplet model (HVT) [arXiv: 1402.4431]
  - Leads to $W'\pm$, and Z', collectively denoted V'
  - Model A: Weakly-coupled model, couplings gH = −0.56, gf = −0.55
  - model B: Strongly-coupled model, couplings gH = −2.9, gf = 0.14

Selection

Analysis	leptons	$E_{T_{miss}}$	jets	b-tags	Discr.
$WW/WZ \to qqqq$	0	Veto	≥2J	-	m_{VV}
$WZ \to \nu\nu qq$	0	Yes	≥1J	0	m_{VV}
$WZ \to \ell\nu qq$	1e, 1μ	Yes	≥2j, ≥1J	0, 1, 2	m_{VV}
$WZ \to \ell\ell qq$	2e, 2μ	-	≥2j, ≥1J	0	m_{VV}
$WZ \to \ell\nu\ell\ell$	$3 \subset (e, \mu)$	Yes	-	0	m_{VV}
$WH \to qqbb$	0	Veto	≥2J	1, 2	m_{VH}
$ZH \to \nu\nu bb$	0	Yes	≥2j, ≥1J	1, 2	m_{VH}
$WH \to \ell\nu bb$	1e, 1μ	Yes	≥2j, ≥1J	1, 2	m_{VH}
$ZH \to \ell\ell bb$	2e, 2μ	Veto	≥2j, ≥1J	1, 2	m_{VH}
$\ell\nu$	1e, 1μ	Yes	-	-	m_T
$\tau\nu$	1τ	Yes	-	-	m_T
$\ell\ell$	≥2e, ≥2μ	-	-	-	$m_{\ell\ell}$



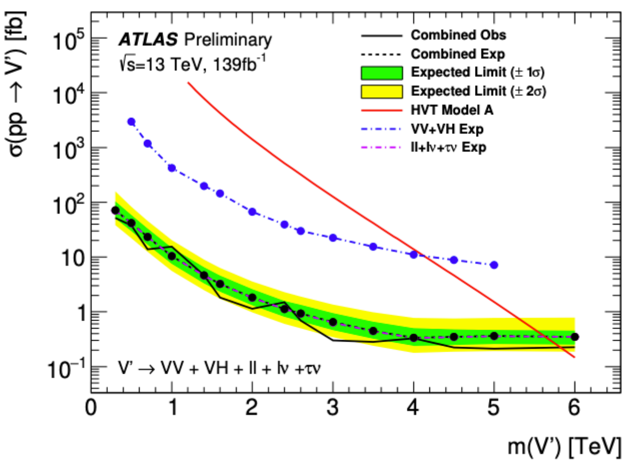
Typical example of p-value scan over the HVT pole masses up to 5 TeV

Combination of searches for heavy resonances

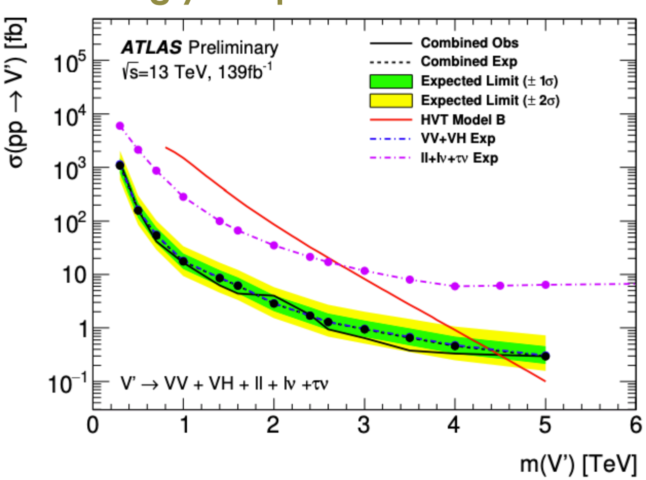
ATLAS-CONF-2022-028

Results interpreted in terms of exclusions limits on masses and coupling constants

Weakly coupled HVT Model A

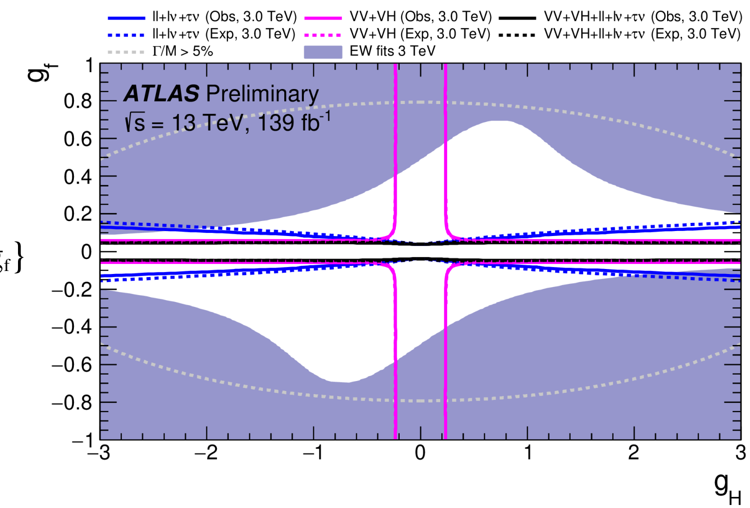


Strongly coupled HVT Model B



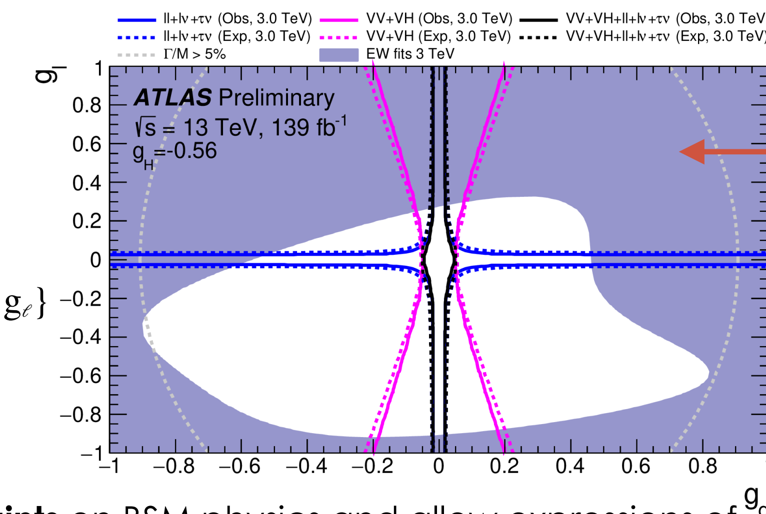
Exclusions for 3 TeV pole mass

$\{g_H, g_f\}$



- VV+VH
- $\ell\ell+\ell\nu+\tau\nu$
- VV+VH+ $\ell\ell+\ell\nu+\tau\nu$

$\{g_q, g_\ell\}$



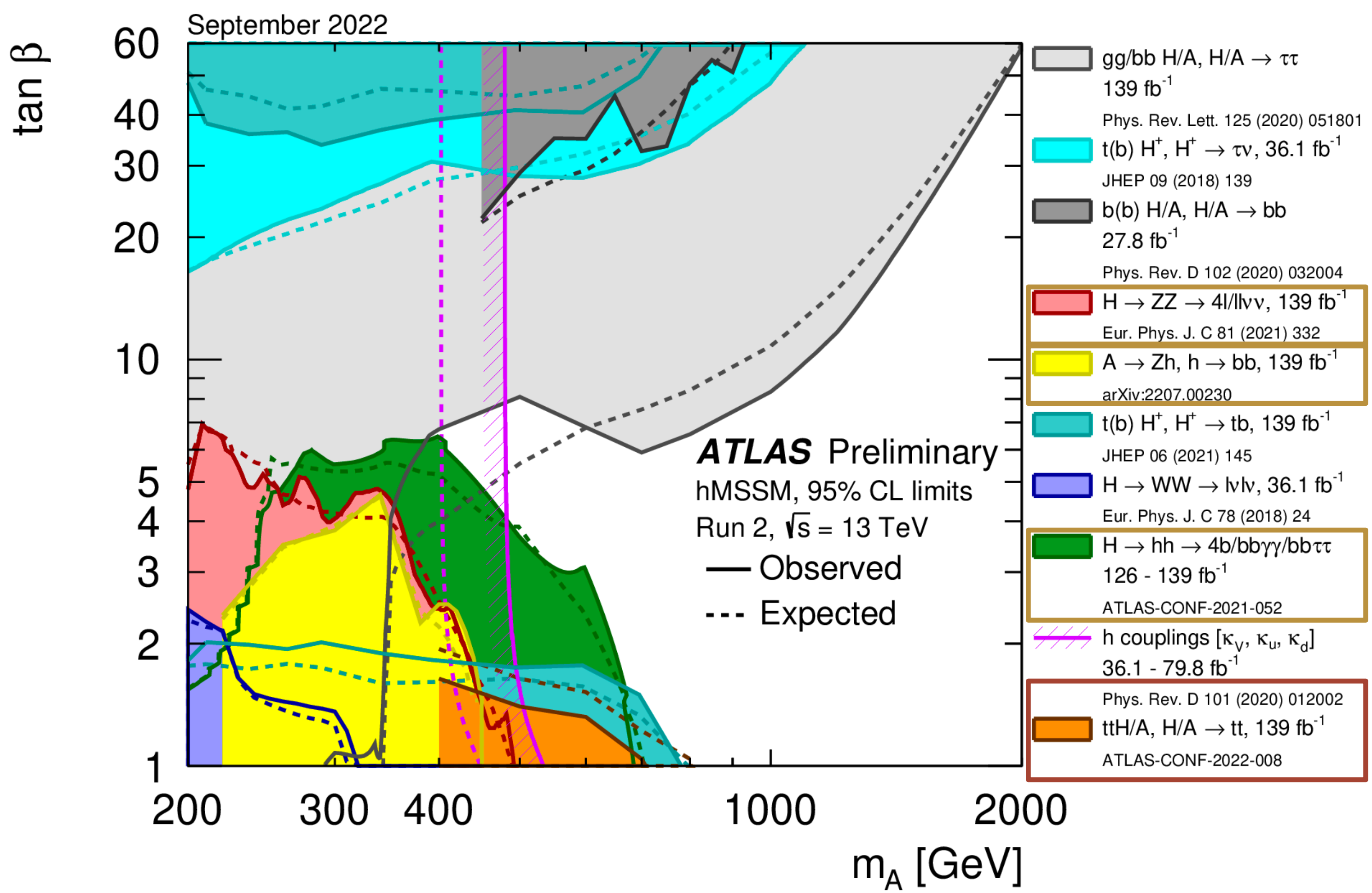
Constraints from EWK measurements

Combined results strengthen the **constraints** on BSM physics and allow expressions of constraints in terms of couplings to quarks, leptons and fermions

Summary for beyond Standard Model Higgs boson benchmarks

ATL-PHYS-PUB-2022-043

- Benchmark scenario for the **Minimal Supersymmetric Standard Model** (MSSM) Higgs sector.



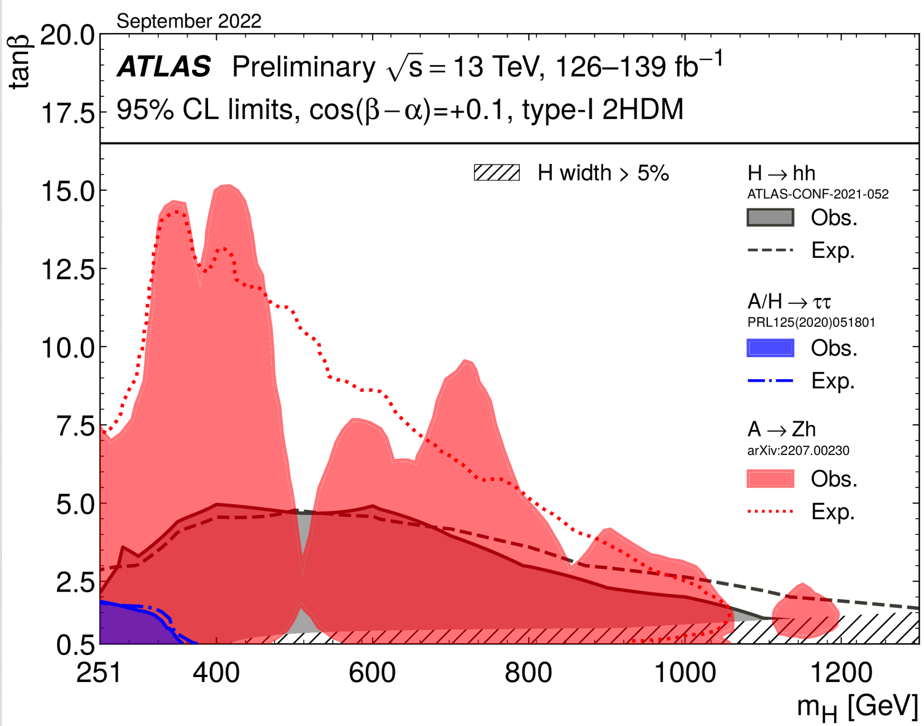
Updated

Newly added

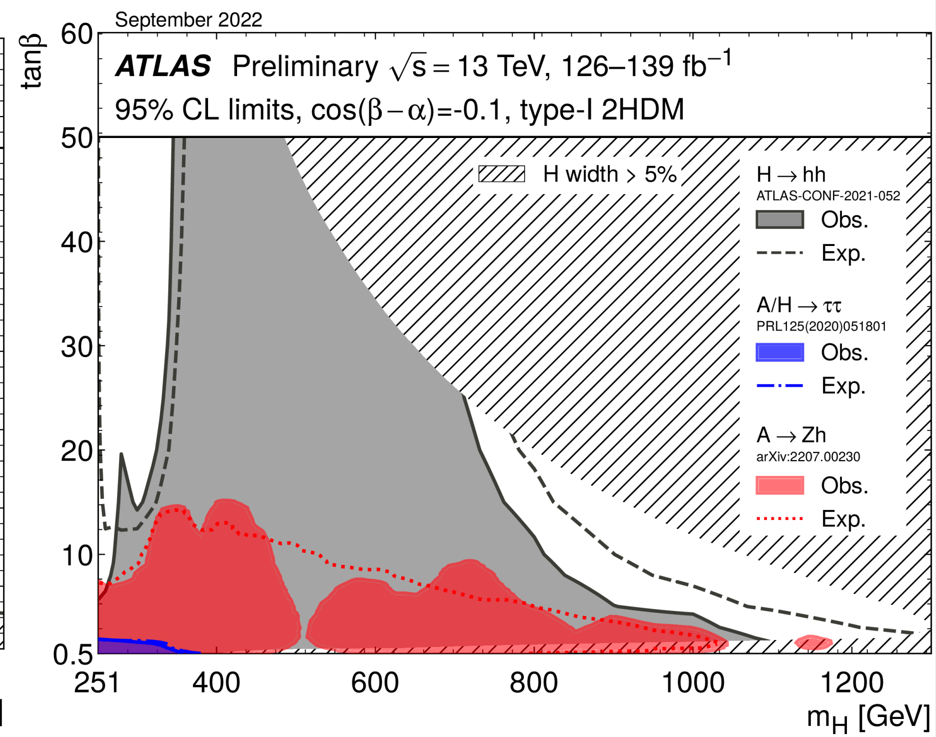
Summary for beyond Standard Model Higgs boson benchmarks

ATL-PHYS-PUB-2022-043

- Benchmark scenario of type-I **2HDM**
  - assumptions: $m_H = m_A = m_{H^\pm}, m_h = 125\ \mathrm{GeV}, m_{12}^2 = m_A^2 \sin\beta\cos\beta$
- Assume a narrow width (< 5%) Higgs boson.



cos(β–α) = +0.1



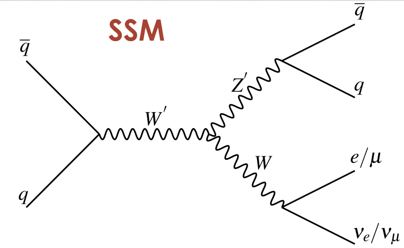
cos(β–α) = -0.1

Search for new phenomena in multi-body invariant masses in events with at least one lepton and two jets

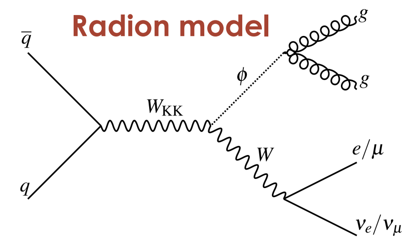
ArXiv. 2211.08945

- Final state signature sensitive to new particles that are
  - Produced in association with a W/Z boson
  - Decays to produce a W/Z boson or lepton along with another particle that decays to two jets
- Searches $jj\ell$, $jj\ell\ell$, $jb\ell$ and $bb\ell$ channels

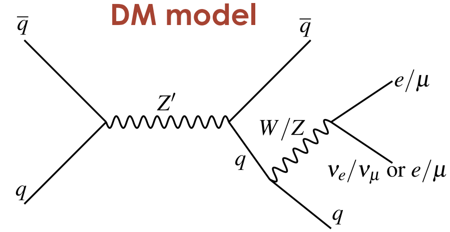
SSM



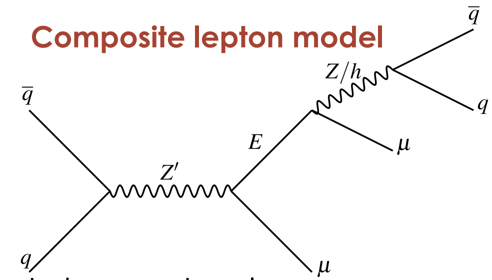
Radion model



DM model



Composite lepton model



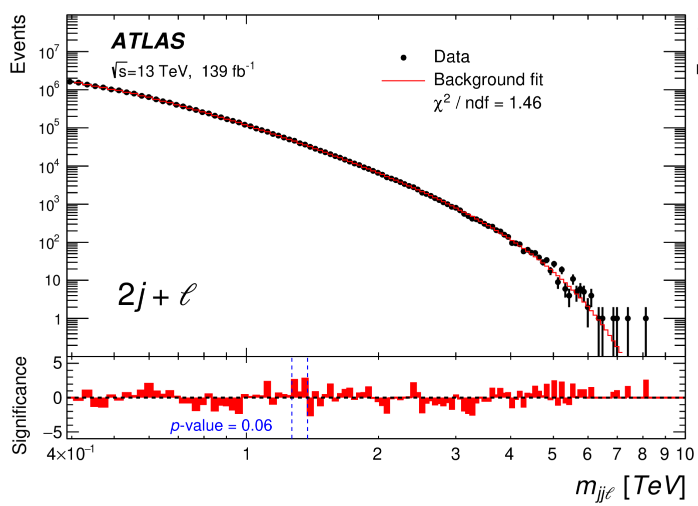
Theory Models

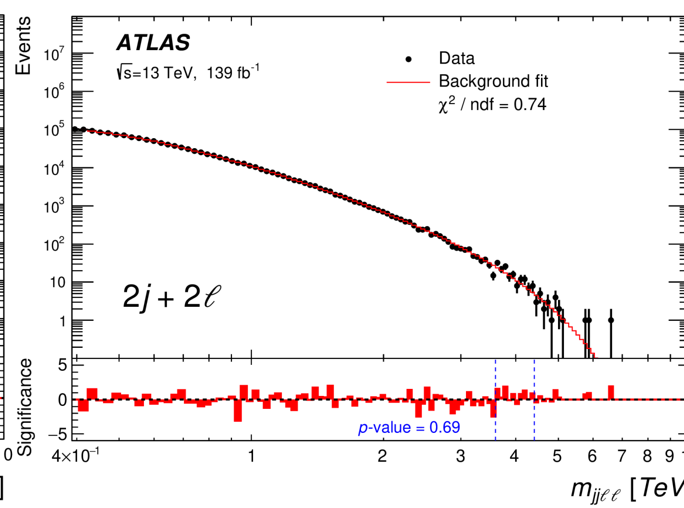
- Sequential Standard Model, SSM
  - Includes new heavy gauge bosons W' and Z'
- Simplified dark matter model with a Z' mediator
- Radion model that includes Kaluza-Klein gauge bosons coupling to a radion that decays to gluons
- Composite lepton model contains two composite SU(2) fermion doublets that mix to create a new vector boson (Z') and lepton (E)

Strategy

- Search for an observable excess of events in multi-body invariant masses ($m_{jj\ell}$, $m_{jj\ell\ell}$) on a smooth, decreasing fitted background.

Results



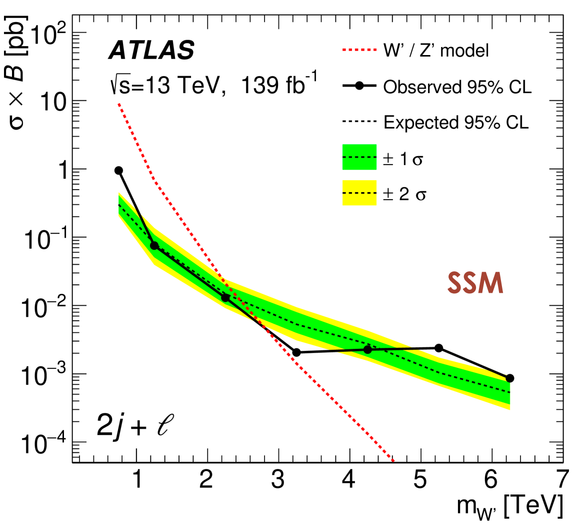


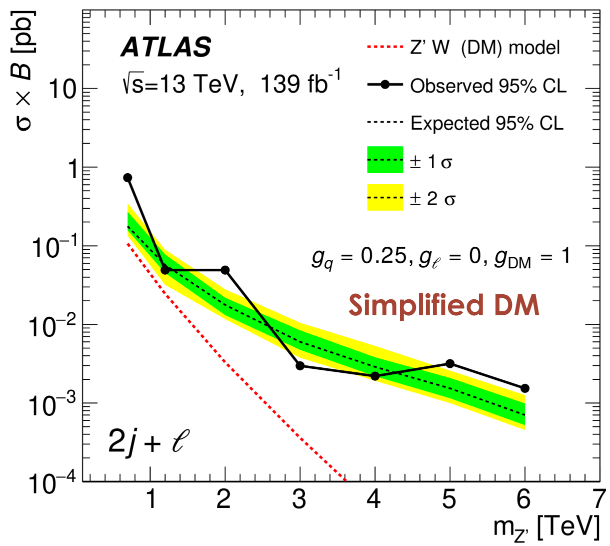
Search for new phenomena in multi-body invariant masses in events with at least one lepton and two jets

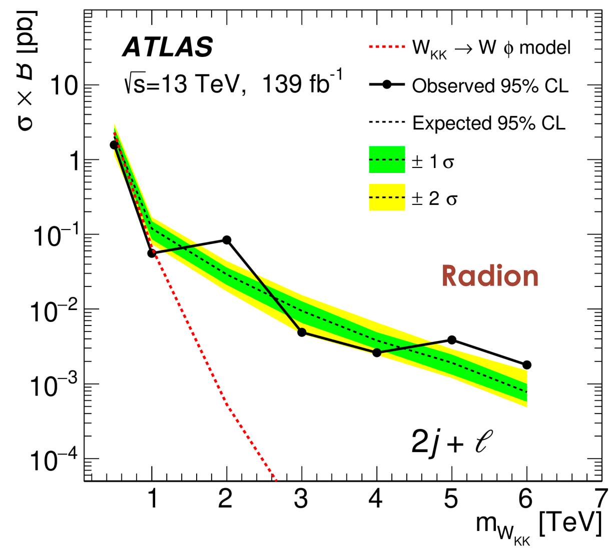
NEW

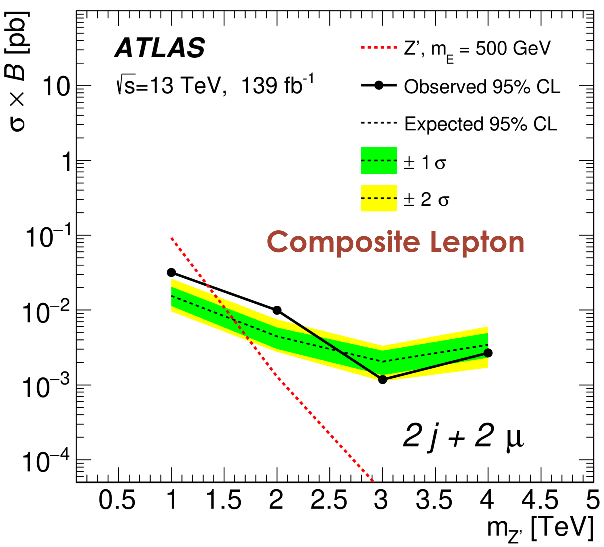
ArXiv. 2211.08945

Results: Limits







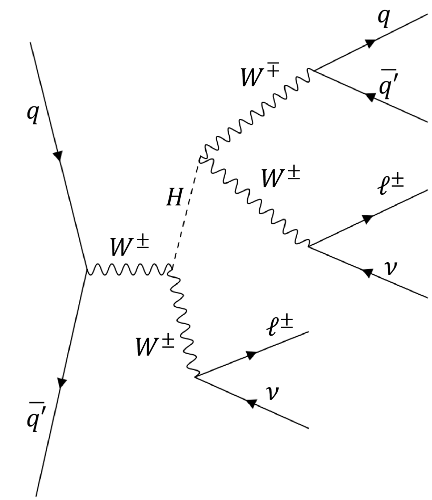


- Able to exclude SSM up to ~2.5 TeV, unable to exclude simplified DM model, and no clear exclusion limit for Radion models
- Able to exclude Z' at ~1.3 TeV for mE = 250 and 500 GeV on composite lepton model

WH(→WW): Search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states

NEW

ArXiv 2211.02617



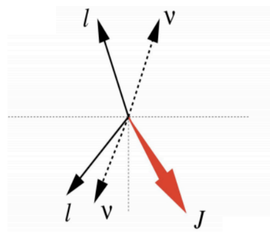
Theory Models

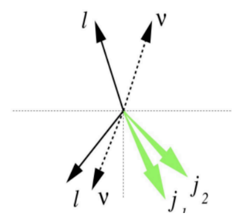
- No hint for CP even heavy Higgs from previous searches at LHC
- Search with higher dimensional operator: **Dim-6 in EFT** [PLB 804 (2020) 135358]
  - Contains a heavy Higgs H
  - Free parameters: Anomalous couplings to vector bosons (fw, fww) and mH

Selection

- Considering associated production of heavy scalar (H) with W
- Two same-sign leptons in **boosted (+W tagger)** and **resolved** categories

WH(WW)

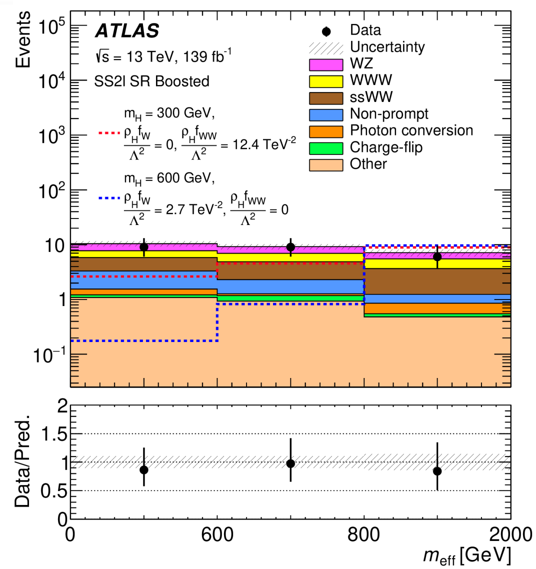


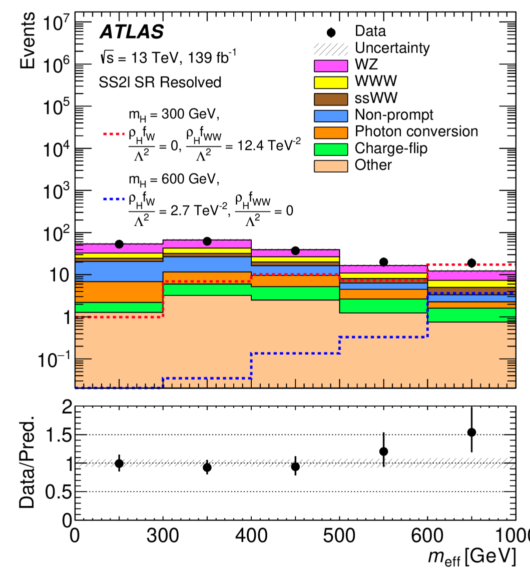


Strategy

- Final Observable:

$$M_{\text{eff}} = \sum p_{\text{T}}^{\text{lepton}} + \sum p_{\text{T}}^{\text{jets}} + E_{\text{T}}^{\text{miss}}$$



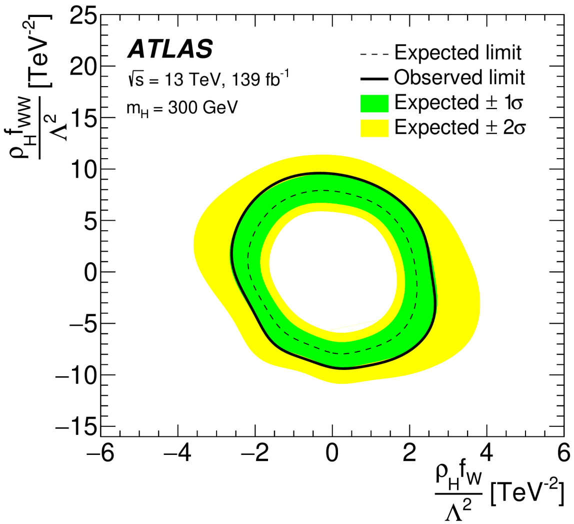


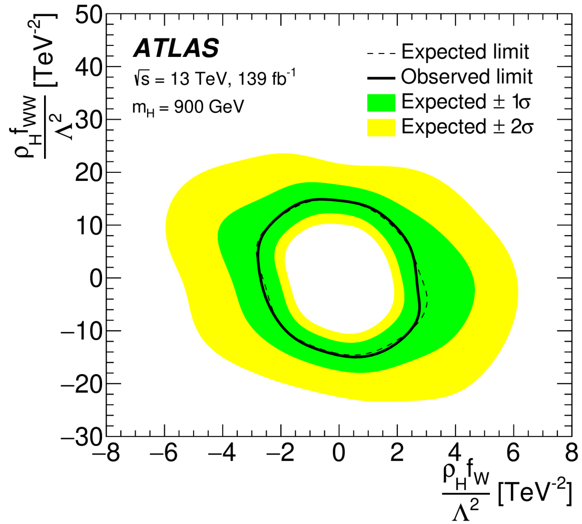
WH(→WW): Search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states

NEW

ArXiv 2211.02617

Results: Exclusion contours

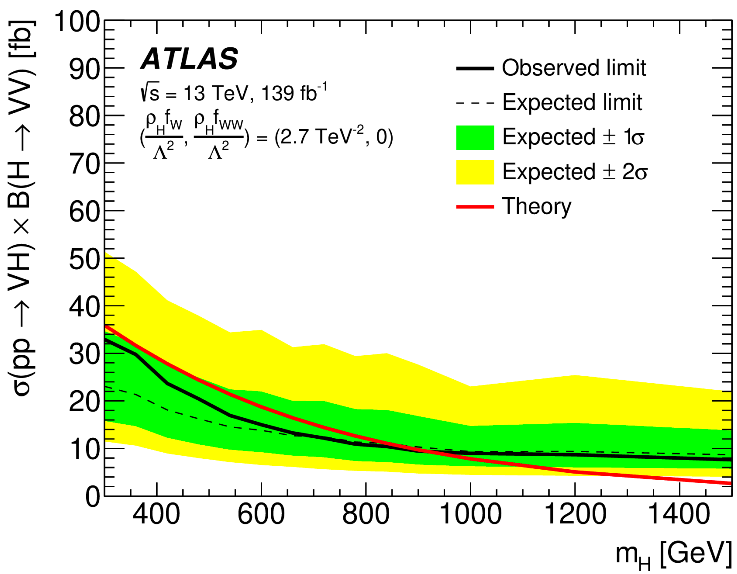




Exclusion

- For $m_H = 300$ GeV: $|\frac{\rho_H f_W}{\Lambda^2}| > 2.7$ and $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 10$
- For $m_H = 900$ GeV: $|\frac{\rho_H f_W}{\Lambda^2}| > 2.9$ and $|\frac{\rho_H f_{WW}}{\Lambda^2}| > 15$

Results: Upper limit



$m_H < 900$ GeV excluded

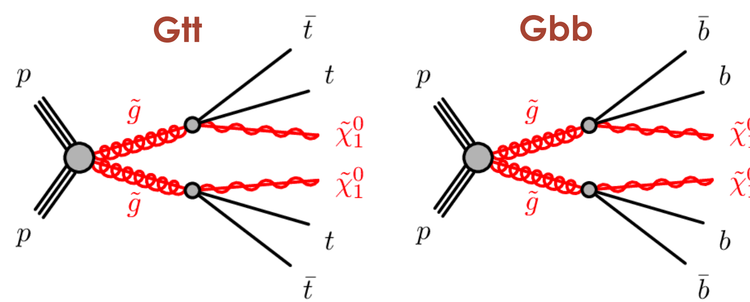
Search for SUSY in final states with missing transverse momentum and three or more *b*-jets

NEW

ArXiv 2211.08028

Theory Model

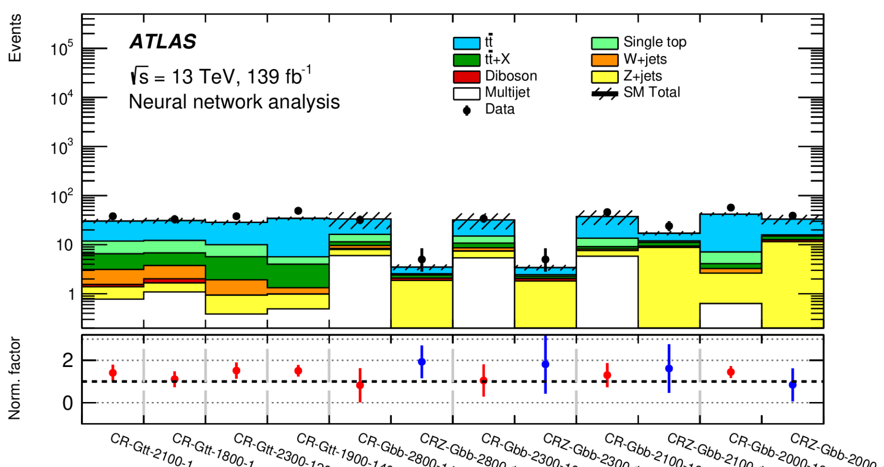
- Search for stops, sbottoms and neutralinos in pair-produced gluino events
- Lightest Stable Particle: $\tilde{\chi}_1^0$
- **Gtt/Gbb**: Simplified models with off-shell stops and sbottoms



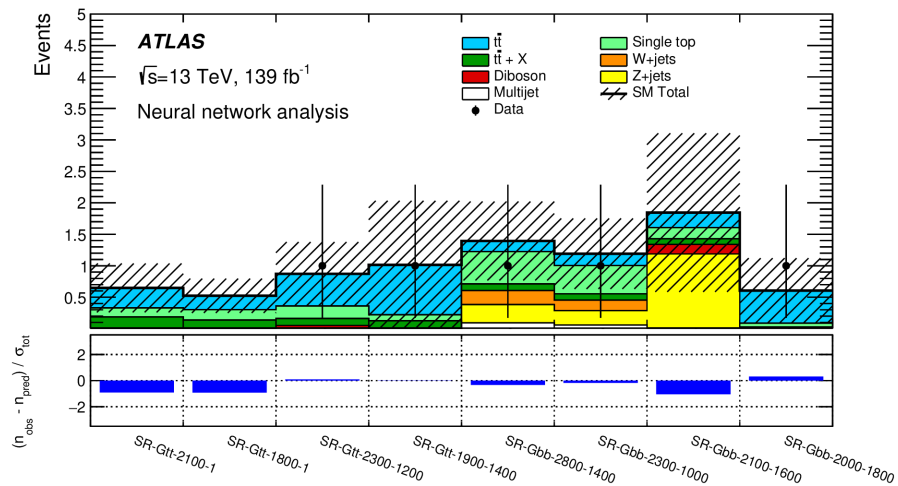
Strategy

- Targeting final states with large amount of MET and many b-jets
- Neural Network (NN) trained on four-vector inputs
  - NN defines the probability of an event to be a Gtt or a Gbb
  - Maximise model-dependent sensitivity to models
- **Gbb**: 4 Signal Regions, 4 Control Regions (CRs) to constraint ttbar & 4 CR for Z+Jets
- **Gtt**: 4 Signal Regions, 4 CRs to constraint ttbar

Control Regions (CRs)



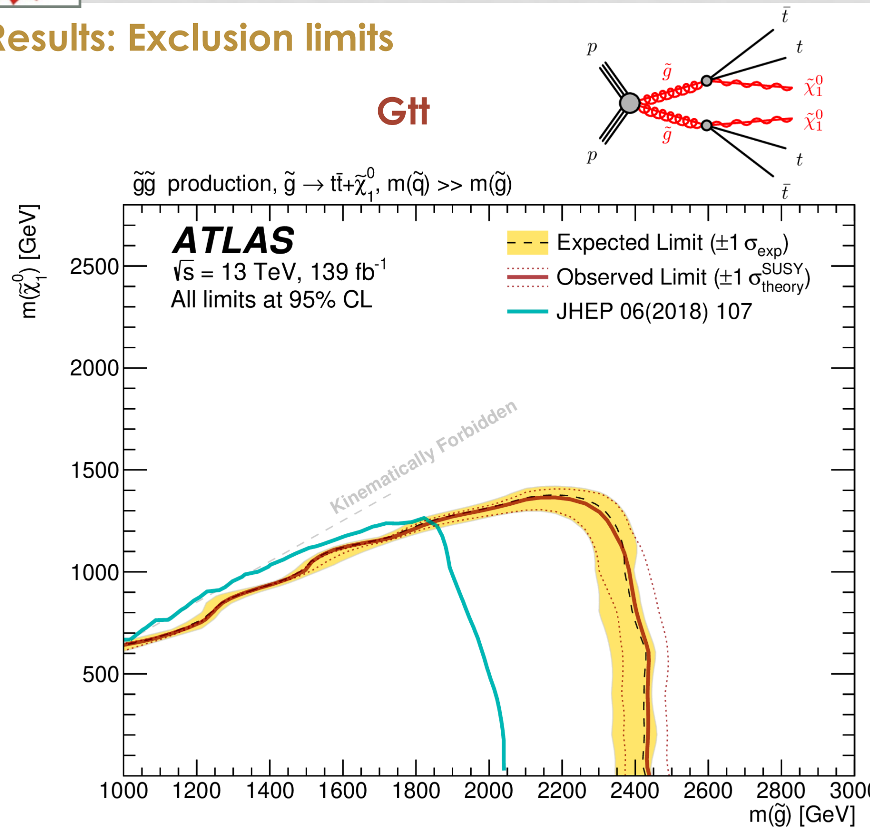
Signal Regions (SRs)

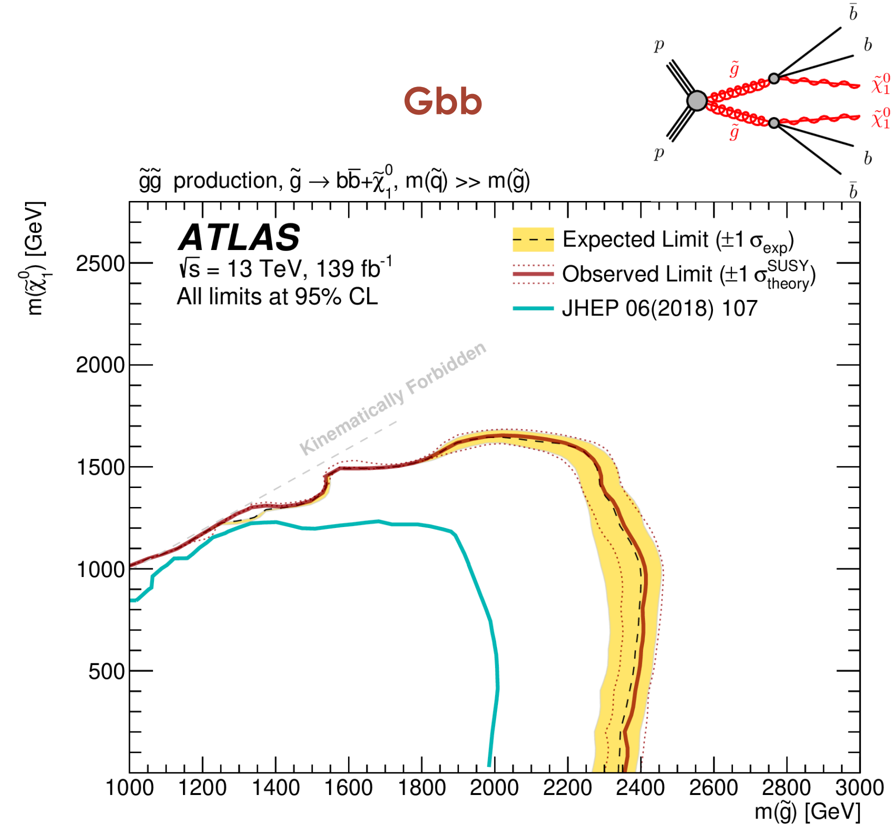


Search for SUSY in final states with missing transverse momentum and three or more *b*-jets

ArXiv 2211.08028

Results: Exclusion limits





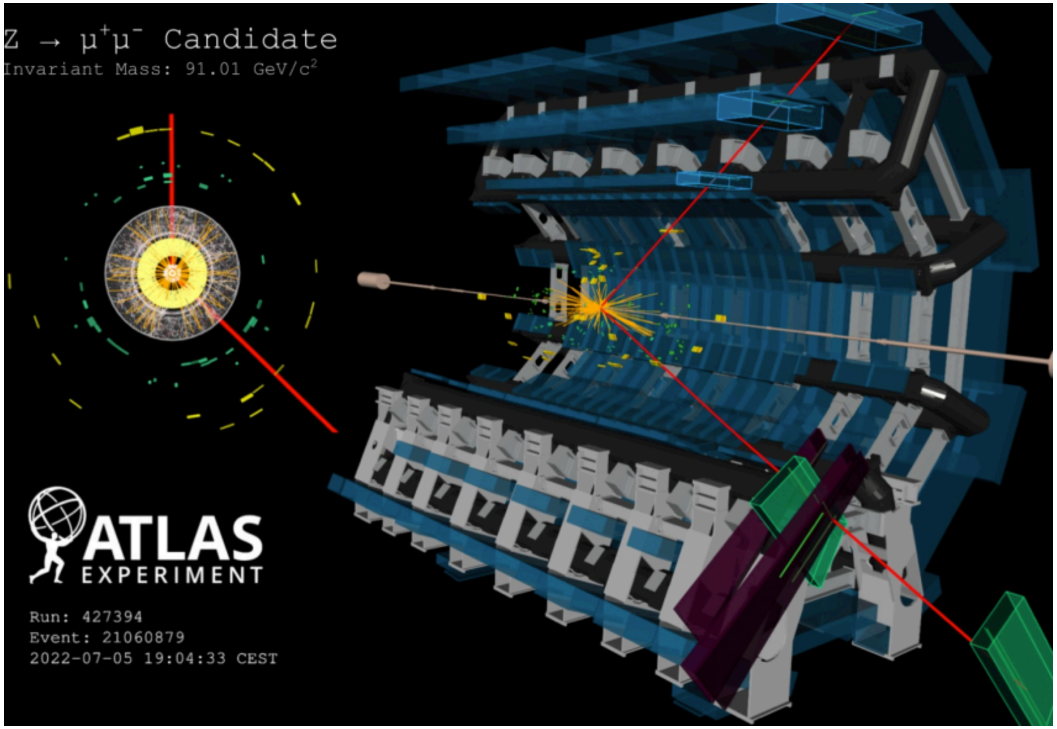
- Gluinos with masses below 2.44 TeV (2.35 TeV) are excluded at 95% CL for massless neutralinos in the Gtt (Gbb) models.
- These limits represent a substantial increase in over previous ATLAS analysis!

- A cut-and count analysis was also performed considering the processes where both gluinos can have different decays in a event (Gtb) in combination of Gbb and Gtt processes. Exclusion limits for gluino branching ratios to $b\bar{b}\tilde{\chi}_1^0$, $t\bar{t}\tilde{\chi}_1^0$ and $t\bar{b}\tilde{\chi}_1^-$, $\bar{t}b\tilde{\chi}_1^+$.

Conclusions

- ATLAS continues exploring the energy frontier: Extensive program for searches for new heavy particles!
- No evidence yet but no shortage of models predicting exotic heavy particles
- Strong constraints have been placed on the production of such new heavy particles and on BSM parameter space.
- More results with full Run 2 data are still being released.

- Run 3 already started!
- Opportunities at Run 3:
  - 13 TeV → 13.6 TeV CM energy
  - Increase in luminosity (x 2, statistics!)
  - Cutting edge analysis techniques

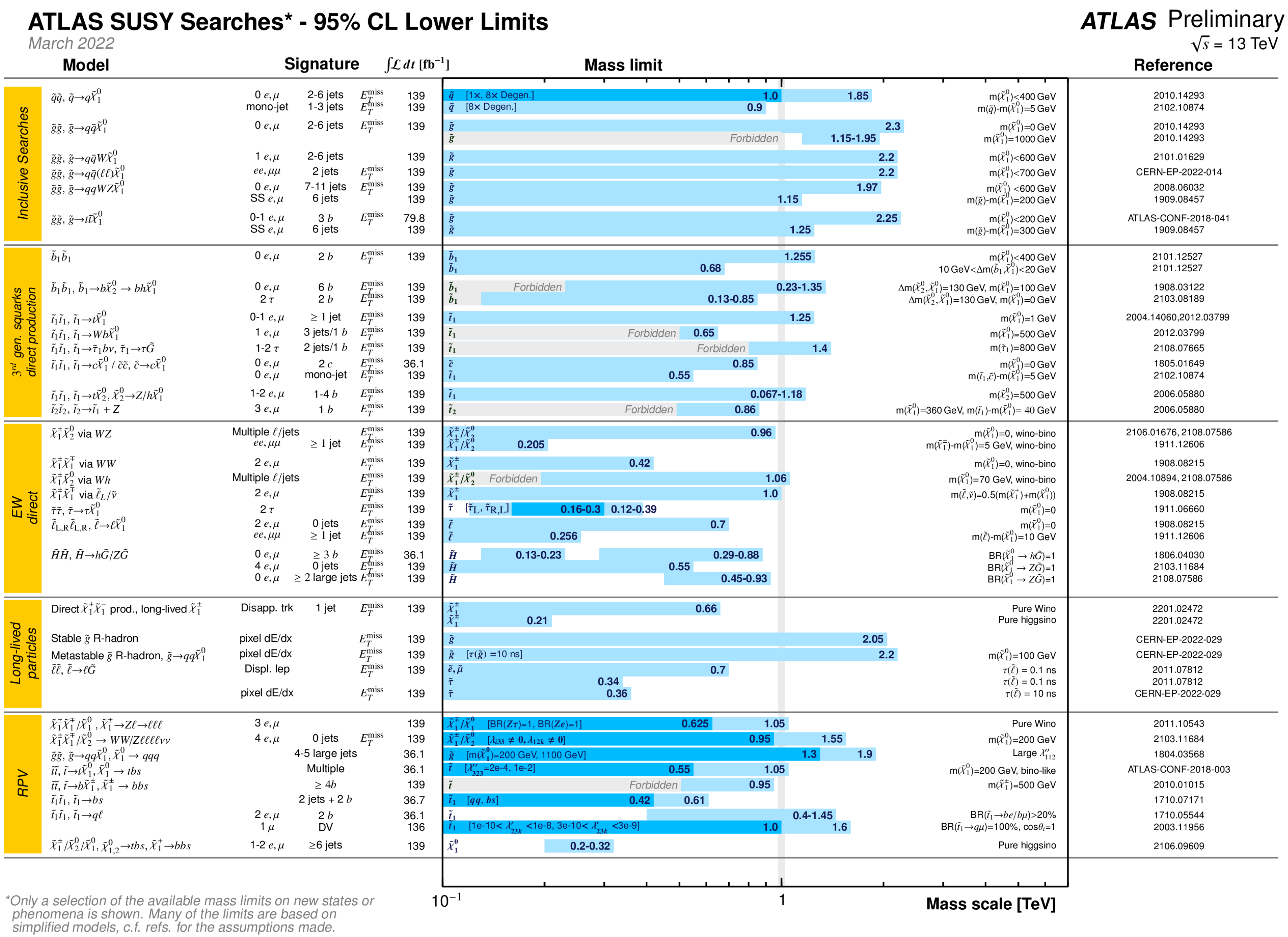


Thank you!

OTHER RESULTS

Limits for SUSY searches

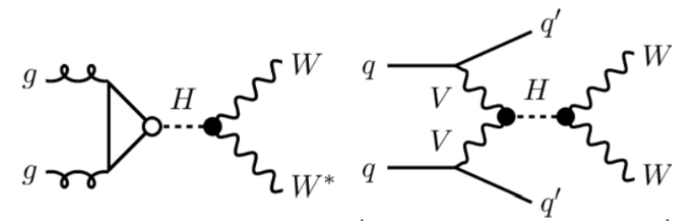
ATL-PHYS-PUB-2022-013



Search for heavy resonances in the decay channel WW→eνμν

ATLAS-CONF-2022-066

- Search for the neutral heavy resonances, e.g. heavy CP even Higgs (ggF + VBF) and neutral GM Higgs (VBF)



Interpretations

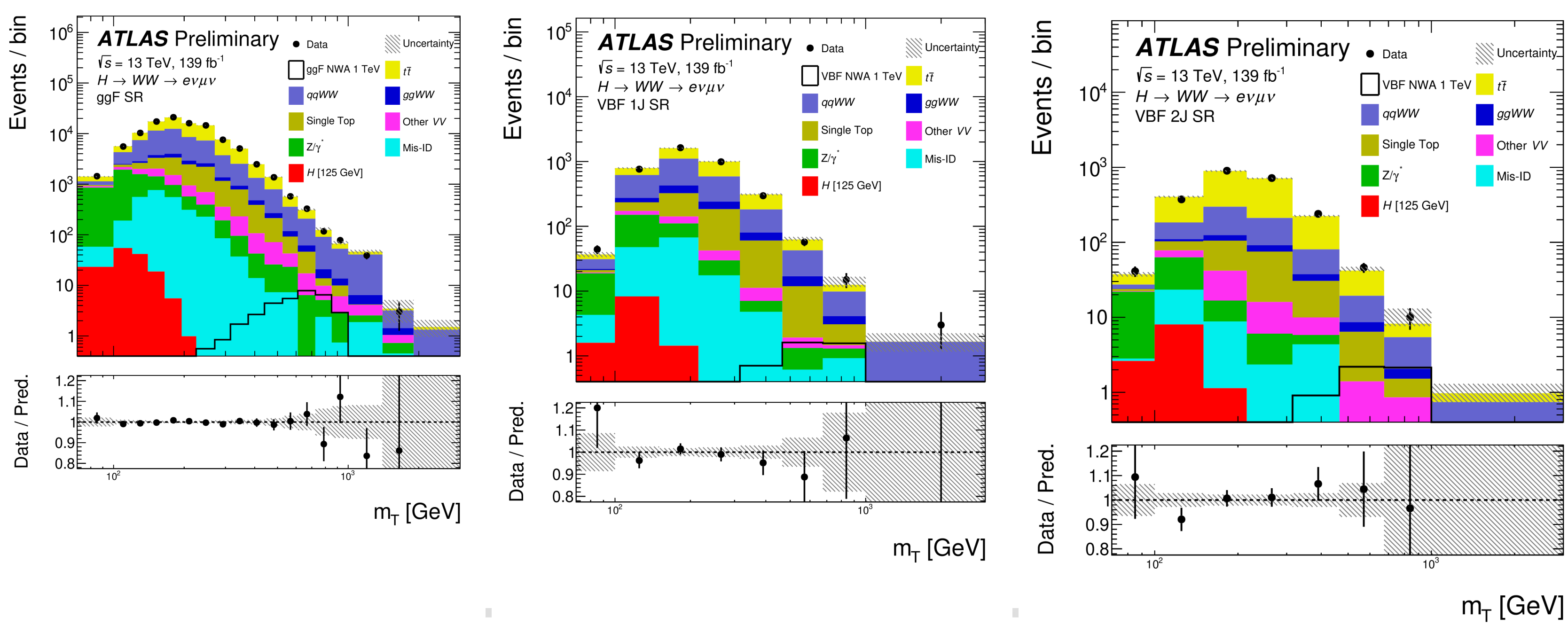
- Interpreted in 5 models
- GM
- 2HDM
- HVT
- Radion in Randall-Sundrum model
- Spin-2 graviton

Selection

- 3 signal categories (ggF, VBF+1jet, VBF+2jets)

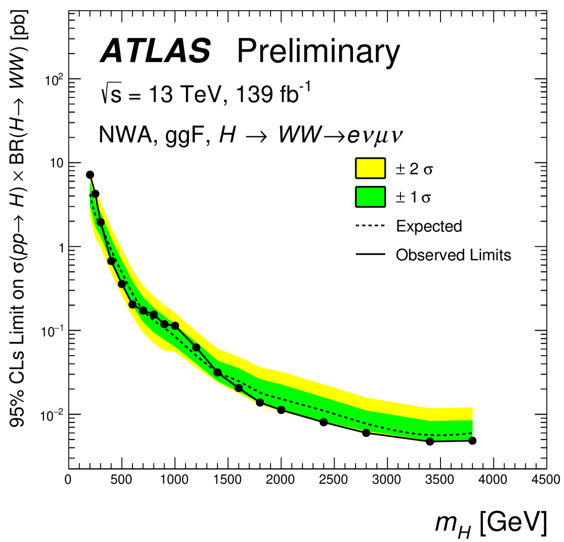
Strategy

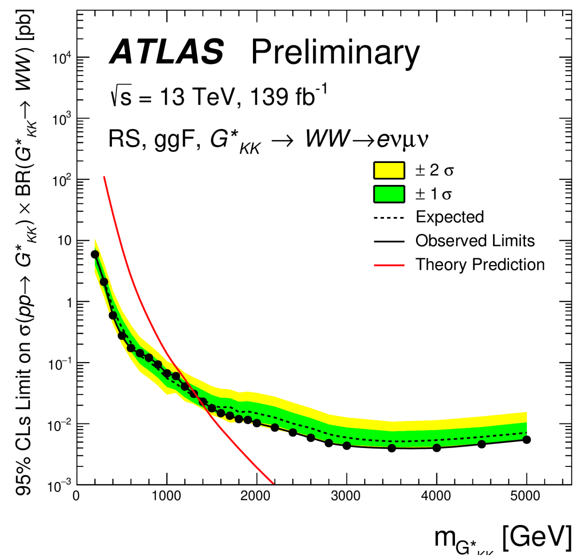
- Discriminating variable: $m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\text{miss}}|^2}$

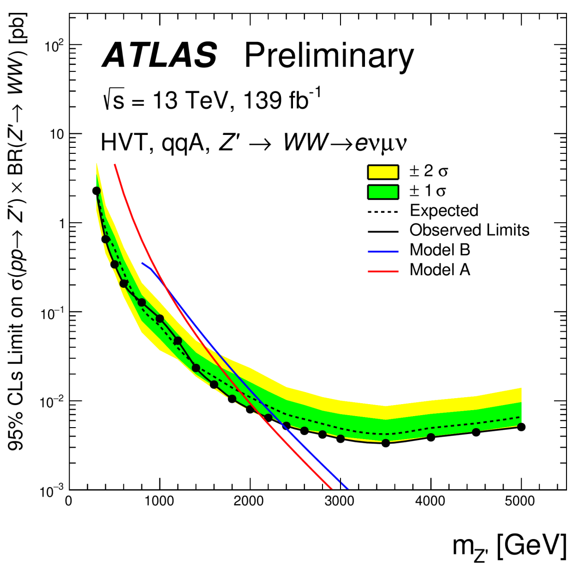


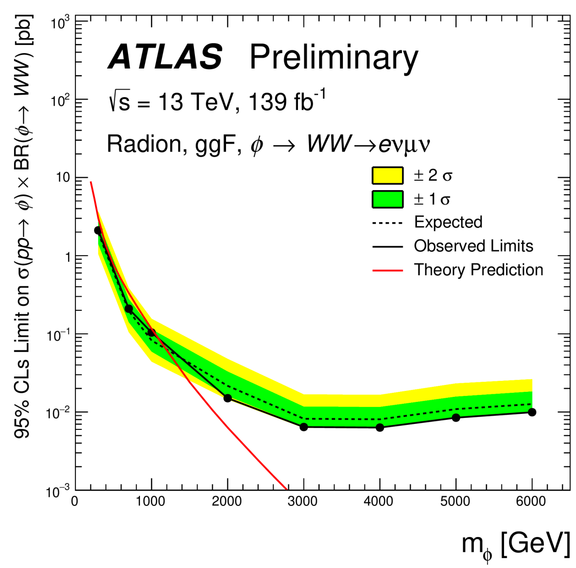
Search for heavy resonances in the decay channel WW→eνμν

ATLAS-CONF-2022-066









$H\pm \rightarrow WZ \rightarrow l\nu l'l'$: Search for resonant WZ→ℓνℓ′ℓ′ production

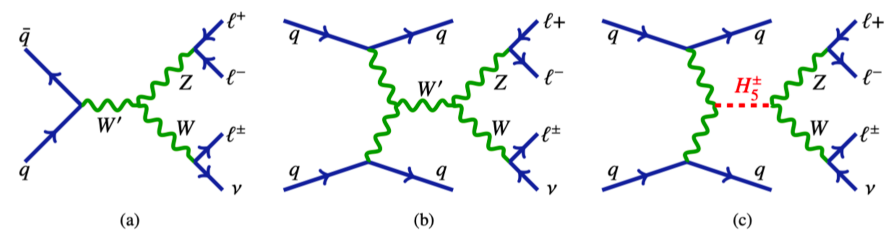
ArXiv 2207.03925

- Search for a WZ resonance in the fully leptonic final state

Interpretation

- Heavy vector triplet model HVT
- Georgi–Machacek (GM) fermiophobic charged Higgs boson from the fiveplet: $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$

Drell-Yan **Vector Boson Fusion (VBF)**

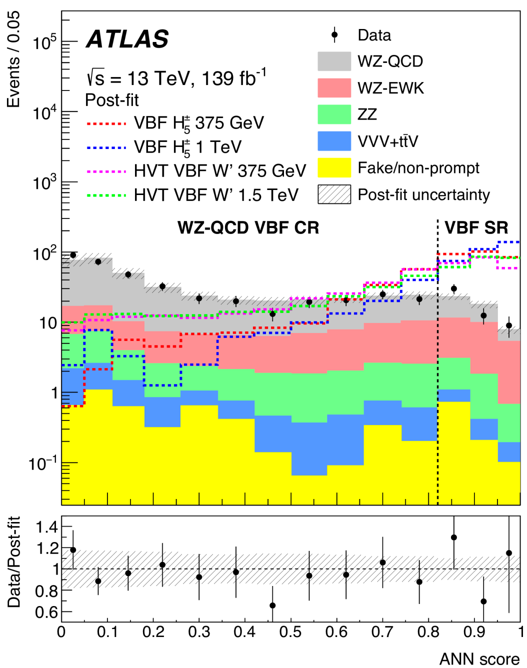


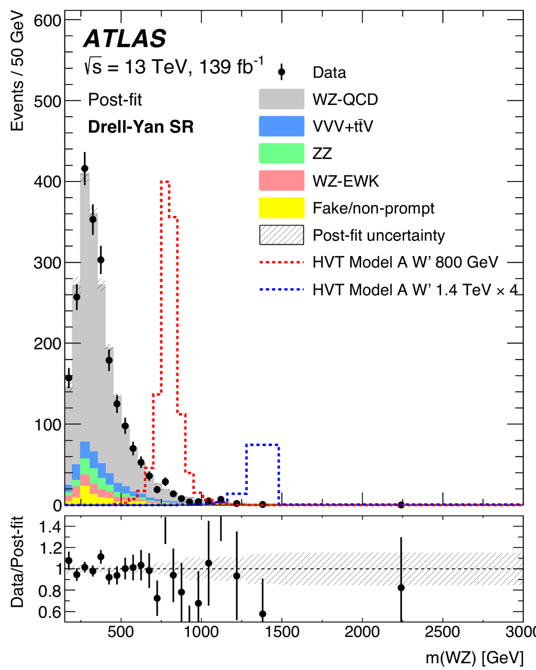
Selection

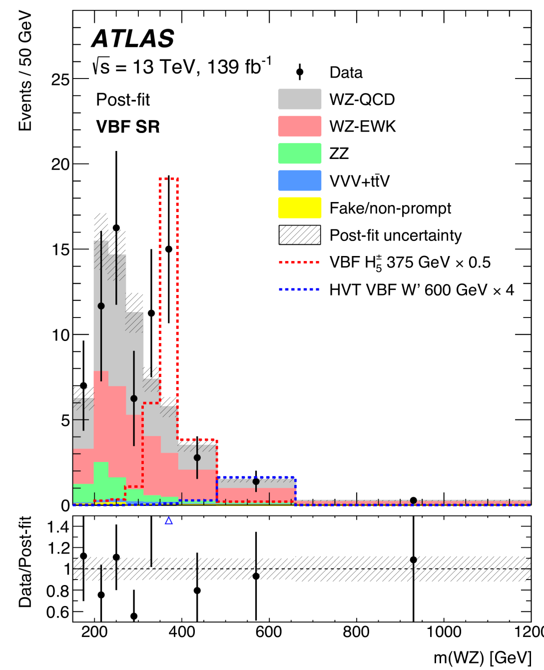
- 2 signal regions: Drell-Yan and VBF

Strategy

- VBF category: NN is adopted to enhance signal
- Drell-Yan category: Selected using pT/m(WZ)





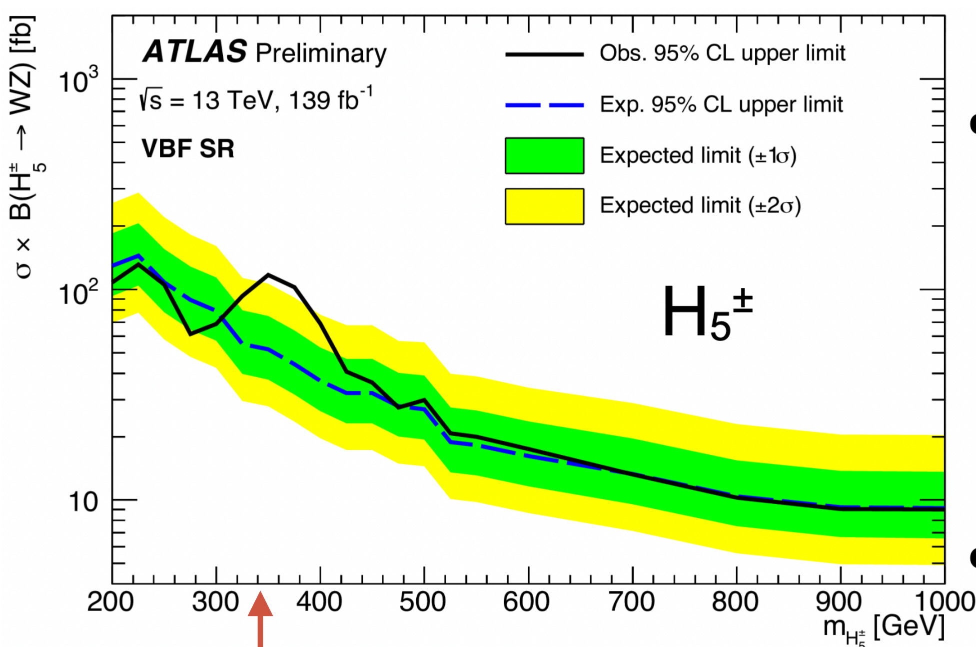


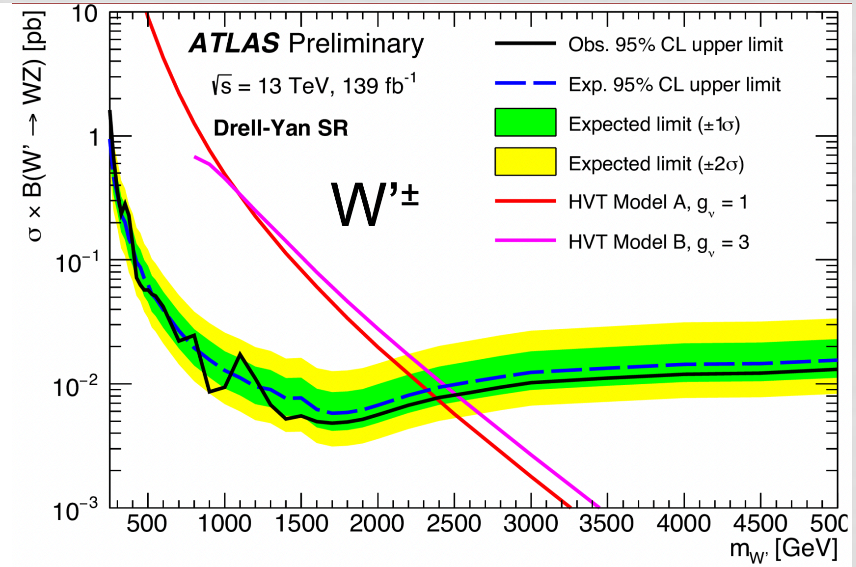
H±→WZ→lνl′l′: Search for resonant WZ→ℓνℓ′ℓ′ production

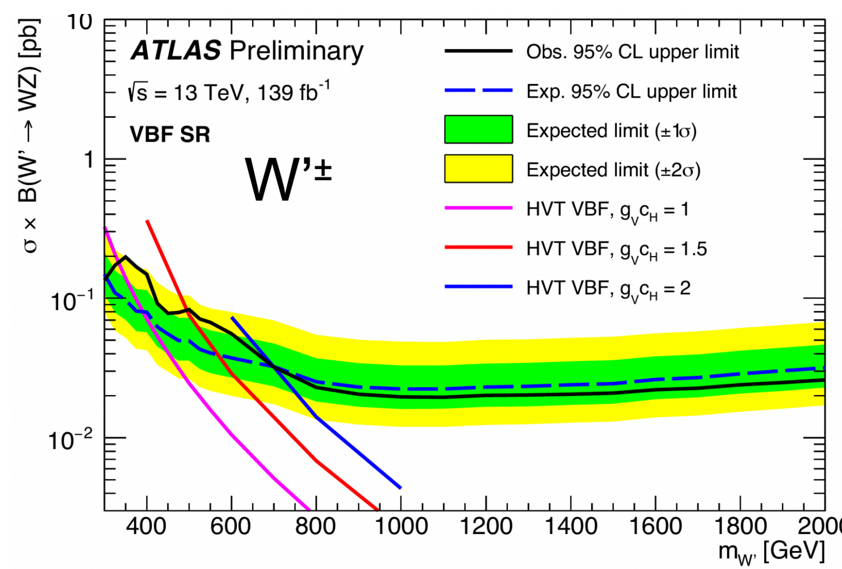
ArXiv 2207.03925

Results

- Limits set on
  - HVT model A,B
  - Fermiophobic HVT model
  - GM model H5±







- VBF Signal Region excess at 375 GeV < 1.6σ (2.8σ local)

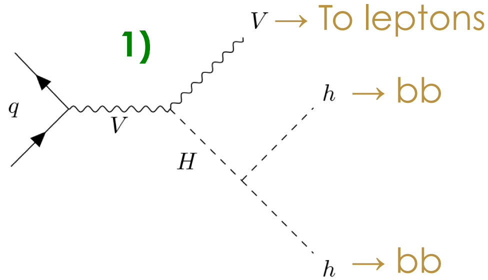
VH(→hh): Search for Higgs boson pair production in association with a vector boson

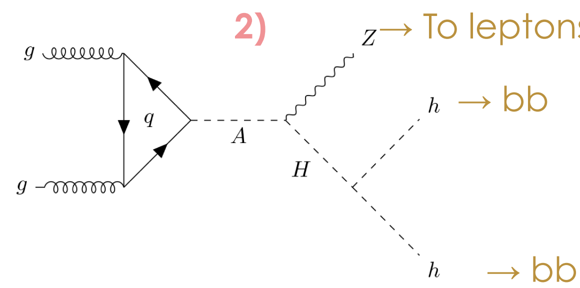
ArXiv:2210.05415

- Search for a neutral heavy CP-even scalar H→hh→bbbb in association with a vector boson (W/Z)
- First analysis targeting Vhh final state.

Interpretation

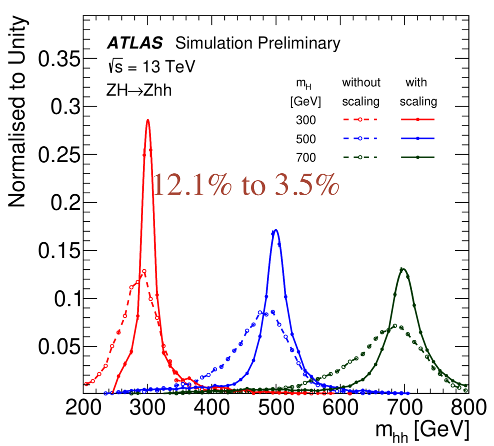
- Two signal scenarios are considered:
  1) Generic neutral CP-even scalar H
  2) CP-odd scalar A decaying into Z and a CP-even scalar H





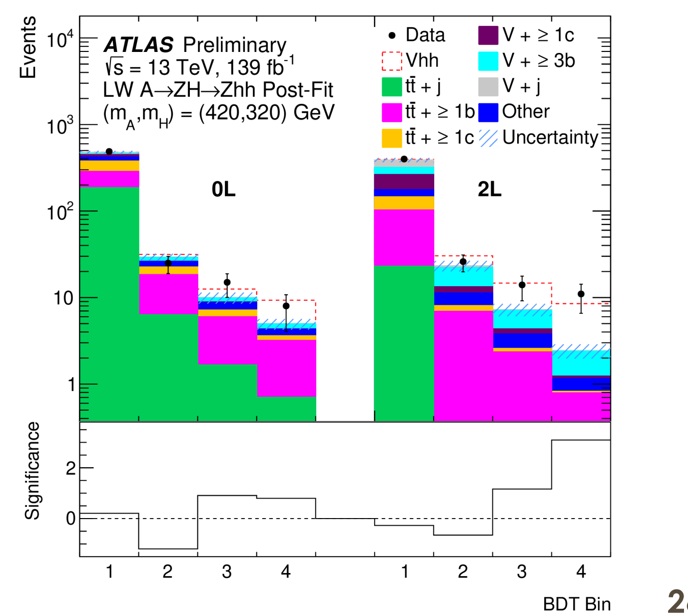
Selection

- Three leptonic channels (0L, 1L, 2L) targeting vvbbbb, lvbbbb, llbbbb final states
- Invariant mass resolution improved by scaling the b-jet momenta with the ratio of the measured di-b-jet mass to 125 GeV.
- The relative mass resolution improves by a factor of ~3!



Strategy

- BDTs used as final discriminants trained with jets kinematic information in each SR

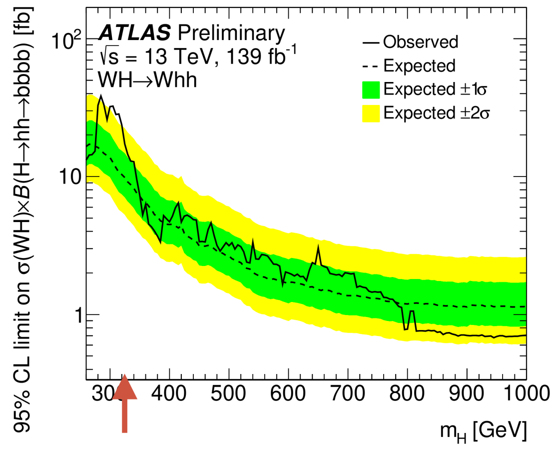


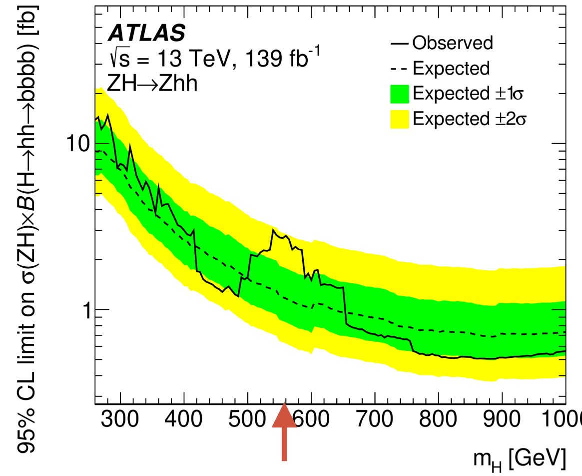
VH(→hh): Search for Higgs boson pair production in association with a vector boson

ArXiv:2210.05415

Results: V→ VH(hh)

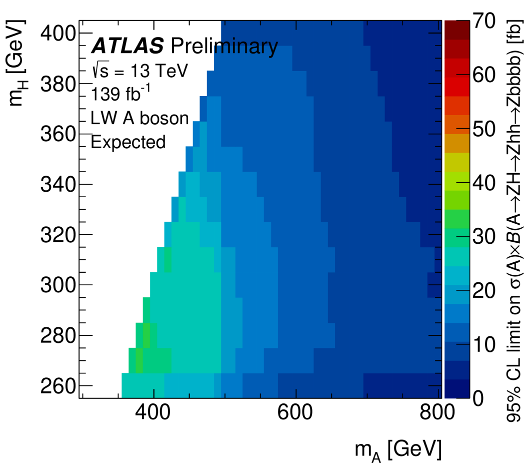
- Largest deviation:
  - **WH** at 315 GeV: local (global) significance 2.5 (1.3) σ.
  - **ZH** at 550 GeV: local (global) significance 2.7 (1.3) σ

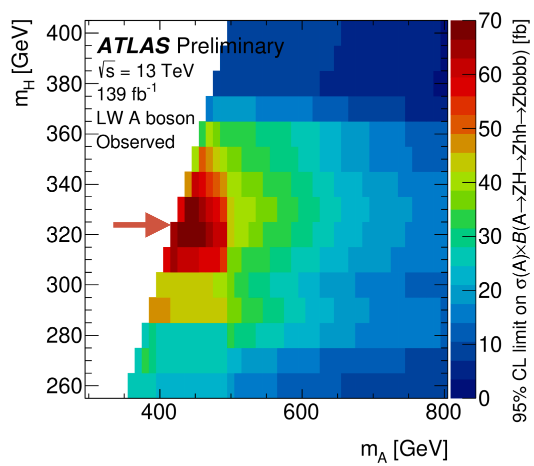




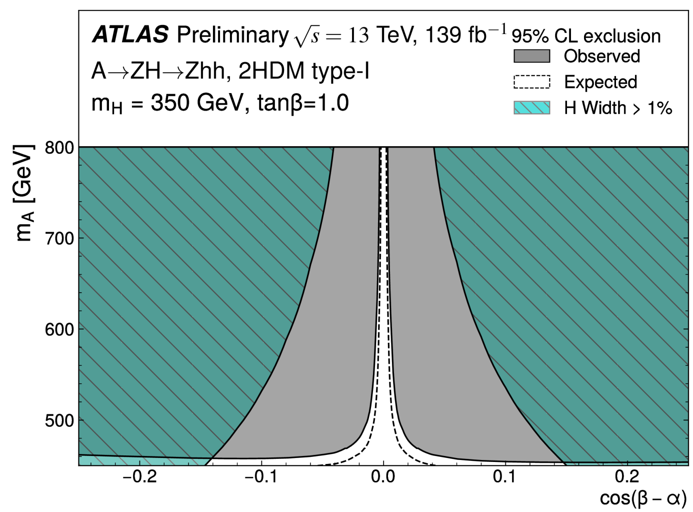
Results: A→ ZH(hh)

- Largest deviation
  - Narrow width A boson
    - (mA, mH) = (800, 300) Local: 3.6 σ Global: 1.6 σ
  - Large-width (20%) A boson
    - (mA, mH) = (420, 320) Local: 3.8 σ Global: 2.8 σ





- Constraints in the 2HDM type-I parameter space



Search for heavy flavour-violating Higgs bosons in multilepton plus b-jets final states

ATLAS-CONF-2022-039

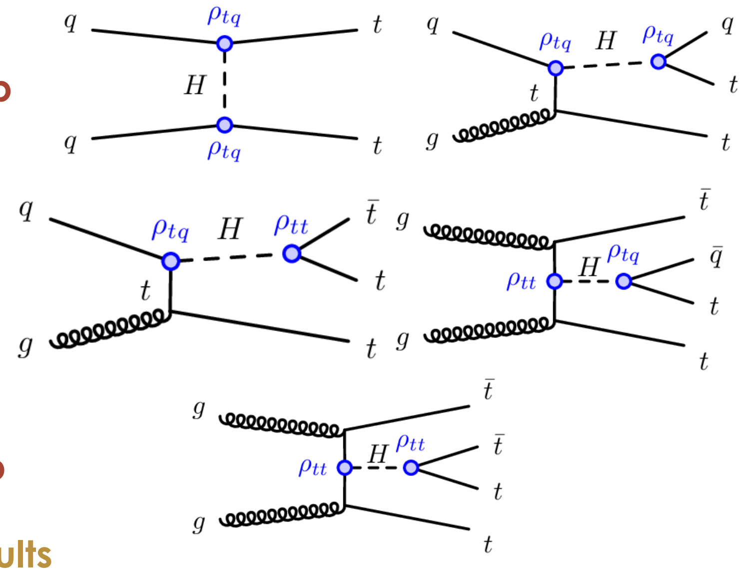
Interpretation

- General two Higgs doublet model (g2HDM) without $Z2$ symmetry, featuring FCNH (Flavour Changing Neutral Higgs) couplings.
  - Couplings of H involving top-quark: ρtt, ρtc, and ρtu.
- First analysis to target BSM production leading to three-top final states and the first to probe g2HDM.
- Sensitive probe of new physics: same-sign (SS) top, 3-top, 4-top final states.

SS Top

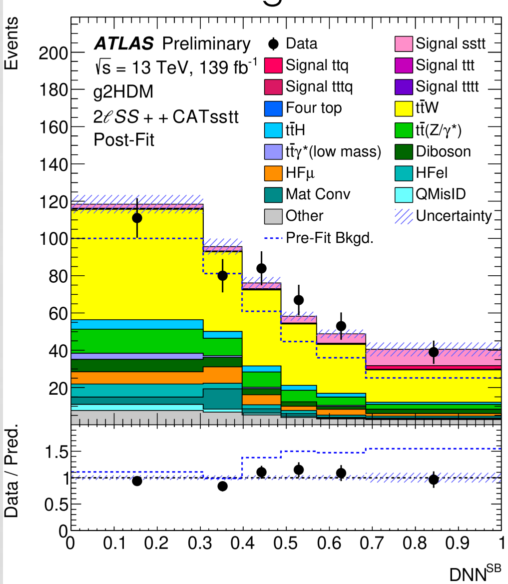
3-Top

4-Top



Strategy

- NN trained to classify the different signal channels



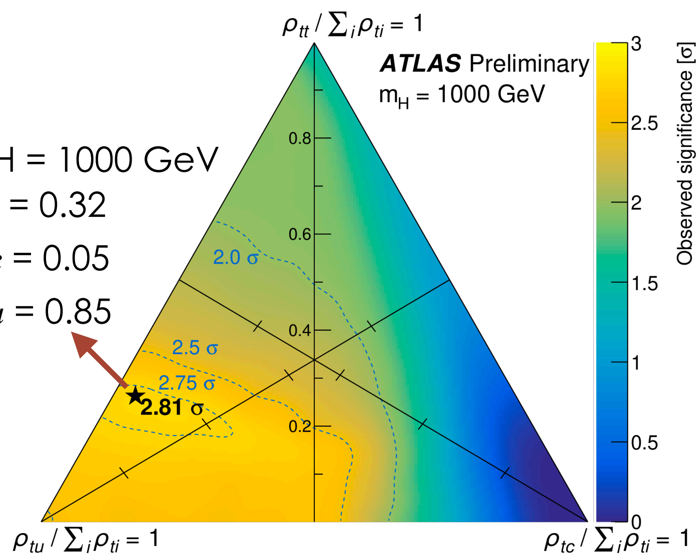
Results

mH = 1000 GeV

ρtt = 0.32

ρtc = 0.05

ρtu = 0.85



- Scan ρtt, ρtc, ρtu couplings and heavy Higgs masses 200 GeV < mH < 1000 GeV
- Most significant deviation observed at mH=1000 GeV with local significance of 2.81σ local
- Results are also interpreted in RPV SUSY model.

Search for type-III seesaw heavy leptons in leptonic final states

ArXiv 2202.02039

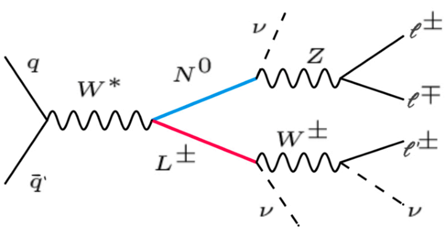
Interpretation

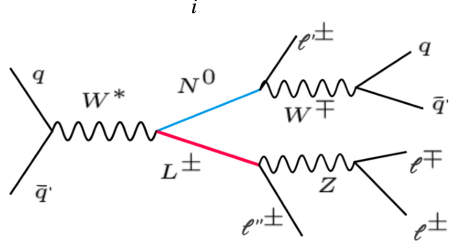
- At least one extra fermionic SU(2)L triplet predicted by the type-III seesaw mechanism:
  - Pair production of new heavy charged ($L^{\pm}$) and neutral (N^0) lepton particles

Selection and strategy

- Three leptons in final state

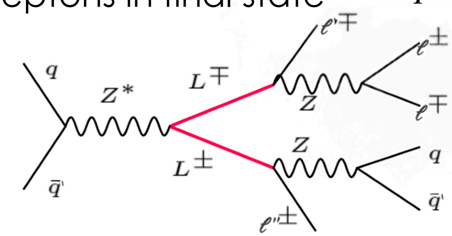
$$m_T^{3\ell} = \left| \sum_i^{3\ell} \vec{p}_{T,i} + \vec{p}_T^{\,miss} \right|$$

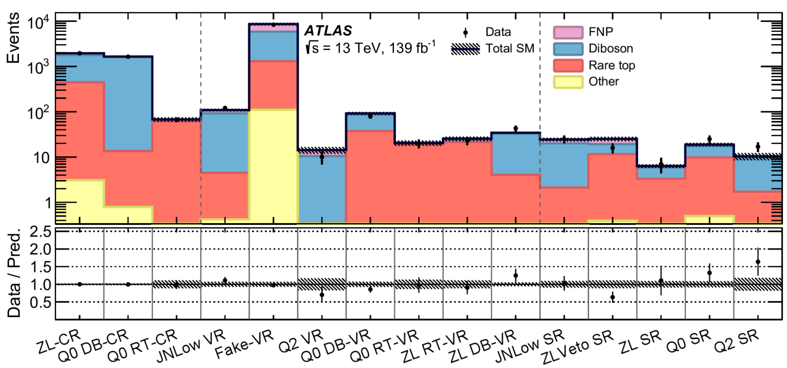




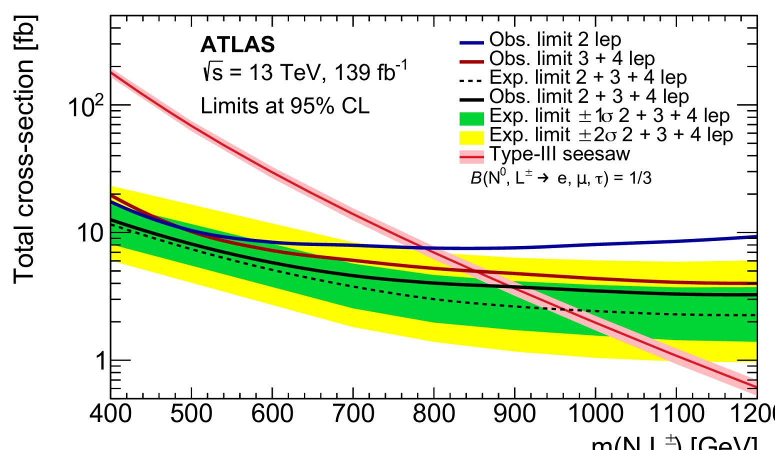
- Four leptons in final state

$$H_T + E_T^{miss}$$





Results



- Observed exclusion limits at 95% CL m(N,L) > 910 GeV

Search for electroweakinos production in final states with one lepton, jets and MET

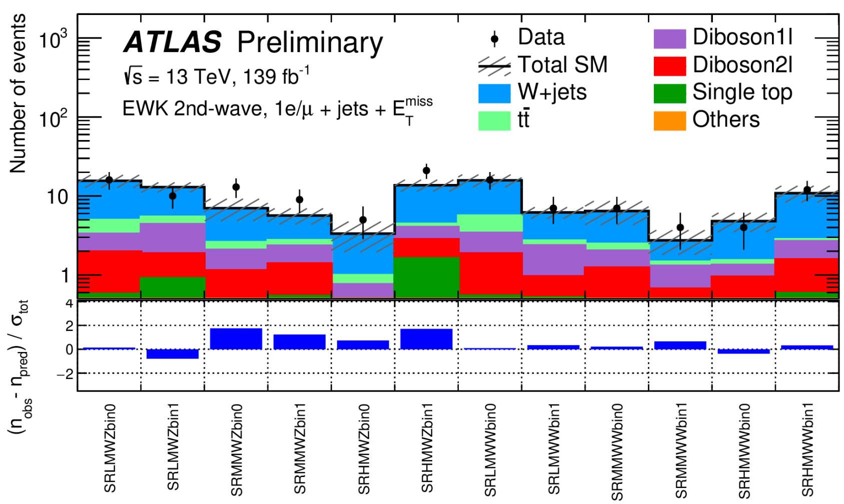
ATLAS-CONF-2022-059

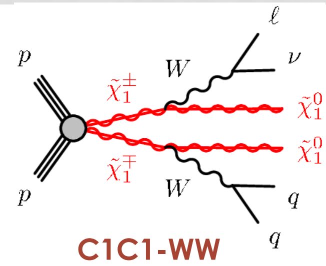
- First search targeting these processes in the 1Lepton channels

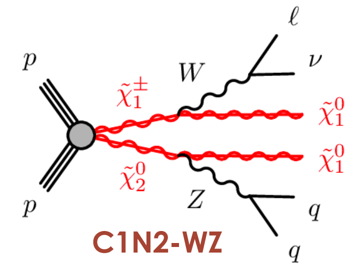
Event Selection

Variable	C1C1-WW model SRLM	C1C1-WW model SRMM	C1C1-WW model SRHM	C1N2-WZ model SRLM	C1N2-WZ model SRMM	C1N2-WZ model SRHM
N_{lep} ($p_{\mathrm{T}} > 25$ GeV)	1					
N_{jet} ($p_{\mathrm{T}} > 30$ GeV)	1 – 3					
$N_{\mathrm{large-Rjet}}$ ($p_{\mathrm{T}} > 250$ GeV)	≥ 1					
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200					
$\Delta\phi(\ell, E_{\mathrm{T}}^{\mathrm{miss}})$	< 2.6					
large-R jet type	W-tagged			Z-tagged		
m_{T} [GeV]	120–200	200–300	> 300	120–200	200–300	> 300
Exclusion SR						
m_{eff} [GeV] (excl.)	[600–850, > 850]			[600–850, > 850]		
m_{jj}[GeV] (excl.)	[70–90, -]			[80–100, -]		
$\sigma_{E_{\mathrm{T}}^{\mathrm{miss}}}$ (excl.)	[> 12, > 15]			[> 12, > 12]		
Discovery SR						
m_{eff} [GeV] (disc.)	> 600	> 600	> 850	> 600	> 850	> 850
m_{jj}[GeV] (disc.)	-	-	-	80–100	-	-
$\sigma_{E_{\mathrm{T}}^{\mathrm{miss}}}$ (disc.)	> 15	> 15	> 15	> 12	> 12	> 12

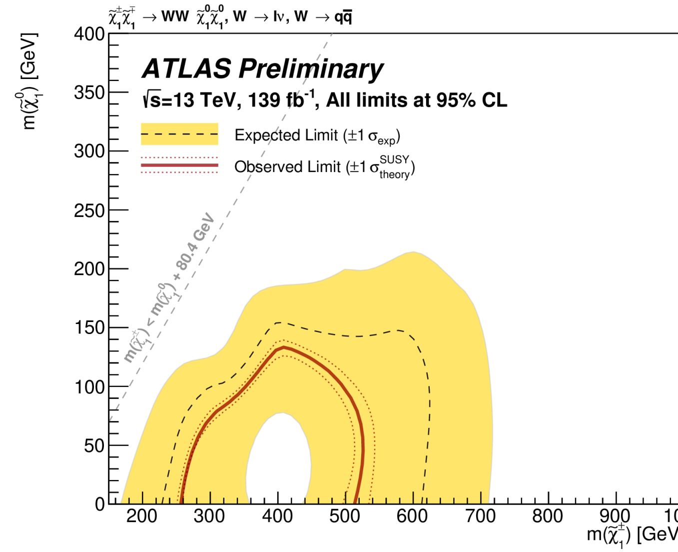
Strategy







Results



- For the χ˜1+ χ˜1- model, chargino masses ranging from 260 to 520 GeV can be excluded for a massless χ˜10
- χ˜1± χ˜20 process, degenerate chargino/ neutralino masses ranging from 260 to 420 GeV can be excluded for a massless χ˜10