Searches for Beyond the Standard Model Resonances in ATLAS

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34th Rencontres de Blois on Particle Physics and Cosmology

May 18, 2023

Introduction

- Many new physics models predict the existence of additional particles.
- Looking for resonances decaying to pairs of bosons, quarks, or leptons is an important focus of the LHC (and ATLAS) search programme.
- Resonance searches can generally be divided into different categories:
  - Leptoquarks
  - Vector-like quarks
  - Heavy resonances
  - Low-mass resonances
  - General searches
- Will present a selection of recent ATLAS analyses in each of these categories, paying particular attention to the novel techniques used to reconstruct/classify the final states.
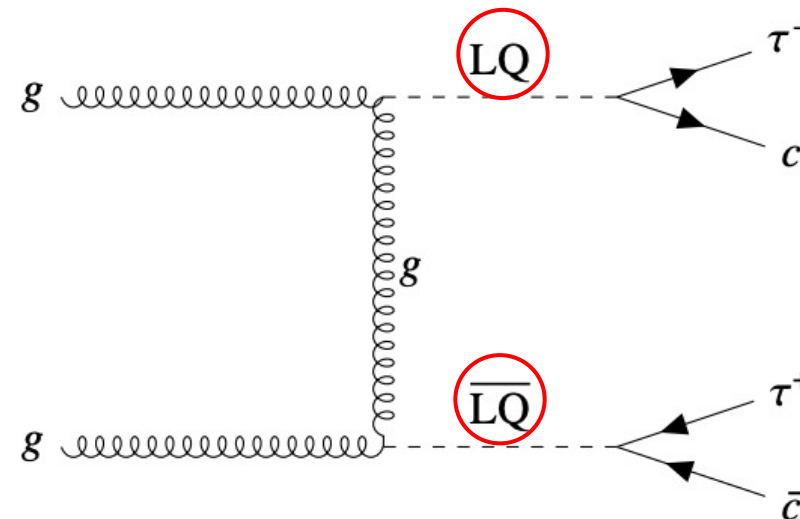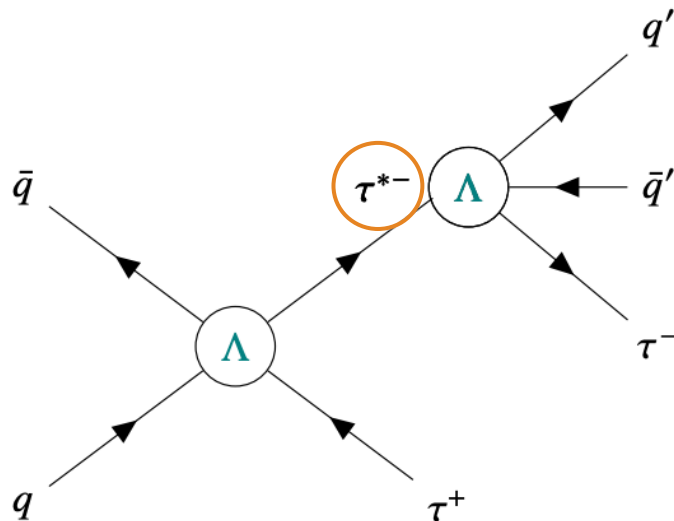
Leptoquarks

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- Leptoquarks (LQs) = coloured bosons that carry both lepton and baryon numbers → couple to quarks and leptons.
- Could help explain Lepton Flavour Universality and g-2 anomalies.
- See Volker Andreas Austrup's talk for more details.

Search for excited τ-leptons and leptoquarks in the final state with τ-leptons and jets [arXiv:2303.09444]
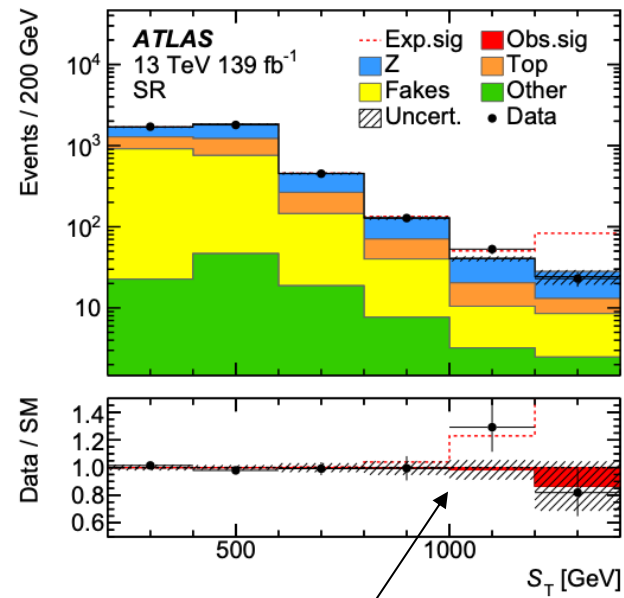
➢ **Signal:** For excited τ, assume effective four-fermion contact interaction as the de-excitation process (no gauge interaction). For scalar LQs, assume BR(LQ → τc) = 1, although could apply to other light quarks since no flavour tagging in signal regions.

➢ **Channel:** Hadronic tau decays + jets.

➢ **Trigger and event selection:** di-τ_{had} trigger with kinematic requirements on the τ's, ≥ 2 jets.
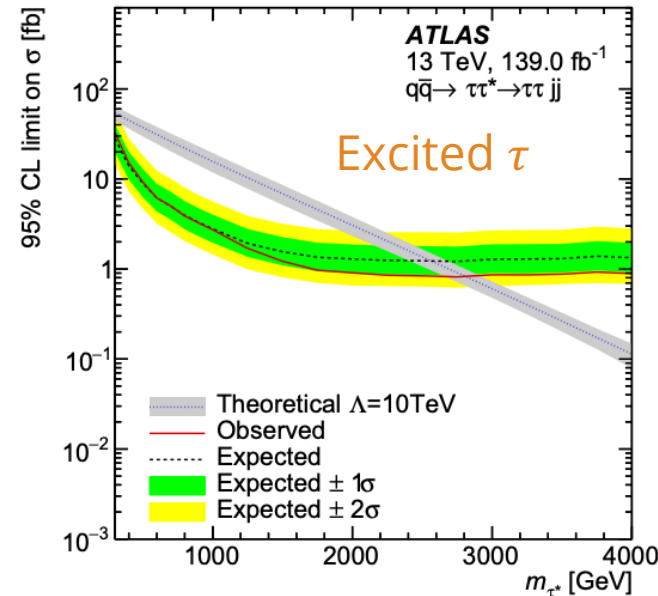
Leptoquarks and excited tau leptons

Search for excited τ-leptons and leptoquarks in the final state with τ-leptons and jets [arXiv:2303.09444]

➤ **Backgrounds:** $t\bar{t}$, single top, and $Z \to \tau\tau$ normalised using floating scale factors in the fit. Backgrounds from fakes estimated using fake-factor method.

➤ **Fit:** Profile likelihood fit with scalar sum of p_T of the 2 leading jets and the two τ's (S_T) as discriminating variable.
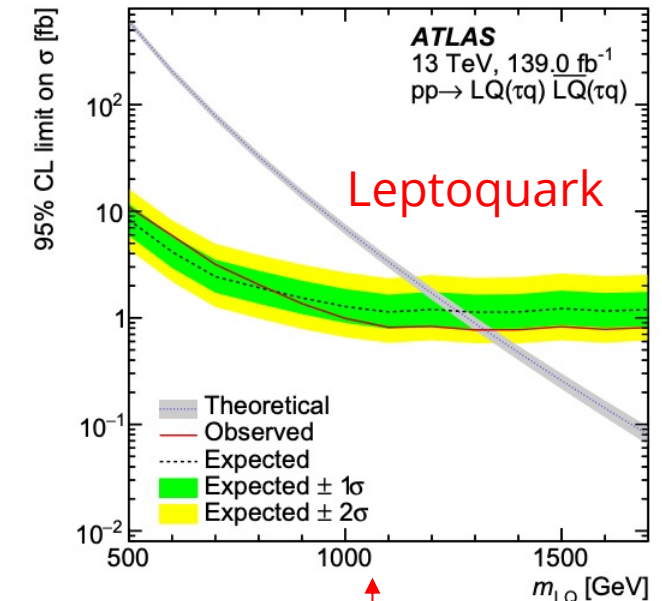

(a) Cross-section limit, $\Lambda = 10$ TeV.

Theory uncertainties for top backgrounds most highly ranked

Λ = scale below which contact interaction holds

Similar CMS search with partial run 2 data in $\tau b \tau b$ channel excluded LQ masses below 1.02 TeV
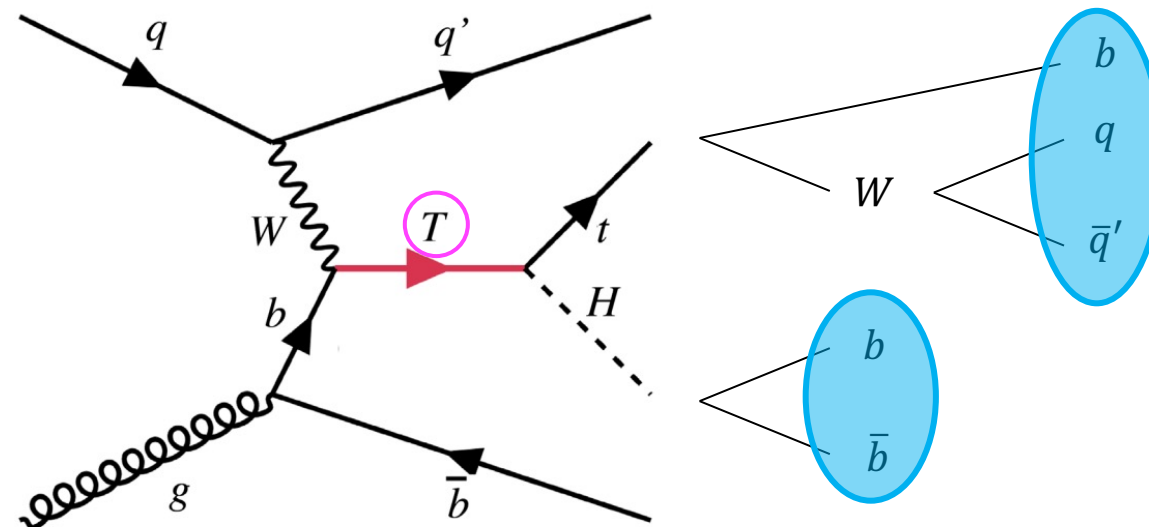
Vector-like quarks

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- Vector-like-quarks (VLQs) = coloured spin-1/2 fermions whose LH/RH components transform in the same way under gauge transformation, and which mix with SM quarks.

- Help to address the hierarchy problem.

- Pair production dominates at low masses, but single production dominates at high masses (see arXiv:2212.05263 and arXiv:2210.15413 for pair production searches).

Search for single production of a vectorlike T quark decaying into a Higgs boson and top quark with fully hadronic final states [PhysRevD.105.092012]

➤ **Signal:** Single production of top partner T, assume singlet representation.

➤ **Channel:** $H \to b\bar{b}$ and hadronic decay of top.

➤ **Reconstruction:** Large-R jets to reconstruct t and H, tagged using jet substructure tagging algorithms.

➤ **Trigger and event selection:** ≥ 2 high-p_T large-R jets.

Search for single production of a vectorlike T quark decaying into a Higgs boson and top quark with fully hadronic final states [PhysRevD.105.092012]

➢ **Backgrounds:** Multijet estimated using data-driven sideband technique.
$t\bar{t}$ normalized using data in dedicated $t\bar{t}$ enriched control region (CR).

➢ **Fit:** Profile likelihood fit using invariant mass of 2 large-R jets as discriminating variable.

Coupling between VLQ and SM bosons
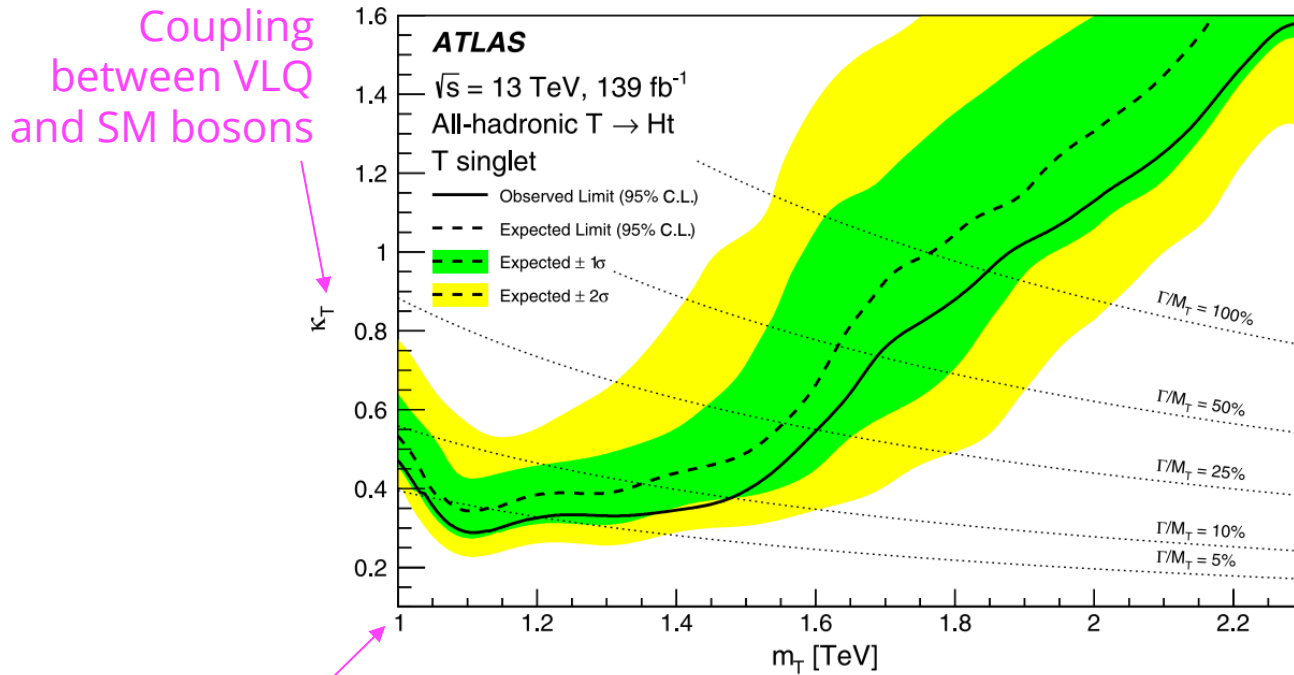
Previous ATLAS search with run 1 data and T → Wb excluded masses below ~1 TeV
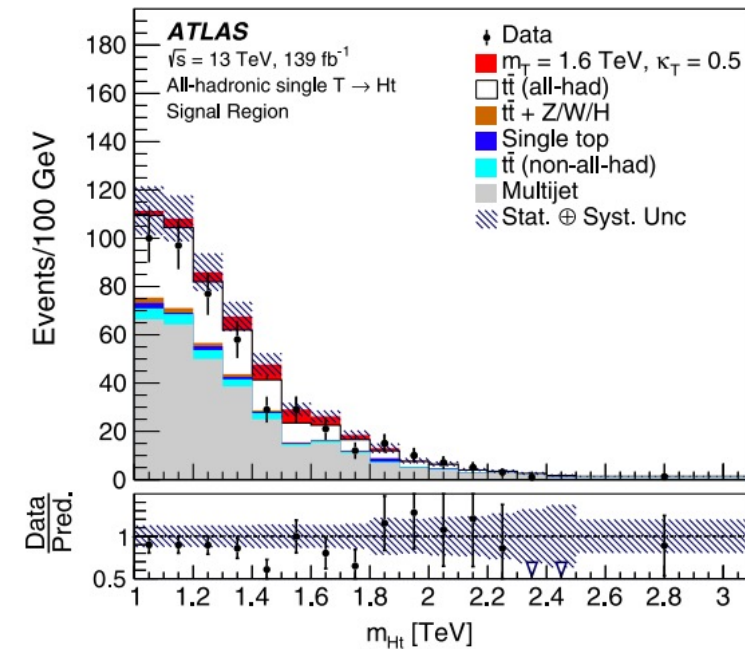
Largest contribution to uncertainty comes from b- and top-tagging.

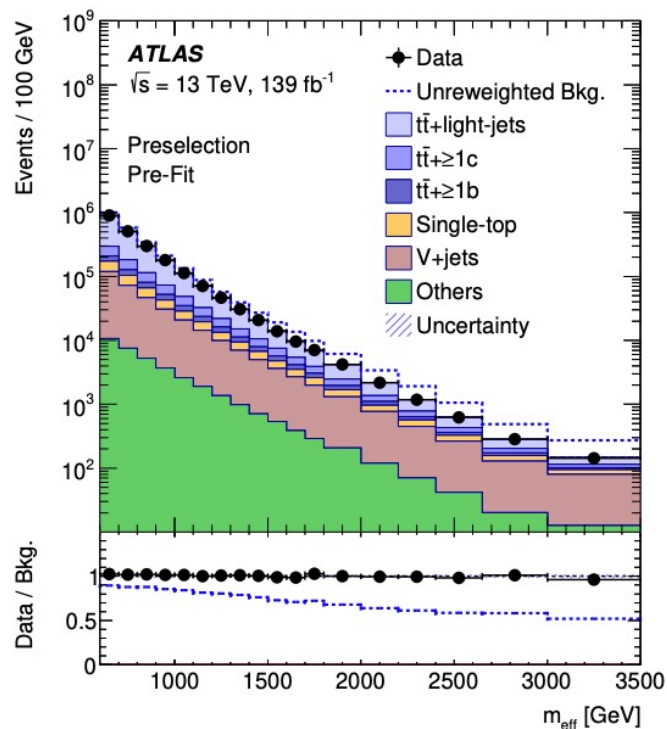Search for single production of vector-like T quarks decaying to Ht or Zt [arXiv:2305.03401]

➢ **Signal:** b- or t- associated production of top partner T (singlet or doublet representation).

➢ **Channel:** Single lepton top-quark channel, assuming a leptonically decaying top quark and a hadronically-decaying Higgs or Z boson.

➢ **Reconstruction:** Variable radius reclustered (vRC) jets to tag and reconstruct t, H, and W/Z.
Leptonic top reconstructed by calculating neutrino p_z using constraints from measured E_T^{miss} and W mass.

➢ **Trigger and event selection:** single-lepton or E_{miss}^T trigger, = 1 lepton, ≥ 3 jets, ≥ 1 b-tagged jet, other kinematic requirements.
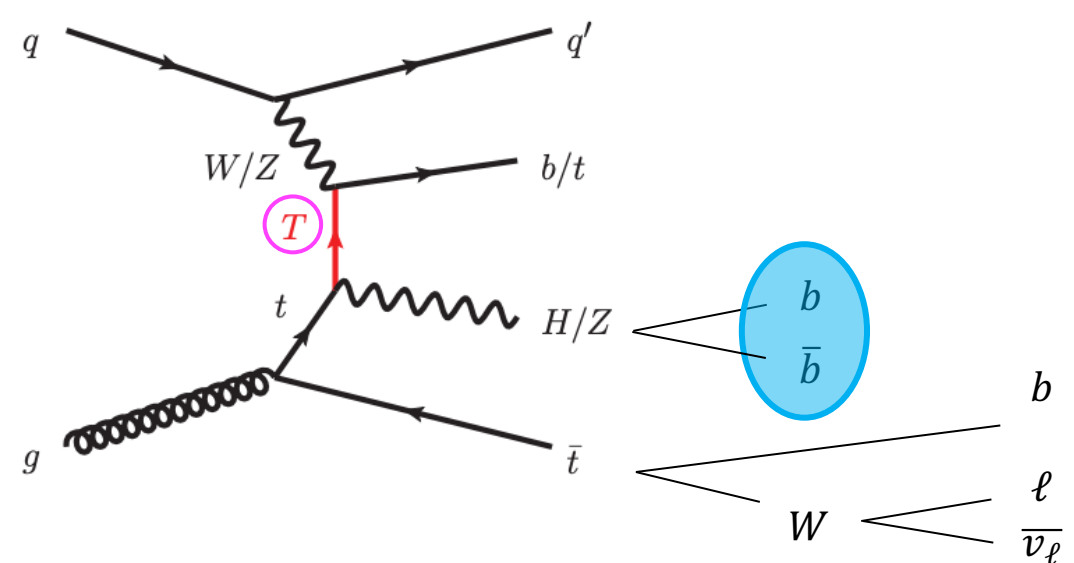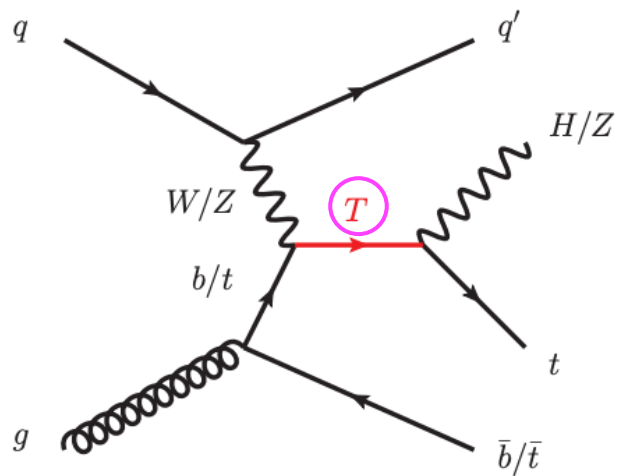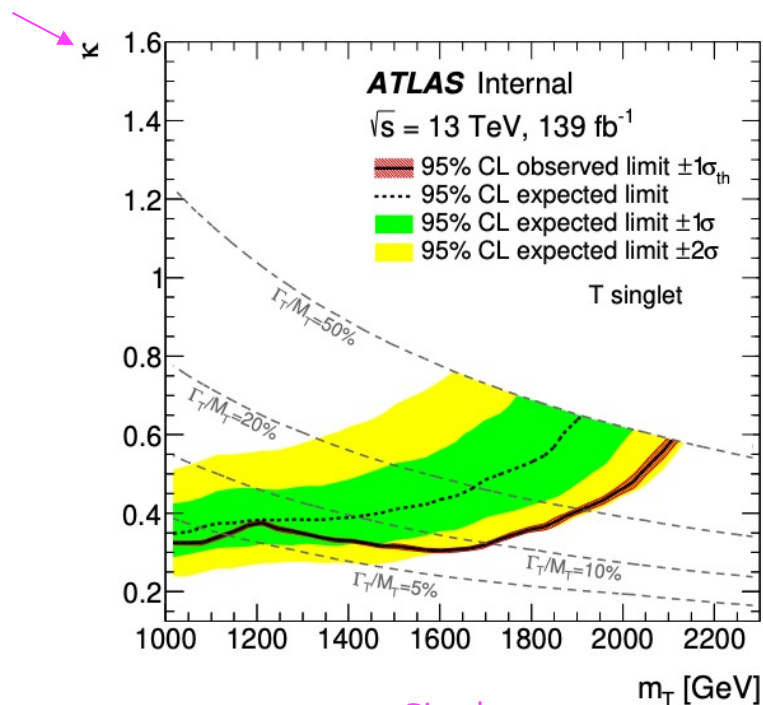
Search for single production of vector-like T quarks decaying to Ht or Zt [arXiv:2305.03401]

➢ **Backgrounds:** $t\bar{t}$, tW, and W+jets. Simulations corrected using data-driven kinematic reweighting.

➢ **Fit:** Profile likelihood fit in 24 regions using effective mass as discriminating variable.
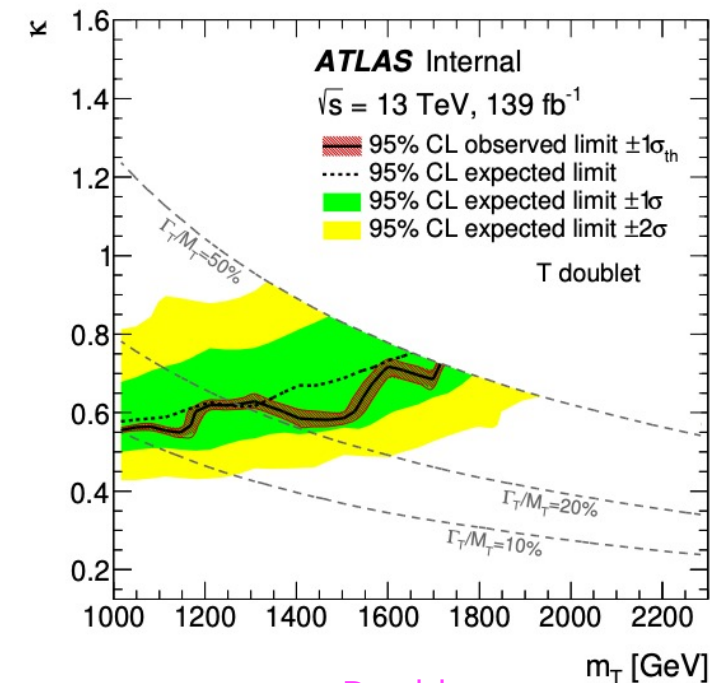

Coupling between VLQ and SM bosons

Uncertainty dominated by systematics
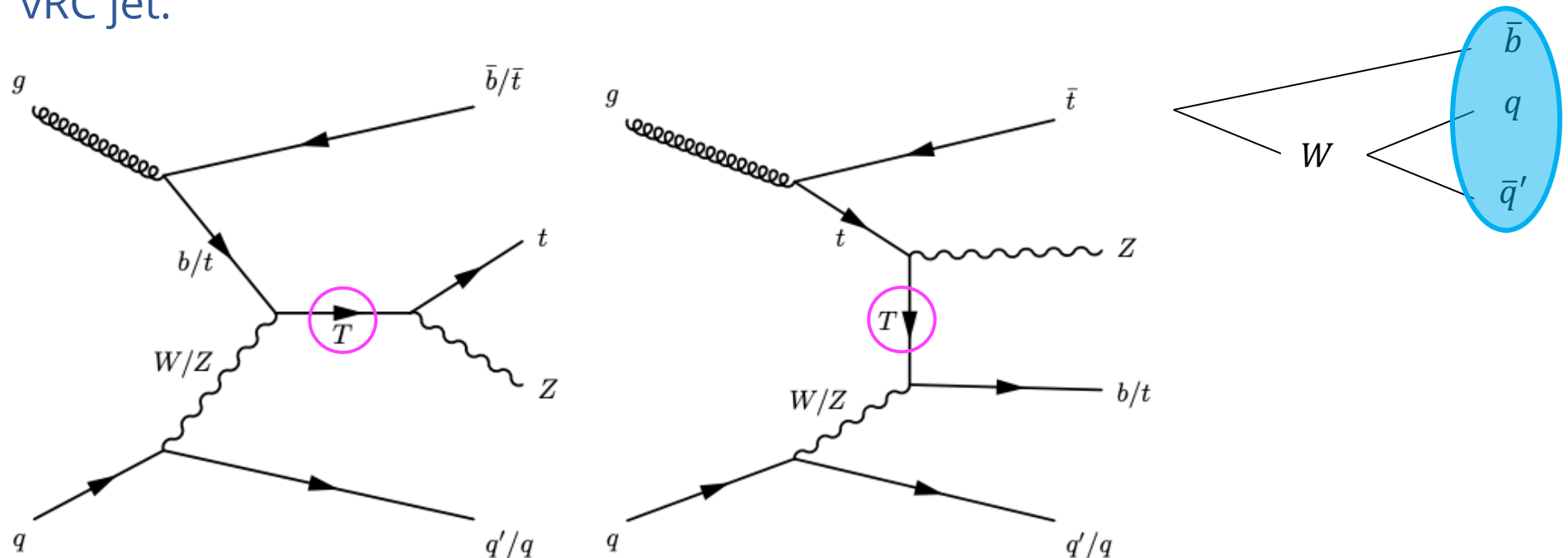
Singlet

Doublet

Search for singly produced vector-like top partners in multilepton final states [ATLAS-CONF-2023-020]

➢ **Signal:** b- or t- associated production of top partner T (singlet or doublet representation)

➢ **Channel:** 2 opposite-sign leptons + hadronic or leptonic top (i.e. 2ℓ or 3ℓ).

➢ **Reconstruction:** vRC jets to tag and reconstruct t (similar to single lepton analysis).

➢ **Trigger and event selection:** single-lepton trigger, at least one opposite sign same flavour lepton pair, ≥ 2 jets or ≥ 1 vRC jet.
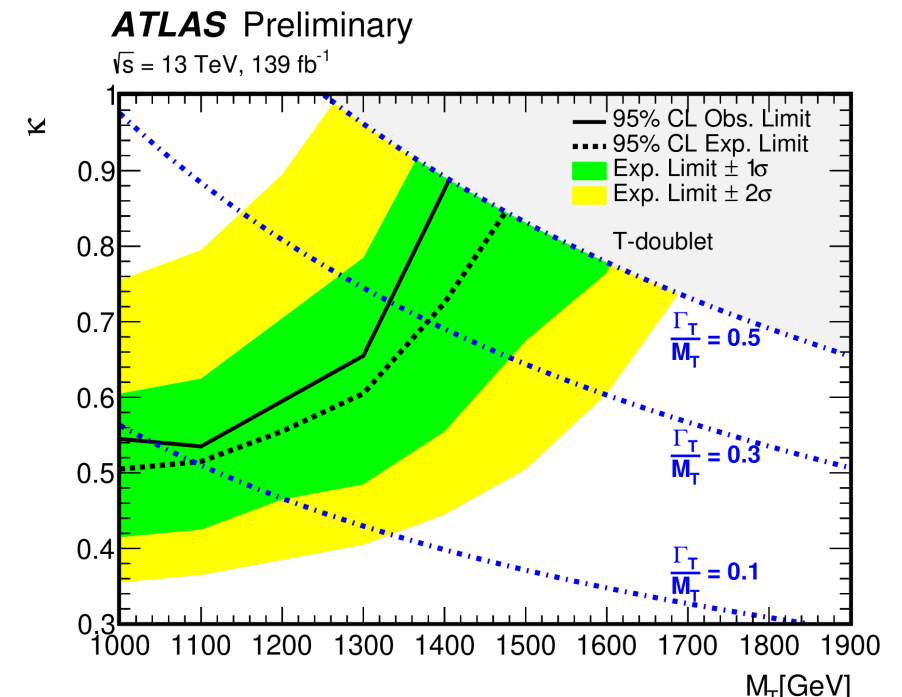
Search for singly produced vector-like top partners in multilepton final states [ATLAS-CONF-2023-020]

➢ **Backgrounds:** Z+jets (in 2ℓ) or VV and $t\bar{t} + X$ (in 3ℓ). Estimated using data-driven reweighting factors.

➢ **Fit:** Profile likelihood fit with $p_T(\ell\ell)$ as discriminating variable.
   Both channels fit independently then combined.
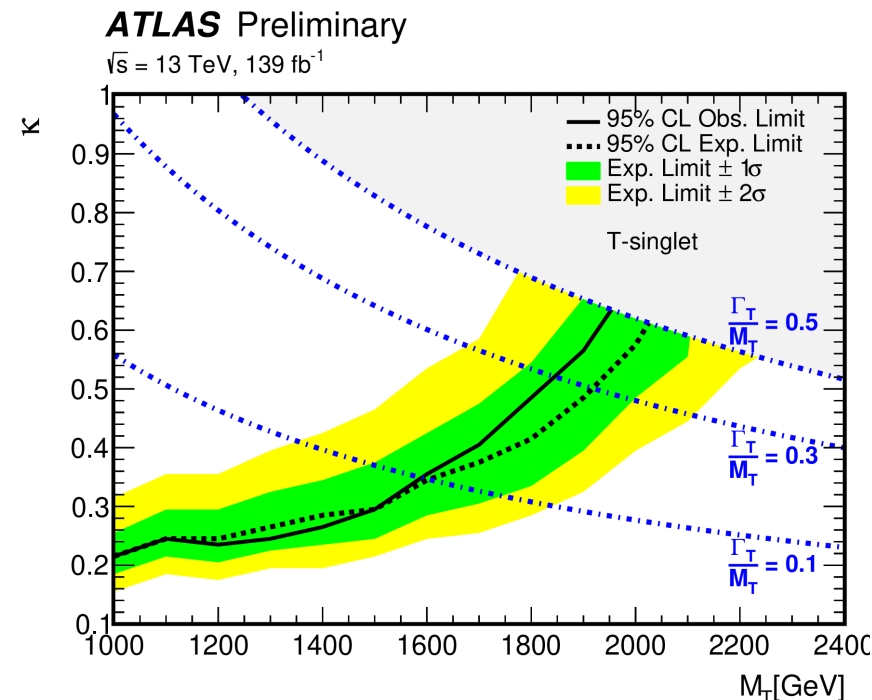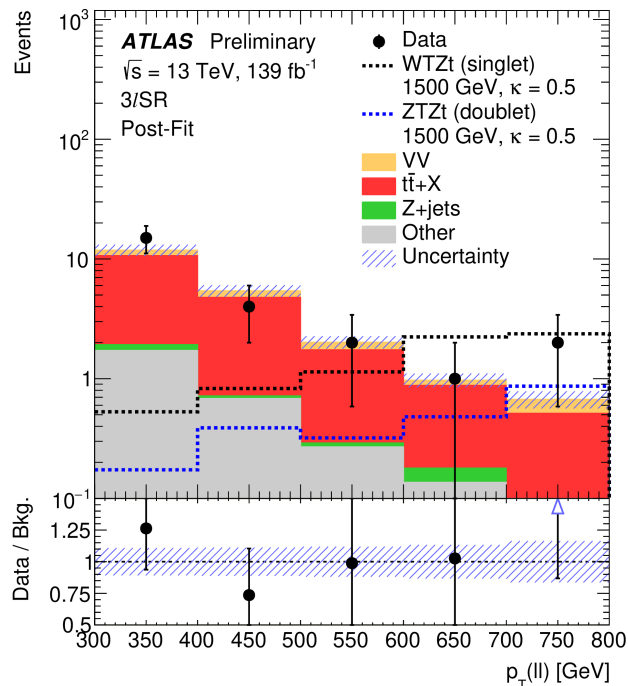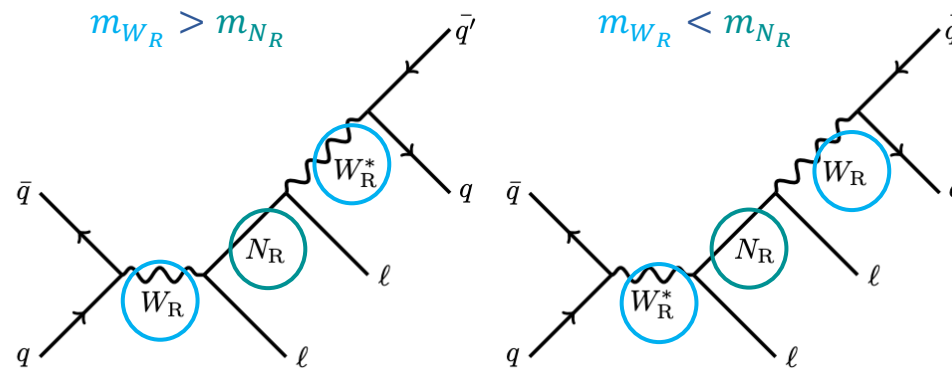

Singlet

Doublet

Heavy resonances

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Heavy neutrinos and RH W bosons

- Seesaw mechanism = proposed solution to the neutrino mass question: light neutrinos acquire their masses through heavy right-handed neutrinos.
- Type I and II seesaw mechanisms can be embedded in Left-Right Symmetric Model (LRSM) → new W_R and Z_R bosons and heavy right-handed neutrinos N_R.

Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets [arXiv:2304.09553]

➤ **Signal:** N_R (Majorana or Dirac) decaying to W_R in Keung-Senjanović (KS) process. Can have $m_{W_R} >$ or $< m_{N_R}$.

➤ **Channels:** Resolved/boosted, corresponding to mass splitting between W_R and N_R of < or > 4 TeV, respectively. Each channel separated in same sign (SS) and opposite sign (OS) lepton channels.

➤ **Reconstruction:** Large-R jet in boosted channel to reconstruct $W_R^{(*)}$.

➤ Trigger and event selection: single- or di-lepton trigger, = 2 leptons and ≥ 2 jets with kinematic requirements.

Search for heavy Majorana or Dirac neutrinos and right-handed W gauge bosons in final states with charged leptons and jets [arXiv:2304.09553]

➢ **Backgrounds:** Z+jets, VV, and $t\bar{t}$ estimated using CRs.
Non-prompt and mis-identified lepton backgrounds estimated separately using data-driven method.

➢ **Fit:** Profile likelihood fit using $m_{jj\ell\ell}$ (resolved, OS, $m_{W_R} > m_{N_R}$) or m_{jj} (resolved, OS, $m_{W_R} < m_{N_R}$) or H_T (resolved, SS) or $m_{J\ell\ell}$ (boosted).

m_{eejj} in resolved channel

Majorana

Dirac

Uncertainty dominated by background normalisation in resolved channel and theory in boosted channel
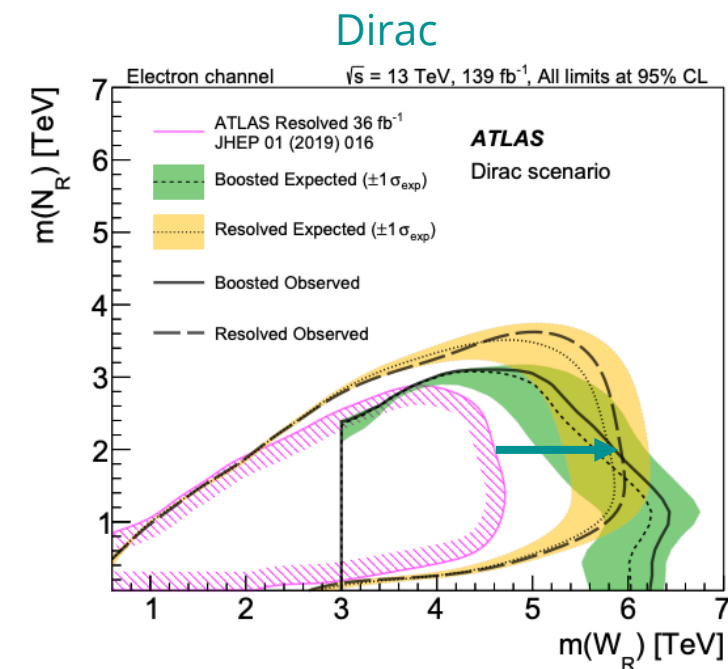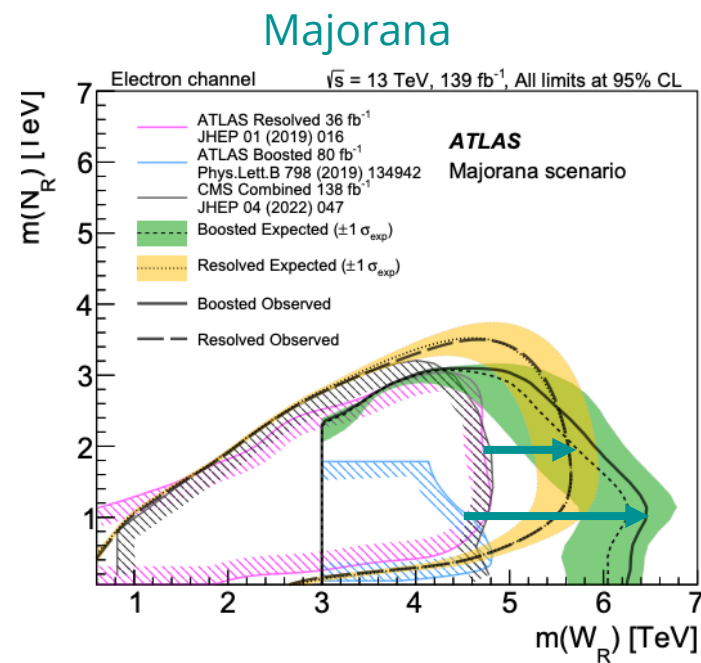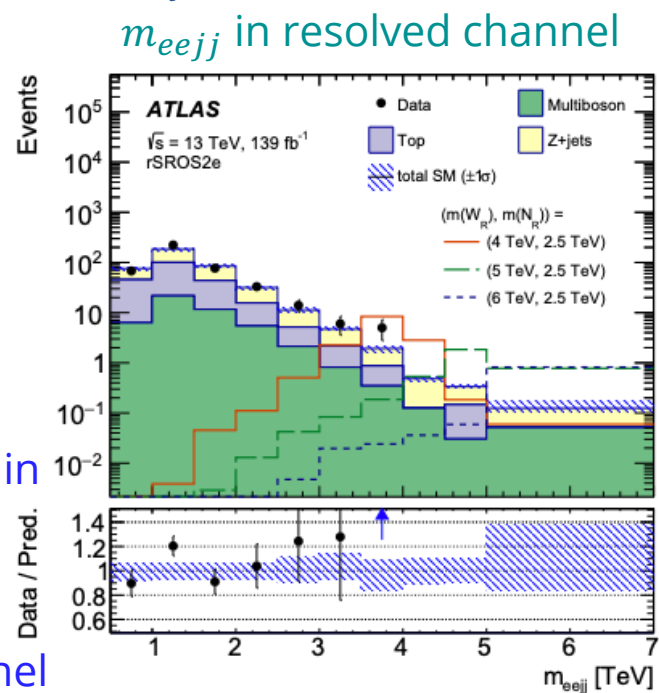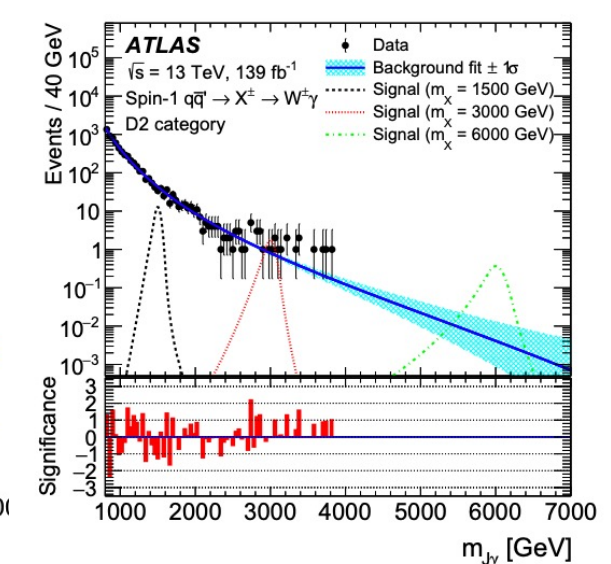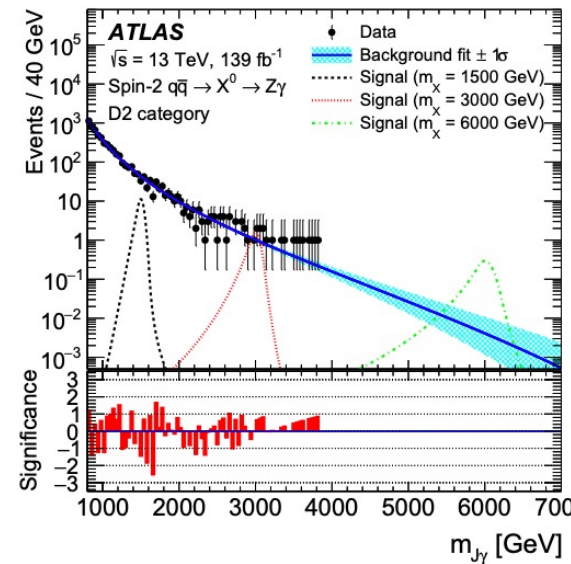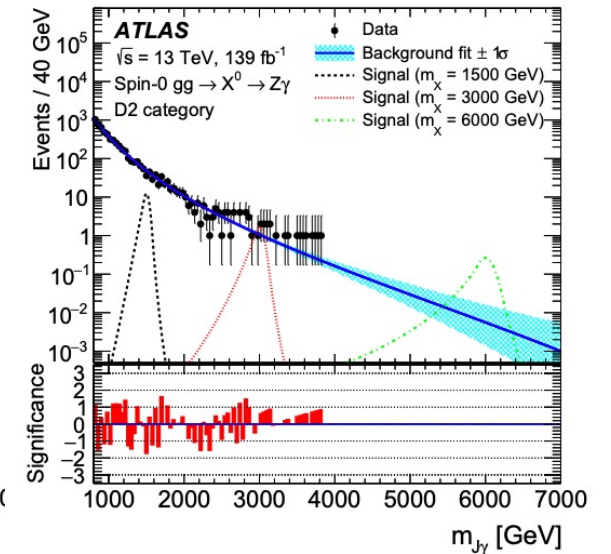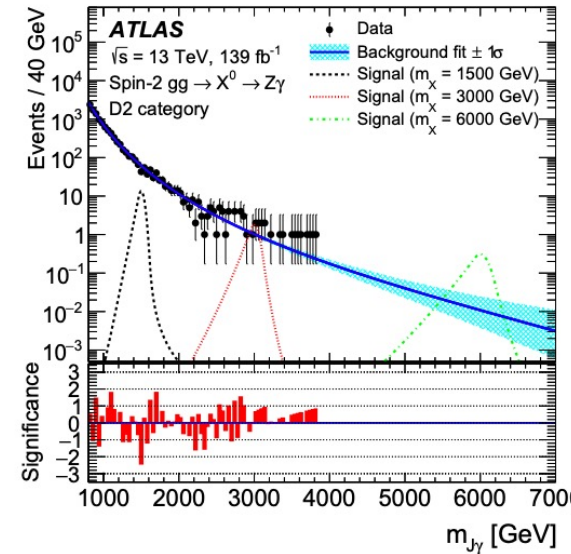
⟶ Improvement WRT previous ATLAS analysis

Search for high-mass $W\gamma$ and $Z\gamma$ resonances using hadronic W/Z boson decays [arXiv:2304.11962]

➤ **Signal:** Generic high-mass boson: spin-1 $X^\pm$ or spin-0/2 X^0. Assume decay width small compared to experimental resolution.

➤ **Channel:** $W\gamma/Z\gamma$ with hadronic decays of W and Z.

➤ **Reconstruction:** large-R jets with 2-pronged substructure for boosted W and Z.

➤ **Trigger and event selection:** single photon trigger, ≥ 1 photon and ≥ 1 jet with kinematic requirements.

Largest local signal significance (2.5σ) for spin-0 $gg \rightarrow X^0 \rightarrow Z\gamma$ at $m_X = 3640$ GeV.

Dominant uncertainties for signal come from jet mass/energy/resolution.

Search for high-mass $W\gamma$ and $Z\gamma$ resonances using hadronic W/Z boson decays [arXiv:2304.11962]

➤ **Backgrounds:** Main SM backgrounds are γ+jets then SM $W\gamma$ and $Z\gamma$.
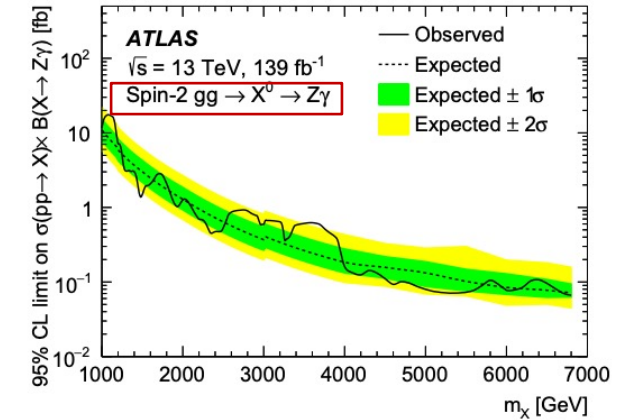
➤ **Fit:** Profile likelihood fit with $m_{J\gamma}$ as discriminating variable.

　　Dijet function used to parametrize background and double-sided Crystal ball function used to parametrize signal.
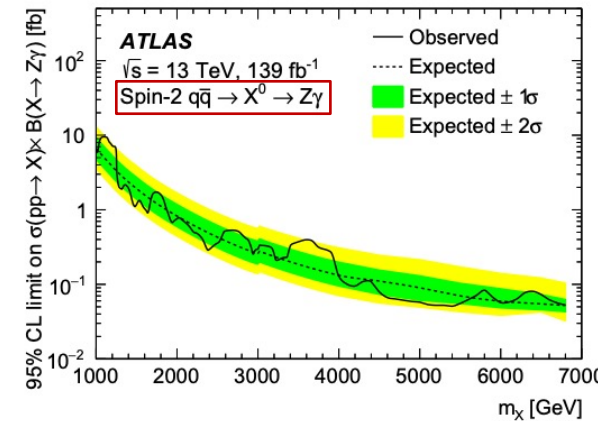
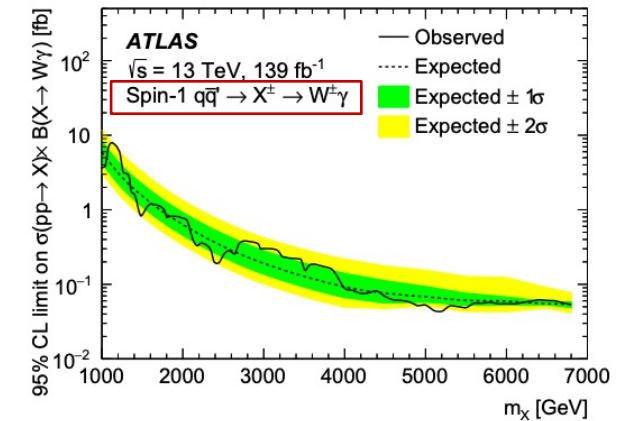　　Asymptotic approximation used for $m_X \leq 4$ TeV, pseudo-experiment sampling for $m_X > 4$ TeV.
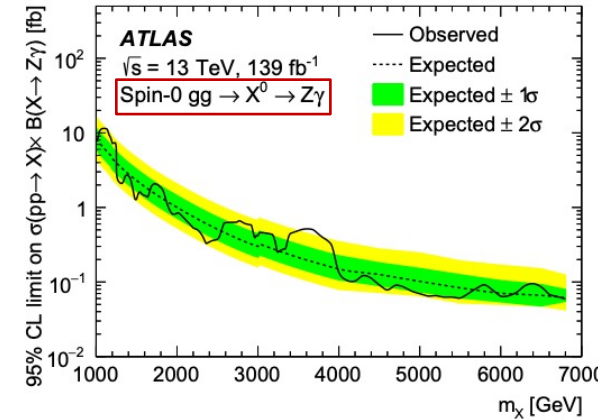

(a)　(b)　(c)　(d)

Limits improved by a factor ~2 compared to partial run 2 ATLAS result

- Typical 2HDM model predicts 5 Higgs bosons and assumes Z_2 symmetry. Decoupling limit corresponds to very heavy extra scalars. Alignment limit corresponds to very small mixing with SM Higgs.
- General 2HDM (g2HDM) model does not assume Z_2 symmetry → alignment automatically emerges when all heavy Higgs quartic couplings are O(1). This leads to flavour-changing-neutral Higgs couplings for heavy scalars but not SM Higgs. Can explain the generation of the baryon asymmetry as well as some recent observations (flavour anomalies, g-2, high $t\bar{t} + W$ and $t\bar{t}t\bar{t}$ yields).

Search for heavy Higgs bosons from a g2HDM in multilepton plus b-jets final states [ATLAS-CONF-2022-039]

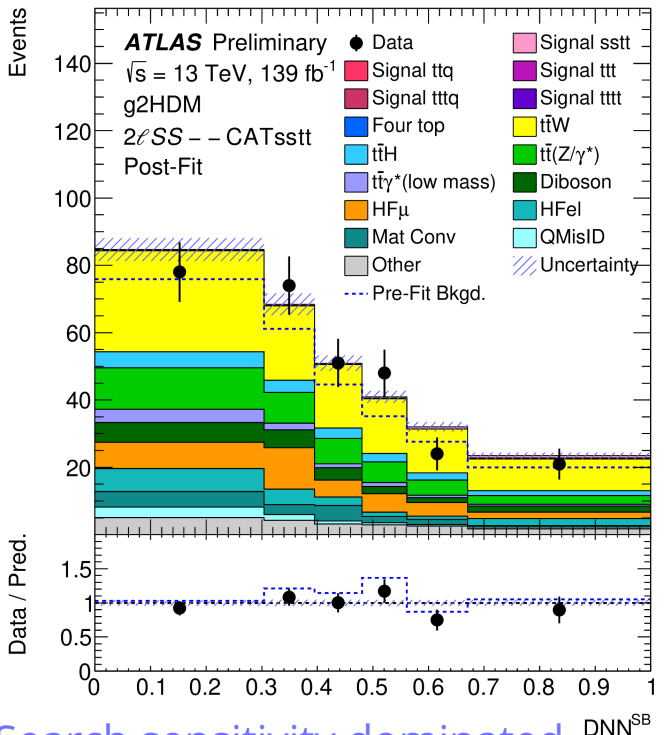➢ **Signal:** Heavy Higgs with couplings ρ_{tt}, ρ_{tu}, ρ_{tc} (+ additional interpretation in terms of RPV SUSY with λ'_{i33} coupling). First analysis to probe g2HDM!

➢ **Channels:** tt, ttq, $t\bar{t}t$, $t\bar{t}t\bar{q}$, $t\bar{t}t\bar{t} \rightarrow 2\ell SS$, 3ℓ, or 4ℓ.

➢ **Reconstruction:** DNN^{CAT} trained to identify each of the five possible production and decay modes of the g2HDM signal. DNN^{SB} trained in each SR (with mass decorrelation) to separate signal from background.
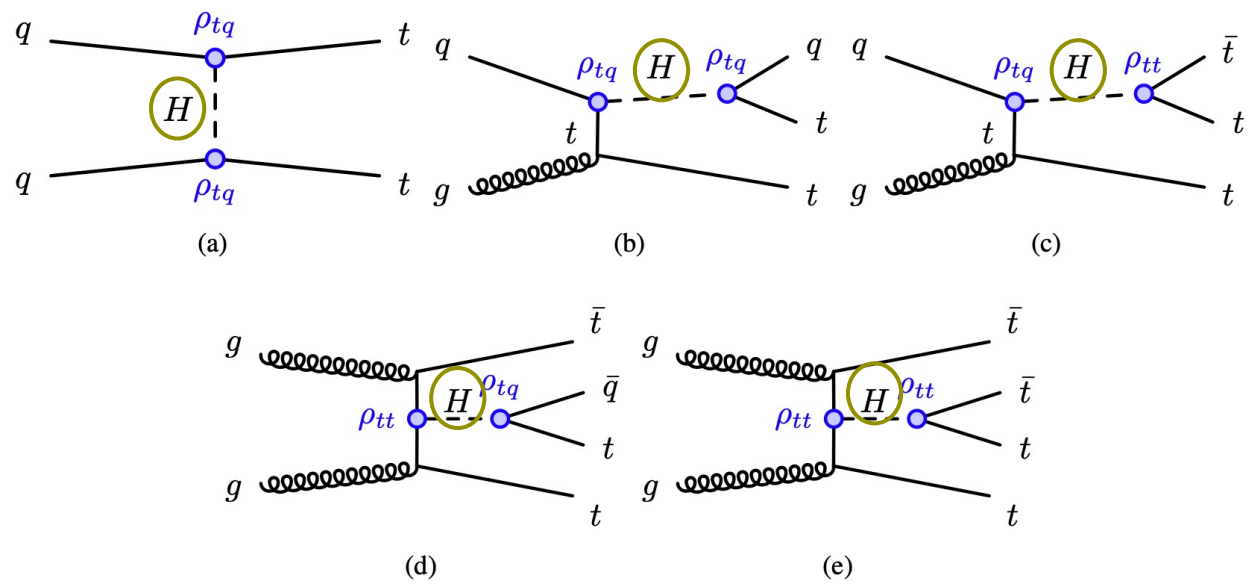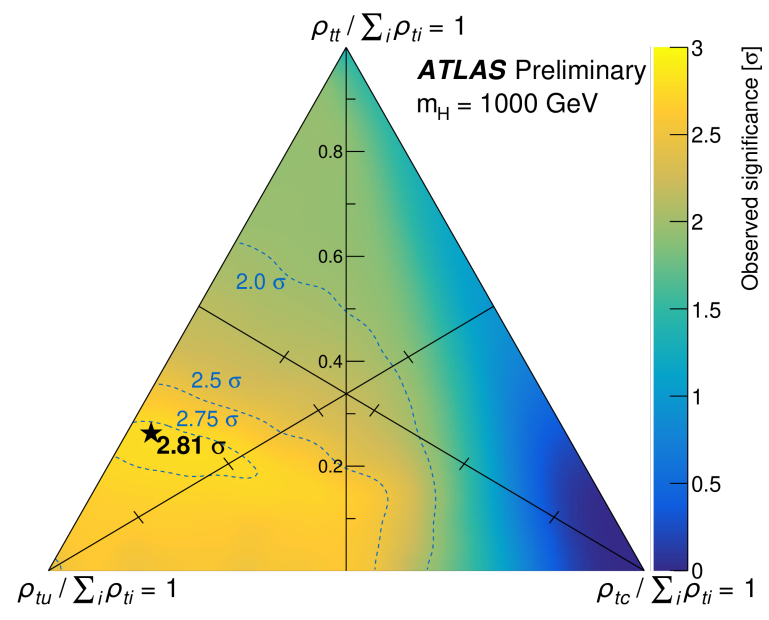
Search for heavy Higgs bosons from a g2HDM in multilepton plus b-jets final states [ATLAS-CONF-2022-039]

➤ **Fit:** Profile likelihood fit with 17 SRs and 10 CRs (for $WZ/t\bar{t}Z$, conversions, and HF non-prompt leptons). DNN^{SB} used as discriminating variable in SRs (other sensitive variables used in CRs).
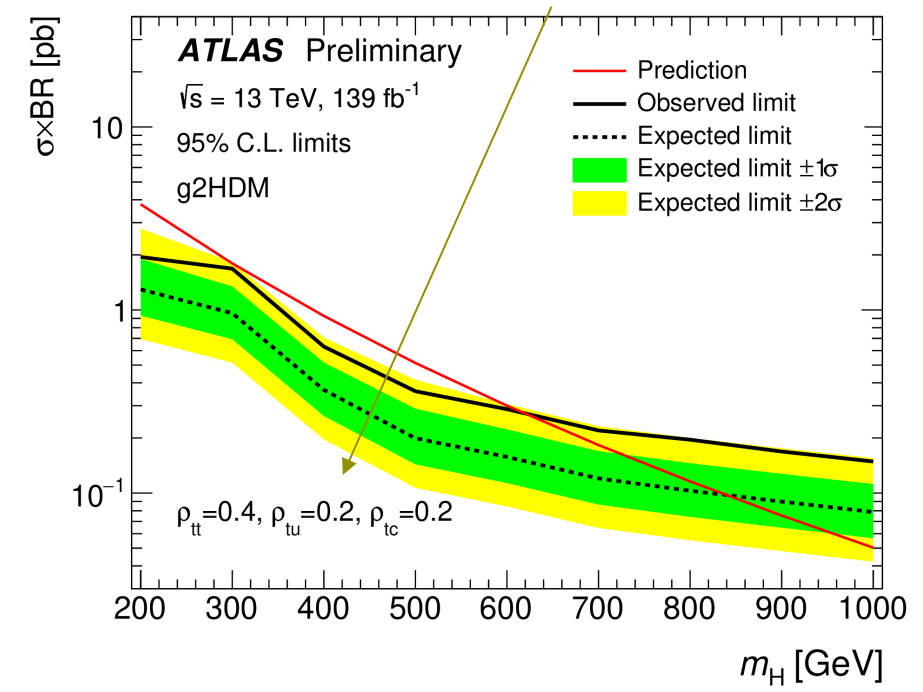
$m_H = 1$ TeV,
$\rho_{tt} = 0.32$, $\rho_{tc} = 0.85$, and $\rho_{tu} = 0.05$)

Couplings motivated by high
$t\bar{t} + W$ and $t\bar{t}t\bar{t}$ yields



Search sensitivity dominated
by stat uncertainties

Low mass resonances

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- $L_\mu - L_\tau$ model extends the SM with an additional $U(1)_{L_\mu - L_\tau}$ symmetry.
- Could address the g-2 anomaly through the Z' loop corrections without contradicting other existing data.
- Ideally suited to address the lepton flavour anomalies measured with the ratio of B-meson decays to muons and electrons.

Search for a new Z' gauge boson in 4μ events [arXiv:2301.09342]

➤ **Signal:** low-mass Z' boson produced from FSR of Drell-Yan process.

➤ **Channel:** $\mu^+\mu^-\mu^+\mu^-$

➤ **Reconstruction:** Z_1 = pair of muons with invariant mass closest to m_Z.
   Z_2= pair of remaining muons with largest invariant mass.
   Parametrized DNN (pDNN) for signal/background separation. Trained separately for
$m_{Z'} < 40$ GeV and $m_{Z'} > 40$ GeV. Cut on pDNN output score defines SRs.
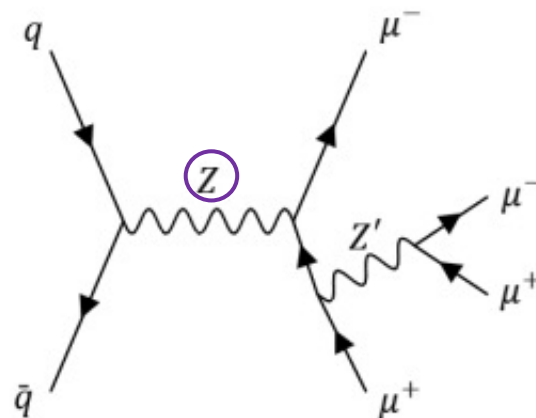
Search for a new Z' gauge boson in 4μ events [arXiv:2301.09342]

➤ **Backgrounds:** SM $Z \rightarrow 4\mu$ estimated using simulation.
$t\bar{t}$, single top, and Z+jets (non-prompt or mis-identified leptons) estimated using data driven fake-factor method.

➤ **Fit:** Profile likelihood fit with m_{Z1} (for $m_{Z'} > 42$ GeV) or m_{Z2} (for $m_{Z'} < 42$ GeV) as discriminating variable.

p_0-value scan across the Z' mass signal regions
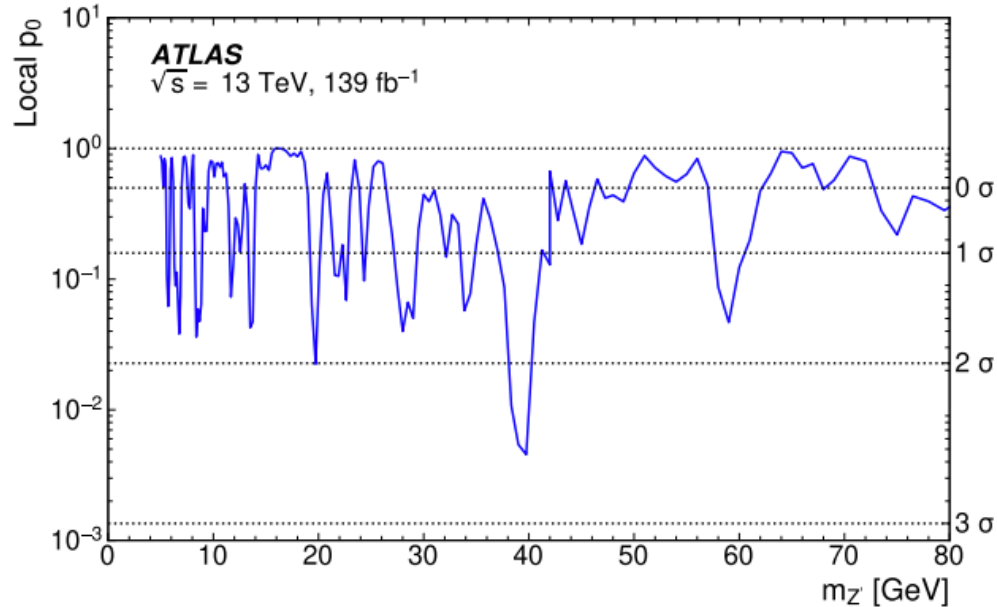
coupling strength of the Z' boson to 2nd and 3rd generation leptons

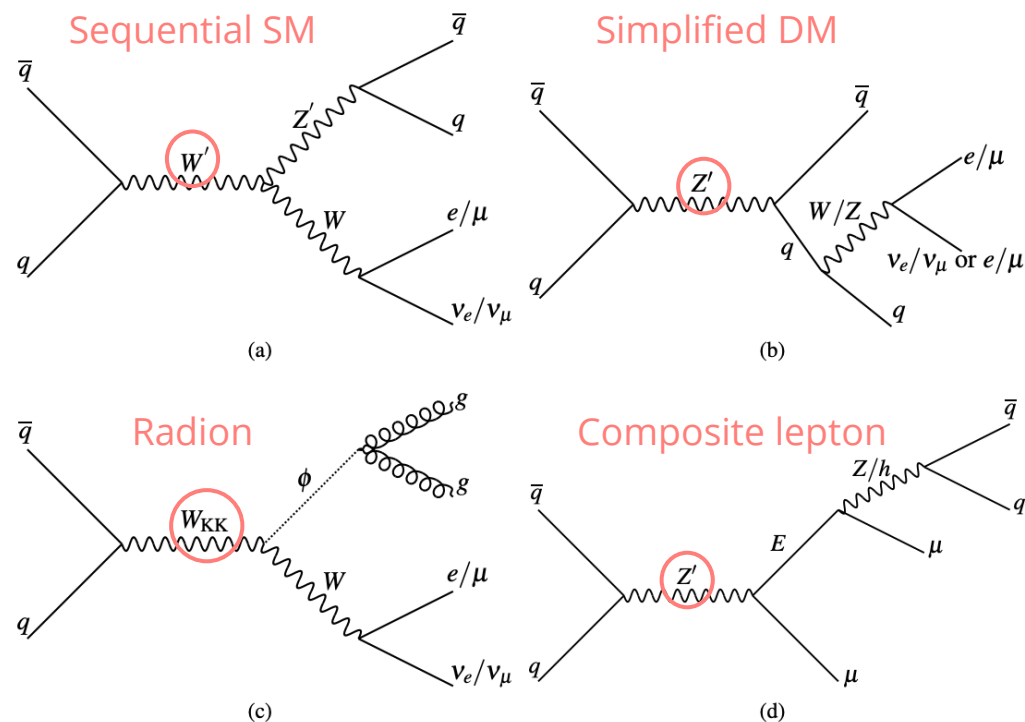Gap in parameter space now largely excluded
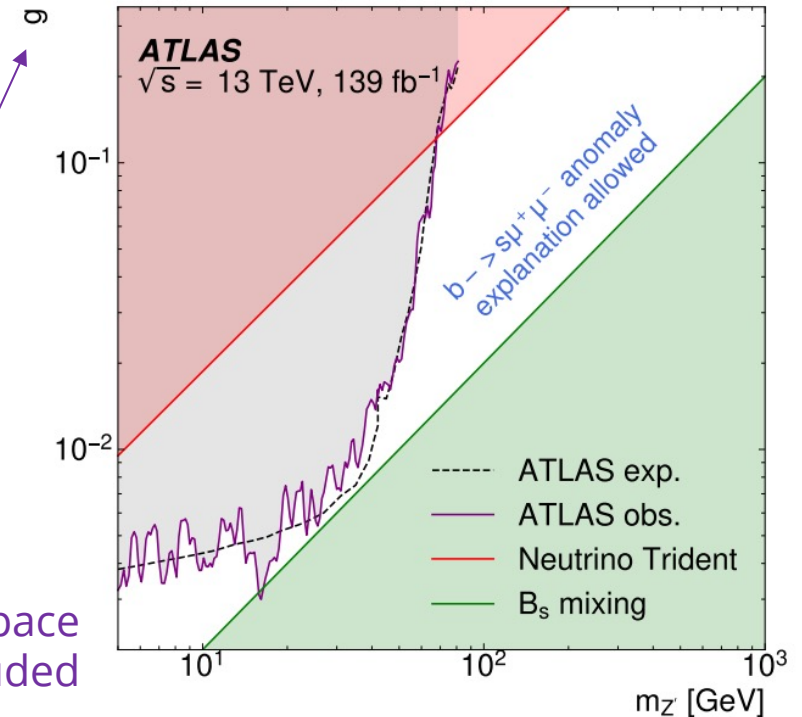
General searches

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Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton and two jets [arXiv:2211.08945]

➤ **Signal:** Generic $X \rightarrow Y\,C$, where Y and C are SM or BSM particles which decay via 2-body decay.

➤ **Channels:** $jj\ell,\ jjl\ell\ell,\ jb\ell,\ bb\ell$

Benchmark models

Search for new phenomena in multi-body invariant masses in events with at least one isolated lepton and two jets [arXiv:2211.08945]

➢ **Backgrounds**: Multijet (misidentified lepton), W+jets, $t\bar{t}$, single top.
All backgrounds estimated together by fitting to 5 parameter function.

➢ **Fit:** Use BumpHunter to find excesses over smoothly falling background.   Model dependent limits
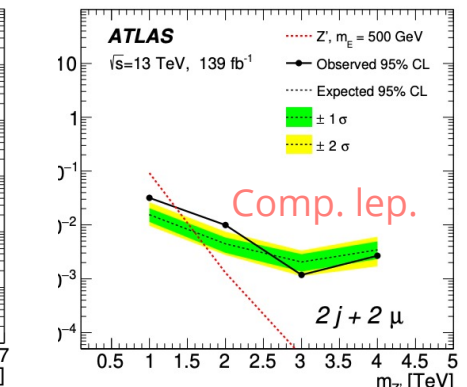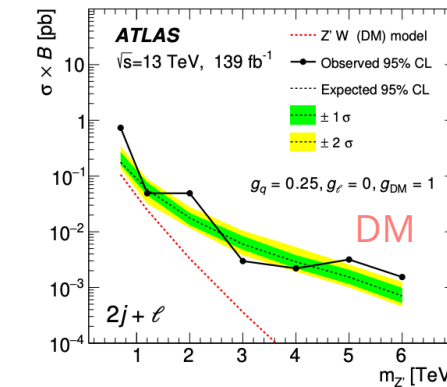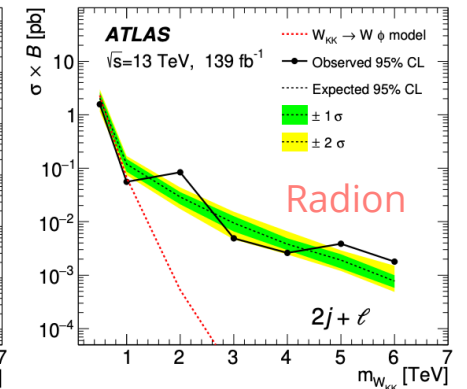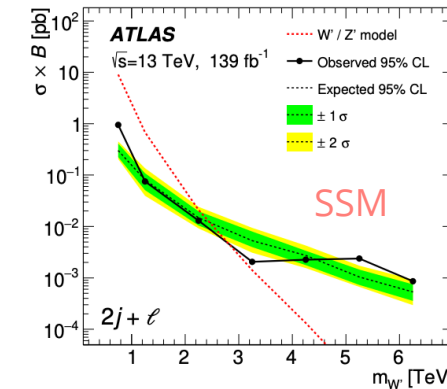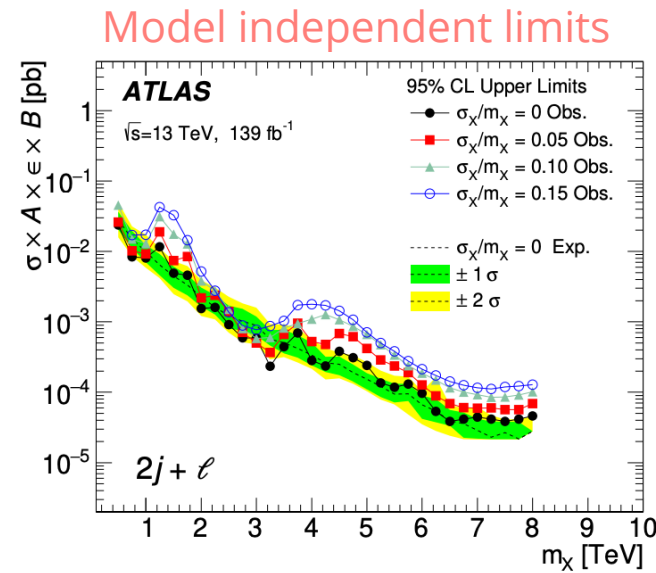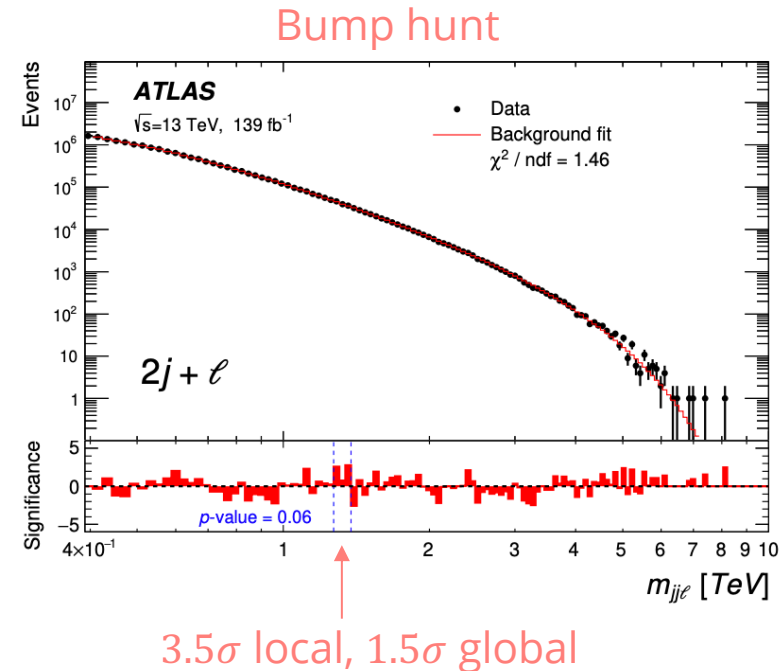
Bump hunt

Model independent limits

3.5σ local, 1.5σ global

SSM

Radion

DM

Comp. lep.

Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states [ATLAS-CONF-2022-045]

➢ **Signal:** Generic Y resonance. Sensitive to X masses spanning several orders of magnitude (~10 GeV - ~1 TeV).

➢ **Channels:** Anomaly detection + boosted and resolved $X \rightarrow q\bar{q}$

➢ **Reconstruction:** NN-based tagger optimized for the boosted $H \rightarrow b\bar{b}$ topology.
Anomaly detection based on jet-level anomaly score using *completely unsupervised* variational recurrent NN.
Merged/resolved regions defined based on jet substructure variables.
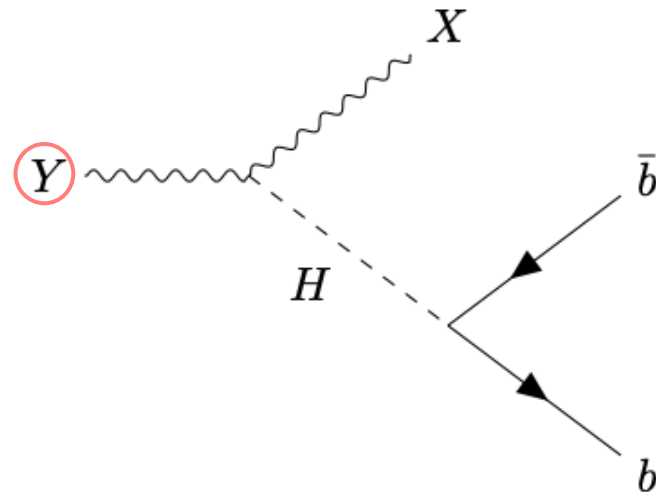
Anomaly detection search for new resonances decaying into a Higgs boson and a generic new particle X in hadronic final states [ATLAS-CONF-2022-045]

➢ **Backgrounds:** Mainly multijet, estimated with a fully data-driven method that incorporates a deep NN-based reweighting.

➢ **Fit:** Use BumpHunter to find excesses in model-independent interpretation.
    Profile likelihood fit with m_Y (invariant mass of reconstructed X and H) as discriminating variable.
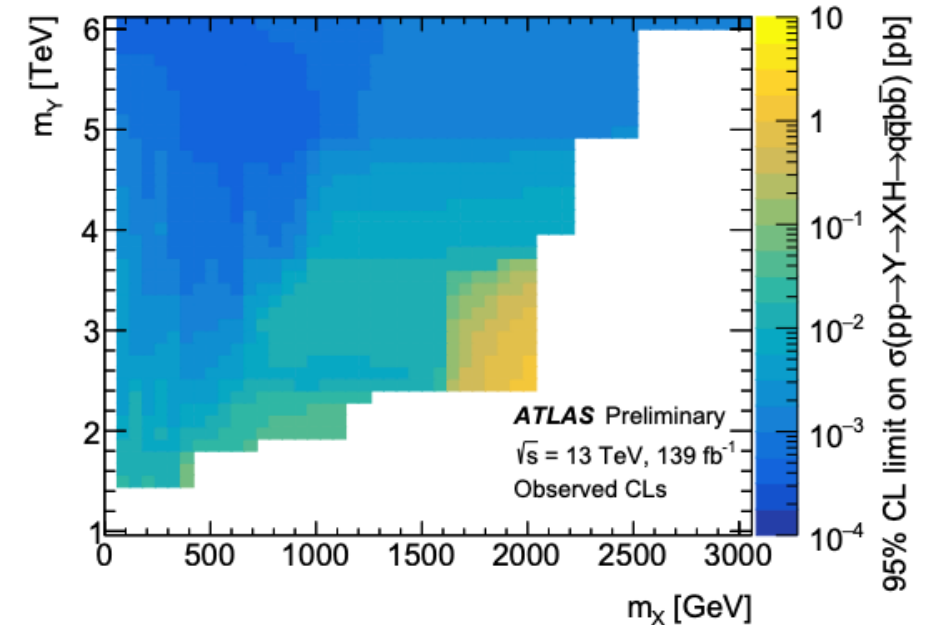
BumpHunter results in Anomaly Detection region
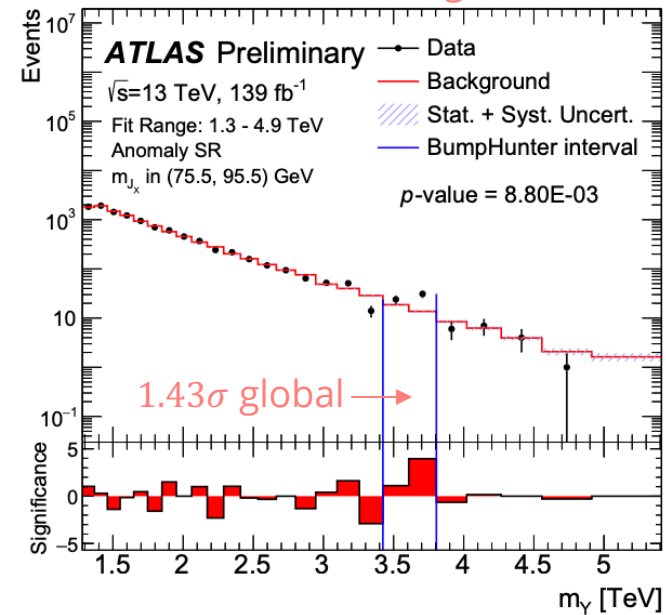
p-value scan in merged channel
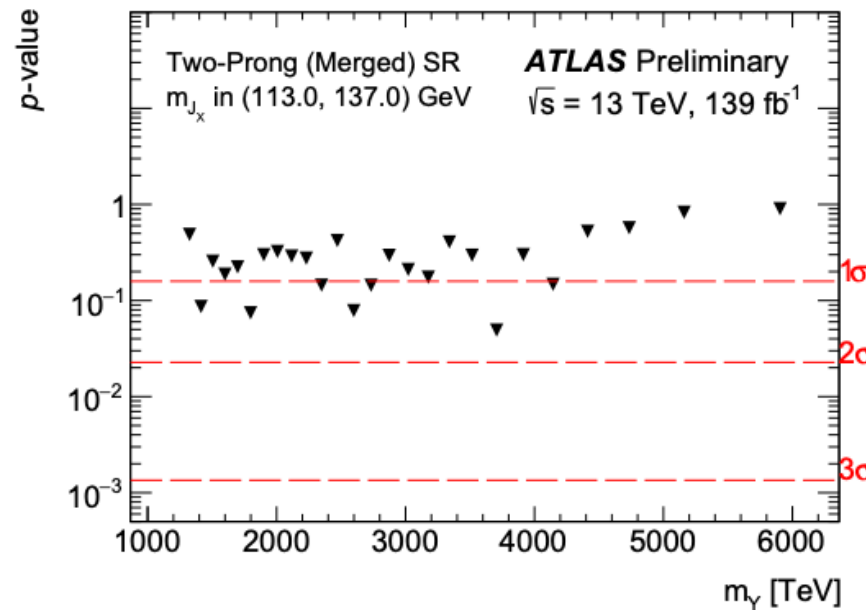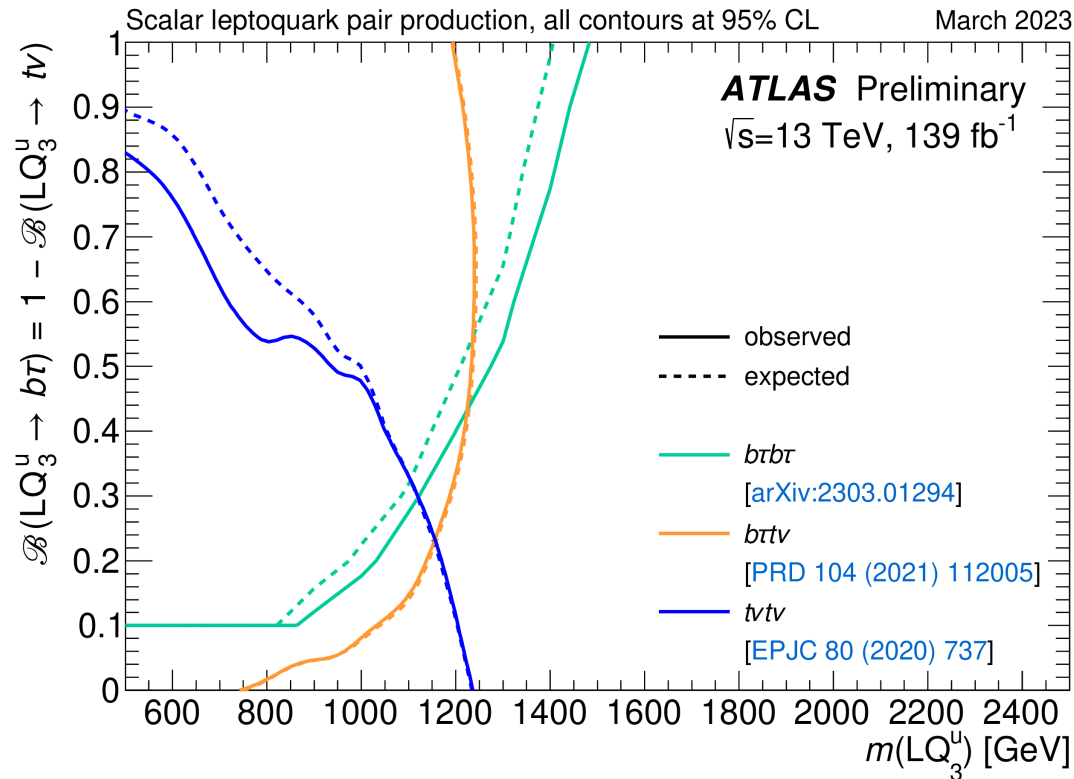
Model-dependent observed limits

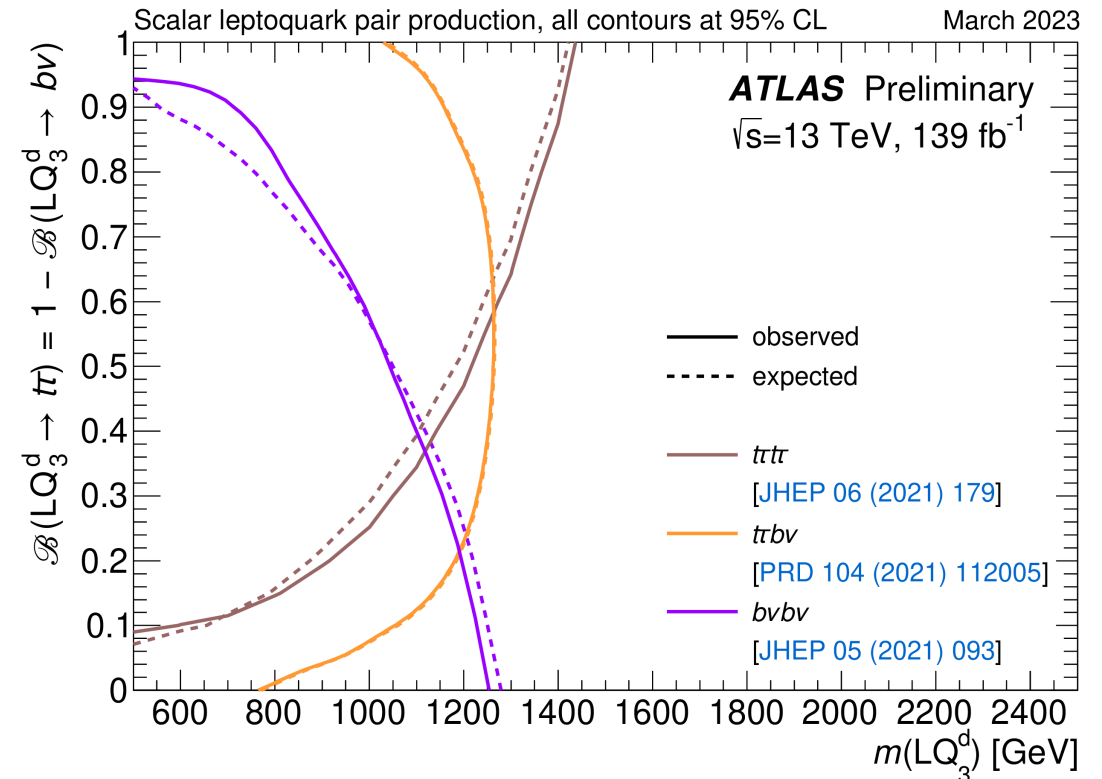Largest uncertainties from DNN and non-closure

Summary plots

[ATL-PHYS-PUB-2023-006]

Scalar third-generation up-type
leptoquarks with decays $LQ_3^u \rightarrow t\nu / b\tau$

Scalar third-generation down-type
leptoquarks with decays $LQ_3^d \rightarrow t\nu / b\tau$

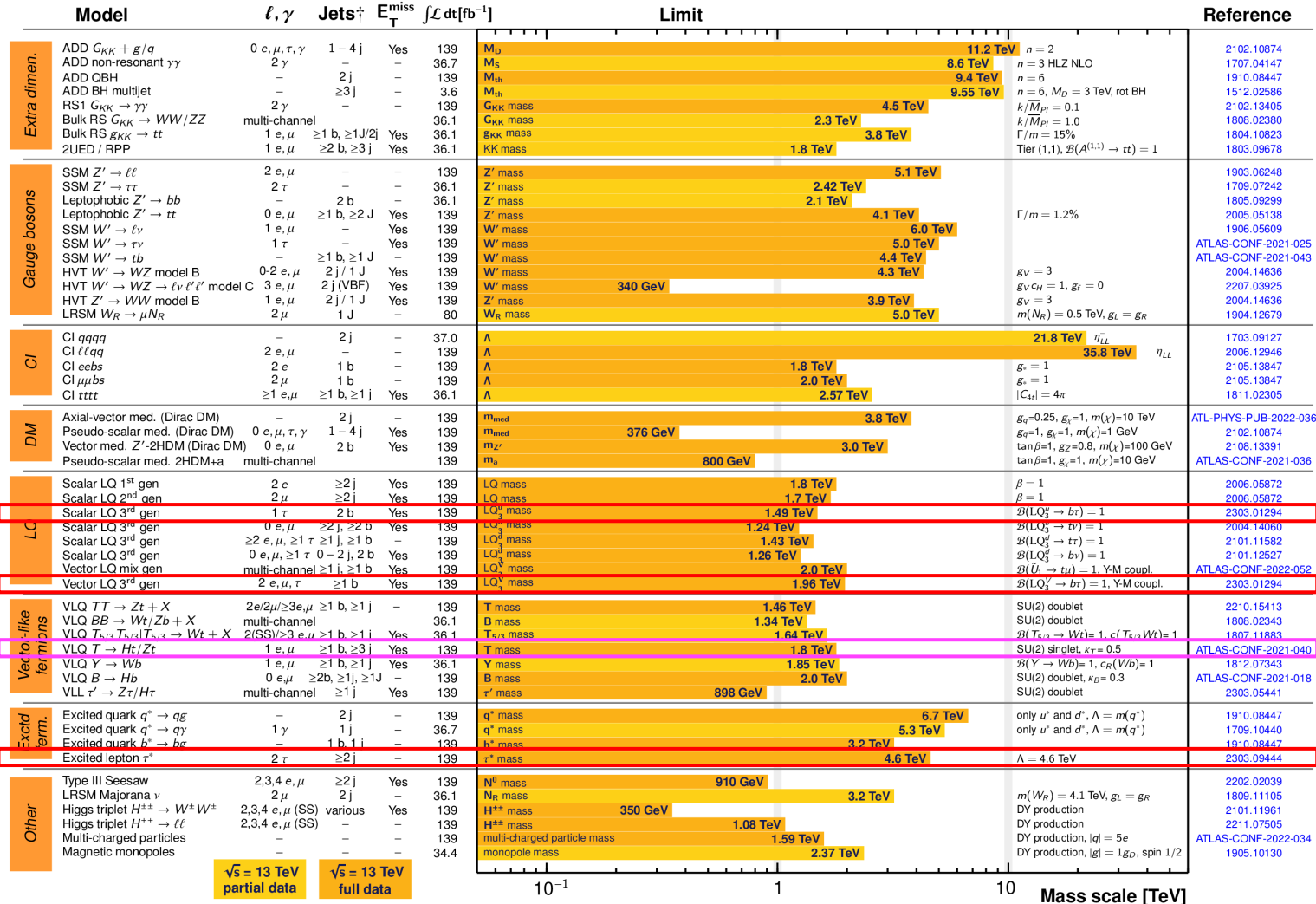ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

*Only a selection of the available mass limits on new states or phenomena is shown.
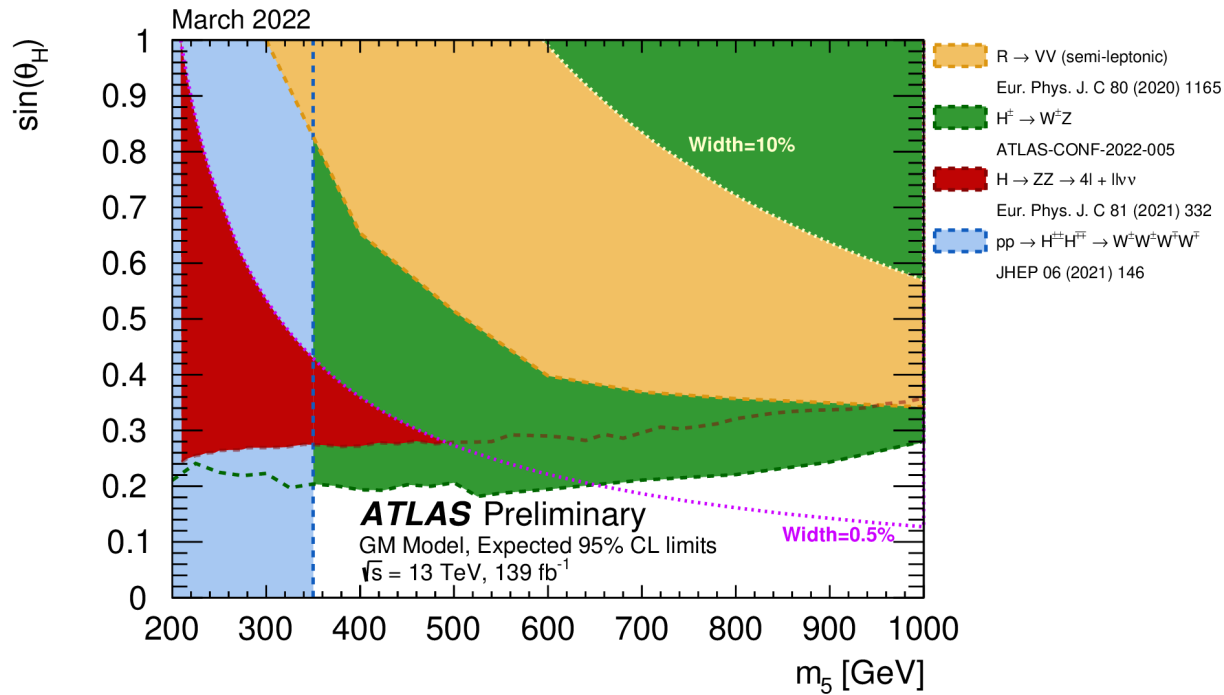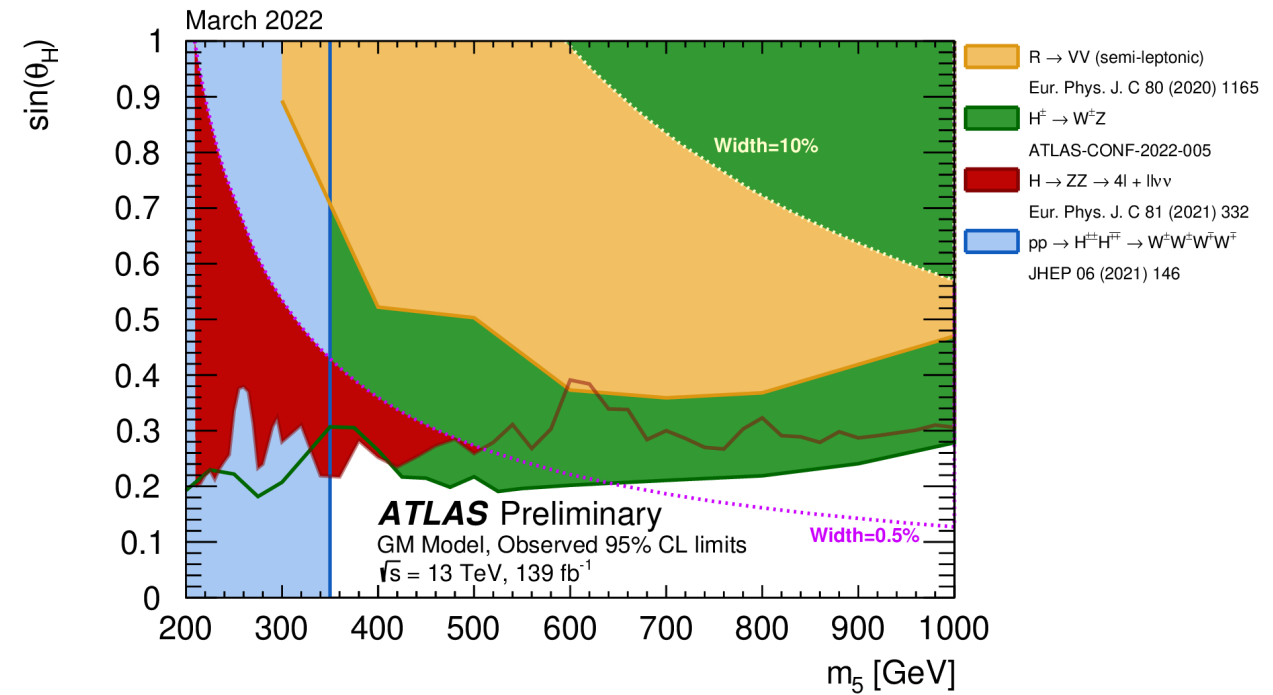†Small-radius (large-radius) jets are denoted by the letter j (J).

[ATL-PHYS-PUB-2022-008]

Expected limits from direct searches
for new, heavy, neutral or charged
Higgs bosons

Observed limits from direct searches
for new, heavy, neutral or charged
Higgs bosons

Conclusion

- ATLAS analyses cover a wide range of resonance searches.

- Many searches motivated by recently observed anomalies (lepton flavour universality, g-2, $t\bar{t} + W$ and $t\bar{t}t\bar{t}$ yields).

- New limits set on a variety of different theoretical models.

- Novel techniques for reconstruction and signal/background discrimination are being developed, many of which use machine learning, and are providing increased sensitivity.

Backup

• • •

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- Leptoquarks (LQs) = coloured bosons that carry both lepton and baryon numbers → couple to quarks and leptons.
- New Physics candidates to explain Lepton Flavour Universality and g-2 anomalies.

Search for leptoquarks decaying into $b\tau$ final state [public link when available]
- **Signal:** Vector LQ (U_1 model) with charge 2/3 and scalar LQ (S_1 model) with charge 4/3, only couples to 3rd generation
- **Channels:** $\tau_{lep}\,\tau_{had}$ and $\tau_{had}\,\tau_{had}$ channels in low and high b-jet p_T categories
- **Backgrounds:** $t\bar{t}$, single top, and $Z \to \tau\tau$ estimated using simulation with data-driven corrections. Multijet background estimated via a data-driven fake-factor method.
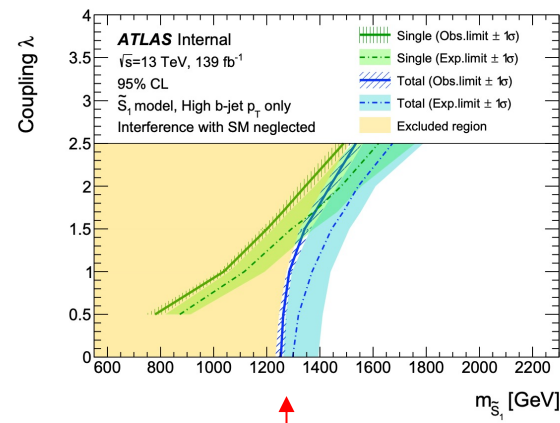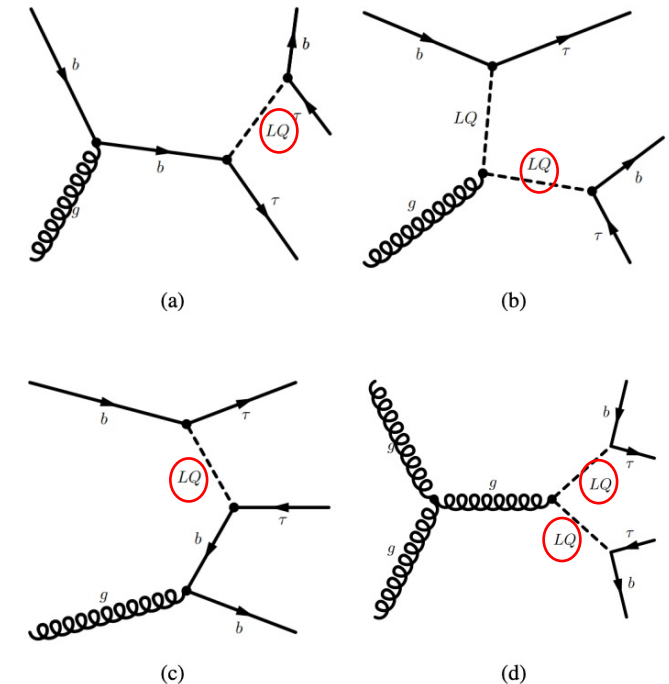
LQ - ℓ, q coupling
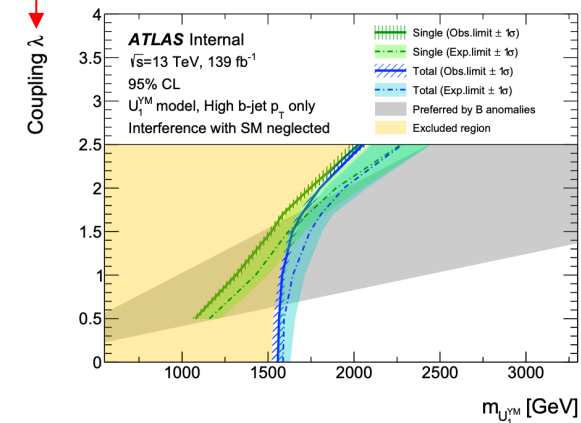
(a)
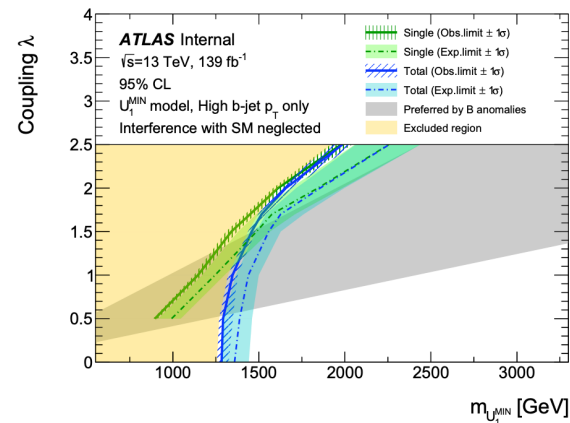
(b)

Vector LQ
(2 coupling scenarios with SM gluons)

Scalar LQ

Heavy resonances decaying to W bosons

Search for heavy resonances in the decay channel $W^+W^- \to e\nu\mu\nu$ [ATLAS-CONF-2022-066]

➤ **Signal:** Heavy neutral particle in 5 different models:
   1. Narrow width approximation (spin-0)   2. Georgi–Machacek model (fermiophobic) (spin-0)
   3. Radion in bulk Randall-Sundrum model (spin-0)   4. Z' boson in heavy vector triplet models (spin-1)
   5. Kaluza-Klein graviton (spin-2)

➤ **Channels:** $W^+W^- \to e\nu\mu\nu$, ggF and VBF (with 1 or ≥ 2 jets) regions.

Heavy resonances decaying to W bosons

(only showing VBF channel here)