Searches for new physics with leptons using the ATLAS detector

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Motivation

- Light charged leptons have a very clean detector signature and are "easy" to reconstruct and identify.
  - ATLAS is adding more and more of analyses with challenging τ in the final state.
- There are multiple open questions regarding lepton properties, e.g.
  - Which mechanism generates neutrino masses?
  - How to explain the flavour dependence of Yukawa coupling strength?
- Recent observations provide some hints on new physics, e.g.
  - Lepton Flavour Universality (LFU) violation in B meson decays (Eur. Phys. J. C 81, 226 (2021)),
  - Muon anomalous magnetic moment $(g-2)_\mu$ discrepancy (Phys. Rev. Lett. 126, 141801).

Searches with ATLAS

… with leptons in the final states (typically isolated, high-pt e, μ, τ)

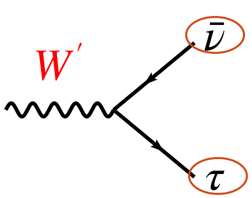
full Run 2 ATLAS dataset (139 fb^{-1})

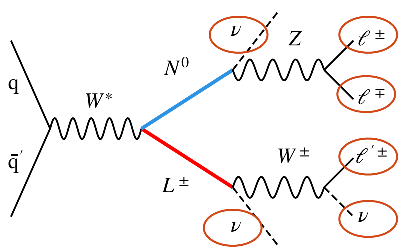
Direct searches

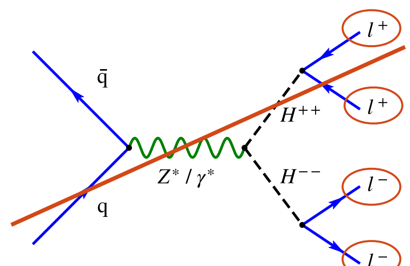
- ★ W' search,
- ★ Vector like τ's
- ★ Type-III seesaw (heavy leptons),
- ★ ~~Doubly Charged Higgs boson~~ (covered by Christian Weber),
- ★ Leptoquarks.

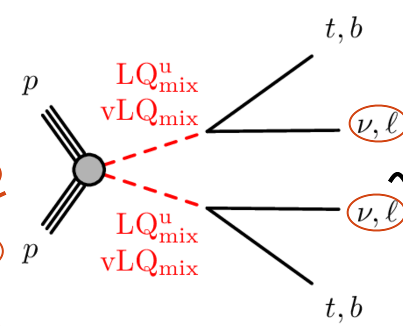
Indirect searches

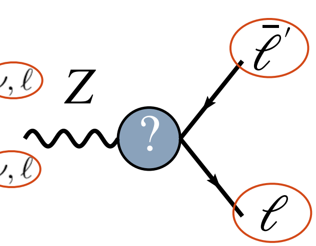
- ★ General multilepton,
- ★ Lepton Flavour Violation (LFV) in Z boson decays,
- ★ Charge/flavour x-sec asymmetry.





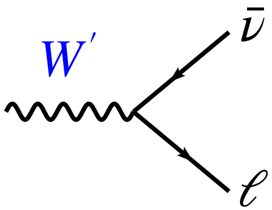


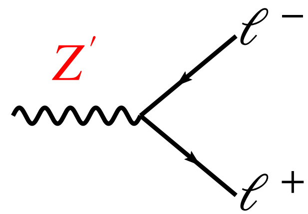


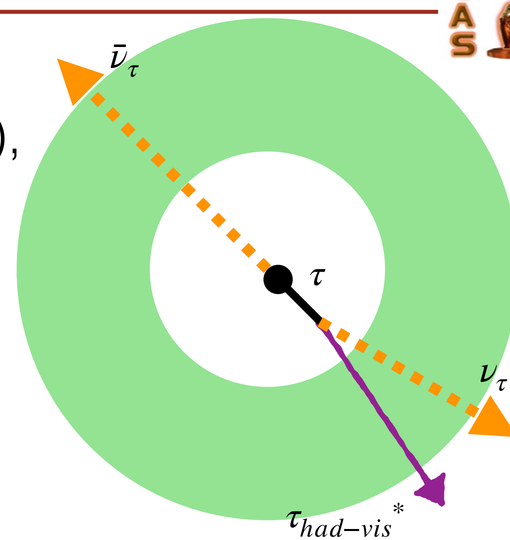


Searches for heavy gauge bosons

★ ATLAS performed searches for the new gauge bosons within the Sequential Standard Model (SSM), which is the flavour-universal benchmark model.





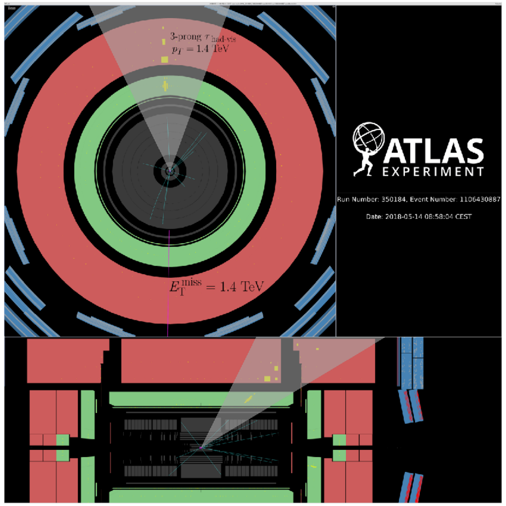


* visible decay products, typically one or three charged pions and up to two neutral pions.

★ Past analyses provided upper mass limits of 6 TeV for the W' boson and 5.1 TeV for the Z' boson at 95% CL from the:

- ★ [EXOT-2018-30]: $W' \to \ell\nu$ decay, where $\ell = e, \mu$;
- ★ [EXOT-2018-08]: $Z' \to \ell\ell$ decay.

★ These results have now been complemented with analysis of $W' \to \tau\nu$ decays: [ATLAS-CONF-2021-025]



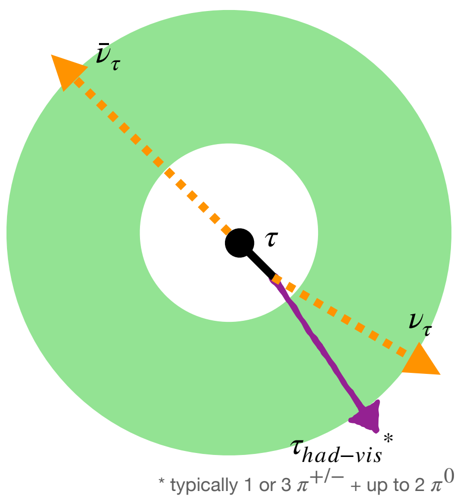
ATLAS-CONF-2021-025

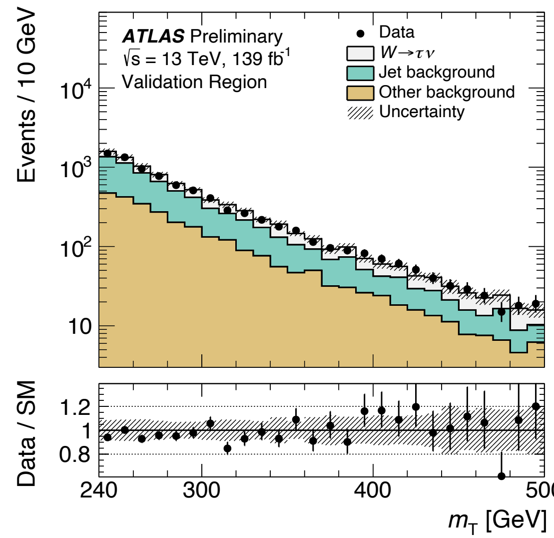
Search for $W' \rightarrow \tau_{had}\nu$ decays I

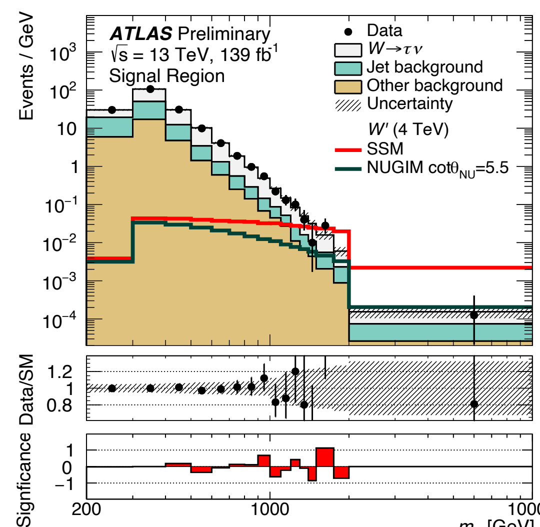
- Only **hadronic** τ decay modes that are identified with a Recurrent Neural Network (RNN) are considered (~65% of all τ decays):
  - RNN uses calorimeter shower shape and tracking information to suppress background.
- Signature of the $W' \rightarrow \tau\nu$ decays:
  - High transverse momentum of τ decays,
  - Large missing transverse momentum, E_T^{miss}.
- Discriminant variable:

$$m_T = \sqrt{2\ E_T^{miss}\, p_T\ (1 - \cos\Delta\phi)}.$$

- Main backgrounds:
  - off-shell $W \rightarrow \tau\nu$ (*simulation*),
  - QCD jets (*data-driven*),
  - Other: $W/Z/\gamma^*$ decays, $t\bar{t}$, single top-quark, VV.





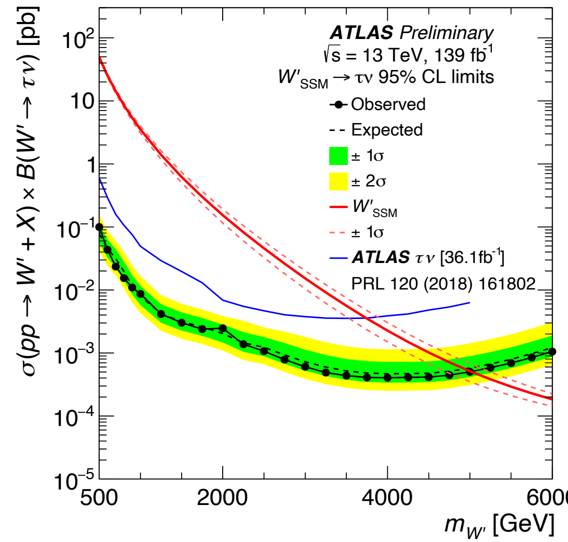


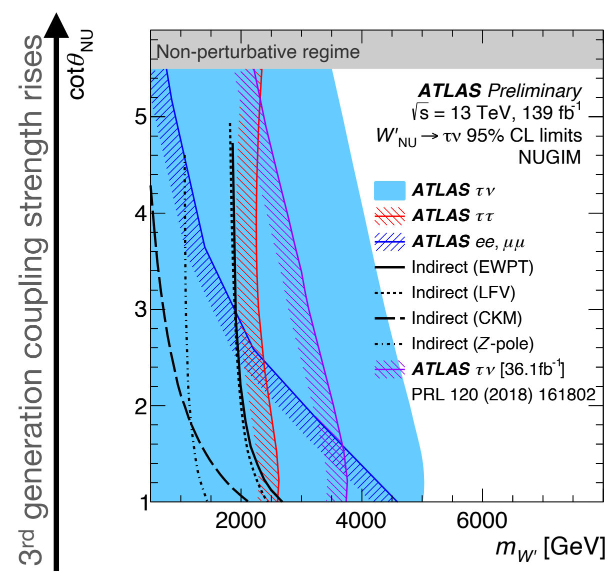
ATLAS-CONF-2021-025

Search for $W' \rightarrow \tau_{had}\nu$ decays II

- ★ **No significant excess** over SM prediction observed.

- ★ Investigated models and their corresponding **limits**:
  - ★ **Sequential Standard Model** (SSM): Heavy W' bosons with masses up to **5.0 TeV** are excluded at 95% CL (SSM assumes the same couplings as for SM W boson).
  - ★ **Non-Universal Gauge Interaction Model** (NUGIM): For non-universal couplings, W' bosons are excluded for masses less than **3.5 – 5.0 TeV**, depending on the model parameters. Values of $\cot\theta_{NU} > 1$ enhance the couplings to the third generation.

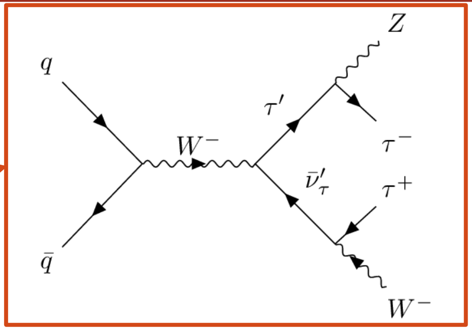




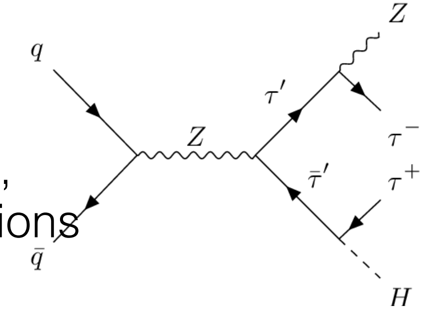
ATLAS-CONF-2021-025

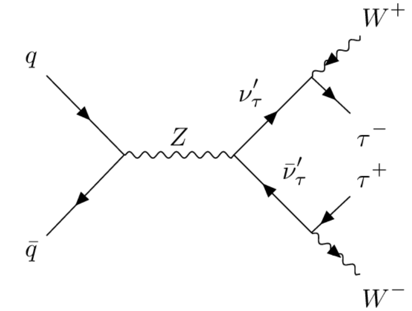
Vector like τ's I

- ★ Search for Third-Generation Vectorlike Leptons (VLL).
  - ★ $L' = (\nu_\tau', \tau')$, ~equal m, couple only to the 3rd gen.



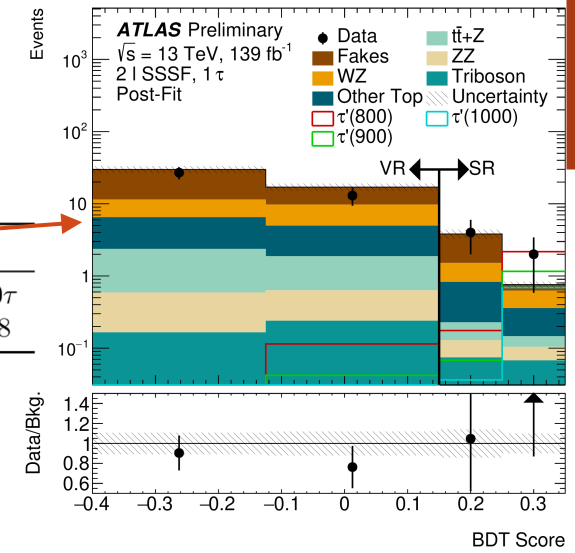
- ★ Production processes:
  - ★ $pp \to \nu_\tau'\tau'$ (dominant),
    $pp \to \tau'^+\tau'^-$ and $pp \to \nu_\tau'\bar{\nu}_\tau'$





- ★ Event selection: at least two light leptons, zero or more hadronic τ's → 7 signal regions

- ★ Boosted Decisions Tree (BDT) algorithm is used as an event classifier.



- ★ Signal Regions and BDT scores:

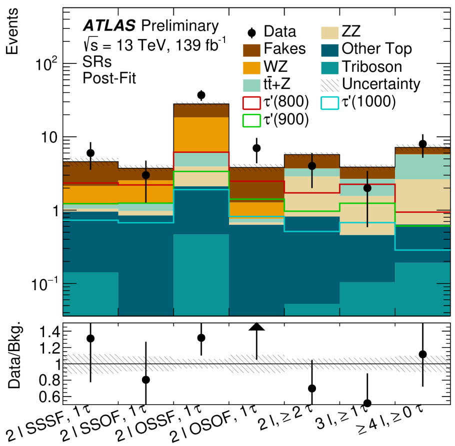
Variables	Signal Regions						
BDT	2ℓ SSSF, 1τ	2ℓ SSOF, 1τ	2ℓ OSSF, 1τ	2ℓ OSOF, 1τ	2ℓ, $\geq 2\tau$	3ℓ, $\geq 1\tau$	4ℓ, $\geq 0\tau$
BDT Score	≥ 0.15	≥ 0.1	≥ 0.1	≥ 0.1	≥ -0.11	≥ 0.08	≥ 0.08

- ★ Background: dominated by $t\bar{t}$, VV and QCD.
  - ★ MC simulation + fake-factor method.

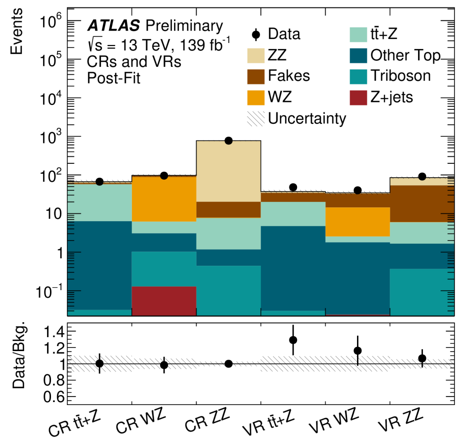
ATLAS-CONF-2022-044

Vector like τ's II

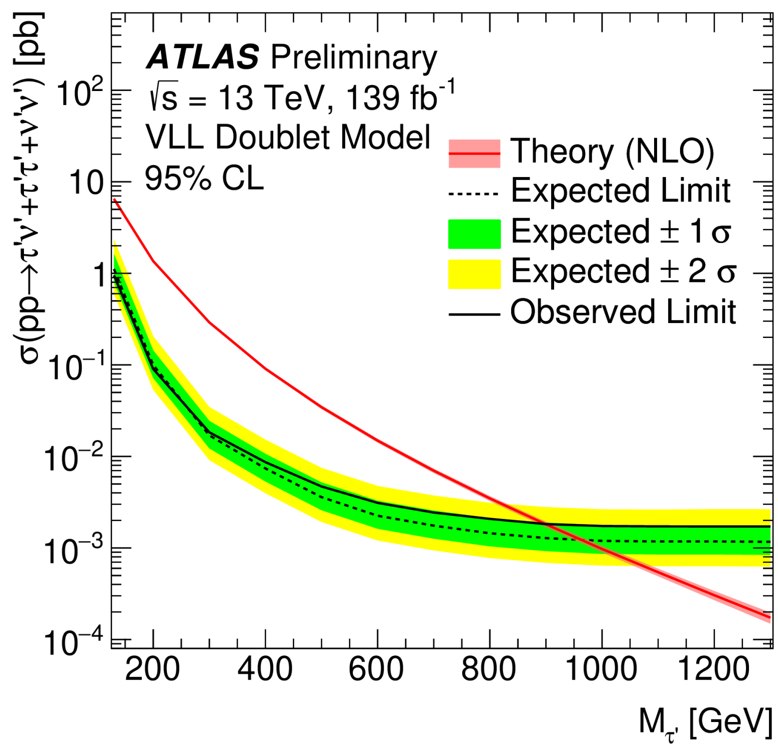
★ No excess of events above SM expectation.



signal regions



control & validation regions



ATLAS-CONF-2022-044

$M(\tau') > 900\ (970)\ GeV$ observed (expected) @ 95% CL.

Type-III seesaw heavy leptons I

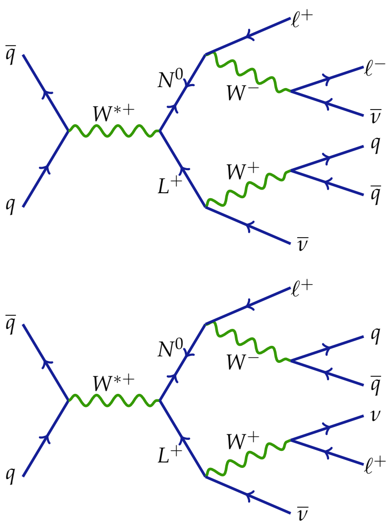
- ★ At least one extra fermionic $SU(2)_L$ triplet predicted by the type-III seesaw mechanism:
  - ★ Pair production of new heavy charged ($L^{\pm}$) and neutral (N^0) leptons.

$$N^0 \rightarrow Z\nu, H\nu, W^{\pm}\ell^{\mp}$$
$$L^{\pm} \rightarrow H\ell^{\pm}, Z\ell^{\pm}, W^{\pm}\nu$$

- ★ A heavy Majorana neutrino could explain the small masses of SM neutrinos.

2 leptons in the final state

[EXOT-2018-33]

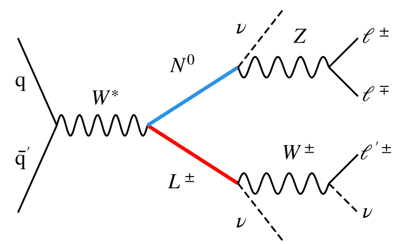


Observables: $H_T + E_T^{miss}$

scalar sum of p_T of all selected objects in the event

3 leptons in the final state

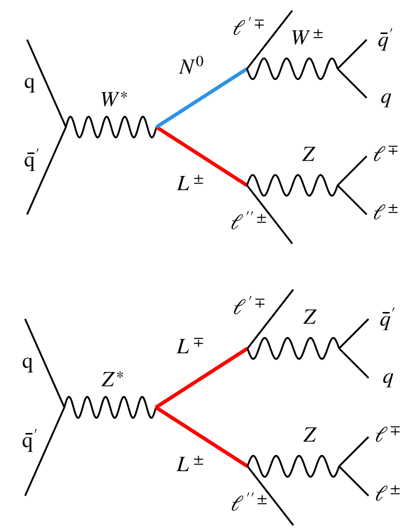
[EXOT-2020-02]



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

4 leptons in the final state

[EXOT-2020-02]

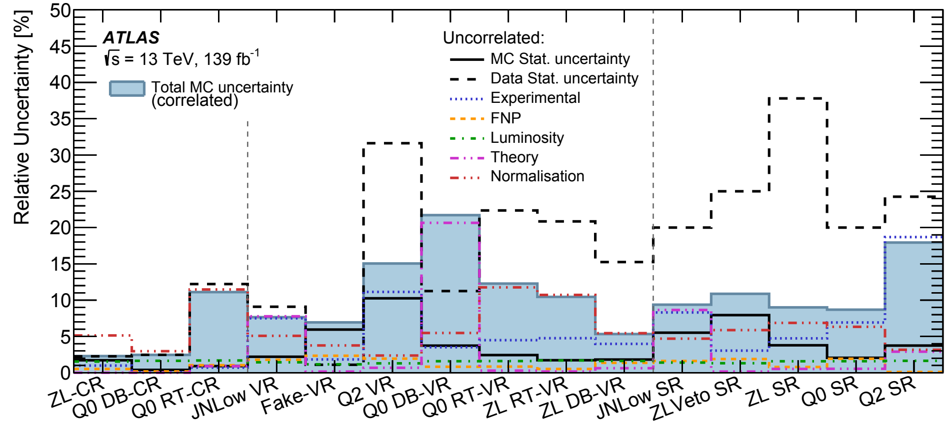


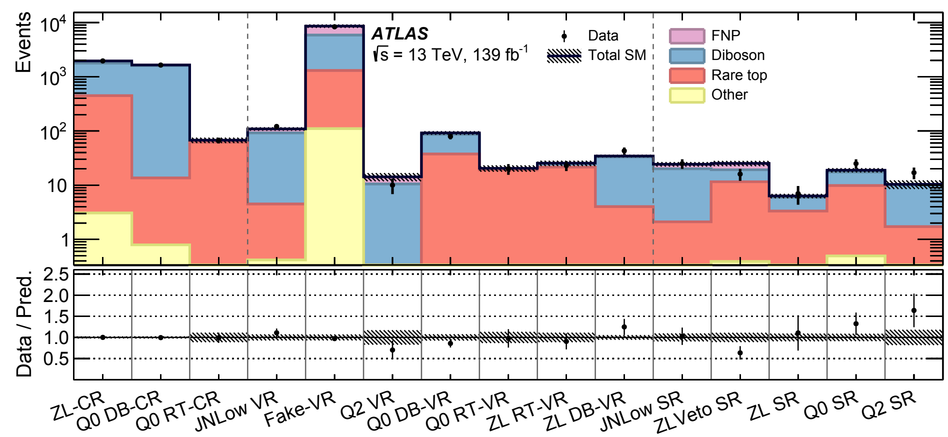
$$H_T + E_T^{miss}$$

arXiv:2202.02039

Type-III seesaw heavy leptons II

- ★ Only **light leptons** (e, μ) considered in the final states with **democratic scenario** $\mathscr{B}_e = \mathscr{B}_\mu = \mathscr{B}_\tau = 1/3$.
- ★ Main backgrounds:
  - ★ Reducible: fake/non-prompt (FNP) leptons,
  - ★ Irreducible: diboson (VV), rare top $(t\bar{t}V)$.
- ★ The measurement is **statistically limited**.

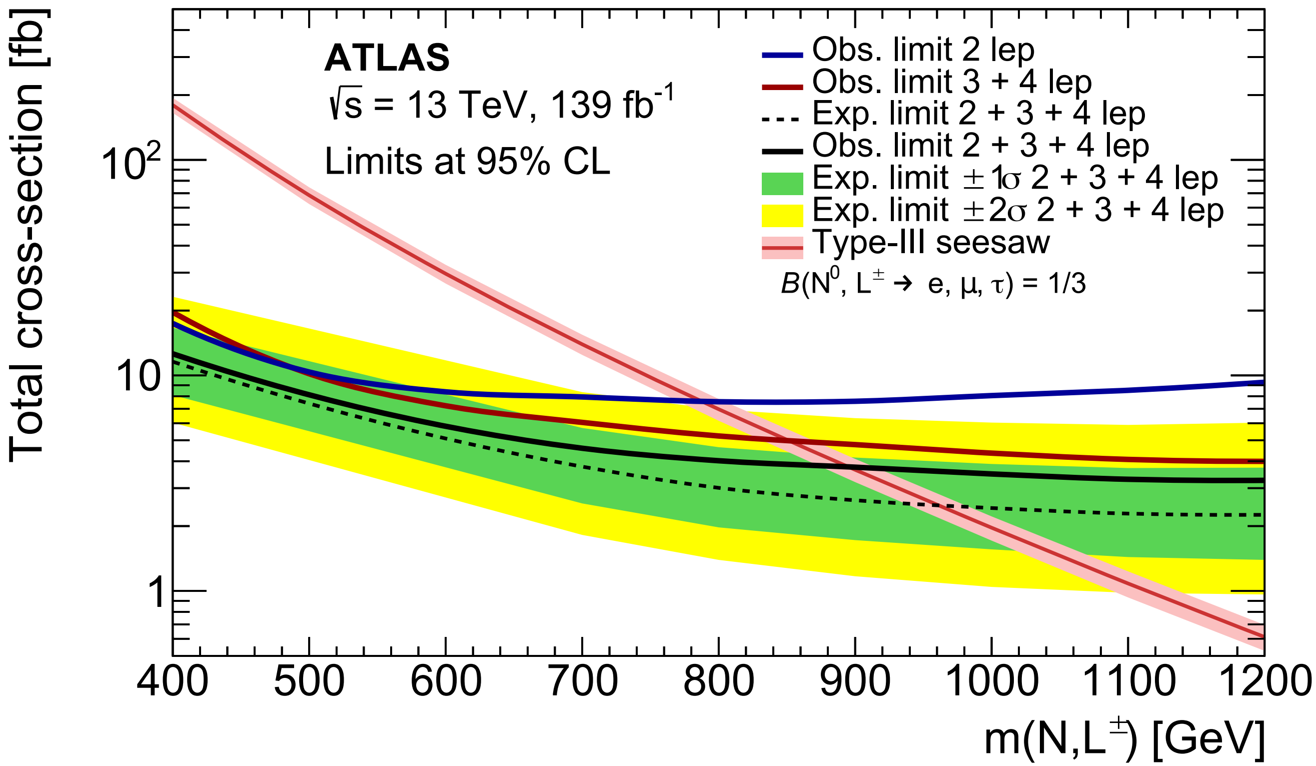




arXiv:2202.02039

Type-III seesaw heavy leptons III

- ★ <u>No significant excess</u> over SM prediction observed.
- ★ Most stringent limits on type-III seesaw models at LHC:



arXiv:2202.02039

$m(N^0, L^{\pm}) > 910\ (960^{+90}_{-80})\ GeV$ observed (expected) @ 95% CL.

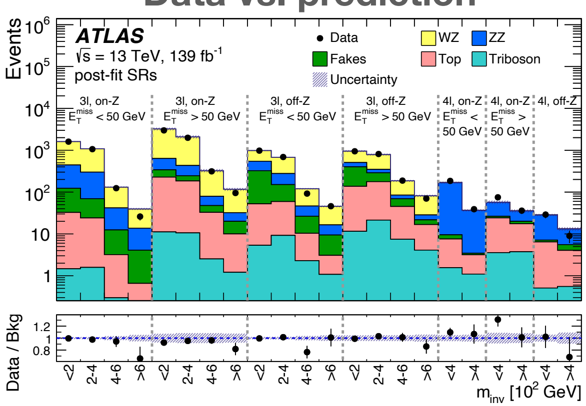
2+3+4 leptons

Model independent 3 or 4-lepton events

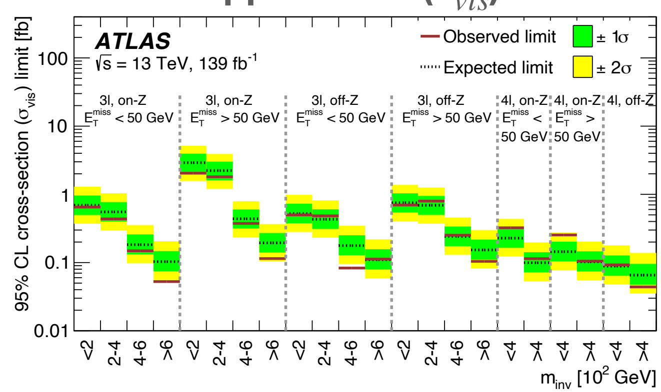
- As seen in previous slides, several BSM theories give multi-lepton ($3\ell+, \ \ell = e, \mu$) final states.
- A search with minimal model dependence of BSM physics aimed to cover wide range of potential new-physics simultaneously in three- and four-lepton final states.
- ***22 signal regions*** were constructed according to **number** of the leptons, **invariant mass** of the leptons, **the missing transverse momentum** and the presence of leptons originating **from Z boson decay**.

arXiv:2107.00404

Data vs. prediction



Upper limits (σ_{vis})



Model specific limits

Model	Mass [GeV]	σ^{95}_{exp} [fb]	σ^{95}_{obs} [fb]
Type-III Seesaw	400	41^{+17}_{-11}	27
	700	12^{+5}_{-3}	8.8
$H^{\pm\pm}$	300	$0.18^{+0.08}_{-0.05}$	0.12
	500	$0.16^{+0.07}_{-0.05}$	0.11

3ℓ and 4ℓ final states considered, where $\ell = e, \mu$.

Lepton Flavour Violation in Z decays

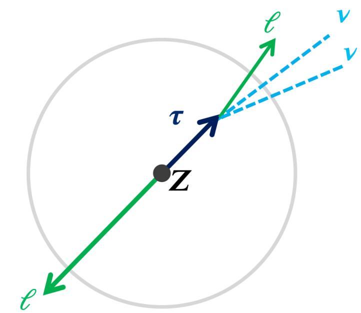
- ★ Lepton Flavour Violation (LFV) is extremely rare within the SM:
  - ★ e.g. possible through neutrino oscillations with $\mathscr{B}(Z \to e\mu) < \sim 10^{-54}$,
  - ★ excellent probe of new physics — deviation would immediately indicate new physics,
  - ★ very small signal in a huge background.
- ★ ATLAS analyses have been published recently:
  - ★ $Z \to e\tau$ and $Z \to \mu\tau$: [EXOT-2018-36] hadronic τ decays results and [EXOT-2020-28] leptonic ones,
  - ★ $Z \to e\mu$: [EXOT-2018-35].
- ★ Machine learning methods have been used to discriminate between signal and background.

LFV in $Z \to e\tau$ and $Z \to \mu\tau$ decays I

- Previous search for Z boson LFV decays involving τ leptons done with τ decaying ***hadronically*** [EXOT-2018-36]:
  - $\mathscr{B}(Z \to e\tau_{had}) < 8.1 \times 10^{-6}$ and $\mathscr{B}(Z \to \mu\tau_{had}) < 9.5 \times 10^{-6}$.

- … were complemented with inclusion of ***leptonically*** decaying τ, which significantly improved the sensitivity reach for the $Z \to \ell\tau$ decays [EXOT-2020-28].

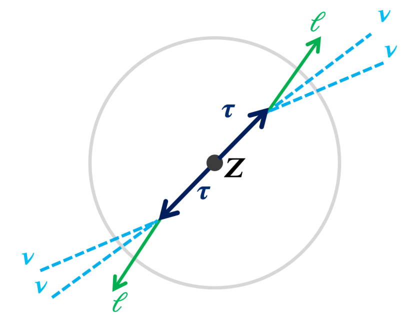
- Signal signature $Z \to \ell^{\pm}\ell'^{\mp} + 2\nu$:
  - two **light** charged leptons (**different flavour + opposite charge**) and two neutrinos,
  - Invariant mass of the final state close to the Z **boson mass**,
  - **two leptons** emitted approximately **back-to-back**,
  - τ is typically **boosted** $\to$ two neutrinos collinear with the light lepton from the τ decay.



signal

arXiv:2105.12491

- Main backgrounds:
  - lepton flavor conserving $Z \to \tau\tau \to \ell\ell' + 4\nu$,
  - $t\bar{t}$, VV, Higgs production,
  - small contribution of $Z \to \ell\ell$ with flavour of one ℓ being misidentified.

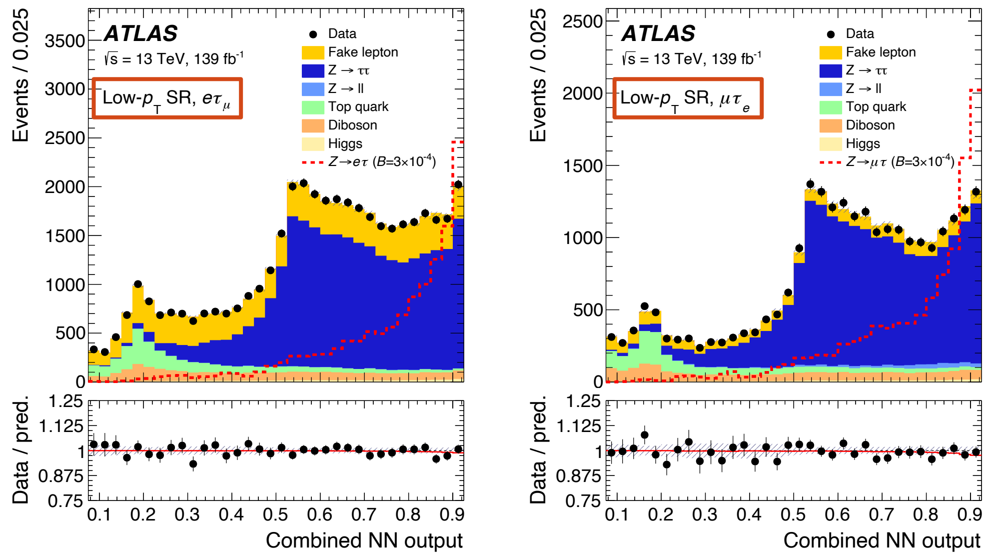


background

LFV in $Z \to e\tau$ and $Z \to \mu\tau$ decays II

- ★ Signal was optimised using deep neural network:
  - ★ It was individually trained on main backgrounds: $Z \to \tau\tau;\ t\bar{t};\ VV$.
- ★ Search is dominated by the **statistical uncertainty**.
- ★ Upper limits improved and are now by a **factor of 2** better compared to LEP limits

Observed and best-fit predicted distributions in the SRs



$Z \to e\tau \to e\ \mu\nu\nu$ $\qquad$ $Z \to \mu\tau \to \mu\ e\nu\nu$

arXiv:2105.12491

LFV Z decay	previous UL	only τ_{lep} decays UL	new combined UL
$\mathcal{B}(Z \to e\tau)$	9.8×10^{-6} [OPAL]	7.0×10^{-6}	5.0×10^{-6}
$\mathcal{B}(Z \to \mu\tau)$	12×10^{-6} [DELPHI]	7.2×10^{-6}	6.5×10^{-6}

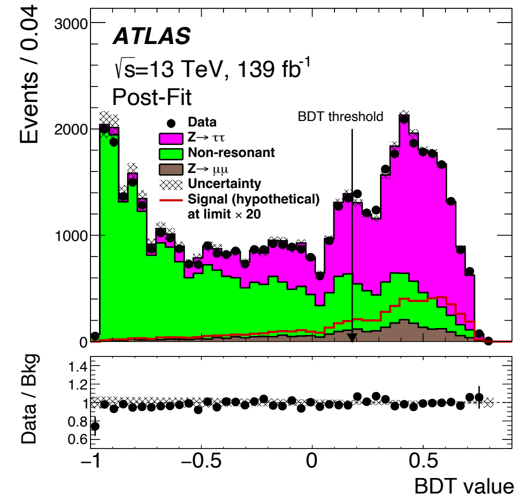
@ 95% CL

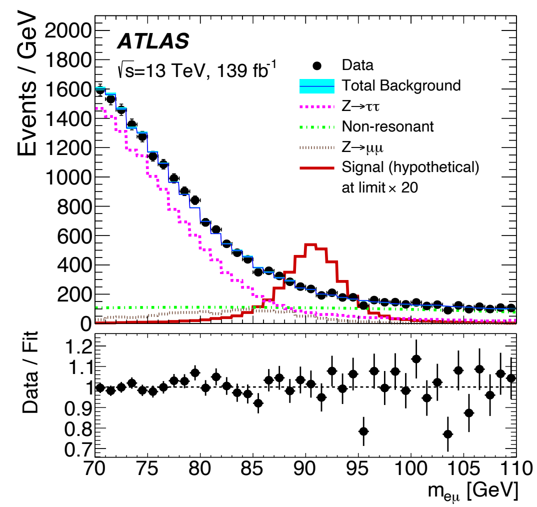
LFV in $Z \to e\mu$ decays

- Search for a $Z \to e\mu$ peak in the $m_{e\mu}$ invariant mass distribution.
- Main backgrounds:

  estimated from MC
  - $Z \to \tau\tau \to e\mu\nu_e\nu_\mu\nu_\tau\nu_\tau$,
  - $Z \to \mu\mu$ with μ misidentified as an electron,
  - $t\bar{t} \to e\mu\nu\bar{\nu}b\bar{b}$ and $WW \to e\mu\nu\bar{\nu}$.

  flat polynomial fit
- Analysis strategy:
  - Veto events with high-p_T jets and large E_T^{miss},
  - Further signal optimisation and background rejection by BDT and b-veto.
- Analysis is **statistically limited** both in data and simulation.





$\mathscr{B}(Z \to e\mu) < 2.62\ (2.37) \times 10^{-7}$ observed (expected) @ 95% CL.

arXiv:2204.10783

Search for $e^+\mu^-$ to $e^-\mu^+$ asymmetry I

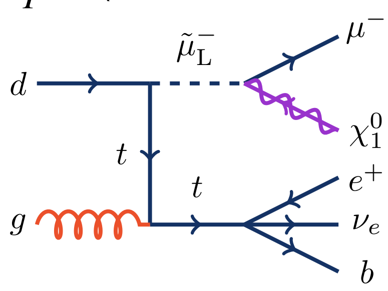
- Novel search at ATLAS compares production cross-sections for $e^+\mu^-$ and $e^-\mu^+$ pairs to constrain BSM physics processes [EXOT-2018-29].

- Standard Model predicts the ratio to be 1, but several BSM theories predict ρ to be significantly greater than one:
  - **R-parity-violating (RPV) SUSY** models with smuons $\tilde{\mu}_L$,
  - **scalar leptoquark** with couplings permitting $S_1 \to ue^-, c\mu^-$.

$$\rho \equiv \frac{\sigma(pp \to e^+\mu^- + X)}{\sigma(pp \to e^-\mu^+ + X)}$$

- Signal regions designed to address these scenarios:

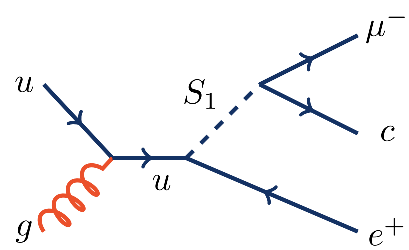
A. High E_T^{miss} (**SR-MET** and **SR-RPV**)



observable:

$$M_{T2} = \min_{\vec{a}+\vec{b}=\vec{p}_T^{miss}} \max\left(m_T(e,\vec{a}), m_T(\mu,\vec{b})\right)$$

B. High jet multiplicity (**SR-JET** and **SR-LQ**)

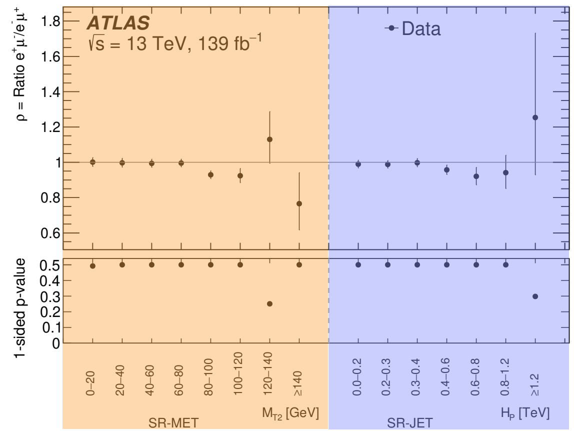


observable: $H_P = |\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\mu}| + |\vec{p}_T^{\,j_1}|$

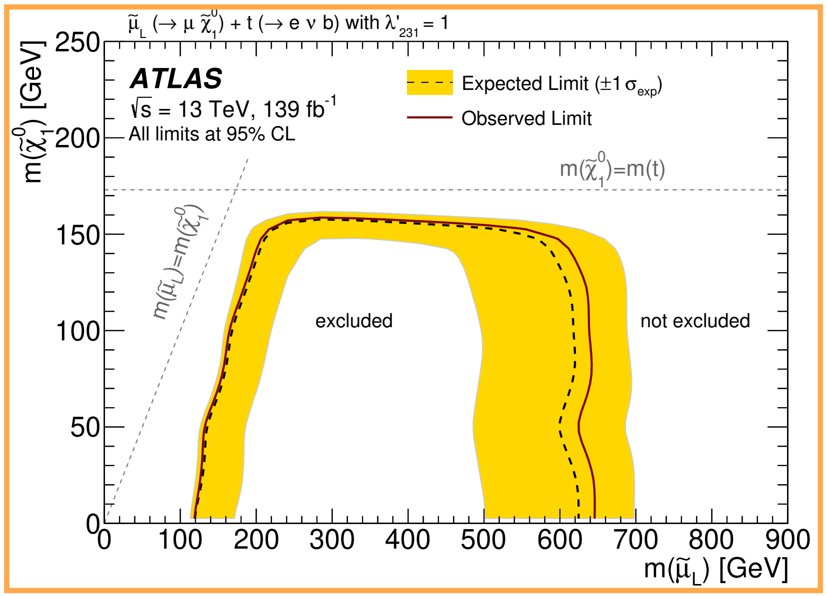
arXiv:2112.08090

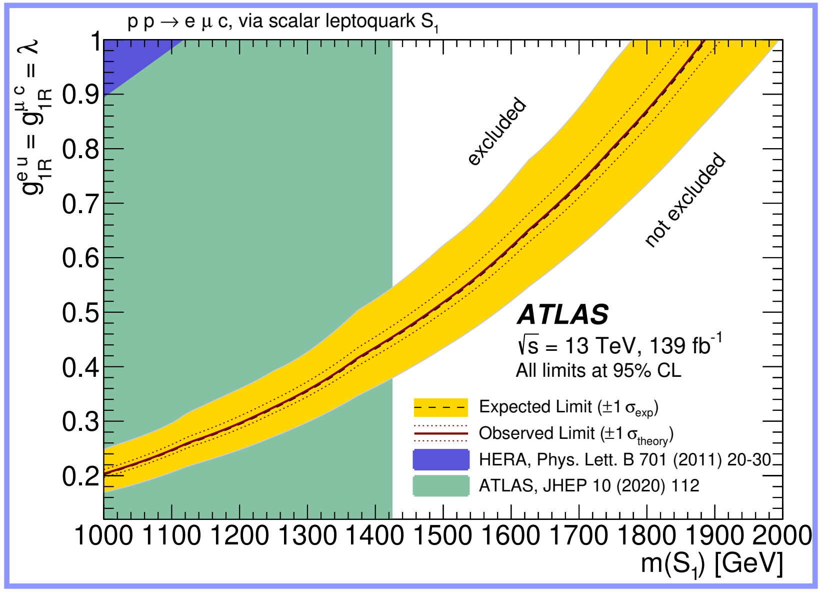
Search for $e^+\mu^-$ to $e^-\mu^+$ asymmetry II

- ★ Experimental effects bias the measured ratio (ρ) downwards, e.g. mis-ID e vs. μ, $\sigma(W^+j) > \sigma(W^-j)$ — analysis is searching for positive deviations of ρ.
- ★ Analysis is almost completely **data-driven** (mis-ID leptons, detector effects in muon reconstruction).
- ★ Data is consistent with the SM hypothesis, so upper limits on **RPV SUSY** and **LQ** models are set.



arXiv:2112.08090





Leptoquarks I

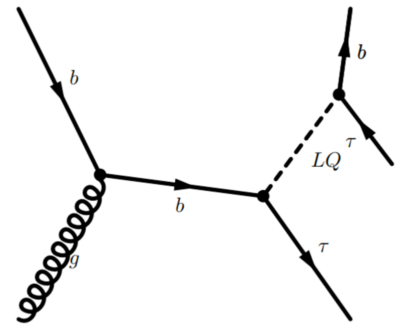
- ★ Good candidates to explain observed $B-$anomalies and $(g-2)_\mu$ prediction-measurement discrepancy.

- ★ Search for scalar and vector leptoquarks singly-produced or pair-produced with the ATLAS detector

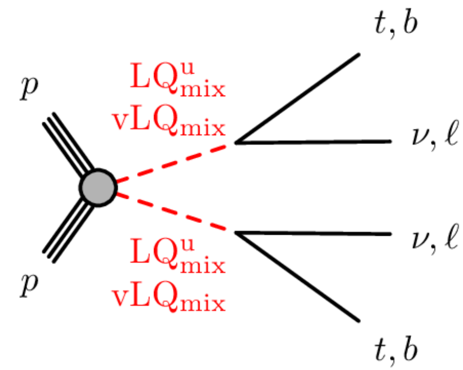
  - ★ $LQ_s \to b\tau_{had}/b\tau_{lep} \ldots + \tau_{had}$
    $(4/3e,\ 3B+L=-2)$

  - ★ $LQ^{u(d)}_{mix} LQ^{u(d)}_{mix} \to t\nu b\ell / t\ell b\nu$
    $(s: -1/3e,\ s\ \&\ v: 2/3e,\ \ell = e, \mu)$

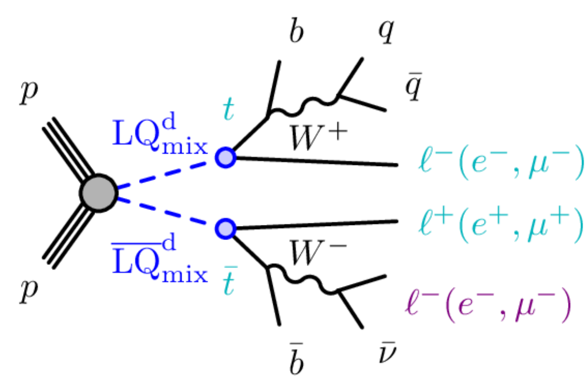
  - ★ $LQ^{d}_{mix} LQ^{d}_{mix} \to t\ell t\ell$
    $(-1/3e,\ \ell = e, \mu)$



ATLAS-CONF-2022-052



ATLAS-CONF-2022-009



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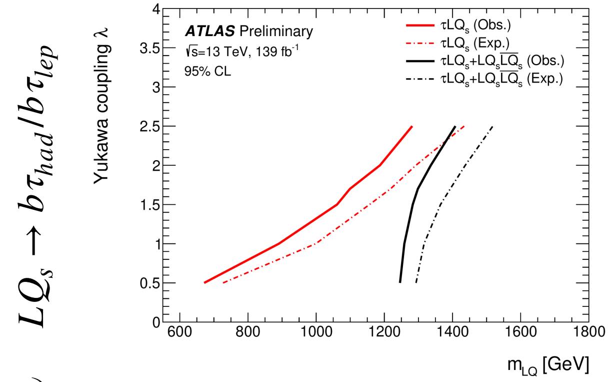
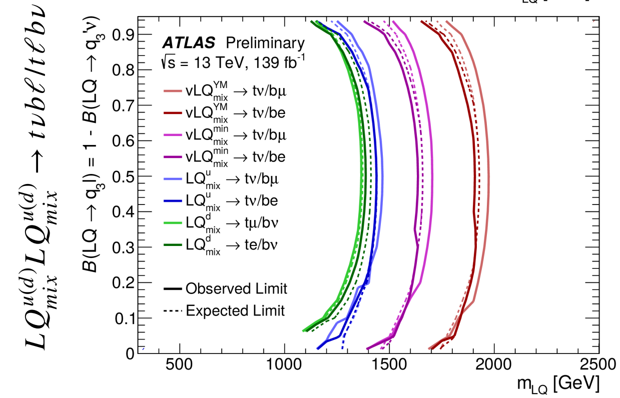
Leptoquarks II

- ★ Event selections:
  - ★ lepton+τ or $\tau\tau$, opposite charge, ≥ 1 b-jets…
  - ★ MET trigger, ≥ 4 jets, ≥ 1 b-jets
  - ★ Single and di-lepton triggers, ≥ 2 jets, ≥ 1 b-jets
- ★ Main backgrounds:
  - ★ $t\bar{t}$, single t, fake τ
  - ★ W + jets, $t\bar{t}$, single t
  - ★ $t\bar{t}W$, $t\bar{t}Z$, VV, non-prompt ℓ
- ★ No significant excess above SM predictions
- ★ The limits for masses excluded set for different decay scenarios, branching ratios and coupling strengths



ATLAS-CONF-2022-052



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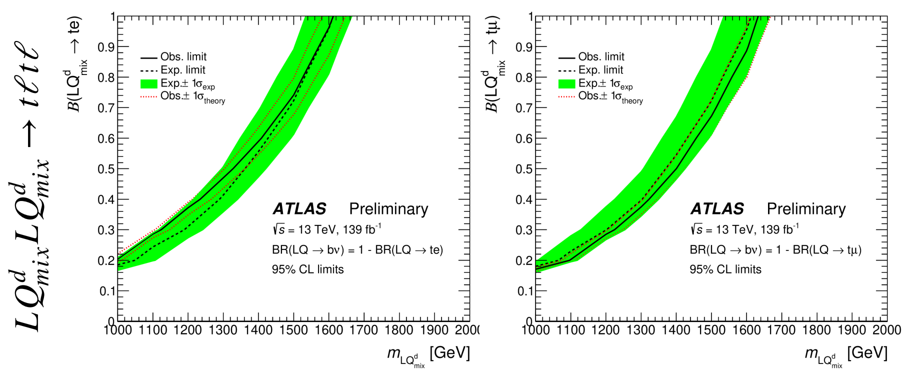

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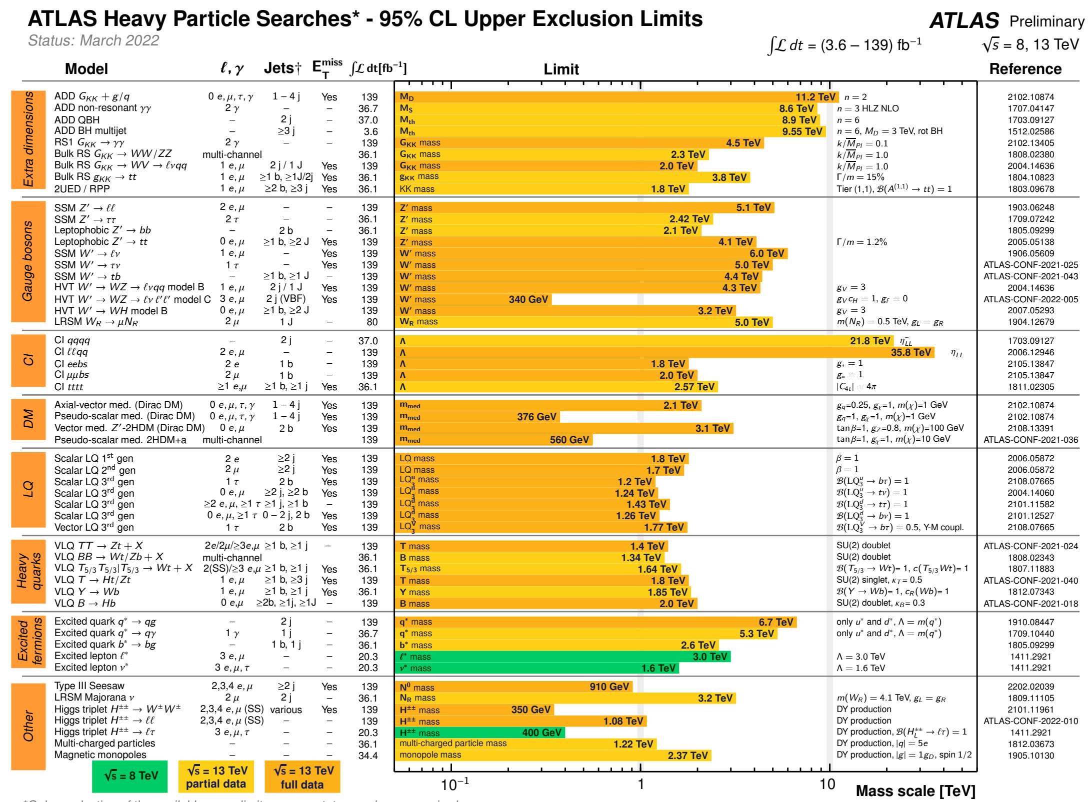
Summary

★ No evidence was found (yet) looking at many final states containing leptons.

★ The lower/upper limits are still improving with more and more data being available and new analysis techniques developed.

★ We are all excited to see new fresh 'Run 3' data being already recorded!

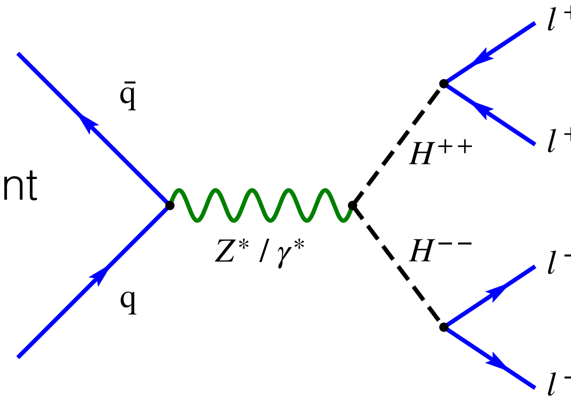


*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Backup

Doubly charged Higgs I

- ★ Searching for $H^{\pm\pm}$ pair production in all lepton flavour and charge combinations: $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}, \quad \ell, \ell' = e, \mu, \tau$.

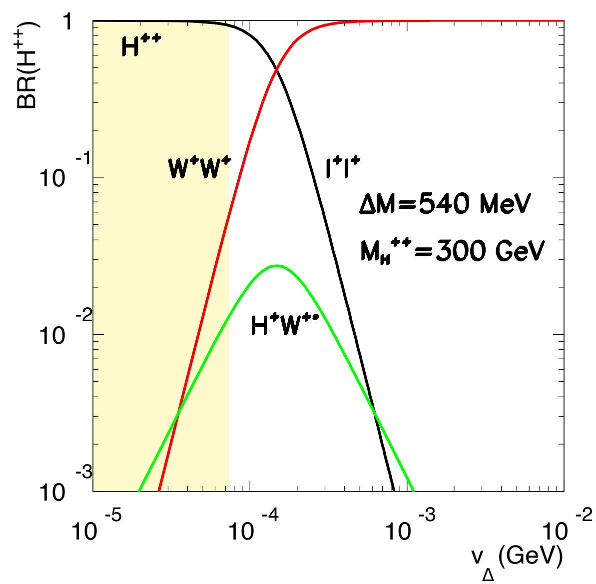


- ★ Left-Right Symmetric Model (LRSM) within type-II seesaw mechanism: two chiralities $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ (different production cross-section due to different coupling to Z).

- ★ Type-II seesaw mechanism: arguably **simplest** known way to account for the smallness of the neutrino masses.

- ★ Lepton-Flavour Violation is allowed.

- ★ Three possible $H^{\pm\pm}$ decay modes:
  - ★ leptonic: $H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}$,
  - ★ bosonic: $H^{\pm\pm} \to W^{\pm}W^{\pm}$,
  - ★ mixed: $H^{\pm\pm} \to H^{\pm}W^{\pm}$.



- ★ The value of the free model parameter $v_\Delta \to 0\ GeV$: exclude decays to bosons.

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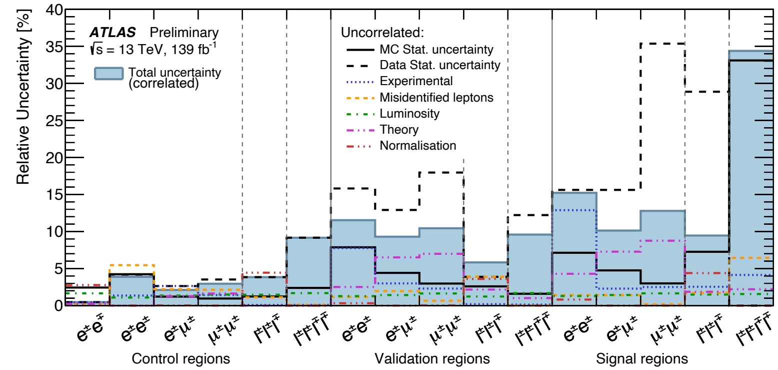
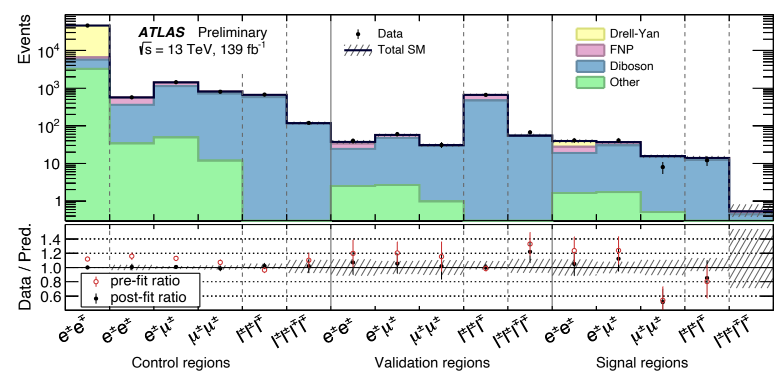
Doubly charged Higgs II

- ★ Only **light leptons** (e, μ) considered in the final states with democratic scenario:
$$\mathscr{B}_{ee} = \mathscr{B}_{e\mu} = \mathscr{B}_{e\tau} = \mathscr{B}_{\mu\mu} = \mathscr{B}_{\mu\tau} = \mathscr{B}_{\tau\tau} = 1/6.$$



- ★ Analysis signature: **prompt, isolated, same-charge, high-p_T *lepton pairs***.

- ★ Main backgrounds:
  - ★ Reducible: fake/non-prompt (FNP) leptons,
  - ★ Irreducible: diboson (VV), Drell-Yan.



- ★ The measurement is **statistically limited**.

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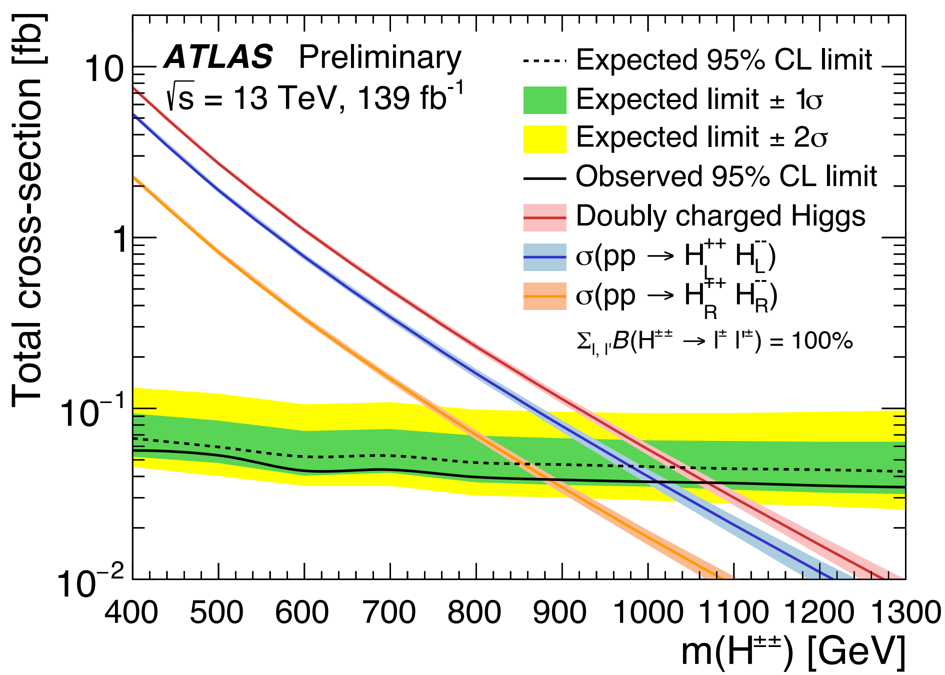
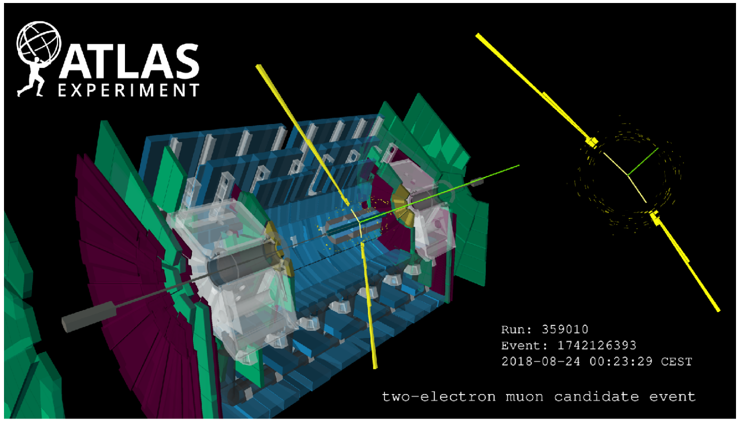
Doubly charged Higgs III

- ★ No significant excess, $H_L^{\pm\pm}$ with masses below **1010 GeV** and $H_R^{\pm\pm}$ with masses below **880 GeV** are excluded at 95% CL.

- ★ Can be **interpreted in multiple models**.





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$m(H^{\pm\pm}) > 1080\ (1040^{+40}_{-60})\ GeV$ observed (expected) @ 95% CL.

observed combined lower limit