Searches for new physics with leptons using the ATLAS detector

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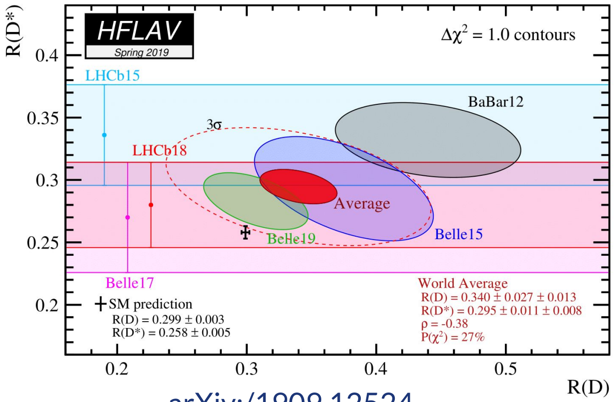
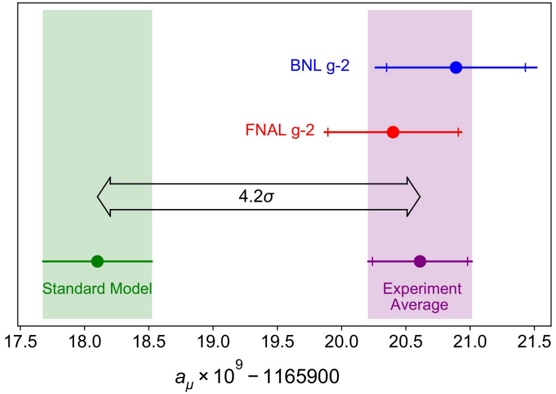
Introduction

- SM is a very successful theoretical framework
  → Still many open questions
- Answers might be in new physics related to the leptonic sector, e.g. for neutrino masses (via Type-III seesaw mechanism)
- On top of that recent hints of discrepancies with SM: e.g. in B-meson decays and $(g-2)_\mu$ anomaly or R(K*) (*See Alexander Mann's talk* here)
- Explanation may be found in:
  Supersymmetry, Leptoquarks, new gauge bosons, Heavy Leptons, ...
- ATLAS wide search program for such scenarios:
  - Search for charge flavour symmetry violation
  - Lepton Flavor violating Z decays
  - Searches for new heavy gauge bosons
  - Searches for Heavy Leptons



arXiv:/1909.12524



arXiv:/2104.03281

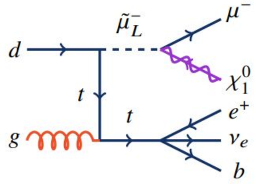
Measurement of the ratio $e^+\mu^-/e^-\mu^+$

- Novel data-driven analysis, attempts to measure the ratio [ATLAS-CONF-2021-045]:

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

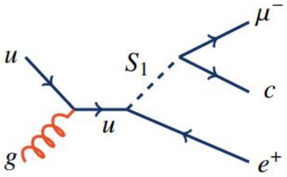
- $\rho = 1 \rightarrow$ Standard Model
  Taking into consideration detector and experimental effects $\rightarrow \rho < 1$

- Analysis used several Signal Regions, sensitive to:
  a) high missing E_T (**SR-MET**), e.g. R-parity violating SUSY

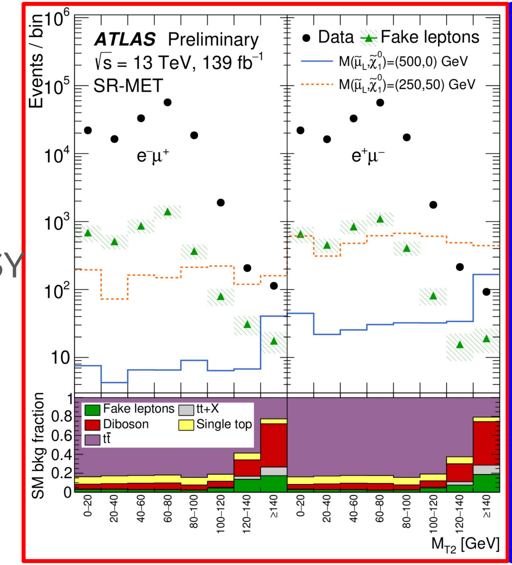


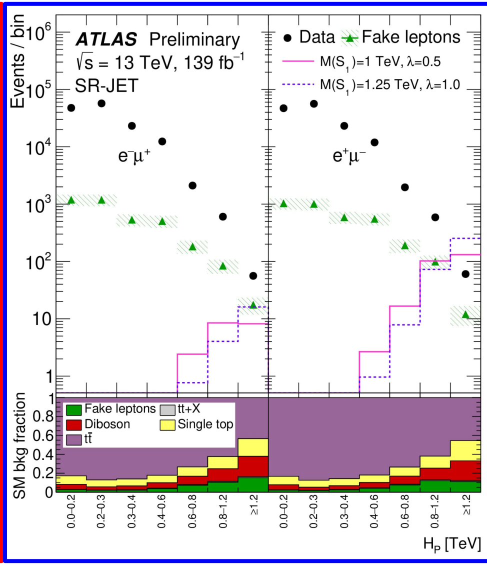
$$M_{T2} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_T^{\,miss}} \max\left[m_T(e,\vec{a}), m_T(\mu,\vec{b})\right]$$

  b) high jet multiplicity (**SR-JET**), e.g. LQ



$$H_P \equiv |\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\mu}| + |\vec{p}_T^{\,j_1}|$$





- Data were corrected for muon charge mis-reconstruction effects and sagitta bias

Measurement of the ratio $e^+\mu^-/e^-\mu^+$

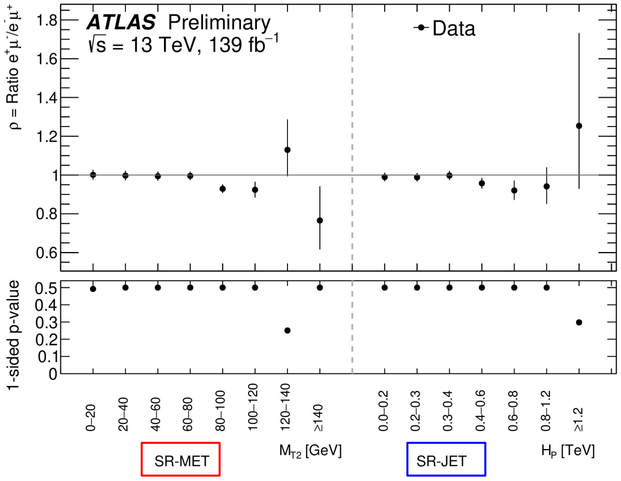
ATLAS-CONF-2021-045

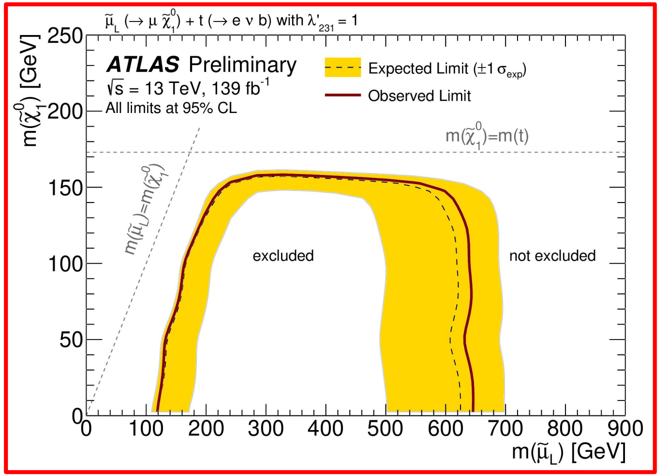
- Novel data-driven analysis, attempts to measure the ratio:

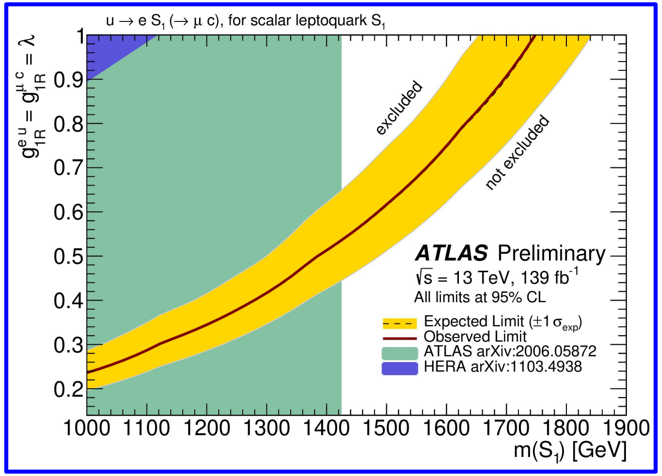
$$\rho \equiv \frac{\sigma(pp \rightarrow e^+\mu^- + X)}{\sigma(pp \rightarrow e^-\mu^+ + X)}$$

- Data consistent with SM hypothesis

- No significant ρ>1 was observed →
95% C.L. upper limits set (**RPV SUSY** and **LQ** models)
from a subset of SRMET and SRJET



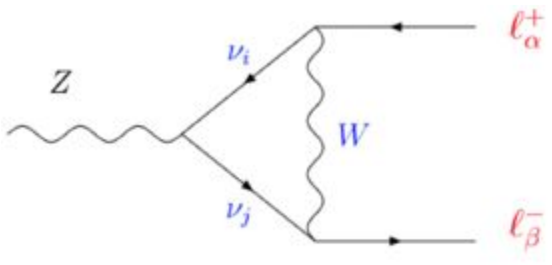


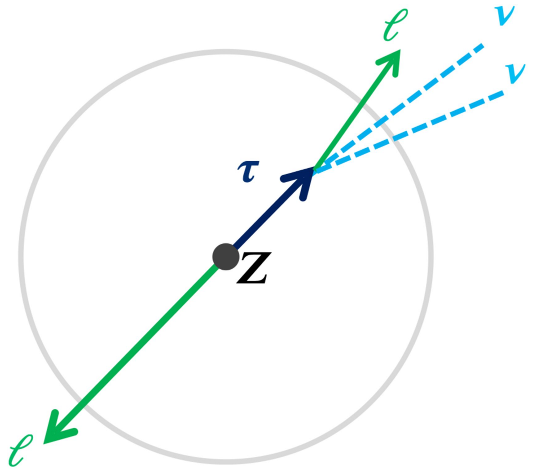


Lepton Flavor Violation

EXOT-2020-28, EXOT-2018-36 ,ATLAS-CONF-2021-042

- Lepton symmetry is an accidental symmetry of SM
- Observation of LFV → clear indication of new physics
  e.g. SM probability ~10^{-54} while Heavy Neutrino theories increase it to ~10^{-5}
- Searches for Z → ℓℓ' (ℓ = e ,μ) and in particular:
  - Z → ℓτ (hadronic+leptonic τ-decays) [EXOT-2020-28, EXOT-2018-36]
  - Z → eμ [ATLAS-CONF-2021-042]
- Machine Learning methods to discriminate signal - background





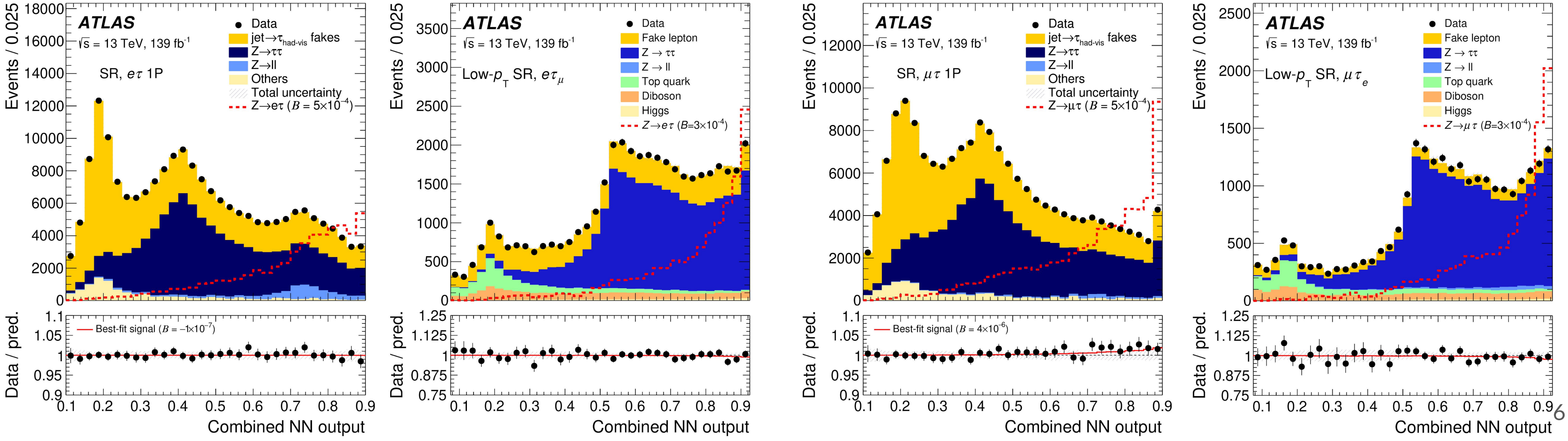
Lepton Flavor Violation ($Z \to \ell\tau$)

EXOT-2020-28, EXOT-2018-36

- Signal searched in NN output
- Dominant backgrounds : $Z \to \tau\tau$. Fake background
- Largest impact on $\mathcal{B}$ uncertainty: statistical uncertainties
- **Result (Run 1+ Run 2)**:
  $\mathcal{B}(Z \to e\tau) < 5.0 \times 10^{-6}$ (DELPHI :12.0×10^{-6})
  $\mathcal{B}(Z \to \mu\tau) < 6.5 \times 10^{-6}$ (OPAL : 9.8×10^{-6})

Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
E_T^{miss}, jets and flavor tagging	±2.1	±2.4
E_T^{miss}	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \to \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

$Z \to e\tau \to e\tau_{had}\nu$ $\quad$ $Z \to e\tau \to e\mu\nu\nu$ $\quad$ $Z \to \mu\tau \to \mu\tau_{had}\nu$ $\quad$ $Z \to \mu\tau \to \mu e\nu\nu$



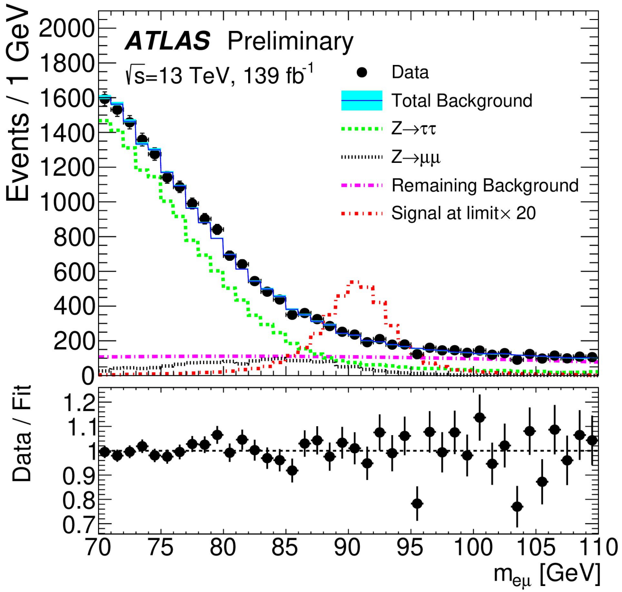
Lepton Flavor Violation ($Z \rightarrow e\mu$)

ATLAS-CONF-2021-042

- Signal searched in $m_{e\mu}$
- Dominant backgrounds : $Z \rightarrow \tau\tau$, $Z \rightarrow \mu\mu$, WW and top
- Event selection:
  - Veto events with jets with large p_T, missing E_T and b-tagged jets
  - BDT used for further background rejection
- Analysis statistically limited (**data** and **simulation**)
- **Result**:

$\mathcal{B}(Z \rightarrow e\mu) < 3.04 \times 10^{-7}$ (ATLAS : 7.5×10^{-7})

Source of uncertainty	Degradation of $\mathcal{B}^{95\%\mathrm{CL}}(Z \rightarrow e\mu)$
Limited simulated events	9.5%
$Z \rightarrow \tau\tau$	4.7%
$Z \rightarrow \mu\mu$	6.1%
All other sources	2.4%
Jet energy scale and resolution	1.2%
Pile-up	1.2%
Electron energy scale and resolution	0.8%
Lepton efficiency	0.7%
b-tagging	0.6%
Muon resolution and bias correction	0.6%



Search for heavy gauge bosons (τν)

ATLAS-CONF-2021-025

- New heavy gauge bosons appear in extensions of SM

- Benchmark model : Sequential Standard Model (SSM) → Same couplings to fermions as the SM

- Searches for new bosons decaying to leptons:
    - W′ → ℓν (ℓ = e , μ) [EXOT-2018-30]
    - Z′ → ℓℓ [EXOT-2018-08]

  have been performed and exclude SSM boson masses below 6 TeV (W′) and 5.1 TeV (Z′)

- **New results** in searching for W′ → τν [ATLAS-CONF-2021-025]

- Searches in 3rd generation final states:
  interesting for explaining B-meson anomalies or high mass of top quark

Search for heavy gauge bosons (τν)

ATLAS-CONF-2021-025

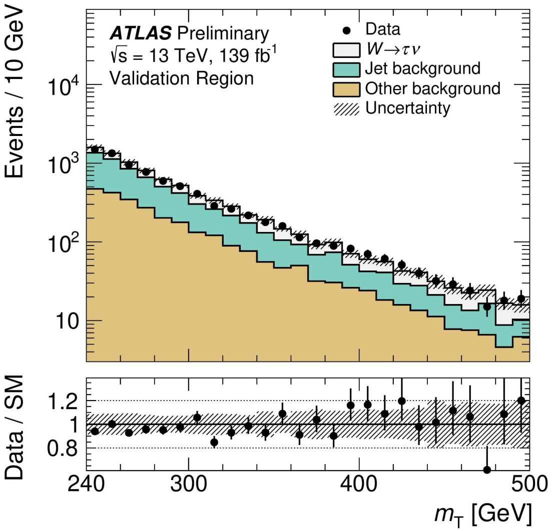
- Signal Region :
  Large E_T^{miss}
  back-to-back and balanced τ_{had} & E_T^{miss}

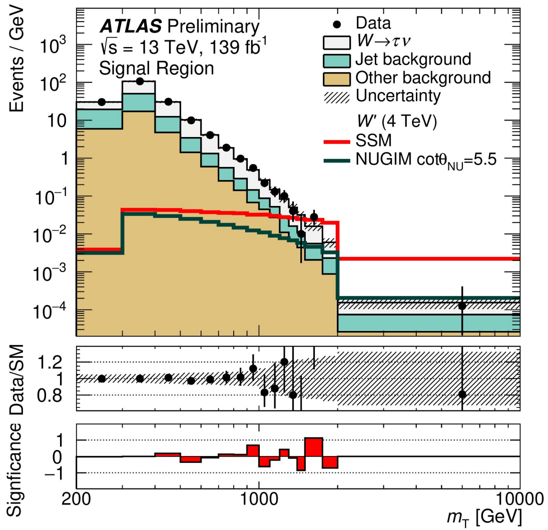
- Main Backgrounds :
  Offshell production of W → τν (Simulation)
  Jets misidentified as τ (Data driven)

- Signal-background separation:

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

- No significant excess observed over SM expectation

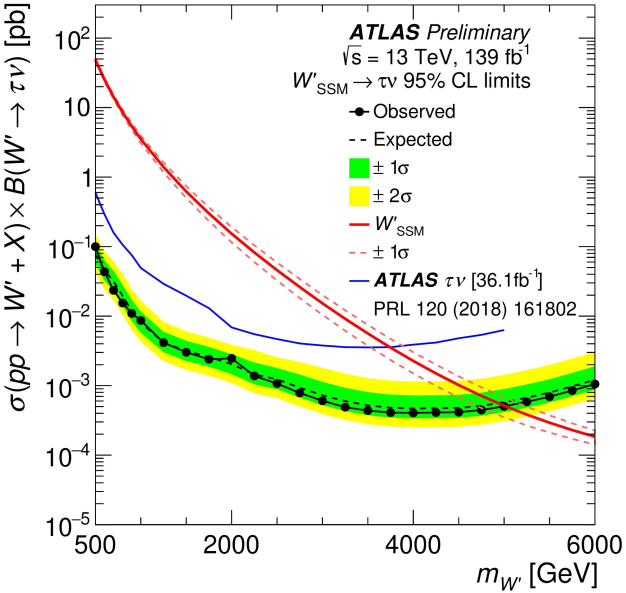


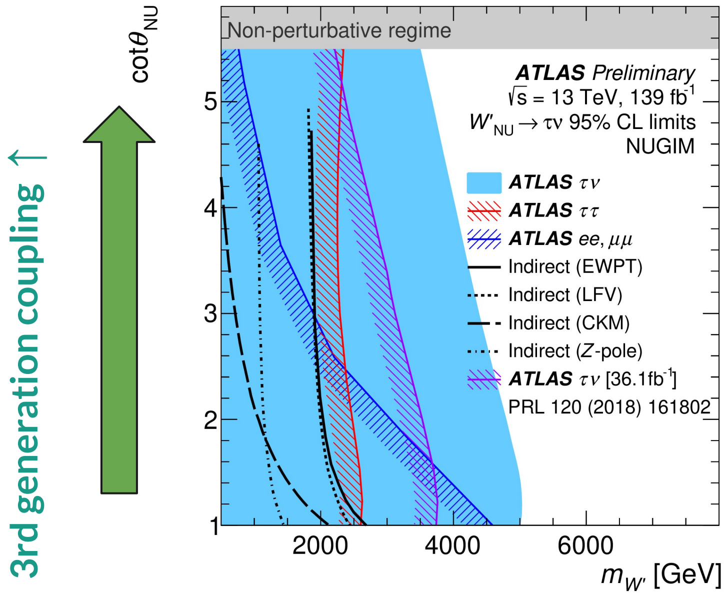


Search for heavy gauge bosons (τν)

ATLAS-CONF-2021-025

- Model Interpretations
  → Sequential Standard Model (SSM) :
  same couplings to fermions as SM
  → Non-Universal Gauge Interaction Models (NUGIM) :
  Enhanced coupling to 3rd generation ~ $\cot\theta_{NU}$
  (possible links to LFV or high-mass of the top quark)
- Exclude W′ up to **5 TeV (SSM)** and **3.5-5 TeV (NUGIM)**

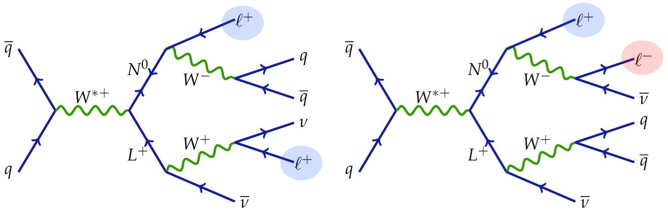




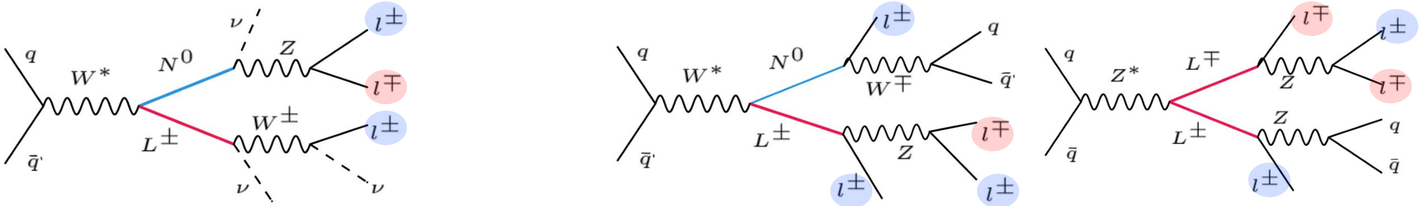
Search for Heavy Leptons

EXOT-2018-33 , ATLAS-CONF-2021-023

- Searches for Heavy Leptons (HL) in multilepton channel (combined):
    - 2 leptons [EXOT-2018-33]



- 3/4 leptons [ATLAS-CONF-2021-023]

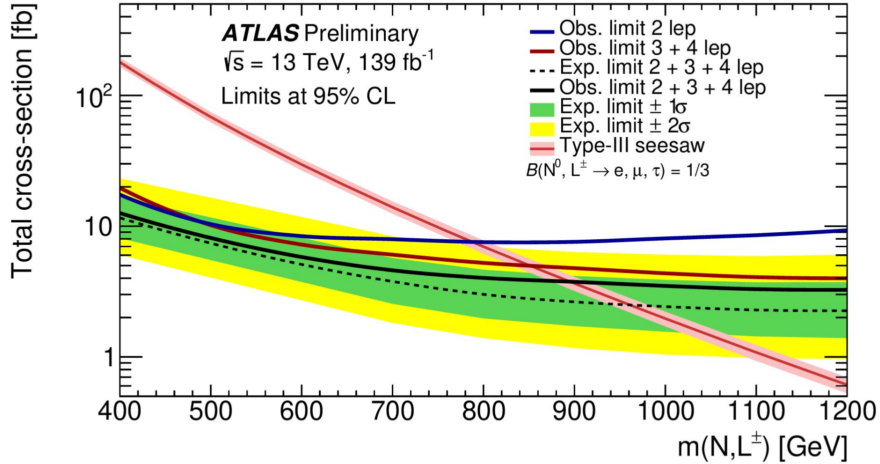


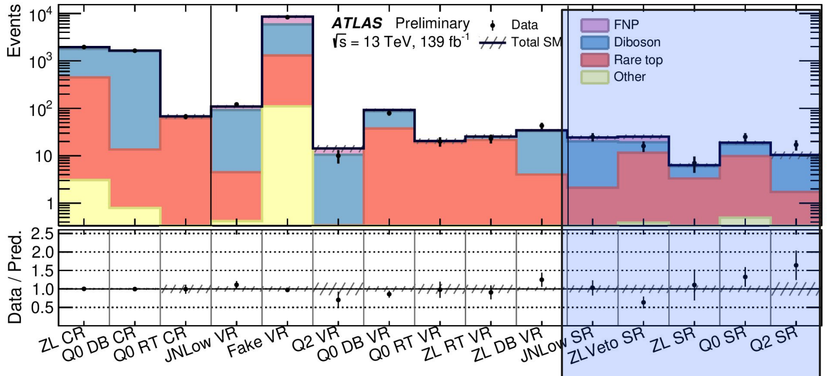
- Linked to light mass of neutrino (Seesaw mechanism) and muon g-2 anomaly (Vector-like Leptons)

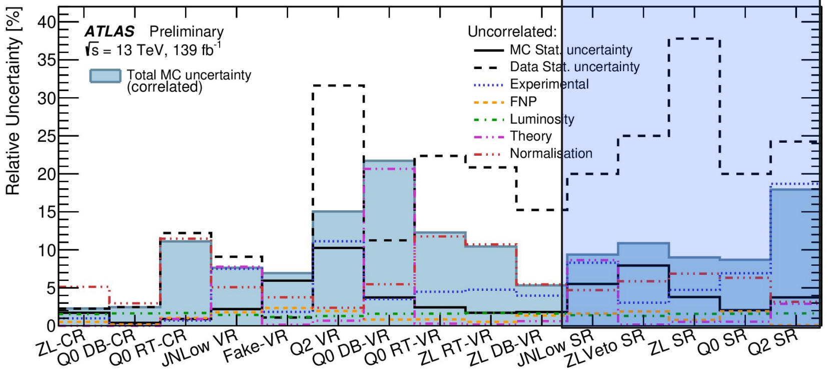
Search for Heavy Leptons

EXOT-2018-33 , ATLAS-CONF-2021-023

- Search performed in various **Signal Regions** to capture the different event topologies of the various decays
  → Dominant uncertainty from data statistics
- Interpretation : Type-III seesaw
- Exclude HL masses below **910 GeV** @95% C.L.
- Most stringent limits



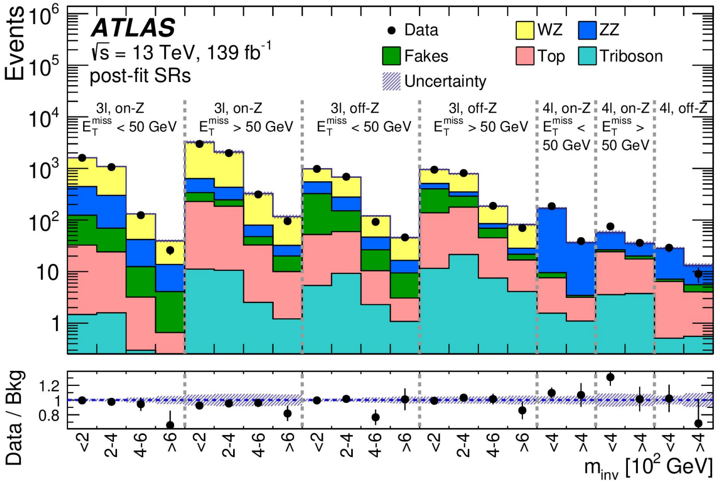


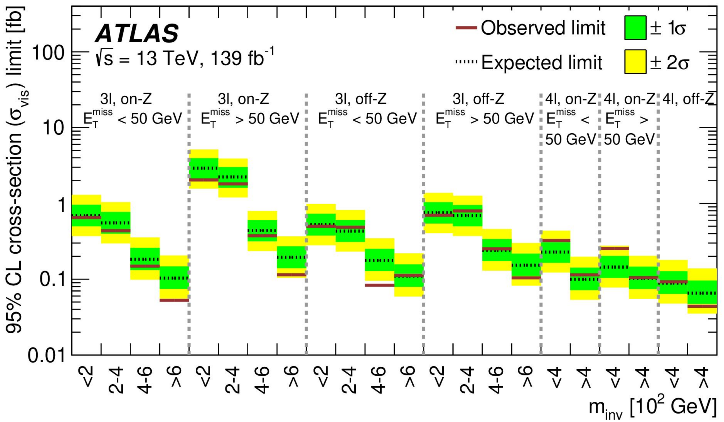


Model independent multilepton searches

- Several BSM theories can also give multilepton (3, 4 -lepton) final states (SUSY, $H^{\pm\pm}$, type-III seesaw)
- Aim to derive visible cross section limits while covering for a large variety of BSM [EXOT-2019-36]
  → led to 22 Signal Regions
- Upper limits also derived for $H^{\pm\pm}$ and type-III seesaw models

Model	Mass [GeV]	Best single SR	m_{inv}	$A \times \epsilon$	σ^{95}_{exp} [fb]	σ^{95}_{obs} [fb]
Type-III Seesaw	400	3ℓ, Off-Z, $E_T^{\text{miss}} > 50$ GeV	> 600 GeV	0.0036	41^{+17}_{-11}	27
	700	3ℓ, Off-Z, $E_T^{\text{miss}} > 50$ GeV	> 600 GeV	0.012	12^{+5}_{-3}	8.8
$H^{\pm\pm}$	300	4ℓ, Off-Z	> 400 GeV	0.37	$0.18^{+0.08}_{-0.05}$	0.12
	500	4ℓ, Off-Z	> 400 GeV	0.40	$0.16^{+0.07}_{-0.05}$	0.11





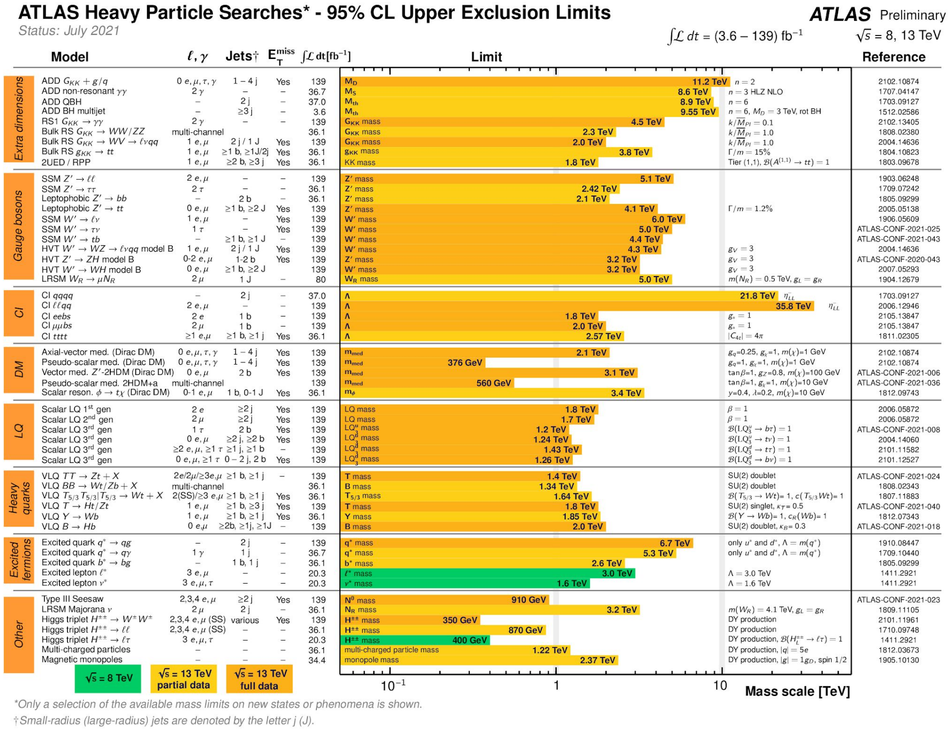
Summary

- Recent discrepancies between SM and observations make searches for new physics in leptonic final states interesting

- ATLAS performs a wide search for such phenomena
  → best worldwide constraints on LFV Z decays with τ
  → large exclusion limits on new gauge bosons and heavy leptons

- Improvements expected by the increased luminosities coming with the post Run-2 data collection at LHC

- New possibilities to look for new models and final states

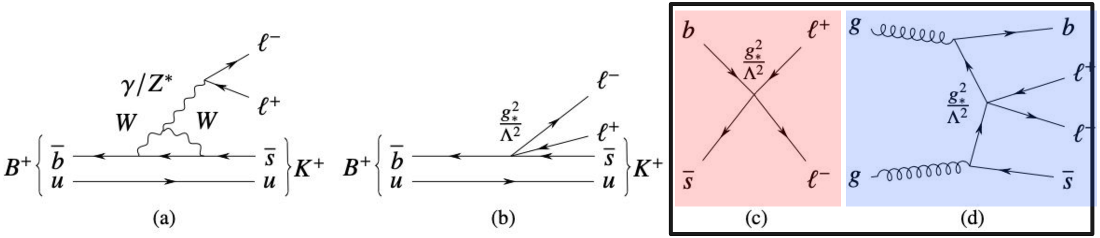


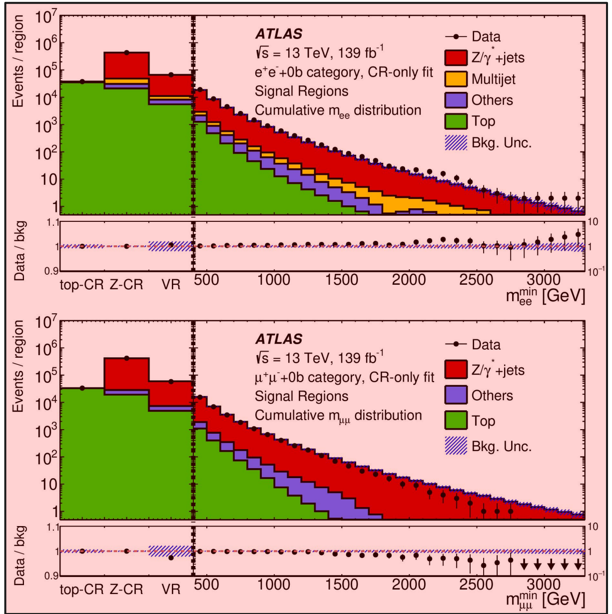
ATL-PHYS-PUB-2021-033

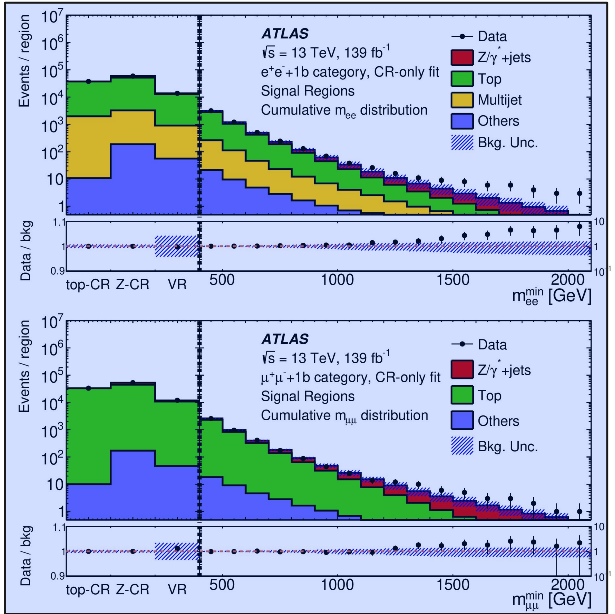
Additional Material

bsℓℓ contact interactions

- Recent hints for LFV in rare B-decays
- New physics via **EFT** at scale Λ **with** and **without** b-jet and same-flavor leptons in the final state [EXOT-2018-16]
- Various Signal Regions by scanning a cut on minimum $m_{\ell\ell}$ (>400 GeV) and counting events above this threshold

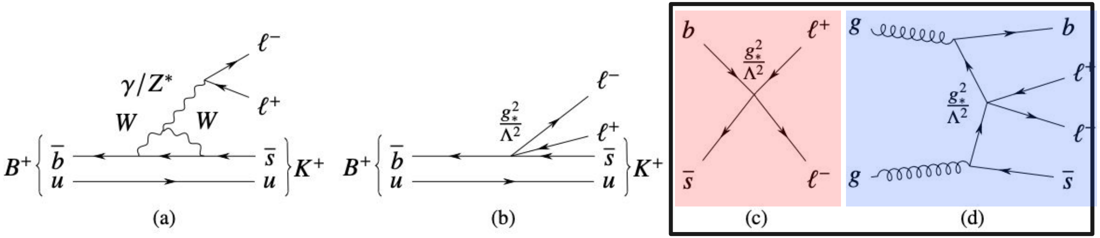


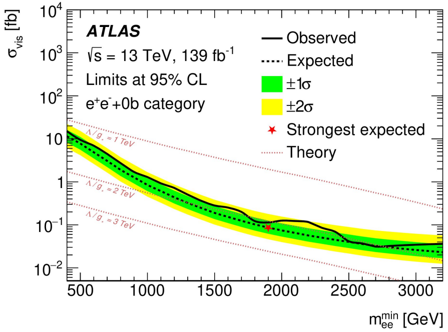


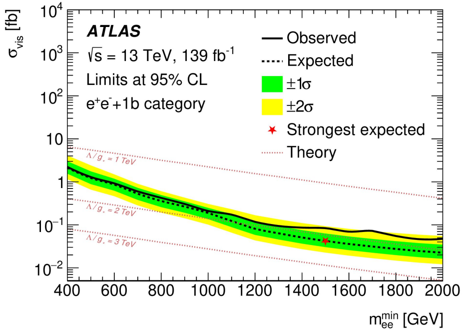


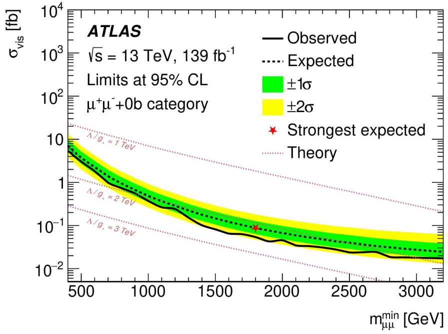
bsℓℓ contact interactions results

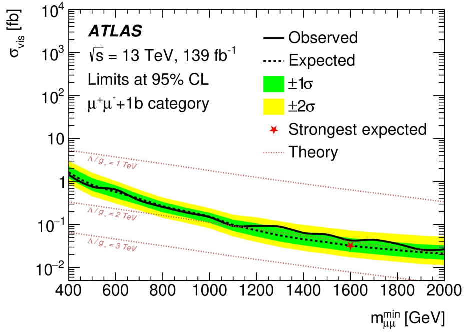
- No significant excess observed
  → Derivation of limits on visible cross section and Λ/g_* :
  $(\Lambda/g_*)_\mu$ > 2.4 TeV
  $(\Lambda/g_*)_e$ > 2.0 TeV
- Λ/g_* limits still lower than prediction that resolves B-meson anomalies







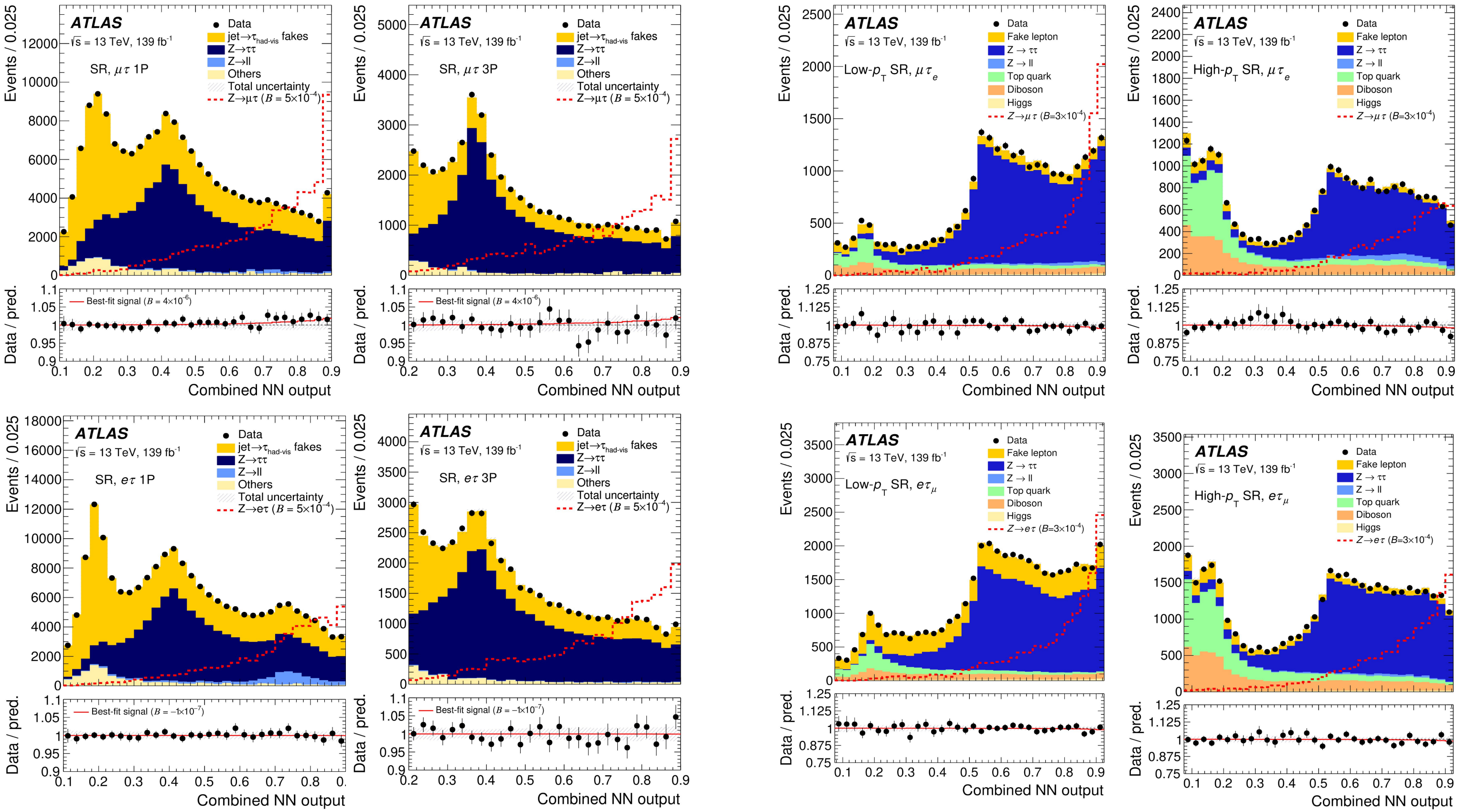




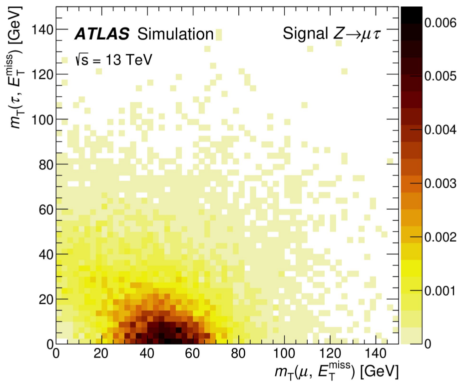
Z→ ℓτ (distributions)

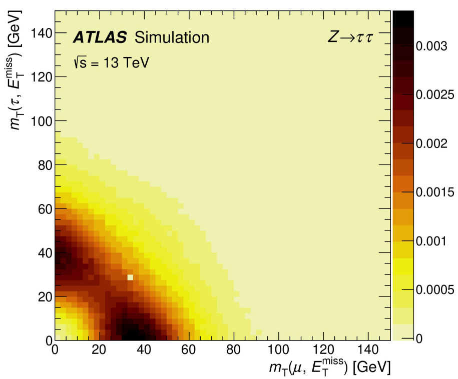
Split in lepton p_T for better fake background categorization

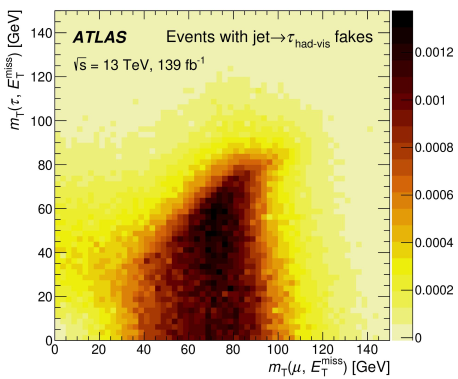
1-prong tau | 3-prong tau | low-p_T lepton | high-p_T lepton



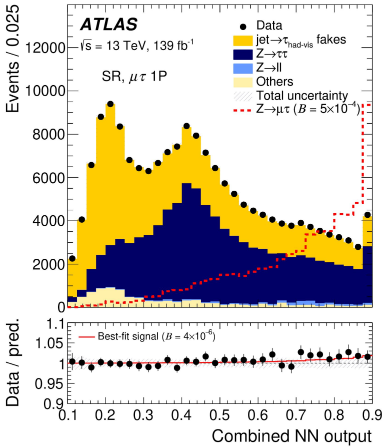
Z→ ℓτ (Neural Network)







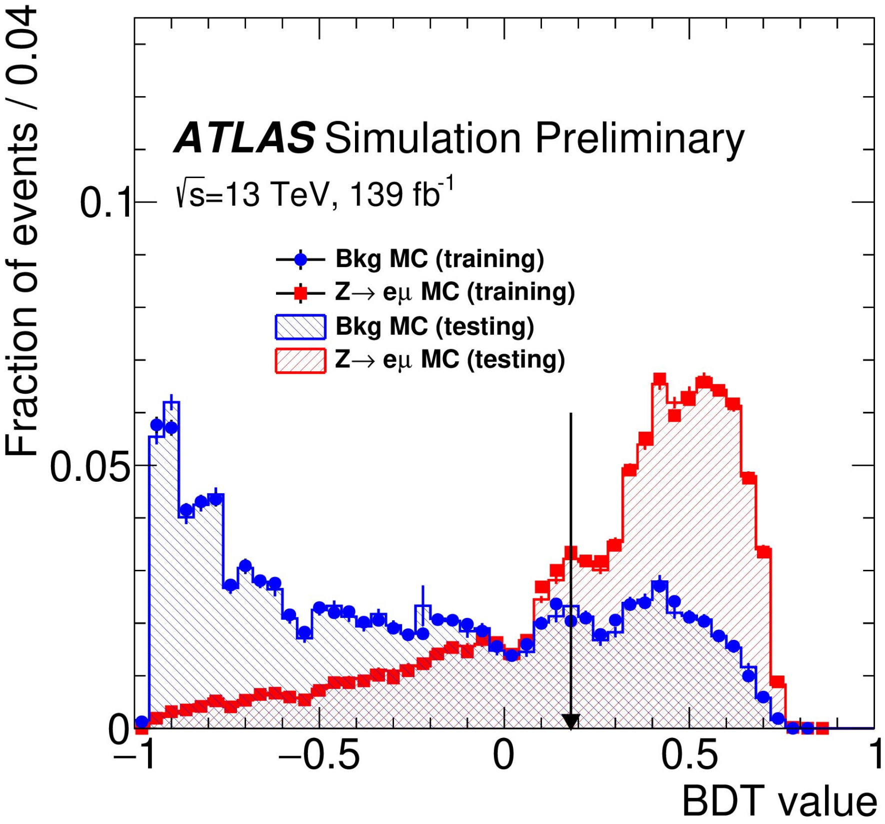
$$\text{Combined NN output} = 1 - \sqrt{\frac{1}{3}\sum_{\text{bkg}}(1 - \text{NN}_{\text{bkg}})^2}$$



$Z \rightarrow \ell\tau$ (selection)

Selection criterion	**Purpose**
Exactly two isolated light leptons (ℓ_0, ℓ_1) with opposite electric charge and different flavor (e or μ); $p_T(\ell_0) > p_T(\ell_1)$	Select events consistent with signal decays.
No $\tau_{\text{had-vis}}$ candidate	Orthogonality with $\ell\tau_{\text{had}}$ channel.
Transverse mass[1] $m_T(\ell_1, E_T^{\text{miss}}) < 35$ GeV $\lvert\Delta\phi(\ell_0, E_T^{\text{miss}})\rvert > 1$ rad No b-tagged jets (using the 77% efficiency working point)	Reject top-quark and diboson events.
Invariant mass of the ℓ_0–ℓ_1 pair $m(\ell_0, \ell_1) > 40$ GeV	Reject events incompatible with Z-boson decays.
Neural network (optimized for signal vs. $Z \rightarrow \tau\tau$) output > 0.2	Ensure selection is orthogonal to the CRZ$\tau\tau$ region.
In $\mu\tau_e$ channel: $p_T^{\text{track}}(e)/p_T^{\text{cluster}}(e) < 1.1$	Reject $Z \rightarrow \mu\mu$ events.

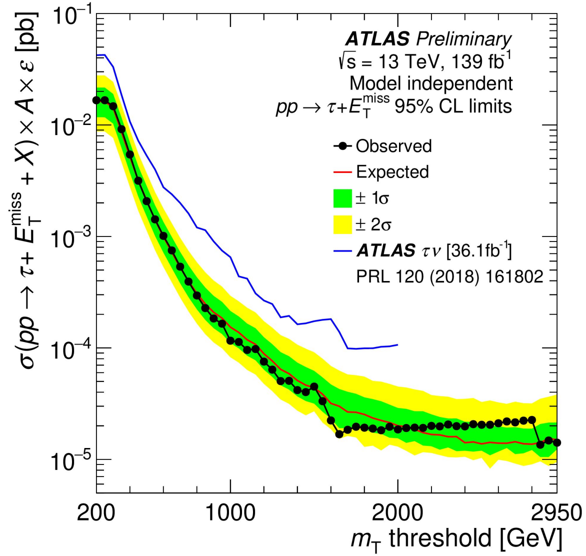
Z→ eμ BDT



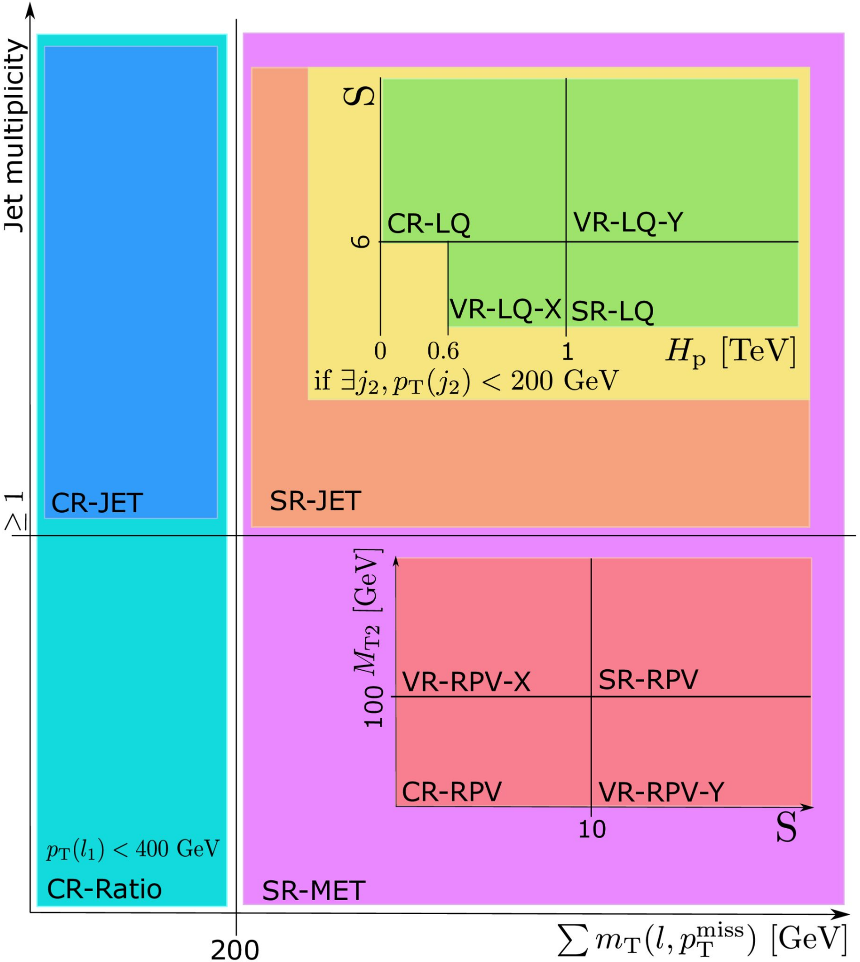
ATLAS Simulation Preliminary
√s=13 TeV, 139 fb-1
Bkg MC (training)
Z→ eμ MC (training)
Bkg MC (testing)
Z→ eμ MC (testing)
Fraction of events / 0.04
BDT value
0.1
0.05
0
−1
−0.5
0
0.5
1

Search for heavy gauge bosons (W' → τν)

	Preselection				
E_T^{miss} trigger	$70, 90, 110$ GeV				
Event cleaning	applied				
$\tau_{had\text{-}vis}$ tracks	1 or 3				
$\tau_{had\text{-}vis}$ charge	± 1				
$\tau_{had\text{-}vis}$ p_T	> 30 GeV				
$\tau_{had\text{-}vis}$ $p_T^{leadTrack}$	> 10 GeV				
Lepton veto	applied				
$\Delta\phi(\tau_{had\text{-}vis}\ p_T, E_T^{miss})$	> 2.4 rad				
	Region requirements				
	SR	**CR1**	**CR2**	**CR3**	**VR**
Tau identification	L	VL \ L	L	VL \ L	L
E_T^{miss}	> 150 GeV	> 150 GeV	< 100 GeV	< 100 GeV	> 150 GeV
p_T/E_T^{miss}	$\in [0.7, 1.3]$	$\in [0.7, 1.3]$	–	–	< 0.7
m_T	–	–	–	–	> 240 GeV

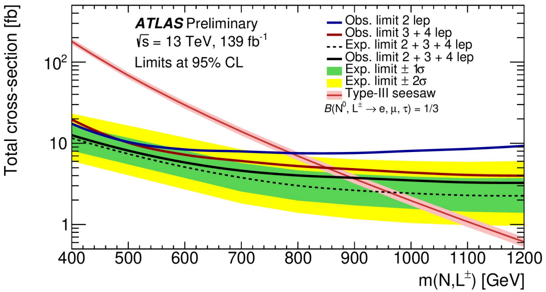


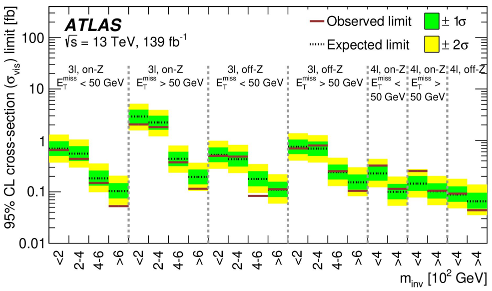
Measurement of charge asymmetry

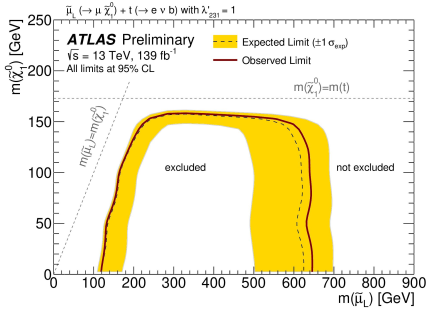


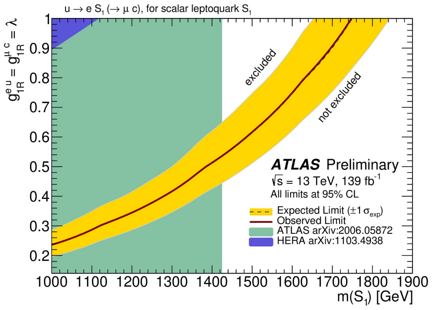
Summary

- Late discrepancies between SM and observations make searches for new Physics in leptonic final states interesting
- ATLAS performs a wide search for such phenomena

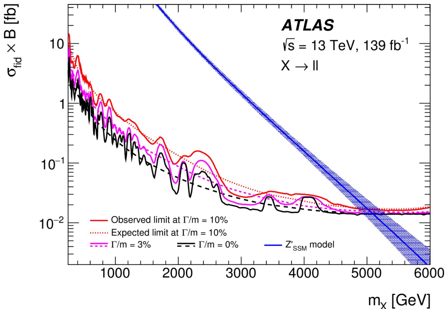


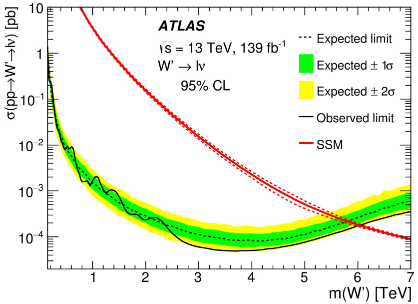


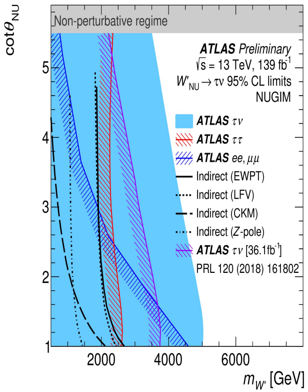


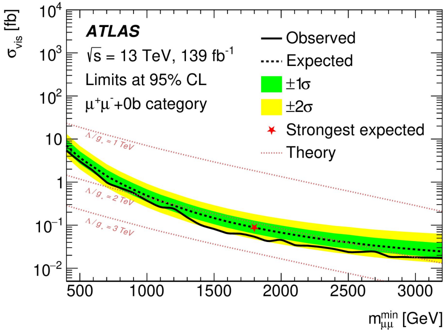


$\mathcal{B}(Z \to e\mu)$	3.04×10^{-7}
$\mathcal{B}(Z \to e\tau)$	5.0×10^{-6}
$\mathcal{B}(Z \to \mu\tau)$	6.5×10^{-6}









Search for heavy gauge bosons

- New heavy gauge bosons appear in extensions of SM
- Benchmark model : Sequential Standard Model (SSM) → Same couplings to fermions as the SM
- Searches for them decaying to leptons:
  - $W' \to \ell\nu$ (ℓ= e , μ) [EXOT-2018-30]
  - $Z' \to \ell\ell$ [EXOT-2018-08]

  Have been performed and exclude SSM boson masses below 6 TeV (W′) and 5.1 TeV (Z′)

- Additional models investigated for various resonant widths