



Istituto Nazionale di Fisica Nucleare

Searches for new physics with Leptons using the ATLAS detector

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## Searching new physics

- \* The SM is a very successful theory, but not everything still understood
- \* Hints that new physics might be hidden into the leptonic sector:

  - violation of lepton flavour universality (LFU)
    in B-meson decays (<u>see talk by Luca Fiornini</u>)
- \* Many models propose possible solutions at TeV scale: lepto-quarks, heavy leptons, new gauge bosons, SUSY smuons, ...







### Oulline

- \* Inputs from different searches are needed to confirm or disprove physics BSM
- \* ATLAS is moving in this direction with a broad program of searches
- **\*** Test of SM symmetries
  - Lepton Flavour Violation searches in  $Z \to \ell \ell'$  with  $(\ell, \ell' = e, \mu, \tau)$
  - Solution Measurement of  $(e^+\mu^-/e^-\mu^+)$  ratio
- \* Search for new heavy particles predicted in UV-complete SM extensions
  - Search for type-III seesaw heavy leptons
  - $\$  Search for  $W' \to \ell \tau$







Lepton Flavour Violation in Z decay

- \* Violation of lepton flavour conservation (LFV) not forbidden by any fundamental symmetry in SM
  - $\Rightarrow$  Any observation is a clear indication of new physics!
- \* ATLAS search for  $Z \to \ell \ell'$  complementary to electroweak energy-scale searches
  - $\approx Z \rightarrow \ell \tau$  where  $\ell = e, \mu$  and  $\tau$  may decay both hadronic [Nature Physics (2021)] and leptonic [EXOT-2018-36]. Combined limit extracted.
  - $\Rightarrow$  Z  $\rightarrow$  eµ [<u>ATLAS-CONF-2021-042</u>]
- **\* Challenge:** look for tiny signal in background using Machine Learning methods for signal/bkg discrimination







Search for  $Z \rightarrow \ell \tau$ 

- \* Signal searched in Neural Network output, studying  $\tau$  polarisation effects
- **\* Dominant backgrounds:**  $Z \rightarrow \tau \tau$ , fake-lepton background

\* Largest impact on *B* uncertainty given by statistical uncertainties





### Nature Physics (2021) EXOT-2020

	Uncertainty in $\mathcal{B}(Z \rightarrow \ell \tau)$ [×10 <sup>-6</sup> ]	
Source of uncertainty	e au	$\mu au$
Statistical	$\pm 3.5$	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	$\pm 0.4$
$E_{\rm T}^{\rm miss}$ , jets and flavor tagging	$\pm 2.1$	$\pm 2.4$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$\pm 0.4$	$\pm 0.8$
Jets	$\pm 1.9$	$\pm 2.2$
Flavor tagging	$\pm 0.5$	$\pm 0.9$
Z-boson modeling	< 0.1	$\pm 0.1$
$Z \rightarrow \mu \mu$ yield	—	$\pm 0.8$
Other backgrounds	$\pm 0.1$	$\pm 0.6$
Fake leptons (systematic)	$\pm 0.4$	±0.9
Total	$\pm 4.4$	±5.2





Search for  $Z \rightarrow \ell \tau$ 





![](_page_5_Picture_3.jpeg)

### Nature Physics (2021) EXOT-2020-28

![](_page_5_Picture_8.jpeg)

![](_page_5_Picture_9.jpeg)

## Search for Z

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

Source of uncertainty	Degradation of $\mathcal{B}^{95\%CL}(Z \to e\mu)$
Limited simulated events	9.5%
$Z \to \tau \tau$	4.7%
$Z  o \mu \mu$	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%

![](_page_6_Picture_8.jpeg)

### LAS-CONF-2021-042

![](_page_6_Figure_11.jpeg)

Result:  $\mathscr{B}(Z \rightarrow e\mu) < 3.04 \times 10^{-7}$  $(\text{ATLAS-Run1}: 7.5 \times 10^{-7})$ 

![](_page_6_Picture_17.jpeg)

![](_page_6_Picture_18.jpeg)

## search for heavy gauge bosons (w)

- \* New heavy gauge bosons (W', Z') appear in many extensions of SM
- \* Searches for new bosons decaying to leptons:
  - $W' \rightarrow \ell_V (\ell = e, \mu) [EXOT-2018-30]$
  - $\subseteq Z' \rightarrow \ell \ell \left[ \underline{EXOT-2018-08} \right]$
  - $\square$  have been performed and exclude SSM boson masses below 6 TeV (W') and 5.1 TeV (Z')
- **\* New results** searching for  $W' \rightarrow \tau v [ATLAS-CONF-2021-025]$ 
  - transverse energy  $E_T^{miss}$
  - mass of top quark

![](_page_7_Picture_9.jpeg)

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

 $\approx$  Search for high-mass resonances in events with hadronically decaying  $\tau$ , lepton and missing

x Searches in 3rd generation final states: interesting for explaining B-meson anomalies or high

![](_page_7_Picture_20.jpeg)

![](_page_7_Picture_21.jpeg)

Search for heavy gauge bosons (TV)

\* Signal events expected to have:  $\Rightarrow \text{ back-to-back and balanced}$   $\tau_{had} \text{ and } E_T^{miss}$   $\Rightarrow \text{ high } m_T = \sqrt{2E_T^{miss}p_T(1 - \cos \Delta \phi)}$ 

★ Dominant backgrounds:  $\Rightarrow$  Off-shell MC production of  $W \rightarrow \tau \nu$   $\Rightarrow$  events with jets misidentified as  $\tau_{had}$ (DataDriven)

![](_page_8_Picture_3.jpeg)

![](_page_8_Figure_5.jpeg)

![](_page_8_Picture_8.jpeg)

## Search for heavy gauge bosons (w)

\* No significant excess observed over SM expectation

### **\* Model Interpretations**

- Sequential Standard Model (SSM): W' couplings to fermions as W
- Models (NUGIM):

☆ Enhanced coupling to 3rd generation ( $\cot \theta_{NU} > 1$ )

![](_page_9_Figure_7.jpeg)

![](_page_9_Picture_8.jpeg)

### \* Exclude W' up to 5 TeV (SSM) and 3.5-5 TeV (NUGIM)

![](_page_9_Picture_15.jpeg)

## Search for Heavy Leptons

- \* Searches for Heavy Leptons in multi-lepton final states,
  - ☆ 2-lepton channel [<u>Eur. Phys. J. C 81 (2021) 218</u>]
  - ☆ 3 and 4-lepton channel [ATLAS-CONF-2021-023]
- \* Combination of all the channels, for the first time!
- \* Benchmark model: type-III seesaw model which provides a heavy Majorana neutrino that could explain small neutrino mass

![](_page_10_Picture_6.jpeg)

![](_page_10_Figure_10.jpeg)

![](_page_10_Figure_11.jpeg)

Not yet considered decay channels including au

![](_page_10_Picture_15.jpeg)

## Search for Heavy Leptons

- decays  $\rightarrow$  combined together in the fit (2+3+4 leptons)
- **\* Dominant uncertainty** form data statistic
- \* Exclude HL masses below **910 GeV** @95% C.L.

![](_page_11_Figure_5.jpeg)

![](_page_11_Picture_6.jpeg)

![](_page_11_Picture_8.jpeg)

\* Search performed in various Signal Regions to categorise the different event topologies of all the possible

![](_page_11_Picture_12.jpeg)

![](_page_11_Picture_13.jpeg)

## Model independent multi-lepton search

- Signal Regions targeting different final states.
- \* Upper limits also derived for  $H^{\pm\pm}$  and <u>type-III seesaw</u> models

![](_page_12_Figure_4.jpeg)

![](_page_12_Picture_5.jpeg)

\* Several BSM theories can also give similar multi-lepton (>2 leptons) final states (SUSY, H±±, type-III seesaw)

**\* Goal:** obtain cross section limits covering for a large variety of BSM scenario [EXOT-2019-36]. Building 22

![](_page_12_Picture_12.jpeg)

# Measurement of the ratio e+µ-/e-µ+

\* Measure of the ratio  $\rho = \frac{\sigma \left( p \to e^+ \mu^- + X \right)}{\sigma \left( p \to e^- \mu^+ + X \right)}$  where SM predicts  $\rho_{SM} = 1$ 

\* Any findings of  $\rho \neq 1$  would lead to new physics (scalar LQ, SUSY, ...)

\* Analysis almost completely **data-driven**:

- Mis-identified leptons estimate with a likelihood-matrix-method
- Muon charge-dependent detector effects in reconstruction correction

![](_page_13_Picture_6.jpeg)

![](_page_13_Figure_10.jpeg)

![](_page_13_Figure_11.jpeg)

![](_page_13_Figure_12.jpeg)

![](_page_14_Figure_0.jpeg)

![](_page_14_Picture_1.jpeg)

![](_page_14_Picture_5.jpeg)

### Conclusion

- **\*** Growing evidence for anomalies in lepton interactions
- **\*** ATLAS is pushing the search for new phenomena in lepton interactions on several fronts
- \* Need more attention on the 3rd generation channel, including taus final states, starting already!

![](_page_15_Picture_4.jpeg)

### Status: July 2021

### Model

![](_page_15_Picture_7.jpeg)

![](_page_15_Picture_10.jpeg)

### $\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$ **Jets** $T = \mathbf{E}_{T}^{miss} \int \mathcal{L} dt [fb^{-1}]$ *l*,γ Limit 0 e, μ, τ, γ Yes 139 **11.2 TeV** n = 22γ 36.7 **8.6 TeV** *n* = 3 HLZ NLO \_ 37.0 2 j **8.9 TeV** *n* = 6 ≥3 j 3.6 **9.55 TeV** $n = 6, M_D = 3$ TeV, rot BH 2γ 139 $k/\overline{M}_{PI} = 0.1$ 4.5 TeV 36.1 $k/\overline{M}_{Pl} = 1.0$ multi-channel 2.3 TeV KK mass 1 e,μ 2j/1J 139 2.0 TeV $k/\overline{M}_{Pl} = 1.0$ KK mass Yes ≥1 b, ≥1J/2j Yes $\Gamma/m = 15\%$ 1 e,μ 36.1 <mark>gкк</mark> mass Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ 1 e, μ ≥2 b, ≥3 j Yes 36.1 K mass 1.8 TeV 2 e, µ 139 5.1 TeV mass 2.42 TeV $2 \tau$ 36.1 ' mass 2.1 TeV 2 b 36.1 ' mass 0 e,μ $\Gamma/m = 1.2\%$ ≥1 b, ≥2 J 139 ' mass 4.1 TeV $1 e, \mu$ 139 W' mase 6.0 TeV $1\tau$ Yes 139 W' mas 5.0 TeV ≥1 b, ≥1 J 139 W' mas 4.4 TeV $g_V = 3$ HVT $W' \rightarrow WZ \rightarrow \ell \nu q q$ model B 1 e,μ 139 2i/1JN' mase 4.3 TeV Yes 0-2 e, μ 1-2 b 139 $g_V = 3$ Yes ' mass 3.2 TeV 3.2 TeV 0 e,μ ≥1 b, ≥2 J 139 $g_V = 3$ W' mass 2μ 80 $m(N_R) = 0.5 \text{ TeV}, g_L = g_R$ 1 J 37.0 **21.8 TeV** η<sub>LL</sub> 139 2 e, µ 35.8 TeV 139 1.8 TeV $g_* = 1$ 2 e 1 b 2μ 1 b 139 2.0 TeV $g_* = 1$ ≥1 b, ≥1 j Yes $|C_{4t}| = 4\pi$ ≥1 e,µ 36.1 2.57 TeV 2.1 TeV $g_q=0.25, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ $0 e, \mu, \tau, \gamma$ 139 Yes Pseudo-scalar med. (Dirac DM) 139 $g_q=1, g_{\chi}=1, m(\chi)=1 \text{ GeV}$ 0 e, μ, τ, γ 1 – 4 j Yes 376 GeV Vector med. Z'-2HDM (Dirac DM) $\tan\beta=1, g_Z=0.8, m(\chi)=100 \text{ GeV}$ 2 b 139 0 e,μ Yes 3.1 TeV $\tan\beta=1, g_{\chi}=1, m(\chi)=10 \text{ GeV}$ AT multi-channel 139 560 GeV Scalar reson. $\phi \rightarrow t\chi$ (Dirac DM) 0-1 e,μ 1 b, 0-1 J Yes 36.1 3.4 TeV $y=0.4, \lambda=0.2, m(\chi)=10 \text{ GeV}$ ≥2 j ≥2 j 1.8 TeV eta=1139 2 e Yes eta=1139 2μ Yes 1.7 TeV ) mass 2 b $\mathcal{B}(LQ_3^u \to b\tau) = 1$ Yes 139 mass $1\tau$ 1.2 TeV AT $\mathcal{B}(LQ_3^{\bar{u}} \to t\nu) = 1$ mass ≥2 j, ≥2 b Yes 0 e,μ 139 1.24 TeV 139 2<sup>d</sup> mass $\geq 2 e, \mu, \geq 1 \tau \geq 1 j, \geq 1 b$ $\mathcal{B}(LQ_3^d \to t\tau) = 1$ 1.43 TeV 139 2<sup>d</sup> mass $\mathcal{B}(\mathrm{LQ}_3^d \to b\nu) = 1$ $0 e, \mu, \ge 1 \tau 0 - 2 j, 2 b$ Yes 1.26 TeV $2e/2\mu/\geq 3e,\mu \geq 1$ b, $\geq 1$ 139 1.4 TeV SU(2) doublet AT mass SU(2) doublet multi-channel 36.1 1.34 TeV mass $\mathcal{B}(T_{5/3} \rightarrow Wt) = 1, c(T_{5/3}Wt) = 1$ $2(SS)/\geq 3 e, \mu \geq 1 b, \geq 1 j$ Yes . 5/3 mass 1.64 TeV 36.1 ≥1 b, ≥3 j SU(2) singlet, $\kappa_T = 0.5$ 1 e,μ Yes 139 1.8 TeV mass 36.1 139 ≥1 b, ≥1 j $\mathcal{B}(Y \rightarrow Wb) = 1, c_R(Wb) = 1$ Yes 1 e, μ / mass 1.85 TeV $\geq$ 2b, $\geq$ 1j, $\geq$ 1J – 0 e,µ 2.0 TeV SU(2) doublet, $\kappa_B = 0.3$ 139 6.7 TeV only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ $1\gamma$ 1 i 36.7 only $u^*$ and $d^*$ , $\Lambda = m(q^*)$ \* mass 5.3 TeV 1 b, 1 j 36.1 2.6 TeV 20.3 3 e, µ $\Lambda = 3.0 \text{ TeV}$ mass 3.0 Te 3*e*,μ,τ 20.3 1.6 TeV $\Lambda = 1.6 \text{ TeV}$ 2,3,4 e, µ ≥2 j 910 GeV Yes 139 $m(W_R) = 4.1 \text{ TeV}, g_L = g_R$ 2μ 2 j 36.1 3.2 TeV R mass 2,3,4 $e, \mu$ (SS) various Yes 139 H<sup>±±</sup> mass 350 GeV DY production H<sup>±±</sup> mass 870 GeV DY production 2,3,4 *e*, μ (SS) 36.1 DY production, $\mathcal{B}(H_{\ell}^{\pm\pm} \rightarrow \ell \tau) = 1$ 3 e.u. T 20.3 1.22 TeV DY production, |q| = 5e36.1 multi-charged particle mass DY production, $|g| = 1g_D$ , spin 1/234.4 2.37 TeV monopole mass . . . . . . √s = 13 TeV √s = 13 TeV √s = 8 TeV **10**<sup>-1</sup> partial data 10 full data Mass scale [TeV]

\*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).* 

ATLAS

5	Pre	lim	inary
5	= 8,	13	TeV
R	efere	enc	е

2102.10874 1707.04147 1703.09127 1512.02586 2102.13405 1808.02380 2004.14626
1804.10823 1803.09678
1903.06248 1709.07242 1805.09299 2005.05138 1906.05609 LAS-CONF-2021-025 LAS-CONF-2021-043 2004.14636 LAS-CONF-2020-043 2007.05293 1904.12679
1703.09127 2006.12946 2105.13847 2105.13847 1811.02305
2102.10874 2102.10874 LAS-CONF-2021-006 LAS-CONF-2021-036 1812.09743
2006.05872 2006.05872 LAS-CONF-2021-008 2004.14060 2101.11582 2101.12527
LAS-CONF-2021-024 1808.02343 1807.11883
1812.07343 LAS-CONF-2021-040 LAS-CONF-2021-018
1910.08447 1709.10440 1805.09299 1411.2921 1411.2921
LAS-CONF-2021-023 1809.11105 2101.11961 1710.09748 1411.2921 1812.03673 1905.10130

![](_page_15_Picture_19.jpeg)

## Additional Material

Search for  $Z \rightarrow \ell \tau$ 

![](_page_17_Figure_1.jpeg)

![](_page_17_Picture_2.jpeg)

### Nature Physics (2021) EXOT-2020-28

![](_page_17_Figure_7.jpeg)

![](_page_17_Figure_8.jpeg)

![](_page_17_Picture_9.jpeg)