PROCEEDINGS OF SCIENCE

PoS(LHCP2023)254

# ATLAS Run 2 Search for Direct Stau Production using Machine Learning

**Dominic Jones[a] on behalf of the ATLAS Collaboration**

[a] *University of Cambridge,*
*Cavendish Laboratory, Cambridge, United Kingdom*

*E-mail:* dominic.matthew.jones@cern.ch

In Supersymmetry, staus are the proposed super-partners of the Standard Model tau-leptons and have previously been searched for at the Large Hadron Collider by the ATLAS and CMS Collaborations, so far with no evidence for their existence being found. However, previous stau searches performed with the ATLAS experiment have only been sensitive to staus with masses between 100 GeV and 400 GeV, the sensitivity in part being limited by challenging Standard Model backgrounds. This poster presents a new search for staus with the ATLAS experiment [1] which utilises multiple Boosted Decision Trees to improve the sensitivity reach compared to previous searches. The new search obtains the first sensitivity to $\tilde{\tau}_R$-only production with the ATLAS experiment. More details of the search can be found in reference [2].

*The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)*
*22-26 May 2023*
*Belgrade, Serbia*

## 1. Introduction

Supersymmetry (SUSY) [3–9] is a proposed extension to the Standard Model (SM) that posits the existence of new super-partner particles, specifically a new fermion (boson) for each SM boson (fermion). Motivations for SUSY include the gauge hierarchy problem [10] and grand unification [11]. SUSY models in which $R$-parity [12] is conserved can also provide compelling dark matter candidates [13, 14]. In particular, models in which staus ($\tilde{\tau}$), the super-partner of the SM tau-lepton, are relatively light and can decay to the lightest neutralino ($\tilde{\chi}_1^0$) are of particular interest as such scenarios can yield a dark matter relic density consistent with astrophysical observations [15]. A signature of such models would be direct stau production in which opposite-sign staus are pair produced via electroweak interactions and each stau decays into a tau-lepton and a $\tilde{\chi}_1^0$. This signature is characterised by a final state consisting of two opposite-sign tau-leptons and missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) originating from the two $\tilde{\chi}_1^0$.

Searches for direct stau production at the Large Hadron Collider (LHC) have been performed by the ATLAS [16–18] and CMS [19–21] experiments using the Run 1, partial Run 2 and full Run 2 datasets. These searches found no significant excesses with respect to SM predictions and set exclusion limits on a simplified model of direct stau production in which the only SUSY particles accessible at the LHC are the $\tilde{\tau}$ and $\tilde{\chi}_1^0$. For the case in which the super-partners of the left and right-handed tau-lepton ($\tilde{\tau}_L$ and $\tilde{\tau}_R$ respectively) are mass degenerate, models for which the stau mass is between 90 GeV and 400 GeV are excluded at 95% confidence level (CL) for $\tilde{\chi}_1^0$ masses up to 150 GeV. Additionally, searches performed at LEP were able to exclude staus with masses below 86 GeV [22]. Here and in reference [2], a new search for direct stau production with the full Run 2 dataset collected by the ATLAS experiment is presented which extends the sensitivity reach with respect to the previous Run 2 search by the ATLAS experiment [18] by using machine learning for the event selection. Only the final state in which both tau-leptons decay hadronically is targeted. The new search also benefits from using the Recurrent Neural Network (RNN) based hadronic tau-lepton identification (tau-ID) algorithm [23].



## 2. Analysis Strategy

Four signal regions (SRs) are defined which target different $\tilde{\tau}$ and $\tilde{\chi}_1^0$ mass ranges, as the kinematics of the direct stau signal varies with $\tilde{\tau}$ and $\tilde{\chi}_1^0$ mass. A common preselection is applied across all the signal regions and is detailed in Table 1. Predictions for the SM backgrounds passing this preselection are estimated using a mixture of Monte Carlo (MC) simulation and data-driven methods, detailed below. Together with MC simulation for the direct stau signal, these predictions are used to train Boosted Decision Trees (BDTs) to separate the direct stau signal from the SM backgrounds.

Separate BDTs are trained for the different $\tilde{\tau}$ and $\tilde{\chi}_1^0$ mass ranges. The grouping of the direct stau signal into these ranges is determined by a dedicated clustering algorithm which uses the shapes of sixteen high level kinematic variables. These variables are also used to train the BDTs, each of which is a binary classifier. For each signal group, a three-fold cross validation procedure is used to ensure events are evaluated with BDTs for which they were not part of the training data. The four SRs are defined by requiring upper bounds on the BDT output scores from the BDTs trained on each

**Table 1:** Selection requirements for the SRs (Table 1 in reference [2]). "Medium" in the first line refers to the working point of the RNN tau-ID algorithm, "OS" stands for opposite-sign. The asymmetric di-tau trigger requires two hadronic tau-lepton candidates with transverse momenta ($p_T$) greater than 95 GeV and 60-75 GeV, the latter value varying across the data taking periods. The $m_{T2}$ variable is the stransverse mass [24, 25] of the two (highest $p_T$) tau-leptons for which the masses of the invisible daughter particles are set to zero, $m(\tau_1, \tau_2)$ is the invariant mass of the two tau-leptons and $\Delta R(\tau_1, \tau_2)$ is their angular separation, defined in reference [2].

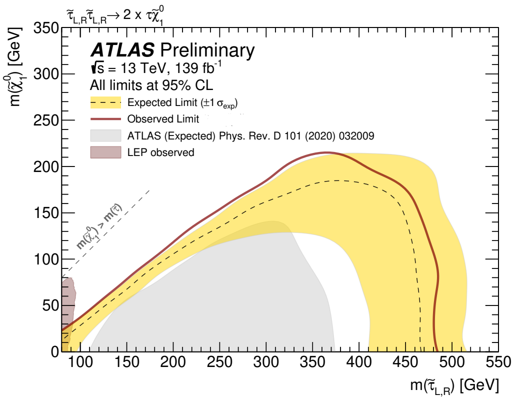
| | BDT Training Preselection | | | |
|---|---|---|---|---|
| | $\geq 2$ "medium" $\tau$ (OS)<br>asymmetric di-tau Trigger<br>$e$, $\mu$, $b$-jet veto<br>$E_T^{miss} > 20$ GeV<br>$m_{T2} > 30$ GeV<br>$m(\tau_1, \tau_2) > 120$ GeV<br>$\Delta R(\tau_1, \tau_2) < 4$ | | | |
| | SR-BDT1 | SR-BDT2 | SR-BDT3 | SR-BDT4 |
| Target scenario | Low $m_{\tilde{\tau}}$ Small $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ | Mid $m_{\tilde{\tau}}$ Large $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ | Mid $m_{\tilde{\tau}}$ Small $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$ | High $m_{\tilde{\tau}}$ |
| | veto additional tau candidates | | | |
| BDT score bin 1 | $\in (0.73, 0.78)$ | $\in (0.78, 0.82)$ | $\in (0.79, 0.86)$ | $> 0.64$ |
| BDT score bin 2 | $> 0.78$ | $> 0.82$ | $> 0.86$ | – |

of the respective signal groups, and are denoted SR-BDTX with X $\in [1, 4]$. To further enhance the sensitivity, two bins in the BDT score are defined for SR-BDT1, SR-BDT2 and SR-BDT3.

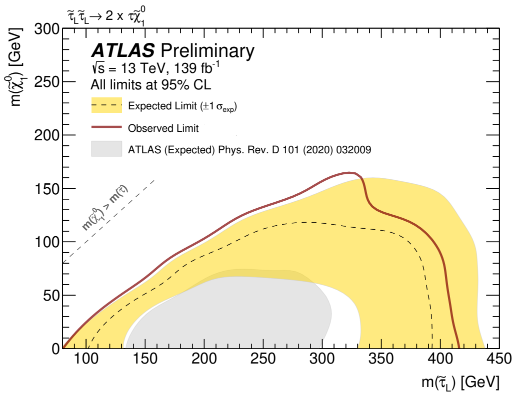
The main SM backgrounds passing the preselection are; multi-jet events in which jets fake two hadronic tau-lepton candidates; $Z$+jets in which the $Z$-boson decays to two hadronically decaying tau-leptons; $W$+jets in which the $W$-boson decays to a hadronically decaying tau-lepton and a jet fakes another hadronic tau-lepton candidate; backgrounds from events containing a top quark(referred to collectively as the top background); and multi-boson events. There is also a minor contribution from events containing a Higgs boson. A data-driven ABCD method is used to estimate the multi-jet background by inverting the SR requirements on the tau-ID, relative sign of the two tau-leptons and $m_{T2}$. MC simulation is used to model the kinematics of the other backgrounds. Control regions (CRs) enriched in each of the $Z$+jets, $W$+jets and top backgrounds are defined in order to determine the normalisation of these processes, while MC is used for the normalisation of the multi-boson and Higgs boson backgrounds. Dedicated validation regions (VRs) are defined for each of the main backgrounds in order to validate the accuracy of the predictions. Additionally, an inclusive validation region is defined to verify the compatibility of the different background estimation methods together. Experimental and theoretical uncertainties are evaluated on the signal and background predictions. Agreement at the level of one standard deviation or better is seen in each of the VRs.

## 3. Results

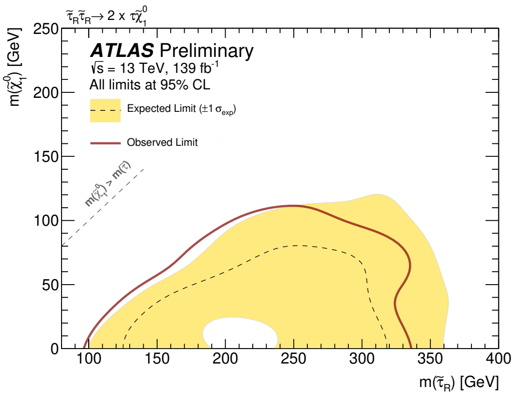
No significant discrepancies with the SM predictions are seen in any of the SRs, thus no evidence for direct stau production is obtained. Exclusion limits are set on the simplified direct stau model using the CL$_s$ method [26] for the case where $\tilde{\tau}_L$ and $\tilde{\tau}_R$ are mass degenerate and also for $\tilde{\tau}_L\tilde{\tau}_L$ and $\tilde{\tau}_R\tilde{\tau}_R$ production individually. The 95% CL exclusion contours for the different cases are shown in Figure 1, alongside the results of the previous ATLAS experiment search [18] and the limits obtained from LEP [22]. Compared to the results from the previous ATLAS experiment search, shown in light grey, the sensitivity reach is significantly extended at both low and high stau mass. In particular, a gap in sensitivity between the previous ATLAS experiment search and the LEP limits is closed. The sensitivity to the $\tilde{\tau}_R\tilde{\tau}_R$ only case is the first to be obtained by the ATLAS experiment at 95% CL and demonstrates how the depth of the sensitivity has also been improved.




(a) Mass degenerate $\tilde{\tau}_L\tilde{\tau}_L + \tilde{\tau}_R\tilde{\tau}_R$




(b) $\tilde{\tau}_L\tilde{\tau}_L$ only




(c) $\tilde{\tau}_R\tilde{\tau}_R$ only

**Figure 1:** The 95% CL exclusion contours for simplified models of direct stau production (from Figure 11 in reference [2]). The solid (dashed) lines show the observed (expected) exclusion contours. The band around the expected limit shows the $\pm 1\sigma$ variations, including all uncertainties except theoretical uncertainties in the signal cross-section. The dotted lines around the observed limit indicate the sensitivity to $\pm 1\sigma$ variations of the theoretical uncertainties in the signal cross-section. The observed limit from the previous ATLAS experiment search [18] is shown in light grey and the limits from the LEP experiments [22] in dark grey.

## References


[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003. 437 p.

[2] ATLAS Collaboration, *Search for electroweak SUSY production in final states with two $\tau$-leptons in $\sqrt{s}$ = 13 TeV $pp$ collisions with the ATLAS detector*, 2023. tech. rep., ATLAS-CONF-2023-029, http://cds.cern.ch/record/2861058.

[3] Y. Golfand and E. Likhtman, *Extension of the Algebra of Poincare Group Generators and Violation of P Invariance*, JETP Lett. **13** (1971) 323.

[4] D. Volkov and V. Akulov, *Is the neutrino a goldstone particle?*, Phys. Lett. B **46** (1973) 109.

[5] J. Wess and B. Zumino, *Supergauge transformations in four dimensions*, Nucl. Phys. B **70** (1974) 39.

[6] J. Wess and B. Zumino, *Supergauge invariant extension of quantum electrodynamics*, Nucl. Phys. B **78** (1974) 1.

[7] S. Ferrara and B. Zumino, *Supergauge invariant Yang-Mills theories*, Nucl. Phys. B **79** (1974) 413.

[8] A. Salam and J. Strathdee, *Super-symmetry and non-Abelian gauges*, Phys. Lett. B **51** (1974) 353.

[9] S. P. Martin, *A Supersymmetry Primer*, Adv. Ser. Direct. High Energy Phys. **18** (1998) 1, arXiv:hep-ph/9709356.

[10] S. Dimopoulos and G. F. Giudice, *Naturalness constraints in supersymmetric theories with nonuniversal soft terms*, Phys. Lett. B **357** (1995) 573–578, arXiv:hep-ph/9507282 [hep-ph].

[11] M. G. A.J. Buras, J.Ellis and D. Nanopoulos, *Aspects of the grand unification of strong, weak and electromagnetic interactions*, Nuclear Physics B **135** (1978) 66–92.

[12] G. R. Farrar and P. Fayet, *Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry*, Phys. Lett. B **76** (1978) 575.

[13] H. Goldberg, *Constraint on the Photino Mass from Cosmology*, Phys. Rev. Lett. **50** (1983) 1419.

[14] J. Ellis, J. Hagelin, D. V. Nanopoulos, K. A. Olive, and M. Srednicki, *Supersymmetric relics from the big bang*, Nucl. Phys. B **238** (1984) 453.

[15] D. Albornoz Vásquez, G. Bélanger, and C. Bœhm, *Revisiting light neutralino scenarios in the MSSM*, Phys. Rev. D **84** (2011) 095015, arXiv:1108.1338 [hep-ph].




PoS(LHCP2023)254

[16] ATLAS Collaboration, *Search for the direct production of charginos, neutralinos and staus in final states with at least two hadronically decaying taus and missing transverse momentum in $pp$ collisions at $\sqrt{s}$ = 8 TeV with the ATLAS detector*, JHEP **10** (2014) 096, arXiv:1407.0350 [hep-ex].

[17] ATLAS Collaboration, *Search for the electroweak production of supersymmetric particles in $\sqrt{s}$=8 TeV $pp$ collisions with the ATLAS detector*, Phys. Rev. D **93** no. 5, (2016) 052002, arXiv:1509.07152 [hep-ex].

[18] ATLAS Collaboration, *Search for direct stau production in events with two hadronic $\tau$-leptons in $\sqrt{s}$ = 13 TeV $pp$ collisions with the ATLAS detector*, Phys. Rev. D **101** (2020) 032009, arXiv:1911.06660 [hep-ex].

[19] CMS Collaboration, *Search for electroweak production of charginos in final states with two $\tau$ leptons in pp collisions at $\sqrt{s}$ = 8 TeV*, JHEP **04** (2017) 018, arXiv:1610.04870 [hep-ex].

[20] CMS Collaboration, *Search for direct pair production of supersymmetric partners to the $\tau$ lepton in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Eur. Phys. J. C **80** no. 3, (2020) 189, arXiv:1907.13179 [hep-ex].

[21] CMS Collaboration, *Search for direct pair production of supersymmetric partners of $\tau$ leptons in the final state with two hadronically decaying $\tau$ leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Phys. Rev. D **108** no. 1, (2023) 012011, arXiv:2207.02254 [hep-ex].

[22] LEP SUSY Working Group (ALEPH, DELPHI, L3, OPAL), Notes LEPSUSYWG/01-03.1 and 04-01.1, http://lepsusy.web.cern.ch/lepsusy/Welcome.html.

[23] ATLAS Collaboration, *Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment*, CERN, Geneva, Aug, 2019. tech. rep., ATL-PHYS-PUB-2019-033, https://cds.cern.ch/record/2688062.

[24] C. G. Lester and D. J. Summers, *Measuring masses of semiinvisibly decaying particles pair produced at hadron colliders*, Phys. Lett. B **463** (1999) 99–103, arXiv:hep-ph/9906349.

[25] A. Barr, C. Lester, and P. Stephens, *m(T2) : The Truth behind the glamour*, J. Phys. G **29** (2003) 2343–2363, arXiv:hep-ph/0304226.

[26] A. L. Read, *Modified frequentist analysis of search results (the $CL_s$ method)*, 2000. Tech. Rep. CERN-OPEN-2000-205, CERN-OPEN-2000-205, https://cds.cern.ch/record/451614.