# Prospects of searches for excited neutrinos at the LHC

Charles University

ICHEP Conference, 18-24 July 2024

Gabriela Martinovicová

## Motivation

- Excited neutrinos are one of the possible manifestations of new physics beyond the Standard Model (SM)
- Last search for excited tau neutrinos at the LHC was performed by the ATLAS Collaboration using the 2012 8 TeV $pp$ data [1] and the limit on the excited tau neutrino mass was set to 1.6 TeV

## The Baur, Spira, and Zerwas model

- Model of composite quarks and leptons predicts the excited neutrinos produced in proton-proton collisions via contact interaction (CI) [2] that is described by an effective four-fermion Lagrangian

$$\mathcal{L}_{CI} = \frac{g_*^2}{2\Lambda^2}\frac{1}{2}j^\mu j_{\mu'}$$

  - Single production via $q\bar{q} \to l\bar{l}^*, l^*\bar{l}$
  - Pair production via $q\bar{q} \to l^*\bar{l}^*$
- The excited neutrinos can decay to an SM neutrino via CI or through the mediation of a gauge boson, gauge interaction (GI)
- The transition of excited neutrinos to the SM neutrinos via GI is described by the effective Lagrangian

$$\mathcal{L}_{GI} = \frac{1}{2\Lambda^2}\bar{\Psi}_R^*\sigma^{\mu\nu}\left(gf\frac{\tau}{2}W_{\mu\nu} + g'f'\frac{Y}{2}B_{\mu\nu}\right)\Psi_L + h.c.$$

- Final state includes missing transverse energy and zero to three charged leptons and/or jets

## Excited Tau Neutrino Decay Modes

- Decay modes of excited tau neutrino:
  - Contact interaction (CI): $\nu_\tau^* \to \nu_\tau f\bar{f}, (f = q, l, \nu)$
  - Gauge interaction (GI): $\nu_\tau^* \to \nu_\tau Z, \tau W$
- Relative branching ratios for decays of excited tau neutrinos $\nu_\tau^*$ depend on the coupling constants $f$, $f'$ and the ratio of the mass of the excited tau neutrino $m_{\nu_\tau^*}$ and compositeness scale $\Lambda$
- The variation of the branching fractions of the different decay channels as a function of $m_{\nu_\tau^*}/\Lambda$ for different combinations of the coupling constants $f$ and $f'$ is shown in Fig. 1,2
- The CI dominates the region of high $m_{\nu_\tau^*}/\Lambda$ or the region of low $f, f'$
- The GI dominates the region of low $m_{\nu_\tau^*}/\Lambda$ and high $f, f'$

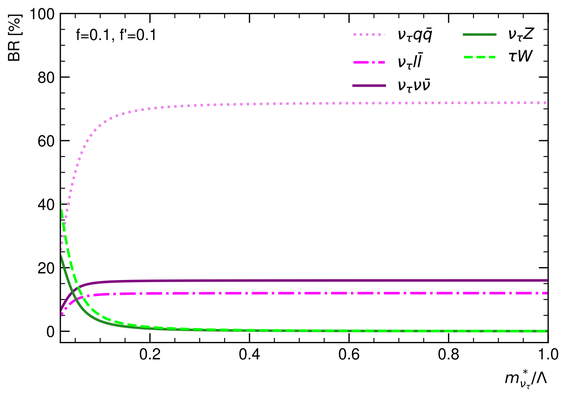


Fig 1: $f = f' = 0.1$

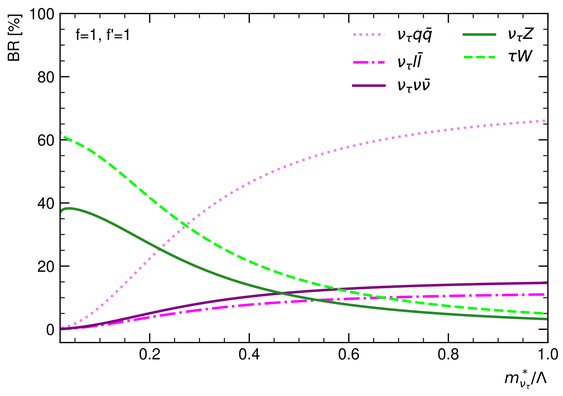


Fig 2: $f = f' = 1$

## Acknowledgements

This work was supported by Charles University, project GA UK No. 284222

## References

[1] ATLAS Collaboration. Search for new phenomena in events with three or more charged leptons in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector. *JHEP*, 08 (2015) 138.

[2] U Baur, M Spira, and P M Zerwas. Excited-quark and -lepton production at hadron colliders. *Phys. Rev. D*, 42 (1990) 815.

[3] ATLAS Collaboration. Search for new phenomena in events with an energetic jet and missing transverse momentum in $pp$ collisions at $\sqrt{s} = 13$ TeV with the atlas detector. *Phys. Rev. D*, 103, Jun 2021.

[4] T. Sjostrand, S. Mrenna, and P.Z. Skands. A Brief Introduction to PYTHIA 8.1. *Comput. Phys. Commun.*, 178 (2008) 852.

[5] J. de Favereau, C. Delaere, P. Demin, A. Giammanco, V. Lemaître, A. Mertens, and M. Selvaggi. DELPHES 3, A modular framework for fast simulation of a generic collider experiment. *JHEP*, 02 (2014) 057.

## Simple Reinterpretation of the ATLAS Monojet Search

- Scanning the possible final state scenarios depending on the model parameter values one can identify searches on LHC that can be reinterpreted as a search for the excited tau neutrinos
- One of such searches is the Monojet search by the ATLAS Collaboration [3]
- Searches for new physics produced at the LHC in proton-proton collisions at $\sqrt{s} = 13$ TeV, using events with energetic jets and large missing transverse momentum
- Signal region is defined by the presence of up to four jets with leading jet $p_T > 150$ GeV and missing transverse energy $E_T^{miss} > 200$ GeV, which can also be sensitive to the $\nu_\tau^*$
- Publicly available results of ATLAS Monojet Search can be reinterpreted as a search for excited tau neutrinos by replacing signal samples with samples for $\nu_\tau^*$ generated by Pythia 8.3 [4] and Delphes 3 [5]
- Syst+stat uncertainty of the background estimate is taken as a total syst+stat uncertainty of the background estimate from original search
- ATLAS Monojet Search uses following control regions: $W \to \mu\nu$, $Z \to \mu\mu$, $W \to e\nu$, $Z \to ee$, Top
  - Need to check the signal contamination of the control regions
  - The ratio of the number of generated signal events that passed selection criteria of CR to the number of background in the CR for $W \to \mu\nu$ CR with different combinations of strength of coupling constants $f$, $f'$ and $m_{\nu_\tau^*}$ is shown in Fig. 3
  - In $W \to \mu\nu$ CR the Sig/Bkg ratio reaches no more than 5 % including the syst+stat uncertainties
  - Sig/Bkg ratio in $W \to e\nu$ CR is up to 3 %, for $Z \to \mu\mu$ CR up to 5 %, for $Z \to \mu\mu$ CR up to 3 %, for Top CR up to $6 \times 10^{-3}$ %

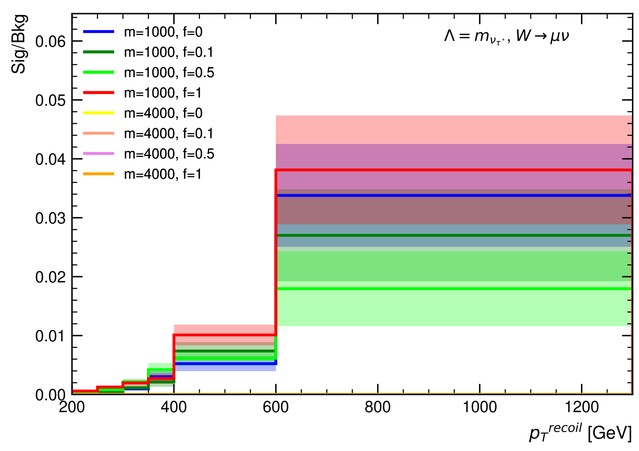


Fig 5: Signal/Background ratio in $W \to \mu\nu$ CR

## Limit on Excited Tau Neutrino Mass

- Using reinterpreted ATLAS Monojet Search as a search for excited tau neutrinos, the rough limit on the $m_{\nu_\tau^*}$ can be estimated
- $\nu_\tau^*$ events are generated for different values of the $m_{\nu_\tau^*}$ with the compositeness scale set to $\Lambda = m_{\nu_\tau^*}$ and coupling constants $f = f' = 0$ which corresponds to the CI only
- The upper 95 % CL limit on the $\nu_\tau^*$ production cross-section as a function of $m_{\nu_\tau^*}$ is shown in Fig. 4
- $\nu_\tau^*$ with masses below 4 TeV can be excluded at 95 % CL in scenario with CI only and $\Lambda = m_{\nu_\tau^*}$
- The reinterpretation of the ATLAS Monojet Search can considerably improve the limit on the excited tau neutrino mass compared to the previous ATLAS search [1] where the limit was set to 1.6 TeV

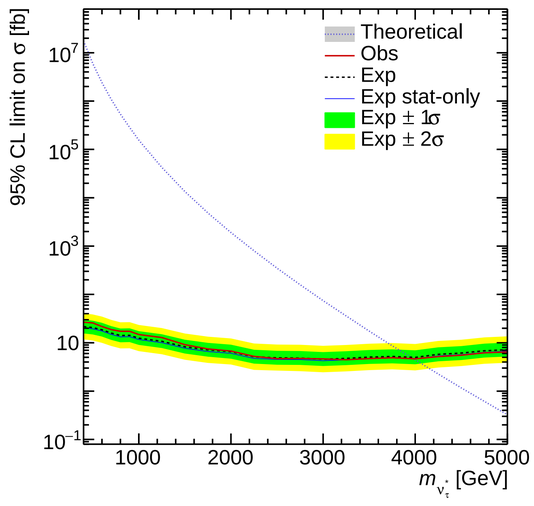


Fig 4: Upper 95 % CL limit on the $\nu_\tau^*$ production cross-section