Report on the PhD thesis by Ms. Chainika Chauhan titled „Search for New Phenomena using the Production of Four Top Quarks at the Large Hadron Collider“

The dissertation thesis of Mrs. Chainika Chauhan deals with a very interesting topic of searching for new physics in 4-top final states with the ATLAS experiment at the Large Hadron Collider. The recently discovered 4t process is an ideal ground for looking for new phenomena possibly modifying its production rate or kinematics due to the large energy scale involved in the process.

The student first describes relevant features of the Standard Model as a local calibration symmetry field theory, then in depth also the ATLAS experiment she has analyzed the data from. She devotes substantial sections to the description of ATLAS physics objects identification as well as systematics uncertainties treatment in the analysis, ranging from detector systematics to theory and simulation related modelling uncertainties. There is also a nice description of the 2 Higgs Doublet Model as well as of the 4t production mechanisms, including example Feynman diagrams of SM as well as BSM processes.

The work also includes a valuable and almost textbook-like description of the statistical analysis, including the growing usage of the ATLAS' package TRExFitter, nicely explaining individual statistical tests like expected nuisance parameters effect on the fitted variable of interest (the signal strength).

The author clearly states her many and wide contributions to the analysis, being the important steps of fitting, vast validation procedures; and systematics implementation and tuning, all indispensable for obtaining credible physics resuls of a complex analysis and a search. She also evaluated limits on the cross-section of the BSM models under study and set limits on some model parameters, also presenting a combination of her results with a previous analysis, and interpreting the data in terms of a sgluon model, for the first time in a specific channel.

Besides all this she also contributed to the ATLAS detector upgrade by her qualification task within the ATLAS Inner Tracker upgrade project.

In results presentation, there is a thorough discussion of the cases where the fit nuisance parameters are pulled close to the 1 standard deviation, with proposed interpretations with an insight into their connection to physics modelling, e.g. the 4 vs. 5 flavour schemes setups for tt+heavy flavour backgrounds.

The language of the thesis is at a high level, although spell-check would be useful be applied in few places and some formulations could be made more fluent. Nonetheless, the text is well readable and presents her contributions clearly and in an interesting way. Presented results are clearly marked, also those taken from the final ATLAS publication. Plots and formulas are clear and well-referenced in text. There are more than 200 references cited, too.

Overall, the presented results clearly demonstrate her major contribution to a vast and important results of the ATLAS experiment; she also presented the results at international conferences. She has extended the landscape of knowledge stemming from the physics potential of the ATLAS experiment, towards constraining signs of possible new physics processes.

Concerning the presented physics analyses, I have the following main comments

1. It is stated that the pruning procedure removes 80% if systematics sources (pg. 110). Was it checked that the results are stable and the total uncertainty is not underestimated?
2. It is stated that the post-fit plots exhibit improved agreement between the data and background (page 130) – was this checked for the individual distributions by some figure of merit, or just visually?
3. Figure 4.28 does not show whether the uncertainties are statistical or systematics, could a fixed version of the plot be shown?
4. It is argued that the signal strength excess in the 400 GeV mass point might be due to low statistics – but isn't the data stats. the same for all tested mass points?
5. It seems like the ttbb 4FS Shape systematics is consistently pulled, which is interpreted as the 5FS being preferred by data. Could this fit result be used for other measurements to diminish the 4FS/5FS modelling uncertainty design?
6. Did ATLAS/you take a look into kinematics of events in the excess region in the few highest bins of the GNN output score as in Fig. 3.39?
7. Could the author discuss what more ATLAS data would bring to the analysis in terms of stat. and syst. uncertainties and what the possible fit to the signal+background hypothesis might result to?

Last, as a few remarks, not crucial to be discussed in detailed slides:

- Page 29, process ttbb: the scale defined as 4th root: is the argument really a sum, or should it rather be a product, making the scale a geometric mean?
- Pg. 68: the Z boson mass window is perhaps larger than just 89 GeV?
- Some abbreviations like NP or MET are mentioned and defined only later.
- It is unclear whether the ‚gamma' nuisance parameters in the fitter scale the uncertainties just of the Monte Carlo backgrounds or also of the signal templates.
- As a remark, photon is not directly the vector boson of the $U_Y(1)$ symmetry as suggested by the statement on page 11, being rather a combination of the neutral bosons from the SM U(1) and SU(2) groups as better clarified later in the Section.
- Also, SM does not predict 3 families, only indicates 3 families of light neutrinos, and prefers the same number of lepton and quark families.
- Not sure Eq. 1.6 is correct: running of the coupling is usually expressed in terms of dalpha/dmu?

- In the BEH boson mechanism, the mass terms for fermions are put in by extra gauge invariant terms, it's only the vector boson masses that are generated by the SSB. The motivation of gauge non-invariant terms should ideally precede the discussion. The Higgs boson was also discovered in the WW channel:)
- It is now also known that some ttbar threshold bound effects may be observed.
- Also, masslessness of the force carrier is not the sufficient condition for the corresponding interaction being long ranged, as suggested for the electromagnetic force on page 15 (c.f. the massless gluons and the strong force).
- Tables 3.5 and 3.7 and would actually be better presented as 2D colored plots, possibly with the TEXT option in ROOT.
- Are Figures 1.1 and 1.2 author's own graphics, or were taken from some source? Fig. 1.2 is not „Standard Model“, but rather its particle content.
- Eq. 3.20 is not a Poisson distribution but rather a product of Poissonian terms.
- Fig. 3.40 would better indicate the uncertainties are total also in the Caption, not just in text.
- Page 142: better typesetting of the ‚exp‘ would be welcome.

I regard the author's work in several areas presented as a demonstration of her own ability to pursue scientific research. The presented results are novel and constitute an important achievement of the ATLAS collaboration, with her direct and substantial contribution. I thus fully recommend her thesis to be accepted in fulfilment of the PhD degree.

In Olomouc, 9th September 2025

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