TAE 2023
Lectures on LHC Physics – Tutorial

1. **Discuss the pros/cons of hadron colliders compared to lepton colliders. What is the best collider to: (a) measure the top-quark mass with <100 MeV precision, (b) measure the Hγγ coupling, (c) measure the Hμμ coupling, and (d) discover a 2.5 TeV vector-like quark? Offer a reasoned answer.**
   Hadron colliders allow to reach higher energies for particle collisions, but the final state is more complex and the centre-of-mass energy event-by-event is not known. In addition, theoretical predictions are more challenging, since they need to be computed at higher orders in QCD, and have in general worse precision. On the other hand, hadron colliders offer a rich spectrum of initial-state configurations in terms of flavor and energies that are not available at lepton colliders. (a) an e+e- collider, through threshold scan in e+e-→ttbar; clean top mass definition; (b) LHC, given the high Higgs production rate, since H→γγ has a low branching ratio; (c) a muon collider, through the μμ→H process (cross-section proportional to coupling squared); and (d) a hadron collider at 100 TeV (FCC-hh), since the cross-section to produce a 2.5 TeV VLQ at the LHC would be too small.

2. **How can we experimentally establish that the top quark has an electric charge of 2/3e? How can we measure the top-quark width at the LHC in the most model-independent way?**
   The most model-independent way is to reconstruct the top charge in the t→Wb decay. This requires to be able to measure the b-jet charge, which can be done based on the tracks inside the jet but with poor resolution. In this way the hypotheses of charge +2/3e vs -4/32 can be tested. Another possibility is to measure the cross-section for the ttbar+photon process, which is proportional to the ttγ coupling squared (i.e. more than just the top charge, if there are anomalous couplings). To measure the top width, one should be able the partial width of t→Wb and the branching ratio for t→Wb: $\Gamma = \Gamma(t\to Wb)/BR(t\to Wb)$. The former can be determined by measuring the tWb coupling through a combination of single top and ttbar measurements, to determine the Lorentz structure and strength of the tWb coupling. The t→Wb branching ratio can be determined by comparing precise ttbar cross-section measurements (which requires t→Wb explicitly, e.g. in eμ final state) and cross-section prediction.

3. **What are the main experimental challenges for a precise measurement of the top-quark mass via direct reconstruction? Explain why and how they can be mitigated.**
   The main challenges arise from the jet energy calibration, and the physics modeling of the ttbar processes. The former can be partly addressed by exploiting the in-situ calibration of the light-jet energy scale via the W→qq decay. However, this doesn't really constrain the b-jet energy scale. This requires good understanding of the b-jet fragmentation, which can be constrained via measurements in ttbar events, and the b-to-light jet

response ratio, which can be constrained through detailed simulation studies supported by single-pion response measurements in data. The modeling of ttbar production and decay requires careful tuning of the MC generators. Some of these modeling uncertainties can be constrained in data thanks to the large ttbar samples available, but need to ensure having a physical model of systematic uncertainties to avoid unreasonable overconstraints.

4. **How can be probe the existence of a new heavy large-width resonance preferentially coupled to the top quark? Discuss what experimental strategy should be followed, and the main challenges faced, to unambiguously establish such signal.**
   Such a heavy resonance could be probed through its decay into ttbar. What production mode to exploit depends on its couplings to lighter quarks. If sufficiently large, it can be searched in qq→X→ttbar. The large width makes it hard to search for a bump on a steeply falling background, and it may be manifested mainly through a deviation in the tail of the mttbar spectrum. Therefore, a precise differential cross section measurement is needed as a function of mttbar. The lepton+jets final state of the ttbar system would be suitable, since it would reduce multijet backgrounds. At very high mass, the resulting boosted top quarks would require to use advanced experimental tools: e.g. boosted top tagging for the hadronically decaying top, no isolation cut on the lepton for the leptonically decaying top (lepton merged with the b-jet from the top). A very precise SM theoretical prediction would be needed to compare it against the measured spectrum and infer the presence of New Physics. This would require to take into account higher-order QCD and EW corrections, and make sure the most precise possible PDF is used.

5. **What kind of physics analysis would be best to search for a FCNC tug coupling? And to search for a FCNC tcH coupling?**
   A tug coupling would result in t→ug decays. However, the branching ratio can be exceedingly small, as it competes with the large t→Wb partial width. Also, establishing the t→ug decay would be very challenging experimentally. The best way would be to take advantage of the large u-quark PDF and search for ug→t(→Wb) production. The large charge asymmetry would help in suppressing/controlling SM backgrounds. To search for a FCNC tcH coupling, one needs to look for t→cH decay, using ttbar→WbHc events. Different Higgs decay modes can be used to unambiguously establish the Higgs in the final state and suppress SM backgrounds, such as H→$\gamma\gamma$.

6. **What are the experimental tests required to establish the H(125) particle as a Higgs boson?**
   The main properties to be verified are: spin 0, CP even interactions with bosons and fermions, couplings proportional to mass, Higgs self-coupling. All of these measurements (and more) and underway at the LHC.

7. **Discuss two possible ways to determine experimentally whether the Higgs boson is an elementary or a composite particle.**

One way is by measuring the Higgs couplings to SM particles which, in the case of a composite particle, would typically be reduced compared to the SM prediction (for an elementary scalar). This is analogous to the measurement of the proton structure function in e.g., deep inelastic ep scattering. Another way is by studying longitudinal vector-boson (VBS) scattering: if the Higgs boson is not an elementary particle, it does only partly the job of unitarizing the VBS amplitudes, which would exhibit a rise with energy (and be unitarized by resonances from the new strong interaction, as in the case of QCD).

8. **How can we indirectly detect the existence of new heavy colored particles that couple to the Higgs boson? And of new heavy electrically-charged particles? And how would we actually discover them?**
   New heavy colored particles that couple to the Higgs boson would in principle affect the ggF production cross-section, via their contribution to the gg→H loop. Since the top quark provides the dominant contribution, a model-independent determination of such BSM contribution requires to "resolve" the loop. This can be done through independent determination of the top-Higgs Yukawa coupling, by measuring the ttH cross-section, and/or by studying gg→H production at very high pT. The $H \rightarrow \gamma\gamma$ branching ratio is primarily sensitive to BSM contributions that are electrically charged, since they would contribute to the $H\gamma\gamma$ loop. Since also the top quark and the W boson contribute to it, they also need to be constrained independently (other loop-induced decays, such as $H \rightarrow Z\gamma$, can slso provide sensitivity). If deviations are detected in either the gg→H cross-section or the $H \rightarrow \gamma\gamma$ branching ratio, this can be used to constrain the coupling/mass ratio from such contributions (assuming one particle dominates), and be complementary to direct searches. E.g., in the context of SUSY, the top squark contributes to both the Hgg and $H\gamma\gamma$ couplings, whereas charginos or sleptons would contribute to the $H\gamma\gamma$ coupling. For all these particles there are already dedicated searches ongoing.

9. **What kind of physics analysis would be most suitable to probe Higgs-boson decays to dark matter particles? How can we set bounds on the existence of *any type* of undetected Higgs-boson decay modes? Why limits on such branching ratios even at the level of 10% are still quite powerful?**
   The most sensitive channel to search for invisible Higgs decays is VBF production due to the large cross section and the possibility to suppress backgrounds via the VBF topology. The Higgs coupling measurements can be used to set bounds on the sum of invisible+undetected modes (with some mild assumptions). The combination of H→invisible bounds and Higgs coupling measurements can be used to set bounds on undetected Higgs decay modes. The reason why even mild bounds on BSM branching ratios at the level of 10% can be quite constraining, is thanks to the extremely small Higgs width in the SM, of only ~4 MeV. BSM contributions can easily compete with it and be detectable.

10. **Imagine that eventually a 4-top cross-section that is significantly different from the SM prediction is measured. What are the implications for Higgs physics?**
One possible explanation is contamination from 4-top signal via heavy Higgs production, ttH/A->4-tops. The study of the event kinematics of the 4-top excess may provide information about the mass of the particle. Determining whether it comes from the production of an additional scalar particle using just 4-top production will require large statistics. In that case, one expects also production via ggF: gg→H/A→4-top, which would have much higher cross-section, but be affected by interference with the SM ttbar background. Still, the combination of both processes can help determine the mass, couplings, and CP properties of the excess. If confirmed, this would indicate the presence of an extended Higgs sector. Additional production and decay modes can be searched for to try to pin down its structure.