Strange Quark as a probe for new physics in the Higgs Sector

M.J. Basso[(a)], V.M.M. Cairo[(b)], U. Heintz[(c)], J. Luo[(c)], M. Narain[(c)], R. S. Orr[(a)], A. Schwarzman[(b)], D. Su[(b)], E. Usai[(c)], C. Vernieri[(b)], C. Young[(b)]

(a) University of Toronto, Toronto ON - Canada
(b) SLAC National Accelerator Laboratory, Stanford CA - USA
(c) Brown University, Providence RI - USA

The experimental program at the LHC has clearly established Yukawa couplings of the 125 GeV Higgs (*h*) to the third generation of fermions. The ATLAS and CMS experiments have recently reported evidence that the Higgs boson decays into two muons, which indicates for the first time that the Higgs boson interacts with second-generation leptons. At the same time, this is just a hint and not yet a complete exploration of the second generation Yukawa couplings, because these rare Higgs decay modes (i.e. to charm or strange quarks) are very challenging or nearly impossible to detect with the current detector capabilities. Furthermore, the large multi-jet background at the LHC inhibits the study of light quark couplings with inclusive $h \to q\bar{q}$ decays, in addition to the dominant *h* to *b*-quarks decay mode.

At the LHC new algorithms for the identification of jets originating from the hadronisation of *c*-quarks (*c*-tagging) are gradually becoming available. This has enabled new searches for the decay of the Higgs boson to charm quarks that will be a flagship probe for future e^+e^- colliders. Current projections for the inclusive $h \to c\bar{c}$ measurements at future colliders predict that it could be measured at 1% accuracy at e^+e^- machines [1].

Less literature, instead, is available about searches of Higgs boson decays to light quarks [2-7]. Searches for exclusive Higgs boson decays to a φ or ρ(770) meson and a photon have been suggested and experimentally tested [7] as a probe of the Higgs boson couplings to the strange-quark, or the up- and down-quarks, respectively. For these Higgs couplings there are no projections available and it will most likely remain out of direct experimental reach unless they are enhanced compared to SM expectations. In fact, when considering scenarios that allow for extended Higgs sectors, the possibilities open up dramatically. A class of BSM models [8], where the origin of the first and second generation fermion masses is an additional source of electroweak symmetry breaking, predicts large deviations from the SM values. A simple example is the two Higgs doublet model (2HDM) where one doublet (approximately identified as the 125 GeV Higgs) couples mainly to the third generation, while the second doublet couples mainly to the first and second generation. This results in very different decay branching ratios of the additional heavy Higgs bosons (*H*). The largest production mode of the neutral Higgs bosons would be from a $c\bar{c}$ initial state, while the charged Higgs bosons would be dominantly produced from a cs initial state. The most interesting decay modes include $H/A \to cc, tc, \mu\mu, \tau\mu$ and $H^{\pm} \to cb, cs, \mu\nu$.

A dedicated algorithm for the identification of jets that originate from the hadronisation of strange quarks (strange tagging) would allow us to tag exclusive Higgs decays and open new opportunities in direct $h \to s\bar{s}$ searches. If used in conjunction with c-tagging, it would also allow to probe new physics models, in particular those that foresee increased branching ratios for final states with flavour mixing, such as the $H^{\pm} \to cs$ scenario mentioned above. This would not only allow to break into new flavor changing currents, but also the tagging practicality of only one leg of the challenging strange tagging will make it experimentally easier to reach meaningful sensitivity to actual models.

The main idea behind strange taggers is that strange quarks mostly hadronise to prompt kaons that carry a large fraction of the jet momentum. Recognising strange jets (in Z decays) has been attempted before at DELPHI [9] and SLD [10]. Other studies released recently [2-4], which assume LHC-like experiments, focus on the separation between strange and down quark jets by exploiting information from the energy deposited in the calorimeters and/or the momentum of short-lived neutral kaons that decay-in-flight to charged pion pairs within the inner tracking region.

Calorimeter longitudinal segmentation is an important handle to separate neutral kaons from neutral pions, more common in down-quark jets, as the latter decay promptly to pairs of photons that deposit energy in the electromagnetic calorimeter.

The reconstruction of strange hadrons, in particular strange baryons, has been notoriously difficult at the LHC. Since strange baryons tend to decay within the detector volume, especially if they have low momentum, they often do not leave enough hits to reconstruct a track, leading to a track reconstruction efficiency of approximately 0.3% as estimated by the ATLAS Collaboration [11].

The studies in Refs [2-4] show that the proposed strange tagging suffers from low efficiency and very large mis-tag probability from u and d quarks, even when using sophisticated machine learning algorithms. This indicates that the observables currently exploited with the LHC-like detector design are not enough to achieve good tagging performance. New detector concepts can enable particle identification and provide the necessary handles to make strange tagging a reality.

General purpose detectors, like ATLAS, provide a measurement (with a typical resolution of 10%) of the specific energy loss dE/dx for tracks [12,13]. This allows to define a method for non-relativistic particle identification, based on the well-known dE/dx dependence on $\beta\gamma$. Current applications of this pion-kaon-proton identification method are limited to the lowest momenta measured in ATLAS (typically below 1 GeV) and are related to soft QCD issues (e.g. φ or Λ production) or to Quantum Mechanical tests (e.g. Bose-Einstein Correlations of identical particles).

Charged particle identification can alternatively be achieved with the use of precise timing information, as planned for the upgrades of the LHC experiments and even more for detectors at future colliders: a velocity can be deduced that, in combination with the standard measurement of momentum from track curvature in the magnetic field, yields a measure of the charged particle mass. Improvements in the time resolution per track for timing detectors at future colliders with respect to those proposed for High-Luminosity LHC (30-50 ps) could extend particle identification capabilities from a few GeV to much larger momenta [2] and as such would become very relevant for strange tagging by providing an additional handle for separation between light quarks. Another very effective way to achieve particle identification is through Cherenkov detectors, as done in the ALICE and LHCb experiments at the LHC. In either scenario, kaons beyond the 10 GeV range will have to be identified in order for this to be relevant for strange tagging.

The most powerful high momenta $K^{\pm}$ tags with dedicated particle identification detectors may be an exclusive territory of e^+e^- colliders, while hadron colliders still have the leading V^0s (K^0_s and Lambda) as a handle thanks to their distinctive 2-prong vertices. Once working towards higher mass extended Higgs sectors, one actually needs to examine detector designs very carefully to ensure that they are capable of capturing the high momenta V^0s that can decay deep into the tracker.

Modern machine learning techniques, including jet-imaging and End-to-End deep learning techniques [14-16] have been very successful in distinguishing between heavy-flavor and light jets. We plan to deploy similar methods which will take into account Kaon identification for tagging jets with strange quarks.

In summary, we are at a very interesting junction to test the nature of the Yukawa coupling and their universality. While the exploration so far is mostly focusing on the 125 GeV Higgs, the searches for new heavy Higgs bosons with non-universal Yukawa couplings will be a new avenue with many interesting possibilities such as intriguing flavor violating decays and also requires more conscious strategies to bear in mind the non-universal couplings. This exploration can already start at HL-LHC and further extend its reach in energy and precision at future hadron and lepton colliders. The investigation of the non-universality of the Higgs Yukawa couplings can be a crucial window to allow us to re-approach one of the most fundamental mysteries of the three fermion generations, which will also require a reinvigorated theoretical effort to map out the most promising scenarios.

In order to enter a new era for particle identification at colliders, it is fundamental to push the requirements on instrumentation and to guide the development of a dedicated R&D program on advanced particle identification detectors which can enable crucial physics goals. More specifically, in the context of Snowmass 2021, we propose to study the feasibility of the measurement of Higgs boson couplings to light quarks, in particular to strange quarks, as of paramount importance to complete the understanding of the Higgs sector. The emphasis will be put on future lepton colliders since the branching ratio for $h \rightarrow ss$ is below the level of 10^{-3} [6] in the SM and the measurement requires a large number of Higgs bosons in a very clean environment, but important information on the usage of advanced 4D tracking capabilities can also be learned in the HL-LHC context. This study strongly aims at motivating the development of strange tagging techniques and at providing requirements to future tracking algorithms and timing detectors performance.

Bibliography

[1] “*Physics Briefing Book*”, European Strategy for Particle Physics Preparatory Group, https://arxiv.org/abs/1910.11775.

[2] “*Strange jet tagging*”, Yuichiro Nakai, David Shih, Scott Thomas, https://arxiv.org/abs/2003.09517.

[3] “*A tagger for strange jets based on tracking information using long short- term memory*”, J. Erdmann 2020 JINST 15 P0102.

[4] “*Probing the strange Higgs coupling at e^+e^- colliders using light-jet flavor tagging*”, J. Duarte-Campderros, G. Perez, M. Schlaffer and A. Soffer, https://arxiv.org/abs/1811.09636.

[5] “*Search for a light charged Higgs boson decaying to csbar in pp collisions at sqrt(s)= 8 TeV*”, CMS Collaboration, https://link.springer.com/article/10.1007/JHEP12(2015)178.

[6] “*Electroweak Symmetry Breaking at the LHC*”, A. Djouadi, R.M. Godbole, https://link.springer.com/chapter/10.1007%2F978-81-8489-295-6_5, https://arxiv.org/abs/0901.2030.

[7] “*Search for exclusive Higgs and Z boson decays to φγ and ργ with the ATLAS detector*", ATLAS Collaboration, https://link.springer.com/article/10.1007%2FJHEP07%282018%29127.

[8] “*Collider Signatures of Flavorful Higgs Bosons*”, W. Altmannshofer et al., Phys Rev. D94 (2016), 11, 115032.

[9] “*Measurement of the strange quark forward- backward asymmetry around the Z peak*”, E. Boudinov, P. Kluit, F. Cossutti, K. Huet, M. Gunther, and O. Botner, CONF, DELPHI-98-115, ICHEP’98, 1998.

[10] “*First Direct Measurement of the Parity-Violating Coupling of the Z0 to the s quark*”, SLD Collaboration, Phys. Rev. Lett. 85, 5059, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.85.5059.

[11] “*Charged-particle distributions in pp interactions measured with the ATLAS detector at the LHC*”, ATLAS Collaboration, https://doi.org/10.1016/j.physletb.2016.04.050.

[12] “*dE/dx measurement in the ATLAS Pixel Detector and its use for particle identification*”, ATLAS Collaboration, https://cds.cern.ch/record/1336519.

[13] “*Hadronic Interaction Vertices Analysis with the ATLAS Detector*”, N. Mahmood, https://cds.cern.ch/record/2641664.

[14] “*End-to-End Jet Classification of Quarks and Gluons with the CMS Open Data*”, M. Andrews et al., https://arxiv.org/abs/1902.08276.

[15] “*ParticleNet: Jet tagging with Particle Clouds*”, H. Qu and L. Gouskos, https://arxiv.org/abs/1902.08570.

[16] “*End-to-end particle and event identification at the Large Hadron Collider with CMS Open Data*”, J. Alison et al., https://arxiv.org/abs/1910.07029.