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Strange quark as a probe for new physics in the Higgs sector

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One of the most interesting yet-to-be answered questions in Particle Physics is the nature of the Higgs Yukawa couplings and their universality. Key information in our understanding of this question arises from studying the coupling of the Higgs boson to second generation quarks. Some puzzles in the flavor sector and potential additional sources of CP violation could also have their origins in an extended Higgs sector. Rare Higgs decay modes to charm or strange quarks are very challenging or nearly impossible to detect with the current experiments at the Large Hadron Collider, where the large multi-jet backgrounds makes it difficult to study light quark couplings with inclusive $h \to q\bar{q}$ decays. Future e^+e^- machines are thus the perfect avenue to study such phenomena.

This contribution presents the development of a novel algorithm for tagging jets originating from the hadronisation of strange quarks (strange-tagging) and the first application of such a strange-tagger to a direct Higgs to strange ($h \to s\bar{s}$) analysis. The work is performed with the International Large Detector (ILD) concept at the International Linear Collider (ILC), but it is easily applicable to other Higgs factories. The study includes as well a preliminary investigation of a Compact Ring Imaging Cerenkov system (RICH) capable of maximising strange-tagging performance in future Higgs factory detectors.

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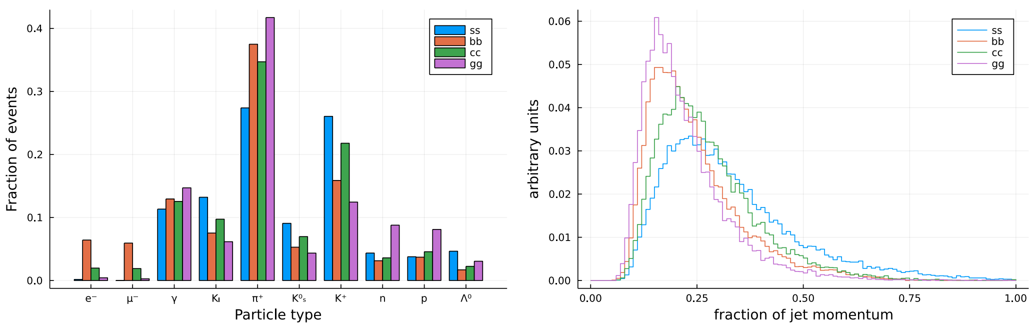
1. Introduction

In 2012, the ATLAS and CMS collaborations announced the discovery of a particle compatible with the Higgs Boson. In the last ten years, we have studied many of its properties and couplings. The measurements of the couplings of the Higgs Boson with the W and Z vector bosons as well as its Yukawa coupling to the top and bottom quark confirm its compatibility with the Standard Model (SM) Higgs Boson (h). The coupling of the Higgs boson to lighter generation fermions is yet to be proven. The ATLAS and CMS collaboration reported the first evidence that the Higgs boson decays into two muons, indicating its relation with the second-generations leptons, but the path towards understanding the universality of the Yukawa interactions has just began. Rare Higgs decay modes such us those to charm or strange quarks are very challenging or nearly impossible to detect with the existing detectors due to both the detector capabilities and the overwhelming multi-jet production rate at the LHC which inhibits the study of strange, up, and down quark couplings with inclusive $h \to q\bar{q}$ decays, in addition to the dominant $h \to b\bar{b}$ decay mode.

This talk summarises the work published in Ref. [**?**] which presents a new flavour tagging algorithm to identify jets originating from the strange quark hadronisation (strange-tagging) with the future International Large Detector (ILD) at the International Linear Collider (ILC), but it is easily applicable to other Higgs factories. The $P(e^-, e^+) = (-80\%, +30\%)$ polarisation scenario was used for this preliminary result, corresponding to $900 fb^{-1}$ of the initial proposed $2000 fb^{-1}$ of data which will be collected by ILD during its first 10 years of data taking at $\sqrt{s} = 250$ GeV. The study includes an investigation of particle identification (PID) techniques to discriminate kaons from pions and proposes a modern Compact Ring Imaging Cerenkov system (RICH) with Silicon Photomultipliers (SiPMs – also referred to as SiPMTs) to maximise strange-tagging performance in future Higgs factory detectors.

2. Strange-tagging at future e^+e^- colliders



(a) Leading particle fractions **(b)** Jet momentum fraction carried by leading particle

Figure 1: (a) Leading particle fractions and (b) the fraction of the jet's momentum carried by the leading particle for reconstructed jets from $h \to s\bar{s}/b\bar{b}/c\bar{c}/gg$ events. In (a), all of the bars of a particular colour sum to 1 by definition.

Tagging strange jets is a complex problem. While bottom and charm jets can be differentiated based on the presence of tracks with large impact parameters as well as of 2 or 1 secondary vertices,

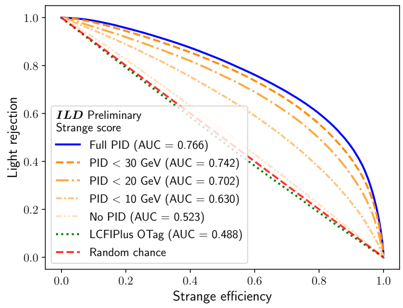


Figure 2: ROC curves for various output nodes of the jet flavour tagger with PID for any particle momentum ("Full PID"), as well as for the jet flavour taggers without PID ("No PID") and with partial PID ("PID $< X$ GeV").

strange jets, which, excluding V^0s, have 0 secondary vertices and are only differentiated from light (i.e., up or down) jets based on the ability to reliably tag the presence of a strange hadron within the jet. Strange hadrons are also most often the leading particle in strange jets, as evident from Fig. 1a and, as shown in Fig. 1b, the leading particle more often carries a larger fraction of the strange jet's momentum as compared to other jet flavours. Therefore having π/K discrimination at moderate to high particle momentum (i.e., $>$10 GeV), is the key at future detectors for measurements of decays to strange jets. To better quantify the impact of PID on strange-tagging, a recurrent Neural Network tagger for classifying jet-flavor was developed. All the details can be found in Ref. [2]. It was trained on full simulation $Z(inv)(h \to q\bar{q}/h \to gg)$ samples produced with the International Large Detector (ILD) concept at the proposed International Linear Collider. The tagger includes per-jet level inputs and kinematic information about the 10 leading particles in each jet, including PDG-based likelihoods (for electrons, muons, pions, kaons/strange hadrons and protons), to make the study of general validity. Fig. 2 shows the ROC curve for the strange-tagging efficiency and the light-jet rejection in several scenarios: with PID for any particle momentum ("Full PID"), as well as for the jet flavour taggers without PID ("No PID") and with partial PID ("PID $< X$ GeV"). As expected, the performance are poor when no PID is included in the tagger while, for example, a 50% strange tagging efficiency with about 80% light-jet rejection is achieved when PID is included in the full momentum range. The possibility of having PID at high momentum boosts the performance dramatically: as an example, for a fixed 80% rejection, the strange-tagging efficiency increases by a factor of 1.5, 2.0 and 2.5 when the momentum range of PID goes up to 10, 20 or 30 GeV, respectively. A much smaller gain is observed when including PID above 30 GeV. This provides clear evidence that to tag strange jets at future colliders, PID capabilities up to 30 GeV are of paramount importance.

2.1 $h \to s\bar{s}$ analysis with the ILD at the ILC

It is now of interest to apply the newly developed strange-tagger to a direct search for Zh, $h \to s\bar{s}$ with the ILD concept at the ILC. The Feynman diagram of the process can be seen in Fig. 3. The ILC is foreseen to run at several centre-of-mass energies, including a dedicated 250 GeV run for Higgs couplings studies. At such energy, the dominant Higgs boson production mechanism is via

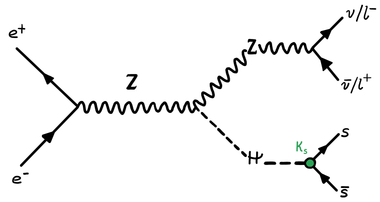


Figure 3: Tree-level Feynman diagram for production of a Higgs boson in association with a Z boson. The Higgs decays hadronically to strange quarks (with Yukawa coupling strength modifier κ_s) and the Z decays leptonically to charged leptons or neutrinos. Drawing by F. Cairo.

associated Zh production, with a cross-section of about 200 fb. The branching ratio of the SM Higgs boson to strange quark is approximately 2×10^{-4}. As a back-of-the-envelope calculation, assuming $2000\,\text{fb}^{-1}$ of data collected at the ILC after 10 years of data-taking and a Higgs boson production cross section of about 200 fb, ~400,000 Higgs bosons would be produced where only 80 of those feature a $h \to s\bar{s}$ event. As a point of comparison, ~200,000 $h \to b\bar{b}$ and ~12,000 $h \to c\bar{c}$ events are expected. Nevertheless, when considering Beyond the Standard Model (BSM) scenarios that allow for extended Higgs sectors, the scenario changes. A particular class of models with additional Higgs doublets (2HDM) have new Yukawa matrices which need not be directly proportional to the SM fermion masses. One such class of models are those exhibiting spontaneous flavour violation (SFV) [**?**], which allows for new Yukawa couplings either to the up or the down quarks with no relation to the quark masses. A two Higgs doublet model with up-type SFV, for example, could thus have large couplings to the d and s quarks, and the new Higgs states would be produced in quark fusion, with decays to gauge and Higgs bosons and quarks [**?** **?**]. If the observed 125 GeV Higgs boson is an admixture of a SM-like Higgs and one of the new Higgs states, its couplings to the first or second generation quarks can be significantly larger than predicted in the SM, leading to large deviations in the Higgs boson branching ratios.

Fig. 4 illustrates schematically the Zh, $h \to s\bar{s}$ analysis flow, more detailed information can be found in Ref. [2]. The events are required to have two jets and either 0 or 2 same-flavour opposite-sign leptons. A series of kinematic cuts is then applied to reject the major backgrounds arising from single of double vector boson production as well as Zh with the Higgs boson decaying to flavours other than the strange. The sum of the leading and sub-leading strange-jet tagging score is used as the final signal discriminant to extract the constraints on the strange Yukawa coupling modifier, κ_s, which is found to be $k_s \lesssim 7$. Fig. 5 shows that these results, when interpreted as bounds on the SFV 2HDM model on the are the strongest throughout the parameter space considered, exceeding even those expected from measurements performed at the High Luminosity LHC (HL-LHC) except for a small range of parameters. Therefore, tests of SFV 2HDMs are expected to be highly competitive at future lepton colliders like the ILC.

2.2 Particle Identification

When we talk about particle identification for strange-tagging, we are specifically talking about identifying hadrons. Hadrons are identified by their mass, in turn determined by combining

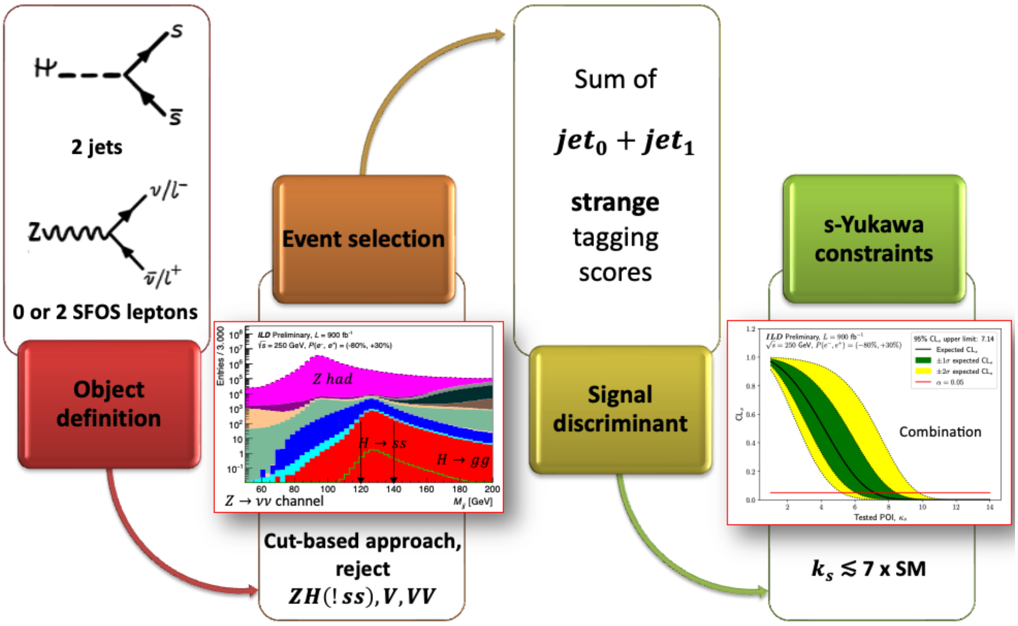


Figure 4: Flow chart of the Zh with $h \to s\bar{s}$ analysis. A more detailed description of the figures can be found in Ref. [2].

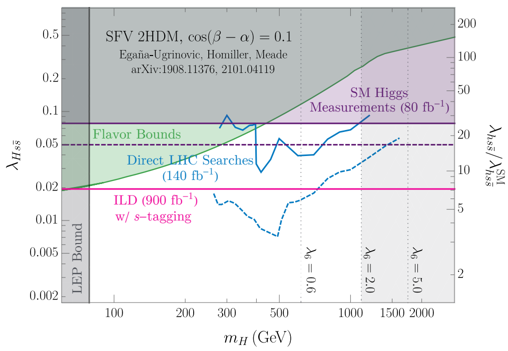


Figure 5: CL$_s$ upper limit for κ_s in the context of the SFV 2HDM framework. For more details on its interpretation, see Ref.[2].

momentum and velocity (see more in [?]). Assuming that the momentum is inferred from the radius of curvature in a magnetic field, the remaining question is to measure the velocity. There exists several techniques to determine the velocity, for example Time-of-flight (TOF), ionization losses dE/dx or cluster counting dN/dx, transition radiation or Cherenkov radiation [1]. The momentum range covered by these techniques is illustrated in Fig. 6. The ILD concept has 3 double-layer pixel detectors for vertexing followed by 2 double-layer pixel detectors, a Time Projection Chamber (TPC), and 1 double-layer strip detector for tracking. The TPC additionally provides PID via

[1]The latter two techniques rely on effective detection of photons and require single photon sensitivity, high efficiency and good spatial granularity

measurements of energy loss from charged particles due to ionisation (dE/dx) which is envisioned to be completed by time-of-flight (TOF) measurements in the TPC's silicon envelope or in the electromagnetic calorimeter. From the studies presented in [**?**], a π/K separation with a 3σ significance is reached in such a system only up to 20 GeV, as the performance scale with the tracker volume. Therefore we have investigated alternative layouts which could extend particle identification to higher momentum in future detector concepts.

3σ *separation for* π/K				
dE/dx in silicon	TOF via Fast Timing in silicon envelopes or calorimetry	dE/dx in Time Projection or Drift Chambers	dN/dx	RICH
≲ 5 GeV	≲ 5 GeV	≲ 30 GeV (scales with volume)	O(tens of GeV)	O(tens of GeV)

Figure 6: Sketch illustrating various particle identification techniques and the expected momentum range that can be covered.

2.3 A Compact RICH proposal

The Ring Imaging Cherenkov Detector (RICH) is the system that pioneered PID and, as shown in Ref. [**?**], represents a favourable approach at high momentum when using gas as radiators. The important question to address is whether it will possible to accommodate a *compact* RICH system while preserving performance in tracking and calorimetry at future multi-purpose detectors. Our proposed concept to address this question is illustrated in Fig. **??**. This Compact RICH detector is designed using spherical mirrors and Silicon Photomultipliers (SiPMs – also referred to as SiPMTs) as photon detectors.[2]. The layout resembles the gaseous RICH detector of the SLAC Large Detector's (SLD's) Cherenkov Ring Imaging Detector (CRID) [**?**]; however, introducing SiPM-based design improves the PID performance by a factor of two compared to the SLD's and DELPHI's gaseous RICH detectors. Although we have selected a specific type of SiPM in this paper in order to do the calculation (a commercially-available Hamamatsu SiPM), we believe that the photon technology will improve over the next 15 years in terms of noise performance, timing capability, pixel size, and detection efficiency. Fast timing SiPM (< 100 ps) can provide timing information to reject background photons and, at the same time, a TOF system covering the lower momentum range and complementing the RICH. The overall aim is to make this RICH detector with as low mass as possible because we do not want to degrade the calorimeter. This speaks for mirrors made of beryllium [**?**] and the structure made of low mass carbon-composite material. Another important aspect is to make the RICH detector depth as thin as possible in order to reduce the cost of the calorimeter. Our initial choice of 25 cm could be reduced further if the detection efficiency of future photon detectors improve. For example, if the detection efficiency improves by ~50%, the radial depth can be reduced to 10–15 cm, in turn reducing the magnetic smearing contribution to

[2]The present design with SiPM detectors requires that the total neutron dose at RICH's location is less than ~ $5 \times 10^{10}\, n_{\mathrm{eq}}/10$ years, for which the SiPM damage is expected to be low.

Cherenkov angle resolution[3]. All the details on the gas choice as well as on the Cherenkov angle resolution can be found in Ref. [2]. The estimated performance of the Compact RICH is shown in Fig. **??** for a C_4F_{10} gas as a function of Cherenkov angle resolution. A Cherenkov angle resolution of up to 3 mrad will allow to achieve the desired performance of $\sigma > 3\sigma$ π/K separation up to 30 GeV. Alternative layouts capable of reaching higher momenta include pressurised gas, as presented in Ref. [3**?**]. However, one would need to deal with a vessel holding a pressurised gas and the increase in detector mass becomes significant ($X/X_0 \sim 10\%$), while higher momentum ranges have been proven not to increase strange-tagging drastically. We believe that our design can, instead, be built with $X/X_0 \sim$ 3–4%. This simple study indicates that modern and compact RICH detectors at ILD- or SiD-like experiments operating at 5 T are a promising solution for PID at future e^+e^- accelerators and justify a full Geant4 simulation.

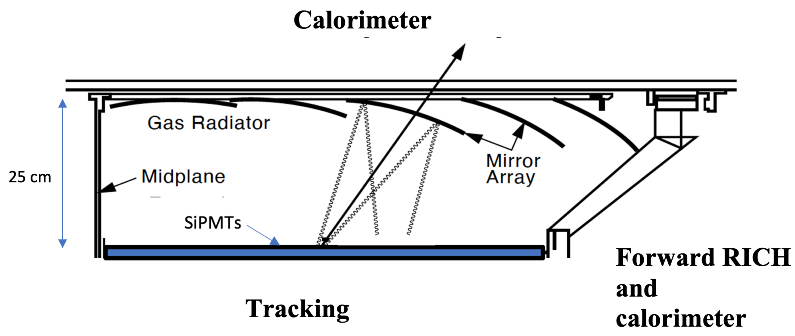


Figure 7: Proposed gaseous RICH detector. The relative placement of the tracking, calorimetry, and forward instrumentation is indicated.

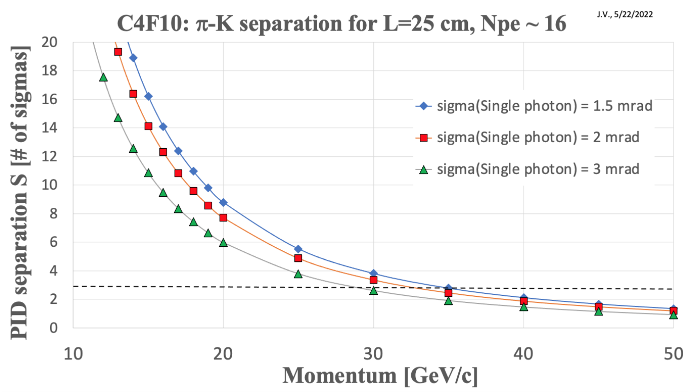


Figure 8: Expected PID performance as a function of momentum and single-photon Cherenkov angle resolution. A resolution higher than 4 mrad starts severely affecting the performance. Here, we assume 16 photoelectrons per ring and a tracking error of 0.5 mrad.

[3]The Cherenkov ring is smeared in the focal plane due to the helical motion of the particle in a large magnetic field. The study assumes a 5 T magnetic field as a conservative estimate, but Ref. [2] describes the performance also with other scenarios.

3. Conclusions

Testing the universality of the Higgs Yukawa coupling is a key benchmark for future Higgs factories. Our ordinary matter is composed by electron and light quarks and none of the Higgs boson couplings to such particles has been verified yet. The Large Hadron Collider as well as its High Luminosity operations will ramp down in about two decades. It is thus a very exciting time to look ahead and think about the design of a future Higgs factory and it detectors, which will allow us to solve some of the yet-to-be answered questions in Particle Physics. Probing the Strange Yukawa coupling is both a challenge and an opportunity at Future Colliders, with the interplay between detector design, performance and analysis techniques being the key to success. Many unexplored physics benchmarks rely on strange tagging (not only the study of the Higgs boson, but also of Z,W vector bosons as well as the top quark and flavour physics in general). Strange tagging, in turn, is enabled by π/K discrimination at high momenta, which we show can potentially be achieved with a modern Compact RICH. The study shown here demonstrates that stringent constraints can be derived via a direct search for the SM $h \to s\bar{s}$ and the phase space for new physics can be reduced to $k_s \lesssim 7$ with only 900 fb^{-1} of data at an ILC-like future collider.

References

[1]

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