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Impact of Advances in Detector Techniques on Higgs Measurements at Future Higgs Factories

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While the particle physics community is eagerly waiting for a positive sign for the construction of the next frontier collider, developments continue to advance the detector capabilities. New methods and algorithms are being implemented in order to exploit the precious collisions at a Future Higgs Factory (FHF) as well as possible, informing at the same time, which detector aspects are of particular importance or in fact currently limiting. I this work, three new methods are briefly introduced and put into context of hardware development for an FHF detector. While they use data from a large Geant4-based detailed MC production of the International Large Detector (ILD) at the proposed International Linear Accelerator (ILC) at an e^+e^- center-of-mass energy of 250 GeV [5], the conclusions are applicable to any FHF.

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1. Introduction

While it is a consensus among the particle physics community that the next big collider should be an e^+e^- Higgs factory, there are a number of competing proposals which collider and detector(s) should be built in order to achieve this. In the current phase of optimising the detector layouts and comparing potentially competing concepts, it is vital to inform the detector development by making the connection between subdetector and system performance and physics observables. Recently, new methods and algorithms have been developed and implemented in order to exploit the clean conditions at a lepton collider and the advances in hardware development which have been achieved or are foreseen for the next collider. This work shows the impact of these methods and their requirements, exampling three: Error Flow, neutrino correction and strange tagging. They apply (mostly) to jets originating from b, c and s quarks. These are particularly interesting decay modes of the Higgs itself, but also a considerable background from Z decays. The reconstruction of the invariant mass of the mother boson and a tagging capability are important observables in many analyses like the measuring the Higgs self coupling in the most common decay mode $HH \rightarrow b\bar{b}b\bar{b}$ and setting limits on the Higgs-strange coupling, with the leading Feynman diagrams shown in Figure 1.

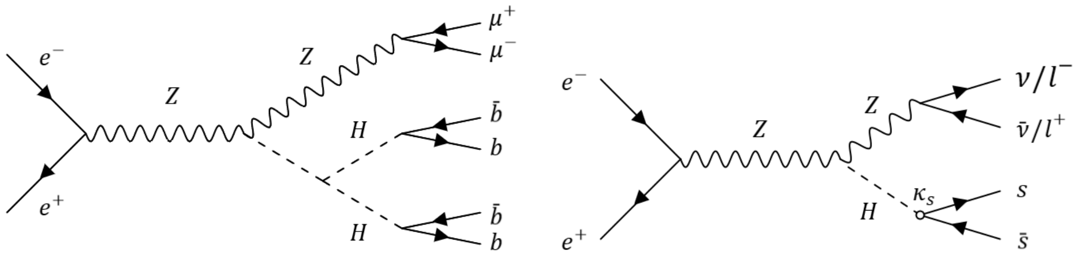

Figure 1: Example Feynman diagrams of particularly interesting channels: Higgs self-coupling and Higgs to strange decay.

2. Error Flow

Kinematic fitting [1] is used to re-assess the measured observables of an event, taking into account external constraints. Lepton colliders provide particularly strong general constraints such as the fixed center-of-mass energy or momentum conservation in each direction, but constraints can also be specific to an analysis. The properties of measured particles, usually Particle Flow Objects (PFOs), or combined objects, like reconstructed jets, are then varied within their uncertainties until the constraints are met and the resulting χ^2 is minimised. In the classical approach, the general detector resolutions, e.g. momentum or jet energy resolution, are used as uncertainties, but the fit result can be much improved by using individual errors for each property of each individual PFO. This approach is called Error Flow [2, 3] and requires an accurate assessment of these individual uncertainties. Recent improvement to the implementation of ErrorFlow included usage of a full covariance matrix for the uncertainties, i.e. taking into account correlations between different measurement dimensions, as well as a rescaling of the errors assigned to each measurement dimensions in order for the resulting pulls to have a unity width (width of $(< x > -x_i)/\sigma_x = 1$). This lead to a uniform distribution of the χ^2 value shown in Figure 2. The resulting improvement in reconstruction is shown in Figure 3: The reconstructed invariant 2-jet mass is shown for the channels $e^+e^- \to ZH/ZZ \to \mu\bar{\mu}b\bar{b}$ for events with at least one semi-leptonic decay in the $b\bar{b}$ system. Here, the generally much more abundant Z decays create a substantial background for the Higgs peaks, which one usually aims to isolate. The black curves show the situation before the kinematic fit: The missing neutrino energy widens the invariant mass peaks and creates large tails to low energies, with a large overlap between the Z and H peaks. Ater the kinematic fit with ErrorFlow (green curves) the peaks are much narrower and easier to separate.

In order to utilise Error Flow, it is crucial to not only minimise measurement uncertainties but to have *correct* uncertainties for each PFO. This requires the usage of Particle Flow, which in turn needs a very low momentum tracker.

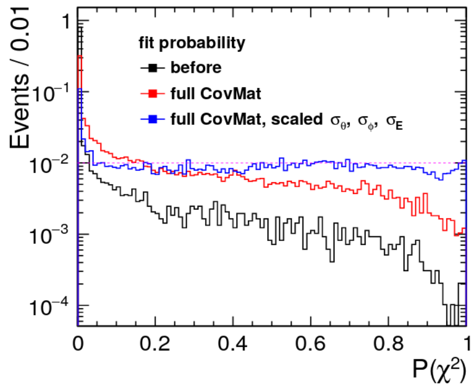

Figure 2: χ^2 distribution of a kinematic fit before and after the implementation of a full covariance matrix and rescaling of underlying measurement uncertainties. The theoretically optimal curve is a constant line. [2]

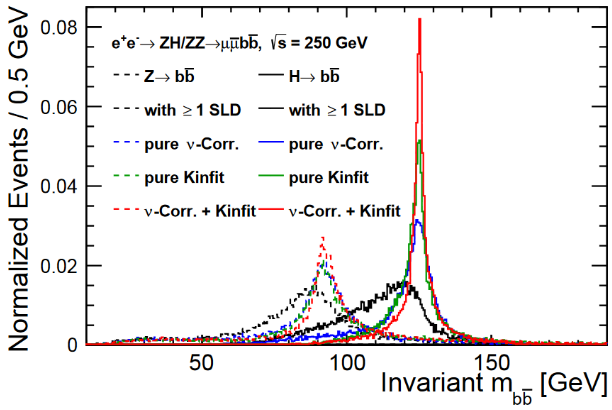

Figure 3: Reconstructed invariant masses of 2 jets from hadronic Z or H decays which include at least one semi-leptonic decay. [3]

3. Neutrino Correction

While the missing neutrino energy in semileptonic decays can be compensated to some degree already with a kinematic fit, at a lepton collider it is possible to fully mathematically reconstruct the missing neutrino from the observed particles and the center-of-mass constraints. This works up to a sign ambiguity in the end, which can be resolved within a kinematic fit again, as shown in [2]. This neutrino correction allows to fully mitigate effect of the energy loss on the reconstructed invariant mass reflected in the blue curves in Figure 3. When the effects of both the Error Flow kinematic fit and the neutrino correction are combined, they result in the red curves. Here, the width of the reconstructed Z peak is limited by the natural width of the Z and the reconstructed Higgs peak width is limited by the detector resolution, crucially not anymore by the reconstruction algorithm.

The neutrino correction capability requires to find all visible particles coming from the semi-leptonic decay, i.e. 4π hermiticity and high efficiency tracking down to very low momenta, identification of the B/C-meson decay via a secondary vertex, i.e. excellent vertexing capability, as well as identification of the electron or muon from the leptonic decay, i.e. e/μ-PID including in the few-GeV range.

4. Strange Tagging

Second-generation fermion-Higgs couplings are of particular interest to test the universality of the Higgs mechanism. An FHF will not only be able to measure the Higgs-charm coupling, but also to set limits on the Higgs-strange coupling, as has been recently shown [4], provided detector requirements are met. Here, for a partial ILC data set of 900 fb^{-1} at 250 GeV, a cut-based analysis was performed to select Higgs decays to $s\bar{s}$. As final step, an optimised cut on the score of a newly developed strange tagger was applied to further reduce background. The tagger uses the properties of the 2 jets including secondary vertex information, as well as the properties of the 10 leading particles in the two reconstructed jets, crucially including charged hadron PID information, and was trained via a BDT. In Figure 4 the effect of the tagger is shown: while the (stacked) backgrounds peak to low strange scores, the (unstacked) green signal curve peaks to higher values. The optimal signal/background ratio was achieved to a cut at a strange score of 0.35 in this analysis, indicated by the orange arrow. This reduced the background by a factor of 3 while leaving the signal largely intact. The signal is still very small compared to the background, but it is possible to calculate an upper limit on the Higgs-strang coupling expressed as κ_s in the κ-framework. With a reduced dataset of about half of the ILC data at 250 GeV and a cheated (i.e. perfect) charged hadron ID, the upper limit is $\kappa_s \leq 7.14$, shown in Figure 5. The implementation of the full dataset and realistic PID are ongoing, and it is expected that doubling the statistics is more beneficial than reducing the PID efficiency is detrimental, and thus that the limit should improve.

The requirements for successful strange-tagging are excellent vertexing, in order to veto b and c jets, as well as identification of strange hadrons, which contain a large fraction of the momentum in an s jet. Most strange hadrons are charged kaons, $K^{\pm}$, but notable contributions come also from K_S^0 and Λ^0.

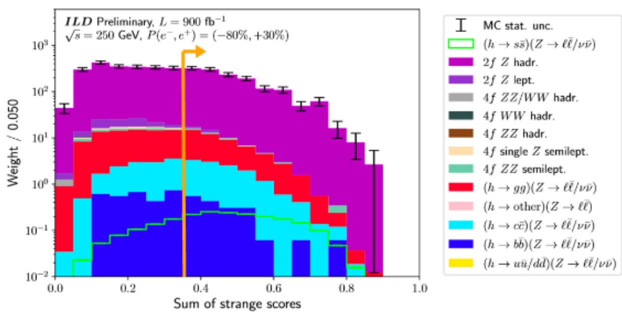

Figure 4: Last step of an analysis looking for $H \rightarrow s\bar{s}$ events: application of the cut on the strange score. [4]

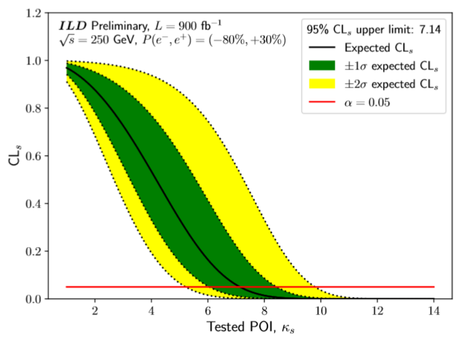

Figure 5: Result of the $H \rightarrow s\bar{s}$ analysis: upper limit on κ_s. [4]

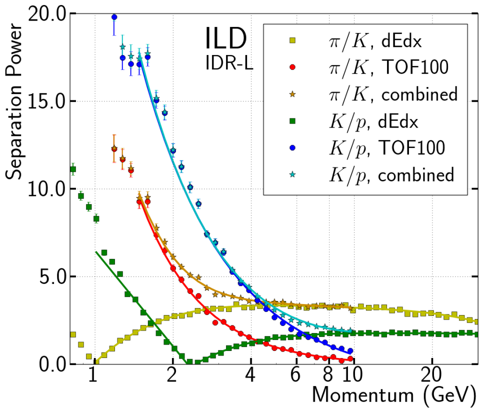

Figure 6: Combination of PID performance via dE/dx and TOF at the ILD. [5]

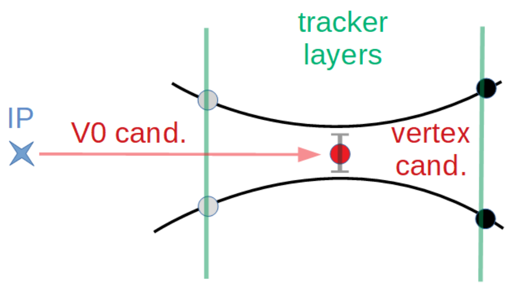

Figure 7: Scheme of V0 finding.

5. Detector Requirements

In summary, the detector requirements to allow for the newly developed methods presented in this work are partly 'standard', such as the usage of Partice Flow with a correspondingly low material tracker, hermiticity or excellent vertexing capability. The other aspects, however, deserve dedicated attention: high tracking efficiency at very low momenta puts a additional stress on the material budget of the inner tracking system, in particular considering that the momentum resolution of most proposed FHFs is limited by multiple scattering, rather than the asymptotic term, up to several 10 GeV, which contains the vast majority of all tracks. Furthermore, particle ID recently has received increased attention, especially in view of flavour physics studies the the Z-pole and the W threshold. Electron/muon ID is largely covered by most detector concepts through the use of separate electromagnetic and hadronic calorimeters as well as muon systems. However, at energies of up to a few GeV the e/μ-ID efficiency via these systems tends to drop and dedicated PID measurements are advised. Even more crucial are PID systems for charged hadron ID, namely for charged kaons. This can be achieved via dE/dx or dN/dx (cluster counting) in gaseous trackers, time-of-flight measurements (TOF) at the transition of outer tracker to ECal, or a dedicated incorporation of a RICH system. Example performance curves for a combined TPC-dE/dx and TOF are shown in Figure 6 for ILD [5]. The identification of neutral strange hadrons, K^0_S and Λ^0, gives additional information for tagging. Since they are semi-stable they mostly decay inside the tracking volume and can be identified via their oppositely charged decay products, which creates a V shape in the tracker. For their reconstruction, the so-called V0 finding sketched in Figure 7, a continuous tracking, i.e. gaseous tracking, is beneficial.

6. Conclusion

The development of algorithms to exploit the precious collisions at FHFs in order to measure the Higgs to the best of our abilities not only increases the utilisation of current detector concepts but also informs which aspects are of particular interest. These conclusions are summarised in

Figure 8. Not only the well-established characteristics are crucial, but an increasing stress is put on particle identification, which calls for the development of new and improvement of existing dedicated PID systems.

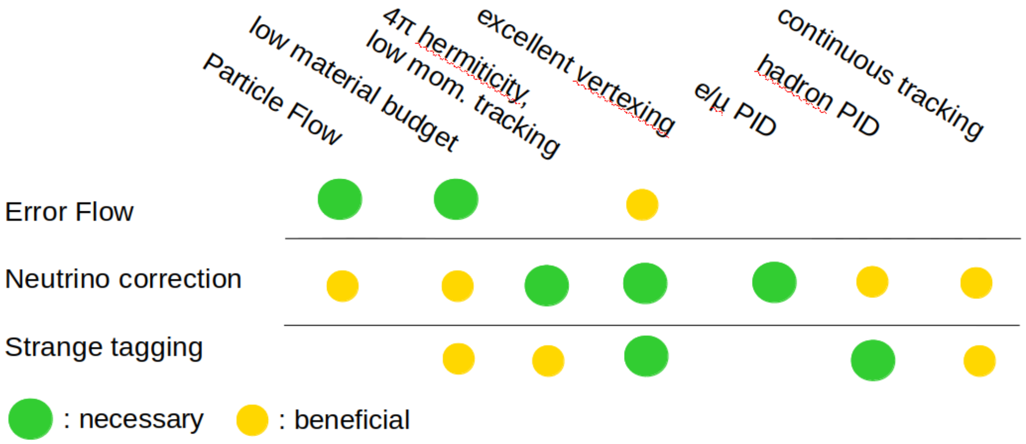

Figure 8: Conclusion table.

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