Particle identification for Higgs physics at future electron-positron collider

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Particle Identification (PID) plays a key role in heavy flavor physics in high-energy physics experiments. However, its impact on Higgs physics is still not clear. In this note, we will explore some of the potential of PID to improve the identification of heavy-flavour jets by using identified charged Kaons in addition to the traditional vertexing information. This could result in a better measurement of the Higgs-charm Yukawa coupling at the future e+e- colliders.

I. INTRODUCTION

The observation of the Higgs boson (H) by ATLAS and CMS in July 2012 [1, 2] marked the completion of the standard model (SM) and opened the way to explore the Higgs sector that is responsible for electroweak symmetry breaking (EWSB). The HL-LHC will probe the Higgs physics at an unprecedented level. The planned future lepton collider (ILC, CEPC or FCC-ee) seems to be the next logical machine [3–5]. By running at multiple center of mass energies at Z-pole, $W^+W^-$, $ZH$, and possible $tt$ thresholds the new machine will allow the Higgs coupling to be measured precisely at or below a percent level, as well as to constrain the BSM physics via direct search and precision electroweak data.

In order to achieve these physics goals, the proposed detector concept must meet the stringent performance requirements in a large solid-angle coverage for excellent particle identification, precise particle energy/momentum measurement, efficient vertex reconstruction, and superb jet reconstruction and measurement, as well as the flavor tagging. One of the tracking concepts is to use a full silicon tracker (FST), which consists of a pixel vertexing detector and a double-sided silicon strip detector. It has excellent spatial resolution and granularity to separate tracks in the dense jets and high occupancy from beam-related backgrounds at high luminosities, but on the other hand, it has limited dE/dX resolution for particle identification (PID) compared to other proposed tracking options such as TPC or draft chamber [4, 5].

In this short note, we explore some of the potential of PID to improve identification for charge and flavor of the heavy-flavour jets. The identified charged Kaon particles inside the jets are used to improve the discrimination between b- and c- jets, which could result in a better measured value for the Higgs-charm Yukawa coupling at the future e+e- collider.

II. CASE STUDY FOR PID

We used several ZH samples generated using CEPC v4 detector configuration where $Z \rightarrow \mu^+\mu^−$ and the Higgs boson decays into $bb$, $cc$, $gg$, and $ss$ [6]. The jets are reclustered using anti-kt algorithm with the particle flow objects after removing the muon tracks from Z decay. Each event is forced to have a di-jet topology. The tracks inside the jets are selected after matching to the Monte Carlo truth. The charged particle Pt are shown in Fig. 1 for selected Pion, Kaon and Proton tracks from $H \rightarrow bb$, $cc$, $gg$, and $ss$, respectively. The integrated cumulative distribution is also shown at the bottom of plot. Most tracks are $P_T < 30$ GeV/c. The signed impact parameter of these tracks (sd0) with respect to the jet direction is also shown in Fig. 2. The sign is defined as $cos(\phi_{trk} + \pi/2 * sign(d0) - \phi_{jet})$ where $\phi_{trk}$, $\phi_{jet}$, and d0 are the azimuth angles of track and jet, and the impact parameter, respectively.

To illustrate the importance of PID, we select charged Kaon particles inside the jets used to improve the discrimination between b- and c- jets, which could result in a better measured value for the Higgs-charm Yukawa coupling at the future e+e- collider.

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FIG. 1: The track $P_t$ distribution for pion, kaon, and proton from $H \rightarrow B\bar{B}$, $C\bar{C}$, $GG$, and $S\bar{S}$ and their accumulative fractions.

FIG. 2: The track signed $D_0$ distributions for pion, kaon, and proton from $H \rightarrow B\bar{B}$, $C\bar{C}$, $GG$, and $S\bar{S}$.

improve jet-pairing in the construction of $H \rightarrow VV \rightarrow 4j$ in the all-harmonic final states, where $V$ stands for $W$ or $Z$ boson decaying into di-jets.

FIG. 3: The leading kaon charge for $b/c$-jet and for $\bar{b}/\bar{c}$-jet.

The PID can also be used to improve the charm jets tagging by identifying the charged Kaon tracks inside the jet. The dominated background for charm tagging is due to the contamination of b-jet. The $b$- and $c$-jets are currently identified by ILCbtag using a BDT trained on the displaced tracks. The output of BDT for the $b$- and $c$-jets are shown in Fig. 4 as $B_{tag}$ and $C_{tag}$. We select a charm enriched sample with $C_{tag} > 0.2$ to test the idea whether the PID is useful for improving the existing charm tagging. A new BDT is trained using the identified charged Kaon tracks and the displaced tracks with a significance of the signed impact parameter ($|d\eta| > 2.0$) inside the jets, as well as other variables listed below:

- **LeadkPt**: the $P_t$ for identified the leading charged Kaon in GeV.
- **Summed charges**: the summed charge of the leading Kaon and displaced tracks.
- **Mass**: the invariant mass of the leading Kaon and displaced tracks.
• SumPt: the summed $P_T$ of the leading Kaon and displaced tracks.

The comparison of distributions from the $c$-jet(signal) and the $b$-jet (background) are shown in Fig. 5. The new trained BDT and the ROC curve are shown in Fig. 6. The improvement is about 10% in terms of rejection while keeping the same efficiency. Further improvements are possible by seeding the vertex reconstruction using the identified charged Kaon particles. The $c$-jet usually contains one secondary vertex from $c \rightarrow s$ decay while the $b$-jet contains two secondary vertices from $b \rightarrow c$ and $c \rightarrow s$ decays. The identified leptons from $b$- or $c$ decay are also useful to separate the $b$- and $c$-jet as well.

FIG. 4: The standard btag output for track $P_T$ distribution for pion, kaon, and proton from $H \rightarrow B\bar{B}$, $C\bar{C}$, $GG$, and $S\bar{S}$ and their accumulative fractions.

FIG. 5: The input variables are compared between $H \rightarrow c\bar{c}$ and $H \rightarrow b\bar{b}$ for leading kaon $P - T$, the summed charge, the invariant mass, and the summed $P - T$ of the leading kaon and displaced tracks, respectively.

FIG. 6: The over-trained BDT and the ROC curve are shown with and without additional kaon variables.

III. PID OPTIONS FOR FULL SILICON TRACKER

We present a proposal for using fast timing and the Ring Image of Cherenkov (RICH) detectors to improve the particle identification capabilities for the full silicon tracker detector option for future $e^+e^-$ colliders. The last two outer-strip layers can be replaced with the high granularity fast silicon photomultipliers detectors (SiPM) \cite{7,8}, which can be used to detect both charged tracks and a single photon with a timing resolution of $\approx 30$ ps and a spatial resolution of $10 \, \mu m$.

These two SiPM layers can also be used for detection of the Cherenkov lights when the particle passes through a dielectric medium. The fast timing and the RICH detector could provide particle identification with at least $3 \, \sigma$ separation between $K^\pm$ and $\pi^\pm$ up to 30 GeV/c, which covers most particles from Higgs decay as shown in Fig. \ref{fig:1}.
The momentum reach of a RICH detector \[9\] depends on the dielectric medium and the photon detection spatial resolution. In order to have Kaon and Pion separation of 3 \(\sigma\), we need to have two type of dielectric medium for RICH:

- First is an aerogel crystal bar with a refrax index of 1.025 and 2 cm thick, located at the radius of 1.2 m, such that the Cherenkov lights can be detected by the SiPM layer at a radius of 1.4 m. The extra material from Aerogel is about 1.5% of the radiation length. The momentum range coverage is \(5 < P_T < 15\ \text{GeV/c}\).

- Second is a \(C4F10\) radiator with a reflax index of 1.0014, a pressure of 0.01 atmosphere, and 30 cm think at a radius of 1.7 m. The Cherenkov photons are focused and reflexed by a set of mirrors to a second SiPM layer, at the radius of 1.7 m. The additional material length is about 2% of the radiation length including both the gas and the mirror. The momentum coverage is \(15 < P_T < 30\ \text{GeV/c}\).

A possible configuration for the full silicon tracker with fast timing and RICH detector option is shown in Fig. 7 for both in the barrel and endcap regions. The RICH adds extra material with 5% of the radiation length at the tracking volume. There might be a way to reduce the total material budget by replacing the rest of the double-sized strip layers with the CMOS pixelate layers once the technology is available and affordable.

![FIG. 7: A possible schematic for a full silicon tracker with TOF and RICH options.](image)

However the timing detector still requires significant R&D efforts in order to detect both the charged track and Cherenkov light at the same time. There are other options possible, for example, using two types of detection separately for the charged tracks and the Cherenkov light. Work is ongoing to access various options using detailed detector simulation.

### IV. CONCLUSION

Particle Identification (PID) plays a key role in heavy flavor physics in high-energy physics experiments. However, its impact on the Higgs physics is still not clear. We have explored some of potential of PID to improve the identification of heavy-flavour jets using identified charged Kaons in addition to the traditional vertexing information, which could result in improving the Higgs Yukawa coupling at the future e+e- collider.

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