Snowmass2021 - Letter of Interest

Heavy flavor substructure and its application in $g \to Q\bar{Q}$ analysis in lepton collider

Thematic Areas: (check all that apply □/■)

■ (EF01) EW Physics: Higgs Boson properties and couplings
□ (EF02) EW Physics: Higgs Boson as a portal to new physics
□ (EF03) EW Physics: Heavy flavor and top quark physics
□ (EF04) EW Precision Physics and constraining new physics
□ (EF05) QCD and strong interactions: Precision QCD
□ (EF06) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF07) QCD and strong interactions: Heavy Ions
□ (EF08) BSM: Model specific explorations
□ (EF09) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders
□ (Other) *[Please specify frontier/topical group]*

Contact Information:
Name (Institution) [email]: Yu Bai (Physics School, Southeast University)baiy@seu.edu.cn
Collaboration (optional): CEPC Study Group

Authors: Ji-Dong Du, Jing-Ze Chen, Han-ting Meng, Yong-quan Luo, Zhao Li

Abstract: The lepton colliders provide an ideal place for precise measurements on electroweak physics. Yet these measurements can often be challenging when hadronic final states are involved, as the result of the complexity in jet clustering and jet energy resolution. Meanwhile many of these measurements have heavy flavor quarks being included in the final states. The heavy flavor hadron in these events can provide important information about the distribution of heavy flavor quarks before fragmentation and hadronization. In this project, we are trying to resolve the hadronic event topology by making the utility of the heavy flavor hadron distribution. The $H \to gg$, followed by one gluon splitting process $g \to Q\bar{Q}$, will be used as a benchmark measurement. We hope the outcome of this study can be helpful to a variety of analysis, like higgs decay branch ratio measurements and precision QCD measurements, and provide performance target to the detector designement.

Context

Hadronic jets play an essential role in the analysis with hadronic final states in high energy collider experiment. The jet reconstruction algorithms were developed to recombine the decay products of hadrons after fragmentation, and extracting as much information about the primordial partons as possible. Over the last four decades, the jet reconstruction algorithms have been evolved from the old-fashioned fixed R algorithm[1], to the infrared-safe and collinear-safe anti-K_T algorithm[2]. Traditionally in analysis, the reconstructed jets are a composite particle and treated in representation of the primordial partons. In recent years, jet substructure[3] has been intensely studied, driven by physics topics in high energy frontier. One branch of this field concerns about the cases when sub-jets are heavy flavor ones. This technique can be very helpful to the measurements like gluon to heavy flavor quark splitting ($g \to Q\bar{Q}$) ratio.

This project will focus on $g \to Q\bar{Q}$ measurement at CEPC[4], while the gluons are directly from the Higgs decay, as a benchmark measurement. There are motivations from both physics and experiment to choose this channel:

- Unlike previous study of $g \to Q\bar{Q}$ in lepton colliders, the gluon are from direct decay of Higgs rather than being from radiation by quarks, making it less model dependent. The momentum of quarks are high ($\sim M_H/2$), providing a unique perspective to the QCD fragmentation in high momentum region.
- The hadronic decay of Higgs have been thoroughly studied with full simulation data sets in CEPC[5;6]. The higgs signal with hadronic final states, can be cleanly identified. The key techniques such as flavor tagging and particle identification have been well established.
- The $CP-$phase of Higgs boson can cause considerable interference between $H \to Q\bar{Q}$ and $H \to gg \to g + Q\bar{Q}$ in collinear region between $Q\bar{Q}$[7].

We hope to develop algorithms which can identify $g \to Q\bar{Q}$ events from backgrounds like $H \to Q\bar{Q}$, indirect Higgs hadronic decay such as $H \to WW^*/ZZ^* \to \mathrm{hadrons}$ and non-Higgs-production background. The capability to identify the heavy flavor sub-jets should be a major consideration. Other relevant analysis may also be benefit from this project. For example, in hadronic final states measurement of ZH channel, the two fermions background ($e^+e^- \to q\bar{q}$) is one of the major background. Among them, events with gluon radiation and gluon splitting via $q\bar{q} \to q\bar{q} + g \to q\bar{q} + Q\bar{Q}$, contribute most of the contamination to signals. The techniques developed in this project may be helpful to identify such background. In addition, $H^0 \to ZZ^*$ process followed by hadronic decays of vector bosons can be hard to distinguished from direct hadronic decay like $H^0 \to qq/gg$, especially when the off-shell boson Z^* is highly boosted. It is possible to identify this kind of events by the techniques presented here.

This project employs the heavy flavor objects as the skeleton of hadronic event topology. The identification of heavy flavor jets(heavy flavor tagging, specifically b-jets and c-jets tagging) generally make utility of the following properties of heavy flavor quarks:

1. The heavy flavor quarks (and the heavy flavor hadrons including these quarks) decay slowing(typically $c\tau \sim 10^{-4}$ m). So that their production vertices have measurable displacement with respect to the primary vertices (secondary vertex or impact parameter tagger).
2. The heavy flavor hadrons retain a high fraction of the momentum and energy of the primordial heavy flavor partons (SV1 taggers).
3. Semi-leptonic decay of heavy flavor hadrons produce detectable lepton in jets (soft-lepton tagging)

4. (for b-jet tagging) The cascade decay of b-hadrons (b→c→ligt flavor) can be identified by assuming the b-hadron and c-hadron decay vertices are aligned (JetFitter algorithm).

The first property makes it possible to find the secondary vertices, corresponding to the weak decay of heavy flavor hadrons, or find tracks which are inconsistent with the hypothesis that they came from the primary vertices. The second property is useful when the secondary vertices are found and the fraction of vertices momentum over jet momentum can be calculated. The feature of heavy flavor components in sub-jet level put new requirements on flavor tagging. In $g \to Q\bar{Q}$ analysis, the two heavy quarks are tend to be collinear. As the result, two heavy flavor sub-jets are close in direction. The heavy flavor tagger not only need to decide the existence, but also need to count the multiplicity of heavy flavor sub-jets. The difficulty in clustering two collinear jets is also a challenge, in the sense that if one is trying to calculate the momentum fraction of secondary vertex over the jets. In addition, the distribution of the momentum between two flavor partons can be very asymmetric, making it more difficult to identify the softer one.

Despite these difficulties, the basic idea of flavor tagging can be migrated to this study. The taggers based on spatial information can also be well worked in the scenarios concerned here. The secondary vertices and impact parameters can be well reconstructed or calculated. The difference is that one need to count the multiplicity of secondary vertices, or the multiplicity of unreconstructed vertices which the tracks with high impact parameter stemmed from. The direct identification of soft leptons and heavy flavor mesons ($D-$mesons e.g.) can also be very useful. All these will provide information of the performance requirement of detector design, especially on track and vertex spatial resolution as well as particle identification.

References

[1] Sterman, G., and S. Weinberg, 1977, Phys. Rev. Lett. 39, 1436.

[2] Cacciari, M., G. P. Salam, and G. Soyez, 2008a, JHEP04, 063

[3] R. Kogler, B. Nachman, A. Schmidt, L. Asquith, E. Winkels, M. Campanelli, C. Delitzsch, P. Harris, A. Hinzmann, D. Kar, C. McLean, J. Pilot, Y. Takahashi, N. Tran, C. Vernieri, and M. Vos, 2019, Rev. Mod. Phys. 91, 045003

[4] CEPC Study Group, 2018, CEPC Conceptual Design Report: Volume 2 - Physics and Detector, https://arxiv.org/abs/1811.10545

[5] Fenfen An $et\ al.$, 2019, Chin. Phys. C, 43, 043002

[6] Yu Bai, Chun-Hui Chen, Ya-Quan Fang, Gang Li, Man-Qi Ruan, Jing-Yuan Shi, Bo Wang, Pan-Yu Kong, Bo-Yang Lan and Zhan-Feng Liu, 2020, Chin. Phys. C, 44, 013001

[7] Qi Bi, Kangyu Chai, Guo Jun, Yiming Liu, Hao Zhang, Edmond L.Berger, Investigating Bottom-Quark Yukawa Interactions at Higgs Factory, to be published.