Decoding Higgs Boson Branching Ratios from event shapes

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Abstract. This contribution will discuss a novel strategy for the simultaneous measurements of Higgs boson branching ratios into gluons and light quarks at a future lepton collider, operating in the Higgs-factory mode. The method is based on template fits to global event-shape observables, and in particular fractional energy correlations, thereby exploiting differences in the QCD radiation patterns of quarks and gluons. This approach is orthogonal to measurements based on traditional tagging methods based mainly on displaced vertices and allows for an extraction of limits on both Higgs boson to gluon- and light quark branching ratios separately. Additionally, state-of-the-art calculations for the relevant observables are commented on.

1 Introduction

A future Higgs boson factory is a very attractive option for the next lepton collider accelerator experiments [1–4]. Such a facility will probe the properties of the Higgs boson at high precision, including its width, kinematic properties of decay products and branching ratios. This will at a minimum allow for a determination of these parameters of the standard model, and allow for an incredible test of its self-consistency. It will also enable a diligent search for deviations, which one might parameterise in the context of effective field theories [5–7]. One of the observables under major consideration is the branching ratio of the Higgs boson into gluons. At a hadron collider like the LHC, the coupling to gluons is determined only via the gluon-fusion production mode, implicitly constraining the decay within certain standard model like assumptions.

At a future e^+e^- collider, this decay can be studied directly in events where the Higgs boson decays into jets, in an incredibly clean environment. Apart from the irreducible background from other standard model processes, the gluon decay mode can be extracted by anti-tagging heavy quark jets, *i.e.* vetoing QCD events which contain b and c hadrons [8]. This procedure is widely used at the current LHC experiments [9–12] to study heavy quark processes. The remaining hadronic events are from Higgs decays are then due Higgs couplings to light u, d and s quarks. This contribution is negligible in the standard model, hence anti-tagging heavy quark decays allows for a percent level measurement of the coupling of the Higgs boson to gluons [13, 14].

Next to this method relying on the assumption that the light Higgs couplings are at least not significantly enhanced relative to the standard mode, the question arises how well we

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can control theoretical uncertainties related to the inputs for these measurements, both now and at the time of a future experiment. While it has a long-standing proposed solution [15] and significant promising developments in this direction [16–21], the lack of a theoretically clean definition of flavoured jets that is in line with experimental procedures hinders access to higher-order calculations in perturbative QCD. In standard tagging procedures, raw inputs from jet physics would be heavily processed, often using techniques from machine learning. While this produces the most performant taggers, their systematic uncertainties from theoretical inputs remains hard to trace. As an alternative, previous studies have been performed treating well understood observables like event- or jet shapes as theoretically well-behaved taggers [22–24]. Going a step further, one can imagine stopping the assigning of a definite flavour to any given event, but instead determine the overall flavour composition of a given sample by fitting the dependence of an event shape variable on the flavour composition to data directly. In related studies, jet angularities in different processes have been used to study quark and gluon jets at hadron colliders like the LHC and RHIC [23, 25–31].

2 Fitting branching ratios with event shapes

Such a strategy was proposed in [32]. It relies on two qualitative effects in QCD radiation patterns. Firstly, quarks and gluons belong to different representations of SU(3), leading to a ratio $C_A/C_F = 9/4$ of colour charges implying significantly more emissions from gluons. Secondly, for gluon emissions from quarks, the finite masses of heavy quarks shield the collinear divergence. This is also known as the "dead cone" effect [33].
Let us consider a generic event shape v, which is assumed to be normalised such that $0 < v < 1$ and such that $v \sim 0$ corresponds to the soft-collinear "pencil-like" limit, while more and harder radiation drives it to higher values. This is for example the case for the classic thrust observable $\tau = 1 - T$ [34, 35], the so-called C-parameter [36, 37] as well as the class of event shapes introduced in [38–40] that has been used extensively, together with the closely related jet-angularities for hadron collisions, in systematic quark-gluon tagging studies in the past [25–28, 30]:

$$\mathrm{FC}_x \equiv \sum_{i \neq j} \frac{E_i E_j |\sin\theta_{ij}|^x (1 - |\cos\theta_{ij}|)^{1-x}}{(\sum_i E_i)^2} \Theta\left[(\vec{q}_i \cdot \vec{n}_T)(\vec{q}_j \cdot \vec{n}_T)\right] \tag{1}$$

According to the argument presented above, one would expect a picture where $H \to gg$ events develop a larger value of v compared to light quarks, due to the color factor enhancement $\propto C_A/C_F$. The corresponding distribution for a heavy quark on the other hand would be shifted towards smaller values due to the dead cone effect. This simple picture is significantly modified by fragmentation and especially in the following decays of hadrons. Specifically, since an event with a heavy quarks will typically lead to a heavy hadron that subsequently decays, the distribution from b-hadron jets is predicted to end up peaking at a larger value of v than jets from lighter quarks. Numerical results can be obtained by simulating e^+e^- collisions at a centre-of-mass energy of $\sqrt{s} = 240$ GeV. This is in the preferred energy range of a Higgs factory producing Higgs bosons via the Higgsstrahlung process $e^+e^- \to ZH$. For an overview of the current status of event generators see [41]. This study uses the SHERPA [42] event generator. The Z boson is assumed to decay leptonically and the particle level final state resulting from the Higgs decay into one of the partonic channels is reconstructed after the parton shower and hadronisation.
The study discussed here followed the selection cuts of Ref. [8], identifying Z boson candidates as pairs of opposite-sign leptons within ±5 GeV of the nominal Z mass. The reconstructed Z boson is required to have at least a transverse momentum of $p_{T,Z} > 10$ GeV and

a longitudinal momentum of at most 50 GeV. To suppress irreducible backgrounds from ZZ events, an opening angle between the two leptons of $\theta_{l^+l^-} < 100^\circ$ is required. Additionally, the total hadronic mass of all other particles has to be at least $m_{\text{had}} > 75$ GeV. Constraining the recoil mass of the lepton pair, defined as

$$m^2_{\text{recoil}} = s + m^2_Z - 2\sqrt{s}(E_{l^+} + E_{l^-})\,, \tag{2}$$

to $120\,\text{GeV} < m_{\text{recoil}} < 130\,\text{GeV}$, selects events where the hadronic final state is likely to originate from a decaying Higgs boson.
A selection of event shapes can be calculated based on charged-particle tracks in the rest frame of the decaying Higgs boson and be used to build a stacked distribution as the sum over all decay channels:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}v} = \sum_{i\in\{q\bar{q},c\bar{c},b\bar{b},gg,WW,ZZ\}} \mu_i \frac{\mathrm{d}\sigma_i}{\mathrm{d}v} + \frac{\mathrm{d}\sigma_{ZZ}}{\mathrm{d}v}\,, \tag{3}$$

where the additional coefficients μ_i parameterise a deviation of the branching ratio into the corresponding channel i from the standard model value. The last term includes the background from the production of two Z bosons. Different distributions can now be produced for varying values of μ_g and μ_s, modifying the Higgs coupling to gluons and strange quarks, under the assumption that the overall cross section for hadron production from a Higgs boson does not change. In practice the difference is absorbed into μ_b. A scan of this parameter space can be easily performed using the Contur [43, 44] framework, to derive 2-dimensional limits on (μ_g, μ_s). The most stringent limits come from observables like Eq. (1) with a relatively large value of x (the study analysed $x \in (0.5, 1, 1.5)$). This is reasonable since the main contribution to those will come from rather collinear emissions off the original hard partons. One can further improve the performance by considering 2-dimensional distributions of the observable in the two hemispheres defined by the thrust axis, in analogy to a 2-tag requirement in a traditional tagging approach. In the best-case scenario, this can lead to expected limits at 68% confidence level of $\mu_{gg} = 1 \pm 0.05$ and $\mu_{q\bar{q}} < 21$ based on 5 ab^{-1} luminosity.

3 Precision calculations of event shapes

For a full exploitation of the results presented in the previous section, a solid theoretical understanding of event shapes in different Higgs decay channels is necessary. The second part of this contribution report on a calculation of such event shapes, particularly for Higgs decays to gluons and quarks, presented in [45]. The results are calculated based on fixed order calculations from the EERAD program [46–48], which has been extended to study distributions in Higgs decays recently [49–51]. This is combined with resummed calculations for the corresponding event shapes in the CAESAR formalism [38] that is implemented in the SHERPA [42] Monte Carlo program [52, 53]. The program has in the past been used together with SHERPA's internal matrix element generators COMIX [54] and AMEGIC [55], to produce results for event shapes, including complications arising from grooming techniques, at the LEP [56], the LHC [57] and HERA [58–62] experiments.
In line with expectations, the impact of NLO corrections has been found to be small over the bulk of the logarithmic observable range. The exact size of the corrections is, of course, an observable dependent statement. For example, for the C-parameter, corrections are enhanced by the presence of large Sudakov-shoulder effects. For almost all event-shape observables considered in [45], the general expectation about the difference between $H \to gg$ and $H \to b\bar{b}$, as explained above, is fulfilled, *i.e.* the distributions in $H \to gg$ decays peak at larger observable values than in $H \to b\bar{b}$ decays.

While only the "traditional" event shapes have been considered in this calculation, the implementation straightforwardly extends to other (infrared-safe) observables that fall in the category of being treatable by the CAESAR formalism. This includes the family of observables defined in Eq. (1) also discussed in the previous section.

These results are an important step towards precision calculations for Higgs boson studies at future lepton colliders and providing benchmarks for the assessment [63–66] and development [67–74] of parton-shower algorithms with higher logarithmic accuracy.

Going towards higher precision goals, all contributions, especially one- and two-loop amplitudes, needed for NNLO corrections to three-jet observables in $H \to b\bar{b}$ decays [51, 75, 76] and $H \to gg$ decays [51, 77–84] are known in fully analytic form. Similarly, the resummation should be lifted to the next-to-next-to-leading logarithmic level, *e.g.*, using the ARES [85] framework. When combined, NNLO+NNLL′ accuracy could be achieved. Progress has also been reported on the inclusion of finite-mass effects in resummed calculations [86–90], which will alleviate the calculations relevant for the $H \to b\bar{b}$ channel,

4 Outlook

Further scrutinising the Standard Model of particle physics through precision measurements of Higgs boson couplings forms a central task for experiments at a possible future lepton collider. This especially includes studies of hadronic Higgs boson decays. Of particular interest here is an extraction of the Higgs-gluon-gluon coupling. Complementary to techniques that rely on displaced vertices due to weak decays of flavoured hadrons, event-shape observables offer another avenue to achieve discriminatory power between the various possible hadronic Higgs boson decay channels, in particular between the decay modes $H \to b\bar{b}$ and $H \to gg$ but also to Higgs decays to light flavours. Hence, the precision and accuracy of QCD predictions will be crucial for the full exploitation of future colliders. While precise determinations of event shapes are already used for the determination of fundamental parameters like the strong coupling constant, see [91] for a recent overview, this contribution has shown a way to use these theoretically well-controlled observables in the context of hadronic Higgs decays and the determination of the corresponding branching ratios.

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