Final-state interactions of the Higgs boson in quark-gluon matter

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The final-state interactions of the Higgs boson in a dense quark-gluon medium are studied. Taking into account the leading in-medium diagrams, typical Higgs–parton scattering cross sections are found to be of a few mb in the kinematical range of relevance at current and future hadron colliders. In-medium scatterings effectively lead to an enhancement of the Higgs decays into a pair of jets, mostly via $gH \rightarrow gg$, and thereby to a depletion of its visible yields in the $H \rightarrow \gamma\gamma, ZZ^\ast(4\ell)$ discovery channels compared to the accurate theoretical predictions for its production and decay in the absence of final-state interactions. By embedding Higgs bosons, with transverse momentum distributions computed at NNLO+NNLL accuracy, in an expanding quark-gluon medium modeled with 2D+1 viscous hydrodynamics with various QCD equations of state, we present realistic estimates of their suppressed yields as functions of transverse momentum $p_T^H$, and medium space-time size in pp, PbPb, and PbPb collisions at LHC and FCC energies. A 10–15% depletion is expected in central PbPb collisions, mostly for $p_T^H \lesssim 50$ GeV.

INTRODUCTION

The Standard Model (SM) Higgs boson with a mass of $m_H \approx 125$ GeV [1] has a very narrow width $\Gamma_H \approx 4$ MeV [2], and, hence, a lifetime $1/\Gamma_H \approx 50$ fm much larger than the Quantum Chromodynamics (QCD) time-scales of $1/\Lambda_{QCD} \approx 1$ fm typical of parton hadronization [3] and/or Quark-Gluon-Plasma (QGP) formation [4]. Since the lifetime of the QGP created in ultrarelativistic heavy-ion collisions is of $\mathcal{O}(10 \text{ fm})$ [5], any Higgs boson produced in such collisions can scatter with the surrounding partons before decaying in the vacuum. Since the scalar boson couples to quarks proportionally to their masses and to massless gluons via the dominant top-quark loop –and given the lightness of $u, d, s$ quarks masses– the direct $gH$ interactions predominate. The Born-level Higgs–parton scatterings in a quark-gluon medium are dominated by $gH \rightarrow gg$, $Q\bar{Q}$, where $Q = b, c$ indicates bottom and charm quarks (Fig. 1 a, b), whereas $qH \rightarrow qq$ (Fig. 1 c) are comparatively much more reduced. Higher-order diagrams, such as those from quarks emitting a gluon that subsequently collides with the scalar boson, represent nonetheless a significant contribution to the total Higgs scattering cross section, as discussed later. The interaction of a Higgs boson with surrounding partons will result in its medium-induced decay into pairs of gluons or (heavy) quarks, and thereby in its effective “disappearance” in the “clean” diphoton and four-lepton discovery channels, $H \rightarrow \gamma\gamma, ZZ^\ast(4\ell)$ [6, 7]. One may argue that the scalar boson could still be potentially observed in the correspondingly medium-enhanced $(g)H \rightarrow bb$ final state given that $H \rightarrow bb$ has the largest Higgs decay branching fraction and that, for the moderately soft gluon–Higgs collisions, the resulting $b$-jet pairs will basically retain an invariant mass matching $m_H$. Beyond the intrinsic difficulty of reconstructing fully-hadronic decay modes in the “noisy” heavy-ion environment, such $b$-jets will further lose energy through “jet quenching” [8], and thereby remain unobservable above the huge QCD jet background. Thus, if the parton–Higgs cross section $\sigma_{Hq\bar{q}}$ and/or the ambient parton density $\rho$ are large enough, the resulting Higgs mean free path $\lambda_H = 1/(\sigma_{Hq\bar{q}} \cdot \rho)$ will be commensurate with the medium length, and its final yields will be visibly reduced. We show here that both conditions are actually met in nuclear collisions at the center-of-mass (c.m.) energies of the LHC and Future Circular Collider (FCC) [9, 10].

At variance with other proposed QGP probes in heavy-ion collisions such as quarkonia ($Q\bar{Q}$) suppression [11] or jet quenching [12], the production and final-state interactions of the Higgs boson can be precisely calculated. First, its production cross section in hadronic collisions, dominated by gluon-gluon fusion $(gg \rightarrow HX)$, is determined today at the highest degree of accuracy in perturbative QCD (pQCD) through computations at next-to-next-to-next-to-leading-order (N^3LO) accuracy [13] including next-to-

![Fig. 1. Representative leading-order (LO) diagrams of Higgs boson scattering with gluons: (a) $gH \rightarrow gg$, (b) $gH \rightarrow Q\bar{Q}$, and with quarks: (c) $qH \rightarrow qq$ (gluon-exchanged dominated, with other gauge bosons strongly suppressed).](image)
leading-log (NLL) soft gluon resummation \cite{14}, with few-
percent corrections due to (anti)shadowing of the nuclear par-
ton distribution functions (PDF) \cite{15}. Second, the Higgs bos-
on is an elementary particle whose final-state interactions
with other particles can be theoretically computed at the same
level of accuracy as its production cross sections. Last but
not least, the scalar boson is free from complications affecting
the interpretation of the interaction of energetic partons (jets)
and/or \( J/\psi \) and 'T mesons in the plasma, such as from com-
peting radiative and collisional energy losses, hadronization,
bound-state formation, feeding from heavier resonance de-
cays, or in-medium regeneration. Of course, the drawback of
the Higgs boson as a QGP probe is its tiny production ac-
cross section in comparison to the other much more abundant
particles. Notwithstanding this difficulty, recent studies \cite{15}
have demonstrated the experimental feasibility of measuring
the Higgs boson in p\( p\)b and Pb\( p\)b collisions at the LHC at
nucleon-nucleon c.m. energies \( \sqrt{s_{NN}} \) = 5.5–8.8 TeV (integ-
rating \( \times 30–40 \) more luminosities than the nominal ones), and
at the FCC at \( \sqrt{s_{NN}} \) = 39, 63 TeV with the nominal luminosities
per year \cite{10}. The study of the Higgs yield modifications in
heavy-ion collisions compared to theoretical predictions with-
out final-state effects would provide a novel and extremely
well calibrated probe of the created quark-gluon medium. In
particular, as shown below, by comparing the amount of Higgs
boson suppression to the results of pQCD+hydrodynamics
calculations including the space-time evolution of the pro-
duced matter, one can explore the thermodynamic properties
of the produced QGP.

ESTIMATE OF THE HIGGS BOSON CROSS SECTIONS IN
QUARK-GLUON MATTER

The LO cross sections for the Higgs–parton scattering pro-
cesses (Fig. 1) are computed with the CalcHEP (v3.7) \cite{16}
code, for Higgs–parton c.m. energies \( \sqrt{s} = m_H \approx 0–20 \) GeV.
Cross-checks carried out with whizard (v2.4) \cite{17} yield con-
sistent results. All calculations include the effective (loop-
induced) Higgs–gluon coupling, and are run with renormal-
ization scale \( \mu_R = \sqrt{s} \), QCD coupling \( \alpha_s = 0.118 \), and
Higgs and heavy-quark masses set to their latest PDG val-
ues \cite{18}. The Born-level Higgs–parton cross section is driven
by gluon scattering diagrams yielding diquark and \( Q\bar{Q} \) final-
states (Fig. 1 a,b; both of the same size), with the \( cc \) final-
state being about \( \tilde{m}_c(m_H) / \tilde{m}_c(m_H) \approx 20 \) times larger
than the \( bb \) one, as given by the ratio of the bottom to charm
masses at the Higgs scale. The direct quark–Higgs scattering
diagrams (Fig. 1 c), have a cross section about \( 10^4 \) times
smaller (among them, those with radiated/exchanged \( Z, W, \)
and \( \gamma \), are even more suppressed) than those from \( gH \) scat-
terings. The dependence on the Higgs–parton c.m. energy of
the computed Higgs “absorption” cross section is found to be
accurately reproduced by a power-law fit of the form

\[
\sigma_{Hqg}(\sqrt{s}) = K \cdot A(\mu b) \cdot \left( \frac{\sqrt{s} - m_H}{\text{GeV}} \right)^{-n},
\]  

with amplitude \( A = 2 \mu b \) and exponent \( n = 3 \). We assume a
\( K = 3 \) factor to account for missing higher-order corrections
obtained from the \( N^3\text{LO}/\text{LO} \) ratio of the \( gg \to H + X \) produc-
tion cross sections \cite{13,14} which share the same (crossed)
diagrams. Among the large higher-order corrections, there
are many contributions from processes where one or both in-
coming partons are a medium quark that radiates a gluon that
subsequently scatters with the scalar boson following the LO
diagrams shown in Fig. 1. Our calculation of Higgs-parton
scattering cross section neglects additional corrections due to
the emission/absorption of gluons from the \( H \to gg, q\bar{q} \) de-
cays into/from the heat bath. Incorporation of such terms is
needed to cancel out all infrared divergences generically ap-
pearing in the full calculation of scattering rates in a thermal
medium \cite{19,20}, such as the one given by the inverse power
dependence of Eq. (1). To our knowledge, such terms have
never been computed for the case of interest here, namely for a
scalar boson interacting with a bath of vector bosons (gluons)
and fermions (quarks) with Higgs-type couplings. For this
first exploratory study, the use of different thermal mass pre-
scriptions for the medium partons, as explained below, avoids
any cross section divergence in our setup, and provides finite
Higgs-parton scattering rates commensurate with the \( \sigma(\mu b) \)
prefactor computed for Eq. (1).

Knowing the Higgs boson energy \( (E_H) \), the energy \( (E_{q,g}) \)
and effective mass \( (m_{q,g}) \) of the surrounding partons, and
their relative scattering angle \( (\theta) \), the Higgs–parton c.m. energy
reads

\[
\sqrt{s} = [m_H^2 + m_{q,g}^2 + 2E_HE_{q,g} \beta_{q,g} \cos \theta]^{1/2},
\]

with Lorentz factors \( \beta_{q,g} = p_{q,g} / E_{q,g} \). Thus, from the relevant
Higgs \( (E_H) \) and partons \( (E_{q,g}) \) kinematics at a given collider
energy, one can determine \( \sqrt{s} \) via Eq. (2), and thereby the
associated Higgs “absorption” cross section via Eq. (1). The
Higgs survival probability in a quark-gluon medium of den-
sity \( \rho \) can then be computed from the expression

\[
\mathcal{A}_H = \exp \left[ - \int_{\tau_0}^{\tau} \sigma_{Hqg}(\sqrt{s}) \cdot \rho(\tau) \: d\tau \right],
\]

where \( \tau_{rel} \) is the Higgs–parton relative velocity. We consider
the generic case where the surrounding medium is expanding,
and therefore all relevant quantities are space-time dependent.
An order-of-magnitude Higgs survival probability can be de-
ferred by plugging a few indicative numbers in the latter equa-
tions. For a typical Higgs with momentum \( p_H \approx 10 \) GeV col-
iding with partons with average momenta \( p_{q,g} \approx 1 \) GeV,
the “absorption” cross section is \( \sigma_{Hqg}(\sqrt{s} \approx 126 \text{ GeV}) \approx 10 \mu b \).
Unlike partons, which are always relativistic \( (\beta_{q,g} \approx 1) \), the
Higgs boson is a heavy and slow probe of the surrounding
medium with non-relativistic Lorentz factors \( (\beta_{q,g} < 1) \)
on a large range of momenta \( (p_H \leq m_H) \). Assuming a
static medium, i.e., time-independent quantities in Eq. (3) and
\( \tau_{rel} = 1 \), with average parton density \( \rho \approx 15 \) fm\(^{-3} \) and average
lifetime \( \Delta \tau = \tau_f - \tau_0 \approx 10 \) fm, we obtain \( \mathcal{A}_H \approx 85\% \). Namely,
in a dense static partonic medium the Higgs mean free path is
Higgs boson suppression in nuclear collisions

In order to assess the amount of Higgs boson suppression in high-energy hadronic collisions, one needs realistic estimates for all kinematical ingredients entering in Eqs. (2) and (3). Our case study is that of a Higgs boson produced around midrapidity \( y = 0 \) (where its production yields are maximal, and where total and transverse momenta are equivalent, \( p_H \approx p_T^H \)) in pp, pPb, and PbPb collisions at nucleon–nucleon c.m. energies of \( \sqrt{s_{NN}} = 5.5, 8.8, 14, 39, 63, \) and 100 TeV, traversing a final-state parton medium that is expanding along the transverse plane. First, the Higgs transverse momentum distribution, \( f(p_T^H) \), is computed at NNLO+NNLL accuracy with HoT (v2.2) \cite{22} for all collider c.m. energies considered. Second, the momentum distribution of the sur-

\[\sigma_{Hgq}(\sqrt{s})\] at each space-time point via Eqs. (1) and (2), and determining the local value of the parton density \( \rho = g(T) \cdot T^3 \) from the corresponding temperature profile. The function \( g(T) \) is derived from two different EoS with varying degrees of freedom in order to gauge the dependence of the suppression on the underlying medium properties. We use the lattice QCD EoS of Ref. \cite{24}, and the non-ideal quasiparticle EoS of Ref. \cite{31}, with total number of active degrees of freedom \( g = 2(N_c^2 - 1) + 7/2 N_f N_f \) (for \( N_f = 3 \) colors) varied from \( N_f = 3 \) (\( u, d, s \)) to \( N_f = 4 \) (to assess the possible impact of a thermalized charm component). The Higgs boson production points, \( P(x_0, y_0) \) with respect to the center of the collision, are distributed according to the binary-collision density given by a Glauber MC simulation \cite{32} for each system, with azimuthal direction \( \phi_0 \) sampled uniformly over \( [0, 2\pi] \) in the transverse plane. The final Higgs suppression factor is obtained integrating over space (over all Higgs production points \( (x_0, y_0) \) and directions \( \phi_0 \) in the transverse plane) and time (from \( \tau_0 \) to \( \tau_f \)):

\[ R_H = \frac{\int dP(x_0, y_0) d\phi_0 \exp \left( -\int_{\tau_0}^{\tau_f} \hat{\sigma}_{Hgq}(\tau) \cdot \hat{p}(\tau) \cdot d\tau \right)}{\int dP(x_0, y_0) d\phi_0}, \tag{4} \]

where \( \hat{\sigma}_{Hgq}(\tau) = \int \sigma_{Hgq}(\sqrt{s}) f_c(E_{gq}) d^3\hat{p}_{gq}(\tau) \) is integrated over all parton energies and Higgs–parton relative angles \( \theta \), and where \( \hat{\rho}(\tau) = \rho(x_0 + \beta_H \tau \cos \phi_0, y_0 + \beta_H \tau \sin \phi_0, \tau) \).

The dependence of the Higgs suppression factor on its transverse momentum is shown in Fig. 2 for centrality-integrated (“minimum bias”, MB) PbPb collisions at 5.5 and 39 TeV, for the two EoS and \( N_f \) choices discussed above. The suppression is rather constant around 0.85 at low \( p_T^H \), and it starts to rapidly disappear above \( p_T^H \approx 50 \text{ GeV} \). Higgs bosons with \( p_T^H \gtrsim 300 \text{ GeV} \) have a negligible absorption cross section. The exact amount of yield deficit is sensitive to the underlying EoS of the QCD medium, its effective active number of quark flavors, and other relevant (quasi)particle properties (thermal masses). Table 4 summarizes the hydrodynamics.

\( \lambda_H \approx 70 \text{ fm}, \) and \( \sim 15\% \) of the bosons will scatter and produce a pair of gluons or quarks, leading to a visible reduction of its yields in electroweak decay channels.
TABLE I. Relevant properties of the considered Higgs boson suppression scenarios. For each colliding system, we quote the centrality, c.m. energy $\sqrt{s_{NN}}$, expected midrapidity particle density $dN/dy|_{y=0}$, lifetime of the produced medium $\Delta\tau$, initial temperature $T_0$, and space-time-averaged values of the density $\langle \rho \rangle$, Higgs absorption cross section $\langle \sigma_{Hq} \rangle$, and suppression factor $\langle R_H \rangle$ computed for the lattice QCD EoS with $N_f = 3$. The $\langle R_H \rangle$ uncertainties are determined from half the difference between the quasiparticle and lattice-QCD ($N_f = 4$) EoS results.

| System | Centrality | $\sqrt{s_{NN}}$ (GeV) | $dN/dy|_{y=0}$ | $\Delta\tau$ (fm) | $T_0$ (GeV) | $\langle \rho \rangle$ (fm$^{-3}$) | $\langle \sigma_{Hq} \rangle$ (µb) | $\langle R_H \rangle$ |
|--------|------------|-----------------------|----------------|-----------------|------------|-----------------|----------------|----------------|
| pp     | central (0–5%) | 14 TeV               | 21             | 1.9             | 0.37       | 8.6             | 29.0           | 0.98 ± 0.01   |
| pp     | central (0–5%) | 100 TeV              | 32             | 2.0             | 0.43       | 11.3            | 27.0           | 0.98 ± 0.01   |
| PpPb   | central (0–5%) | 8.8 TeV              | 60             | 2.7             | 0.37       | 7.6             | 31.2           | 0.97 ± 0.01   |
| PpPb   | central (0–5%) | 63 TeV               | 90             | 2.8             | 0.43       | 9.3             | 29.7           | 0.97 ± 0.01   |
| PbPb   | MB (0–100%)   | 5.5 TeV              | 515            | 9.2             | 0.51       | 8.7             | 40.0           | 0.88 ± 0.04   |
| PbPb   | MB (0–100%)   | 39 TeV               | 1028           | 10.4            | 0.62       | 12.8            | 31.6           | 0.89 ± 0.03   |
| PbPb   | 0–5%         | 39 TeV               | 3700           | 11.7            | 0.90       | 16.4            | 36.5           | 0.88 ± 0.04   |
| PbPb   | 20–30%       | 39 TeV               | 1500           | 8.5             | 0.85       | 15.6            | 36.5           | 0.91 ± 0.03   |
| PbPb   | 60–70%       | 39 TeV               | 200            | 4.3             | 0.59       | 7.4             | 43.2           | 0.96 ± 0.02   |

FIG. 3. Transverse-momentum integrated Higgs boson suppression factor as a function of the lifetime of the quark-gluon medium produced in various colliding systems. The vertical error bars are obtained from half of the difference between the quasiparticle and lattice-QCD ($N_f = 3$) EoS. The dashed curve reflects the result of $\exp(-\tau/\lambda_{H})$ fit with an effective Higgs mean free path of $\lambda_{H} = 100$ fm.

CONCLUSIONS

The final-state interactions of the SM Higgs boson in a surrounding medium of quarks and gluons have been studied. Higgs boson scatterings with partons result effectively in a medium-induced enhancement of its QCD decays ($H \rightarrow gg, bb, cc$), thereby depleting its observability in the clean $H \rightarrow \gamma\gamma, ZZ(4\ell)$ discovery modes. The tree-level $2 \rightarrow 2$ scattering cross sections of the scalar boson with partons have been computed, and found to be well described by a power-law dependence on the Higgs–parton center-of-mass energy. Including higher-order corrections via a $K = 3$ factor, the average Higgs absorption cross sections are around 35 µb in the kinematical regime of current and future hadron colliders. The Higgs boson suppression factor has been computed using a realistic 2D+1 hydrodynamics description of the spacetime expanding medium produced in pp, pPb, and PbPb collisions at LHC and FCC c.m. energies, with varying QCD equation-of-state. In PbPb collisions suppressed yields by up to 15% are expected, mostly in the region $p_T^H \lesssim 50$ GeV. Our analysis reveals that the Higgs boson, an elementary particle with precisely-known production and suppression mechanisms, can be used as the ultimate probe of the thermodynamic properties of quark-gluon matter produced in hadronic collisions. Further promising studies include the differential Higgs suppression patterns, e.g., as a function of rapidity, azimuth with respect to the elliptic-flow plane, their dependence...
on the transport properties (viscosities) of the QCD matter, or the possible impact of late Higgs–hadron interactions. From a more fundamental perspective, this work calls for a detailed theoretical study of the temperature-dependence of the total and individual decay widths of a Higgs boson in a thermal QCD medium, including all relevant real and virtual absorption and emission corrections.

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