Higgs boson suppression in quark-gluon matter

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Work with David d'Enterria (see arXiv:1809.06832)

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Higgs boson suppression in quark-gluon matter

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The final-state interactions of the Higgs boson in a dense quark-gluon medium are studied. Typical Higgs-parton scattering cross sections are found to be $\sigma_{\text{H}g} \approx 1-100 \mu b$ 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 $gH \rightarrow ggQ\bar{Q}$, and thereby to a depletion of its visible yields in the $H \rightarrow \gamma\gamma, ZZ\,(4\ell)$ 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 $p_T$, and medium space-time size in pp, pPb, and PbPb collisions at LHC and FCC energies. A 10–20% depletion of yields is expected in central PbPb collisions, mostly for $p_T \lesssim 50$ GeV.
Introduction

- SM boson ($\Gamma_H = 4$ MeV) has a lifetime $\tau = 1/\Gamma_H \sim 50$ fm $> \tau_{QGP} \sim 10$ fm. Once produced it will outlive the QGP and decay in vacuum.

- The SM Higgs couples to QGP gluons (through the dominant top loop) and quarks (via Yukawa Coupling).
  → May provoke an earlier decay

- What's the effect of the gluons and quarks in QGP on the scalar boson?

- Recap: what are the production cross sections & visible counts after analysis cuts in pPb, PbPb colls at LHC and/or FCC?
  (see D.d.E, arXiv:1701.08047)
Higgs production cross section in AA

- Production mechanisms are the same as in p-p. Cross sections:
  \[ \sigma_{pPb \rightarrow H} = A \times \sigma_{pp \rightarrow H} = 208 \times \sigma_{pp \rightarrow H}, \quad \sigma_{PbPb \rightarrow H} = A^2 \times \sigma_{pp \rightarrow H} = 4 \cdot 10^4 \times \sigma_{pp \rightarrow H} \]
  modulo small (<5%) mods. of the nuclear g,q, PDFs

- Gluon fusion
  ~85% of \( \sigma_H \)

- Vector Boson fusion
  ~10% of \( \sigma_H \)

- Assoc. W,Z prod.
  ~5(3)% of \( \sigma_H \)

- Assoc. ttbar prod.
  ~1(4)% of \( \sigma_H \)
Higgs production cross section vs $\sqrt{s_{NN}}$

- Pb-Pb:
  - LHC (5.5 TeV) = 550 nb
  - FCC (39 TeV) = 10 $\mu$b

- p-Pb:
  - LHC (8.8 TeV) = 5.5 nb
  - FCC (63 TeV) = 100 nb

- p-p (reference):
  - LHC (5.5 TeV) = 12 pb
  - LHC (8.8 TeV) = 27 pb
  - FCC (39 TeV) = 270 pb
  - FCC (63 TeV) = 490 pb

Cross-sections increase by about $\times 20$ from LHC to FCC

**Nuclear modification**

- **LHC:** Small antishadowing: \( R_{AA} \sim 1.07, \ R_{pA} \sim 1.03 \)
- **FCC:** Mild shadowing: \( R_{AA} \sim R_{pA} \sim 0.97 \)

- EPS09 nuclear g,q PDFs modify only slightly x-sections wrt. pp PDFs:
  - **LHC:** Small antishadowing: \( R_{AA} \sim 1.07, \ R_{pA} \sim 1.03 \)
  - **FCC:** Mild shadowing: \( R_{AA} \sim R_{pA} \sim 0.97 \)

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- **Higgs boson cross sections**
  - **MCFM, NNLO (ggF+VBF+VH)**
  - **PDF=CT10, nPDF=EPS09**

Uncertainties from 30 EPS09 eigenvalues

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\[ Q^2 \propto M_H^2 \]
Expected yields after cuts

Analysis based on NNLO MCFM pseudo-data for $H(\gamma\gamma)$ and $\gamma\gamma$ backgrounds after typical CMS/ATLAS cuts

<table>
<thead>
<tr>
<th>System</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>$L_{int}$</th>
<th>$\sigma_{tot}$</th>
<th>$\rightarrow \gamma\gamma$ yields</th>
<th>$\rightarrow ZZ^*(4\ell)$ yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbPb</td>
<td>5.5</td>
<td>10 nb$^{-1}$</td>
<td>500 nb</td>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>pPb</td>
<td>8.8</td>
<td>1 pb$^{-1}$</td>
<td>6.0 nb</td>
<td>7</td>
<td>0.4</td>
</tr>
<tr>
<td>PbPb</td>
<td>39</td>
<td>33 nb$^{-1}$</td>
<td>11.5 $\mu$b</td>
<td>450</td>
<td>25</td>
</tr>
<tr>
<td>pPb</td>
<td>63</td>
<td>8 pb$^{-1}$</td>
<td>115 nb</td>
<td>950</td>
<td>50</td>
</tr>
</tbody>
</table>

- **LHC (nominal $L_{int}$):** $\sim 10$ Higgs bosons/month visible in Pb-Pb, p-Pb
- **HE-LHC:** $\sim 40$ Higgs bosons/month in Pb-Pb, p-Pb
- **FCC (nominal $L_{int}$):** $\sim 500-1000$ H bosons/month in Pb-Pb, p-Pb (*)

(*) latest lumi estimates increased by factor 3
Gluon-H + quark-H interaction cross section

- LO x-sections obtained with CalcHEP (and WHIZARD) for $p_H, E_{q,g} \sim 1-10$ GeV
- "Direct" gluon-Higgs scatterings dominate the LO diagrams:
  Quark-Higgs contributions through higher-order corrections via cases where medium quark emits gluon that then scatters with H
- $K$ factor = 3 assumed from ratio of (N3LO+NLL)/LO gluon fusion x-sections
  → Resulting cross section of $0.5-100 \mu b$ for low $E^*$ between 0.4-2.3 GeV
Absorption cross section

- The interaction of 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 diphoton and four-lepton discovery channels

→ “Absorption” cross section

- Estimate expected suppression using

\[ S \equiv \exp(-L/\lambda) = \exp(-\sigma \rho L) \]

- Example static case: \( \rho = 15 \text{fm}^{-3}, L = 10 \text{fm}, \)

\[ S = 0.99 \text{ for } \sigma = 1 \mu b, \]
\[ S = 0.85 \text{ for } \sigma = 10 \mu b, \]
\[ S = 0.22 \text{ for } \sigma = 100 \mu b, \]

- In reality: \( \sigma = \sigma(\tau), \rho = \rho(\tau, x, y), v_{\text{rel}}, \text{ path – dependent} \)

- Regulation at low \( E^* \):

\[ \sqrt{\hat{s}} - m_H = \left[ m_H^2 + m_{g,q}^2 + 2E_H E_{g,q} (1 - \beta_H \beta_{g,q} \cos \theta) \right]^{1/2} - m_H \]

\[ = \sqrt{m_{g,q}^2 + p_{g,q}^2} \text{ for } \beta_H \ll 1 \quad \text{Parton in-medium mass important!} \]
Dynamic calculation

\[ R_H(p_T^H) = \frac{\int \dd P(x_0, y_0) \, \dd \phi_0 \, \exp \left( - \int_{\tau_0}^{\tau_f} \overline{\sigma}_{Hqg}(\tau) \cdot \overline{\rho}(\tau) \cdot \overline{v}_{\text{rel}}(\tau) \, \dd \tau \right)}{\int \dd P(x_0, y_0) \, \dd \phi_0} \]

- Medium described by a 2D+1 hydrodynamical model (superSONIC)
  - Tuned such that expected final state multiplicity is described
  - Provides T(x,y) in slices of \( \tau \)

\[ \eta/s = 0.08 \]
\[ \zeta/s = 0.01 \]

Many thanks to P. Romatschke and R. Weller for providing the calculations
Dynamic calculation

\[
R_H(p_T^H) = \frac{\int dP(x_0, y_0) \ d\phi_0 \ \exp \left( - \int_{\tau_0}^{\tau_f} \overline{\sigma_{Hgg}}(\tau) \cdot \overline{\rho}(\tau) \cdot \overline{v}_{rel}(\tau) \ d\tau \right)}{\int dP(x_0, y_0) \ d\phi_0}
\]

- Medium described by a 2D+1 hydrodynamical model (superSONIC)
  - Tuned such that expected final state multiplicity is described
  - Provides T(x,y) in slices of \(\tau\)

- Momentum spectrum of medium partons at T(x,y;\(\tau\)) given by
  \[
  f_{\tau}(E_{g,q}) = (\exp[E_{g,q}/T] \mp 1)^{-1} \text{ with } E_{g,q} > 0.2 \text{ GeV}
  \]

- Absorption cross section at T (and Higgs p_T)
  \[
  \overline{\sigma}_{Hgg}(T) = \int \sigma_{Hgg}(\sqrt{s}) v_{rel} f_{\tau}(E_{g,q}) \ d^3 \overline{p}_{g,q}
  \]

- Density \(\rho(x,y;\tau)\) from EOS
  \[
  \overline{\rho}(\tau) = \rho(x_0 + \beta_H \tau \cos \phi_0, y_0 + \beta_H \tau \sin \phi_0, \tau)
  \]

- Geometry from Glauber Ncoll distributions
  (or from the earliest hydro profiles in case of the small systems)
EoS + resulting absorption cross sections

- EoS with quarks/gluons and quasiparticles have vastly different $M(T)$ dependence and lead to significantly different $\sigma(T)$
Significant suppression ($R_H \approx 0.85$) in heavy ion collisions

- $R_H$ increase above 50 GeV, and is 1 at 300 GeV.
- Depending on EOS and $N_f$ variations by about $\pm 10\%$
Comparison with other collision systems

| System | Centrality | $\sqrt{s_{NN}}$ (GeV) | $dN_{ch}/dy|_{y=0}$ | $\Delta\tau$ (fm) | $T_0$ (GeV) | $\langle \rho \rangle$ (fm$^{-3}$) | $\langle \sigma_{HqS} \rangle$ (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      |
| pPb    | central (0–5%) | 8.8 TeV               | 60                   | 2.7              | 0.37      | 7.6                   | 31.2                | 0.97 ± 0.01      |
| pPb    | 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      |

- **Average suppression across systems**

  \[
  \langle R_H \rangle = \int \frac{d\sigma}{dp_T^H} R(p_T^H) \, dp_T^H / \int \frac{d\sigma}{dp_T^H} \, dp_T^H
  \]

- **Essentially no suppression for small systems, while expected trend with centrality for large (PbPb) systems**
Average suppression factor

Suppression driven by lifetime (and size) of the system

→ Stimulated decay rate of about 100 fm for all systems


Drawn errors from variations to quasi-particle EOS and Nf=4
Conclusions

- Higgs parton interactions found to be large; on the level of 1-100μb
  → K=3 assumed from production diagrams

- Our studies lead to a universal stimulated decay rate, resulting larger systems to exhibit a suppression of up to 15%
  → May be accessible at FCC (HE-LHC), where in 1 (10) month ~500 visible Higgs signal counts

- Suppression sensitive to the EOS and mass dependence of the partons leading to about 10% variation

- Our work calls for a theoretical study of the Higgs widths modifications in a QCD medium, compared to the electroweak vacuum.
NNLO theoretical setup

- **MCFM** v.8 NNLO event calculator with nuclear PDFs:
  - Parton densities:
    - Proton PDF: **CT10 NNLO**
    - Pb nPDF: **EPS09 NLO** (central + 30 error sets)
    - Isospin (u,d quark) effects included.
  - Scales choices: $\mu_F = \mu_R = m_{\text{top}}$, $\mu_F = \mu_R = m_H/2$
    (scale variations not considered: Cancel in $R_{AA}$).

- **Higgs production** (ggF: total & differential discovery $\gamma\gamma$, 4l decays):
  - \begin{align*}
      & 119 \quad H(\to \gamma(p_3) + \gamma(p_4)) \\
      & 116 \quad H(\to Z(\to e^-(p_3) + e^+(p_4)) + Z(\to \mu^-(p_5) + \mu^+(p_6)))
  \end{align*}
  - Plus total $\sigma_H$ for nproc=215 (VBF), 91 (assoc. WH), 101 (assoc. ZH)

- **Higgs $\gamma\gamma$, 4l backgrounds**:
  - \begin{align*}
      & 285 \quad f(p_1) + f(p_2) \to \gamma(p_3) + \gamma(p_4) \\
      & 90 \quad Z(\to e^-(p_3) + e^+(p_4)) + Z(\to e^-(p_5) + e^+(p_6))
  \end{align*}
  - All x-sections scaled to state-of-the-art NNLO+NNLL
    (as per LHC-HXSWG, K-factors ~20%)
Gluon fusion at various orders

Choice of K-factor = 3 rather conservative for production cross section
History of previously shown results

H boson quenching in the QGP?

- Results of a Glauber model (including QGP longitudinal expansion) for a Higgs “absorption” x-section of $\sigma = 10 \mu$b:
  - Average Higgs suppression factor in PbPb(39 TeV): $\sim 25\%$
  - Higgs survival probability as a function of PbPb centrality:

\[
R(b) = \int n(b, x, y) S_{b}(b, x, y) \, dx \, dy
\]

survival probability:

\[
S_{b} = \exp \left(-\tau_{b, \rho}(b, x, y) \ln n_{\rho}(b, x, y)\right)
\]

binary collisions $\propto$ QGP opacity:

\[
n(b, x, y) = \sigma_{T}(x + b/2, y) T_{b}(x - b/2, y)
\]

[De/C. Loizides, in preparation]

H boson suppression in the QGP

- SM boson ($\Gamma_{H} = 4$ MeV) lifetime $\tau = 1/\Gamma_{H} \sim 50$ fm $> \tau_{QGP} \sim 10$ fm.
  Once produced it will traverse the QGP and decay outside the medium. What are its $qg$ scattering x-sections?

- Survival probability computed embedding Higgs in QGP (2D+1 viscous SuperSonic hydrodynamics):

  - Higgs suppression factor in PbPb: $\sim 15\%$, dominantly at $p_{T} < 100$ GeV.

- Enough motivation to convince proton-proton community to run for 2 years PbPb at HE-LHC?

Result shown June 2018 used SU3 EOS, leading to similar suppression.

Results in 2017 (FCC workshop CERN and QM17) used average absorption and only Glauber as model of the medium, and hence overestimated the effect.
Average suppression versus lifetime of the system