Production and hadronic decays of higgs bosons in heavy-ion collisions

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Based on
Work in collaboration with E. L. BERGER, J. Gao and H. Zhang (arXiv: 1804.06868)

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• Discovery of the higgs boson at the LHC opens a new era in high energy physics and validated the standard model (SM) as a low energy (~EW scale) Description of nature.

• Several phenomena (e.g. dark matter) cannot be accounted/explained in the SM. Can be looked for in
  ❖ direct searches; production of high mass resonances, new Particles in association with SM pairs.
  ❖ the tail of various distributions; USEFUL for e.g. SM EFT interpretations.
  ❖ precise measurements of Higgs boson couplings; sensitive to TREE LEVEL modifications and/or loop-effects in bsm.

• To assess sM predictions and look for new physics; the full Lagrangian involving the higgs bosons needs to be explored.

  Yukawa sector (very poorly explored).
  Gauge sector (better explored).
  Higgs self couplings (necessary to reconstruct the full potential).
Higgs Decays in the SM

Most of the Higgs bosons decay into hadrons (either directly or through intermediate gauge bosons)

Only about 2 Higgs bosons in 1000 decay in $\gamma\gamma$!

BUT! measurement of Higgs decays into hadrons is very difficult; e.g. $H \rightarrow b\bar{b}$ was observed very recently

Alternative to $pp$ collisions at the LHC are needed to be exploited/tested:

- Lepton Colliders (ILC/CEPC/FCC-ee/CLIC) running at the threshold of producing $HZ$ is a reasonable alternative.
- Heavy-ion collisions? I will tell you why.
- Others?
Heavy-ion collisions?

• Colliding nucleus (Pb-Pb, Xe-Xe...etc) to produce a medium with a high-density and temperature; Quark-gluon plasma (QGP)
  ❖ the main degrees of freedom (constituents) in the medium are not hadrons but quarks and gluons.
  ❖ The formation and cooldown of the QGP happens in time scales of about 11 fm/c

• Therefore?
  ❖ the medium being formed is a good probe of the early moments in the universe.
  ❖ many studies have been performed/ongoing to assess the properties of the medium and related theoretical questions.
  ❖ Using jet quenching to probe the medium and the properties of the particles passing through it.
HOW WE CAN EXPLOIT THIS PROPERTY?

• NOTE THAT W AND Z BOSONS, AND TOP QUARK HAVE VERY SHORT LIFETIME UNLIKE THE HIGGS BOSON

\[ \tau_t \approx 0.1 < \tau_{QGP} \approx 11 < \tau_H \approx 47 \] (units are in fm/c)

• SO? THE DECAYS PRODUCTS OF TOP QUARKS AND GAUGE BOSONS (AND ALSO PROMPT JETS) WILL EXPERIENCE SIGNIFICANT ENERGY LOSS DUE TO THE INTERACTION WITH THE QGP WHILE THE HIGGS WILL DECAY OUTSIDE THE QGP.

• ENHANCEMENT OF SIGNAL-TO-BACKGROUND RATIO?
STRATEGY

• USE THE MOST SENSITIVE CHANNEL AT THE LHC (PROOF-OF-PRINCIPLE); $pp \rightarrow HZ$ (MAJOR BACKGROUNDs ARE $t\bar{t}$ production and $Zb\bar{b}$).

• APPLY SIMPLIFIED MODELS FOR JET QUENCHING ON THE BACKGROUND PROCESS

  \[ \langle \delta p_T \rangle = a \ p_T + b \log(p_T) + c, \ (a, b \text{ and } c \text{ are tunable parameters}) \]

• CARRY A SIMPLE SELECTION SETUP TO DETERMINE THE MINIMUM LUMINOSITY REQUIRED TO OBSERVE THIS PROCESS IN HEAVY-ION COLLISIONS AT $\sqrt{s} = 5.5, 11$ and $39.4$ TeV.

• BESIDES CUTS ON THE INVARIANT MASS, TRANSVERSE MOMENTUM...ETC, A GOOD DISCRIMINATOR VARIABLE IS THE MOMENTUM IMBALANCE BETWEEN THE DILEPTON PAIR AND B-JET PAIR; PEAKED AROUND 1 FOR UNQUENCHED JETS AND HAS A LOWER PEAK IN THE QUENCHED CASE.
Shift of $x_{jZ}$ distribution for quenched compared to the unquenched case. Good agreement with JEWEL predictions for both 0-10% (and 0-30%) centrality class is observed.

Same finding holds for $\gamma +$ jet production (not shown here).

BECAUSE THERE ARE NO MC GENERATORS FOR $t\bar{t}$ and $Zb\bar{b}$ PRODUCTION IN HEAVY-ION COLLISIONS; WE NEED TO VALIDATE THE SIMPLIFIED MODELS FOR QUENCHING AGAINST EXISTING DATA AND JEWEL PREDICTIONS FOR $\gamma +$JET AND $Z +$ JET PRODUCTION.
RESULTS

• $p_T^\ell \geq 15$ GeV, $|\eta^\ell| < 2.5$ and $\Delta R_{\ell\ell} > 0.2$
• $p_T^j \geq 30$ GeV, $|\eta^j| < 1.6$ and $\Delta R_{\ell\ell} > 0.3$
• A pair of SFOS leptons with $|m_{\ell\ell} - M_Z| < 10$ GeV.
• Exactly two jets (both are b-tagged) with $\Delta R_{bb} < 2$.
• $p_T^Z \equiv p_T^{\ell\ell} \geq 100$ GeV (reduce significantly the $t\bar{t}$ background).
RESULTS

We further require

- \( x = \frac{p_T^{b\bar{b}}}{p_T^{\ell\ell}} > 0.75 \) and
- \( p_T > 60 \) GeV for the leading jet at the LHC and \( p_T > 50 \) GeV for the sub-leading jet at FCC-hh.

| lumi.(pb\(^{-1}\)) | strong | medium | mild | vacuum |
|---------------------|--------|--------|------|--------|
| LHC                 | 16(5.9)| 27(9.8)| 26(9.3)| 48(17) |
| HE-LHC              | 11(4.0)| 20(7.2)| 20(7.2)| 34(12) |
| FCC-hh              | 8.0(2.9)| 14(5.0)| 14(5.0)| 23(8.2) |

Quite high luminosity needed for PbPb (which might not be achieved at the LHC)

Should we give up? **NO!**
CONCLUSIONS AND OUTLOOK

- We have provided a new idea of exploiting heavy-ion collisions to study Higgs boson hadronic decays.
  - FAIRLY POSSIBLE AT FUTURE COLLIDER (FCC-HH).
  - CAN BE POSSIBLE AT THE LHC; WITH USES OF OTHER CHANNEL LIKE E.G. 0-LEPTON AND 1-LEPTON CATEGORIES IN HV PRODUCTION AND SOME OTHER OBSERVABLES SUCH AS JET SHAPES (DIFFERENT FOR QUENCHED AND UNQUENCHED CASES).
  - POSSIBILITY TO USE IT AS A TOOL TO STUDY PROPERTIES OF THE QGP MEDIUM.

- New Directions in Top/Higgs/New Physics in Heavy-ion collisions are promising
  - USING TOP QUARK TO STUDY QGP LIFETIME and QUENCHING; Liliana Apolinario, Jose Guilherme Milhano, Gavin P. Salam, and Carlos A. Salgado (2017).
  - NEW PHYSICS IN HEAVY-ION COLLISIONS THROUGH DISPLACED VERTICES; Marco Drewes, Andrea Giammanco, Jan Hajer, Michele Lucente, and Olivier Mattelaer (2018).
  - HIGGS PAIR PRODUCTION IN THE FULL HADRONIC FINAL STATE; Edmond L. Berger, Jun Gao, AJ, Hao Zhang (in progress).
  - OTHERS?