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Top-quark and Higgs boson perspectives at heavy-ion colliders

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Abstract

The perspectives for measuring the top quark and the Higgs boson in nuclear collisions at the LHC and Future Circular Collider (FCC) are summarized. Perturbative QCD calculations at (N)NLO accuracy, including nuclear parton distribution functions, are used to determine their cross sections and visible yields after standard analysis cuts in PbPb and pPb collisions at the LHC ($\sqrt{s_{_{NN}}}$ = 5.5, 8.8 TeV) and FCC ($\sqrt{s_{_{NN}}}$ = 39, 63 TeV). In their "cleanest" decay channels, $t\bar{t} \to b\bar{b}\,2\ell\,2\nu$ and $H \to \gamma\gamma;\ 4\ell$, about 10^3 (10^5) top-quark and 10 (10^3) Higgs-boson events are expected at the LHC (FCC) for their total nominal integrated luminosities. Whereas the $t\bar{t}$ observation is clearcut at both colliders, evidence for Higgs production, perfectly possible at the FCC, requires integrating ×30 more luminosities at the LHC.

Keywords: Top quark, Higgs boson, heavy-ions, LHC, FCC

1. Introduction

The top quark and the Higgs boson (together with the τ lepton) are the only elementary Standard Model (SM) particles that remain unobserved so far in nuclear collisions. Their production cross sections in hadronic collisions are dominated by gluon-gluon fusion processes ($g\,g \to t\bar{t} + X; H + X$), computable today at the highest degree of theoretical accuracy: NNLO+NNLL for the top quark [1], and N^{3}LO for the H boson [2]. The study of their yield modifications in heavy-ion compared to pp collisions would provide novel extremely well calibrated probes of the initial and final pA and AA states. Both elementary particles, the heaviest known, have very different decay channels and lifetimes, and can thereby be used to uniquely probe various aspects of strongly-interacting matter in nuclear collisions. On the one hand, the top-quark decays very rapidly before hadronizing ($\tau_0 = \hbar/\Gamma_t \approx 0.1$ fm/c, much shorter than typical O(1 fm/c) QGP formation times) into $t \to W\,b$ with ~100% branching ratio, with the W themselves decaying either leptonically ($t \to W\,b \to \ell\,\nu, b$, 1/3 of the times) or hadronically ($t \to W\,b \to q\,\bar{q}\,b$, 2/3 of the times). The kinematical distributions of the charged leptons ($\ell = e, \mu$ unaffected by any final-state interactions) from $t\bar{t} \to b\bar{b}\,2\ell\,2\nu$ $t\bar{t}$ decays provide accurate information [3] on the underlying nuclear gluon distribution function in the unexplored high-x region where "antishadowing" and "EMC" effects are supposed to modify its shape compared to the free proton case [4]. On the other hand, the Higgs boson has a lifetime of $\tau_0 \approx 50$ fm/c and, once produced, traverses the produced medium and scatters with the surrounding partons, resulting in a potential depletion of its yields compared to the pp case [5]. The amount of Higgs boson suppression can be thereby used to accurately determine the final-state density of the produced QGP. The perspectives of t-quark [3] and Higgs boson [6] measurements in nuclear collisions at current and future colliders are summarized here.

The theoretical cross sections and yields in pPb and PbPb are obtained with MCFM at NLO (v.6.7) for top-quarks [7], and at NNLO (v.8.0) for the Higgs boson [8], using CT10 proton PDFs [9] and EPS09 nPDFs (including its 30 eigenvalues sets) for the Pb ion [4]. The following MCFM processes are run: `141` for $t\bar{t}$, `161,166,171,176,181,186` for single-top in the t-,s-channels and associated with W [3]; and `119,116` for gluon-fusion $H \to \gamma\gamma$, 4ℓ (plus `285,90`

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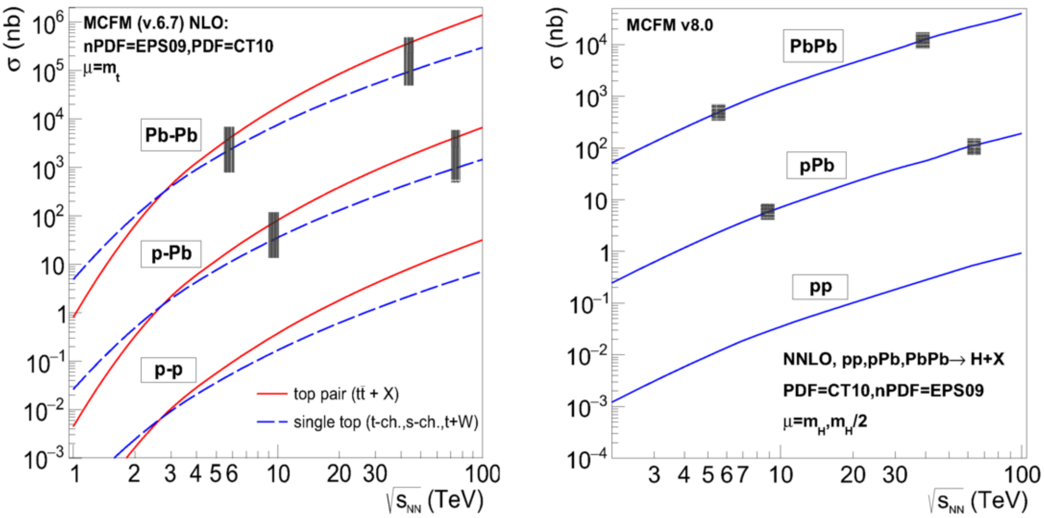

Figure 1: Total production cross sections for top-pair and single-top at NLO (left) [3] and for the Higgs boson at NNLO (right) [6] in pp, pPb and PbPb collisions as a function of $\sqrt{s_{\rm NN}}$ (the shaded boxes indicate the nominal LHC and FCC energies).

Table 1: Cross sections, and expected number of counts after standard acceptance and efficiency cuts, for $t\bar{t}$ and single-top (s-,t- and tW channels combined) at NLO (total, and in their respective leptonic decays) [3] and Higgs boson (total, and di-γ and 4-lepton channels, at NNLO) [6] in pPb and PbPb collisions at LHC and FCC. Maximum theoretical (scale and PDF) uncertainties (not quoted) are around 10%.

System	$\sqrt{s_{\rm NN}}$ (TeV)	$\mathcal{L}_{\rm int}$	$t\bar{t}$ $\sigma_{\rm tot}$	$t\bar{t}\to b\bar{b}\ell\ell\nu\nu$ yields	single-t $\sigma_{\rm tot}$	$tW\to b\ell\ell\nu\nu$ yields	H $\sigma_{\rm tot}$	$H\to\gamma\gamma$ yields	$H\to ZZ^*(4\ell)$ yields
PbPb	5.5	10 nb^{-1}	3.4 μb	450	2.0 μb	30	500 nb	6	0.3
pPb	8.8	1 pb^{-1}	59 nb	750	27 nb	50	6.0 nb	7	0.4
PbPb	39	33 nb^{-1}	300 μb	1.5×10^5	80 μb	8000	11.5 μb	450	25
pPb	63	8 pb^{-1}	3.2 μb	4×10^5	775 nb	2.1×10^4	115 nb	950	50

for the corresponding $\gamma\gamma$, 4ℓ backgrounds), as well as `91,101,215,540` corresponding to the rest of Higgs production channels (vector-boson-fusion, and associated with W, Z and top) to obtain the total H cross sections [6]. All numerical results have been obtained with the latest SM parameters [10], and fixing the default renormalization and factorization scales at $\mu_F = \mu_R = m_t$ for $t\bar{t}$ and single-top, $\mu_F = \mu_R = p_{T,\min;b-\rm jet} = 50$ GeV for tW, and $\mu_F = \mu_R = m_H/2$ for Higgs. These calculations reproduce very well the top and Higgs cross sections measured in pp collisions at $\sqrt{s} = 7, 8, 13$ TeV at the LHC. The collision energy dependence of the total top-quark and Higgs boson cross sections are shown in Fig. 1. The cross sections increase by a factor of ×55–90 for $t\bar{t}$ and ×20 for the Higgs boson between LHC and FCC energies. The cross sections at the nominal LHC and FCC energies are listed in Table 1. Compared to the corresponding pp results at each c.m. energy, antishadowing nPDF modifications increase the total top-quark yields by 2–8%, whereas the Higgs cross sections are just slightly enhanced (depleted) by ~3% at the LHC (FCC). The PDF uncertainties, obtained adding in quadrature the CT10 and EPS09 uncertainties, are around (below) 10% for the top (Higgs) case. The $\mathcal{O}(5-10\%)$ theoretical μ_F, μ_R scale uncertainties, not quoted either, cancel out in the ratios of (pPb,PbPb)/(pp) cross sections at the same colliding energy.

2. Top quark measurement

Top quarks decay almost exclusively to a b quark and a W boson and, in a heavy-ion environment, it is the W leptonic decays that can be best resolved