



Top quark production from black holes at the CERN LHC

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ABSTRACT

LHC is expected to be a top quark factory. If the fundamental Planck scale is near a TeV, then we also expect the top quarks to be produced from black holes via Hawking radiation. In this Letter we calculate the cross sections for top quark production from black holes at the LHC and compare it with the direct top quark cross section via parton fusion processes at next-to-next-to-leading order (NNLO). We find that the top quark production from black holes can be larger or smaller than the pQCD predictions at NNLO depending upon the Planck mass and black hole mass. Hence the observation of very high rates for massive particle production (top quarks, Higgs or supersymmetry) at the LHC may be an useful signature for black hole production.

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1. Introduction

Andrew Chamblin was a very good friend and a much valued collaborator—we greatly miss him. This Letter was initiated by Andrew.

It is now generally accepted that the scale of quantum gravity *could be* as low as one TeV [1] and hence there can be graviton, radion and black hole production at LHC [2–18]. If such processes occur then LHC collider experiments [19,20] can probe TeV scale quantum gravity. One of the most exciting aspects of this will be the production of black holes in particle accelerators. These ‘brane-world’ black holes will be our first window into the extra dimensions of space predicted by string theory, and required by the several brane-world scenarios that provide for a low energy Planck scale [21]. As the black hole masses at the LHC are relatively small (3–7 TeV) and the temperatures of the black holes are very high (~ 1 TeV) the black holes can be a source for top quark production via Hawking radiation. In fact there can be an enormous amount of heavy (supersymmetry and Higgs) particle production from black holes [22,23], much more than expected from normal pQCD processes. This comes about from two competing effects as the Planck scale increases: (1) top quark production from black holes increases because the temperature of the black

holes increases as the Planck scale increases for fixed black hole masses (see below) and (2) the cross section for black hole production decreases [24–27]. Reviews of this exciting field are given in [28].

In this Letter we calculate top quark production cross sections from TeV scale black hole at the LHC via Hawking radiation and compare them with the direct pQCD parton fusion processes at next-to-next-to-leading order (NNLO). We find that the top quark production cross sections from black holes at the LHC can be larger or smaller than those from pQCD processes at NNLO depending on the value of the TeV scale Planck mass and the black hole masses. We find that as long as the temperature of the black holes is of the order of TeV, the top quark production cross section from the black holes does not depend very much on the top quark mass M_t . On the other hand the direct pQCD production cross section at NNLO is sensitive to M_t . This provides us with an important conclusion: if TeV scale black holes are indeed formed at the LHC, then one signature of this will be an unusually copious production of massive (top quarks, Higgs and SUSY) particles, which is not possible via pQCD processes. Hence if we observe very high rates for massive particle production at the LHC, this might provide indirect evidence that TeV scale black holes are being produced.

The Letter is organized as follows. In Section 2 we present the computation for the rate of top quark production from black holes via Hawking radiation at the LHC. In Section 3 we sketch the pQCD techniques at NNLO for top quark production at the LHC. In Section 4 we present and discuss our results.

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2. Top quark production from black holes at the LHC

If black holes are formed at the LHC then they will quickly evaporate by emitting thermal Hawking radiation. The emission rate per unit time for top quark with momentum $p = |\vec{p}|$ and energy $Q = \sqrt{p^2 + M_t^2}$ can be written [14] as

$$\frac{dN}{dt} = \frac{c_s \sigma_s}{8\pi^2} \frac{dp p^2}{(e^{Q/T_{\text{BH}}} + 1)}, \quad (1)$$

where σ_s is the grey body factor and T_{BH} is the black hole temperature, which depends on the number of extra dimensions and on the TeV scale Planck mass. c_s is the multiplicity factor. The temperature of the black hole is given in [3], namely

$$T_{\text{BH}} = \frac{d+1}{4\pi R_S} = \frac{d+1}{4\sqrt{\pi}} M_P \left[\frac{M_P}{M_{\text{BH}}} \frac{d+2}{8\Gamma(\frac{d+3}{2})} \right]^{\frac{1}{d+1}}, \quad (2)$$

where R_S is the Schwarzschild radius of the black hole, M_P is the TeV scale Planck mass, M_{BH} is the mass of the black hole and d is the number of extra dimensions. The grey body factor in the geometrical approximation is given by [24–26]

$$\sigma_s = \Gamma_s 4\pi \left(\frac{d+3}{2} \right)^{2/(d+1)} \frac{d+3}{d+1} R_S^2, \quad (3)$$

where we take $\Gamma_s = \frac{2}{3}$ for spin half particles. The total number of top quarks emitted from the black holes is thus given by:

$$N_{\text{top quark}} = \int_0^{t_f} dt \int_0^{M_{\text{BH}}} dp \frac{c_s \sigma_s}{8\pi^2} \frac{p^2}{(e^{\sqrt{p^2 + M_t^2}/T_{\text{BH}}} + 1)}, \quad (4)$$

where t_f is the total time taken by the black hole to completely evaporate, which takes the form [4]:

$$t_f = \frac{C}{M_P} \left(\frac{M_{\text{BH}}}{M_P} \right)^{\frac{d+3}{d+1}}. \quad (5)$$

C depends on the extra dimensions and on the polarization degrees of freedom, etc. However, the complete determination of t_f depends on the energy density present outside the black hole which is computed in [27] where the absorption of the quark-gluon plasma [29] by a TeV scale black hole at the LHC is considered (this time is typically about 10^{-27} s). The value we use throughout this Letter is $t_f = 10^{-3}$ fm which is the inverse of the TeV scale energy.

This result in Eq. (4) is for top quark emission from black holes of temperature T_{BH} . To obtain the top quark production cross section from all black holes produced in proton–proton collisions at the LHC we need to multiply the black hole production cross section with the number of top quarks produced from a single black hole. The black hole production cross section σ_{BH} in high energy hadronic collisions at zero impact parameter is given in [3,15], namely

$$\begin{aligned} \sigma_{\text{BH}}^{AB \rightarrow \text{BH}+X}(M_{\text{BH}}) &= \sum_{ab} \int_{\tau}^1 dx_a \int_{\tau/x_a}^1 dx_b f_{a/A}(x_a, \mu^2) \\ &\times f_{b/B}(x_b, \mu^2) \hat{\sigma}^{ab \rightarrow \text{BH}}(\hat{s}) \delta(x_a x_b - M_{\text{BH}}^2/s). \end{aligned} \quad (6)$$

In this expression x_a (x_b) is the longitudinal momentum fraction of the parton inside the hadron A (B) and $\tau = M_{\text{BH}}^2/s$, where \sqrt{s} is the hadronic center-of-mass energy. Energy–momentum conservation implies $\hat{s} = x_a x_b s = M_{\text{BH}}^2$. We use $\mu = M_{\text{BH}}$ as the scale at

which the parton distribution functions are measured. \sum_{ab} represents the sum over all partonic contributions. The black hole production cross section in a binary partonic collision is given by [3]

$$\hat{\sigma}^{ab \rightarrow \text{BH}}(\hat{s}) = \frac{1}{M_P^2} \left[\frac{M_{\text{BH}}}{M_P} \left(\frac{8\Gamma(\frac{d+3}{2})}{d+2} \right) \right]^{\frac{2}{d+1}}, \quad (7)$$

where d denotes the number of extra spatial dimensions. The total cross section for top quark production at LHC is then given by

$$\sigma_{\text{top quark}} = N_{\text{top quark}} \sigma_{\text{BH}}. \quad (8)$$

We will compare this cross section for top quark production via black hole resonances with the top quark cross section produced via pQCD processes at NNLO, as will be explained in the next section.

3. Top quark production via pQCD processes at the LHC

The top quarks at LHC are mainly produced in $t\bar{t}$ pairs. At the LHC proton–proton collider, the QCD production process involves quark–antiquark and gluon–gluon fusion mechanism. The gluon–gluon fusion processes give the dominant cross section (about 90 percent). This subprocess at high energy is the main reason for larger rate of the cross section compared to Tevatron at Fermilab. The single top quark production occurs via electroweak process. The single top quark production cross section (~ 300 pb) is smaller compared to $t\bar{t}$ total cross section (~ 970 pb) at LHC at $\sqrt{s} = 14$ TeV pp collisions. Hence we will not consider the single top quark production cross section [30] in this Letter. We will consider $t\bar{t}$ pair production using parton fusion processes at LHC and will compare them with the top quark production cross section from black holes.

At the next-to-next-to-leading order (NNLO) one needs to compute the following partonic subprocesses. On the leading-order (LO) level we have

$$q + \bar{q} \rightarrow t\bar{t}, \quad g + g \rightarrow t\bar{t}. \quad (9)$$

In NLO we have in addition to the one-loop virtual corrections to the above reaction the following two-to-three body processes

$$\begin{aligned} q + \bar{q} &\rightarrow t\bar{t} + g, & g + q(\bar{q}) &\rightarrow t\bar{t} + q(\bar{q}), \\ g + g &\rightarrow t\bar{t} + g. \end{aligned} \quad (10)$$

At NNLO level we receive the two-loop virtual corrections to the LO processes in Eq. (9) and one-loop virtual corrections to NLO reactions in Eq. (10). To these contribution one has to add the results obtained from the following two-to-four body reactions

$$\begin{aligned} g + g &\rightarrow t\bar{t} + g + g, & g + g &\rightarrow t\bar{t} + q + \bar{q}, \\ g + q(\bar{q}) &\rightarrow t\bar{t} + q(\bar{q}) + g, \\ q + \bar{q} &\rightarrow t\bar{t} + g + g, & q + \bar{q} &\rightarrow t\bar{t} + q + \bar{q}, \\ q + q &\rightarrow t\bar{t} + q + q, & \bar{q} + \bar{q} &\rightarrow t\bar{t} + \bar{q} + \bar{q}, \\ q_1 + q_2 &\rightarrow t\bar{t} + q_1 + q_2, & q_1 + \bar{q}_2 &\rightarrow t\bar{t} + q_1 + \bar{q}_2. \end{aligned} \quad (11)$$

After the phase space integrals has been done the partonic cross section $\hat{\sigma}$ is rendered finite by coupling constant renormalization, operator renormalization and the removal of collinear divergences. The renormalization scale μ_R is set equal to the mass factorization scale μ_F . The cross section for top quark production in proton–proton collisions at the LHC is given by

$$\sigma = \sum_{a,b=q,\bar{q},g} \int dx_1 \int dx_2 f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \hat{\sigma}_{ab} \quad (12)$$

where $\hat{\sigma}_{ab}$ is the partonic level cross section for top quark production. For the details, see [31,32]. Reviews of present status of top quark physics at LHC can be found in [33].

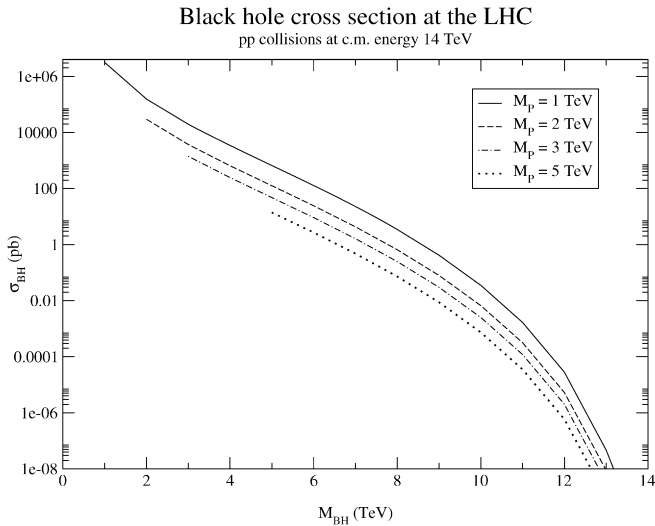


Fig. 1. Total cross sections for black hole production at the LHC.

4. Results and discussions

In this section we will compute the top quark production cross section from black hole at $\sqrt{s} = 14$ TeV in pp collisions and will compare them with the top quark production via parton fusion processes at NNLO. The top quark production from black holes is described in Section 2. For the black hole production we choose the factorization and normalization scale to be the mass of the black hole. As the temperature of the black hole at the LHC is ~ 1 TeV there is not much difference in the top quark production cross section from black holes if the top quark mass M_t is increased from 165 to 180 GeV. For black hole mass M_{BH} much closer to the Planck mass M_P the string corrections are important. In this situation string ball production becomes important [15]. For this reason we will choose black hole mass M_{BH} to be larger than the Planck mass M_P [15,22,23,27] in our computations below.

In Fig. 1 we present the black hole production cross section at the LHC. The y-axis is the black hole production cross section σ_{BH} in pb and the x-axis is the black hole mass M_{BH} in TeV. The solid, dashed, dot-dashed and dotted curves are for Planck masses of 1, 2, 3 and 5 TeV, respectively. The number of extra dimensions $d = 4$. As can be seen from the figure the cross sections decrease rapidly when both the Planck and black hole masses increase. These black hole production cross sections will be multiplied with the number of top quarks produced from a single black hole to obtain the top quark production cross section from a black hole at the LHC.

In Fig. 2 we present results for the average number of top quarks produced from a single black hole as a function of top quark mass. The y-axis is the average number of top quark production from a single black hole and the x-axis is the mass of the top quark in GeV. The upper two lines are for black hole masses equal to 3 and 5 TeV, respectively with the Planck mass equal to 1 TeV in each case. The lower two lines are for black hole masses equal to 6 and 10 TeV respectively with the Planck mass equal to 2 TeV in each case. It is clear that the average number of top quark produced from a single black hole is much larger for smaller black hole mass. This is because as the mass of the black hole becomes smaller the temperature becomes larger (\sim TeV) and the thermal radiation of top quarks are enhanced. This is the case from a single black hole emission. The black hole production cross section itself decreases at LHC as the mass of the black hole increases. Hence the total cross section of top quark production from black holes at LHC is a competitive effect from the above two factors (see Eq. (8)).

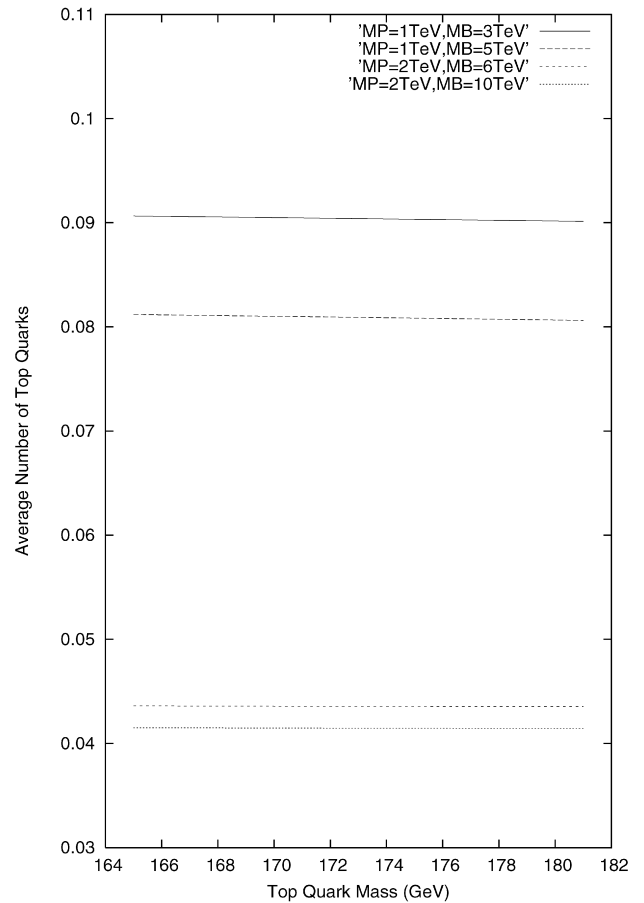


Fig. 2. Average number of top quark production from a single black hole at LHC. The upper two lines are for black hole masses equal to 3 and 5 TeV respectively with the Planck mass equal to 1 TeV in each case. The lower two lines are for black hole masses equal to 6 and 10 TeV respectively with the Planck mass equal to 2 TeV in each case.

In Fig. 3 we present the total top quark production cross section from black hole production and compare them with the pQCD predictions at NNLO. The former is given for Planck mass $M_P = 1$ TeV and for two different choices of the black hole mass, namely $M_{BH} = 3, 5$ TeV, respectively. We plot for comparison the NNLO top quark cross section from [32] with $\mu_F = \mu_R = M_t$. The two middle curves are NNLO results and the upper and lower curves are from black holes. The upper NNLO curve is for MRST 2006 PDF and the lower NNLO curve is for CTEQ6.6 PDF. The upper black hole curve is for black hole mass equal to 3 TeV and the lower black hole curve is for black hole mass equal to 5 TeV with the Planck mass being 1 TeV in both the cases. For larger Planck mass the cross section becomes even smaller and hence we do not plot them. It is clear that the total cross section via black hole production is larger than the pQCD cross section for small M_P and M_{BH} and is not sensitive to the increase in top quark mass.

In summary, we have computed top quark production cross section from black holes in proton-proton collisions at the LHC at $\sqrt{s} = 14$ TeV via Hawking radiation within the model of TeV scale gravity and have compared it with the pQCD cross sections at NNLO. As the temperature of the black hole is ~ 1 TeV there is a huge amount of top quark production from black holes at the LHC if the Planck mass is ~ 1 TeV and the black hole mass is ~ 3 TeV. We also find that, unlike Standard Model predictions, the top quark production from black hole is not sensitive to the increase in top quark mass. Hence we suggest that the measurement of an increase in cross section for heavy particle (top quark

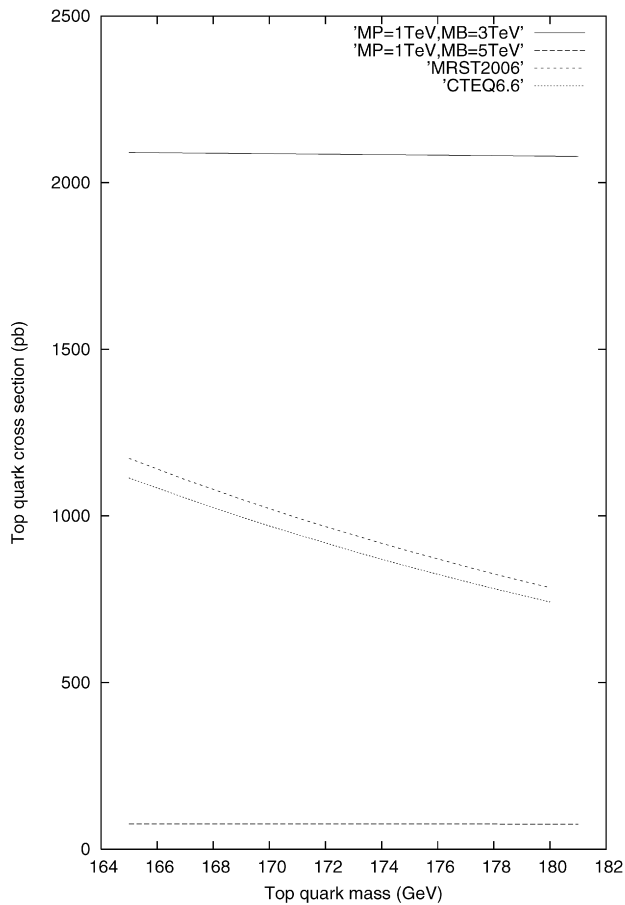


Fig. 3. Total cross section for top quark production at LHC from black holes and from direct pQCD processes at NNLO. The two middle curves are NNLO results and the upper and lower curves are from black holes of masses 3 and 5 TeV respectively with the Planck mass equals 1 TeV in each case.

or Higgs [23] or SUSY [22]) production at the LHC can be a useful signature for black hole production.

We make a brief comment about the grey body factor used in this Letter. The grey body factor which is used in section (3) is only valid in the regime of massless quanta and when the energy of the emitted particle is small compared to the black hole mass. Therefore, the computed cross Eq. (8) gives only an approximation to the actual cross section. Since this approximation improves for more massive black holes, our conclusions should remain valid. Finally, we warn the reader that the Planck mass $M_P = 1$ TeV used in this Letter is somewhat at odds with the constraints posed by LEP data on contact interactions [34] which suggests the Planck mass is greater than 2.2 TeV. If these constraints are true, then black hole production at the LHC, albeit exciting, may not lead to measurable contributions even if the large extra dimension scenario is realized.

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