Heavy dilepton in nucleus nucleus collision at LHC energy

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Abstract
We present a study of $\tau^+\tau^-$ lepton pair production in Pb + Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. The larger mass of tau lepton compared to electron and muon leads to considerably small hadronic contribution to the $\tau^+\tau^-$ pair invariant mass (M) distribution relative to the production from thermal partonic sources. The quarkanti-quark annihilation processes via intermediary virtual photon, Z and Higgs bosons have been considered for the tau lepton production. The contribution from DrellYan process is found to dominate over thermal yield for $\tau^+\tau^-$ pair mass from 4 to 20 GeV at the LHC energy. We also present the ratio of $\tau$ lepton pair yields for nucleusnucleus collisions relative to yields from p + p collisions scaled by number of binary collisions at LHC energies as a function $\tau$ lepton pair invariant mass. The ratio is found to be significantly above unity for the mass range 4 to 6 GeV. This indicates the possibility of detecting $\tau^+\tau^-$ pair from quarkgluon plasma (QGP) in the mass window 4 to 6 GeV.

1 Introduction
The heavy dilepton pairs namely $\tau^+\tau^-$ created in Pb-Pb collision at LHC energy is discussed in this work. The major advantage of looking at $\tau^+\tau^-$ dilepton pair arises due to the mass of the $\tau$ ($\sim 1.77$ GeV). The $\tau$ pair mass distribution would then start beyond known contribution of hadronic resonances ($\omega$, $\rho$ and $\phi$) which dominates in the respective mass regions in $e^+e^-$ and $\mu^+\mu^-$ sector. This would in turn mean the remaining contribution for $\tau$ production are due to thermal sources from partonic medium, pion annihilation in hadronic medium and Drell Yan Mechanism. We think that the results will definitely provide some useful baseline for experimental search and further detailed studies.

2 Source of $\tau$ Lepton Pair in Heavy Ion Collision
The main source of heavy dilepton $\tau^\pm$ pair production we have considered in this work is quark and anti-quark annihilation through photon, Z and Higgs bosons intermediumiated process. The corresponding Feynman diagrams are shown in Fig. 1. They all contribute to thermal production of $\tau^\pm$ pair in quark gluon plasma. The productions for these processes are evaluated

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from the matrix elements indicated below. The matrix element for the process \(q\bar{q} \rightarrow Z \rightarrow \tau^+\tau^-\) is given by,

\[
M_Z = \frac{g^2}{4\cos^2\theta_w} \frac{1}{(q^2 - m_z^2)} [v(p_2)\Gamma_q u(p_1)] [u(k_1)\Gamma_{\tau} v(k_2)]
\]  
(1)

where,

\[
\Gamma_q = \gamma^\mu (c_V q^\mu - c_A q^\mu q^5)
\]

\[
\Gamma_{\tau} = [\gamma^\mu - q^\mu q^\nu m_{\tau}^2 / m_{\tau}^2] [c_V - c_A \gamma^5]
\]

Finally putting the values of the parameters we have,

\[
|M_Z|^2 = \frac{g^4}{16\cos^2\theta_w} \left[ 0.5742[(s + t - m_q^2 - m_{\tau}^2)^2 + (m_q^2 + m_{\tau}^2 - t)^2
\right.
\left. + (s + t - m_q^2 - m_{\tau}^2)^2(1 - s / 2m_Z^2)] + s(0.858m_q^2 + 1.14m_{\tau}^2)
\right.
\left. - 0.59m_q^2m_{\tau}^2 - 0.0041s^2m_q^2m_{\tau}^2 + 0.002s^2m_q^2m_{\tau}^2 \right]
\]  
(2)

Similarly, for the photon mediated process we have:

\[
|M_\gamma|^2 = \frac{e_q^2e^2}{s^2} \left[ \frac{1}{4}[(m_q^2 + m_{\tau}^2 - t)^2 + (s + t - m_q^2 - m_{\tau}^2)^2] + (s - m_q^2)m_{\tau}^2 \right]
\]  
(3)

\(e_q\) is the average charge of quarks, \(e\) is the electronic charge. The matrix element of the interference term is \(M_ZM_\gamma^* + M_\gamma^*M_Z\).

\[
M_ZM_\gamma^* + M_\gamma^*M_Z = \frac{g^2e_qe}{4\cos^2\theta_w} \frac{1}{s(s - m_Z^2)} [(m_q^2 + m_{\tau}^2 - t)^2
\right.
\left. - (s + t - m_q^2 - m_{\tau}^2)^2[0.0912 + 12(4 - s / m_Z^2)] + 0.0912s^3 / m_Z^3
\right.
\left. - 0.1824s^2 / m_Z^2 + 0.5472s^2m_q^2m_{\tau}^2 + 0.1824s^2m_q^2m_{\tau}^2 - 1.09m_q^2m_{\tau}^2 \right]
\]  
(4)
Finally, the matrix element for the Higgs mediated process is:

$$|M_H^2| = \frac{m_q^2 m_{\tau}^2}{\text{vev}(s - m_H^2)^2} [2m_q^2 - \frac{s}{2}] [2m_{\tau}^2 - \frac{s}{2}]$$  \hspace{1cm} (5)

Here, $m_q$, $m_{\tau}$, $m_Z$, $m_H$, are the masses of quarks, $\tau$ leptons, $Z$ boson and Higgs respectively. ($p_1$, $p_2$) and ($k_1$, $k_2$) are initial state and final state momenta respectively. The total production cross section ($\sigma_\tau$) of $\tau^+ \tau^-$ is obtained by taking a coherent sum of the matrix elements given in Eqs. (2), (3), (4) and (5) with the following values of various parameters: $m_Z = 91$ GeV, $M_\tau = 1.78$ GeV, $m_H = 120$ GeV, $\sin \theta_W = 0.234$, $C_A = 0.5$, $C_V = 0.19$, $C_A = -0.5$, $C_V = -0.03$ and Higgs vev = 246 GeV.

3 τ Lepton From Drell-Yan Process

The total production cross-section $\sigma_\tau$ is folded by the parton distribution functions to obtained the $\tau$ lepton pair yield in p-p collisions. In the present work CTEQ5M PDF [1] have been taken to obtain this. The DY production of $\tau$ lepton in Pb-Pb collision is;

$$\frac{dN}{dM^2 dy} = \frac{N_{\text{coll}}(b)}{\sigma_{\text{in}}^{pp}} \times \frac{d\sigma_{pp}}{dM^2 dy}$$

where, $N_{\text{coll}}(b)$ is the number of binary nucleon nucleon collisions an impact parameter b calculated using Glauber model and $\sigma_{\text{in}}$ is the inelastic cross section for p-p interaction. We have taken $\sigma_{\text{in}} = 60$ mb and $b = 3.6$ fm corresponding to 0 − 5% centrality at $\sqrt{s_{NN}} = 5.5$ TeV. The shadowing of parton distribution functions has been taken from [2].

4 Space-Time Evolution Of τ Lepton Pairs

The space time evolution of the system formed in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV has been studied by using ideal relativistic hydrodynamics [3] with longitudinal boost invariance [4] and cylindrical symmetry. Our assumption is that the system reaches equilibration at a time $\tau_i = 0.08$ fm/c after the collision. The initial temperature, $T_i$ is considered to be 700 MeV and is calculated assuming the hadronic multiplicity (dN/dy) to be of the order of 2100 [5]. The equation of state (EOS) obtained from the Lattice QCD calculations by the MILC collaboration [6] for the partonic phase is used here. For the hadronic phase EOS all the resonances with mass 2.5 GeV have been considered [7]. The transition temperature ($T_c$) between hadronic phase and partonic phase is taken to be 175 MeV [8]. We consider kinetic freeze out temperature, $T_f = 120$ MeV. In this context we want to mention that the gluon fusion process was found to be dominant for mass of lepton pair greater than the mass of W boson. Our results are concentrated in the mass range of 4 to 20 GeV, where the contribution from such process is found to be orders of magnitude smaller compared to the rest of the sources of $\tau^\pm$ pair production.
5 Results

The yield \( \frac{dN}{dMdy} \) for \( \tau \) dilepton pair as a function of \( \tau^+\tau^- \) pair invariant mass for Pb+Pb collisions at \( \sqrt{s_{NN}} = 5.5 \) TeV is shown in figure 2(a). The contributions from Drell Yan (DY, dashed line) and thermal partonic medium (QGP, solid line) are shown. As evident from the figure, the Drell Yan contribution is higher than the thermal contribution for all the mass range studied. The difference seems to increase with increase in \( \tau^+\tau^- \) pair mass.

Figure 2(b) shows the ratio \( \frac{dN^{PbPb}}{dMdy} / [N_{coll} \frac{dN^{PP}}{dMdy}] \) where \( dN^{PbPb}/dMdy \) is the sum of all the contributions shown in figure 2(a) from Pb+Pb collisions. The \( [N_{coll} \frac{dN^{PP}}{dMdy}] \), is the number of binary collisions scaled contribution from DY process. This contribution can be estimated from the measurement in p+p collisions at the same energy \( \sqrt{s} = 5.5 \) TeV. If there is no QGP formation then the ratio should always be equal to unity indicating the fact that the dilepton yield in the nucleus-nucleus collision is the collection of individual nucleon-nucleon collision only. However, we observe that the ratio is above unity for the mass range of 4 to 6 GeV. Starting with a value of 1.4 at mass of 4 GeV it decreases towards unity beyond mass of 6 GeV. This indicates that one should be able to extract a clear information of thermal contribution from partonic source at LHC energies using heavy dilepton pair measurement within the mass window of 4 to 6 GeV.
6 Summary

A study of τ dilepton pair production at LHC energy has been carried out in this work. We have considered Pb+Pb collisions at midrapidity for √s_{NN} = 5.5 TeV. It is expected that this energy should allow a significant production of τ leptons. The main motivation of considering the τ lepton is its mass. Because of heavy mass the tau lepton yield is expected not to suffer from the huge background production. The main sources for τ pair production considered here by quark and anti-quark annihilation mediated through photon, Z and Higgs boson. The contribution from pion annihilation process is few orders of magnitude small compared to both thermal and Drell Yan contributions. The Drell Yan contribution is found to be higher than the thermal contribution from partonic sources for the entire mass range studied. The non-thermal contributions could be measured experimentally through p+p collisions, then the ratio of yields from nucleus-nucleus collisions to the yields for the binary collision scaled p+p collisions is found to be above unity for the mass range of 4-6 GeV. This indicates the window in mass region for τ dilepton pair where the thermal production can be studied at LHC energy using heavy dilepton pairs as an observable.

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