The estimation of neutrino fluxes produced by proton-proton collisions at $\sqrt{s} = 14$ TeV of the LHC

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ABSTRACT: Intense and collimated neutrino beams are produced by charm and beauty particle decays from proton-proton collisions at the LHC. A neutrino experiment would be run parasitically without interrupting the LHC physics program during the collider run. We estimate the neutrino fluxes from proton-proton collisions at $\sqrt{s} = 14$ TeV of the LHC with the designed luminosity, $10^{34}$ cm$^{-2}$ s$^{-1}$. By mounting about 200 tons of fiducial volume of a neutrino detector at 300 m away from the interaction point, about 150,000 of charged current neutrino events per year can be observable.

KEYWORDS: Hadron-Hadron Scattering.
1. Introduction

The main objectives of the LHC (Large Hadron Collider) at CERN are to search for an origin of electroweak symmetry breaking and to probe a new physics in the TeV scale. When the LHC is fully operational, it will have proton-proton collisions at center-of-mass energy of 14 TeV with a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. In a long term, the LHC is planning to upgrade to the super-LHC (sLHC), which is under evaluation. The sLHC will deliver 10 times more luminosity, $10^{35}$ cm$^{-2}$s$^{-1}$, than the LHC.

In such a huge luminosity at the LHC, there will be intense and collimated neutrino beams from particle decays produced by the collisions. The neutrino and anti-neutrino production rates at the interaction point would be equal in forward and backward directions. By mounting a neutrino detector at ~300 m away from the interaction point, one can perform a neutrino experiment parasitically without interrupting the LHC physics program during the collider run. And also, this detector would provide an unique opportunity for a long-lived metastable particle search, for example, the scalar tau lepton in Supersymmetric extension of gravity, as well as neutrino physics. Another advantage of this experiment is that the neutrino fluxes and momentum spectrum could be well understood since the collider detectors, CMS and ATLAS, at LHC can be used for monitoring production rates of major neutrino sources, Pions, Kaons, heavy mesons and etc..

In Ref [4], the neutrino fluxes from decays of charm and beauty mesons produced at the collision point of LHC at center-of-mass energy of 16 TeV with an luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ were estimated. The Quark Gluon String Model was used for the estimation of the inclusive production rates for charm and beauty mesons, and Hagedorn's thermodynamic model adopted for describing the transverse momentum distributions for the produced heavy mesons. About 1,000 of charged current $\nu_{\tau}$ and $\bar{\nu}_{\tau}$ interactions per year were expected with 2.4 (62.4) tons of detector locating at 100 (500) m from the interaction point.

In this paper, we use the PYTHIA event generator with the parameter set tuned by experimental data from Tevatron and LEP to estimate neutrino fluxes from the
Table 1: Summary of the average neutrino energy and the number of neutrinos including antineutrino per year for neutrino within 3 mrad of cone in either forward or backward direction with $10^{34}$ cm$^{-2}$s$^{-1}$ of the nominal luminosity. The columns for Light, Heavy and All show the contributions from light, heavy, and light and heavy particle decays, respectively.

2. Estimation of Neutrino Fluxes

Since main sources of neutrinos from pp collisions at $\sqrt{s} = 14$ TeV are Pions, Kaons, charm and beauty particles, the yields and transverse and longitudinal momentum spectra of those particles should be well understood for the estimation of neutrino fluxes. We use the PYTHIA program with the tuned parameter set, which is widely used and intensively tested with real data for the LHC experiments at $\sqrt{s} = 7$ TeV. Although the yields for Kaons and beauty mesons are not well agreed with the PYTHIA [9, 10, 11], the shape for transverse momentum spectra of those particles are generally good. Recent measurement for $\sigma(pp \rightarrow b\bar{b}X)$ at $\sqrt{s} = 7$ TeV is found to be $(284 \pm 20 \pm 49)$ $\mu$b [13], and PYTHIA estimation is 226.7 $\mu$b, which is about 20 % lower. This suggests that we may underestimate the neutrino flux by about 20 % level.

In order to estimate neutrino fluxes from particle decays produced by pp collisions at $\sqrt{s} = 14$ TeV of the LHC, we generate a large sample of events with the QCD $2 \rightarrow 2$ processes, $qq \rightarrow qq$, $q\bar{q} \rightarrow q\bar{q}$, $q\bar{q} \rightarrow gg$, $q + g \rightarrow qg$, $gg \rightarrow q\bar{q}$ and $gg \rightarrow gg$, in the PYTHIA. In addition, we update branching fractions for charm and beauty particles reported in the PDG book [12] in the PYTHIA program since those heavy particle decays are main sources for $\nu_\tau$, for example, the decay $D_s^+ \rightarrow \tau^+ \nu_\tau$, and also for $\nu_e$ and $\nu_\mu$ production at a few hundred meter away from the interaction point. The total cross-section for the QCD processes is found to be 54.7 mb. In particular, the cross sections for charm and beauty particles are 14.3 mb and 495.7 $\mu$b, respectively.

The produced unstable particles, even pions and muons, are allowed to decay with their natural life times. Since it is difficult to estimate yields and directions for the particles after they are interacted with beam pipe and detector material, the transverse decay vertexes for neutrinos from the particle decays have to be less than 3 cm to ensure that the particles are decayed before hitting the beam pipe. Since two-separated proton rings at the LHC are merged to the common ring around the interaction point at the LHC, the longitudinal decay vertexes for neutrinos are required to be within 50 m from the interaction point to
guarantee particle decays inside the beam pipe. With the requirement of the transverse vertex, neutrinos are produced by the decays from mainly charm and beauty particles.

The average neutrino-beam energy and the number of neutrinos including anti-neutrinos per year within 3 mrad of cone in either forward or backward direction with the nominal luminosity are listed in Table 1. Since neutrinos are associated production with leptons

Figure 1: Energy distributions for $\nu_e$ (Top), $\nu_\mu$ (Middle) and $\nu_\tau$ (Bottom) with arbitrary scale.
Table 2: Summary of the number of neutrino (anti-neutrino) CC events per year with the neutrino detector, liquid argon time projection chamber with 203.3 tons of fiducial-volume, for the nominal LHC luminosity. The columns for Light, Heavy and All show the contributions from light, heavy, and light and heavy particle decays, respectively.

| Neutrino Beam | Expected the number of CC events per year |
|--------------|------------------------------------------|
|              | Light | Heavy | All   |
| $\nu_e$      | 200 (99) | 31466 (15524) | 31666 (15623) |
| $\nu_\mu$    | 4908 (2421) | 67990 (33542) | 72898 (37184) |
| $\nu_\tau$   | -     | 209 (103) | 209 (103) |

from semileptonic decays of charm and beauty particles and the mass of tau lepton is much heavier than electron and muon, the energy spectrum and production angle for $\nu_\tau$ are different from ones for $\nu_e$ and $\nu_\mu$. Figure 1 shows the energy distributions for neutrino and anti-neutrino beams produced within 3 mrad with respect to proton beam. The production angle distributions for the neutrino beam are shown in Fig. 2.

3. Proposed Neutrino Experiment at the LHC

As the neutrino beam is produced at the interaction point by pp collisions at the LHC, a possible location of neutrino detector is about 300 m away from the interaction point for high luminosity experiments, CMS and ATLAS experiments. Figure 3 shows the layout of one half of 546-m-long straight section [14] for high luminosity experiments.

In order to detect $\nu_e$, $\nu_\mu$ and $\nu_\tau$ charged current (CC) events with high efficiency, a neutrino detector should have excellent capabilities for particle identification and background rejection. A liquid argon time projection chamber [15], which gives high-resolution tracking information and acting as hadronic and electromagnetic calorimeter, would be the best option in current technology. The CC events for neutrino interacting with detector material are identified by the detection of the charged lepton. Identification of $\tau$ leptons from $\nu_\tau$ CC interactions can be performed by detecting a relatively large kink angle and missing transverse momentum of lepton from the decay $\tau^- \rightarrow l^- \nu \nu_\tau$ ($l = e, \mu$) compared to $\nu_e$ and $\nu_\mu$ CC events. The neutrino and anti-neutrino CC cross sections ($\sigma_\nu$) [12] for isoscalar targets are given below,

$$\sigma_\nu/E_\nu = \sigma_0 \times 10^{-38} \text{cm}^2/\text{GeV},$$

where $\sigma_0 = 0.677 \pm 0.014$ (0.334 ± 0.008) for neutrino (anti-neutrino) and $E_\nu$ is the neutrino energy.

For the estimation of the number of CC events, we assume that the detector is located at 300 m from the interaction point, and the active target for CC event detection is subtended 3 mrad in the forward direction and 50 m long with a density of 1.36 g/cm$^3$ for liquid argon. The total fiducial volume of this detector is 203.3 tons.

Using the estimated neutrino fluxes per year for $\nu_e$, $\nu_\mu$ and $\nu_\tau$ within 3 mrad in either forward or backward direction with the nominal LHC luminosity, the number of CC events
Figure 2: Production angle distributions for $\nu_e$ (Top), $\nu_\mu$ (Middle) and $\nu_\tau$ (Bottom) with arbitrary scale.

$(N_{CC})$ per year is estimated as follows,

$$N_{CC} = N_{\nu} \sigma_{\nu} N_A \rho L,$$
where $N_{\nu_l}$ is the neutrino flux for $\nu_l$ ($l = e$, $\mu$, $\tau$), $N_A$ Avogadro’s number, $\rho$ the density of detector target material and $L$ the length of detector. In the estimation of $\tau$ neutrino CC events, we require that the energy of $\nu_\tau$ has to be larger than the threshold energy for $\tau$ lepton production, 3.45 GeV/$c^2$. Table 2 is a summary of the number of neutrino and anti-neutrino CC events per year for the neutrino detector described above with assumption of 100% of detection efficiency.

4. Summary

We estimate the neutrino fluxes from proton-proton collisions at $\sqrt{s} = 14$ TeV with the designed luminosity, $10^{34}$ cm$^{-2}$s$^{-1}$ by using the PYTHIA program with the tuned parameter set. The estimated fluxes for $\nu_e$, $\nu_\mu$ and $\nu_\tau$ including its anti-neutrino from mainly the decays of charm and beauty particles produced by pp collisions at the LHC are $2.93 \times 10^{12}$, $7.26 \times 10^{12}$ and $7.1 \times 10^{10}$, respectively. For a 203.3 ton detector subtending 3 mrad at 300 m away from the interaction point, the number of charged current events for $\nu_e$ ($\bar{\nu}_e$), $\nu_\mu$ ($\bar{\nu}_\mu$) and $\nu_\tau$ ($\bar{\nu}_\tau$) are found to be 31,666 (15,623), 72,898 (37,184) and 209 (103). Our estimated the number of charged current events for $\nu_\tau$ is lower than one in Ref. [4] by about a factor of three. This is mainly due to that in our estimation, the production rate for $D_s^+$ is about 0.81 mb while the authors in Ref. [4] use the production rate for $D_s^+$ with 2 mb.

Acknowledgments

This work was supported in part by the KICOS.

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