Excited neutrino search potential of the FCC-based electron-hadron colliders

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Abstract

The production potential of the excited neutrinos at the FCC-based electron-hadron colliders, namely the ERL60⊗FCC with $\sqrt{s} = 3.46$ TeV, the ILC⊗FCC with $\sqrt{s} = 10$ TeV, and the PWFA-LC⊗FCC with $\sqrt{s} = 31.6$ TeV, has been analyzed. The branching ratios of the excited neutrinos have been calculated for the different decay channels and shown that the dominant channel is $\nu^* \rightarrow eW^+$. We have calculated the production cross sections with the process of $ep \rightarrow \nu^*q \rightarrow eW^+q$ and the decay widths of the excited neutrinos with the process of $\nu^* \rightarrow eW^+$. The signals and corresponding backgrounds are studied in detail to obtain accessible mass limits. It is shown that the discovery limits obtained on the mass of the excited neutrino are 2452 GeV for $L_{int} = 100$ $fb^{-1}$, 5635 GeV for $L_{int} = 10$ $fb^{-1}$ (6460 GeV for $L_{int} = 100$ $fb^{-1}$), and 10200 GeV for $L_{int} = 1$ $fb^{-1}$ (13960 GeV for $L_{int} = 10$ $fb^{-1}$), for the center-of-mass energies of 3.46, 10, and 31.6 TeV, respectively.

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I. INTRODUCTION

The Standard Model (SM) of the particle physics has so far been in agreement with the results of numerous experiments. The discovery of the Higgs boson \cite{1} has also increased the reliability of the SM. However, there are some problems which have not been entirely solved by the SM such as quark-lepton symmetry, family replication, number of families, fermion’s masses and mixing pattern, hierarchy problems etc. A number of theories beyond the SM (BSM), including extra dimensions, supersymmetry (SUSY), compositeness and so on, have been proposed for solving these problems. One of the most important of these theories is compositeness in which quarks and leptons have a substructure called preon \cite{2}. The composite models have been characterized by an energy scale, namely compositeness scale, $\Lambda$. A typical consequence of the compositeness is the appearance of excited leptons and quarks \cite{3,4}. Charged ($e^*, \mu^*, \tau^*$) and neutral ($\nu^*_e, \nu^*_\mu, \nu^*_\tau$) excited leptons are predicted by the composite models. The SM fermions are considered as ground states of a rich and heavier spectrum of the excited states. An excited spin-1/2 lepton is considered to be the lowest radial and orbital excitation. Excited states with spin-3/2 are also expected to exist \cite{5}.

No evidence for excited lepton production is found in studies using data samples collected by the experiments, namely LEP \cite{6}, HERA \cite{7}, Tevatron \cite{8}, CMS \cite{9} and ATLAS \cite{10} collaborations. For the excited electron \cite{11,12}, muon \cite{13} and neutrino \cite{14-17}, there are some phenomenological studies at the future high energy colliders.

Current experimental lower bounds on the masses of the excited neutrinos are $m_{\nu^*} > 102.6$ GeV \cite{6} from LEP - L3 collaboration (pair production) assuming $f = -f' = 1$, $m_{\nu^*} > 213$ GeV \cite{18} at 95% C.L. from HERA-H1 collaboration (single production) assuming $f = f' = 1$ and $m_{\nu^*} > 1.6$ TeV \cite{18}, namely the strongest limit, from LHC-ATLAS collaboration (pair production) assuming $f = f' = 1$.

The Future Circular Collider (FCC) is a post-LHC accelerator project \cite{19}, with $\sqrt{s} = 100$ TeV, proposed at CERN and supported by European Union within Horizon 2020 Framework Programme for Research and Innovation. Besides the $pp$ option, it includes $e^+e^-$ collider option (TLEP) at the same tunnel \cite{20}. Construction of the future $e^+e^-$ and $\mu^+\mu^-$ colliders tangential to the FCC will also provide several $ep$ and $\mu p$ collider options \cite{21}.

In this paper we analyze the potential of the FCC-based $ep$ colliders, namely
**Table I: Main parameters of the FCC-based ep colliders.**

| Colliders         | $E_e$ (TeV) | CM Energy (TeV) | $L_{int}$ ($fb^{-1}$ per year) |
|-------------------|-------------|-----------------|-------------------------------|
| ERL60⊗FCC         | 0.06        | 3.46            | 100                           |
| ILC⊗FCC           | 0.5         | 10              | 10-100                        |
| PWFA-LC⊗FCC       | 5           | 31.6            | 1-10                          |

ERL60⊗FCC, ILC⊗FCC and PWFA-LC⊗FCC, for the excited neutrino searches. The ERL60 denotes energy recovery linac proposed for the LHeC main option [22], and can also be used for the FCC-based ep colliders. The ILC and the PWFA-LC mean International Linear Collider [23], and Plasma Wake Field Accelerator Linear Collider [24], respectively. The FCC-based ILC⊗FCC and PWFA-LC⊗FCC colliders have been proposed in ref. [25]. Center-of-mass energy and luminosity values of the FCC-based ep colliders are given in Table I [25, 26].

We introduce the effective Lagrangian, the decay widths, and the branching ratios of the excited neutrinos in Section II. In Section III, we analyze the signal and backgrounds for the process $ep \rightarrow \nu^*q \rightarrow eW^+q$, and finally we summarize our results in Section IV.

**II. PRODUCTION OF THE EXCITED NEUTRINOS**

The interaction between a spin-1/2 excited lepton, a gauge boson ($V = \gamma, Z, W^\pm$) and the ordinary leptons is described by $SU(2) \times U(1)$ invariant Lagrangian [4, 27, 28] as

$$L = \frac{1}{2\Lambda} \overline{l_R} \sigma^{\mu\nu} \left[ fg \frac{\tau}{2} \cdot W_{\mu\nu} + f' g' \frac{Y}{2} B_{\mu\nu} \right] l_L + h.c.,$$

where $\Lambda$ is the new physics scale that responsible for the existence of the excited leptons; $W_{\mu\nu}$ and $B_{\mu\nu}$ are the field strength tensors, $g$ and $g'$ are the gauge couplings, $f$ and $f'$ are the scaling factors for the gauge couplings of $SU(2)$ and $U(1)$; $\sigma^{\mu\nu} = i(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)/2$ where $\gamma^\mu$ are the Dirac matrices, $\tau$ denotes the Pauli matrices, and $Y$ is hypercharge.

The excited neutrinos have three decay modes, namely radiative decay $\nu^* \rightarrow \nu\gamma$, neutral weak decay $\nu^* \rightarrow \nu Z$, and charged weak decay $\nu^* \rightarrow eW^+$. The branching ratios (BR) of the excited neutrino for the coupling of $f = f' = 1$ and $f = -f' = 1$ are given in Fig. 1. One may note that the electromagnetic interaction between the excited neutrino and ordinary...
Figure 1: The branching ratios (%) depending on the mass of the excited neutrino for $f = f' = 1$ (left) and $f = -f' = 1$ (right).

The branching ratio for the individual decay channels reaches to the constant values 60% for the W-channel, 12% for the Z-channel, and 28% for the $\gamma$-channel at higher mass values. Since the charged weak decay ($\nu^* \rightarrow eW^+$) is dominant for both cases, we preferred this channel for the investigation of the excited neutrino in this paper.

Neglecting the SM lepton mass, we find the decay width of excited leptons as

$$\Gamma(l^* \rightarrow lV) = \frac{\alpha m^{*3}}{4\Lambda^2} f_V^2 (1 - \frac{m_V^2}{m^{*2}})^2 (1 + \frac{m_V^2}{2m^{*2}}), \quad (2)$$

where $f_V$ is the new electroweak coupling parameter corresponding to the gauge boson $V$ and $f_\gamma = (f - f')/2$, $f_Z = (f\cot\theta_W + f'\tan\theta_W)/2$, $f_W = f/\sqrt{2}\sin\theta_W$, where $\theta_W$ is the weak mixing angle, and $m_V$ is the mass of the gauge boson. The total decay widths of the excited neutrino for the scale of $\Lambda = m_{\nu^*}$ is given in Fig. 2.
Figure 2: The total decay widths of the excited neutrino for the scale of $\Lambda = m_{\nu^*}$ with the coupling of $f = f' = 1$.

III. SIGNAL AND BACKGROUND ANALYSIS

We analyze the potentials of the future $ep$ collider machines to search for the excited neutrinos via the single production reaction $ep \rightarrow \nu^* X$ with subsequent decay of the excited neutrino into an electron and $W^+$ boson. So, we deal with the process $ep \rightarrow W^+eX$ and subprocesses $eq(\bar{q}) \rightarrow W^+eq(\bar{q})$. The signal and background analysis were done at the parton level by using the high energy simulation program of CALCHEP (ver. 3.6.25). In our calculations we have used the parton distribution functions library of CTEQ6L.

For a comparison of different FCC-based $ep$ colliders, the signal cross sections for excited neutrino production are presented in Fig. 3, assuming the coupling parameter of $f = f' = 1$. 
Figure 3: The total cross sections as a function of the excited neutrino mass with the coupling of $f = f' = 1$, and the energy scale of $\Lambda = m_{\nu^*}$ at the $ep$ colliders with various center-of-mass energies.

A. ERL60⊗FCC Collider

The machine of ERL60⊗FCC is a FCC-based future $ep$ collider with the center-of-mass energy of 3.46 TeV. Keeping in mind that the lower bound on the mass of the excited neutrino is 1.6 TeV ($m_{\nu^*} > 1.6$ TeV), we have explored the mass limits for discovery of the excited neutrinos in the range of 1.6 and 3.46 TeV for the ERL60⊗FCC collider. Firstly, we have applied initial kinematical cuts on the final state particles (electron, $W^+$ boson, and jets) to form signal and backgrounds as $p^e_{T, W, J} > 20$ GeV, where the $p_T$ is the transverse momentum of the final state detectable particles. The SM cross section after the application of these cuts has been calculated as $\sigma_B = 3.96$ pb. In order to define the kinematical cuts best suited for discovery, we have plotted the normalized transverse momentum and the normalized pseudorapidity distributions of the final state particles. Fig. 4 shows the $p_T$ distributions of the final state $W^+$ bosons and the $\eta$ (pseudorapidity) distributions of the final state electrons for the excited neutrino masses of 1000 and 2000 GeV versus the backgrounds. The $p_T$ distributions of $W^+$ bosons are the same for the final state electrons. As can be seen from the Fig. 4, the selection of the kinematical cuts as $p^W_T > 200$ GeV (same for the electron) and $-5 < \eta^e < -1$, drastically reduces the background while keeping the signal
Figure 4: The normalized transverse momentum distributions of the final state $W^+$ bosons (left) and the normalized pseudorapidity distributions of the final state electrons (right) with the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$ at the ERL60⊗FCC collider.

almost unaffected. As for the kinematical cut of $\eta$ distributions (see Fig. 5 (right)) of final state $W^+$ bosons, it was determined as $-4.5 < \eta^W < -2$. The Fig. 5 (left) shows the invariant mass distributions of the $eW^+$ system after application of the all kinematical cuts for discovery. It is clearly seen that the background is suppressed.

A natural way of extracting the excited neutrino signal, and the same time suppressing the SM background is to impose a cut on the $eW^+$ invariant mass in addition to kinematical cuts for discovery. Therefore, we have specified the cuts of mass window as $m_{\nu^*} - 2\Gamma_{\nu^*} < m_{eW} < m_{\nu^*} + 2\Gamma_{\nu^*}$.

By using the all kinematical cuts, we have calculated the statistical significance (SS) values of the expected signal yield using the following formula,

$$SS = \frac{|\sigma_{S+B} - \sigma_B|}{\sqrt{\sigma_B}} \sqrt{L_{int}},$$

where $L_{int}$ is the integrated luminosity of the collider. In the Table 2, we have presented the signal (with the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$) and the background cross sections in $eW^+$ invariant mass bins since the signal is concentrated in a small region proportional to the invariant mass resolution. As can be understood from the Table II, the ERL60⊗FCC collider can discover the excited neutrino in $\nu^* \rightarrow W^+e$ decay mode for the coupling of $f = f' = 1$ up to the mass of 2452 GeV taking into account the discovery criteria ($SS \geq 5$).
Figure 5: The invariant mass distributions of the excited neutrino signal and the corresponding background (left), and the normalized pseudorapidity distributions of the final state $W^+$ bosons (right), with the energy scale of $\Lambda = m_{\nu^*}$ and the coupling of $f = f' = 1$ at the ERL60⊗FCC collider.

Table II: The statistical significance (SS) values and the cross sections of the excited neutrino signal and relevant backgrounds at ERL60⊗FCC collider with $\sqrt{s} = 3.46$ TeV and $L_{int} = 100$ fb$^{-1}$ assuming the energy scale of $\Lambda = m_{\nu^*}$ and the coupling of $f = f' = 1$.

| Mass (GeV) | $\sigma_{S+B}$ (pb) | $\sigma_B$ (pb) | SS |
|------------|---------------------|-----------------|-----|
| 1600       | $7.21 \times 10^{-3}$ | $1.86 \times 10^{-4}$ | 162.9 |
| 1800       | $2.47 \times 10^{-3}$ | $9.60 \times 10^{-5}$ | 76.5 |
| 2000       | $7.65 \times 10^{-4}$ | $4.15 \times 10^{-5}$ | 35.5 |
| 2200       | $2.09 \times 10^{-4}$ | $1.49 \times 10^{-5}$ | 15.9 |
| 2300       | $1.03 \times 10^{-4}$ | $8.48 \times 10^{-6}$ | 10.2 |
| 2400       | $4.82 \times 10^{-5}$ | $4.64 \times 10^{-6}$ | 6.4 |
| 2500       | $2.14 \times 10^{-5}$ | $2.41 \times 10^{-6}$ | 3.8 |
| 2600       | $8.85 \times 10^{-6}$ | $1.19 \times 10^{-6}$ | 2.2 |
| 2700       | $3.32 \times 10^{-6}$ | $5.41 \times 10^{-7}$ | 1.1 |
Figure 6: The normalized transverse momentum distributions of the final state electrons (left) and the normalized pseudorapidity distributions of the final state $W^+$ bosons (right) with the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$ at the ILC⊗FCC collider.

B. ILC⊗FCC Collider

The ILC⊗FCC collider with the center-of-mass energy of 10 TeV can search the excited neutrino in a wider mass range compared to the ERL60⊗FCC collider. We have explored the mass limits for discovery of the excited neutrinos in the range of 1.6 and 10 TeV. In order to perceive the excited neutrino signals from the background we have put the same initial kinematical cuts, namely $p_T^{e,W,j} > 20$ GeV, with the ERL60⊗FCC collider. The SM background cross section for the ILC⊗FCC collider is found to be $\sigma_B = 15.74$ pb after the application of these cuts. The normalized transverse momentum distributions of the final state electrons and the pseudorapidity distributions of the final state $W^+$ bosons are presented in Fig. 6. For these distributions, we have determined the kinematical cuts for discovery as $p_T^e > 200$ GeV and $-3.4 < \eta^{W^+} < 0.4$. Transverse momentum distributions and its kinematical cuts of the final state electrons and $W^+$ bosons are the same. Fig. 7 shows the normalized pseudorapidity distributions of the final state electrons, and the invariant mass distributions of the $eW^+$ system after application of the all kinematical cuts for discovery. The kinematical discovery cut of this distributions was determined as $-5 < \eta^e < 1$.

Table 3 presents the signal and background cross sections in $eW^+$ invariant mass bins satisfying the condition of $m_{\nu^*} - 2\Gamma_{\nu^*} < m_{eW} < m_{\nu^*} + 2\Gamma_{\nu^*}$.

When we look at the calculated SS values for $SS \geq 5$ criteria in Table III, for the energy scale of $\Lambda = m_{\nu^*}$, the ILC⊗FCC collider can probe the excited neutrino (assuming
Figure 7: The invariant mass distributions of the excited neutrino signal and the corresponding background (left), and the normalized pseudorapidity distributions of the final state electrons (right), with the energy scale of $\Lambda = m_{\nu^*}$ and the coupling of $f = f' = 1$ at the ILC⊗FCC collider.

the coupling of $f = f' = 1$) up to the masses of 5635 and 6460 GeV for the integrated luminosities of $L_{int} = 10 fb^{-1}$ and $L_{int} = 100 fb^{-1}$, respectively.
Table III: The statistical significance (SS) values and the cross sections of the excited neutrino signal and relevant background at the ILC⊗FCC collider with √s = 10 TeV assuming the coupling of f = f' = 1 and the energy scale of Λ = mν⋆.

| Mass (GeV) | σ_B (pb) | σ_{S+B} (pb) | \( L_{\text{int}} = 10 \text{ fb}^{-1} \) | SS | \( L_{\text{int}} = 100 \text{ fb}^{-1} \) |
|------------|----------|---------------|---------------------------------|-----|----------------------------------|
| 2000       | 1.81 x 10^{-3} | 1.47 x 10^{-1} | 342.1                           | 1081.9 |
| 2500       | 1.24 x 10^{-3} | 5.85 x 10^{-2} | 162.9                           | 515.1 |
| 3000       | 7.37 x 10^{-4} | 2.43 x 10^{-2} | 86.8                            | 274.7 |
| 3500       | 3.94 x 10^{-4} | 1.03 x 10^{-2} | 49.6                            | 157   |
| 4000       | 1.85 x 10^{-4} | 4.28 x 10^{-3} | 30                               | 95.1  |
| 4500       | 8.27 x 10^{-5} | 1.74 x 10^{-3} | 18.1                            | 57.4  |
| 5000       | 3.58 x 10^{-5} | 6.69 x 10^{-4} | 10.5                            | 33.4  |
| 5500       | 1.47 x 10^{-5} | 2.43 x 10^{-4} | 5.9                             | 18.8  |
| 6000       | 6.07 x 10^{-6} | 8.15 x 10^{-5} | 3                               | 9.6   |
| 6500       | 2.26 x 10^{-6} | 2.49 x 10^{-5} | 1.5                             | 4.7   |
| 7000       | 7.83 x 10^{-7} | 6.69 x 10^{-6} | 0.6                             | 2.1   |
| 7500       | 2.37 x 10^{-7} | 1.49 x 10^{-6} | 0.2                             | 0.8   |

C. PWFA-LC⊗FCC Collider

If the excited neutrinos had not been observed at the ERL60⊗FCC and the ILC⊗FCC colliders, they would have been explored up to the mass of 31.6 TeV at the PWFA-LC⊗FCC collider that has the widest research potential. We have explored the mass limits for discovery of the excited neutrinos in a broad mass spectrum from 1.6 to 31.6 TeV. The SM background cross section is found to be σ_B = 58.15 pb after application of the same initial kinematical cuts. Fig. 8 shows the \( p_T \) distributions of the final state \( W^+ \) bosons and the \( \eta \) distributions of the final state electrons for the excited neutrino masses of 5000, 10000, 15000, and 20000 GeV versus the backgrounds. \( p_T \) distributions of the \( W^+ \) bosons are the same for the final state electrons. It is seen from the Fig. 8 that the selection of the kinematical cuts as \( p_T^{W} > 400 \text{ GeV} \) (same for the electron) and \(-5 < \eta^e < 2.5\), essentially suppress the
Figure 8: The normalized transverse momentum distributions of the final state $W^+$ bosons (left) and the normalized pseudorapidity distributions of the final state electrons (right) with the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$ at the PWFA-LC\(\otimes\)FCC collider.

Figure 9: The invariant mass distributions of the excited neutrino signal and the corresponding background (left), and the normalized pseudorapidity distributions of the final state $W^+$ bosons (right), with the energy scale of $\Lambda = m_{\nu^*}$ and the coupling of $f = f' = 1$ at the PWFA-LC\(\otimes\)FCC collider.

background, whereas the signal remains almost unchanged. The normalized pseudorapidity distributions of the $W^+$ bosons, and the invariant mass distributions of the $eW^+$ system obtained after application of the all discovery cuts are given in Fig. 9. According to this Figure, the discovery cut of the normalized pseudorapidity distributions of the final state $W^+$ bosons was determined as $-2.5 < \eta^W < 1$. In addition to these cuts, we have also applied the cuts to the $eW^+$ invariant masses using the $m_{\nu^*} - 2\Gamma_{\nu^*} < m_{eW} < m_{\nu^*} + 2\Gamma_{\nu^*}$. 
The signal and the background cross sections for PWFA-LC⊗FCC collider with the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$ are presented in Table 4 for two integrated luminosity values, namely $L_{int} = 1 \, fb^{-1}$ and $L_{int} = 10 \, fb^{-1}$. For the energy scale of $\Lambda = m_{\nu^*}$, the PWFA-LC⊗FCC collider can probe the excited neutrino up to the masses of 10200 and 13960 GeV for the integrated luminosities of $L_{int} = 1 \, fb^{-1}$ and $L_{int} = 10 \, fb^{-1}$, respectively, as can be understood from the Table 4.

Table IV: The statistical significance (SS) values and the cross sections of the excited neutrino signal and relevant background at the PWFA-LC⊗FCC collider with $\sqrt{s} = 31.6 \, TeV$ assuming the coupling of $f = f' = 1$ and the energy scale of $\Lambda = m_{\nu^*}$.

| Mass (GeV) | $\sigma_B$ (pb) | $\sigma_{S+B}$ (pb) | $L_{int} = 1 \, fb^{-1}$ SS | $L_{int} = 10 \, fb^{-1}$ SS |
|------------|-----------------|-------------------|-----------------------------|-----------------------------|
| 2000       | $1.16 \times 10^{-3}$ | $2.92 \times 10^{-1}$ | 270.5 | 855.6 |
| 4000       | $1.03 \times 10^{-3}$ | $9.00 \times 10^{-2}$ | 87.6 | 277.2 |
| 6000       | $6.30 \times 10^{-4}$ | $2.42 \times 10^{-2}$ | 29.7 | 93.9 |
| 8000       | $3.59 \times 10^{-4}$ | $7.47 \times 10^{-3}$ | 11.8 | 37.5 |
| 10000      | $1.78 \times 10^{-4}$ | $2.45 \times 10^{-3}$ | 5.3 | 17.0 |
| 12000      | $6.55 \times 10^{-5}$ | $8.02 \times 10^{-4}$ | 2.8 | 9.1 |
| 14000      | $2.27 \times 10^{-5}$ | $2.57 \times 10^{-4}$ | 1.5 | 4.9 |
| 16000      | $7.71 \times 10^{-6}$ | $7.66 \times 10^{-5}$ | 0.7 | 2.4 |
| 18000      | $2.51 \times 10^{-6}$ | $2.06 \times 10^{-5}$ | 0.3 | 1.1 |
| 20000      | $7.42 \times 10^{-7}$ | $4.85 \times 10^{-6}$ | 0.1 | 0.4 |

IV. CONCLUSION

This work has shown that the FCC-based $ep$ colliders have a great potential for the excited neutrino searches. We give the realistic estimates for the excited neutrino signal and the corresponding background at three different colliders, namely the ERL60⊗FCC ($\sqrt{s} = 3.46 \, TeV$), the ILC⊗FCC ($\sqrt{s} = 10 \, TeV$), and the PWFA-LC⊗FCC ($\sqrt{s} = 31.6 \, TeV$). The simulations have been performed for the energy scale of $\Lambda = m_{\nu^*}$ and the coupling parameter of $f = f' = 1$. The mass limits for exclusion, observation, and discovery of the
excited neutrinos at the three colliders are given in Table V, for the different integrated luminosity values. As a result, these three FCC-based \( ep \) colliders offer the possibility to probe the excited neutrino over a very large mass range.

Table V: The mass limits for the exclusion (2\( \sigma \)), the observation (3\( \sigma \)), and the discovery (5\( \sigma \)) of the excited neutrinos at the different \( ep \) colliders assuming the coupling of \( f = f' = 1 \) and the energy scale of \( \Lambda = m_{\nu} \).

| Colliders      | \( L_{int}(fb^{-1}) \) | 2\( \sigma \) (GeV) | 3\( \sigma \) (GeV) | 5\( \sigma \) (GeV) |
|----------------|------------------------|----------------------|----------------------|----------------------|
| ERL60\( \otimes \)FCC | 100                    | 2618                 | 2547                 | 2452                 |
| ILC\( \otimes \)FCC   | 10                     | 6300                 | 6000                 | 5635                 |
|                | 100                    | 7025                 | 6790                 | 6460                 |
| PWFA-LC\( \otimes \)FCC | 1                      | 13050                | 11850                | 10200                |
|                | 10                     | 16500                | 15450                | 13960                |

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