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Study of Dark Matter at e^+e^- Collider using KISTI-5 Supercomputer

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This is an excellent paper selected from the papers presented at ICCC 2020.

Abstract: *Dark matter is barely known because it cannot be explained using the Standard Model. In addition, dark matter has not been detected yet. It is currently being explored through various ways. In this paper, we studied dark matter in an electron-positron collider using MadGraph5. The signal channel is* $e^+e^- \rightarrow \mu^+\mu^- A'$ *where* A' *decays to dimuon. We studied the cross-section by increasing the center-of-mass energy. Central processing unit (CPU) time of simulation was compared with that using a local Linux machine and a KISTI-5 supercomputer (Knight Landing and Skylake). Furthermore, one or more cores were used for comparing CPU time among machines. Results of this study will enable the exploration of dark matter in electron-positron experiments. This study also serves as a reference for optimizing high-energy physics simulation toolkits.*

Keywords: High performance computing (HPC); Dark matter; Dark photon; e^+e^- collider

1. Introduction

Computational science, which includes theory, experimentation, and simulation, is becoming increasingly important for studying dark matter in the area of particle physics [1-3]. Even if the Standard Model (SM) was well established in particle physics, the SM cannot provide a description of dark matter. Dark matter is not well known, and is thus still being researched using various methods [1]. Because the cross-section of dark matter is extremely tiny compared to that of the Standard Model (SM), a significant amount of calculation is required [3]. Hence, optimizing the central processing unit (CPU) time is important for increasing the efficiency of research in particle physics [4-6]. Herein, dark matter was studied at electron-positron colliders using MadGraph5 as the simulation toolkit [7, 8]. Moreover, the study analyzed the CPU time and dark matter cross-section depending on center-of-mass (CM) energies. The signal investigated here was a dark photon decaying into dimuon [9]. The theoretical model, used for generating events in MadGraph5, was a simplified model that includes the SM, dark matter, and dark photon particles [10]. For comparison of CPU time of simulation, we used the KISTI-5 supercomputer (Nurion KNL, SKL) and a local Linux machine with one or more cores. We studied three cases. The first is to compare one core and one node in physics simulation only. The second is to study CPU times for the full simulation which performed not only physics simulation but also detector simulation. The third is to study the efficiency of parallel processing depending on the number of jobs among the machines.

2. Methods

To compare the CPU time of the simulation, the local Linux machine and the KISTI-5 supercomputer of Knight Landing (KNL) and Skylake (SKL) were used. The operating system (OS) of the KNL and SKL is the

CentOS 7.4 and the OS of the local Linux machine is Scientific Linux 6.5. The KNL (many-core) comprises 8,305 nodes, and each node has 68 cores of Intel Xeon Phi 7250. The SKL (multicore) comprises 132 nodes, and each node has 40 cores of Intel Xeon 6148. The local Linux machine (multicore) has one node with 32 cores of Intel Xeon CPU X5560 [4]. Figure 1 shows a flowchart of the steps performed for the physics simulation only and full simulation. The physics simulation was performed using MadGraph5 [8] based on the simplified model [10], and the event simulation was performed on the Pythia8 framework [11]. Next, the detector simulation was performed using Delphes [12]. Finally, the physics reconstruction was performed using MadAnalysis5 [13].

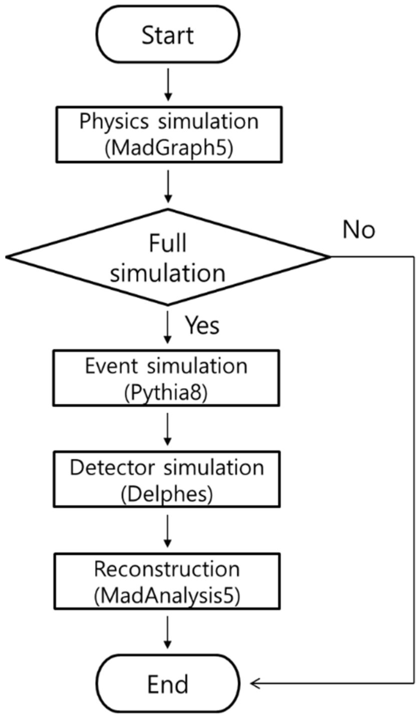

Figure 1. Flowchart of the physics simulation only and the full simulation.

3. Study of dark matter at e^+e^- Collider

Dark matter studies include direct detection, indirect detection and particle collider detection [1, 3]. In the paper, we studied dark matter with particle collider detection, especially at present and future electron-positron colliders. The range of center of mass energy is from 10 GeV to 500 GeV by considering Belle II (10.58 GeV), Circular Electron-Positron Collider (CEPC, 90, 160 and 240 GeV), Future Circular Collider (FCC)-ee (90, 160, 250 and 350 GeV), Compact Linear Collider (CLIC, 380 GeV) and International Linear Collider (ILC, 250 and 500 GeV). The signal process of the dark photons (A') is $e^+e^- \rightarrow \mu^+\mu^-A'$ where A' decays to dimuon. The theoretical model of this study is the simplified dark matter model used for the next leading order (NLO) [10]. Figure 2 shows the Feynman diagram of the simplified model of a signal process obtained at the electron-positron collider. The simplified model includes SM, dark matter, and mediator particles (namely, dark photons). This model is placed between the ultraviolet (UV) model and effective field theory. The UV model includes supersymmetry (SUSY) particles and extra dimensions, whereas the effective field theory (EFT) includes the SM and dark matter particles. The UV model's SUSY and extra dimensions have many secondary particles, making decay channels overly complex. Meanwhile, EFT does not contain dark photons because it has no mediator. Therefore, we used a simplified model that compensated for the shortcomings of these UV models and EFT. The simplified model was imported into MadGraph5 to generate the signal events [14].

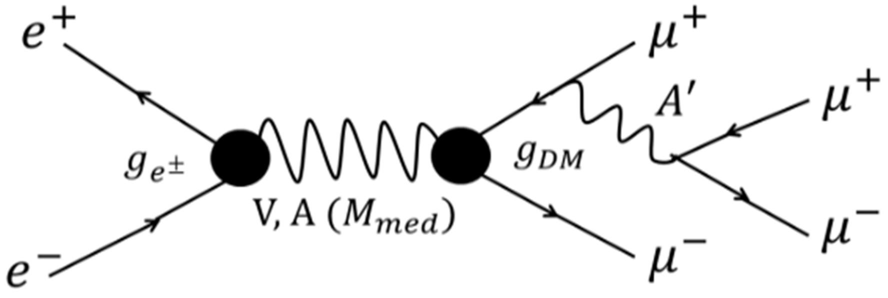

Figure 2. Feynman diagram of the simplified model representing the signal process at the electron-positron collider.

The signal events were generated using MadGraph5 v2.6.4 with the local Linux machine. The imported model is the simplified mode and the number of events was 10,000. Two processes were considered in this study: (a) $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-A'$ where A' decays to dimuon and (b) $e^+e^- \rightarrow \mu^+\mu^-A'$ where A' decays to dimuon. Process (a), which includes only photon interaction, appeared dominantly when the CM energy was less than 30 GeV; meanwhile, process (b) is the signal process, which includes all the mediators - γ (photon), Z boson, and A' (dark photon). The primary/secondary interactions of the modes of process (b) have also been listed in Table 1. Mode 1, which primarily has a Z boson mediator, contributes to the peak at 90 GeV. Mode 2 primarily has a photon mediator. Modes 3, 4, 5, and 6 have two primary mediators and no secondary interaction.

Table 1. Primary and secondary mediators of the signal process.

	Primary mediator	**Secondary mediator**
Mode 1	Z boson	A'
Mode 2	γ	A'
Mode 3	A', γ	–
Mode 4	γ, A'	–
Mode 5	A', γ	–
Mode 6	A', Z boson	–

Figure 3 shows the cross-section depending on CM energies, which was increased from 10 GeV to 500 GeV by 10 GeV. The mass of dark photon was fixed at 0.3 GeV, and the decay width was 6.7×10^{-6} GeV. The coupling constant was 0.1. At energies less than 30 GeV, process (a) was implemented. A peak was observed at the Z boson mass of 90 GeV. After 90 GeV, the cross-section decreased, as the CM energy increased.

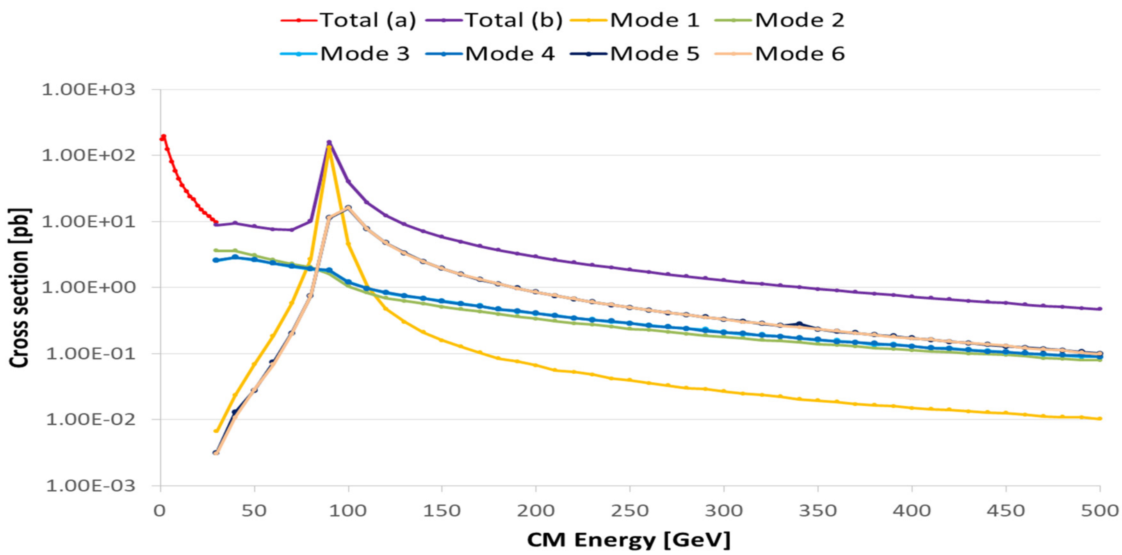

Figure 3. Cross-section depending on CM energies.

4. Results

Three cases were considered in this study. In Case 1, only a physics simulation was considered. Case 2 included the full simulation which performed not only physics simulation but also detector simulation (Pythia8, Delphes, and MadAnalysis5). Case 3 involved examining the efficiency of parallel processing, depending on the number of jobs among the machines. Table 2 shows the configuration of the three cases, namely, physics simulation only, full simulation, and physics simulation with parallel processing. For all three cases, a simplified model was used, and the signal process was $e^+ \ e^- \to \gamma \to \ \mu^+ \ \mu^- \ A'$ where A' decays to dimuon. The number of events was 10,000. The CM energy was 10.58 GeV (7 and 4 GeV for the electron and positron, respectively). The mass of dark photon was 0.3 GeV with the width, 6.7×10^{-6} GeV. The coupling constant was 0.1.

Table 2. The configuration for the three cases.

Item		Case 1 Physics simulation only	Case 2 Full simulation	Case 3 Physics simulation only with parallel processing
A'mass (width) [GeV]		0.3 (6.7×10^{-6})	0.3 (6.7×10^{-6})	0.3 (6.7×10^{-6})
Physics simulation		On	On	On
Detector simulation		Off	On	Off
No. of jobs	KNL	15	15	1, 3, 6, …, 60, 63, 66
	SKL	15	15	1, 3, 6, …, 27, 30, 33
	Local	15	15	1, 3, 6, 9, 12, 15
Iteration		1	1	10

In Case 1, for the physics simulation only, the events were generated using MadGraph5. A total of 15 jobs were performed via parallel processing across all three machines. Figure 4 shows the results of the wall-clock time when using the KNL, SKL, and local Linux machines. One core and one node (68, 40, and 32 cores for the KNL, SKL, and local Linux machine, respectively) were used for determining the wall-clock time. For a single core, it was noted that the wall-clock time of the SKL was faster than that of the KNL and the local Linux machine by a factor of 4.9 and 4.3, respectively. Compared to the one-core case, the wall-clock time of one node (multiple cores) of the KNL, SKL, and local Linux machine was observed to be reduced by a factor of 6.8, 5.3, and 1.4, respectively. In wall-clock time of one node, the computation time of the SKL was 3.8 times faster than the KNL and 16 times faster than the local Linux machine. This result indicates that the efficiency of parallel processing for the 15 jobs inputted into the KISTI-5 supercomputer (KNL and SKL) was higher than that of the local Linux machine.

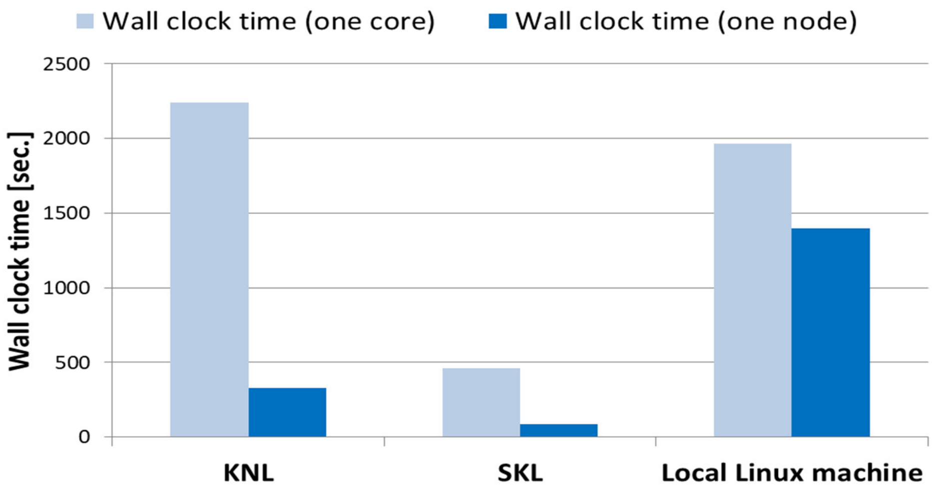

Figure 4. Wall-clock time with 1 or 15 cores taken by different machines for the physics simulation only with 15 jobs.

In Case 2, for the full simulation, Pythia8, Delphes, and MadAnalysis5 software were employed. Again, 15 jobs were calculated using a single core (serial processing). Figure 5 shows the wall-clock time taken by the KNL, SKL, and local Linux machine for the full simulation. Compared to physics simulation only, the full simulation was faster, with the following order: SKL > local Linux machine ≳ KNL. The calculation time for the SKL was 5.5 times faster than the KNL and 5.3 times faster than the local Linux machine.

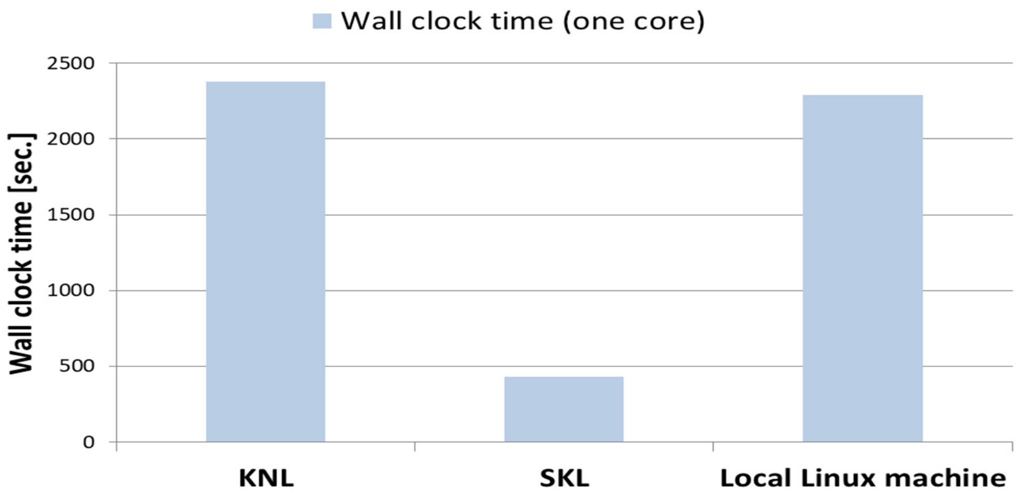

Figure 5. Wall-clock time with one core taken by different machines, while performing the full simulation with 15 jobs.

In Case 3, the dependence of the efficiency of parallel processing on the number of jobs was examined for the machines. We have performed physics simulation only. We have repeated this processing 10 times in order to reduce statistical error. Figure 6 shows the wall-clock time as the number of jobs increases for different machines. The plotted data are the average values obtained from 10 individual processing using each machine. A higher efficiency of parallel processing corresponds to a smaller slope. In the ideal case, the slope is expected to be zero for the highest efficiency achieved during parallel processing. Figure 6 indicates that the parallel processing efficiency of the local Linux machine is lower than that of the KNL and SKL. The efficiency of parallel processing as a function of the number of jobs of the SKL is much higher than that of the local Linux machine. The parallel processing efficiency was 4.1 and 22 times higher than that of the KNL and local Linux machine, respectively.

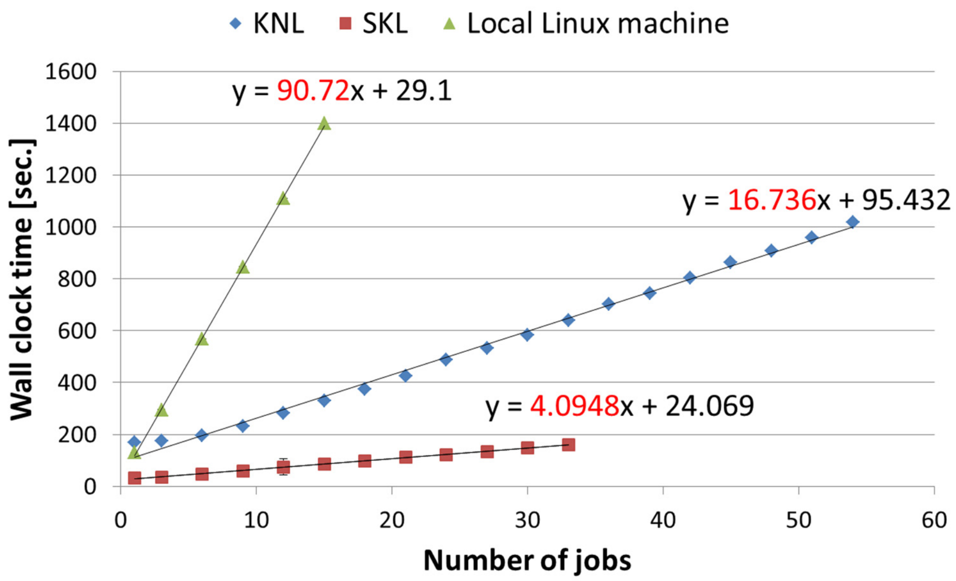

Figure 6. Wall-clock time as the number of jobs increase for different machines.

5. Conclusions

Dark matter was studied in the electron-positron collider using the MadGraph5 simulation toolkit. Using the simplified model, the cross-section was investigated depending on CM energies in the signal channel. When the CM energy was 90 GeV, the peak of the cross-section was observed around the mass of Z boson. This result will be a reference for present and/or future electron-positron collision experiments for dark matter research. To compare CPU time, we have used KISTI-5 supercomputer (KNL and SKL) and the local Linux machine with one core or more cores. For the physics simulation only, the wall-clock time of one node taken by the SKL was 3.8 times faster than the KNL and 16 times faster than the local Linux machine. For the dependence of the efficiency of parallel processing on the number of jobs, the SKL was 4.1 times higher than the KNL and 22 times higher than the local Linux machine. The results show that utilizing numerous cores in supercomputers can help in significantly reducing the computation time of particle physics simulations. This in turn will help in optimizing the particle physics software using high performance computing.

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Conflicts of Interest: The authors declare no conflict of interest.

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