Heavy Meson Production via Photon Beam Timelike Compton Scattering off the Nucleon

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Abstract

This experiment focused on hadronic physics with particular interest into heavy mesons. Understanding how composite particles, such as mesons, function is integral to the expansion of particle physics. This study consists of the creation of a meson production event generator that was added onto a more general event generator initially created by Dr. Marie Boër to generate a dataset for further analysis. This simulated the usage of a photon beam on a polarized target to produce the J/ψ heavy meson. The data produced then was analyzed using C++ and ROOT code to understand the kinematics postproduction of the J/ψ particles. This then gives insight into how heavy meson production modelled after the Timelike Compton Scattering (TCS) reaction could be used to find the Generalized Parton Distributions (GPDs) of the nucleon. This opens up room for analysis of how long an experiment should run to produce viable results at a facility such as Jefferson Laboratory located in Newport News, Virginia. This will serve as the setup to future feasibility studies for future practical experiments into heavy meson kinematics and the internal structure of nucleons. The experiment will provide a framework to generate collision events that can be used to allow for the setting of realistic experimental expectations needed to extract GPDs and better understand the quark gluon composition of the nucleon. This will allow for the proper allocation of research in practical experimentation. This project was undertaken with the guidance of advisor, Dr. Marie Boër.

Introduction

Since the inception of the quark model in the 1970s, a central theme of hadronic and nuclear physics has been about finding ways to probe the nucleon and understand its contents. One of the potential ways to do this is through the process of TCS, see Figure 1, that allows a target to be bombarded with high energy beams to interact with the quarks that represent the core of the nucleon. The quark structure of the nucleon accessible in TCS can be parameterized by the so-called GPDs, which provide access to the quark (or gluon) transverse position versus its longitudinal momentum. Accessing GPDs from TCS is indirectly done by measuring other functions called "Compton Form Factors". This can be quite difficult as solving for them requires the measuring of many observables and the solving of linear equations to extract each value. The process known as Deeply Virtual Compton Scattering (DVCS) also examines these GPDs [1]. This process and other deeply virtual exclusive processes can be found in [2] where there is an examination of π^0 meson productions for these types of processes. The TCS process is typically viewed as the opposite of the DVCS process in that the outgoing photon that then produces the lepton pair seen in Figure 1 is virtual and the incoming is real. This is reversed in the case of DVCS [3]. One of the main reasons to study TCS is to complement DVCS observables to extract the GPDs, as well as comparing the GPDs extracted from DVCS in order to demonstrate universality. On the other side, studying exclusive meson production allows for accessing GPDs at different kinematic values. It is also of particular interest for the GPD flavor decomposition. Indeed we measure GPDs of the nucleon, not directly of the quarks and gluons. Depending on the meson's flavor content, we obtain different decomposition. For instance, the reason why J/ψ is so interesting and why it is worth studying in future experiments, is that the J/ψ meson provides access to the GPDs of the gluons at the leading order.

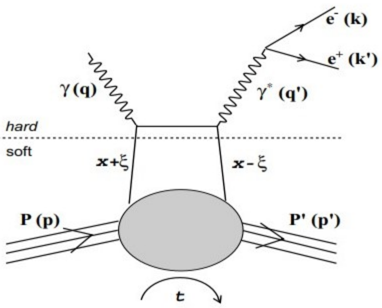

Figure 1: TCS reaction off of a proton producing electron positron pair. This was found in [4].

The resulting kinematics of the particles created gives insight into the GPDs and particles. The GPDs are mathematical representations of the internal structure of the nucleon as there exists a sea of gluons and quarks between the valence quarks that are typically associated with the hadrons [5]. When calculating the cross sections for exclusive processes, the GPDs are matrix elements coming in the amplitudes, which characterize different polarization states (spin of the nucleon vs. quark or gluon helicity). In the case of this study, Figure 1 was used as the basic structure of the process in question, the exclusive photoproduction of a J/ψ meson with a muon antimuon decay mode (see Figure 2).

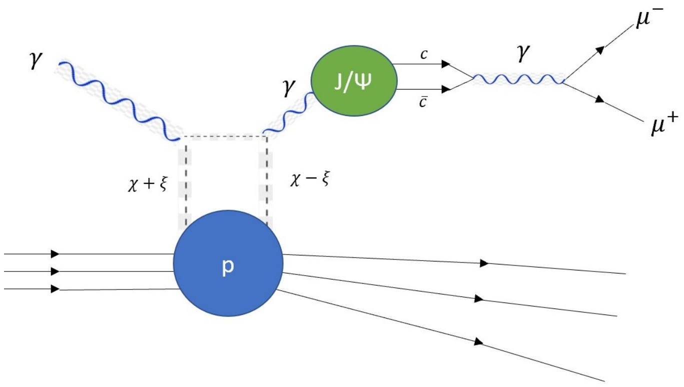

Figure 2: TCS reaction with real photon producing a J/ψ meson that then decays into the muon-antimuon decay mode of the J/ψ.

The process from Figure 2 occurs at higher energies than that of TCS, DVCS, or light meson production (such as that of the ρ meson) as the J/ψ has a mass of 3.096900 ± 0.000006 GeV and the process evaluated in [4] focused on the production between 2 and 3 GeV to avoid meson production regions. The production of the J/ψ as seen in Figure 2 requires the initial photon beam to be of high enough energy to support the stable ejection of a $c\bar{c}$ quark pair that makes up the meson. Mesons with this quark makeup are often referred to as being charmonium states in reference to their similarity to electron positron bound states. J/ψ was the first heavy meson discovered in 1974 and has since been a focus of intrigue to all kinematics relating to heavy mesons [6]. This heavy meson interest is just another reason for the overall interest in the process depicted in Figure 2.

The main interest of studying proton GPDs with the J/ψ meson, is that given that the process needs to create a pair of heavy quarks, $c\bar{c}$ in this case, the gluon composition is being indirectly probed. Indeed the proton does not have a charm valence quark. This leaves the only way of producing them resulting from a gluon that is forced to split into a $c\bar{c}$ pair. The process of the photon beam bombardment creates an environment where the gluons can be excited to the point splitting into quark anti-quark pairs. This is not possible in TCS, DVCS, or light meson production. J/ψ is one of the lower laying heavy mesons composed of a quark antiquark pair and therefore makes it an optimal candidate for indirectly probing into gluon composition of the nucleon.

Actually investigating any of the processes seen above takes a considerable investment of time and resources. Much modern experimental work now requires considerable preliminary research into what the expected results ought to be with the hope of saving some of these resources. Additionally, preliminary evaluation can give researchers indicators of how long to run an experiment to achieve a viable dataset, or where detectors should be placed for any particular enquiry. All of these factors often create the need for the creation of simulators to model the events given as many factors as possible. This then allows for expectations to be set prior to actual experimentation.

This project utilized collision simulation code provided by Dr. Boër and created versioning that could account for the production of J/ψ mesons from a TCS process. This simulation code already had the handling of the momentum imparted by the TCS collision of a photon beam on a polarized target. This then needed to be expanded upon to model the occurrences of J/ψ meson production due to these events. The TCS process strikes the internal quarks of a nucleon, in this case a proton, to then scatter off into simulated detectors before using those results to build backwards to see each occurrence [4]. The results found below show this implementation for the production of J/ψ mesons and provides interesting insight into the potential implications of utilizing the production of heavy mesons to extract the GPDs of nucleons. Interacting directly with the quarks present within nucleons allows for the peeling back to some of the layers at the bottom of physics. This study and implementation of meson generation stands as only a very small part of a puzzle that attempts to understand the building blocks of all of the universe.

Methods

The implementation of meson production to the larger collision generator was a multifaceted project that required both study and trial and error. This process began with the aid of Dr. Boër providing literature for background as well as hosting physics lessons focused on all relevant material from the most basic review of the Standard Model of particle physics to the details of GPD extraction using collision events.

The project was able to begin once granted remote access to one of Virginia Tech's Linux machines. This process first required a thorough examination of existing simulator code. This consisted largely of commenting and reformatting the existing code with direct plain text translation that made the TCS reaction process easier to follow. In C++ code a file option for the user to select the production on the energy scale for a J/ψ meson with a muon antimuon decay mode was added. This allowed for the user to the select J/ψ mesons generated using the kinematics of the process in Figure 2. Additionally, the input file used for this study called for a consistent polarization among the target nucleons producing a consistent target to give more reliable and expected results to prove the successful implementation of the meson option. A range for the exit momentum of the muon antimuon generation of 3.8 GeV^2 to 9.2 GeV^2 was selected because of this being within the accepted range for the J/ψ meson according to current standards. This exit momentum can be defined as the variable Q'^{2} which would be the acceptable energy present within the ejected photon that goes into the creation of the J/ψ meson before its quick decay into the muon antimuon pair. A large angle range for the detection was selected to allow for the detection of any productions within the angles possible after the collision.

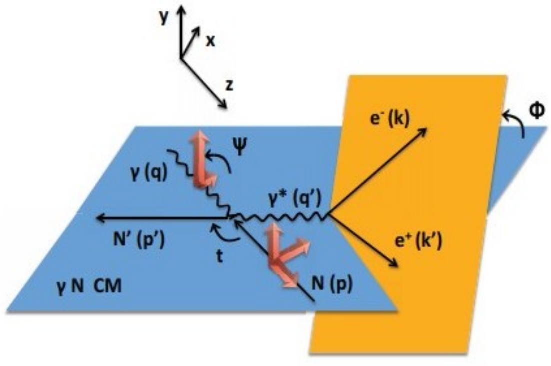

Figure 3: TCS reaction showing the azmuthal angle ϕ in the center of mass frame. Retrieved from [4].

Figure 3 shows the angle structure present within the normal TCS electron positron production, but the kinematics hold for the $J\psi$ meson production where the ejection angle determines the momentum each generated particle will have. The TCS calculations are done with four vectors containing the energy and dimensional momentum. These outgoing particles are then captured in detectors that record the four vectors of the results. This concludes the generation process and then outputs the data to files of type ROOT that was created by CERN to handle large datasets particularly for those used in particle generator simulators.

While the process above covers the main generation steps necessary for the TCS process the J/ψ meson generation requires more points of note. The expected distribution for the particles showing the momentum related to the J/ψ meson is expected to follow that of a simple Gaussian distribution. This meant that the acceptable values for the random events generated needed to be constrained to Q'^2 values falling along a Gaussian distribution with the mean expected mass of 3.096900 ± 0.000006 GeV with a corresponding expected deviation. This was done by constraining the output using a Box-Muller transform scheme to quickly constrain output values along the desired Gaussian. The Box-Muller method used was translated into C++ from *Numerical Recipes*. This method generates random values conforming to a discretized version of the Gaussian function desired through weighted variation being applied to a randomly generated number until with the results showing conformity to the Gaussian more accurately as more generations occur [7]. This allowed the expected detection to be bent up at the J/ψ meson mass to model how it would stand out as a favorable state as compared to other mass generations.

The above processes were all implemented into the existing generator code while adding necessary dependencies and checks to constrain any data. This could then be used to produce ROOT files containing any number of collision events. Processing the data required the creation and modification of analysis code to ensure that the correct mass distributions expected for the J/ψ meson were being produced. This was done by modifying existing analysis code that used C++ as a proxy for ROOT and could be used to create various graphs and perform kinematic calculations based solely on the detector readings generated. The results of this analysis can be found within the next section of this text. Examining the mass of the generated particle by combining the momentum of the muon antimuon pair that was generated allows for the reconstruction of the particle that created the pair.

$$Source\ Particle\ Mass = \sqrt{p^2_{\mu^-_{lab}} + p^2_{\mu^+_{lab}}} \tag{1}$$

Equation (1) shows the mathematical process used to find the source particle that created the muon antimuon pair for each event as the analysis code looped through any generated event within the ROOT file. This accounts for the momentum in each direction and allows researchers to know the mass of the initial particle that became the pair. This is only possible because it is known that the pair consists of the only thing generated from any particular event. In a real world experiment knowing that all generated particles for each event were captured is harder and can limit the rate at which viable events are detected. The values calculated by processing events through Equation (1) could then be confirmed by comparing them to the values of the square root of Q'^2 for each event as the two values should match, meaning that all energy in the ejected particle was dispersed into the decay.

$$Mass\ Check = \sqrt{Q'^{\,2}} \tag{2}$$

Equation (2) shows the check described. This was implemented into analysis code to ensure the proper production was occurring. These values could then be properly shown in a pleasing format through the use of filling histograms and displaying the results along with fits to examine the viability of the generator.

Results

The methods previously worked through were all performed with the goal of producing viable event generation. The generation needed to be constructed to match the expected notions of a Gaussian distribution over the J/ψ mass range. This could then be use to confidently attribute events to the expected presence of J/ψ mesons through analysis as would happen with a real world experiment.

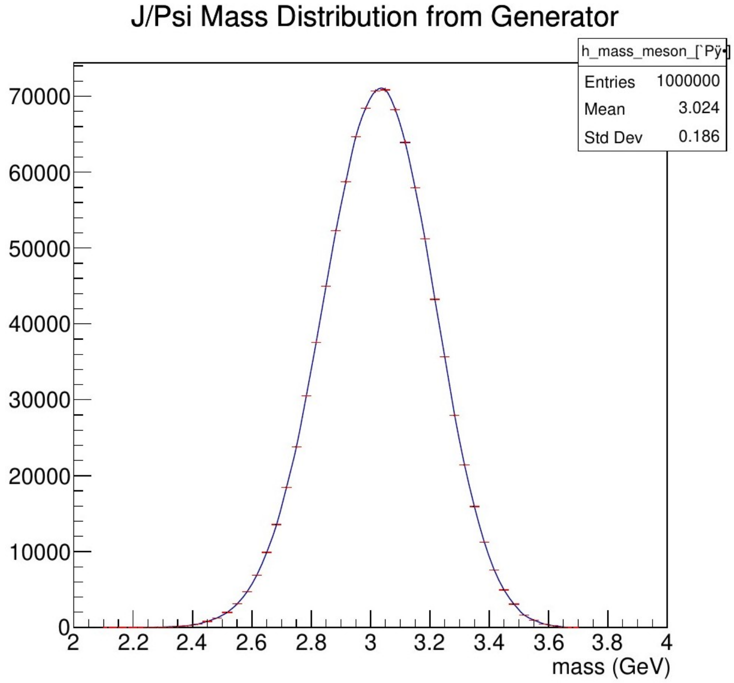

Figure 4: J/ψ meson mass as generated by the process described in the Methods section.

Figure 4 shows the results of an isolated generation of J/ψ particles along the expected range of generation. The line is the best fit line connecting the different bins of the histograms that were plotted. Upon visual inspection, the best fit line shows the characteristics expected with a Gaussian distribution of mass values. The mean value reported on the distribution is 3.024 GeV that can have its error from the accepted value accounted for by the inaccuracies present in representing a continuous function through the connection of discrete events. The red hashes present on Figure 4 represent the check values referred to by Equation (2). They lay directly on top of histogram hashes that represent the results of calculations shown in Equation (1) so precisely that the secondary hashes cannot be seen. This acts as confirmation that the mass calculated from the momentum of the muon antimuon pair matches the constrained output momentum from the generator program. These results were obtained through the generation of a million distinct events. They were then confirmed as accurate by generating multiple times with extremely similar results with only random variation indicating differences in the events generated. These results can be viewed as a successful generation of the J/ψ meson to a degree of reliability acceptable for further development.

Interpretations

The results found through the implementation of J/ψ meson into the event generator mean nothing in a vacuum. The generation of events around the mass of the J/ψ meson in a perfect world can be useful for examination of the GPDs of the gluons that caused their generation in the collision. However, one reason that finding GPDs is challenging is that generating isolated events like those in Figure 4 is impossible. Allowing for placement amongst other realistically generated data leading into and out of the J/ψ meson event spike means that more valid interpretations can be theorized.

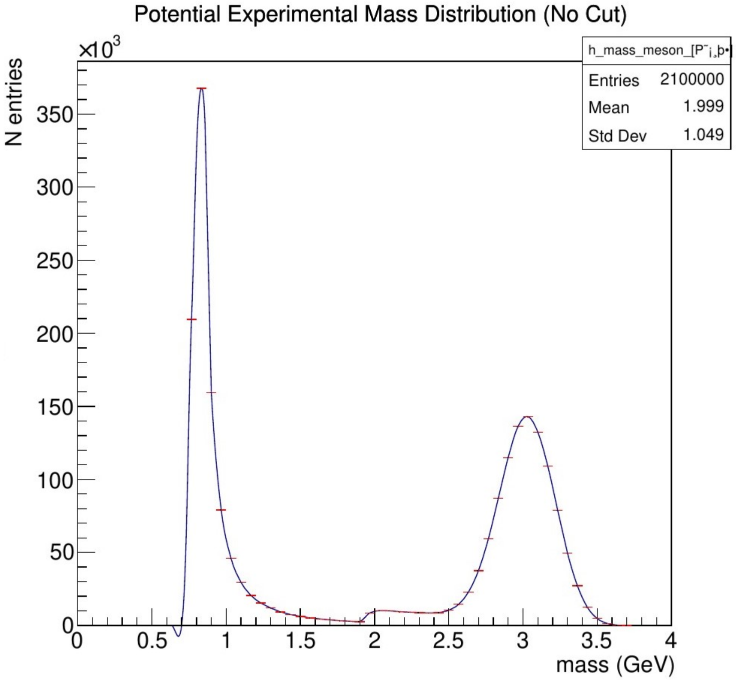

Figure 5: Semi-realistic event generation signal.

Figure 5 attempts to show a more realistic signal from a photon beam TCS collision on a proton. This makes use of data provided to by Brendan Lorn and Zeyu Gao with the permission of Dr. Boër. The events displayed are meant only to show semi-relative sizes of event occurrences possible in a real life signal and not the exact occurrences expected over the shown mass range. Figure 5 concatenates the results produced through an investigation into a TCS probe into a proton for the production of the $\rho(770)$ meson, general TCS collision events possible at inter-meson masses, and finally the J/ψ data that was displayed in Figure 4. As a note, there exists a small, but unexpected jump in the signal shown in Figures 5 and 6 just below 2 GeV that was a resulting artifact from the process of concatenating the files and having some of the energy ranges overlap. This can be disregarded as pertaining to the realistic interpretation of the data without effecting any of the takeaways. The initial spike at about 0.770 GeV represents a spike that would be expected to be detected in a particle collider representing the $\rho(770)$ meson generation that would be present in that region. However, it does not help research into the production of the J/ψ meson that this project is concerned with. Due to this, researchers can apply cuts to the signal detected to focus in on particular observables. In sticking with the theme of examining solely mass, researchers can perform a simple cut at 1.5 GeV that cuts out the $\rho(770)$ meson instances fairly reliably.

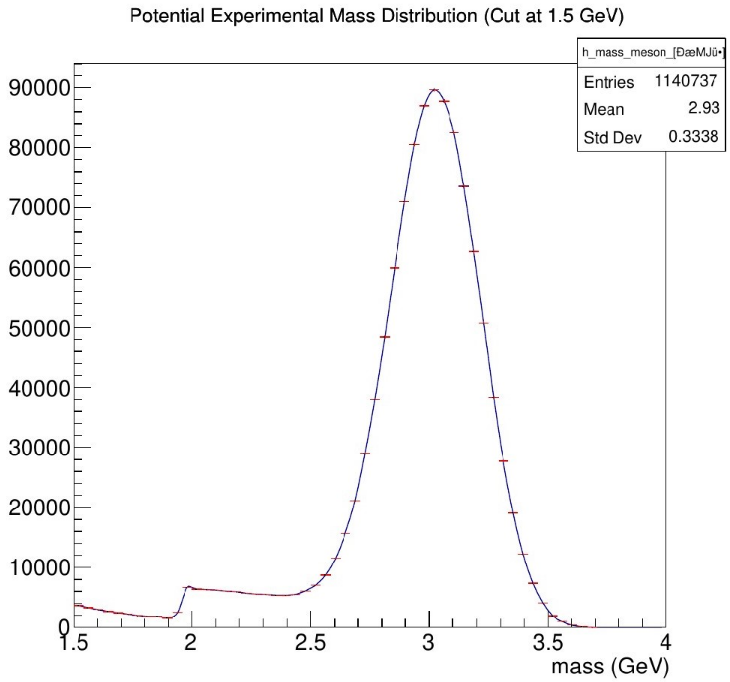

Figure 6: Semi-realistic event generation signal with a cut at 1.5 GeV.

Figure 6 shows a representation of the signal after applying the suggested cut. This brings the mean much closer to the mass of interest. However, it is important to note that many of the events were simply cut off therefore reducing the accuracy of further calculations. Although, some could argue that this cut still leaves a lot of data from the TCS region examined in [4] and that it could lead to too much noise in later calculations. This then allows the signal to be further cut at 2.3 GeV from a visual examination of where it seems like the TCS signal loses its dominance.

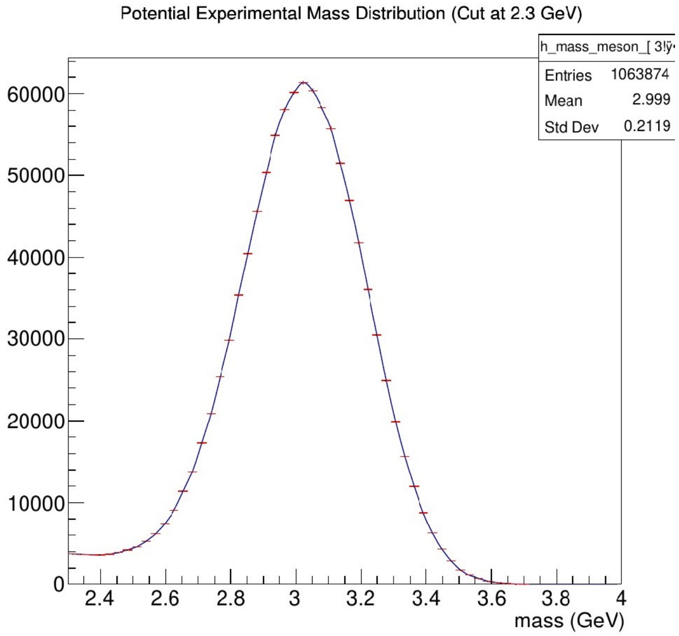

Figure 7: Semi-realistic event generation signal with a cut at 2.3 GeV.

Figure 7 shows this secondary cut being made to examine the J/ψ events more closely. However, the same problem of cutting signal persists. The cutting processes shown in Figures 6 and 7 show considerations that must be taken when analyzing real experimental results that are produced in particle colliders. The more that the detected signal is cut, the more time is necessary to observe enough events for viability. In colliders this can mean millions of dollars of research investment depending on event rates. This shows that accurate simulated event generation can allow for easier and less resource intensive setting of expectations when using given parameters. Events of interest can be generated at places like Jefferson Lab in Newport News, Virginia where this data will most likely be applied. Examining these kinematics allows for the extrapolation of the GPDs present within nucleons and opening a window into how quark gluon structures form. Now with the generation of J/ψ mesons possible within the generator realistic signal models in the regions at the energy level of the J/ψ meson are possible. Examination of the GPDs that are extractable for these observables would be the next steps to be taken. This could go to show the expected idea that GPDs are universal to each nucleon, no matter the conditions, and could then give a mathematical model of the structure to a relatively large degree of certainty of hadronic particles like protons and neutrons. This would then be able to be applied to other hadronic particles that can be probed this way giving insight into the formation of quark gluon structures. Additionally, the J/ψ meson in particular could be of interest in this particular decay mode as it could be telling for understanding the structure of the heavier mesons that are currently not well understood. This study largely serves as a set-up study that implements the J/ψ meson into an event generator to be examined more wholly after its initial implementation.

Conclusion

The implementation of mesons into event generators serves to give a more realistic modelling of TCS-like collisions and could prove to be very important to the extraction of the GPDs of nucleons. Particularly the J/ψ meson implementation would be important as it sits near the top of the energy spectrum that can be reached in colliders such as the halls at Jefferson Lab. This gives a model of the upper end of expected outcomes. The isolated generation of J/ψ mesons through the TCS process occurred within a tolerable error from the expected mass of 3.096900 ± 0.000006 GeV. When coupled with event generations at lower energies to produce more realistic signals, cutting signals can be insightful into setting realistic expectations. This could lead to a paring down of extraneous signal and allow for extraction of GPDs using generated observables. However, there is also a loss of accuracy due to cutting out large portions of data. Results from future analysis could serve as justification for use of a particle collider such as the various halls of Jefferson Lab. This could then lead to experimental extraction of the parameters of the system of equations that makes up the structure present within nucleons and potentially other hadrons. Understanding gluon quark structures could lead to a better understanding of the underlying forces and movements that create the nucleons in the first place. This study concludes that successful generation of J/ψ mesons from TCS-like collisions on a polarized target from a photon beam was created opening great avenues for further research development.

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