Monte-Carlo simulations on the two-photon Breit-Wheeler process

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Abstract

Current developments in laser technology open up the possibility to directly investigate a fundamental process of astrophysics[2]. The direct production of electron-positron pairs from two-photon collisions is a common phenomenon in the vicinity of dense stellar objects, but has not been observed in experiments so far. In the light of projects like ELI or Apollon we investigate the linear Breit-Wheeler(BW) process[1] using a Monte-Carlo code. This code is developed in order to become a module for the PIC-code CALDER[3]. With this extension to CALDER in the context of the LAPHIA project we aim to investigate the optimal experimental settings for investigating the linear, two-photon BW process.

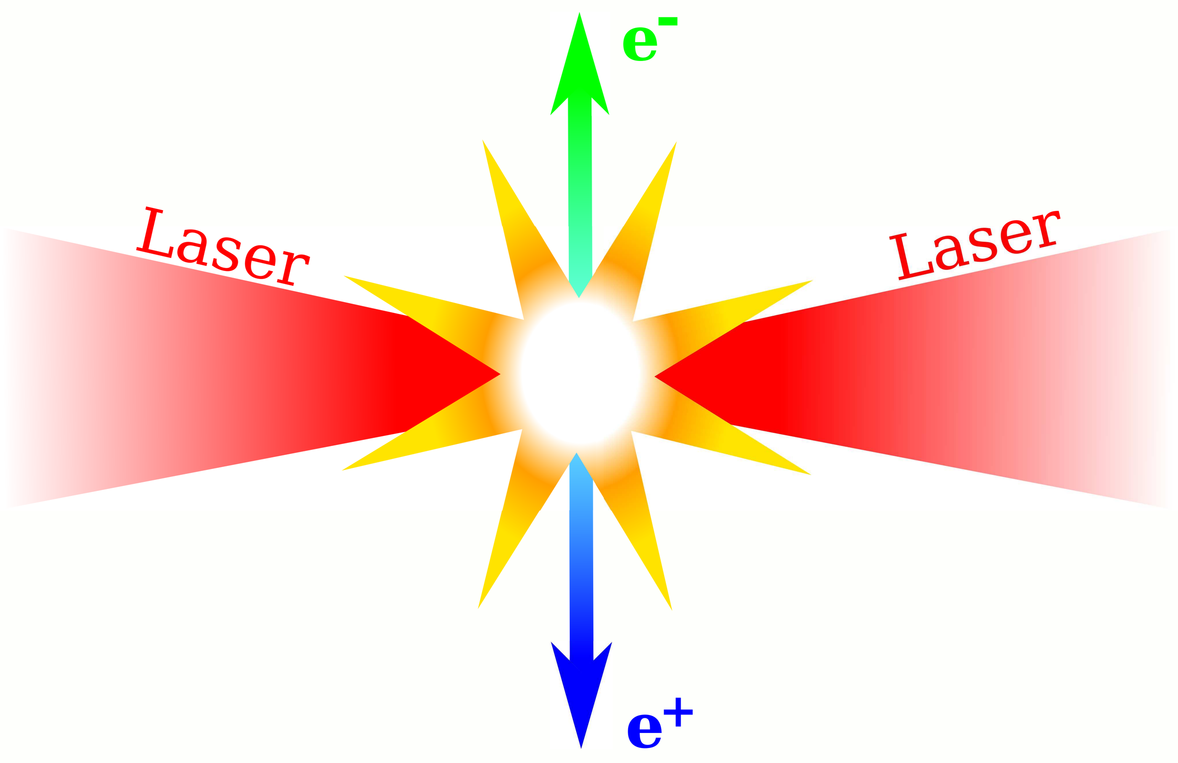

Fig. 1: Two beams of high energy photons collide and create particle pairs according the linear Breit-Wheeler process.

The Breit-Wheeler process

The Breit-Wheeler process is very common phenomenon in astrophysics, especially nearby extremely heavy stellar objects. As the inverse process to the Dirac annihilation of one electron and one photon, the BW process is a relative simple quantum-mechanical process. However, it is detrimental to the understanding of the collapse of stars into a black hole and the linear BW process has not been observed isolated in experiments, yet. The nonlinear, multi-photon BW process, involving four and more photons, has been observed experimentally[7] using GeV electrons, accelerated by the SLAC-accelerator, in order to create the necessary photons. Unfortunately, even though the effort for such an experiment is rather high, the cross section for this kind of process is slow small, that in about 20000 laser shots only about 100 positrons were created. The reason for this small cross section is the fact, that two photons in the SLAC-experiment did not carry enough energy for the pair creation. For or more photons (6.44 in average) had to collide in order to create one pair.

However, in the linear, two-photon regime the cross section can be described with

$$\sigma_{\gamma\gamma}(s) = \frac{\pi}{2} r_e^2 (1-\beta^2)\left[-2\beta(2-\beta^2) + (3-\beta^4)\ln\frac{1+\beta}{1-\beta}\right], \qquad (1)$$

where $\beta = \sqrt{1-1/s}$ and $s = E_{\gamma_1}E_{\gamma_2}(1-\cos\theta/(2m_e^2c^4))$. E_{γ_i} are the energies of the involved gamma quanta, while θ is the angle of incident and r_e and m_e are the classical electron radius and the electron mass.

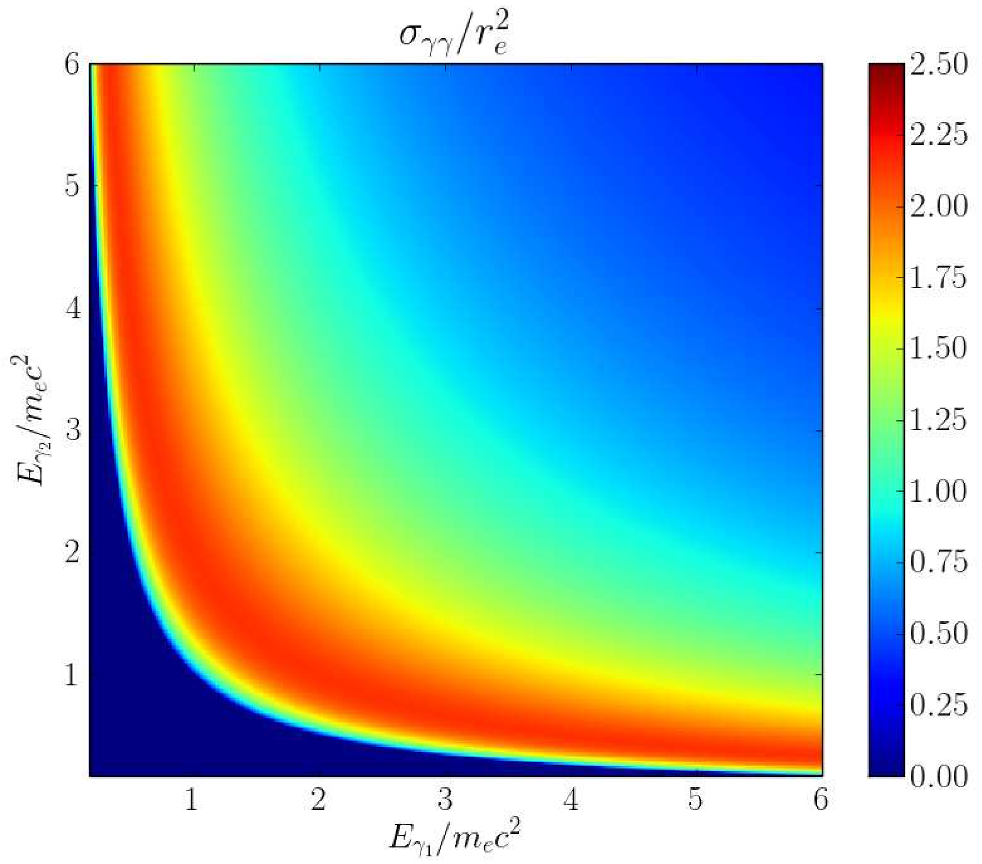

Fig. 2: Cross section of the linear BW process as a function of the energy of both photons. The angle of incident is fixed as $\theta = \pi$.

A plot of the cross section as a function of the energies (with a fixed incident angle $\theta = \pi$) is shown in picture 2. Here it can be seen, that an optimum is achieved for $s \approx 2$. With the parameter suggested in the experiment above, one would expect a cross section of about

$$\sigma_{\gamma\gamma}(s_0) \approx 10^{-25} cm^2. \qquad (2)$$

The cross section for the two-photon, linear BW process can easily be higher several order of magnitudes, if one would be able to meet the required energy threshold of

$$E_{\gamma_1}E_{\gamma_2} \geq \frac{2m_e^2c^4}{1-\cos\theta}. \qquad (3)$$

In a set-up similar to the SLAC-experiment, an electron beam of about $200GeV$ would have been required. However, even with the very impressive SLAC-accelerator, only electrons of less then $60GeV$ were available. Therefore, alternative set-ups might prove useful.

Concept of the proposed experiment

The experiment (see figure 3), proposed by Ribeyre et al.[8], aims to improve known concepts[4] in order to create electron-positron pairs within the regime of the two-photon BW process. The main features of this experiment include a high contrast of BW pairs from electron-positron pairs created by other means (Bethe-Heitler, Trident). This is accomplished by having the colliding photons interact without the need of any high z materials nearby. Another key feature is the low requirements on the photons. While still high energy photons are required, the required energy per photon is just in the single digit MeV-range and not in the GeV range. Such photons can be produced with Laser-matter interaction techniques (i.e. Bremsstrahlung), which could be performed routinely at facilities such as ELI[5] and APOLLON[6].

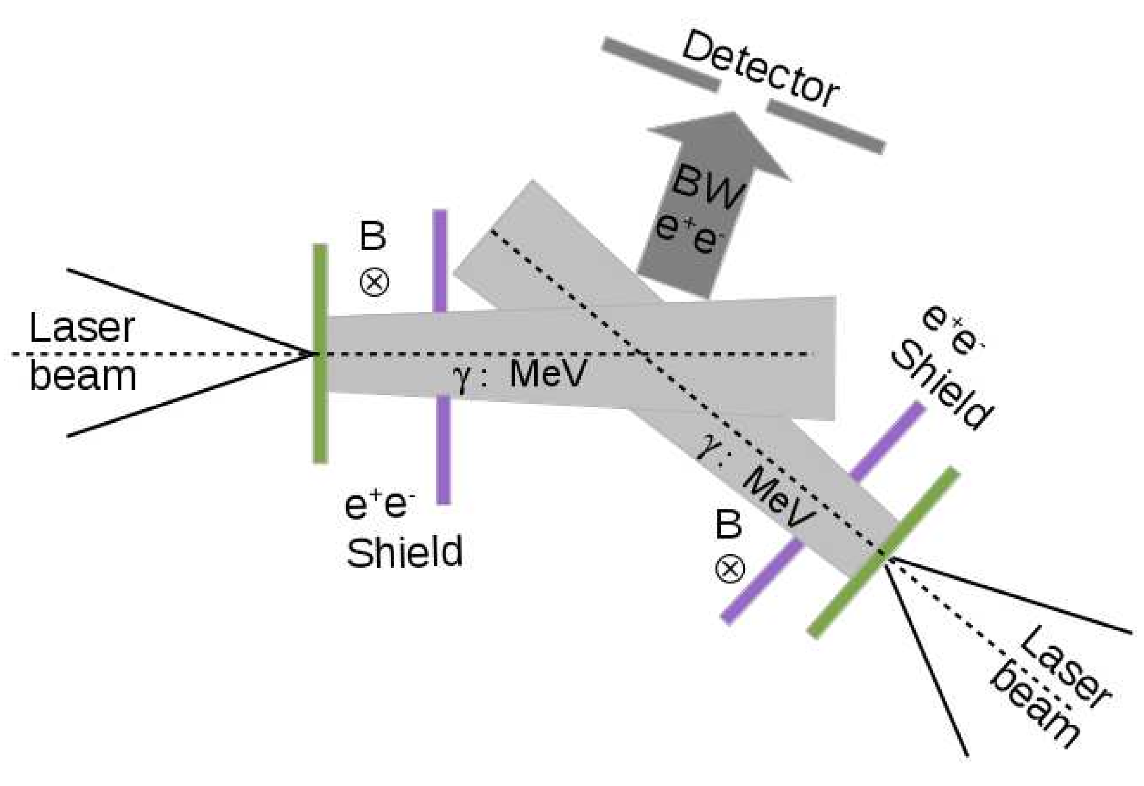

Fig. 3: MeV photon beams are created by Laser-matter interaction. Both beams interact at a significant distance from their sources and are shielded from emitted electrons or positrons.

First calculations suggest, that two beams of $1J$ consisting of $1MeV$ electrons would be able to create about 10^4 electron-positron pairs.

CALDER

CALDER is a multi-dimensional, relativistic Particle-in-Cell (PiC) code. Developed by CEA, DAM and DIF it is massively parallelised and can include amongst others modules for radiation transport, hydrodynamics and the non-linear Breit-Wheeler process.
CALDER is a powerful tool in order to investigate the optimal source for high energy photons for the proposed experiment.

BW-MCiC

One of the two numerical tools in order to study optimal conditions for future BW experiments is the BW-MCiC code. Since the experiment, we are interested in, requires to beams of many ($\sim 10^{14}$) high energy photons colliding with each other, one would expect to use a PIC-code. In fact, several works have been accomplished with PIC simulations regarding electron-positron generation. However, in almost all of these cases, high energy photons collided with thermal background photons over a large length scale. With a large enough interaction length, one can define a optical thickness τ of the thermal photon background. This τ can be used to sample propagation distances, which a high energy photon can travel, before colliding with thermal photons in a BW process. However, experimental reality reduces either the photon density significantly (and thus makes it almost impossible to witness any BW process) or reduces the interaction length to the micro metre range. Also, with two collimated, high energy photon beams the picture of a thermal photon background is not applicable.
For this reason, we chose to develop a code, that treats the collision between photons as such instead of relying on a optical thickness. The BW-MCiC code is writen in Fortran in order to become an optional module for the highly parallelised PIC-code CALDER[3]. However, at the moment, development is more focussed on it as a stand-alone solution. This is partly due to the fact, that the source of radiation proposed above comes from the interaction of a Laser beam with a thin, high z target, but the interaction volume of the two photon beams is spatially far removed from this source. This would pose unnecessary strains on a PIC code, which makes it more reasonable to use two different simulations.

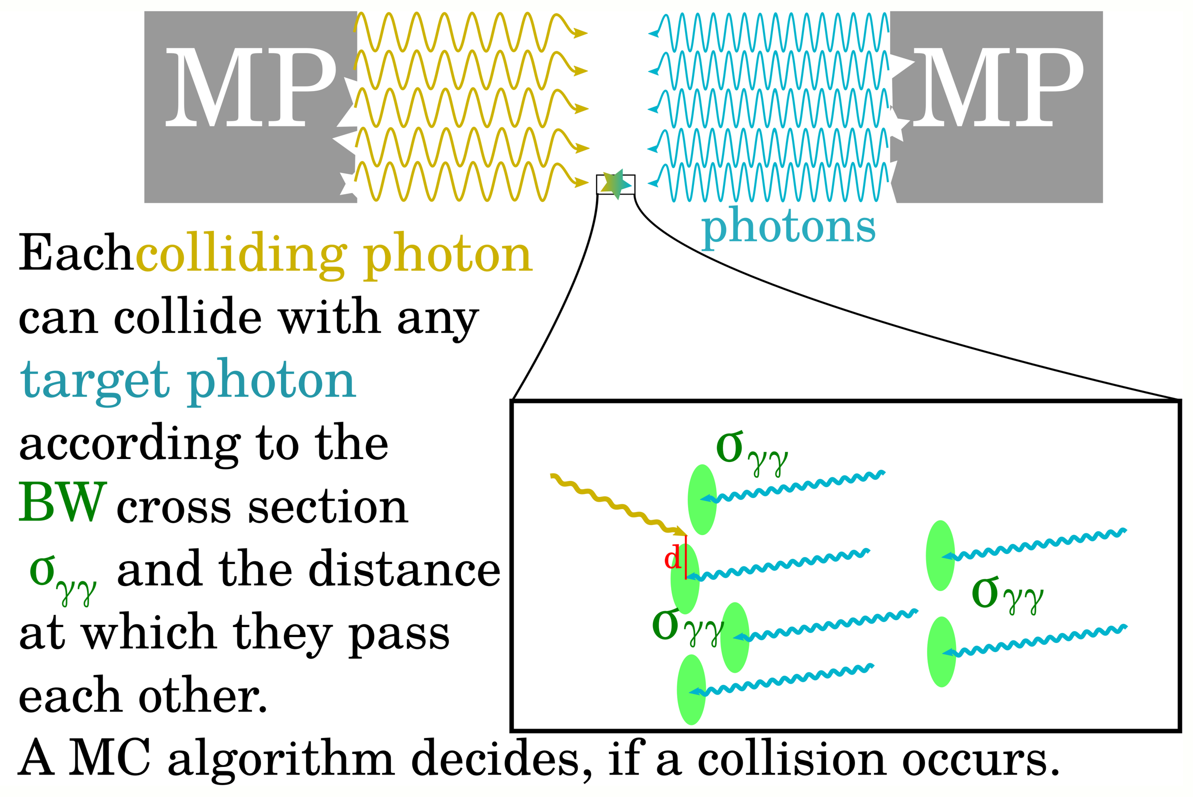

Fig. 4: Two colliding macro-photons are chosen and divided into corresponding "real" photons. Each individual photon has the same momentum, but a slightly different position. For each pair of photons the distance d, at which they pass each other, together with the BW cross section defines a probability for a BW process to occur.

In a BW-MCiC simulation, we treat photons as macro-particles until they collide. Since the cross section of the BW process is still much smaller than the length scale in the PIC simulation, only PIC particles, that overlap can collide. Two colliding macro-particles then are split into corresponding "real" particles for which collision according to their BW cross section is checked.

References

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