

An event generator for crystal source Application of the CLIC positron baseline

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Abstract. A high energy electron beam propagating at glancing angles along a mono crystal axis experience a collective scattering from many crystal atoms and may hence, be channeled; it performs an oscillating trajectory and emits a large number of photons. This property is used to obtain an intense beam of photons which generate a large number of e^+e^- pairs in an amorphous target. The radiation in crystals is handled by dedicated programs as FOT while the interaction between charged particles and amorphous material is well described in Monte Carlo codes such as Geant4 or EGS. Thus a Monte Carlo code associating the crystal program FOT with Geant4 has been worked out and a presentation is given for this new program named G4Fot. An application to the future positron baseline of the Compact Linear Collider (CLIC) using a tungsten crystal oriented on its $\langle 111 \rangle$ axis and an amorphous material, the so called hybrid source is also presented.

1. Introduction

A fast charged particle interacting with the atoms of a material produces radiation. In amorphous media the contributions from the interactions with the individual atoms as bremsstrahlung and pair production are added incoherently. Those interactions are well described by the Bethe-Heitler mechanism which is included in various codes as EGS [1], Fluka [2] or Geant4 [3]. If the particle is entering in a crystal with glancing incidence along the axes or planes, instead of being incoherently scattered by the atoms, it will be submitted to correlated deflections from the atoms of the rows or planes ; the particles trajectory can then be calculated averaging the crystal potential along the crystalline direction with two consequences : a larger radiated energy with a softer radiation spectrum than with the bremsstrahlung and consequently a much larger number of photons. The radiated energy becomes higher in such process than with the bremsstrahlung above certain incident energy value, as for example 1 GeV for the tungsten crystal [4]. The photon spectrum produced by 5 GeV energy electrons beam impinging with normal incidence on an amorphous and a crystal tungsten target oriented on its $\langle 111 \rangle$ axis is presented figure 1. Both targets have the same thickness of 1.4 mm. In this figure the vertical scale is $E \times dN/dE$, where E is the photon energy. In an amorphous target, the bremsstrahlung spectrum has a $1/E$ behaviour and exhibits on the figure an almost constant shape. On the other hand, in the crystal an enhancement of soft photons production is observed. Moreover the difference of the photon yield, defined as the number of photons produced at the exit of the

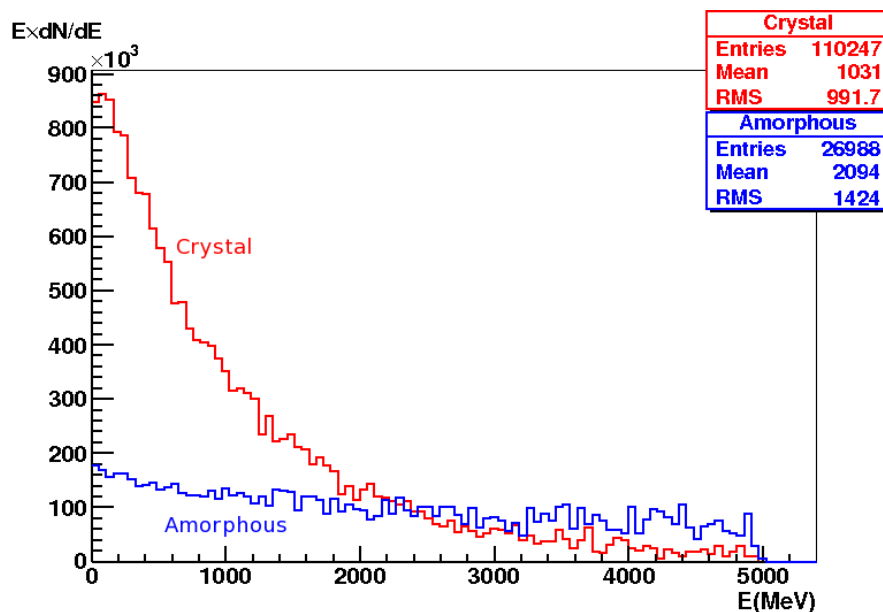


Figure 1. Emerging photons from 6000 electrons at 5 GeV impinging on 1.4 mm of tungsten crystal oriented on its $\langle 111 \rangle$ axis and amorphous target. Normal incidence of the electrons with respect to the targets was considered.

crystal divided by the number of incident electrons, between crystal and amorphous material is around 4.5. The larger number of photons and their softer energy are interesting for using such process to generate large numbers of e^+e^- pairs for positron source applications. This method has been proposed some years ago in the framework of future lepton colliders [5].

The simulations worked out to describe this method have used a dedicated code *Fot* [6] calculating the crystal effects, written by X. Artru from IPN-Lyon and associated to *EGS* to derive the positron production. In order to carry out much more intensive simulations the crystal code *Fot* has been associated to *Geant3* code by A. Jejcic [7]. The combined codes have been used to analyze the results of the *Proof of Principle* experiment at Orsay [8]. That combined program was precise enough but rather slow in term of computing point of view. In order to develop very intensive simulations for the preparation and analysis of the CERN experiment WA103, another crystal program simulation, more rapid, written by V.M. Strakhovenko from BINP (call *VMS* simulation later on) has been used and also associated to *Geant3*. The discrepancies between the two combined codes were within 10%. With the goal of using *Fot* as an event generator for *Geant4* and for adding new functionalities, the *Fot* program written in *Fortran* has been converted into *C++*. The new combined program, called *G4Fot* has already provided some results which are presented hereafter.

2. Simulations

The radiation emitted from the interaction between a fast electron and the the individual atoms of an amorphous media is called incoherent bremsstrahlung (IB). In crystalline targets and when the electron trajectory is close enough to a major crystallographic axis the amplitudes of the bremsstrahlung emission at certain wavelengths may interfere constructively. This will result in an enhancement of the intensity at this wavelength compared to ordinary incoherent emission. This type of radiation is called coherent bremsstrahlung (CB). Moreover if particles enter with glancing angle to axis they may be trapped in "channels" performing stable periodical

trajectories along atomis rows or planes. This radiation is then called channeling radiation (CHR) or Kumakhov radiation. Those physics processes have been implemented in the **Fot** simulation. The basic principles of this simulation will now be presented. For more details the reader can refer to the original X. Artru's article [6].

2.1. Fot simulation

Taking advantage of the stronger axis potential with respect to the planar one, the incident electrons are crossing the crystal longitudinal axis z at glancing angles. They will feel a continuous potential, equal for the transverse coordinate r_{\perp} to :

$$\bar{V}(r_{\perp}) = \langle \langle V(r_{\perp}, z) \rangle \rangle_t .$$

Where $V(r_{\perp}, z)$ is the atom potential at the location of the projectile and $\langle \rangle_t$ means average over t ; This implies conservation of the transverse energy, defined by :

$$E_{\perp} = \frac{1}{2}E\psi^2 - e\bar{V}(r_{\perp}), \quad (1)$$

where ψ is the particle angle to the axis. For $E_{\perp} = 0$ an angle can be defined as the critical angle for channeling radiation. Derived from the relation 1, this critical angle or Lindhard angle is defined by :

$$\psi_c = \sqrt{\frac{2eV_0}{E}}. \quad (2)$$

If the incident angle is somewhat larger than the critical angle, the electrons may cross planes or strings at regular intervals and interferences are occurring providing CB with shorter wavelengths than with channeling. Electrons can also develop ordinary bremsstrahlung when they cross the crystal with random orientation. In order to evaluate the radiation rate, **Fot** calculates the electron trajectories in the crystal and the subsequent photon emission probabilities. This program is using the semi-classical Baier-Katkov formula for radiation in a non-uniform field, taking into account the multiple scattering [9].

Two mains parameters could be defined in the simulation : the maximal transverse angle ψ_{\perp}^{\max} and the maximal transverse energy E_{\perp}^{\max} . Typically $\psi_{\perp}^{\max} = 10^{-2}$ rad and $E_{\perp}^{\max} = 100$ keV, decreasing those cut off will increase the computing time simulation. The transverse angle and the transverse energy of an electron must then be less than the maximums values to be trapped in the crystal channel. More precisely three different cases can occur during the electron propagation in the crystal :

- (i) $\psi \gg \psi_{\perp}^{\max}$ and/or $E_{\perp} \gg E_{\perp}^{\max}$, only IB radiation occurred ;
- (ii) $\psi > \psi_{\perp}^{\max}$ and $E_{\perp} > E_{\perp}^{\max}$, CB plus IB radiation ;
- (iii) $\psi < \psi_{\perp}^{\max}$ and $E_{\perp} < E_{\perp}^{\max}$, CHR+CB and IB.

A radiated photon could then, if is energy is above $2 \times m_e$, where m_e is electron mass, produce in the crystal an e^+e^- pair. Besides the incoherent pair creation which is similar to what happens in an amorphous medium, two other kinds are expected. The coherent pair creation which is associated to the coherent bremsstrahlung and the pair production in strong fields which appears at very high energy. For the tungsten crystal at room temperature the associated threshold is for the latter around 22 GeV and go down to 13 GeV at $T = 77$ K [10]. For the cases considered in this paper which concern incident electron energies up to 10 GeV, the only process assumed will be the incoherent pair production well described by standard simulation of particle matter interaction such as **Geant4**.

The crystal temperature should also be taken into account in the axis potential. The temperature increase in the crystal due to energy deposition leads to thermal vibration with, as a consequence, the lowering of the available channeling potential.

2.2. *G4Fot simulation*

Since **Fot** simulation do not take into account the e^+e^- pair creation, this process will be simulated using **Geant4**. Towards this goal **Fot** have been converted into **C++** (**Fot++**), the common **Fortran** becomes **C++** classes and the original algorithm is kept¹.

For an event, ie one incident electron impinging on a crystal target, the phase space of all radiated gamma (from IB, CB and CHR processes) simulated by the **Fot++** are stored in memory. When the electron exits the target the simulation stops. The created photons in the target are then simulated by **Geant4** and the material is considered as a pure amorphous target (figure 2).

In the case where the electron is dechanneled before exiting the crystal, it is not anymore simulated by **Fot++**. The dechanneled electron is then also simulated by **Geant4** for the rest of is propagation in the material since it could radiate IB. If their energies are enough (typically in

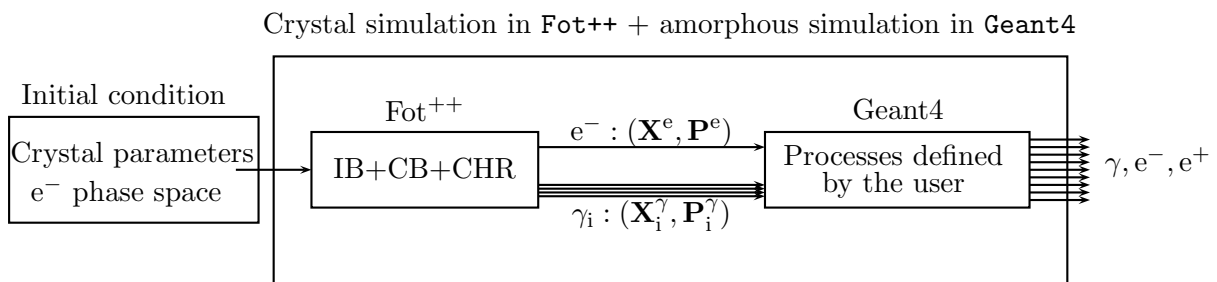


Figure 2. When an e^- impinges a crystal target **Fot++** simulate all the produced photons from IB, CHB and CHR processes. Since the simulation can not take into account the pair creation process, photons phase space are keep in memory and simulated in an amorphous material using in **Geant4**. In the case where the electron is dechanneled before exiting the crystal, he s then also simulated by **Geant4** for the rest of is propagation in the material considered as an amorphous one.

the GeV range) and the angle small enough the e^+e^- pairs created could also radiate in their turn photons from CB or CHR processes. Those second generation photons are not taken into account in **G4Fot** .

2.3. *G4Fot benchmark*

The photon flux produced in the crystal depends on the energy, the divergence of the electron beam and the crystal thickness. In the context of the positron source using the hybrid scheme for the future linear collider, a normal incidence to the $\langle 111 \rangle$ plane of the crystal has been considered. To limit the energy density deposition in the crystal the energy of the impinging electron taken below 10 GeV. Moreover, to have a reasonable number of positron produce, the energy should be greater than 3 GeV. According to the beam energy, different radiator thicknesses have been chosen, they correspond to some optimum values [7]. For instance at 10 GeV the crystal thickness is 1 mm and increases up to 1.6 mm for 3 GeV.

As already mentioned, the e^+e^- created in the crystal could in their turn be rechanneled and emits again some CB and/or CHR. This second generation photons is not taken into account in the simulation. Then, in principle, it underestimates somehow the number of produced photons. Since those photons populates the lower part of the energy spectrum compared to pure bremsstrahlung (see figure 1), the photons mean energy is slightly overestimated. This

¹ It is important to mention that the first goal was to obtain the same results with the two codes. It is why some classes, historically described in the **Fortran** code, have been implemented while the Standard Template Library from **C++** could be used.

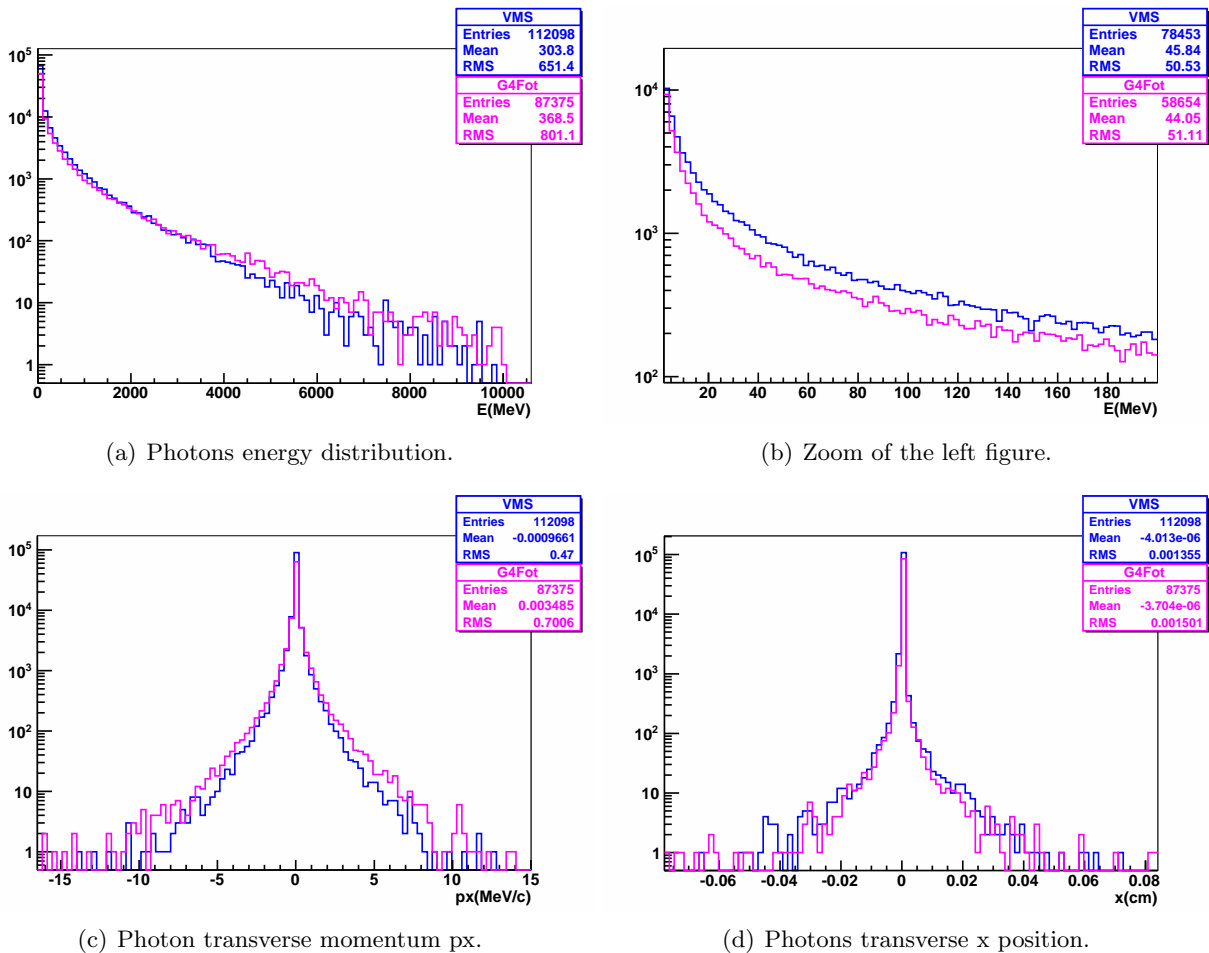


Figure 3. A 10 GeV electron beam energy impinge 1 mm of crystal target thickness. Figures above presents the photons phase space at the exit of the crystal, produced by G4Fot and VMS simulations. The Simulations was done using 5000 incident electrons.

could be observed on figure 3(a) and figure 3(b) where a 10 GeV electron beam impinges on 1 mm crystal tungsten target. The other consequence is the lack of created pairs in the crystal as shown as the statistics boxes figure 4(a) and figure 4(c).

Systematics comparison of the particles phase space at the exit of the crystal have been performed between both simulations using different incident electron beam energies. The comparison has shown a discrepancy between 10% and 20% depending on the incident electron beam energy considered.

3. CLIC positron baseline

The CLIC study considers the hybrid source using channeling as the baseline for unpolarized positron production. It uses a 5 GeV electron beam impinging on a tungsten crystal target of 1.4 mm. With the crystal oriented on its $\langle 111 \rangle$ axis the resulting intense photon beam is then impinging on a 10 mm amorphous tungsten target producing positrons by e^+e^- pair creation. Downstream the amorphous target, a capture section based on an adiabatic matching device followed by a 2 GHz Pre-Injector Linac focuses and accelerates the positron beam up to around 200 MeV (figure 5). The separation between the crystal and the amorphous is then used to bend

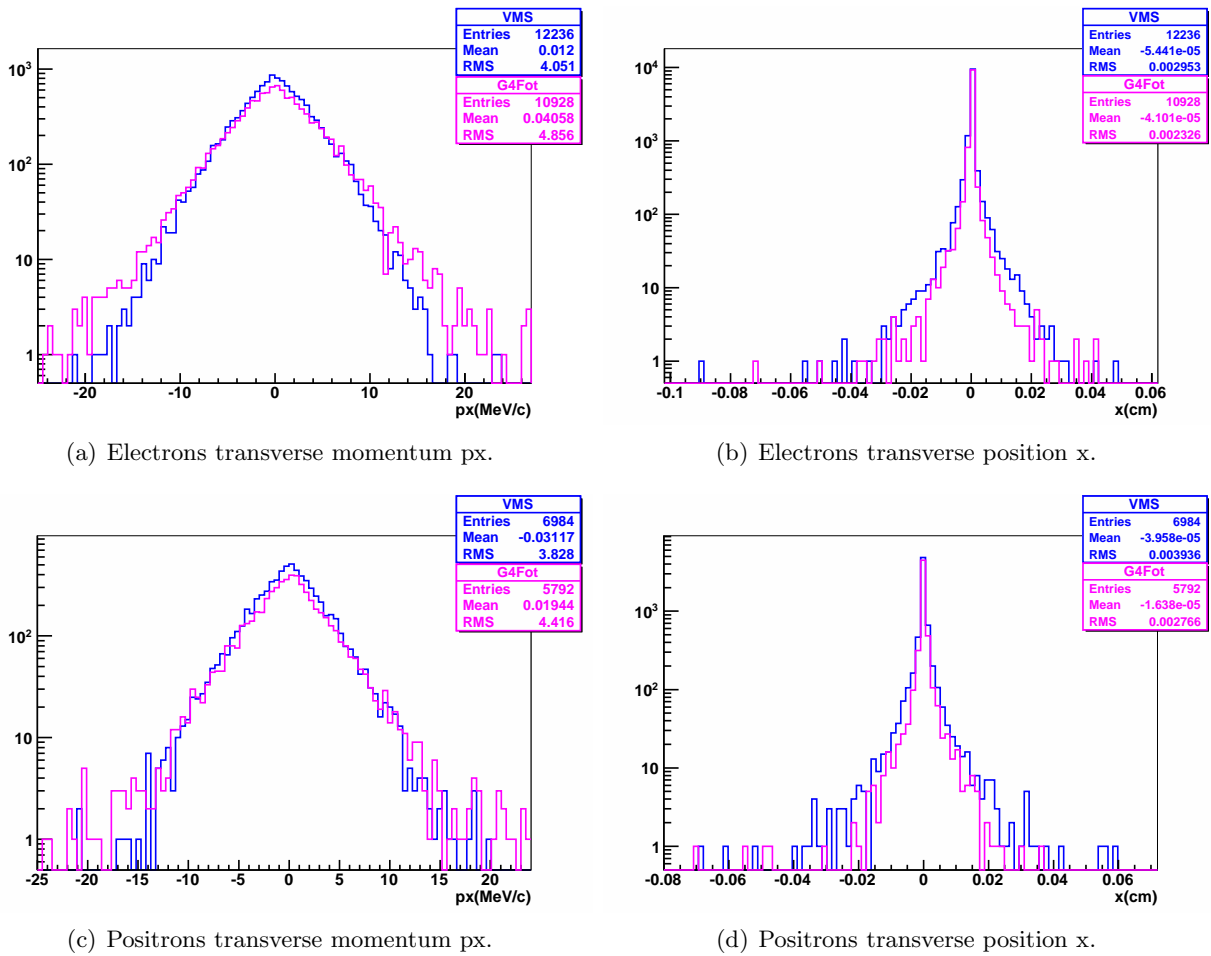


Figure 4. A 10 GeV electron beam energy impinge 1 mm of crystal target thickness. Figures above presents electrons and positrons phase space at the exit of the crystal, produced by G4Fot and VMS simulations. The Simulations was done using 5000 incident electrons.

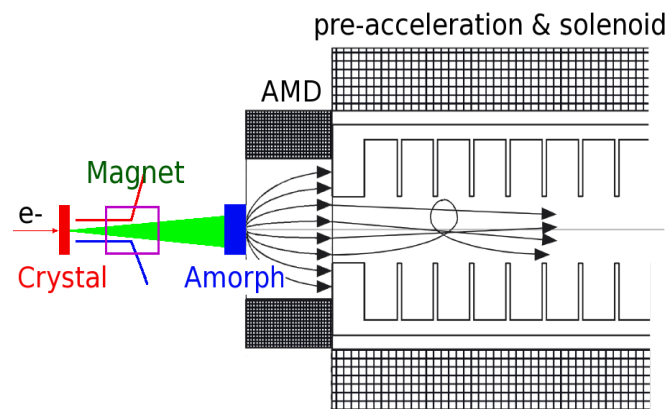


Figure 5. CLIC positron generator (adapted from Figure 4 of [20]).

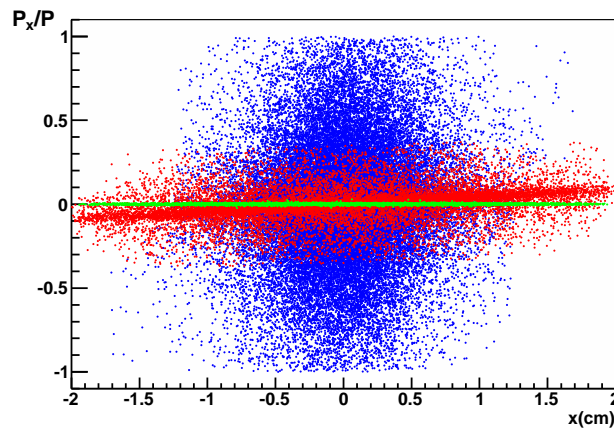


Figure 6. Positrons emittance at the exit of the amorphous target, the AMD and the Pre-Injector Linac at 200 MeV.

the charged particles produced by the crystal radiator [17]. This limits the energy desposition in the tungsten amorphous target. After the amorphous target, the AMD transform the positron phase space after the target into a larger dimension and smaller momentum spread which is easier to transport in the Pre-Injector Linac (figure 6). At the exit of the Pre-Injector Linac a positron yield of 0.8 is obtained. This yield do not fulfill the CLIC requirements. However, recent studies suggest that the incident electron beam intensity should be increased to obtain the requested number of e^+ captured into the Pre-Damping Ring. Nevertheless an increase of the electron beam intensity of 25% to 35% is still acceptable to keep in the energy deposition limitation.

4. Conclusion

The CLIC positron baseline using a crystal and an amorphous tungsten target have been presented. This very promising method, specially to produce the high intensity positron beam requested for future linear collider (a scheme for ILC can be found here [21]), can now be simulated using one simulation named *G4Fot*. This simulation described in this paper have been compared to an another simulation and for the energy considered namely between 3 and 10 GeV an agreement between 10 and 20 % have been found.

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