Nonperturbative processes in strong-field QED / ProQED

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1. “State of the art” in the field

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Quantum electrodynamics (QED) is one of the most successful theories in physics. Its predictions have been verified with a very high accuracy. They are described by an ordinary perturbation expansion in fine structure constant α. However, there are also observables which cannot be considered as ordinary perturbation and whose prediction lacks an experimental verification. Among them, the most famous is the rate of spontaneous electron-positron pair production in a strong electrostatic field E [1–3].

They are produced from QED vacuum fluctuations. This mean that the QED vacuum behaves like a polarizable medium that modifies classical behavior, leading to novel quantum effects [4–8].

Classical electrodynamics describes electromagnetic interactions through a system of coupled linear differential equations - Maxwell's equations. The linearity of the theory means that the sum of two Maxwell solutions is also a solution of Maxwell's equations.

Two coherent intersecting rays of light add up their electric (and magnetic) fields and pass on in summed form. Therefore, classical electrodynamics makes it impossible to describe the photon-photon elastic scattering, their fields can only be composed linearly.

In Quantum Electrodynamics (QED) we can describe γ-γ scattering if the energy (frequency) of photons is high enough to observe their corpuscular behavior when they can create e^+e^- virtual pairs. One photon scatters from the transient vacuum fluctuations of the other one (**Fig.1**)

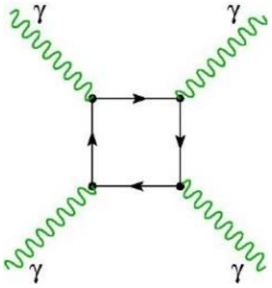

Fig 1. Feynman diagram for γ-γ scattering

The QED effect like electron–positron avalanche pair production to appear spontaneously from vacuum requires a very high, Schwinger electric field $E_S = 1.3\ 10^{18}$ V/m. This would require focusing a high-power laser to very high Schwinger intensity of $I_S = 2.3\ 10^{33}$ W/m^2. The problem is that the Schwinger intensity is significantly larger than the intensities experimentally achievable even with the new, extremely powerful laser facilities under construction [9] like, for example, a 2 x 10 PW, I > 10^{26} W/m^2 facility [10-12] and a 100 PW, I > 10^{27} W/m^2 facility [13].

The Schwinger effect has not been observed so far, due to extremely high value of the requested stationary electric field. However, the production of e^+e^- pairs can take place by tunneling at lower field values, but the probability of production decreases exponentially with the inverse value of the electric field E namely $\sim exp(-E_{cr}/E)$ with $E_{cr} = 10^{18}\ V/m$ (Schwinger limit).

With the current technological possibilities, a series of proposals have been made for mechanisms that would allow the catalysis of the production of e^+e^- pairs for lower values of the electric field. For example, the pair production rate can be significantly increased by time-dependent electric fields [11,12,17] using high-intensity lasers. Several laser facilities (ELI, SEL, SHINE) [11,16,17] are very close to reaching electric fields that will allow rethinking the observation of the Schwinger effect. This has led to intense collaboration between theorists and experimenters in various fields: high energy physics, lasers, plasma, fusion and accelerators, for the development of various experimental approaches to observing the Schwinger effect.

Construction of such ultra-powerful, femtosecond, lasers is made possible by the discovery of the *chirped pulse amplification* (CPA) technique by Strickland and Mourou [14] which was rewarded with a share in the 2018 Nobel Prize in Physics. Mourou went on to champion the construction of the extreme light infrastructure (ELI) in Europe as well as other such facilities worldwide, pushing the power of the laser pulses to the extreme, towards the high field physics regime. Anyway, the planned lasers ultra-high intensities will still be much lower than I_S, this could be overcome by using the geometry of colliding two PW laser pulses at ELI-NP: (a) the first PW laser pulse accelerates an electron bunch to relativistic energies of several GeV/electron, using either gas or solid targets; and (b) the second PW laser pulse is focused to the maximum intensity on the relativistic electron bunch in order to generate the QED effects. The relativistic electron experiences a much larger electric field in its own frame of reference than the actual laser electric field in the laboratory frame of reference.

ELI-NP will have laser intensities of about $10^{24} – 10^{25}\ W/m^2$, which will allow obtaining strong electric ($I \sim E^2$), or $E(V/cm) = 27.4 \sqrt{I}\ (W/cm^2)$. Reaching the Schwinger electric field threshold $E_{cr}=1.3 \cdot 10^{18}\ V/m$ necessary for the spontaneous creation of e^+e^- pairs in vacuum, requires intensities of $2.3 \cdot 10^{33}\ W/m^2$, quite far from the ELI-NP possibilities. However, at intensities of the order of $\sim 10^{27} W/m^2$, can be obtained fields as $E = 8.7 \cdot 10^{14}\ V/m$.

R. Schuetzhold, et al. [18] proposed "Dynamically Assisted Schwinger Mechanism" by the combined action of a slow, low-frequency laser pulse (in the optical domain) with a high intensity and a fast high-frequency pulse (in the X domain) with a low intensity. The fast pulse will give a multi-photon contribution that allows the extracted electron from the vacuum to tunnel the barrier caused by the slow, long pulse. So, an experimenttal test was proposed by A. Di Piazza et al. "Barrier control in tunneling e^+e^- photoproduction" [19].

Some of the QED effects predicted by theory, that can be investigated experimentally are: (a) nonlinear, multiphoton, inverse Compton scattering; (b) radiation reaction; (c) electron-positron pair production.

2. Place of the project in the framework/context of the ELI-NP White Book /TDRs

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The study of γ-γ scattering as well as other nonlinear vacuum QED effects are among the current objectives of research around the world, preparing experimental works aiming at reaching the Schwinger threshold. These processes have been little studied and observed experimentally.

The ELI-NP facility has a unique laser facility for colliding 10 PW laser pulses [12]. Pumped with a CPA titanium-sapphire laser system from Thales Optronique, France, the laser system has two identical laser amplifier arms which provide 10 PW laser pulses each. The two 10 PW laser pulses are seeded from the same laser oscillator pulse which is split into two and these two resulting pulses are amplified in the two amplifier chains. Therefore, the two 10 PW pulses are naturally coherent.

The project aims to study experimental works at ELI-NP for Probing the Pair Creation from the Vacuum in the Focus of Strong Electrical Fields with a High Energy Gamma Beam and / or Electron Beam - ELI-NP White-Book, Section 5.3 Scientific Case of ELI Nuclear Physic Pillar.

The E6 interaction chamber at ELI-NP is dedicated to QED experiments with two colliding 10 PW laser pulses with $I > 10^{22}\ W/cm^2$ [11,12,20]. (a) the first PW laser pulse accelerates an electron bunch to relativistic energies of several GeV/electron, using either gas or solid targets; and (b) the second PW laser pulse is focused to the maximum intensity on the relativistic electron bunch in order to generate the QED effects. The relativistic electron experiences a much larger electric field in its own frame of reference than the actual laser electric field in the lab frame. QED effects predicted by theory and under experimental investigation are: (a) nonlinear, multiphoton, inverse Compton scattering; (b) radiation reaction; (c) electron-positron pair production; (d) vacuum birefringence [22-31].

We will study some possible experimental schemes:

- The first scheme [22] use two counter propagating laser pulses focused on the gas targets. They can produce bright gamma-photon emission and copious electron–positron pair.
- The second scheme [23] include two colliding elliptically polarized 10 PW laser pulses incident onto two diamond like carbon foils simultaneously. The produced electrons are accelerated by the laser radiation pressure and interact with the other intense laser pulse. This configuration enables efficient Compton back-scattering and results in ultra-bright gamma photon emission.
- The third scheme [24–26] will replace the second colliding PW laser pulse by the reflection of the first pulse plasma mirror. The first laser pulse travelling through the plasma is reflected by the mirror and interacts with the high energy electron bunch generating gammas and positrons.
- The fourth scheme [27] assumes two colliding linearly polarized laser pulses irradiating a thin Al foil from both sides. About 20% of the laser energy is predicted to convert into a burst of gamma photons with a flux exceeding 10^{14} s^{-1}. The conversion efficiency to gammas in the case of two-side irradiation would be three times higher than that in the case of one-side irradiation with a single laser pulse. The predicted electron–positron plasma generated with colliding laser pulses would be eight-fold denser compared to the irradiation with only one laser pulse. The predicted laser-driven relativistic jets formation could be used to study energetic astrophysical phenomena in laboratory
- The fifth scheme [31] employs the two 10 PW-scale colliding lasers obliquely incident on a solid target. A high yield ($3 \cdot 10^{10}$) over-dense (~10^{22} cm^{-3}) positron bunch is predicted. Such positron yield is fifty times higher than that produced from a single laser with the same peak power.

3. Project objectives

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Objectives of this project is to increase scientific knowledge by a number of publications in ISI-listed journals and to increase the number of participations in communication sessions and prestigious international scientific conferences. So, we propose to test experimentally some nonperturbative QED provisions with the ELI-NP 10 PW laser facility in photon - matter interactions, exploiting its particular advantages:

A. highest power and short laser pulses
B. highest electromagnetic field – ultra-intense laser field
C. the possibility for light to accelerate electrons and ions at relativistic velocities
D. generation of high energy radiation, X or γ
E. ultra-intense QED laser field vacuum interactions

1. Study of nonperturbative processes in the laser high-field QED physics.
    a. Theory of strong-field QED in intense laser fields
    b. The relativistic transformation of the electric and magnetic components of the EM field.
    c. Investigation of strong-field quantum effects, like the recoil due to emitted photons (radiation reaction) and the pair production according to the Breit-Wheeler process [32]
    d. Nonlinear Compton scattering, single photon emission
    e. Real photon-photon elastic scattering

2. Study of the pair production using two colliding 10 PW laser pulses to reach the QED regime in experiments with focused laser intensities I = $10^{22} - 10^{23}$ W/cm^2 and above.
    a) Laser strong field - matter interactions
    b) Pair production in the presence of a Coulomb field,
    c) Local Constant Field Approximation (LCFA) to derive the rate of nonlinear Breit-Wheeler pair production.
    d) Particle scattering in ultra-intense field QED
    e) Nonlinear Compton scattering of an ultra-intense laser pulse
    f) Multiphoton Breit-Wheeler pair production,
    g) Radiation reaction in laser-electron beam collisions
    h) Trident process,
    i) Spontaneous pair production via Schwinger mechanism (‘vacuum breakdown’).

3. Preparation of a Blue paper for experimental test of some QED nonperturbative effects.

4. Special lectures on the project theme for education and training the necessary competencies in the specific scientific and technical fields for our present and future collaborators.

5. Increasing the level of dissemination of the project results for young people and high school students and for general public by organizing specific lectures to understand and increase their interest in pursuing careers in science or technology. To inform on the new opportunities this multidisciplinary facility offers for future research to study the fundamental processes unfolded during light-matter interaction.

4. Description of the methodology and of the activities

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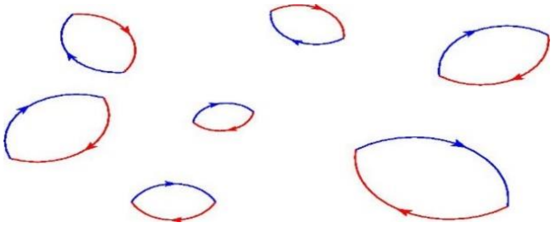
The e^+e^- pair production can occur spontaneously in the presence of a strong stationary electric field. It is a QED prediction for matter creation by strong electric or magnetic fields. The effect was described in 1951 by J. Schwinger [3] (Schwinger effect).

Under normal conditions, the physical vacuum, due to the quantum fluctuations, is in a permanent "boiling", with production and annihilation of virtual particle-antiparticle pairs.



According to the Heisenberg principle, locally, on short time intervals Δt, there are energy fluctuations ΔE, so the product cannot be smaller than $\hbar$.

$$\Delta E \cdot \Delta t \geq \hbar$$

where $\hbar$ – reduced Planck constant.

$\hbar = 1.054571817 \times 10^{-34}\, J \cdot s$

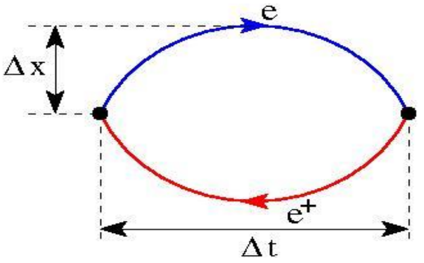
$= 6.582119569 \times 10^{-16}\, eV \cdot s$

Then, on Δt time intervals, we have ΔE energy fluctuations that allow production of e^+e^- pairs:

$\Delta E \approx 2\, m_e c^2 = 2 \cdot 0.511\, MeV \approx 10^6\, eV$

$\Delta t < 10^{-22}$ s

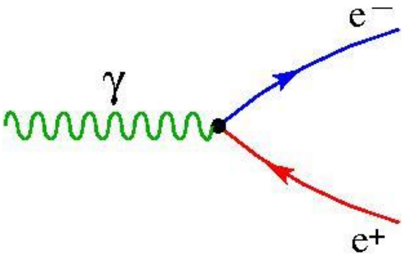
Locally it is possible to produce an electron-positron pairs, which live on average a Δt time, then they annihilate.



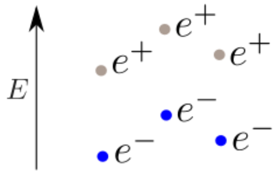
The space region for these processes is the nucleon size.

$$\Delta x \sim c\cdot\Delta t \leq 3\cdot 10^{8}\ m/s\cdot 10^{-22}\ s$$
$$\sim 10^{-14}\ m = 10\ fm$$

Some quantum interactions can transfer enough energy as to transform the virtual pair into a real pair. The pair is no more locally confined and can be detected and measured at large distance.



The existence of virtual particle-antiparticle pairs in Quantum Electrodynamics (QED) tell the vacuum can be described as a polarizable medium, with possibility to observe some nuclear or atomic behaviors (Lamb shift or electron and muon anomalous magnetic moment).



An external field E can extract an e^+e^- pair from the vacuum if the energy $W = 2m_e c^2$ is transferred to create an e^+e^- pair:

$W = F\cdot d = e\,E\cdot d = 2m_e\,c^2$

e – electron charge

$d = 2\,\Delta x = \frac{2\,m_e c^2}{eE}$ distance for E field action

it is given by the Δt time action on e^+e^- pair.

From the Heisenberg uncertainty relation, we saw:

$$\Delta t \geq \frac{\hbar}{\Delta E} \qquad \Delta t = \frac{\hbar}{2\,m_e c^2} \approx 10^{-22} s$$

hence the characteristic distance the electric field must act to produce e^+e^- pairs is given by electron Compton wavelength λ_C

$$d = 2\Delta x = 2c\Delta t = \frac{\hbar}{m_e c} = \lambda_C$$

The virtual e^+e^- pair becomes a real one if a <u>minimum energy W</u> is transferred by the electric field E:

$$W = F\cdot d \equiv F\cdot\lambda_C = \frac{\hbar e E}{m_e c} > 2m_e c^2$$

or the <u>minimum value of the electric field</u> is

$$E > \frac{2m_e^2 c^3}{\hbar e} = 2E_{cr}$$

the <u>critical value of the electric field</u> E_{cr} (Schwinger field) i.e. the starting value for spontaneously production of real e^+e^- pairs, in laser field - vacuum interaction is:

$$E_{cr} = \frac{m_e^2 c^3}{\hbar e} \equiv \frac{m_e c^2}{\lambda_c\, e} = 1.3 \cdot 10^{18}\,\text{V/m}$$

Under these conditions the electromagnetic field becomes nonlinear, we no longer have a linear superposition of the fields produced by multiple sources.

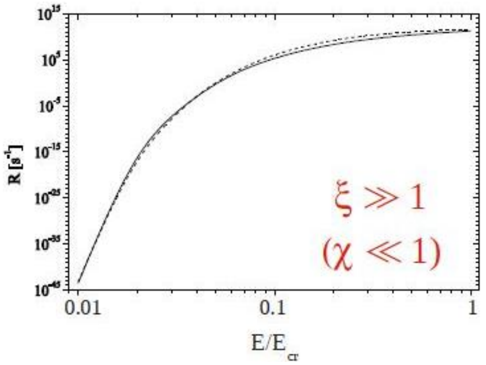
The probability of e^+e^- pair production by tunneling depends exponentially on the electric field E:

$$P \sim \exp\left(-\frac{d}{\lambda_C}\right) = \exp\left(-2\frac{m_e^2 c^3}{\hbar e E}\right) = \exp\left(-2\frac{E_{cr}}{E}\right)$$

In this nonperturbative tunneling regime,

The tunneling rate is: R ~ exp(-E_{cr}/E)

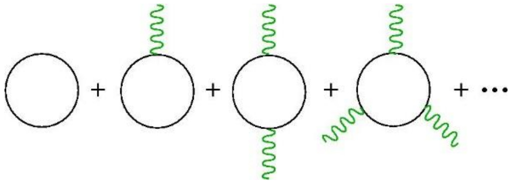
relative coupling constant $\xi = eA/m_e c^2$



The production rate of the Schwinger e^+e^- pairs per unit volume is [4,5]:

$$R = \frac{dN}{d^3x \cdot dt} = \frac{(eE)^2}{4\pi^3 c\hbar^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\frac{\pi m_e^2 c^3}{eE\hbar}\right) = \frac{(eE)^2}{4\pi^3 c\hbar^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\frac{\pi E_{cr}}{E}\right)$$

The terms of the above sum are represented by a Feynman diagram series:



The relativistic connection between electric and magnetic components are given by Lorentz transformations for two relative moving reference systems:

$$\overrightarrow{E'_{\parallel}} = \overrightarrow{E_{\parallel}}$$

$$\overrightarrow{B'_{\parallel}} = \overrightarrow{B_{\parallel}}$$

$$\overrightarrow{E'_{\perp}} = \gamma\left(\overrightarrow{E_{\perp}} + \vec{v} \times \vec{B}\right)$$

$$\overrightarrow{B'_{\perp}} = \gamma\left(\overrightarrow{B_{\perp}} - \frac{1}{c^2} \times \vec{E}\right)$$

$$E'_x = E_x$$

$$E'_y = \gamma\left(E_y - vB_z\right)$$

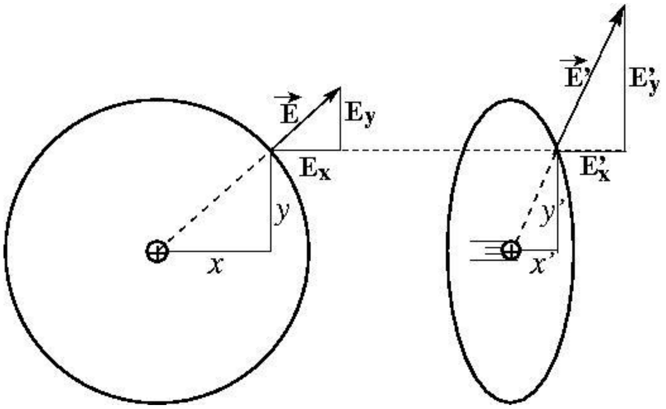
$$E'_z = \gamma\left(E_z + vB_y\right)$$

$$B'_x = B_x$$

$$B'_y = \gamma\left(B_y + \frac{v}{c^2}E_z\right)$$

$$B'_z = \gamma\left(B_z - \frac{v}{c^2}E_y\right)$$

The moving electron produces a transversal E_y' field of $\gamma_e = E_e/m_e$ times larger than the same component E_y in its rest system. For an electron energy $E_e = 1\ GeV$; $\gamma_e = 10^3\ MeV/0.5\ MeV = 2 \cdot 10^3$. The electron produces an electric field $\gamma_e E > E_{cr}$, which interacts and extract from the vacuum the e^+e^- pair, just like a *GeV* γ photon interacts with the vacuum.
The same it happens in the moving electron system when it "sees" an external *E* field.



Quantum theory of pair production in strong laser fields implies solving:

Schrodinger equation for the particle in the EM field:	$i\hbar\frac{\partial\psi}{\partial t} = \frac{1}{2m}\left(\vec{p} - \frac{e}{c}\vec{A}\right)^2 \psi$
Dirac equation for the particle in an EM field (expressed by the 4-potential A_μ), is:	$\left(ic\gamma^\mu\partial_\mu - e\gamma^\mu A_\mu^{ext} - mc^2\right)\psi = 0$ A_μ^{ext} is the classical EM wave (plane wave).
with relative coupling constant	$\xi = eA^{ext}/mc^2$
The theoretical development for strong QED fields was done by Furry's description:	$\left[ic\gamma^\mu\partial_\mu - e\gamma^\mu\left(A_\mu + A_\mu^{ext}\right) - mc^2\right]\psi = 0$

The standard QED calculation of the processes in a strong background laser field crucially depends on the exact solution of the Dirac equation in the presence of the field. Unfortunately, to solve the Dirac equation in a general background field exactly and analytically is technically impossible. Nevertheless, it can be solved in particular cases.

5. Milestones and expected results

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Presentation of the milestones (name, duration) and the expected results for each of them.

Theoretical support

Theoretical calculations and simulations will be needed at different stages of the present proposal.

1. Study of nonperturbative processes in the laser high-field QED physics
   Duration: 1-st Oct 2020 – 1-st Oct 2021
   Expected results: Conference participation and a peer reviewed publication

   a. Strong QED field in intense laser fields.
   b. Investigation of strong-field quantum effects and the pair production by Breit-Wheeler process.
   c. Nonlinear Compton scattering, single photon emission.
   d. Real photon-photon elastic scattering.

2. Study of the pair production using two colliding 10 PW laser pulses to reach the QED regime in experiments with focused laser intensities I ~ 10^{22} – 10^{23} W/cm^2 and above.
   Duration: 1-st Oct 2021 – 1-st Oct 2022
   Expected results: Conference participation and a peer reviewed publication

   a) Laser strong field - matter interactions
   b) Pair production in the presence of a Coulomb field,
   c) Local Constant Field Approximation (LCFA) to derive the rate of nonlinear Breit-Wheeler pair production.
   d) Particle scattering in ultra-intense field QED
   e) Nonlinear Compton scattering of an ultra-intense laser pulse
   f) Multiphoton Breit-Wheeler pair production,
   g) Radiation reaction in laser-electron beam collisions
   h) Spontaneous pair production via Schwinger mechanism (‘vacuum breakdown’).

Implementation scheme

3. Preparation of a *blue paper* for experimental test of some QED nonperturbative effects.
   Duration: 1-st Oct 2022 – 1-st Oct 2023
   Expected results: Blue paper presentation to ISAB ELI-RO. It will be issued to implement an experimental setup, mounted and put into operation in the E6 area of ELI-NP, for the experimental testing of some nonperturbative QED provisions.

Training of scientific and technical staff

4. Special lectures on the specific topics to the present and future collaborators in order to create a strong theoretical and experimental team, aiming to prepare future experimental works at ELI-NP.
   Duration: 1-st Jan 2021 – 1-st Oct 2023
   Expected results: Periodical Seminars within research group

5. Preparation of bachelor theses and master dissertation carried out within the project.
   Duration: 1-st Jan 2021 – 1-st Oct 2023
   Expected results: Periodical Seminars within research group

6. Lectures on the ELI-NP projects in order to help young people and high school students increase their understanding and interest in pursuing careers in science or technology. To inform on the new opportunities this multidisciplinary facility offers for future research which will provide to study the fundamental processes unfolded for light-matter interaction.
   Duration: 1-st Jan 2021 – 1-st Oct 2023
   Expected results: 12 lectures for about 50 persons, every Saturday mornings two times per year.

6. **Deliverables** and outcome of the project

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Reports, publications, joint patents, know-how, mock-ups, other (specify); indicate also the time of accomplishment.

1. First Scientific Report - December 2021
2. Special Lecture Collection based on seminars for staff members – December 2021
3. Scientific Publication – December 2022
4. Lecture collection based on Saturday Morning Physics for young people and high school students – December 2022
5. Blue paper – December 2023

7. Project impact

(maximum 1 page, Times New Roman 11 pt, 1.15 pt spacing)
Estimated impact of the project: scientific, technological, industrial, economic, educational and formative, social etc.

The project is expected to break new grounds in fundamental science, to complement the final implementation stage by preparing and undertaking new research work in the field of QED nonperturbative vacuum effects.

The present proposal will optimize the use of advanced laser light sources in efficient implementation of the fundamental unsolved questions raised by the QED theory.

Improve the quality and relevance of higher education by training diploma, master and PhD students to high-level skills strongly connected to the practical needs of the large-scale laser facilities, but also laboratories and industrial companies.

Development of high-quality work by creating intensive training sessions based on the inventory of skills required by collaborators and for any other ELI-NP laser facility user. Enhancing digital integration in learning, teaching, training and youth work at various levels with the creation of practical and innovative pedagogical tools.

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