RAPORT ŞTIINŢIFIC FINAL-EN

TITLE: QED Nonperturbative processes in strong-field QED / ProQED

1. <u>Summary of scientific accomplishments of the project</u> (max. 3 pages)

The commissioning of the high power laser facility ELI-NP allows in-depth study of nonlinear interactions in Strong Field Quantum Electrodynamics (SF-QED). The present project analyzes the “Vacuum strong field QED interaction processes at ELI-NP facility”, see https://arxiv.org/pdf/2307.09315.pdf .

QED vacuum is a polarizable medium that modifies classical behavior, leading to novel quantum effects [1–5]. The QED effect of e^+e^- pair production requires a very strong, Schwinger critical electric field E_{cr} = 1.3 10^{16} V/cm. This would require focusing a high-power laser to the Schwinger intensity of I_S=2.3 10^{29} W/cm^2. It is significantly larger than the intensities experimentally achievable with the new, extremely powerful laser facilities [6] as the 2 x 10 PW, $I > 10^{22}$ W/cm^2 facility [7-9], or a 100 PW, $I > 10^{23}$ W/cm^2 facility [10].

While even the planned lasers ultra-high intensities will still be much lower than I_S, this could be overcome by using two colliding PW laser pulses at ELI-NP (see **Fig 1**): (a) the first PW laser pulse accelerates an electron bunch to relativistic energies of several GeV/electron, using either gas or solid targets; (b) the second PW laser pulse is focused to the maximum intensity on the relativistic electron bunch in order to generate the <u>QED effects</u>. 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 and produces a high energy γ photon. (c) the γ photon interacts with the same PW laser pulse and produces the e^+e^- pair by Breit-Wheeler process.

The <u>QED effects</u> predicted by theory are: (a) nonlinear, multiphoton, inverse Compton scattering; (b) high energy gamma production; (c) Breit-Wheeler and/or Bethe-Heitler electron-positron pair production.

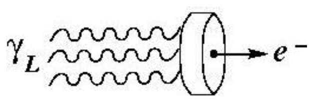
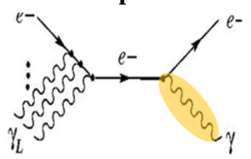
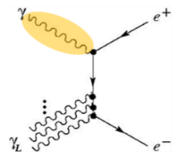
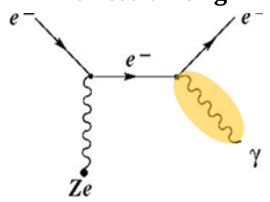
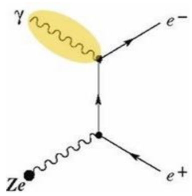
multi-photon electron acceleration	multi-photon (or nuclear) high-energy γ production	multi-photon (or nuclear) $e^+ e^-$ pair production
Wakefield electron aceleration 	**Inverse Compton scattering** 	**Breit-Wheeler pair production** 
	Bremsstrahlung 	**Bethe-Heitler pair production** 

Fig. 1 $e^- e^+$ pair production by SF-QED multi-photon and/or nuclear laser beam interactions

SF-QED processes possible to be investigated at ELI-NP

After a brief review of the first experiment (E-144 SLAC) [11-13] confirming the existence of nonlinear QED interactions of electrons with photons of a laser beam, we presented the current worldwide results and analyzed them along with the main steps necessary for the design of the SF-QED experiments at ELI-NP.

The SF-QED interactions with virtual particles of the QED vacuum, possible to be studied at ELI-NP are: multi-photon inverse Compton scattering, e^+e^- pair production, e^+e^- pair annihilation, e^-e^- Moller scattering, e^+e^- Bhabha scattering, electron self-energy, photon self-energy and vacuum energy.
Finally are presented some similar upcoming experiments, in different stages of implementation [14].

The main steps of the SF-QED interaction experiments at ELI-NP are:

In the I-st step (**Fig.1**), the laser intensity (multi-photon interaction) enables the energy transfer from the laser field to electron by laser wakefield acceleration (LWFA) process.

In the II-nd step (**Fig.1**), a coherent multi-photon laser interaction with constructive superposition of the electric field component ensures a total field E_L, and produces by Inverse Compton Scattering a high energy γ photon. This energy is higher the higher the photon density (laser intensity).

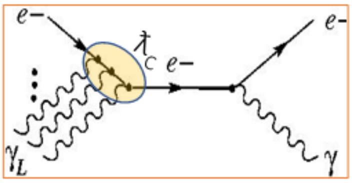


Fig. 2 Electron multi-photon laser interaction

The laser intensity parameter ξ evaluates the work of the laser field over the electron Compton wavelength (**Fig.2**). At ELI-NP for λ_L= 0.815 μm and pulse intensity $I_L \sim 10^{22}$ W/cm^2, we have at least $\xi \cong 50$. Based on the relation: $E_L(V/m) = 1944\sqrt{I_L}\,(W/cm^2)$, for ELI-NP intensity $I_L \approx 10^{22} - 10^{23}$ W/cm^2, laser light pulses lead to field intensity $E_L \approx 10^{14} - 10^{15}$ V/m at the focal point, on several wavelengths distance. This electric field in the l.s. is three orders of magnitude lower than the critical field E_{cr}. Nevertheless, in the rest system of a relativistic electron the transverse component of the laser electric field E is boosted by γ_e Lorentz factor and reaches $E^* = \gamma_e \cdot E$. For an electron beam energy ε_e = 1 GeV, the Lorenz factor is $\gamma_e = \varepsilon_e / m_e c^2 \approx 2\cdot 10^3$ and if a laser beam collides it head-on, electron "sees" a boosted laser field $E^* \approx 2 \cdot 10^{17}$ V/m, still less than the critical value $E_{cr} = 1.3\ 10^{18}$ V/m. But, this can be reached with another multi-photon interaction.

In the III-rd step (**Fig.1**) the photon - multi-photon interaction leads finally to e^+e^- pair production.

- **The ELI-NP laser beams permit us to perform a a lot of works**:

- Systematic studies of the dynamics of fundamental QED processes possible to approach with high power lasers, to evaluate the amplitude of various processes such as: γ-e inverse Compton scattering [15-19], Breit-Wheeler e^+e^- pair production [20], Bethe-Heitler e^+e^- pair production [21], Dirac e^+e^- pair annihilation, e^-e^- Moller scattering, e^+e^- Bhabha scattering, electron self energy, photon self energy, vacuum energy [22].

- Proposal of experimental works for the measurement of physical properties related to the production of e^+e^- pairs (Schwinger mechanism) in the photon-multiphoton interaction (nonlinear Breit-Wheeler), the multiphoton-virtual photon interaction of the nucleus field (nonlinear Bethe-Heitler).

- Designing and carrying out experimental works to measure some fundamental processes, using high-power lasers at ELI-NP.

To prepare an experiment at ELI-NP, both the kinematic analysis and evaluation of the dynamics of the interaction processes are necessary. Therefore, we first reviewed the kinematics of the linear QED processes and also the corresponding Feynman diagrams, shown in **Table 1**.

For nonlinear, non-perturbative multi-photon QED interactions, the Feynman diagram technique must be adapted from linear to nonlinear processes. This is done by switching to quantum fields described by Dirac-Volkov dressed states of particles in an intense EM field [23,24]. This allows the evaluation of the amplitude of the physical processes and finally the determination of the cross-sections of these processes.

The SF-QED processes of multi-photon interactions with strong laser fields must be investigated taking into account the characteristics of the ELI-NP facility in the context of strong laser field. Therefore it is necessary to use the corresponding Feynman diagrams with dressed particles. The evaluation of the Feynman diagrams allows to determine the invariant amplitude and the $\hat{S}$ matrix elements, using the electromagnetic $\hat{A}_\mu(x)$ and Dirac $\hat{\psi}(x)$ and $\hat{\bar{\psi}}(x)$ field operators with the corresponding Fourier annihilation and creation components. Finally the cross section could be calculated for experimantal design.

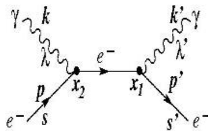
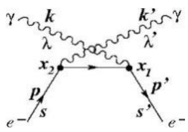
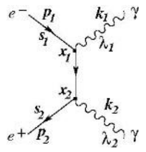
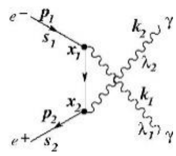
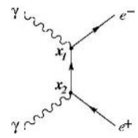
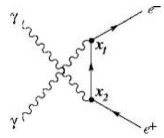
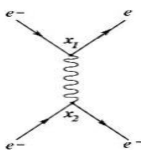
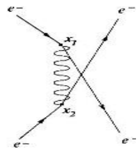
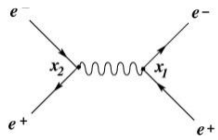
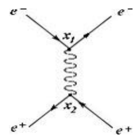
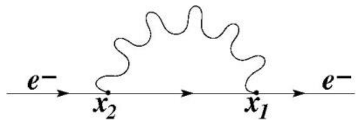
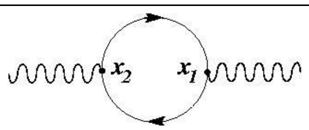
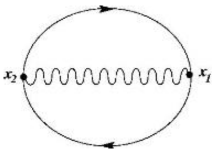
On the other hand, production of a large number of positrons with MeV energies opens the door to new avenues of antimatter research, including understanding the physics of various processes and phenomena in astrophysics, such as black holes and gamma-ray bursts [25,26] or from plasma physics [27,28].

Finally, presented the Organizational Chart with the necessary staff to prepare and realize the experimental project. The first important step assumes formation of a Task Force team and organize workshops, conferences and finally to prepare Letter of Intent, Conceptual Design Report and Technical Design Report.

Task Force objectives:

- Cross section evaluation for the SF-QED processes by Feynman diagrams with Volkov states
- Events generator of the physical process on the final states phase space
- Characteristic theoretical distributions of the physical process
- Experimental setup description and the setup detection parameters
- Detector simulation response and plot characteristic parameter distributions
- Particle transport and detector signal simulation
- Trigger organization, data acquisition and measuring process
- Data analysis and plot of measured physical quantities
- Real and background events selection with trigger and cut conditions on the ntuple experimental spectra
- Evaluation, interpretation and publication of the results

Table 1. The Feynman diagrams of some QED processes possible to be studied at ELI-NP.

Process	Feynman diagrams		$\hat{S}$ matrix element
photon-electron scattering $\gamma + e^- \rightarrow \gamma + e^-$ photon-positron scattering $\gamma + e^+ \rightarrow \gamma + e^+$			$\langle \gamma, e^- \vert \hat{S} \vert \gamma, e^- \rangle$ $\langle \gamma, e^+ \vert \hat{S} \vert \gamma, e^+ \rangle$
e^+e^- pair annihilation $e^+ + e^- \rightarrow \gamma + \gamma$			$\langle \gamma, \gamma \vert \hat{S} \vert e^-, e^+ \rangle$
e^+e^- pair production $\gamma + \gamma \rightarrow e^+ + e^-$			$\langle e^-, e^+ \vert \hat{S} \vert \gamma, \gamma \rangle$
e^-e^- Møller scattering $e^- + e^- \rightarrow e^- + e^-$ e^+e^+ Møller scattering $e^+ + e^+ \rightarrow e^+ + e^+$			$\langle e^-, e^- \vert \hat{S} \vert e^-, e^- \rangle$ $\langle e^+, e^+ \vert \hat{S} \vert e^+, e^+ \rangle$
e^+e^- Bhabha scattering $e^+ + e^- \rightarrow e^+ + e^-$			$\langle e^+, e^- \vert \hat{S} \vert e^+, e^- \rangle$
Electron self energy $e^- \rightarrow e^-$ Positron self energy $e^{-+} \rightarrow e^{-+}$			$\langle e^- \vert \hat{S} \vert e^- \rangle$ $\langle e^+ \vert \hat{S} \vert e^+ \rangle$
Photon self energy $\gamma \rightarrow \gamma$			$\langle \gamma \vert \hat{S} \vert \gamma \rangle$
Vacuum energy Vacuum → Vacuum			$\langle 0 \vert \hat{S} \vert 0 \rangle$

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Important Note

A. Leading ELI-NP topic has been sadly neglected

We observe a continuous degradation of Romania's position in most academic and research rankings, very far from the level corresponding to at least an average performance. This continuous involution and an obviously brain drain, have been known for many years, but there are no public signals that would really concern the public research organizations. We would like to improve the situation, in a priority area of at least our research organization. Specifically, involvement in the present topic of non-perturbative QED at ELI-NP could be brought forth, as it is specified in the **ELI-NP White-book,** Table 1 (p.7) "Overview of the main areas of the scientific case of ELI-NP"

> as the first priority in Basic science: (see https://www.eli-np.ro/whitebook.php p.7)
> 1. Fundamental physics of perturbative and non-perturbative high-field QED: pair creation, high energy γ rays, birefringence of the quantum vacuum.
>
> Project:
> 5.3.1 "Probing the Pair Creation from the Vacuum in the Focus of Strong Electrical Fields with a High Energy γ Beam" R. Sch¨utzhold et al.
>
> The experiments will allow for a new experimental window into the largely unexplored domain of non-perturbative quantum electrodynamics (QED). This has implications not just for QED, but also for fundamental issues in quantum field theory, as well as nuclear, atomic, plasma, gravitational and astro-physics.

With „ELI as the most advanced user facility in the world in the field of laser-driven science" (F.Negoita, 20-11-2020), it seems that Romania and especially IFIN-HH, as the major user of ELI-NP facility, could take advantage and invest in experimental studies of nonperturbative QED processes with high intensity lasers. For example, in the „IFIN-HH Strategy for the period 2020-2025" (p.7) is explicitly pointed out the IFIN-HH participation at ELI-NP as major user:

> 2.4. Action directions of the 2020-2025 stage.
> The following directions of the strategic objectives:
> a) Fundamental research ...
> - active involvement in the realization of ELI-NP and participation as a major user, after the system is put into use see https://www.nipne.ro/public_docs/strategy/Strategia_IFIN_2020-2025_Ro.pdf (p.7)

With the new possibilities offered by laser performances in the first decade of the 2000s, the ELI-NP 10 PW HPL was built. Concrete proposals were made in this regard in the ELI-NP White Book. This way it has opened up the possibility to use it in a new challenging field of non-linear QED vacuum interaction processes. With this in mind, we proposed the project "Nonperturbative processes in Strong Field QED".

Meanwhile, the possibility of addressing such research topics has also been expanded abroad with the construction of other such laser facilities (see A. Gonoskov et al. , Rev.Mod.Phys. 94, 2022, https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.94.045001 TABLE II. p. 54-55)

This subject has aroused special interest and has been included in the research programs of other important centers (Apollon (Papadopoulos et al., 2016), Station of Extreme Light (Cartlidge, 2018), Center for

Relativistic Laser Science (CoReLS) (Yoon et al., 2021), J-KAREN-P (Kiriyama et al., 2020), Omega Laser Facility (Bromage et al., 2019), Zetawatt-Equivalent Ultrashort Pulse Laser System (ZEUS) (Nees et al., 2020), LUXE (Abramowicz et al., 2019; Meuren, 2019)).

As a result, abroad, in these centers, important human, material and financial resources have been allocated to switch to the experimental works. Thus, the topic becomes a particularly attractive and stimulated an international scientific competition.

The ELI laser from Szeged (Hungary) will use the Heisenberg uncertainty relation between position and momentum to observe the evolving electron coordinates. So, they will instrumentalize the 2023 Nobel prize researches. The ELI laser from Magurele will still use the Heisenberg relation, but between time and energy, to instrumentalize the light-matter conversion by Breit-Wheeler and/or Bethe-Heitler production.

It is time that Romania also joins these endeavors and allocates all necessary attention and resources to this research proposition. Our project "Nonperturbative processes in Strong Field QED" of the ELI-RO program should be viewed as competitive with similar projects already undergoing at other facilities. Our preliminary research created the possibility to have a theoretical approach and an evaluation of the physical processes possible to be studied experimentally at 10 PW laser system. It aroused the interest of collaborations from abroad (see **3. External interest (contacts)** my emails correspondence below).

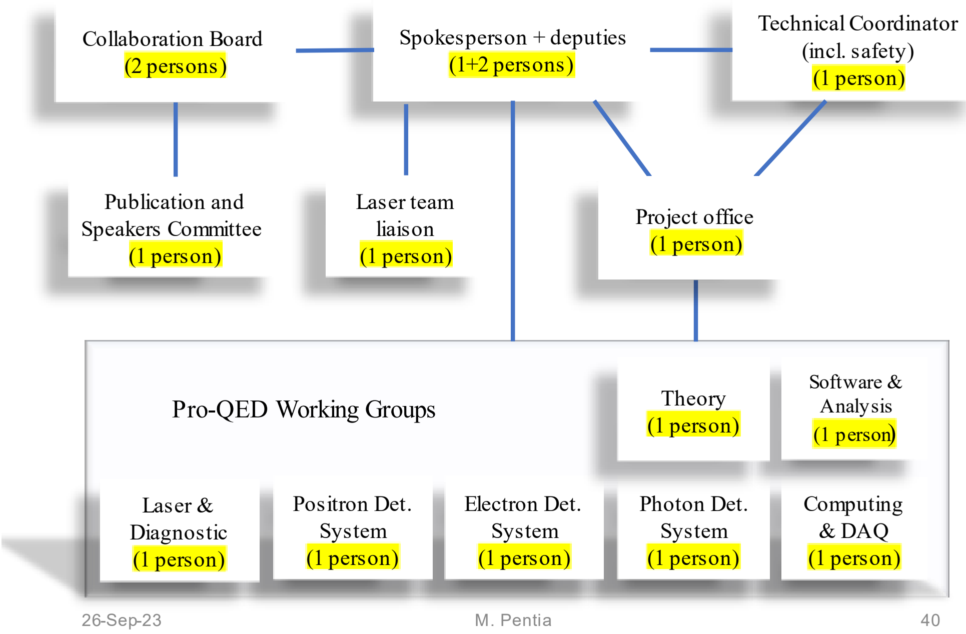
Therefore, I want to draw attention of the importance, potential and priorities offered by ELI-NP facility to host conversion of light to matter studies of fundamental research, as Breit-Wheeler and Bethe-Heitler pair production processes. To realize this experimental work, it is necessary to have access to qualified staff, specific equipment and materials, to bring to fruition this new valuable scientific research.

B. The need of financial support

All the statements mentioned above, require a strong managerial, manpower, material and financial support. The present-day funding of our project was completely unsatisfactory (see the Full Time Equivalent in the project, in "**Group members**" table).

The financing of such project should be prioritized based on the extraordinary scientific merit and attention it generates on the international stage.

Our project requires for the preparation and development of the works the management staff presented in the **Organizational chart** in Figure below.



I would like to draw attention to the importance and opportunity of this project, as it has already been noticed with great interest in the international community (see my received emails). Even with a delayed start of this strategic research direction, considering all the results accomplished during these 3 years of our project, with a proper funding and a good team in the future, there are real chances to get remarkable findings using the unique capabilities of ELI-NP.

1. Experimental programs at major petawatt laser facility include such research projects

Today experiments on radiation emission and pair creation in the strong-field regime form part of the planned experimental programs at almost every major petawatt or multi petawatt laser facility, including the

- Extreme Light Infrastructure (ELI) (Weber et al., 2017; Gales et al., 2018),
- Apollon (Papadopoulos et al., 2016),
- Station of Extreme Light (Cartlidge, 2018),
- Center for Relativistic Laser Science (CoReLS) (Yoon et al., 2021),
- J-KAREN-P (Kiriyama et al., 2020),
- Omega Laser Facility (Bromage et al., 2019),
- Zetawatt-Equivalent Ultrashort Pulse Laser System (ZEUS) (Nees et al., 2020),
- conventional accelerator facilities (Abramowicz et al., 2019; Meuren, 2019).

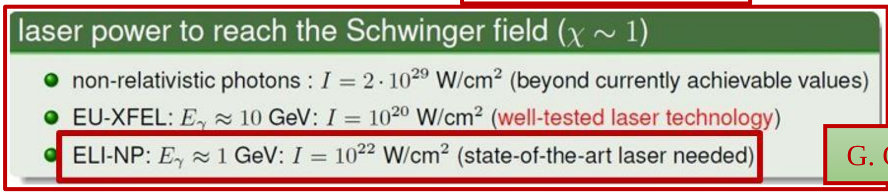
(cited from A. Gonoskov, T. G. Blackburn, M. Marklund, S. S. Bulanov, REVIEWS OF MODERN PHYSICS, VOLUME 94, OCTOBER–DECEMBER 2022.)
https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.94.045001

2. Similar projects are waiting for the ELI-NP experiment.

For example, LUXE (at DESY) project proposal (nine years later then our proposal of ELI-NP White Book) already has:

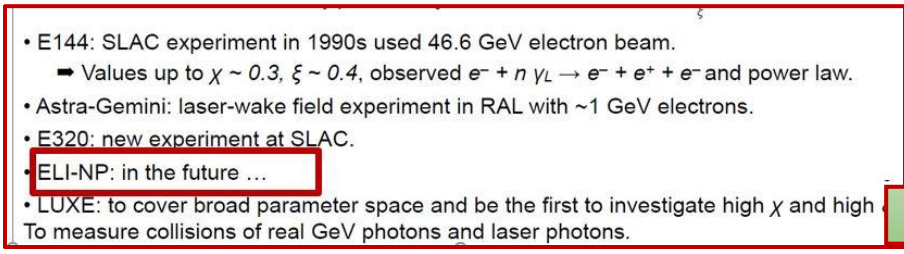
- **Letter of Intent for the LUXE Experiment** (H. Abramowicz et al.) **2019,** https://arxiv.org/abs/1909.00860v1
- **Conceptual Design Report for the LUXE Experiment (**H. Abramowicz, et al.) **2021**, https://arxiv.org/abs/2102.02032
- **Technical Design Report for the LUXE Experiment** (H. Abramowicz, et al.) **2023**, https://arxiv.org/abs/2308.00515

LUXE remarks



G. Grzelak, LUXE slides, 2020

https://indico.cern.ch/event/882870/contributions/3720001/attachments/1974963/3286730/The_LUXE_GG_Seminar.pdf



Wing (LUXE) slides, 2022

https://indico.desy.de/event/33338/contributions/117406/attachments/74703/95812/LUXE_PRC_May2022.pdf