Nonperturbative processes in Strong-Field QED (Pro-QED)

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The Pro-QED project proposed vacuum Strong Field QED (SF-QED) interaction processes to be studied at the ELI-NP laser light infrastructure https://arxiv.org/pdf/2307.09315.pdf. These processes were analyzed in 52 seminars and collected in a 582 pages book.

The investment for ELI-NP took into account the study of SF-QED, presented long time ago in the *ELI-NP White-Book* https://www.eli-np.ro/whitebook.php, page 7, under "Basic Science" and underlined as first priority for "Fundamental physics of perturbative and non-perturbative high-field QED: pair creation, high energy γ rays, birefringence of the quantum vacuum".

The studies of fundamental interactions in Electrodynamics always were of high interest, even awarded with Nobel Prizes (see **Figure 1**). This year, the Nobel Prize in physics was awarded to a specific subject explored at ELI-ALPS (Hungary) laser pillar. The topic was presented some time ago in the *ELI-ALPS White-Book* https://www.eli-alps.hu/files/Documents/file_eng/ELI-Book_low_res_version_1.pdf.

Now, the ELI-NP, with such equipment, could realistically be the next nominee.

The record laser power of 10 PW was achieved and now is ready for transition to the SF-QED experiments, able to capitalize on this unique asset. Meanwhile, the topic become of great interest worldwide. With the development of high-power lasers (see **Table 1**), similar works began to be prepared in other research centers, see **Table 2** https://arxiv.org/abs/1905.00059v1 and ELI-NP is seen as an important competitor.

The SF-QED interaction processes study is conditioned by the record power of 10 PW of the ELI-NP as to reach a sufficiently strong field, close to Schwinger critical threshold $Ecr = 1.3\ 10^{18}$ V/m.
The possibility to turn light into matter, suggested almost 90 years ago by G. Breit & J. A. Wheeler, *Collision of two light quanta*, Phys. Rev. 46(12), 1087 (1934), can now be tested experimentally, benefiting from the laser light intensity available at ELI-NP.

Our project proposes experimental works on vacuum Strong Field QED interaction processes with extreme light beams, which include:

- Systematic studies of the dynamics of fundamental SF-QED processes possible to approach at ELI-NP
- Evaluation of the amplitude and cross section, using “dressed” Dirac-Volkov states of quantum fields and propagators for charge particles in strong EM field, for the following processes: γ-e inverse Compton scattering, Breit-Wheeler e^+e^- pair production, Bethe-Heitler e^+e^- pair production, Dirac e^+e^- pair annihilation, e^-e^- Moller Scattering, e^+e^- Bhabha Scattering, Electron Self Energy, Photon Self Energy, Vacuum Energy (see **Table 3**).
- Designing the experimental works to measure some fundamental SF-QED processes, using high-power lasers at ELI-NP.
- Carrying out experimental works to measure 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).

The project proposes an Organizational Chart for the scientific staff of the experimental works.
The ELI-NP laser’s top performances to be used in SF-QED experiments, include (see **Fig.2**)
- Laser Wakefield Acceleration (LWFA) of the electrons at high energy, GeV order.
- Production of high-energy gamma photons, of GeV order (inverse Compton and Bremstrahlung)
- Light-matter conversion (Breit-Wheeler or Bethe-Heitler processes) as e^+e^- pair creation from light.

We hope our proposal will find the interest and support of the public research institutions in Romania.

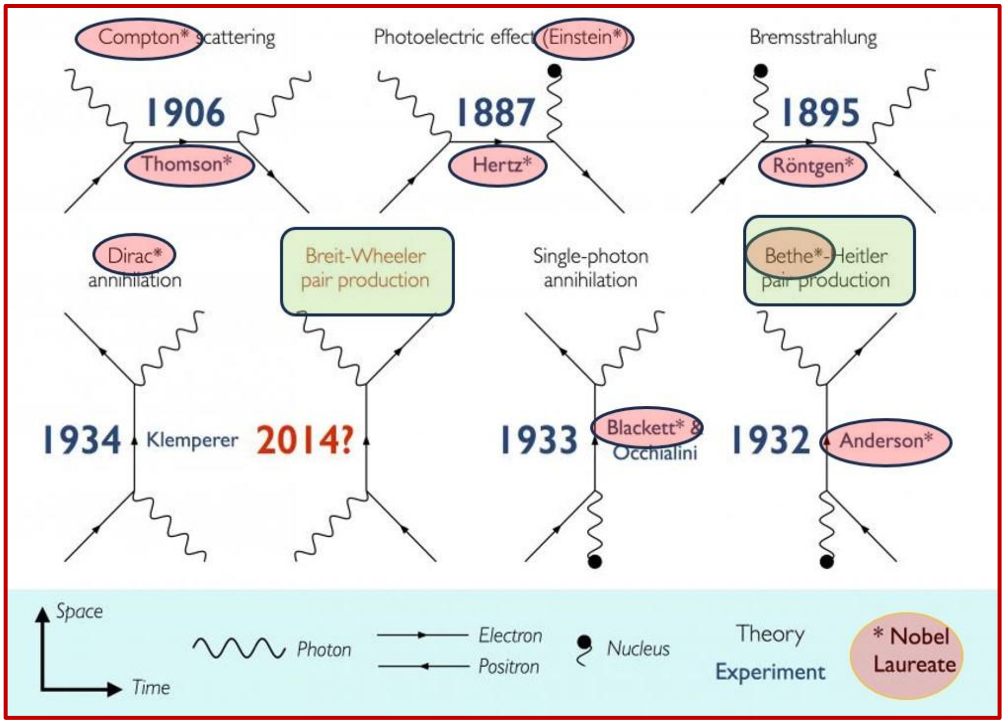


Figure 1. Diagrams of light-matter QED interactions. The linear Breit-Wheeler production of electron – positron pairs from the photon – photon interaction could not yet be demonstrated experimentally - Credit O. Pike https://phys.org/news/2014-05-scientists-year-quest.html

Tabel 1.

A.Gonoskov, T. G. Blackburn, and M. Marklund, S. S. Bulanov,
Charged particle motion and radiation in strong electromagnetic fields, Rev.Mod.Phys, V.94, Oct-Dec 2022
https://journals.aps.org/rmp/pdf/10.1103/RevModPhys.94.045001

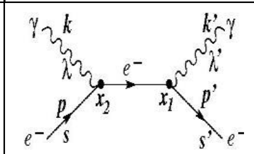
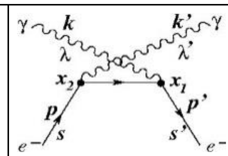
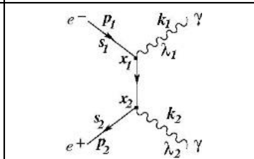
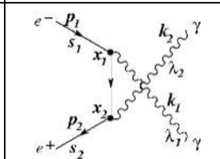
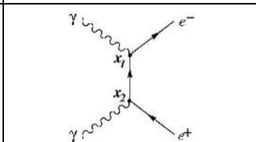
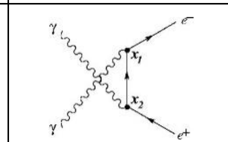
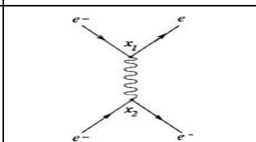
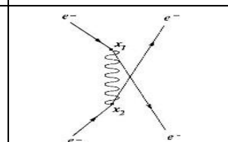
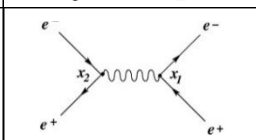
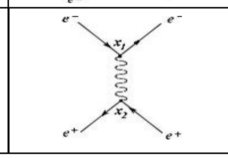
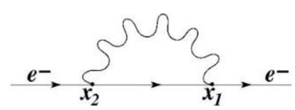
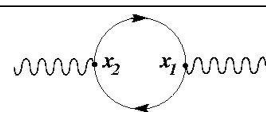
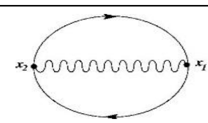
"Today experiments on radiation emission and pair creation in the strong-field regime form part of the planned experimental programs at almost every major petawatt or multi petawatt laser facility, including the

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

Table 2

Name	Year	$a_0^{\max}$	$\chi^{\max}$	Laser			e beam
				Power [TW]	A [μm^2]	λ [nm]	
E144	1990s	0.36	0.3	1	100	$500-1000$	$E_e = 46.6$ GeV, RF
Astra Gemini	2017	9.0	$0.15-0.3$	200	25	$800-1000$	$E_e \approx 1-2$ GeV LWFA
ELI-NP	2018	100	10	10000	10	800	up to 10 GeV, LWFA
FACET-II	2020	7.2	0.85	20	10	800	$E_e = 10$ GeV, RF
LUXE-I	2021	1.5	0.3	10	100	800	$E_e = 17.5$ GeV, RF
LUXE-II	2025	6.8	1.4	200	100	800	$E_e = 17.5$ GeV, RF

Table 3

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

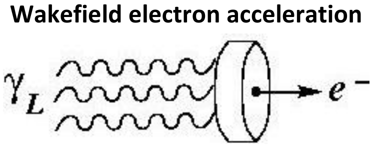
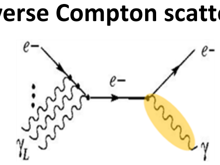
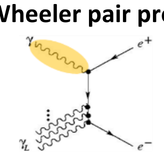
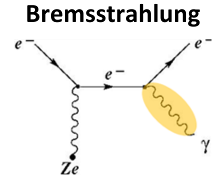
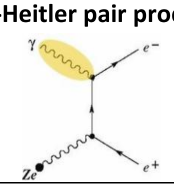
multi-photon electron acceleration	multi-photon (or nuclear) high-energy γ production	multi-photon (or nucleaer) $e^+ e^-$ pair production
Wakefield electron acceleration 	**Inverse Compton scattering** 	**Breit-Wheeler pair production** 
	Bremsstrahlung 	**Bethe-Heitler pair production** 

Fig. 2 $e^- e^+$ pair production by SF-QED multi-photon and/or nuclear - laser beam interactions