

Nonperturbative Processes

in strong field QED (Pro-QED)

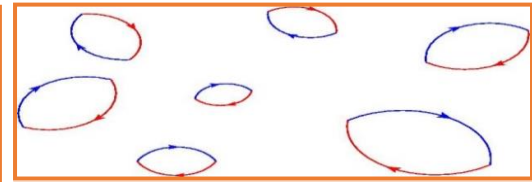
M.Pentia ISAB ELI-RO 7 Nov. 2023

Outline

1. Vacuum interactions – Schwinger effect
2. QED interaction processes (theory & exp.)
3. ELI-NP possibilities for SF-QED study
4. SF-QED upcoming experiments
5. Pro-QED results (see our Book:
“QED processes in Strong Laser Field” - 582 pages)
6. Task Force, plan and resources

1.1 QED Vacuum fluctuation - Schwinger field E_{cr}

Under normal conditions, the physical vacuum, due to the quantum fluctuations, is in a permanent "boiling", with local 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 their product cannot be smaller than \hbar .

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

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

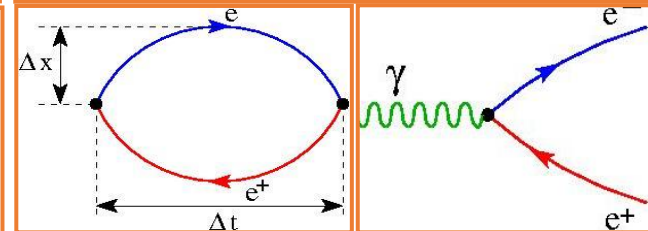
$$= 6.582119569 \times 10^{-16} \text{ eV} \cdot \text{s}$$

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

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

$$\Delta t \geq \hbar / 2m_e c^2 = 10^{-22} \text{ s}$$

Locally on Δx space can be produced electron-positron pairs, which live on the average Δt time, then they annihilate. A strong electric field can transfer enough energy to transform virtual pairs into real pairs.



The characteristic range $2\Delta x$ the electric field can produce e^+e^- pairs is given by *electron reduced Compton wavelength*

$$2\Delta x \approx 2c\Delta t = \frac{\hbar}{m_e c} = \lambda_c \approx 386 \cdot 10^{-15} \text{ m}$$

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

$$W = F \cdot \lambda = \frac{eE\hbar}{m_e c} > 2m_e c^2$$

or minimum value of the electric field is

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

The critical value of the electric field E_{cr} (*Schwinger field*) i.e. starting value for spontaneously production of real e^+e^- pairs from laser field - vacuum interaction:

$$E_{cr} = \frac{m_e^2 c^3}{\hbar e} = 1.323 \cdot 10^{18} \text{ V / m}$$

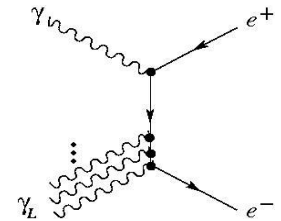
1.2 Pair creation from the vacuum - conversion of light to matter

One of the **amazing predictions of the QED** as a fundamental EM interaction, little studied experimentally, is the conversion of light to matter. Their nonperturbative and nonlinear features can shed a light on the properties of the **QED vacuum**.

QED vacuum is a polarizable medium of virtual e^-e^+ pairs, they can be converted into real e^-e^+ pairs \rightarrow conversion to matter.

Such **particle creation from the EM field** is possible:

- in a static electric field – **Schwinger effect**,
- in a laser (coherent) photon field – **Breit-Wheeler production**, or
- in a combination of the two – **Bethe-Heitler production**,

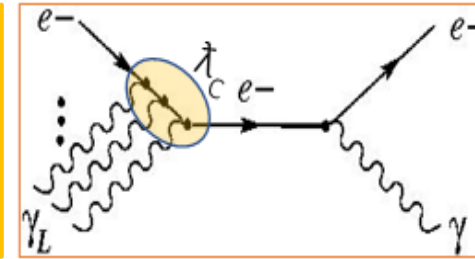


has been of interest the crossover between the two pair production mechanisms:

- **due to strong constant electric fields** but less than critical value $qEl < 2mc^2$ and
- **due to spatial or temporal variations** but less than critical value $\hbar\omega < 2mc^2$

1.3 Generation of the E_{cr} Schwinger critical field

In a coherent multi-photon laser interaction, the constructive superposition of the electric field component ensures a total electric E_L value close to the Schwinger critical field $E_{cr} = 1.323 \cdot 10^{18} \text{ V/m}$. This E_L value is higher the higher the photon density (laser intensity).



The laser intensity parameter ξ - the work of the laser field over the electron Compton wavelength:

$$\xi = \frac{eE_L}{m_e c \omega_L} = eE_L \frac{\lambda_c}{\hbar \omega_L} = eE_L \frac{\lambda_L}{m_e c^2} \quad \text{where} \quad \lambda_c = \frac{\hbar}{m_e c} \quad \lambda_L = \frac{c}{\omega_L}$$

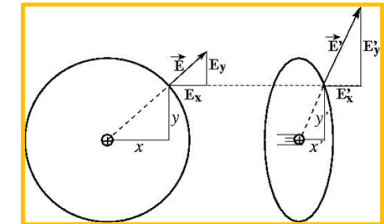
The ξ^2 measures the average intensity of the laser beam $I_L = \epsilon_0 c \langle E_L^2 \rangle \implies E_L = 1944 \cdot \sqrt{I_L}$

for ELI-NP intensity $I_L \approx 10^{22} - 10^{23} \text{ W/cm}^2$, laser light pulses lead to field intensity $E_L \approx 10^{14} - 10^{15} \text{ V/m}$

$$\xi^2 = 3.65 \times 10^{-19} I_L \lambda_L^2 \quad \text{for} \quad I_L \text{ in } \text{W/cm}^2 \text{ and } \lambda_L \text{ in } \mu\text{m}$$

At ELI-NP for wavelength $\lambda_L = 0.815 \mu\text{m}$ and pulse intensity $I_L \sim 10^{23} \text{ W/cm}^2$, we have at least $\xi \cong 500$

E_L in the rest frame of a relativistic, counter-propagating electron with laboratory energy E_e and Lorentz factor $\gamma_e = E_e / mc^2 \gg 1$ the laser electric field strength appears boosted to $E^* = 2\gamma_e E_L$



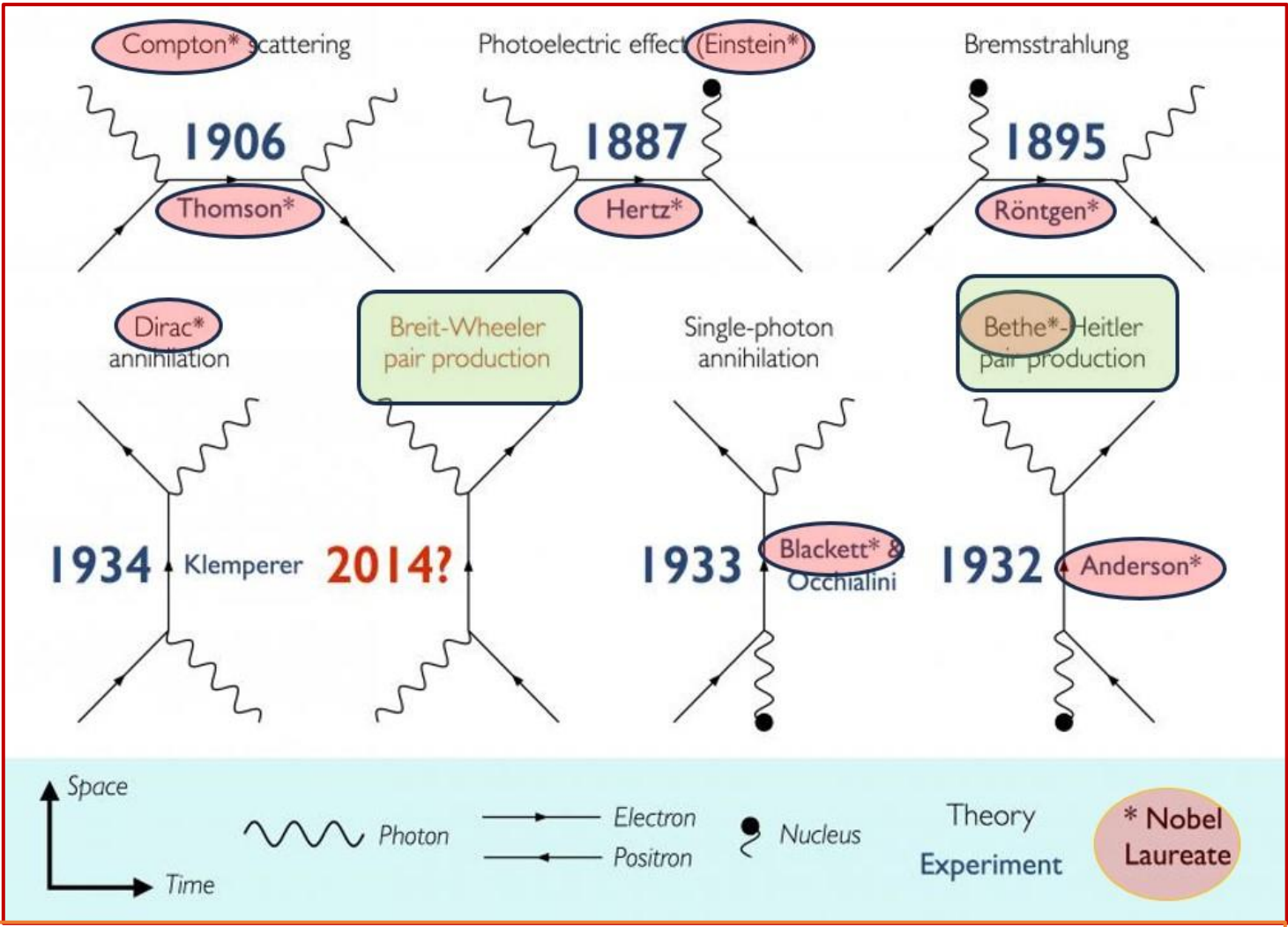
for an electron beam energy $\epsilon_e = 10 \text{ GeV}$, the Lorentz factor is $\gamma_e = \epsilon_e / m_e c^2 \approx 2 \cdot 10^4$ and if a laser beam collides it head-on, electron "sees" a boosted laser field $E^* \approx 2 \cdot 10^{18} \text{ V/m}$

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2.1 QED interaction processes – nowadays ones of the most interesting topics

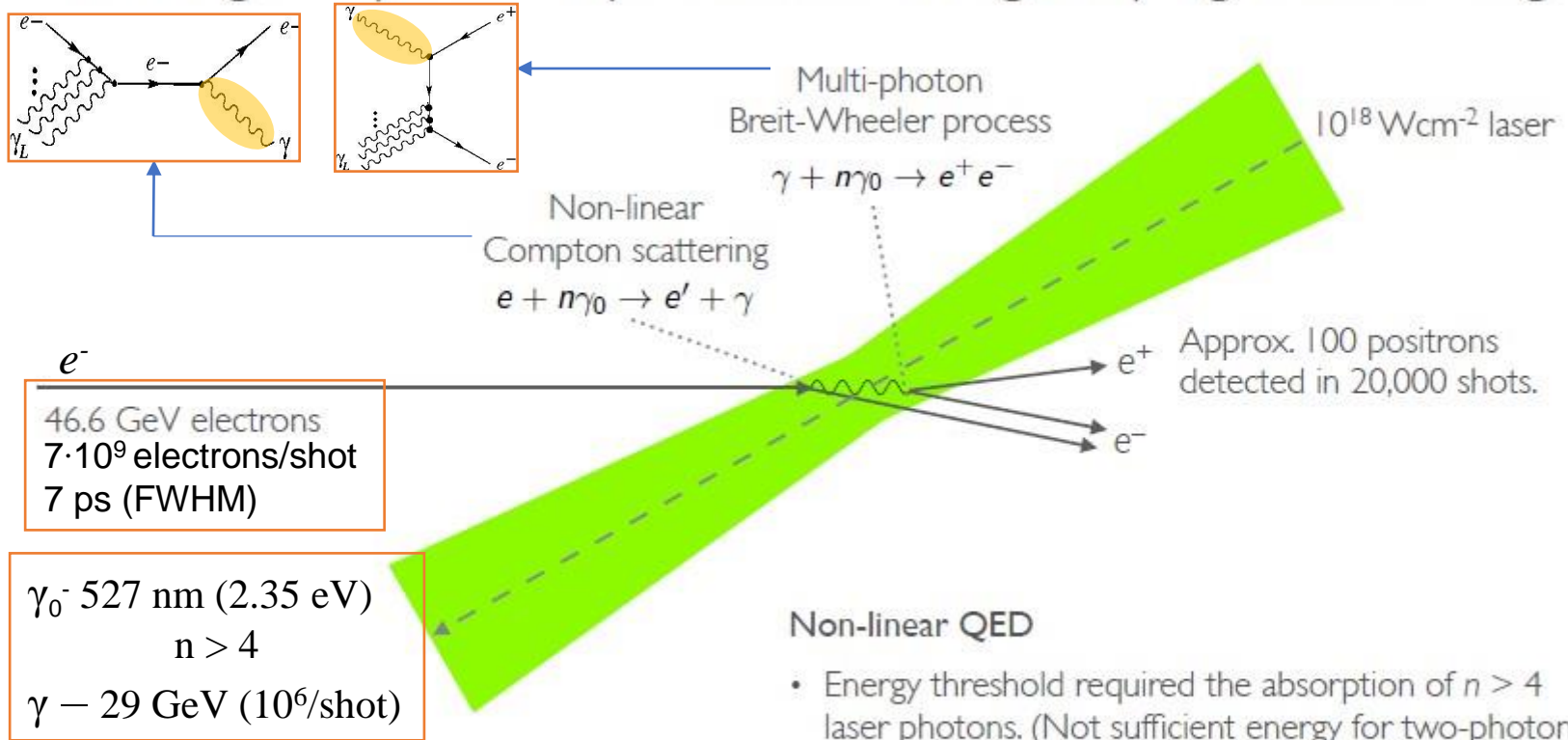
The Feynman diagrams for the QED light – matter interactions. Breit-Wheeler pair production has not yet been demonstrated experimentally.
 credit O. J. Pike, F. Mackenroth, E. G. Hill and S. J Rose,
 “A photon-photon collider in a vacuum hohlraum”
Nature Photonics 8, 434-436 (2014).
 doi:10.1038/nphoton.2014.95



- The **ELI-ALPS laser** (Szeged - Hungary) will use the Heisenberg uncertainty relation $\Delta x \Delta p \geq \hbar/2$ to observe the evolving electron coordinates → instrumentalize the 2023 **Nobel prize** winner’s researches
- The **ELI-NP laser** (Magurele) will still use the same Heisenberg uncertainty relation $\Delta t \Delta E > \hbar/2$ to instrumentalize the light - matter conversion by **Breit-Wheeler and/or Bethe-Heitler pair production** with laser light

2.2 E-144 SLAC Experiment (electron – laser collision) - 1997

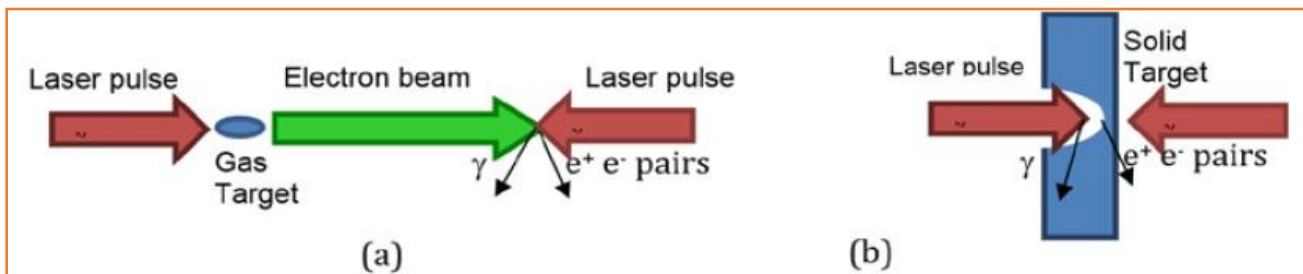
SLAC E-144 experiment:
first sign of positron production in light-by-light scattering



Burke et al., PRL 79, 1626 (1997)
Hu & Müller, PRL 107, 090402 (2010)

- Non-linear QED**
- Energy threshold required the absorption of $n > 4$ laser photons. (Not sufficient energy for two-photon interaction.)
 - Recently shown that, on average, $n = 6.44$ laser photons were absorbed.

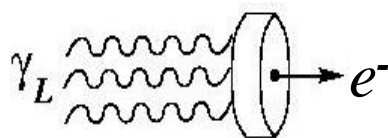
2.3 The race for experimental test of light to matter conversion



Fundamental interactions in SF-QED

multi-photon
electron acceleration

Wakefield acceleration

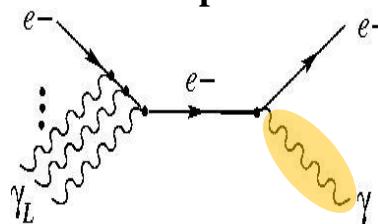


$$eEl < 2mc^2$$

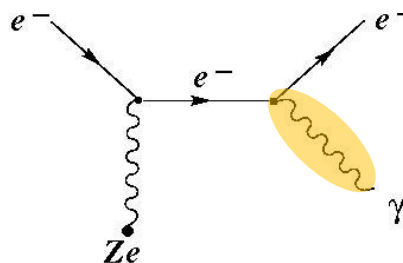
$$\hbar\omega < 2mc^2$$

multi-photon (or nuclear)
high-energy γ production

Inverse Compton scattering

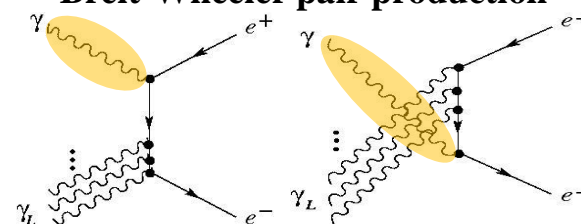


Bremsstrahlung

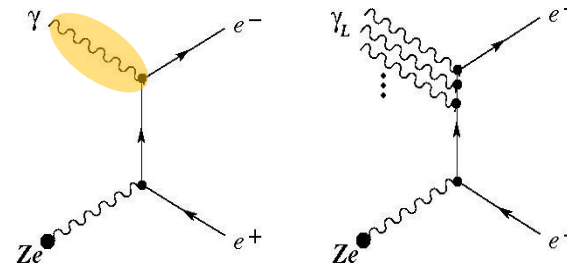


multi-photon (or nuclear)
 e^+e^- production

Breit-Wheeler pair production



Bethe-Heitler pair production



*ELI-NP is a jewel for such research topics
(noted in 2010, ELI-NP White Book)*

2.4 ELI-NP White Book - Scientific Case of ELI-NP (2010)

“The high power laser allows for intensities of up to 10^{24} W/cm². Here very interesting synergies are achievable with the γ beam and the brilliant high energy electron beam to study new fundamental processes in high field QED. When the γ beam is injected into the focus of the high intensity laser, which in this special case consists of a standing E-field of two focused lasers, *the most recent (2009) nonperturbative QED calculations predict that one can observe already at 10^{24} W/cm² the catalytic pair creation from the vacuum [2–4]. If confirmed, this would constitute a very basic non-perturbative textbook QED result.*”

- [2] G. V. Dunne, H. Gies and R. Schützhold, Phys. Rev. D 80, 111301 (2009) [arXiv:0908.0948 [hep-ph]].
 [3] V. N. Baier and V. M. Katkov, “Pair creation by a photon in an electric field,” arXiv:0912.5250 ; (2009).
 [4] N.B. Narozhny, Zh. Eksp. Teo. Fiz. 54, 676 (1968).

Table 1: Overview of the main areas of the scientific case of ELI-NP

Science Case of ELI-NP	
Basic Science	Applications
Fundamental physics of perturbative and non-perturbative high-field QED: – pair creation, high energy γ rays, birefringence of the quantum vacuum	Developing nuclear resonance fluorescence (NRF) for nuclear materials and radioactive waste management: – ²³⁵ U, ²³⁹ Pu, minor actinides, neutron poison
High-resolution nuclear spectroscopy: (γ, γ'), (γ, n), (γ, p), (γ, α), (e, e'), ($e, e'\gamma$), (γ, f) – neutron halo isomers, chaotic properties of nuclear states, nuclear potential landscape, parity-violating meson-nucleon coupling, pygmy dipole resonance	Brilliant γ , X, n, e ⁺ , e ⁻ micro beams in material science and life science: – (γ, n) reaction at threshold for low energy neutrons, (γ, e^+e^-) reaction at 2-3 MeV for cold positrons
Astrophysics of the r-, s-, p-processes in nucleosynthesis: – masses of waiting point nuclei, pygmy resonance	Developing techniques of laser acceleration and of a brilliant γ beam for nuclear physics: – relativistic mirrors

2.5 Upcoming Experiments

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 (Kiriya et al., 2020)
Zetawatt-Equivalent Ultrashort Pulse Laser System (ZEUS – Michigan Univ.) (Nees et al.,2020)	LUXE (Abramowicz et al, 2019; Meuren, 2019”

Name	Year	a_0^{\max}	χ^{\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

LUXE Workshop 2019 <https://arxiv.org/abs/1905.00059v1>

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3.1 ELI-NP QED Proposal History

Dream 2009

G. V. Dunne (University of Connecticut) in the paper “*New strong-field QED effects at extreme light infrastructure*” in Eur. Phys. J. D 55, 327–340 (2009) remarked “**the ELI project open up an entirely new non-perturbative regime of QED**, and of quantum field theories in general. There are many experimental and theoretical challenges ahead. Theoretically, the biggest challenge in the non-perturbative arena is to develop efficient techniques, both analytical and numerical, for computing the effective action and related quantities, in external fields that realistically represent the experimental laser configurations. A lot of progress has been made in this direction, but new ideas and methods are still needed”.

Plan 2010

ELI-NP White-book, „Table 1: Overview of the main areas of the scientific case of ELI-NP” (p.7) as the first priority in Basic science:

- **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. Schützhold 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.

Today

- **C. E. Turcu et al.** in the paper “*Quantum electrodynamics experiments with colliding petawatt laser pulses*” in High Power Laser Science and Engineering, Vol. 7, e10 (2019) **Now the 2 x 10 PW laser beams of the ELI-NP laser facility has the interaction chambers dedicated to QED experiments [42-44]**
- **M. Pentia et al.** “*Vacuum strong field QED interaction processes at ELI-NP facility*” in <https://arxiv.org/pdf/2307.09315.pdf> **Studies of fundamental QED processes possible to be investigated with high power lasers**

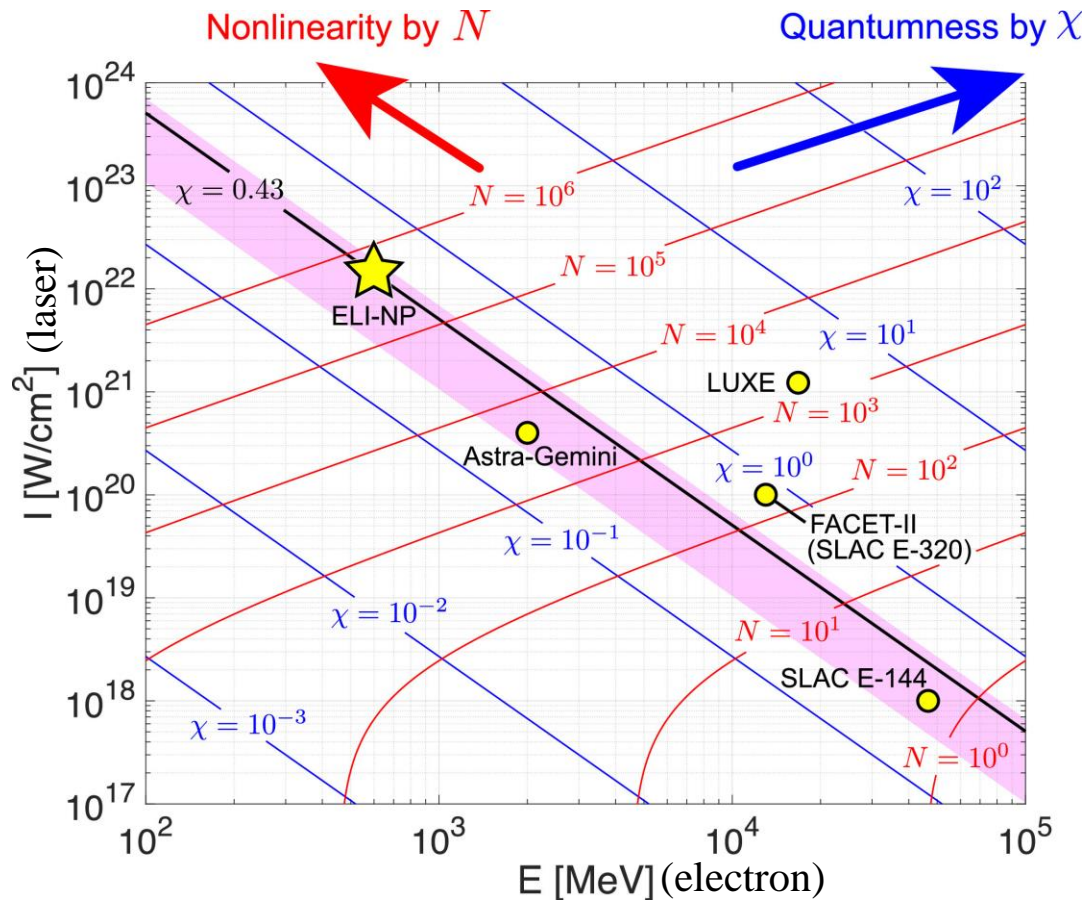
Tomorrow

Letter of Intent – Conceptual Design Report – Technical Design Report

- Proposal of experimental works for measuring physical properties related to the production of e^+e^- pairs (Schwinger mechanism) in photon-multiphoton interaction (Breit-Wheeler), photon-electron or photon-nucleus (Bethe-Heitler) interaction and production and measurement of QED bound states (positronium).
- Experimental measurement of some fundamental QED processes with High Power Lasers at ELI-NP.

(conditioned by adequate support for manpower, equipment and materials)

3.2 ELI-NP possibilities (K.Seto 2021)



Before collision (e + laser)

$$\begin{pmatrix} E \\ p \end{pmatrix} + N \times \begin{pmatrix} \hbar\omega \\ \hbar k \end{pmatrix} = \begin{pmatrix} E' \\ p' \end{pmatrix} + \begin{pmatrix} \hbar\omega' \\ \hbar k' \end{pmatrix}$$

After collision (e + gamma)

$$\chi \propto \hbar \times \text{electron energy } (E) \times \sqrt{\text{laser intensity } (I)}.$$

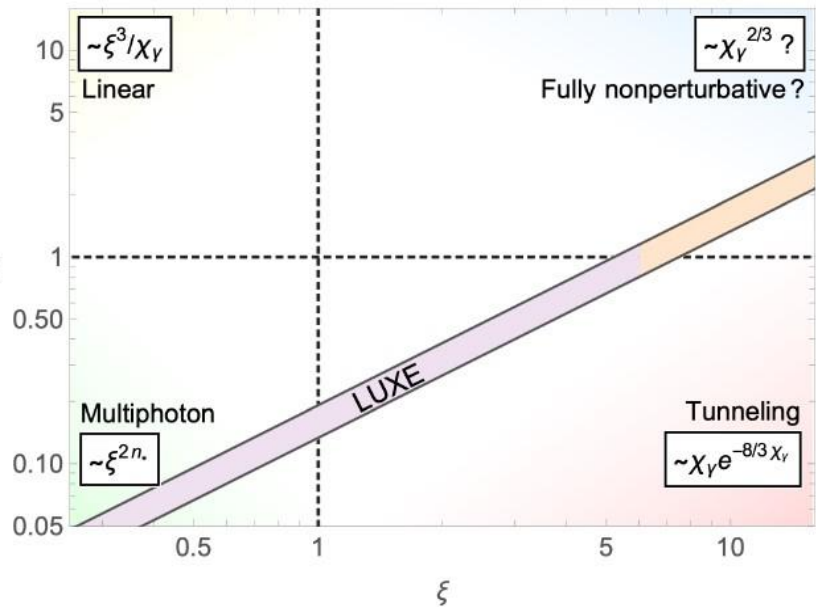
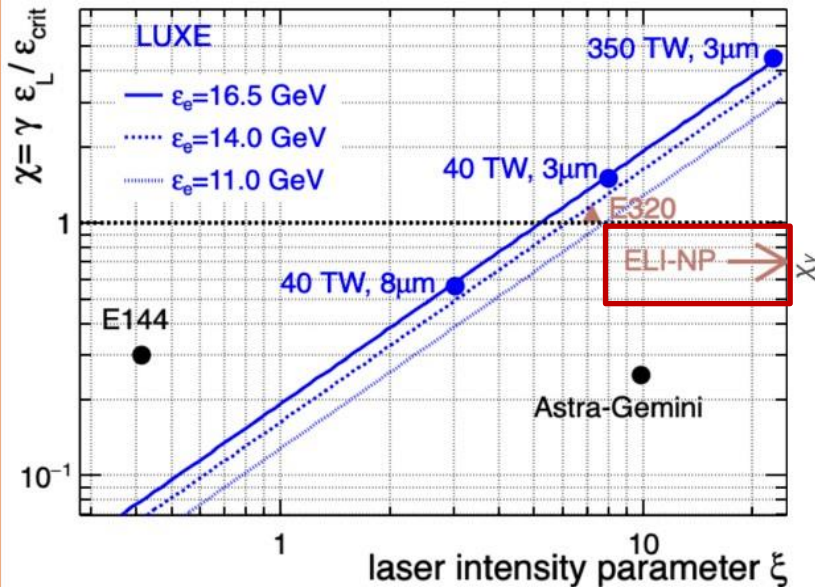
$$N \propto \frac{\hbar\omega'}{E - \hbar\omega'} \times \frac{I}{E}, \quad \hbar\omega' = \frac{E}{2}.$$

So, consider the uses of photons from 10 keV to GeV-class !

(K. Seto, Seminar 2021)

The physical regime diagram of RR. The curves at given N and χ are shown in the diagram. N is the number of absorbed laser photon and χ is intensity parameter. Here, an emitted photon energy $\hbar\omega'$ is selected as $\hbar\omega' = E/2$ for an electron energy E , $\theta_{\text{in}} = 155^\circ$ and $\hbar\omega = 1.5$ eV are taken into account to estimate where the proposed experiment at ELI-NP is. The pink ribbon represents the domain as $\chi \in [0.2, 0.5]$. We consider “linear” Compton scattering in the area where $N \leq 1$ (a single laser photon absorption) by given $\hbar\omega'$ and E . The star symbol shows the parameter set at ELI-NP. (K. Seto, Seminar 2021)

Strong-field QED parameter space



- E144: SLAC experiment in 1990s used 46.6 GeV electron beam.
 - ➔ Values up to $\chi \sim 0.3$, $\xi \sim 0.4$, observed $e^- + n \gamma_L \rightarrow e^- + e^+ + e^-$ and power law.
- Astra-Gemini: laser-wake field experiment in RAL with ~ 1 GeV electrons.
- E320: new experiment at SLAC.
- **ELI-NP: in the future ...**
- LUXE: to cover broad parameter space and be the first to investigate high χ and high ξ . To measure collisions of real GeV photons and laser photons.

5

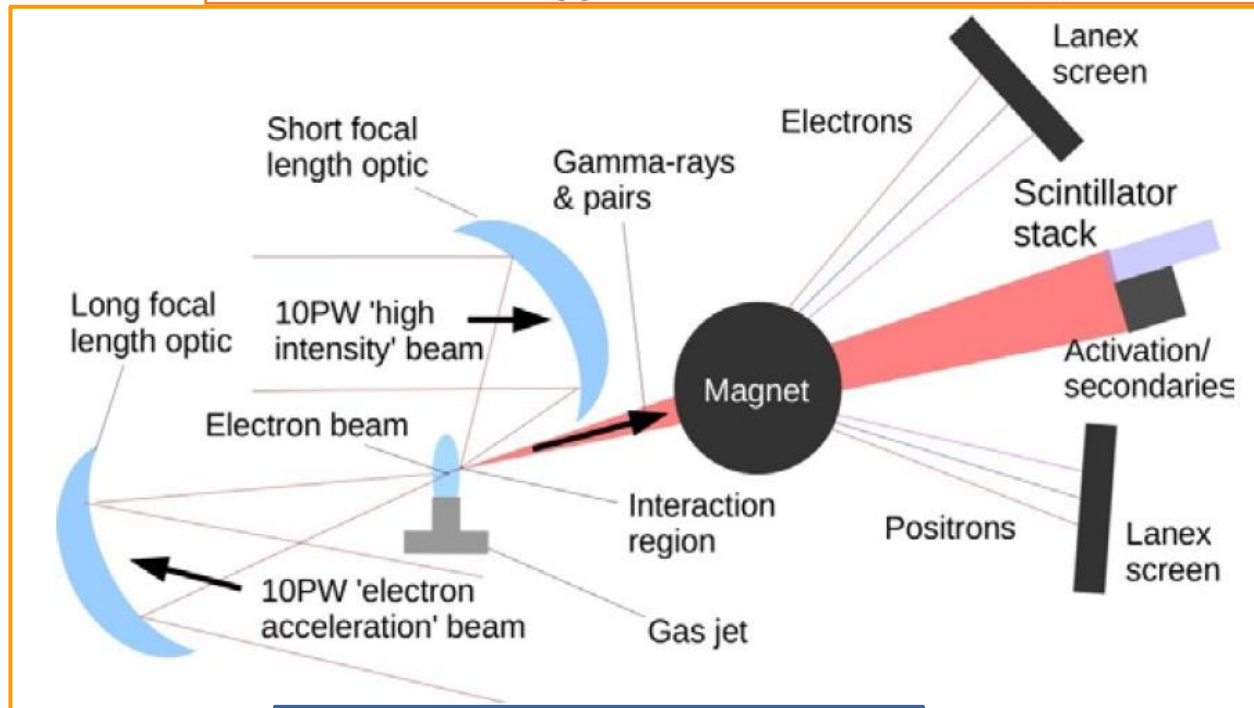
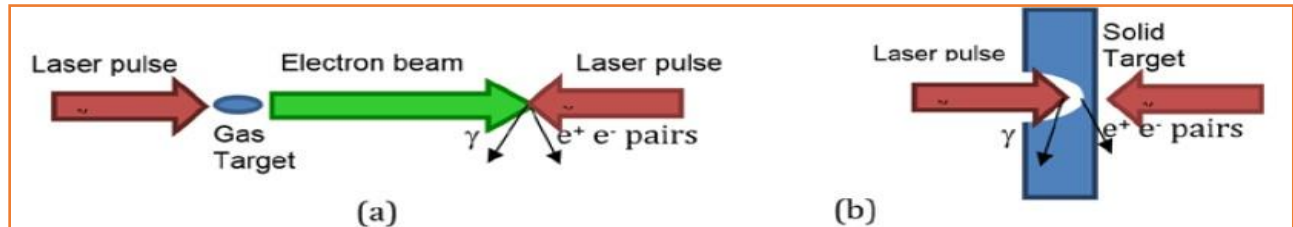
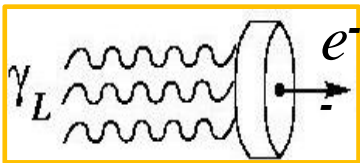
3.4 ELI-NP possibility to study QED Processes

I.C.E. Turcu et al, "High field physics and QED experiments at ELI-NP", Rom. Rep. Phys. 68, Supplement, S145 (2016).

ELI-NP facility will enable for the first time the use of two 10 PW laser beams for QED experiments.

- The first beam will accelerate electrons to relativistic energies.
- The second beam will subject relativistic electrons to the strong electromagnetic field generating QED processes: intense gamma ray radiation and electron-positron pair formation.

Wakefield acceleration



3.5 ELI-NP possibility to study QED Processes

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The experimental area E6 at ELI-NP is ready for investigating high field physics and QED for production of electron-positron-pairs and of energetic gamma-rays.

Two pump-probe colliding 10 PW laser beams are proposed for the E6 interaction chamber. The focused pump laser beam accelerates the electrons to relativistic energies. The accelerated electron bunches interact with the very high EM field of the focused probe laser beam.

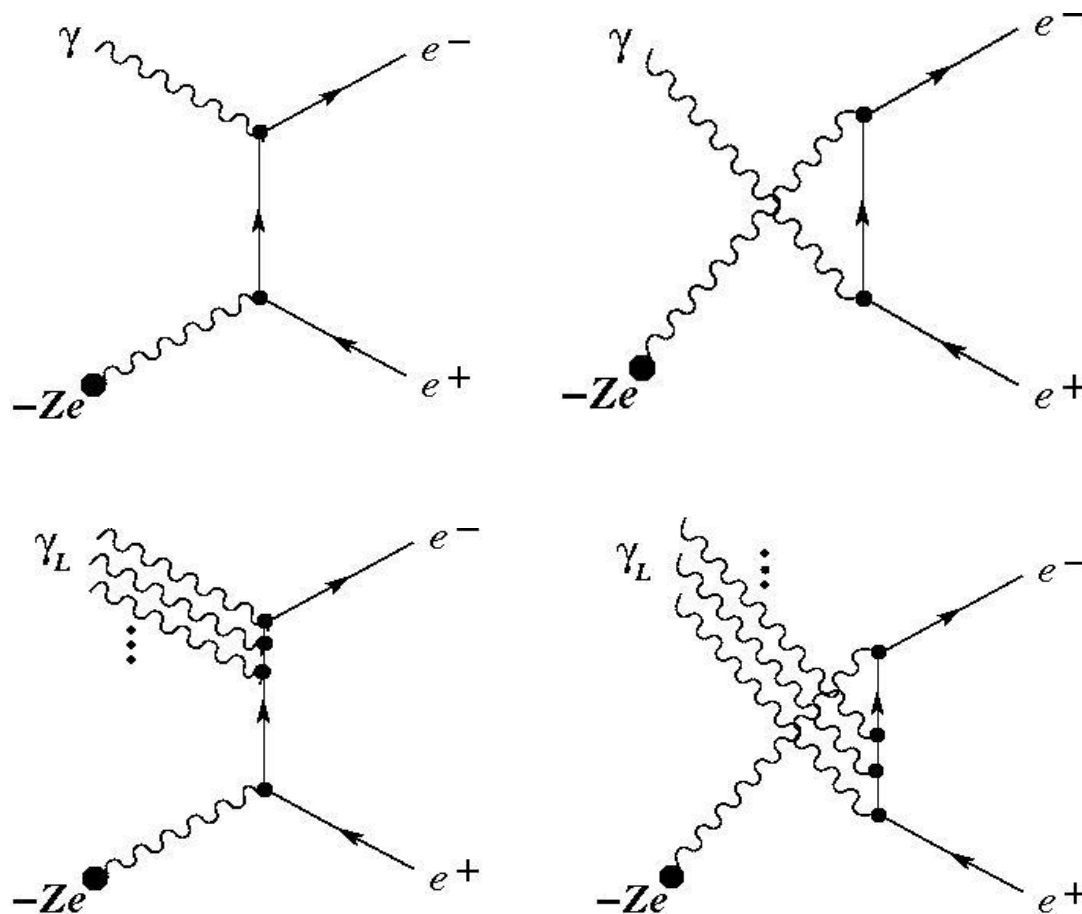
Proposed two main types of experiments with: (a) *gas targets* in which the pump laser-beam is focused by a long focal length mirror and drives a wakefield in which the electron bunch is accelerated to multi-GeV energies and then exposed to the EM field of the probe laser which is tightly focused; (b) *solid targets* in which both the pump and probe laser beams are focused on the solid target, one accelerating the electrons in the solid and the other, delayed, providing the high electric field to which the relativistic electrons are subjected.

We propose to use the unique capabilities of ELI-NP to:

1. Observe the transition to the very **nonlinear Compton scattering** regime,
2. Measure the **nonlinear Breit-Wheeler pair production**.
3. Measure the **nonlinear Bethe-Heitler pair production** (nuclear physics)

3.6 Bethe-Heitler laser interaction with nuclei – specific to ELI-NP

Bethe-Heitler pair production by laser beam interaction with nuclei - special interest for ELI-NP



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4.1 LUXE (Laser Und XFEL Experiment) at DESY

<https://luxe.desy.de/>

launched nine years later then our proposal in ELI-NP White Book, published 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>

laser power to reach the Schwinger field ($\chi \sim 1$)

- non-relativistic photons : $I = 2 \cdot 10^{29}$ W/cm² (beyond currently achievable values)
- EU-XFEL: $E_\gamma \approx 10$ GeV: $I = 10^{20}$ W/cm² (well-tested laser technology)
- ELI-NP: $E_\gamma \approx 1$ GeV: $I = 10^{22}$ W/cm² (state-of-the-art laser needed)

G. Grzelak, LUXE slides, 2020

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

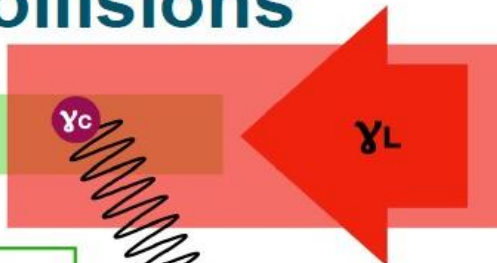
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To measure collisions of real GeV photons and laser photons.

Wing (LUXE) slides, 2022

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

LUXE: electron-laser collisions

High-energy electrons
(16.5 GeV XFEL beam)



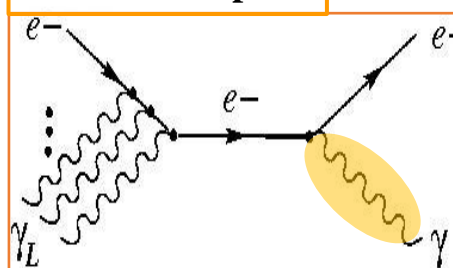
High-intensity LASER
(Tera-Watt, 800nm)
→ large E-field

note: in reality, LASER
crossing angle $\theta=17.2^\circ$

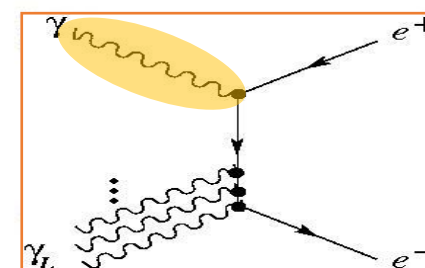
Lorentz boost:
electrons “see” larger
E-field of the LASER
in their rest frame:
 $E^* = \gamma_e \mathcal{E}_L (1 + \cos \theta)$

**electron-positron
pair production**

Inverse Compton



+



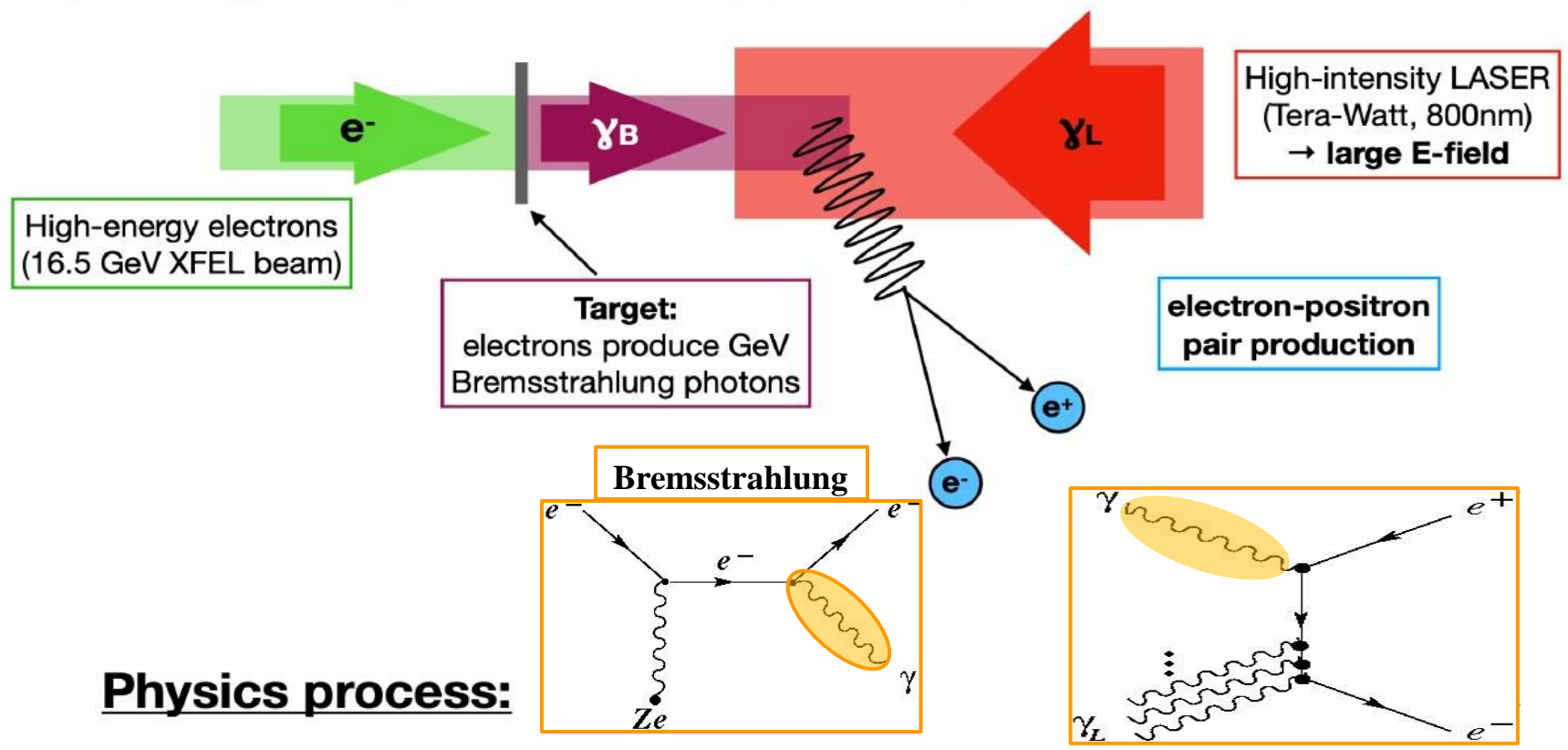
Physics processes:

- 1 **Non-linear Compton Scattering:** $e^- + n\gamma_L \rightarrow e^- + \gamma_C$
- 2 **Non-linear Breit-Wheeler pair production:** $\gamma_C + n\gamma_L \rightarrow e^+ + e^-$

• LUXE main goals:

- ➔ Measure Compton scattering (and edge position) versus laser intensity.
- ➔ Measure positron rate versus laser intensity.

LUXE: photon-laser collisions



Non-linear Breit-Wheeler pair production : $\gamma_B + n\gamma_L \rightarrow e^+ + e^-$

Outline

1. Vacuum interaction – Schwinger effect
2. QED interaction processes (theory & exp.)
3. ELI-NP possibilities for SF-QED study
4. SF-QED upcoming experiments
5. Pro-QED results (see our Book:
“QED processes in Strong Laser Field” - 582 pages)
6. Task Force, plan and resources

5.1 Feynman Diagrams for QED Processes

PROCES	INTERACTIA	ELEMENT MATRICE \hat{S}	PROCES	INTERACTIA	ELEMENT MATRICE \hat{S}
Imprăștiere foton-electron $\gamma + e^- \rightarrow \gamma + e^-$		$\langle \gamma, e^- \hat{S} \gamma, e^- \rangle$	Imprăștierea Bhabha $e^- + e^+ \rightarrow e^- + e^+$		$\langle e^-, e^+ \hat{S} e^-, e^+ \rangle$
Imprăștiere foton-pozitron $\gamma + e^+ \rightarrow \gamma + e^+$		$\langle \gamma, e^+ \hat{S} \gamma, e^+ \rangle$	Anihilare perechi e^+e^- $e^- + e^+ \rightarrow \gamma + \gamma$		$\langle \gamma, \gamma \hat{S} e^-, e^+ \rangle$
Anihilare perechi e^+e^- $e^- + e^+ \rightarrow \gamma + \gamma$		$\langle \gamma, \gamma \hat{S} e^-, e^+ \rangle$	Energie proprie electron $e^- \rightarrow e^-$		$\langle e^- \hat{S} e^- \rangle$
Producere perechi e^+e^- $\gamma + \gamma \rightarrow e^- + e^+$		$\langle e^-, e^+ \hat{S} \gamma, \gamma \rangle$	Energie proprie pozitron $e^+ \rightarrow e^+$		$\langle e^+ \hat{S} e^+ \rangle$
Imprăștierea Møller e^- $e^- + e^- \rightarrow e^- + e^-$		$\langle e^-, e^- \hat{S} e^-, e^- \rangle$	Energie proprie foton $\gamma \rightarrow \gamma$		$\langle \gamma \hat{S} \gamma \rangle$
Imprăștierea Møller e^+ $e^+ + e^+ \rightarrow e^+ + e^+$		$\langle e^+, e^+ \hat{S} e^+, e^+ \rangle$	Energie vacuum Vacuum \rightarrow Vacuum		$\langle 0 \hat{S} 0 \rangle$

$$\hat{A}_\mu(x) = \int \frac{d^3\vec{k}}{(2\pi)^3} \frac{1}{2\omega} \left[\underbrace{\hat{a}_\lambda(\vec{k}) \epsilon_\mu^\lambda e^{-ik \cdot x}}_{\sim \hat{A}_\mu^-(x)} + \underbrace{\hat{a}_\lambda^\dagger(\vec{k}) \epsilon_\mu^\lambda e^{ik \cdot x}}_{\sim \hat{A}_\mu^+(x)} \right]$$

$$\hat{\psi}(x) = \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{m}{\omega} \left[\underbrace{\hat{b}(\vec{p}) u(\vec{p}) e^{-ip \cdot x}}_{\sim \hat{\psi}^-(x)} + \underbrace{\hat{c}^\dagger(\vec{p}) v(\vec{p}) e^{ip \cdot x}}_{\sim \hat{\psi}^+(x)} \right]$$

$$\hat{\bar{\psi}}(x) = \int \frac{d^3\vec{p}}{(2\pi)^3} \frac{m}{\omega} \left[\underbrace{\hat{c}(\vec{p}) \bar{v}(\vec{p}) e^{-ip \cdot x}}_{\sim \hat{\bar{\psi}}^-(x)} + \underbrace{\hat{b}^\dagger(\vec{p}) \bar{u}(\vec{p}) e^{ip \cdot x}}_{\sim \hat{\bar{\psi}}^+(x)} \right]$$

$$\hat{A}_\mu^-(x) \rightarrow \hat{a} - \text{anihilare foton în } x \quad \hat{A}_\mu^+(x) \rightarrow \hat{a}^\dagger - \text{creare foton în } x$$

$$\hat{\psi}^-(x) \rightarrow \hat{b} - \text{anihilare electron în } x \quad \hat{\psi}^+(x) \rightarrow \hat{c}^\dagger - \text{creare pozitron în } x$$

$$\hat{\bar{\psi}}^-(x) \rightarrow \hat{c} - \text{anihilare pozitron în } x \quad \hat{\bar{\psi}}^+(x) \rightarrow \hat{b}^\dagger - \text{creare electron în } x$$

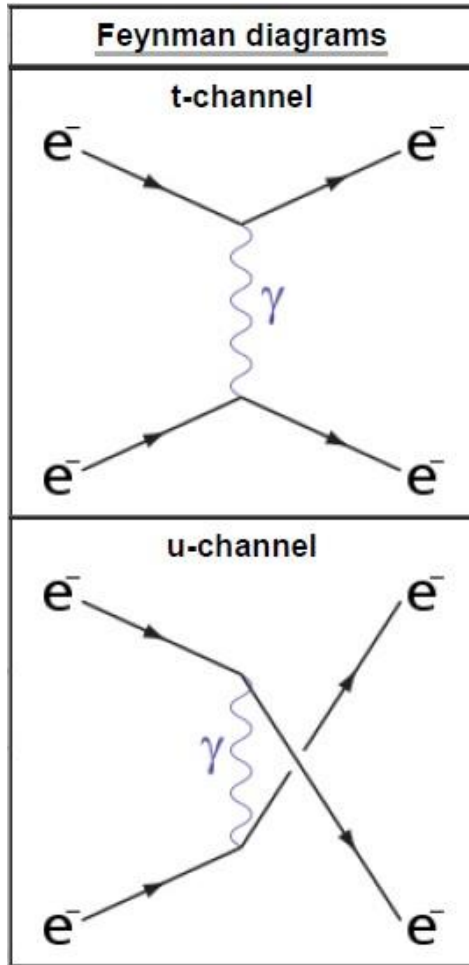
5.2 Feynman Diagrams Evaluation for Nonlinear SF-QED Processes

Linear, single-photon QED interaction processes described by Feynman diagrams presented before, can be studied in the multi-photon regime using the same Feynman diagrams, but with "dressed" (Dirac-Volkov) particle states and propagators, because the particle is moving in the oscillating EM field.

The **Strong Field Feynman rules** are summarized in [28]:

1. External incoming or outgoing electrons with momentum p are represented by laser **dressed Dirac-Volkov state** $\hat{\psi}(x)$ or $\hat{\bar{\psi}}(x)$ respectively.
2. For incoming and outgoing positrons, one uses the corresponding negative energy **dressed Dirac-Volkov wave function**.
3. An internal fermion line corresponds to the **Dirac-Volkov propagator**.
4. Internal and external photon lines are translated into the **free photon propagator** and the **free photon wave functions**, respectively.
5. Each interaction vertex corresponds to a factor $-ie\gamma_\mu$ and an integral d^4x .
6. Symmetry factors for identical particles are the same as in usual QED.

5.3 Cross section (example) – linear e^-e^- scattering



$$d\sigma = \frac{|\mathcal{M}|^2}{F} dLips$$

$$i\mathcal{M}_t = (-ie)^2 \bar{u}(p_3) \gamma^\mu u(p_1) \frac{-i}{t} \bar{u}(p_4) \gamma_\mu u(p_2)$$

$$i\mathcal{M}_u = (-ie)^2 \bar{u}(p_3) \gamma^\mu u(p_2) \frac{-i}{u} \bar{u}(p_4) \gamma_\mu u(p_1)$$

$$i\mathcal{M} = i(\mathcal{M}_t - \mathcal{M}_u)$$

$$= -i(-ie)^2 \left[\frac{1}{t} \bar{u}(p_3) \gamma^\mu u(p_1) \bar{u}(p_4) \gamma_\mu u(p_2) - \frac{1}{u} \bar{u}(p_3) \gamma^\mu u(p_2) \bar{u}(p_4) \gamma_\mu u(p_1) \right]$$

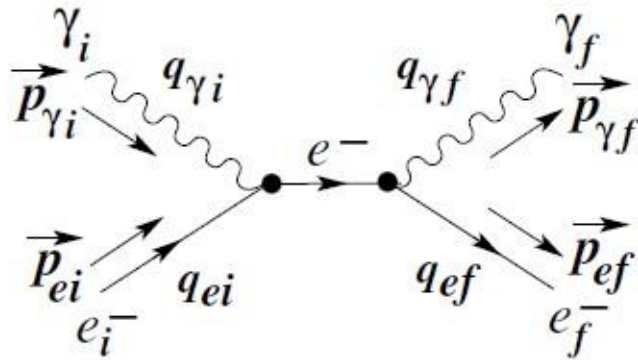
$$p_1 = (E, 0, 0, p), \quad p_2 = (E, 0, 0, -p)$$

$$p_3 = (E, p \sin \theta, 0, p \cos \theta), \quad p_4 = (E, -p \sin \theta, 0, -p \cos \theta)$$

$$\begin{aligned} \overline{|\mathcal{M}|^2} &\equiv \frac{1}{4} \sum_{\text{spins}} |\mathcal{M}|^2 \\ &= 2e^4 \left\{ \frac{1}{t^2} (s^2 + u^2 - 8m^2(s+u) + 24m^4) \right. \\ &\quad + \frac{1}{u^2} (s^2 + t^2 - 8m^2(s+t) + 24m^4) \\ &\quad \left. + \frac{2}{tu} (s^2 - 8m^2s + 12m^4) \right\} \end{aligned}$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{E_{CM}^2 p^4 \sin^4 \theta} \left[4(m^2 + 2p^2)^2 + (4p^4 - 3(m^2 + 2p^2)^2) \sin^2 \theta + p^4 \sin^4 \theta \right]$$

5.4 Kinematics of the γ - e scattering



$$\epsilon_\gamma = \hbar\omega \quad \vec{p}_\gamma = \frac{\epsilon_\gamma}{c} \vec{n}_\gamma$$

$$\epsilon_e = \gamma_e m_e c^2 \quad \vec{p}_e = \gamma_e m_e \vec{v}_e = \frac{\epsilon_e}{c^2} \vec{v}_e = \frac{\epsilon_e}{c} \vec{\beta}_e$$

$$q \equiv \left(\frac{E}{c}, \vec{p} \right) \quad \text{metric: } g_{\mu\mu} = (1, -1, -1, -1)$$

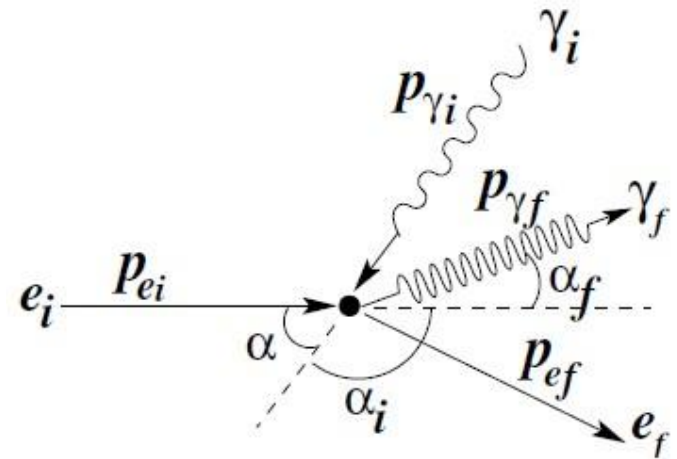
$$q^2 = \frac{E^2}{c^2} - \vec{p}^2 = m_e^2 c^2$$

$q_{\gamma i} = \frac{\epsilon_{\gamma i}}{c} (1, \vec{n}_{\gamma i})$	$q_{\gamma f} = \frac{\epsilon_{\gamma f}}{c} (1, \vec{n}_{\gamma f})$	$\beta_e = \frac{p_e c}{\epsilon_e} = \frac{v_e}{c}$
$q_{e i} = \frac{\epsilon_{e i}}{c} (1, \vec{\beta}_{e i})$	$q_{e f} = \frac{\epsilon_{e f}}{c} (1, \vec{\beta}_{e f})$	$\gamma_e = \frac{\epsilon_e}{m_e c^2} = \frac{1}{\sqrt{1 - \beta_e^2}}$

A. Kinematics of the $e_i \gamma_i \rightarrow e_f \gamma_f$ scattering

The 4-momentum conservation, see Fig.7:

$$q_{\gamma i} + q_{e i} = q_{\gamma f} + q_{e f}$$



$$\epsilon_{\gamma f} = \frac{\epsilon_{e i}}{1 + \frac{m_e^2 c^4}{\epsilon_{\gamma i} \epsilon_{e i}} \frac{1}{(1 + \beta_{e i} \cos \alpha)}}$$

1. Strong QED field in intense laser fields

- a) <https://indico.eli-np.ro/event/90/attachments/256/457/01-ProQED-Grad-Div-Rot-Unde-EM.pdf>
- b) <https://indico.eli-np.ro/event/90/attachments/256/458/02-ProQED-Ec-Maxwell.pdf>
- c) <https://indico.eli-np.ro/event/90/attachments/256/459/03-ProQED-Campuri-Clasice.pdf>
- d) <https://indico.eli-np.ro/event/90/attachments/256/460/04-ProQED-Mec-Cuantica.pdf>
- e) <https://indico.eli-np.ro/event/90/attachments/256/461/05-ProQED-1-Osci-Mec-Long-Transv.pdf>
- f) <https://indico.eli-np.ro/event/90/attachments/256/463/06-ProQED-Oscilatii-Mecanice.pdf>
- g) <https://indico.eli-np.ro/event/90/attachments/256/464/07-ProQED-Transf-Calibrare.pdf>
- h) <https://indico.eli-np.ro/event/90/attachments/256/465/08-ProQED-Camp-Calibrare.pdf>
- i) <https://indico.eli-np.ro/event/90/attachments/256/466/09-ProQED-Camp-Clasic-Cuant.pdf>
- j) <https://indico.eli-np.ro/event/90/attachments/256/467/10-ProQED-Osc-Arm-Camp-ClasCuant.pdf>
- k) <https://indico.eli-np.ro/event/90/attachments/256/431/11-ProQED-proiect.pdf>
- l) <https://indico.eli-np.ro/event/90/attachments/256/468/12-ProQED-Camp-Clasic-Cuant.pdf>
- m) <https://indico.eli-np.ro/event/90/attachments/256/469/14-ProQED-De-la-Mec-Camp-Cuant.pdf>
- n) <https://indico.eli-np.ro/event/90/attachments/256/470/15-ProQED-Cuantif-camp-EM.pdf>
- o) <https://indico.eli-np.ro/event/90/attachments/256/471/16-ProQED-Camp-clasice.pdf>
- p) <https://indico.eli-np.ro/event/90/attachments/256/472/17-ProQED-Teoria-perturbatii.pdf>
- q) <https://indico.eli-np.ro/event/90/attachments/256/473/18-Pro-QED-Serii-Dyson.pdf>
- r) <https://indico.eli-np.ro/event/90/attachments/256/474/19-Pro-QED-particle-in-strong-EM.pdf>

5.5 Works

2. Strong-field quantum effects and pair production by Breit-Wheeler process

- a) <https://indico.eli-np.ro/event/90/attachments/256/477/20-Pro-QED-Diag-Feynman.pdf>
- b) https://indico.eli-np.ro/event/90/attachments/256/479/21_ProQED-Peak-Intensity.pdf
- c) <https://indico.eli-np.ro/event/90/attachments/256/480/22-ProQED-Diag-Feynman-cont.pdf>
- d) <https://indico.eli-np.ro/event/90/attachments/256/489/23-ProQED-Laser-physics.pdf>
- e) <https://indico.eli-np.ro/event/90/attachments/256/487/24-ProQED-Sect-efic-diag-Feynman.pdf>
- f) <https://indico.eli-np.ro/event/90/attachments/256/490/25-ProQED-photon-photon-scatt.pdf>
- g) <https://indico.eli-np.ro/event/90/attachments/256/575/26-ProQED-el-gama-interact-Mandelstam.pdf>

3. Laser strong field - matter interactions

- a) <https://indico.eli-np.ro/event/90/attachments/256/492/27-PeOQED-Relativistic-Plasma-Mirrors.pdf>
- b) <https://indico.eli-np.ro/event/90/attachments/256/501/28-ProQED-rezumat-Feynman.pdf>
- c) <https://indico.eli-np.ro/event/90/attachments/256/494/29-Pro-QED-Generare-pulsuri-laser-PW.pdf>
- d) <https://indico.eli-np.ro/event/90/attachments/256/507/30-ProQED-propagatori-Feynman.pdf>
- e) <https://indico.eli-np.ro/event/90/attachments/256/515/31-Pro-QED-Compton.pdf>
- f) <https://indico.eli-np.ro/event/90/attachments/256/576/32-Pro-QED-el-scatt.pdf>
- g) <https://indico.eli-np.ro/event/90/attachments/256/520/33-Pro-QED-g-g-e-e+pair-creation.pdf>
- h) <https://indico.eli-np.ro/event/90/attachments/256/523/34-Pro-QED-procese-perturbative-ordin-I.pdf>
- i) <https://indico.eli-np.ro/event/90/attachments/256/528/35-Pro-QED-HPLS.pdf>

4. Spontaneous pair production via Schwinger mechanism

- a) <https://indico.eli-np.ro/event/90/attachments/256/574/36-Pro-QED-curenti-si-propagatori.pdf>
- b) <https://indico.eli-np.ro/event/90/attachments/256/577/37-Pro-QED-Cuantificare-Campuri.pdf>
- c) <https://indico.eli-np.ro/event/90/attachments/256/586/38-Pro-QED-Cuantif-camp-Dirac.pdf>
- d) <https://indico.eli-np.ro/event/90/attachments/256/588/39-Pro-QED-Cuantif-energie-camp-Dirac.pdf>
- e) <https://indico.eli-np.ro/event/90/attachments/256/590/40-Pro-QED-Cuantificare-Camp-KG.pdf>
- f) <https://indico.eli-np.ro/event/90/attachments/256/592/41-Pro-QED-Rel-comutare-camp-EM.pdf>
- g) [https://indico.eli-np.ro/event/90/attachments/256/593/42-Pro-QED-Cuantif-camp-EM\(Coulomb\).pdf](https://indico.eli-np.ro/event/90/attachments/256/593/42-Pro-QED-Cuantif-camp-EM(Coulomb).pdf)
- h) <https://indico.eli-np.ro/event/90/attachments/256/597/43-Pro-QED-Gauge-Theory.pdf>
- i) <https://indico.eli-np.ro/event/90/attachments/256/608/44-Pro-QED-Op-evol-interact-picture.pdf>
- j) <https://indico.eli-np.ro/event/90/attachments/256/611/45-Pro-QED-Propagatori-Feynman.pdf>
- k) <https://indico.eli-np.ro/event/90/attachments/256/612/46-Pro-QED-Teorema-Wick.pdf>
- l) <https://indico.eli-np.ro/event/90/attachments/256/618/47-Pro-QED-calc-propagator-Feynman.pdf>
- m) <https://indico.eli-np.ro/event/90/attachments/256/632/48-Pro-QED-Sol-Volkov-ec-Dirac-in-camp-EM.pdf>
- n) <https://indico.eli-np.ro/event/90/attachments/256/639/49-Pro0QED-propagator-contractii-VEV.pdf>
- o) <https://indico.eli-np.ro/event/90/attachments/256/674/50-Pro-QED-Feynman-proc-QED.pdf>
- p) <https://indico.eli-np.ro/event/90/attachments/256/683/51-ProQED-Cinematica-Compton.pdf>

5.5 Works

5. Blue paper for experimental test of some QED nonperturbative effects

Title: “*Vacuum strong field QED interaction processes at ELI-NP facility*”

Authors: M. Pentia, C. R. Badita, D. Dumitriu, A. R. Ionescu, H. Petrascu

Corresponding Author: M. Pentia pentia@nipne.ro

<https://arxiv.org/pdf/2307.09315.pdf>

6. 52 Lectures on specific topics for collaborators to create a strong theoretical and experimental team

(<https://indico.eli-np.ro/event/90/>)

7. 12 Lectures for young people and high school students "Saturday Morning Physics"

(<https://indico.eli-np.ro/event/74/>)

8. List of talks of group members (title, conference or meeting, date);

- WORD QUANTUM DAY – April 14 2023

QED processes at ELI-NP 30m

Speaker: Prof. Mircea Pentia (DFN, IFIN-HH, Magurele)

<https://indico.nipne.ro/event/247/>

<https://indico.eli-np.ro/event/90/attachments/256/676/Pro-QED-Quantum.pdf>

- Scientific session - Bucharest University Faculty of Physics 2023

Title: Studies of Strong Field QED Processes at ELI-NP

Mircea PENTIA, Chivuta BADITA, Dana DUMITRIU, Amilcar IONESCU, Horia PETRASCU

<https://ssffb.fizica.unibuc.ro/SSFFB/Section.php?SectID=221>

<https://indico.eli-np.ro/event/90/attachments/256/697/Prezentare-Fac-Fiz-2023-Pro-SFQED.pdf>

9. List of papers:

- “Investigation of K^+K^- pairs in the effective mass region near $2m_K$ ”
B. Adeva ... M. Pentic et al. (DIRAC Collaboration)
Corresponding Author: M. Pentic *pentic@nipne.ro*
published in Phys. Rev. D 106, 032006 (2022)
<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.106.032006>
- “The Strong Field QED approach of the vacuum interaction processes at ELI-NP”
M. Pentic, C.R. Badita, D. Dumitriu, A.R. Ionescu, H. Petrascu
Corresponding Author: M. Pentic *pentic@nipne.ro*
<https://arxiv.org/abs/2307.09315> (2023).

9. Book (in Romanian)

Title: “**QED processes in Strong Laser Field**” (582 pages)

Author: *M. Pentic* pentic@nipne.ro

<https://indico.eli-np.ro/event/90/attachments/279/713/0-pro-qed.pdf>

Outline

1. Vacuum interaction – Schwinger effect
2. QED interaction processes (theory & exp.)
3. ELI-NP possibilities for SF-QED study
4. SF-QED upcoming experiments
5. Pro-QED results (see our Book:
“QED processes in Strong Laser Field” - 582 pages)
6. Task Force, plan and resources

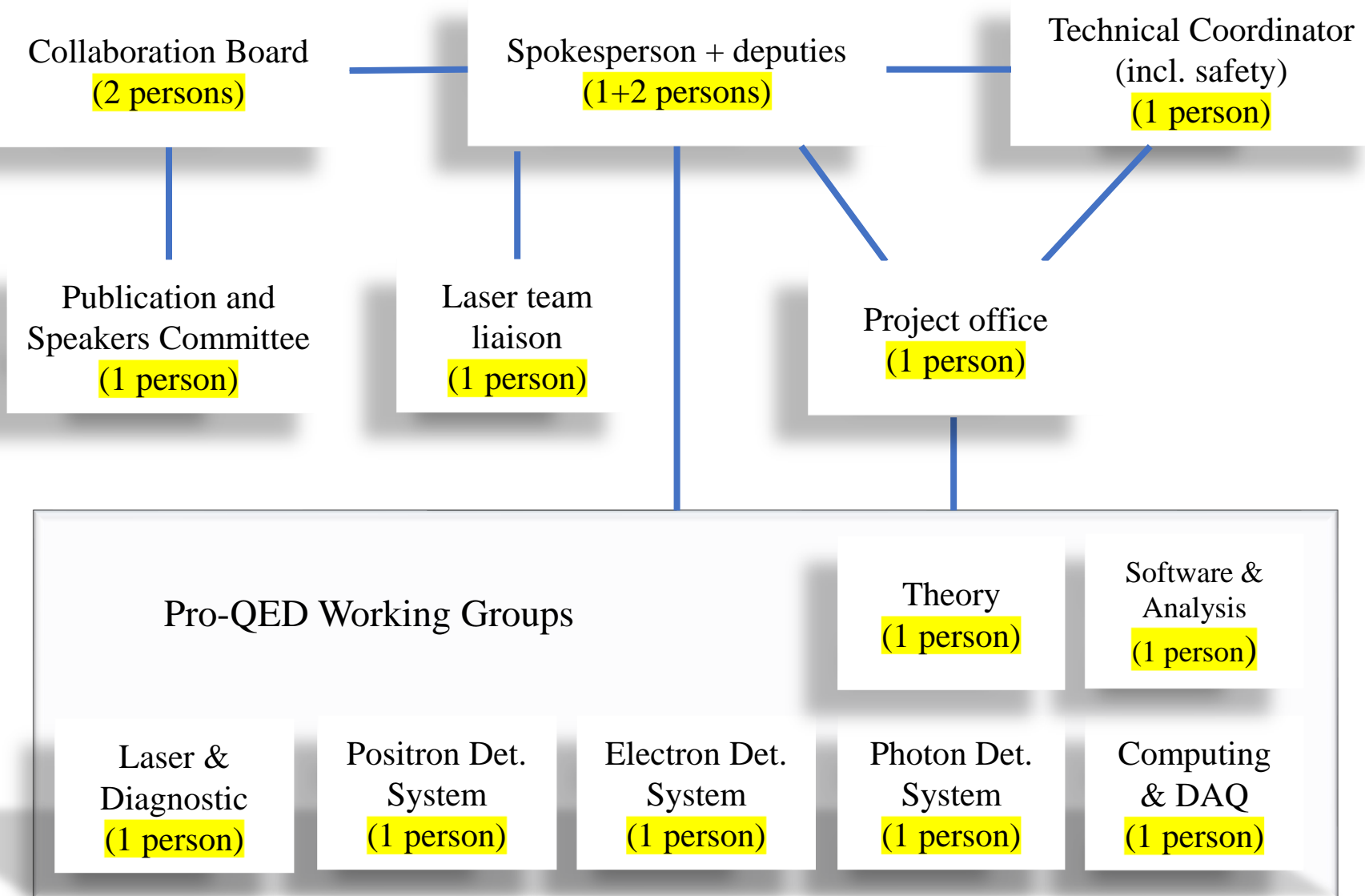
6.1 SF-QED Task Force plan

The experimental project assumes Task Force international team to organize workshops, conferences and finally to prepare Letter of Intent, Conceptual Design Report and Technical Design Report.

Theoretical, Simulation & Experimental tasks:

- **Cross section** for 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
- **Detector simulation response** and plot characteristic parameter distributions
- **Experimental setup** description and the setup detection parameters
- **Particle transport** and detector signal simulation
- **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**

6.2 Organizational Chart



Summary

- Pro-QED project - study of fundamental QED processes in an unexplored region of QED into the non-perturbative regime, possible to search at ELI-NP.
- Presented the state of the art and current results of experimental searches for particle production in light – matter interactions.
- Have intensive seminars on fundamental QED processes.
- Evaluation of the ELI-NP possibility to be used in the unexplored QED non-perturbative processes studies.
- Outreach works for “Saturday Morning Physics at ELI-NP”.
- A Task Force to deliver the Letter of Intent, Conceptual Design Report and Technical Design Report for an experimental preparation to search for laser light to matter conversion
(**Note – needs adequate funding for manpower and materials**).

Financial Report Oct. 2020 – Sept. 2023

					RON .
	Total	2020	2021	2022	2023
Allocated budget:	752.321,00	150.465,00	225.696,00	225.696,00	150.464,00
Realized budget:	752.321,00	150.465,00	225.696,00	225.696,00	150.464,00

Full Time Equivalent (FTE*)					
First Name, Last Name	Academic Degree	2020 (3 months)	2021 (12 months)	2022 (12 months)	2023 (9 months)
MIRCEA-CONSTANTIN PENTIA	SR I	0,14	0,95	0,94	0,73
HORIA PETRASCU	SR II	0,14	0,07	0,02	0,00
DANA-ELENA DUMITRIU	SR III	0,14	0,01	0,04	0,00
REMUS-AMILCAR IONESCU	SR III	0,14	0,07	0,02	0,00
ANDREEA SUVAILA	Economist	0,00	0,00	0,00	0,00

* FTE = Number of planned work hours / (number of work hours per year)

Thank you

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