Nonperturbative Processes in strong field QED (Pro-QED)

M. Pentia ISAB ELI-NP 17 Nov. 2022

Outline

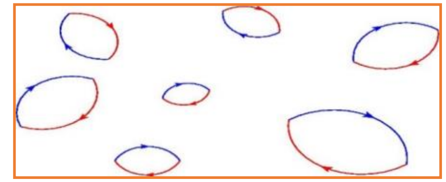
1. General Introduction
2. Goal of the Project
3. Work up to June 2022
4. Future Plans
5. Summary

1. Introduction

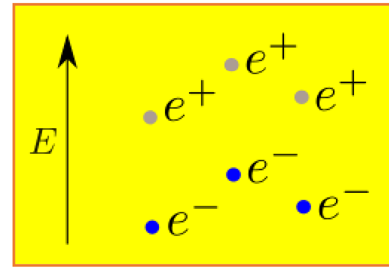
One of the fundamental electromagnetic interaction processes, little studied experimentally, is the **conversion of light to matter.** Particle production from the e.m. field, one of the amazing predictions of the QED, is possible, at least in principle, in connection with the vacuum particle pair production:

- in a static electric field – **Schwinger effect** [1].
- in a photon field – **Breit-Wheeler production** [2], or
- in a combination of the two – **Bethe-Heitler production** [6].

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.



The existence of virtual particle-antiparticle pairs in 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).



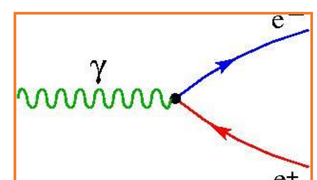
the <u>characteristic range</u> l the electric field act to produce e^+e^- pairs is given by electron Compton wavelength λ_C

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

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

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

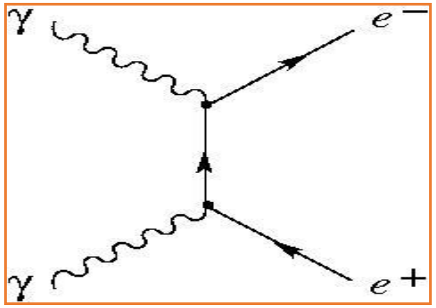
Some quantum interactions can transfer enough energy to trans-form the virtual pair into a real pair. The pair is no more locally confined and can be detected and measured at large distance.



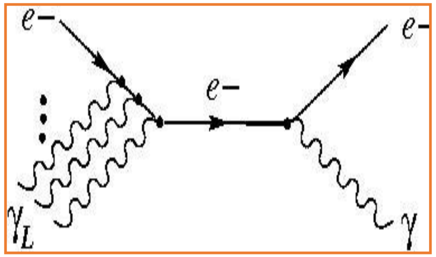
1. QED Processes under study

So far, the current theoretical and experimental works with high-power lasers have highlighted a series of QED processes and confirmed the possibility to approach them experimentally.

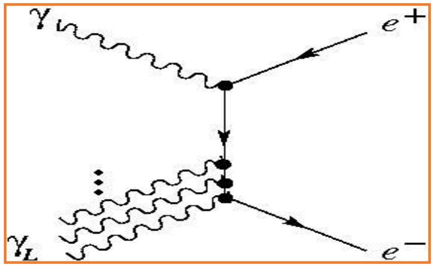
- The linear Breit-Wheeler (BW) process [2] $\gamma + \gamma \rightarrow e^- + e^+$
has been studied in the theoretical framework of quantum electrodynamics (QED) [24]. To date, the linear BW process has not been observed in the laboratory with **real photons** due to the lack of suitably bright sources of photons with sufficient energy.



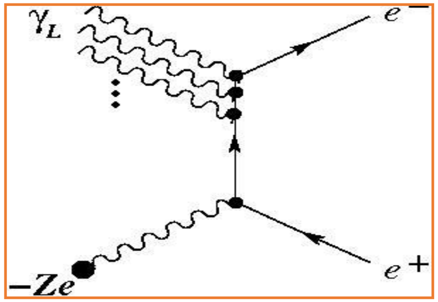
- Nonlinear (multiphoton) inverse Compton scattering $e^- + n\,\gamma_L \rightarrow e^- + \gamma$
where the electron, e^-, absorbs multiple, n laser photons γ_L, and radiates hard photons γ. Up to 40% of the energy of the laser accelerated electrons is re-radiated as gamma photons in the presence of the laser field [26]



- Nonlinear (multiphoton) Breit–Wheeler process: $\gamma + n\,\gamma_L \rightarrow e^- + e^+$
where the electron - positron pair is generated. Hence for the energy of multiple laser photons, pure energy is transformed into the mass of the particles: electrons and positrons. Light is transformed into matter [27]

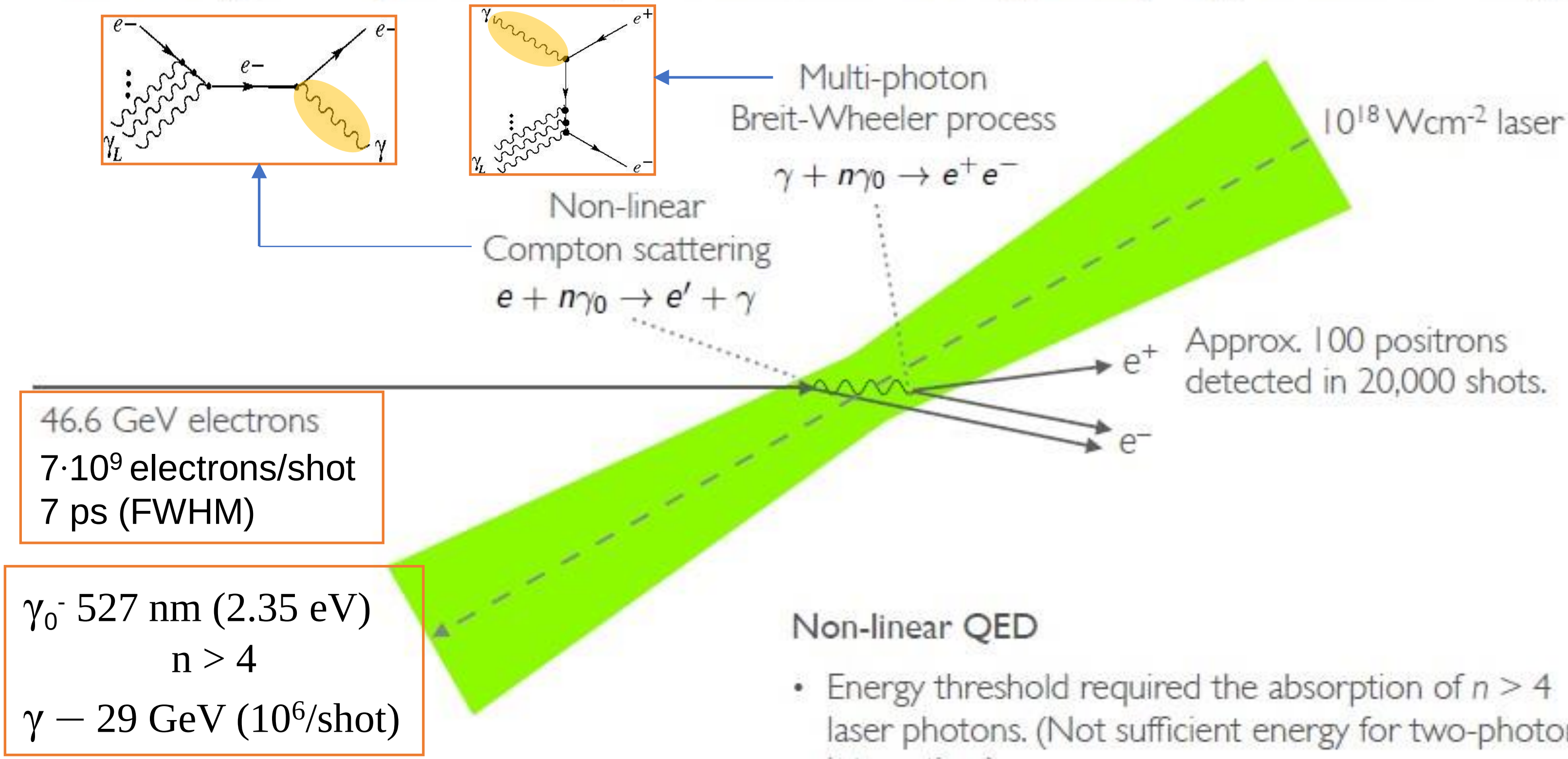


- Bethe-Heitler (BH) interaction process with nuclei [28] $n\,\gamma_L + \gamma_V \rightarrow e^- + e^+$
where the multiple laser photons in interaction with the **virtual photon** of the nucleus field, transfer energy to $e^+ e^-$ production process.



1. E-144 SLAC Experiment (electron – laser collision)

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



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.

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

2. Goal of the Project

In 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".
On the other hand, production of large numbers of MeV positrons in the laboratory opens the door to new avenues of antimatter research, including an understanding of the physics underlying various astrophysical phenomena such as black holes and gamma ray bursts [45,46], pair plasma physics [47,48], positronium production.

Now the 2 x 10 PW laser beams of the ELI-NP laser facility has the interaction chambers dedicated to QED experiments [42-44]. So, we can move on to fruition this possibility **to in-depth study of nonlinear QED processes** with such laser beams to perform the following steps:

- Systematic studies of the dynamics of fundamental QED processes possible to approach with high power lasers. They refer to the fundamental QED processes in order to experimentally reveal the characteristic properties of the processes. We have in view: Dirac e^+e^- pair annihilation, Breit-Wheeler e^+e^- pair production, Bethe-Heitler e^+e^- pair production, e^-e^- Moller Scattering, e^-e^+ Bhabha Scattering, Electron Self Energy, Photon Self Energy, Vacuum Energy.
- Proposal of experimental arrangements 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/or production and measurement of QED bound states (positronium).
- At the same time, we aim to create a well-qualified team for the preparation of proposals for specific experimental works and their implementation at the ELI-NP facility.

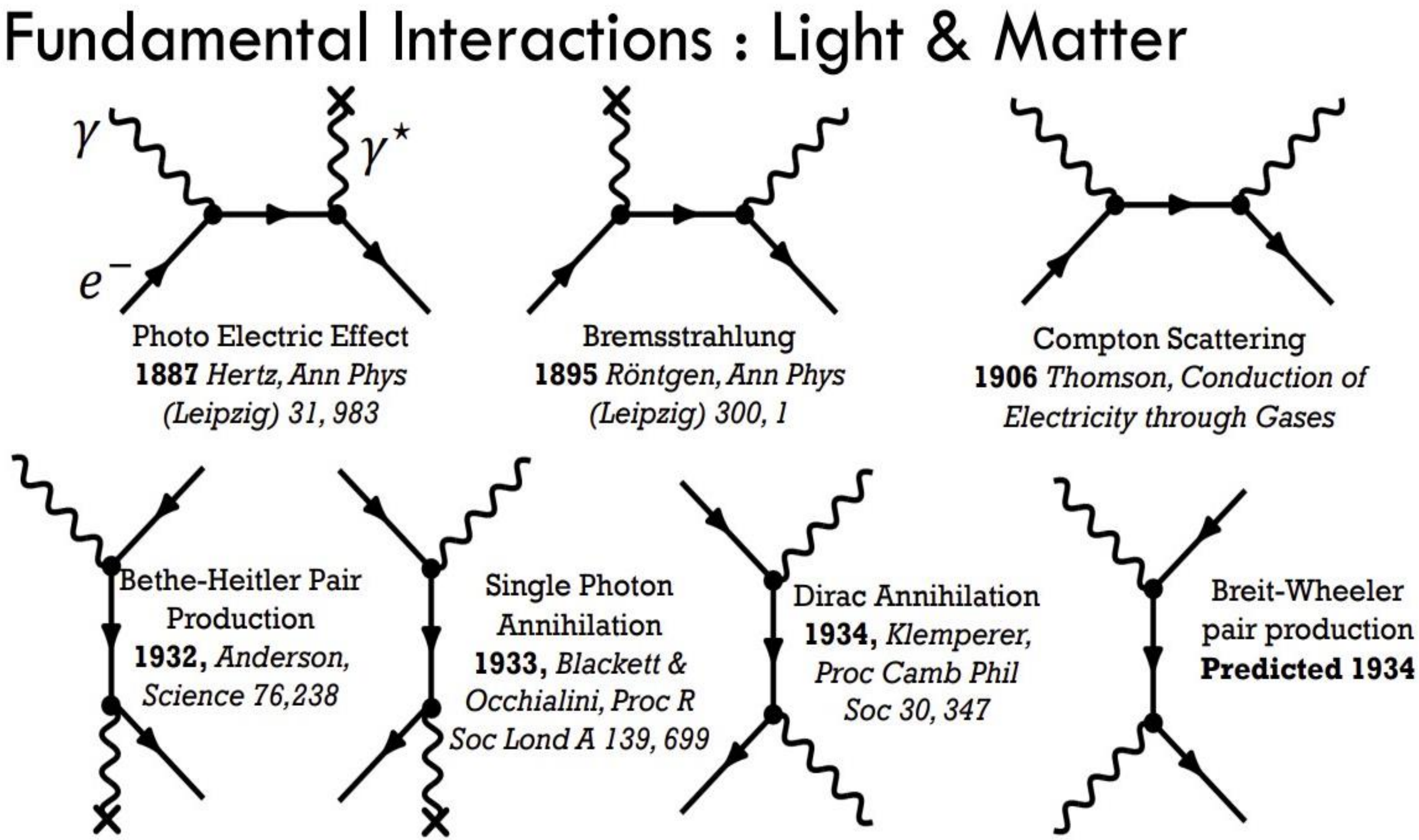
Final goal: Elaboration of a "Letter of Intent" for testing and experimental measurement of some fundamental QED processes with High Power Lasers at ELI-NP facility.

2. Study of QED interaction processes

(illustrative slide)

The simplest QED interaction processes between light and matter possible to be measured at ELI-NP Facility. Feynman diagrams evaluations.

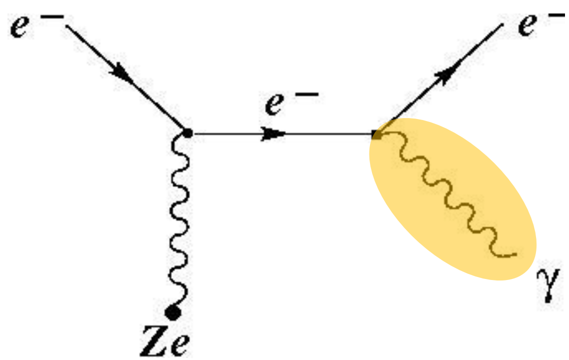
Fundamental Interactions : Light & Matter



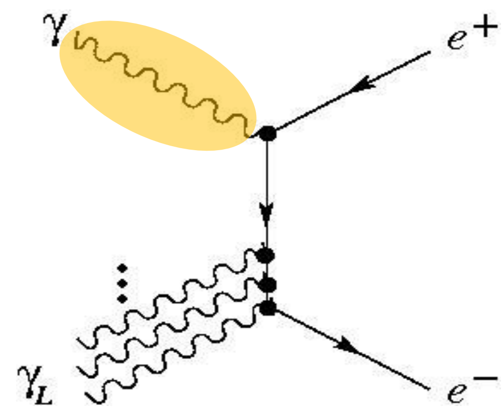
MeV γ sources

Pair production

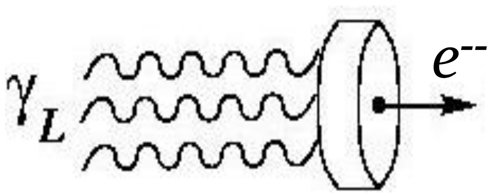
Bremsstrahlung



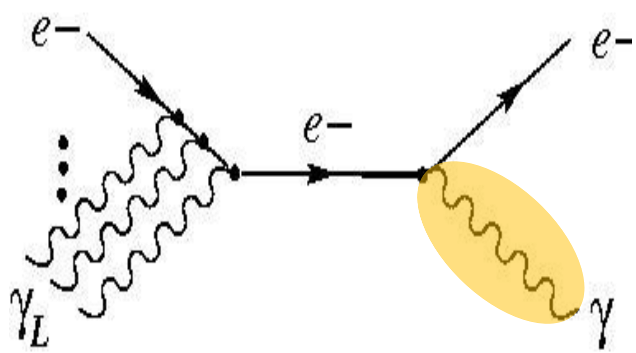
Multiphoton Breit-Wheeler



Wakefield acceleration

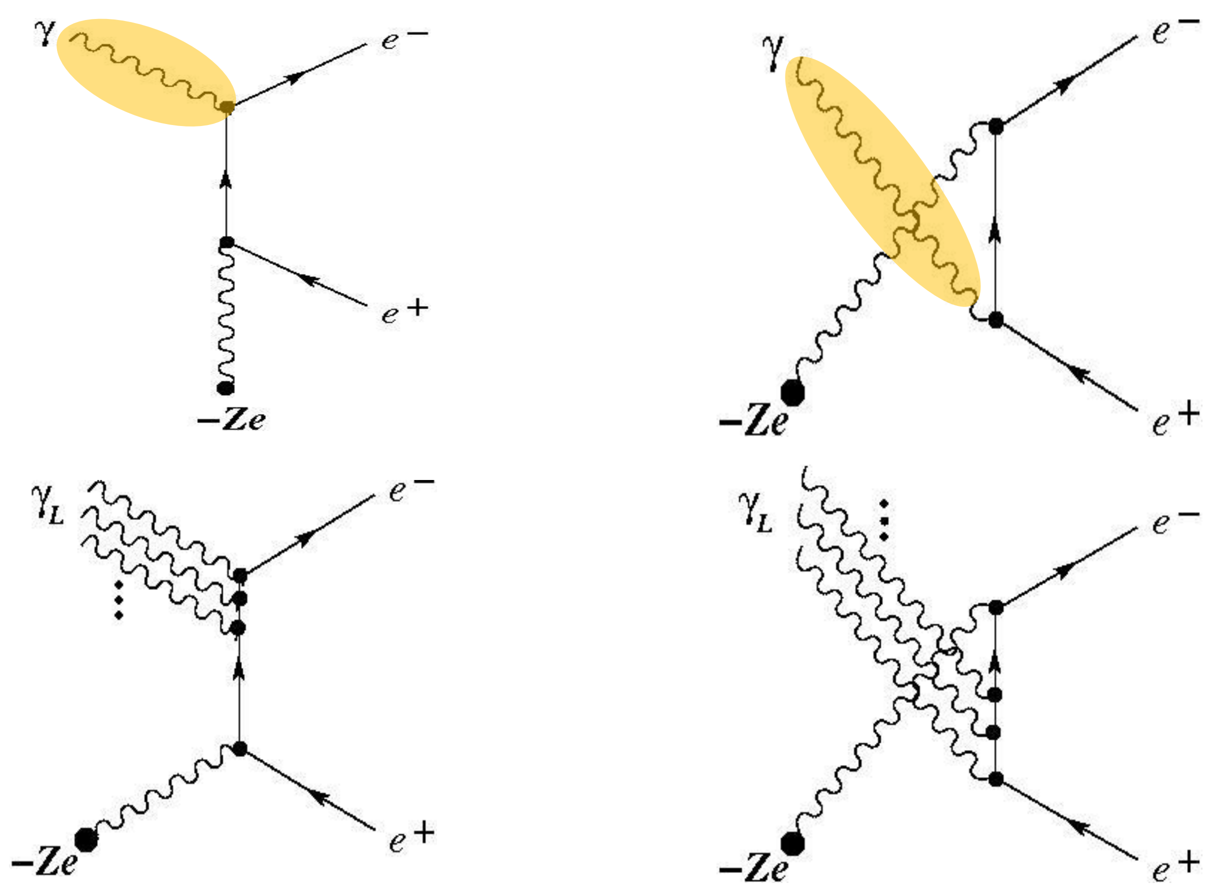


Inverse Compton scattering



2. Particular interest - multiphoton Bethe-Heitler pair production

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



3. Works done up to June 2022 (lectures)

(illustrative slide)

The works performed **according to the project** can be seen at https://indico.eli-np.ro/event/90/

1. Strong QED field in intense laser fields
    a) High Power Laser System ELI-NP (https://indico.eli-np.ro/event/90/attachments/256/528/35-Pro-QED-HPLS.pdf)
    b) Intense laser fields (https://indico.eli-np.ro/event/90/attachments/256/489/23-ProQED-Laser-physics.pdf)
    c) Tera and Petawatt Puls Generation (https://indico.eli-np.ro/event/90/attachments/256/494/29-Pro-QED-Generare-pulsuri-laser-PW.pdf)
    d) Electron – Gamma interaction in QED (https://indico.eli-np.ro/event/90/attachments/256/575/26-ProQED-el-gama-interact-Mandelstam.pdf)

2. Strong-field quantum effects and pair production by Breit-Wheeler process
    a) Photon-photon scattering - zero momentum frame (https://indico.eli-np.ro/event/90/attachments/256/490/25-ProQED-photon-photon-scatt.pdf)
    b) Dominance of γ-γ electron-positron pair creation in a plasma driven by high-intensity lasers (https://indico.eli-np.ro/event/90/attachments/256/520/33-Pro-QED-g-g-e-e%2Bpair-creation.pdf)
    c) Compton scattering (https://indico.eli-np.ro/event/90/attachments/256/493/28-ProQED-Coulomb-Scattering.pdf)
    d) QED Feynman Diagrams (https://indico.eli-np.ro/event/90/attachments/256/477/20-Pro-QED-Diag-Feynman.pdf)
    e) Cross Section based on Feynman amplitude (https://indico.eli-np.ro/event/90/attachments/256/487/24-ProQED-Sect-efic-diag-Feynman.pdf)
    f) Particle Real and Virtual States (https://indico.eli-np.ro/event/90/attachments/256/574/36-Pro-QED-curenti-si-propagatori.pdf)
    g) Propagator Evaluation for Feynman Diagrams (https://indico.eli-np.ro/event/90/attachments/256/618/47-Pro-QED-calc-propagator-Feynman.pdf)

3. Works done up to June 2022 (lectures)

(illustrative slide)

3. Spontaneous pair production via Schwinger mechanism
   a) Feynman Propagators (https://indico.eli-np.ro/event/90/attachments/256/611/45-Pro-QED-Propagatori-Feynman.pdf)
   b) Moller Scattering (https://indico.eli-np.ro/event/90/attachments/256/576/32-Pro-QED-el-scatt.pdf)
   c) Wick Theorem (https://indico.eli-np.ro/event/90/attachments/256/612/46-Pro-QED-Teorema-Wick.pdf)
   d) Reflecting Petawatt lasers off relativistic plasma mirrors: a realistic path to the Schwinger limit (https://indico.eli-np.ro/event/90/attachments/256/492/27-PeoQED-Relativistic-Plasma-Mirrors.pdf)

4. Laser strong field - matter interactions
   a) Field Quantization (https://indico.eli-np.ro/event/90/attachments/256/577/37-Pro-QED-Cuantificare-Campuri.pdf, https://indico.eli-np.ro/event/90/attachments/256/586/38-Pro-QED-Cuantif-camp-Dirac.pdf, https://indico.eli-np.ro/event/90/attachments/256/588/39-Pro-QED-Cuantif-energie-camp-Dirac.pdf, https://indico.eli-np.ro/event/90/attachments/256/590/40-Pro-QED-Cuantificare-Camp-KG.pdf, https://indico.eli-np.ro/event/90/attachments/256/592/41-Pro-QED-Rel-comutare-camp-EM.pdf, https://indico.eli-np.ro/event/90/attachments/256/593/42-Pro-QED-Cuantif-camp-EM%28Coulomb%29.pdf)
   b) Gauge Theories (https://indico.eli-np.ro/event/90/attachments/256/597/43-Pro-QED-Gauge-Theory.pdf
   c) Evolution Operator – S-Matrix (https://indico.eli-np.ro/event/90/attachments/256/608/44-Pro-QED-Op-evol-interact-picture.pdf)
   d) Classical charged particle in strong plane wave (https://indico.eli-np.ro/event/90/attachments/256/474/19-Pro-QED-particle-in-strong-EM.pdf)
   e) Peak Laser Intensity – Nonideal Vacuum Role (https://indico.eli-np.ro/event/90/attachments/256/479/21_ProQED-Peak-Intensity.pdf)

3. Works done up to June 2022 (publication)

(illustrative slide)

5. Lectures on specific topics for collaborators to create a strong theoretical and experimental team (https://indico.eli-np.ro/event/90/)

6. Lectures for young people and high school students "Saturday Morning Physics" (https://indico.eli-np.ro/event/74/)

7. Experimental possibilities for detection and measurement of particle pairs:

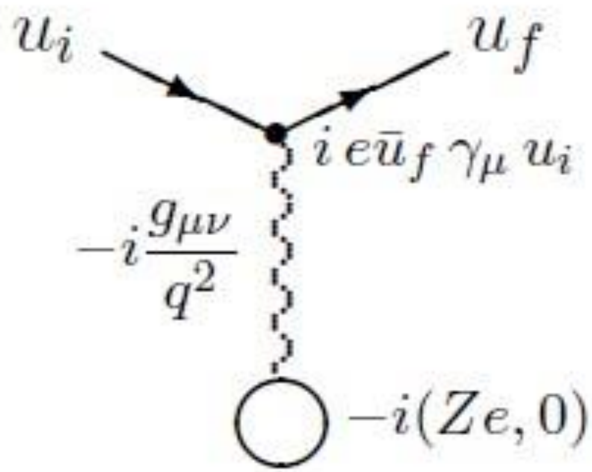
"Investigation of K^+K^- pairs in the effective mass region near $2m_K$" *B. Adeva ... M. Pentia et al. (DIRAC Collaboration)*

Corresponding Author: M. Pentia *pentia@nipne.ro*

published in Phys. Rev. D 106, 032006 (2022)

https://journals.aps.org/prd/pdf/10.1103/PhysRevD.106.032006

3. Feynman diagrams evaluation (example - Coulomb Scattering)



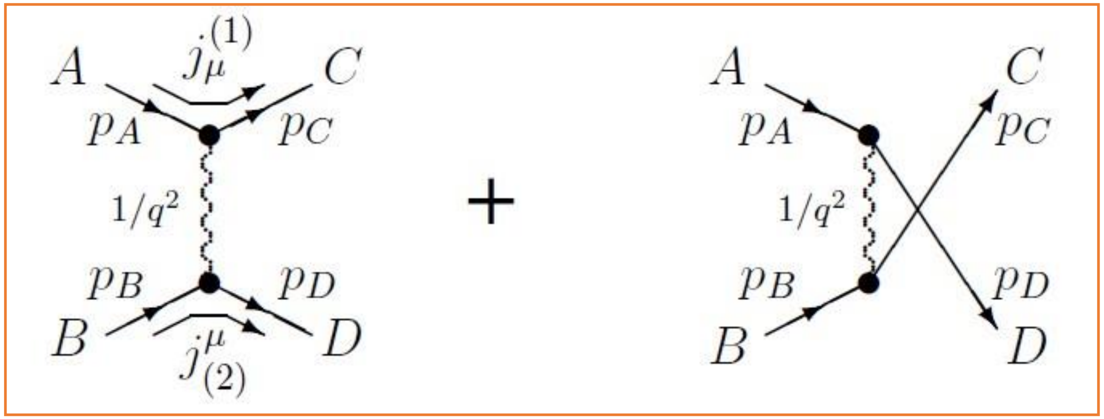
$$-i\mathcal{M} = \left(i\,e\,\bar{u}_f\,\gamma_0\,u_i\right)\left(\frac{-i}{q^2}\right)\left(-\,i\,Ze\right)$$

$$q^2 = (p_f - p_i)^2 = 2m^2 - 2p_i \cdot p_f = 2m^2 - 2\,(E_i E_f - \vec{p}_i \cdot \vec{p}_f)$$
$$= 2m^2 - 2E_i E_f + 2|\vec{p}_i||\vec{p}_f|\cos\theta = 2\,(m^2 - E^2) + 2|\vec{p}|^2\cos\theta$$
$$= -2|\vec{p}|^2(1 - \cos\theta) = -4|\vec{p}|^2\sin^2(\theta/2)$$

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

$$\frac{d\sigma}{d\Omega} \sim |\mathcal{M}|^2 \sim \frac{1}{\sin^4(\theta/2)}$$

3. Feynman diagrams evaluation (example - Moller e$^-$e$^-$ Scattering)



$$\left.\frac{d\sigma}{d\Omega}\right|_{scm} = \frac{1}{64\pi^2 s}\frac{|\vec{p}_f|}{|\vec{p}_i|}|\mathcal{M}|^2$$

$$-i\mathcal{M} = \left(i\,e\,\bar{u}_C\,\gamma^\mu\,u_A\right)\left(\frac{-ig_{\mu\nu}}{q^2}\right)\left(i\,e\,\bar{u}_D\,\gamma^\mu\,u_B\right)$$

$$\mathcal{M} = -\,e^2\frac{(\bar{u}_C\,\gamma_\mu\,u_A)(\bar{u}_D\,\gamma^\mu\,u_B)}{(p_C - p_A)^2} + e^2\frac{(\bar{u}_D\,\gamma_\mu\,u_A)(\bar{u}_C\,\gamma^\mu\,u_B)}{(p_D - p_A)^2}$$

$$|\mathcal{M}|^2 \longrightarrow \overline{|\mathcal{M}|^2} \equiv \frac{1}{(2s_A+1)(2s_B+1)}\sum_{\substack{\text{toate stă-}\\ \text{rile de spin}}}|\mathcal{M}|^2$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{scm} = \frac{1}{64\pi^2 s}\frac{|\vec{p}_f|}{|\vec{p}_i|}|\mathcal{M}|^2 = \frac{m^2c^4\alpha^2}{16p^4}\left(\frac{1}{\sin^4\frac{\theta}{2}} + \frac{1}{\cos^4\frac{\theta}{2}} - \frac{1}{\sin^2\frac{\theta}{2}\cos^2\frac{\theta}{2}}\right)$$

3. Works done up to June 2022 – Saturday Morning Physics at ELI-NP

(illustrative slide)

https://indico.eli-np.ro/event/74/

Saturday Morning Physics topics

(illustrative slide)

https://indico.eli-np.ro/event/74/

- **2 Mai: Introducere în fizica de la ELI**
  Dr. Daniel Ursescu, ELI-NP
- **9 Mai: Lumina – undă electromagnetică (ecuațiile luminii)**
  Dr. Mircea Penția, IFIN-HH
- **16 Mai: Teoria Relativității specială**
  Dr. Mircea Penția, IFIN-HH
- **23 Mai: Mecanica cuantică - teoria proceselor subatomice**
  Dr. Mircea Penția, IFIN-HH
- **30 Mai: Câmpuri de particule**
  Dr. Mircea Penția, IFIN-HH
- **6 Iunie: Câmpul electromagnetic și cuantificarea câmpului**
  Dr. Mircea Penția, IFIN-HH
- **13 Iunie: Simetrie și antimaterie**
  Dr. Adriana Răduță, IFIN-HH
- **20 Iunie: Cărămizile universului și forțele fundamentale de interacție**
  Dr. Mircea Penția, IFIN-HH
- **27 Iunie: Stări entangled în mecanica cuantică: de la disputele Einstein-Bohr la aplicații în tehnologiile cuantice**
  Dr. Ștefan Ataman, ELI-NP
- **9 Mai: Experimentele de la ELI-NP cu sisteme laser de putere inaltă**
  Dr. Andi Cucoaneș, ELI-NP
  Dr. Ștefan Ataman, ELI-NP
- **4 Iulie: Experimente de spectroscopie nucleară și astrofizică cu fascicule γ**
  Dr. Cătălin Matei, ELI-NP
  Dr. Paul Constantin, ELI-NP
- **11 Iulie: Aplicații și dezvoltări industriale relevante la ELI-NP**
  Dr. Violeta Iancu, ELI-NP
  Dr. Mihail Cernăianu, ELI-NP

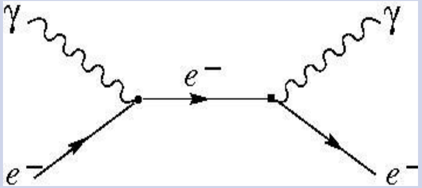
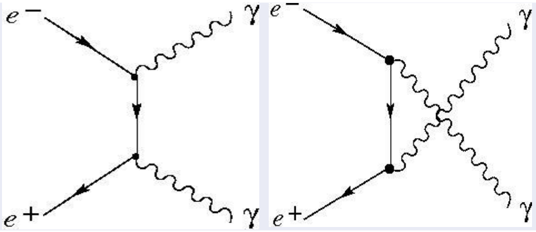
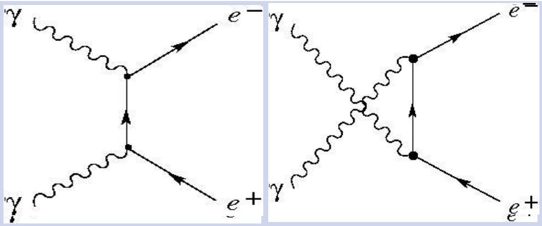
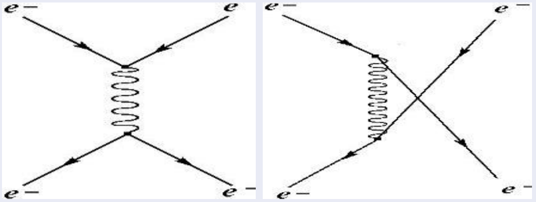
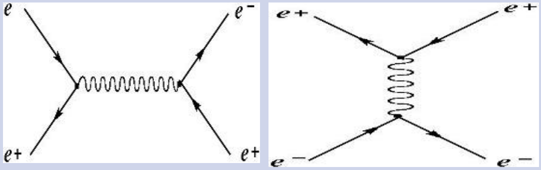
4. Future Plans - QED elementary processes

(illustrative slide)

QED PROCESS	INTERACTION	S MATRIX ELEMENT
Compton Scattering $e^-\gamma$	$\gamma + e^- \rightarrow \gamma + e^-$	$\langle \gamma, e^- \| S \| \gamma, e^- \rangle$
Compton Scattering $e^+\gamma$	$\gamma + e^+ \rightarrow \gamma + e^+$	$\langle \gamma, e^+ \| S \| \gamma, e^+ \rangle$
Pair annihilation e^+e^-	$e^- + e^+ \rightarrow \gamma + \gamma$	$\langle \gamma, \gamma \| S \| e^-, e^+ \rangle$
Pair production e^+e^-	$\gamma + \gamma \rightarrow e^- + e^+$	$\langle e^-, e^+ \| S \| \gamma, \gamma \rangle$
Moller Scattering e^-e^-	$e^- + e^- \rightarrow e^- + e^-$	$\langle e^-, e^- \| S \| e^-, e^- \rangle$
Moller Scattering e^+e^+	$e^+ + e^+ \rightarrow e^+ + e^+$	$\langle e^+, e^+ \| S \| e^+, e^+ \rangle$
Bhabha Scattering	$e^- + e^+ \rightarrow e^- + e^+$	$\langle e^-, e^+ \| S \| e^-, e^+ \rangle$
Electron Self Energy	$e^- \rightarrow e^-$	$\langle e^- \| S \| e^- \rangle$
Positron Self Energy	$e^+ \rightarrow e^+$	$\langle e^+ \| S \| e^+ \rangle$
Photon Self Energy	$\gamma \rightarrow \gamma$	$\langle \gamma \| S \| \gamma \rangle$
Vacuum Energy	Vacuum $\rightarrow$ Vacuum	$\langle 0 \| S \| 0 \rangle$

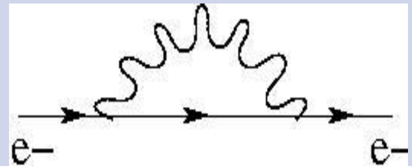
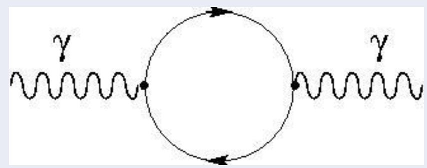
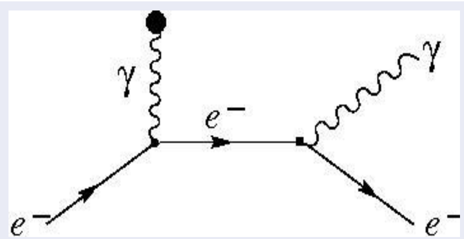
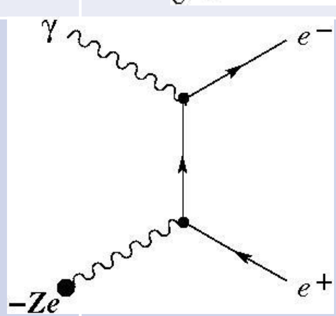
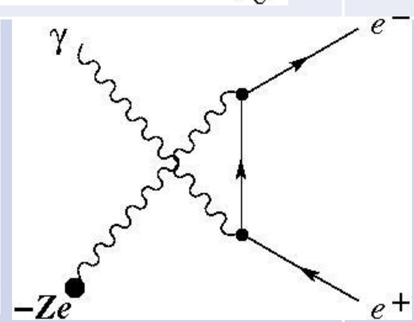
4. Future Plans - QED elementary processes

(illustrative slide)

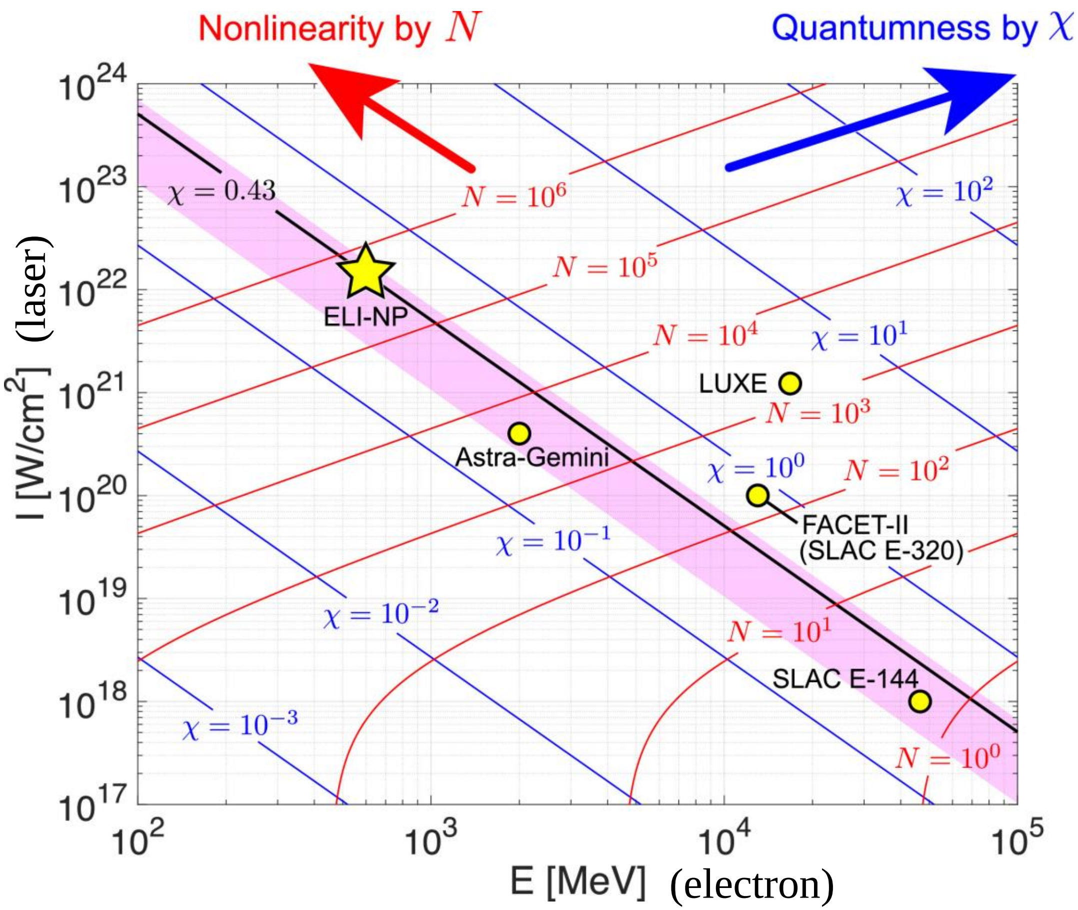
QED PROCESS	INTERACTION	S MATRIX ELEMENT
Compton Scattering $e^- \gamma$		$\langle \gamma, e^- \vert S \vert \gamma, e^- \rangle \quad \langle \gamma, e^+ \vert S \vert \gamma, e^+ \rangle$
Dirac pair annihilation e^+e^-		$\langle \gamma, \gamma \vert S \vert e^-, e^+ \rangle$
Breit-Wheeler pair production e^+e^-		$\langle e^-, e^+ \vert S \vert \gamma, \gamma \rangle$
Moller Scattering e^-e^-		$\langle e^-, e^- \vert S \vert e^-, e^- \rangle \quad \langle e^+, e^+ \vert S \vert e^+, e^+ \rangle$
Bhabha Scattering		$\langle e^-, e^+ \vert S \vert e^-, e^+ \rangle$

4. Future Plans - QED processes

(illustrative slide)

QED PROCESS	INTERACTION	S MATRIX ELEMENT
Electron Self Energy		$\langle e^- \vert S \vert e^- \rangle$ $\quad$ $\langle e^+ \vert S \vert e^+ \rangle$
Photon Self Energy		$\langle \gamma \vert S \vert \gamma \rangle$
Vacuum Energy		$\langle 0 \vert S \vert 0 \rangle$
Bremsstrahlung		$\langle \gamma, e^- \vert S \vert \gamma_V, e^- \rangle$
Bethe-Heitler	 	$\langle e^-, e^+ \vert S \vert \gamma, \gamma_V \rangle$

4. Future Plans - ELI-NP possibilities (K.Seto 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, $\theta_{in} = 155^0$ 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)

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)

4. Future Plans - ELI-NP possibilities

(LUXE remark)

Dimensionless Intensity parameter (field energy density) ξ^2

$$\xi^2 = \left(\frac{eE_L}{m_e\omega_L}\right)^2 = \left(\frac{m_e E_L}{\omega_L E_{cr}}\right)^2 \quad ; \quad E_{cr} = \frac{m_e^2}{e} \quad ; \quad c = \hbar = 1$$

For $\xi \leq 1$ probability of net absorption of *n* laser photons $\propto \left(\xi^2\right)^n \sim \alpha^n$

Dimensionless Intensity quantum parameter (quantumness) χ_e

$$\chi_e = \left(2\gamma_e \frac{\omega_L}{m_e}\right)\xi = 2\gamma_e \frac{E_L}{E_{cr}}$$

χ_e accounts of the quantum nonlinear effect in *e*-γ laser collision.

Ratio of the laser RMS field E_L (in the e^- rest frame) to the critical field E_{cr}

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)

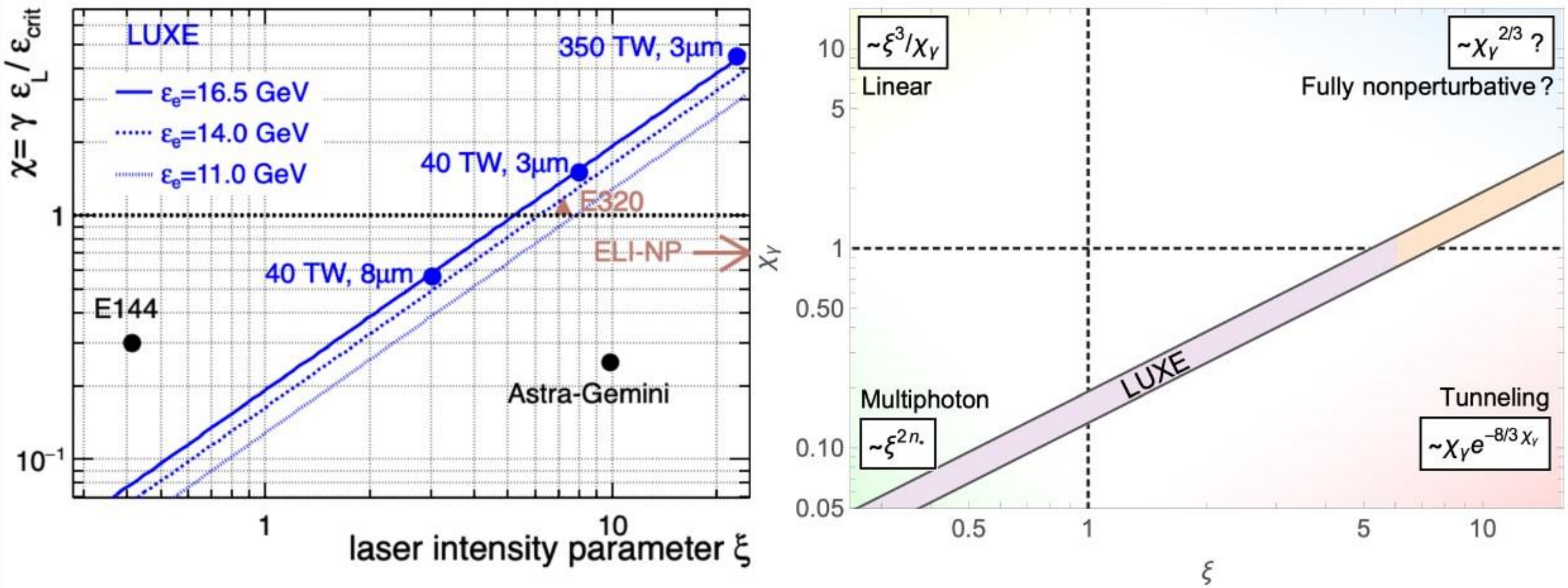
G. Grzelak, LUXE slides, 2020

4. Future Plans - ELI-NP possibilities – no any proposal

(LUXE remark)

LUXE UCL

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 $e^- + n\,\gamma_L \to e^- + e^+ + e^-$ 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 …

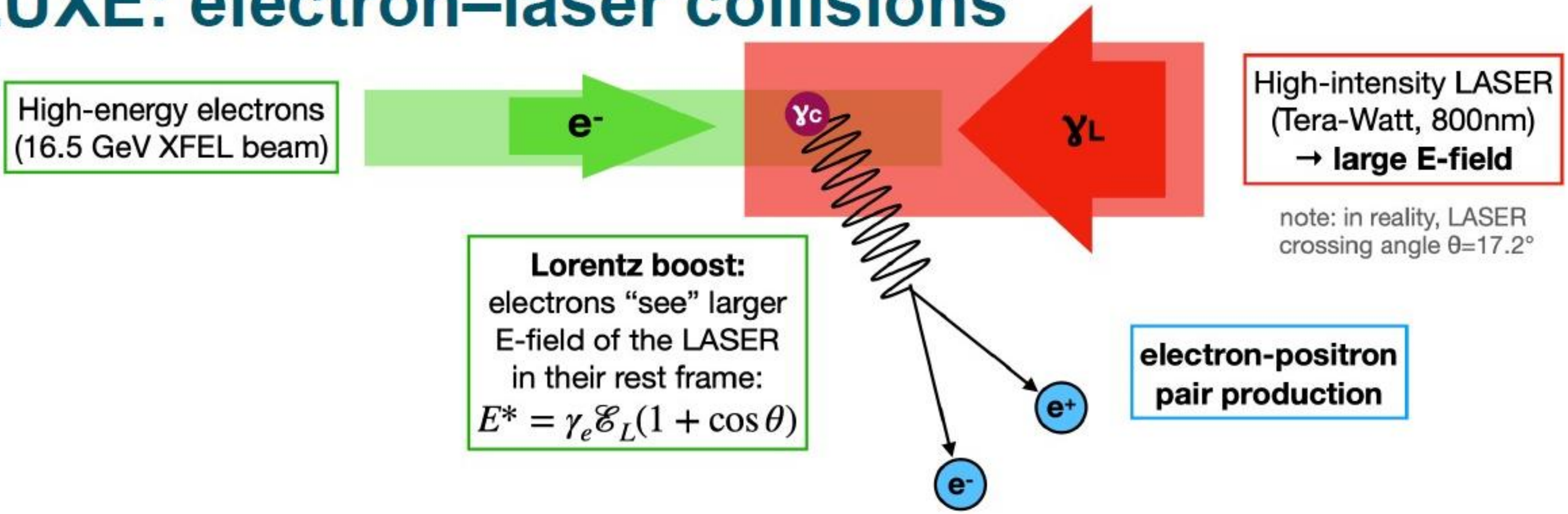
- LUXE: to cover broad parameter space and be the first to investigate high χ and high ξ.

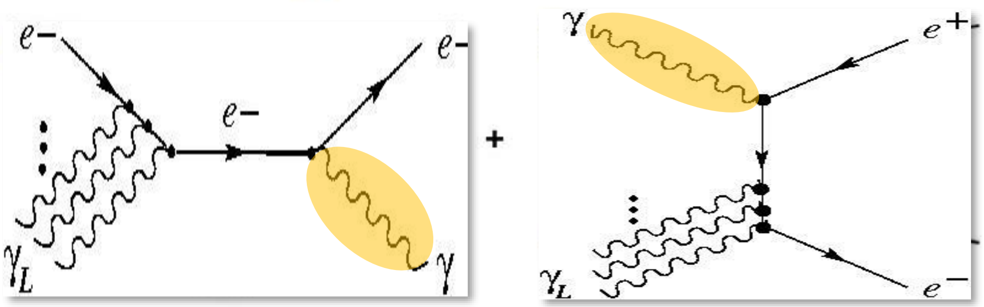
To measure collisions of real GeV photons and laser photons.

Wing (LUXE) slide 2020

4. DESY project: electron - laser interaction studies

LUXE: electron–laser collisions



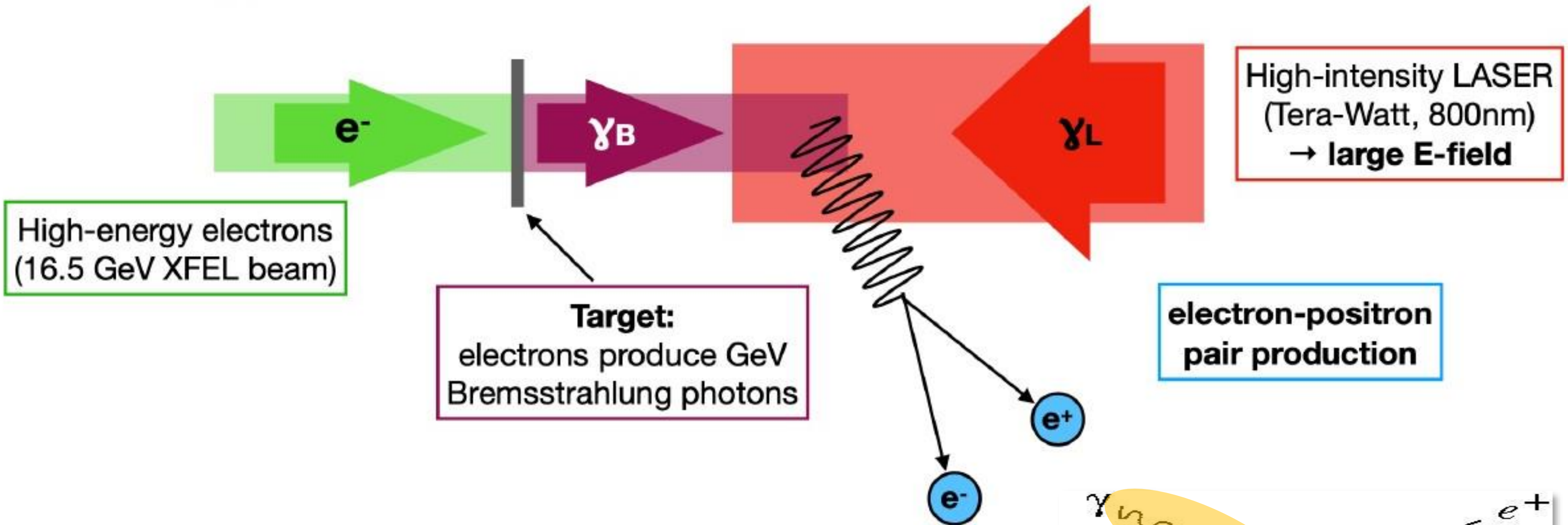


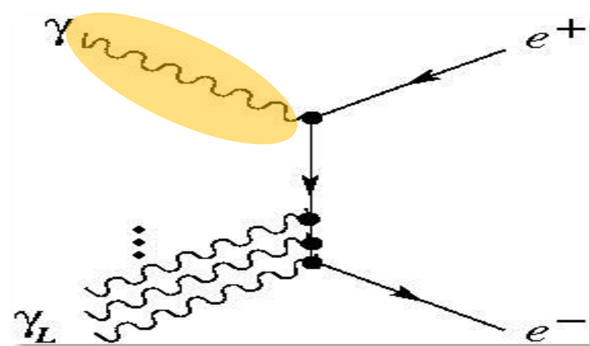
Physics processes:

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





Physics process:

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

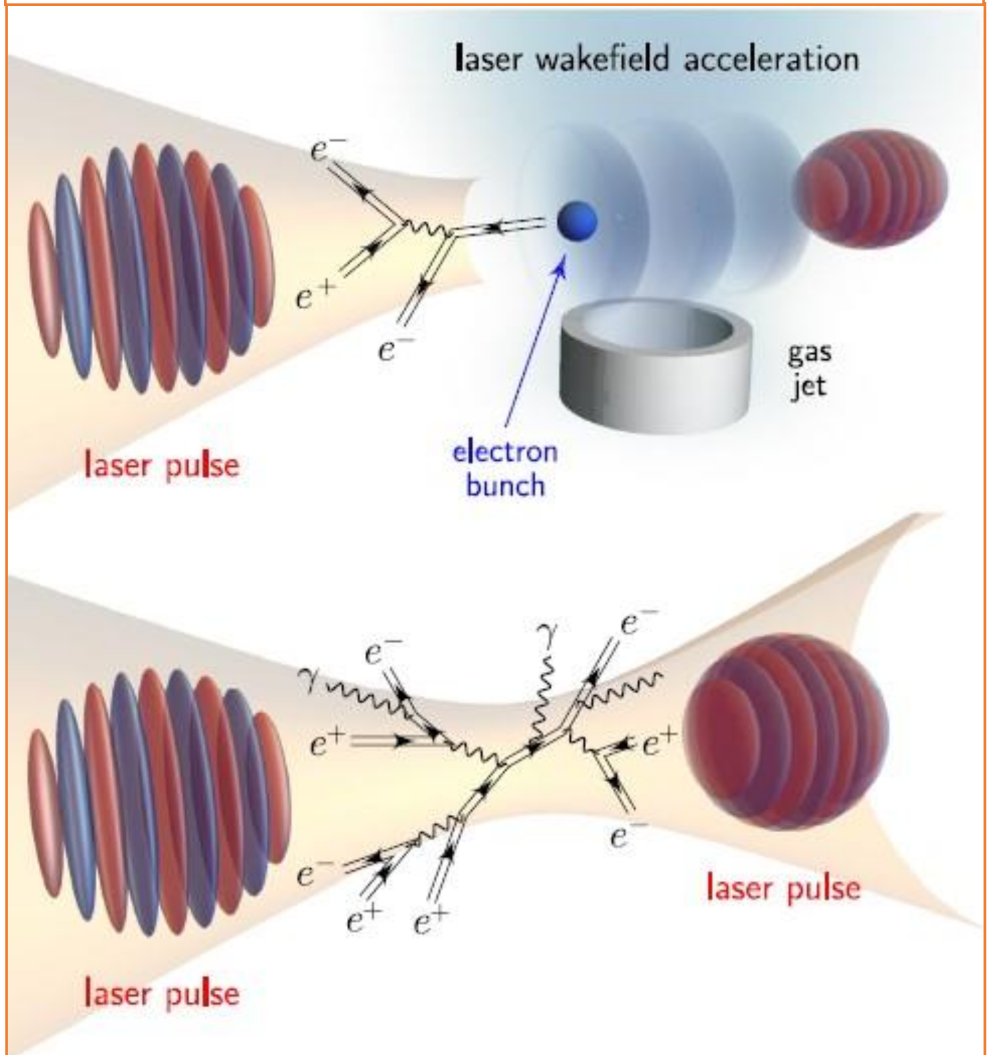
- LUXE: directly measure photon–photon collisions in strong fields.

4. Simulation laser - laser interaction studies

Charged particle motion and radiation in strong electromagnetic fields

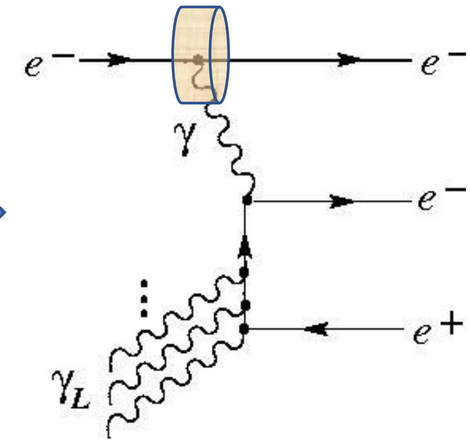
A. Gonoskov, T. G. Blackburn, M. Marklund, S. S. Bulanov

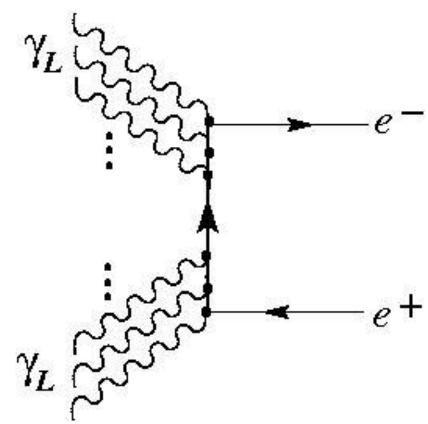
Rev. Mod. Phys., 94, Oct-Dec 2022



Multiphoton Breit-Wheeler Process:

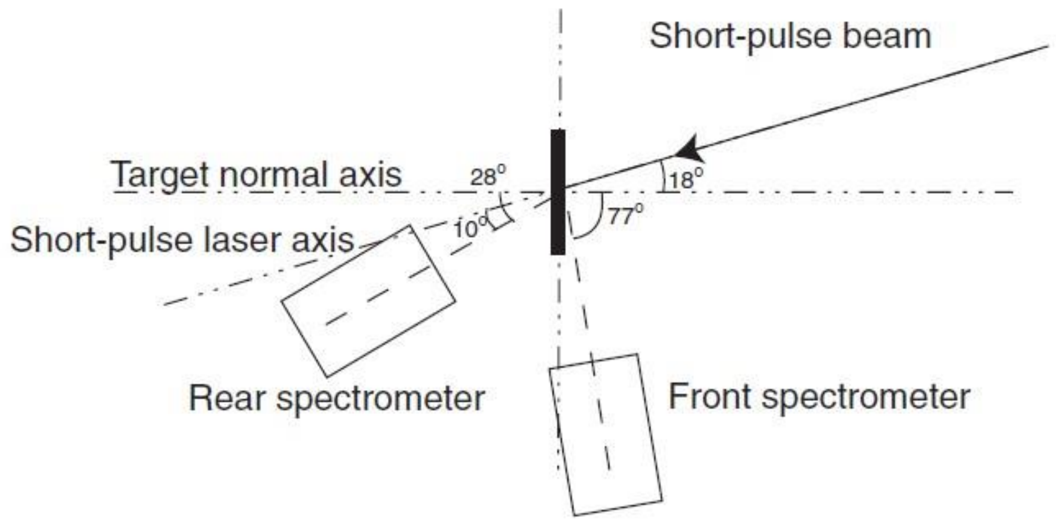
$\gamma + n\,\gamma_L \longrightarrow e^+ e^-$

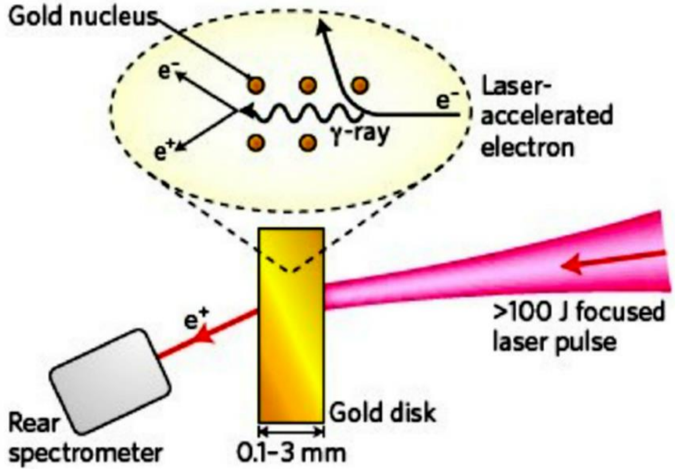




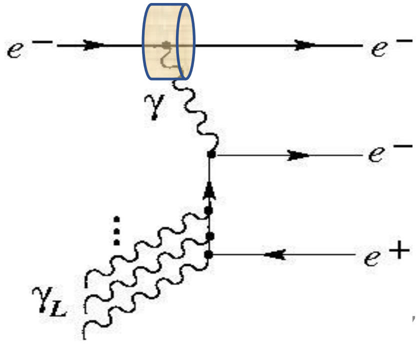
4. National Ignition Facility: Bethe – Heitler interaction

So far, relatively simple experimental works have been done.
Hui Chen et al. in *"Relativistic Positron Creation Using Ultraintense Short Pulse Lasers"* [28] with the Titan laser, one of the two lasers in the Jupiter facility at the National Ignition Facility (USA), with an energy of 250 J, by irradiating a high-Z target (Au ~1 mm) with laser pulses of 1054 nm, duration ~1 ps, intensity ~1 x 10^{20} W/cm^2 (see Fig.), 2 x 10^{10} positrons/sr were obtained, with energy < 20 MeV, with an anisotropic angular distribution, where the number of positrons recorded in the -77^0 direction being 10 times higher than the one on the 28^0 direction from the normal on the surface of the target.





Positrons are produced predominately by the **Bethe-Heitler process** and have an effective energy of 2–4 MeV, with the distribution peaking at 4–7 MeV [28]. In this process the electrons, resulting from the interaction of the laser pulse with the target, produces bremsstrahlung gamma radiation of the order of MeV, which in turn, in the interaction with the electric field of the nucleus, generates electron-positron pairs. Such studies were further carried out with ultra-intense laser [35-41].



5. 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 lectures on fundamental QED processes.
- Evaluation of the ELI-NP possibility to be used in the unexplored QED non-perturbative processes studies.
- A strong team must be prepared as to deliver a **Letter of Intent** for an experimental setup and finally the ability to **perform the experiment** leading to exciting physics results
  (conditioned by an adequate funding for manpower, equipment and materials).
- Outreach program "Saturday Morning Physics at ELI-NP"
  (no financial support till now).

Financial Report

Group members (table):

First Name, Last Name	Academic Degree	Realized FTE 2020	Realized FTE 2021	Realized FTE 2022 (30 June)
PENȚIA MIRCEA	CS I	0,14	0,95	0,46
PETRAȘCU HORIA	CS II	0,14	0,07	0,00
DUMITRIU DANA ELENA	CS III	0,14	0,01	0,01
IONESCU REMUS AMILCAR	CS III	0,14	0,07	0,00
ȘUVĂILĂ ANDREEA	Ec.	0,00	0,00	0,00

Full Time Equivalent (FTE) time in project. The FTE formula to be used is:
FTE = Total number of worked hours /Total number of hours per reporting period;

Financial Report Oct. 2020 –30 June 2022

RON

	TOTAL	2020	2021	2022*
Allocated budget:	601.857,00	150.465,00	225.696,00	225.696,00
Realized budget:	470.655,00	150.465,00	225.696,00	94.494,00

*) Realized value for 2022: 1 January 2022 - 30 June 2022

Financial Report

Oct. 2020 –30 June 2022

according to the regulations from H.G. 134/2011

lei

Type of expenditures		TOTAL 2020 - 2022		2020		2021		2022	
		Planned	**Realized**	**Planned**	**Realized**	**Planned**	**Realized**	**Planned**	**Realized (30 June)**
1	**PERSONNEL EXPENDITURES**, from which:	**371.238,00**	**313.279,00**	**100.310,00**	**100.099,00**	**135.464,00**	**149.284,00**	**135.464,00**	**62.996,00**
	1.1. wages and similar income, according to the law	363.069,00	305.506,00	98.103,00	97.897,00	132.483,00	145.999,00	132.483,00	61.610,00
	1.2. contributions related to wages and assimilated incomes	8.169,00	6.873,00	2.207,00	2.202,00	2.981,00	3.285,00	2.981,00	1.386,00
2	**LOGISTICS EXPENDITURES**:	**40.000,00**	**1.391,25**	**0,00**	**211,00**	**20.000,00**	**1.180,25**	**20.000,00**	**0,00**
	2.1. capital expenditures	30.000,00	0,00			15.000,00		15.000,00	0,00
	2.2. stocks expenditures	10.000,00	1.391,25	0,00	211,00	5.000,00	1.180,25	5.000,00	0,00
	2.3. expenditures on services performed by third parties, including:								
3	**TRAVEL EXPENDITURES**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**	**0,00**
4	**INDIRECT EXPENDITURES** – (OVERHEADS) * 50% of the direct cost excluding capital expenditures	**190.619,00**	**156.884,75**	**50.155,00**	**50.155,00**	**70.232,00**	**75.231,75**	**70.232,00**	**31.498,00**
TOTAL EXPENDITURES (1+2+3+4)		**601.857,00**	**470.655,00**	**150.465,00**	**150.465,00**	**225.696,00**	**225.696,00**	**225.696,00**	**94.494,00**

Thank you

References

[1] F. Sauter, *"Über das Verhalten eines Elektrons im homogenen elektrischen Feld nach der relativistischen Theorie Diracs*" Z. Phys. 69 (1931) 742;
W. Heisenberg, H. Euler, „*Folgerungen aus der Diracschen Theorie des Positrons*" Z. Phys. 98 (1936) 714;
J. S. Schwinger, *„On Gauge Invariance and Vacuum Polarization"*, Phys. Rev. 82, 664 (1951).
[2] G. Breit and J.A. Wheeler, *"Collision of Two Light Quanta",* Phys. Rev. 46, 1087 (1934).
[3] H. R. Reiss, *"Absorption of light by light",* J. Math. Phys. 3, 59 (1962).
[4] N. B. Narozhny, A. I. Nikishov, and V. I. Ritus, *"Quantum Processes in the Field of a Circularly Polarized Electromagnetic Wave"*, Sov. Phys. JETP 20, 622 (1965).
[5] V. I. Ritus, "*Quantum effects of the interaction of elementary particles with an intense electromagnetic field",* J. Sov. Laser Res. 6, 497 (1985).
[6] H.A. Bethe and W. Heitler, *"On the stopping of fast particles and on the creation of positive electrons"*, Proc. Roy. Soc. A146, 83 (1934).
[7] O.C. De Jager et al., *"Estimate of the intergalactic infrared radiation field from γ-ray observations of the galaxy Mrk421",* Nature 369, 294 (1994).
[8] O. Pike – interview *"Light into matter",* Nature Photonics, Vol 8, 2014
[9] D. B. Blaschke et al., *"Influence of Laser Pulse Parameters on the Properties of* e^-e^+ *Plasmas Created from Vacuum"*, Contrib. Plasma Phys. 53, 165 (2013).
[10] A. I. Titov, B. Kampfer, H. Takabe, and A. Hosaka, *"Breit-Wheeler process in very short electromagnetic pulses",* Phys. Rev. A 87, 042106 (2013)
[11] G. V. Dunne, H. Gies, and R. Schutzhold, *"Catalysis of Schwinger vacuum pair production",* Phys. Rev. D 80, 111301 (2009).
[12] P. H. Bucksbaum, G. V. Dunne et al., *„Understanding the Fully Non-Perturbative Strong-Field Regime of QED"* SNOWMASS-2021, LoI to Theory Frontier (2020).
[13] C. Bula et al. [E144], *"Observation of nonlinear effects in Compton scattering,"* Phys. Rev. Lett. 76, 3116-3119(1996)
[14] D. Burke et al. [E144], *"Positron production in multi-photon light by light scattering",* Phys. Rev. Lett. 79, 1626-1629 (1997)
[15] M. Altarelli, R. Assmann, F. Burkart, B. Heinemann, T. Heinzl, T. Koffas, A. Maier, D. Reis, A. Ringwald and M. Wing, *"Summary of strong-field QED Workshop",* arXiv:1905.00059 (2019).
[16] H. Abramowicz et al., *"Letter of Intent for the LUXE Experiment",* arXiv:1909.00860 (2019).
[17] S. Meuren on behalf of the E-320 Collaboration, *"Probing Strong-field QED at FACET-II (SLAC E-320)"* (2019)
[18] I. Turcu et al, *"High field physics and QED experiments at ELI-NP",* Rom. Rep. Phys. 68, Supplement, S145 (2016).

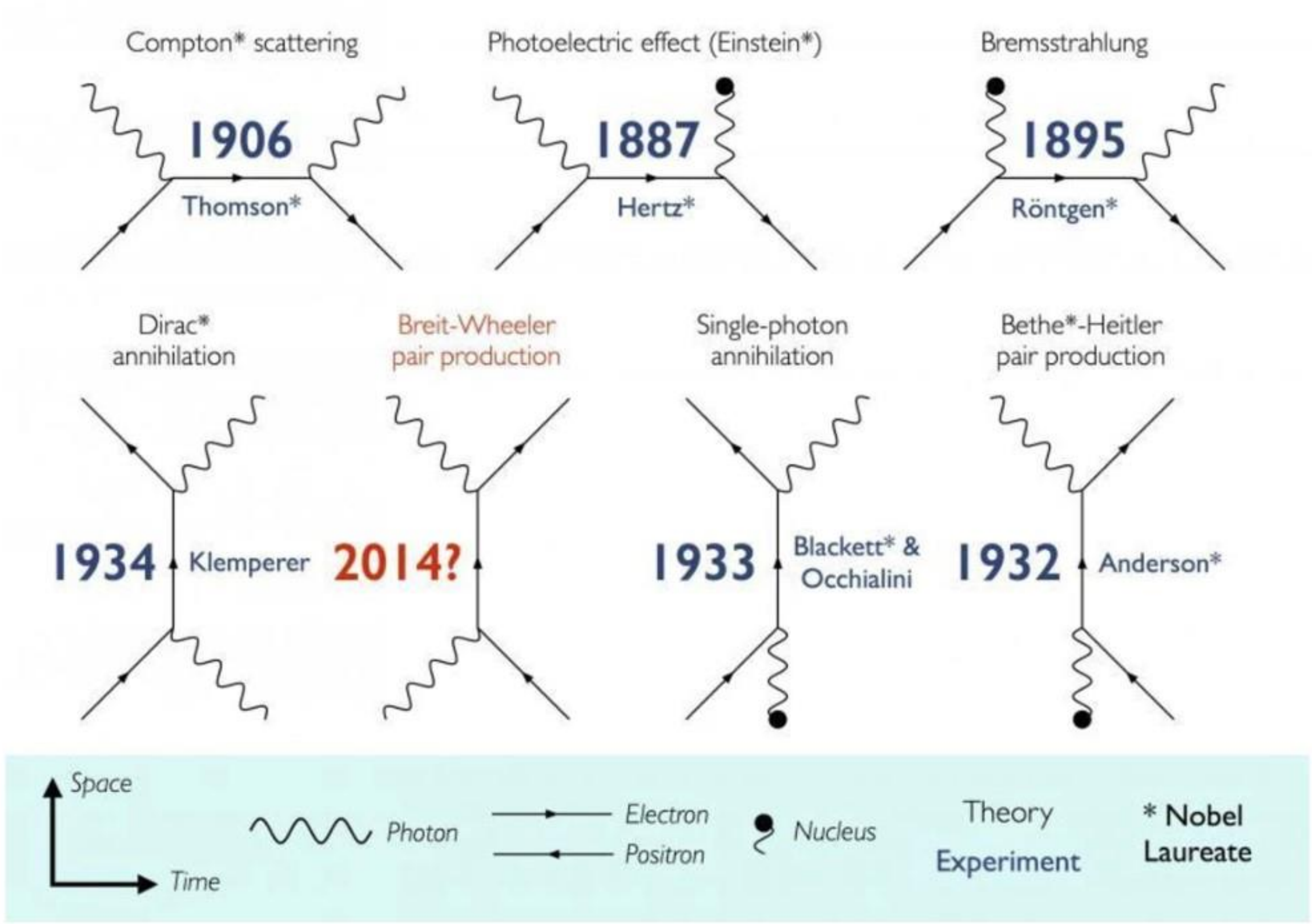
References

[19] R. Falcone, F. Albert, F. Beg, S. Glenzer, T. Ditmire, T. Spinka, and J. Zuegel, *"Workshop Report: Brightest Light Initiative",* arXiv:2002.09712 (2020).
[20] S. Baalrud, N. Ferraro, L. Garrison, N. Howard, C. Kuranz, J. Sarff, E. Scime, and W. Solomon, *"A Community Plan for Fusion Energy and Discovery Plasma Sciences – Report of the 2019–2020 American Physical Society Division of Plasma Physics Community Planning Process",* APS-DPP-CPP, 1-186 (2020).
[21] S. Meuren, P. H. Bucksbaum, N. J. Fisch, F. Fiúza, S. Glenzer, M. J. Hogan, K. Qu, D. A. Reis, G. White and V. Yakimenko, *"On Seminal HEDP Research Opportunities Enabled by Colocating Multi-Petawatt Laser with High-Density Electron Beams",* arXiv:2002.10051 (2020).
[22] V. Yakimenko, S. Meuren, F. Del Gaudio et al., *"Prospect of Studying Nonperturbative QED with Beam-Beam Collisions",* Phys. Rev. Lett. 122, no.19, 190404 (2019).
[23] 2019 SLAC workshop: Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime.
[23] Extremely High Intensity Laser Physics Conference: EXHILP 2019.
[24] Greiner W. and Reinhardt J. 2008 „Quantum Electrodynamics" (Berlin: Springer)
[25] B Kettle et al. *"A laser–plasma platform for photon–photon physics: the two photon Breit–Wheeler process" New J. Phys.* **23** 115006, (2021)
[26] Bula C. et al, *"Observation of Nonlinear Effects in Compton Scattering" (SLAC),* Phys.Rev.Lett. 76 3116 (1996)]
[27] Bula C. (E-144 SLAC), *"Positron Production in Multiphoton Light-by-Light Scattering"* AIP Conference Proceedings 396, 165 (1997)
[28] Hui Chen et al., *"Relativistic Positron Creation Using Ultraintense Short Pulse Lasers",* Phys. Rev. Lett. 102, 105001 (2009).
[29] M. Jirka et al., "Electron dynamics and γ and e-e+ production by colliding laser pulses", Phys. Rev. E 93, 023207 (2016).
[30] J. M. Cole, et al., "Experimental evidence of radiation reaction in the collision of a high-intensity laser pulse with a laser-wakefield accelerated electron beam", Phys. Rev. X 8, 011020 (2018).
[31] Hartin, A. Ringwald, and N. Tapia*, "Measuring the boiling point of the vacuum of quantum electrodynamics",* Phys. Rev D 99, 036008 (2019)
[32] T. N. Wistisen, A. Di Piazza, H. V. Knudsen, and U. I. Uggerhøj, *"Experimental evidence of quantum radiation reaction in aligned crystals",* Nat. Commun. 9, 795 (2018)
[33] K. Poder et al., *"Experimental signatures of the quantum nature of radiation reaction in the field of an ultraintense laser",* Phys. Rev. X 8, 031004 (2018).
[34] W. Heitler, *"The Quantum Theory of Radiation"* (Clarendon Press, Oxford, 1954)]

References

[35] E. P. Liang, S. C.Wilks, M. Tabak, *"Pair Production by Ultraintense Lasers",* Phys. Rev. Lett. 81, 4887 (1998).
[36] B. Shen and J. Meyer-ter-Vehn, *"Pair and γ-photon production from a thin foil confined by two laser pulses",* Phys. Rev. E 65, 016405 (2001).",
[37] P. L. Shkolnikov et al., *"Positron and gamma-photon production and nuclear reactions in cascade processes initiated by a sub-terawatt femtosecond laser",* Appl. Phys. Lett. 71, 3471 (1997).
[38] D. A. Gryaznykh, Y. Z. Kandiev, and V. A. Lykov, *"Estimates of electron-positron pair production in the interaction of high-power laser radiation with high-Z targets",* JETP Lett. 67, 257 (1998).",
[39] V. I. Berezhiani, D. P. Garuchava, and P. K. Shukla, *"Production of electron–positron pairs by intense laser pulses in an overdense plasma",* Phys. Lett. A 360, 624 (2007).
[40] T. E. Cowan et al., "*High energy electrons, nuclear phenomena and heating in petawatt laser-solid experiments"* Laser and Particle Beams 17, 773 (1999).
[41] C. Gahn et al., *"Generating positrons with femtosecond-laser pulses",* Appl. Phys. Lett. 77, 2662 (2000)
[42] I. C. E. Turcu et al., *"High field physics and QED experiments at ELI-NP"*, Rom. Rep. Phys. 68, S145 (2016)
[43] F. Negoita, et al. *"Laser Driven Nuclear physics at ELI-NP"*, Rom. Rep. Phys. 68, S37 (2016).
[44] S. Gales, et al., *"The extreme light infrastructure-nuclear physics (ELI-NP) facility: new horizons in physics with 10 PW ultra-intense lasers and 20 MeV brilliant gamma beams"*, Rep. Prog. Phys. 81, 094301 (2018)
[45] J. Wardle et al., *"Electron–positron jets associated with the quasar 3C279",* Nature (London) 395, 457 (1998).
[46] P. Meszaros, *"Theories of Gamma-Ray Bursts"*, Annual Rev. Astron. Astrophys. 40, 137 (2002).
[47] H. A. Weldon, *"Measuring T_c of the quark-gluon plasma with e^+e^- pairs".* Phys. Rev. Lett. 66, 293 (1991).
[48] E. G. Blackman and G. B. Field, *"Ohm's law for a relativistic pair plasma",* Phys. Rev. Lett. 71, 3481 (1993).
[49] A. Gonoskov, T. G. Blackburn, and M. Marklund, "*Charged particle motion and radiation in strong electromagnetic fields*", Rev. Mod. Phys., 94. 045001 (Oct–Dec 2022).
[50] Kun Xue et al, *"Generation of arbitrarily polarized GeV lepton beams via nonlinear Breit-Wheeler process",* Fundamental Research 2 (2022) 539-545
[51] Y. I. Salamin, S.X. Hu, K.Z. Hatsagortsyana, C.H. Keitel, "*Relativistic high-power laser–matter interactions*", Phys. Rep. 427 (2006) 41
[52] D.L. Burke et al., "*Positron Production in Multiphoton Light-by-Light Scattering*" Phys. Rev. Lett. 79 (1997) 1626.
[53] C. Bamber et al., "*Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses*", Phys. Rev. D 60 (1999) 092004.

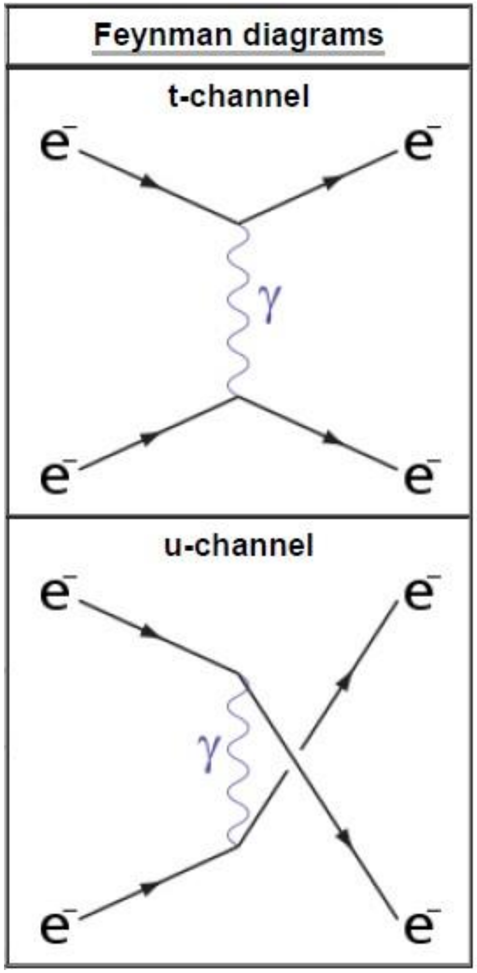
2. Light – Matter interaction processes



This chart shows Feynman diagrams that describe the interaction of matter and light. Breit-Wheeler pair production has not yet been demonstrated experimentally.

Oliver Pike / Imperial College London

Feynman Diagram - Moller Scattering



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

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

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

$$\begin{aligned} i\mathcal{M} &= i(\mathcal{M}_t - \mathcal{M}_u) \\ &= -i(-ie)^2 \left[\frac{1}{t}\bar{u}(p_3)\gamma^\mu u(p_1)\bar{u}(p_4)\gamma_\mu u(p_2) - \frac{1}{u}\bar{u}(p_3)\gamma^\mu u(p_2)\bar{u}(p_4)\gamma_\mu u(p_1)\right] \end{aligned}$$

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

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

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

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

Organizational Chart