Phase-space description of effective mass signatures in the multiphoton regime of pair production

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Introduction

At field strengths of the order of $E_0 = 1.3 \cdot 10^{18}\ V/m$ the QED vacuum becomes unstable and decays into electrons and positrons. We aim at investigating this pair production process in the multiphoton regime via a phase-space approach [1]. By this way, we introduce an effective mass m_* and demonstrate, that specific observables show sensitive signatures of this effective mass [2, 3]. Furthermore, mimicking the field decrease in one spatial direction we obtain an indication of ponderomotive forces [4, 5].

Effective mass model

The effective mass m_* summarizes all interactions between particle and environment to a single number. Instead of treating an interacting particle with bare mass m, we consider a free quasi-particle with modified mass m_*. In a monochromatic plane wave this yields

$$m_* = m\sqrt{1+\xi^2}, \quad \text{where} \quad \xi = \frac{e}{m}\sqrt{-\langle A^\mu A_\mu \rangle}. \tag{1}$$

Various distinctive features of the complex pair production process can then be interpreted in terms of this simple effective mass model.

Model for the field

In order to mimic a monochromatic electric pulse as well as to describe its inhomogeneity we propose the following model

$$E\left(x,t\right) = \varepsilon\ E_0\ \exp\left(-\frac{x^2}{2\lambda^2}\right)\ \cos^4\left(\frac{t}{\tau}\right)\ \cos\left(\Omega t\right)\mathbf{e}_x. \tag{2}$$

Here, ε gives the peak field strength, τ the pulse duration, Ω the field frequency and λ the spatial extent.

DHW formalism

Within the DHW approach using a Hartree approximation one determines several(here: $\mathbb{w} = (\mathbb{s}, \mathbb{v}, \mathbb{p}, \mathbb{v}_0)$) phase-space quantities making a system of coupled integro-differential equations

$$\left(D_t \mathbb{1} + \partial_x \hat{A} + 2p_x \hat{B} \right) \mathbb{w} = \hat{M}\ \mathbb{w}, \tag{3}$$

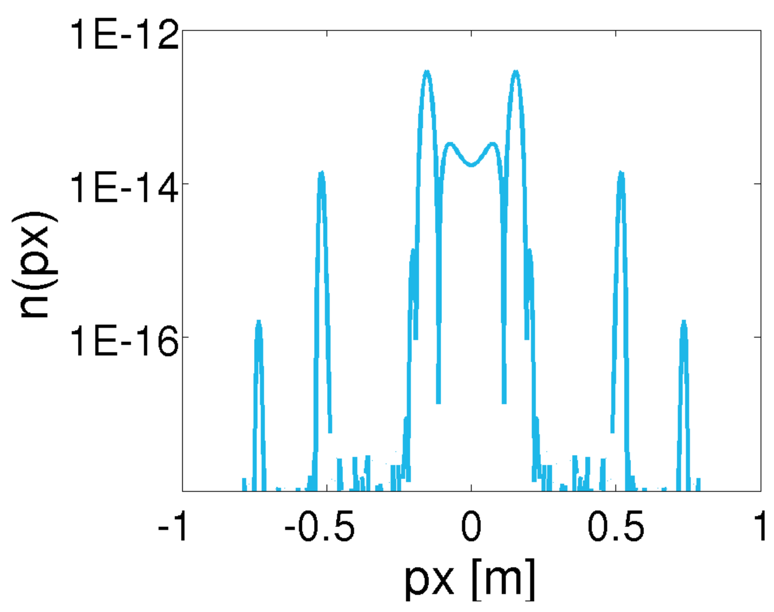
where $\hat{}$ denotes matrices. The differential operator is given by

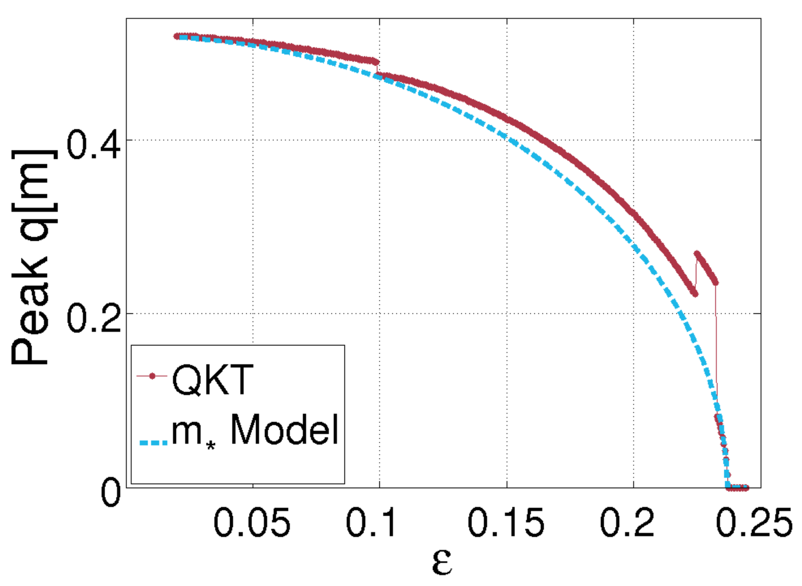
$$D_t = \partial_t + e\int d\xi E\left(x + \mathrm{i}\xi\partial_{p_x}, t\right)\partial_{p_x}. \tag{4}$$

Pair production is analyzed by solving the system of PDEs and evaluating the particle distribution function at asymptotic times

$$N = \int n\left(p_x\right)\ dp_x\ = \int dx\ \frac{m\ \mathbb{s} + p_x\ \mathbb{v}}{\sqrt{m^2+p_x^2}} \tag{5}$$

Particle distribution and Channel closing

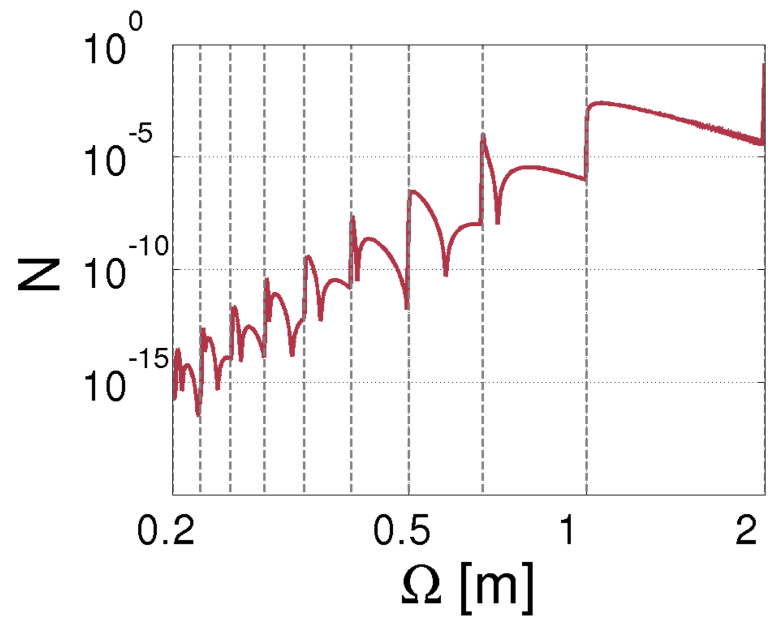


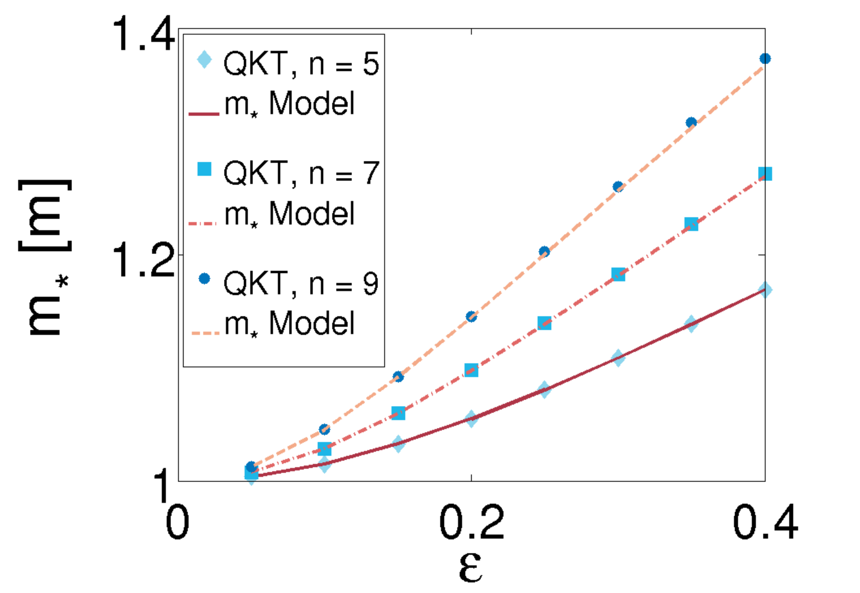


In the multiphoton regime one obtains characteristic peaks in the particle distribution function $n\left(p_x\right)$. These peaks can be related to n-photon absorption processes including above-threshold pair production. Due to energy conservation and a field-dependent effective mass m_* also the characteristic momentum of the peaks become a function of ε:

$$\left(\frac{(n+s)\ \Omega}{2}\right)^2 = m_*^2 + q_{n+s}^2 \tag{6}$$

Effective mass signatures



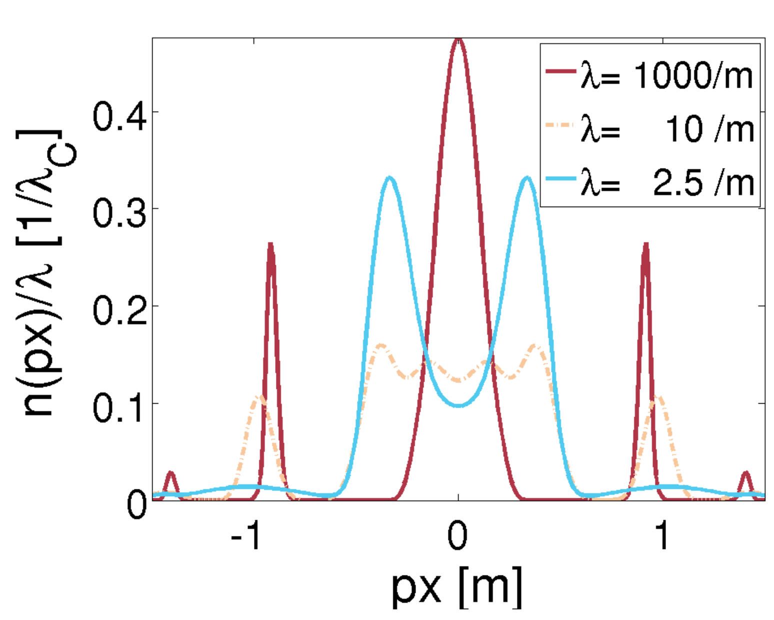


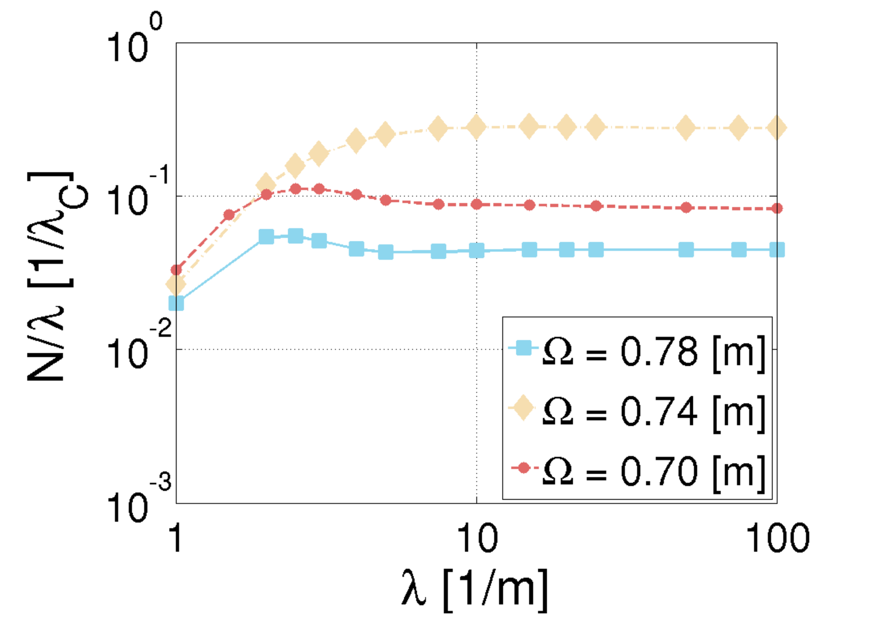
The particle yield exhibits an oscillating structure reflecting n-photon thresholds which satisfy

$$n\Omega = 2m_*. \tag{7}$$

Comparison of the effective mass model with the masses extracted from the threshold frequencies of the particle yield reveals almost perfect agreement.

Ponderomotive forces





In spatially inhomogeneous fields particles are pushed to weak-field regions due to ponderomotive forces

$$F_p\ \approx\ \boldsymbol{\nabla}\ m_*. \tag{8}$$

Calculation of the particle distribution reveals a splitting and broadening of peaks for smaller spatial extents (stronger F_p). Due to ponderomotive forces the reduced particle yield shows non-monotonic behaviour as a function of the spatial extent.

Conclusion and Outlook

Based on numerical results of a phase-space approach for pair production in oscillating electric fields we have shown various signatures of an effective mass. We have further demonstrated that the particle yield decreases slower than linear with decreasing spatial extent.

In order to understand the impact of ponderomotive forces on the pair production rate in arbitrary pulses further investigations are needed.

Acknowledgements

We thank the organizers of the ExHILP Conference for the possibility to present our work. CK was funded by the Austrian Science Fund, FWF, through the Doctoral Program on Hadrons in Vacuum, Nuclei and Stars(FWF DK W1203-N16). We thank the University of Graz' research core area "Models and Simulation" for support.

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