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Testing strong-field CED and QED with intense laser fields

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OUTLINE

- Introduction
- Radiation reaction in CED and in QED
- Radiation-reaction effects in laser-plasma interaction
- Strong-field QED processes in strong atomic and laser fields
- Conclusion

For more information see the review:

A. Di Piazza et al., Extremely high-intensity laser interactions with fundamental quantum systems, Rev. Mod. Phys. **84**, 1177 (2012)

Ackowledgments

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Typical scales of QED

- The Lagrangian of QED depends on two parameters:
  - Electron rest mass m=9.1×10^{-28} g
  - Electron charge e, with $|e|$=4.8×10^{-10} esu
- The parameters m and e, together with the fundamental constants $\hbar$ and c, determine all the typical scales and regimes of QED
- Strength of the electromagnetic interaction: $\alpha=e^2/\hbar c=1/137$
- Energy scale: mc^2=511 keV(time scale: $\hbar/mc^2$=1.3×10^{-21} s)
- Momentum scale: mc=511 keV/c (length scale: $\lambda_C=\hbar/mc=$ 3.9×10^{-11} cm, Compton wavelength)
- Critical field of QED: $F_{cr}= mc^2/|e|\lambda_C=1.3\times10^{16}$ V/cm=4.4×10^{13} G, corresponding to an intensity of 4.6×10^{29} W/cm^2

Strong-field QED in a strong laser field

A particle (e^-, e^+ or γ) with energy ϵ for an electron or a positron ($\hbar\omega$ for a photon) collides head-on with a plane wave with amplitude E_L and angular frequency ω_L (wavelength λ_L)

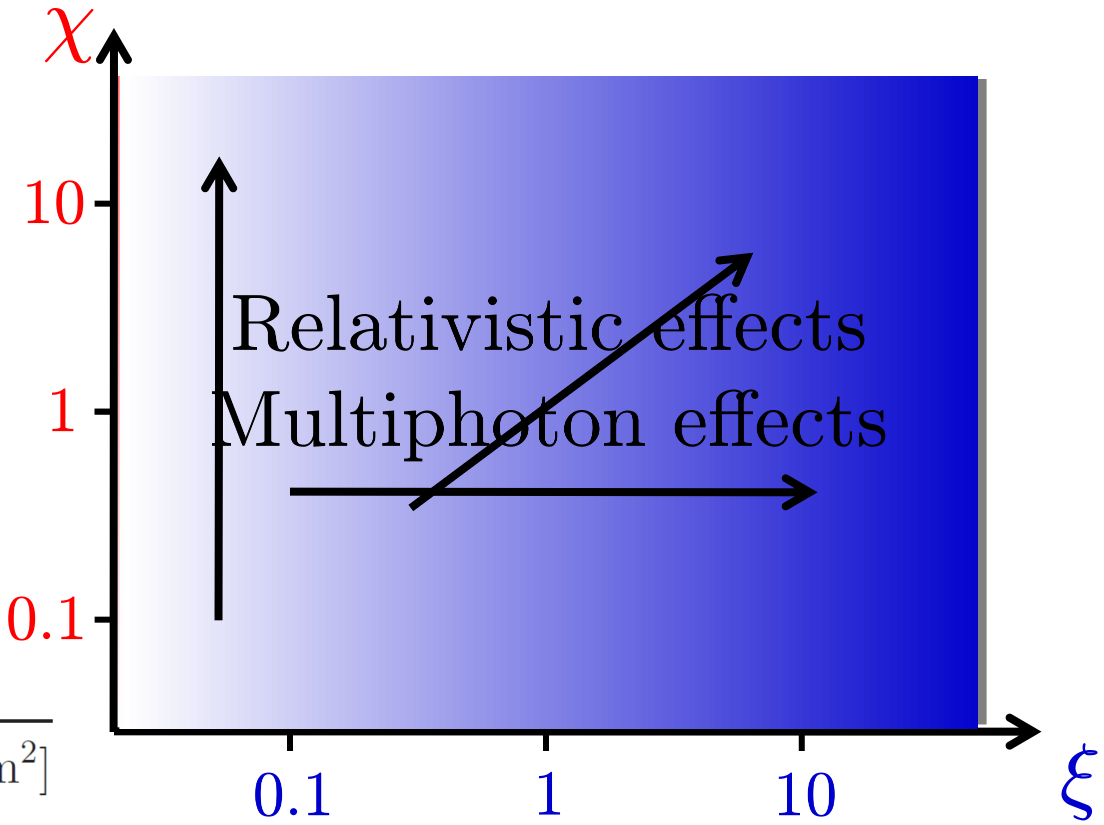
Relevant parameters (Ritus 1985, Di Piazza et al., 2012):

$$\xi = \frac{1}{2\pi}\frac{|e|E_L\lambda_L}{mc^2} = \frac{|e|E_L\lambda_C}{\hbar\omega_L}$$

$$\chi = 2\frac{\hbar\omega}{mc^2}\frac{E_L}{E_{cr}} = \left.\frac{E_L}{E_{cr}}\right|_{\text{r.f.}}$$

$$\xi = 7.5\frac{\sqrt{I_L[10^{20}\ \text{W}/\text{cm}^2]}}{\hbar\omega_L[\text{eV}]}$$

$$\chi = 5.9\times10^{-2}\,\epsilon[\text{GeV}]\sqrt{I_L[10^{20}\ \text{W}/\text{cm}^2]}$$



Radiation reaction in classical electrodynamics

What is the equation of motion of an electron in an external, given electromagnetic field $F^{\mu\nu}(x)$?

Units with $\hbar$=c=1

- The Lorentz equation

$$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu$$

  does not take into account that while being accelerated the electron generates an electromagnetic radiation field and it loses energy and momentum

- One has to solve self consistently the coupled Lorentz and Maxwell equations

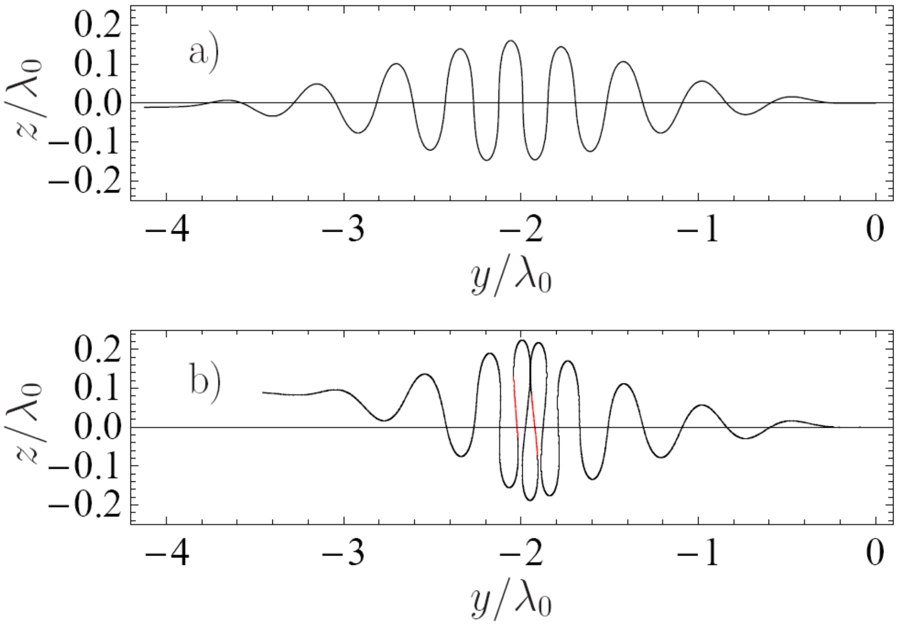
$$m_0\frac{du^\mu}{ds} = eF_T^{\mu\nu}u_\nu$$
$$\partial_\mu F_T^{\mu\nu} = e\int ds\delta(x-x(s))u^\nu$$

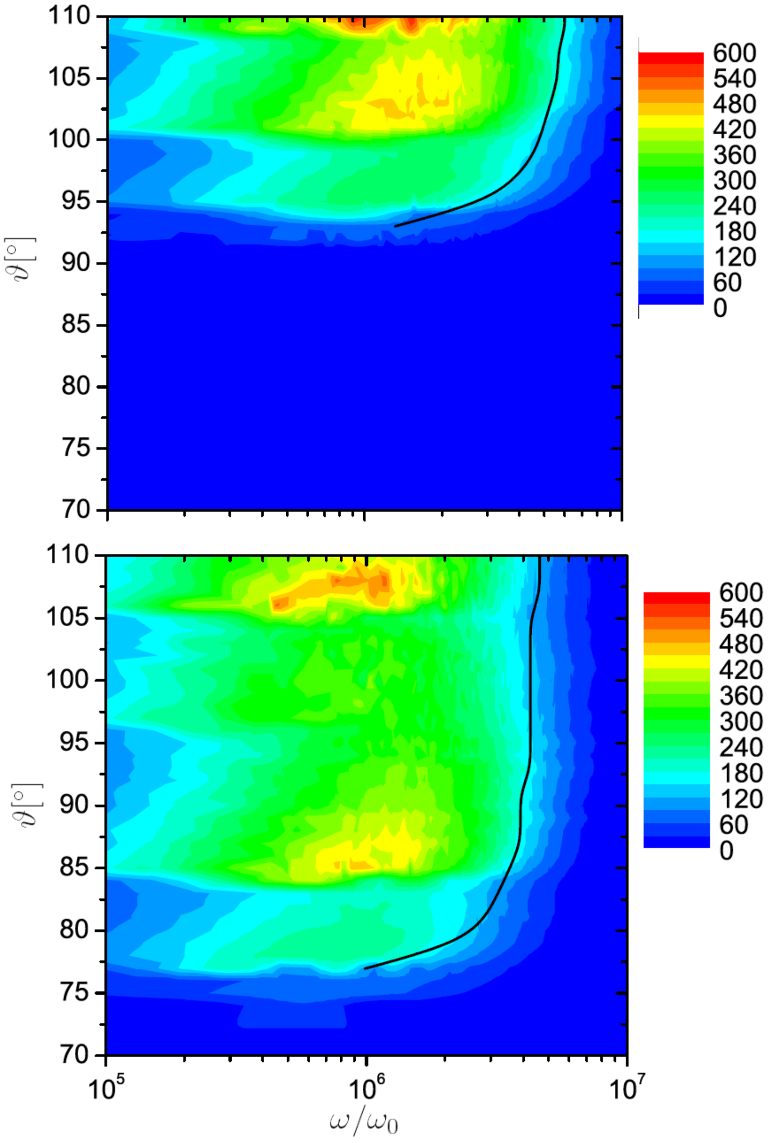
  where now m_0 is the electron's bare mass and $F_{T,\mu\nu}$ is the total electromagnetic field (Dirac 1938)

- If quantum effects are negligible, solving these equations is equivalent to solve the equation (Landau and Lifshitz, 1947)

$$m\frac{du^\mu}{ds} = eF^{\mu\nu}u_\nu+\frac{2}{3}\alpha\left[\frac{e}{m}(\partial_\alpha F^{\mu\nu})u^\alpha u_\nu-\frac{e^2}{m^2}F^{\mu\nu}F_{\alpha\nu}u^\alpha+\frac{e^2}{m^2}(F^{\alpha\nu}u_\nu)(F_{\alpha\lambda}u^\lambda)u^\mu\right]$$

- Numerical parameters: electron energy 40 MeV ($2\gamma_0=156$), laser wavelength 0.8 μm, laser intensity 5×10^{22} W/cm^2 ($\xi=150$), pulse duration 30 fs, focused to 2.5 μm
- Electron trajectories and emission spectra without and with radiation reaction





- The red parts of the trajectory are those where the longitudinal velocity of the electron is positive
- The black lines indicate the cut-off position from the formula $\omega_c=3\omega_0\gamma^3$

A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, Phys. Rev. Lett. **102**, 254802 (2009)

Radiation reaction in quantum electrodynamics

- We introduced the problem of radiation reaction in CED by saying that the Lorentz equation has to be modified as it does account for the energy-momentum loss of the accelerating and then emitting electron
- Thus one could be tempted to say that radiation reaction is automatically taken into account in QED already in the "basic" emission process (nonlinear single Compton scattering)

  because photon recoil, i.e., the energy-momentum subtracted by the photon to the electron is automatically included
- However, this cannot be the case because

  1. in the classical limit $\chi \ll 1$, the spectrum of nonlinear Compton scattering goes into the classical spectrum calculated via the Lorentz equation, i.e., without radiation reaction
  2. the photon recoil $\hbar\omega$ is proportional to $\hbar$ and it does not have a classical analogue
  3. radiation reaction would always be a small correction classically, which is not the case in the radiation dominated regime

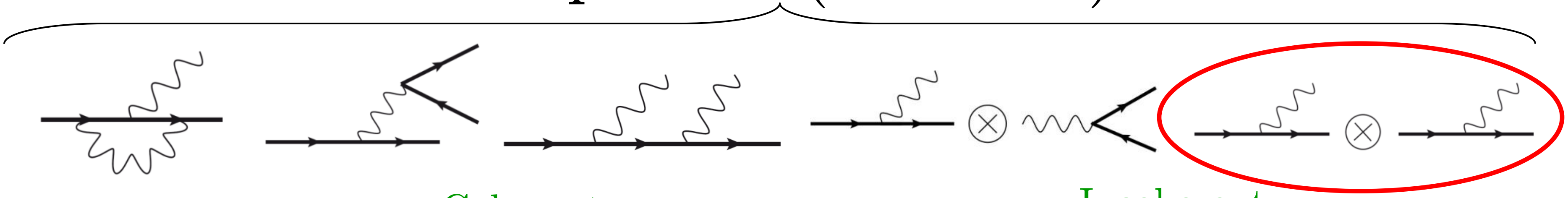
- To take into account radiation reaction classically amounts to solve self-consistently Maxwell and Lorentz equations

$$m_0\frac{du^\mu}{ds} = eF_T^{\mu\nu}u_\nu$$

$$\partial_\mu F_T^{\mu\nu} = e\int ds\delta(x-x(s))u^\nu$$

- This corresponds in QED to determine the evolution of a single-electron state in background field+radiation field generated by the electron

$|t=-\infty\rangle = |e^-\rangle \longrightarrow$ Complete evolution operator (S-matrix) $\longrightarrow |t=+\infty\rangle$



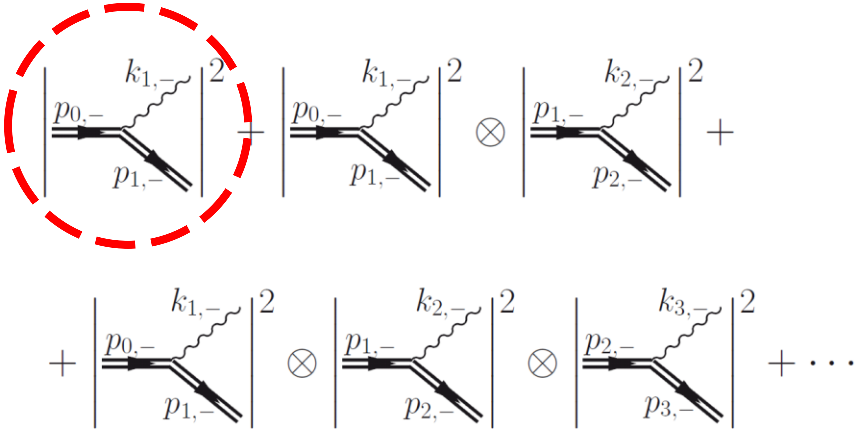
Radiative corrections

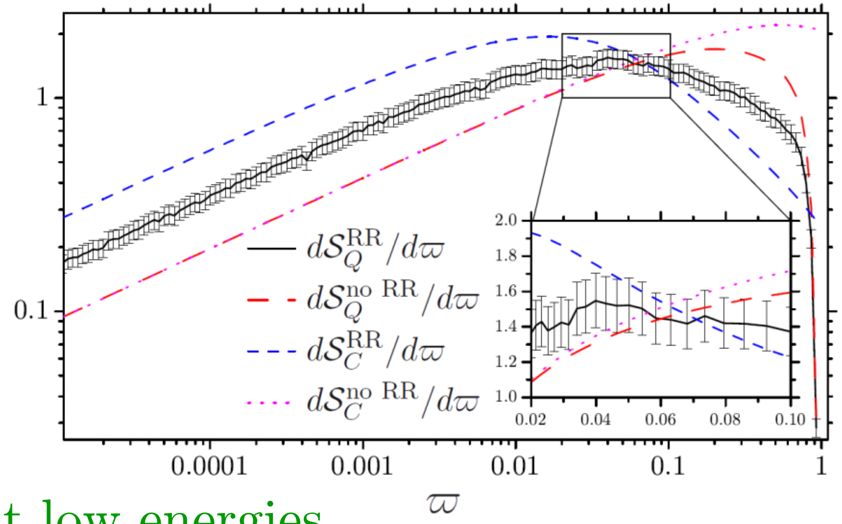
Coherent high-order processes

Incoherent high-order processes

- In QED radiation reaction is the effect of all possible high-order quantum processes beyond the tree-level one-photon emission
- At $\xi \gg 1$ and $\chi \sim 1$ the multiple incoherent emission gives the main contribution (Di Piazza et al., Phys. Rev. Lett. **105**, 220403 (2010))

- We calculated the average energy emitted per unit of electron energy (emission spectrum) in the realm of strong-field QED, by taking into account the incoherent emission of $N>1$ photons (quantum radiation reaction)
- Numerical parameters: electron energy 1 GeV, laser wavelength 0.8 μm, laser intensity 5×10^{22} W/cm^2 ($\xi=150$) corresponding to $\chi=1.8$, laser pulse duration 5 fs

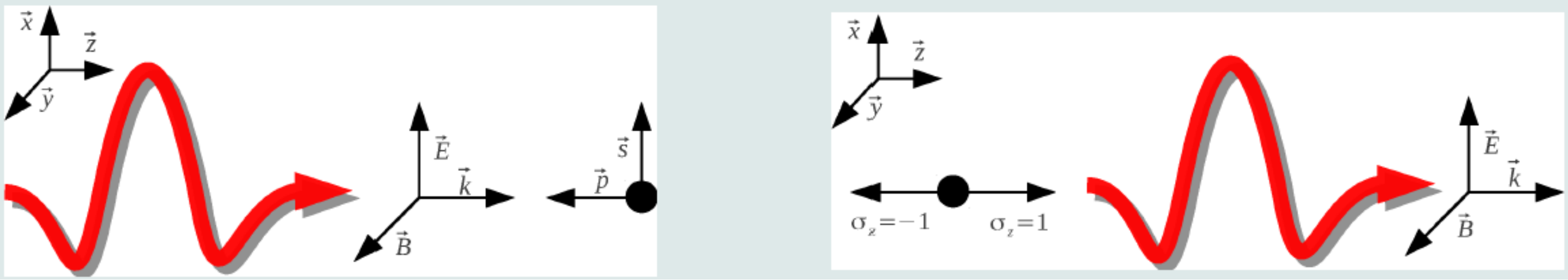




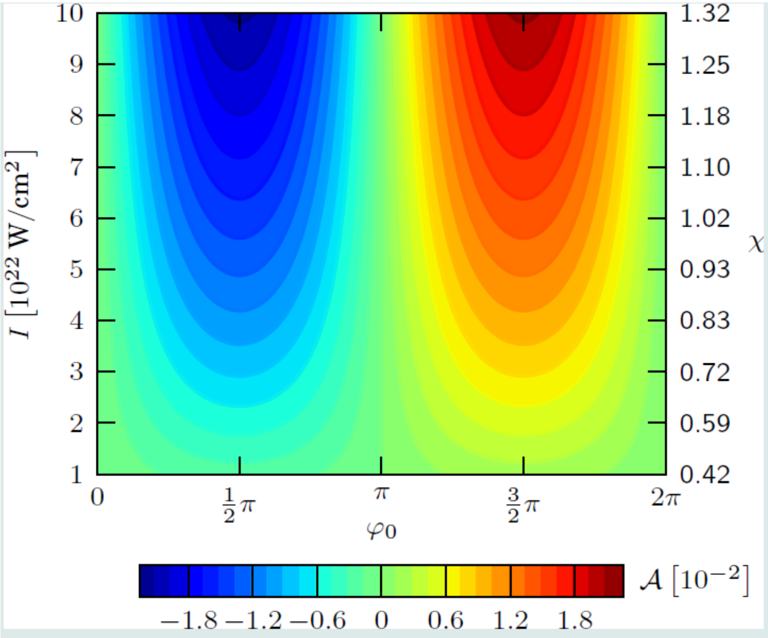
- Effects of radiation reaction:
  1. increase of the spectrum yield at low energies
  2. shift to lower energies of the maximum of the spectrum yield
  3. decrease of the spectrum yield at high energies
- Classical radiation reaction artificially amplifies all the above effects
- Classical spectra both without and with radiation reaction give unphysical results at high photon energies

A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, Phys. Rev. Lett. **105**, 220403 (2010)

- Also if the electron does not emit photons in a laser field, the interaction with its own near-field changes the spin dynamics (radiatively-corrected Volkov states)



- Asymmetry in the final spin distribution depending on the carrier envelope phase φ_0 (electron energy of 500 MeV, 3-cycle pulse with photon energy of 1.55 eV)
- Asymmetries of 1 % are nowadays measurable at electron energies of 1 GeV



S. Meuren and A. Di Piazza, Phys. Rev. Lett. **107**, 260401 (2011)

Radiation-reaction effects in laser-plasma interaction

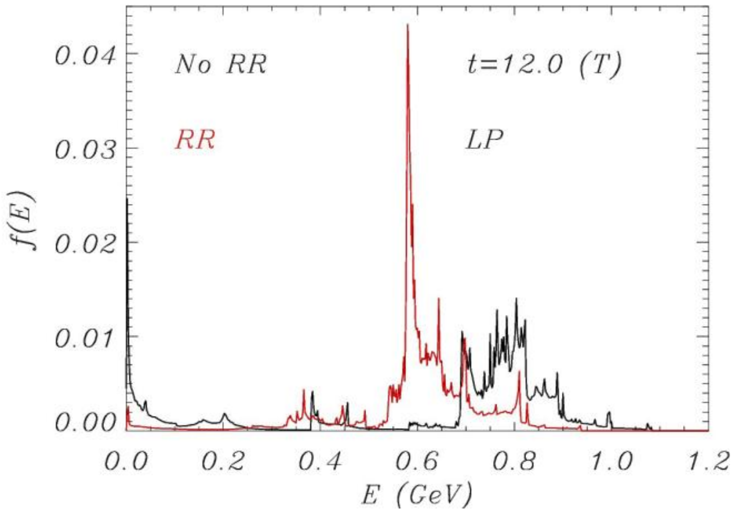
- Radiation-reaction effects become important at optical lasers intensities of the order of $10^{22}\div10^{23}$ W/cm^2
- Based on the Landau-Lifshitz equation, one can include radiation-reaction effects in a PIC code by modifying the Vlasov equation as (Tamburini et al., New J. Phys. **12**, 123005 (2010))

$$\partial_t f + \boldsymbol{\nabla}_{\boldsymbol{q}} \cdot (f\boldsymbol{v}) + \boldsymbol{\nabla}_{\boldsymbol{p}} \cdot (f\boldsymbol{F}) = 0$$

where $\boldsymbol{F}=\boldsymbol{F}(\boldsymbol{q}, \boldsymbol{p}, t)$ are the spatial components of the four-force

$$f^\mu = eF^{\mu\nu}u_\nu + \frac{2}{3}\alpha\left[\xcancel{\frac{e}{m}(\partial_\alpha F^{\mu\nu})u^\alpha u_\nu} - \frac{e^2}{m^2}F^{\mu\nu}F_{\alpha\nu}u^\alpha + \frac{e^2}{m^2}(F^{\alpha\nu}u_\nu)(F_{\alpha\lambda}u^\lambda)u^\mu\right]$$

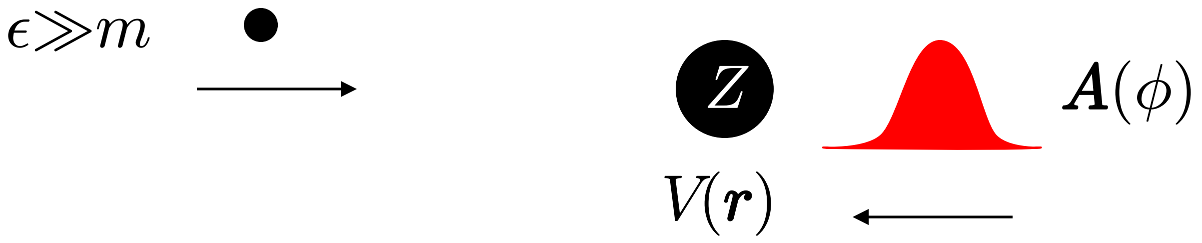
- Numerical parameters: linear laser polarization, laser wavelength 0.8 μm, laser intensity 2.33×10^{23} W/cm^2, laser pulse duration 7 cycles, plasma density $n=100n_c$ and plasma thickness 0.8 μm
- No radiation-reaction effects for circular polarization



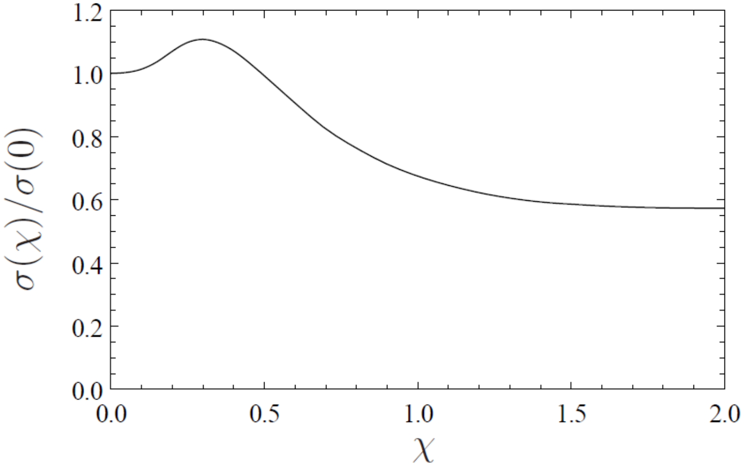
Strong-field QED in a strong atomic field

Highly-charged ions are sources of very strong fields (Bethe and Heitler 1934, Bethe and Maximon 1954). The important parameter here is the Lorentz- and gauge-invariant parameter $Z\alpha$. For Uranium 91^+ it is $Z\alpha\approx0.66$ (corresponding to $I\sim10^{28}$ W/cm^2).

- There exist many calculations of QED processes in atomic and laser fields but the atomic field is taken into account at the leading order (Born approximation) (Yakovlev 1965, Mueller et al. 2003, Loetstedt et al. 2009, Di Piazza et al. 2009)
- By employing the operator technique (Schwinger 1951), we calculated the electron propagator in the leading-order quasi-classical approximation by including exactly both the atomic and the laser field at $Z\alpha, \chi \sim 1$ and $\xi \gg 1$.
- The physical scenario is the following:



- At $Z = 83$ (Bismuth) we observed a suppression of the cross section of 40 % at $\chi = 1$, which corresponds to a laser intensity of 10^{22} W/cm^2 at an incoming photon energy of $\omega = 10$ GeV



- The suppression of the cross section is caused by the deviation in the transverse direction due to the laser field, which reduces the formation length of the process. In this sense, it is the analogous in the laser field of the Landau-Pomeranchuk-Migdal (LPM) effect, where the reduction of the formation length is induced by the multiple scattering of the charged particle in matter
- The LPM effect for the Bethe-Heitler process in matter has never been observed experimentally, as photon energies of the order of 1 TeV are required (Baier and Katkov 2005)

A. Di Piazza and A. I. Milstein, arXiv:1204.2502 (Phys. Lett. B, in press)

Conclusion

- Present and next-generation lasers can offer a unique possibility of accessing new extreme regimes of interaction, where the effective strength of the electromagnetic fields becomes close to the critical fields of QED
- New effects are predicted to occur by classical and quantum electrodynamics, which can be tested in such extreme conditions. In particular,
  1. the electron dynamics is strongly dominated by radiation-reaction and quantum effects
  2. the electron spin dynamics can be altered by the interaction of the electron with its own electromagnetic field
  3. new laser-plasma interaction regimes are envisaged