Electron-positron photoproduction in strong laser fields: total probability, semiclassical description and recollision processes

Extremely High-Intensity Laser Physics (ExHILP)

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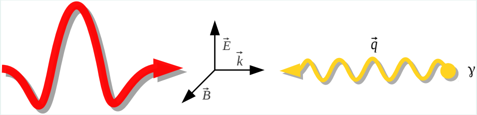
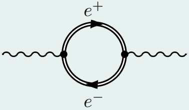
Overview

Light-by-light scattering

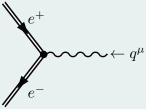


Laser (intensity: $\sim 10^{22}\ \mathrm{W/cm^2}$, photon energy: $\sim \mathrm{eV}$) – GeV gamma photon collisions

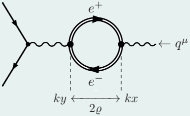
Strong-field QED processes



Photon dispersion relation

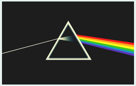


Pair creation



Electron-positron recollisions

Analogue in atomic physics



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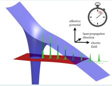
Light inside a medium



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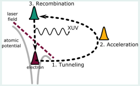
Tunnel ionization



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Electron-atom recollisions

Importance of real pair creation

Critical field

- $E \geq E_{\rm cr}$: real pair creation
- Missing energy: $\sim mc^2$
- Life time: $\tau \sim \hbar/(mc^2)$
- Work by the field: $\sim E\,|e|\,c\tau$

Quantum nonlinearity parameter

Real pair creation is sizable if

$$\chi = \frac{|e|\,\hbar}{m^3c^4}\sqrt{q^\mu f^2_{\mu\nu} q^\nu} = (2\hbar\omega_\gamma/mc^2)(E/E_{cr}) \gtrsim 1$$

[last relation holds for head-on collisions]

- $E_{\rm cr} = m^2c^3/(\hbar|e|) = 1.3 \times 10^{16}$ V/cm implies $I_{\rm cr} = 4.6 \times 10^{29}\ \mathrm{W/cm^2}$
- $E_{\rm cr}$ not achievable even with next-generation laser systems:

Future facilities	$\hbar\omega$	I (intensity)
ELI, CLF, XCELS	$1\,\mathrm{eV}$	$10^{24-25}\ \mathrm{W/cm^2}$
XFEL, LCLS (goal)	$10\,\mathrm{keV}$	$10^{27}\ \mathrm{W/cm^2}$

- The electric field is not a Lorentz scalar
- A highly-energetic charged particle/photon leads to a Lorentz boost
- The critical field is obtainable in the boosted frame

Classification of the laser field strength

Classical intensity parameter

The laser intensity is measured by

$$\xi \equiv \frac{|e|\sqrt{-a_\mu a^\mu}}{mc} = \frac{|e|\,E}{mc\,\omega}$$

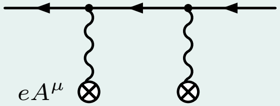
ω: laser central angular frequency

E: laser peak field strength

$F^{\mu\nu} \sim f^{\mu\nu}$, $f^{\mu\nu} = k^\mu a^\nu - k^\nu a^\mu$

Laser coupling

$$\frac{\not{p}+m}{p^2-m^2} \sim \frac{1}{m}$$



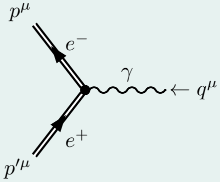
A single laser coupling scales with ξ

Perturbative regime $\xi \ll 1$	Each coupling suppressed by ξ^2 (probability) n-photon absorption scales as ξ^{2n}
Nonperturbative regime $\xi \gtrsim 1$	Laser must be included exactly
Semiclassical regime $\xi \gg 1$	Probability amplitude is highly oscillating, classical interpretation of stationary points

- The regime $\xi \gtrsim 1$ is also called relativistic regime (electron at rest becomes relativistic within one laser half-cycle)

Semiclassical picture: SM, C. H. Keitel, and A. Di Piazza, arXiv:1503.03271 (2015)

Total/Differential probability



- Photon: four-momentum q^μ $(q^2 = 0)$
- Electron: four-momentum $p^\mu = (\epsilon_{\boldsymbol{p}}, \boldsymbol{p})$
- Positron: four-momentum $p'^\mu = (\epsilon_{\boldsymbol{p}'}, \boldsymbol{p}')$

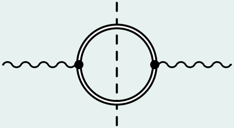
$$\epsilon_{\boldsymbol{p}} = \sqrt{m^2 + \boldsymbol{p}^2}, \quad \epsilon_{\boldsymbol{p}'} = \sqrt{m^2 + \boldsymbol{p}'^2}$$

$$W(q) = \sum_{\text{spin}} \int \frac{d^3p\, d^3p'}{(2\pi)^3\, 2\epsilon_{\boldsymbol{p}} 2\epsilon_{\boldsymbol{p}'}}\, \delta^{(-,\perp)}(p + p' - q)\, \frac{1}{2kq}\, |\mathcal{M}(p, p'; q)|^2,$$

$\delta^{(-,\perp)}(\cdots) \to p^\mu + p'^\mu = q^\mu + nk^\mu$: momentum only partially conserved

$\mathcal{M}$: reduced S-matrix element; k^μ: laser photon four-momentum

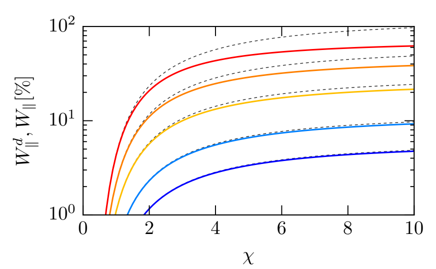
Optical theorem

$\mathrm{i}\mathcal{P}^{\mu\nu} = q_2$  q_1, $\quad W(q) = \dfrac{1}{kq} \left[\dfrac{\Im \epsilon_\mu \epsilon^*_\nu \mathcal{P}^{\mu\nu}(q_1, q_2)}{(2\pi)^3 \delta^{(-,\perp)}(q_1 - q_2)} \right]_{q_1 = q_2 = q}$

SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRD **91**, 013009 (2015)

Total pair-creation probability: Numerical results

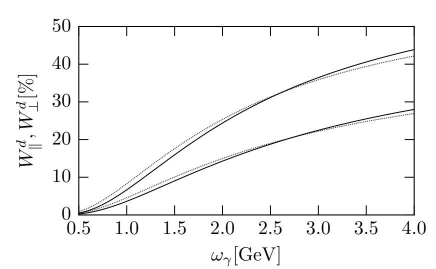
By combining available optical petawatt lasers with existing GeV gamma sources, the pair-production probability can become very large



dashed lines: without wave-function decay

$\xi = 10, 20, 50, 100, 200$ ($N = 5$)

$F^{\mu\nu}(x) = f^{\mu\nu} \sin^2[\phi/(2N)] \sin(\phi)$, $\phi = kx$



solid: $F^{\mu\nu}(x) = f^{\mu\nu} \sin^2[\phi/(2N)] \sin(\phi)$

dashed: $F^{\mu\nu}(x) = f^{\mu\nu} \sin^4[\phi/(2N)] \sin(\phi)$

$\xi = 100$, $N = 5$, $\omega = 1.55\,\mathrm{eV}$

Problem: For certain values of χ/ξ the evaluation of the leading-order Feynman diagram violates unitarity

Solution: The back-reaction of the decay on the photon wave function must be taken into account

SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRD **91**, 013009 (2015)

Exact photon wave function

- The exact photon wave function [$\Phi_q^{\mathrm{in}\mu}(x)$ and $\Phi_q^{*\mathrm{out}\mu}(x)$] is defined via the Schwinger-Dyson equation:

$$-\partial^2\Phi_q^{\mathrm{in}\mu}(x) = \int d^4y\, P^{\mu\nu}(x,y)\Phi_{q\nu}^{\mathrm{in}}(y)$$

a) Exact photon wave function (includes radiative corrections)

b) Polarization operator (all one-particle irreducible diagrams)

- For $\xi \gg 1$ we can replace $\Phi_{q\nu}^{\mathrm{in/out}}(y)$ by $\Phi_{q\nu}^{\mathrm{in/out}}(x)$ (local approximation)
- The obtained ordinary differential equation can be solved:

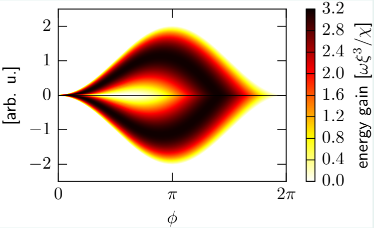
$$\Phi_{q,j}^{\mathrm{in}\mu}(x) = \epsilon_j^\mu \exp\left[-\mathrm{i}qx - \mathrm{i}\frac{1}{2kq}\int_{-\infty}^{kx} d\phi'\,\mathfrak{p}_j(\phi')\right]$$

ϵ_j^μ: polarization four-vector, $\mathfrak{p}_j(\phi)$: coefficients related to the PO

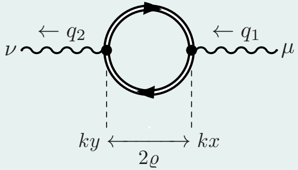
Real part of the phase: vacuum birefringence/photon mass

Imaginary part of the phase: exponential wave-function decay

Classical trajectories



Polarization operator



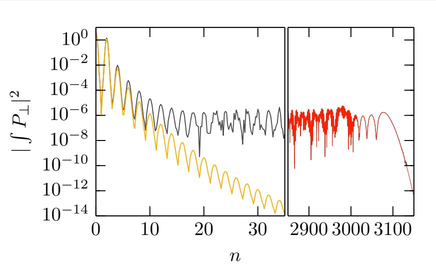
- Creation vertex: *kx*
- Annihilation vertex: *ky*

- The polarization operator mainly describes vacuum fluctuations (annihilation of the pair within one formation length)
- If real pair creation is sizable (i.e. for $\chi \gtrsim 1$) also recollision processes contribute to the polarization operator (for a linearly polarized laser)
- Recollisions can be explained semi-classically as a three-step process:
  1. Pair creation inside a constant-crossed field ($\xi \gg 1$)
  2. Acceleration of the pair by the laser field
  3. Collision after one or more cycles

SM, K. Z. Hatsagortsyan, C. H. Keitel, and A. Di Piazza, PRL **114**, 143201 (2015)

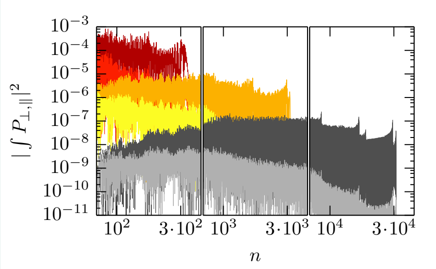
Recollisions of laser-generated electron-positron pairs

Quasistatic/recollision contribution



- Quasi-static (yellow curve) vs. recollision contribution (red curve)
- During a recollision many laser photons can be efficiently absorbed from the laser

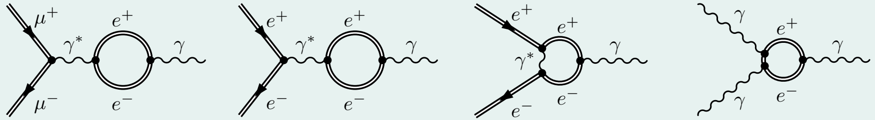
Scaling of the plateau region



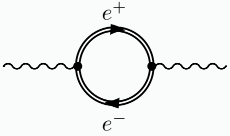
$\chi = 1$, $N = 5$, $\xi = 10^{2/3}$ (red), $\xi = 10$ (yellow), $\xi = 10^{4/3}$ (gray)

- The plateau width scales as $3.17\,\xi^3/\chi$
- The height of $|P_\perp|^2$ scales as $\chi^{10/3}/\xi^6$

Possible secondary reactions

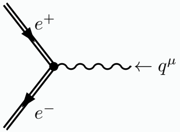


Summary



Polarization operator

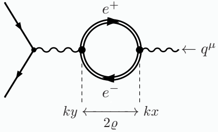
SM, C. H. Keitel, and A. Di Piazza,
PRD **88**, 013007 (2013)



Breit-Wheeler pair creation / Exact photon states

SM, K. Z. Hatsagortsyan, C. H. Keitel, and
A. Di Piazza, PRD **91**, 013009 (2015)

SM, C. H. Keitel, and A. Di Piazza
arXiv:1503.03271 (2015)



Recollision processes

SM, K. Z. Hatsagortsyan, C. H. Keitel, and
A. Di Piazza, PRL **114**, 143201 (2015)

Thank you for your attention and your questions!