QED processes in intense laser fields

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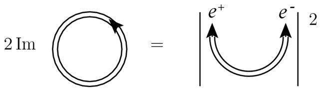
- Phys.Rev.Lett. **106** (2011) 020404.
- Phys. Lett. **B692** (2010) 250.
- With C. Harvey, F. Hebenstreit, T. Heinzl, M. Marklund.

Euler-Heisenberg

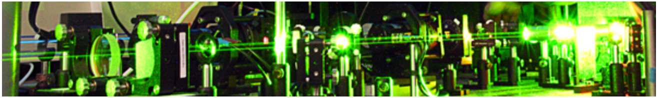
- Optical theorem.
- Loops $\to$ trees.
- Schwinger pair production.

$$S = -i \log \mathrm{Det}(i\not{D} - m)$$



$\implies$ Trees and scattering.

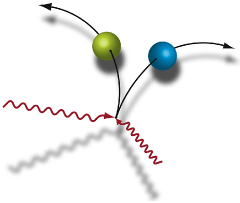
Outline



1. Scattering in background fields.
2. Pair production and the effective mass.
3. Trident pair production.

Intensity in QED

- Modern laser pulses: short, focussed.
  - Pulse duration: $30 - 100$ fs.
  - Focal width: 10^{-6} m.
  - High intensity: $\sim 10^{21} - 10^{24}$ W/cm^2
- Radiography, hadron therapy, attosecond imaging....



- High intensity/low energy QED.
- Theory: QED + background (laser) field.
- How to calculate.
- What to calculate.

Processes in background fields

- Intensity parameter: $e\mathcal{A}_{\mathsf{cl}} \sim a_0 \equiv \dfrac{eE\lambda\!\!\!^{-}}{mc^2} \sim \sqrt{I}$.
- Energy gain of e^- over a laser wavelength.
- $a_0 > 1$ relativistic. Modern optical lasers: $a_0 \gg 1$.

T. Heinzl, A. Ilderton, Opt.Commun. 282 (2009) 1879

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T. Heinzl, A. Ilderton, Opt.Commun. 282 (2009) 1879

1. Background fields: $\overline{\psi}\not{A}\psi \longrightarrow \overline{\psi}(\not{A} + \not{\mathcal{A}}_{\text{cl}})\psi$
2. Dressed fermion propagators. $[i\not{\partial} - e\not{\mathcal{A}}_{\text{cl}} - m]^{-1} =$ 
3. Interactions: ordinary QED vertices. $ie\overline{\psi}\not{A}\psi$

W. H. Furry, Phys. Rev. 81 (1951) 115.

Loops . . .

- Vacuum birefringence

  Toll, PhD thesis, 1952

  Heinzl et al., Opt.Commun. 267 (2006) 318.

  Heinzl and Schröder, J.Phys.A A39 (2006) 11623

- Photon emission/splitting/scattering

  Adler, Annals Phys. 67 (1971) 599

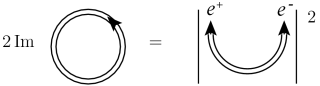
  Lundstrom *et al.*, Phys.Rev.Lett. 96 (2006) 083602

- Schwinger pair production

  Schwinger, Phys. Rev. 82 (1951) 664.

  Dunne, Gies, Schützhold, Phys.Rev.Lett.101 (2008) 130404,

  Dunne, Gies, Schützhold, Phys.Rev.D80 (2009) 111301



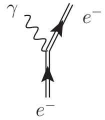
. . . and trees.

- Nonlinear Compton scattering

  Periodic fields: Nikishov and Ritus, Sov.Phys.JETP 19 (1964) 529

  Pulses: Mackenroth, Di Piazza, Phys.Rev. A83 (2011) 032106

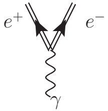
  Seipt, Kämpfer, Phys.Rev. A83 (2011) 022101



- Stimulated pair production

  Periodic fields: Nikishov and Ritus, Sov.Phys.JETP 19 (1964) 529

  Pulses: Heinzl, Ilderton, Marklund, Phys.Lett. B692 (2010) 250

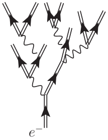


- Cascades

  Fedotov, et al. Phys.Rev.Lett. 105 (2010) 080402

  Sokolov et al. Phys.Rev.Lett. 105 (2010) 195005

  Elkina et al, Phys. Rev. ST Accel. Beams **14** (2011) 054401.



Laser field models

- Periodic plane waves.

  Nikishov, Ritus, Narozhny 1964

- Pulsed plane waves: finite size effects.

  Heinzl, Ilderton, Marklund, Phys.Lett. B692 (2010) 250

  Mackenroth, Di Piazza, Phys.Rev. A83 (2011) 032106

- Gaussian beams, other exact solutions.

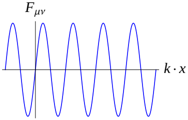
  Davis Phys. Rev. A19 (1978) 1177

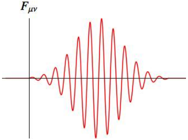
  Bulanov et al, Phys.Lett. A330 (2004) 1

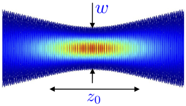
▷ Furry picture: essentially only plane waves.

$$F_{\mu\nu} \equiv F_{\mu\nu}(k.x) \ , \qquad k.x \equiv k_+ x^+ .$$

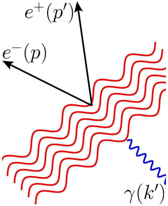
- 'One dimensional'. Lightfront.

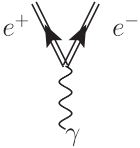






Stimulated pair production





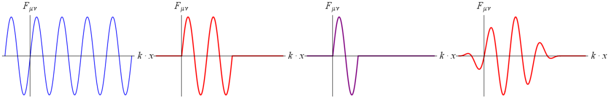
- Incoming photon creates a pair.

$$\gamma(k') \xrightarrow[\text{laser}]{} e^-(p) + e^+(p')$$

- Background energy puts particles on shell:

$$k'_\mu + (\text{background}) = p_\mu + p'_\mu$$

- Periodic vs. short pulse backgrounds.



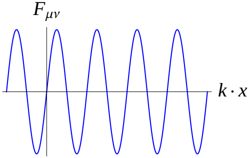
Old results: very long pulses.

- Periodic waves. Infinite duration.

  Niksihov, Ritus, Sov.Phys.JETP 19 (1964) 529

- Charges: rapid quiver motion.

$\rightarrow$ Quasi-momentum $q_\mu = \langle p_\mu \rangle$.



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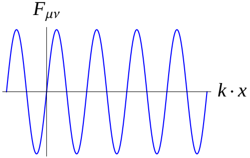

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- Charges: rapid quiver motion.

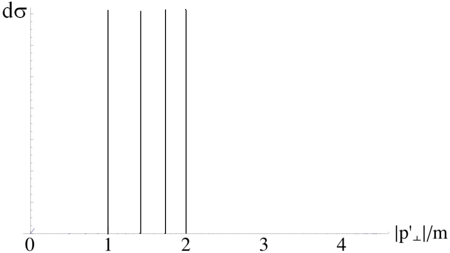
→ Quasi-momentum $q_\mu = \langle p_\mu \rangle$.

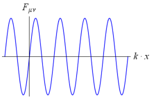
- S-matrix element: $k'_\mu + n k_\mu = q_\mu + q'_\mu$
- Shifted mass: $\boxed{q^2 = m_*^2 \equiv m^2(1 + a_0^2).}$
- Basic intensity effect. Sengupta, 1952

? Pair production threshold: $n > \dfrac{2m_*^2}{k.k!}$.

- ELI optical laser: $m_* \sim 10^2 m!$ Extreme Light Infrastructure

The role of the shifted mass

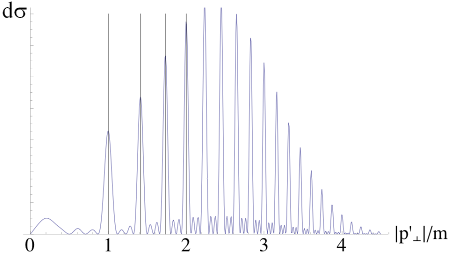


Periodic wave: 

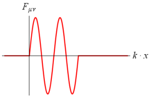
- Line spectrum.
- Shifted threshold.
- $k.k' > 2m^2(1 + a_0^2)$

- Differential cross-section.
- (arb. units)
- Energies: $0 \sim m$ and $1 \sim m_*$.

The role of the shifted mass



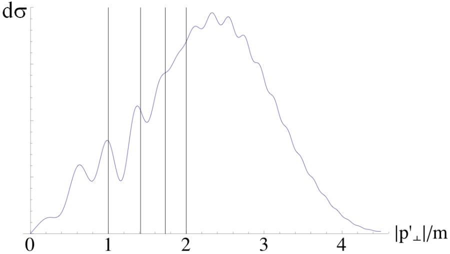
Wavetrain:
few cycles



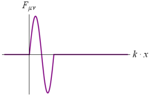
- Substructure.
- Sub-threshold behaviour
- Peaks = resonances.

- Resonance condition: (lightfront momentum transfer):
- Average = multiple of driving frequency ω.
- Looks like: enough energy to produce m_* pairs.

The role of the shifted mass



Wavetrain:
one cycle

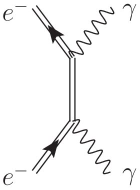


- Different structure.
- Clear signal between m and m_*.

$\Longrightarrow$ Mass $\leftrightarrow$ shifted mass dominance.

- m_* not 'in control'.
- Smooth pulses: new $m_*(k.x)$ effects.

Some higher order processes



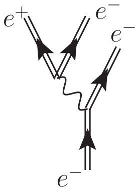
- Strong field Compton.

  V.P. Oleinik. Sov. Phys. JETP 25 (1967) 697

  Ya.B. Zeldovich. Sov Phys JETP 24 (1967) 1006

- Two-photon pair production.

  A. Hartin, PhD thesis, 2006



- Trident pair production.

  H. Hu, C. Müller, C. H. Keitel, Phys. Rev. Lett. 105, 080401 (2010).

- Møller scattering.

  F. Ehlotzky, Rep. Prog. Phys. **72** (2009) 046401.

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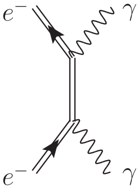

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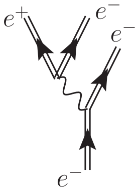

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- Complicated external field dependence.
- Lowest order perturbative: messy but straightforward.

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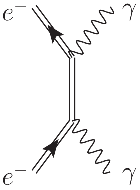

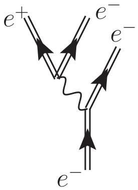

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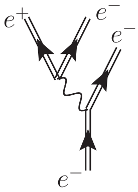
- Higher orders and nonperturbative: divergent.
- Use trident to illustrate.

Trident pair production: physics

- Intermediate photon: on- or off-shell.

$$\frac{1}{k^2} \to \frac{1}{0} \quad \ddot{\frown}$$



- Two different processes contributing.

1. One step: $e^- + (\text{laser}) \to e^- + e^- + e^+$
2. Two step:

Nonlinear Compton scattering: $e^- + (\text{laser}) \to \gamma$

Stimulated pair production: $\gamma + (\text{laser}) \to e^- + e^- + e^+$

- Physics: no problems here.
- SLAC E144.

Bamber *et al.*, Phys.Rev.**D**60 (1999) 092004

Poles and imaginary parts

- Internal lines ‘usually’ off-shell.
- When not.... the pole prescription tells us what to do.

$$\lim_{\epsilon\to 0} \frac{1}{k^2+i\epsilon} = \frac{P}{k^2} - i\pi\delta(k^2)$$

Poles and imaginary parts

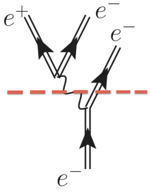
- Internal lines ‘usually’ off-shell.

- When not.... the pole prescription tells us what to do.

$$\lim_{\epsilon\to 0}\frac{1}{k^2+i\epsilon}=\frac{P}{k^2}-i\pi\delta(k^2)$$

- Real/ imaginary parts $\to$ off/on-shell.

- Unitarity: intermediate on-shell states.

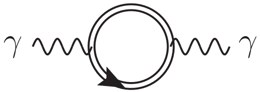


:) The divergence was never there.

A. I., Phys.Rev.Lett. **106** (2011) 020404

Looking for new physics

- Birefringence: what's in the loop?
- Axions....? Minicharges?
  See talk by F. Karbstein.



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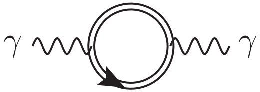
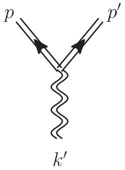


? Spacetime noncommutativity? $[x^\mu, x^\nu] = i\theta^{\mu\nu}$

- Photon is self-interacting.
- Deviations from standard model:

$$\Delta = a_0\, k_\mu \theta^{\mu\nu} k'_\nu$$



- Intensity + noncommutative effects.

Difficult! But possible.

A. Ilderton, J. Lundin, M. Marklund, SIGMA 6 (2010) 041

T. Heinzl, A. Ilderton, M. Marklund, Phys.Rev. D81 (2010) 051902

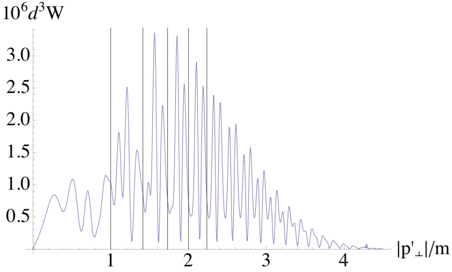
Conclusions

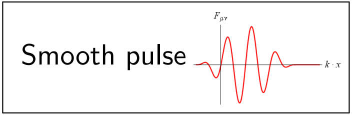
- QED + background fields.
- Intensity effects in pair production: mass shift.

- Pair production: threshold blueshift.
- Physics = resonance effect.
- Trident: interesting theory, even at tree level.

- Quantum kinetics: talk by C. Dumlu.
  (Also: Hebenstreit, Ilderton, Marklund, arXiv:1109.3712)
- Loop effects: talk by T. Heinzl.

Extra slide





- Different structure.
- Shifted peaks.

- $m_* \to M(k.x, k.y)$.