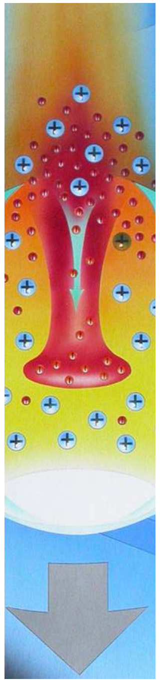
Vacuum Pair Production by Optical Laser Colliders

Gerd Röpke (Rostock University, Germany)



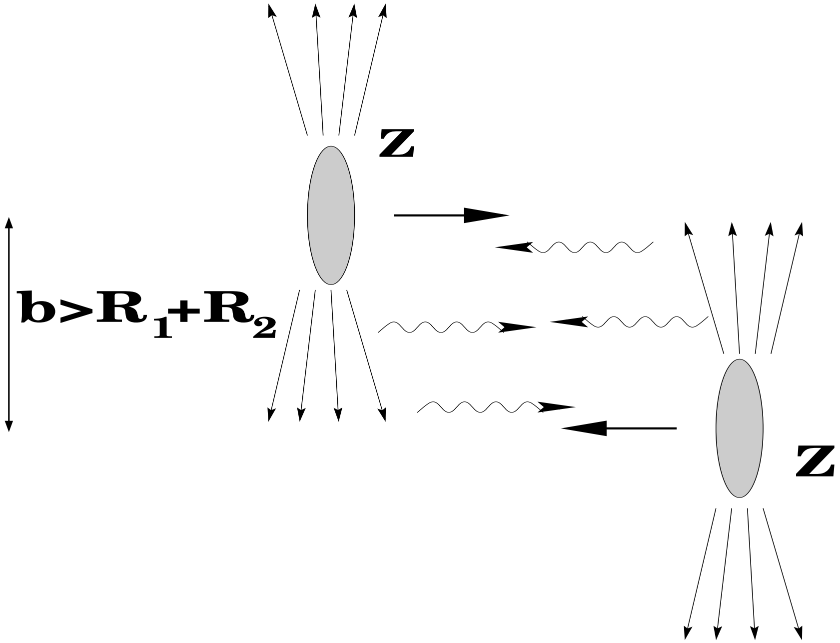
- Introduction: Schwinger Effect
- Kinetic formulation of pair production
- Application to pair production in subcritical laser fields
- Experimental verification of e^+e^- pair density
- Astra-Gemini Laser experiment: below the Schwinger limit
- ELI: towards the Schwinger limit and beyond QED
- Role of Decoherence? Observe $\pi^\pm$ production in its $\mu^\pm$ decay pattern !

Collaboration:
David Blaschke (Univ. Wroclaw, Poland & JINR Dubna, Russia)
Gianluca Gregori (Univ. Oxford & Rutherford Appleton Lab, UK)
Craig Roberts (Argonne National Laboratory, USA)
Sebastian Schmidt (Forschungszentrum Jülich, Germany)
Alexander Prozorkevich, Stanislav Smolyansky, Alexander Tarakanov (Saratov Univ., Russia)

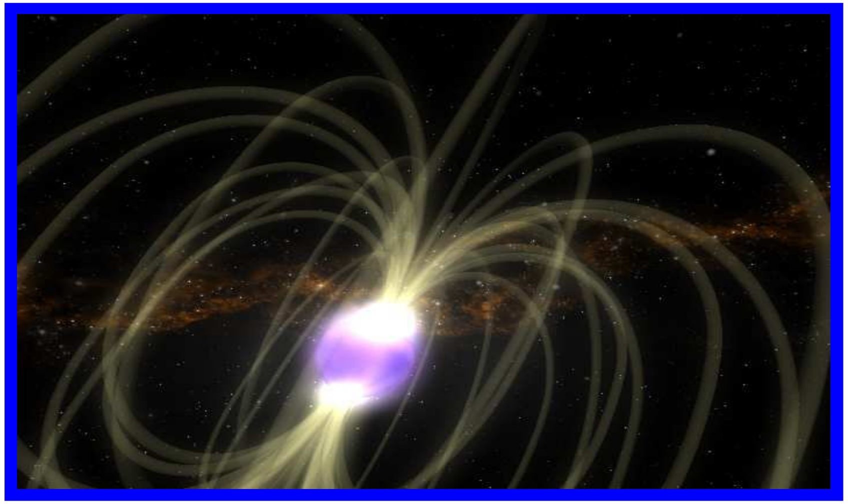
Recent review: Eur. Phys. J. D 55, 341 (2009); arXiv:0811.3570 [physics.plasm-ph]

Pair Creation in Strong Electromagnetic Fields

- Magnetars: B$\sim 10^{15}$G $\Longrightarrow$
  Problem: unclear conditions!
- Ultra-Peripheral Heavy Ion Coll.



Problem: extremely short $\sim 10^{-29}$ s



Artist view of a Magnetar (NASA)

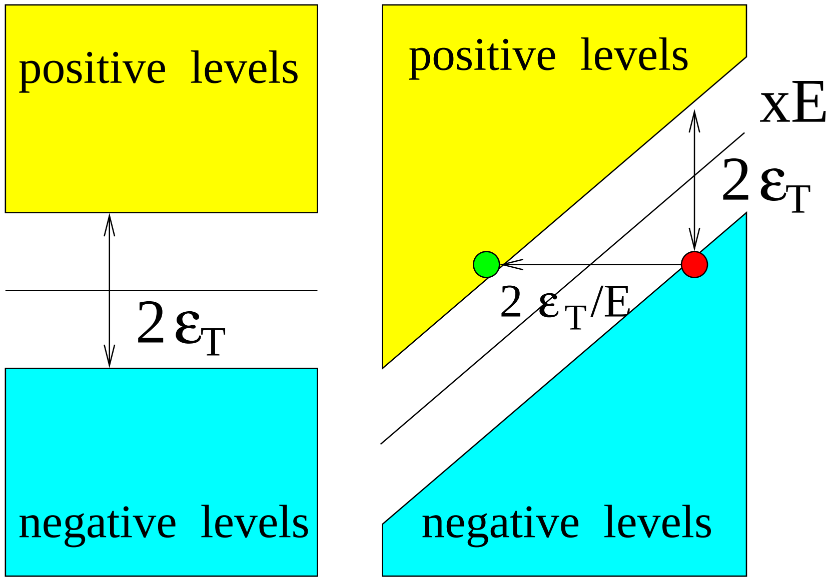
- ELI: Optical $\rightarrow$ X-Ray @ 1 EW:
  $I_0 \sim\ 10^{25}$ W/cm^2 $\rightarrow I_{CHF} \sim\ 10^{36}$ W/cm^2

  \+ Long lifetime:
  $\tau \sim 10^{-15} \ldots 10^{-18}$ s $\gg\ 10^{-22}$ s

  \+ Condition for pair creation:
  $E^2 - B^2 \neq 0$, (crossed lasers)

Schwinger Effect: Pair Creation in Strong Fields

Pair creation as barrier penetration
in a strong constant field



Schwinger result (rate for pair production)

$$\frac{dN}{d^3x dt} = \frac{(eE)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-n\pi \frac{E_{\rm crit}}{E}\right)$$

- To "materialize" a virtual e^+e^- pair in a constant electric field E the separation d must be sufficiently large

$$eEd = 2mc^2$$

- Probability for separation d as quantum fluctuation

$$P \propto \exp\left(-\frac{d}{\lambda_c}\right) = \exp\left(-\frac{2m^2c^3}{e\hbar E}\right) = \exp\left(-\frac{2E_{\rm crit}}{E}\right)$$

- Emission sufficient for observation when $E \sim E_{\rm crit}$

$$E_{\rm crit} \equiv \frac{m^2c^3}{e\hbar} \simeq 1.3 \times 10^{18} {\rm V/m}$$

- For time-dependent fields: Kinetic Equation approach from Quantum Field Theory

J. Schwinger: "On Gauge Invariance and Vacuum Polarization", Phys. Rev. 82 (1951) 664

Kinetic Theory from Nonequilibrium QED I

- Many-particle QED for radiative processes in plasmas with relativistic electrons and non-relativistic heavy particles
- no “golden rule”, no “collisions” *vs.* “asymptotic free states“
- ”virtual“ photons (interaction between particles) *vs.* ”resonant“ photons (propagate, weakly damped), the same for electrons
- Density matrix theory (correlated initial state) *vs.* real-time Green’s functions method (quasiparticle approach for weakly coupled plasmas)
- Transport and mass-shell equations for the fluctuations of the electromagnetic field
- Correlation functions can be decomposed into sharply peaked (non-Lorentzian) part that describe resonant (propagating) photons and off-shell parts corresponding to virtual photons

$$a_{\rm res}(X,k) = \frac{4(k_0\Gamma)^3}{\left[(k^2 - {\rm Re}\pi^+)^2 + (k_0\Gamma)^2\right]^2}$$

- Analogous decomposition for the correlation function of relativistic electrons
- Derivation of kinetic equations for the resonant part with finite spectral width
- Off-shell parts are essential to recover vacuum QED

V.G. Morozov, G. Röpke: “Kinetic Theory of Radiation in Nonequilibrium Relativistic Plasmas”
Ann. Phys. (N.Y.) 324, 1261 (2009)

KINETIC THEORY FROM NONEQUILIBRIUM QED II

Path-ordered Green's function for Dirac field operators

$$G(\underline{1}\,\underline{2}) \;=\; -i\,\langle T_C[S\,\psi_I(\underline{1})\bar{\psi}_I(\underline{2})]\rangle / \langle S\rangle\,, \qquad S = T_C \exp\left\{-i\int d\underline{1}\,\hat{A}^\mu_I(\underline{1})\,J^{(\mathrm{ext})}_\mu(\underline{1})\right\},$$

and for the (transverse) fluctuations of the electromagnetic fields

$$D^{\mu\nu}(\underline{1}\,\underline{2}) \;=\; \frac{\delta A^\mu(\underline{1})}{\delta J^{(\mathrm{ext})}_\nu(\underline{2})} = -i\langle T_C\,\Delta\hat{A}^i(\underline{1})\,\Delta\hat{A}^j(\underline{2})\rangle$$

Equations of motion, self-energy, vertex functions and polarization matrix
Wigner transform (X,k) and decomposition $(d_s^{\gtrless}, d_s^+)$
differences and sums: transport and mass shell equations

$$\left\{k^2 - \mathrm{Re}\,\pi_s^+, d_s^{\gtrless}\right\} + \left\{\mathrm{Re}\,d_s^+, \pi_s^{\gtrless}\right\} = i\,(\pi_s^>\,d_s^< - \pi_s^<\,d_s^>)\,,$$

$$\left\{\mathrm{Im}\,\pi_s^+, d_s^{\gtrless}\right\} + \left\{\mathrm{Im}\,d_s^+, \pi_s^{\gtrless}\right\} = 2\,(k^2 - \mathrm{Re}\,\pi_s^+)\left(d_s^{\gtrless} - \left|\,d_s^+\right|^2\pi_s^{\gtrless}\right),$$

$$\left\{k^2 - \pi_s^{\pm}, d_s^{\pm}\right\} = 0, \qquad\qquad (k^2 - \pi_s^{\pm})\,d_s^{\pm} = 1$$

with the four-dimensional Poisson bracket

$$\{F_1(X,k), F_2(X,k)\} \;=\; \frac{\partial F_1}{\partial X^\mu}\frac{\partial F_2}{\partial k_\mu} - \frac{\partial F_1}{\partial k^\mu}\frac{\partial F_2}{\partial X_\mu}$$

V.G. Morozov, G. Röpke: "Kinetic Theory of Radiation in Nonequilibrium Relativistic Plasmas"
Ann. Phys. (N.Y.) 324, 1261 (2009)

KINETIC THEORY FROM NONEQUILIBRIUM QED III

Resonant spectral function

$$\widetilde{a}_s(X,k) \;=\; i\left(\widetilde{d}_s^{>} - \widetilde{d}_s^{<}\right) = \frac{4\,(k_0\Gamma_s)^3}{\left[(k^2 - \mathrm{Re}\,\pi_s^{+})^2 + (k_0\Gamma_s)^2\right]^2}$$

Photon distribution function

$$\widetilde{d}_s^{<}(X,k) \;=\; -i\,\widetilde{a}_s(X,k)N_s^{<}(X,k), \qquad \widetilde{d}_s^{>}(X,k) = -i\,\widetilde{a}_s(X,k)N_s^{>}(X,k),$$

where

$$N_s^{>}(X,k) - N_s^{<}(X,k) \;=\; 1$$

Kinetic equation for resonant photons

$$\widetilde{a}_s\left[\left\{k^2 - \mathrm{Re}\,\pi_s^{+}, N_s^{<}\right\} - \frac{k^2 - \mathrm{Re}\,\pi_s^{+}}{k_0\Gamma_s}\left\{k_0\Gamma_s, N_s^{<}\right\} - i\left(\pi_s^{>}N_s^{<} - \pi_s^{<}N_s^{>}\right)\right] \;=\; 0$$

Distribution fuctions in spinor space

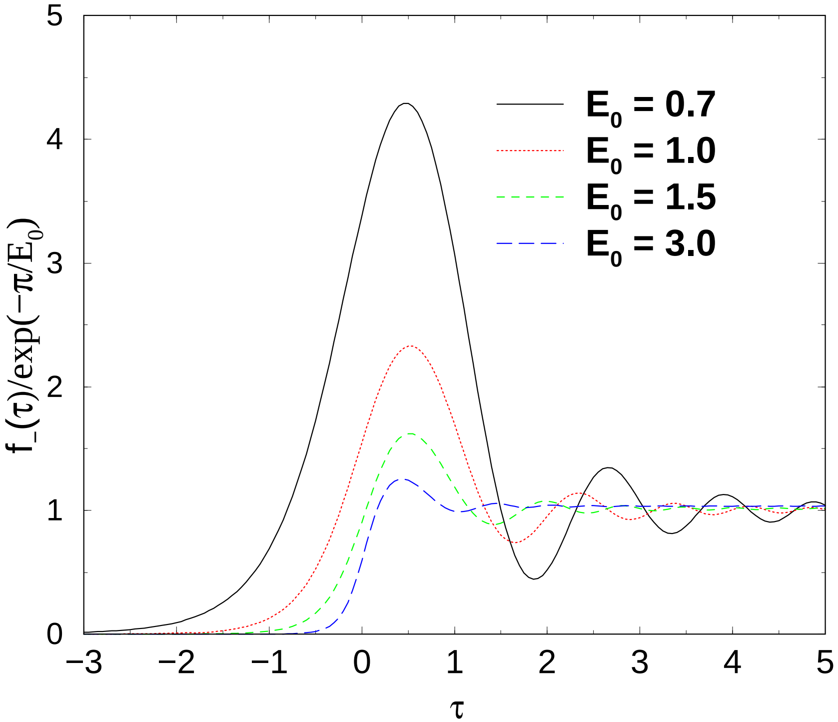
$$\widetilde{G}^{\gtrless}(X,p) \;=\; \mp\frac{i}{2}\left(\widetilde{\mathcal{A}}(X,p)\,\mathcal{F}^{\gtrless}(X,p) + \mathcal{F}^{\gtrless}(X,p)\,\widetilde{\mathcal{A}}(X,p)\right),$$

$$\mathcal{F}^{>}(X,p) + \mathcal{F}^{<}(X,p) \;=\; I$$

V.G. Morozov, G. Röpke: "Kinetic Theory of Radiation in Nonequilibrium Relativistic Plasmas"
Ann. Phys. (N.Y.) 324, 1261 (2009)

Kinetic formulation of pair production

Kinetic equation for the single particle distribution function $f(\bar{P},t) =< 0|a^\dagger_{\bar{P}}(t)a_{\bar{P}}(t)|0 >$



$$\frac{df_\pm(\bar{P},t)}{dt} = \frac{\partial f_\pm(\bar{P},t)}{\partial t} + eE(t)\frac{\partial f_\pm(\bar{P},t)}{\partial P_\parallel(t)}$$

$$= \frac{1}{2}\mathcal{W}_\pm(t)\int_{-\infty}^{t} dt'\mathcal{W}_\pm(t')[1 \pm 2f_\pm(\bar{P},t')]\cos[x(t',t)]$$

Kinematic momentum $\bar{P} = (p_1, p_2, p_3 - eA(t))$,

$$\mathcal{W}_-(t) = \frac{eE(t)\varepsilon_\perp}{\omega^2(t)} ,$$

where $\omega(t) = \sqrt{\varepsilon_\perp^2 + P_\parallel^2(t)}$, with $\varepsilon_\perp = \sqrt{m^2 + \bar{p}_\perp^2}$
and $x(t',t) = 2[\Theta(t) - \Theta(t')]$.

$$\Theta(t) = \int_{-\infty}^{t} dt'\omega(t')$$

Constant field: Schwinger limit reproduced

$$f(\tau \to \infty) = \exp\left(\frac{-\pi}{E_0}\right)$$

Schmidt, Blaschke, Röpke, et al:
Non-Markovian effects in strong-field pair creation
Phys. Rev. D 59 (1999) 094005

PAIR PRODUCTION IN SUBCRITICAL FIELDS (I)

Kinetic formulation for $E(t) = -\dot{A}(t)$ in the Hamiltonian gauge $A^\mu = (0,0,0,A(t))$

$$\frac{df(\mathbf{p},t)}{dt} = \frac{1}{2}\Delta(\mathbf{p},t)\int_{t_0}^{t} dt'\,\Delta(\mathbf{p},t')\,[1-2f(\mathbf{p},t')] \times \cos\left[2\int_{t'}^{t} dt_1\,\varepsilon(\mathbf{p},t_1)\right],$$

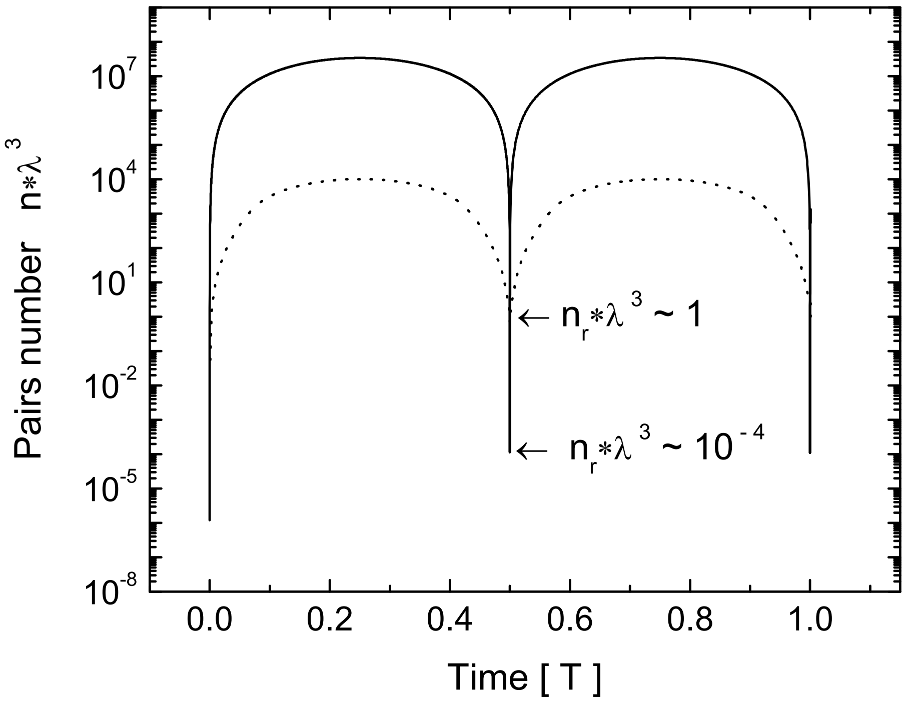
where

$$\Delta(\mathbf{p},t) = eE(t)\frac{\sqrt{m^2+p_\perp^2}}{\varepsilon^2(\mathbf{p},t)},$$

$$\varepsilon(\mathbf{p},t) = \sqrt{m^2+p_\perp^2+[p_3-eA(t)]^2}$$

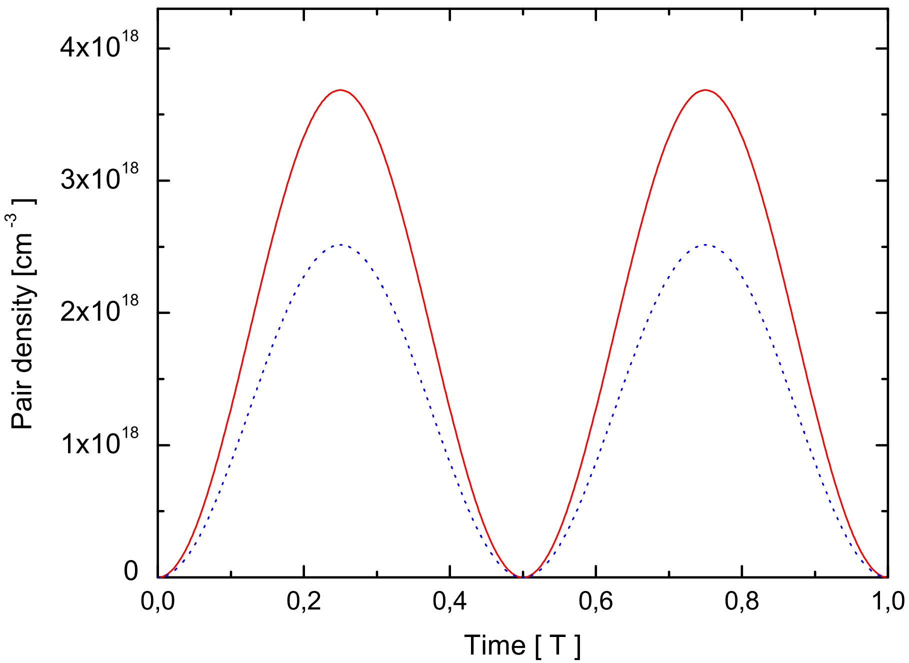
The particle number density

$$n(t) = 2\int \frac{d\mathbf{p}}{(2\pi)^3} f(\mathbf{p},t)$$



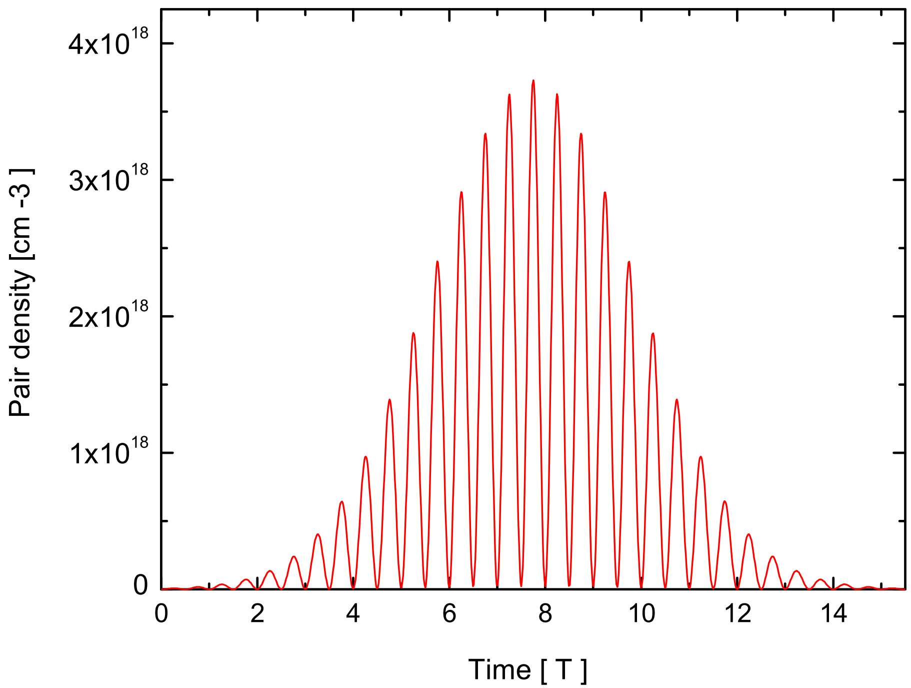
Number of e^+e^- pairs in the volume λ^3 for a weak field (Jena Ti:AlO$_3$ laser, solid line) and for near-critical field $E_m/E_{\rm crit} = 0.24$, $\lambda = 0.15$ nm (X-FEL, dashed line).

e^+e^- PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (II)



Time dependence of the density $n(t)$ for a monochromatic field

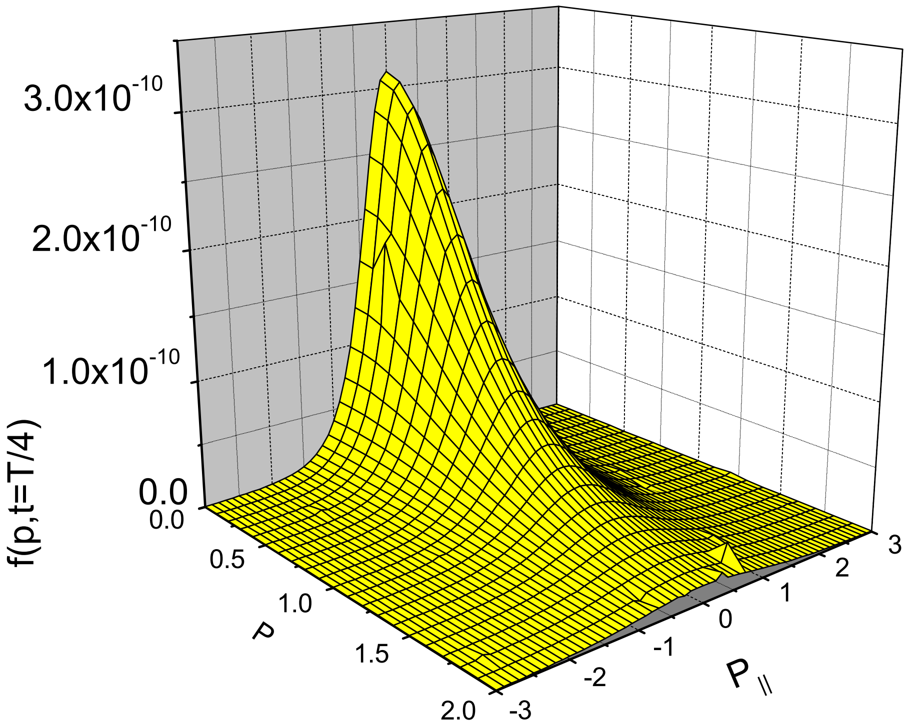
$$E(t) = E_m \sin \omega t, \quad 0 \leq t \leq NT, \quad T = \frac{2\pi}{\omega}$$



Time dependence of the density $n(t)$ for a Gaussian wave packet

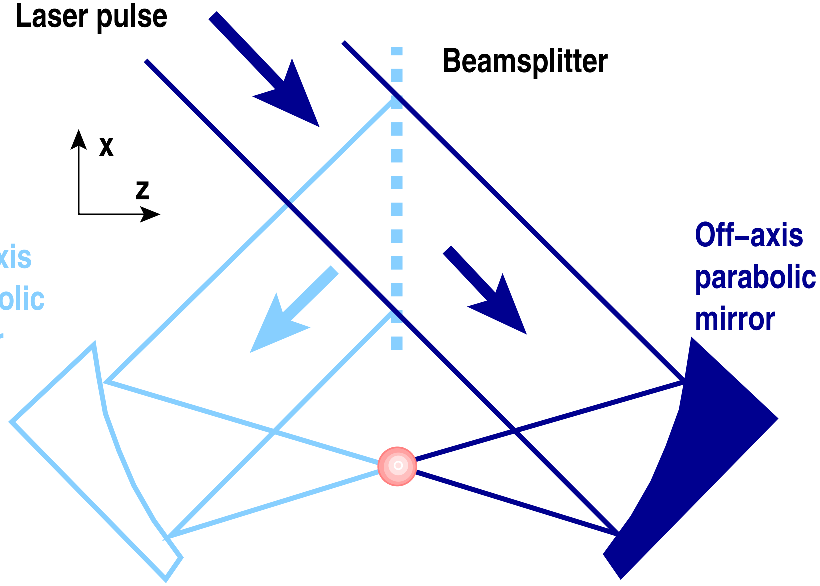
$$E(t) = E_m e^{-(t/\tau_L)^2} \sin \omega t.$$

Application to subcritical laser fields



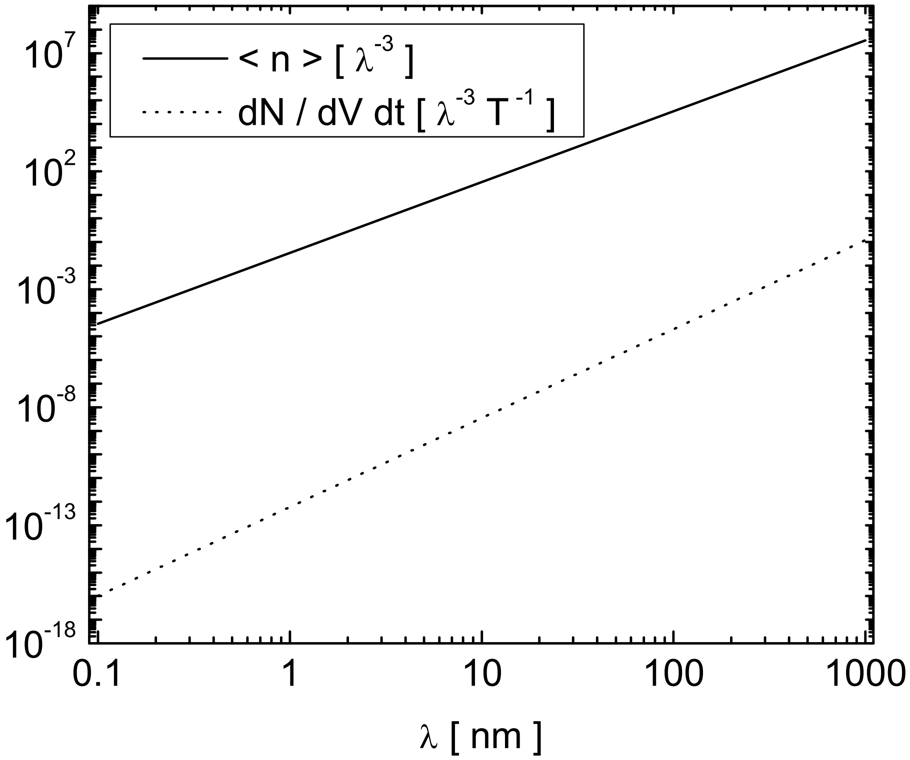
Equilibrium-like momentum distribution at the time of maximal field amplitude $t = T/4$.

Setup of the Jena Laser Exp. (2005)

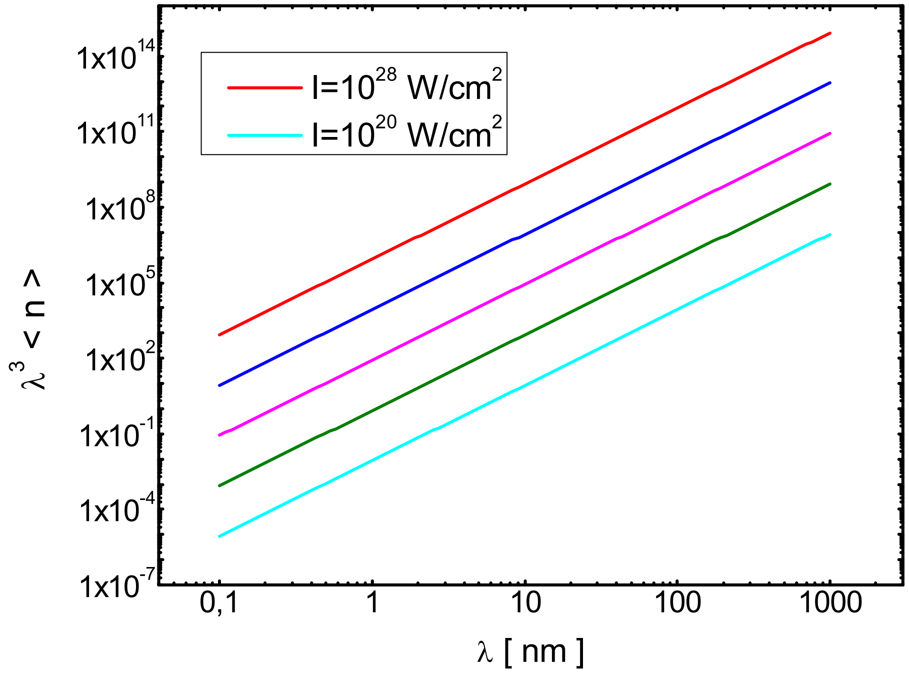


Heinzl, et al., Opt. Commun. 267, 318 (2006)

Application to subcritical laser fields (III)



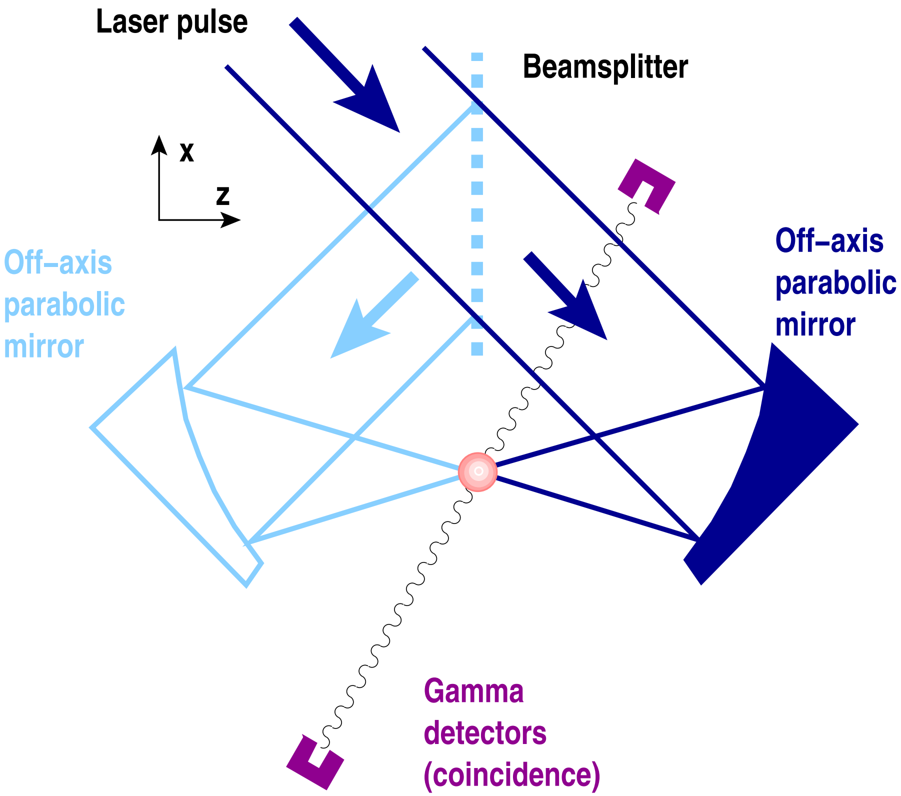
Wavelength dependence of the mean density of e$^+$e$^-$ pairs (solid line) and their annihilation rate (dotted line). $E = 3 \times 10^{-5} E_{cr}$.

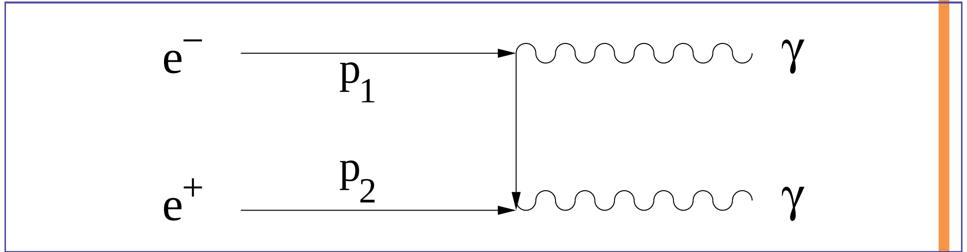


Wavelength dependence of the mean density of e^+e^- pairs for different E/E_{cr}

Perspectives for e^+e^- pairs @ optical lasers (I)

Observable: photon pair $(e^+ + e^- \to 2\ \gamma)$





$$\frac{d\nu}{dV\,dt} = \int d\mathbf{p}_1 d\mathbf{p_2}\, \sigma(\mathbf{p}_1, \mathbf{p}_2) f(\mathbf{p}_1, t) f(\mathbf{p}_2, t)$$
$$\times \sqrt{(\mathbf{v}_1 - \mathbf{v}_2)^2 - |\mathbf{v}_1 \times \mathbf{v}_2|^2},$$

cross-section σ of two-photon annihilation

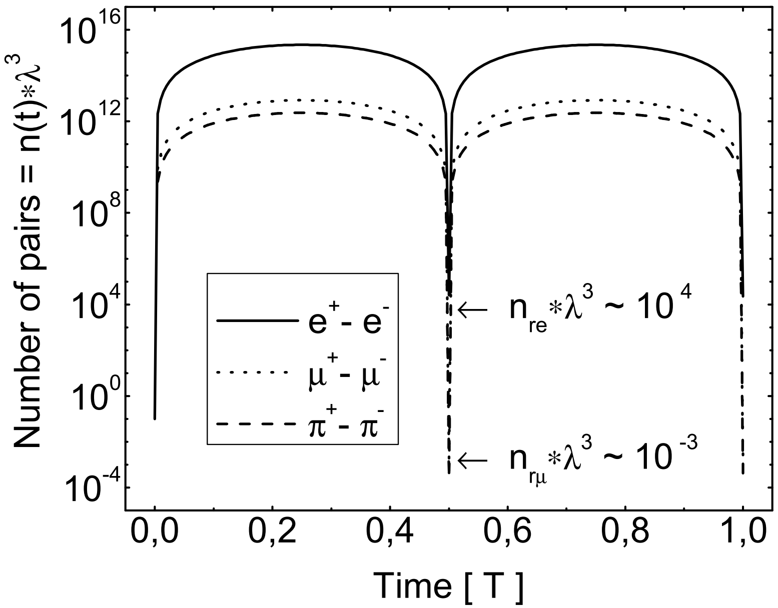
$$\sigma(\mathbf{p}_1, \mathbf{p}_2) = \frac{\pi e^4}{2m^2\tau^2(\tau - 1)}\Big[(\tau^2 + \tau - 1/2)$$
$$\times \ln\left\{\frac{\sqrt{\tau} + \sqrt{\tau - 1}}{\sqrt{\tau} - \sqrt{\tau - 1}}\right\} - (\tau + 1)\sqrt{\tau(\tau - 1)}\Big],$$

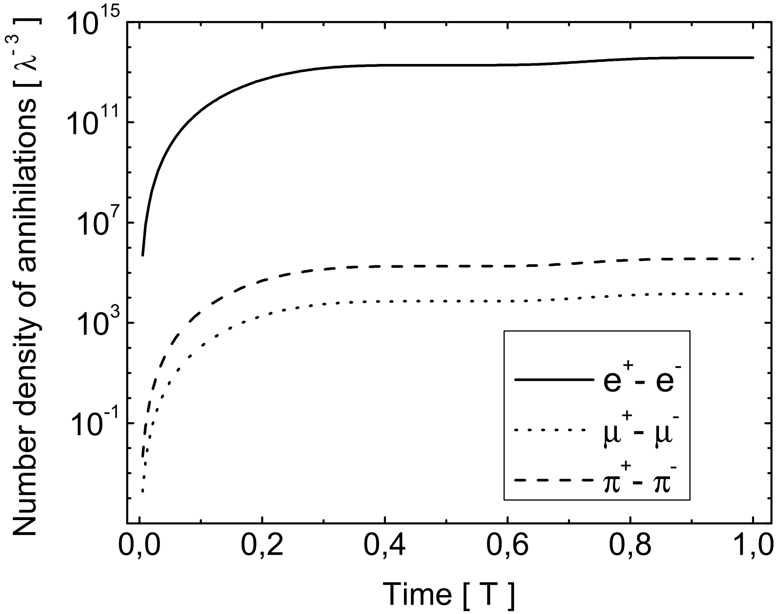
t-channel kinematic invariant

$$\tau = \frac{(p_1 + p_2)^2}{4m^2} = \frac{1}{4m^2}[(\varepsilon_1 + \varepsilon_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2].$$

Project: G. Gregori et al. (2008)
at RAL Astra-Gemini Laser

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (I)





Time dependence of the pair density (left) and the number of annihilations (right) in the volume λ^3 for a periodic field (T - period) with $E_m = 10^{15}$ V/cm and $\lambda = 800$ nm for the different particle species. Laser intensity $3 \cdot 10^{27}$ W/cm^2.

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (II)

Pion pair creation kinetics, including decay into muons:

$$\frac{\partial f_\pi(\mathbf{p},t)}{\partial t} = \frac{1}{2}\Delta_\pi(\mathbf{p},t)\int_{t_0}^{t} dt'\Delta_\pi(\mathbf{p},t')\cos\theta_\pi(\mathbf{p},t',t) - f_\pi(\mathbf{p},t)\int d\mathbf{q}d\mathbf{k}w(\mathbf{p},\mathbf{q},\mathbf{k},t),$$

$$\frac{\partial f_\mu(\mathbf{p},t)}{\partial t} = \frac{1}{2}\Delta_\mu(\mathbf{p},t)\int_{t_0}^{t} dt'\Delta_\mu(\mathbf{p},t')\cos\theta_\mu(\mathbf{p},t',t) + \int d\mathbf{q}d\mathbf{k}w(\mathbf{q},\mathbf{p},\mathbf{k},t)f_\pi(\mathbf{q},t),$$

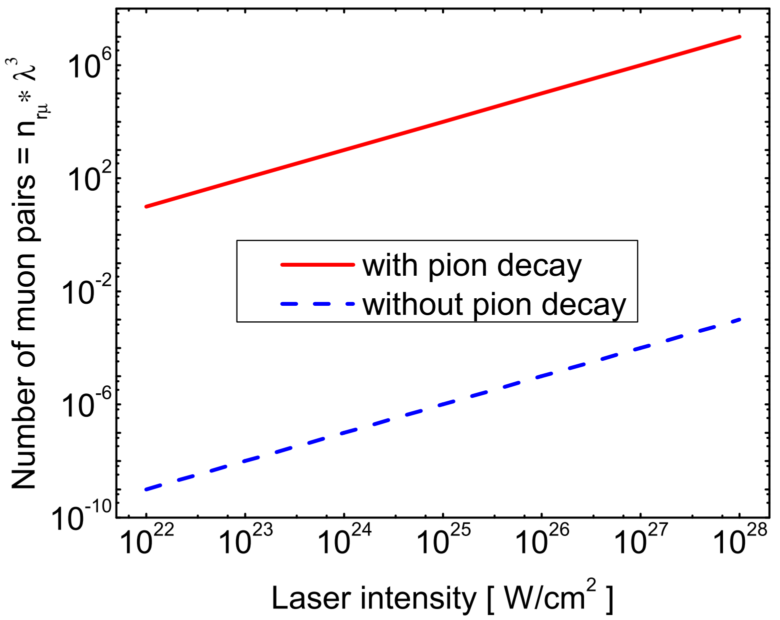
Stochastic pion decay with rate $w(\mathbf{p},\mathbf{q},\mathbf{k},t)$.

$$w(\mathbf{p},\mathbf{q},\mathbf{k},t) \approx w(\mathbf{p},\mathbf{q},\mathbf{k}) = \frac{1}{2}\left(\frac{Gm_\mu F_\pi}{2\pi}\right)^2 \frac{q\cdot k}{\varepsilon_p\varepsilon_q\varepsilon_k}\delta^{(4)}(p-q-k),$$

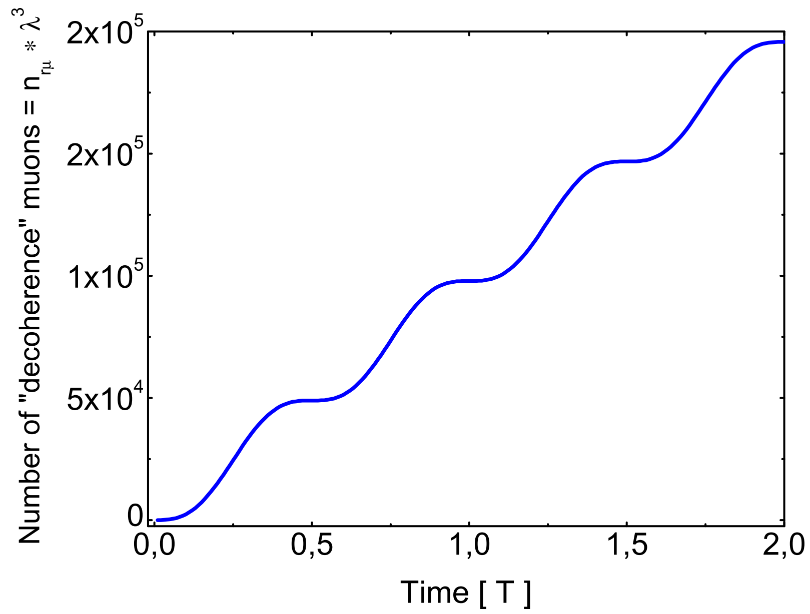
Muons seen by a detector with the time resolution δt

$$\delta n_\mu(t) \approx \frac{\delta t}{\tau_\pi} n_\pi(t) = \frac{\delta t}{\tau_\pi}\int_{t_0}^{t} dt' e^{(t'-t)/\tau_\pi} s_\pi(t')$$

$\pi^+\pi^-$ PAIR PRODUCTION IN SUBCRITICAL LASER FIELDS (III)



Number of muons as a function of the laser intensity at an optical wavelength $\lambda \sim 800$ nm.

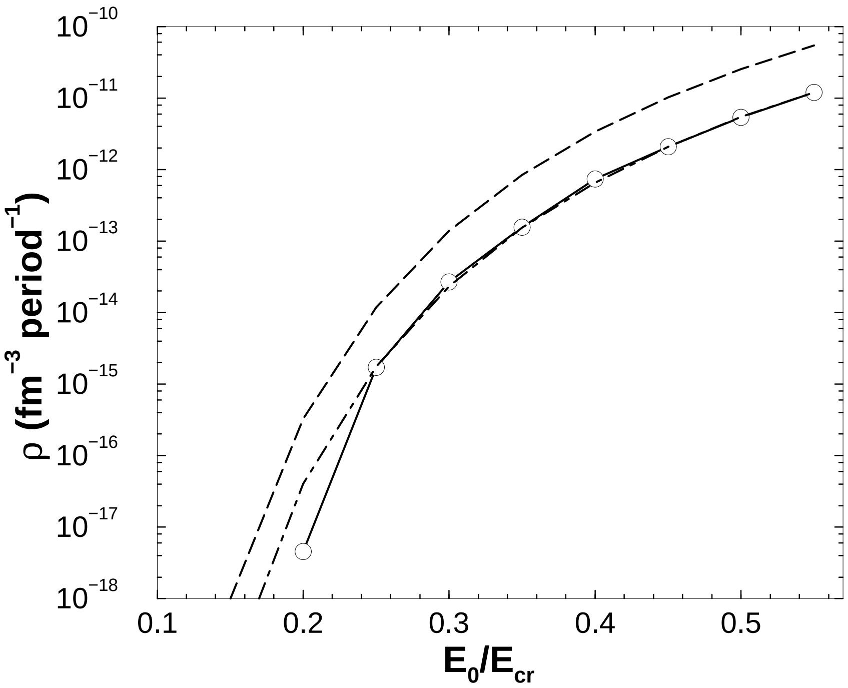


Time dependence of the number of decay muons produced in a volume λ^3, seen in a muon detector with time resolution $\delta t \sim 0.1$ fs

Blaschke, Prozorkevich, Roberts, Röpke, Schmidt, Smolyansky; in preparation (2010)

ACCUMULATION EFFECT IN NEAR-CRITICAL FIELDS

Particle number density $n(T;E_0) = a_0(E_0)\sin^2(2\pi T) + \rho(T,E_0)T \quad , \quad T = t/\lambda$



Results are nicely fitted with

$$\rho(T,E_0) = \rho(E_0) + \rho'(E_0)T \ .$$

For $E = 0.5\ E_0$, $a_0 = 1.2 \times 10^{-11}$ fm^{-3}, $\rho = 5.4 \times 10^{-12}$ fm^{-3}/period, $\rho'/\rho = 0.0033$/period.

Comparison with Schwinger rate

$$\rho = a\frac{m^4\lambda}{4\pi^3}\left[\frac{E_0}{E_{cr}}\right]^2 e^{-b\pi E_{cr}/E_0}$$

Accumulation rate $\rho(0,E_0)$ (solid), Schwinger rate $a = 1,\ b = 1$ (dashed), $a = 0.305,\ b = 1.06$ (dot-dashed)

Attention:
$E_0 \sim 0.35\ E_{cr}$ backreactions become important!

Roberts, Schmidt, Vinnik: "Quantum effects with an X-Ray Free-Electron Laser", Phys. Rev. Lett (2002) 153901

EXPERIMENT FOR SUBCRITICAL VACUUM PAIR PRODUCTION

Project: G. Gregori et al. at the RAL Astra-Gemini laser facility → Summer 2010

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A proposal for testing subcritical vacuum pair production with high power lasers

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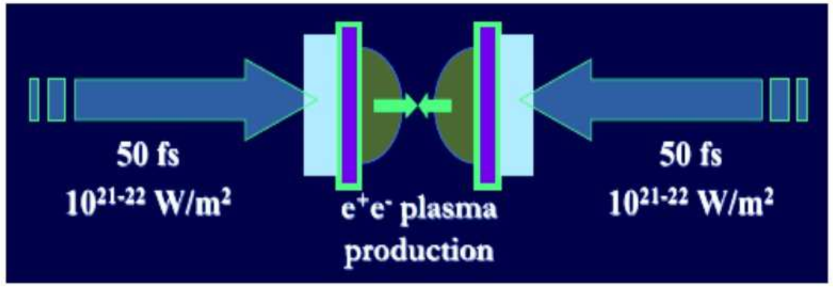
doi:10.1016/j.hedp.2009.11.001

Pair Production at RAL: Astra Gemini Laser

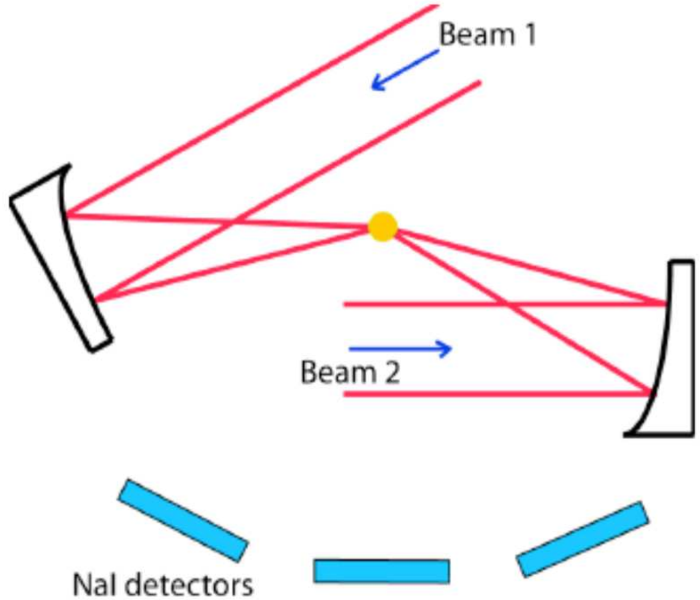
Part of an experimental campaign to explore nonperturbative and nonequilibrium QFT regimes: (1) Pair production, (2) Nonlinear mixing, (3) Unruh effect

(1-A) Pair production in high-Z foils



(1-B) Vacuum pair production
with different schemes:

- vacuum polarization
- refraction index
- $\gamma - \gamma$ coincidence
- ...



Kinetics of the $e^+e^-\gamma$ plasma in a strong laser field

The photon correlation function is defined as

$$F_{rr'}(\mathbf{k},\mathbf{k}',t) = \langle A^+_r(\mathbf{k},t)A^-_{r'}(\mathbf{k}',t)\rangle \ ; \quad A_\mu(\mathbf{k},t) = A^{(+)}_\mu(\mathbf{k},t) + A^{(-)}_\mu(-\mathbf{k},t).$$

Lowest truncation of BBGKY hierarchy $\rightarrow$ photon KE for zero initial condition

$$\dot{F}(\mathbf{k},t) = -\frac{e^2}{2(2\pi)^3 k}\int d^3p \int_{t_0}^{t} dt' K(\mathbf{p},\mathbf{p}-\mathbf{k};t,t')[1+F(\mathbf{k},t')]$$
$$[f(\mathbf{p},t')+f(\mathbf{p}-\mathbf{k},t')-1]\cos\{\int_{t'}^{t} d\tau[\omega(\mathbf{p},\tau)+\omega(\mathbf{p}-\mathbf{k},\tau)-k]\},$$

Markovian approximation; averaging the kernel: $K(\mathbf{p},\mathbf{p}-\mathbf{k};t,t') \rightarrow K_0 = -5$
Subcritical field case: $E \ll E_c$, lead to $(\delta = 2m - k$, frequency mismatch)

$$F(\mathbf{k},t) = \frac{5e^2 n(t)}{2k\delta^2} \ , \quad n(t) = 2\int d^3p f(\mathbf{p},t)/(2\pi)^3$$

Photon distribution in the optical region $k \ll m$ is characteristic for the flicker noise

$$\boxed{F(k) \sim 1/k}$$

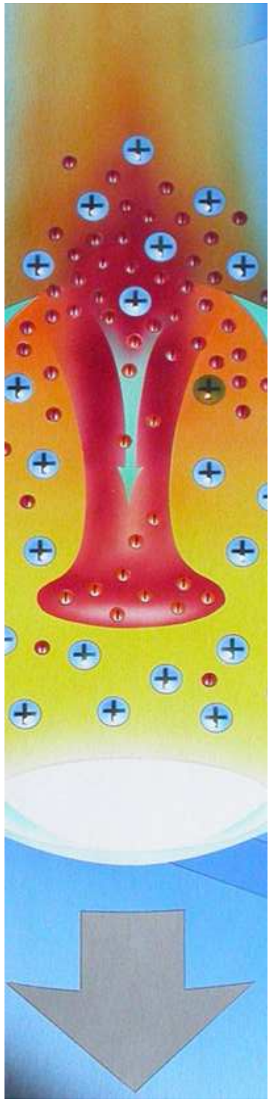
D.B. Blaschke et al., Contr. Plasma Phys. 49, 602 (2009); arxiv:0912.0381 [physics.plasm-physics]

Challenges of future Lasers for the Schwinger effect

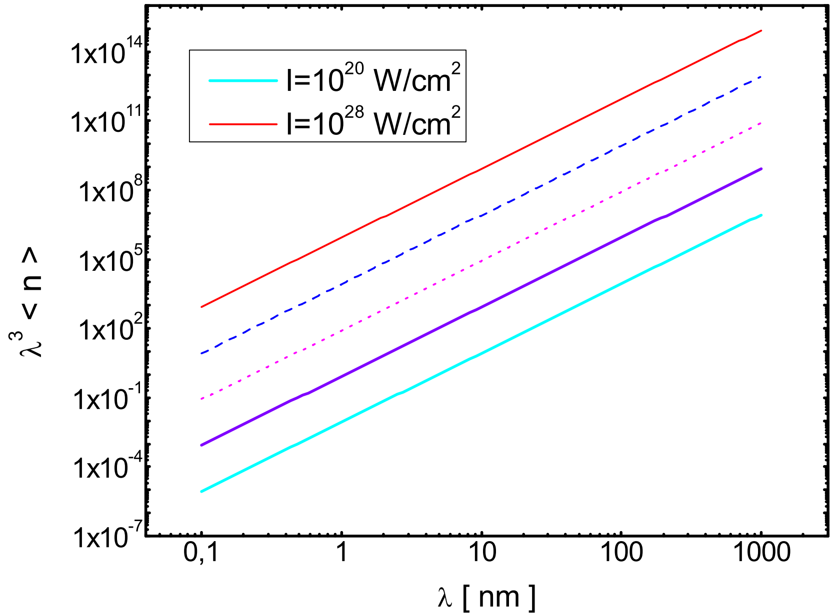
- First experimental tests to theories of pair production, e.g. kinetic approach
- Simplest laser field model predicts production of dense electron-positron plasma in the focus of counter-propagating laser fields
- Observable manifestations testable, e.g., at ASTRA-Gemini:
  - several gamma-pairs per laser pulse
  - refraction index measurable by intereference with test beam
  - higher harmonics generation, in particular 3^{rd}
- Towards/Beyond Schwinger limit, e.g., at ELI:
  - Quantum statistics: Pauli-Blocking/ Bose Condensation; Backreactions
  - Pion production limit: signalled by muons
  - Pion condensation (?) and quark-gluon-plasma formation ...
- Laser acceleration of ion beams (see arxiv:0811.3570 [physics.plasm-ph])

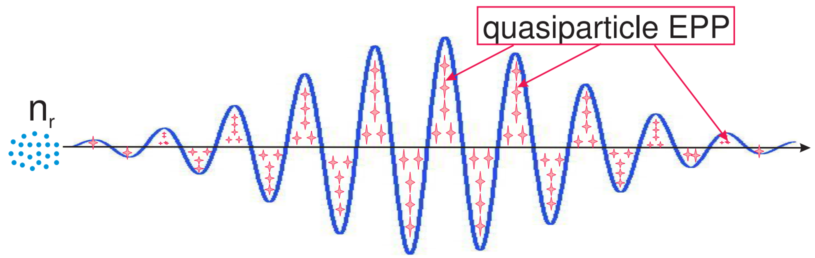
Thanks to: D. Habs (Munich), G. Mourou (Paris), R. Sauerbrey (Rossendorf)

INTENSE THEORY-EXPERIMENT INTERACTION ...



How to 'see' e^+e^- pairs @ optical lasers (III)





Measurement of refraction index

Interference condition: $D = \lambda_p/2$

Refraction index:

$n = 1/\sqrt{1+\eta^2[(2+\eta^2)/(1+\eta^2)]}$

Langmuir frequency ω_L:

$\eta = \omega_L/\omega_p = 10^4\sqrt{\rho_{e+e-}[cm^{-3}]}$

Probe frequency: $\omega_p = 10\ \omega_0$

Condition fulfilled for:

$\rho_{e+e-} = 10^{23}$ cm^{-3}, i.e. $I \approx 10^{23}$ W/cm^2

Angular dependence testable:

number of 'pancakes' crossed varies

with incidence angle: from 3-4 to 20-30

Suggestion: R. Sauerbrey; Estimate: **Blaschke, Prozorkevich, Smolyansky, in prep.**

Comparison with imaginary time method

V.S. Popov, Phys. Lett. **A 298** (2002) 83

- imaginary time method (time indep.)
- number of pairs only after full period T
- no distribution function

$\gamma \ll 1, \quad \gamma = \frac{\hbar\omega}{mc^2}\frac{E_{cr}}{E}$

$$N(\lambda^3 T) \sim \left(\frac{m}{\nu}\right)^4 \left(\frac{E}{E_{cr}}\right)^{5/2} \exp\left[-\frac{\pi E_{cr}}{E}\right]$$

$\gamma \gg 1$

$$N(\lambda^3 T) \approx 2\pi \left(\frac{m}{\nu}\right)^{3/2} \left(\frac{e}{4\gamma}\right)^{2m/\nu}$$

Very large differences for $E \ll E_{cr}$

Here: Grib, Mamaev, Mostepanenko (1988)

- Bogoliubov transformation (time dep.)
- pair number during field evolution
- distribution function

$\gamma \ll 1$

$$\lambda^3 n_r \sim \left(\frac{m}{\nu}\right)^4 \left(\frac{E}{E_{cr}}\right)^2 \exp\left[-1.05\frac{\pi E_{cr}}{E}\right]$$

$\gamma \gg 1$ (mean)

$$\lambda^3 \langle n \rangle \sim \left[\frac{(eE_m)}{m^2}\right]^2 \left[\frac{m\lambda}{2\pi}\right]^3, \qquad \frac{n_r}{\langle n \rangle} \sim \frac{\omega^2}{m^2}$$

$\gamma \gg 1$ (residual)

$$n_r \sim \left(\frac{m}{\nu}\right)$$

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QED with High Power Lasers

Pair production experiment

Dr Gianluca Gregori

Oxford University and
Rutherford Appleton Laboratory

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List of collaborators (more to add…)

- This is the first attempt to observe measurable QED effects with high power lasers – need to include all interested organizations

- If you are not in the proposal, just let me know and you'll be included!

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QED with high power lasers

- The proposed work is part of a large experimental campaign aimed at the exploitation of high power lasers to explore non-perturbative and non-equilibrium QFT regimes

  - **Pair production**: 1st experiment scheduled for winter 2010. Simplest beam arrangement and feasible on the current Gemini system.

  - **Nonlinear mixing**: vacuum polarization via four-wave mixing using a nonlinear stimulated process. It is possible to show that by interacting three beams into a high vacuum region, a fourth beam of photons with unique wavelength will be generated.

  - **Unruh radiation**: interaction of a high intensity laser with relativistic electrons (> 1 GeV) can access regimes where the electrons, in their rest frame, experience a ultra-high intensity field such as the one found at the event horizon of a black hole.

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QED with high power lasers

- ➔ High risk experiments (!) but high payoff from their success
- ➔ Pair production experiment: de-risking strategy
  - Measure vacuum pair production with a variety of schemes (vacuum polarization / γ-γ co-incidence detection)
  - Pair production is high-Z foils (already demonstrated)

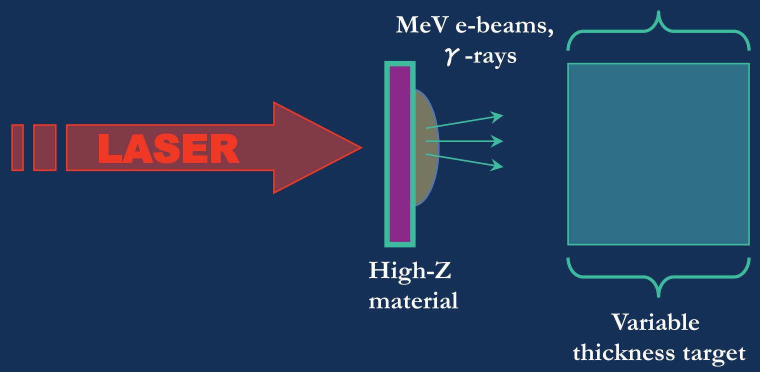
Pair production in high-Z foils

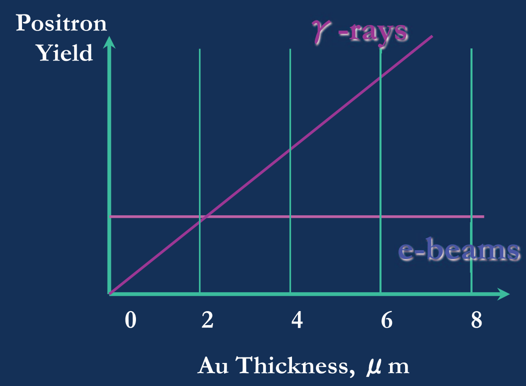
a) electron-beam ⇨ positrons

$$e^- + Z \rightarrow 2\,e^+ e^- + Z$$

b) γ-ray ⇨ positrons

$$\gamma + Z \rightarrow e^+ e^- + Z$$





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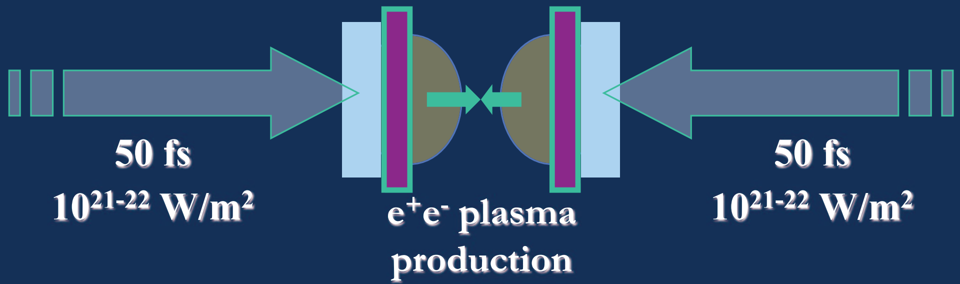
Pair production in high-Z foils

➔ Proposed two-foil experiment



➔ Detailed modelling of the experiment is required:

- Numerical calculations of pair number vs foil thickness
- Optimization w.r.t. pulse length and laser intensity
- Polarization dependence?

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Pair production in vacuum

- ➔ Need to estimate the quality of vacuum (!) – Can we produce ultrahigh vacuum?
  - Detailed calculations are required in order to determine residual effect of residual atoms
  - Can we use the laser pre-pulse (nanosecond pedestal) to expel the ions from the laser focal spot?

Simple estimate: assuming 100 residual atoms in the focal spot (p~1 mTorr), we expect 0.01 pairs per laser shot (Heitler, 1954)

Pair production in vacuum – simple theory

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- ➔ The basic of this process is multi-body interaction of a large number of optical photons – non-perturbative process
- ➔ Described within the non-equilibrium quantum field theory framework: quantum Vlasov equation

$$\frac{df_k(t)}{dt} = \frac{\dot{\Omega}_k}{2\Omega_k} \int_{-\infty}^{t} dt' \frac{\dot{\Omega}_k}{2\Omega_k}(t') \left[1 - f_k(t')\right] \cos\left[2\int_{t'}^{t} d\tau \Omega_k(\tau)\right]$$

$$\Omega_k^2 = (\mathbf{k} - e\mathbf{A})^2 + m^2$$

$$N_{ep}(t) = 2V \int \frac{d^3k}{(2\pi)^3} f_k(t)$$

- ➔ Which is the physical meaning of the time-dependent particle number?

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Pair production in vacuum – simple theory

- The particle number does not commute with the Hamiltonian – it is not a well defined quantity!

$$\Delta E \Delta t = \Delta(N_{ep} m)\Delta t \sim 1$$
$$\rightarrow \Delta N_{ep} \sim 1/(m\Delta t)$$

- Hence, the particle number is well defined at asymptotic times (*t* very large) or for classical particles (large mass)
- In our case, we need to account for the change of particle number during the time the laser is on…

$$\Delta N_{ep} \sim \frac{1}{m\Delta t} + \left|\frac{dN_{ep}}{dt}\right| \Delta t$$
$$\rightarrow \Delta t \sim \frac{1}{\left(m\left|\frac{dN_{ep}}{dt}\right|\right)^{1/2}} \sim \frac{m}{eE}$$

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Pair production in vacuum – simple theory

- Similarly, particles are produced in pairs (i.e., they are initially entangled) – this is elucidated by the cosine term in the quantum Vlasov equation
- In the case of spatially homogeneous weak fields the disentanglement time is

$$\Delta t \sim \frac{1}{\Omega_k} \sim \frac{1}{m}$$

For the proposed Gemini experiment

$$\begin{cases} (\Delta t)_{Heisenberg} = \dfrac{m}{eE} \approx 8.9 \times 10^{-18} s \\ (\Delta t)_{Entanglement} = \dfrac{1}{m} \approx 1.3 \times 10^{-21} s \end{cases}$$

- Hence, the particle number is well defined during the laser period !
- However, are this particles on the mass shell? Experiment is the only way to test the validity of NeqQFT approach

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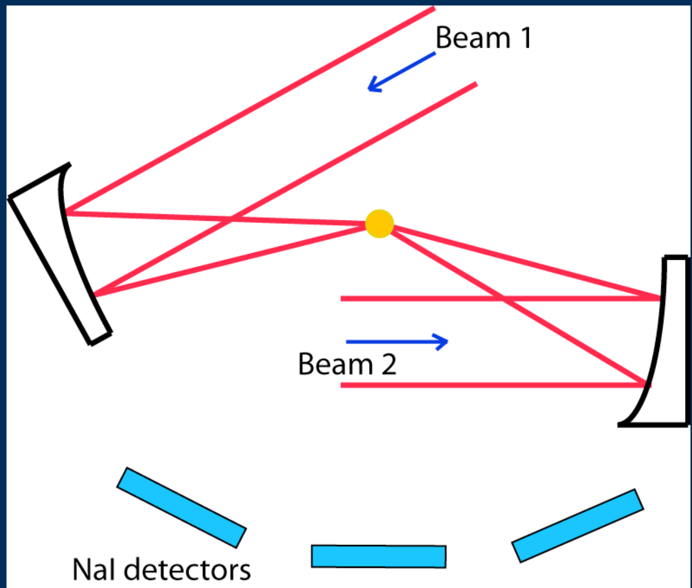
Proposed experiment (ϒϒ co-incidence)



- ➔ Solution of the quantum Vlasov equation for idealized (spatially homogeneous and sinusoidal field) gives N_{ep}~6x10^8 at the peak of the laser pulse and then ~0 after the pulse
- ➔ Those pairs can annihilate due to collisions in the laser spot volume, giving *Nγγ*~7-20 per laser shot
- ➔ More precise calculations are needed for the actual laser configuration (beam profile, spatial and temporal overlap…)

- ➔ Background level of γγ event is ~0.4 per laser shot (measured in-situ)
- ➔ Predicted signal is significantly above background level

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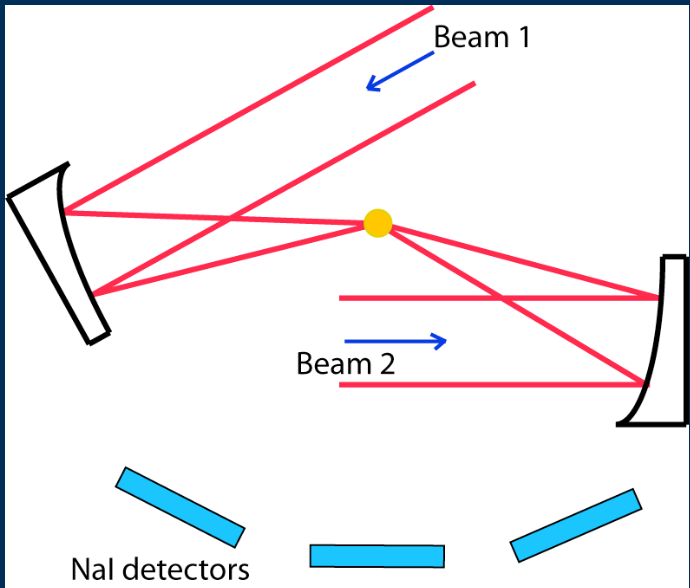
Proposed experiment (vacuum polarization)



➔ The presence of electron-positron pairs changes the index of refraction

$$n = \left(1 + \eta^2 + \frac{\eta^2}{1+\eta^2}\right)^{-1/2}$$

$$\eta^2 = \frac{e^2 N_{ep}/\lambda^3}{\epsilon_0 m \omega^2}$$

➔ The corresponding reflectivity of the vacuum is

$$R = \left(\frac{1-n}{1+n}\right)^{1/2} \left(\frac{2\pi\lambda_c}{\lambda}\right)^3$$

➔ Expect ~5 backscattered photons per laser shot

➔ Difficult to distinguish from the noise background but worth to try!