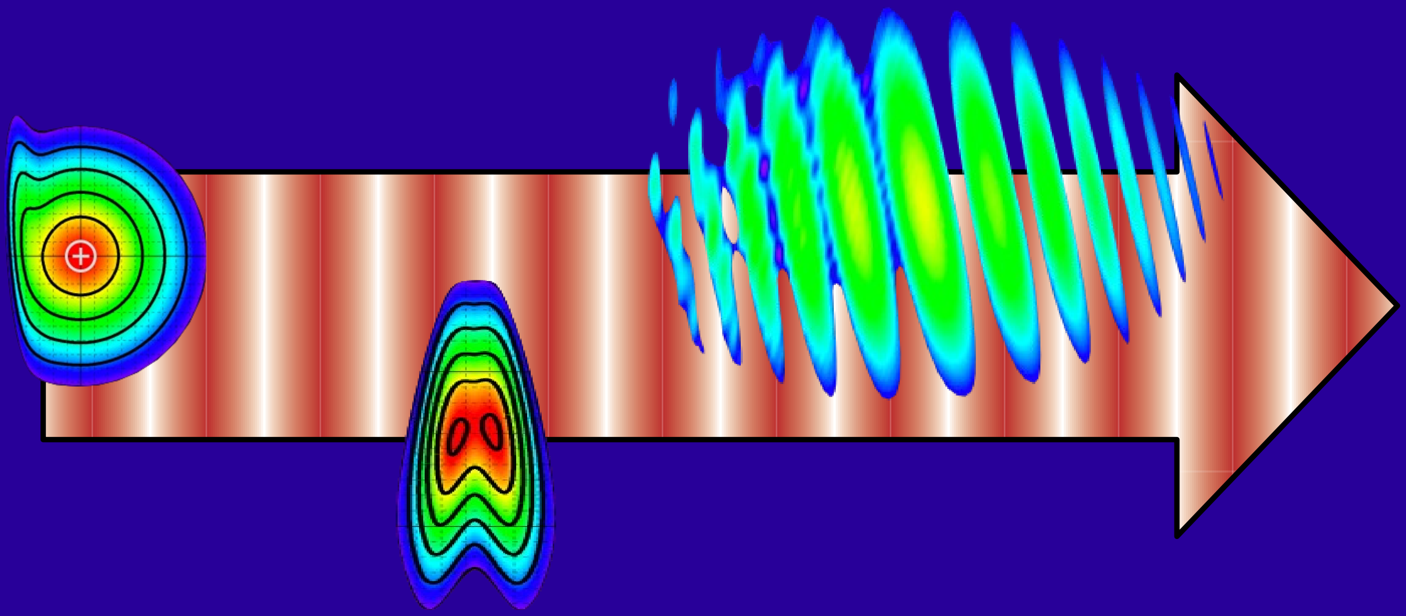
High-energy processes in super-strong laser fields



K. Z. Hatsagortsyan, A. Di Piazza, C. Műller,
and C. H. Keitel

EMMI, 14-15 May 09, JIHT, Moscow

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut
für Kernphysik

Content

- Radiation dominated dynamics in Thomson scattering
- Vacuum polarization in laser fields.

Light-by-light diffraction. The role of the laser beam focusing

Enhancement of vacuum polarization effects in plasma

Photon merging in laser-proton beam collision.

- Pair producation in counterpropagating laser beams.

The role of photon momenta

- Laser-driven collider

Radiation dominated dynamics in Thomson scattering

Classical effect of radiation reaction / radiation damping.

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Can radiation reaction effects be observable in strong laser fields?

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Is the radiation reaction always perturbation?

Does exist an interaction regime when the electron dynamics is determined by the radiation reaction?

Radiation dominated dynamics in Thomson scattering

In non-relativistic classical electrodynamics the radiation reaction is perturbation:

$$m\dot{\mathbf{v}} = e\mathbf{E} + \frac{e}{c}[\mathbf{vH}] + \frac{2e^2}{3c^3}\ddot{\mathbf{v}}.$$

$$\mathbf{f} = \frac{2e^3}{3mc^3}\dot{\mathbf{E}} + \frac{2e^4}{3m^2c^4}[\mathbf{EH}].$$

$$r_0 \ll \lambda$$

$$E \ll E_c/\alpha$$

perturbation conditions

$$r_0 \ll \lambda_c \ll \lambda \quad E \ll E_c \ll E_c/\alpha$$

the realm of the classical physics

$\lambda_c = h/mc$ - Compton wavelength

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Lorentz-Abraham-Dirac equation:

$$mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + g^i.$$

$$g^i = \frac{2e^2}{3c}\left(\frac{d^2u^i}{ds^2} - (u^i u^k)\frac{d^2u_k}{ds^2}\right).$$

In relativistic electrodynamics the radiation reaction is perturbation in the rest frame.

$$\gamma E \ll E_c / \alpha$$

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H. Spohn, EPL 50,287 (2000)

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$$f_x = -\frac{2e^4}{3m^2c^4}\frac{(E_y - H_z)^2 + (E_z + H_y)^2}{1 - v^2/c^2}$$

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Radiation dominated dynamics in Thomson scattering

Radiation dominated regime in strong laser fields: $\delta\varepsilon_{rad} \sim \varepsilon_0$ $\omega\tau \sim 1$

$$R=(2/3)r_0\gamma_0(1+\beta_0)\xi^2\omega/c \sim 1$$

$$\xi = eE/mc\omega$$

J. Koga et al. PP 12, 093106 (2005)

γ=300 ξ=100 (ε~150 MeV, I~10^{22} W/cm^2)

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$$\gamma_{drift}\sim\xi\sim\gamma_0\gg 1$$

Radiation dominated dynamics: $\delta p_z\sim p_z$

Radiation dominated dynamics in Thomson scattering

Exact solution of Landau-Lifshitz equation in a laser field:

$$R=(2/3)r_0\gamma(1+\beta)\xi^2\omega/c$$

$$\xi=eE/mc\omega$$

$$u^\mu(\phi)=\frac{1}{h(\phi)}\begin{pmatrix}\gamma_0+\frac{\omega_0}{2m\eta_0}[h^2(\phi)-1+\xi^2\mathcal{I}^2(\phi)]\\ 0\\ -\beta_0\gamma_0+\frac{\omega_0}{2m\eta_0}[h^2(\phi)-1+\xi^2\mathcal{I}^2(\phi)]\\ -\xi\mathcal{I}(\phi)\end{pmatrix}$$

In this expression $\eta_0=\omega_0\gamma_0(1+\beta_0)/m$ and

$$h(\phi)=1+R\int_{\phi_0}^{\phi}d\zeta\psi^2(\zeta),\qquad E=E_0\psi(\phi)$$

$$\mathcal{I}(\phi)=\int_{\phi_0}^{\phi}d\zeta\left[h(\zeta)\psi(\zeta)+\frac{R}{\xi^2}\frac{d\psi(\zeta)}{d\zeta}\right],$$

Di Piazza, Lett. Math. Phys. 83, 305 (2008)

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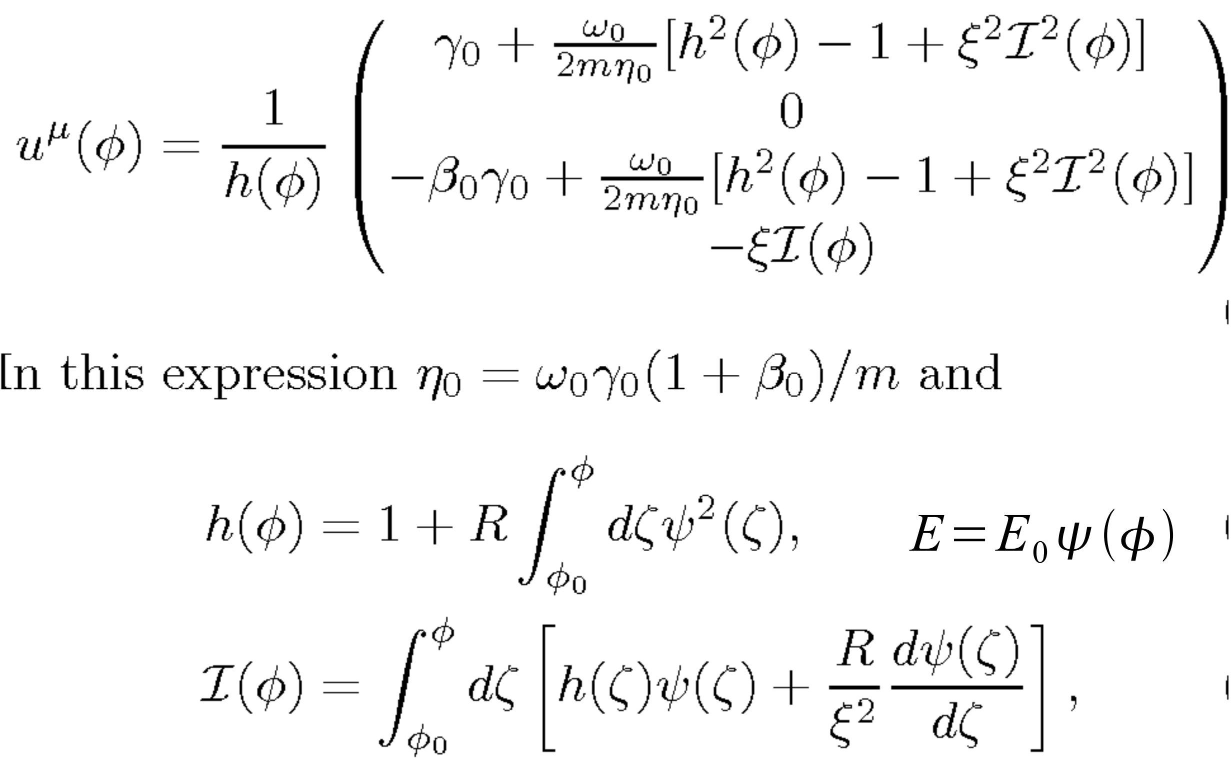

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$$R\ll 1$$

$$u_y(\phi)>0$$

$$2\mathrm{R}\,\xi^2 g(\phi)>4\gamma^2-\xi^2 I_0^2(\phi)>0$$

$$I\approx I_0(\phi)+Rg(\phi)$$

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J. Koga et al. PP 12, 093106 (2005)

laser beam electron

$$\gamma_{drift} \sim \xi \sim \gamma_0$$

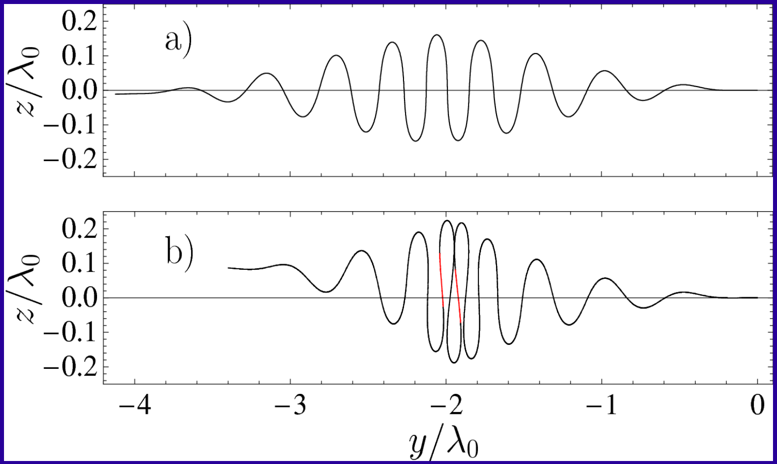
Radiation dominated dynamics: $\delta p_z \sim p_z$ at R<<1

$$R \sim (4\gamma_0^2 - \xi^2)/2\xi^2$$

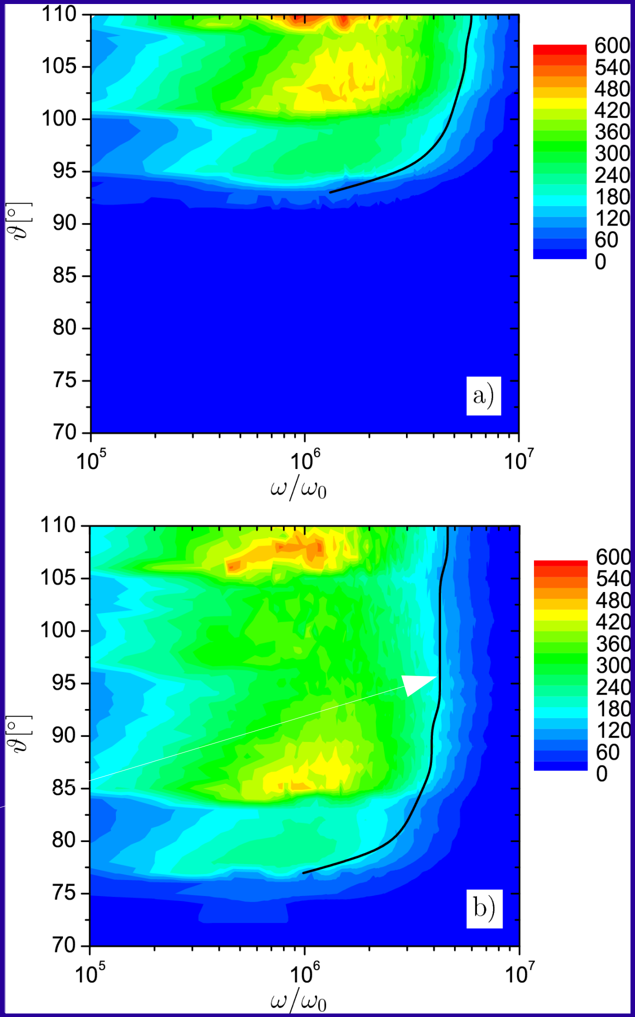
γ=80 ξ=150 (ε~40 MeV, I~5x10^{22} W/cm^2)

Radiation dominated dynamics in Thomson scattering

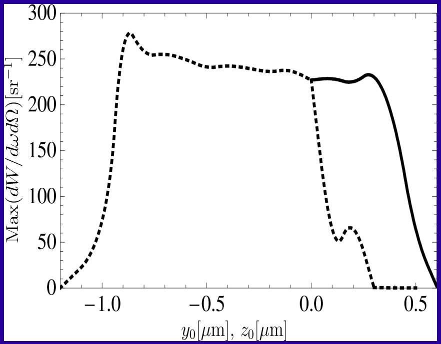
Electron trajectory



Angle resolved radiation spectra



Maximum of intensity at θ=80°



Dependence on the electron position in laser focus

w_0=2.5 μm

γ=80 ξ=150

(I~5x10^{22} W/cm^2)

$$\pi\gamma^2 v/\omega_c \approx \rho/\gamma$$

Radiation dominated dynamics in Thomson scattering

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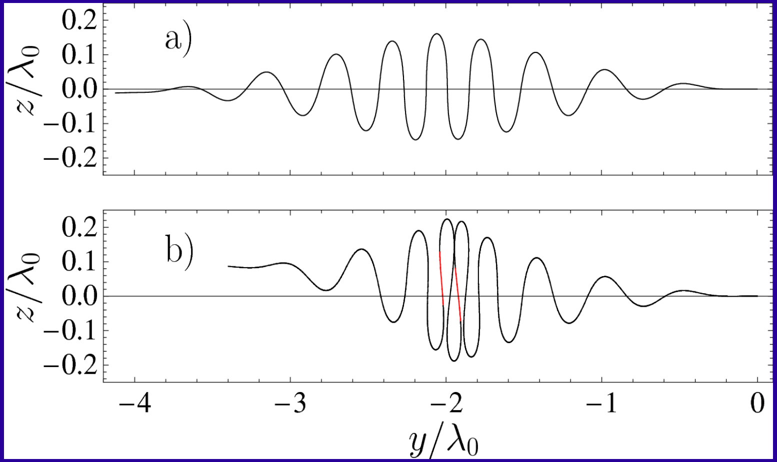

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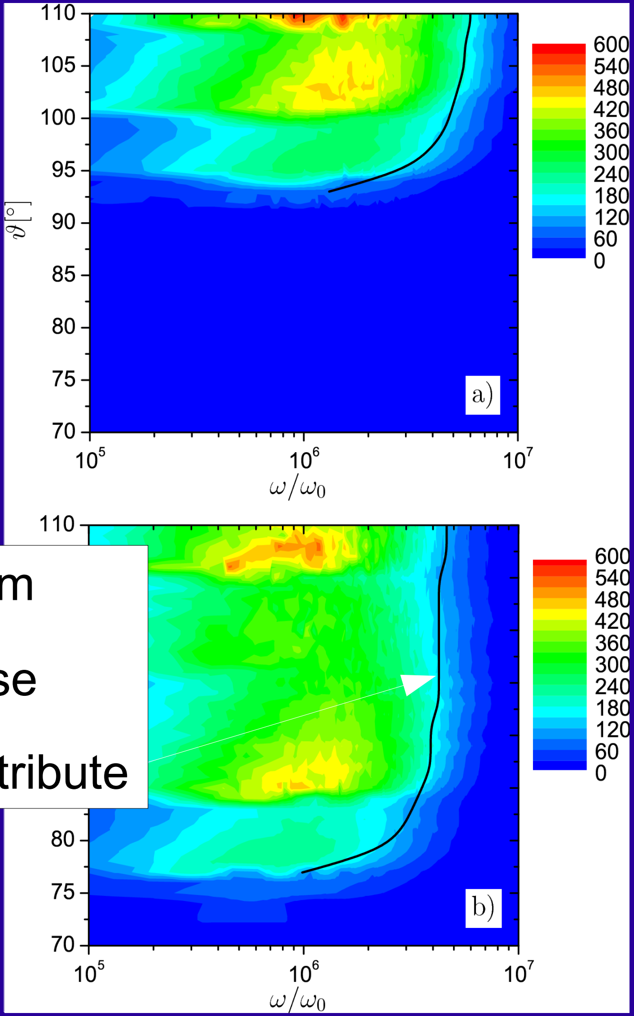

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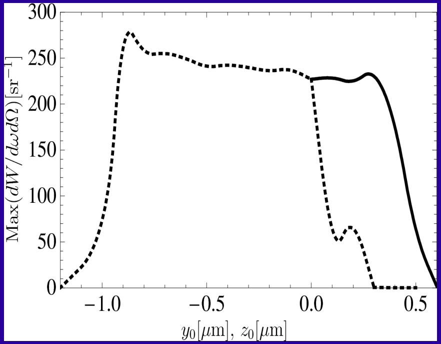

Dependence on the electron position in laser focus

10^9 electrons in beam

10^4 photons per pulse

1% of electrons contribute

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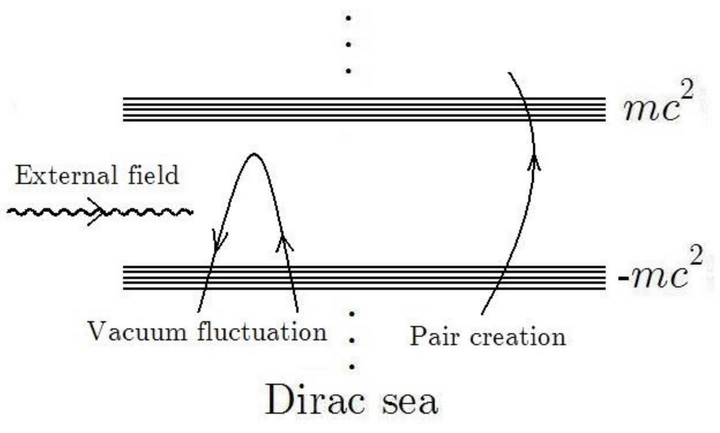
Vacuum polarization in laser fields

Quantum vacuum is a region of space-time which contains no real particles (electrons, positrons, photons etc)

Virtual particles are present:



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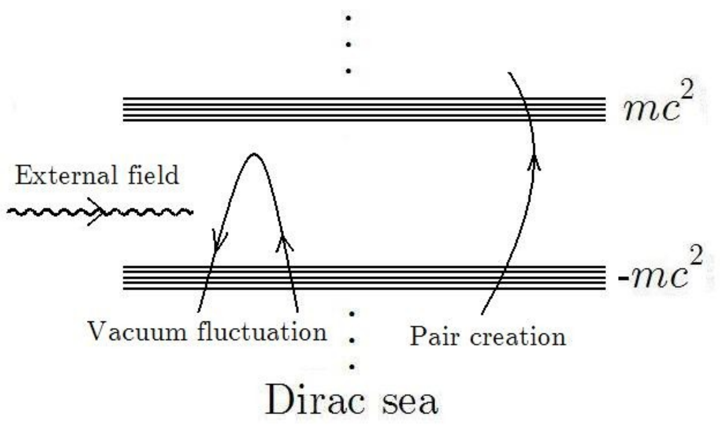

$eE\lambda_c = mc^2$

$E = E_c = m^2c^3/eh = 1.3\text{x}10^{16}$ V/cm

$I_c = cE_c^2/8\pi = 2.3\text{x}10^{29}$ W/cm^2

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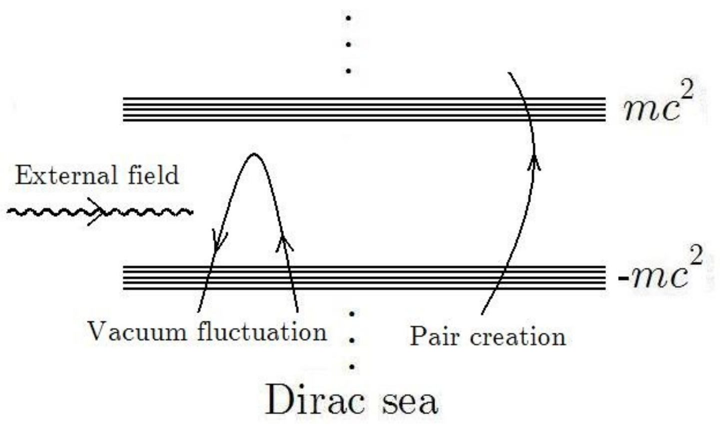

$$\xi = e\sqrt{A_\mu A^\mu}/m = eE\lambda_c/\omega$$
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$$\chi = \frac{e\sqrt{(F_{\mu\nu}p^\nu)^2}}{(mc^2)(mc)}\lambda_c = \left.\frac{eE\lambda_c}{mc^2}\right|_{r.f.} = \left.\frac{E}{E_{cr}}\right|_{r.f.} \quad or \quad = \left.\frac{\Omega}{m}\frac{E}{E_{cr}}\right|_{r.f.}$$

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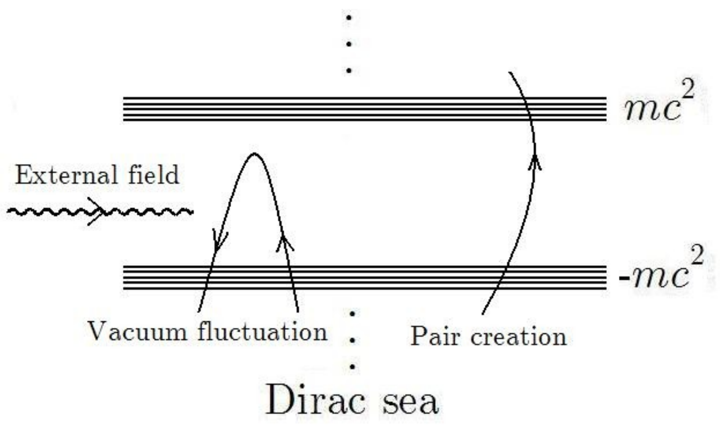

ξ is multiphoton parameter

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χ=1, I≈10^{29} W/cm^2

Spontaneous electron-positron pair production

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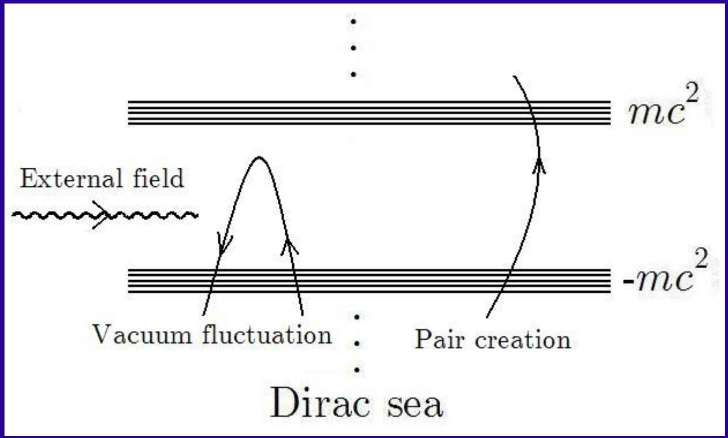

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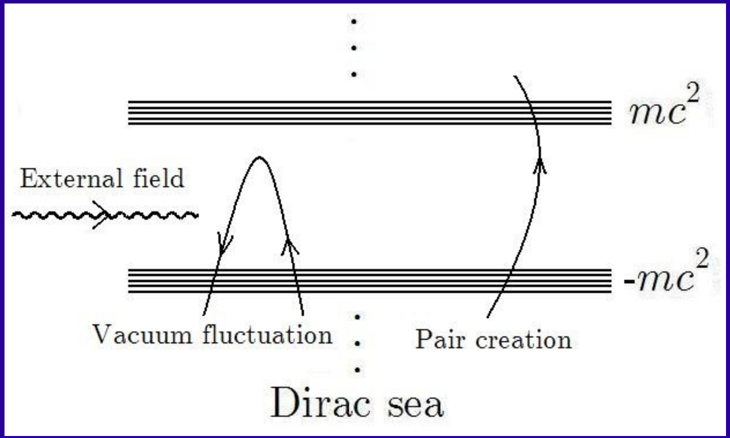

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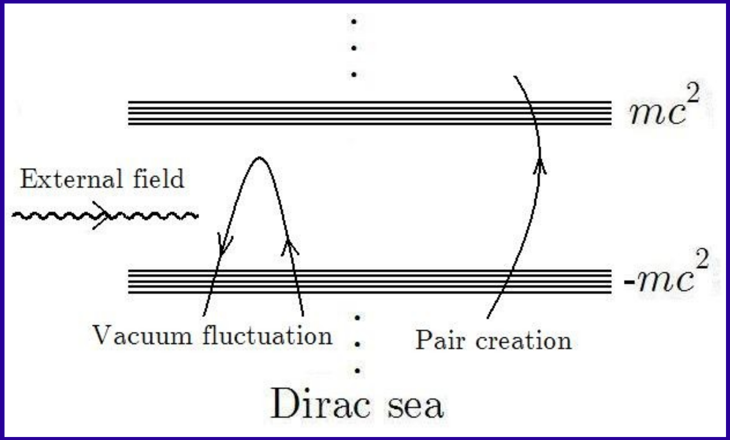

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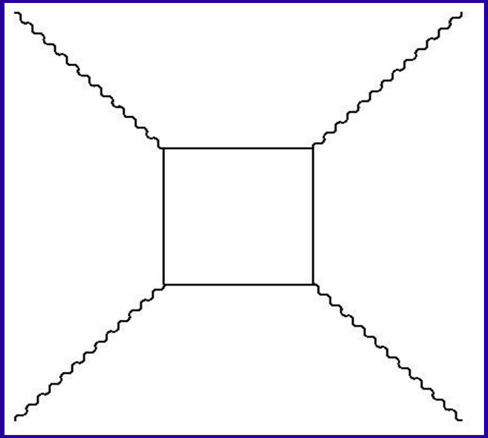
Vacuum is polarizable

Light-by-light diffraction

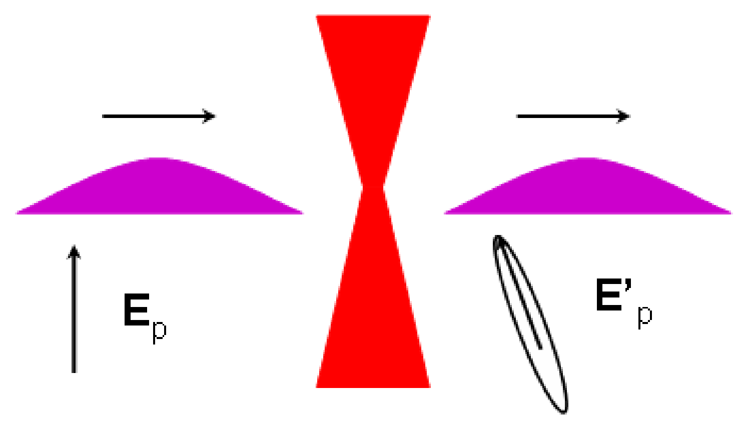
Euler-Heisenberg Lagrangian density:

$$L=\frac{1}{2}\left(E^2-B^2\right)+\frac{2\alpha^2}{45\,m^4}\left[\left(E^2-B^2\right)^2+7\left(\vec{E}\cdot\vec{B}\right)^2\right]$$



Polarization current:

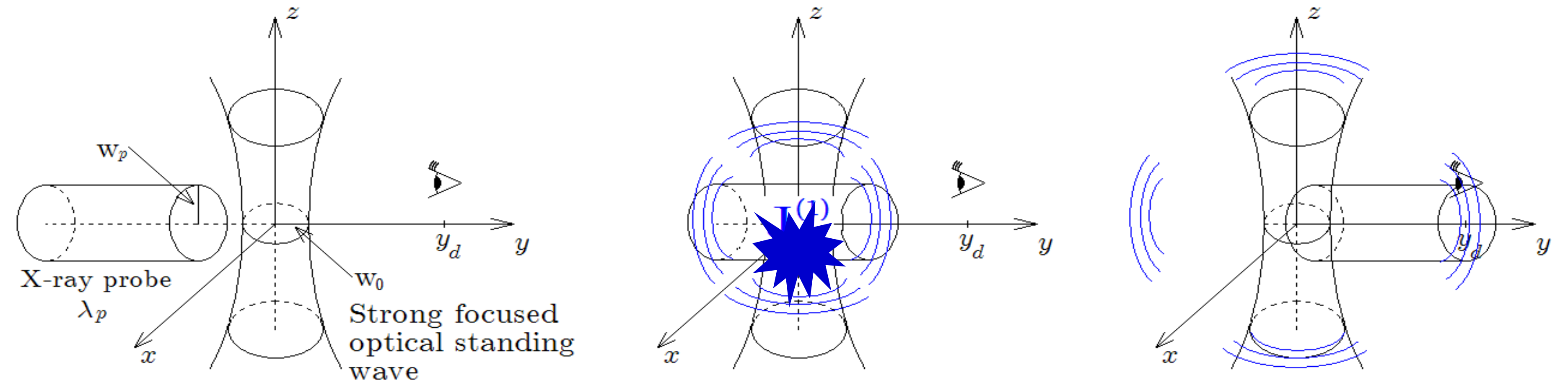
$$\nabla^2\vec{E}-\partial_t^2\vec{E}=\vec{J}\,;\quad \vec{J}\propto F^3$$



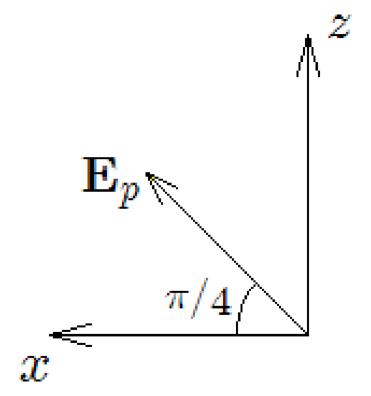
$$n(\text{vacuum+field})=1+\frac{\alpha}{45\pi}\frac{E^2}{E_{cr}^2}$$

Interaction of an x-ray beam with a strong standing wave

In far zone the probe diffraction is important



Probe polarization before the interaction



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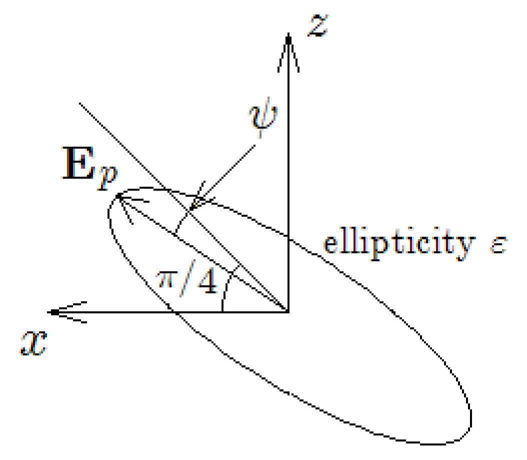

Di Piazza et al. PRL 97, 083603 (2006)

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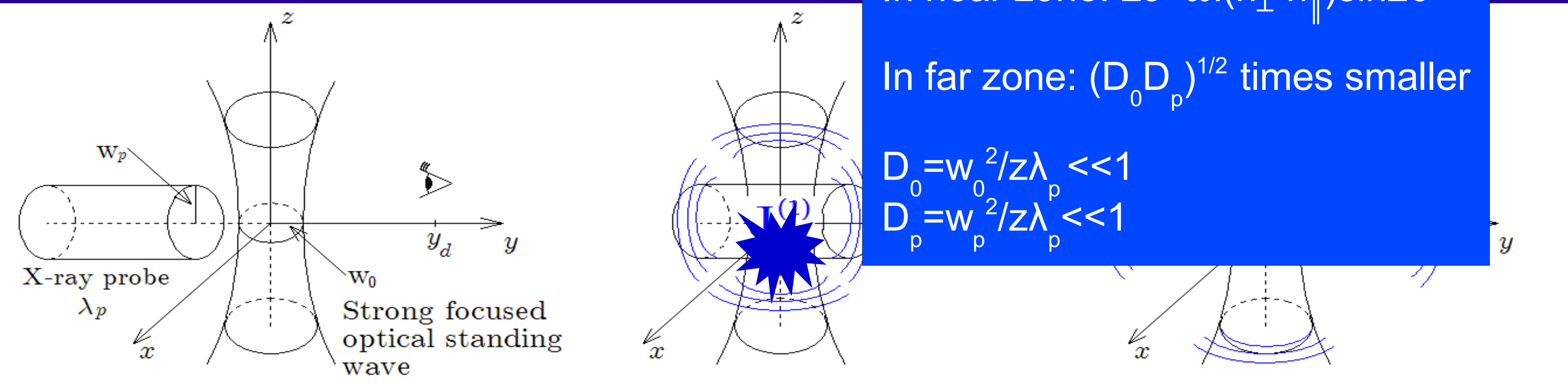

In near zone: $2\varepsilon=\omega l(n_\perp-n_\parallel)\sin 2\theta$

In far zone: $(D_0 D_p)^{1/2}$ times smaller

$D_0=w_0^2/z\lambda_p <<1$
$D_p=w_p^2/z\lambda_p <<1$

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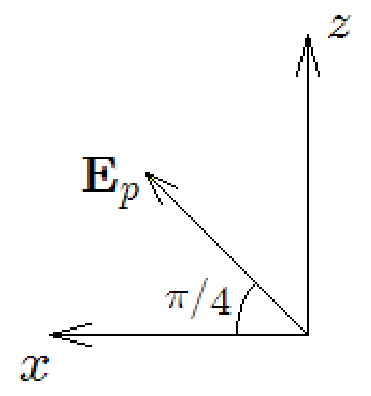
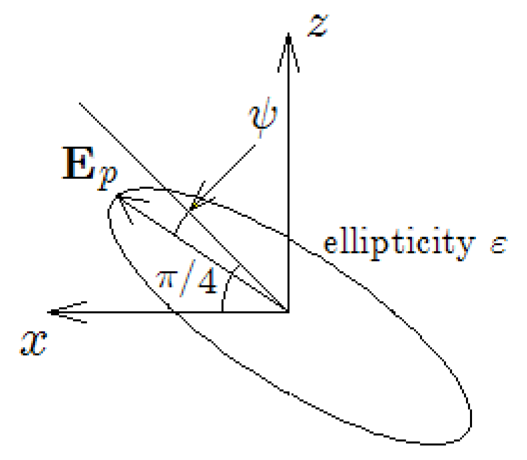


Probe polarization after the interaction



Di Piazza et al. PRL 97, 083603 (2006)

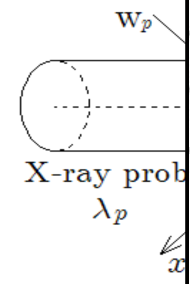
Interaction of an x-ray beam with a strong standing wave

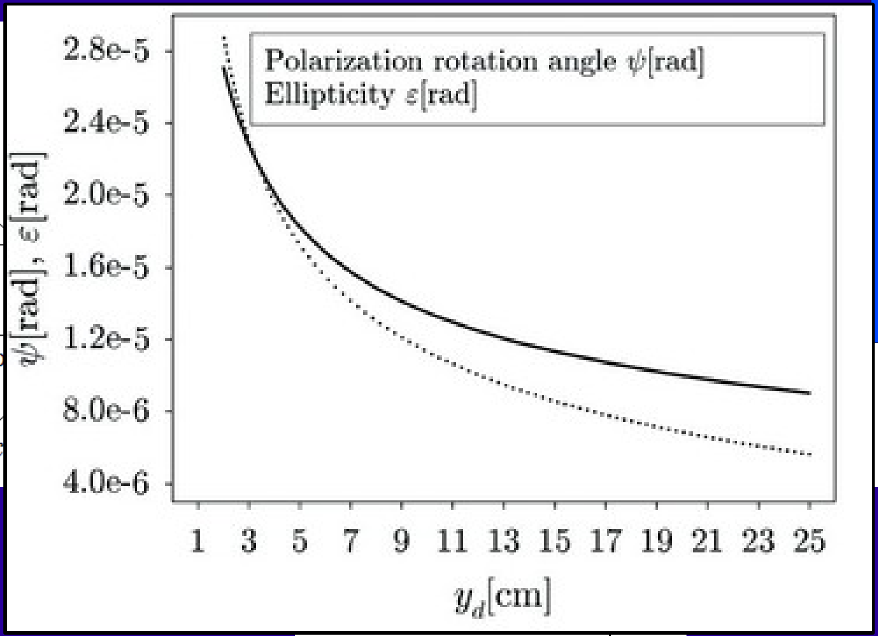
In far zone the probe diffraction is important

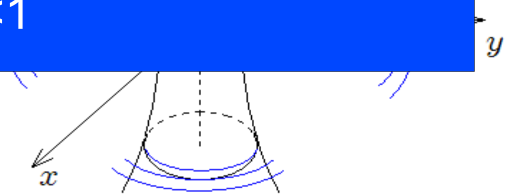
In near zone: $2\varepsilon=\omega l(n_\perp-n_\parallel)\sin2\theta$

In far zone: $(D_0D_p)^{1/2}$ times smaller

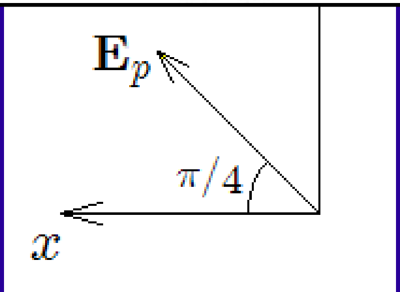
$D_0=w_0^2/z\lambda_p \ll 1$
$D_p=w_p^2/z\lambda_p \ll 1$



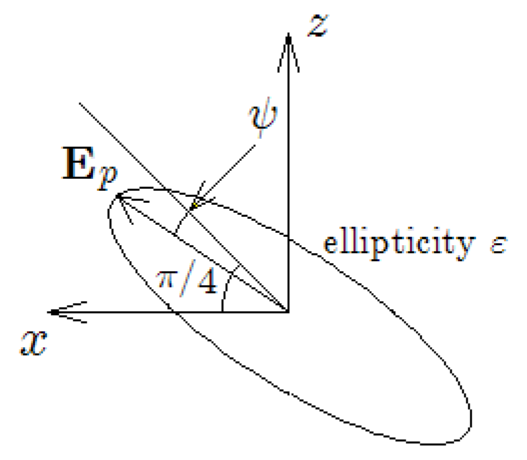




Probe polarization before the interaction



Probe polarization after the interaction



Di Piazza et al. PRL 97, 083603 (2006)

Enhancement of vacuum polarization effects in plasma

When a strong laser pulse propagates through plasma near the threshold of the plasma transparency the vacuum polarization effects are enhanced.

In the proximity of this singular point ω→ω_p, the plasma refractive index tends to zero, the field increases and the vacuum refractive index becomes more visible.

Di Piazza et al. PP 14, 032102 (2007)

$$n^2 = \varepsilon\mu \approx \varepsilon_p + \frac{2\alpha}{45\pi}\frac{E^2}{E_{cr}^2}\left(1-\varepsilon_p^2\right)$$

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2}$$

In plasma:

$$\varepsilon_p \to 0 \Rightarrow n_{pl} \approx \sqrt{\frac{2\alpha}{45\pi}\frac{E^2}{E_{cr}^2}}$$

In vacuum:

$$\varepsilon_p \to 1 \Rightarrow n_{vac} \approx 1 + \frac{\alpha}{45\pi}\frac{E^2}{E_{cr}^2}$$

$$n_{pl} >> n_{vac}$$

VPEs in a plasma (approach)

Equations of a two-fluids, cold, collisional and relativistic plasma including VPEs

$$\boldsymbol{\partial} \cdot \mathbf{E} = -e(N_e - ZN_i) \boxed{+ \rho_{\text{vac}}},$$

$$\boldsymbol{\partial} \cdot \mathbf{B} = 0,$$

$$\boldsymbol{\partial} \times \mathbf{E} + \partial_t \mathbf{B} = \mathbf{0},$$

$$\boldsymbol{\partial} \times \mathbf{B} - \partial_t \mathbf{E} = -e(N_e \mathbf{v}_e - ZN_i \mathbf{v}_i) \boxed{+ \mathbf{J}_{\text{vac}}},$$

$$\partial_t N_e + \boldsymbol{\partial} \cdot (N_e \mathbf{v}_e) = 0,$$

$$\partial_t N_i + \boldsymbol{\partial} \cdot (N_i \mathbf{v}_i) = 0,$$

$$\partial_t \mathbf{p}_e + (\mathbf{v}_e \cdot \boldsymbol{\partial})\mathbf{p}_e = -e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \cancel{\nu_{ei} m_r(\gamma_e \mathbf{v}_e - \gamma_i \mathbf{v}_i)}$$

$$\partial_t \mathbf{p}_i + (\mathbf{v}_i \cdot \boldsymbol{\partial})\mathbf{p}_i = Ze(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) - \cancel{\nu_{ie} m_r(\gamma_i \mathbf{v}_i - \gamma_e \mathbf{v}_e)}$$

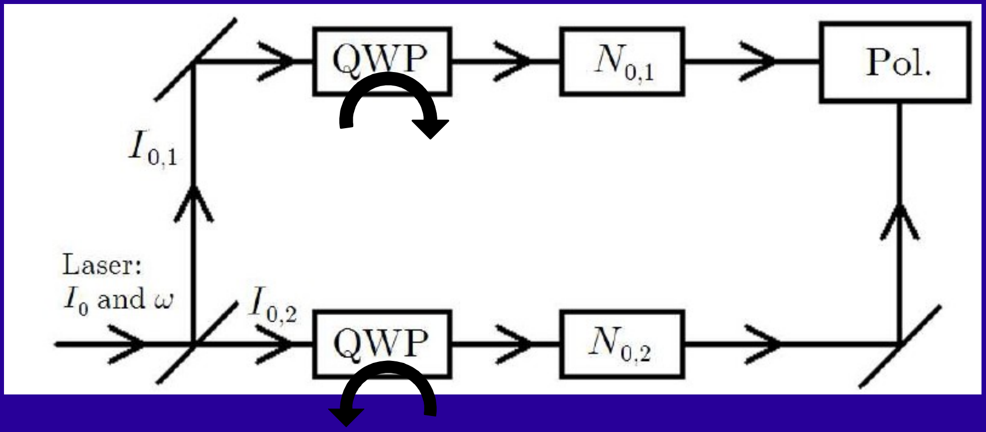
VPEs can be described mathematically as a ‘current’ but

It contains no particles quantities like velocity

It contains only the electromagnetic field to the third power

Collisional effects are important in the regime we are interested in but for simplicity they are neglected here (they can be treated perturbatively)

A possible (ideal) experimental setup



$$\Delta n_{pl} = \frac{\alpha}{45\pi} \frac{E_2^2 - E_1^2}{E_{cr}^2} \frac{(1 - n_{pl,0}^2)^2}{2 n_{pl,0}}$$

Laser data: ω=1 eV

$I_{0,1}=7\text{x}10^{21}$ W/cm^2

$I_{0,2}=3\text{x}10^{22}$ W/cm^2

Plasma data:

Z=46 (palladium)

$N_{0,1}=10^{23}$ cm^{-3}, $N_{0,2}=2I_{0,1}$

L=100 μm, $n_{p0}=5\text{x}10^{-2}$

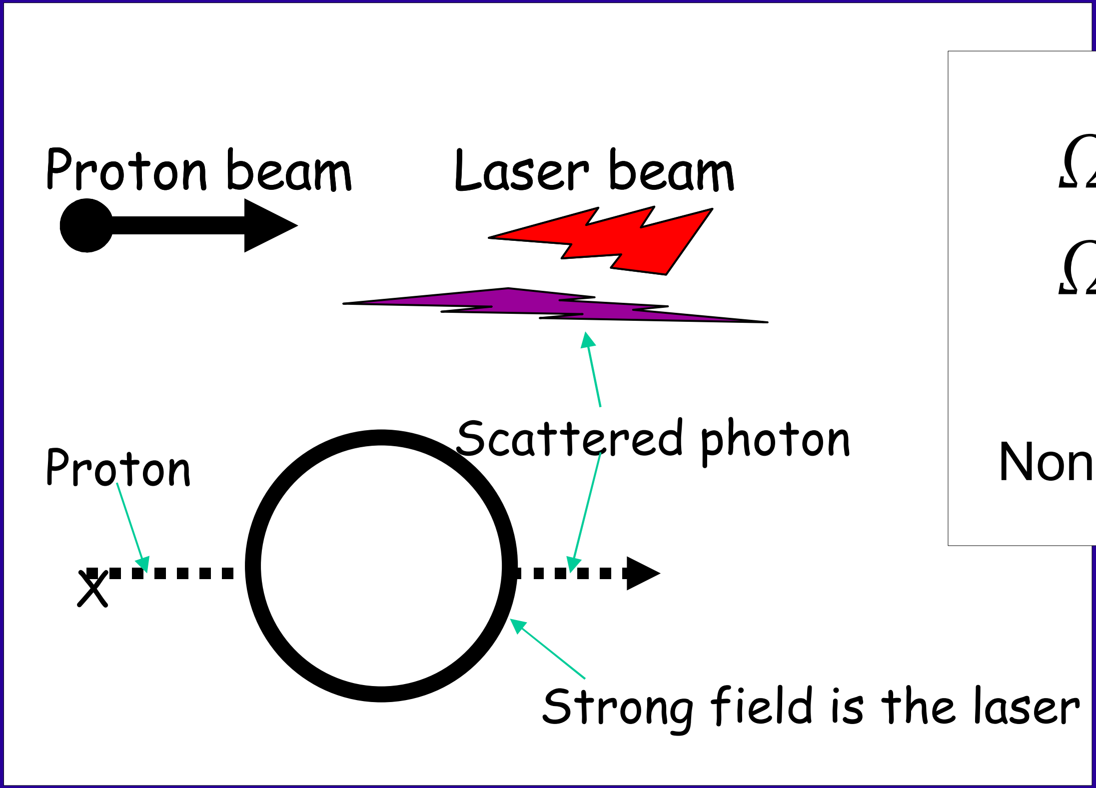
Numerical results and comments:

Rotation of laser polarization: $6.8\text{x}10^{-8}$ rad (more than one order of magnitude with respect to the case of diffraction)

Measurable nowadays

Large densities required because we require close to plasma frequency and high laser intensities

Photon fusion during laser and proton beam collision



$$\Omega \approx 2\gamma\omega_L; \quad E \approx 2\gamma \mathrm{E}_L$$

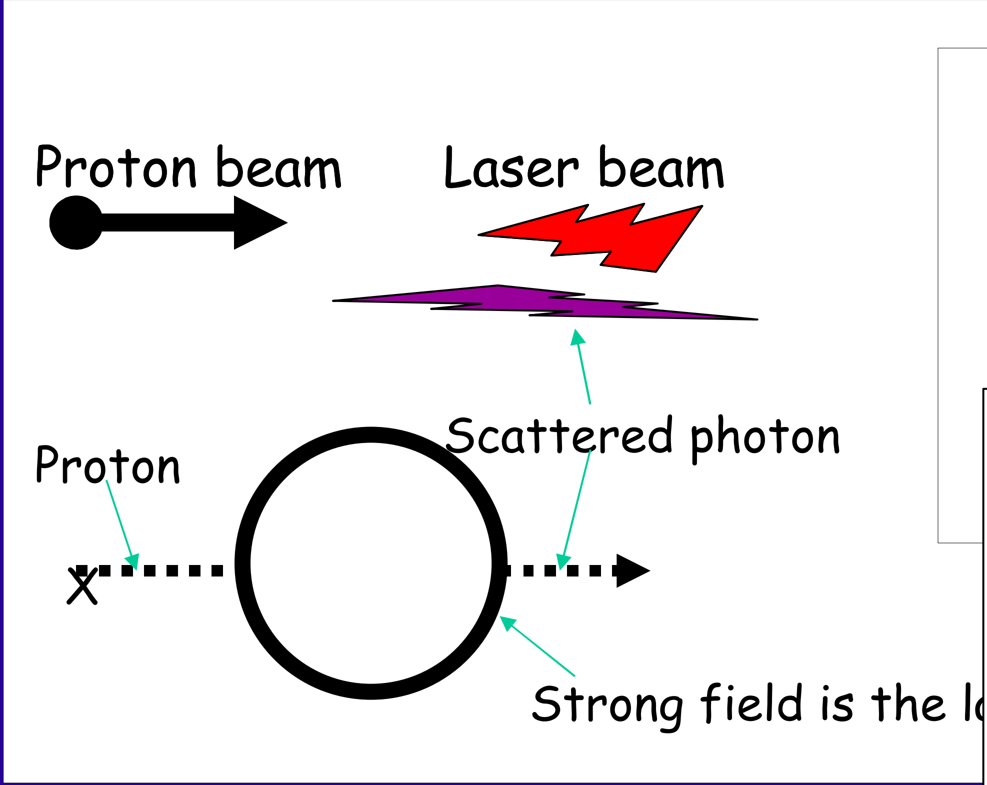
$$\Omega \sim m; \quad E \sim E_{cr}$$

$$\Downarrow$$

Nonliner QED $\quad \chi = \frac{2\Omega}{m}\frac{E}{E_{cr}} >> 1$

Di Piazza et al. PRL 97, 083603 (2006); PRA 78, 062109 (2008)

Photon fusion during laser and proton beam collision



$$\Omega \approx 2\gamma\omega_L; \quad E \approx 2\gamma \mathrm{E}_L$$

$$\Omega \sim m; \quad E \sim E_{cr}$$

Nonliner QED $\chi = \frac{2\Omega}{m}\frac{E}{E_{cr}} >> 1$

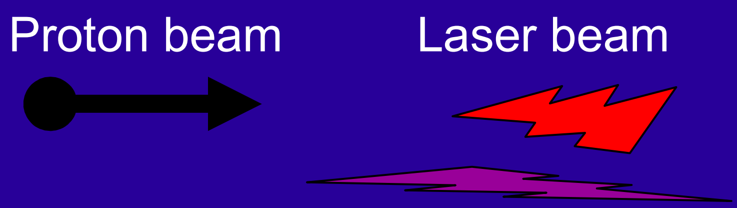
Perturbative: $c_n \sim \chi^{2n}$

Nonperturbative: $c_n \sim \chi^{2/3}$

Opening of multiphoton channels:

$$R_n \sim 1/n^5$$

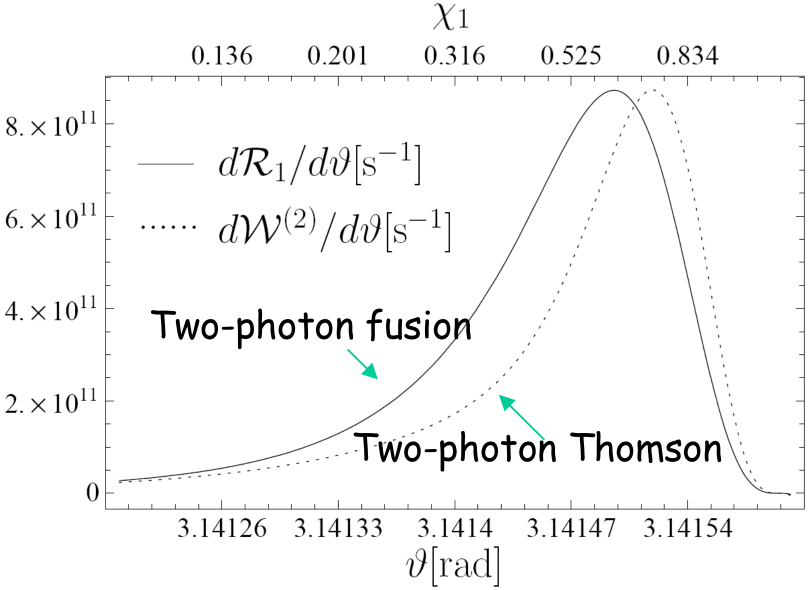
Photon fusion during laser and proton beam collision



Tevatron: Proton energy 980 GeV; $N_p=10^{11}$

XUV Laser : $I=4x10^{22}$ W/cm^2, ω=70 eV

Second harmonic: 500 events/h
4th: 7 events/h

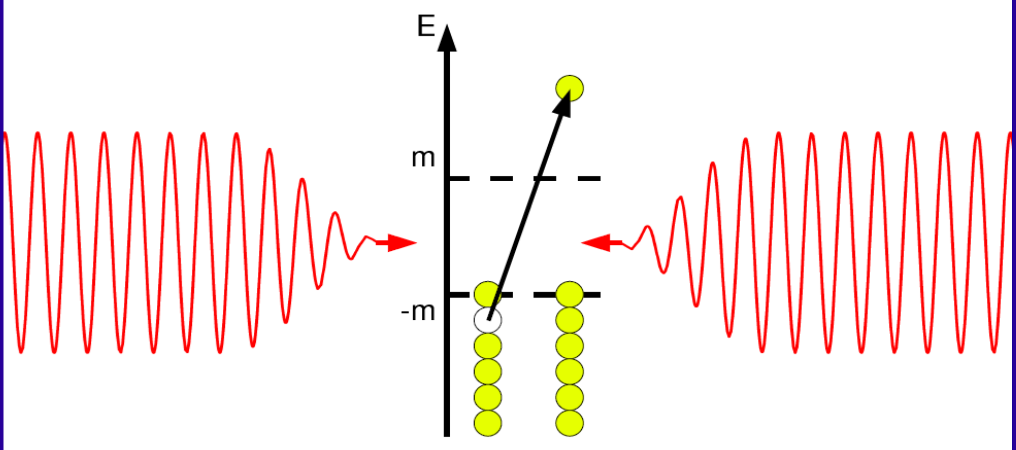


LHC: Proton energy 7TeV; $N_p=10^{11}$

Laser: $I=3x10^{22}$ W/cm^2, IR

Second harmonic: 400 events/h
4th: 6 events/h

Pair creation in counterpropagating laser waves



$$A = A_0\,[\,\sin(wt - kz) + \sin(wt + kz)\,] = 2A_0\sin(wt)\cos(kz)$$

Dipole approximation $\cos(kz) \approx 1$ and $B=0$ is applicable only if

$$l_c << \lambda \quad => \quad \xi = eE/m\omega >> 1$$

$l_c \sim m/eE$ is the pair formation length

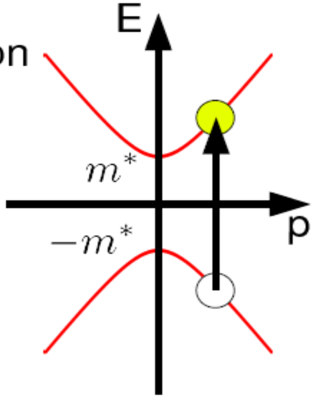
For XFEL/Compton radiation sources $\omega \leq m$ and $\xi \leq 1$, the DA is not valid.

Overview: Pair creation in an oscillating electric field

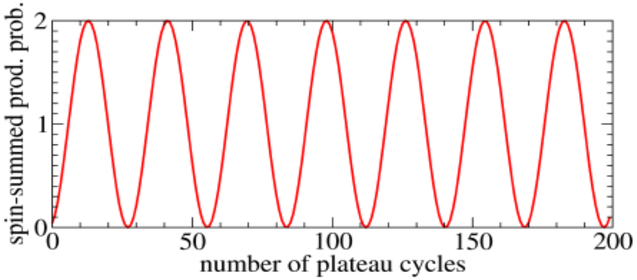
- Pure two level system due to momentum conservation

$$q_0(p) = \frac{1}{T}\int_0^T dt\sqrt{(p-eA(t))^2+m^2}$$

$$m^* \equiv q_0(p=0) \approx 1.21m \quad \text{for} \quad \xi = 1$$

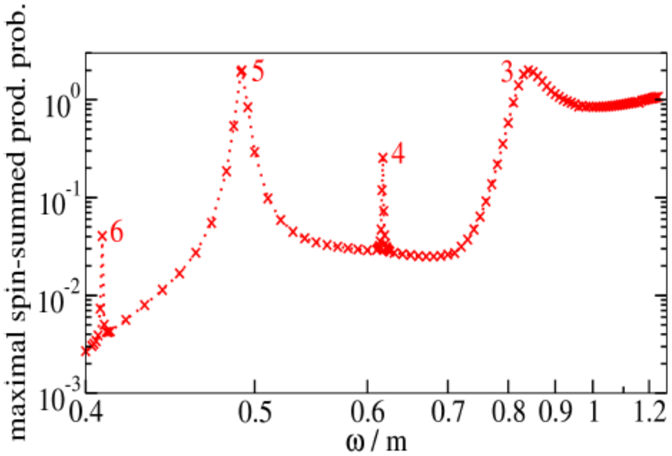


- Rabi-oscillations



- Resonances enforced by energy conservation

$$2q_0(0) = n\omega$$



$w_n \sim \hat{J}_n(U_p)$

$n=m+U_p$

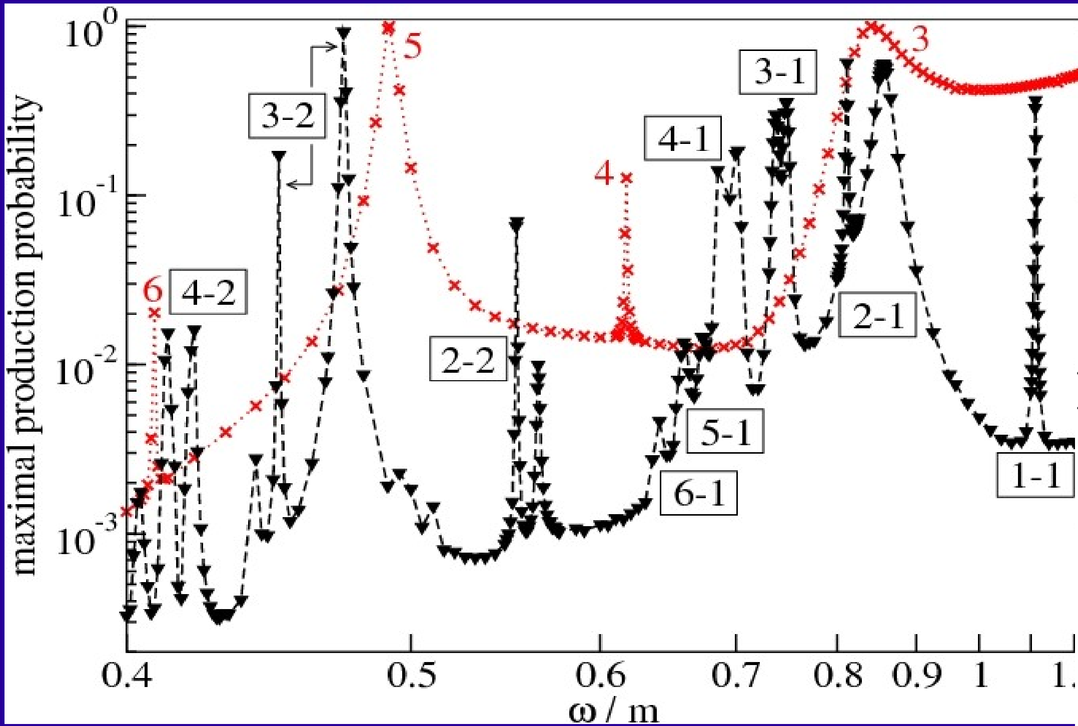
$U_p=\alpha m\xi^2$

$n<U_p$

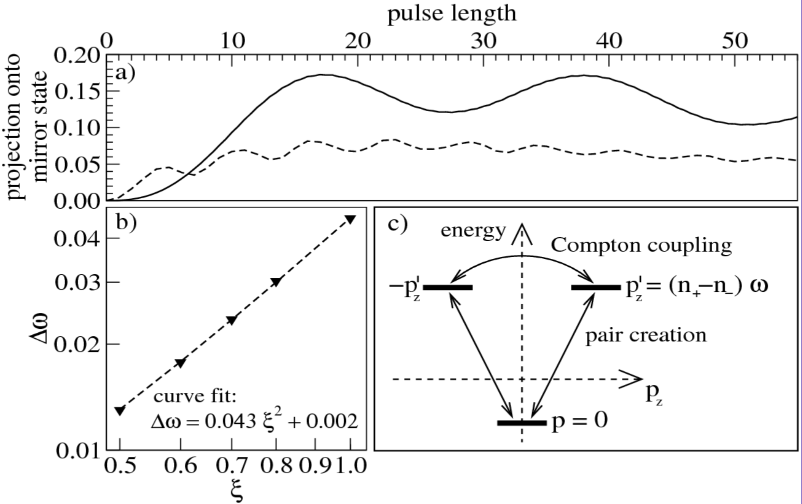
$\xi>>1, \ w_n \sim e^{-E_c/E}$

see, e.g. V. S. Popov,
JETP Lett. 18, 255 (1973) etc

The influence of the magnetic-field component



$$\omega = m_*(n_+ + n_-)/2n_+n_-$$

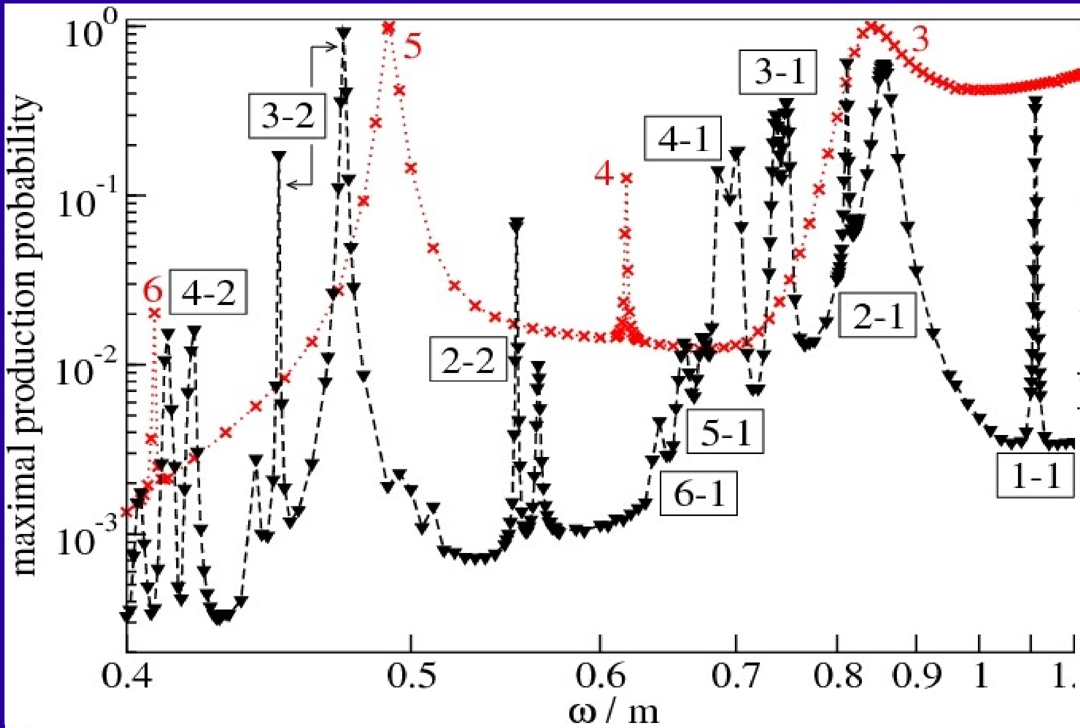


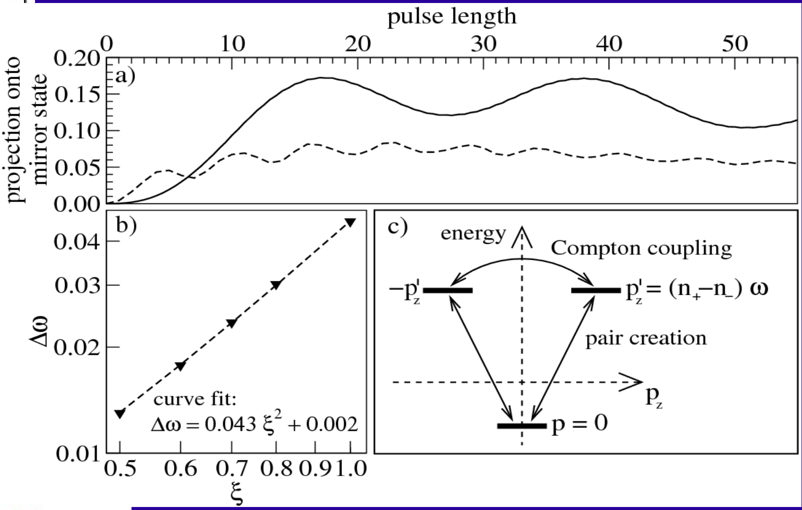
The resonance peaks are shifted and split, due to non-zero photon momentum: For example, n = 5 = 3 (from left) + 2 (from right) = 4 + 1

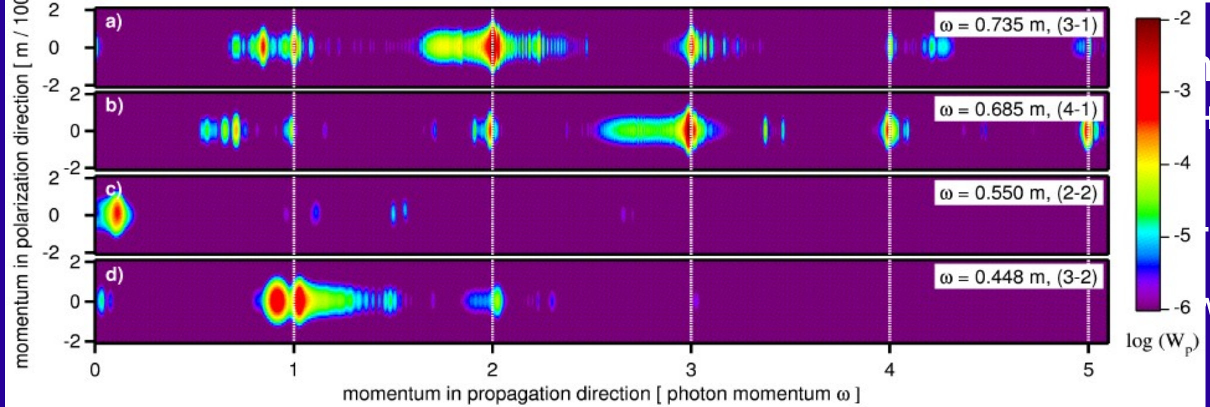
M. Ruf et al. PRL 102, 080402 (2009)

The influence of the magnetic-field component

$\omega = m_*(n_+ + n_-)/2n_+n_-$







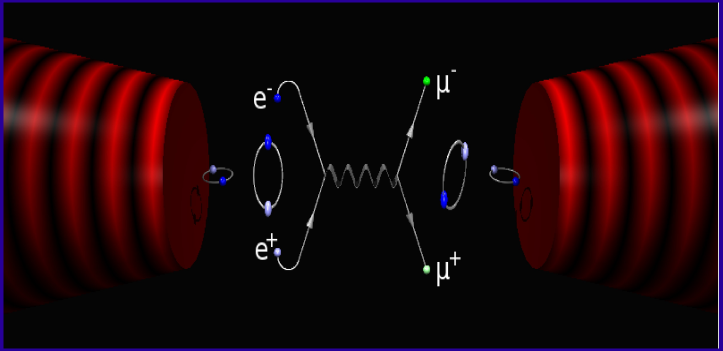
-zero photon momentum:

+ 1

. PRL 102, 080402 (2009)

w

Laser-driven collider



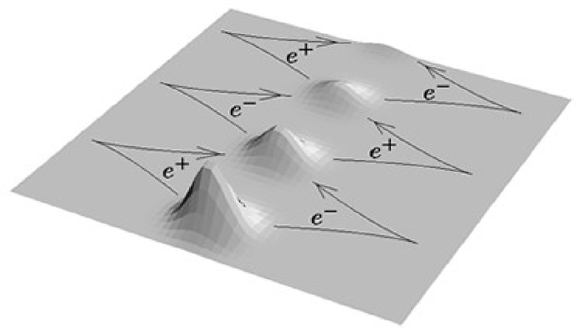
r =1 fm=10^{-13} cm

ε~ ch/r ~1 GeV

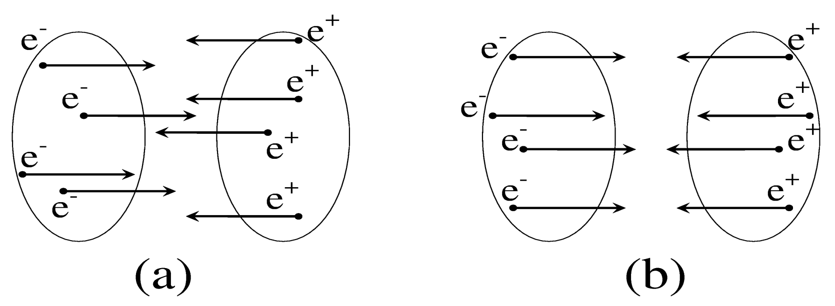
L~10^{26}-10^{27} cm^{-2} s^{-1}

Laser wakefield accelerators ? L~10^{21} cm^{-2} s^{-1}

$$L = \left[\frac{N_e\left(N_e - 1\right)}{a_b^2} + \frac{N_e}{a_w^2} \right] f$$



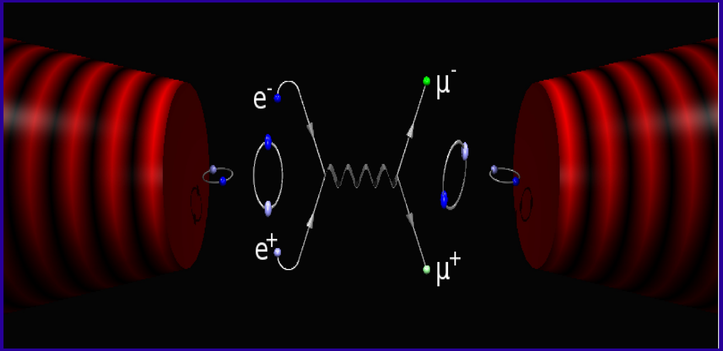
Luminosity is enhanced due to the coherent component



B. Henrich et al. PRL **93,** 013601 (2004)

K. Hatsagortsyan et al. EPL **76**, 29 (2006)

Laser-driven collider



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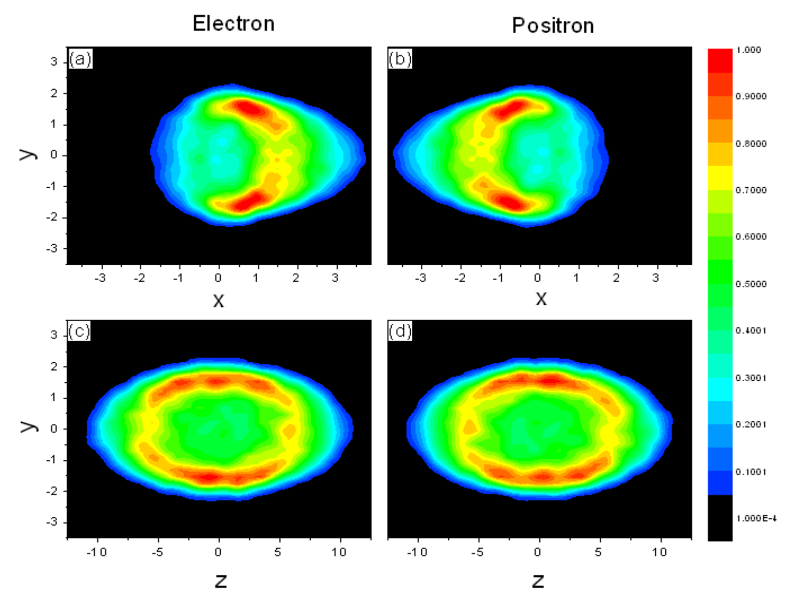
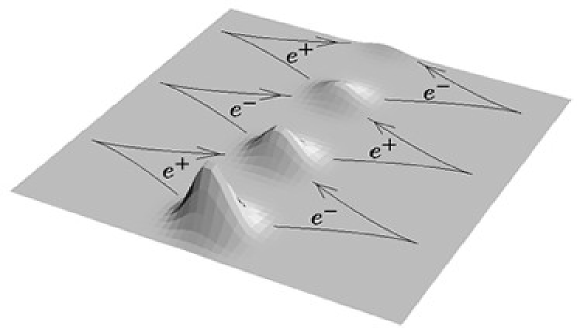
L~10^{26}-10^{27} cm^{-2} s^{-1}

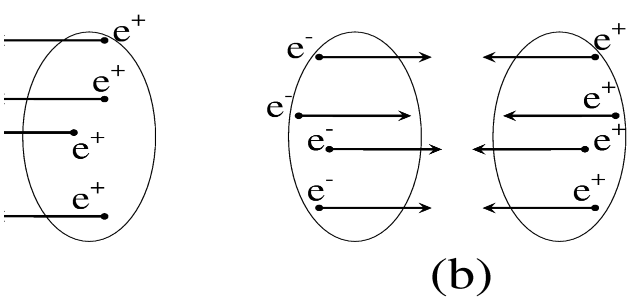
Laser wakefield accelerators ? L~10^{21} cm^{-2} s^{-1}

$$L=\left[\frac{N_e\left(N\right.}{a_l}\right.$$

Luminosity is
the coherent







B. Henrich et al. PRL **93,** 013601 (2004)
K. Hatsagortsyan et al. EPL **76**, 29 (2006)

Laser-driven collider

Short recolision time ~ T/2

Wave packet spreading is not large: $a_o < 4a_B$

Scattering energy: $mc^2\xi$

Coherent collisions with Ps: $N_{Ps} < (a_b/a_w)^2 \sim 10^{11}$

Reaction events per pulse: 10^{-7} at $N_{Ps} = 10^7$; $n=10^{15}$ cm^{-3}

10^{-4} at $n=10^{18}$ cm^{-3} D. B. Cassidy et al. Nature 449, 195 (2005)

One reaction event per sec at f=1 kHz

Eff. Luminosity: $L_{eff}=10^{24}$-10^{27} cm^{-2}s^{-1}

Incoherent collisions with e+e- plasma:

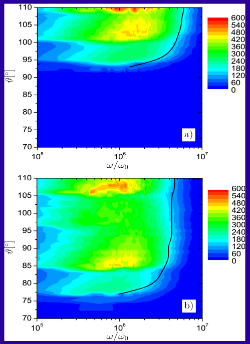
Reaction events per pulse: 10^{-9} at $n = 10^{15}$ cm^{-3}; τ=30 fs

C. M. Surko et al. PP 11, 2333 (2004)

Conclusion

Conclusion

Radiation dominated dynamics below R<<1



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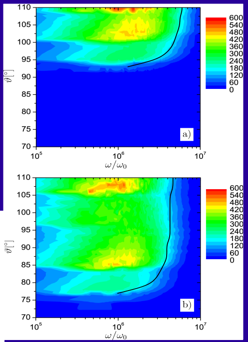
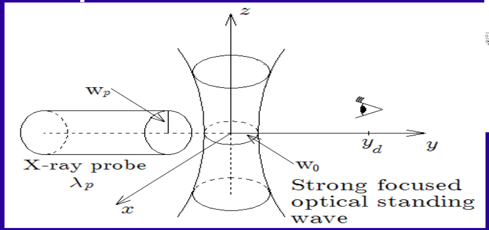


Diffraction decreases the ellipticity due to vacuum polarization



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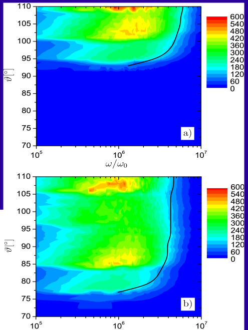

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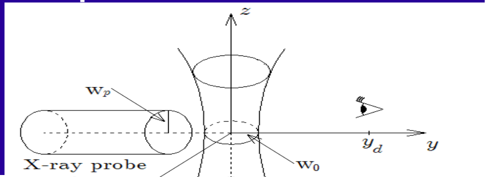
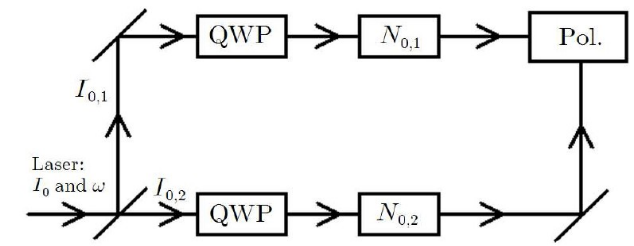
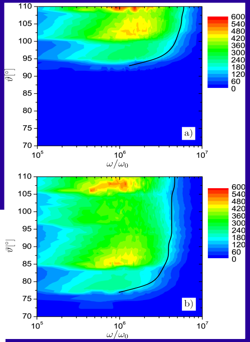




Enhancement of the visibility of vacuum poalrization effect in plasma

Conclusion



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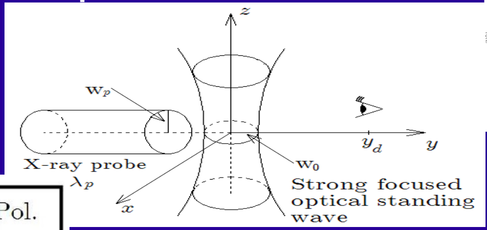
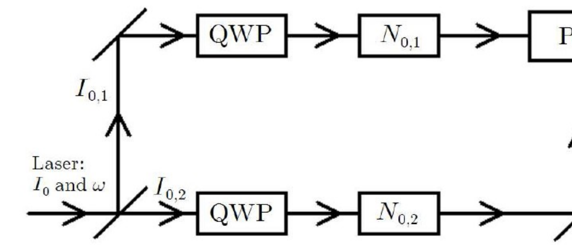
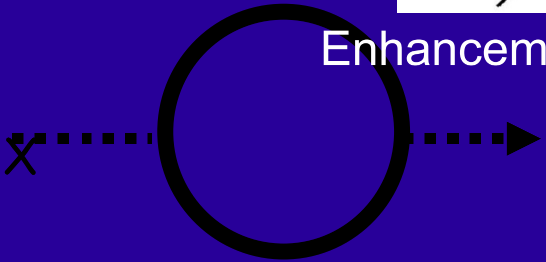




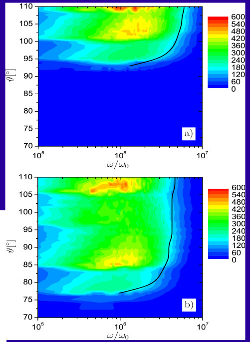


Enhancement of the visibility of vacuum poalrization effect in plasma

Photon merging in laser-proton beam collision

Conclusion

Radiation dominated dynamics below R<<1



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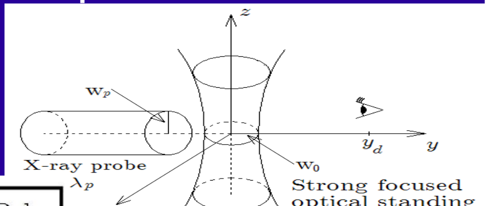

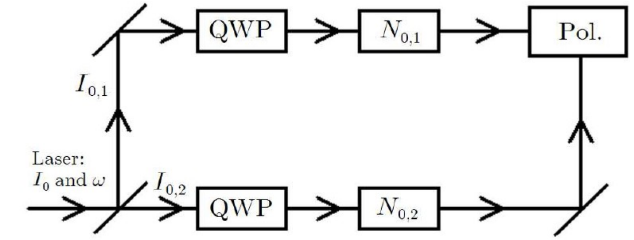

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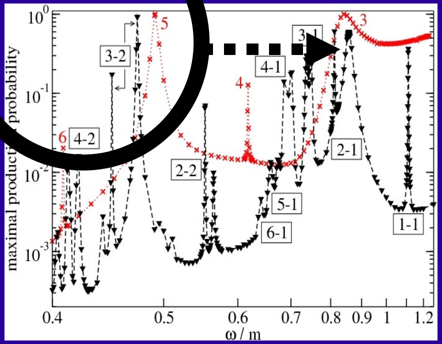

Photon merging in laser-proton beam collision

Autler-Towns effects in pair production process in counterpropagating laser pulses

Conclusion

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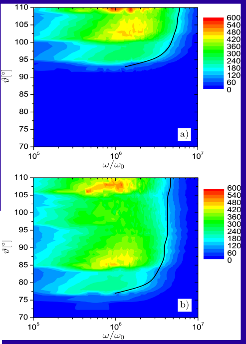
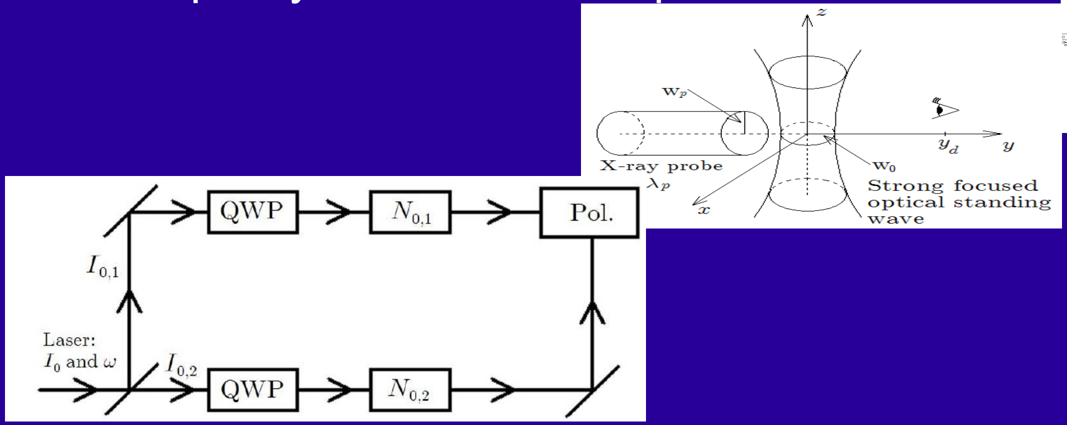
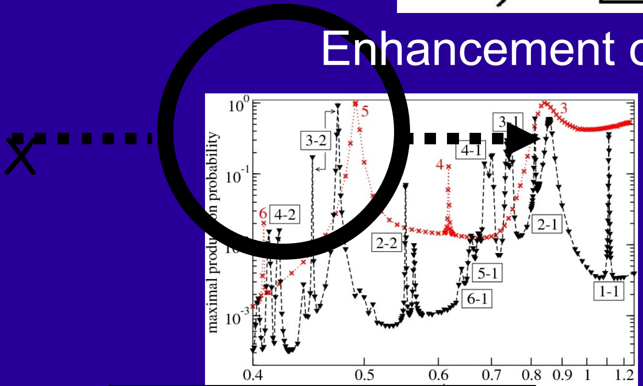


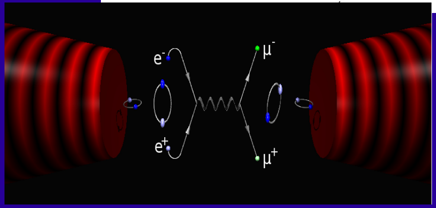


Enhancement of the visibility of vacuum poalrization effect in plasma



Photon merging in laser-proton beam collision

Autler-Towns effects in pair production process in counterpropagating laser pulses



Laser-driven collider; muon production

EMMI, 14-15 May 09, JIHT, Moscow

Thank you for your attention