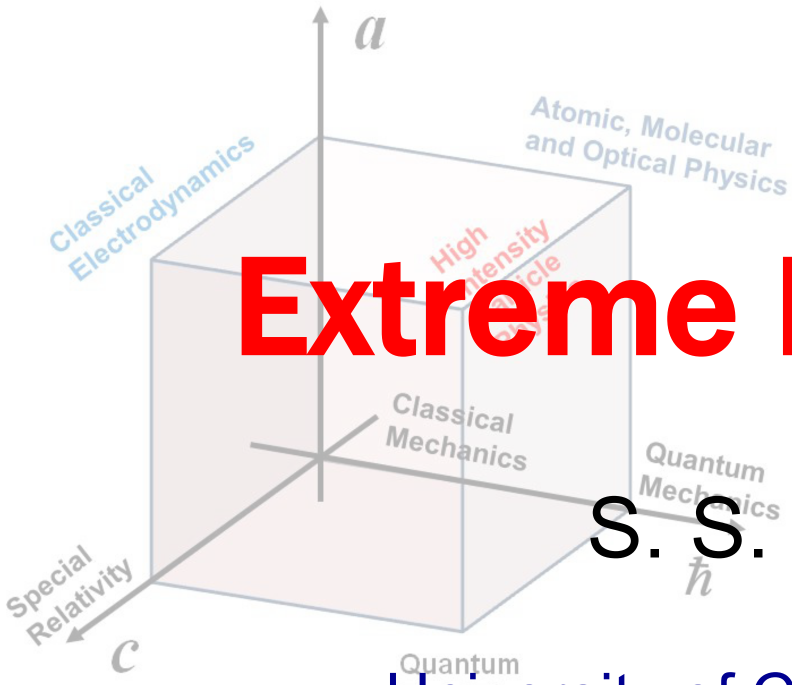
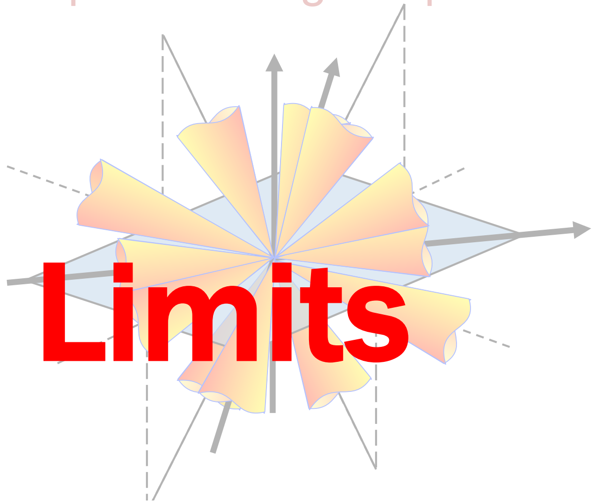
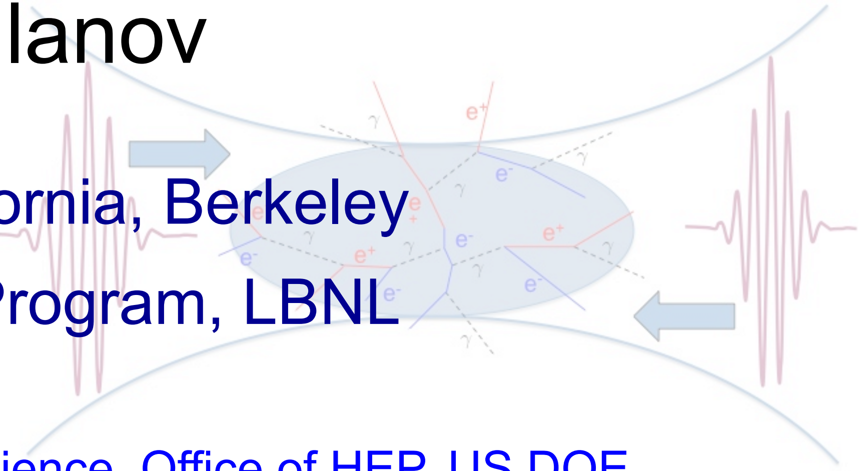
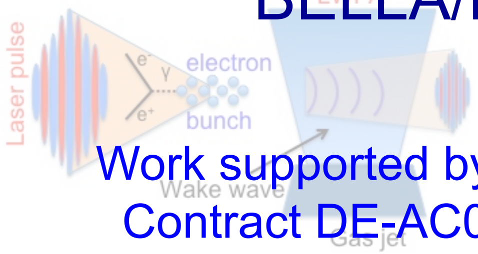
Frontiers of Intense Laser Physics, KITP, Santa Barbara, CA September 9th, 2014



Multiple Colliding EM pulses:







Extreme Field Limits

S. S. Bulanov

University of California, Berkeley

BELLA/LOASIS Program, LBNL

Work supported by Office of Science, Office of HEP, US DOE
Contract DE-AC02-05CH11231 and DE-FG02-12ER41798

In Collaboration with

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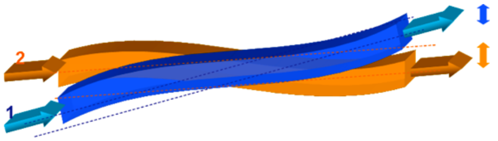
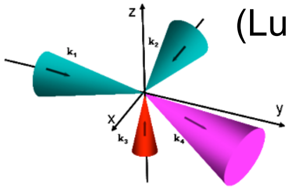
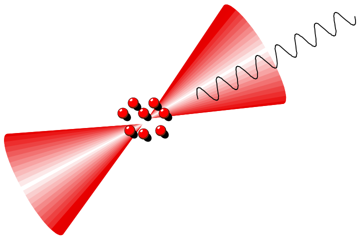
High Intensity Particle Physics

Birefringent e.m. vacuum (Rozanov, 1993)





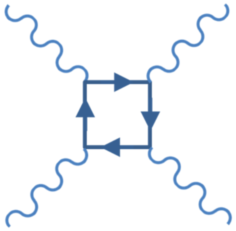
4-wave mixing
(Lundström et al, 2006)



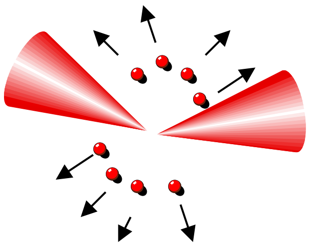
High order harmonic generation
through quantum vacuum interaction
(Di Piazza, Hatsagortsyan,
C. H. Keitel, 2005
Fedotov & Narozhny, 2006)

High Intensity

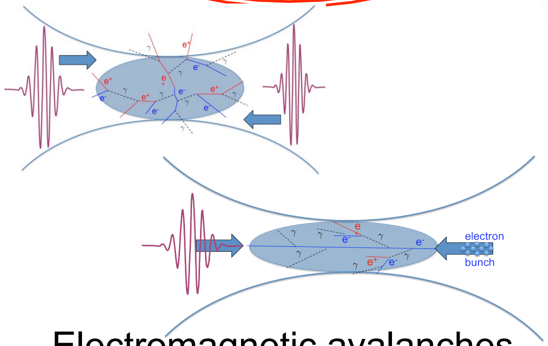
Particle Physics



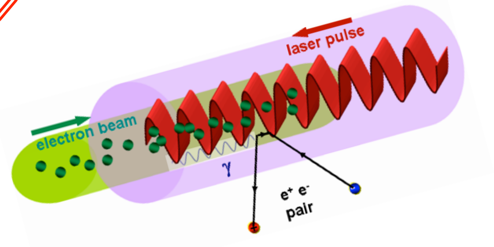
Photon-photon
scattering
via relativistic mirrors
(Koga et al (2012))



Electron positron pair production
from vacuum (Schwinger, 1951)



- Electromagnetic avalanches
- Electromagnetic cascades



Mulitphoton Compton and Breit-Wheeler processes
A. I. Nikishov, V. I. Ritus (1964);
Bula et al (1996); Burke et al (1997)

High Intensity Particle Physics

High Intensity Particle Photon Interactions

- Nonperturbative Quantum Field Theory

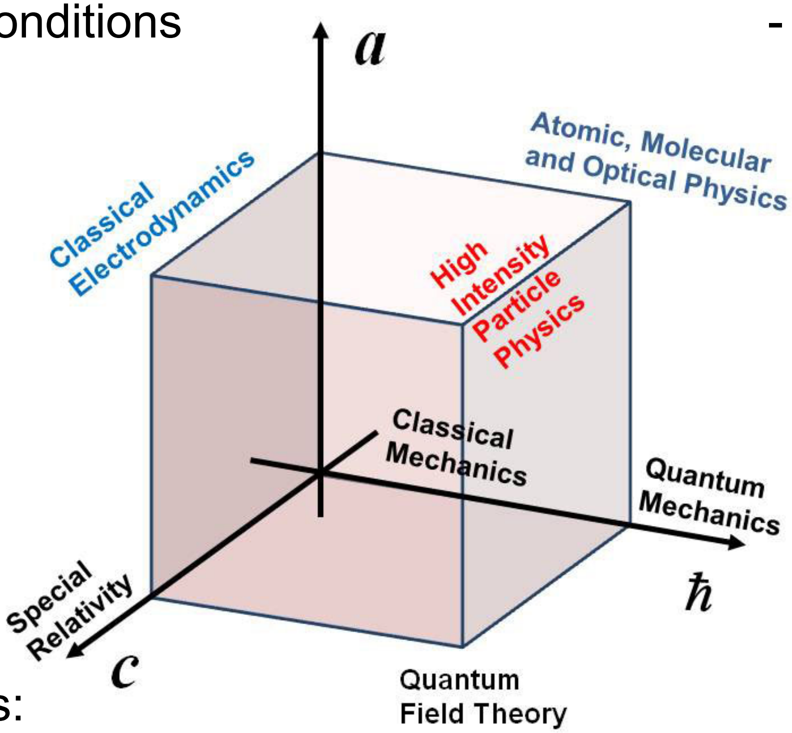
- Matter in extreme conditions

- Electromagnetic Cascades

- Electromagnetic Avalanches

- Ultimate Laser Intensity Limit

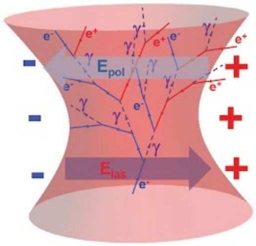
- Next generation lasers:
  - day-to-day operation
  - new laser-matter interaction applications



- Future lepton colliders

- Future γγ colliders

Berkeley Cube



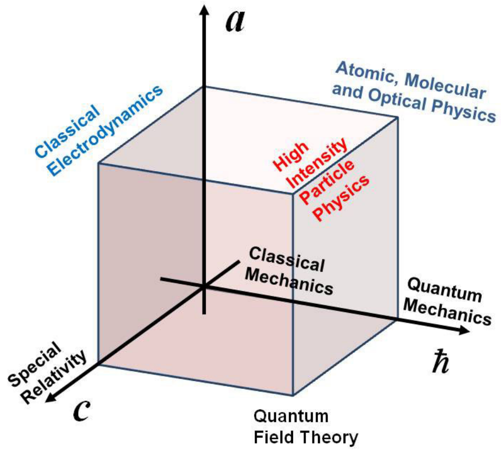
Workshop on
"Nonlinear QED Phenomena
with Ultra-Intense PW-class Lasers"

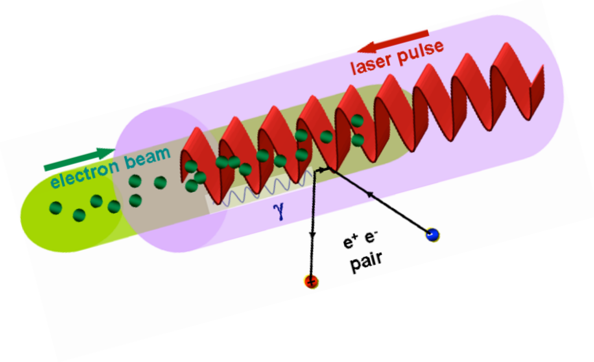
- Various astrophysical phenomena

Unanswered Questions of High Intensity Particle Physics

Theory

-Beyond the plane wave approximation
-Finite size effects
-Beyond the external field approximation
-Electromagnetic Cascades and Avalanches
    - Ultimate limit for attainable laser intensity
-Physics beyond the Standard Model



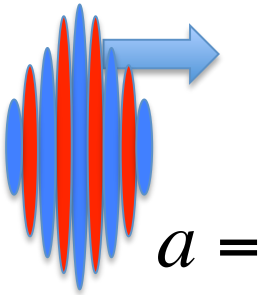


Experiment

-Uncharted region in the parameter space of the Standard Model
-Electromagnetic Cascades and Avalanches
-Test bed for future detector techniques
-Test bed for interactions at future colliders

Parameters of High Intensity Particle Physics

Classical nonlinearity parameter



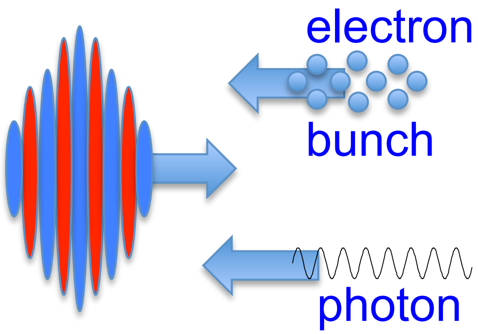
$$a = \frac{eE}{m\omega c}$$ Electron energy gain over laser wavelength in units of *mc*²

$$a = 1 \Rightarrow$$ Relativistic regime of interaction $\lambda = 1\ \mu m$

Critical QED field can create an electron-positron pair at Compton $\lambda_C = 3.86 \times 10^{-11}$ cm length,

$$E_S = \frac{m_e^2 c^3}{e\hbar} = 1.32 \times 10^{16}\ \text{V/cm} \Rightarrow a_S = \frac{\hbar\omega}{mc^2} = 4.1 \times 10^5$$

Quantum Effects



$$\chi_e = \frac{e\hbar\sqrt{\left(F_{\mu\nu}p^\nu\right)^2}}{m^3c^4}$$

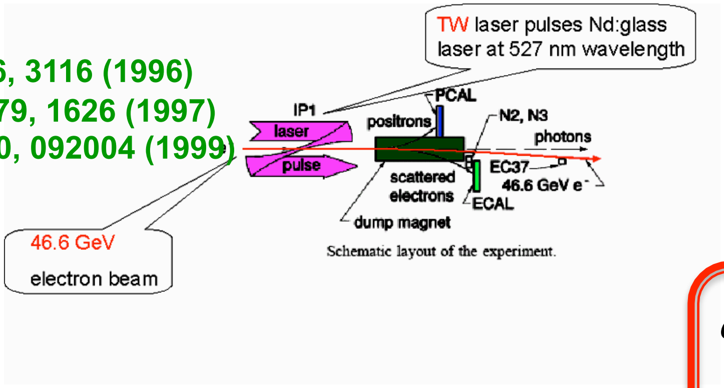
$$\chi_\gamma = \frac{e\hbar\sqrt{\left(F_{\mu\nu}k^\nu\right)^2}}{m^3c^4}$$

counter-propagating laser and electron/photon

$$\chi_e = 2\gamma\frac{E}{E_S}, \quad \chi_\gamma = 2\frac{\hbar\omega}{mc^2}\frac{E}{E_S},$$

Ultra-high intensities for Particle Physics studies

SLAC experiments **(1996)**
C. Bula et al., Phys. Rev. Lett. 76, 3116 (1996)
D. Burke et al., Phys. Rev. Lett. 79, 1626 (1997)
C. Bamber et al., Phys. Rev. D 60, 092004 (1999)

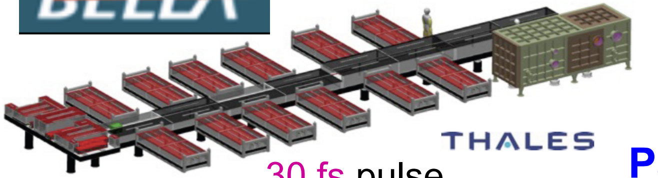


Schematic layout of the experiment.

$$a_0 = 0.6$$
$$\chi_e = 0.3$$
$$\chi_\gamma = 0.15$$

2013

BELLA



30 fs pulse
40 J Energy
10^{23} W/cm^2 Intensity

$$a_0 = 300$$
$$\chi_e = 10$$
$$\chi_\gamma = 1$$

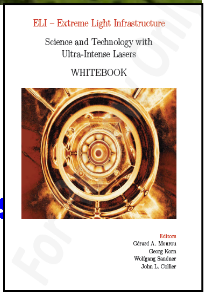
Particle Acceleration,
Future collider studies,
High Field Science

ELI > 2015

$$a_0 = 10^3$$
$$\chi_e >> 1$$
$$\chi_\gamma >> 1$$

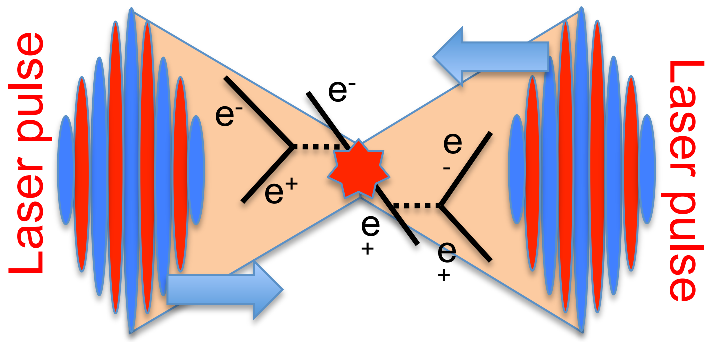
Femtosecond pulse of 10 KJ the intensity above 10^{24} W/cm^2

High Field Science,
Particle Acceleration
Laboratory Astrophys
& Hadron Therapy

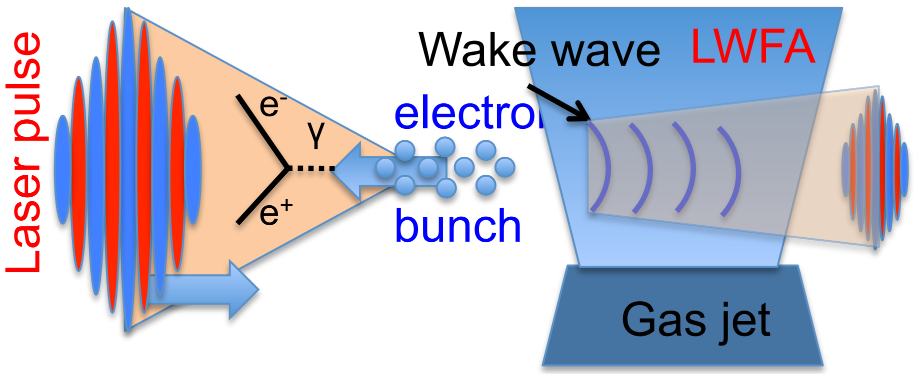

ELI – Extreme Light Infrastructure
Science and Technology with Ultra-Intense Lasers
WHITEBOOK
Editors
Gérard A. Mourou
Georg Korn
Wolfgang Sandner
John L. Collier

Principal schemes of the experiments for the study of extreme field limits.

Colliding laser pulses

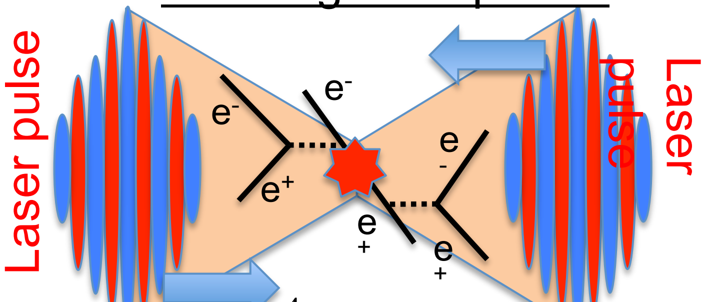


Colliding laser pulse and an electron beam



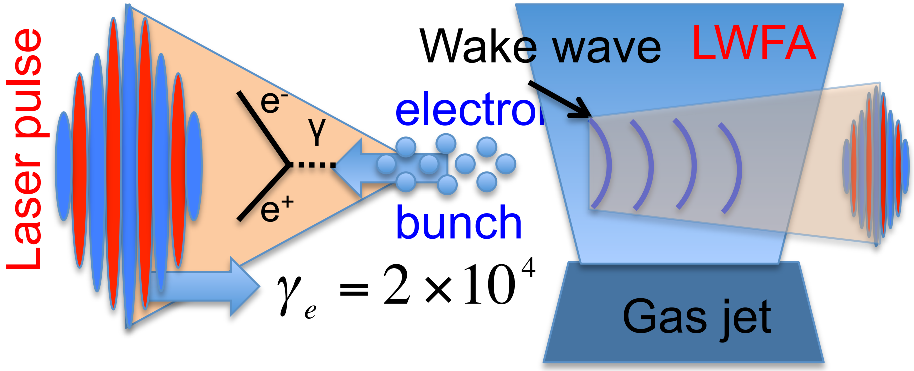
Principal schemes of the experiments for the study of extreme field limits.

Colliding laser pulses



$$\varepsilon_{rad} = \frac{4\pi r_e}{3\lambda_0} = 1.47\times10^{-8}$$

Colliding laser pulse and an electron beam



$$\gamma_e = 2\times10^4$$

1. Radiation effects become dominant $a > a_{rad} = \varepsilon_{rad}^{-1/3} \approx 400$

   $$I_{rad} = 3.5\times10^{23}\ \mathrm{W/cm^2}$$

2. QED effects become dominant

   $$a > a_Q = (2\alpha/3)^2\varepsilon_{rad}^{-1} \approx 1.6\times10^3$$

   $$I_Q = 5.5\times10^{24}\ \mathrm{W/cm^2}$$

3. Schwinger limit

   $$a > a_S = (2\alpha/3)\varepsilon_{rad}^{-1} \approx 3\times10^5$$

   $$I_S = 2.3\times10^{29}\ \mathrm{W/cm^2}$$

1. Radiation effects become dominant

   $$a > a_{rad} = (\omega\tau_{laser}\gamma_e\varepsilon_{rad})^{-1/2} \approx 10$$

   $$I_{rad} = 2\times10^{20}\ \mathrm{W/cm^2}$$

2. QED effects become dominant

   $$a > a_Q = (2\alpha/3)\gamma_e^{-1}\varepsilon_{rad}^{-1} \approx 20$$

   $$I_Q = 10^{21}\ \mathrm{W/cm^2}$$

3. QED cascade

   $$I_C = 10^{23}\ \mathrm{W/cm^2}$$

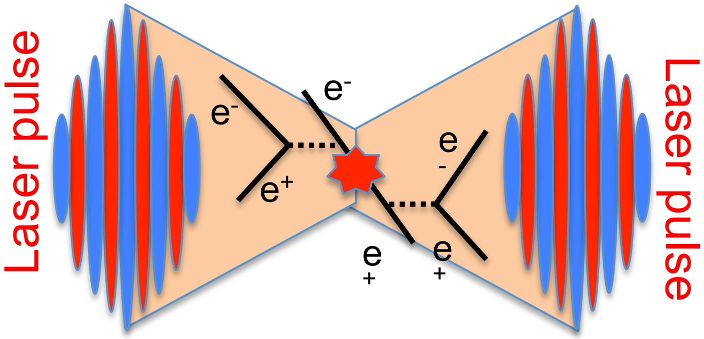
Probing nonlinear vacuum

Electron-positron pair production from vacuum by the Schwinger process

Constant field

F. Sauter (1931)
W.Heisenberg, H.Euler (1936)
J. Schwinger (1951)

Electromagnetic “avalanche”



Time-varying electric field

E.Brezin, C.Itzykson (1970)
V. S. Popov (1971)
N. B. Narozhny and A. I. Nikishov (1974)
V.I.Ritus (1979)
A. Ringwald (2001)

Focused laser pulse
Colliding laser pulses

N. B. Narozhny, S. S. Bulanov, V .D. Mur, and V. S. Popov, Phys. Lett. A 330, 1 (2004)
S. S. Bulanov, A. M. Fedotov, and F. Pegoraro, Phys. Rev E 71, 016404 (2005)
S. S. Bulanov, N. B. Narozhny, V .D. Mur, and V. S. Popov, JETP, 102, 9 (2006)

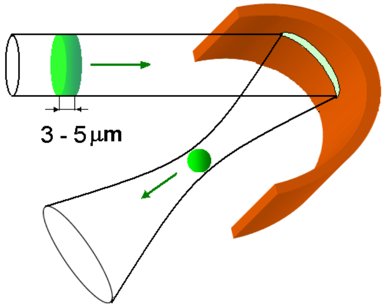
Optimal quantum control of pair production by laser pulse temporal shaping

A. Di Piazza et al., Phys. Rev. Lett. 103, 170403 (2009)
R. Schutzhold et al., Phys. Rev. Lett. 101, 130404 (2009)
G. V. Dunne et al., Phys. Rev. D 80, 111301(R) (2009)
A. Di Piazza et al., Phys. Rev. Lett. 103, 170403 (2009)
C. K. Dumlu, G. V. Dunne, Phys. Rev. Lett. 104, 250402 (2010)

Multiple colliding laser pulses
Optimally Focused Laser Pulses

S. S. Bulanov, N. B. Narozhny, V .D. Mur, J. Nees, and V. S. Popov., Phys. Rev. Lett. 104, 220404 (2010)
A. Gonoskov, et al., Phys. Rev. Lett. 111, 060404 (2013)

Model of the focused pulse electromagnetic field



$$\mathbf{E}^e = iE_0 e^{-i\varphi}\left\{F_1(\mathbf{e}_x \pm i\mathbf{e}_y) - F_2 e^{\pm 2i\phi}(\mathbf{e}_x \mp i\mathbf{e}_y)\right\}$$

$$\mathbf{H}^e = \pm E_0 e^{-i\varphi}\left\{\left(1 - i\Delta^2\frac{\partial}{\partial\chi}\right)\left[F_1(\mathbf{e}_x \pm i\mathbf{e}_y) + F_2 e^{\pm 2i\phi}(\mathbf{e}_x \mp i\mathbf{e}_y)\right] + 2i\Delta e^{\pm i\phi}\frac{\partial F_1}{\partial\xi}\mathbf{e}_z\right\}.$$

$$\varphi = \omega(t - z), \quad \xi = \rho/R, \quad \chi = z/L,$$

$$\rho = \sqrt{x^2 + y^2}, \quad \cos\phi = \frac{x}{\rho}, \quad \sin\phi = \frac{y}{\rho},$$

$$\Delta \equiv 1/\omega R, \quad L \equiv R/\Delta .$$

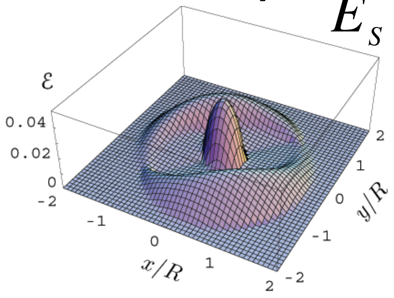
R – focal spot radius, L – diffraction length. If $R \sim \lambda$ then $\Delta \sim 10^{-1}$ and $\Delta \ll 1$

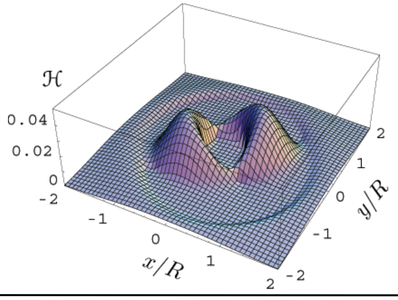
N. B. Narozhny,
M. V. Fofanov,
JETP **90** (2000) 753

Schwinger pair production in EM field of a focused pulse

$$n_{e^+e^-} = \frac{e^2 E_S^2}{4\pi\hbar^2 c}\,\varepsilon\eta\coth\left[\frac{\pi\eta}{\varepsilon}\right]\exp\left[-\frac{\pi}{\varepsilon}\right]$$

$$\varepsilon = \frac{1}{E_S}\sqrt{(F^2+G^2)^{1/2}+F}, \quad \eta = \frac{1}{E_S}\sqrt{(F^2+G^2)^{1/2}-F} \qquad F = \left(\vec{E}^2-\vec{H}^2\right)/2, \quad G = \vec{E}\cdot\vec{H}$$





$$N_{e^+e^-} = \int_V dV \int_0^{\tau} n_{e^+e^-}\,dt \approx \frac{\lambda^4}{4\pi\lambda_C^4}\,\bar{\varepsilon}\bar{\eta}\coth\left[\frac{\pi\bar{\eta}}{\bar{\varepsilon}}\right]\exp\left(-\frac{\pi}{\bar{\varepsilon}}\right)$$

The number of electron-positron pairs produced in the focus of a single pulse or two colliding pulses (**S. S. Bulanov et al., JETP, 102, 9 (2006)**)

I, W/cm^2	E_0/E_s	N_e , single pulse	N_e , two pulses
2.5x10^{26}	4x10^{-2}	-	14
5x10^{26}	5.7x10^{-2}	-	2.6x10^{7}
5x10^{27}	0.18	25	
1x10^{28}	0.25	3x10^{7}	

The backreaction
Should be taken
Into account

Backreaction?

Strong Electromagnetic wave in plasma

$$\vec{A}_\perp = A_0\left[\vec{e}_y \sin(\omega t - kx) - g\vec{e}_z \cos(\omega t - kx)\right]$$

$$g = \pm 1$$

$$\omega^2 = k^2c^2 + \sum_\alpha \frac{\omega_{p\alpha}^2}{\left[1+\left(Z_\alpha a A_0/m_\alpha c^2\right)\right]^{1/2}}$$

$$\omega^2 = k^2c^2 + \Omega^2$$

$$\omega_{p\alpha} = \left(4\pi n_\alpha e^2/m_\alpha\right)^{1/2}$$

$$\boxed{F = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) = \frac{1}{2}\left(\frac{\Omega}{\omega}\right)^2 E^2}$$

Lab frame

Lorentz transformation to the reference frame moving with the group velocity along the direction of the wave propagation

$$V = v_g \qquad v_g = \frac{c^2}{v_{ph}} = \frac{kc^2}{\omega}$$

$$E' = \frac{\Omega}{c} A_0\left(\vec{e}_y \cos\Omega t' + g\vec{e}_z \sin\Omega t'\right)$$

$$\omega' = \Omega \qquad k' = 0$$

Damping of electromagnetic waves due to electron-positron pair production

$$\frac{\partial f_\alpha}{\partial t} + e_\alpha \vec{E}\,\frac{\partial f_\alpha}{\partial \vec{p}} = q_\alpha(\vec{E},\vec{p})$$

The relativistic kinetic equation
in the presence of spatially
homogeneous electric field

$$q_\alpha(\vec{E},\vec{p}) = 2e^2\vec{E}^2(t)\,Exp\left[-\frac{\pi m^2}{\left|e\vec{E}(t)\right|}\right]\delta\left(\vec{p}\right)$$

$$\int q_\alpha \frac{d^3p}{(2\pi)^3} = \frac{\left|e\vec{E}(t)\right|^2}{4\pi^3}\,Exp\left[-\frac{\pi m^2}{\left|e\vec{E}(t)\right|}\right]$$

$$\frac{d\vec{E}}{dt} = -4\pi\,\vec{j}_{tot} = -4\pi\left(\vec{j}_{cond} + \vec{j}_{pol}\right)$$

$$\vec{j}_{cond} = e\sum_{\alpha=+,-}\int f_\alpha(\vec{p},t)\frac{\vec{p}}{\sqrt{m^2+\vec{p}^2}}\frac{d^3p}{(2\pi)^3}$$

$$\vec{j}_{pol} = \frac{\vec{E}}{\left|\vec{E}\right|^2}\sum_{\alpha=+,-}\int q_\alpha(\vec{p},t)\sqrt{m^2+\vec{p}^2}\,\frac{d^3p}{(2\pi)^3}$$

S. S. Bulanov, A. M. Fedotov, F. Pegoraro, Phys Rev E **71**, 016404 (2005)

Damping of electromagnetic waves due to electron-positron pair production

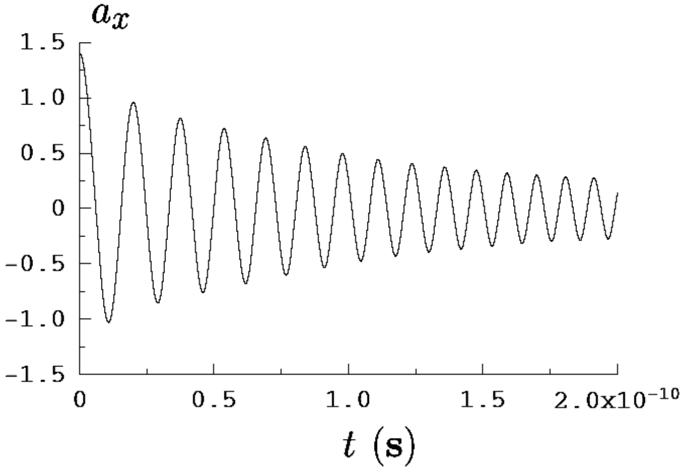
$$\kappa = 8\pi e^2 m^4$$

$$\frac{d\vec{a}(t)}{dt} = -m\vec{e}(t)$$

$$m\frac{d\vec{e}(t)}{dt} = \omega_p^2 \frac{\vec{a}(t)}{\sqrt{1+\tilde{p}_{\|,0}^2+\vec{a}^2(t)}} + \frac{\kappa}{m}\int_0^t \frac{\vec{a}(t)-\vec{a}(t')}{\sqrt{1+\left(\vec{a}(t)-\vec{a}(t')\right)^2}} \frac{\left|\vec{e}(t)\right|^2}{8\pi^3} Exp\left[-\frac{\pi}{\left|\vec{e}(t)\right|}\right] dt' - \frac{em^3}{4\pi^3}\vec{e}(t) Exp\left[-\frac{\pi}{\left|\vec{e}(t)\right|}\right]$$

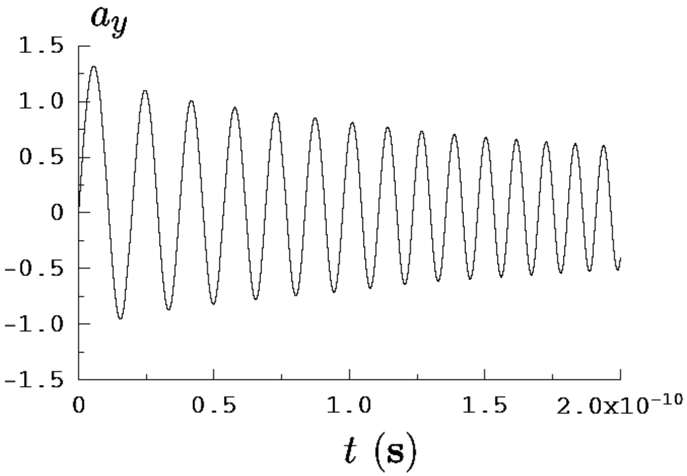
$$\vec{e} = \frac{e\vec{E}}{m^2}$$

$$\vec{a} = \frac{e\vec{A}}{m}$$

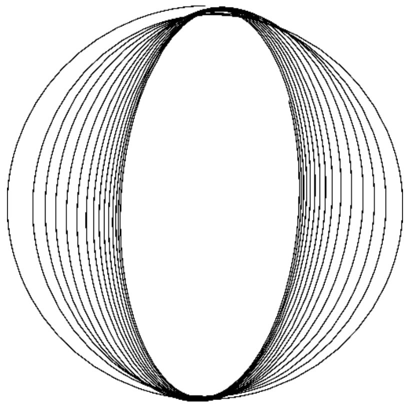


$$a(0) = 1.4\times 10^5$$

$$n_0 = 10^{19}\ cm^{-3}$$



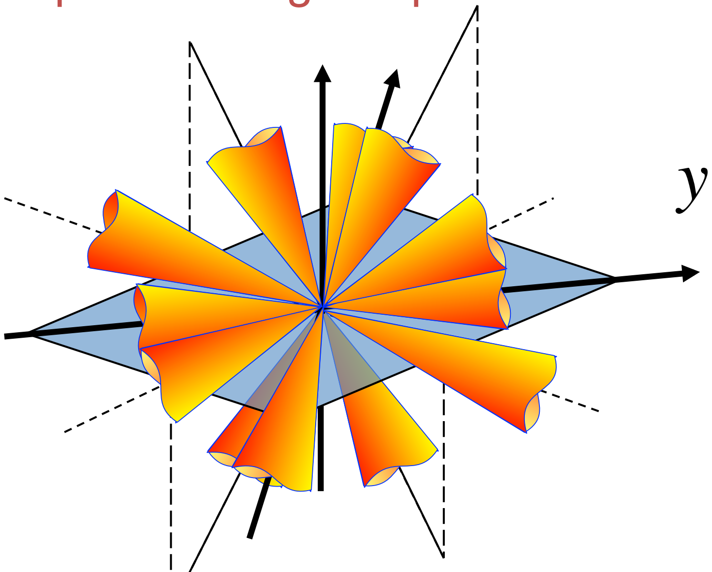
Trajectories of the projections of the electric field polarization vector →

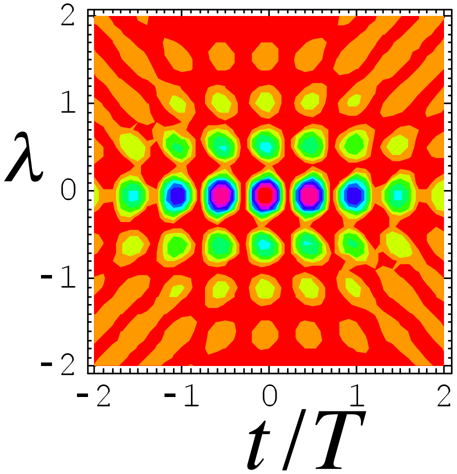


Back to focused pulse pair production

A Way to Lower the Threshold of Pair Production from Vacuum

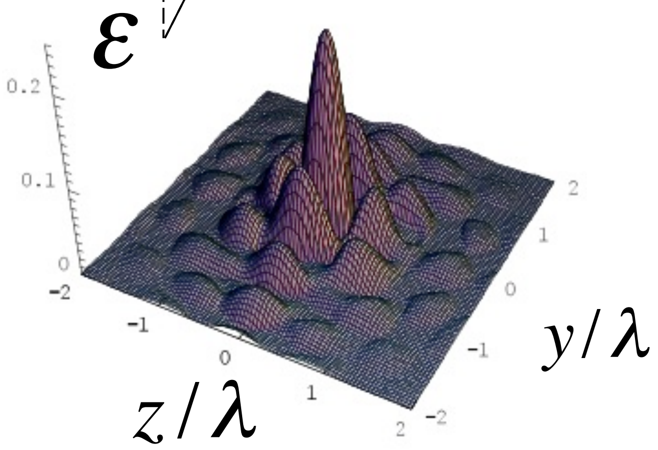
Multiple Colliding EM pulses:





$$N_{e^+e^-} = \frac{c\tau l_x l_y l_z}{64\pi^4 \lambda_C^4}\varepsilon^4 \exp\left[-\frac{\pi}{\varepsilon}\right]$$

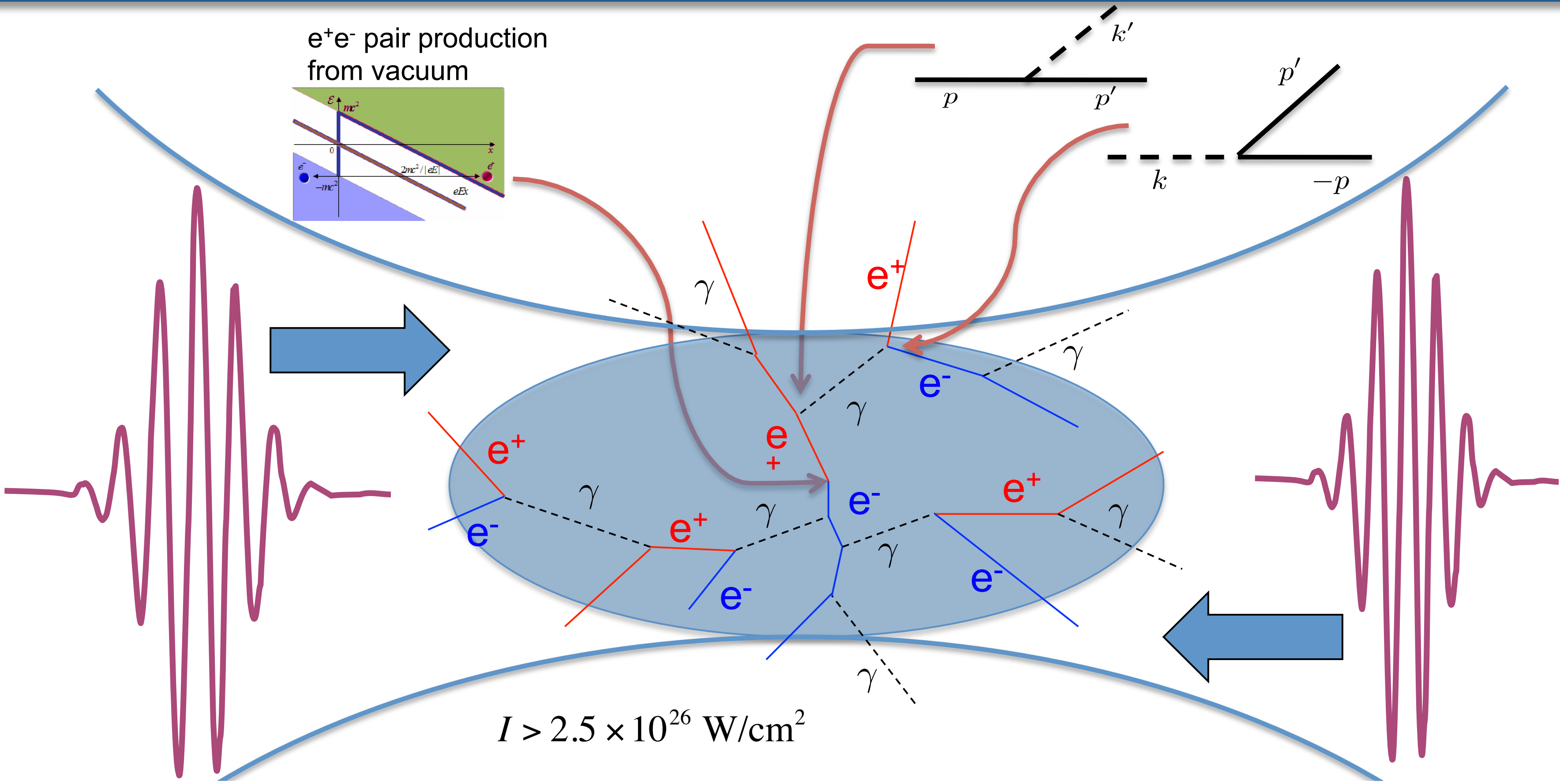
$$c\tau l_x l_y l_z \approx \frac{5^{3/2}\lambda^4}{16\pi^5}\left(\frac{a}{a_S}\right)^2$$



pulses	N_e at W=10 kJ	W_{th}(kJ) to produce one pair
2	9.0×10^{-19}	40
4	3.0×10^{-9}	20
8	4.0	10
16	1.8×10^{3}	8
24	4.2×10^{6}	5.1

S. S. Bulanov, V. D. Mur, N. B. Narozhny, J. Nees, V. S. Popov, Phys. Rev. Lett. 104, 220404 (2010)

Electromagnetic avalanche
- Ultimate laser intensity limit



e^+e^- pair production from vacuum

$I > 2.5 \times 10^{26}\ \mathrm{W/cm^2}$

- A. R. Bell and J. G. Kirk, “Possibility of Prolific Pair Production with High-Power Lasers ” Phys. Rev. Lett. 101, 200403 (2008)
- A. M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, “Limitations on the Attainable Intensity of High Power Lasers” Phys. Rev. Lett. 105, 080402 (2010)
- S. S. Bulanov, T. Zh. Esirkepov, A. G. R. Thomas, J. K. Koga,S. V. Bulanov, “On the Schwinger limit attainability with extreme power lasers” Phys. Rev. Lett., 105, 220407 (2010)
- E. N. Nerush, I. Yu. Kostyukov, A. M. Fedotov, N. B. Narozhny, N. V. Elkina, and H. Ruhl, “Laser Field Absorption in Self-Generated Electron-Positron Pair Plasma” Phys. Rev. Lett. 106, 035001 (2011)
- N. V. Elkina, A. M. Fedotov, I. Yu. Kostyukov, M. V. Legkov, N. B. Narozhny, E. N. Nerush, H. Ruhl “QED cascades induced by circularly polarized laser fields”, Phys. Rev. ST Accel. Beams 14, 054401 (2011)

Electromagnetic avalanche in Colliding EM Waves:

Circularly Polarized vs Linearly Pol ized

The area of active theoretical research

$$\chi_e \approx \left(\frac{a}{a_S^2 \varepsilon_{rad}}\right)^{1/2} \approx 1$$

$$a > \varepsilon_{rad} a_S^2 \approx 5.5 \times 10^3$$

The avalanche sta

$$I_Q \approx 5.5 \quad \text{cm}^2$$

F ajectory bending gnetic field:

$$p_\perp \sim \left(a_0^2 / 6\pi a_S\right)(\omega t)^2$$

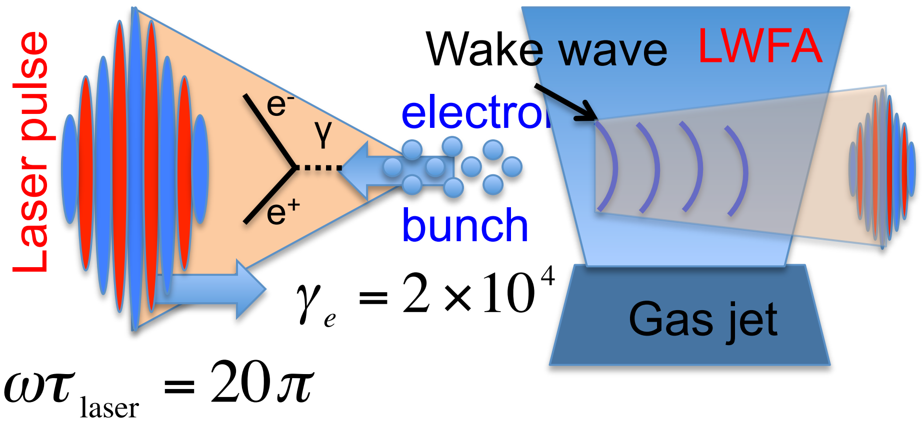
For $\omega t \approx 0.1\pi$ and $\chi_e \sim 1$

The avalanche starts at

$$I_Q \approx 4 \times 10^{27} \ \text{W/cm}^2$$

Interaction of a laser pulse with an ultra relativistic electron beam

Colliding laser pulse and an electron beam



$$\gamma_e = 2\times10^4$$

$$\omega\tau_{\text{laser}} = 20\pi$$

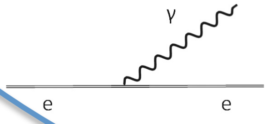
1. Radiation effects become dominant
$$a > a_{rad} = (\omega\tau_{laser}\gamma_e\varepsilon_{rad})^{-1/2} \approx 10$$
$$I_{rad} = 2\times10^{20}\ \text{W/cm}^2$$
2. QED effects become dominant
$$a > a_Q = (2\alpha/3)\gamma_e^{-1}\varepsilon_{rad}^{-1} \approx 20$$
$$I_Q = 10^{21}\ \text{W/cm}^2$$
3. QED cascade
$$I_C = 10^{23}\ \text{W/cm}^2$$

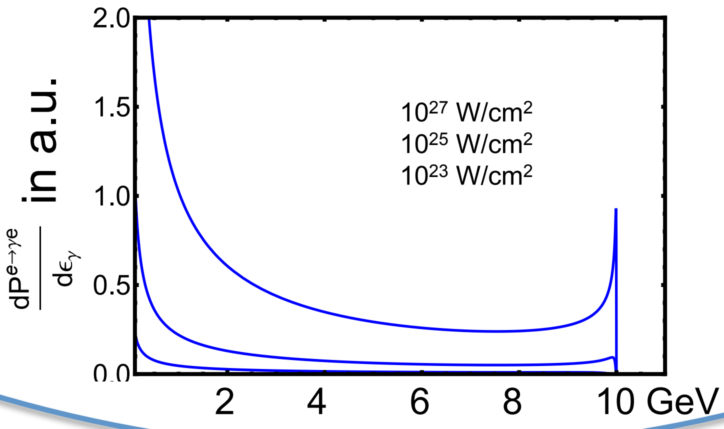
G. Breit and J. A. Wheeler (1934)
H. R. Reiss (1962)
L. S. Brown and T. W. B. Kibble (1964)
A. I. Nikishov and V. I. Ritus (1964)

C. Harvey, T. Heinzl, and A. Ilderton (2009)
A. Di Piazza, K. Z. Hatsagortsyan, and C. H. Keitel (2010)
I. V. Sokolov, J. Nees, V. P. Yanovsky, N. M. Naumova, and G. Mourou (2010)
F. Mackenroth and A. Di Piazza (2011)
A. I. Titov, H. Takabe, B. Kampfer, and H. Hosaka (2012)
K. Krajewska and J. Z. Kaminski (2012)
S. S. Bulanov, C. B. Schroeder, E. Esarey, W. P. Leemans (2013)

EM cascade in strong EM field

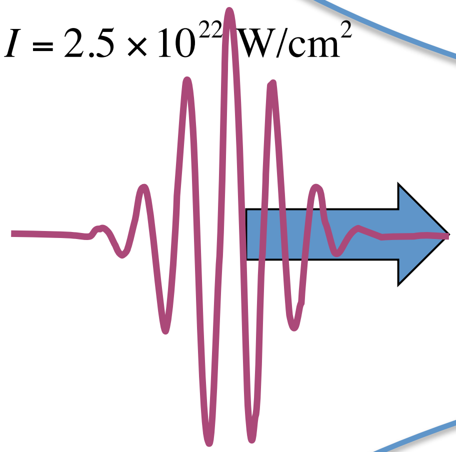
Multiphoton Compton effect

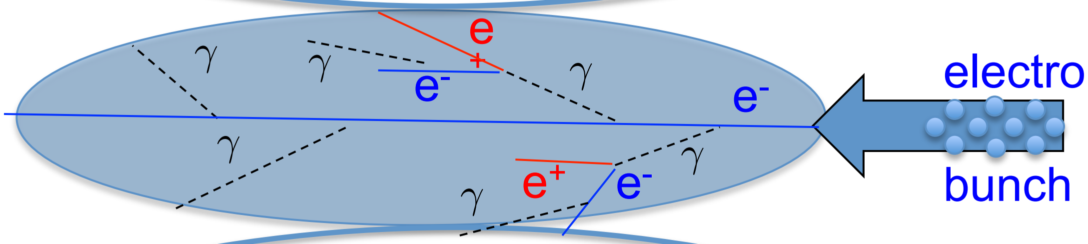




Spectrum of emitted photons

$I = 2.5 \times 10^{22}$ W/cm²

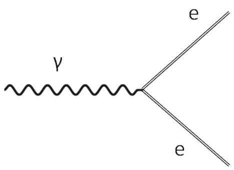


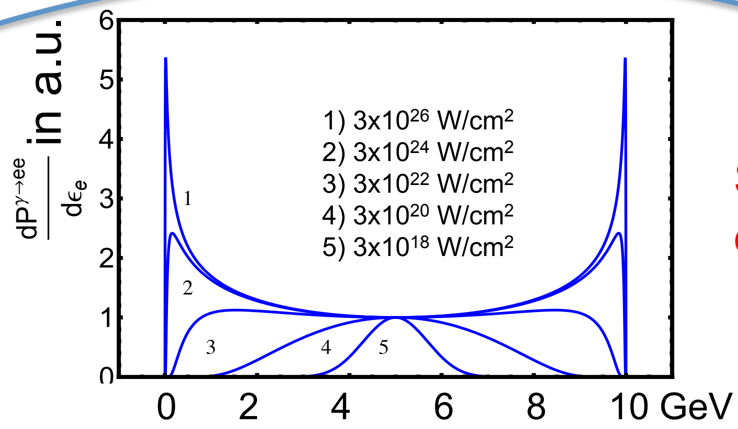


electron bunch

$\varepsilon_e^0 = 10\ \text{GeV}$

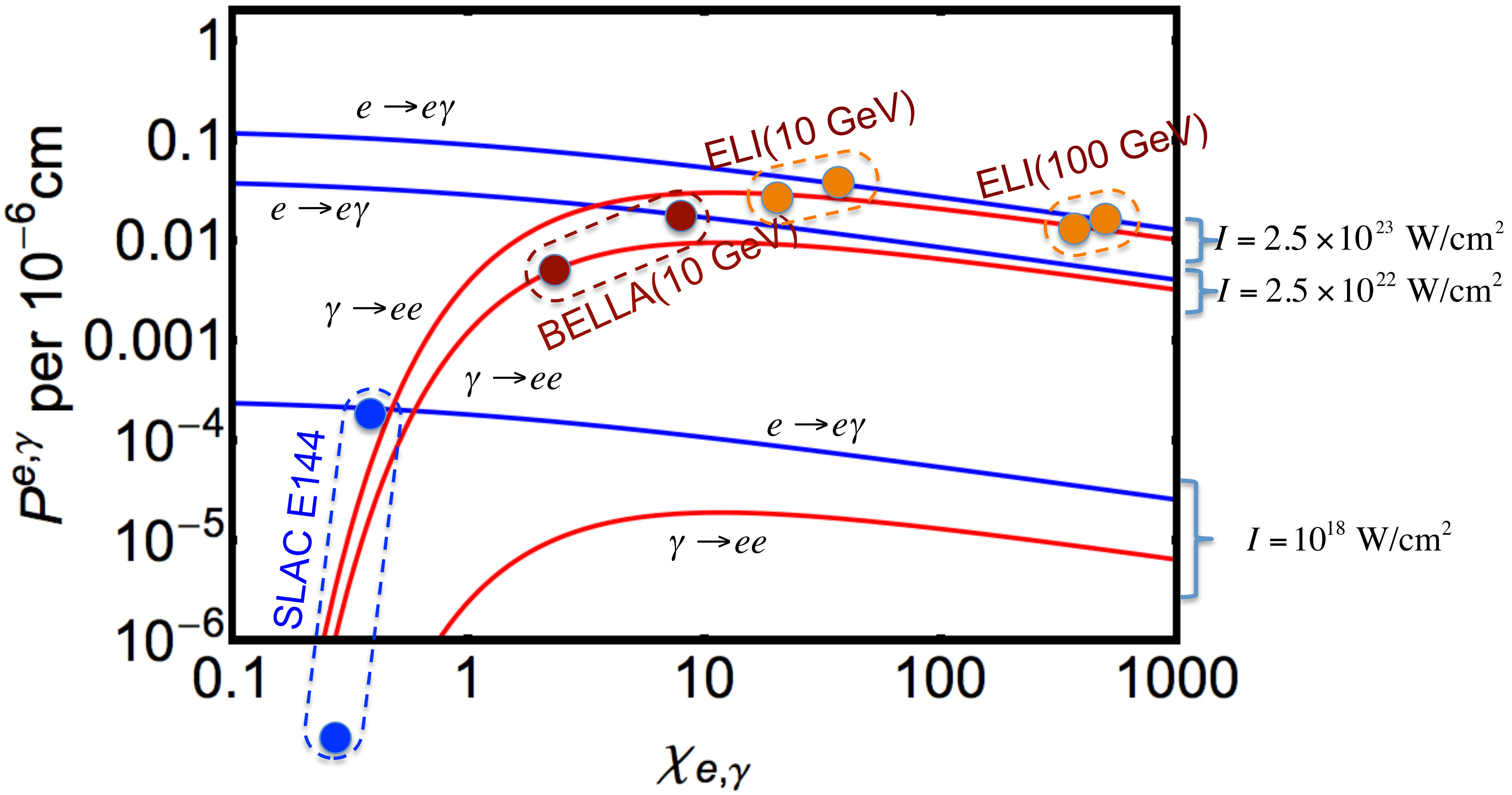
Multiphoton Breit-Wheeler effect





Spectrum of created electrons/positrons

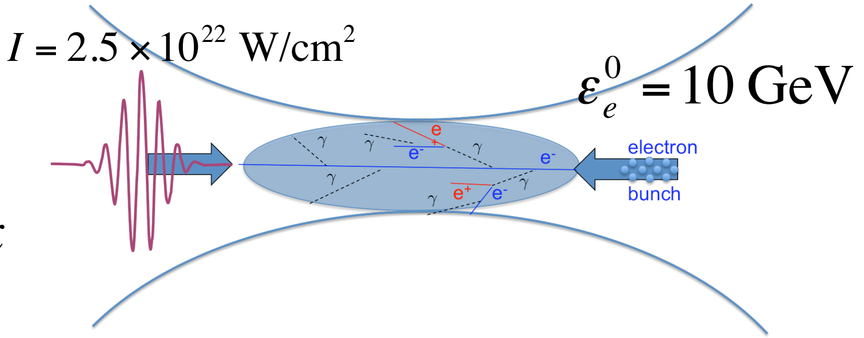
Probabilities of multiphoton Compton and Breit-Wheeler effects



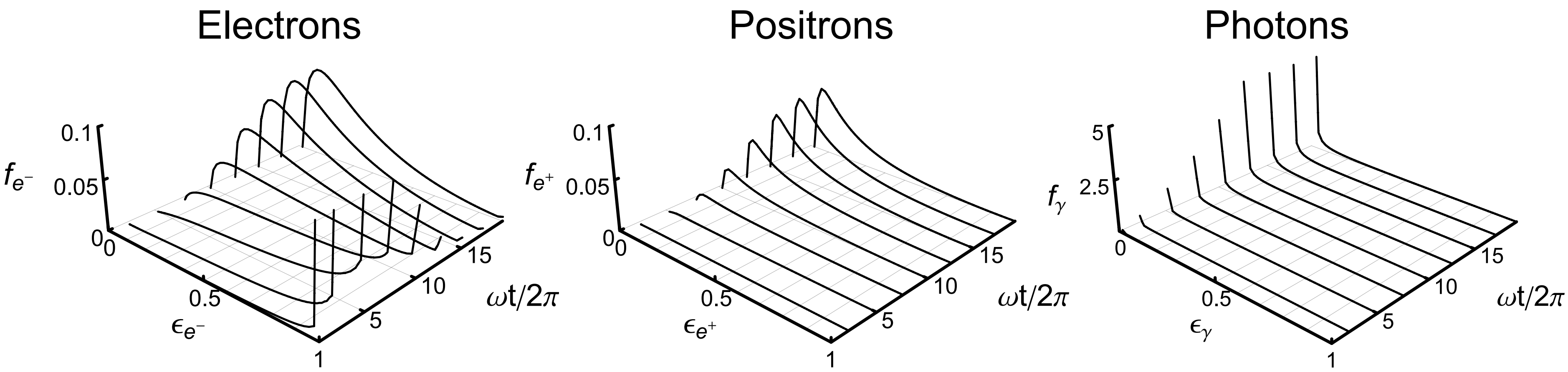
The evolution of electron, positron, and photon distributions during the Electromagnetic Cascade-type Process

$$\frac{df_{e^\pm}}{dt} = -f_{e^\pm}P^e + \int_0^1 \left[f_{e^\pm}P_1 + f_\gamma P_2\right]dx$$

$$\frac{df_\gamma}{dt} = -f_\gamma P^\gamma + \int_0^1 \left[f_{e^+} + f_{e^-}\right]P_3\,dx$$



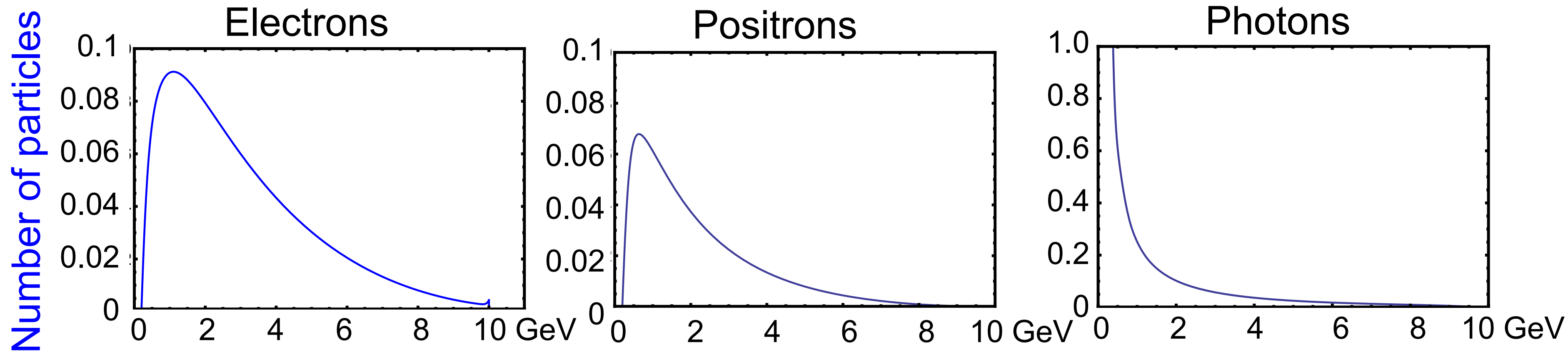
$$P_1 = dP^e/d\varepsilon'_e \qquad P_2 = dP^\gamma/d\varepsilon'_e \qquad P_3 = dP^e/d\varepsilon'_\gamma$$



Quantum effects accessible at BELLA-class PW lasers

BELLA

	e (150 MeV) +PW Laser	LWFA e (1.25 GeV) +PW Laser	LWFA e (10 GeV) +PW laser
γ_e	300	2500	2×10^4
E/E_S	3×10^{-4}	3×10^{-4}	3×10^{-4}
χ_e	0.1	0.6	5
χ_γ	0.01	0.05	1



Comparison with the solution of classical equations of motion in the presence of radiation reaction

$$m_e c \frac{du^\mu}{ds} = \frac{e}{c} F^{\mu\nu} u_\nu + \enclose{circle}{g^\mu}$$

$$\frac{dx^\mu}{ds} = u^\mu$$

Radiation friction force

Radiation friction force in LAD form

$$g^\mu = \frac{2e^2}{3c}\left[\frac{d^2u^\mu}{ds^2} - u^\mu\left(\frac{du^\nu}{ds}\right)\left(\frac{du_\nu}{ds}\right)\right]$$

Radiation friction force in L-L form

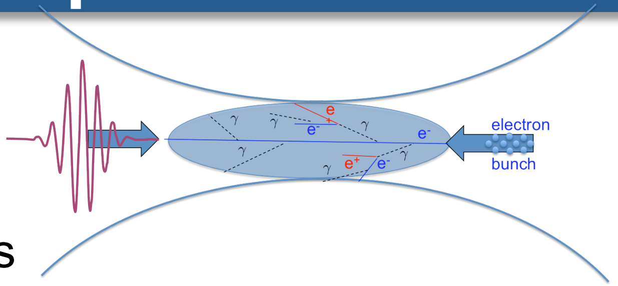
$$g^\mu = \frac{2e^3}{3m_e c^3}\left[\frac{\partial F^{\mu\nu}}{dx^\lambda} u_\nu u_\lambda - \frac{e}{m_e c^2}\left[F^{\mu\lambda}F_{\nu\lambda}u^\nu - \left(F_{\nu\lambda}u^\lambda\right)\left(F^{\nu\kappa}u_\kappa\right)u^\mu\right]\right]$$

Taking into account quantum corrections

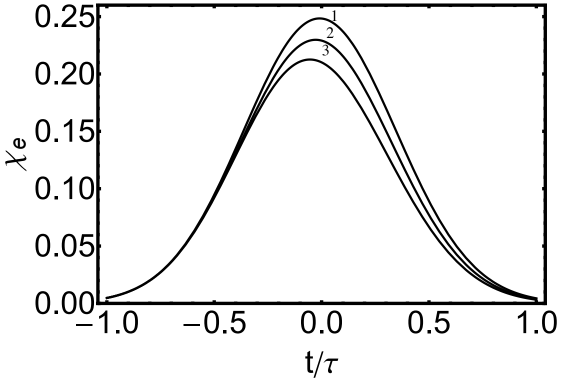
$$I = I_{cl} G(\chi_e) \quad \Rightarrow \quad m_e c \frac{du^\mu}{ds} = \frac{e}{c} F^{\mu\nu} u_\nu + g^\mu G(\chi_e)$$

$$G(\chi_e) = 1 - \frac{55\sqrt{3}}{16}\chi_e + 48\chi_e^2 + \ldots, \quad \chi_e << 1$$

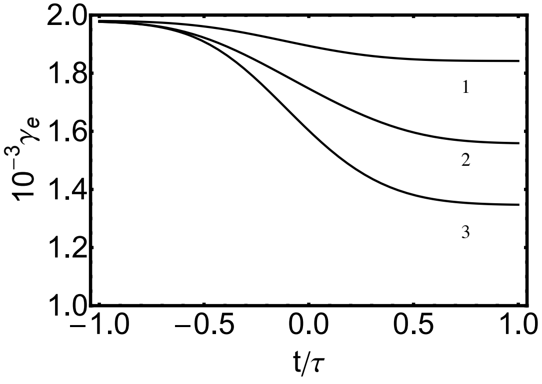
Comparison with the solution of classical equations of motion in the presence of radiation reaction



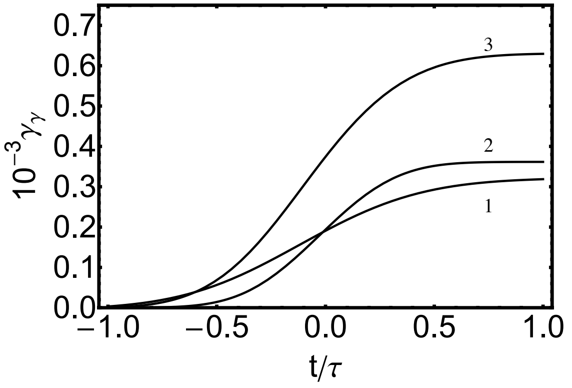
Magnitude of QED effects



Electron energy evolution



Photon energy evolution



1 GeV electron beam interaction with a 10^{21} W/cm^2 laser pulse

1. Solution of equations for electron, positron, and photon distribution functions
2. Solution of “modified” classical Landau-Lifshitz equation
3. Solution of classical Landau-Lifshitz equation

Conclusion

Principal Experimental Schemes:

- laser - laser (long term, $I \propto 10^{25} - 10^{29}\ \mathrm{W/cm^2}$)
- laser - e-beam collisions (near term, $I \propto 10^{20} - 10^{24}\ \mathrm{W/cm^2}$)

The EM avalanche in laser - laser collisions:

- Dependence on polarization?
- Ultimate limit for maximum attainable laser intensity?

New regime of interaction for PW-class laser in laser - e-beam collision scheme ($\chi_e \sim 10$):

- EM cascade
- will lead to experimental demonstration of
  - QED multiphoton processes
  - cascaded multistaged process
- will give insight into the physics of ultimate limit for maximum attainable laser intensity

Thank you!