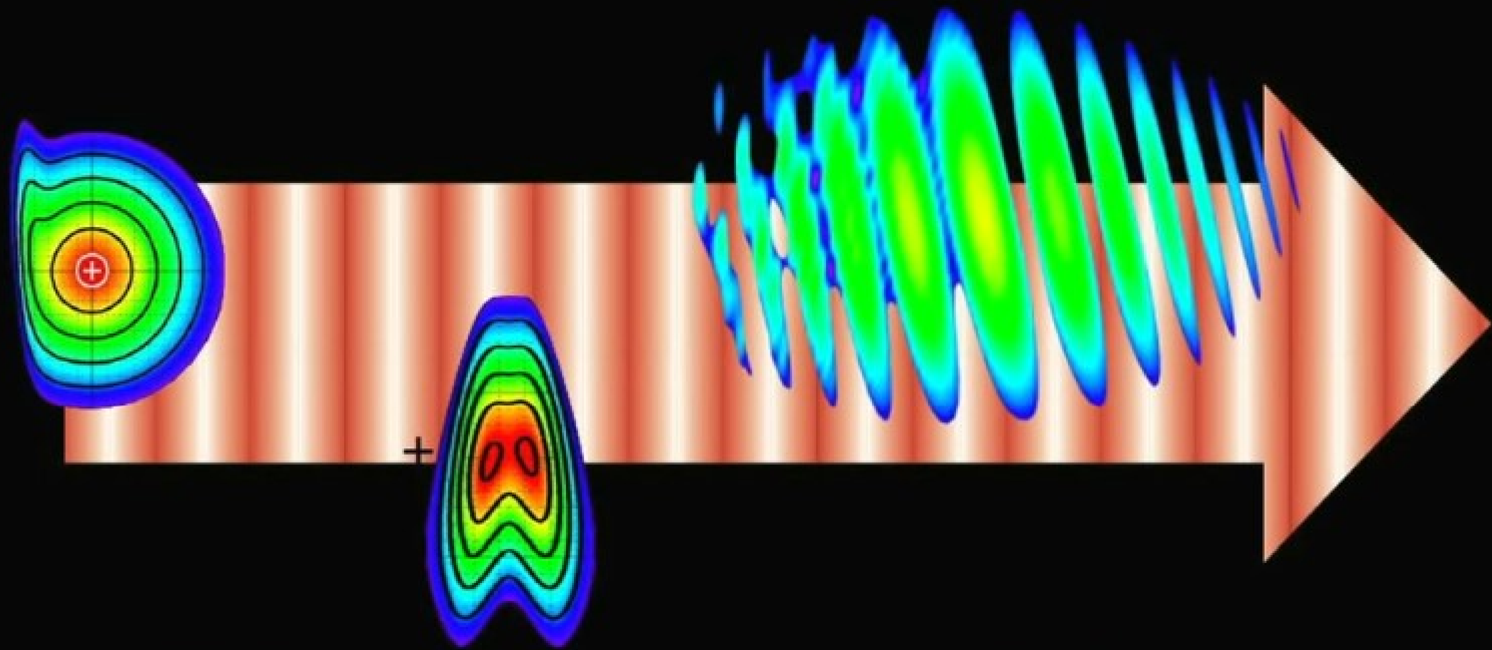
High-energy QED with Lasers



Christoph H. Keitel, Max-Planck-Institute for Nuclear Physics

involved key group members in presented projects:
A. Di Piazza, K. Z. Hatsagortsyan, C. Müller, J. Evers, Z. Harman

Outline

Introduction into quantum vacuum &
Laser-induced relativistic quantum dynamics

<u>Laser-induced Physics in the High-energy Regime:</u>

Vacuum Fluctuations & Pair Creation

Refractive QED: Laser-induced vacuum refractivity

Quantum Interference via Vacuum Fluctuations

Laser Colliders & Laser Particle Physics

Muon Production from Positronium

Applications: ultra-short pulses & medical beams

Quantum Vacuum

- In quantum field theory the vacuum state is the state in which no real particles are present (electrons, positrons, photons etc...)
  - Virtual particles are present
  - They live for a very short time and cover a very short distance ($\tau=\hbar/mc^2$ and $\lambda_c=\hbar/mc$, respectively). For electrons and positrons: $\lambda_c \approx 10^{-11}$ cm and $\tau \approx 10^{-21}$ s.

Optical laser technology ($\hbar\omega_L$=1 eV)	Energy (J)	Pulse duration (fs)	Spot radius (μm)	Intensity (W/cm^2)
State-of-art (Yanovsky et al. (2008))	10	30	1	2×10^{22}
Soon (2010) (Polaris, Astra-Gemini, Phelix, etc...)	10-100	10-100	1	10^{22}-10^{23}
Soon (2010) (PFS)	5	5	1	10^{22}-10^{23}
Vulcan 10 PW(CLF)	300	30	1	10^{23}
Near future (2020) (HiPER, ELI)	10^4	10	1	10^{25}-10^{26}

How is the vacuum affected by intense constant or oscillating fields ?

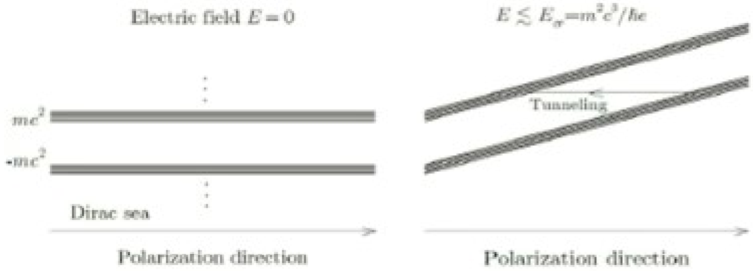
Historical remarks: tunneling e^+-e^- photoproduction

Units: cgs

- In the presence of an electric field E the vacuum is unstable (Sauter ZP 1931, Heisenberg and Euler ZP 1936, Weisskopf KDVS 1936)
- Production probability per unit time and unit volume ($E \ll E_{cr}$)

$$\frac{dP}{dV\,dt} = \frac{1}{8\pi^3}\left(\frac{E}{E_{cr}}\right)^2 \frac{c}{\lambda_c^4} e^{-\pi\frac{E_{cr}}{E}}$$

- Interpretation: tunneling



- In time oscillating electric fields the main role is played by the *adiabaticity parameter* $\gamma=1/\xi=mc\omega_L/eE_L$ (E_L=field amplitude, ω_L=field angular frequency) (Brezin and Itzykson 1970, Popov 1971)

$\gamma \ll 1$: tunneling regime

$$\frac{dP}{dV\,dt} = \frac{1}{8\pi^3}\left(\frac{E_L}{E_{cr}}\right)^2 \frac{c}{\lambda_c^4} e^{-\pi\frac{E_{cr}}{E_L}}$$

$\gamma \gg 1$: multiphoton regime

$$\frac{dP}{dV\,dt} = \frac{1}{32\pi}\left(\frac{E_L}{E_{cr}}\right)^2 \frac{c}{\lambda_c^4}(2\gamma)^{-\frac{4mc^2}{\hbar\omega_L}}$$

- Pair creation in non-uniform fields: Gies and Klingmueller PRD 2005, Dunne JPA 2008, Ruf et al. PRL 2009

Critical fields

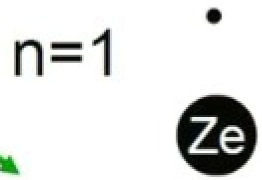
Since virtual particles live for a very short time, then very strong fields are needed to make apparent the effects of their presence

A strength scale is given by the critical fields (here α=1/137)

$$E_{cr}=\frac{m^2c^3}{\hbar e}=1.3\times10^{16}\ \mathrm{V/cm}$$

$$B_{cr}=\frac{m^2c^3}{\hbar e}=4.4\times10^{13}\ \mathrm{G}$$

$$I_{cr}=\frac{cE_{cr}^2}{8\pi}=2.3\times10^{29}\ \mathrm{W/cm^2}$$



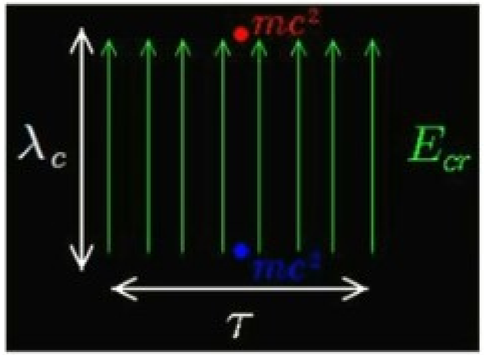
$$d=\frac{a_0}{Z}=\frac{\lambda_c}{Z\alpha}$$

$$E=\frac{Ze}{d^2}=(Z\alpha)^3E_{cr}$$

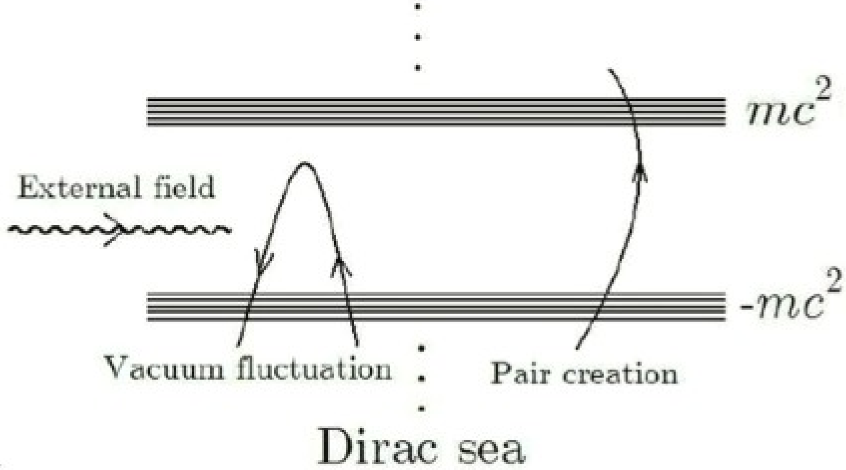
Physical meaning of the critical fields:

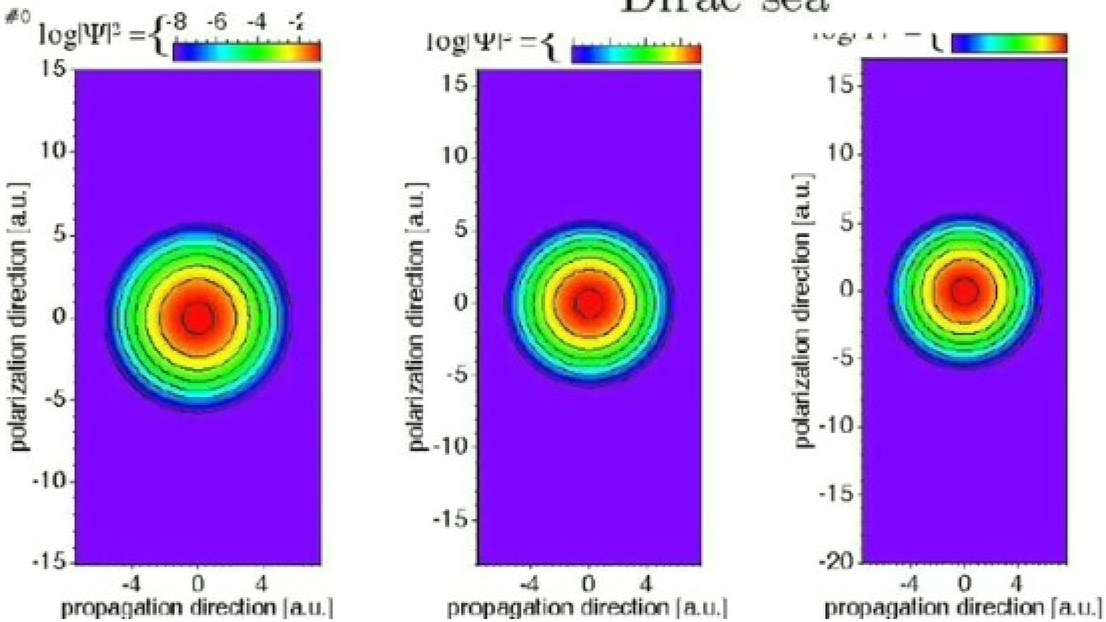
$$\frac{\hbar}{mc}\times eE_{cr}\sim mc^2$$

$$\frac{e\hbar}{mc}\times B_{cr}\sim mc^2$$



High-Energy QED: Real and Virtual Pairs





Dirac dynamics of
an electron with
negative energy in
crossed laser beams:
pairs from 10^{26} W/cm^2

Advances in laser-induced pair creation

1. Experimental pair creation of laser-induced pair creation with the aid of 45 GeV electron beam from traditional cceleration
   D L Burke et al, PRL 79, 1626 (1997)

2. Pair creation in counter propagating focussed laser pulses
   SS Bulanov et al. JETP 102, 9 (2006) & A R Bell and J G Kirk, PRL 101, 200403 (2008)

3. Dynamically assistend Schwinger Mechanism
   R. Schützhold, H. Gies, G Dunne, PRL 130404 (2008)

4. Channeling electron-positron pairs with lasers
   Erik Lötstedt, U D Jentschura & CHK, PRL 101, 203001 (2008)

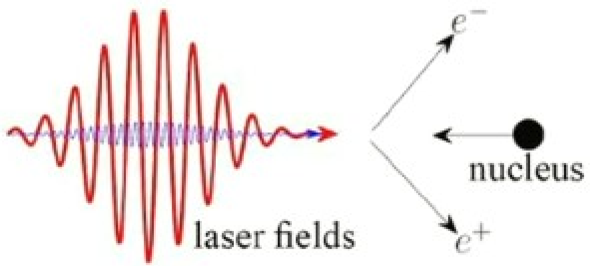
5. Magnetic field effects in laser-induced pair creation
   M. Ruf et al., Phys. Rev. Lett. 102, 080402 (2009)

6. 10^{16} cm^{-3} pair creation at Lawrence Livermore via Bethe Heitler process
   H. Chen et al., PRL 102, 105001 (2009)

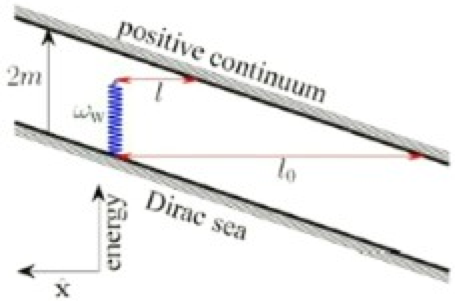
7. Nonperturbative multiphoton pair production
   G. Mocken et al, PRA 81, 022122 (2010)

- Is it possible to observe tunneling pair creation well below the Schwinger level or even with presently available laser sources ?

- Our setup: a weak, high-frequency field and a strong, low-frequency field collide head-on with a high-energy nucleus



- In the reset frame of the nucleus the photon energy of the weak field is below and close to the pair production threshold

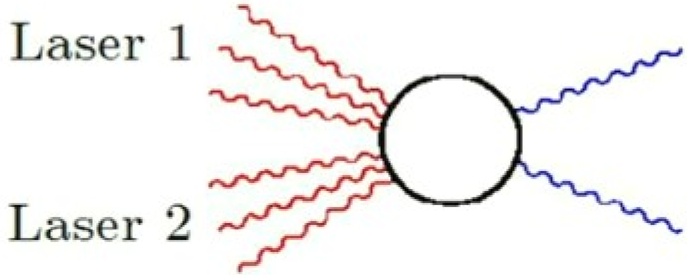


- By changing the frequency of the weak field we can control the tunneling length and enhance the production rate at will

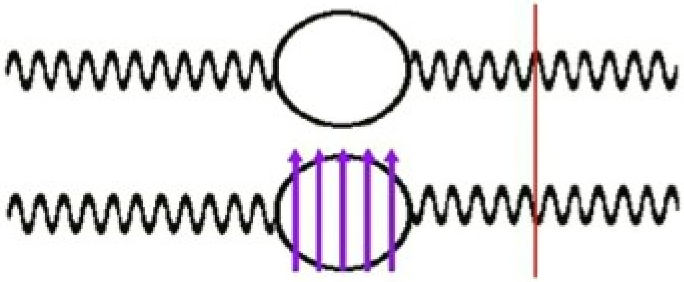
A. Di Piazza, E. Lötstedt, A. I. Milstein and C. H. Keitel, Phys. Rev. Lett. 103, 170403 (2009)

Refractive Vacuum Nonlinearities

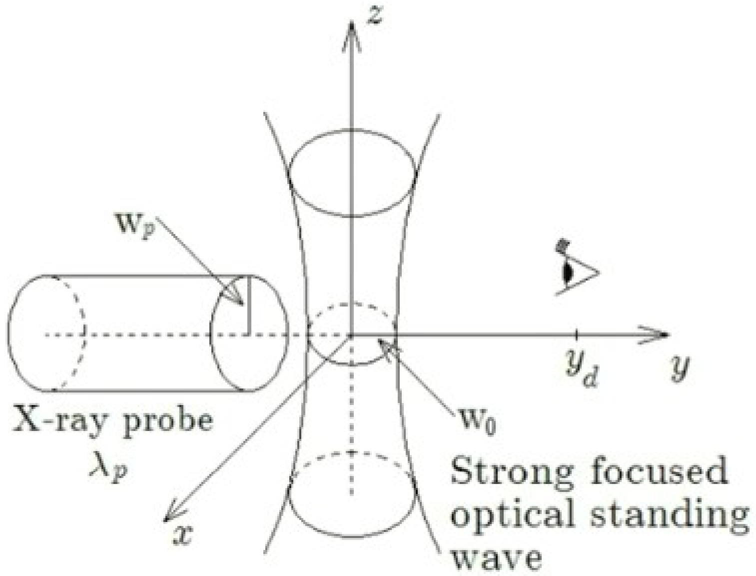
- *Harmonic generation* in vacuum in the collision of two strong laser beams



- Vacuum refractive indices with phase shifts in the presence of a strong standing wave



Vacuum index of refraction: X-rays interact with strong standing wave



For X-ray probes (λ_p=1 nm) and focused optical beams with w_0=1 μm the condition ξ_x>>1 requires y_d<< 1 cm! Diffraction effects have to be taken into account! The strong field intensity has to be large enough that the probe-strong field interaction is detectable ($I_0=10^{25}$-10^{26} W/cm^2, as we will see below)

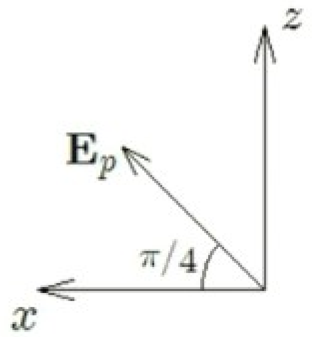
$$\mathscr{L} = \frac{1}{2}(E^2 - B^2) + \frac{2\alpha^2}{45m^4}\left[(E^2 - B^2)^2 + 7(\mathbf{E}\cdot\mathbf{B})^2\right]$$

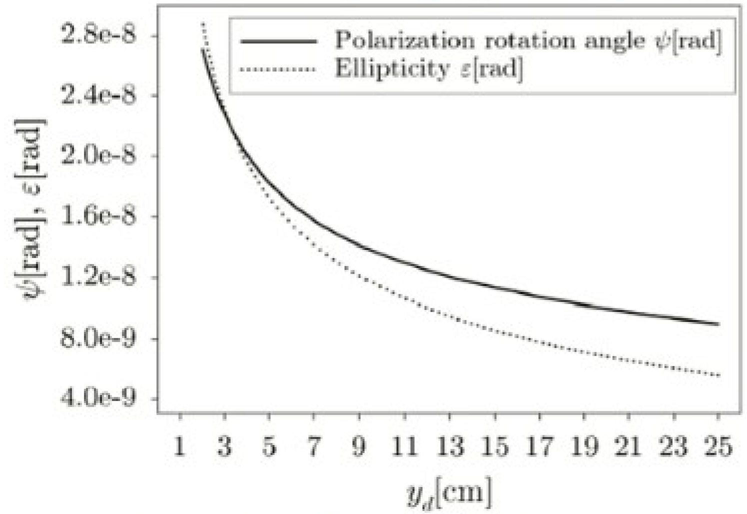
- current **J**(**r**,t) arises in wave eq. because of vacuum fluctuation effects
- **J**(**r**,t) is proportional to $E^3/(E_{cr})^2$ with $E_{cr}=m^2c^3/\hbar e=1.3\times10^{16}$ V/cm
- Generally speaking vacuum corrections are of the order of $(E/E_{cr})^2$<<1

Results with diffraction:

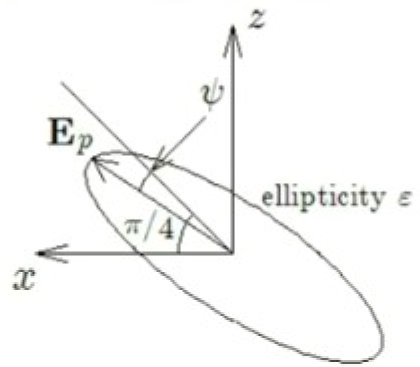
Strong beam: $I_0=10^{23}$ W/cm^2, $w_0=\lambda_0=0.745$ μm
Probe beam: $\lambda_p=0.4$ nm, $w_p=8$ μm
It results: $\xi_x=0.14/(y[cm])$, $\xi_z=16/(y[cm])$

Probe polarization before the interaction





Probe polarization after the interaction



- ψ and ε depend on the observation distance y_d
- The PVLAS expected ellipticities are $\approx 5 \times 10^{-11}$ rad
- The refractive index approach predicts $\psi=0$ and $\varepsilon \approx 4 \times 10^{-7}$ rad (diffraction effects are important!)
- Problems because of low photon statistics can be compensated for with an X-FEL as a probe and a strong field with $I_0=10^{25}$-10^{26} W/cm^2

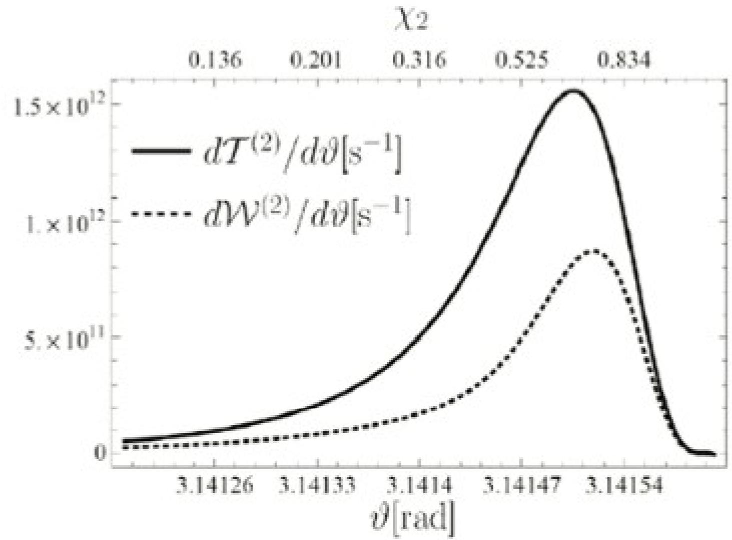
A. Di Piazza, K. Z. Hatsagortsyan and CHK, PRL 97, 083603 (2006)
See also T. Heinzl et al. Opt. Comm. 267, 318 (2006)

Numerical results I (LHC)

Table-top laser parameters (OPCPA):

$I_0=3\times10^{22}$ W/cm^2,
$w_0=\lambda_0=0.745$ μm, $\tau=5$ fs

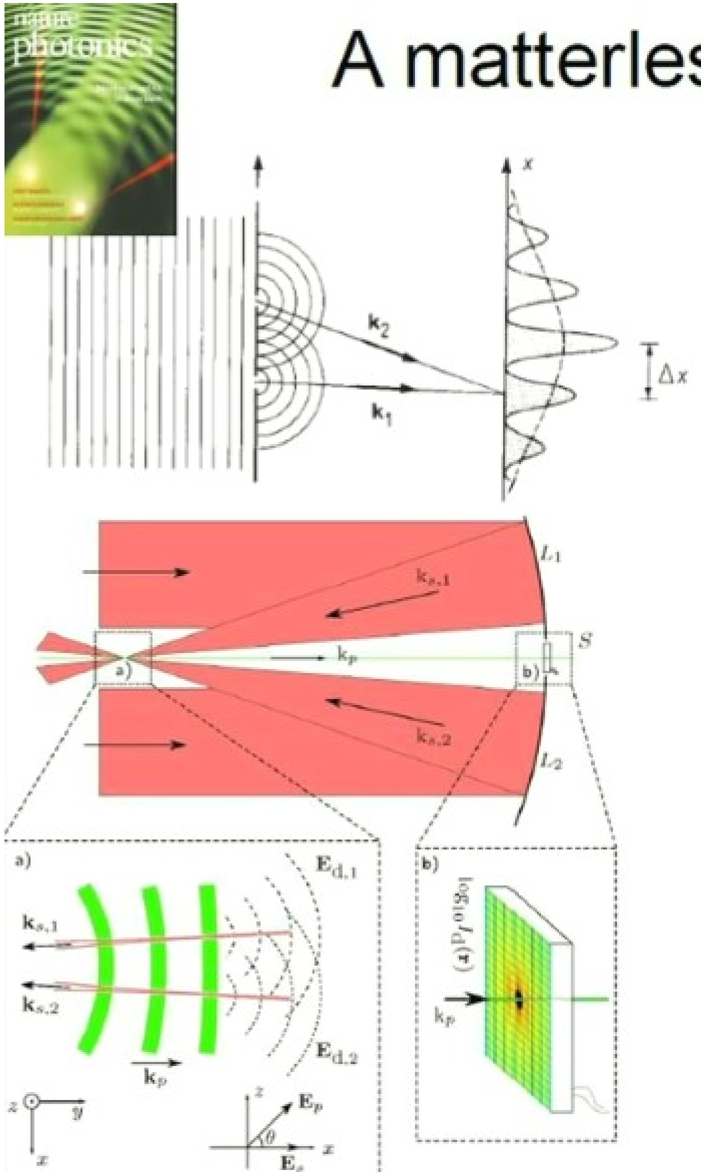
Proton beam parameters (LHC):
E=7 TeV, $N_{bunch}=11.5\times10^{10}$

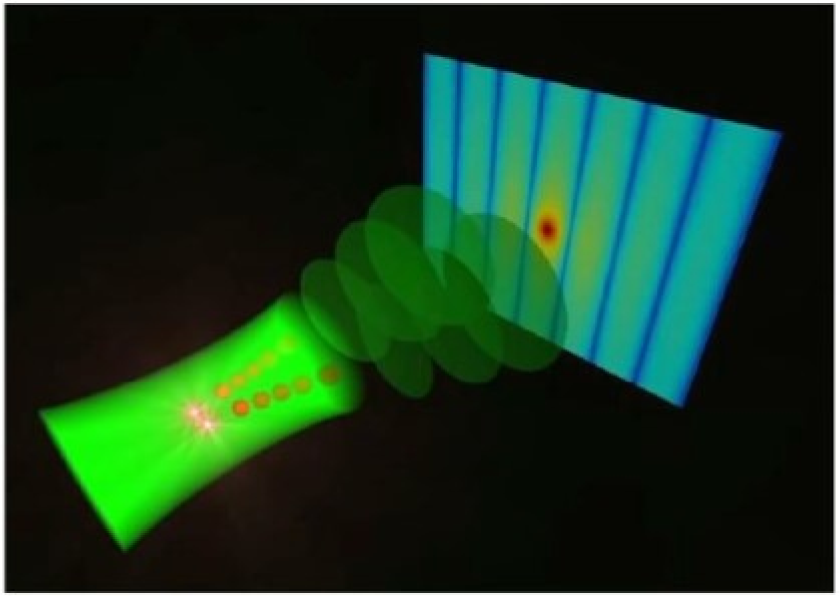


- Total number of photons in one hour via 2-photon Thomson scattering: 320
- Total number of photons in one hour via 2-photon merging: 390
- Total number of photons in one hour via both processes: 670 (destructive interference of a few percent!)
- Also the 4-photon merging could be observable: 5.4 events per hour (multiphoton vacuum effects)

Antonio Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, PRL **100**, 010403 (2008)

A matterless double slit



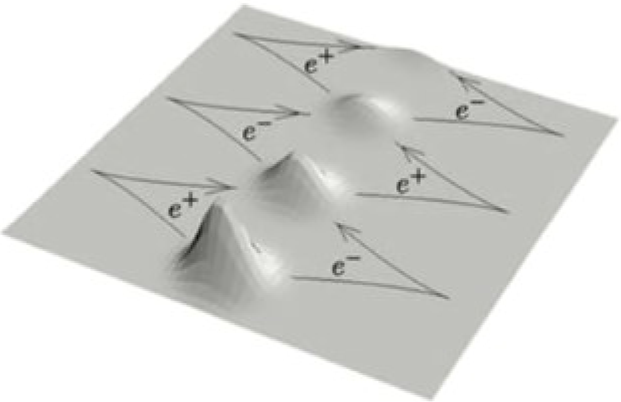


Interaction via vacuum fluctutions induces two different paths for quantum interference to occur

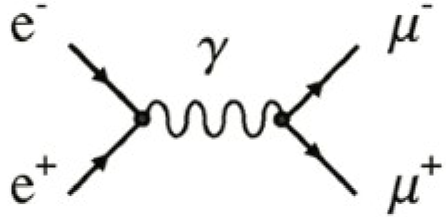
Ben King, Antonio di Piazza, Christoph H. Keitel, Nature Photonics 4, 92 (2010)

Particle Physics with Strong Lasers

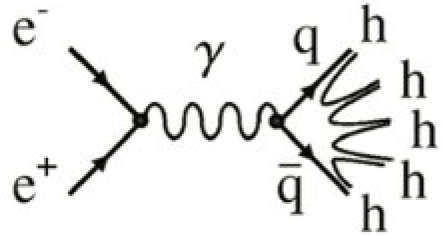
Positronium dynamics
in an intense laser field:



Particle reactions by laser-driven
e^+e^- collisions



muon production
$(m_\mu c^2 = 106$ MeV)



pion production
$(m_\pi c^2 = 140$ MeV)

energetic threshold for muon:

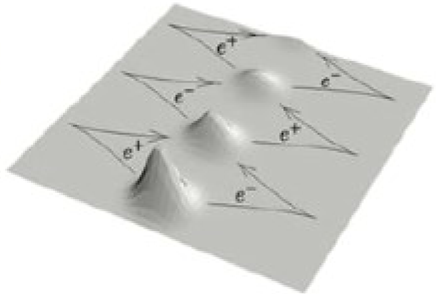
$$2eA \geq 2Mc^2$$

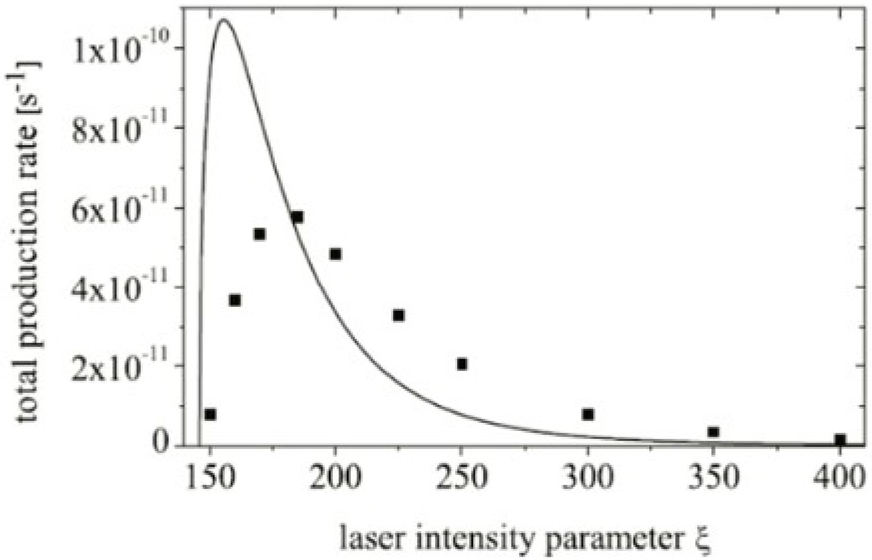
$(I \geq 5\times 10^{22}$ W/cm^2 at $\lambda = 1$ μm)

B. Henrich et al. PRL 93, 013601 (2004) & K. Z Hatsagortsyan et al., EPL (2006),
Obserservation of GeV electrons: W. Leemans et al., Nat. Phys. 2, 696 (2006)

Total production rate

(linear laser polarization)





Simple-man's model:

Total rate can be explained via the free cross-section ♦ and the e^+e^- wave-packet spreading

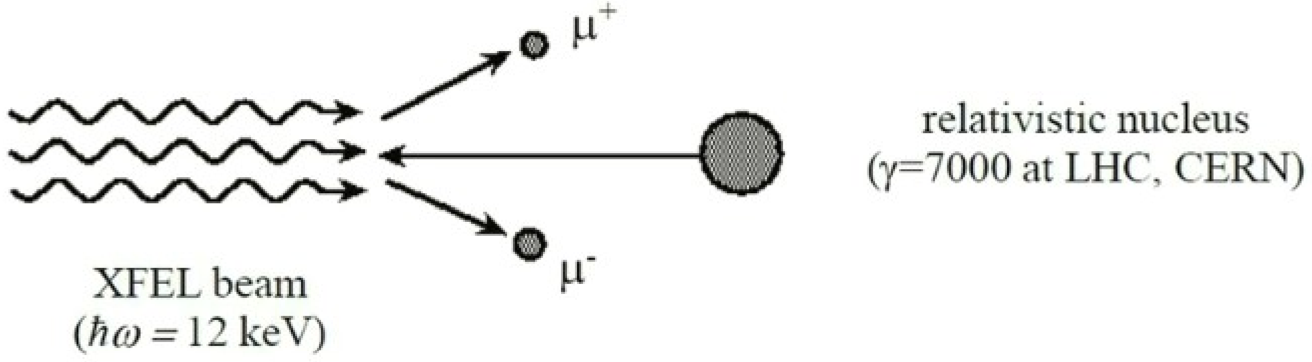
$$R_{\mathrm{Ps}} \sim \frac{\sigma}{\xi(\alpha\xi\lambda)^3}$$

Process observable at high Ps density (10^{18} cm^{-3}) and laser rep rate (1 Hz)

Solid line: analytical approximation
Black squares: numerical results

Müller, Hatsagortsyan & Keitel, Phys. Lett. B 659, 209 (2008)

Muon pair creation in XFEL-nucleus collisions



- Relativistic Doppler shift leads to

  $\hbar\omega' = (1+\beta)\gamma\hbar\omega = 168$ MeV

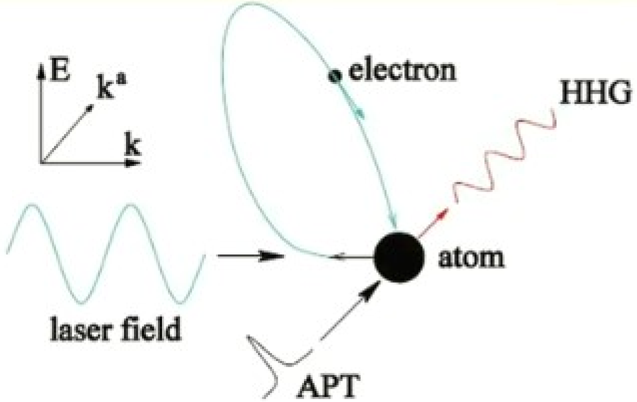
  in nuclear rest frame

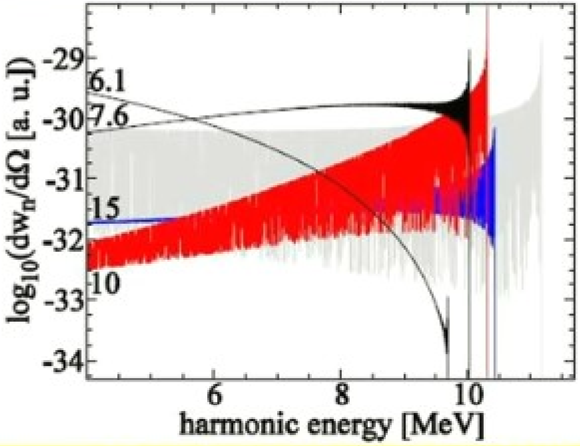
- Energy threshold $\Delta\varepsilon = 2Mc^2 = 211$ MeV for $\mu^+\mu^-$ creation can be overcome by absorption of two x-ray photons

For ion beam with 10^{11} particles and XFEL pulse with 100 fs, 40 kHz and 10^{22} W/ cm ^{2}
=> 1 muon pair per second envisaged

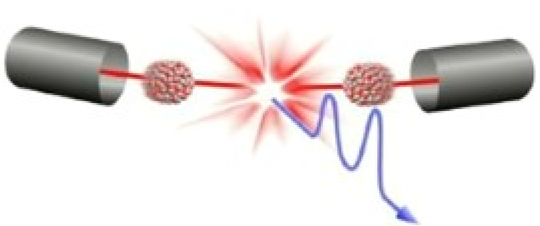
C. Müller, Deneke & Keitel, PRL 101, 060402 (2008)

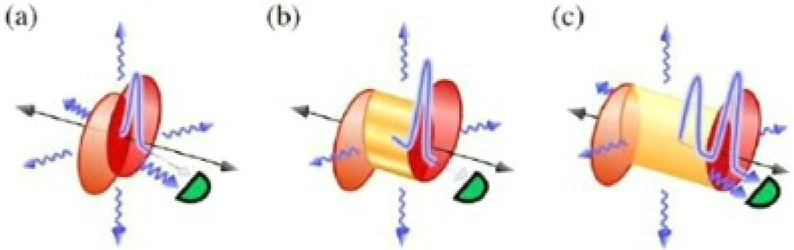
MeV harmonics & zeptosecond γ-ray pulses & beyond





Zeptosecond pulses feasible but yields small: M. Klaiber et al, Opt Lett (2008) & arXiv:0707.2900
alternatives via overdense plasmas (S. Gordienko et al., PRL 93, 115002(2004))
Thomson backscattering (P. Lan et al, PRE 066501(2005))
and yoctosecond photon pulses via quark-gluon plasmas (with double-peak for pump-probe)





A. Ipp, C. H. Keitel, J. Evers, Phys. Rev. Lett. 103, 152301 (2009)

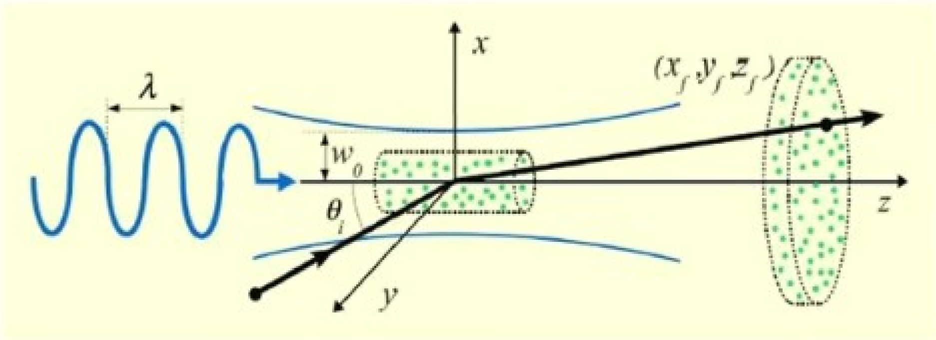
Laser-Ion Acceleration for Cancer treatment

Conventional acceleration of ions: synchrotron

Example: scheme of the Heidelberg Ion-Beam Therapy Centre

Dimensions: half of a soccer field; 3 floors; 2 m thick concrete walls
Construction costs: approx. 150,000,000 EUR

Applying laser acceleration may decrease the cost and physical space required



Direct high-power acceleration:

- laser powers: 100 TW - 10 PW
- ultra-strong fields: tight focusing (sub-wavelength waist radii)
- linearly and radially polarized fields
- relativistic Monte Carlo simulations with 5000 ions shot into the focus

Kinetic energy and its spread after interaction with linearly polarized lasers:

	Power [PW]	$\bar{x}_f$ [λ]	$\bar{K}_l$ [MeV/nucleon]	$\Delta K_l/\bar{K}_l$ [%]
p	0.1	89.6 ± 0.6	3.77 ± 0.05	1.3
	1	283.0 ± 1.7	37.39 ± 0.45	1.2
	10	750.6 ± 41.1	416.5 ± 24.7	5.9
C^{6+}	0.1	44.9 ± 0.3	0.94 ± 0.01	1.2
	1	141.3 ± 0.9	9.32 ± 0.11	1.2
	10	434.3 ± 2.5	89.9 ± 0.9	1.0

Radially polarized lasers: higher & sharper energies

	Power [PW]	$\bar{z}_f$ [λ]	$\bar{K}_r$ [MeV/nucleon]	$\Delta K_r/\bar{K}_r$ [%]
p	0.1	104.7 ± 0.5	4.26 ± 0.03	0.7
	1	430.8 ± 2.3	45.7 ± 0.4	0.8
	10	3347.5 ± 89.6	532.8 ± 13.3	2.5
C^{6+}	0.1	48.5 ± 0.2	1.00 ± 0.01	1
	1	173.7 ± 0.8	10.4 ± 0.1	0.8
	10	876.1 ± 5.3	122.0 ± 1.0	0.8

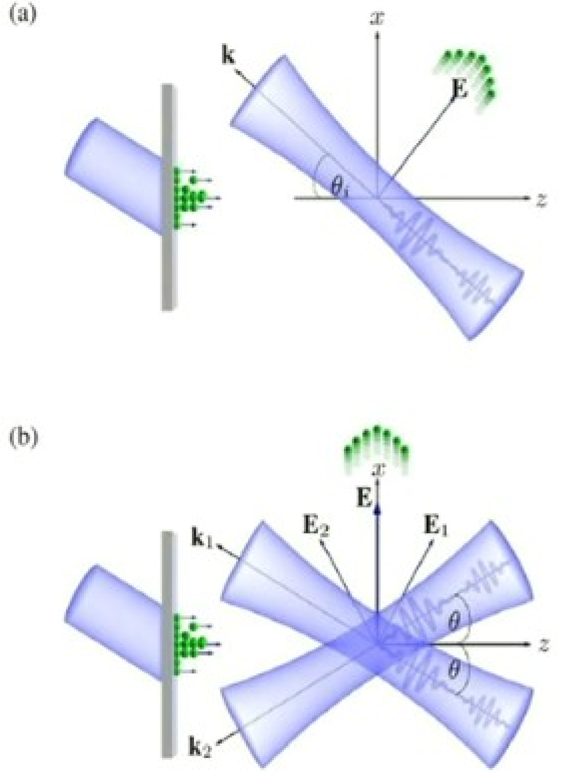
Conclusions:

- Direct laser acceleration of ions for medical purposes seems feasible; it may be utilized in cancer therapy
- Tight focusing is necessary
- Radially polarized lasers produce ion beams of better quality (yet to be produced with high powers)
- Refocusing of ions accelerated by linearly polarized lasers has to be experimentally solved
- Direct acceleration is an appealing alternative to ion production and acceleration by a laser-solid-target method – yield still problematic though

see: Y.I. Salamin, Z. Harman, C.H. Keitel, PRL **100**, 155004 (2008)

Efficient post-acceleration of laser-plasma generated protons

1 vs. 2 crossed, pulsed beams



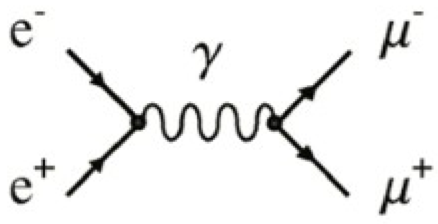
B. Galow, Z. Harman, CHK, *submitted* (2010)

Proton beams for various laser parameters

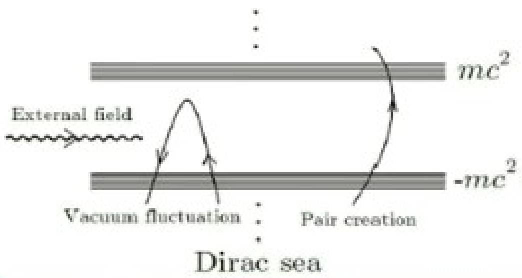
	$\bar{K}$ [MeV]	N_i
	S-LPA source, P=10 PW, Δt=19.2 fs, $w_0 = 1\lambda$	
single	28.1 ± 1.2 %	$1.0{\cdot}10^6$
crossed	59.4 ± 1.0 %	$1.0{\cdot}10^6$
	S-LPA source, P=40 PW, Δt=10.7 fs, $w_0 = 1\lambda$	
single	113.2 ± 1.6 %	$1.0{\cdot}10^6$
crossed	233 ± 1.0 %	$1.0{\cdot}10^6$
	S-LPA source, P=100 PW, Δt=23.8 fs, $w_0 = 2\lambda$	
single	73.2 ± 1.6 %	$1.3{\cdot}10^7$
crossed	152 ± 1.0 %	$1.3{\cdot}10^7$
	TNSA source, P=100 PW, Δt=14.4 fs, $w_0 = 2\lambda$	
single	64.6 ± 0.7 %	$1.0{\cdot}10^5$
crossed	141 ± 0.5 %	$1.0{\cdot}10^5$

The quality requirements
- beam energy
- small energy spread
- number of protons per shot

for clinical applications are fulfilled.



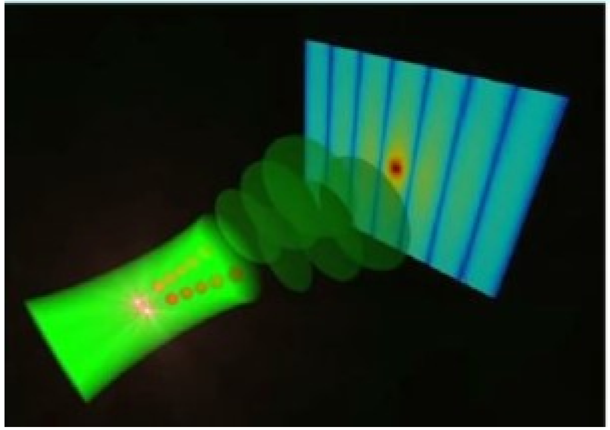
Conclusions

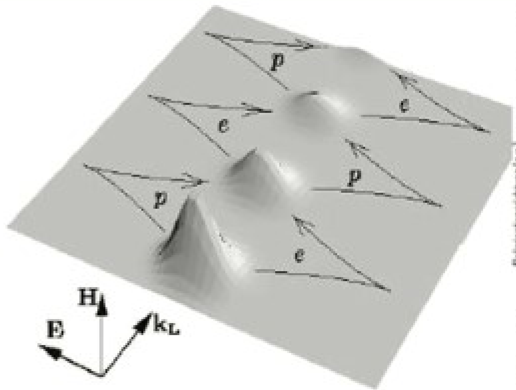


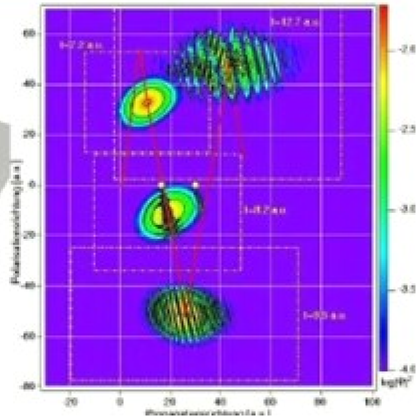
Quantum Vacuum: Laser-modified Vacuum Refractivity, Quantum Interference via Light-Light Interaction

Relativistic Quantum Dynamics: Relativ. Ionisation & Recollisions; Short Pulses and Medical Beams

Particle Physics: GeV laser colliders, Muon Production from Positronium and Ion-Laser Collisions

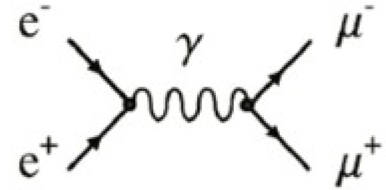






Theory of laser-driven muon creation

Employ Volkov states in the usual amplitude for $e^+e^- \to$ ❍$^+$❍$^-$:



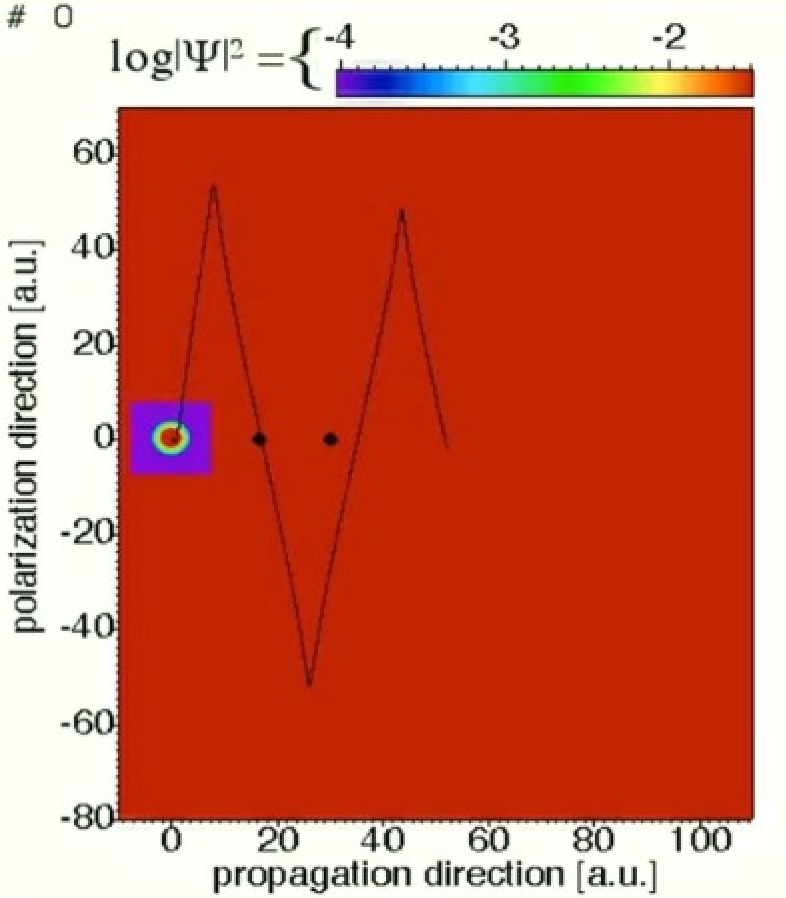
$$\mathcal{S}_{e^+e^-\to\mu^+\mu^-} = -\mathrm{i}\alpha \int d^4x\, d^4y\, \overline{\Psi}_{p_+}(x)\gamma^\mu\Psi_{p_-}(x)$$
$$\times D_{\mu\nu}(x-y)\overline{\Psi}_{P_-}(y)\gamma^\nu\Psi_{P_+}(y)$$

Average over the momentum distribution in the Ps ground state:

$$\mathcal{S}_{\mathrm{Ps}\to\mu^+\mu^-} = \int \frac{d^3p}{(2\pi)^3}\,\Phi(\boldsymbol{p})\,\mathcal{S}_{e^+e^-\to\mu^+\mu^-}$$

Motion & scattering in strong laser pulses

Example: electron double scattering via 2D solution of Dirac euqation



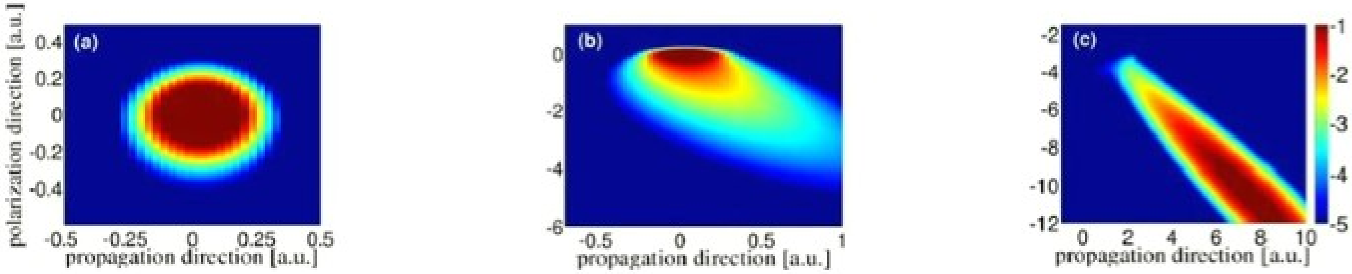
$E= 50$ a.u., $w= 1$ a.u., ca. 36% speed of light, Sn^{50+}

Drift in laser-propagation direction
via magnetic field component
- problem for recollisions

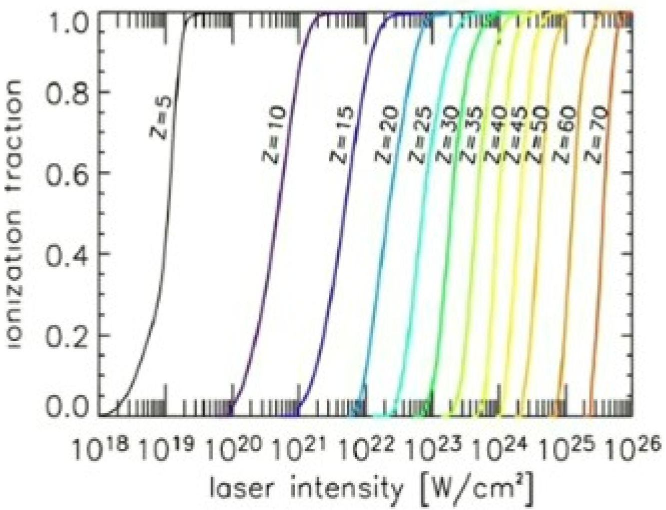
Enhanced quantum spreading
with increased laser intensity
& quantum interference
at scattering processes

Dirac propgation time consuming
- enhanced via adaptive grids

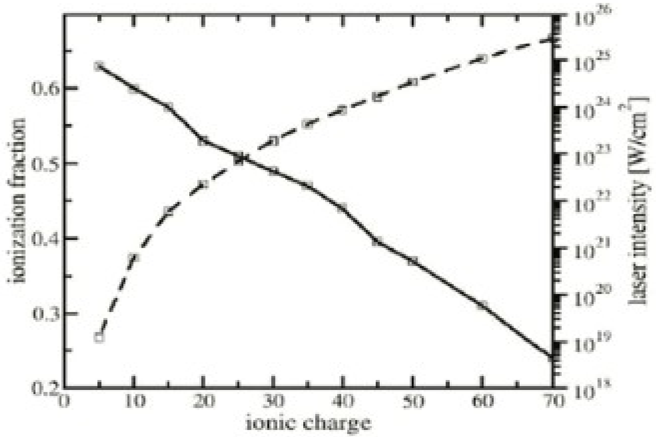
Ionisation: Characterising intense pulses with highly charged ions



Directions and yields of ionisation are characteristic for laser intensity and ionic charge
H G Hetzheim and C H Keitel, Phys. Rev. Lett. 102, 083003 (2009)

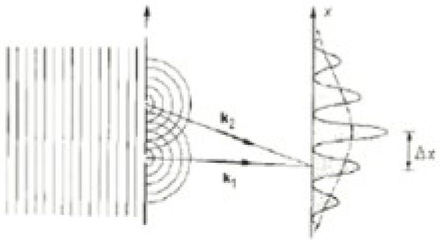


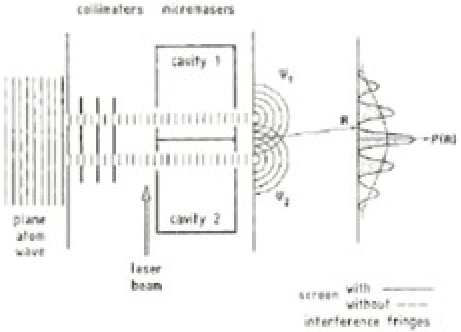
Ionization fraction for several different hydrogen-like ions Z as a function of the maximal laser intensity for single-cycle square-shaped laser pulse; wavelength 1054 nm.



The solid line defines the most sensitively measured ionization fraction (left axis), whereas the dashed line shows the corresponding laser intensity (right axis) as a function of the respective optimal ionic charge Z.

Tests on Quantum Interference





Lindner, F. *et al.* Attosecond double-slit experiment. *Phys. Rev. Lett.* **95**, 040401 (2005).

Kiffner, M., Evers, J. & Keitel, C. H. Quantum interference enforced by time–energy complementarity. *Phys. Rev. Lett.* **96**, 100403 (2006).

Jönsson, C. Elektroneninterferenzen an mehreren künstlich hergestellten Feinspalten. *Z. Phys.* **161**, 454–474 (1961).

Zeilinger, A. *et al.* Single- and double-slit diffraction of neutrons. *Rev. Mod. Phys.* **60**, 1067–1073 (1988).

Carnal, O. & Mlynek, J. Young's double-slit experiment with atoms: a simple atom interferometer. *Phys. Rev. Lett.* **66**, 2689–2692 (1991).

Arndt, M. *et al.* Wave–particle duality of C_{60} molecules. *Nature* **401**, 680–682 (1999).

Andrews, M. R. *et al.* Observation of interference between two bose condensates. *Science* **275**, 637–641 (1997).

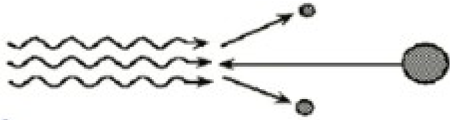
Hackermüller, L. *et al.* Wave nature of biomolecules and fluorofullerenes. *Phys. Rev. Lett.* **91**, 090408 (2003).

Nature **351**, 111 - 116 (09 May 1991)

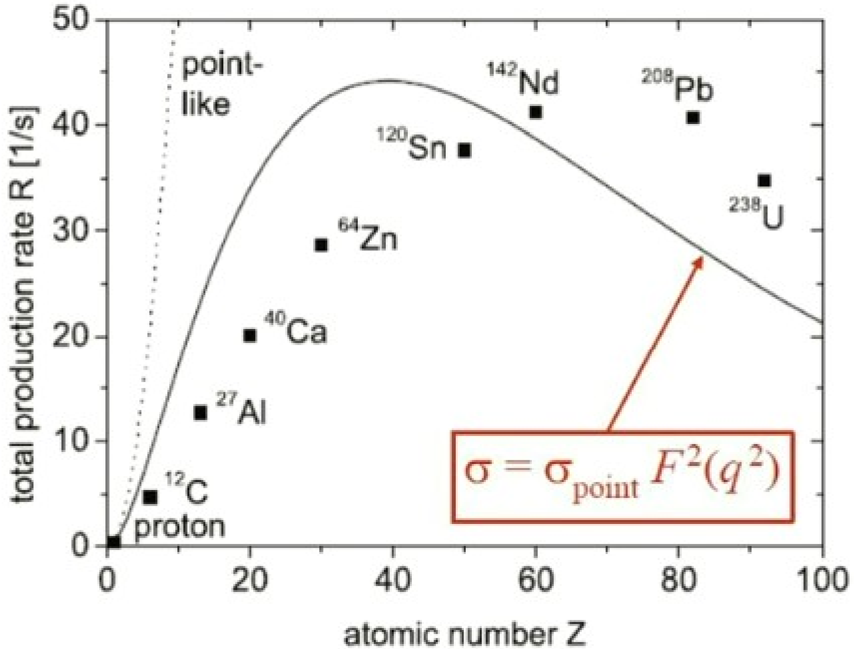
Quantum optical tests of complementarity

Marlan O. Scully, Berthold-Georg Englert & Herbert Walther

Simultaneous observation of wave and particle behaviour is prohibited, usually by the position–momentum uncertainty relation. New detectors, constructed with the aid of modern quantum optics, provide a way around this obstacle in atom interferometers, and allow the investigation of other mechanisms that enforce complementarity.



Muon creation rates in laser-ion collisions



For pointlike nuclei, the muon production rate raises like Z^2.

HOWEVER:

muons are created at typical distances ~ λ_C =1.86 fm

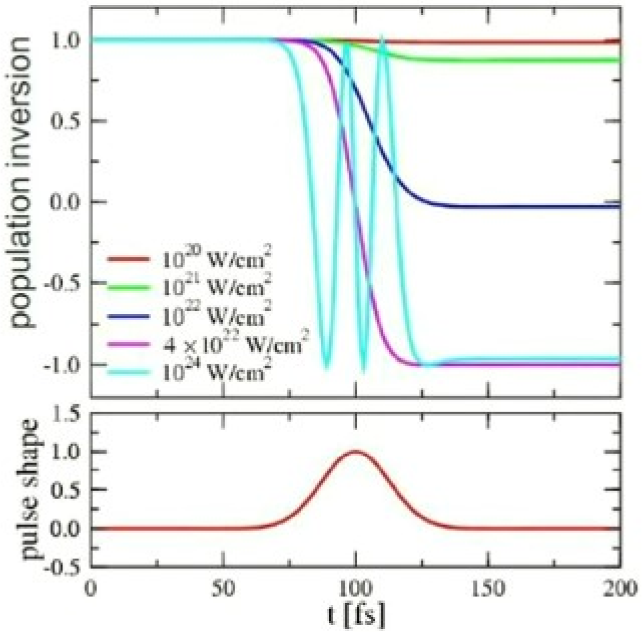
they only see a small part of the total nuclear charge within $R = 0.94$ fm $A^{1/3}$ ~ 3-5 fm

Process is sensitive to the nuclear size and shape
→ it might by utilized for form factor measurements.

C. Müller, Deneke & Keitel, PRL 101, 060402 (2008)

Nuclear Quantum Optics with XFEL: Rabi flopping

- resonant laser-nucleus interaction allows to induce Rabi flopping of nuclear population
- detection e.g. via scattered light, state-selective measurements
- potential application: model-free determination of nuclear parameters



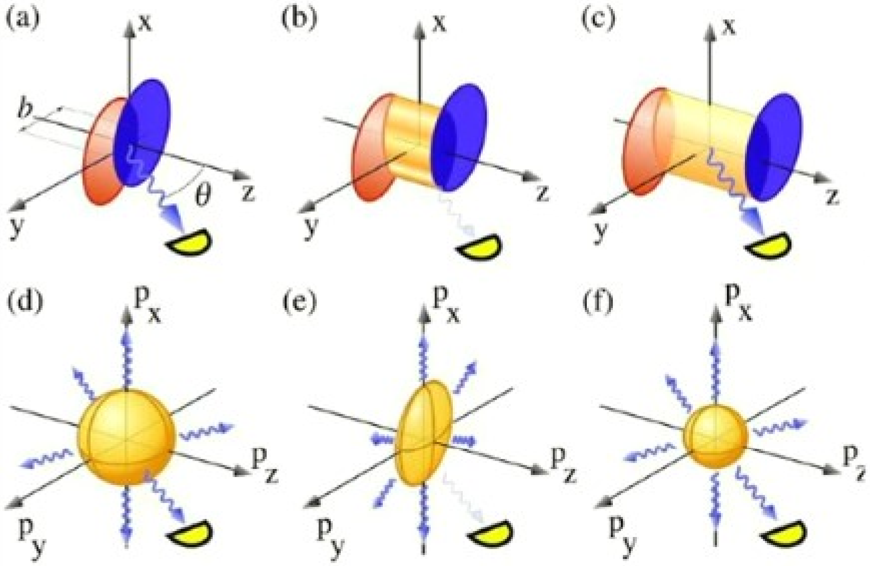
Population inversion in ^{223}Ra for laser parameters as in the DESY TESLA technical design report supplement

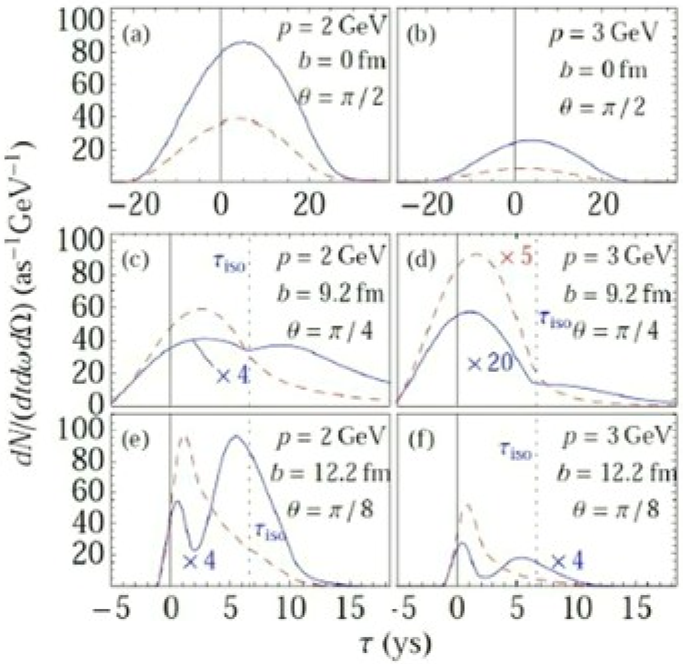
example nuclei:

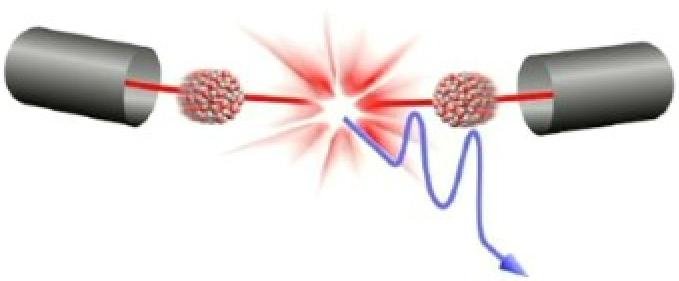
nucleus	transition	ΔE [keV]	μ [e fm]	$\tau(g)$	$\tau(e)$ [ps]
^{153}Sm	$3/2^- \rightarrow 3/2^+$	35.8	>0.75$^{(1)}$	47 h	<100
^{181}Ta	$9/2^- \rightarrow 7/2^+$	6.2	0.04$^{(1)}$	stable	$6 \cdot 10^6$
^{225}Ac	$3/2^+ \rightarrow 3/2^-$	40.1	0.24$^{(1)}$	10.0 d	720
^{223}Ra	$3/2^- \rightarrow 3/2^+$	50.1	0.12	11.435 d	730
^{227}Th	$3/2^- \rightarrow 1/2^+$	37.9	$\ldots^{(2)}$	18.68 d	$\ldots^{(2)}$
^{231}Th	$5/2^- \rightarrow 5/2^+$	186	0.017	25.52 h	1030

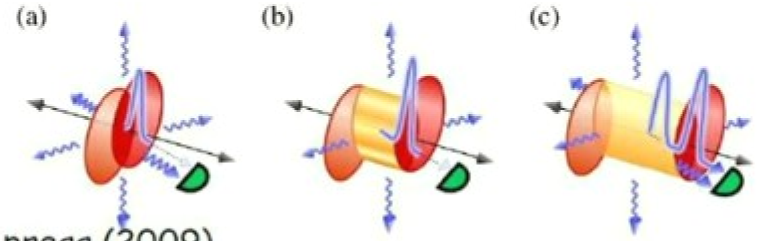
T. Bürvenich, J. Evers and C. H. Keitel, Phys. Rev. Lett. 96, 142501 (2006)
See also Adriana Palffy et al., Phys. Rev C (2007)

Yoctosecond pulses from quark gluon plasma

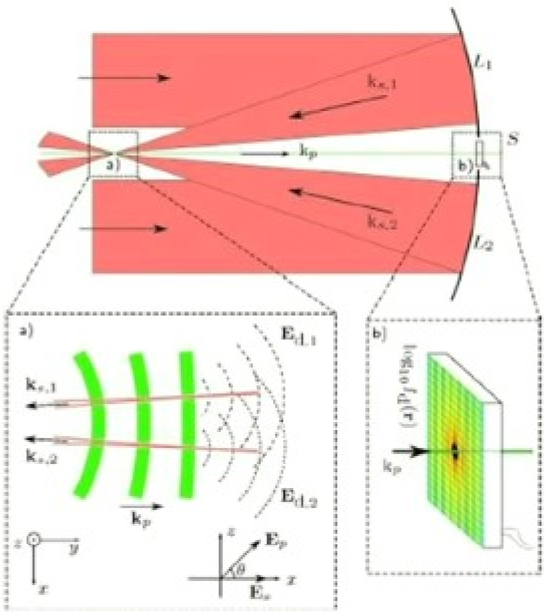


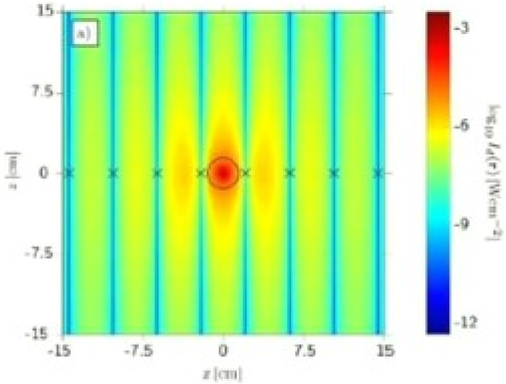


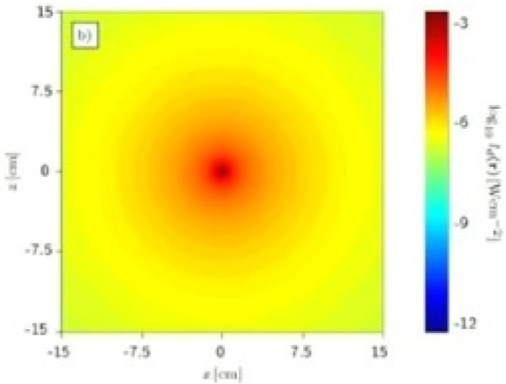


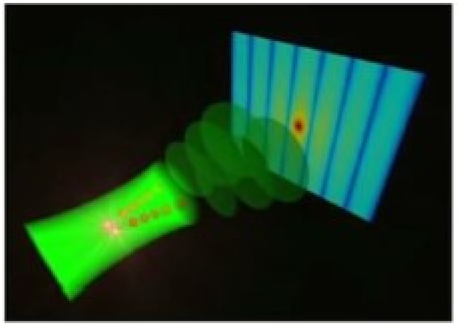


A. Ipp, C. H. Keitel, J. Evers, Phys. Rev. Lett. in press (2009)









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