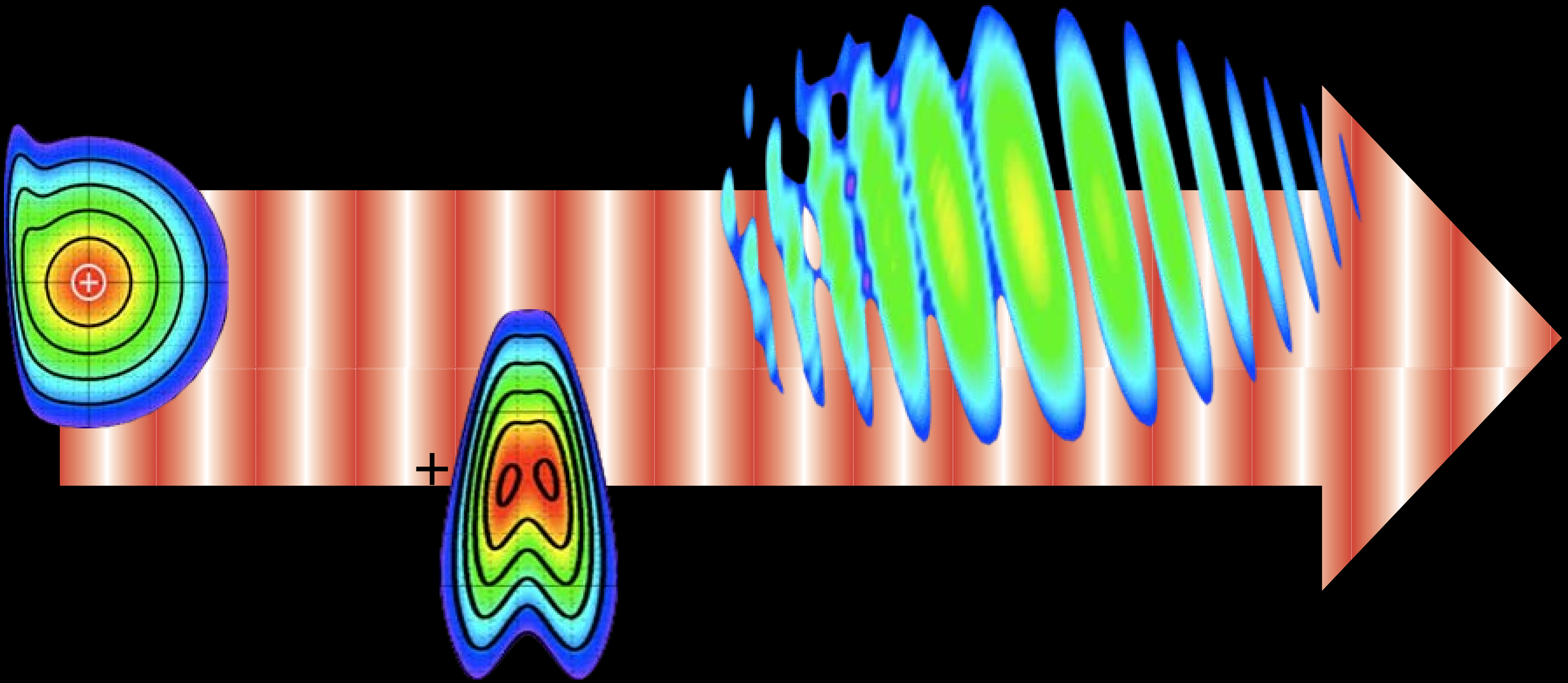
# High-energy quantum dynamics with extremely strong laser pulses



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, A Palffy**

# Outline

Introduction into Laser-Quantum Dynamics& Vacuum
Characterising Extreme Pulses via Particle Interaction

**Laser-induced Physics up to the GeV Regime:**
**Laser Colliders & Laser Particle Physics**
**Pair Creation from Vacuum**
**Refractive QED: Laser-induced vacuum refractivity**
**Laser acceleration and Radiative Reaction**
**Laser-Nuclear Physics**

# Current high-power laser technology

| **Optical laser technology ($\hbar\omega_L$=1 eV)** | Energy (J) | Pulse duration (fs) | Spot radius ($\mu$m) | Intensity (W/cm$^2$) |
|---|---|---|---|---|
| State-of-art (Yanovsky et al. (2008)) | 10 | 30 | 1 | $2\times10^{22}$ |
| Soon (2011) (Polaris, Astra-Gemini, Phelix, etc…) | 10-100 | 10-100 | 1 | $10^{22}$-$10^{23}$ |
| Soon (2011) (PFS) | 5 | 5 | 1 | $10^{22}$-$10^{23}$ |
| Vulcan 10 PW(CLF) | 300 | 30 | 1 | $10^{23}$ |
| Near future (2020) (ELI, HiPER) | $10^4$ | 10 | 1 | $10^{25}$-$10^{26}$ |

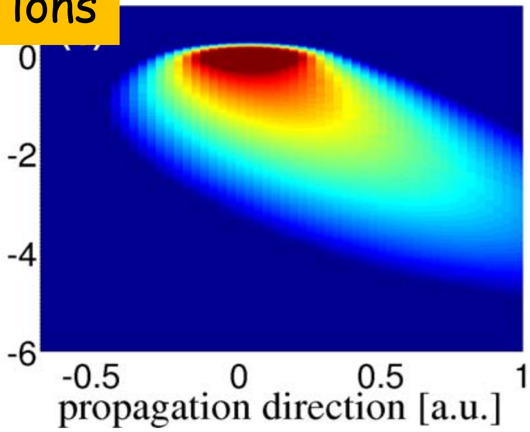
- GeV electron acceleration (Leemans et al 2006)
- Laser induced pair creation demonstrated Burke et al 1996
- High-energy processes feasible

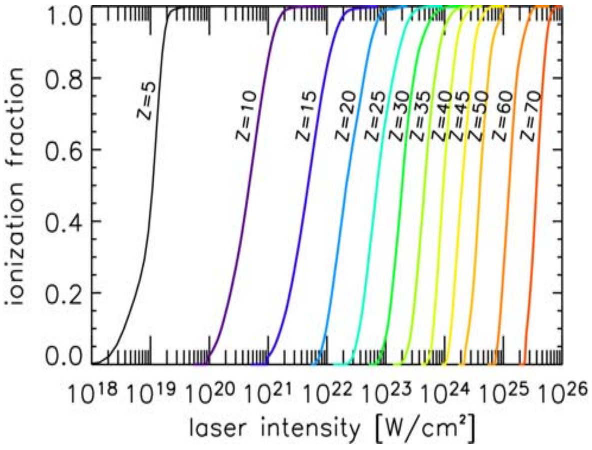
## Quantum Vacuum

- 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: $\lambda_c\approx10^{-11}$ cm and $\tau\approx10^{-21}$ s.

# Characterizing extremely intense laser pulses

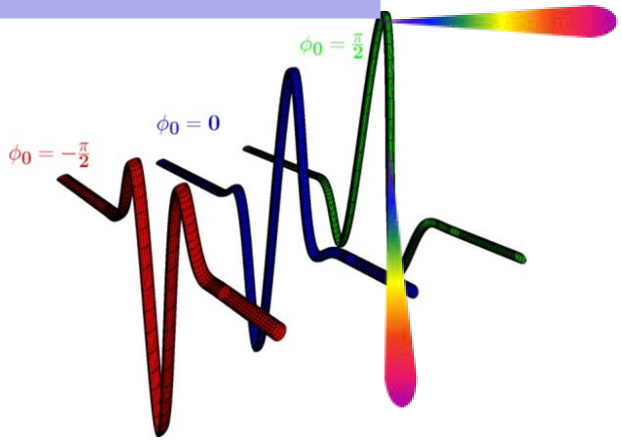
Measure intensity
via ionization of
highly charged ions

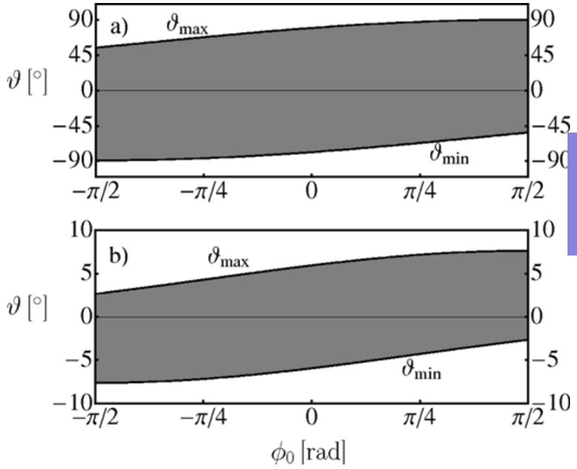




H. G. Hetzheim and C. H. Keitel,
Phys. Rev. Lett. 102, 083003 (2009)

Measure pulse shape
via radiation direction
of injected electron





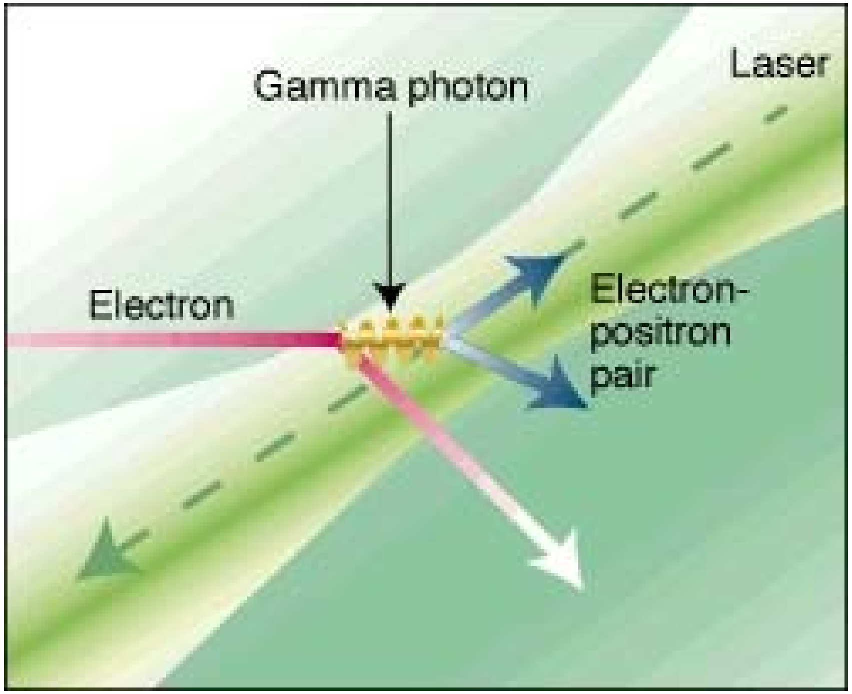
Angular range
of radiation

F. Mackenroth, A. Di Piazza, C.H. Keitel,
Phys. Rev. Lett. 105, 063903 (2010)

# QED in strong laser pulses

## Historical Remark: SLAC Experiment

The first laboratory evidence of multiphoton pair production.



D. Burke et al., Phys. Rev. Lett. 79, 1626 (1997)

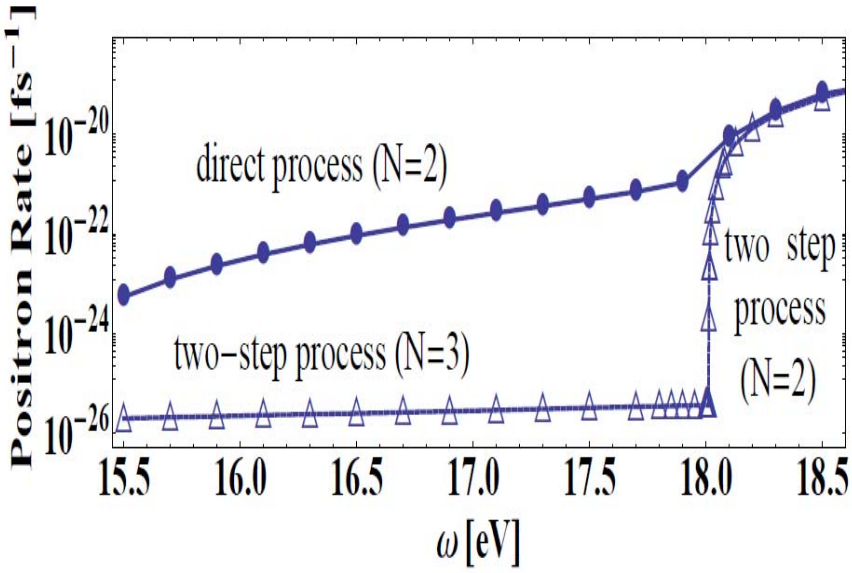
- $3.6\times 10^{18}\, W/cm^2$ optical laser (2.35 eV)
- Electron accelerated to 46.6 GeV
- Energy threshold reached (in center of inertial frame)

Theory: combined treatment of two processes

direct: $e + N\omega \to e' + e^+e^-$
Bethe-Heitler type

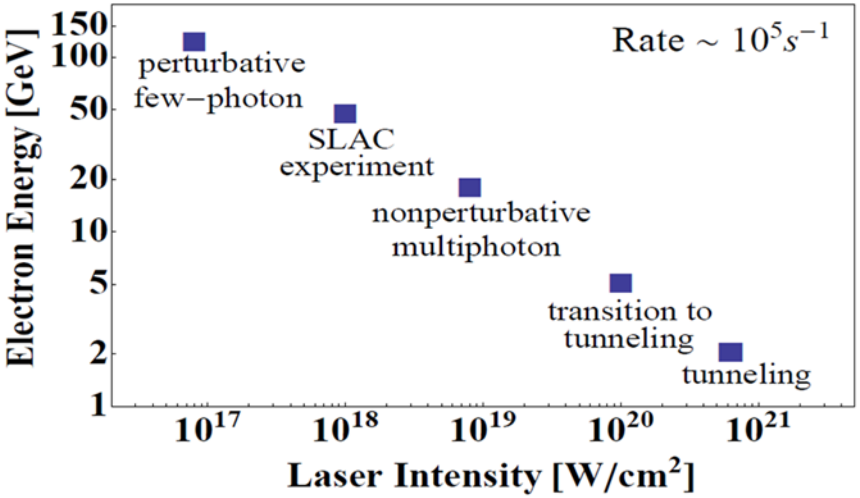
two-step: $e + \omega \to e' + \gamma$
Compton back scattering &
Multiphoton Breit-Wheeler $\gamma + N\omega \to e^+e^-$

# Separate Direct and Two-Step Processes



Direct process and two-step process can be separated by kinematic requirements at VUV intensities $10^{13}\,W/cm^2$ with a 17.5 GeV electron from DESY beamline

- Substantial pair production rate in various interaction regimes
- Novel usage of DESY beamline (17.5 GeV) for pair production
- The future of pair production: all-optical setup



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

# Other recent advances in laser-induced pair creation

1. Pair creation in quantum plasmas
   M. Marklund, B. Eliasson, P. K. Shukla, L. Steflo, M. E. Diekmann,
   and M. Parviainen, JETP Letters 83, 313 (2006)

2. Pair creation in counter propagating focussed laser pulses
   S S Bulanov, N. B. Narozhny, V. D. Mur & V. S. Popov, JETP 102, 9 (2006);
   A R Bell and J G Kirk, PRL 101, 200403 (2008)

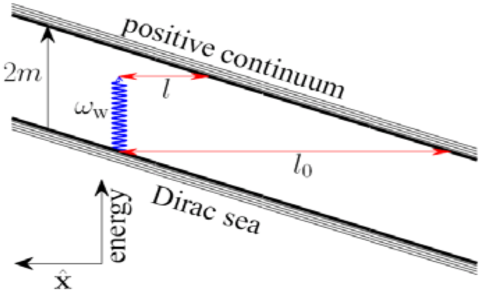
3. Dynamically assistend Schwinger Mechanism
   R. Schützhold, H. Gies, G Dunne, PRL 130404 (2008)

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. Control tunneling barrier with high-frequency photons
   A. Di Piazza, E. Lötstedt, A. I. Milstein & CHK,
   PRL 103, 170403 (2009)



# Electron Positron Pair Avalanches

Prolific pair creation starting from an ensemble of electrons
A. R. Bell and J. G. Kirk, Phys. Rev. Lett. **101**, 200403 (2008)

- Recent results indicate that even the production of a single electron-positron pair may start an avalanche process, which would limit the maximum reachable laser intensity to about $10^{25}$ W/cm$^2$

A.M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn, PRL **105**, 080402 (2010)

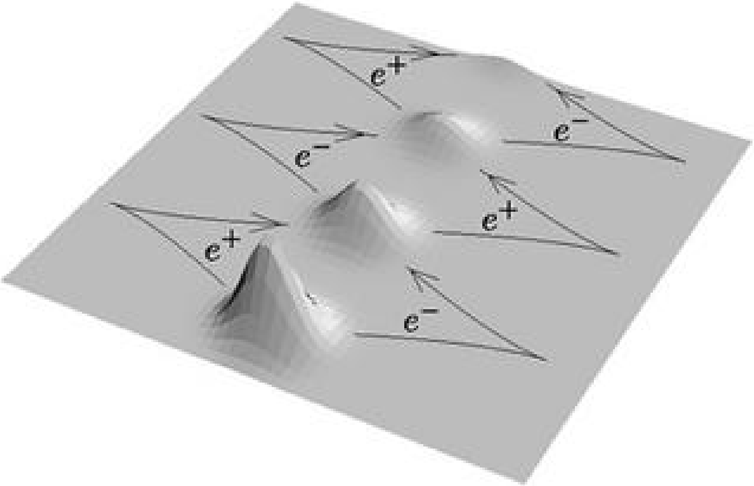
- However, results in the collision of a 46 GeV electron beam with a laser beam of intensity $5*10^{22}$ W/cm$^2$ show that in this case the avalanche process is suppressed by radiation reaction effects

I. V. Sokolov, N. M. Naumova, J. A. Nees, G. Mourou, PRL 105, 196005 (2010), see also E. N. Nerush et al, PRL 106,035001 (2011)

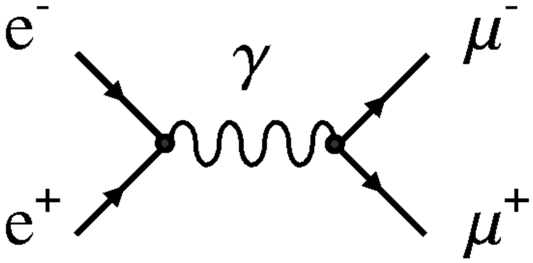
- The availability of laser beams with intensities exceeding $10^{24}$ W/cm$^2$ will help in clarifying this aspect of QED cascades and consequently the fundamental issue of the maximum reachable intensity

# Particle Physics with Strong Lasers

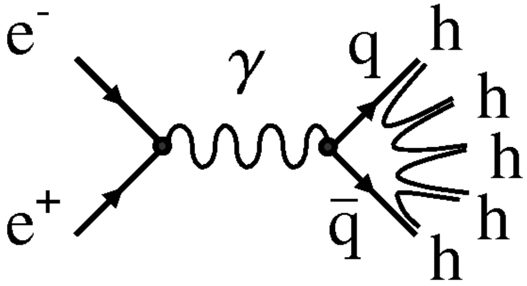
Positronium dynamics
in an intense laser field:



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



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



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

energetic threshold for muon:

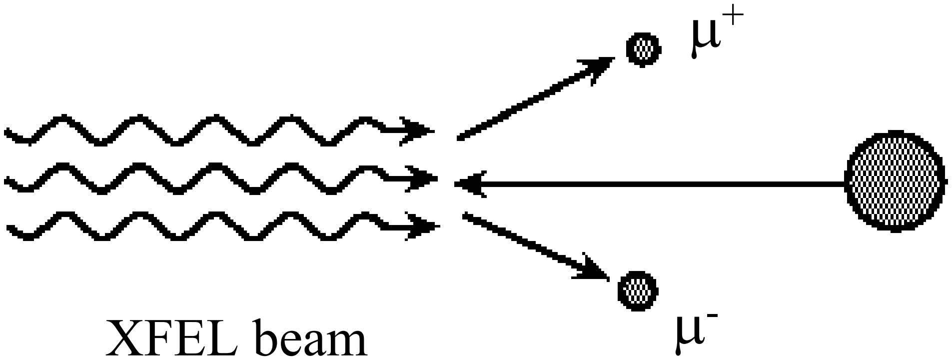
$$2eA \geq 2Mc^2$$

$(I \geq 5\times10^{22}\ \mathrm{W/cm^2}$ at $\lambda = 1\ \mu\mathrm{m})$

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)

Small muon rates: C. Müller, K.Z. Hatsagortsyan, C H Keitel, Phys. Lett. B 669, 209 (2008)

# Muon pair creation in XFEL-nucleus collisions



relativistic nucleus
($\gamma$=7000 at LHC, CERN)

XFEL beam
($\hbar\omega = 12$ keV)

- Relativistic Doppler shift leads to

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

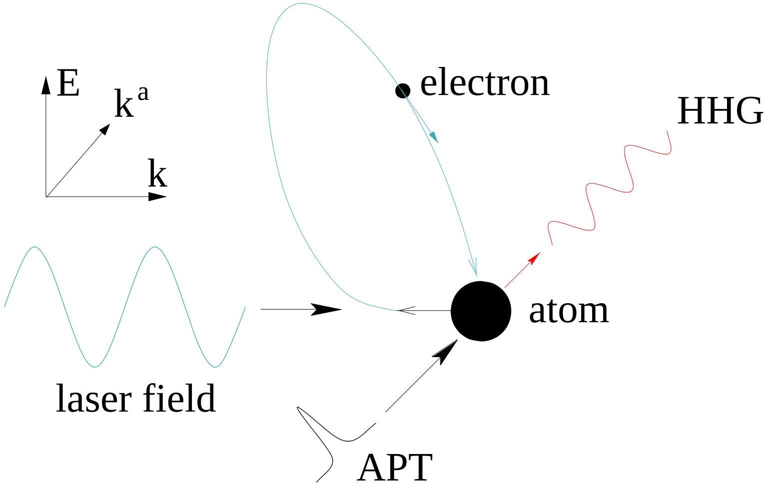
in nuclear rest frame

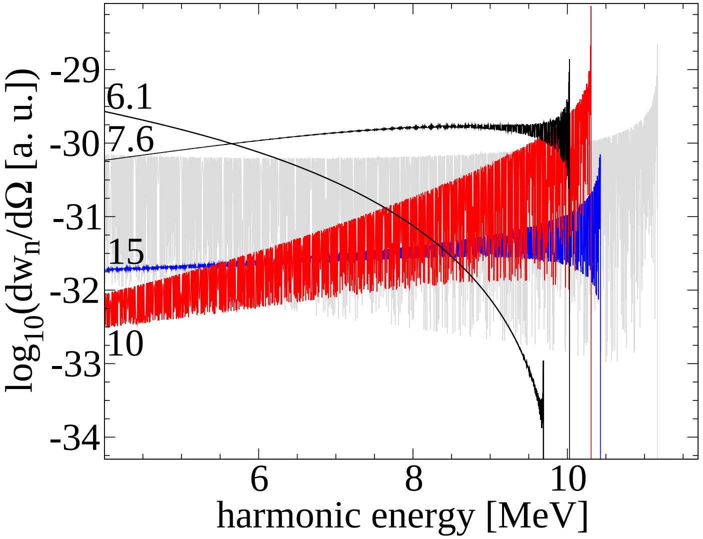
- Energy threshold $\Delta\varepsilon = 2Mc^2 = 211$ MeV for $\mu^+\mu^-$ creation can be overcome by absorption of two x-ray photons

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

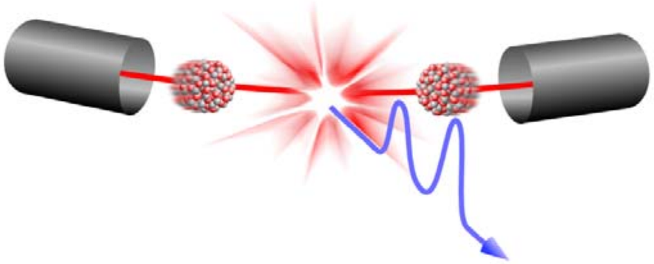
C. Müller, Deneke & Keitel, PRL 101, 060402 (08); see also C. Müller, Phys. Lett. B 672, 56 (09)

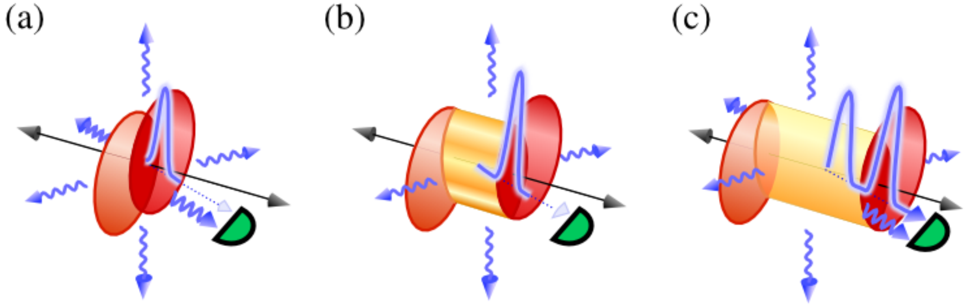
# MeV harmonics & zeptosecond γ-ray pulses & beyond





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)

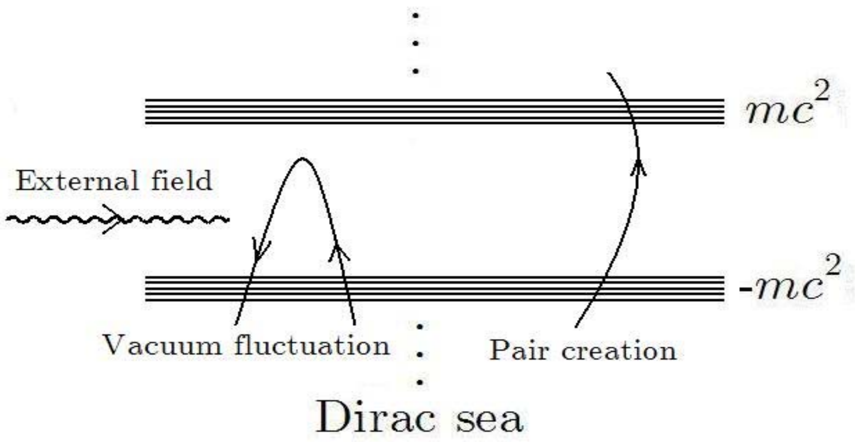


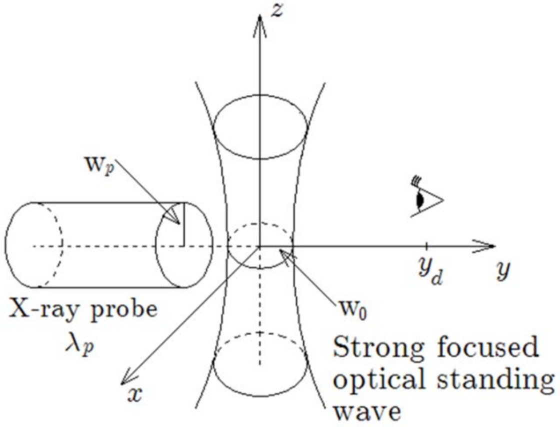


A. Ipp, C. H. Keitel, J. Evers, Phys. Rev. Lett. 103, 152301 (2009)

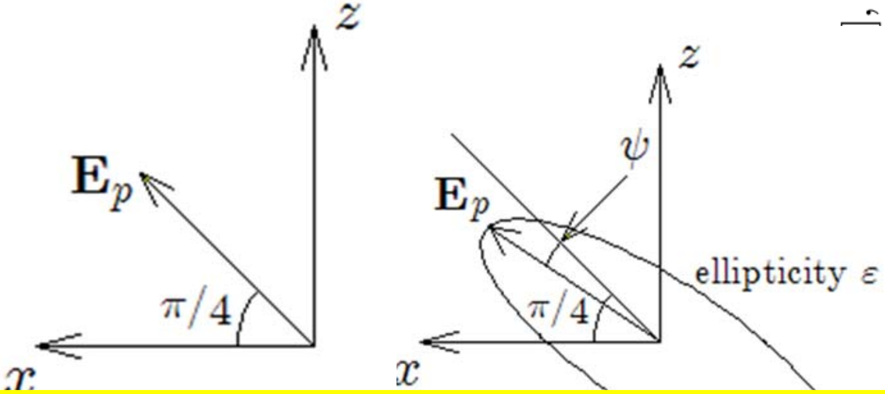
# Effects of vacuum fluctuations for more moderate laser intensities ?

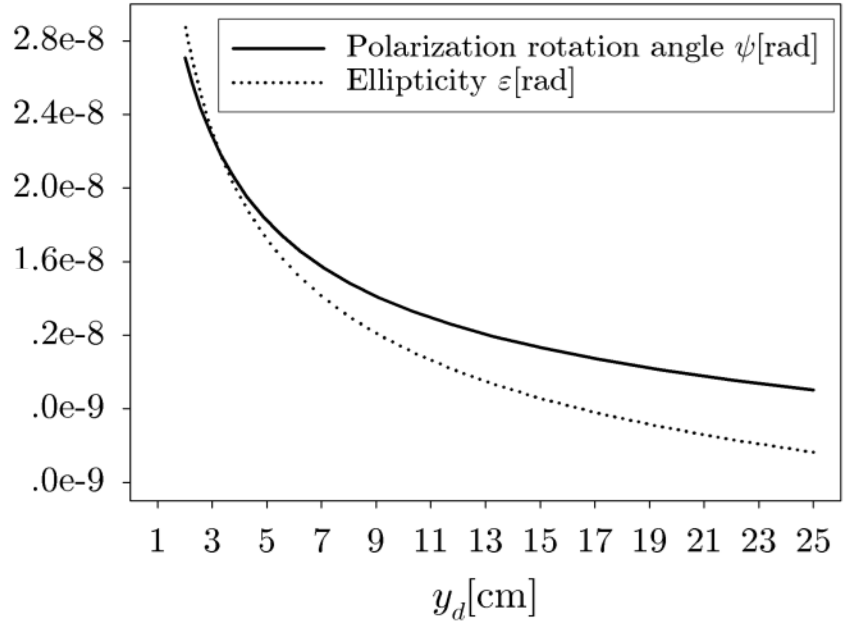
In the presence of strong fields the Maxwell Lagrangian density has to be modified to take into account vacuum fluctuations





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

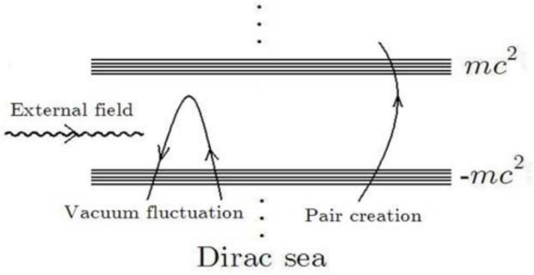




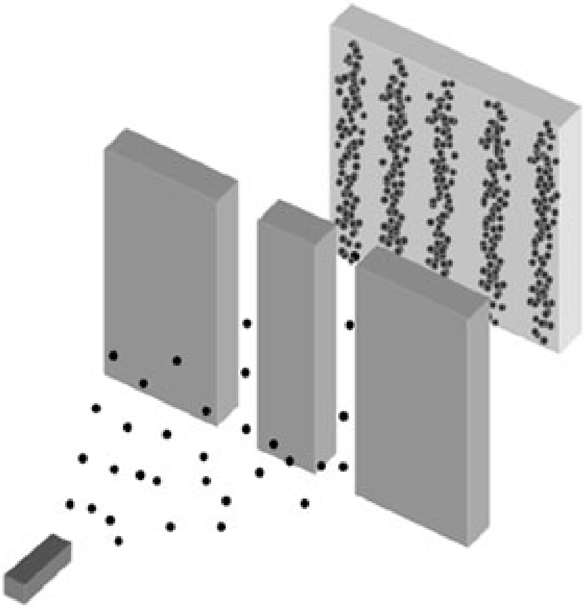
Probe field polarization and elipticity before and after interaction with intense field

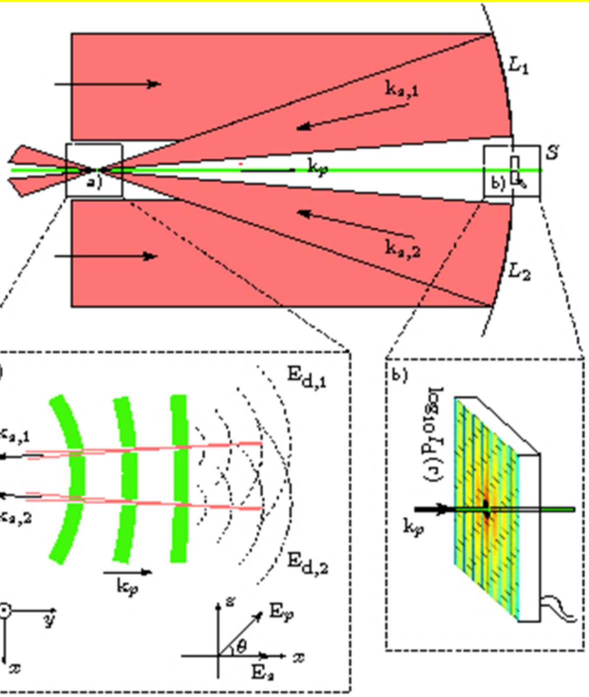
A. Di Piazza et al., PRL 97, 083603 (2006) & see also T. Heinzl et al. Opt. Comm. 267, 318 (2006)

# A matterless double-slit via vacuum fluctuations



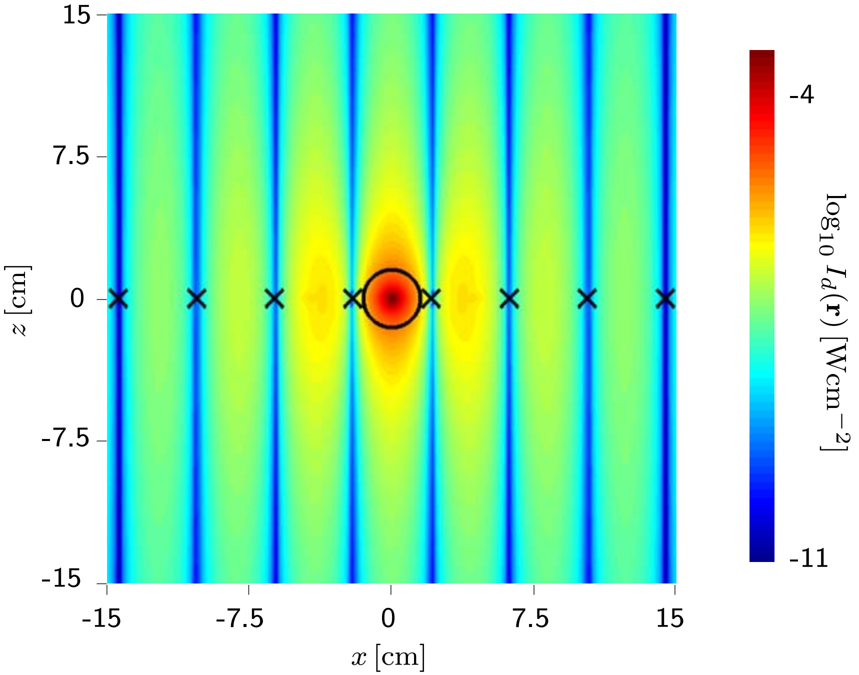
Laser enhanced vacuum fluctuations for a fundamental scenario: double slit set-up having been essential for our understanding of quantum mechanics

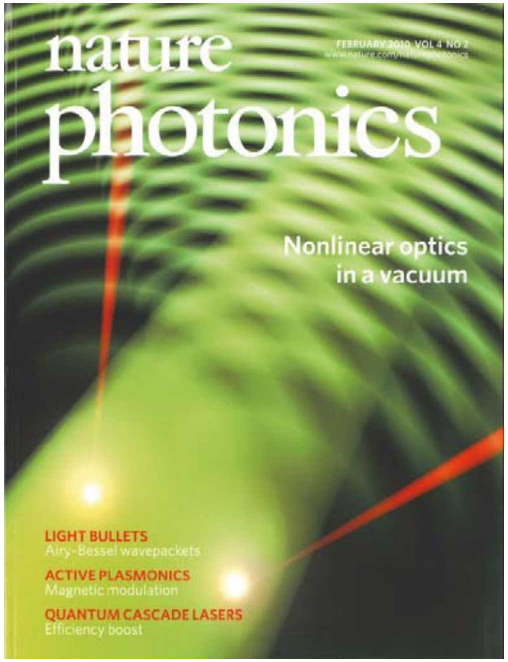




*All double-slit schemes investigated so far have involved matter (either the particles employed like electrons, neutrons etc. or the slits): here only via light-light interaction*

- Strong field's parameters: 10 PW, 800 nm, 30 fs, focused to one wavelength (intensity $10^{24}$ W/cm$^2$)
- Weak field's parameters: 100 TW, 527 nm, 100 fs focused to 290 μm (intensity $7.5*10^{16}$ W/cm$^2$)
- Separation between the two strong beams: 64 μm
- The position of the x in the figure corresponds to the classical formula: $(n+1/2)\lambda_p = D \sin \phi$
- With the above parameters one obtains about 6.4 diffracted photons per shot





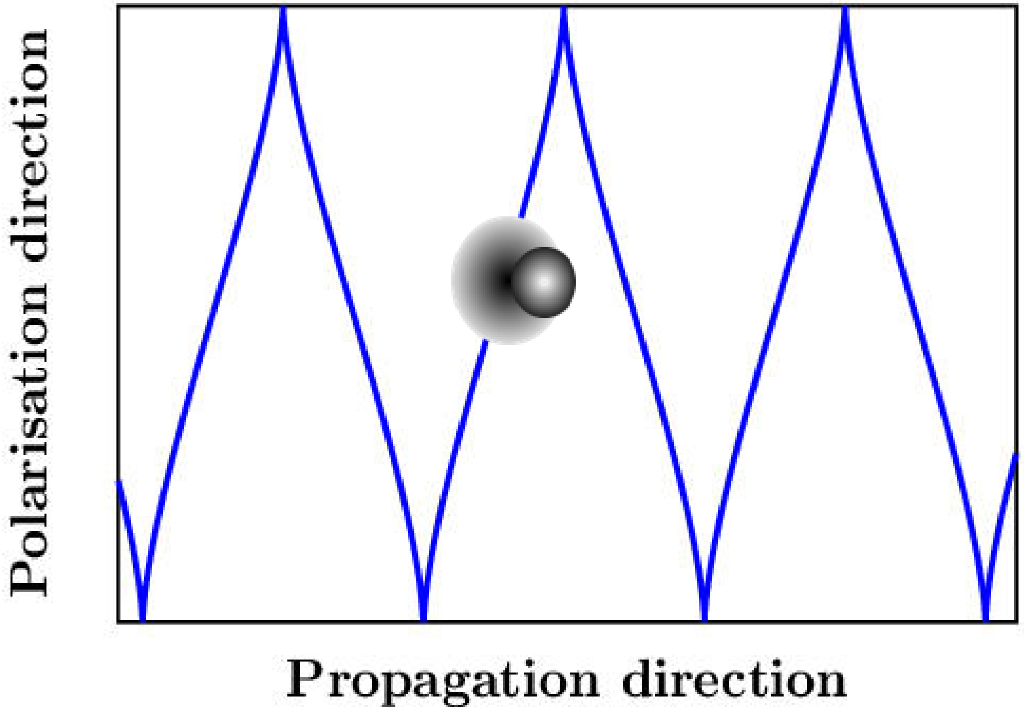
B. King, A. Di Piazza and C. H. Keitel, Nature Photonics **4**, 92 (2010)

# Laser electron acceleration: Radiative reaction

$$m_0 \frac{du^\mu}{ds} = -eF_T^{\mu\nu} u_\nu \longleftarrow$$

$$\partial_\mu F_T^{\mu\nu} = -e \int ds\,\delta(x - x(s))u^\nu \longrightarrow F_T^{\mu\nu}(x) = F^{\mu\nu}(x) + F_S^{\mu\nu}(x)$$

Feed-back of modified fields yields Lorentz-Abraham-Dirac equation.

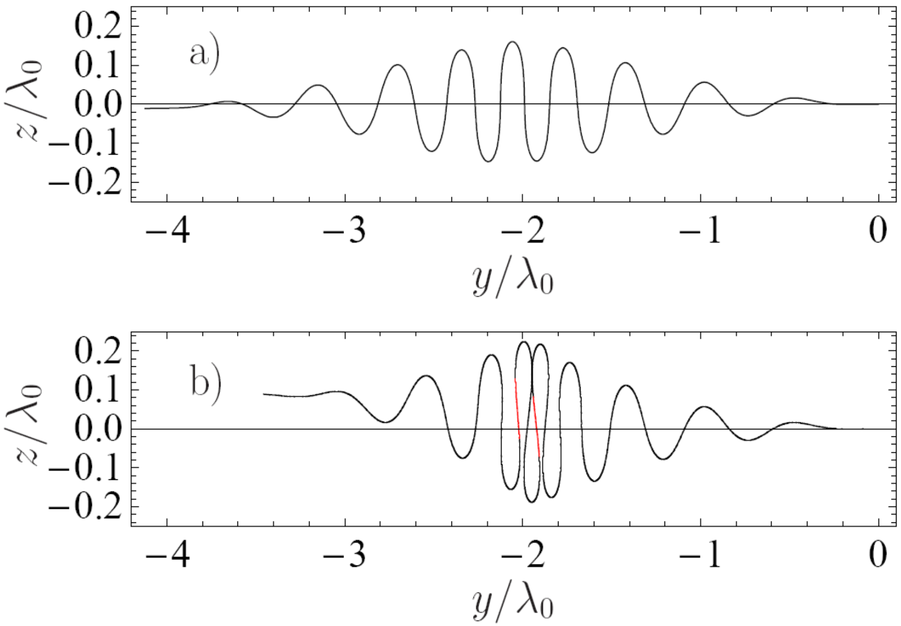


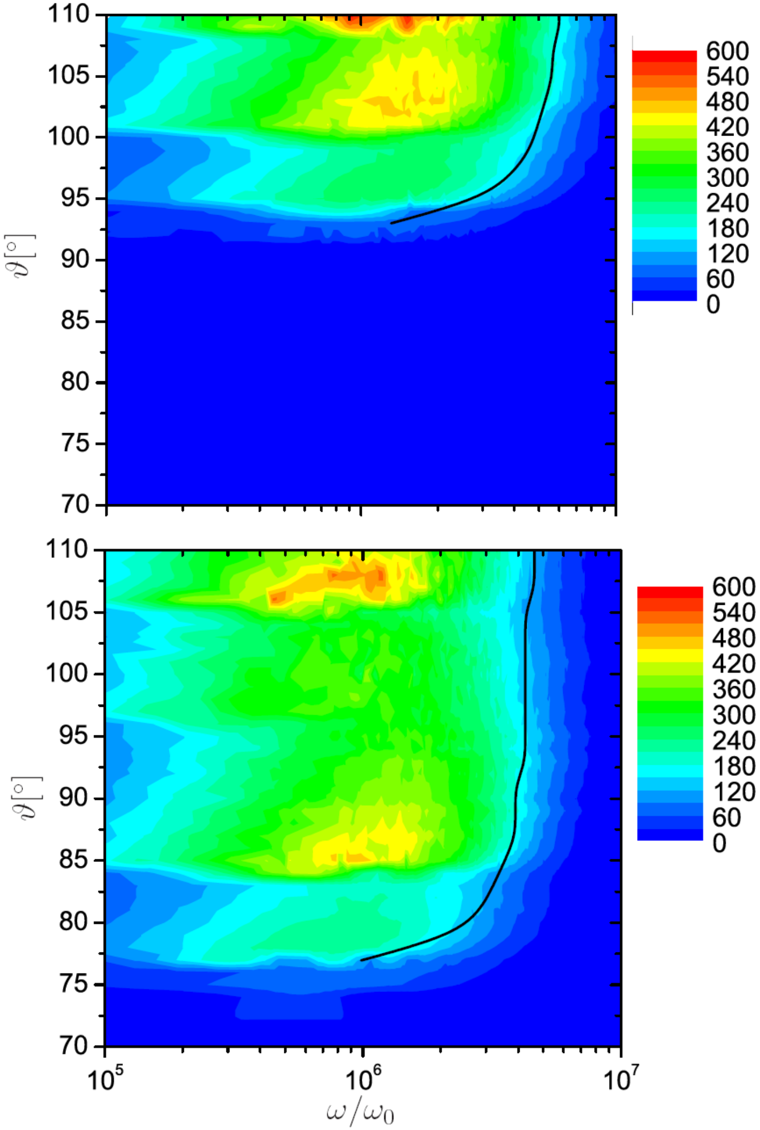
Damping &
Reabsorption
of initially emitted
Light alters Dynamics

CHK, C Szymanowski, PL Knight, A Maquet, JPB 31, L75 (1998)

- One can see that if the initial longitudinal momentum of the electron is almost compensated by the laser field, the resulting angular distribution of the emitted radiation is very sensitive to radiation reaction

- Numerical parameters: electron energy 40 MeV, laser wavelength 0.8 μm, laser intensity $5*10^{22}$ W/cm$^2$, focused to 2.5 μm (10 PW), pulse duration 30 fs

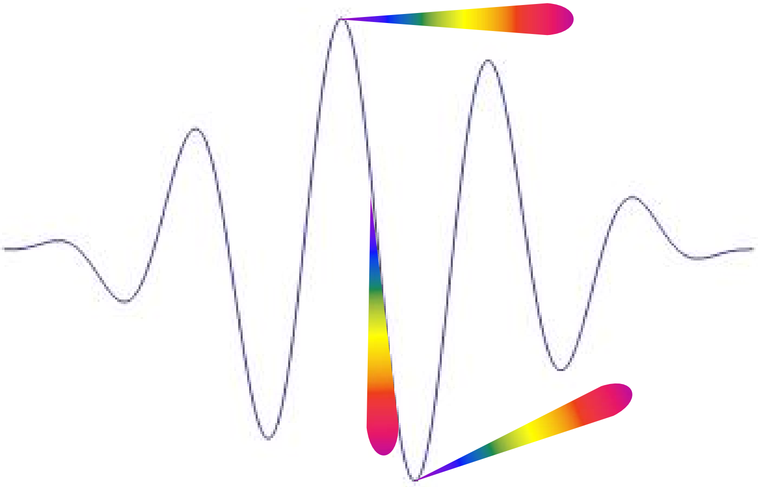




A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, PRL **102**, 254802 (2009)

# Quantum radiation dominated regime

- At the same laser intensity, if one employs an electron beam with energy of 1 GeV, one can enter the so-called Quantum Radiation Dominated Regime (QRDR)
- In the QRDR the electron emits many photons incoherently already in one laser period and in each photon emission recoil is in principle significant

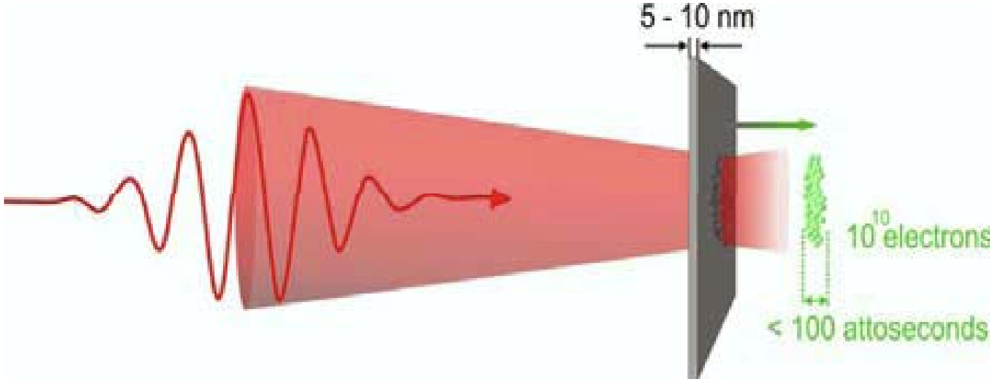


A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, Phys. Rev. Lett. 105, 220403 (2010)

# Radiation reaction effects in plasma

Radiation reaction (RR) is expected to play a relevant role in the interaction between an intense (~$10^{23}$ W/cm$^2$) laser beam and a plasma

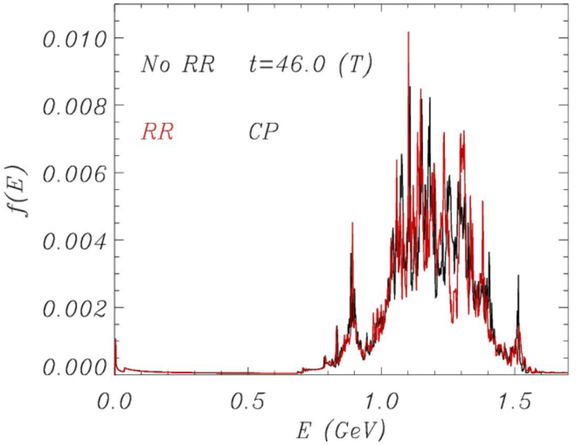
In our setup a strong laser beam interacts with a plasma slab. We have investigated RR effects on the energy spectrum of the generated ion beam



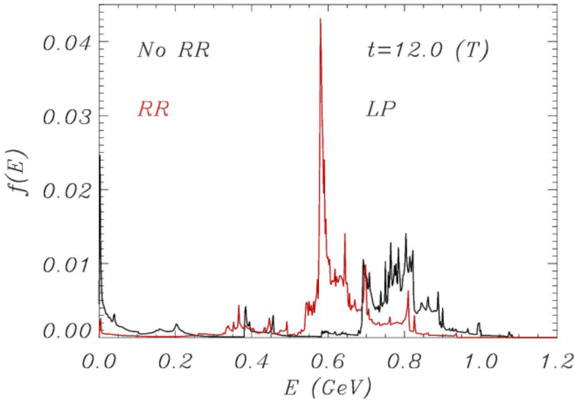
The effects of RR have been taken into account by including in the Vlasov equation new force terms according to the one-particle Landau-Lifshitz equation

Laser and plasma parameters: laser wavelength λ=0.8 μm, laser intensity I=2.33 x $10^{23}$ W/cm$^2$, laser pulse duration 7 cycles, plasma density n=100$n_c$, plasma thickness 1λ.

M. Taburini, F. Pegoraro, A. Di Piazza, C. H. Keitel and A. Macchi, New J. Phys. **12**, 123005 (2010)



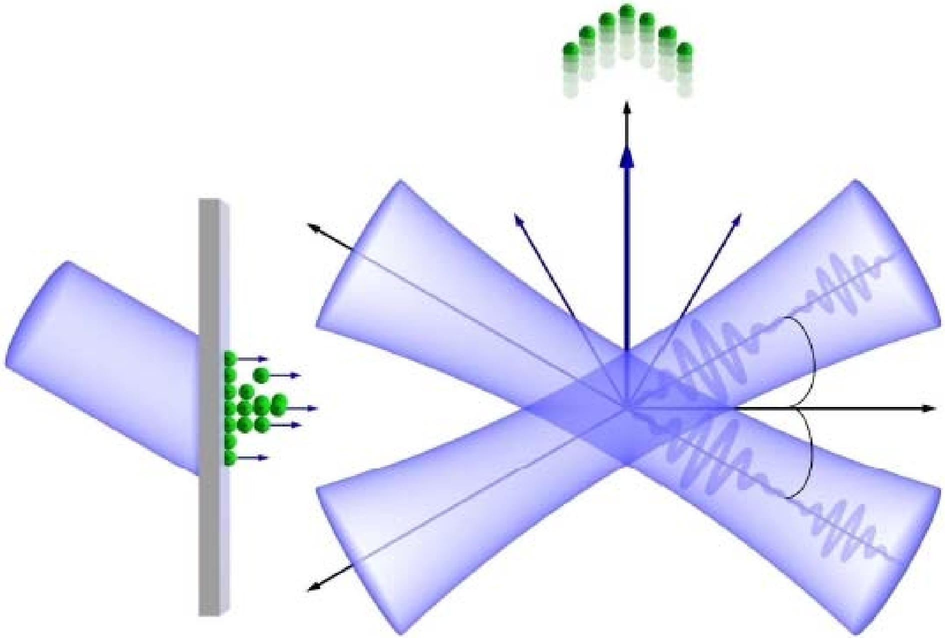
Negligible effects for circular polarization because the laser does not penetrate the plasma



RR effects for linear polarization strongly narrow the ion spectrum

# Laser Nuclear Physics:
# 1. Ion acceleration: Intense high-quality medical ion beams via laser fields

Particle acceleration by **laser fields**:



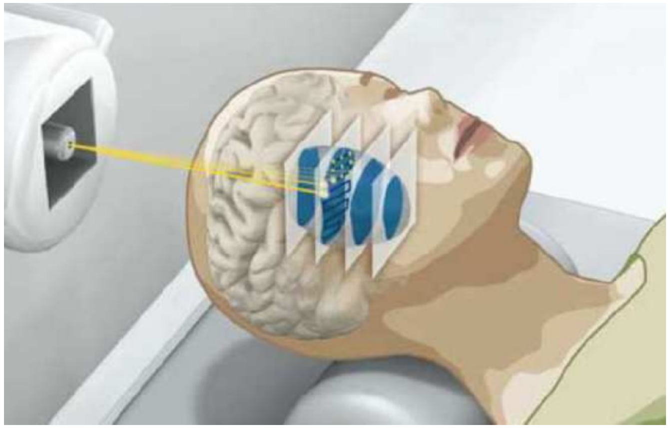
(1) abundant ion generation in a laser-plasma interaction

(2) post-acceleration by a powerful PW-scale laser beam

e.g. simulation results for a tightly focused 40 PW laser pulse:

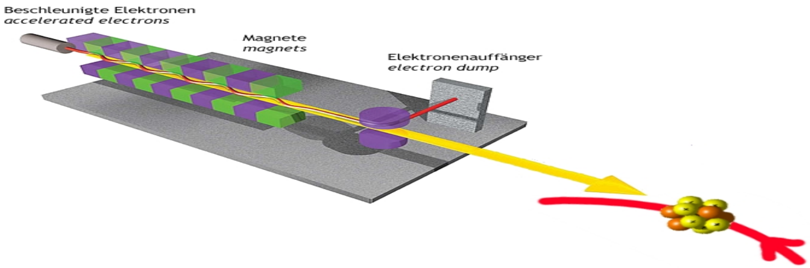
kinetic energy: 233 MeV +/- 1%
number of ions: $10^6$/shot

in the range of **medical applicability**: laser acceleration may be an economic future alternative to conventional accelerators (such as e.g. the HIT facility of the Heidelberg University Hospital)



B. J. Galow, Z. Harman, and C. H. Keitel, Opt. Express **18**, 25950 (2010)

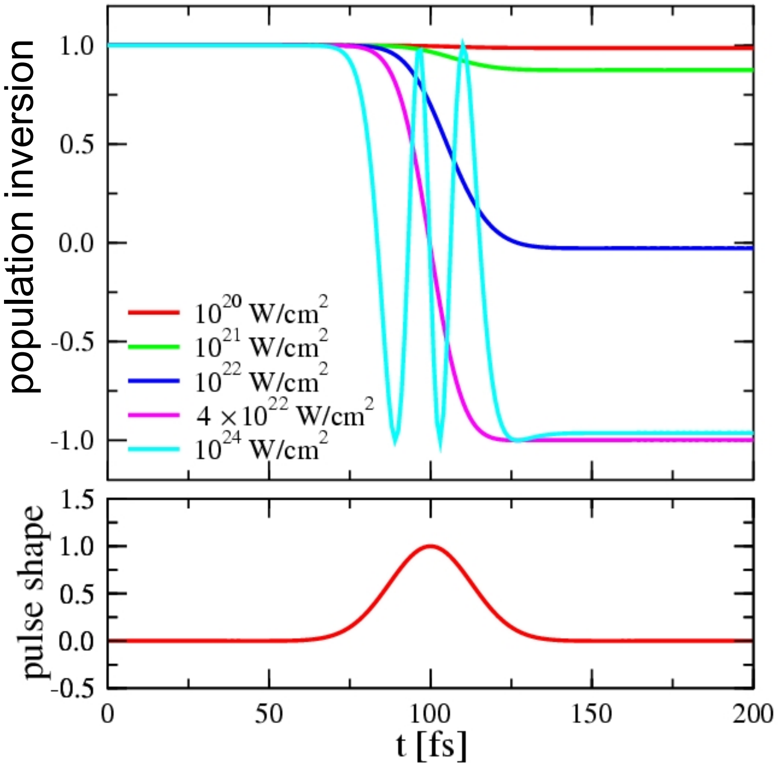
# 2. Nuclear Quantum Optics with XFEL: Rabi flopping



- 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

example nuclei:

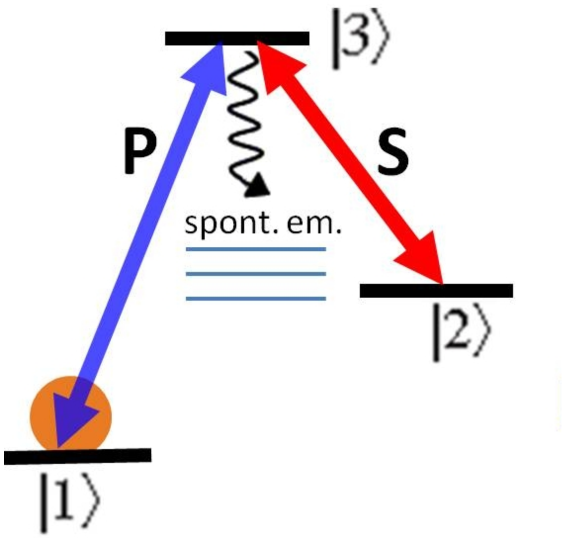
| nucleus | transition | $\Delta E$ [keV] | $\mu$ [$e$ fm] | $\tau(g)$ | $\tau(e)$ [ps] |
|---|---|---|---|---|---|
| $^{153}$Sm | $3/2^- \rightarrow 3/2^+$ | 35.8 | $>0.75^{(1)}$ | 47 h | $<100$ |
| $^{181}$Ta | $9/2^- \rightarrow 7/2^+$ | 6.2 | $0.04^{(1)}$ | stable | $6 \cdot 10^6$ |
| $^{225}$Ac | $3/2^+ \rightarrow 3/2^-$ | 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 |

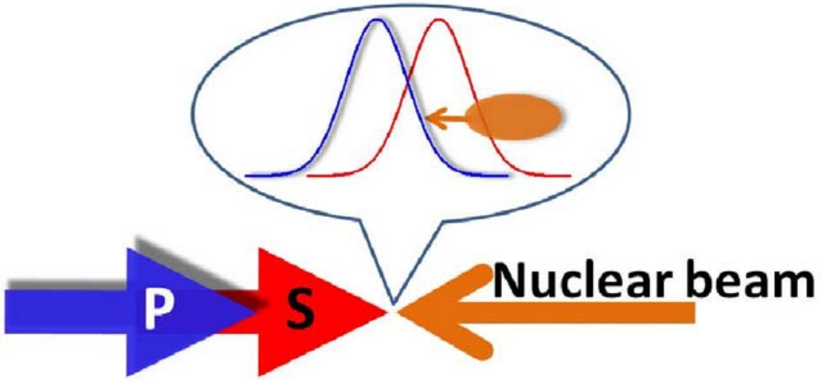


Population inversion in $^{223}$Ra for laser parameters as in the DESY TESLA technical design report supplement

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

# 3. Feasibility of population transfer: STIRAP and the coherent XFEL





$$|D\rangle = \frac{\Omega_s}{\sqrt{\Omega_p^2+\Omega_s^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2+\Omega_s^2}}|2\rangle$$

***Requirements:***

- **accelerated nuclei**
- **two-color**
- **full temporal coherence**

# STIRAP and the coherent XFEL

Seeded
XFEL

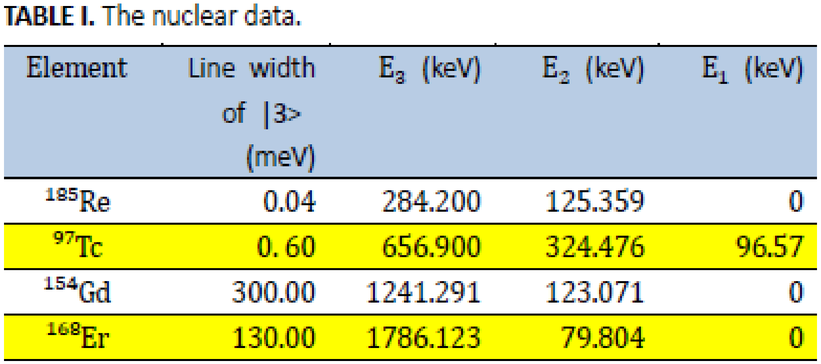
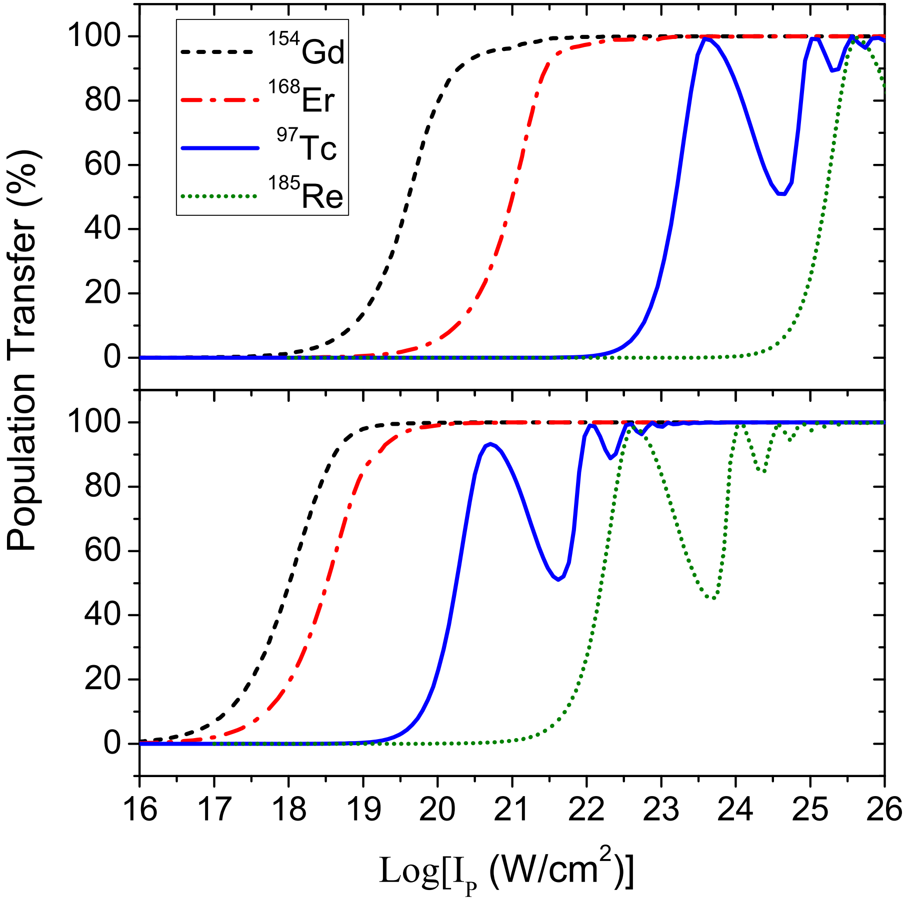


TABLE I. The nuclear data.

| Element | Line width of \|3> (meV) | $E_3$ (keV) | $E_2$ (keV) | $E_1$ (keV) |
|---|---|---|---|---|
| $^{185}$Re | 0.04 | 284.200 | 125.359 | 0 |
| $^{97}$Tc | 0. 60 | 656.900 | 324.476 | 96.57 |
| $^{154}$Gd | 300.00 | 1241.291 | 123.071 | 0 |
| $^{168}$Er | 130.00 | 1786.123 | 79.804 | 0 |

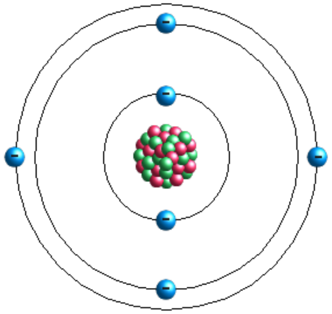
XFEL
O



W-T. Liao, A. Palffy and C. H. Keitel, arXiv:1011.4423v1 [quant-ph]

# 4. X-FEL light in interaction with highly charged ions or nuclei : population transfer and application in high-precision metrology

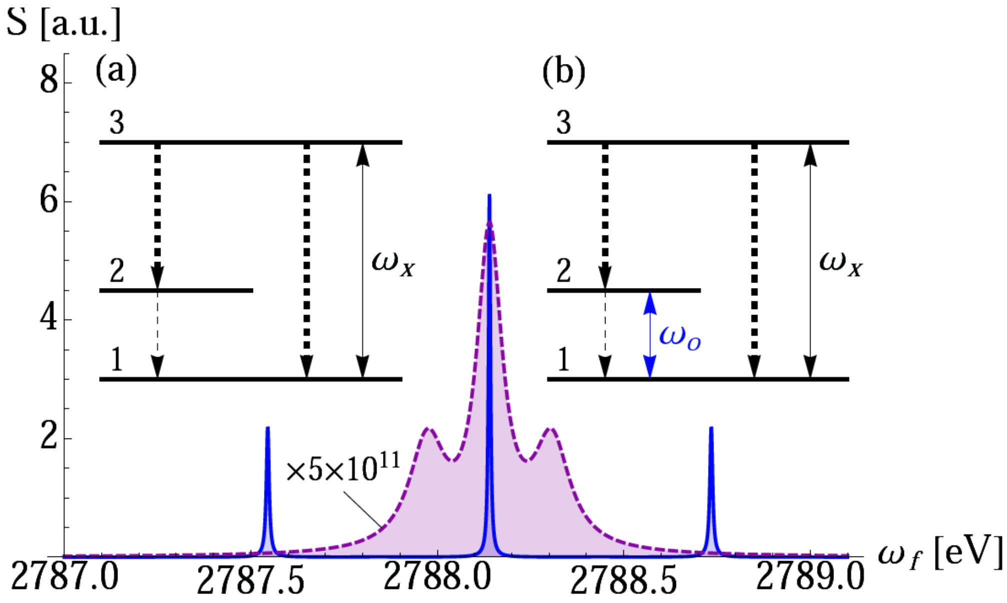
**Highly charged**
**(HCI):** relativistic
systems with a st
nuclear field



Transition data – transition energies and matrix elements - for such ions are required for the modeling of astrophysical or thermonuclear fusion plasmas

**Resonance fluorescence:** excitation by a resonant laser field (XFEL) + spontaneous decay

Line widths can be largely decreased by an additional optical driving: a new tool to measure the **transition matrix elements** of HCI



*Fluorescence photon spectrum for the 2s-2p*$_{3/2}$ *transition in lithiumlike* $^{209}$*Bi (Z=83). Red dashed line: the broad spectrum with x-ray driving between levels 1 and 3 (panel a). Blue line: the narrowed spectrum when an optical laser driving between the hyperfine-split levels 1 and 2 is switched on in addition (panel b)*

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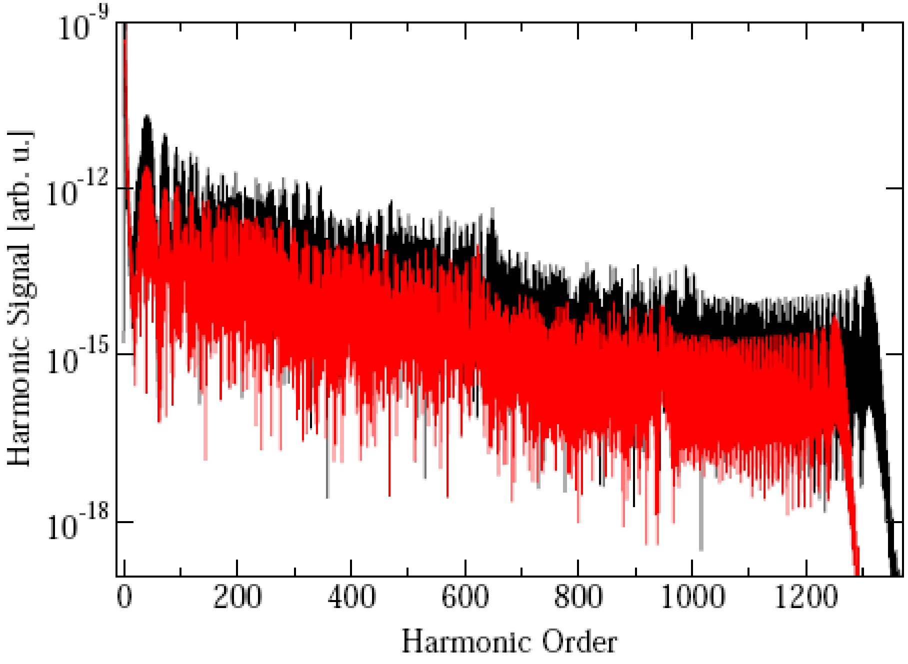
O. Postavaru, Z. Harman, and C. H. Keitel, Phys. Rev. Lett. **106**, 033001 (2011)

# 5. Nuclear mass and charge density via recollisions in muonic atoms

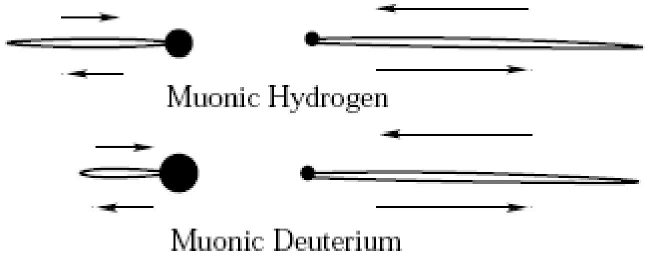
- Muonic atoms represent traditional tool for nuclear spectroscopy with atomic physics techniques (small Bohr radius since $m_\mu = 207\ m_e$ )
- Exploit laser-driven muon as dynamic nuclear probe in HHG process



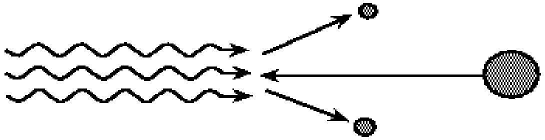
HHG spectra of muonic hydrogen (black) and deuterium (red) at 60 eV and $10^{23}$ W/cm$^2$

Muon in hydrogen/deuterium bound by 2.5 keV and electric field intensity of $4\text{x}10^{25}$ W/cm$^2$

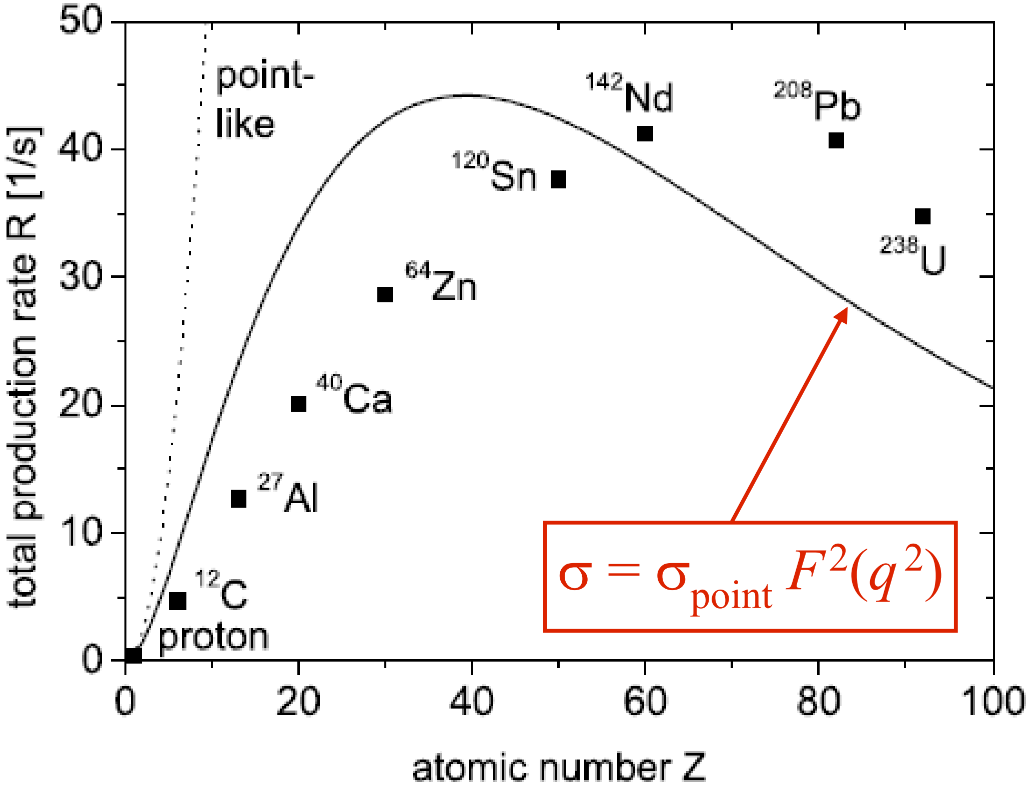
Need to consider relative motion; cutoff determined by reduced mass



A. Shahbaz, C. Müller, A. Staudt, T. Bürvenich, CHK, Phys. Rev. Lett. 98, 263901 (2007)



# 6. Nuclear form factors from muon creation rates in laser-ion collisions



$\sigma = \sigma_{\text{point}} F^2(q^2)$

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

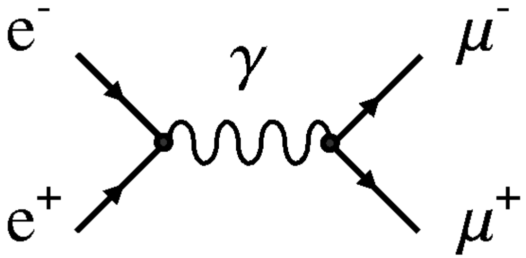
**HOWEVER:**

muons are created at typical distances ~ $\lambda_C$ =1.86 fm

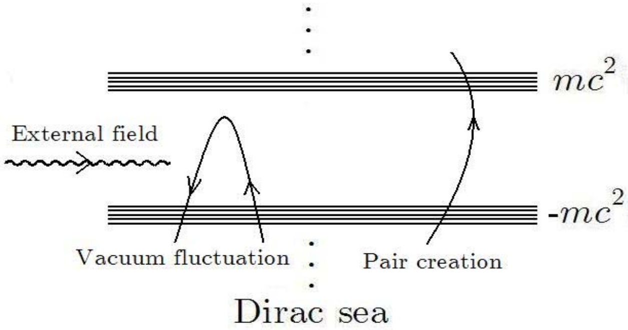
they only see a small part of the total nuclear charge within $R = 0.94$ fm $A^{1/3}$ ~ 3-5 fm

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)



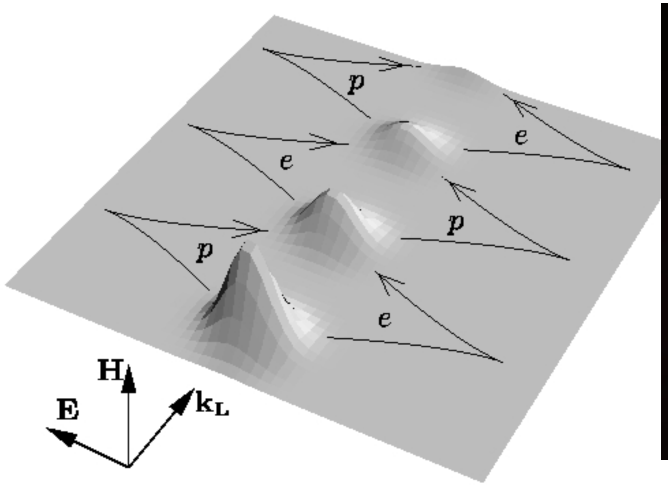
# Conclusions

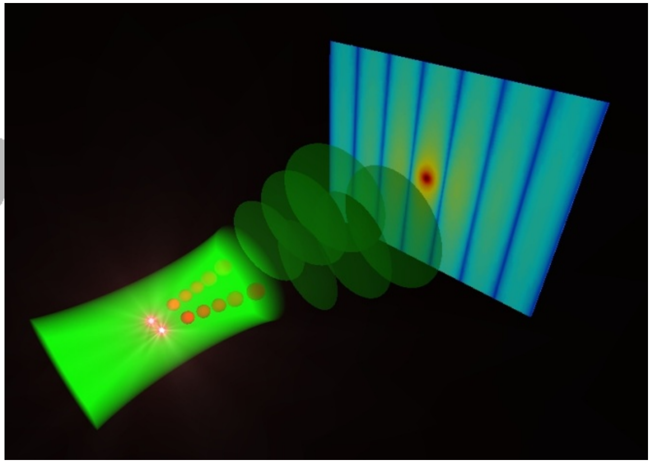


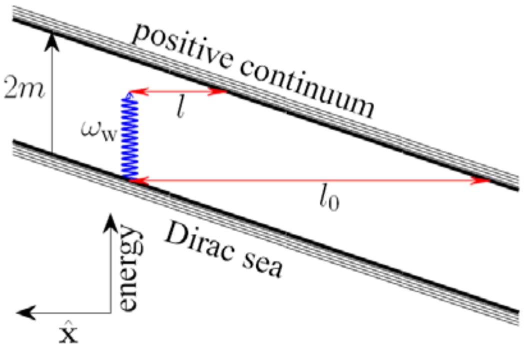
**Relativistic Quantum Dynamics:** Relativistic Ionisation & Recollisions; Dynamics Control & Ultrashort Time Scales

**High-energy Physics:** GeV laser colliders, Muon Production, Vacuum Nonlinearities & Pair creation, Nuclear Processes

**Radiative Reaction:** classical & quantum regime, plasma dynamics, relevant already for scenaria today



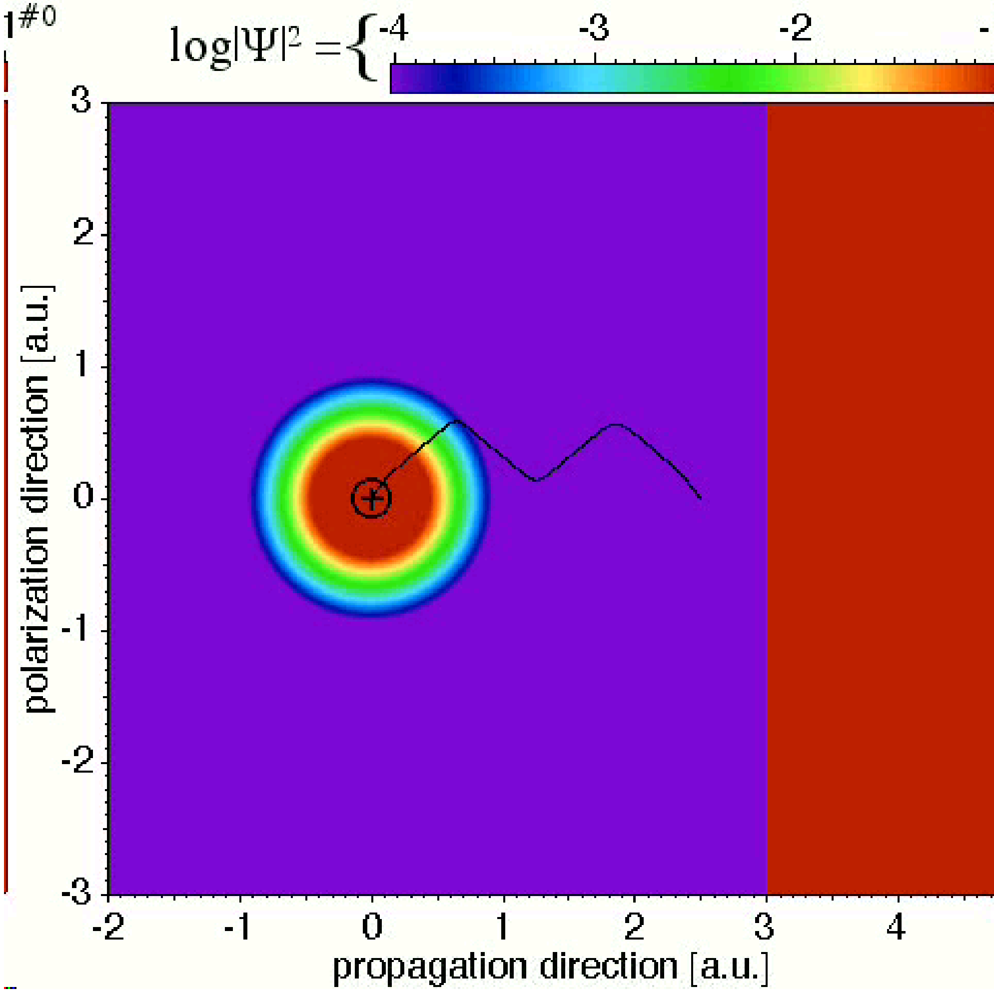




# Laser colliders: various contributions to enhance relativistic recollisions

1. Preaccelerated ions that counter-propagate the laser field… G. Mocken et al., J. Phys. B **37**, L275 (2004)

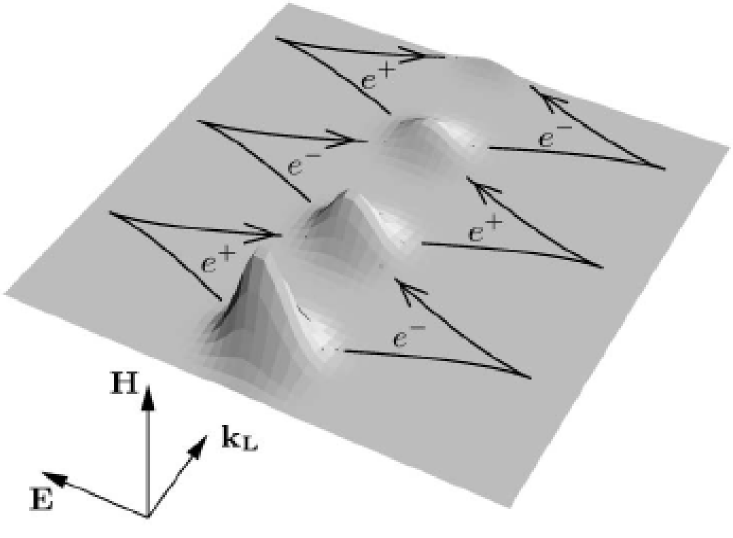
C.C. Chirila *et al*., Phys. Rev. Lett. **93**, 243603 (2004).



# Existing attempts to enhance relativistic recollisions

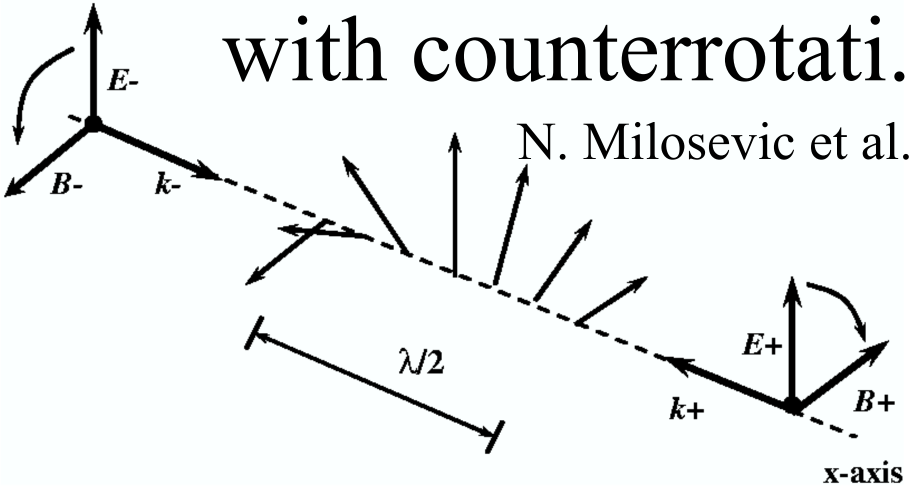
1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…

B. Henrich et al., Phys. Rev. Lett.**93**, 013601 (2004).



# Existing attempts to enhance relativistic recollisions

1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…
3. Applying two counterprop. laser beams with counterrotati. circular polarization



N. Milosevic et al., Phys. Rev. Lett. **92**, 013002 (2004).

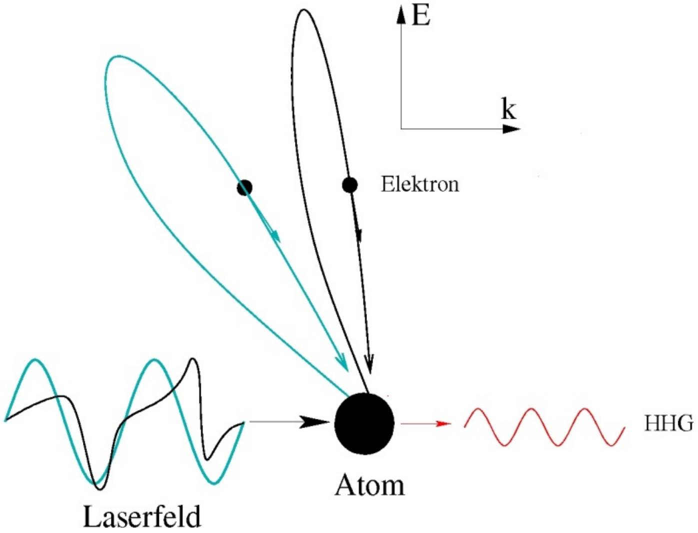
# Existing attempts to enhance relativistic recollisions

1. Using relativistic ions that counter-propagate the laser field…
2. Using the ionization rescattering process of positronium instead of atoms…
3. Applying two counterpropagating laser beams with equally handed circular polarization…
4. Changing the pulse shape

Attosecond pulses avoid drift
M. Klaiber et al, PRA 051803 (R) (2006)

give compensating momentum kick
M. Klaiber et al. 33, Opt. Lett.  411 (2008)

With beams: crossed linear fields favorable
Liu et al., New J. Phys. 11, 105045 (2009)



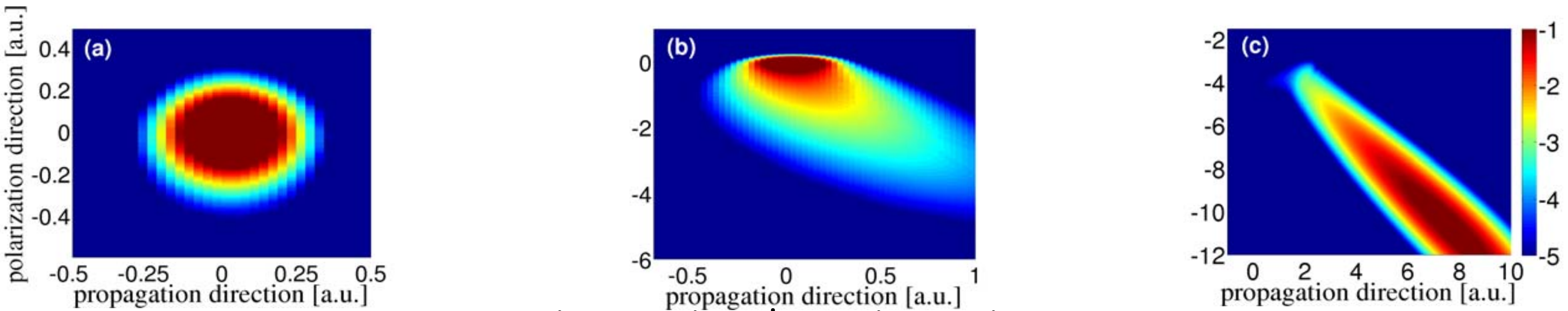
# QED cascades in intense laser beams

- Analysis of electron trajectories in counterpropagating laser beams has shown the possibility of prolific electron-positron pair production already at laser intensities of the order of $10^{24}$ W/cm$^2$

A. R. Bell and J. G. Kirk, Phys. Rev. Lett. **101**, 200403 (2008)

- In PRL **101**, 200403 (2008) electrons are assumed to be already present in the region where the two laser beams collide. What happens if no electrons are present in the interaction region?

# Ionisation: Characterising intense pulses with highly charged ions

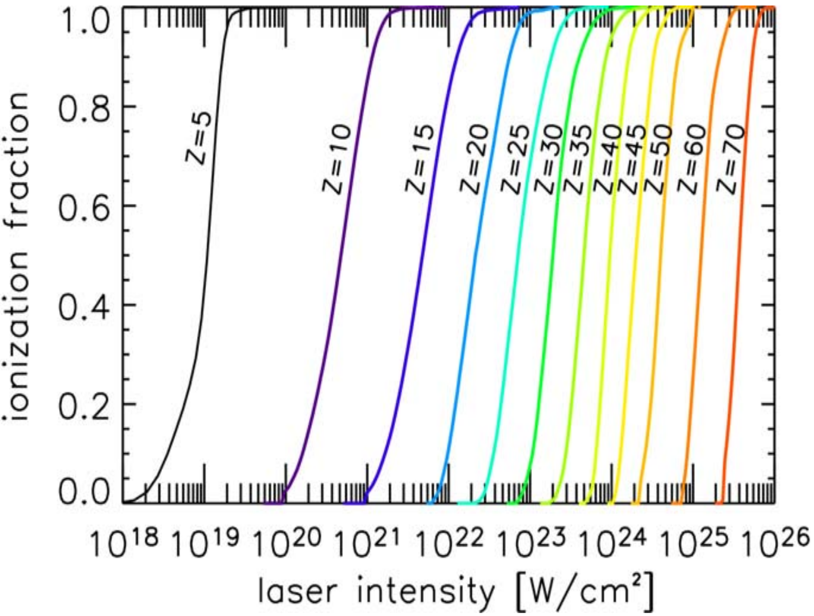


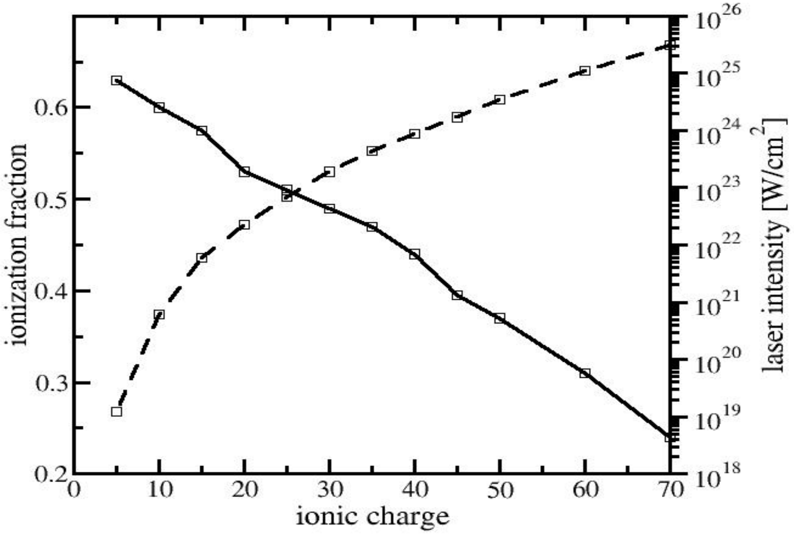
-> increasing laser intensity ->

Directions and yields of ionisation are characteristic for laser intensity and ionic charge

=> Sensitive means of measuring extremely intense laser intensities

H G Hetzheim and C H Keitel, Phys. Rev. Lett. 102, 083003 (2009)

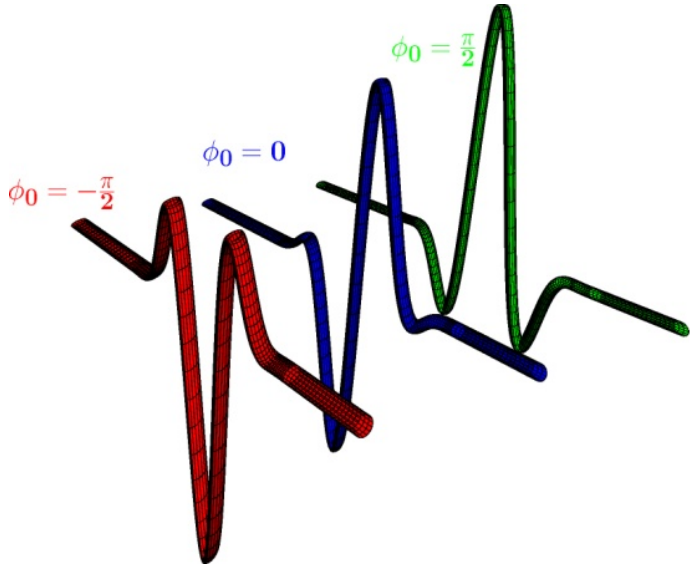


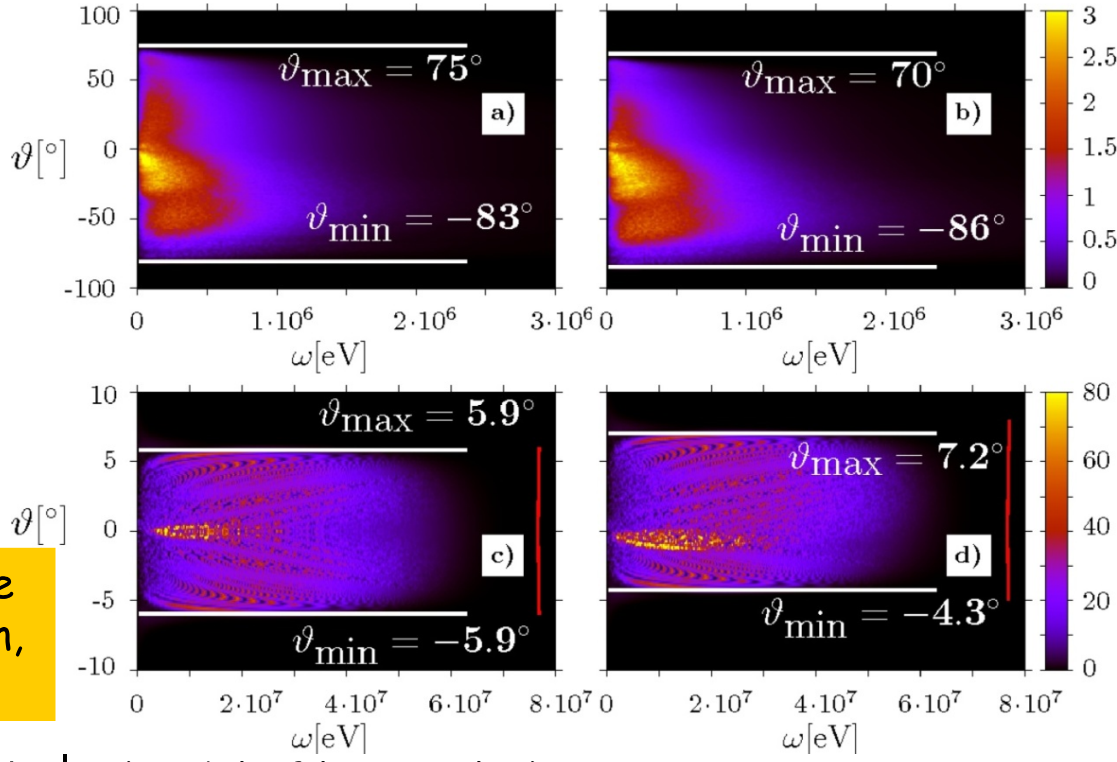


Ionization fraction for several different hydrogen-like ions Z as a function of the maximal laser intensity for single-cycle square-shaped laser pulse; wavelength 1054 nm.

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.

# Radiation: Carrier Envelope Phase Measurement





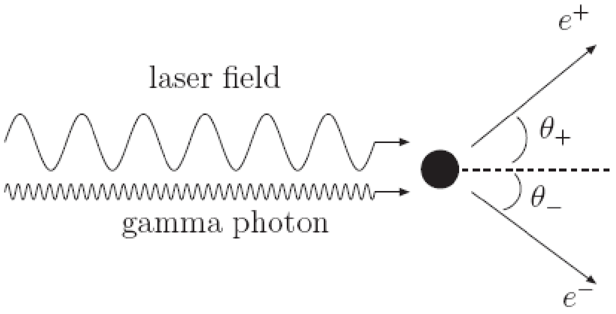
Carrier envelope phase is measurable via spectra of an interacting electron, especially their boundaries

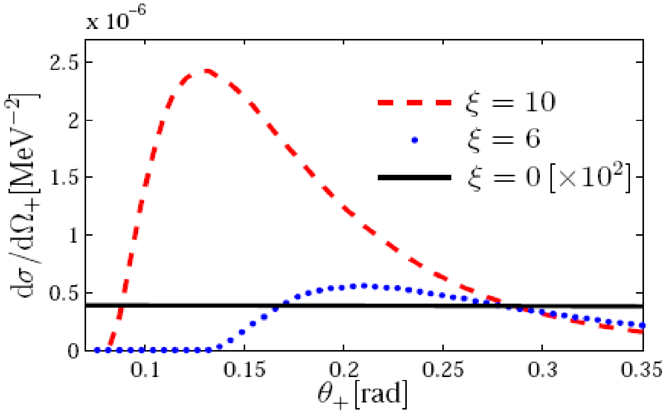
$$\psi_A(\phi,\phi_0)=\sin^4\left(\frac{\phi}{4}\right)\sin(\phi+\phi_0)\quad \phi\in\left[0,4\pi\right]$$ (model of laser pulse)

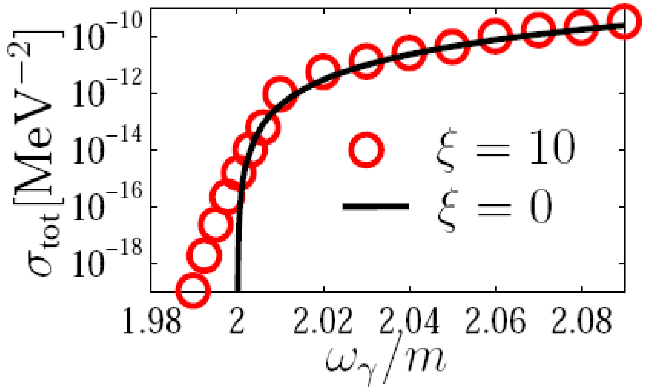
**Photon energy emission spectra** in $\mathrm{sr}^{-1}$ for above pulse model and an electron bunch with central energy $\varepsilon_{\mathrm{mean}}$ = 26 MeV spreaded by $\Delta\varepsilon$=2% and transversal and horizontal beam waists $w_x = w_y$ = 5μm and $w_z$ = 8μm, respectively scattering from a focussed beam (Gaussian) with central frequency $\omega$=1 eV and peak intensity parameter $\xi$ = 100 focussed to $w_0$ = 2μm (parts a),b)) with a CEP of $\phi_0=-\pi/10$ (part a)) and $\phi_0=-\pi/5$ (part b)) (CLASSICAL REGIME)
and a single electron with energy $\varepsilon$ = 7.5 MeV scattering from a plane wave pulse (parts c),d)) with central frequency $\omega$=50 eV and an intensity parameter $\xi$ = 20 with a CEP of $\phi_0$=0 (part c)) and $\phi_0=\pi/4$ (part d)) (QUANTUM REGIME)

F. Mackenroth, A. Di Piazza, C.H. Keitel, Phys. Rev. Lett 105, 063903 (2010)

# Laser Channeling of Bethe-Heitler Pairs







Laser frequency $\omega = 10 eV$

Gamma photon energy $\omega_\gamma = 1.25 MeV$

Peak angle $\theta_+ \approx 1/\xi$

(here at ca. 6° with width ca. 4°)

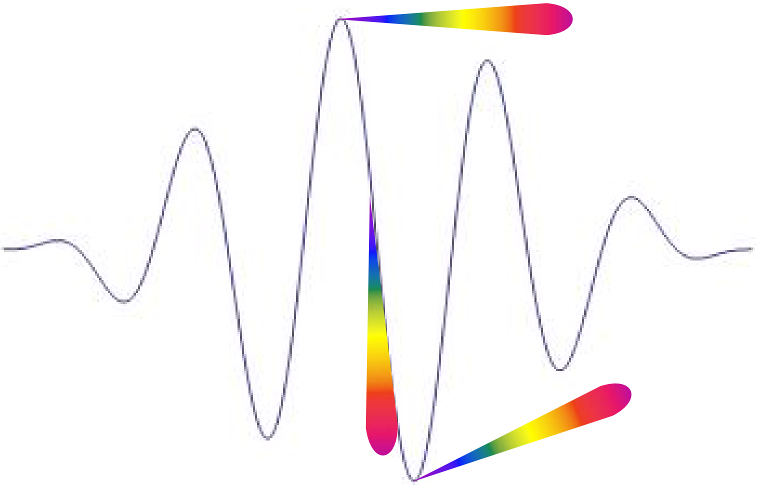
$\xi$ : Classical nonlin. parameter

$\xi = 10 \leftrightarrow I = 10^{22} W/cm^2$

Erik Lötstedt, Ulrich D. Jentschura, and Christoph H. Keitel, PRL 101, 203001 (2008)

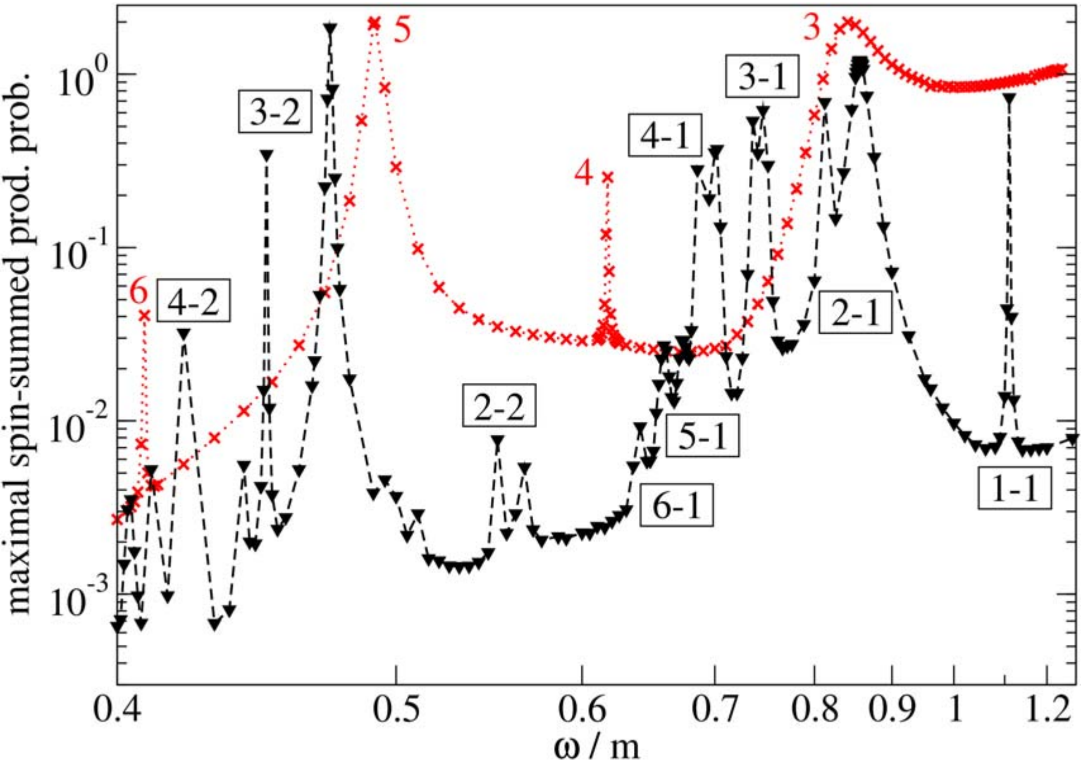
# Quantum radiation dominated regime

- At the same laser intensity, if one employs an electron beam with energy of 1 GeV, one can enter the so-called Quantum Radiation Dominated Regime (QRDR)
- In the QRDR the electron emits many photons incoherently already in one laser period and in each photon emission recoil is in principle significant



A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, Phys. Rev. Lett. 105, 220403 (2010)

# Magnetic-field effects in electron-positron pair creation by counter propagating high-frequency laser pulses



New resonances occur, due to the non vanishing photon momentum

$$\omega = \frac{m^*}{2}\frac{n_+ + n_-}{n_+ n_-}$$

$$m^* \approx 1.11m$$

$$\xi = 1$$

$n_+$ : Number of absorbed laser photons from the left

$n_-$ : Number of absorbed laser photons from the right

red curve: oscillating electric field

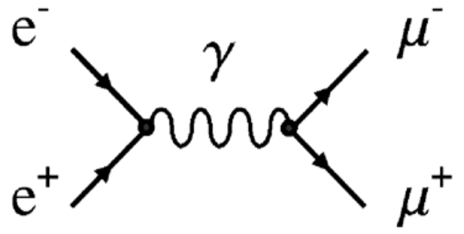
black curve: including magnetic field component

Resonance peaks are split into doublets due to spin-orbit coupling and Compton scattering.

M. Ruf, G.R. Mocken, C. Müller, K.Z. Hatsagortsyan, and C.H. Keitel, Phys. Rev. Lett. 102, 080402 (2009)

# Theory of laser-driven muon creation

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



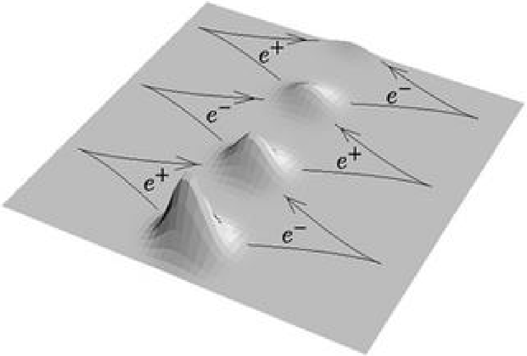
$$S_{e^+e^-\to\mu^+\mu^-} = -\mathrm{i}\alpha \int d^4x\, d^4y\, \overline{\Psi}_{p_+}(x)\gamma^\mu\Psi_{p_-}(x) \times D_{\mu\nu}(x-y)\overline{\Psi}_{P_-}(y)\gamma^\nu\Psi_{P_+}(y)$$

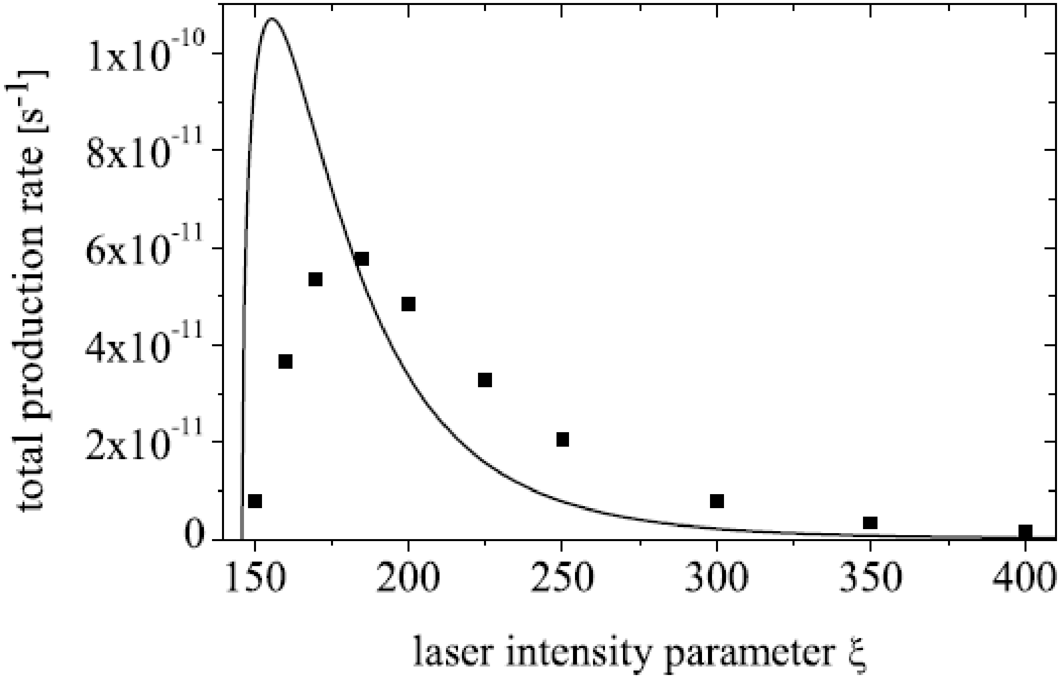
Average over the momentum distribution in the Ps ground state:

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

# 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

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

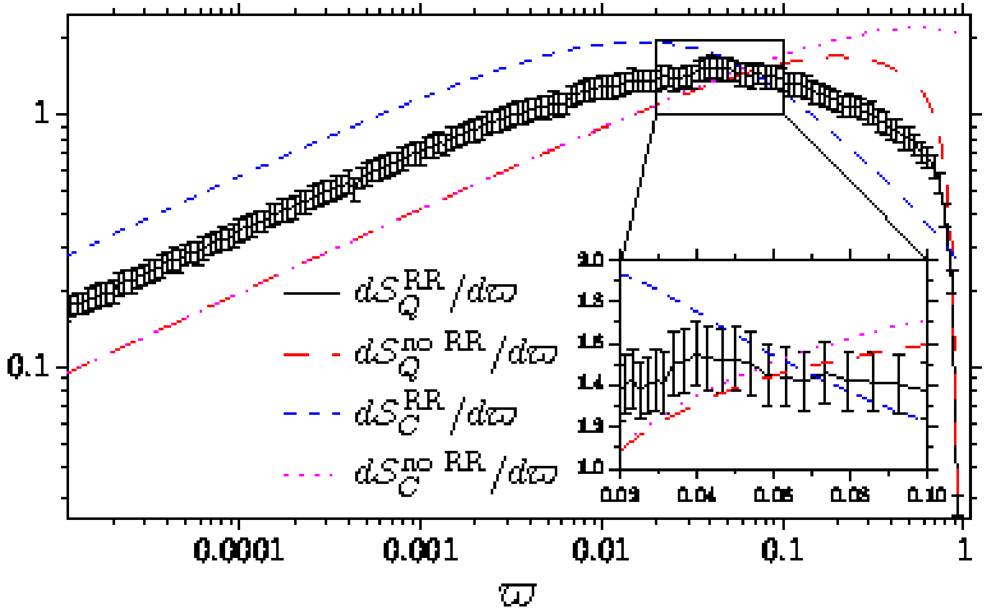
Process observable at high Ps density ($10^{18}$ cm$^{-3}$) and laser rep rate (1 Hz)

Solid line: analytical approximation
Black squares: numerical results

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

- The photon spectra are calculated from the emission of n incoherent photons taking into account the quantum recoil at each emission

- If the laser intensity is I=5*10$^{22}$ W/cm$^{2}$ and the electron energy is 1 GeV, we see the importance of both quantum and radiation reaction effects in emission spectra



# QED cascades in intense laser beams

- Analysis of electron trajectories in counterpropagating laser beams has shown the possibility of prolific electron-positron pair production already at laser intensities of the order of $10^{24}$ W/cm$^2$

A. R. Bell and J. G. Kirk, Phys. Rev. Lett. **101**, 200403 (2008)

- In PRL **101**, 200403 (2008) electrons are assumed to be already present in the region where the two laser beams collide. What happens if no electrons are present in the interaction region?

- Recent results indicate that even the production of a single electron-positron pair may start an avalanche process, which would limit the maximum reachable laser intensity to about $10^{25}$ W/cm$^2$

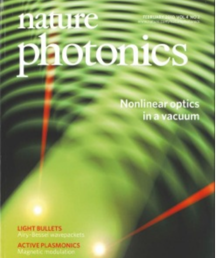
A.M. Fedotov, N. B. Narozhny, G. Mourou, G. Korn,
Phys. Rev. Lett. **105**, 080402 (2010)

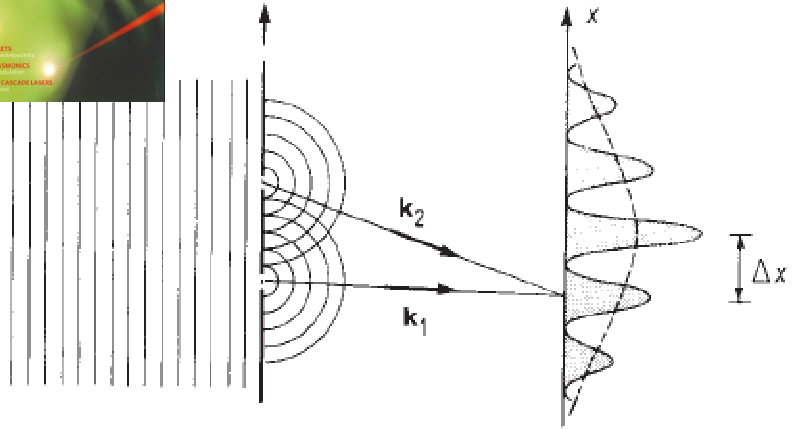
- However, results in the collision of a 46 GeV electron beam with a laser beam of intensity $5*10^{22}$ W/cm$^2$ show that in this case the avalanche process is suppressed by radiation reaction effects

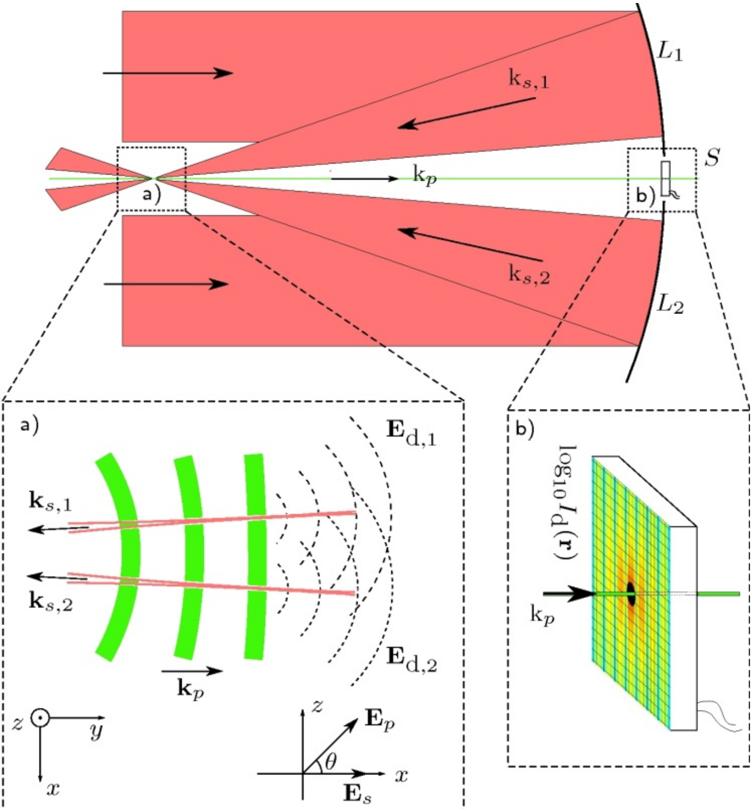
I. V. Sokolov, N. M. Naumova, J. A. Nees, G. Mourou,
Phys. Rev. Lett. 105, 196005 (2010)

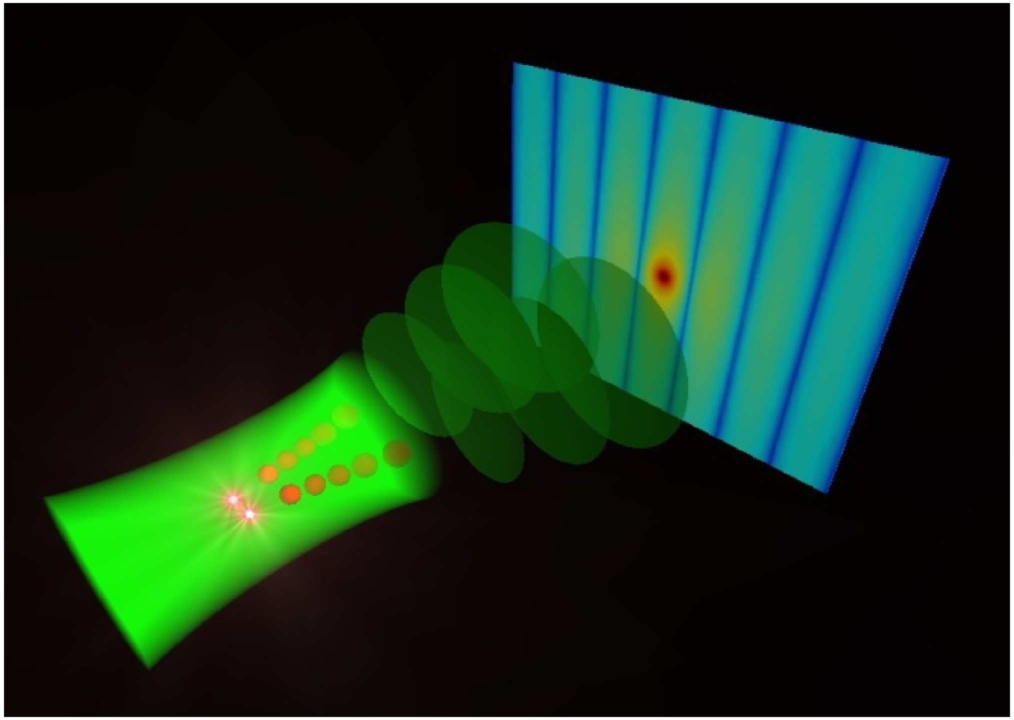
- The availability of laser beams with intensities exceeding $10^{24}$ W/cm$^2$ will help in clarifying this aspect of QED cascades and consequently the fundamental issue of the maximum reachable intensity

# A matterless double slit







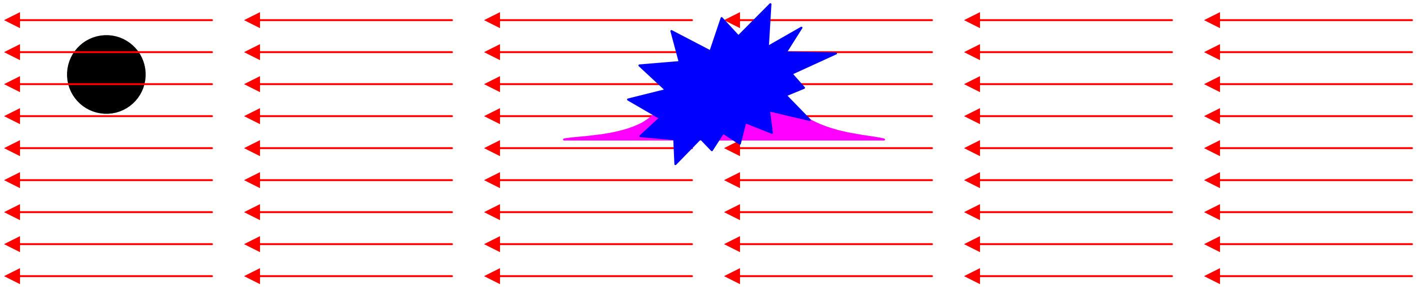


Interaction via vacuum fluctuations induces two different paths for quantum interference to occur

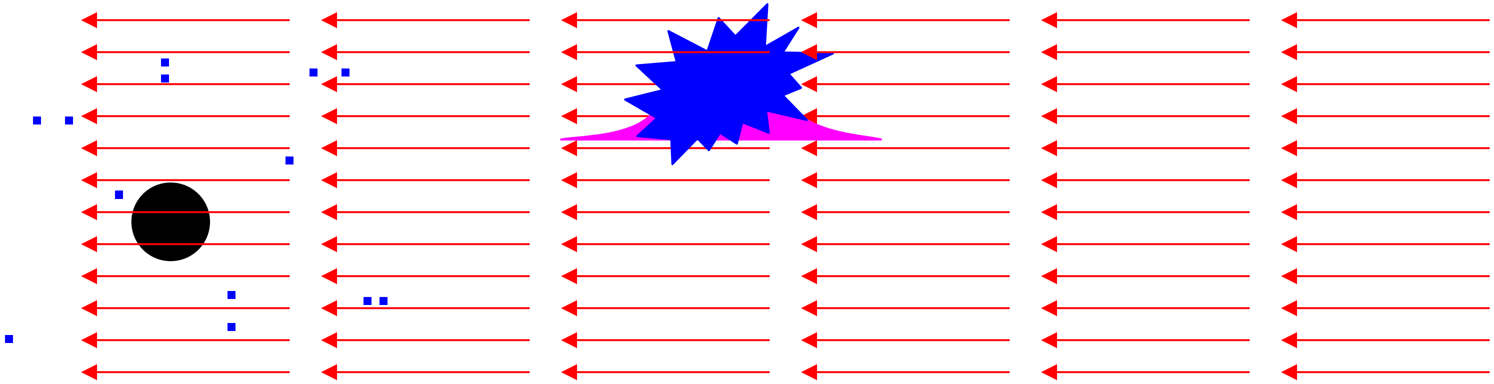
*Ben King, Antonio di Piazza, Christoph H. Keitel, Nature Photonics 4*, 92 (2010)

# Photon merging in laser-proton collisions

Multiphoton Thomson scattering (laser photons are merged by the proton charge)



Laser-photon merging (laser photons are merged by the virtual electron-positron pairs)



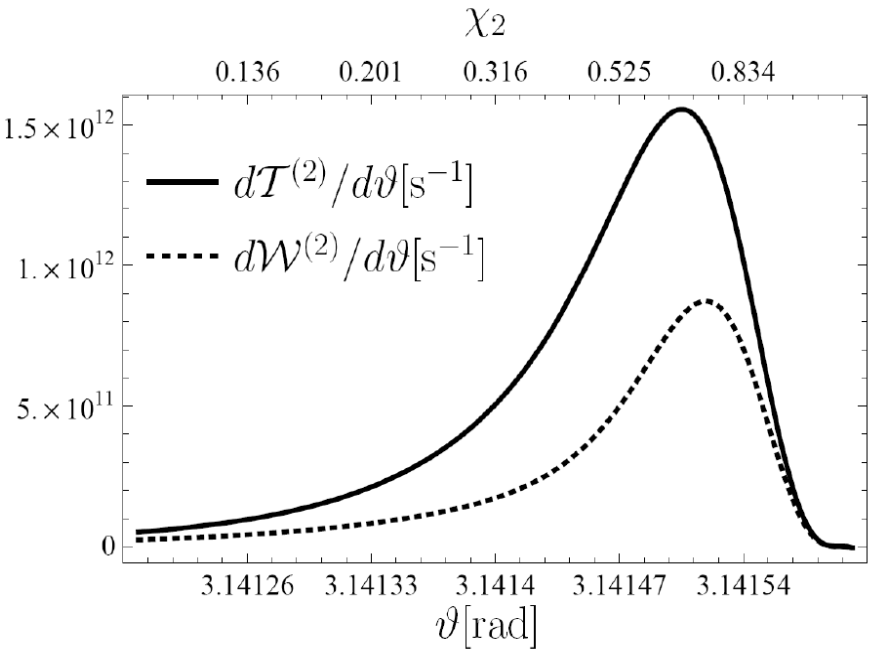
# Numerical results I (LHC)

Table-top laser parameters

(OPCPA):

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

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

# Numerical results II (ELI)

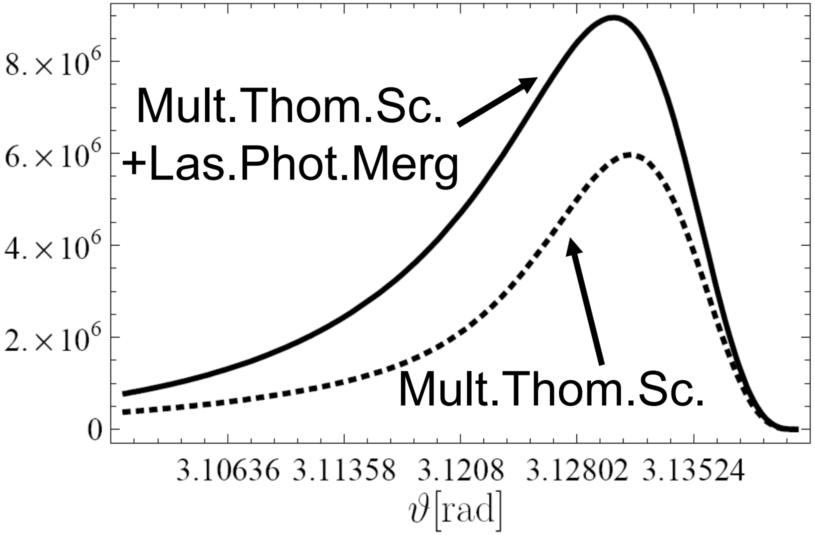
Strong laser parameters

(Tsakiris et al. NJP **8**, 19 (2006)):

I=2.5*$10^{24}$ W/cm$^2$, $\tau$=5 fs, $\sigma$=5 $\mu$m

Attosecond pulse parameters:

$\omega_0$=200 eV, $\tau$=38 as



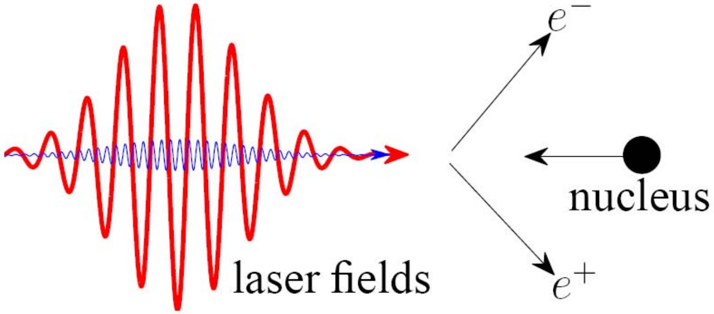
Proton beam parameters (Laser-Piston regime): $E_p$=50 GeV, $N_{bunch}$=2*$10^{12}$, bunch transverse radius=5 $\mu$m, bunch duration=20 fs

- Total number of photons in one shot via 2-photon Thomson scattering: 6.9
- Total number of photons in one shot via 2-photon merging: 5.2
- Total number of photons in one shot via both processes: 12.1

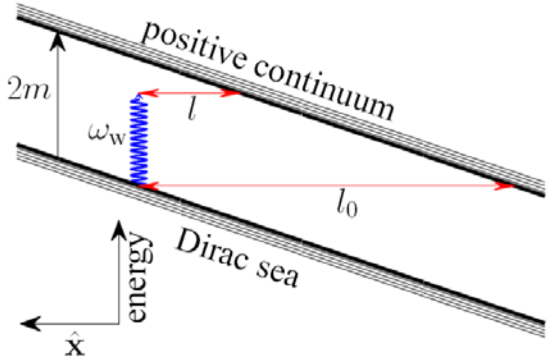
A. Di Piazza, K. Z. Hatsagortsyan and C. H. Keitel, PRA **78**, 062109 (2008)

- 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)

# Critical fields

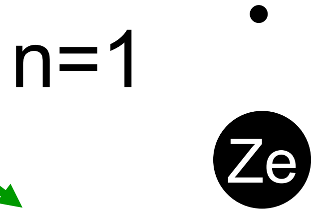
Since virtual particles live for a very short time, then very strong fields are needed to make apparent the effects of their presence

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

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

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

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



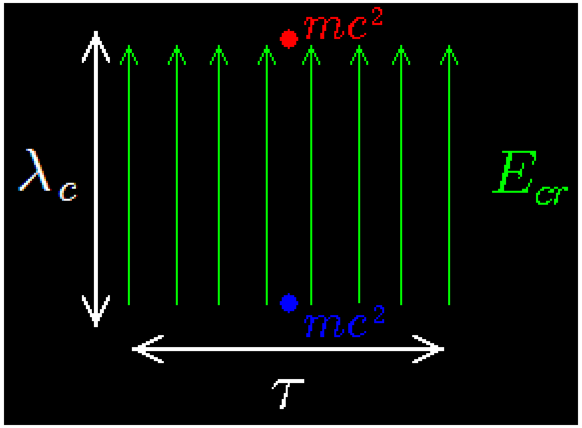
$$d=\frac{a_0}{Z}=\frac{\lambda_c}{Z\alpha}$$

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

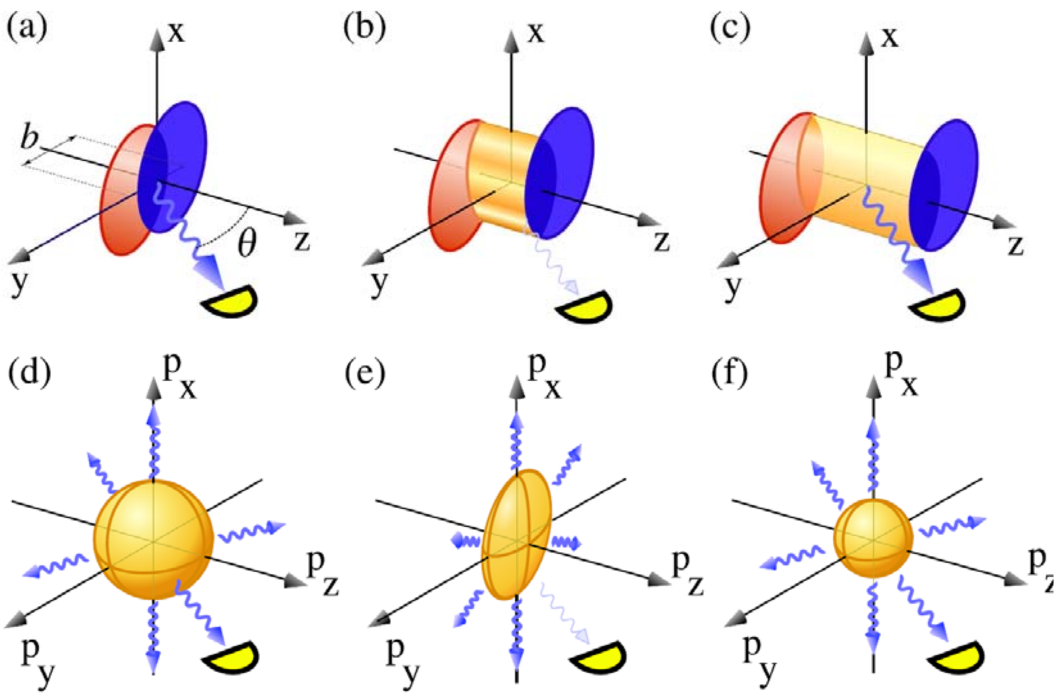
Physical meaning of the critical fields:

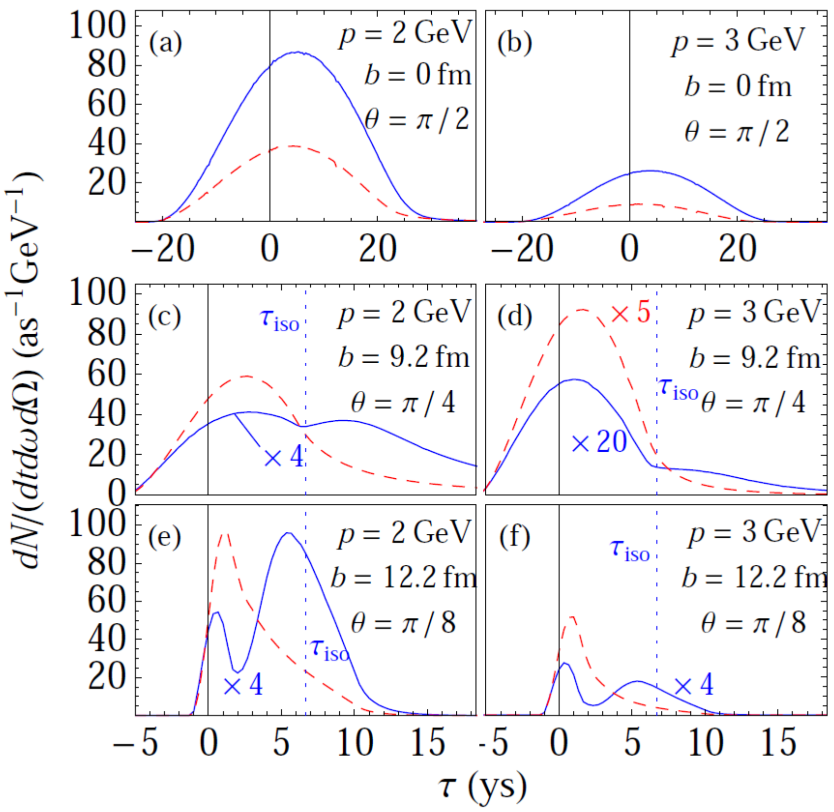
$$\frac{\hbar}{mc}\times eE_{cr}\sim mc^2$$

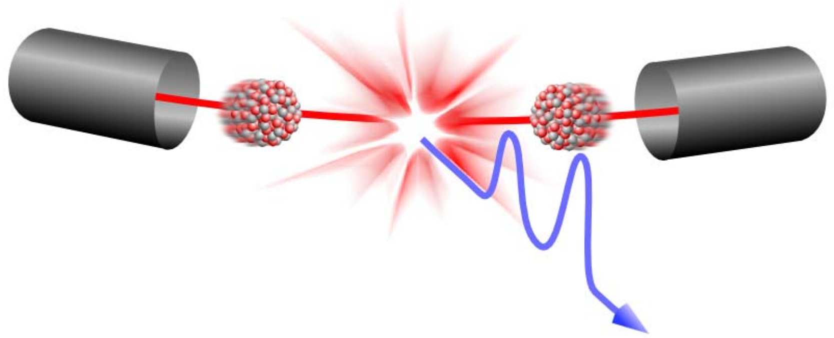
$$\frac{e\hbar}{mc}\times B_{cr}\sim mc^2$$

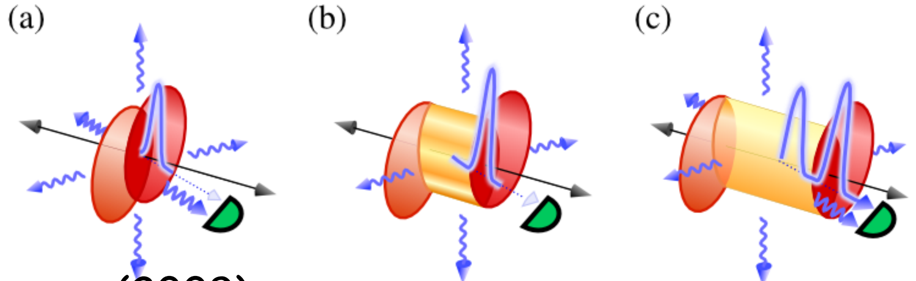


# Yoctosecond pulses from quark gluon plasma









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

- One can solve Maxwell equations exactly with the Green function method

$$\begin{tikzcd}
m_0 \frac{du^\mu}{ds} = -eF_T^{\mu\nu} u_\nu & \\
\partial_\mu F_T^{\mu\nu} = -e \int ds\, \delta(x - x(s)) u^\nu \arrow[r] & F_T^{\mu\nu}(x) = F^{\mu\nu}(x) + F_S^{\mu\nu}(x) \arrow[ul]
\end{tikzcd}$$

and re-substitute the total field into the Lorentz equation:

$$(m_0 + \delta m)\frac{du^\mu}{ds} = -eF^{\mu\nu}u_\nu + \frac{2}{3}\alpha\left(\frac{d^2u^\mu}{ds^2} + \frac{du^\nu}{ds}\frac{du_\nu}{ds}u^\mu\right)$$

- By renormalizing the electron mass (note that δm is infinite!) one obtains the Lorentz-Abraham-Dirac equation

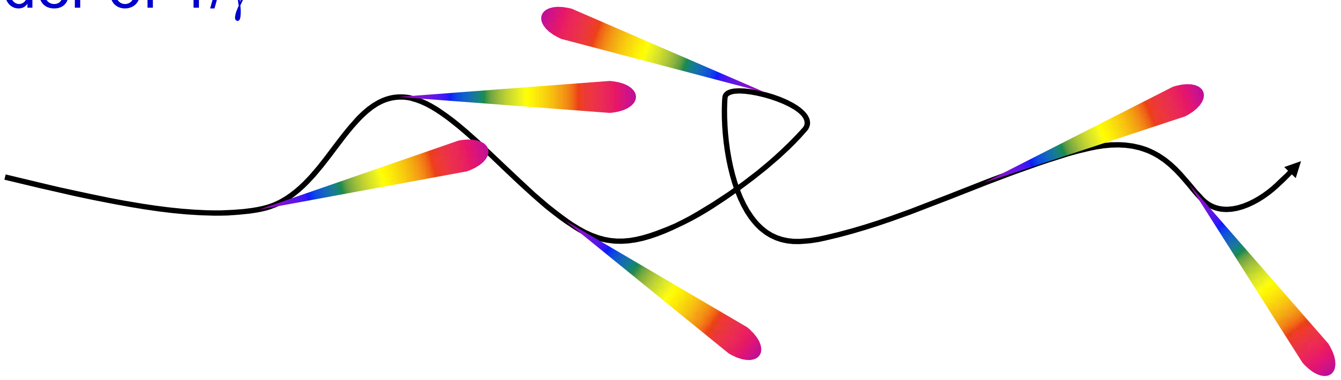
$$m\frac{du^\mu}{ds} = -eF^{\mu\nu}u_\nu + \frac{2}{3}\alpha\left(\frac{d^2u^\mu}{ds^2} + \frac{du^\nu}{ds}\frac{du_\nu}{ds}u^\mu\right)$$

- Radiation field emitted by an electron (Landau and Lifshitz 1947):

$$\mathbf{E}_{\mathrm{rad}}(\mathbf{r},t) = -e\,\frac{\mathbf{n}\times[(\mathbf{n}-\boldsymbol{\beta})]\times\dot{\boldsymbol{\beta}}}{(1-\mathbf{n}\cdot\boldsymbol{\beta})^3\mathcal{R}}\bigg|_{\mathrm{ret}}$$

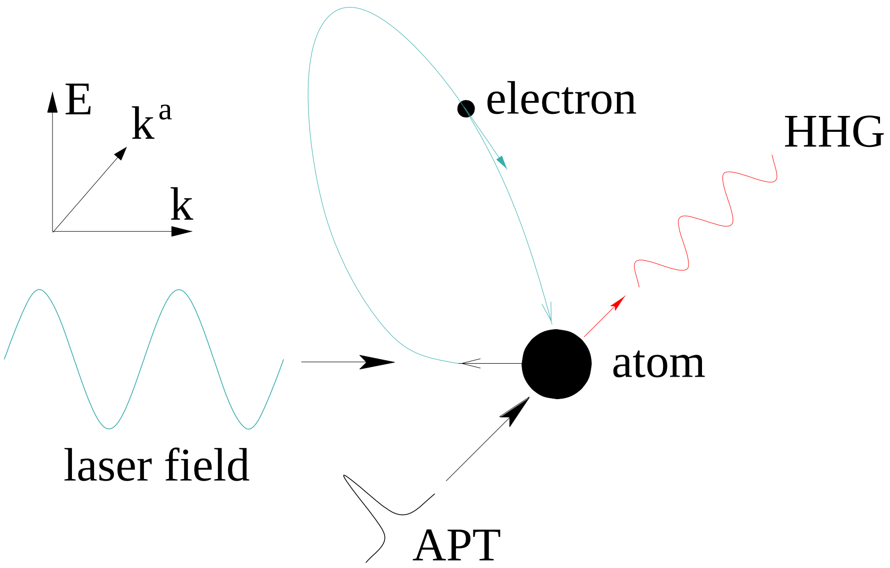
$$\mathbf{B}_{\mathrm{rad}}(\mathbf{r},t) = \mathbf{n}\times\mathbf{E}_{\mathrm{rad}}(\mathbf{r},t)$$

- Main features of the radiation emitted by an ultra-relativistic electron:
  - radiation emitted at each instant mainly along the electron's velocity within a cone with an aperture of the order of $1/\gamma$

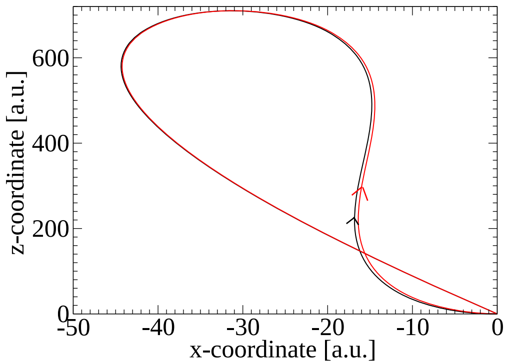


  - radiation emitted at each instant with frequencies up to $\omega_c=3\gamma^3/\rho$, with $\rho$ the curvature radius

# Relativistic HHG with IR laser & APT



Control of the ionization energy and phase by APT



Electron can recollide if it is tunneled with an initial momentum in the laser propagation direction: $p_{z0} \approx -mc\xi^2/4$

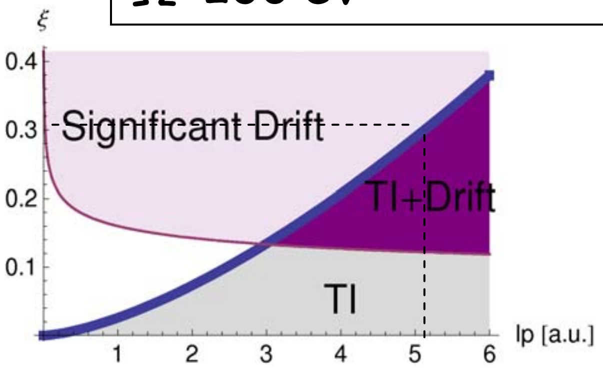
ξ≈0.3; Ip=5.29 a.u. (Ar$^{7+}$)

Ω=230 eV

via tunneling: $W \sim \exp\left\{-\frac{2\left(2mI_p + P_{z0}^2\right)^{3/2}}{3me\hbar\left|E(\eta_0)\right|}\right\}$

with APT: $\varepsilon_0 = \hbar\Omega - I_p$

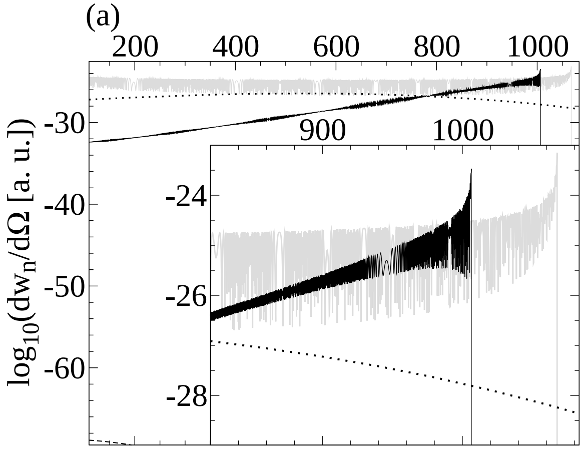
$$\varepsilon_0 \approx p_d^2/2m \approx mc^2\xi^4/32$$



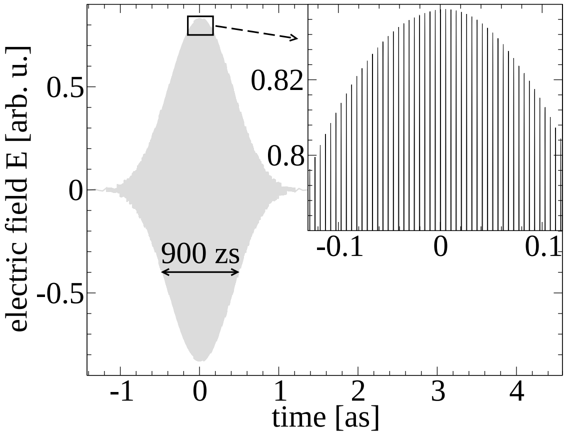
Cutoff energy = 3.17 Up ≈ 39 keV

# Zeptosecond γ-ray pulses

1 MeV cutoff

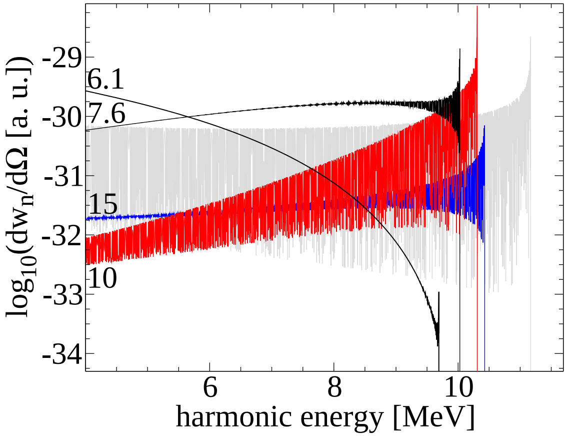


4 keV window



E=88 au, w=0.05, hydrogenic Mg

10 MeV cutoff



E=325 au, w=0.05 au, hydrogenic Ar

Zeptosecond pulse is feasible due to:

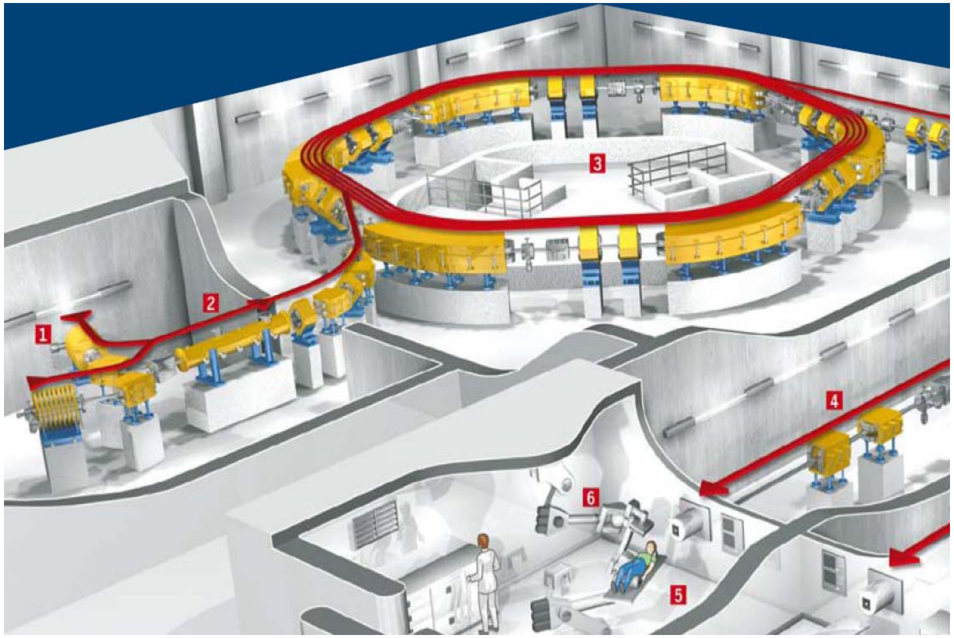
- main contribution for HHG from one trajectory
- harmonic chirp is not significant

Of interest for time-resolved nuclear spectroscopy

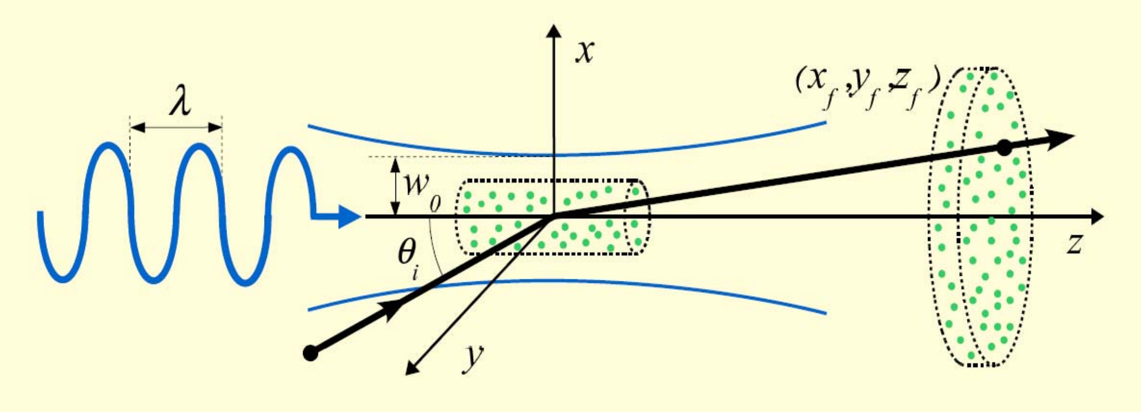
Conventional acceleration of ions: synchrotron

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