A space-time resolved view of the Schwinger effect

Florian Hebenstreit

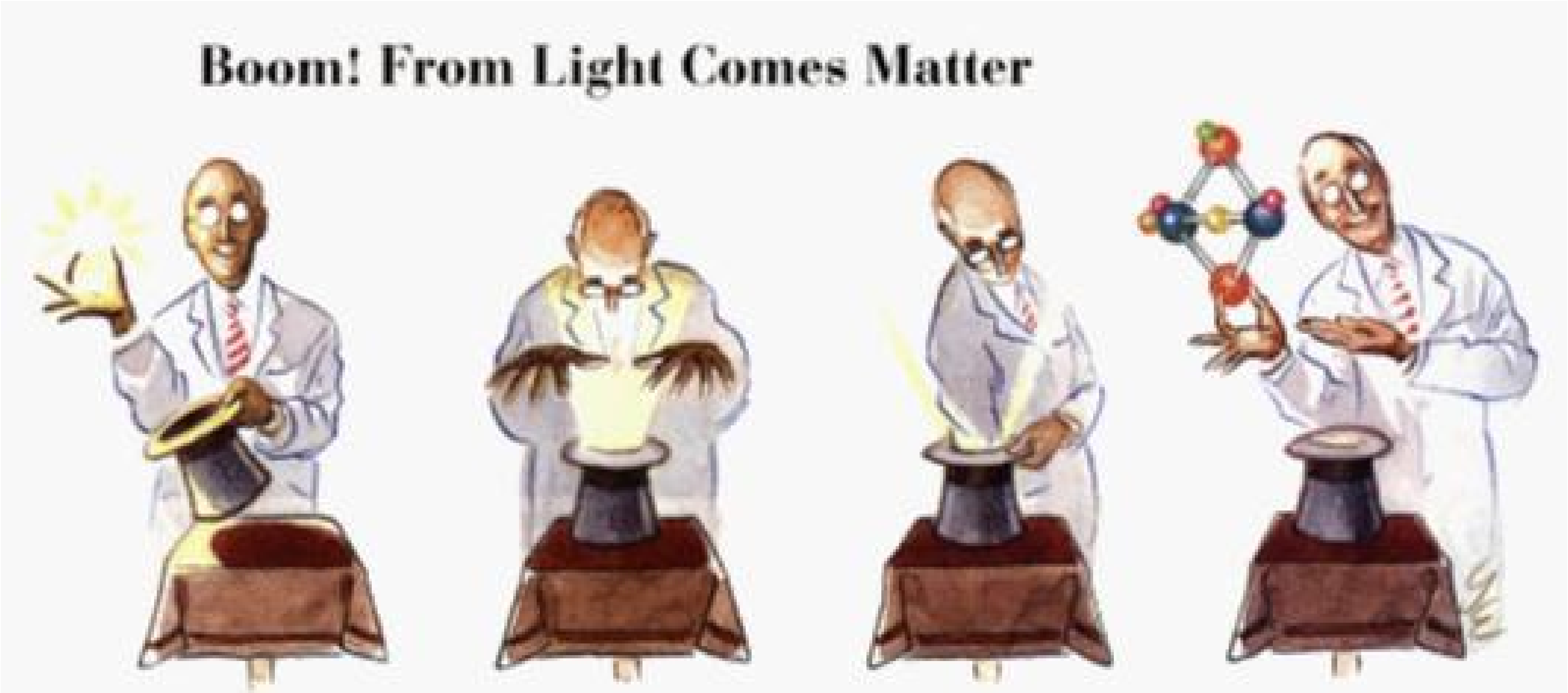
Institute for Theoretical Physics, Heidelberg University

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Unterstützt von / Supported by
Alexander von Humboldt Stiftung/Foundation

Frontiers of intense laser physics – KITP – 07 / 23 / 2014

Motivation: An artist's view



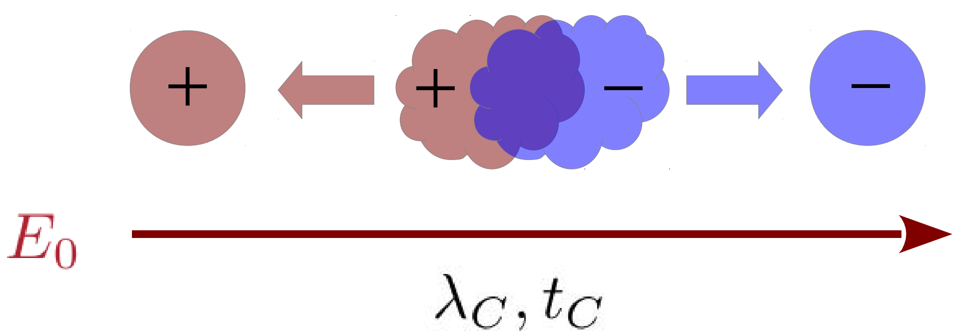
[Gil Eisner]

Motivation: Schwinger effect

- QED vacuum is unstable in the presence of external fields

  vacuum: no particles
  vacuum + electric field: unstable vacuum (particle creation)

- electron-positron pair creation ⟶ delocalization of charges



$$e E_0 \lambda_C \sim m$$
$$\Rightarrow E_0 \sim m^2/e$$

- analytic solution for vacuum decay rate in a static electric field

$$\mathcal{P}[vac] = \frac{(eE_0)^2}{4\pi^3} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n\pi m^2}{eE_0}\right)$$

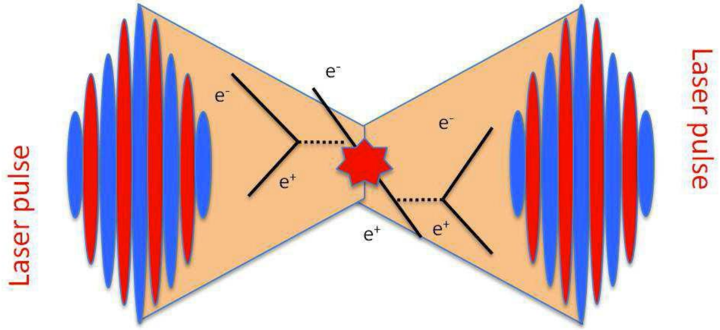
[Schwinger, PR 82 (1951)]

Motivation: Schwinger effect

- experimental prospects (all optical): colliding laser pulses

  * Extreme Light Infrastructure (optical)

  * European XFEL (X-ray)



[Bulanov et al.]

space-time dependent electromagnetic fields

- effect of temporal/spatial structure: momentum spectrum...
- effect of electromagnetic fields: instabilities...
- effect of created particles (backreaction): QED avalanches...

Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

Quantum electrodynamics

- theory of the interaction of matter (electrons) with light (photons)

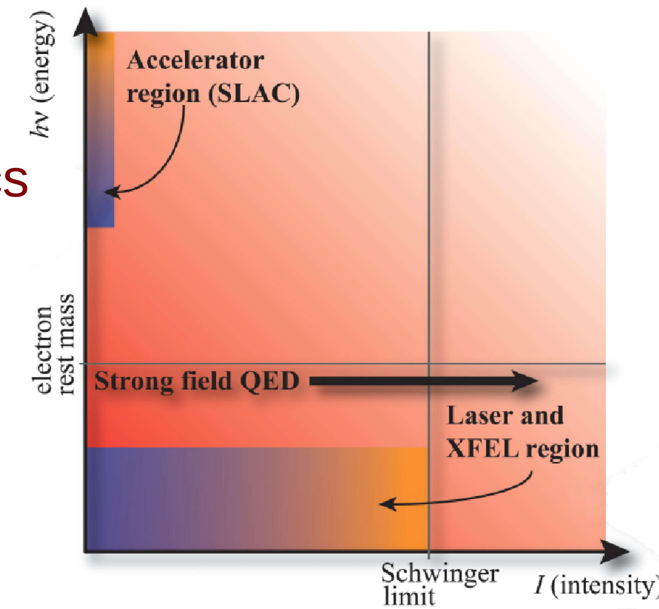
$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - g\bar{\psi}A\!\!\!/\psi$$

- perturbative QED

low intensity – high energy: accelerator physics

- strong field QED

high intensity – low energy: laser physics



[Marklund, Lundin]

Non-equilibrium quantum field theory

time evolution: initial value problem in QFT

$$Z = \int \mathcal{D}\varphi \, e^{iS[\varphi]}$$

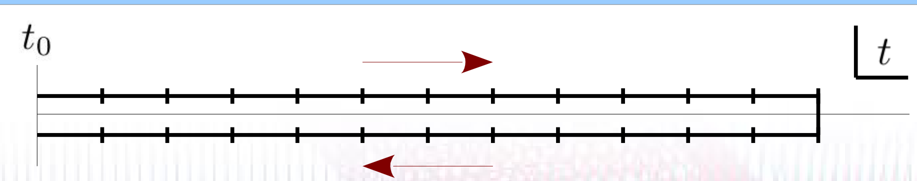
no probability measure
(sign problem!)

- why not use pertubation theory? **SECULARITY**
- non-secular approximation of the generating functional?!

$$Z[J,\eta,\bar\eta] = \mathrm{Tr}\left[\hat\rho(t_0) T_{\mathcal{C}} \exp\left(i \int_{\mathcal{C}} J^\mu A_\mu + \bar\psi\,\eta + \bar\eta\,\psi \right)\right]$$

density matrix at initial time

time-ordering on the Schwinger-Keldysh contour



[Kasper, FH, Berges, PRD 90 (2014)]

Outline of the derivation

- functional integral representation:

$$Z = \int [\mathcal{D}A] \int [\mathcal{D}\psi \mathcal{D}\bar{\psi}]\, \rho_0(\psi, \bar{\psi}, A) \exp\left(i \int_{\mathcal{C}} \mathcal{L}_G[A] + \mathcal{L}_F[\psi, \bar{\psi}, A] \right)$$

- integrate out fermions (non-linear effective theory):

$$Z = \int [\mathcal{D}A]\, \rho_G(A) \exp\left(\mathrm{Tr}_{\mathcal{C}} \log \Delta[A]^{-1} + i \int_{\mathcal{C}} \mathcal{L}_G[A] \right)$$

- Keldysh rotation $A^{\pm} = \bar{A} \pm \widetilde{A}/2$ and expansion in $\widetilde{A}$:

$$\mathrm{Tr}_{\mathcal{C}} \log \Delta[A]^{-1} = \mathrm{Tr}_{\mathcal{C}} \log \Delta[\bar{A}]^{-1} + \frac{g}{2} \mathrm{Tr}_{\mathcal{C}} \left\{ \Delta[\bar{A}]\, \mathrm{sig}_{\mathcal{C}}\, \widetilde{A} \right\} + \mathcal{O}(\widetilde{A}^2)$$

That's the approximation!

[Kasper, FH, Berges, PRD 90 (2014)]

Outline of the derivation

- classical-statistical approximation of the generating functional:

$$Z = \int [\mathcal{D}\bar{A}][\mathcal{D}\widetilde{A}]\,\rho_G(A)\exp\left(i\int_{t_0}^{t_f}\int_{\mathbf{x}}\widetilde{A}^{\nu}\left\{\partial^{\mu}\bar{F}_{\mu\nu}+\frac{g}{2}\,\mathrm{tr}[\Delta_K\gamma_\nu]\right\}\right)$$

$$\Delta_K(x,y)\equiv\left\langle\left[\psi(x),\bar{\psi}(y)\right]\right\rangle_{\bar{A}}$$

sampling over initial conditions

classical equations of motion

$$(i\partial\!\!\!/_x - e\bar{A\!\!\!/}(x) - m)\Delta_K(x,y)=0$$

$$\partial^{\mu}\bar{F}_{\mu\nu}(x) = -\frac{g}{2}\,\mathrm{tr}[\Delta_K(x,x)\gamma_\nu]$$

- observables in classical-statistical approximation:

$$\langle O\rangle_{\mathrm{cl}} = \int [\mathcal{D}\bar{A}][\mathcal{D}\Pi_0]\,\rho_W[\bar{A}_0,\Pi_0]O[\bar{A}]\delta[\mathrm{E.o.M.}]$$

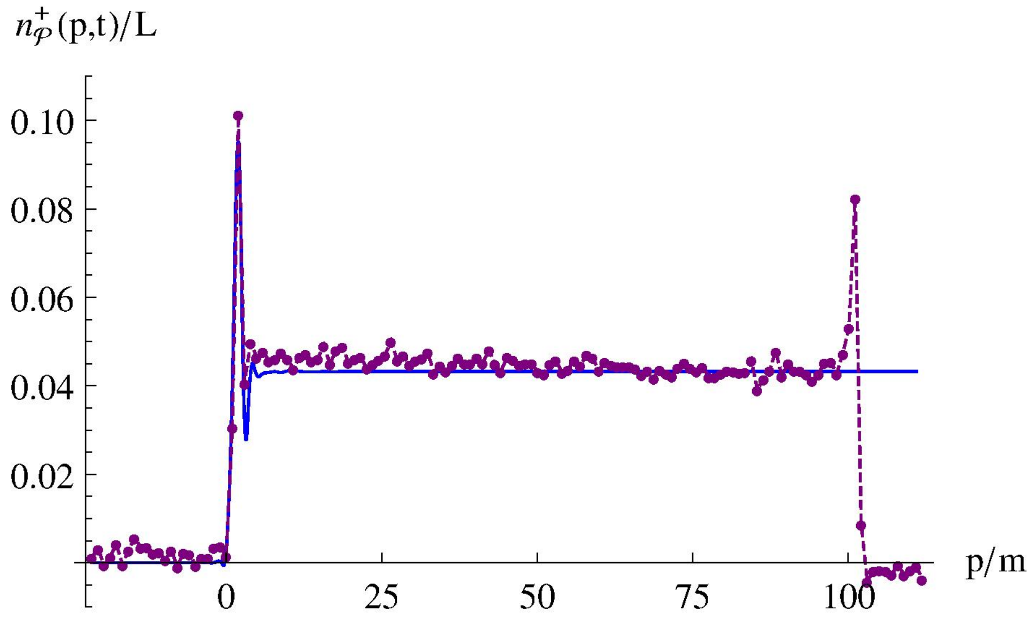
Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

[FH, Berges, Gelfand, PRD 87 (2013)]

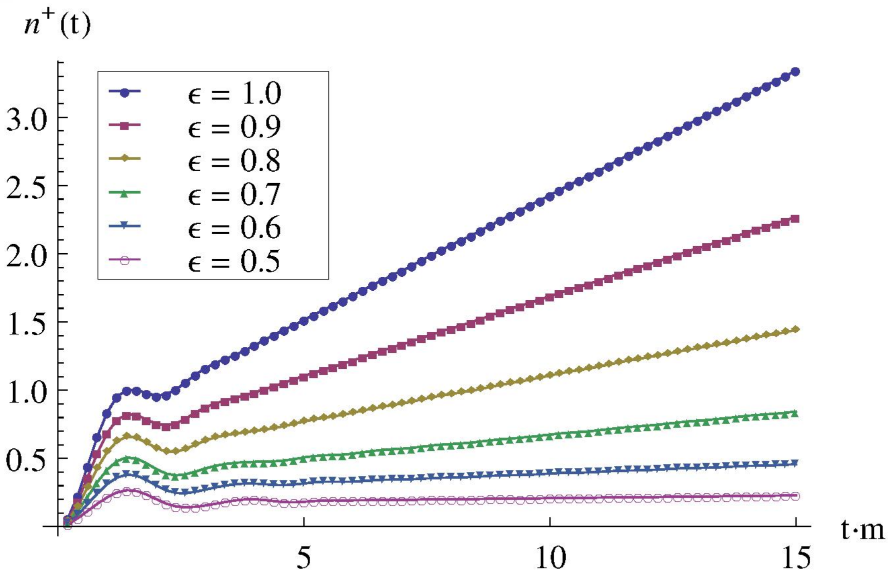
Schwinger formula on the lattice

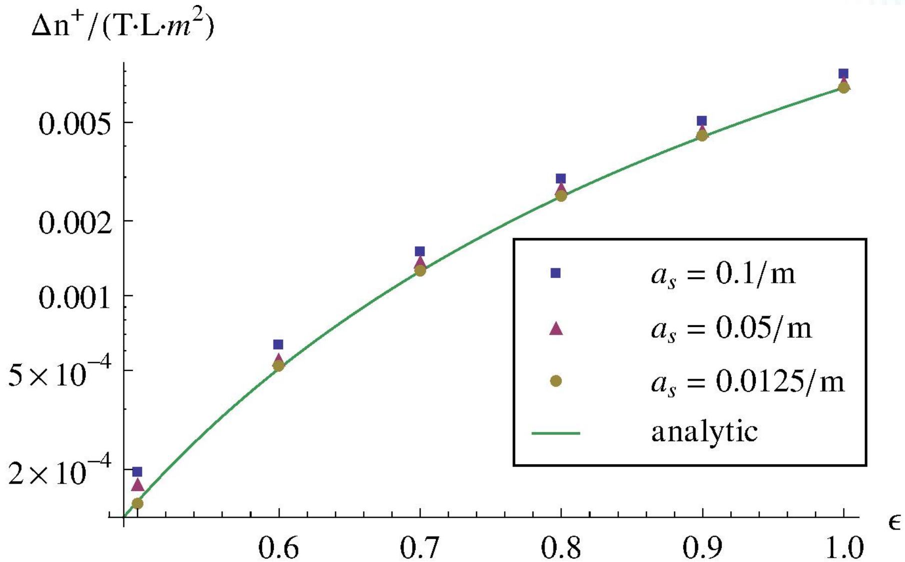
static electric field without backreaction in QED (1+1)



Schwinger formula on the lattice

static electric field without backreaction in QED (1+1)





transient effect

linear growth

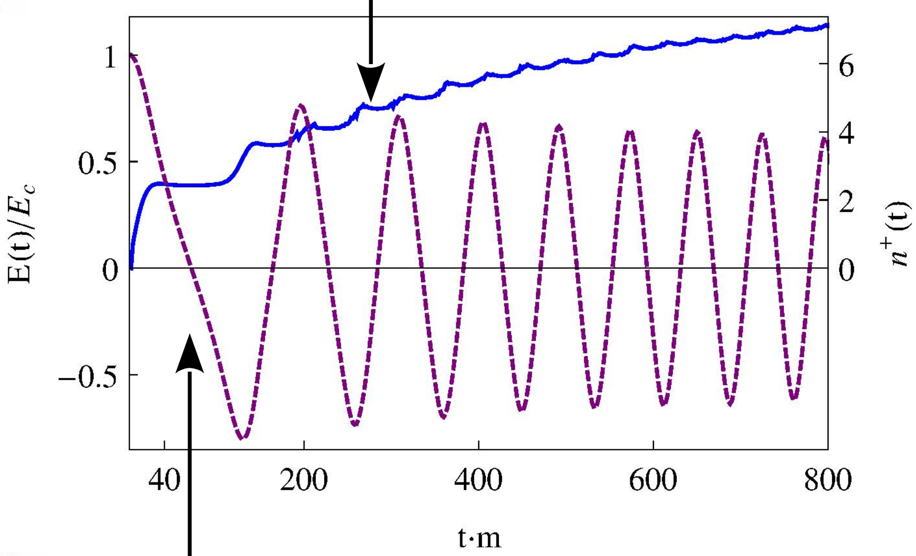
$$\frac{\Delta n^+}{TLm^2} = \frac{\epsilon}{2\pi} \exp\left(-\frac{\pi}{\epsilon}\right)$$

[FH, Berges, Gelfand, PRD 87 (2013)]

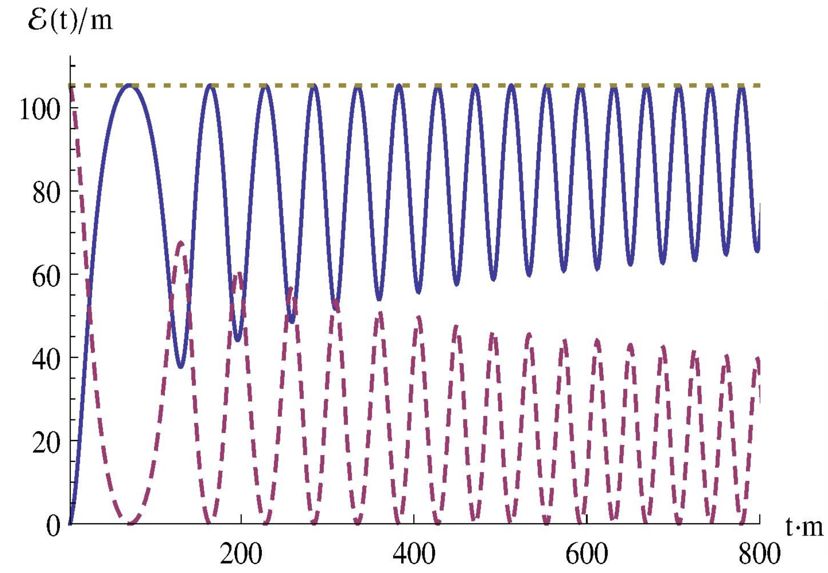
Plasma oscillations

static electric field incl. backreaction in QED (1+1)

number of particles



field strength



energy conservation

[FH, Berges, Gelfand, PRD 87 (2013)]

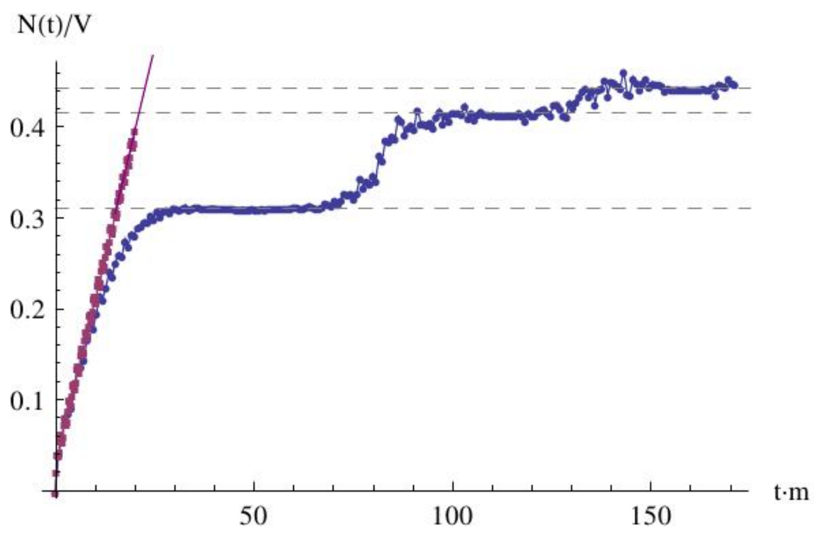
Plasma oscillations

static electric field incl. backreaction in QED (1+1)

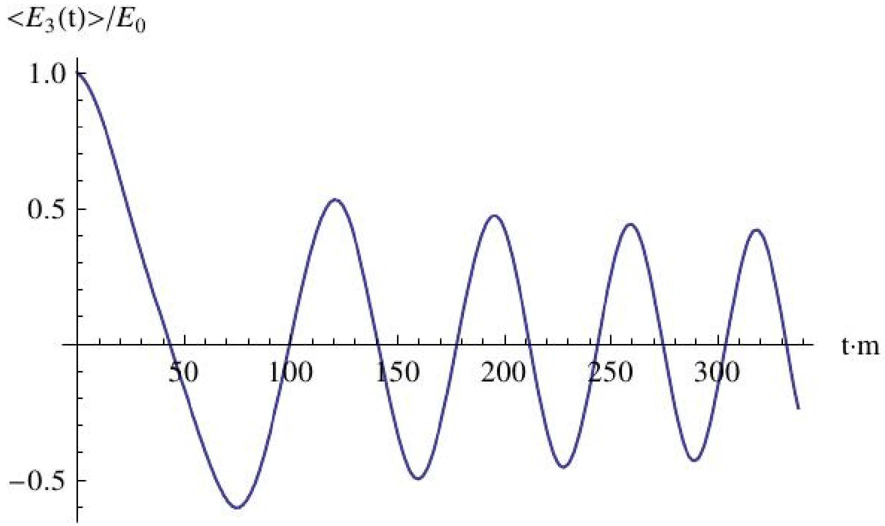
[Kasper, FH, Berges, PRD 90 (2014)]

Plasma oscillations

static electric field incl. backreaction in QED (3+1)



number of particles



field strength

Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

Pulsed field with sub-cycle structure

- Schwinger effect in colliding laser pulses ⟶ simple model:

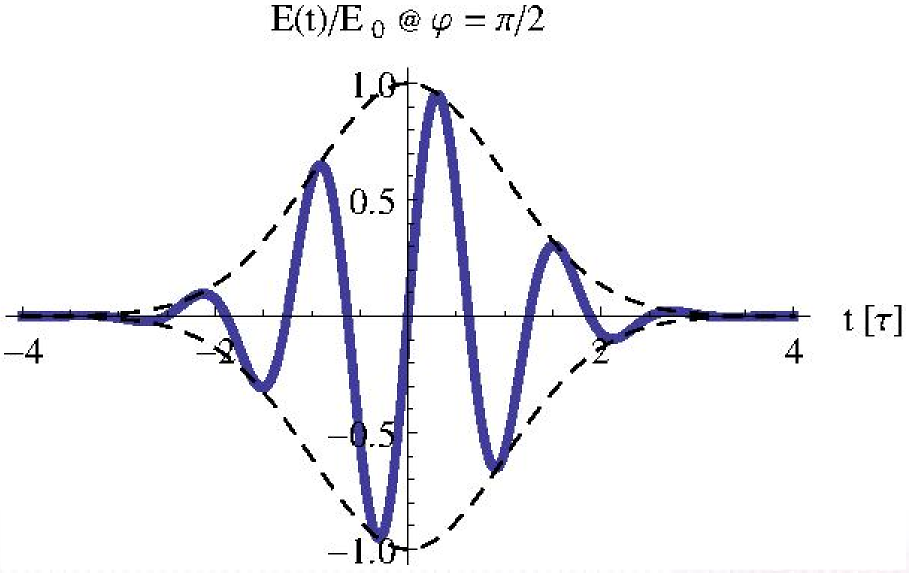
  two counter-propagating laser pulses: standing wave

  in the focus of optical laser systems: t-dependent electric field

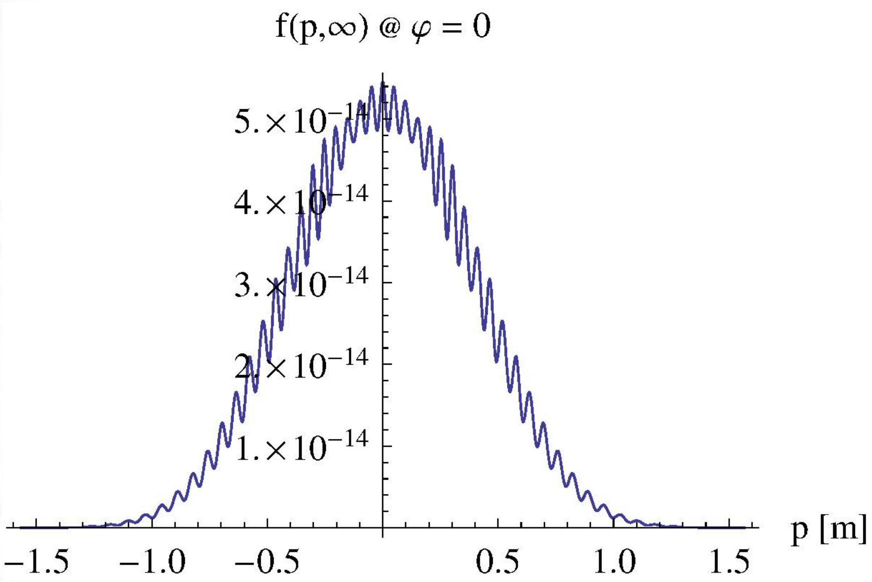
$$E(t) = E_0 \cos(\omega t - \varphi) \exp(-t^2/2\tau^2)$$

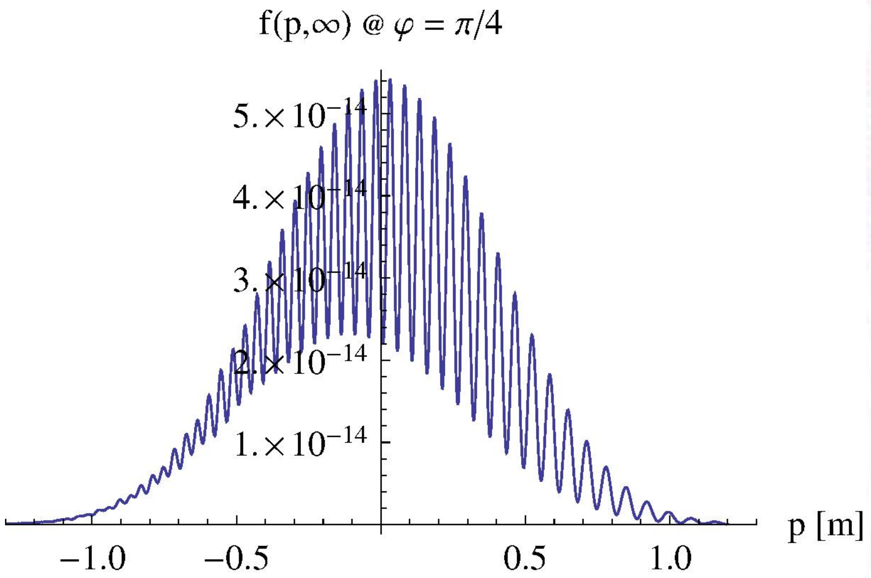
$$\sigma = \omega\tau$$

number of cycles

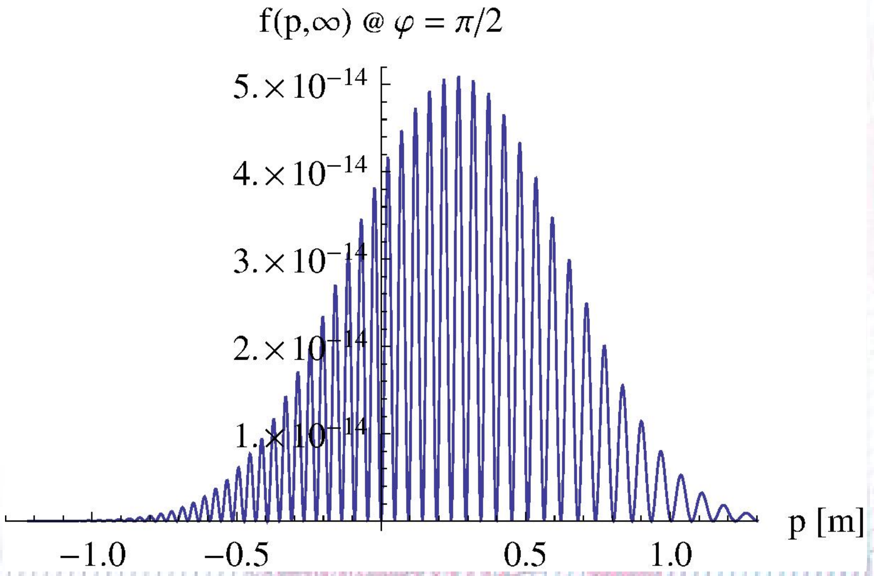


Pulsed field with sub-cycle structure





- extremely sensitive to CEP
  ⟶ resonance phenomenon
- matterless double-slit in time
  ⟶ quantum interference
- in general: temporal variations
  ⟶ distinctive signatures



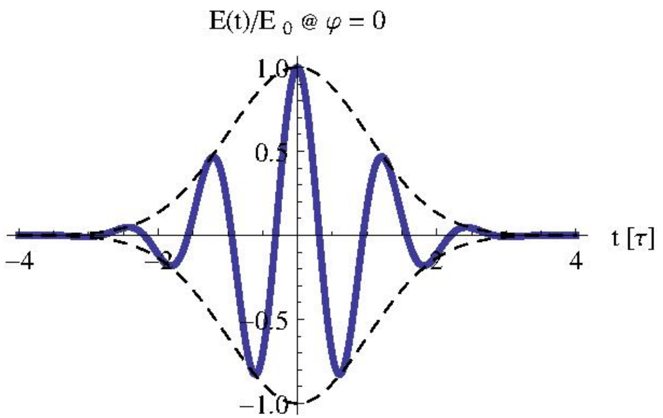
[FH, Alkofer, Dunne, Gies, PRL 102 (2009)]

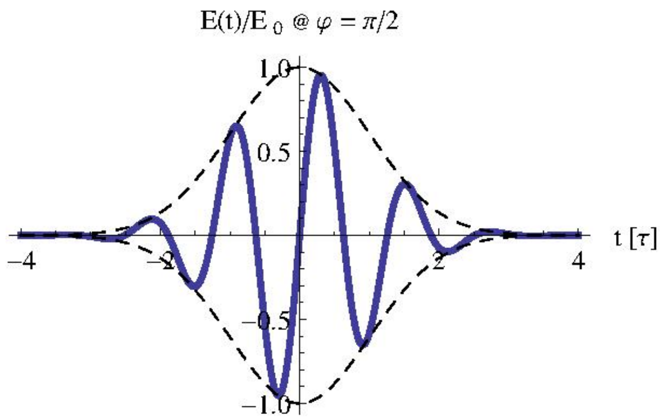
Matterless double slit in time

- 'attosecond double slit experiment' in photoionization

[Lindner et al., PRL 95 (2005)]

- here: interference of temporally separated pair creation events





one dominant production event	two equal production events
=	=
single slit	double slit
weak interference pattern	maximum interference pattern

Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

Bunching in space-time pulse

single electric pulse in space and time in QED (1+1)

$$E(x,t) = E_0 \operatorname{sech}^2(\omega t) \exp(-x^2/2\lambda^2)$$

fermion density   charge density   electric field

Self-bunching in space-time pulse

single electric pulse in space and time in QED (1+1)

- scaling as function of λ

  $\longrightarrow$ $\overline{n}(p,t) = n(p,t)/\lambda$

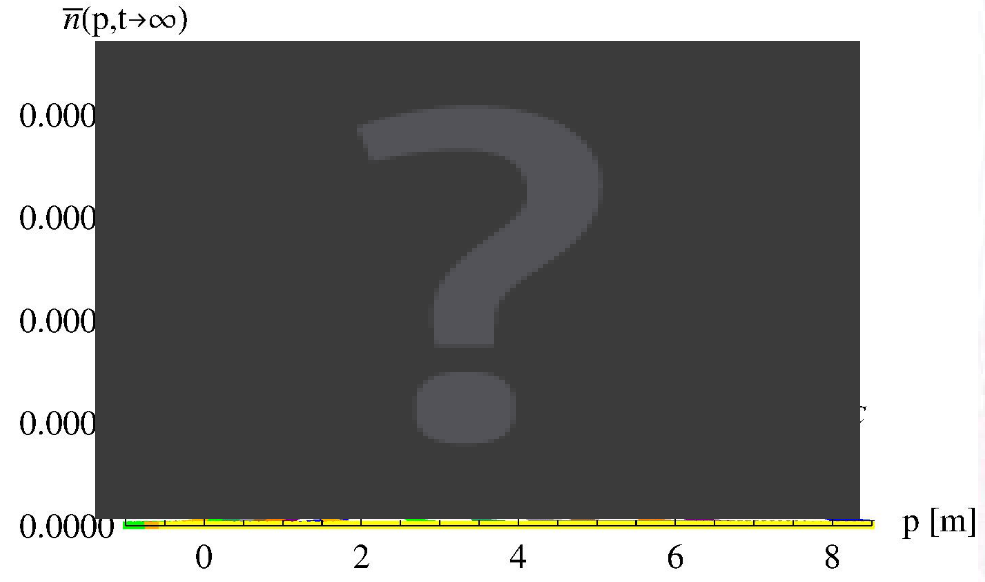
- self-bunching of $\overline{n}(p,t)$

  $\longrightarrow$ higher and narrower

- termination

  $\longrightarrow$ sharp drop for small λ

- interplay: temporal/spatial scales



Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

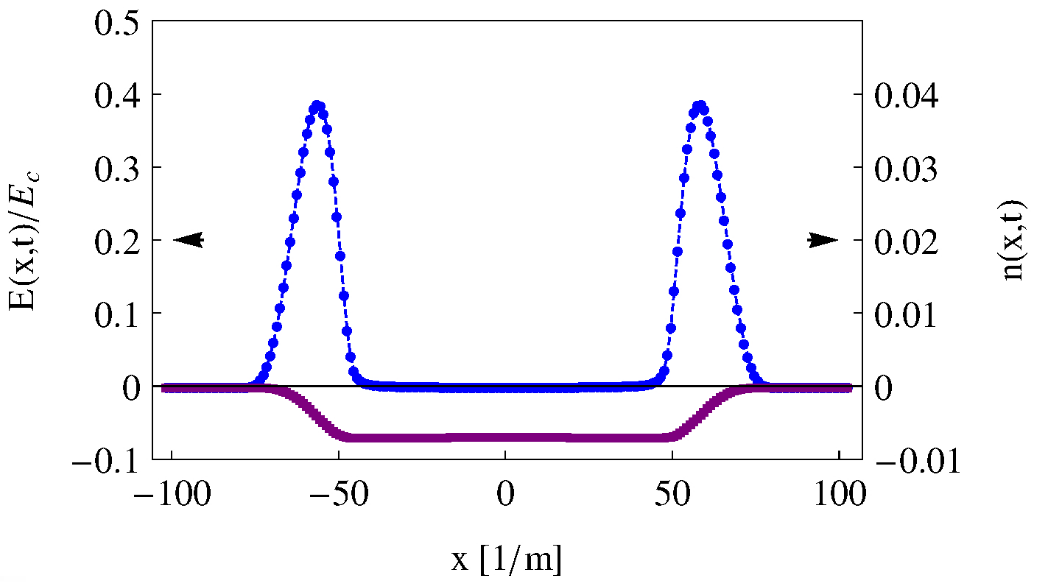
[FH, Berges, Gelfand, PRL 111 (2013)]

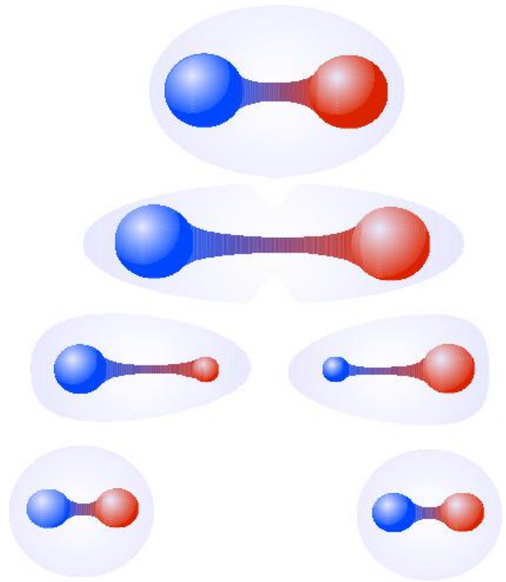
The string breaking analogue

- fermion bunches act as capacitor

  1+1 dimensional geometry: Coulomb potential = linear potential

  cf. QCD string breaking: linear potential due to strong interaction





Can we learn something about the dynamics of string breaking?

[FH, Berges, Gelfand, PRL 111 (2013)]

Dynamics of string breaking

two static charges separated by distance d_C

[FH, Berges, Gelfand, PRL 111 (2013)]

Dynamics of string breaking

two static charges separated by distance d_C

- two-stage process (different scales)
  - ⟶ creation on top of each other
  - ⟶ separation of charges

- Naïve estimate for critical distance

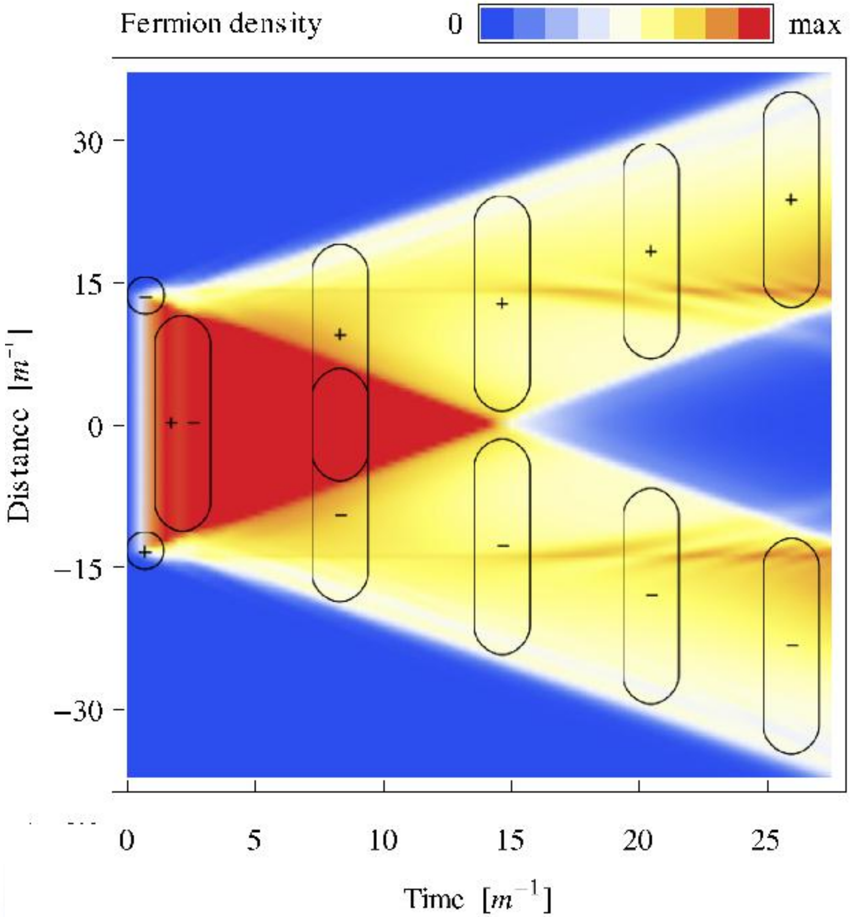
$$V_{\mathrm{str}}[d_C] = 2m$$

$$\Big\downarrow \text{ modified}$$

$$V_{\mathrm{str}}[d_C] = 2m + W[d_C]$$

- very substantial work contribution

$$W[d_C] > 2m$$



[FH, Berges, Gelfand, PRL 111 (2013)]

Dynamics of string breaking

two static charges separated by distance d_C

- two-stage process (different scales)
  - ⟶ creation on top of each other
  - ⟶ separation of charges
- Naïve estimate for critical distance

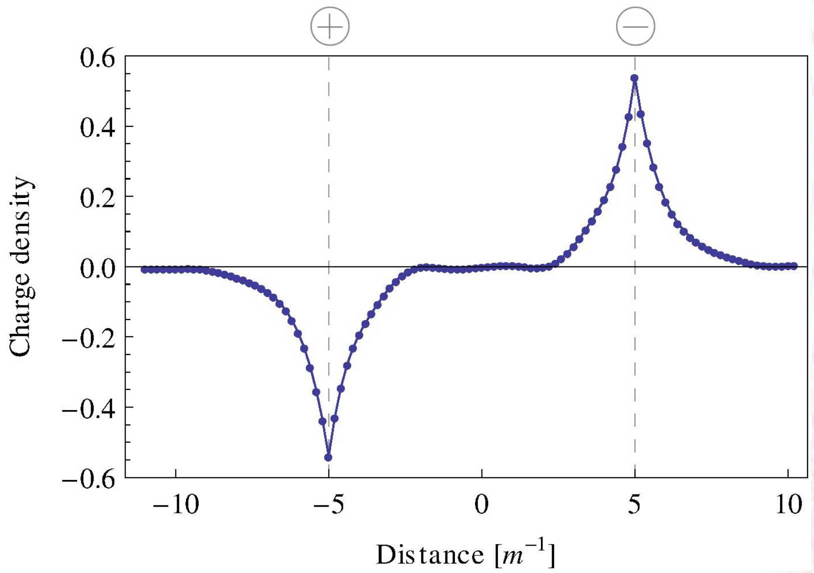
$$V_{\mathrm{str}}[d_C] = 2m$$

$$\big\downarrow \text{ modified}$$

$$V_{\mathrm{str}}[d_C] = 2m + W[d_C]$$

- very substantial work contribution

$$W[d_C] > 2m$$



asymptotic screening

Outline

- real-time gauge theory with fermions
- Schwinger effect and plasma oscillations
- pulsed fields with sub-cycle structure
- self-bunching in space-time pulses
- a model for QCD dynamics & string breaking
- summary
- open questions & ongoing projects

summary (take-home lessons)

(a)

[together with: C. Kohlfürst , R. Alkofer]

Enhancement & pulse optimization

- dynamically assisted Schwinger mechanism
  [Schutzhold, Gies, Dunne, PRL 101 (2008)]
- time-domain multiple slit interference
  [Akkermans, Dunne, PRL 108 (2012)]

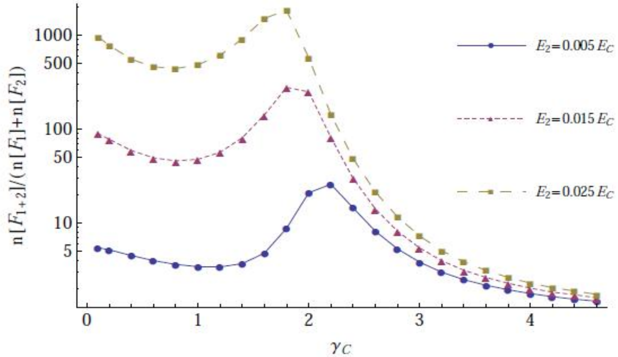


FIG. 1: Enhancement of the particle density in the dynamically assisted Schwinger mechanism. The parameters of the adiabatic pulse are given by $E_1 = 0.1E_c$ and $\omega_1 \sim m/100$. The different curves correspond to different values of E_2 and we change γ_c or, equivalently, ω_2.

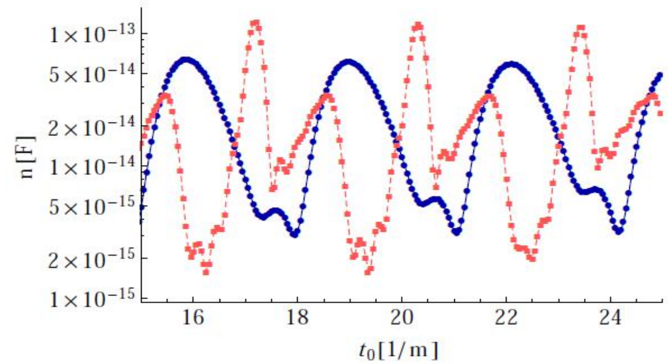


FIG. 2: Particle density for of a comb of 10 single pulses with parameter $|E_i| = 0.02E_c$, $\omega_i = m/6$ for the equal-sign configuration (solid) and the alternating-sign configuration (dashed). The particle number changes quasi-periodically by orders of magnitude as function of the inter-pulse time lag t_0.

- optimal control theory: systematic shaping under constaints
  [Kohlfurst, Mitter, von Winckel, FH, Alkofer, PRD 88 (2013)]
- current investigations: pulse optimization & inverse problem

(b)

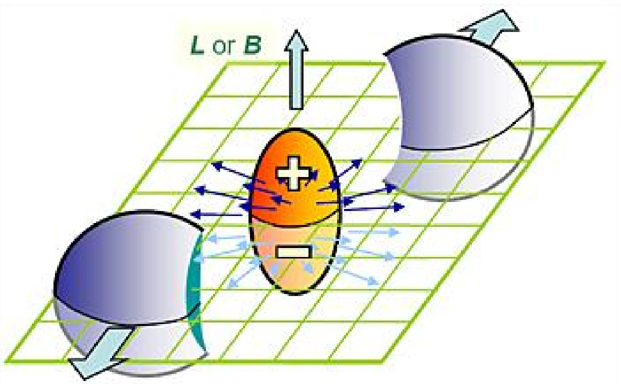
[together with: N. Müller , L. Palhares, J. Berges]

Chiral magnetic effect (in QED)

- possible explanation of charge asymmetry in HIC (STAR '08)

topol. charge + axial anomaly + magnetic field
=
electric current in the perp. direction

[Kharzeev, McLerran, Warringa, Nucl. Phys. A (2008)]

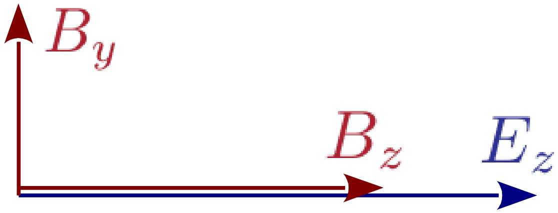


- current investigations: chiral magnetic effect in QED

⟶ topological config.: $B_z E_z$

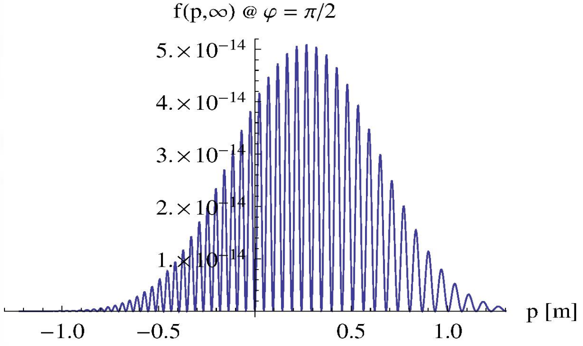
⟶ magnetic field: B_y

⟶ 'proposal': 4 ultrahigh-intensity lasers

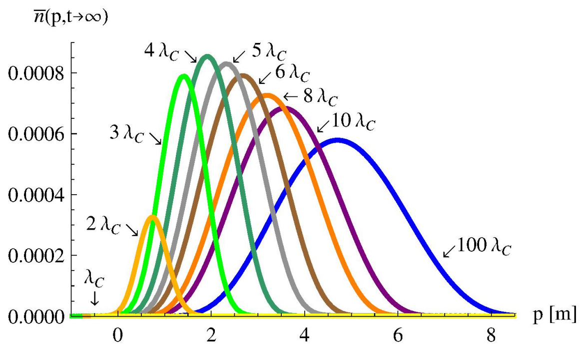


THE END

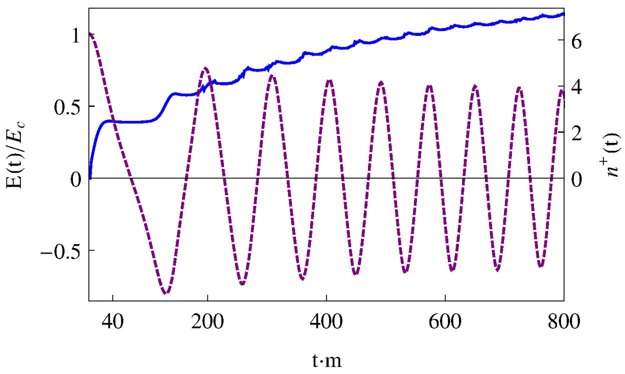
temporal variations

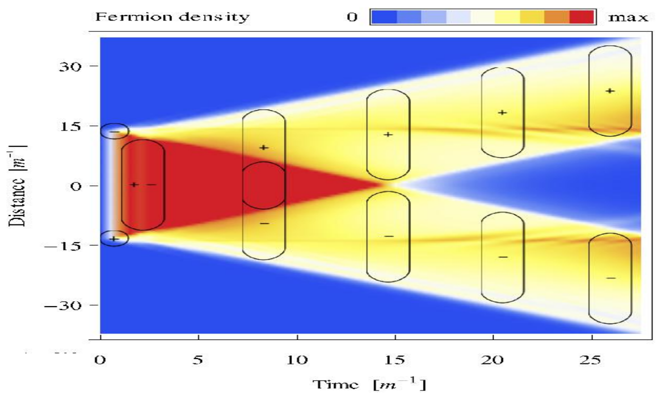


spatial and temporal variations



backreaction and collective phenomena





Thank you!