Pulse shape optimization for electron-positron production

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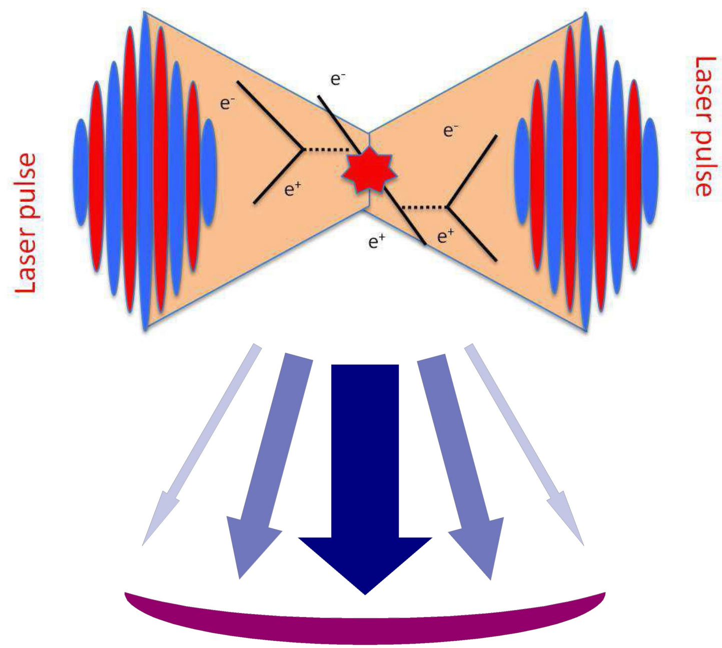
- FH, *The inverse problem for Schwinger pair production*, **PLB 753** (2015)
- F. Fillion-Gourdeau, FH, D. Gagnon, and S. MacLean, *Pulse shape optimization for Schwinger pair production in rotating fields*, **PRD 96** (2017)

particle production & optimization strategies

electron-positron production

all-optical (colliding laser pulses)



My Wishlist

- space-time resolved
- electromagnetic fields
- full QM treatment (QED)
- back(radiation)reaction
- realistic parameters

- identify unique signatures
- maximize detection probability

You can't always get what you want

- spatial homogeneity
- only electric fields

} focus of standing waves [matter of scales]

- external-field approximation: classical field [800nm / 1J / ~10^{20} photons]
- no backreaction: low densities [no depletion or cascades]

dynamical system (Vlasov) for given E(t) determines F(q,T)

optimization strategies

- maximize a quantity that is determined by the distribution F(q,T)

[Kohlfürst, Mitter, von Winckel, FH and Alkofer, **PRD 88 (2013)**]

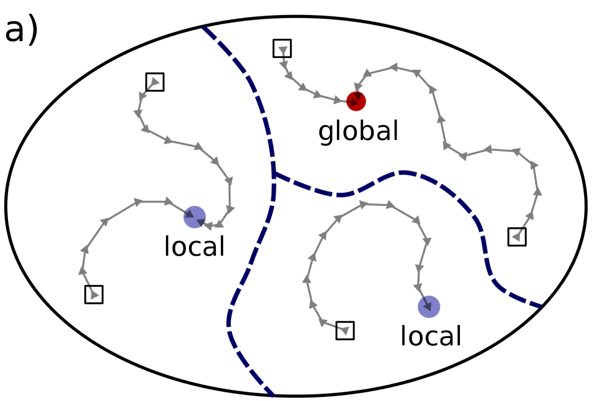
control function: $A\left(\{\phi_{1,...}, \phi_n\}; t\right)$ (vector potential ~ electric field)

cost functional: $J[F[A]; A]$ (e.g.: particle number) + constraints

global optimization problem: $$\tilde{J} = \max_{\{\phi_{1,..}, \phi_n\}} J[F[A]; A]$$

multistart + local search

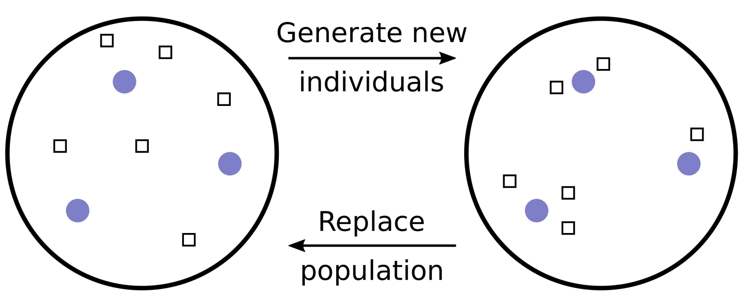
a)



ц convex / few local extrema

population based metaheuristics

b)



ц global optimization strategy

the inverse problem

FH, *The inverse problem for Schwinger pair production*, **PLB 753 (2015)**

inverse problem for pair production

direct problem: given E(t) $\longrightarrow$ solve for F(q,T)
inverse problems: which E(t) results in a predetermined F_0(q)?

- why is this interesting/relevant?
  - theoretical: existence? # of necessary parameters? rate of convergence?
  - experimental: determine parameters to enhance detection probability

- inverse problems are typically ill-posed:
  - non-existence: solution does not exist — approximate solution is fine
  - non-uniqueness: solution is not unique — any 'good' configuration is fine

control function:

$$E(t)=\sum_{j=1}^{n} E_j \sin\left(\frac{\pi(t+T)j}{2T}\right)$$

harmonic superposition

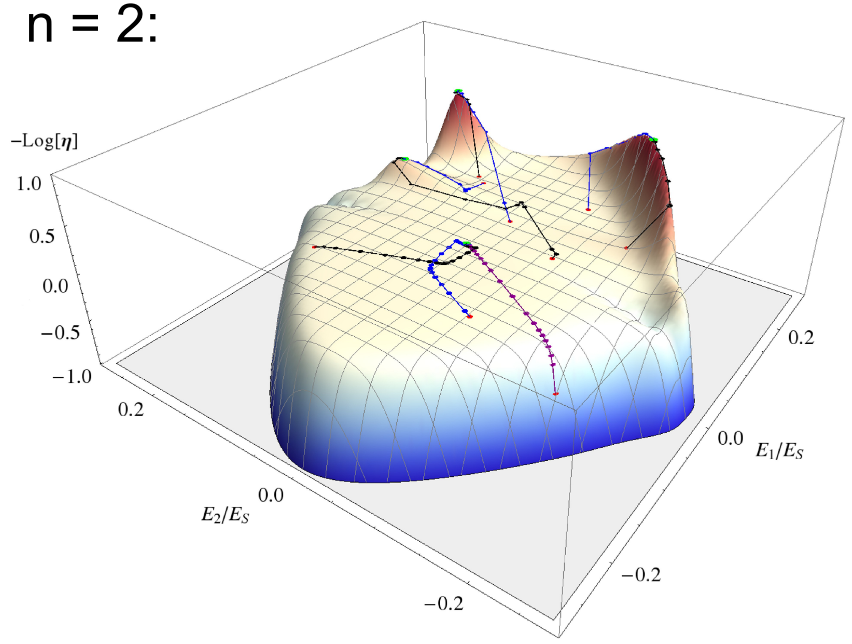
cost functional:

$$\eta_n=\frac{\int [dq][F(q,T)-F_0(q)]^2}{\int [dq]F_0^2(q)}$$

least squares

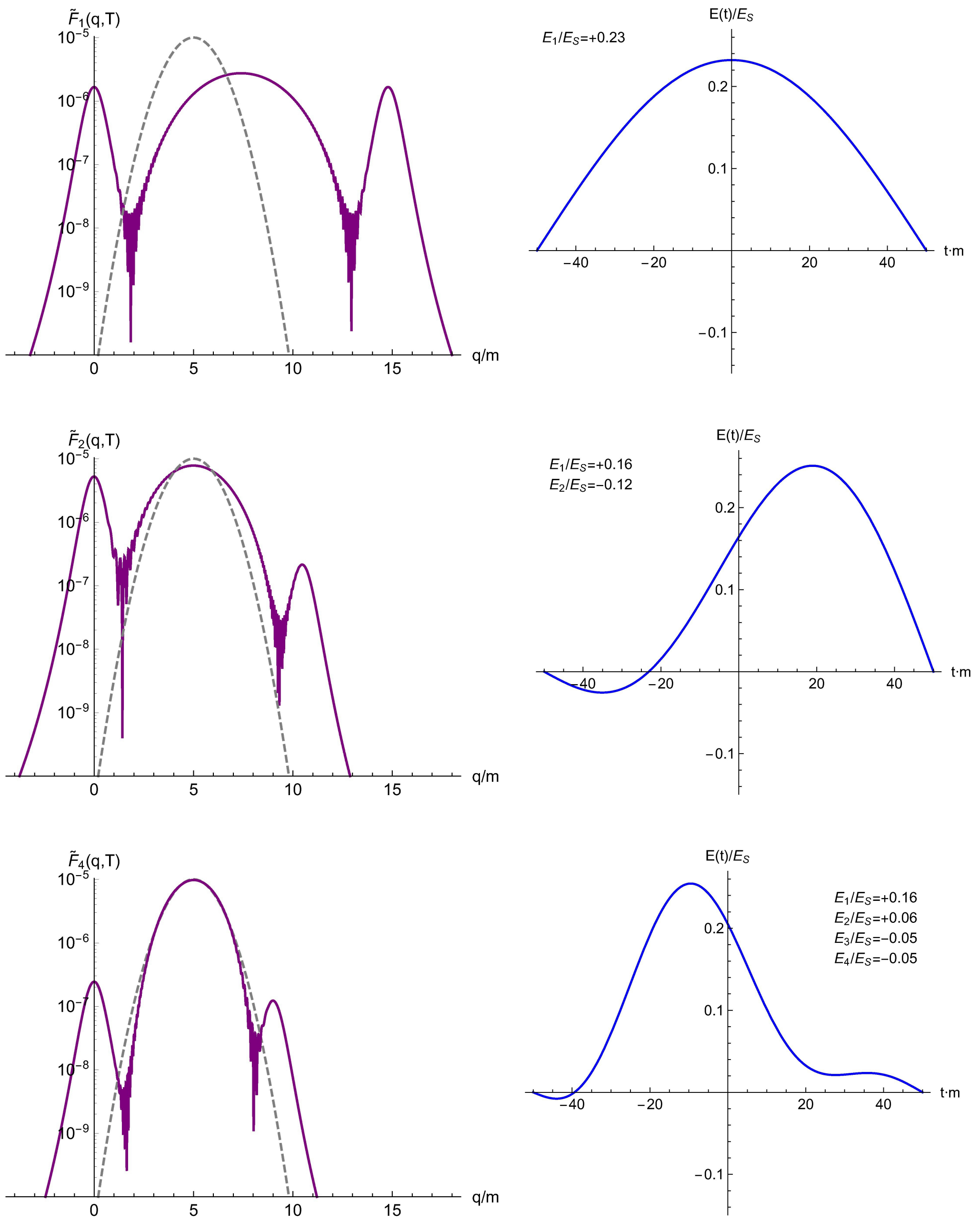
approximating spectral properties

n = 2:

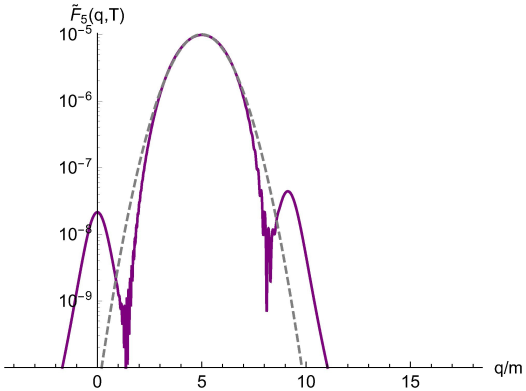


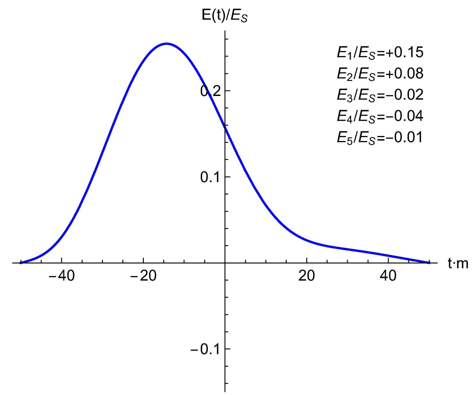
landscape with several
stationary points

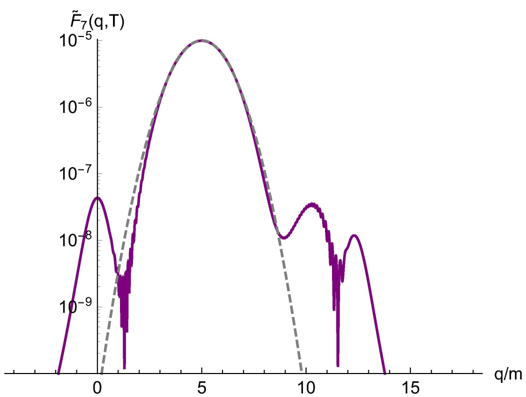
small # of harmonics to
approximate the Gaussian peak

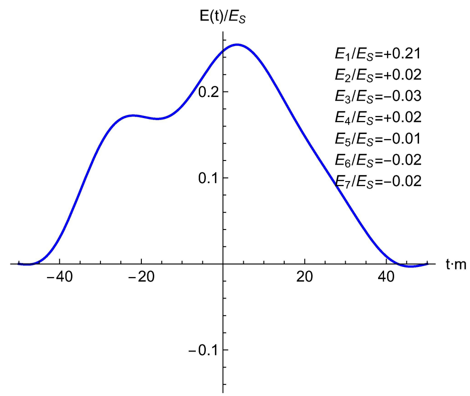


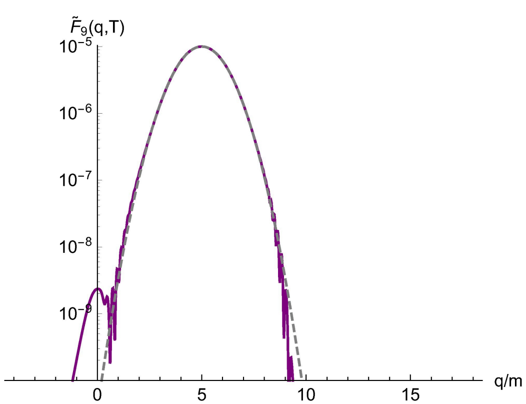
convergence properties

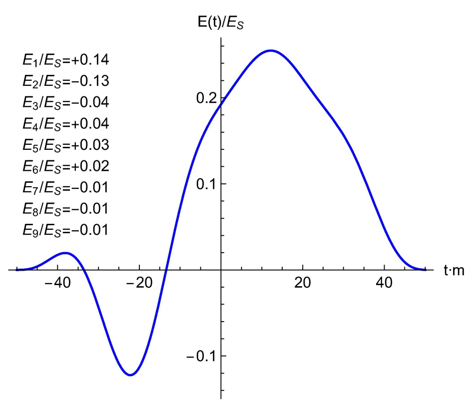




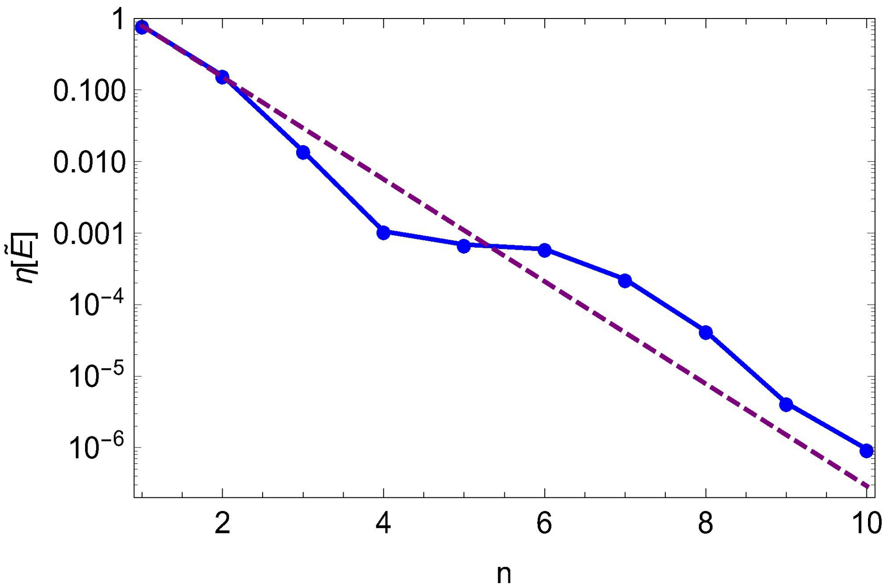








convergence towards objective distribution



exponential improvement as function of n

pulse shape optimization for rotating fields

Fillion-Gourdeau, FH, Gagnon, and MacLean, *Pulse shape optimization for Schwinger pair production in rotating fields*, **PRD 96 (2017)**

pulse shape optimization

maximize the particle number for given fluence (energy density)

- improvements/extensions:
  - field configurations: 2d (rotating) fields [dynamical system: 6 ODE]
  - pulse parametrization: polynomial basis expansion (B-splines)

- parametrization by spectral density $E_k(\omega)$ & phase $\varphi_k(\omega)$ [k=2,3]

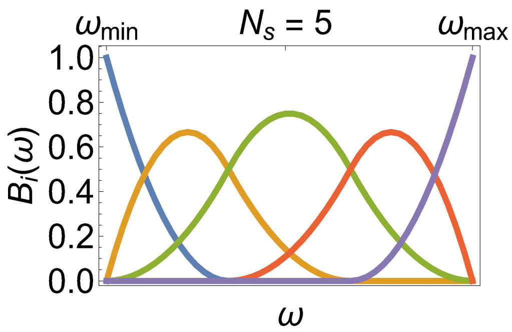
$$E_k(\omega) = \sum_{i=1}^{N_s} a_{k,i}^{(E)} B_i(\omega)$$

$$\varphi_k(\omega) = \sum_{i=1}^{N_s} a_{k,i}^{(\varphi)} B_i(\omega)$$

(i) compact support

(ii) positive definite

(iii) easy to implement



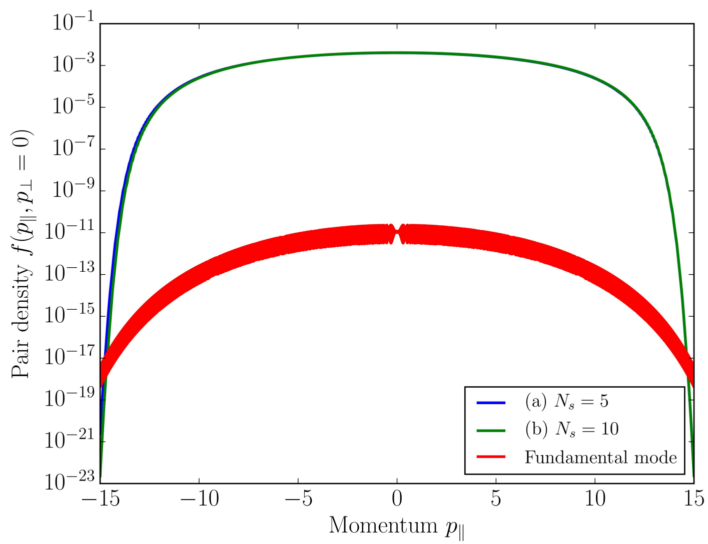
control function: $$E_k(t) = f(t) \sum_{j=0}^{n_\omega \sim 50} E_{k,j} \cos(\omega_j t - \varphi_{k,j})$$

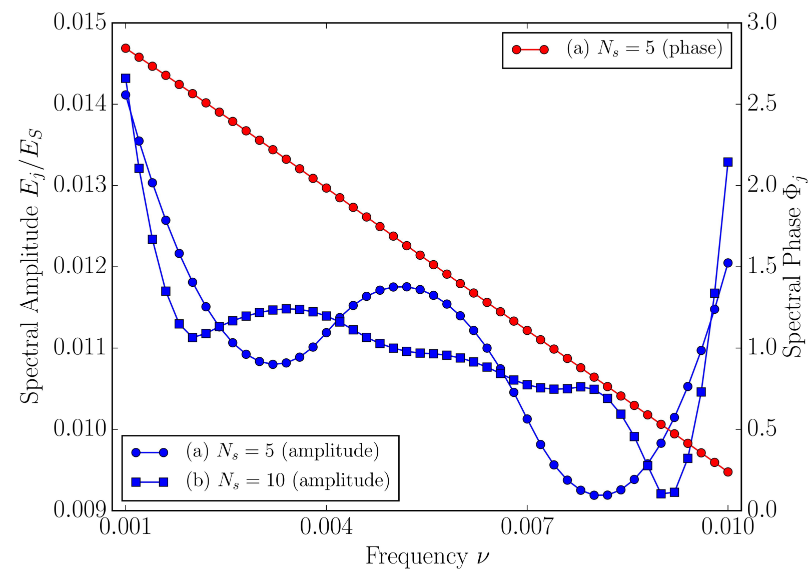
cost functional: $$J = \int_{D_q} [dq]\, F(q,T)$$

constraint: $$\int_{-T}^{T} dt\, \vec{E}^2(t) = const$$

quality of B-splines (d=1)

of components: $n_\omega = 45$
min. freq.: $\omega_{min} = 2\pi / 1000$
max freq.: $\omega_{max} = 2\pi / 100$

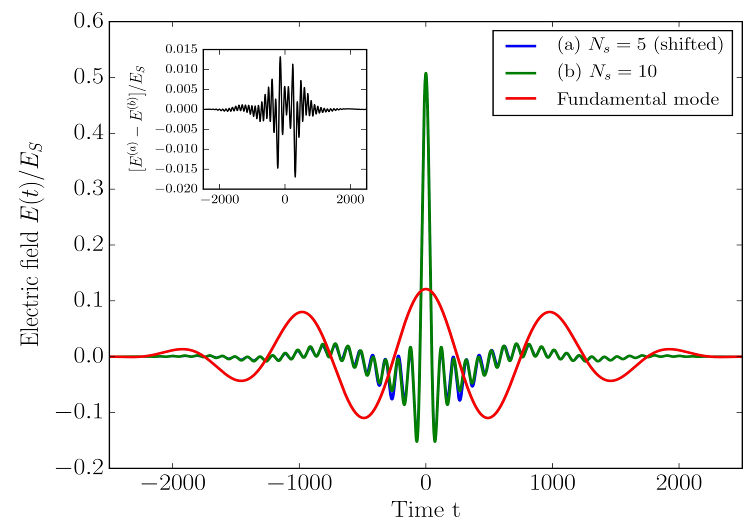




- **optimum = reduction of interferences**
- N_s = 5/10 basically identical

- $\varphi(\omega) \sim \omega$ [irrelevant time shift ⟶ 0]
- $E(\omega)$ unique for fixed N_s
- N_s = 5/10 substantial deviations

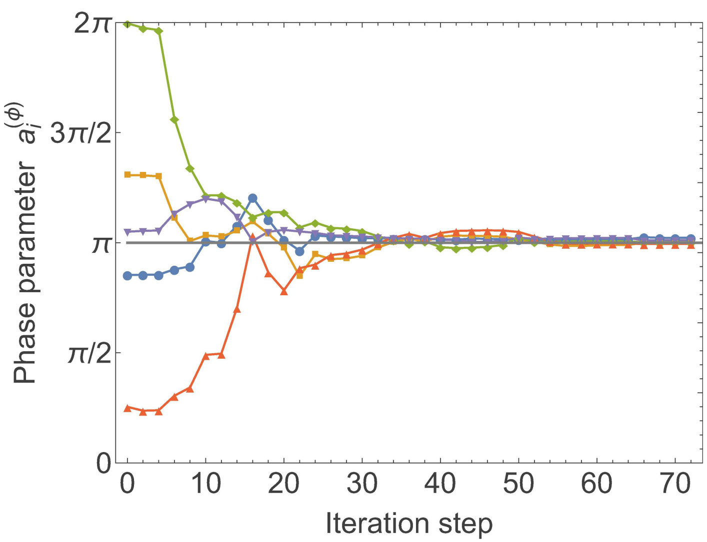
- **optimum = reduction of pulse duration**
- N_s = 5/10 basically identical [max. 3%]

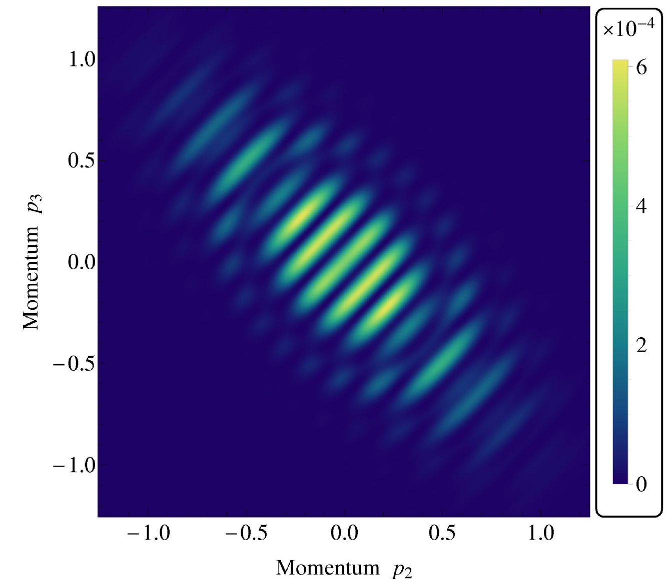


B-splines: $N_s = 5$ captures physics of $n_\omega = 45$ modes

polarization effect (d=2)

of components: $n_\omega = 50$
min. freq.: $\omega_{min} = 4\pi / 100$
max freq.: $\omega_{max} = 6\pi / 100$

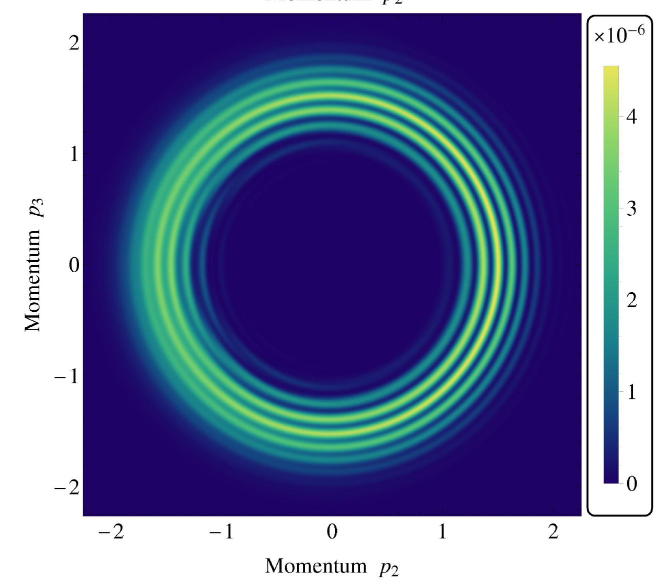




- for fixed $a_{2,i}^{(\varphi)} = 0$, relative phase $a_{3,i}^{(\varphi)} \to \pi$
- all ellipticities vanish
- **optimum = linear polarization**

linear polarization
- orthogonal decay
- peaked at p = 0
- max. ~ $5\text{x}10^{-4}$

circular polarization
- ring structure
- peaked at p/m = 1.5
- max. ~ $5\text{x}10^{-6}$



linear polarization is superior for fixed fluence

conclusions & outlook

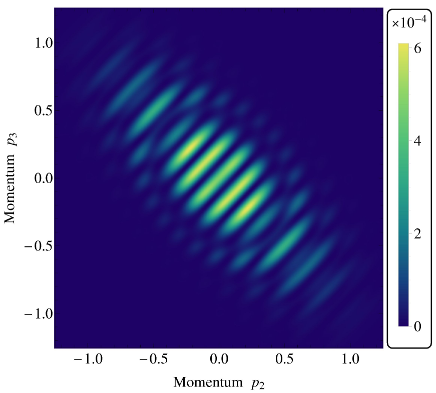
take-home lessons

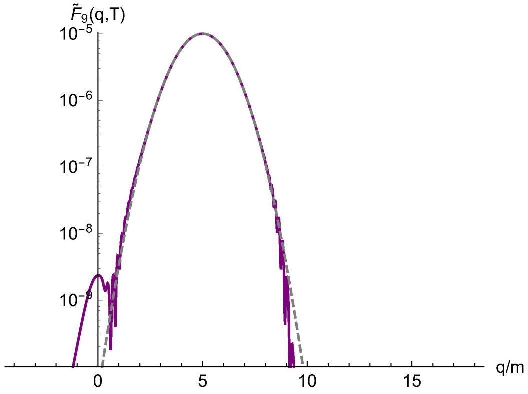
- optimization: powerful tool for studying dynamical processes

  - pulse shaping: which field profile maximizes particle production for given energy

  - inverse problem: which field profile leads to a given distribution $F_0(q)$

  - ...





- shortcomings / open problems

  - realistic experimental situation: is the control sufficient to make use of these predictions?

  - more realistic simulations necessary (field parameters & configurations)

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Thank you!