Anomalous Dynamics and the Chiral Magnetic Effect

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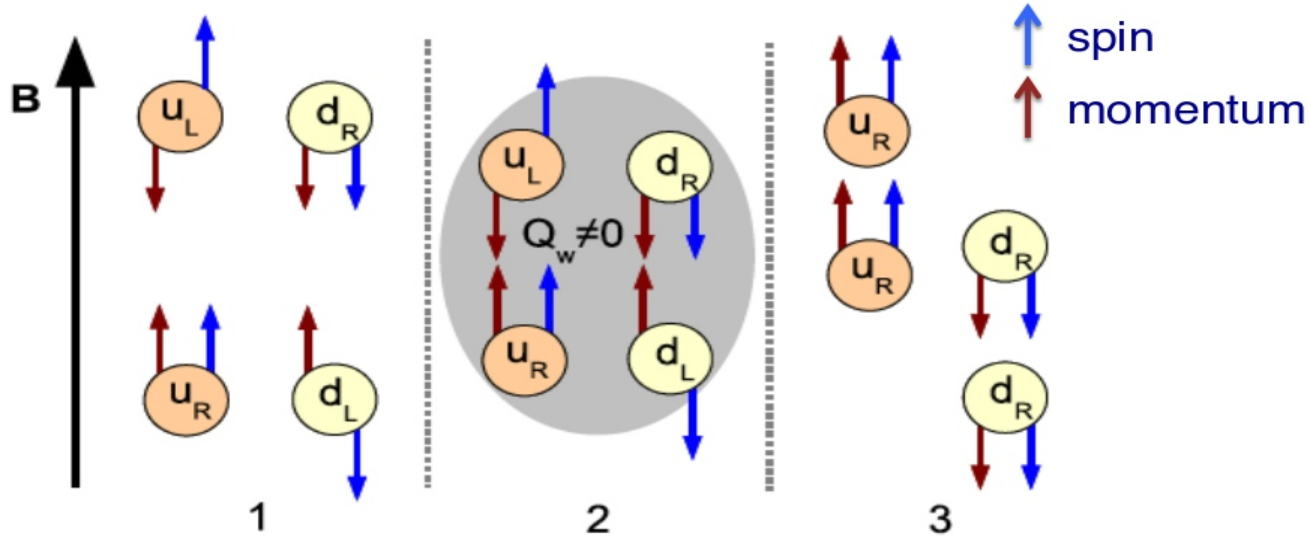
based on work (some of it in progress) with

Soeren Schlichting, Mark Mace, Sayatan Sharma, Florian Hebenstreit, Naoto Tanji, Jürgen Berges

talk at Brookhaven National Laboratory – March 3rd, 2016

Chirality and chiral non-conservation

chirality + magnetic field = current



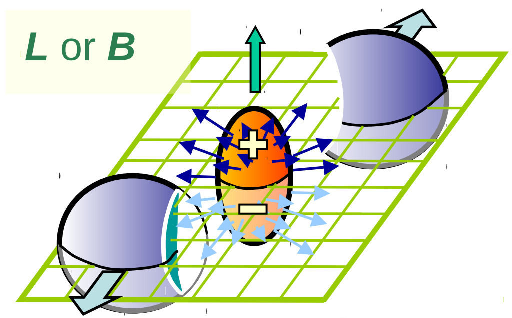
Chiral Magnetic Effect

Kharzeev, McLerran, Warringa 2007

Motivation

Chirality and chiral non-conservation

Possible Effect in **non-central heavy ion-collisions**



$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

Fukushima, Kharzeev, Warringa 2008

learn about chiral anomaly and the topology of gauge theories from a variety of effects:

- Chiral Magnetic Effect
- Chiral Separation Effect
- Chiral Magnetic Wave

Motivation

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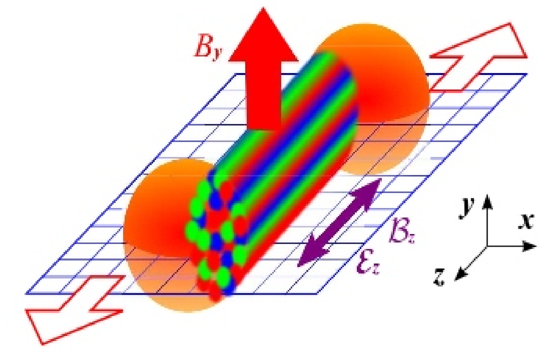
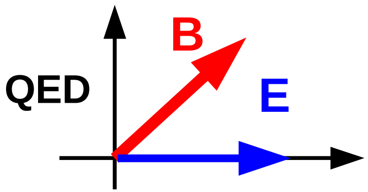
What do I want to show you in this talk?

We can learn about anomalous particle production from contrasting <u>QED vs QCD</u>.

Fukushima, Kharzeev, Warringa (2010):
idea: *"map specific SU(3) color configuration onto Abelian problem."*



- Motivated from flux tube picture
- analytic insight (it's QED!)
- will help us understand the importance of "field strength vs topological properties"

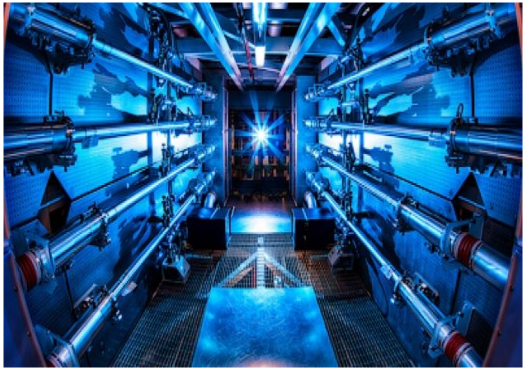


QED should be considered in its own right!

Will show:

→ The Chiral Magnetic Effect will play important role in **QED beyond the Schwinger limit** **(non-linear QED)**

→ Future experiments to deliver clean and direct access to anomalies in gauge theories



"from light comes matter"

Outline

1. Anomalies and the CME in non-linear QED

2. How to simulate large coherent gauge fields and fermions in real time?

3. Simulating non-linear QED and what to expect from future laser beam experiments

4. Connecting simulations to QCD
   → QED vs. QCD and the role of topology

5. Conclusions

1. Anomalous effects in QED

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The (abelian) massless axial anomaly

Manifestation of a classical symmetry broken on the quantum level I

$$\partial_\mu j_5^\mu = -\frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

→ local vs. global properties of the anomaly

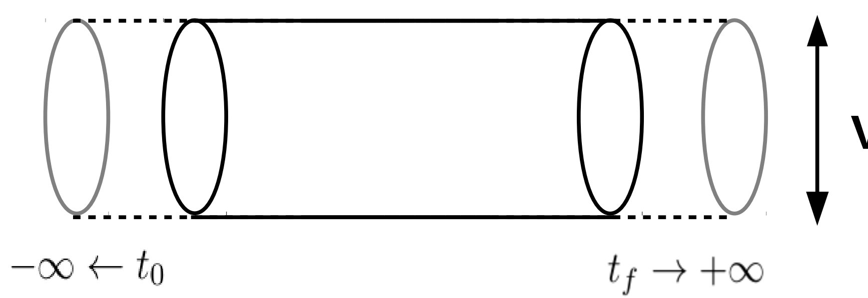
$$F_{\mu\nu}\tilde{F}^{\mu\nu} = \partial_\mu K^\mu = 4\mathbf{E}\cdot\mathbf{B}$$

“divergence of a current”

$$K^\mu = 4\epsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma$$

(+ term A^3 in QCD)

no net effect of the abelian anomaly **in S-matrix scattering** (see N.Christ, 1980) as there are no topological sectors in QED



$$Q_5(t_f) - Q_5(t_i) = -\frac{e^2}{8\pi^2}\int d^3x[K^0(t_f) - K^0(t_i)] = 0$$

1. Anomalous effects in QED

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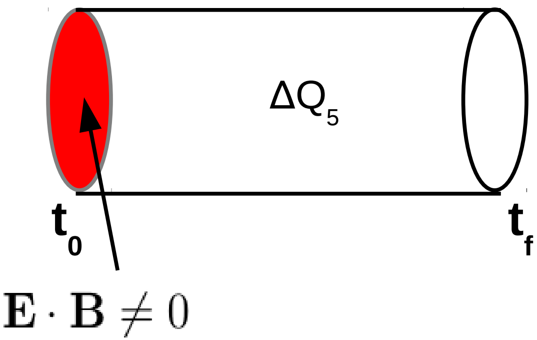
Field strength matters!

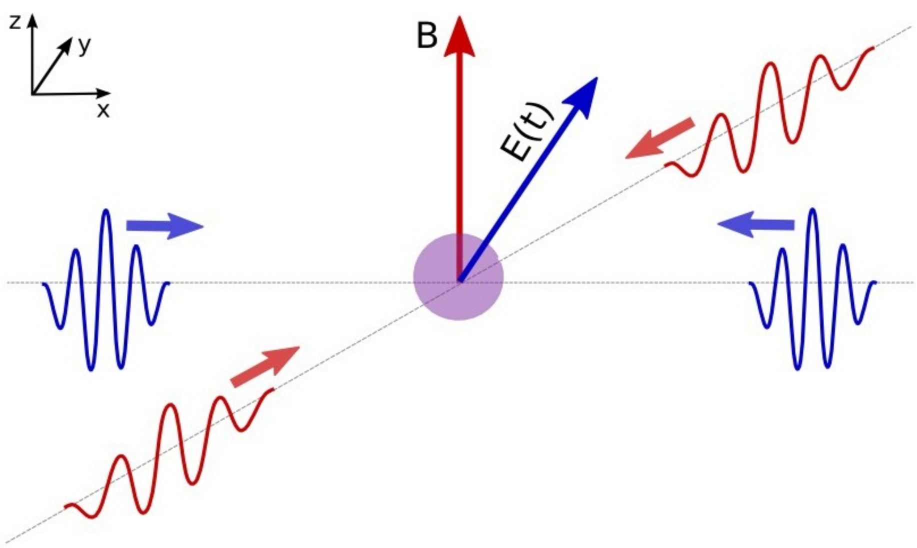


non-equilibrium problems do not start at the infinite past and not necessarily the initial state is vacuum

Initial Conditions with $\mathbf{E}\cdot\mathbf{B}\neq 0$
→ no reason why there should not be net axial production

Could design a **laser beam** experiment with $\mathbf{E}\cdot\mathbf{B}\neq 0$ and test anomalous particle production in QED

→ **nonlinear QED and the Schwinger limit**



1. Anomalous effects in QED

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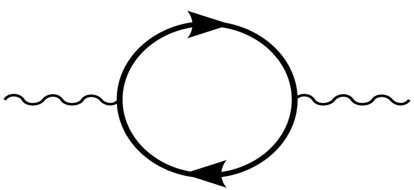
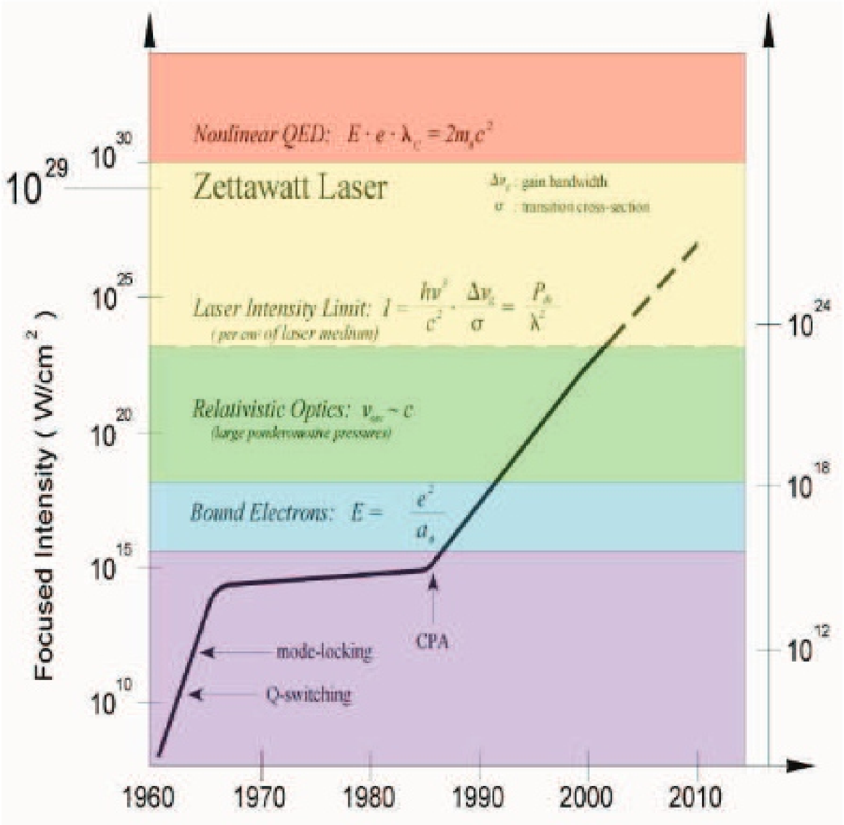
Non-linear QED and the “Schwinger limit”

Sauter (1931), Heisenberg & Euler (1936)
Schwinger (1951)

$$E_S = \frac{m_e^2 c^3}{q_e \hbar} \simeq 1.3 \times 10^{18}\,\mathrm{V/m}$$

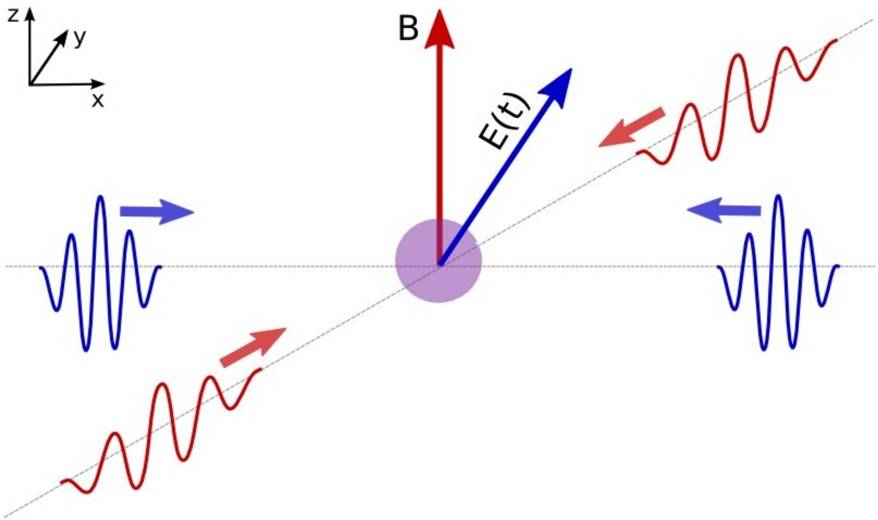
estimate of the scale of an electric field needed, to produce real particles from the quantum vacuum





probing the **intensity limit of QED**, instead of the **high energy limit** as with colliders
→ **some interesting effects here!**

1. Anomalous effects in QED



$$+ \quad \partial_\mu j_5^\mu = -\frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

… far from equilibrium?

How to simulate that?

2. Real-time Simulations

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Classical statistical simulations with fermions

will give only ideas, nice review can be found here: Kasper et al. Phys.Rev. D90 (2014) 2, 025016)

In the presence of large coherent gauge fields or large occupation numbers can use **correspondence principle** → classical field evolution for gauge fields
(actually a non-equilibrium saddle point expansion around the classical solution)

$$\partial_\mu F^{\mu\nu}[A] = j^\nu$$

no correspondence principle for fermions!
→ Still a linear operator equation

$$\left(i\not{D}[A] - m\right)\hat{\psi} = 0$$

use modefunction decomposition to turn operator evolution into evolution of modes (c-numbers)

$$\hat{\psi}(x) = \int_q \sum_\lambda \left(\phi^u_{q,\lambda}(x)\hat{b}_{q,\lambda} + \phi^v_{q,\lambda}(x)\hat{d}^\dagger_{q,\lambda}\right)$$

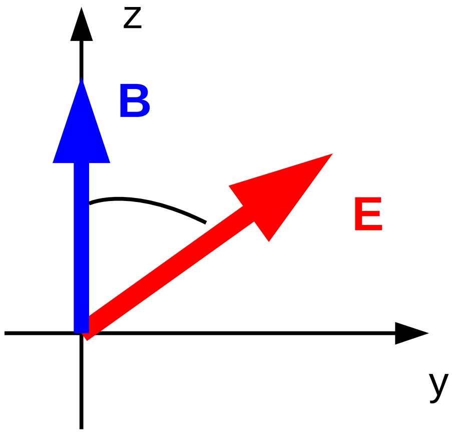
→ construct observables etc.
→ consistent time evolution, does include backcoupling, screening effects etc.
→ breaks down, when occupancies become small

3. Simulations

Real time lattice simulations

- simulating colliding laser beams
- no fermions initially (vacuum)

coherent magnetic and electric fields at initial time in the center of the "collision":



simulations on N_x x N_y x N_z = 40x40x64 (a_x x a_y x a_z = 0.08x0.08x0.04 [m]) grid

- Simulations super hard because **QED is so linear**

- **very large grids required! (and fermions are super expensive)**

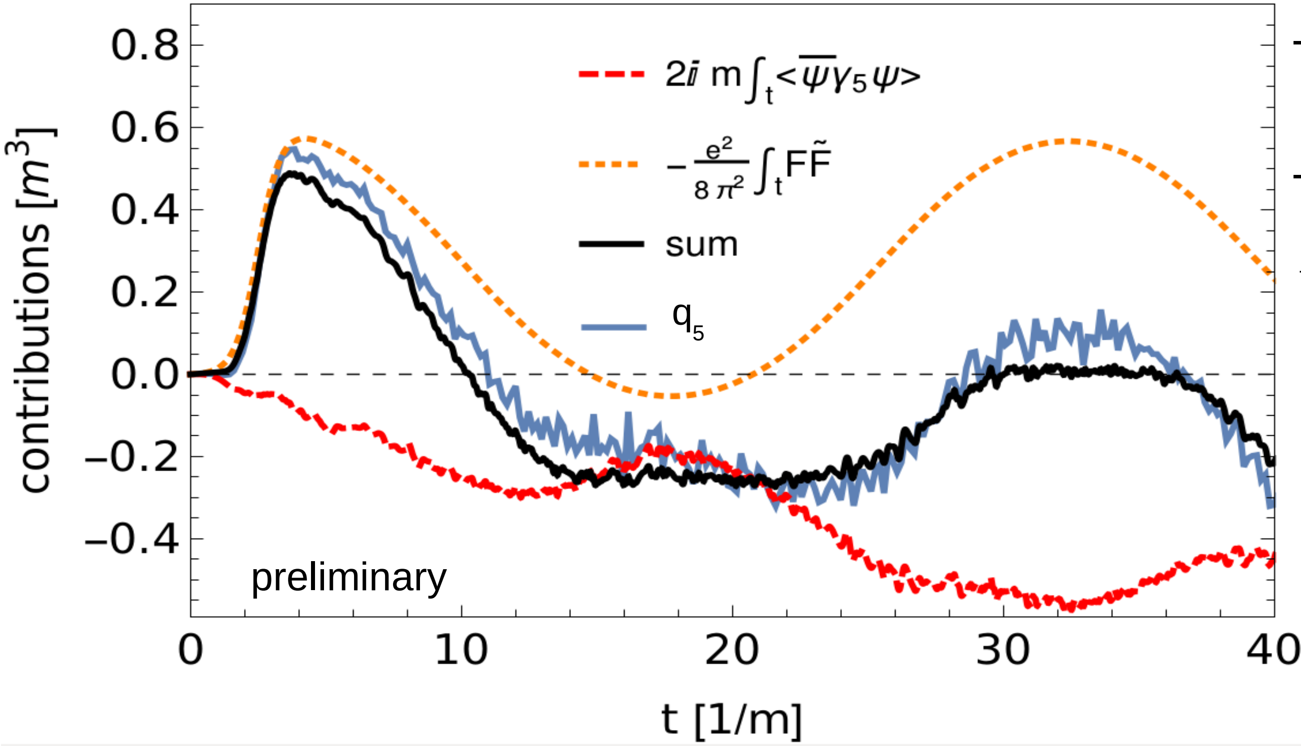
Trick: Trigger particle production by very short *electric field pulse*:

$$E(t) = E_0 \mathrm{sech}^2(\omega(t - t_0))$$

but take the **back-coupling** of the particles produced during that pulse **fully into account**
→ *very efficient in producing particles in short time – no loss of generality of results*

2. Simulations

The anomaly budget in real-time

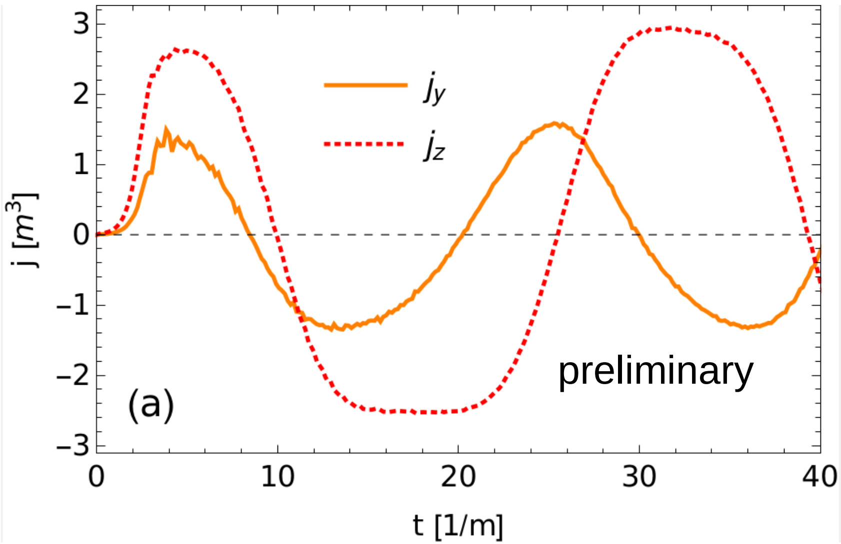


- **net axial production** at finite times
- axial density oscillations

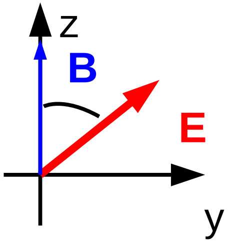
→ Consequences in terms of the chiral magnetic effect?

$$q_5(t) = -\frac{e^2}{2\pi^2}\int_V\int_0^t \mathbf{E}\cdot\mathbf{B}\,dt' + 2im\int_V\int_0^t \langle\bar{\psi}\gamma_5\psi\rangle\,dt'$$

Produced currents and Screening Effects



there are both **"normal" electric currents** (in terms of the Schwinger effect)

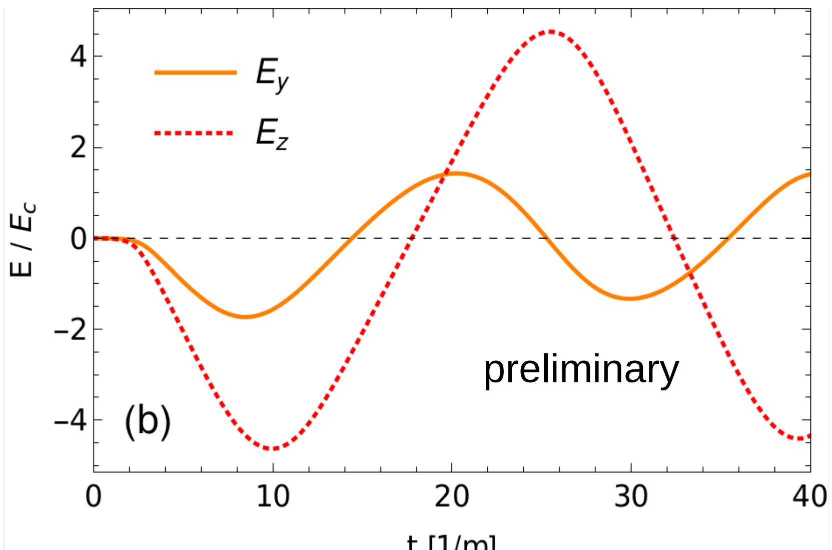


as well as

anomalous currents through the CME produced (along the magnetic field)

- naturally these components are not in phase

- same is true for the electric field components!



Chiral Magnetic Effect in QED causes 'anomalous rotation of the electric field'

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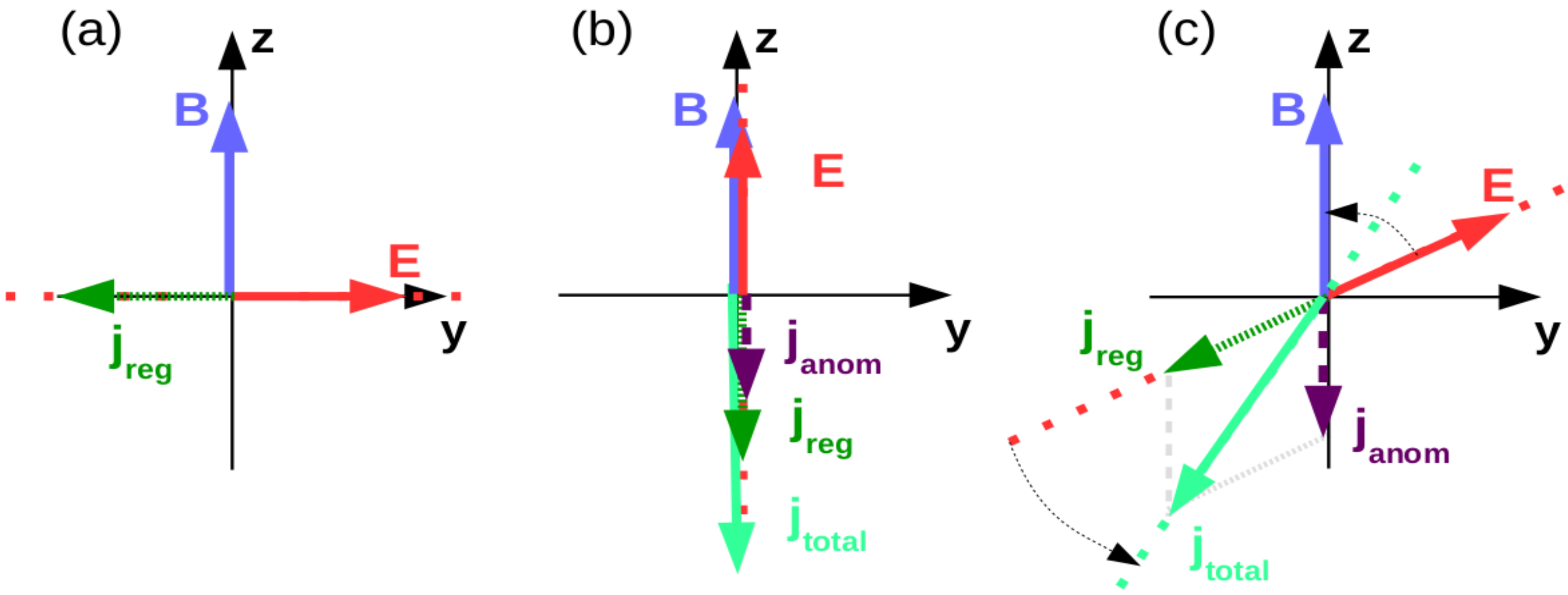
Can we understand this?



no anomalous currents

normal and anomalous currents parallel

“anomalous” off phase

3. Simulations

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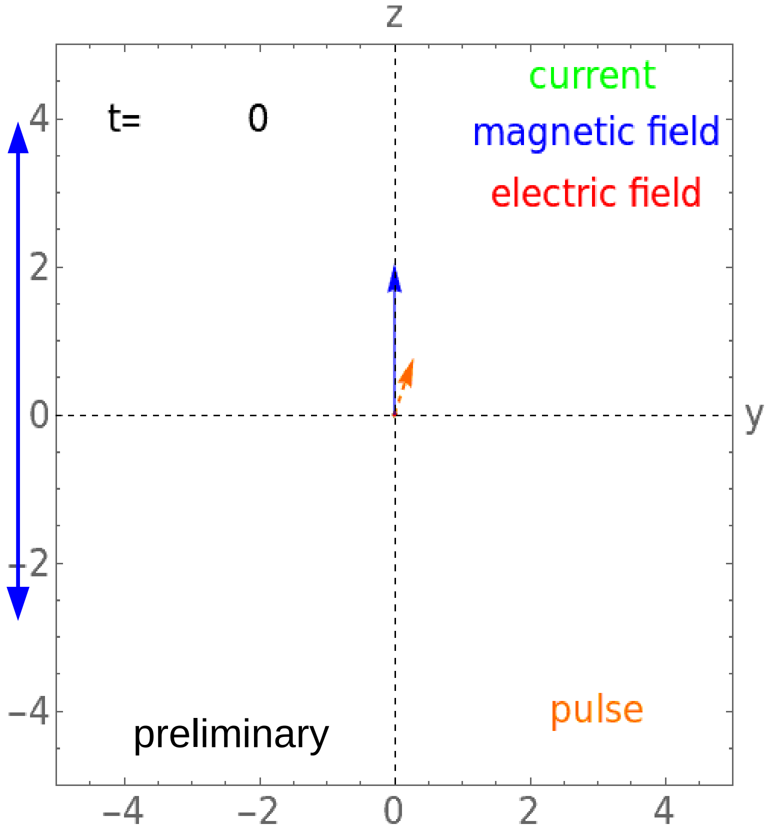
An anomalous rotation takes place!

this direction
is special



Not all angles are equal!

3. Simulations

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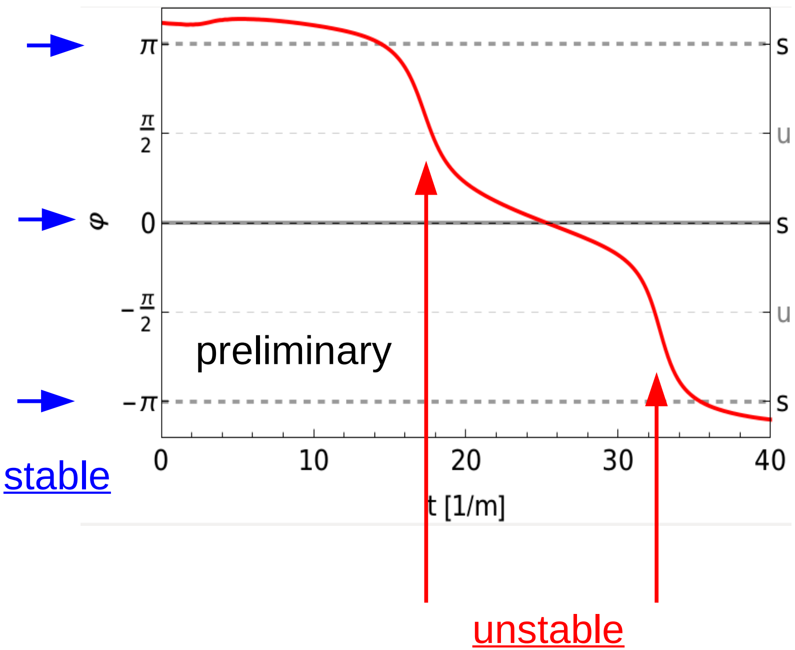
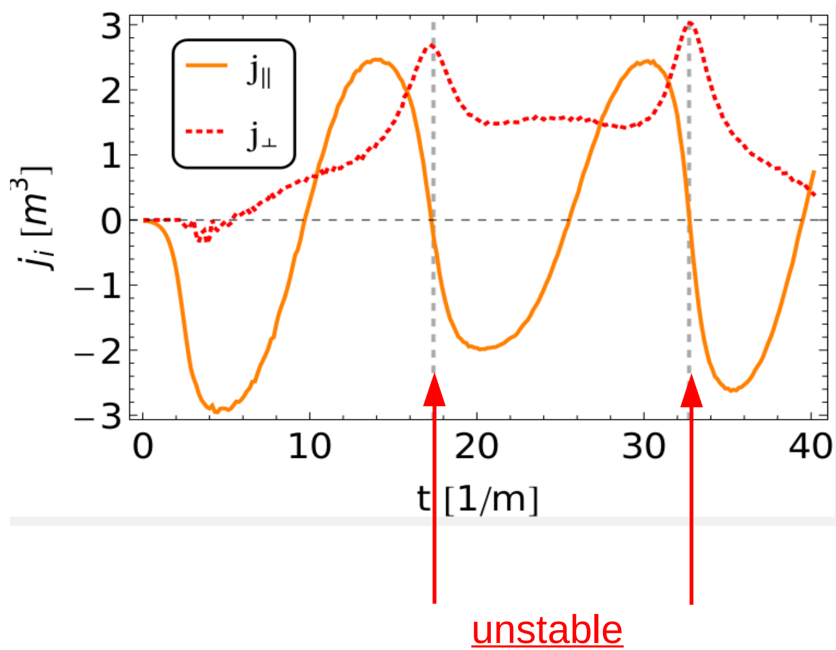
Could there be a focusing effect?





Electric fields seems to prefer being **aligned** with the magnetic field,
maximizing the anomalous current

→ **focusing?**

3. Simulations

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Some Conclusions

- We have investigated anomalous axial production in dynamical strong field QED, using classical statistical simulations

- QED is “topologically trivial”, nevertheless net anomalous axial production at finite times → non-equilibrium feature!

- The Chiral Magnetic Effect in QED generates anomalous currents leading to an anomalous rotation of the electric field.

- Dynamical focusing effect?

4. QED vs. QCD

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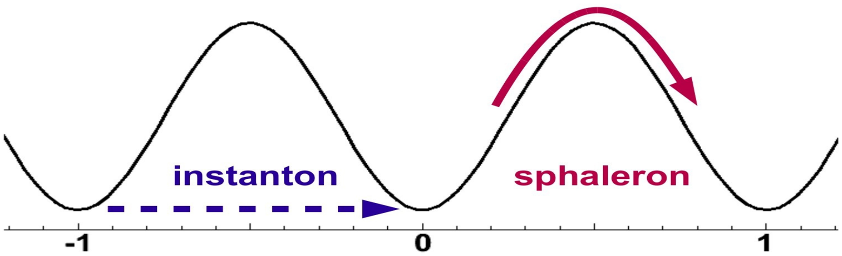
What can we learn from our QED studies?

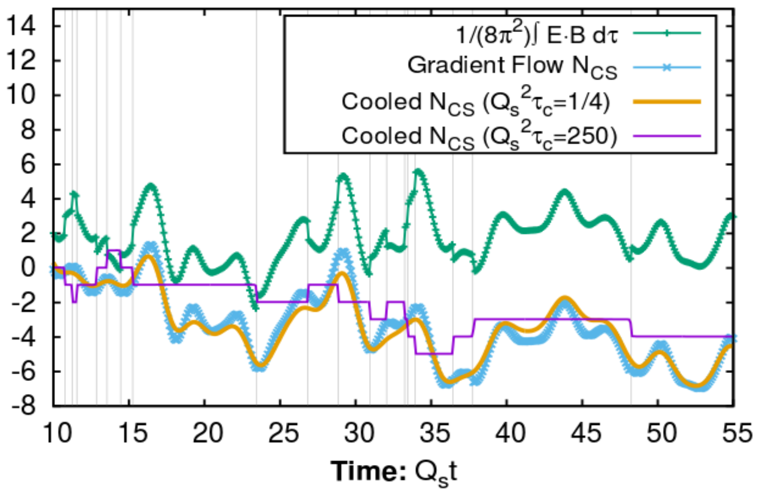
QCD as opposed to QED has a non-trivial vacuum structure!
→ sphaleron transitions will contribute to the anomalous current generation (underlying index theorem)

$$\partial_\mu j^\mu_{5,f} = 2 m_f \bar{q}\gamma_5 q - \frac{g^2}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{\mu\nu}_a$$



Real-time study in pure gauge:
Mace, Schlichting, Venugopalan arXiv:1601.07342

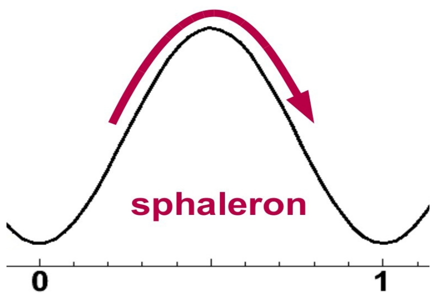
$$\frac{dN_{CS}}{dt} = \frac{g^2}{8\pi^2}\int d^3x\; E^a_i(\mathbf{x}) B^a_i(\mathbf{x})$$



→ **far from equilibrium rates considerably larger than in equilibrium**

4. QED vs. QCD

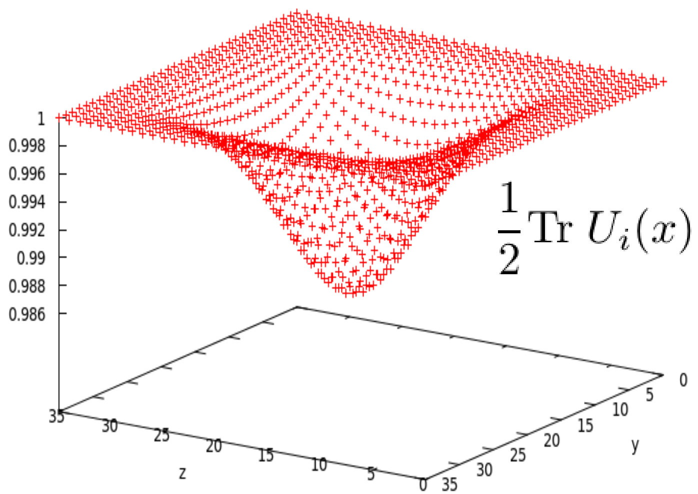
Time and spatial resolved fermion production during a sphaleron transition

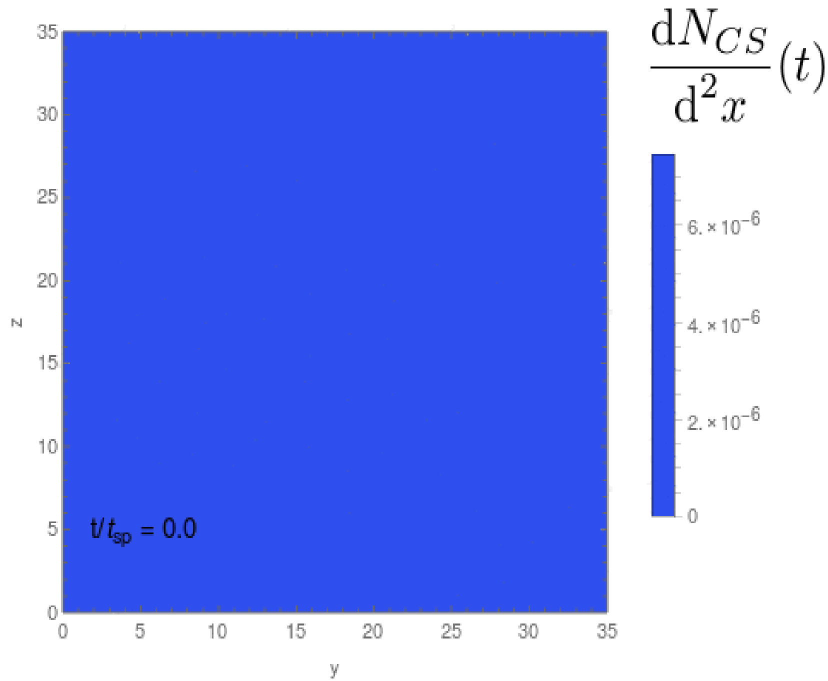


what happens to with fermions during a sphaleron transition? (SU(2) first)

→clear when integrated over space and time (index theorem), but **time and spatially resolved?**

localized topological “lump”





4. QED vs. QCD

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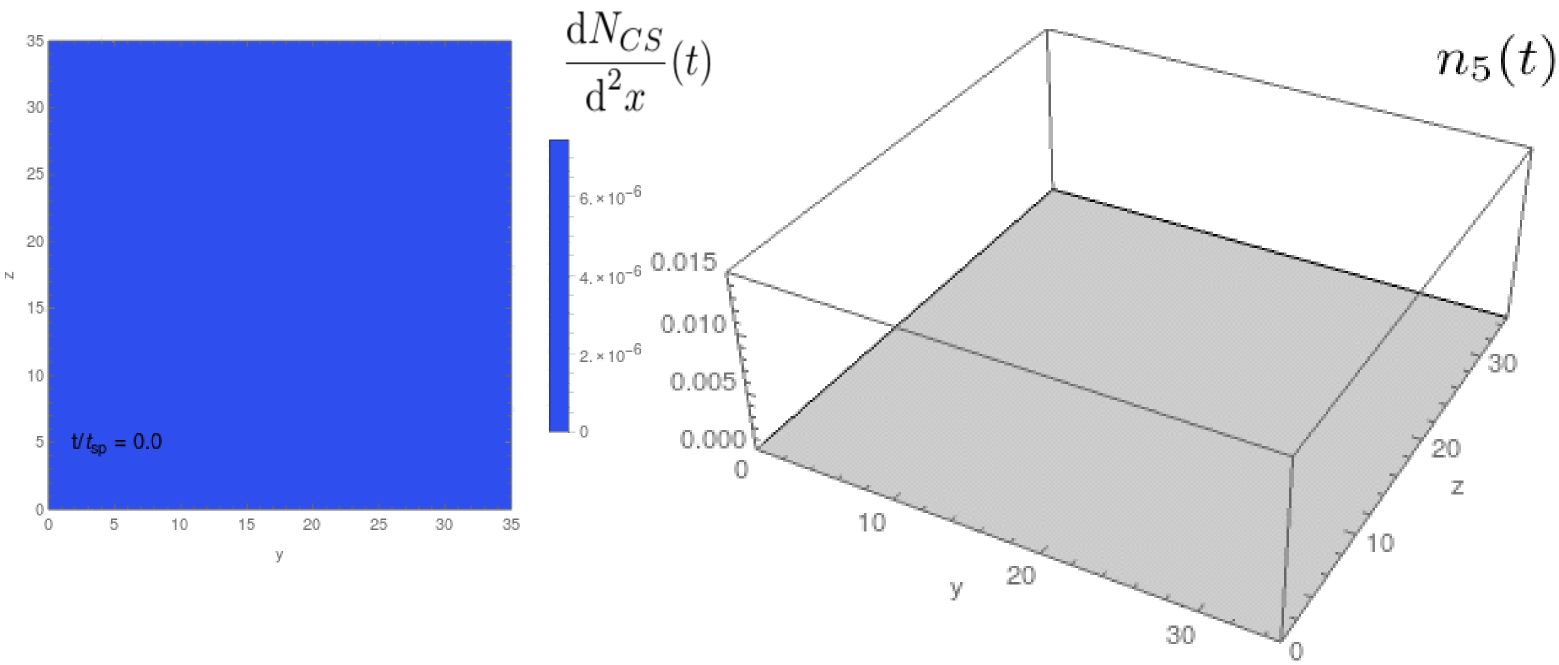
Time and spatial resolved fermion production during a sphaleron transition



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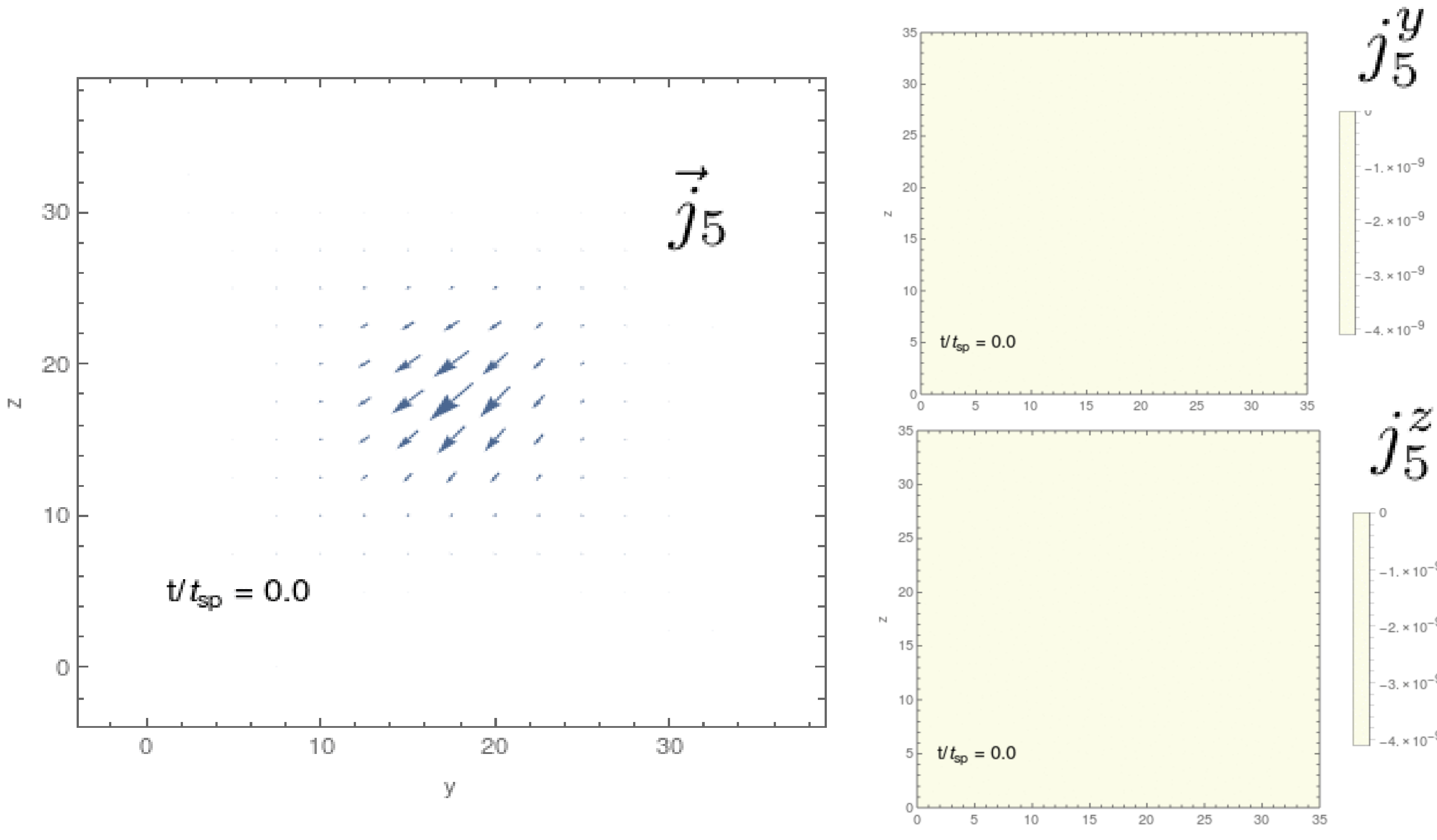
Time and spatial resolved fermion production during a sphaleron transition



4. QED vs. QCD

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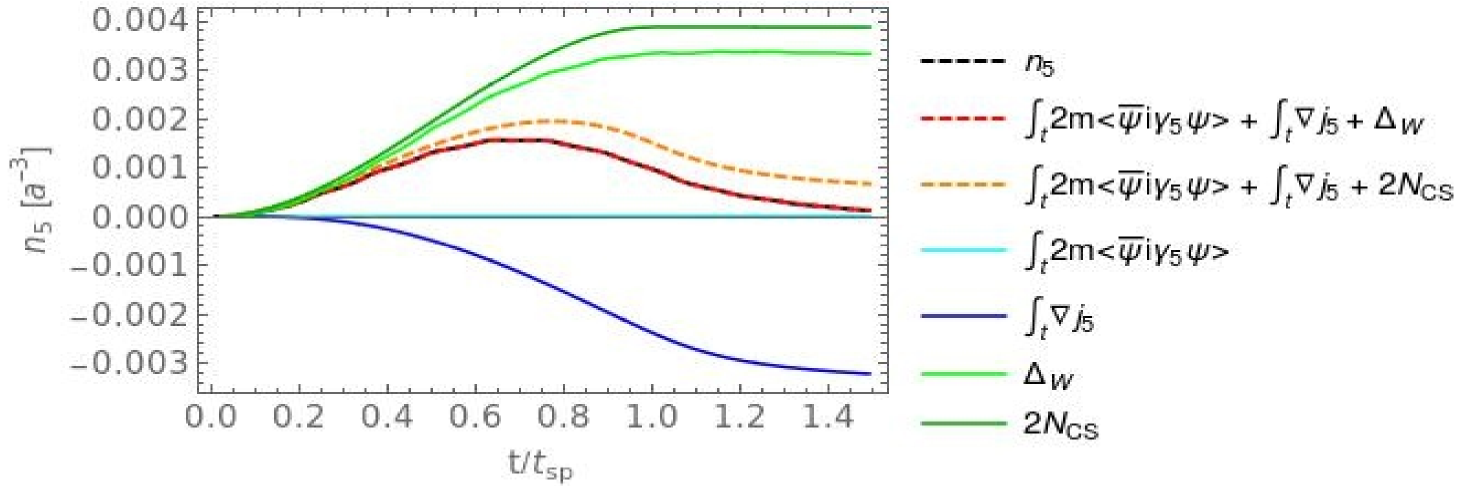
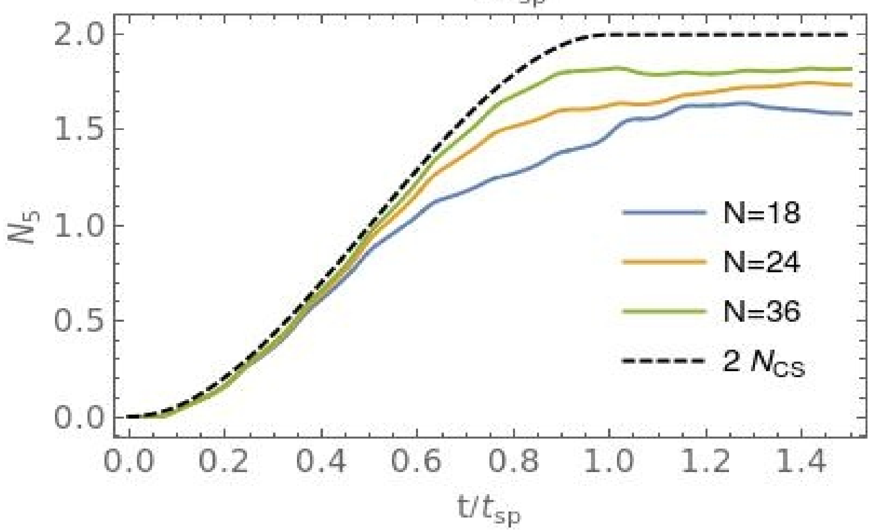
The anomaly budget





4. Conclusions

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Final Conclusions

- Comparing QED and QCD helps to understand the non-equilibrium dynamics of anomalous axial production

- Aim: understand role of field strength vs. topological contributions

- Simulated anomalous fermion production during sphaleron transition

Where to go from here?

→ QCD simulations with **background magnetic fields** from first principle non-equilibrium field theory

→ realistic systems (CGC, expanding systems etc.)

thanks for your attention!

Backup

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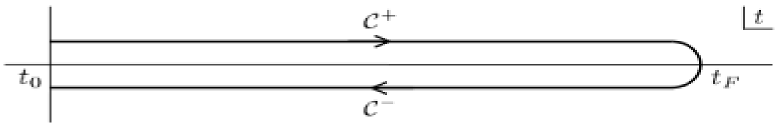
Classical statistical simulations

(see for example Kasper et al. Phys.Rev. D90 (2014) 2, 025016)



typical situation: large **coherent or highly occupied** gauge fields
→ correspondence principle

- initial stages of a heavy ion collision: A ~ 1/g
- colliding laser beams → large and coherent fields

$$A^+_{\mu,n} = \bar{A}_{\mu,n} + \frac{1}{2}\tilde{A}_{\mu,n}\,,$$
$$A^-_{\mu,n} = \bar{A}_{\mu,\bar{n}} - \frac{1}{2}\tilde{A}_{\mu,\bar{n}}\,,$$

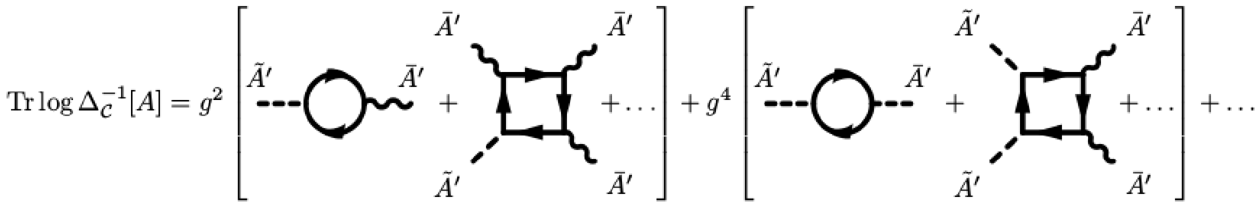
'classical' 'quantum'

The classical-statistical approximation is a systematic expansion of the 'quantum' fields around the 'classical' fields

Fermions are never "classical"

- but they are quadratic!

$$Z_C = \int [dA]\,\rho_G(A)\,\exp\left(\mathrm{Tr}\log\Delta_C[A]^{-1} + iS_G\right)$$



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Anomalies in a quasi-classical description?

Smit & Karsten (1983):

- The axial anomaly and the fermion doubling problem are intimately related

- Lattice theory regularized on the basis of the action already

- Anomaly comes from the non-trivial continuum limit of any regulator you put in to remove doublers