Chiral magnetic effect and anomalous transport from real-time lattice simulations

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Motivation

Novel transport phenomena in the presence of a chirality imbalance have created excitement across physics community [1]

Chiral Magnetic Effect: $\vec{j}_v \propto j_a^0 \vec{B}$ j_a^0: *axial charge density* $\vec{B}$: *magnetic field*

High-energy heavy-ion collisions provide an exciting environment

— *expect axial charge fluctuations due to sphaleron transitions*

— *strong magnetic field eB ~ m_π^2 present over the first ~1 fm/c*

Since life-time of magnetic field is short [2], expect that most of the effect take place during early-time pre-equilibrium stage

Goal: Develop theoretical description to study anomalous transport in out-of-equilibrium situations based on real-time lattice techniques

Simulation Techniques

Classical-statistical lattice gauge theory simulation with dynamical fermions [3-5]

— Discretize theory on 3D lattice in the Hamiltonian formalism

— Solve Dirac equation on the operator level by mode function expansion $i\gamma^0\partial_t\hat{\psi} = (-i\not{D}^s_W + m)\hat{\psi}$

— Extract vector and axial currents to study anomalous transport

Simulations include coupling to SU(N_c) and U(1) gauge fields

So far we ignore back reaction of fermions on the gauge sector and study dynamics during a sphaleron transition in constant magnetic field

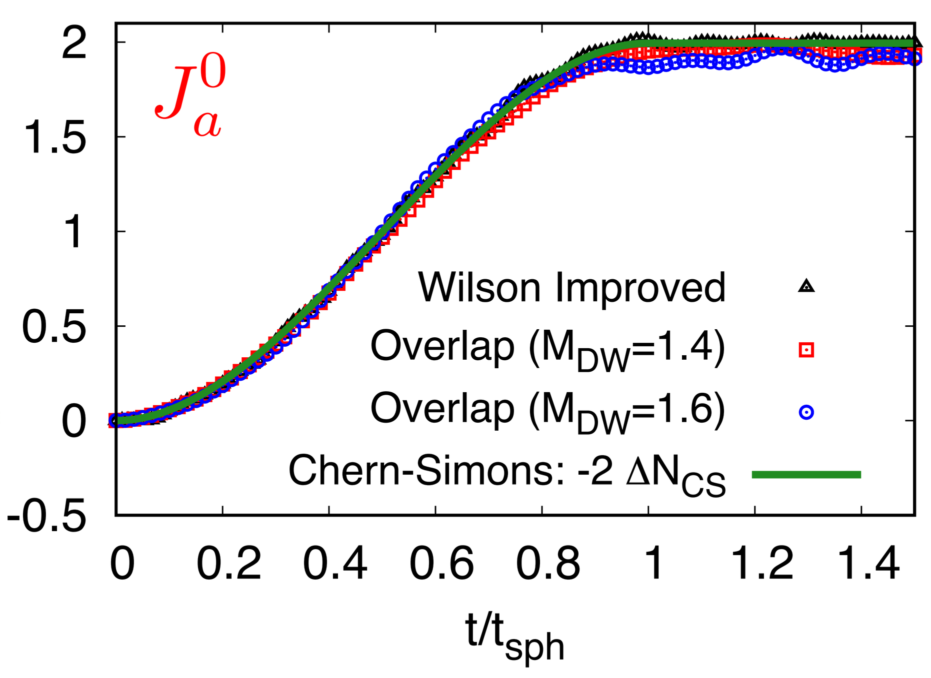
Non-equilibrium dynamics of axial and vector charges

Sphaleron transition & axial charge imbalance

Sphaleron transition corresponds to a unit change of the Chern-Simons number

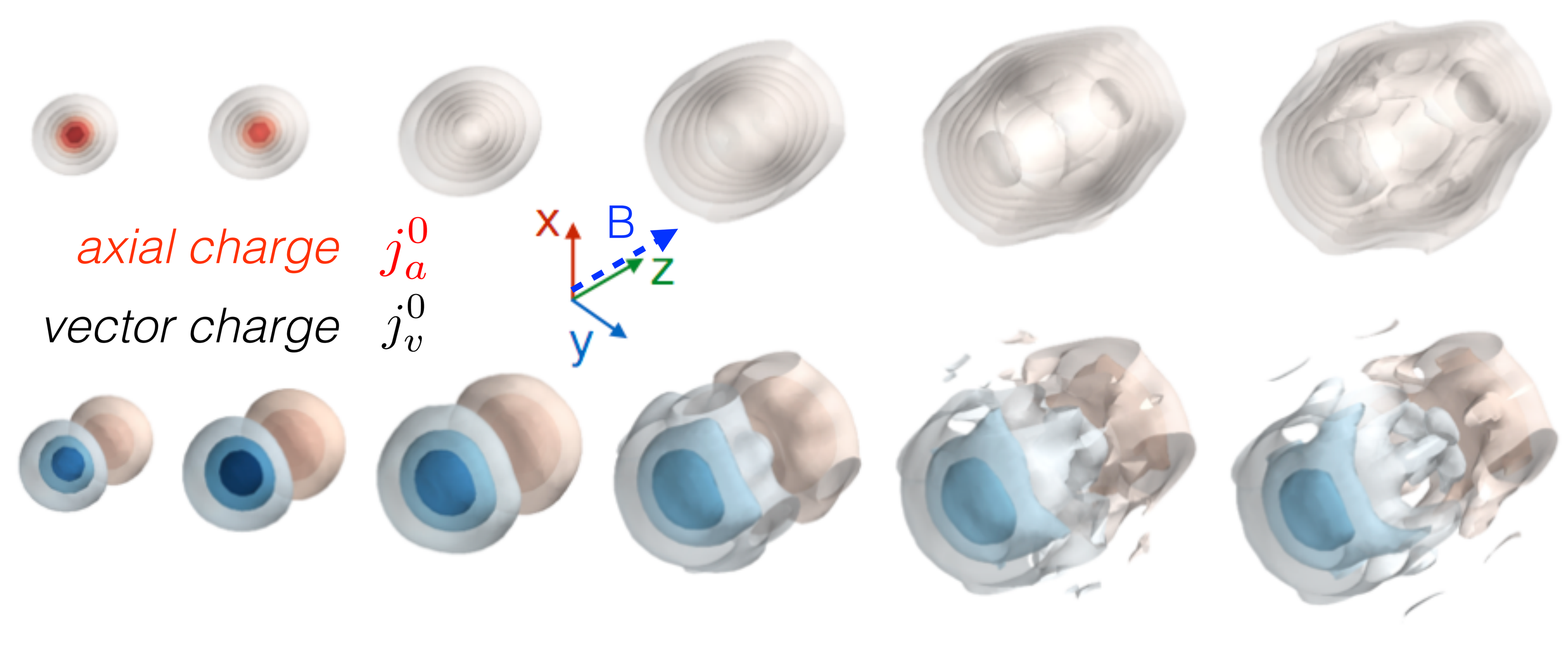
$$\Delta N_{CS} = \frac{g^2}{16\pi^2}\int \mathrm{Tr} F_{\mu\nu}(x)\tilde{F}^{\mu\nu}(x)$$

which induces an imbalance of the axial charge according to the axial anomaly



$$\partial_\mu j_a^\mu(x) = 2im\langle\hat{\bar{\psi}}(x)\gamma_5\hat{\psi}(x)\rangle - \frac{g^2}{8\pi^2}\mathrm{Tr}F_{\mu\nu}(x)\tilde{F}^{\mu\nu}(x)$$

Even though realization of axial anomaly on the lattice is non-trivial anomaly is consistently reproduced with (tree-level) improved Wilson and Overlap fermions.



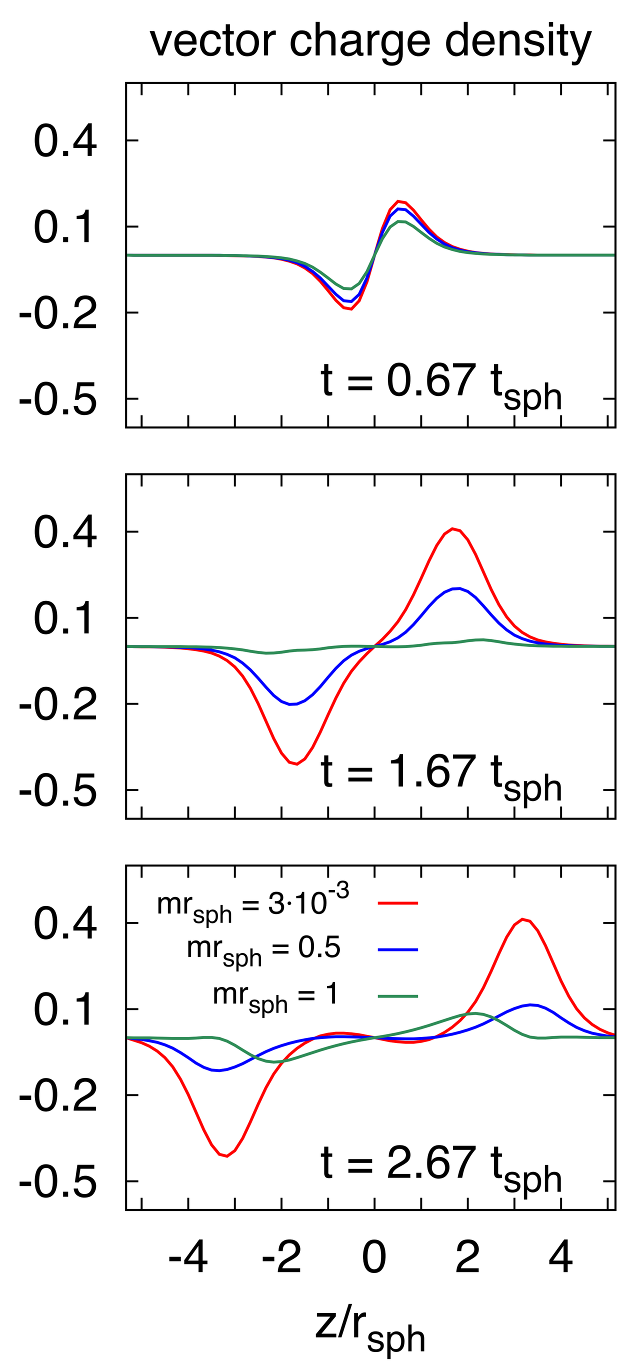
Chiral magnetic effect & Chiral magnetic wave

Axial charge imbalance leads to a vector current $j_v^z \propto j_a^0 B^z$ - chiral magnetic effect

Vector charge j_v^0 separates along the direction of the magnetic field

Vector charge imbalance leads to an axial current $j_a^z \propto j_v^0 B^z$ - chiral separation effect

Chiral magnetic wave propagates along the direction of magnetic field



Light quarks ($\mathrm{m}t_{\mathrm{sph}} \ll 1$)

Non-dissipative transport of axial and vector charges

Evolution at late times well described by anomalous hydrodynamics

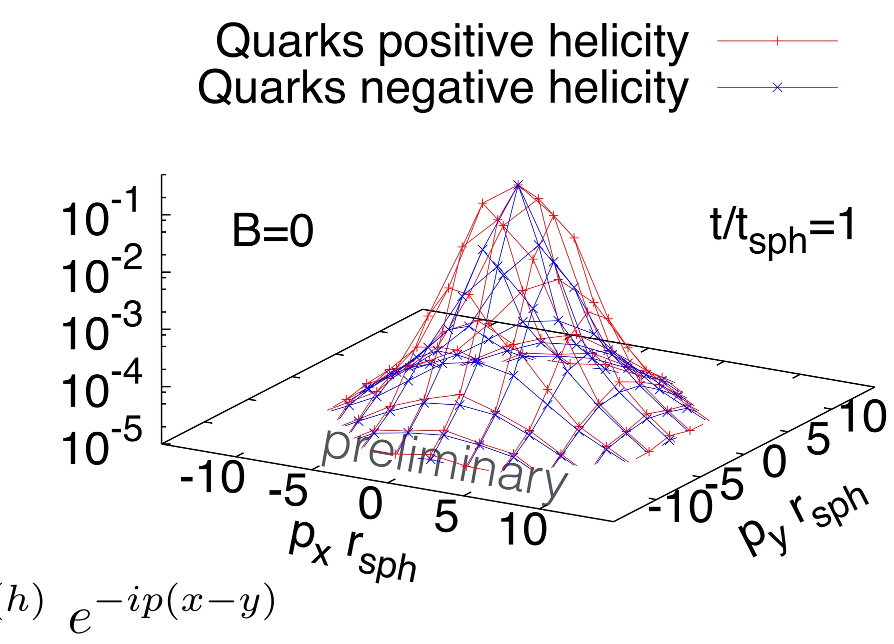
Heavy quarks ($\mathrm{m}t_{\mathrm{sph}} \sim 1$)

Dissipation of axial charge leads to significant reduction of CME & CMW

Spectral properties

Goal: Explore spectral properties to compare to chiral kinetic theory

Defined from quasi-particle projection of gauge invariant two-point correlation function



$$n_h^u(p) = \int u_p^{(h)}\langle\psi^\dagger(x)U_{xy}\psi(y)\rangle u_p^{\dagger(h)}\, e^{-ip(x-y)}$$

Conclusions & Outlook

Developed first-principle techniques to study dynamics of vector and axial charges out-of-equilibrium

First confirmation of CMW from real-time lattice simulations

Extend simulations to include back-reaction and study quark production in heavy-ion collisions

Provide initial conditions for anomalous hydrodynamics

Expect several applications beyond high-energy QCD

Dirac semi-metals, strong field QED

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