Suppression of net-particle production from finite fermion mass: A real-time CME simulation

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High Energy Physics in the LHC Era

Valparaiso. January 9, 2016

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Particle production over a CP breaking domain

Recipe for BAU:

- Baryon number violation
- CP should be violated
- The above interactions should be active when the system is out of thermal equilibrium

Since the 1980's it has been realized that the standard weak interactions contain processes, mediated by sphalerons

Particle production over a CP breaking domain

In strong interactions …RHIC

B on top of a CP breaking background generates a current on the direction of B: The Chiral Magnetic Effect

Exact, non-dissipative

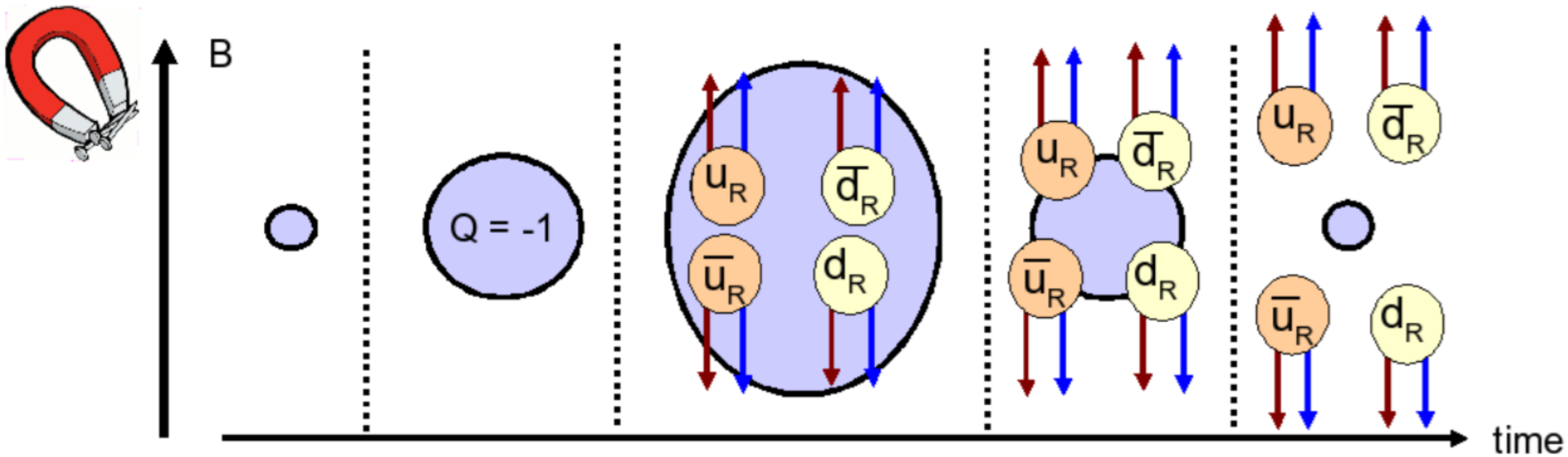
Crucial to the QCD phase diagram

[K. Fukushima and P.M. (2013)]

Chiral magnetic effect (CME)

[A. Vilenkin, '80; K. Fukushima, D. E. Kharzeev, H. J. Warringa, '08; D. E. Kharzeev, L. D. McLerran and H. J. Warringa, '08]

$$\mathbf{j} = \frac{q_e^2 \mu_5}{2\pi^2}\mathbf{B}$$



What is the response time for the chiral magnetic current to get activated?

Experimental confirmation of the CME has started to appear in condense matter physics…

Observation of the chiral magnetic effect in $ZrTe_5$

Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5] A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

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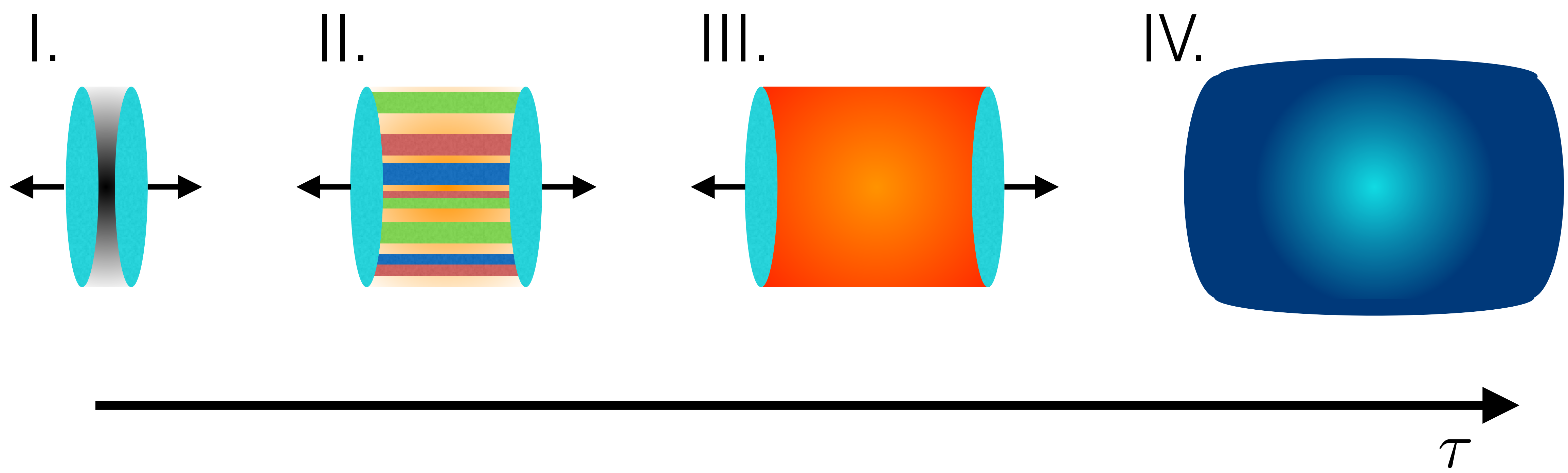
Maybe some will come soon at Heavy ion as well

A bit of relativistic heavy ion collision physics



I. Color-glass-condensate (CGC)

$$\tau \lesssim 1/Q_{sat} \sim 0.1\mathrm{fm}/c$$

II. Glasma

$$\tau \lesssim \tau_0 \sim 1\mathrm{fm}/c$$

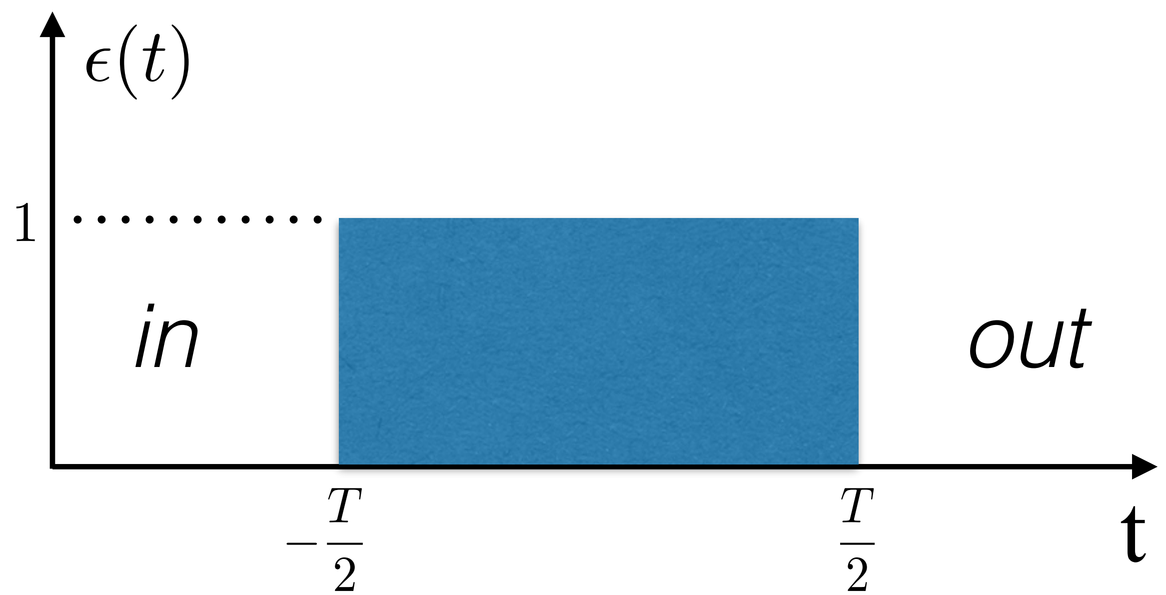
III. Quark gluon plasma (QGP)

$$\tau \lesssim \tau_f \sim 10\mathrm{fm}/c$$

IV. Hadronization

Temporal profile of external field motivated on the glasma dynamics in which external B and chromo-fields decay within the same time scale 0.1 fm/c

Our set-up to tackle this problem…



$$A^x = B_\perp \epsilon(t) z - B_\parallel \epsilon(t) y$$

$$A^y = 0$$

$$A^z = -E_0 \int_{-\infty}^{t} \epsilon(t') dt'$$

We will look at particle and antiparticle mom. distr. asymmetries

Momentum distribution functions

$$\frac{u_+(\mathbf{p}_A)}{\sqrt{2\,\mathrm{E}_{\mathbf{p},A}}}\,e^{-i\mathrm{E}_{\mathbf{p},A}x^0+i\mathbf{p}\cdot\mathbf{x}} \longrightarrow \int \frac{d^3\mathbf{q}}{(2\pi)^3}\left[\alpha_{\mathbf{q},\mathbf{p}}\frac{u_+(\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\,e^{-i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}} - \bar{\beta}^*_{-\mathbf{q},-\mathbf{p}}\frac{v_+(-\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\,e^{i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}}\right]$$

evolution of the wave functions

Momentum distribution functions

$$\frac{u_+(\mathbf{p}_A)}{\sqrt{2\,\mathrm{E}_{\mathbf{p},A}}}\, e^{-i\mathrm{E}_{\mathbf{p},A}x^0+i\mathbf{p}\cdot\mathbf{x}} \longrightarrow \int \frac{d^3\mathbf{q}}{(2\pi)^3}\left[\alpha_{\mathbf{q},\mathbf{p}}\frac{u_+(\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\, e^{-i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}} - \bar{\beta}^*_{-\mathbf{q},-\mathbf{p}}\frac{v_+(-\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\, e^{i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}}\right]$$

evolution of the wave functions

$$\beta_{\mathbf{q},\mathbf{p}} = \int d^3x\, \frac{u_+^\dagger(\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\, e^{i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}} f^{\,+}_{-\mathbf{p}}(x^0,\mathbf{x})$$

$$|\beta_{\mathbf{p}}|^2 = \int \frac{d^3\mathbf{q}}{(2\pi)^3}|\beta_{\mathbf{q},\mathbf{p}}|^2$$

Momentum distribution functions

$$\frac{u_+(\mathbf{p}_A)}{\sqrt{2\,\mathrm{E}_{\mathbf{p},A}}}\, e^{-i\mathrm{E}_{\mathbf{p},A}x^0+i\mathbf{p}\cdot\mathbf{x}} \longrightarrow \int \frac{d^3\mathbf{q}}{(2\pi)^3}\left[\alpha_{\mathbf{q},\mathbf{p}}\frac{u_+(\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\, e^{-i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}} - \bar{\beta}^*_{-\mathbf{q},-\mathbf{p}}\frac{v_+(-\mathbf{q}_{A'})}{\sqrt{2\,\mathrm{E}_{\mathbf{q},A'}}}\, e^{i\mathrm{E}_{\mathbf{q},A'}x^0+i\mathbf{q}\cdot\mathbf{x}}\right]$$

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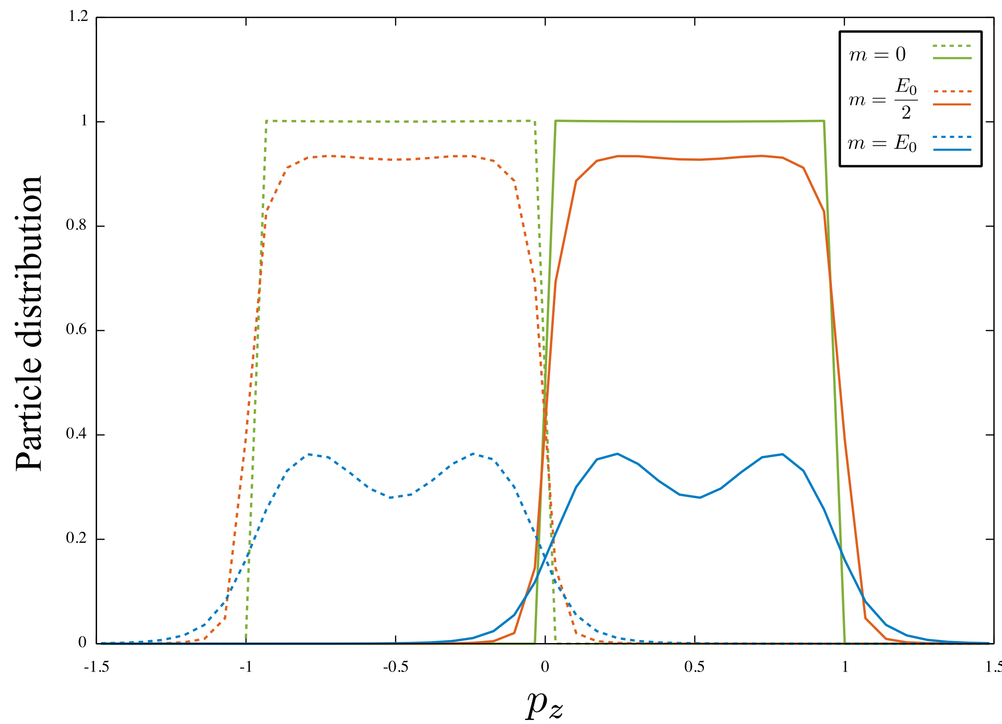
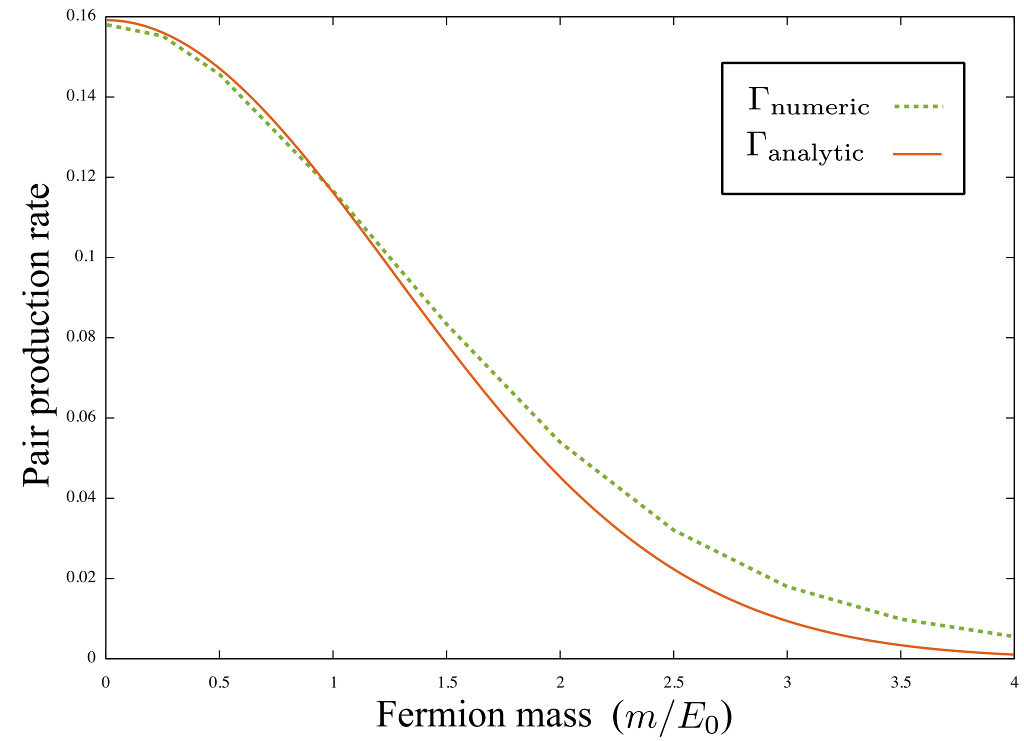
numerical solution to the Dirac eq.

$$|\beta_{\mathbf{p}}|^2 = \int \frac{d^3\mathbf{q}}{(2\pi)^3}|\beta_{\mathbf{q},\mathbf{p}}|^2$$

$$v_+(p_A) = \frac{1}{\sqrt{4|\mathbf{p}_A|E_0}}\frac{1}{\sqrt{2(E_{\mathbf{p},A}+M)}}\begin{pmatrix} -(E_{\mathbf{p},A}+M-|\mathbf{p}_A|)v_R(p_A) \\ (E_{\mathbf{p},A}+M+|\mathbf{p}_A|)v_R(p_A)\end{pmatrix}$$

Schwinger mechanism





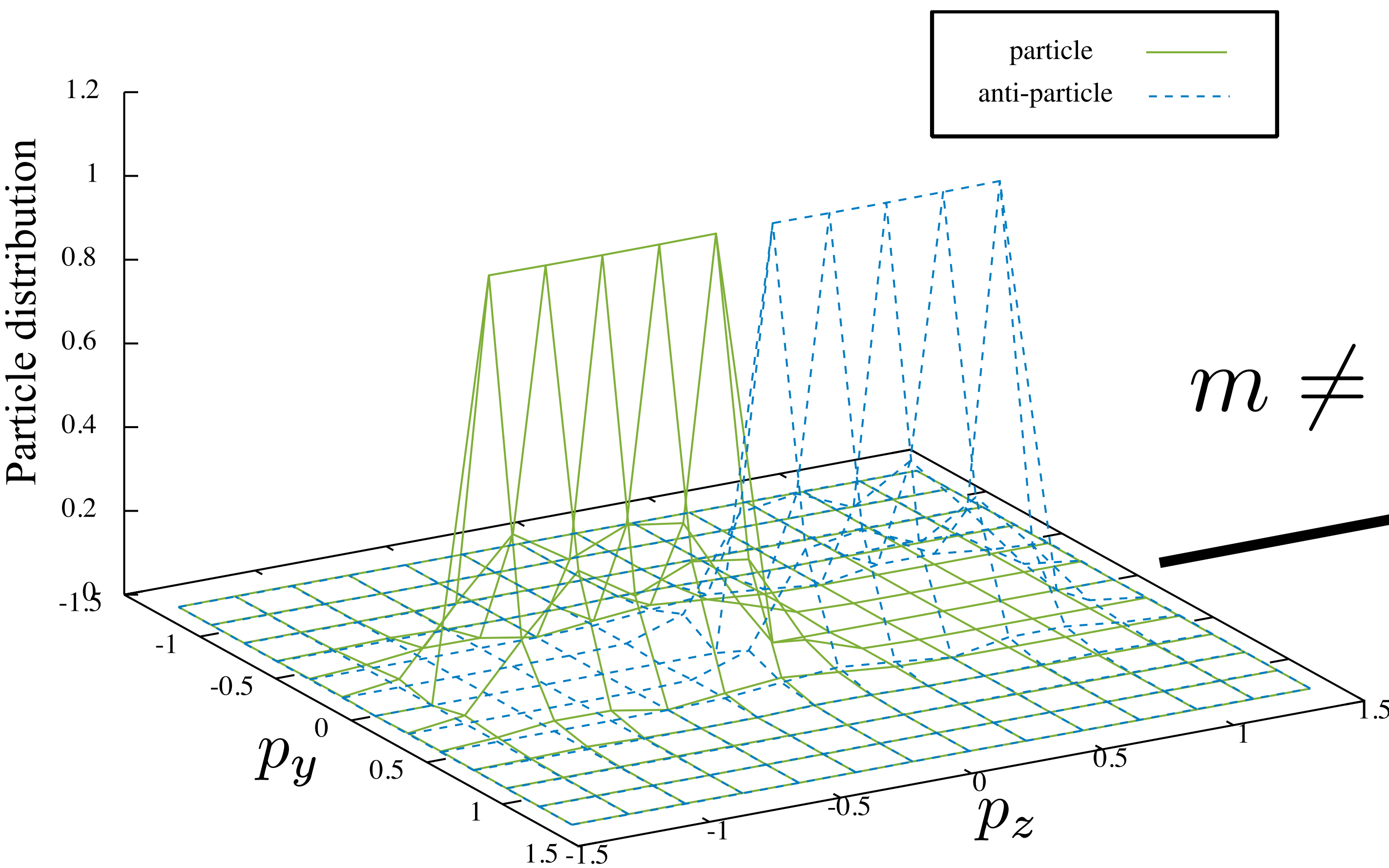
$$\Gamma = e^2 \frac{E_0 B_\parallel}{4\pi^2} \coth\left(\frac{B_\parallel}{E_0}\pi\right) e^{-m^2\pi/|eE_0|}$$

[Nikishov (69')]

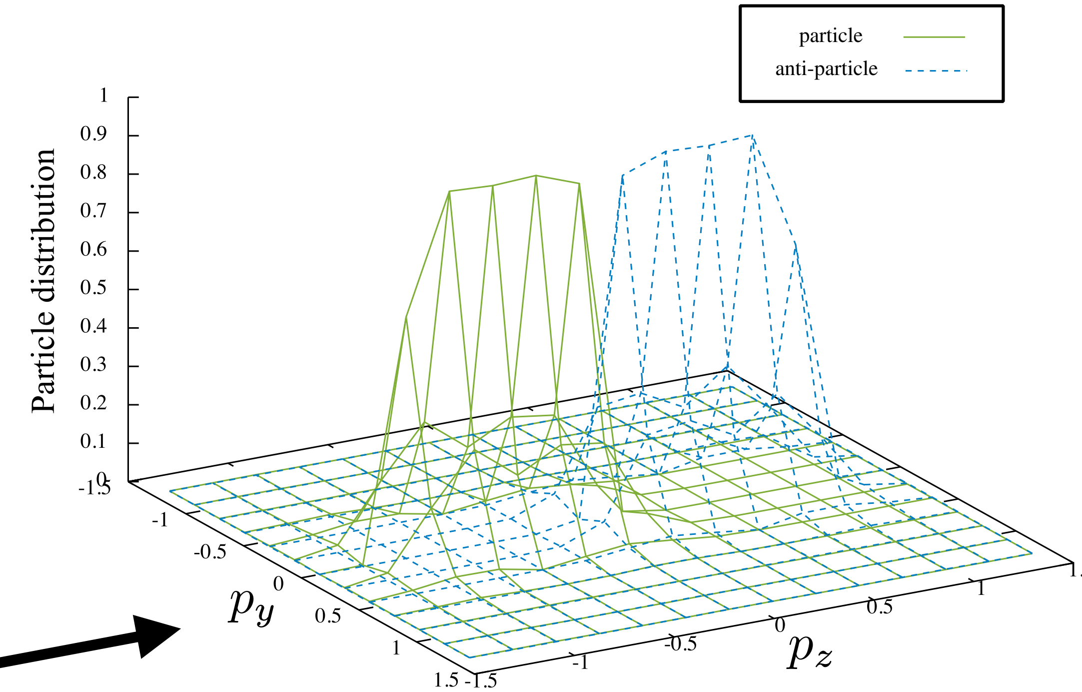
$$\Gamma \xrightarrow{B_\parallel \to 0} \Gamma_{\text{Schwinger}} e^{-m^2\pi/|eE_0|}, \qquad \Gamma_{\text{Schwinger}} = e^2 \frac{E_0^2}{4\pi^3}$$

$$n_0 = \Gamma_{\text{Schwinger}} \cdot t_E$$

Momentum distribution functions



$m \neq 0$



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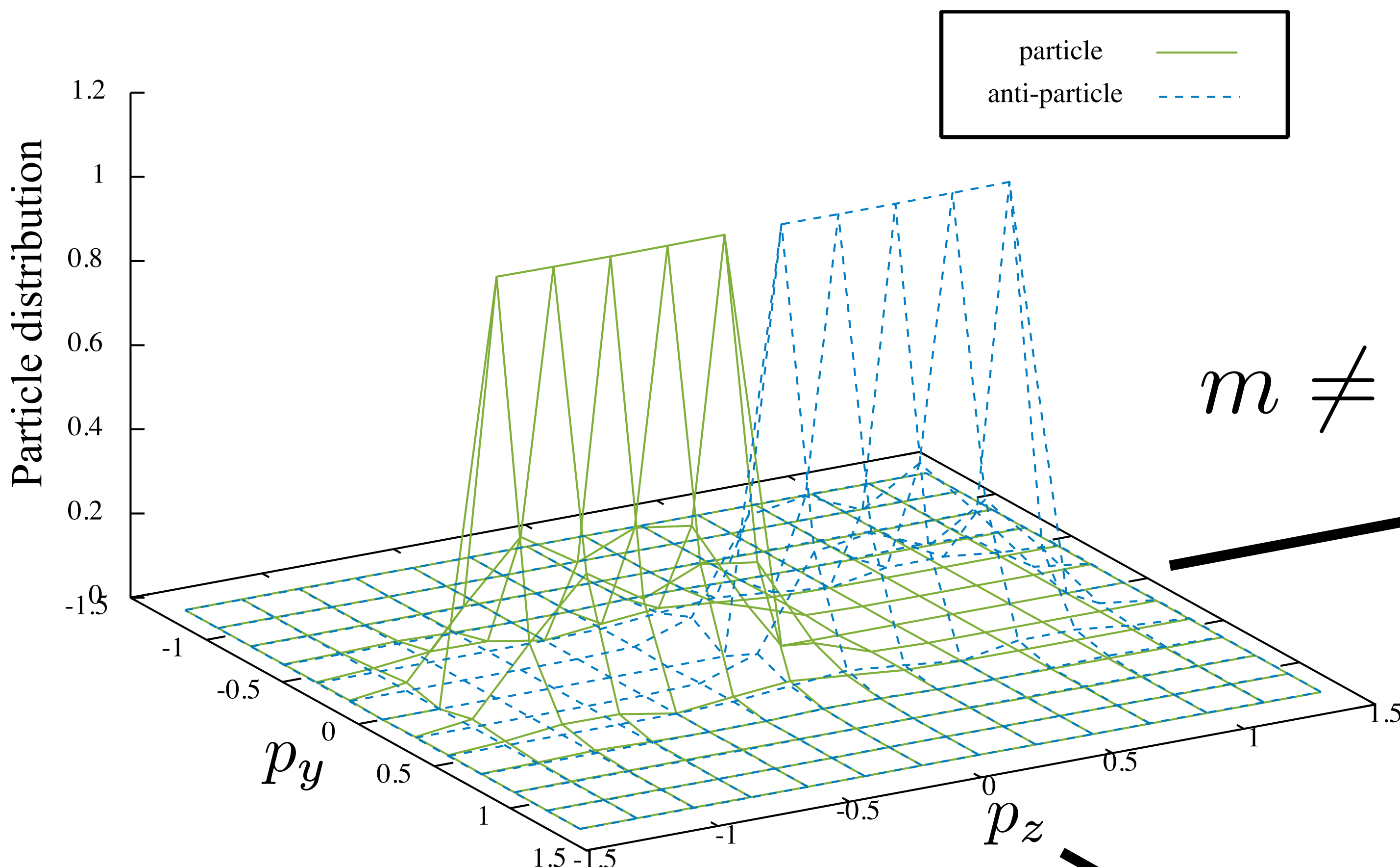

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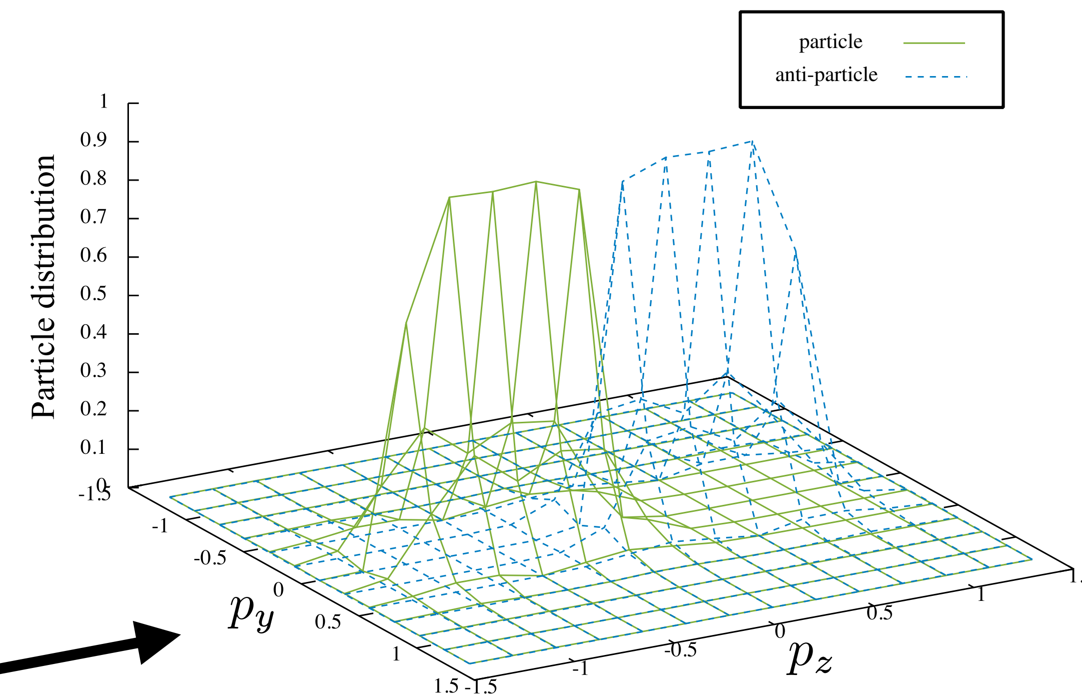
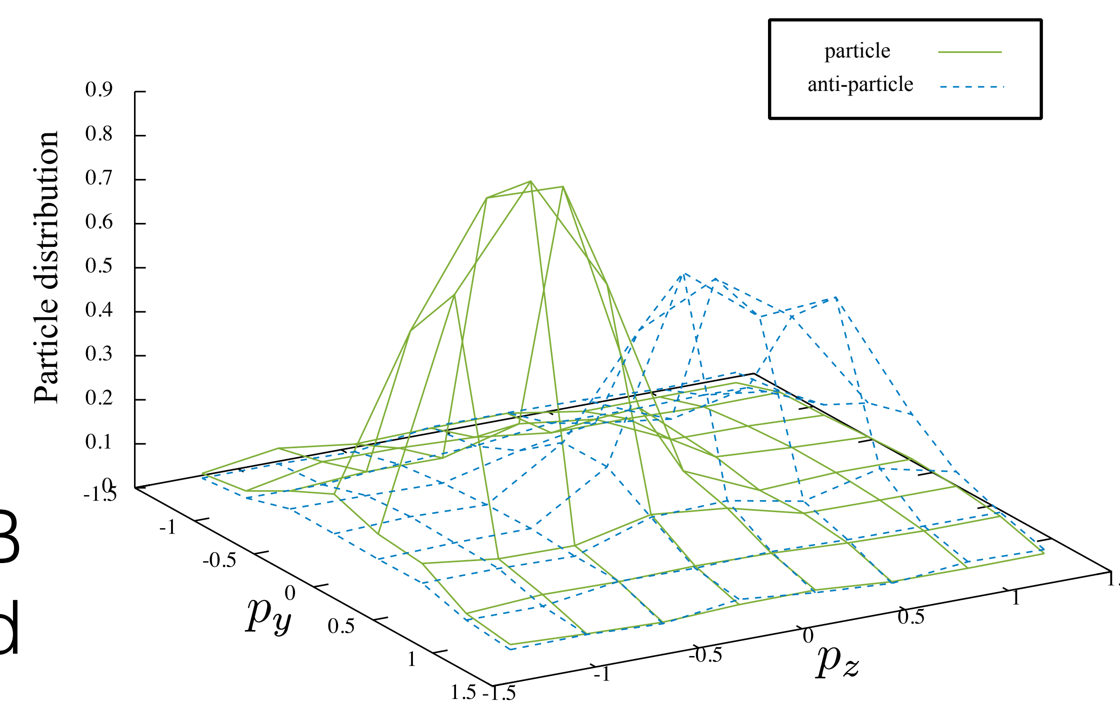


$$B_{||} \neq 0$$



Breaking of CP due to parallel E and B results in an imbalance of the particle and anti-particle distributions

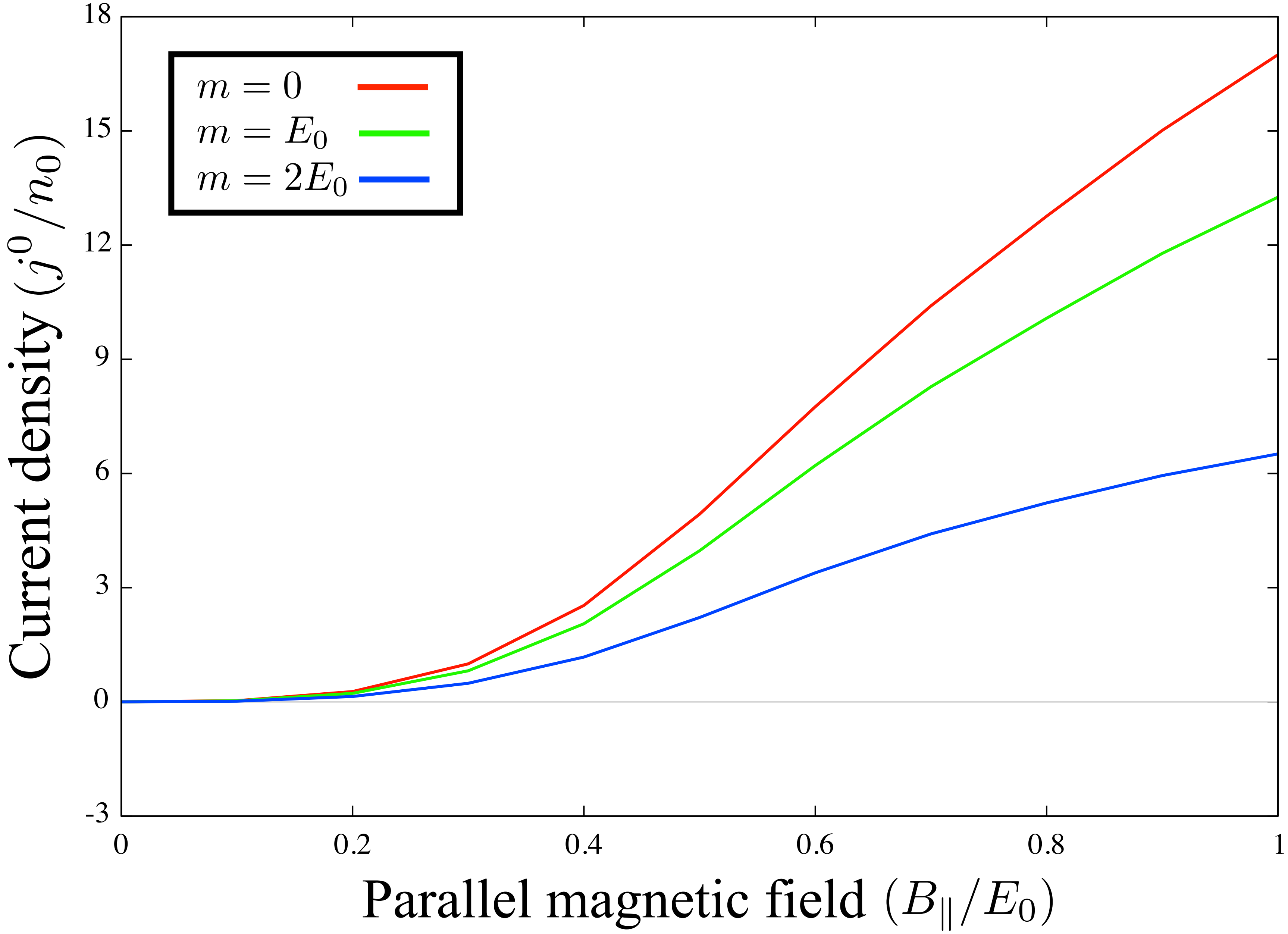
Net particle density and induced currents

Direct computation of this observable yields

$$\langle : J'^{\mu}_{\mathbf{A}'} : \rangle_{\mathbf{A}} = e \int \frac{d^3\mathbf{p}}{(2\pi)^3} \left\{ \frac{p^{\mu}_{A}}{E_{\mathbf{p},A'}} |\beta_{\mathbf{p}}|^2 - \frac{p^{\mu}_{-A}}{E_{\mathbf{p},-A'}} |\bar{\beta}_{\mathbf{p}}|^2 \right\}$$

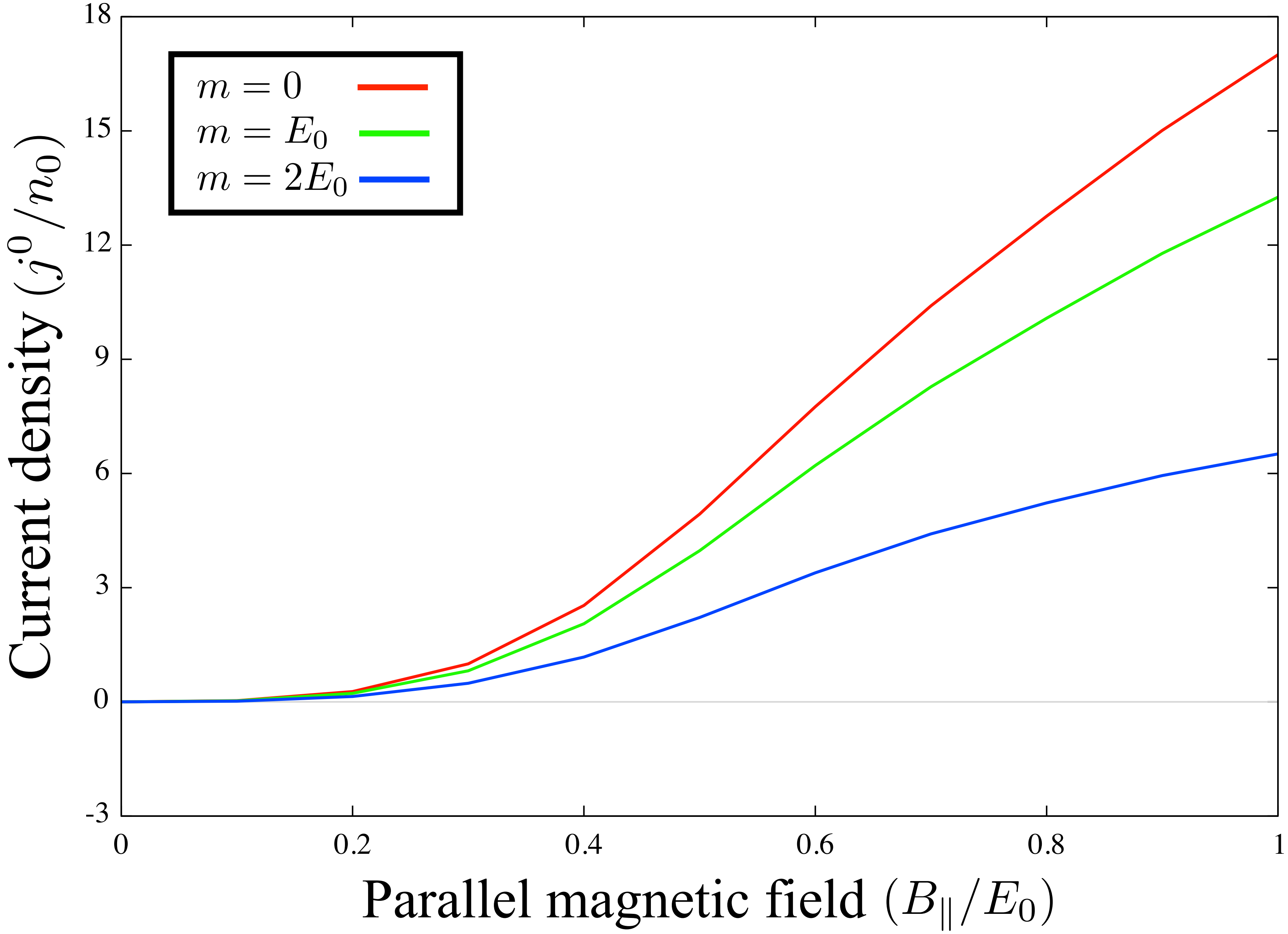
0-component: Excess of +helicity fermions

i-component: Anomalous currents



$m = 0$
$m = E_0$
$m = 2E_0$
Current density (j^0/n_0)
18
15
12
9
6
3
0
-3
0
0.2
0.4
0.6
0.8
1
Parallel magnetic field $(B_\parallel/E_0)$

The orthogonal component of the magnetic field does not generate electric carriers



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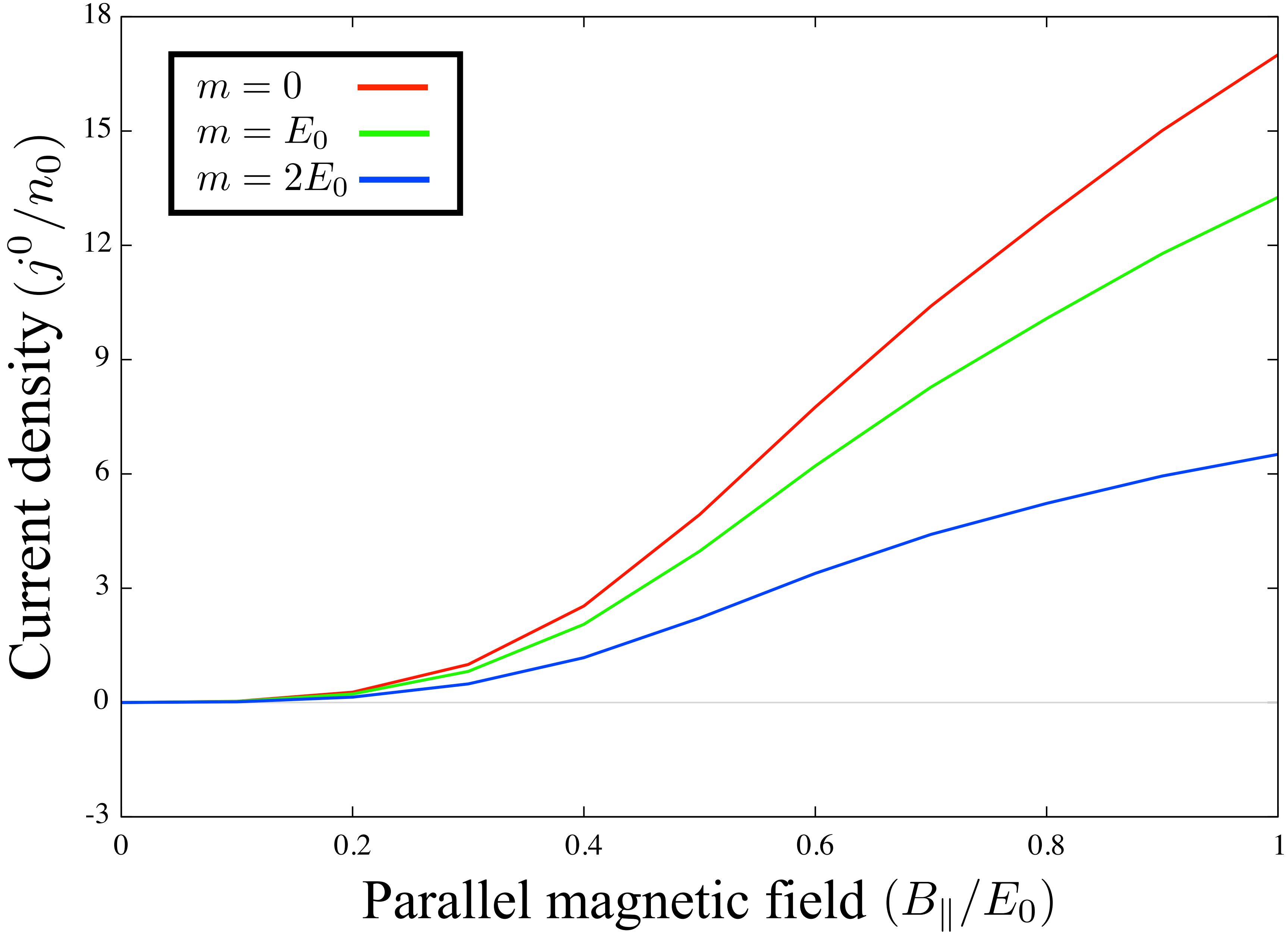
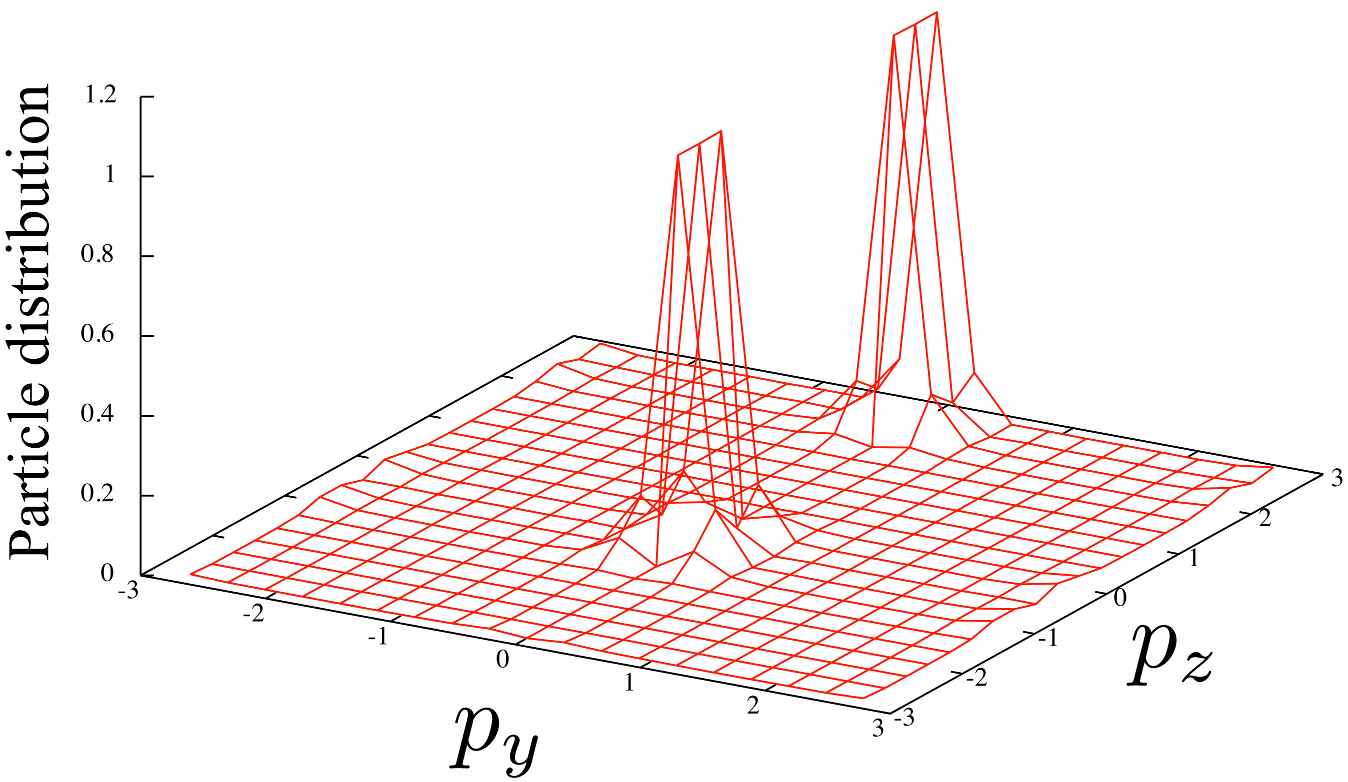


How about the vector component generation (CME)?

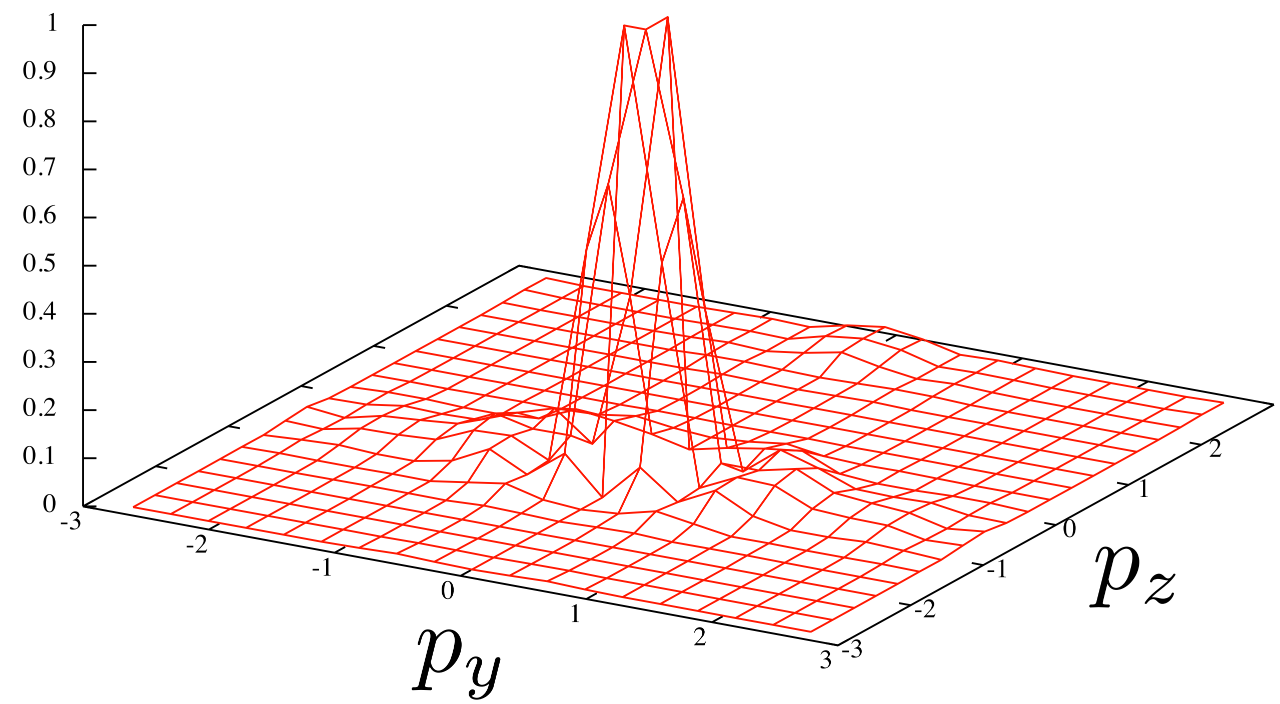
A bit about Brillouin zones…

Wilson term $$S_f - \frac{r}{2}\int d^4x\,\bar{\psi}D_iD^i\psi$$

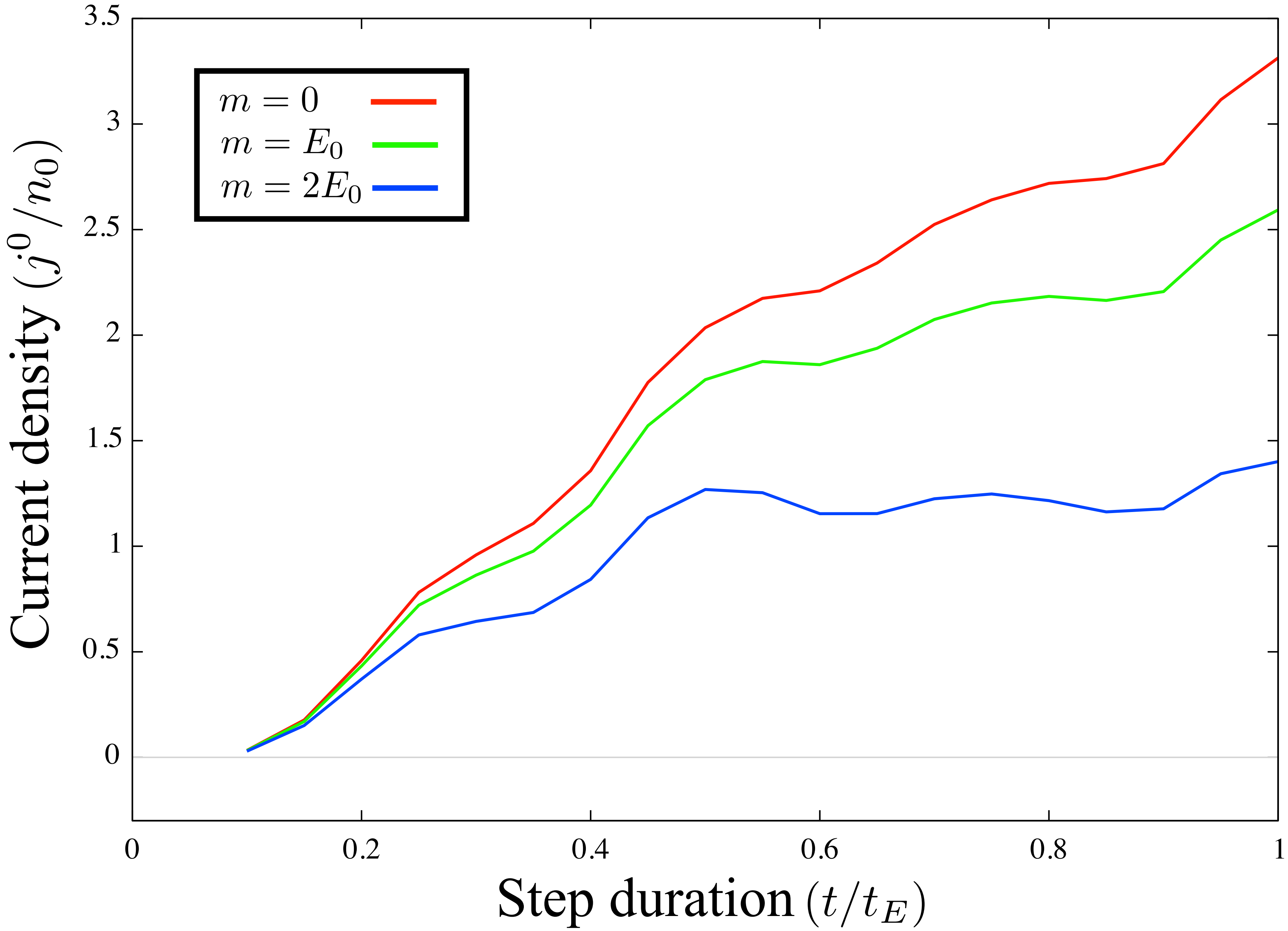
doublers



Exact cancelation of anomaly (Nielsen-Ninomiya)



How is net-particle production suppressed by mass and how does it influence its time evolution?



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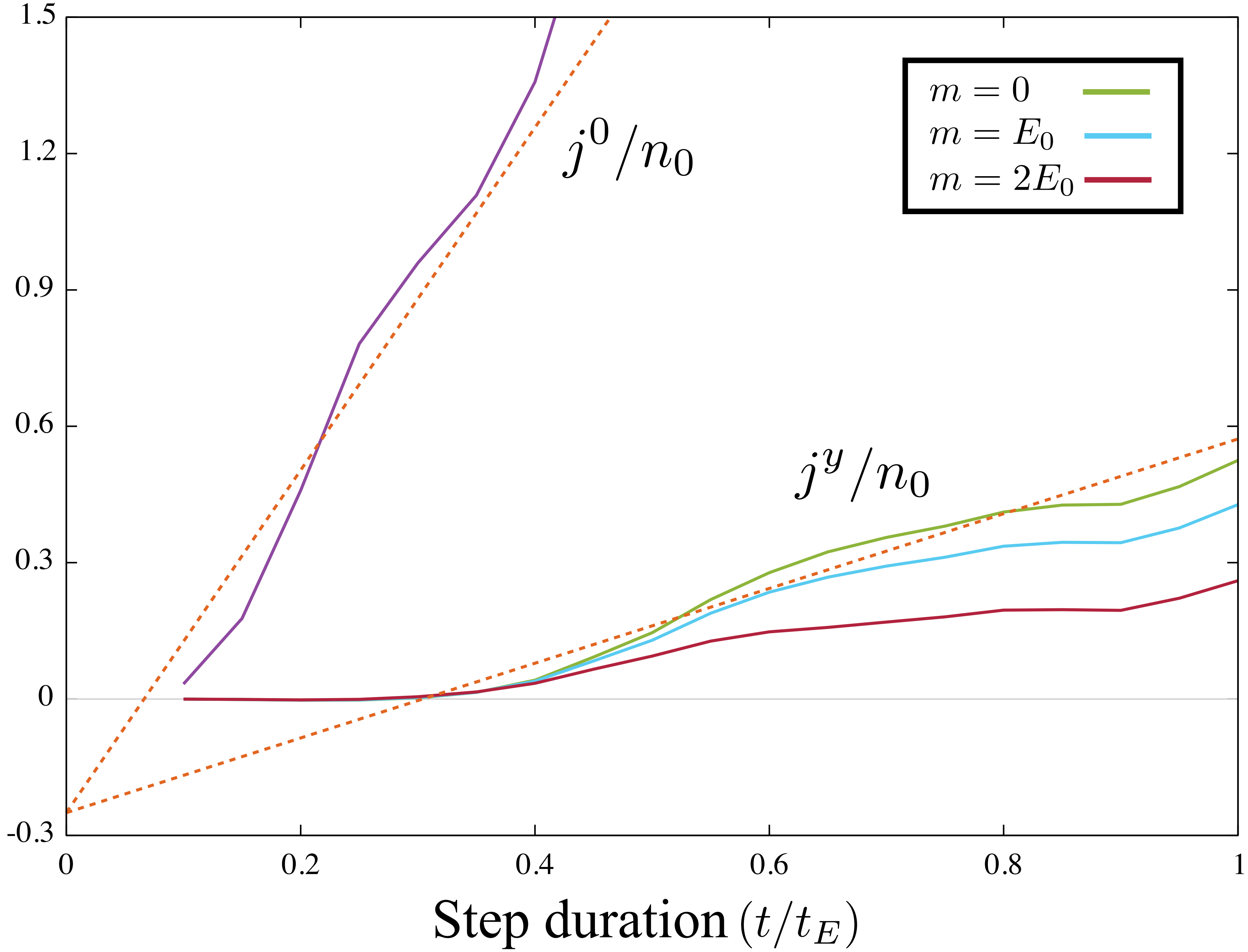

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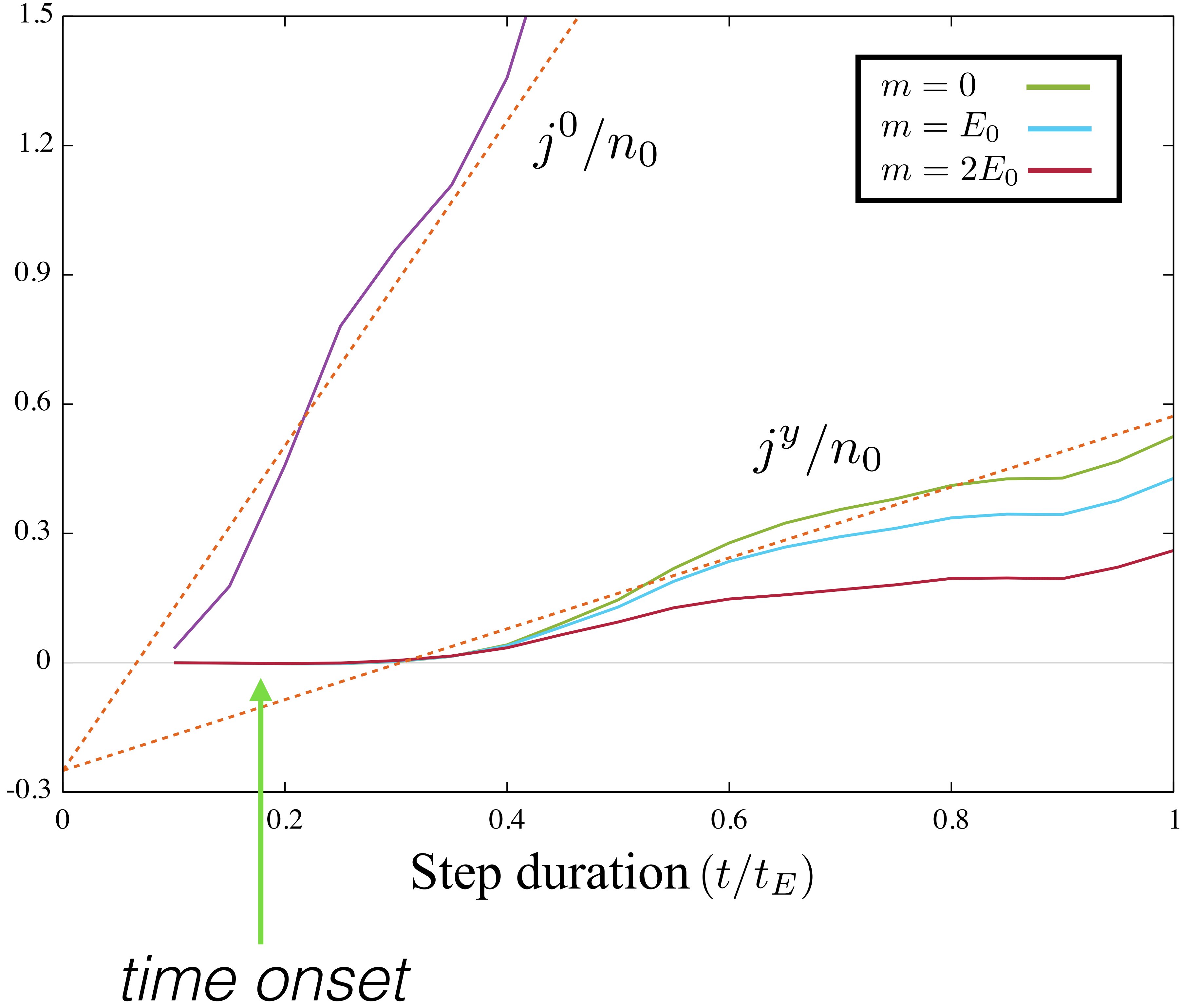

Future Extensions

Convolution with the Glasma simulation for HIC
(in collaboration with K. Fukushima)

Consider back-reaction from gauge field sector

Application to condensed matter physics experiments

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Thank you!