

Gauge/Fermion Production in Axion Inflation

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DESY, HAMBURG

Based on [1806.08769](#) with V. Domcke



1.

Introduction

Introduction

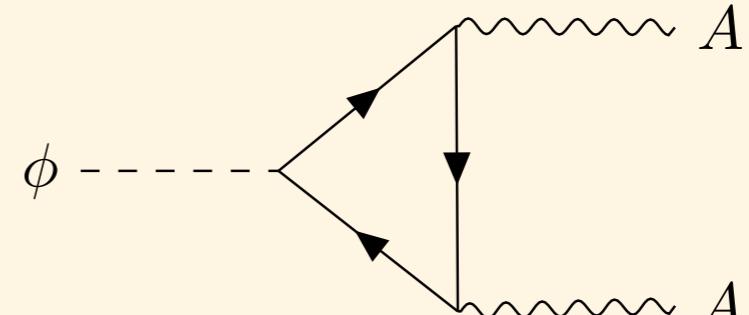
Cosmological Inflation

- ✓ Solves horizon/flatness problem, gives primordial density perturbation
- Requires... a **flat** potential v.s. a **coupling** with the visible sector

PNGB (axion) as Inflaton

- ✓ **Flat** potential protected by (approximate) **shift symmetry**
- ✓ **Reheating** via an anomalous coupling to gauge boson

$$\begin{aligned} & \int_x \frac{g^2}{16\pi^2 f_a} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \\ &= - \int_x \frac{g^2}{8\pi^2 f_a} (\partial_\mu \phi) \epsilon^{\mu\nu\rho\sigma} A_\nu \partial_\rho A_\sigma \end{aligned}$$



Introduction

Helical Gauge Field Production

Turner,Widrow '88;
Garretson, Field, Carroll, 9209238

- **Exponential** production of one of two helicities by $\dot{\phi} \neq 0$.

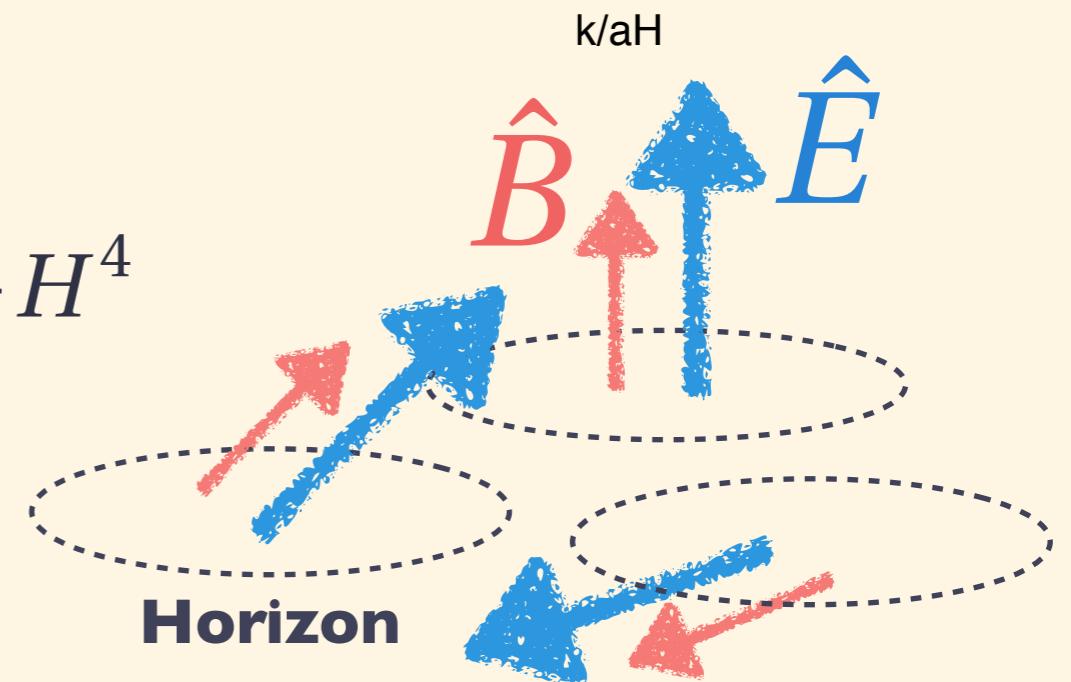
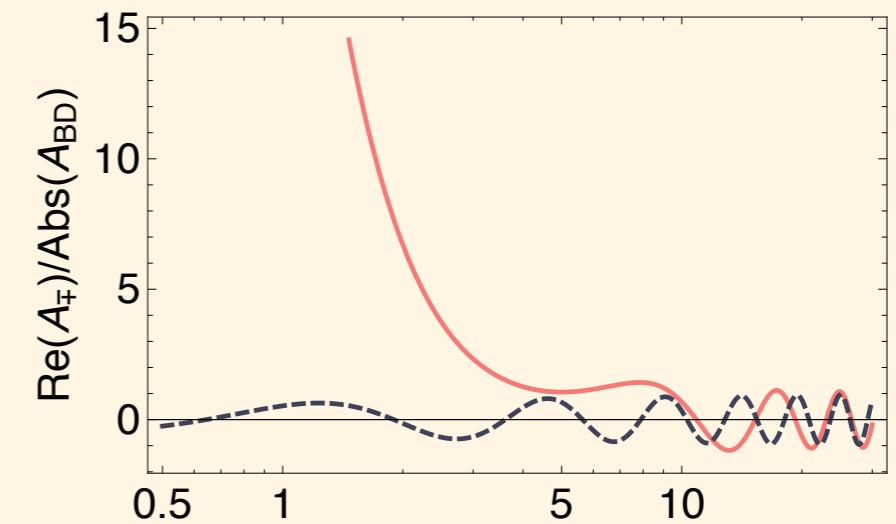
$$0 = \left[\partial_\eta^2 + k(k \pm 2\text{sgn}(\dot{\phi})\xi aH) \right] A_\pm(\eta, k)$$

where $\xi \equiv \frac{a|\dot{\phi}|}{2\pi f_a H}$

- **Helical** gauge field @ horizon scale

$$\langle \hat{E} \cdot \hat{B} \rangle \simeq 2.6 \times 10^{-4} \text{sgn}(\dot{\phi}) \frac{e^{2\pi\xi}}{\xi^4} H^4$$

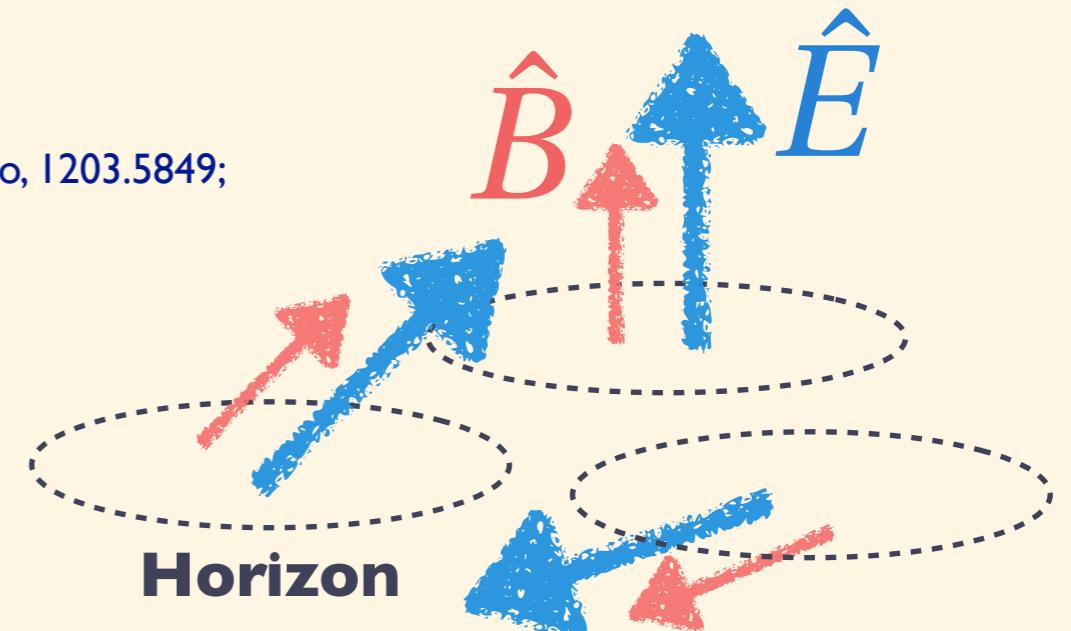
► $\langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle = -4a^4 \langle \hat{E} \cdot \hat{B} \rangle \neq 0$



Introduction

Rich Outcomes!

- ▶ Primordial **magnetogenesis**
 - + **Baryogenesis** via decaying magnetic helicity @ EWPT
Fujita, Namba, Tada, Takeda, Tashiro, 1503.05802; Anber, Sabancilar, 1507.00744; Fujita, Kamada, 1602.02109;
Kamada, Long, 1606.08891; Abshead, Giblin, Scully, Sfakianakis, 1606.08474; ...
- ▶ Enhanced **scalar perturbation & non-Gaussianity**
 - + Production of **Primordial Black Holes** (as DM)
Anber, Sorbo, 1203.5849; Erfani, 1511.08470; Domcke, Muia, Pieroni, Witkowski, 1704.03464;
Garcia-Bellido, Peloso, Unal, 1707.02441; ...
- ▶ Chiral **gravitational waves**
Cook, Sorbo, 1109.0022; Barnaby, Pajer, Peloso, 1110.3327; Anber, Sorbo, 1203.5849;
Domcke, Pieroni, Binetruy, 1603.01287; ...
- ▶ Gravitational **Baryo/Leptogenesis**
Maleknejad, 1604.06520; Caldwell, Devulder, 1706.03765;
Papageorgiou, Peloso, 1708.08007;
Abshead, Giblin, Weiner, 1805.04550; ...



Motivation

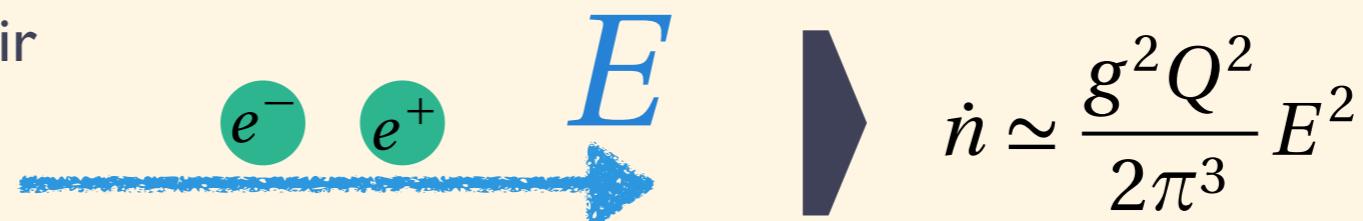
Coupling to the SM Gauge Group?

- ▶ Production of **matters** under the strong gauge field background.
 - **SM chiral anomaly** Helical gauge \Leftrightarrow B+L asym.

$$\partial_\mu J_{B+L}^\mu = \frac{3}{16\pi^2} \left(-g_2^2 W_{\mu\nu}^a \tilde{W}^{a\mu\nu} + g_Y^2 B_{\mu\nu} \tilde{B}^{\mu\nu} \right) \neq 0$$

- **Schwinger effect**

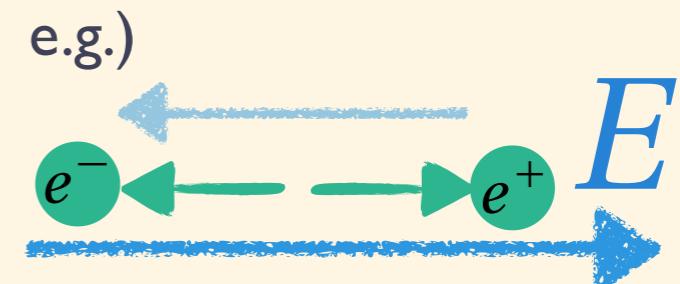
- ❖ In a strong E field, pair production occurs.



- ▶ Produced **matters** backreact to the gauge field.

- **Induced Current**

$$0 = \square A + a \frac{g^2}{4\pi^2} \frac{\dot{\phi}}{f_a} \nabla \times A - g Q J$$



2.

Fermion Production

Setup

Toy Model: Inflaton + masslessQED + CS coupling

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \bar{\psi} i \not{D} \psi \right] + \frac{\alpha \phi}{4\pi f_a} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right\}$$

► Current equations and symmetries

- Vector current $U(1)_V$: $\hat{\psi}_R \mapsto e^{i\theta_V} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{i\theta_V} \hat{\psi}_L$


$$0 = \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \hat{\psi})$$

- Axial current $U(1)_A$: $\hat{\psi}_R \mapsto e^{i\theta_A} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{-i\theta_A} \hat{\psi}_L$


$$\partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi}) = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} (= -Q^2 \partial_\mu K_{CS}^\mu)$$

- Shift symmetry: $\phi \mapsto \phi + \theta$


$$\partial_\mu (\sqrt{-g} f_a g^{\mu\nu} \partial_\nu \phi) - \frac{g^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} = -\sqrt{-g} f_a V'$$

Setup

Toy Model: Inflaton + masslessQED + CS coupling

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$$\rightarrow 0 = \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \hat{\psi})$$

- Axial current $U(1)_A$: $\hat{\psi}_R \mapsto e^{i\theta_A} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{-i\theta_A} \hat{\psi}_L$ **Helical gauge \Leftrightarrow Chiral asym.**

$$\rightarrow \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi}) = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} (= -Q^2 \partial_\mu K_{CS}^\mu) \neq 0$$

- Shift symmetry: $\phi \mapsto \phi + \theta$

$$\rightarrow \partial_\mu (\sqrt{-g} f_a g^{\mu\nu} \partial_\nu \phi) - \frac{g^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} = -\sqrt{-g} f_a V'$$

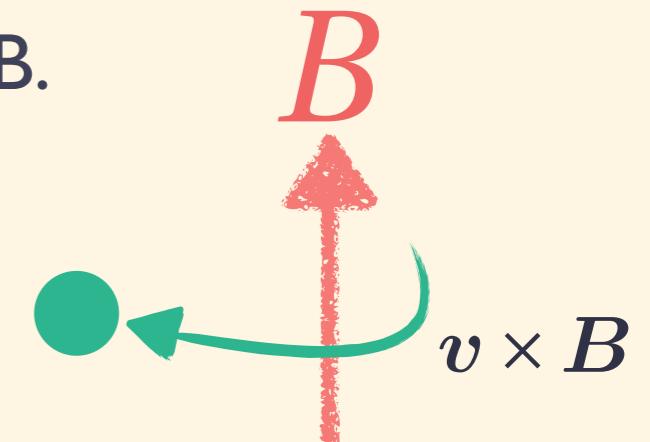
Fermion Production

Landau Levels

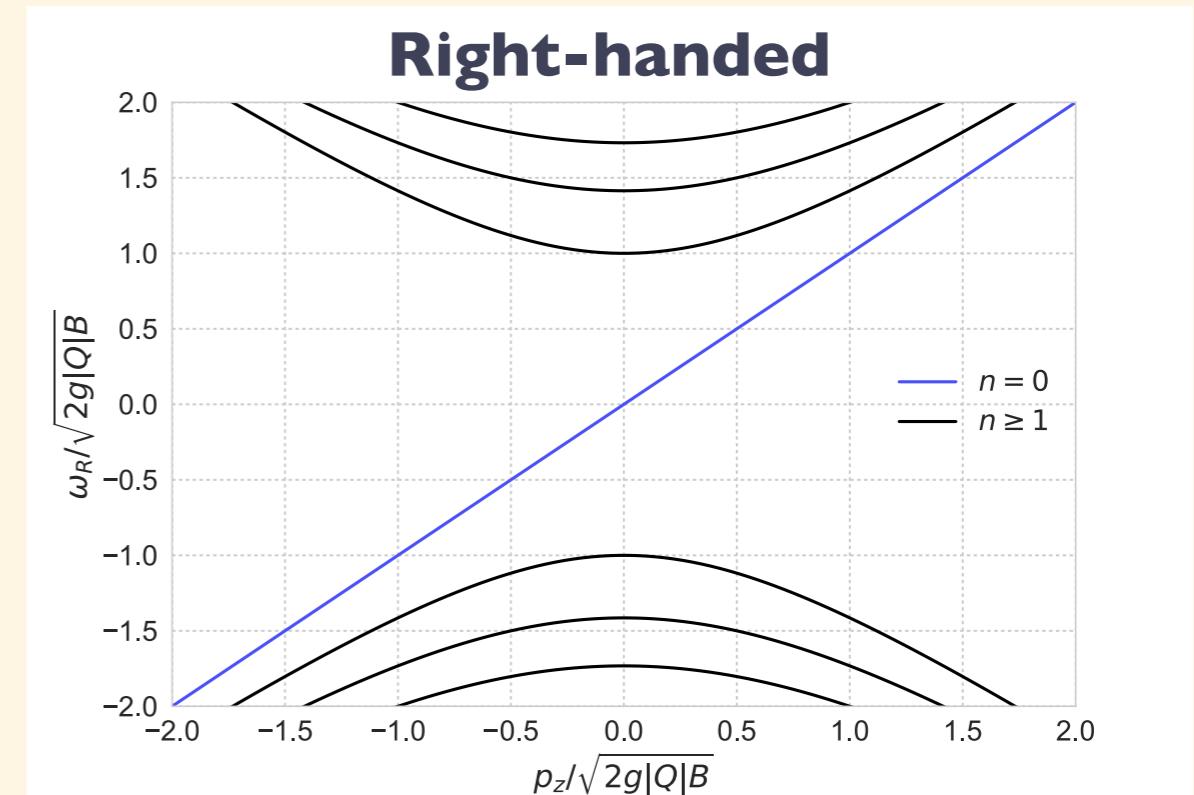
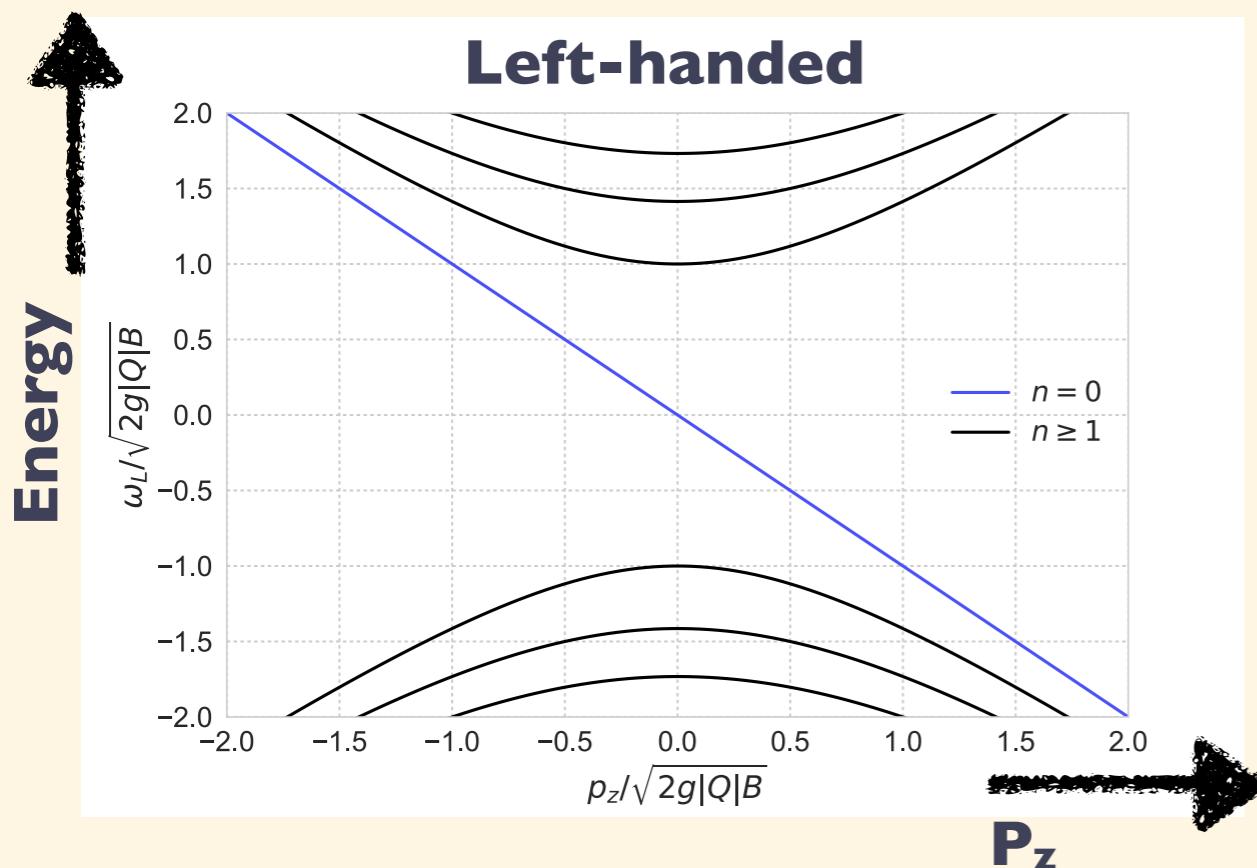
- First, **turn off E** and study the effects of the strong B.

$$0 = (i\partial_\eta \pm i\nabla \cdot \sigma - gQA_0 \pm gQA \cdot \sigma) \psi_{R/L}$$

$$\text{w/ } (A_\mu) = (0, 0, -Bx, 0)$$



♣ $Q > 0$



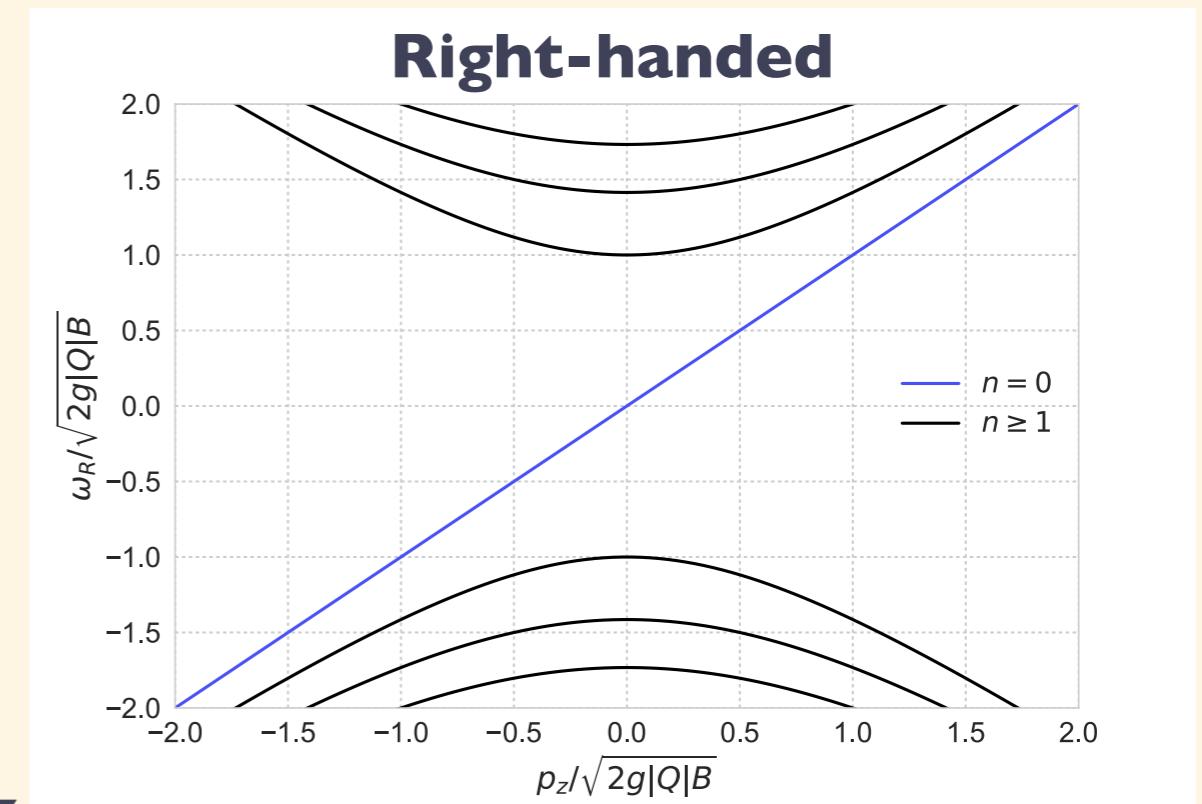
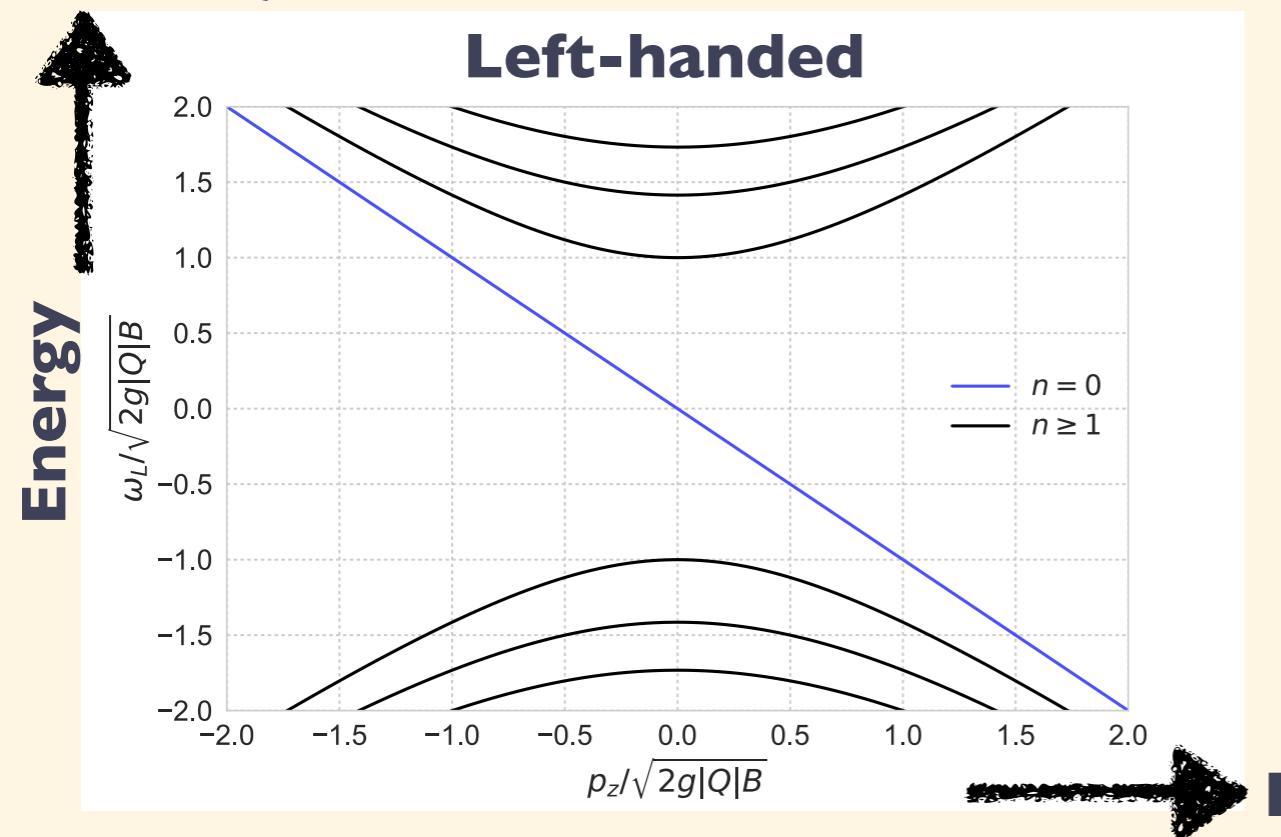
Fermion Production

Lowest Landau Level (n=0) & Chiral Anomaly

► Turn on E and see what happens.

Nielsen, Ninomiya, Phys.Lett. **I 30B** (1983)

❖ $Q > 0$



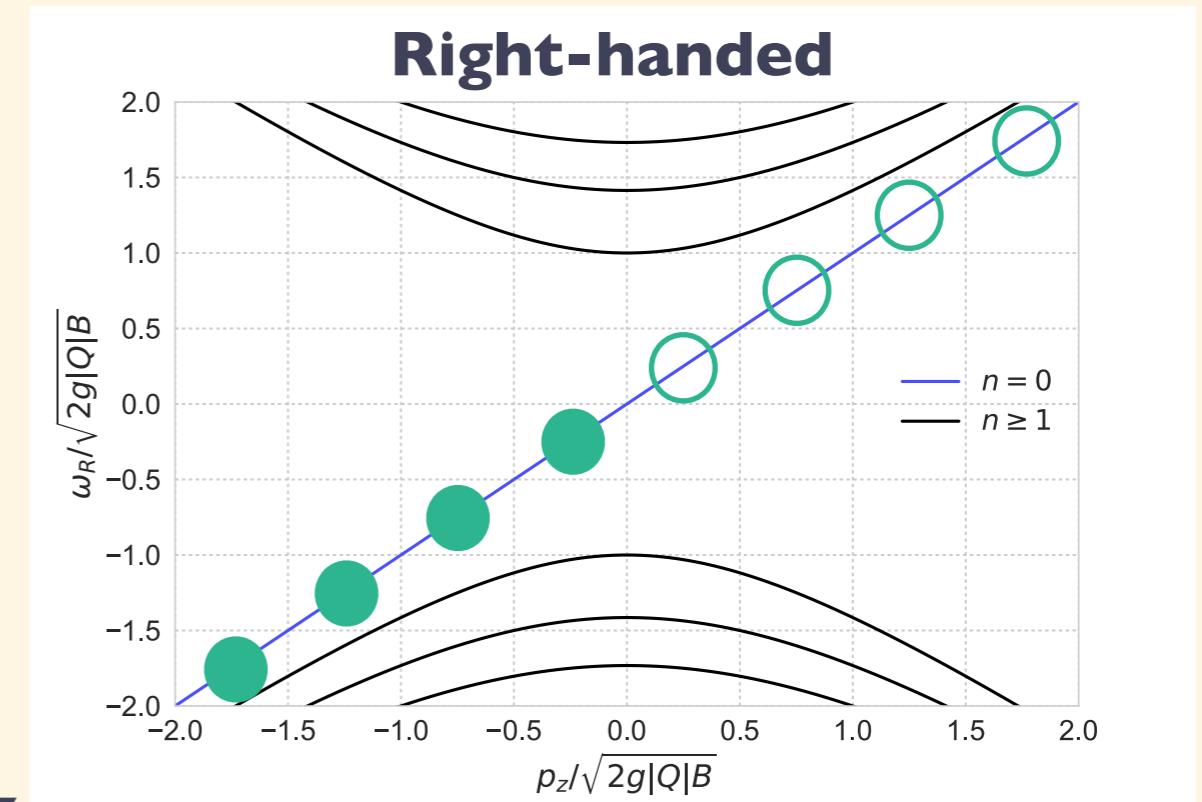
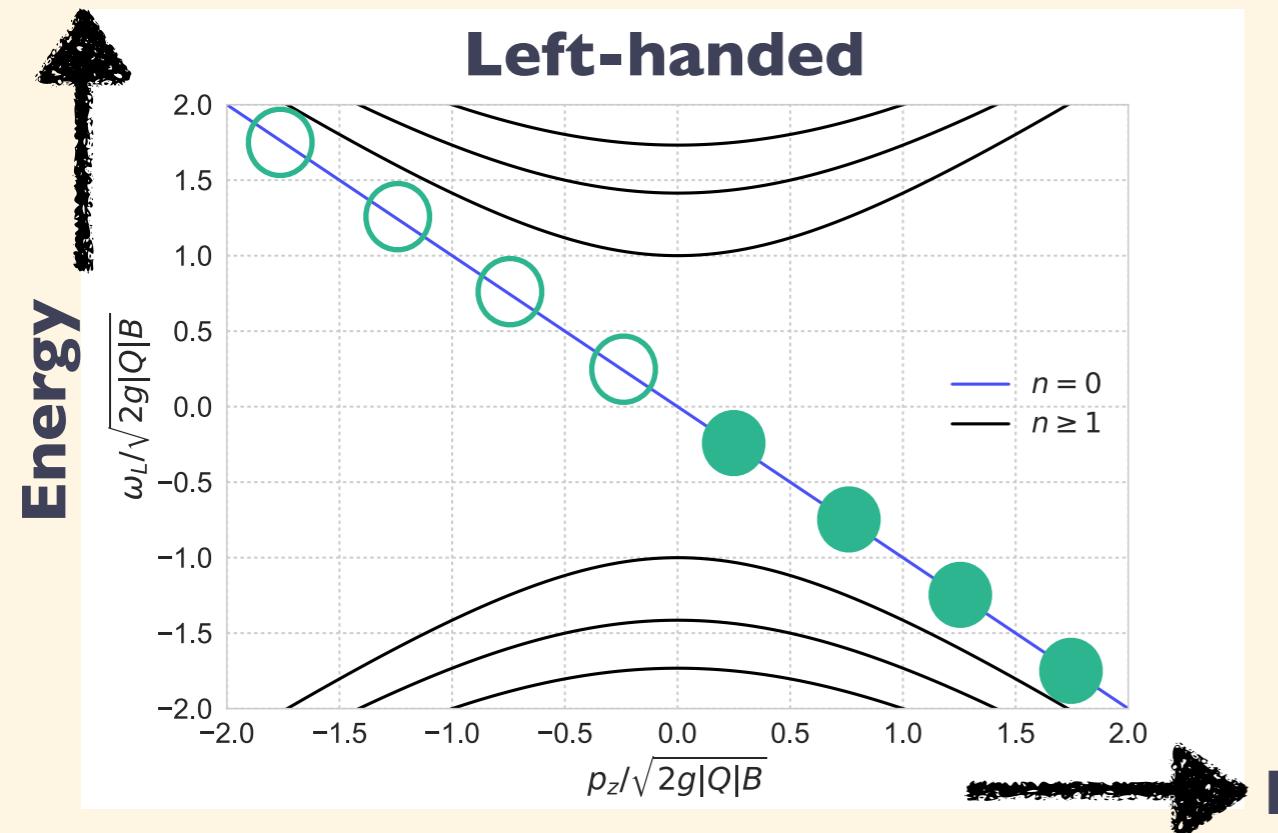
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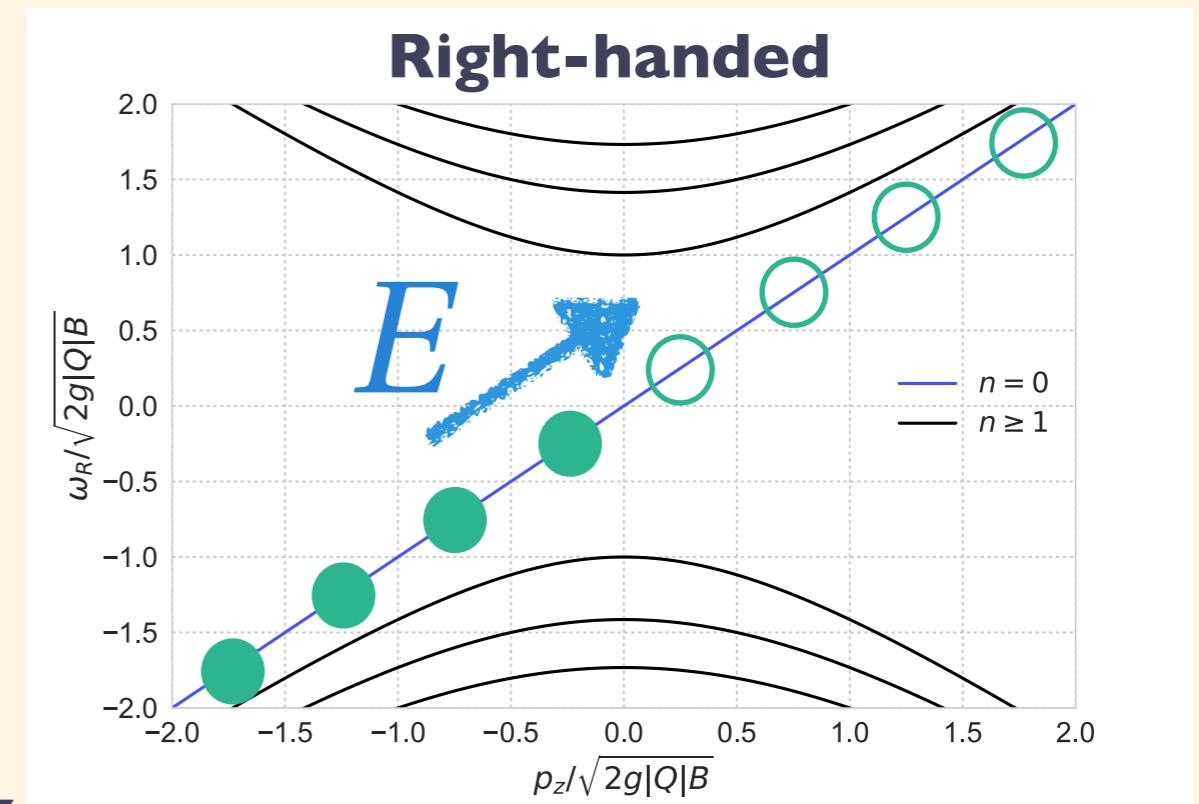
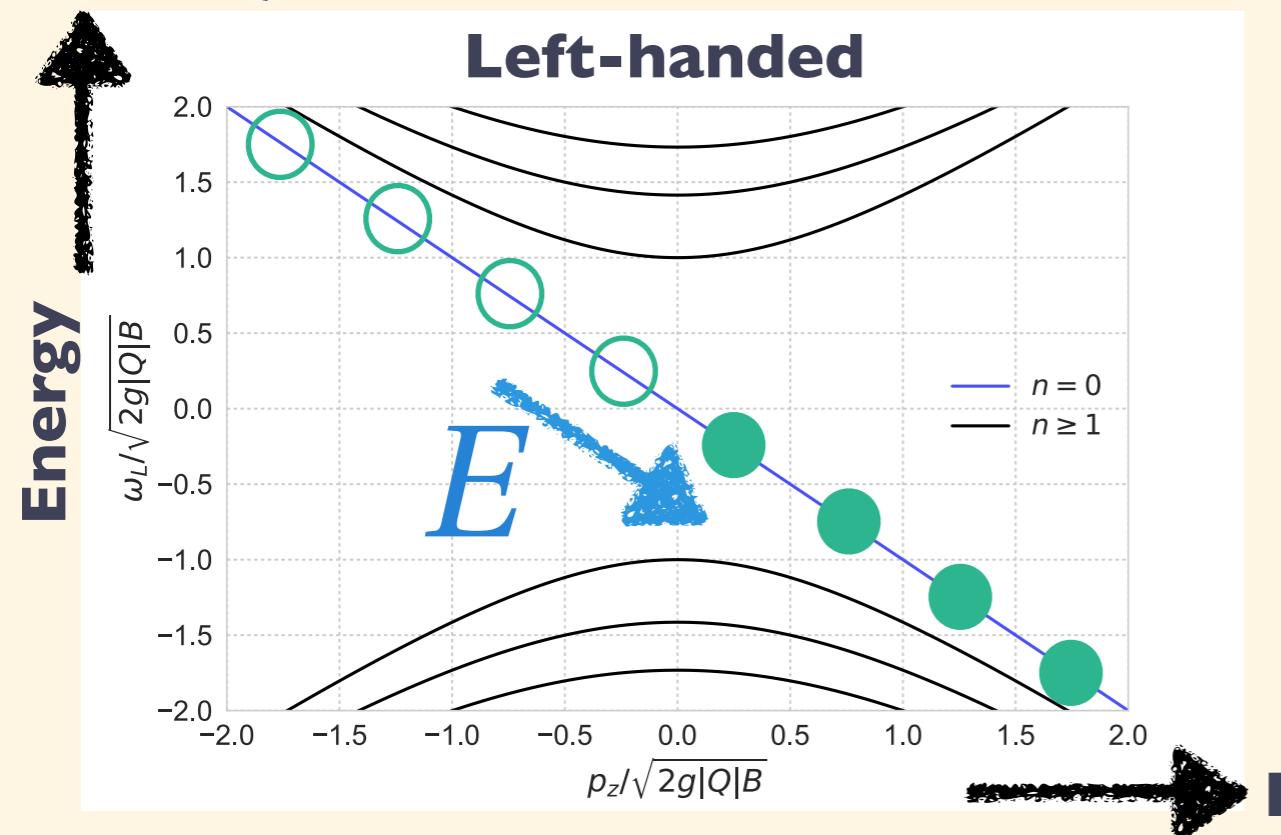
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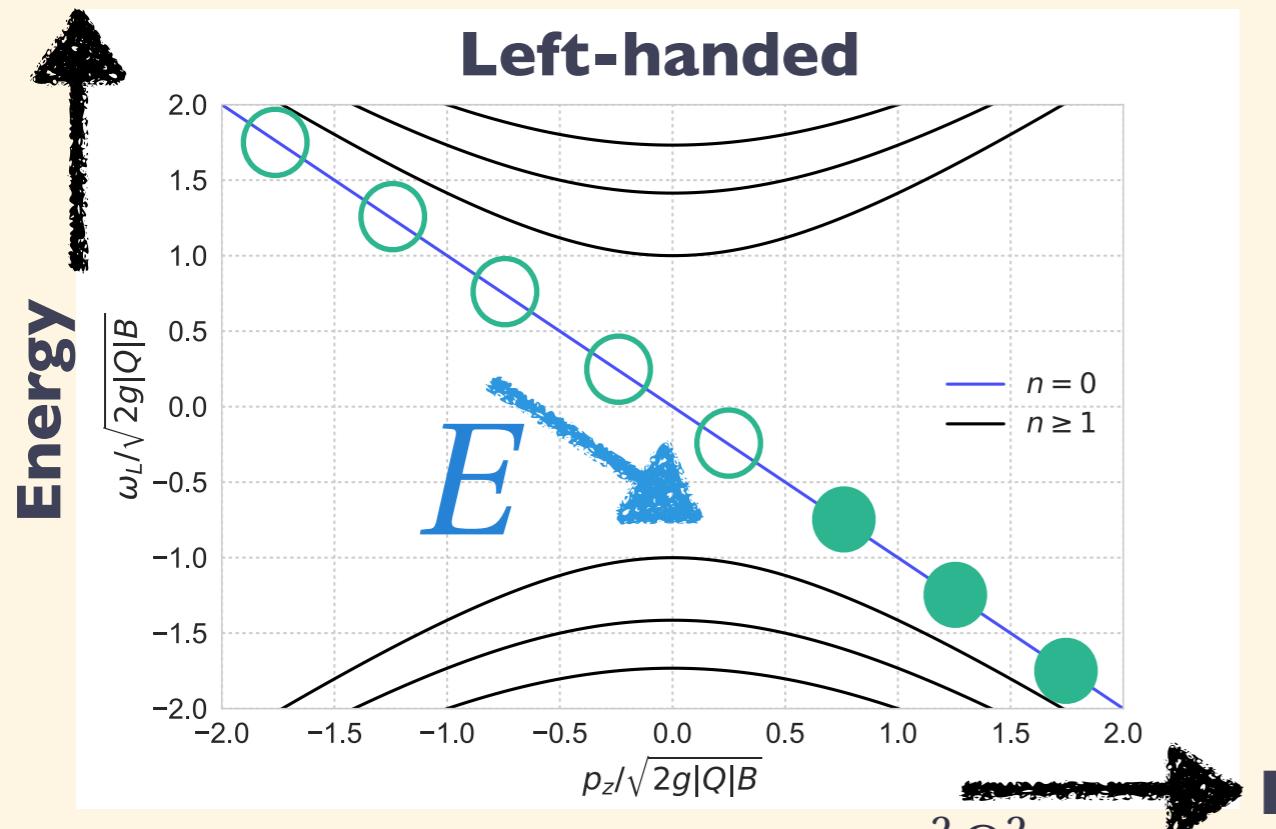
Fermion Production

Lowest Landau Level (n=0) & Chiral Anomaly

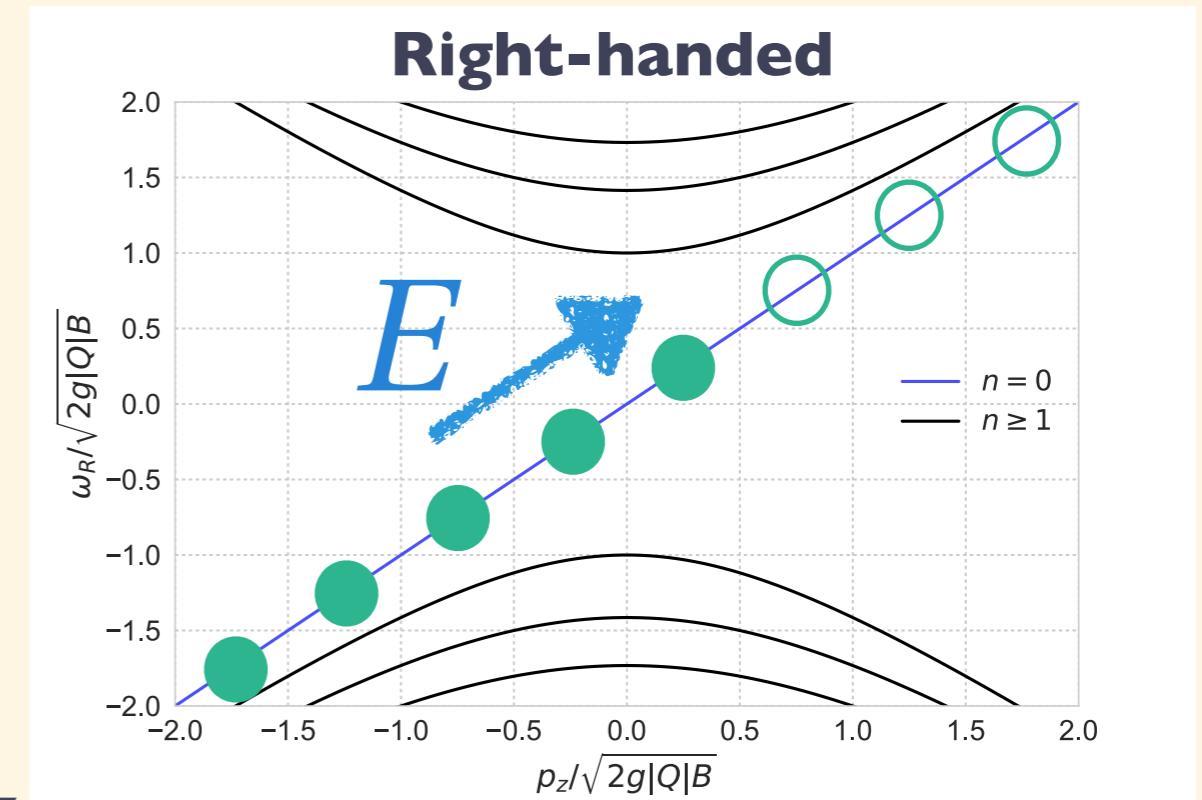
► Turn on E and see what happens.

Nielsen, Ninomiya, Phys.Lett. **I 30B** (1983)

❖ $Q > 0$



$$\text{Anti-particle prod: } q'_L|_{n=0} = -\frac{g^2 Q^2}{4\pi^2} E B < 0$$



$$\text{Particle prod: } q'_R|_{n=0} = \frac{g^2 Q^2}{4\pi^2} E B > 0$$

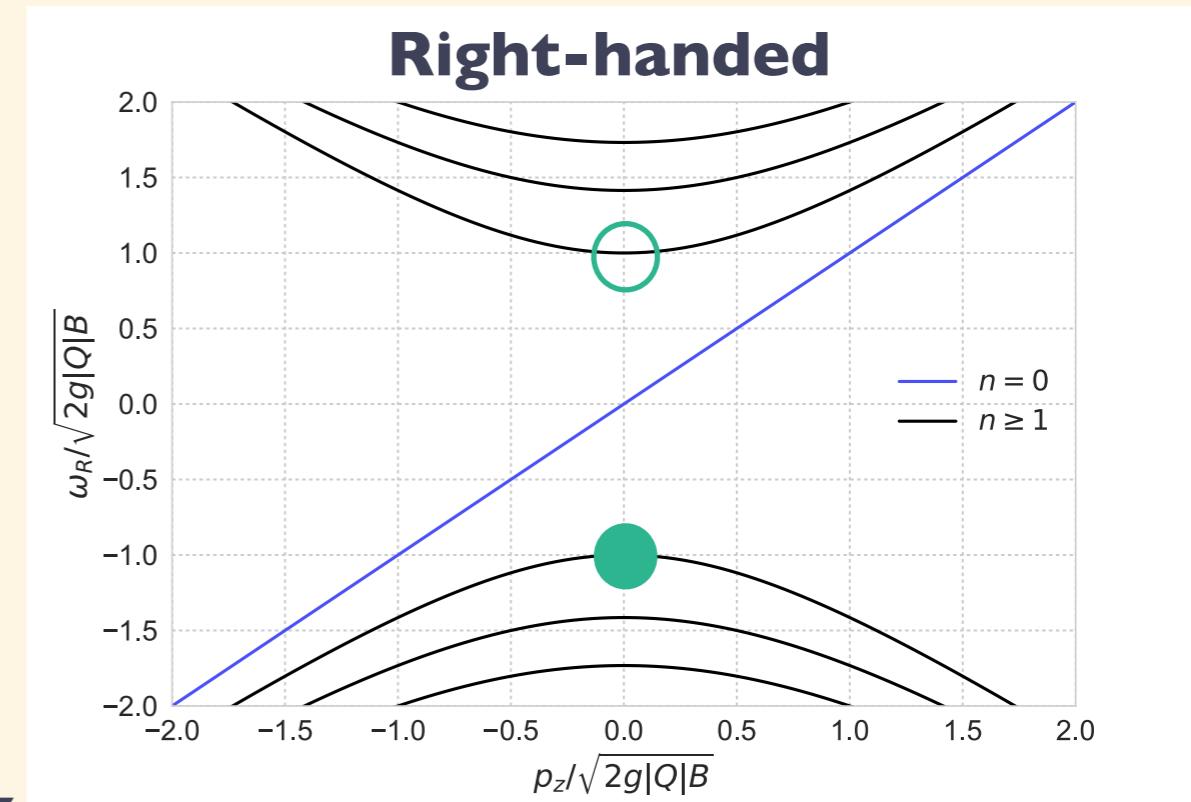
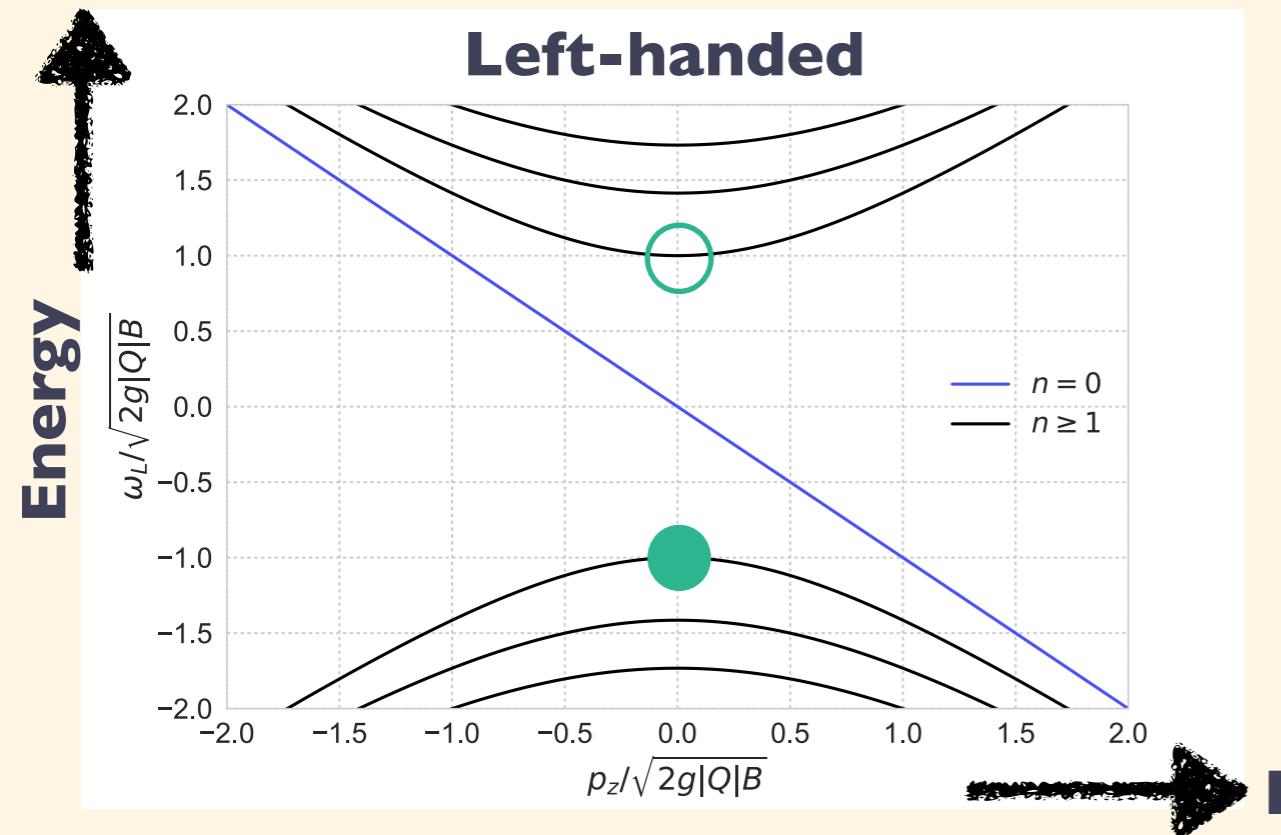
► **ABJ anomaly eq.** $q'_5 = q'_R - q'_L = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$

Fermion Production

Higher Landau Levels ($n \geq 1$) & Pair Production

- ▶ Turn on **E** and see what happens.

❖ $Q > 0$

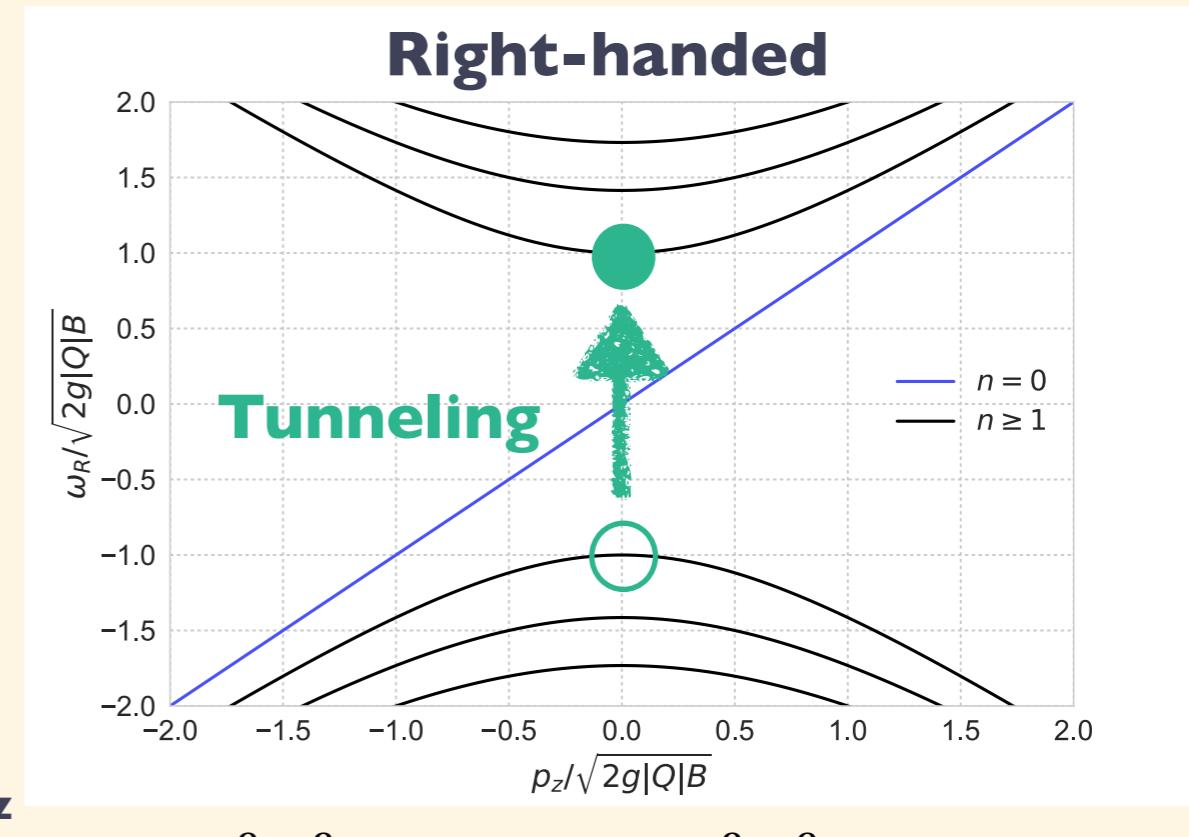
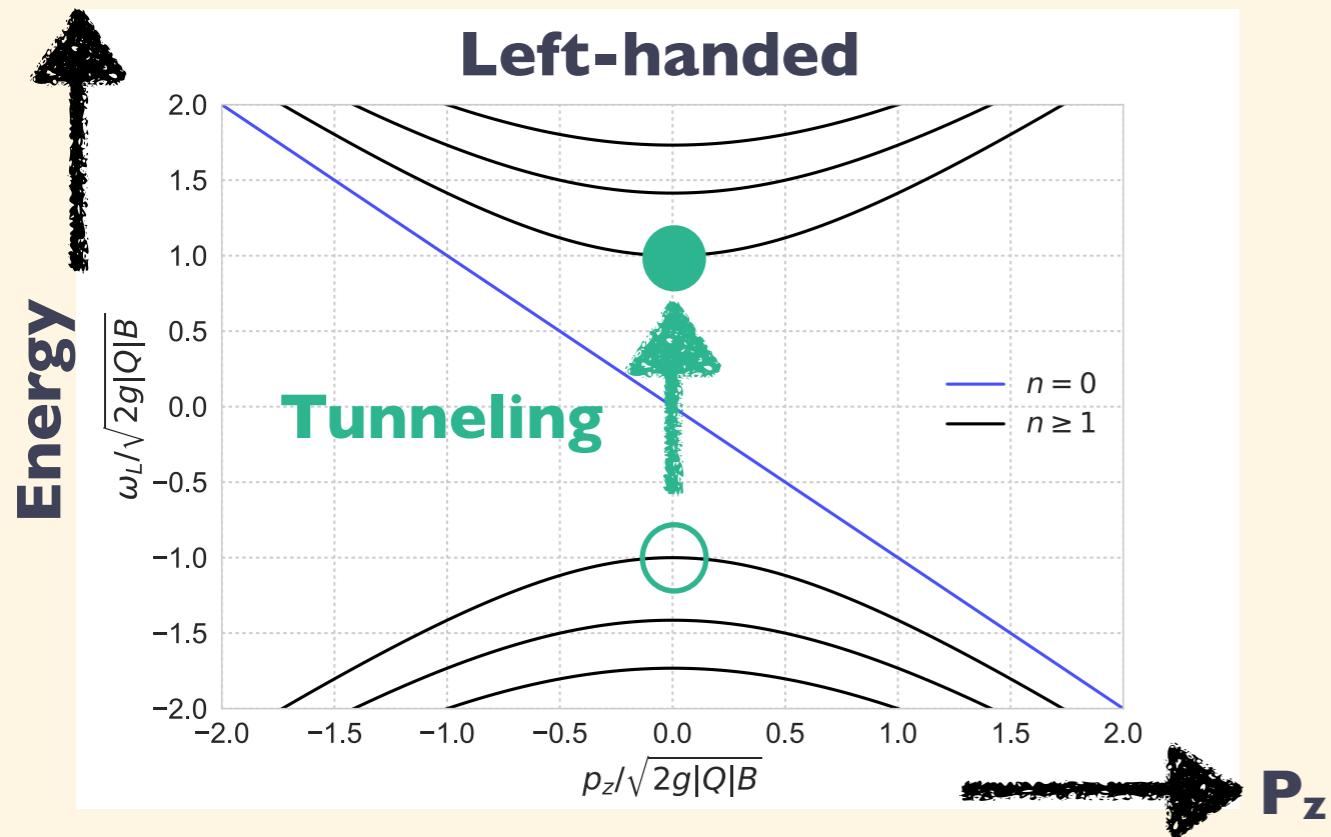


Fermion Production

Higher Landau Levels ($n \geq 1$) & Pair Production

► Turn on E and see what happens.

❖ $Q > 0$



Pair prod: $n'_L|_{n \geq 1} = \bar{n}'_L|_{n \geq 1} = n'_R|_{n \geq 1} = \bar{n}'_R|_{n \geq 1} = \sum_{n=1} \frac{g^2 Q^2}{4\pi^2} E B e^{-\frac{2\pi n B}{E}} = \frac{g^2 Q^2}{4\pi^2} E B \frac{1}{e^{2\pi B/E} - 1}$

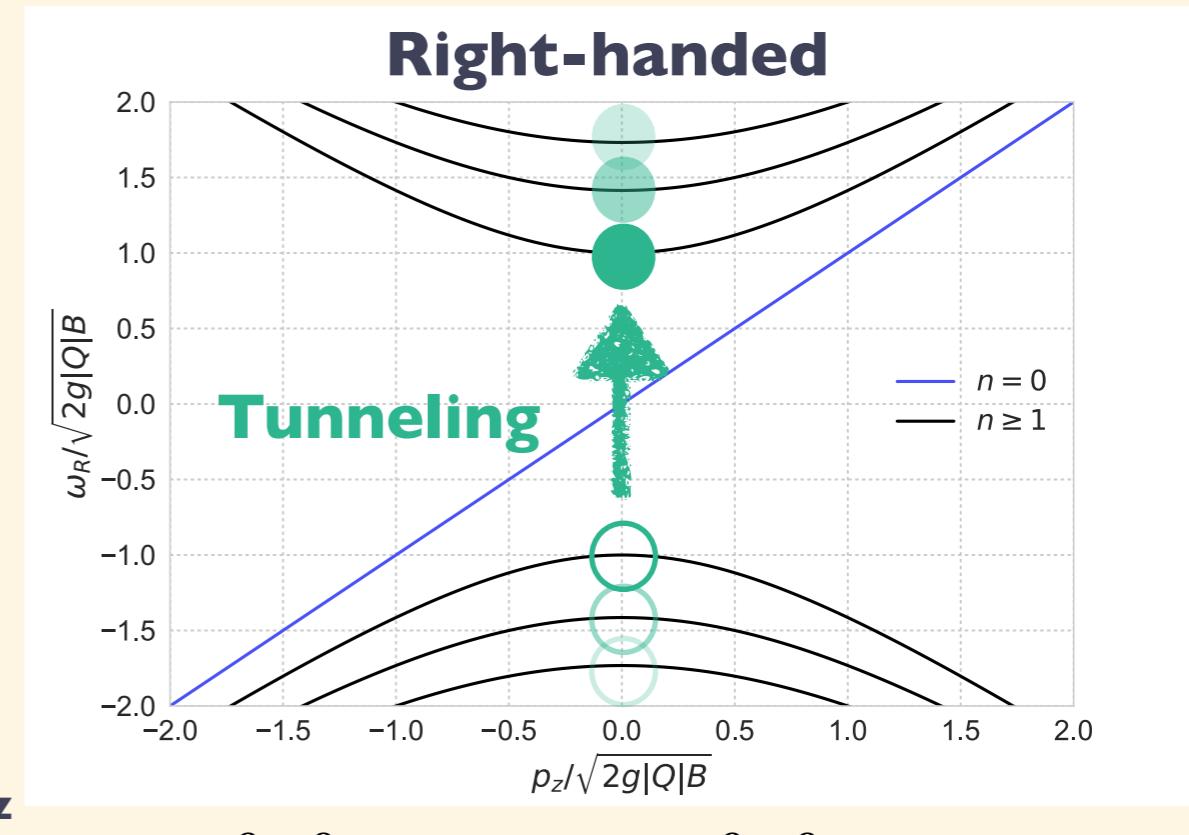
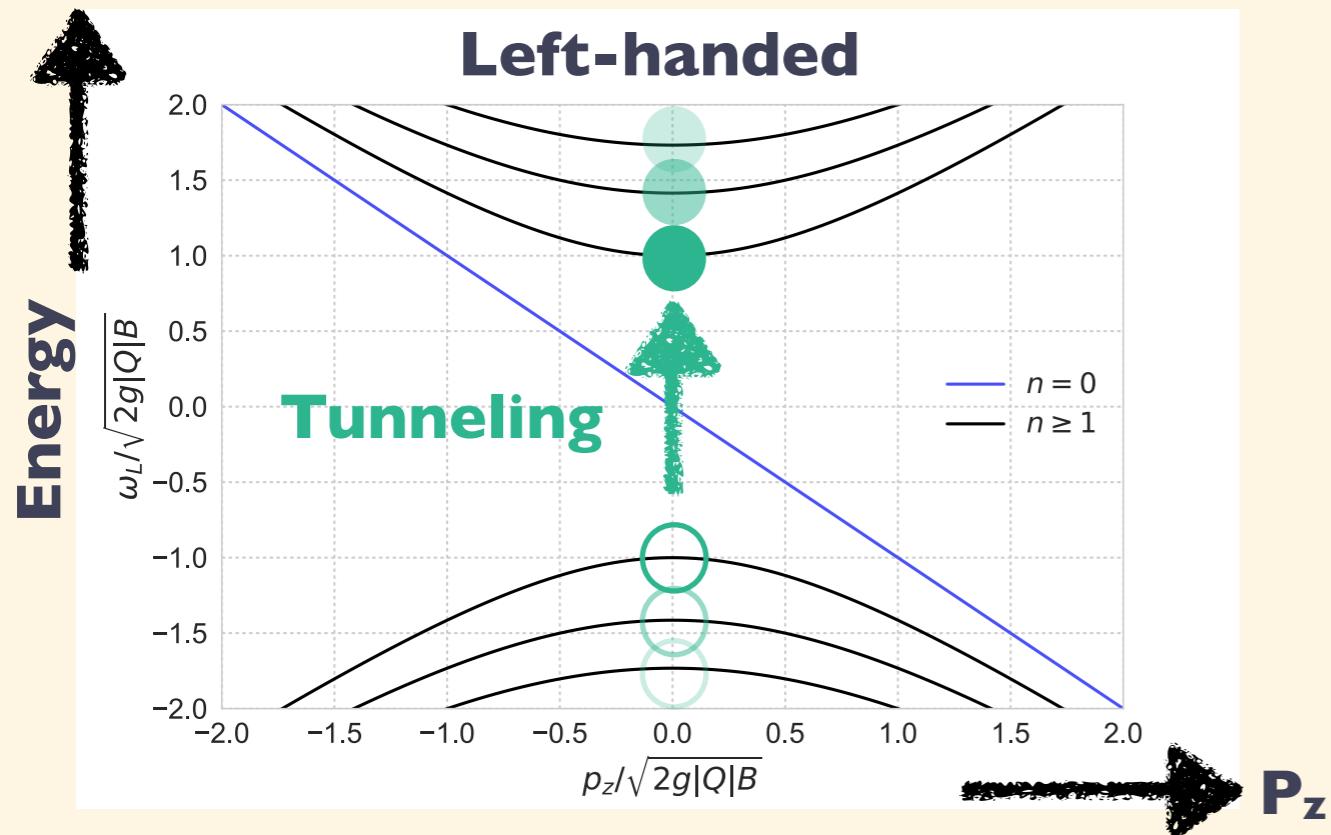
❖ Do not contribute to the asymmetry! $q'_L = n'_L - \bar{n}'_L = 0, \quad q'_R = n'_R - \bar{n}'_R = 0$

Fermion Production

Higher Landau Levels ($n \geq 1$) & Pair Production

- ▶ Turn on E and see what happens.

❖ $Q > 0$



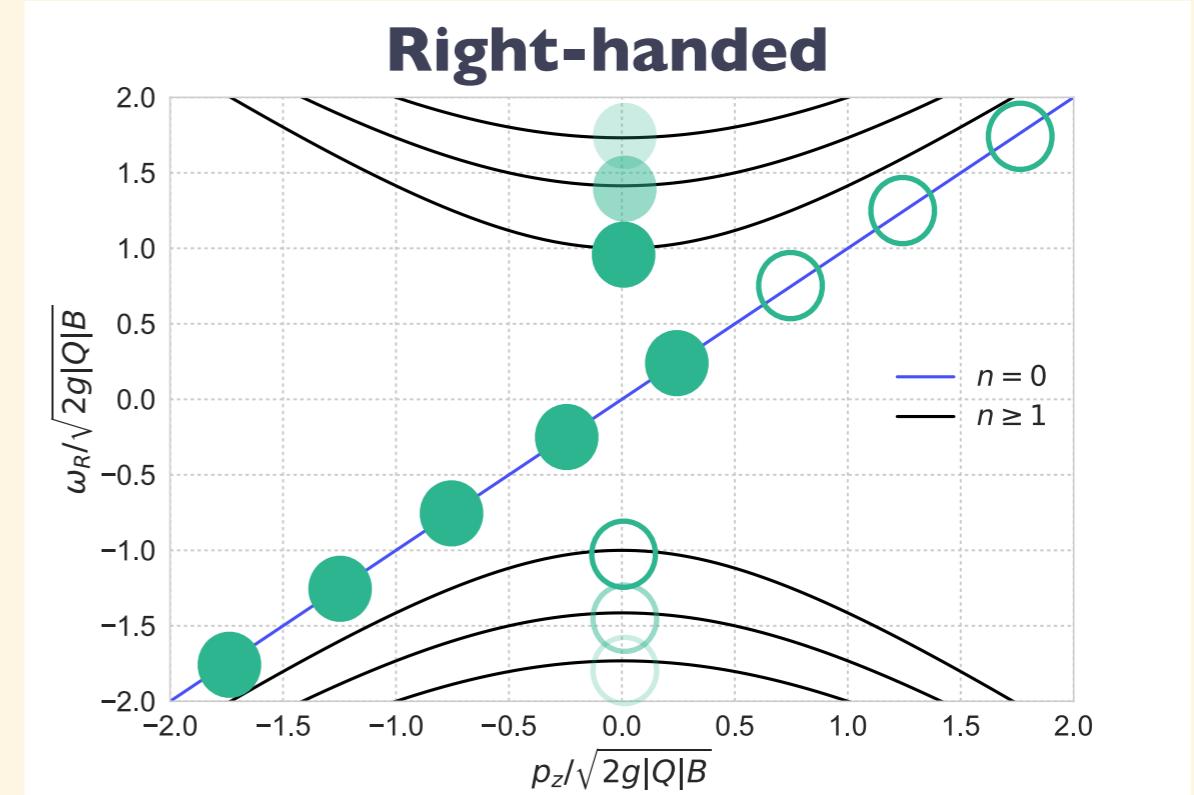
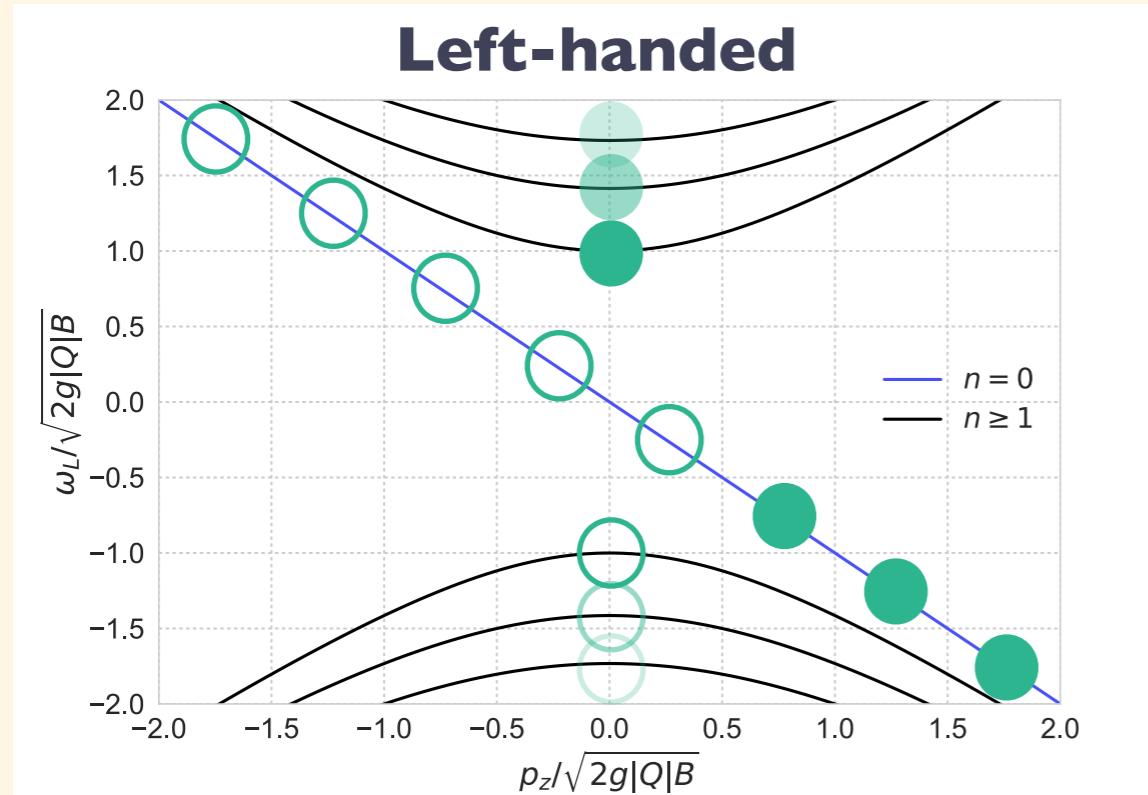
Pair prod: $n'_L|_{n \geq 1} = \bar{n}'_L|_{n \geq 1} = n'_R|_{n \geq 1} = \bar{n}'_R|_{n \geq 1} = \sum_{n=1} \frac{g^2 Q^2}{4\pi^2} E B e^{-\frac{2\pi n B}{E}} = \frac{g^2 Q^2}{4\pi^2} E B \frac{1}{e^{2\pi B/E} - 1}$

❖ Do not contribute to the asymmetry! $q'_L = n'_L - \bar{n}'_L = 0, \quad q'_R = n'_R - \bar{n}'_R = 0$

Fermion Production

Schwinger Effect in $B \parallel E$

❖ $Q > 0$



► **Total production rate**

$$n'_\psi = \frac{g^2 Q^2}{2\pi^2} E B \coth\left(\frac{\pi B}{E}\right) \rightarrow \frac{g^2 Q^2}{2\pi^3} E^2 \text{ for } B \rightarrow 0$$

► **ABJ anomaly from LLL**

$$q'_5 = q'_R - q'_L = -\frac{g^2 Q^2}{8\pi} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Backreaction from Fermion

Backreaction to Gauge Field

- ▶ EoM for gauge field

$$0 = \square A + a \frac{g^2}{4\pi^2} \frac{\dot{\phi}}{f_a} \nabla \times A$$

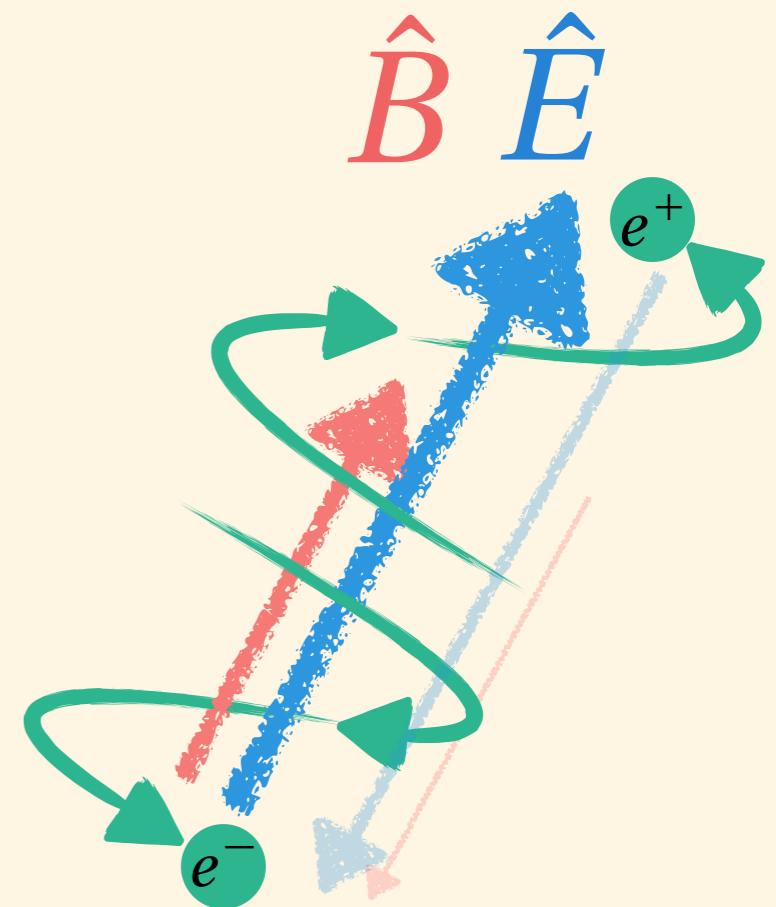
Backreaction from Fermion

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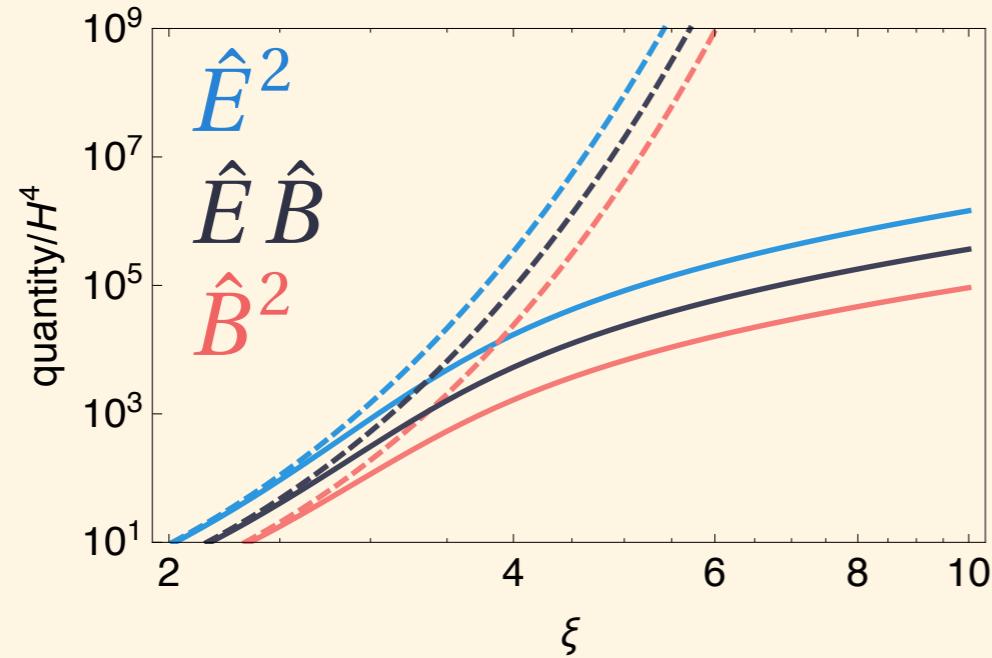
- **Induced current** and EoM for gauge field

$$0 = \square A + a \frac{g^2}{4\pi^2} \frac{\dot{\phi}}{f_a} \nabla \times A - g Q J$$

$$g Q J = -a \left[\frac{g^3 |Q|^3}{6\pi^2} \coth\left(\frac{\pi \hat{B}}{\hat{E}}\right) \hat{B} \right] \frac{\partial}{\partial \eta} A$$



- **Suppressed** gauge field production



- w/o backreaction
 - w/ backreaction
- Backreaction is relevant for $\xi > 4$.
- No exponential dependence in ξ .
- ✿ Assume the existence of constant solutions to get the solid lines.

3.

Implications

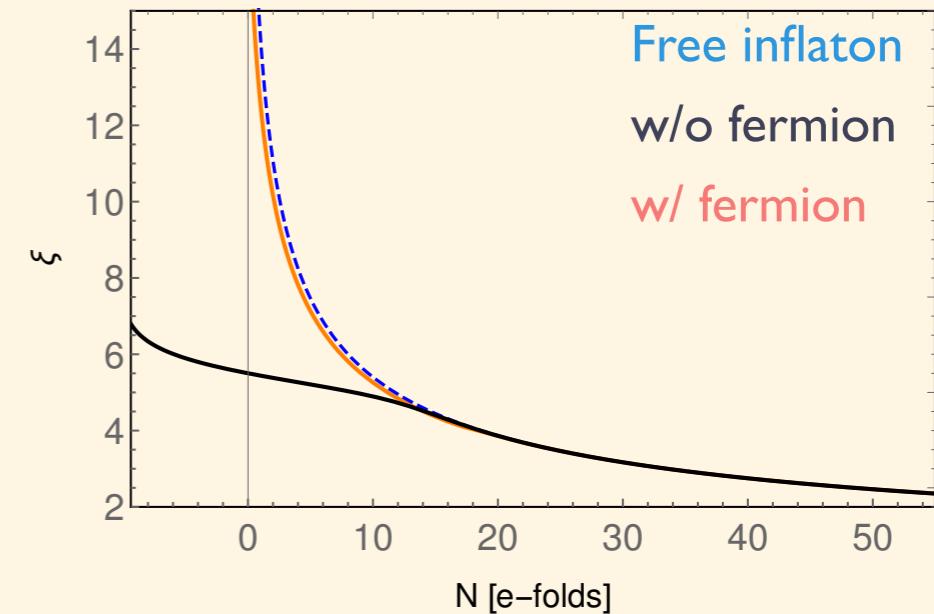
Implication (1)

P_ξ sourced by Gauge Field

- ▶ **Suppressed** backreaction to inflaton

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = -\frac{\alpha}{\pi f_a} \langle \hat{E} \cdot \hat{B} \rangle$$

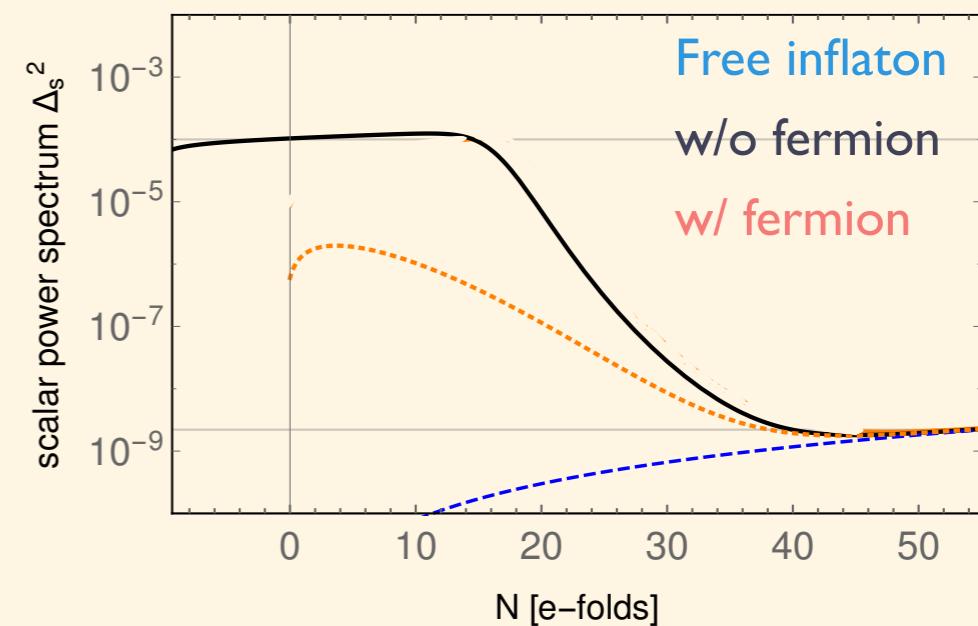
- Depends on $\xi \propto \dot{\phi}$
- Reduced by the fermion production



- ▶ **Reduction of P_ξ sourced by gauge field**

$$\Delta_s^2 \simeq \left(\frac{H^2}{2\pi\dot{\phi}} \right)^2 + \left(\frac{\alpha \langle \hat{E} \cdot \hat{B} \rangle}{3\pi\beta H\dot{\phi}f_a} \right)^2$$

where $\beta = 1 + \frac{2\xi\alpha \langle \hat{E} \cdot \hat{B} \rangle}{3\pi H\dot{\phi}f_a}$



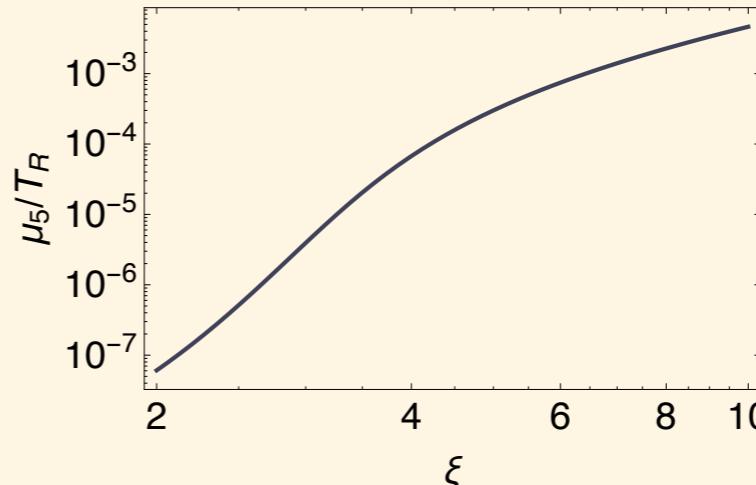
Implication (2)

Evolution after inflation (and Baryogenesis?)

► Primordial \mathbf{Q}_5 generation

$$\hat{\mu}_{5,R} \sim \left. \frac{\hat{q}_5}{\hat{T}^2} \right|_R \sim \frac{\alpha}{\pi} \frac{\langle \hat{E} \cdot \hat{B} \rangle_R}{H_{\text{inf}}^2 M_{\text{Pl}}}$$

- Assume instantaneous reheating and thermalization after inflation.



► \mathbf{Q}_5 decays via producing **opposite-helicity** gauge fields after inflation.

$$0 = \square A - a \hat{\mu}_5 \nabla \times A + a \hat{\sigma} \frac{\partial}{\partial \eta} A$$

@ inflation $0 = \square A + a \frac{g^2}{4\pi^2} \frac{\dot{\phi}}{f_a} \nabla \times A - g Q J$

→ $\partial_\eta q_5 = -\frac{g^2 Q^2}{8\pi^2} \langle F_{\mu\nu} \tilde{F}^{\mu\nu} \rangle < 0$

● Decay Temperature

$$T_{\text{dec}} \sim 10^7 \text{ GeV} \times \left(\frac{\alpha}{0.04} \right)^3 \left(\frac{\hat{\mu}_{5,\text{ini}} / \hat{T}_{\text{ini}}}{10^{-3}} \right)^2$$

✓ May affect baryogenesis via decaying magnetic helicity @ EWPT ?

cf) Y_e becomes efficient for $T \lesssim 10^5 \text{ GeV}$

Summary

Toy Model: Inflaton + masslessQED + CS coupling

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \bar{\psi} i \not{D} \psi \right] + \frac{\alpha \phi}{4\pi f_a} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right\}$$

Fermion prod. \Leftrightarrow Helical gauge field prod.

- ▶ Non-zero **Q₅** from the lowest Landau level: $q'_5 = q'_R - q'_L = -\frac{g^2 Q^2}{8\pi} F_{\mu\nu} \tilde{F}^{\mu\nu}$
- ▶ **Schwinger effect** in $B \parallel E$: $n'_\psi = \frac{g^2 Q^2}{2\pi^2} E B \coth\left(\frac{\pi B}{E}\right)$

Implications

- ▶ **Induced current** suppresses gauge fields and thus **P_ξ** for $\xi > 4$.
- ▶ **Primordial Q₅** annihilates with **helical** gauge fields after inflation.
 - ➡ Implications on **Magnetogenesis/Baryogenesis?** Need further studies including the full matter content, Sphaleron,...

Back up

Equivalence of basis

Toy Model: Inflaton + masslessQED + CS coupling

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \bar{\psi} i \hat{\not{D}} \hat{\psi} \right] + \frac{\alpha \phi}{4\pi f_a} \hat{F}_{\mu\nu} \hat{\tilde{F}}^{\mu\nu} \right\}$$

► Current equations and symmetries

- Vector current $U(1)_V$: $\hat{\psi}_R \mapsto e^{i\theta_V} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{i\theta_V} \hat{\psi}_L$

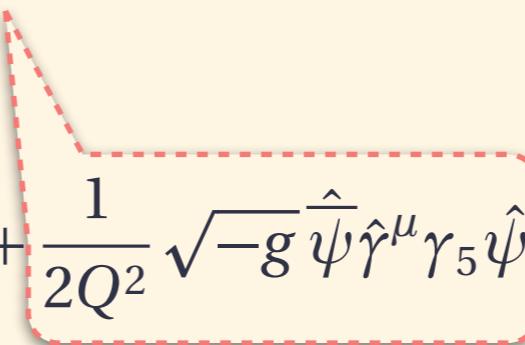
$$\Rightarrow 0 = \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \hat{\psi})$$

- Axial current $U(1)_A$: $\hat{\psi}_R \mapsto e^{i\theta_A} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{-i\theta_A} \hat{\psi}_L$

$$\Rightarrow \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi}) = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} (= -Q^2 \partial_\mu K_{CS}^\mu)$$

○ Shift + Axial:

$$\Rightarrow \partial_\mu \left(\sqrt{-g} f_a g^{\mu\nu} \partial_\nu \phi + \frac{1}{2Q^2} \sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi} \right) = -\sqrt{-g} f_a V'$$



Equivalence of basis

Toy Model: Inflaton + masslessQED + CS coupling

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \hat{\bar{\psi}} i \hat{\not{D}} \hat{\psi} \right] + \boxed{\frac{\alpha \phi}{4\pi f_a} \hat{F}_{\mu\nu} \hat{\tilde{F}}^{\mu\nu}} \right\}$$

► Current equations **Two basis are equivalent**

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \hat{\bar{\psi}} i \hat{\not{D}} \hat{\psi} \right] - \boxed{-\frac{\phi}{2Q^2 f_a} \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi})} \right\}$$

● **Axial** current $U(1)_A$: $\hat{\psi}_R \mapsto e^{i\theta_A} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{-i\theta_A} \hat{\psi}_L$

► $\partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi}) = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} (= -Q^2 \partial_\mu K_{CS}^\mu)$

● **Shift** symmetry: $\phi \mapsto \phi + \theta$

► $\partial_\mu \left(\sqrt{-g} f_a g^{\mu\nu} \partial_\nu \phi + \frac{1}{2Q^2} \sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi} \right) = -\sqrt{-g} f_a V'$

Equivalence of basis

Toy Model: Inflaton + masslessQED + CS coupling

$$S = \int d^4x \left\{ \sqrt{-g} \left[\frac{g^{\mu\nu}}{2} \partial_\mu \phi \partial_\nu \phi - V(\phi) - \frac{1}{4} g^{\mu\rho} g^{\nu\sigma} \hat{F}_{\mu\nu} \hat{F}_{\rho\sigma} + \bar{\psi} i \not{D} \psi \right] + \frac{\alpha \phi}{4\pi f_a} \hat{F}_{\mu\nu} \hat{F}^{\mu\nu} \right\}$$

► Current equations and symmetries

- Vector current $U(1)_V$: $\hat{\psi}_R \mapsto e^{i\theta_V} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{i\theta_V} \hat{\psi}_L$

$$\rightarrow 0 = \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \hat{\psi})$$

- Axial current $U(1)_A$: $\hat{\psi}_R \mapsto e^{i\theta_A} \hat{\psi}_R, \quad \hat{\psi}_L \mapsto e^{-i\theta_A} \hat{\psi}_L$ **Helical gauge \Leftrightarrow Chiral asym.**

$$\rightarrow \partial_\mu (\sqrt{-g} \hat{\bar{\psi}} \hat{\gamma}^\mu \gamma_5 \hat{\psi}) = -\frac{g^2 Q^2}{8\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} (= -Q^2 \partial_\mu K_{CS}^\mu) \neq 0$$

- Shift symmetry: $\phi \mapsto \phi + \theta$

$$\rightarrow \partial_\mu (\sqrt{-g} f_a g^{\mu\nu} \partial_\nu \phi) - \frac{g^2}{16\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} = -\sqrt{-g} f_a V'$$

Induced Current

How does Induced Current look like?

- Suppose that we have $f_\psi(p)$ for charged particles and impose E .

$$gQ \langle J_\psi \rangle \simeq N_{\text{dof}} gQ \int \frac{d^3 p}{(2\pi)^3} \frac{p + gQ \hat{E}\tau}{\omega} f_\psi(p)$$

$$\simeq N_{\text{dof}} (gQ)^2 \hat{E}\tau \int \frac{d^3 p}{(2\pi)^3} \frac{f_\psi(p)}{\omega}$$

where

$$\omega = \sqrt{p^2 + g^2 Q^2 \hat{E}^2 \tau^2}$$

Typical time scale of large angle scatterings.

- Suppose that a typical momentum of $f_\psi(p)$ is \bar{p} .

$$gQ \langle J_\psi \rangle \sim \begin{cases} \frac{g^2 Q^2 \hat{E}\tau}{\bar{p}} n_\psi & \text{for } g|Q|\hat{E}\tau \ll \bar{p}, \\ g|Q|n_\psi e_{\hat{E}} & \text{for } g|Q|\hat{E}\tau \gg \bar{p}, \end{cases}$$