Emergent Particle-hole Symmetry in Composite Fermi Liquids

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References

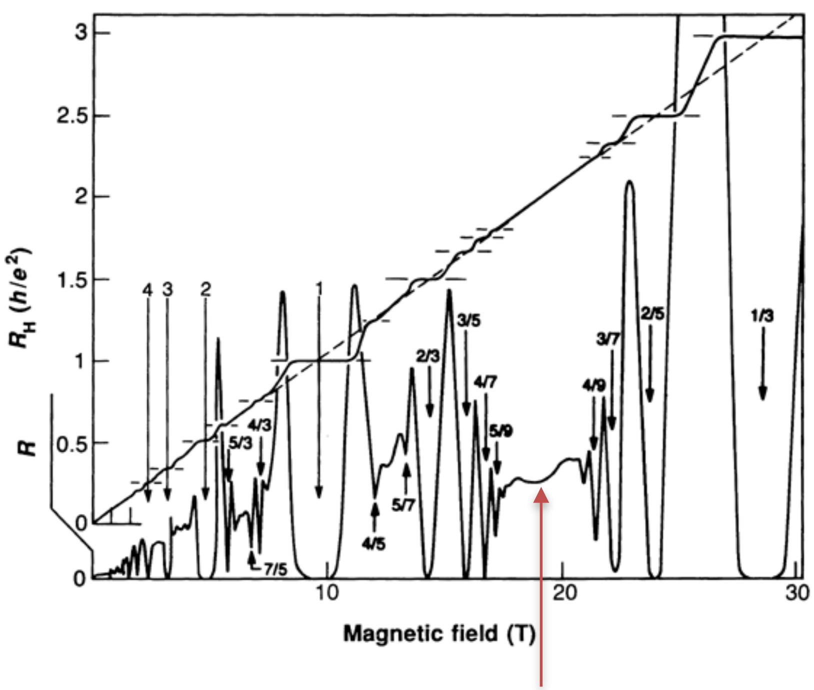
- CW, N. Cooper, B. Halperin, A. Stern, PRX (2017)
- CW, A. Stern, B. Halperin, in progress
- CW, T. Senthil, PRX (2015), PRB (2016)

- Related works:
- Son, PRX (2015)
- Metlitski, Vishwanath, PRB (2016)
- Mross, Alicea, Motrunich, PRL (2016)
- Cheung, Raghu, Mulligan, PRB (2017)
- Levin, Son, PRB (2017)
- ……

Outline

- Introduction: Half-filled Landau level, composite fermions and particle-hole symmetry
- Dirac composite fermion: a particle-hole symmetric theory
- Particle-hole symmetry in Halperin-Lee-Read theory

The “unquantized quantum hall state”



ν=1/2: a metal

- The half-filled Landau level: a metallic state in a strong magnetic field
- The parent state for (perhaps) all the observed quantum hall states
- Keeps surprising us even after 2.5 decades!

Composite fermions

- Composite fermion (CF):
  electron + two vortices (4π-flux)
- At $\nu = \frac{1}{2}$: CF sees no flux on average
  $\rightarrow$ fermi surface $\oplus$ Chern-Simons gauge field
  (Halperin, Lee, Read, 1993)
- At $\nu = \frac{n}{2n+1}$: CF fill Landau levels
  $\rightarrow$ Jain sequence of FQHE

More on HLR

$$\mathcal{L}[\psi, \psi^\dagger, a_\mu + A_\mu] + \frac{1}{8\pi} ada + ...$$

- CF density = Electron density

$$n_{CF} = n_e$$

- CF sees effective magnetic field

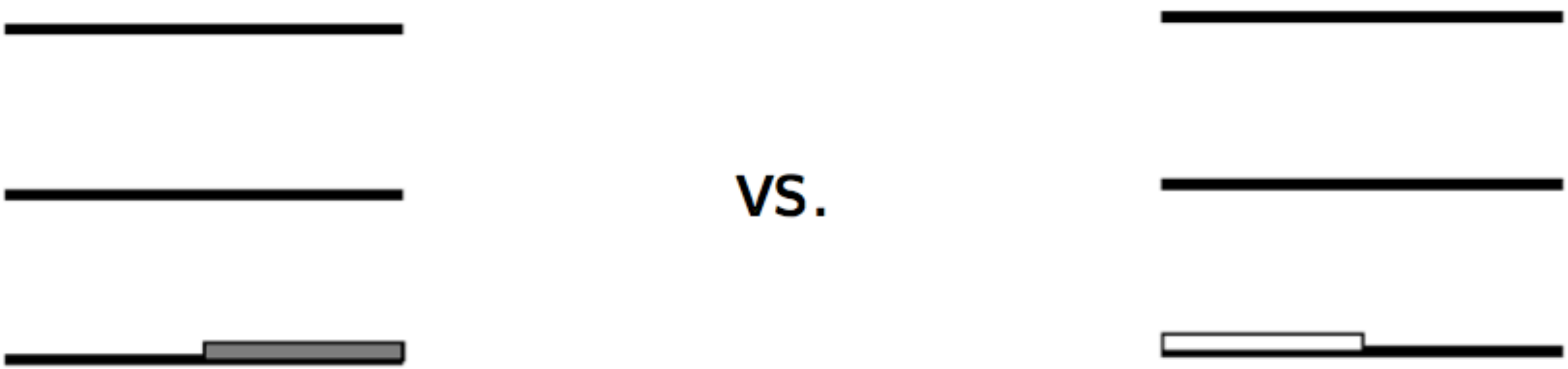
$$B^* = B - 4\pi n_e$$

- At ν=1/2: CF sees no net field → Fermi surface (key signatures experimentally verified)

Issue 1: Lowest Landau level

- If $\omega_c >> V_{int}$ → can project to lowest Landau level (LL)
- Formally need $m_e \to 0$, sick in HLR
- Resolution: view HLR as a low energy effective theory, with many effective parameters (e.g. CF mass m^*)
- Most of these parameters are fixed by microscopic physics in some unknown way

Issue 2: Particle-hole symmetry



- Particle-hole symmetry at lowest LL ($m_e \rightarrow 0$)
- Anti-unitary PH: $c_i \rightarrow c_i^\dagger$
- $B \rightarrow B$, $\nu \rightarrow 1-\nu$, invariant at $\nu=1/2$

HLR and PH symmetry?

- HLR is not manifestly PH symmetric — Spontaneously broken? Secretly hidden?

- This has physical consequences: e.g. PH requires $\boldsymbol{\sigma}_{xy}=1/2$ even with disorder

- The challenge: PH symmetry non-local

- The fun: related to quantum anomaly, topological insulators, U(1) quantum spin liquids

A PH-Symmetric formulation: Dirac composite fermion

$$\mathcal{L}[\psi, a_\mu] = \bar{\psi}(i\partial\!\!\!/ + a\!\!\!/ + \mu\gamma^0)\psi - \frac{1}{4\pi}\epsilon^{\mu\nu\lambda}a_\mu\partial_\nu A_\lambda + \frac{1}{8\pi}\epsilon^{\mu\nu\lambda}A_\mu\partial_\nu A_\lambda$$

(Son, 2015)

- Lagrangian differs from HLR
- CF density $n_{Dirac} = B/4\pi$
- Dirac CF: Fermi surface Berry phase π
- Effective field same as HLR: $B^* = B - 4\pi n_e$

- CF behaves like surface of topological insulator!

- PH symmetry manifest
  → time-reversal on Dirac CF
  (consistent with $n_{Dirac} = B/4\pi$)

- Key signature of π-Berry phase observed in numerics
  (Geraedts, et. al, Science)

- Can be "derived" from a particle-vortex duality for Dirac fermions

(CW, Senthil; Metlitski, Vishwanath; Mross, Alicea, Motrunich; Metlitski)

What about the good old HLR?

- Lagrangian has no particle-hole symmetry
- But the symmetry may emerge at low energy (would be quite nontrivial)
  — simpler examples exist in relativistic field theories
  (Seiberg, Senthil, CW, Witten; Tong, Karch)
- Our approach: shut up and calculate measurable quantities
- Punch line: HLR (very likely) has an emergent PH symmetry, therefore equivalent to Dirac (but often MUCH harder to work with)

Example: Hall Conductance

- Particle-hole symmetry requires

$$\sigma_{xy} = 1/2$$

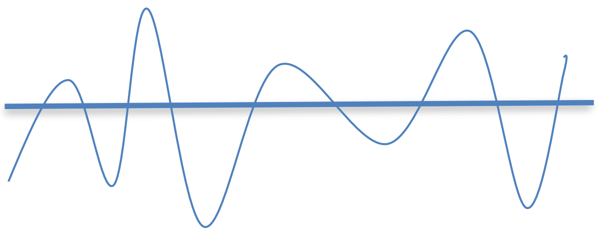
- With disorder, need composite fermions to have

$$\sigma_{xy}^{CF} = -1/2$$

- Where does this come from? — CF sees no net B*
Contradiction?

(Lee, Krotov, Gan, Kivelson, 96)

- Disorder in HLR: random field + random potential



$$\nabla \times \delta\mathbf{a} = -4\pi\delta n_\psi$$

- CFs spend more time in regions with B*<0
  —expect $\sigma_{xy}^{CF} < 0$

- The miracle: within Boltzmann theory

$$\sigma_{xy}^{CF} = -1/2$$

(CW, Cooper, Halperin, Stern, PRX 17)

- Open question: a "topological" derivation?

Emergent Particle-hole Symmetry

- Similar nontrivial PH symmetric results for commensurability oscillations, e.g. magneto-roton spectra, Weiss oscillation…

(CW, Cooper, Halperin, Stern; Cheung, Raghu, Mulligan)

- A common feature: exact microscopic PH symmetry is not needed — low energy, long wavelength properties seem to be automatically PH symmetric!

- True even for composite fermi liquid states at other $\nu=1/m$

(CW, Senthil, PRB 16)

Breakdown at higher energy

- Observables at higher energy/momentum are not expected to be automatically PH symmetric in HLR

- Example: for clean $\nu=1/2$, $\omega \gg v_F q$, PH symmetry requires

$$\sigma_{xy}^{PH} = \frac{1}{2}(1 - q^2/4) + \dots$$

- But HLR gives

$$\sigma_{xy}^{HLR} = \frac{1}{2} + \dots$$

- Related to Hall viscosity

(Levin, Son, PRB 17)

Resolution: vertex correction

- At higher energy/momentum, one should include more symmetry-allowed terms in the effective theory

$$\mathcal{L}_{HLR*} = \mathcal{L}_{HLR}[\psi, a_\mu, A_\mu] + \frac{m_* g}{8\pi}\widehat{z}\cdot(\mathbf{e}\times\mathbf{j}_\psi) + \frac{k}{8\pi}B(\nabla\cdot\mathbf{E}) + \ldots$$

- Coefficients {g, k…} determined by microscopic details in unknown way — but can be fixed by PH symmetry!

- At g=1, k=-1/2, PH symmetry is nontrivially satisfied for
  —Hall viscosity at ν=1/2 and ν=p/(2p+1) (Jain states)
  —Compressibility at ν=p/(2p+1) (Nguyen, Son, unpublished)
  —AC Hall conductivity with disorder

(CW, Stern, Halperin, in progress)

Conclusion

- Dirac CFL: a manifestly particle-hole symmetric theory of the metallic state at ν=1/2
- HLR: Emergent particle-hole symmetry at low energy, long wavelength, even if particle-hole symmetry is microscopically absent
- Vertex corrections are needed at higher energy/ momentum

Thank you!