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Bloch Model Wavefunctions and Pseudopotentials for All Fractional Chern Insulators

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We introduce a Bloch-like basis in a C-component lowest Landau level fractional quantum Hall effect (FQH), which entangles the real and internal degrees of freedom and preserves an $N_x \times N_y$ full lattice translational symmetry. We implement the Haldane pseudopotential Hamiltonians in this new basis. Their ground states are the model FQH wavefunctions, and our Bloch basis allows for a mutatis mutandis transcription of these model wave functions to the fractional Chern insulator (FCI) of arbitrary Chern number $C$, obtaining wavefunctions different from all previous proposals. For $C > 1$, our wavefunctions are related to color-dependent magnetic-flux inserted versions of Halperin and non-Abelian color-singlet states. We then provide large-size numerical results for both the $C = 1$ and $C = 3$ cases. This new approach leads to improved overlaps compared to previous proposals. We also discuss the adiabatic continuation from the FCI to the FQH in our Bloch basis, both from the energy and the entanglement spectrum perspectives.

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Recently, several groups showed that gapped topological phases resembling the fractional quantum Hall (FQH) effects can be stabilized in a flat band with Chern number $C \neq 0$ by strong electronic interactions in the absence of a magnetic field [1–3]. These are named fractional Chern insulators (FCI). Most of the research efforts have been focused on the case of $C = 1$: in various lattice models [4, 7], several groups have provided compelling evidence [1, 4, 8, 22] for the presence of the Read-Rezayi series [9] as well as the composite-fermion [23, 24] FQH states. The correlated phases in Chern bands with $C > 1$ [28, 32], however, are more intricate. Numerical studies found both bosonic [32, 34] and fermionic [33, 35] topological phases resembling the color-SU($C$) version of the Halperin [36] and the non-Abelian spin-singlet [37] (NASS) states [34], but with clear deviations [34].

To understand these novel topological phases, a series of approaches were put forward. For $C = 1$, one can identify the nature of these states 1) through a folding principle [3, 9] that links the FCI and FQH quantum numbers, 2) through the entanglement spectrum [35, 39] of the ground states [3, 10], and 3) through overlaps with model states obtained from replacing the LLL orbitals with hybrid Wannier states, but leaving the occupation-number weights unchanged [29, 40]. After proper gauge fixing [41], high overlaps were obtained [11, 43] from the last approach and FCI-FQH adiabatic continuity was demonstrated [42, 43].

For $C > 1$, the finite-size numerical results are harder to understand. The FCI equivalent of the Halperin states was proposed to occur at Abelian filling factors [29]. The particle entanglement spectrum [34], however, shows clear discrepancy from such states. We are also unable to consistently implement the exclusion principle for colorful FQH model states [44, 45] in the Wannier basis. Naively, a C-component quantum Hall system contains $C$ decoupled copies of LLL, each having a unity Chern number over a Brillouin zone (BZ) consisting of $N_x = N_x N_y / C$ momenta [9]. This appears to be very different from the single Chern number $C$ manifold of the lattice BZ of $N_x N_y$ momenta, especially when $N_x N_y / C \not\in \mathbb{Z}$.

In this Letter, we break away from previous approaches and construct in a C-component LLL a momentum-space basis that mimics the $N_x \times N_y$ Bloch states in the Chern band. These new one-body basis states entangle the color and the real spaces, and form a single $N_x \times N_y$ Brillouin zone with flat Berry curvature and Chern number $C$, regardless of lattice size commensuration with $C$. This leads to a new mapping between FCI with arbitrary $C$ on a lattice of arbitrary size and a C-component FQH system. Our mapping operates directly in Bloch momentum space and utilizes the full lattice translational symmetry, which removes the huge computational cost of $11^3$. For $C = 1$, our construction is equivalent to the Wannier construction [40], except for a new gauge fixing that improves the overlaps (than [11, 43]).

For $C > 1$, our model FCI states are equivalent to a new, color-dependent magnetic-flux inserted version of the Halperin or the NASS states, different from the existing proposal [29]. The FCI wavefunctions produced by our approach have the correct entanglement spectrum [10, 34]. We demonstrate large overlaps for previously unattained sizes between our model FCI wavefunctions and numerics for both $C = 1$ and the uncharted case of $C > 1$.

Consider a translationally-invariant two-dimensional (2D) band insulator on an $N_x \times N_y$ lattice with $N_o$ orbitals per unit cell indexed by $b$. The Bravis lattice is $m_x \mathbf{b}_x + m_y \mathbf{b}_y$, with $(m_x, m_y) \in \mathbb{Z}^2$ and the primitive translation vectors $\mathbf{b}_x$ and $\mathbf{b}_y$. We focus on a single Chern band of Bloch states $|k\rangle$, labeled by momentum $\mathbf{k} = \sum_{\alpha} k_\alpha \mathbf{g}_\alpha$, with $k_\alpha \in \mathbb{Z}$ and $\mathbf{g}_\alpha \cdot \mathbf{b}_\beta = 2\pi \delta_{\alpha \beta} / N_\beta$ ($\alpha, \beta \in \{x, y\}$). We use $|k\rangle$ and $|k_x, k_y\rangle$ interchangeably. The orbital $b$ is embedded at $\epsilon_b$ relative to its unit cell
coordinate in real space \[ \mathbf{R} \]. The projected density in the Chern band is [4, 9, 12]

\[
\rho_q = \sum_{\mathbf{k}} \left[ \sum_b e^{-i \mathbf{q} \cdot \mathbf{b}} u_b^*(\mathbf{k}) u_b(\mathbf{k} + \mathbf{q}) \right] |\mathbf{k}\rangle \langle \mathbf{k} + \mathbf{q}|, \quad (1)
\]

where \( u_b(\mathbf{k}) \) is the periodic part of the Bloch wavefunction. At \( \mathbf{q} = \mathbf{g}_a \), the bracketed factor in Eq. (1) gives the band geometry through the non-unitary exponentiated Abelian Berry connection, \( A_\alpha = \sum_b e^{-i \mathbf{q} \cdot \mathbf{g}_b} u_b^*(\mathbf{k}) u_b(\mathbf{k} + \mathbf{g}_b) \). \( A_\alpha(\mathbf{k}) \) contains the quantum distance between \( |\mathbf{k}\rangle \) and \( |\mathbf{k} + \mathbf{g}_a\rangle \), while \( A_\alpha(\mathbf{k}) = A_\alpha(\mathbf{k})/|A_\alpha(\mathbf{k})| \) is the unitary Berry connection between them. We define \( \rho_\alpha = \rho_{\mathbf{g}_a} \).

The gauge-invariant Wilson loops (geometric phases) can be obtained by parallel transporting around a close loop over the BZ torus. All the contractible loops consist of a product of loops around a single plaquette, namely \( \rho_{\mathbf{q}} \rho_0 \rho_{-\mathbf{q}} \rho_0^{-1} = \sum_{\mathbf{k}} D(\mathbf{k}) W_{BZ}(\mathbf{k}) |\mathbf{k}\rangle \langle \mathbf{k}|. \) Here, \( D(\mathbf{k}) = |A_\alpha(\mathbf{k}) A_{\alpha'}(\mathbf{k} + \mathbf{g}_b) A_{\alpha''}^*(\mathbf{k} + \mathbf{g}_b)|^2 \in \mathbb{R} \) is related to the non-uniqueness of the quantum distance, and \( W_{BZ}(\mathbf{k}) = A_\alpha(\mathbf{k}) A_{\alpha'}(\mathbf{k} + \mathbf{g}_b) A_{\alpha''}^*(\mathbf{k} + \mathbf{g}_b) \) \( \in U(1) \) is the unitary Wilson loop around the plaquette with lower-left corner at \( \mathbf{k} \). For large enough \( N_x \) and \( N_y \), we can unambiguously extract Berry curvature \( \mathbf{f}_k = \frac{i}{2\pi} \exp\{\mathbf{A}(\mathbf{k})\} \), with finite-size normalization convention \( \sum_{\mathbf{k}} BZ \mathbf{f}_k = C \). \( C \) takes the imaginary part in the principal branch \( 3\log(z) \in (-\pi, \pi] \). This gives a sharp finite-size formula for the Chern number, \( C = \frac{1}{2\pi} \text{Tr} \exp\{\mathbf{A}(\mathbf{k})\} \). In addition to \( W_{BZ}(\mathbf{k}) \), there are also two independent non-contractible Wilson loops on the torus, related to charge polarization: the Wilson loop \( W_{BZ}(\mathbf{k}) \) around \( k_y = 0 \), \( W_x = \text{Phase} \{0|\rho_{N_x}^2|0\} = \langle N_x \mathbf{g}_z|0\rangle \prod_{x=0}^{N_x-1} A_x(k\mathbf{g}_x) \), with \( |0\rangle \equiv |\mathbf{k} = 0\rangle \), and the Wilson loop \( W_y \) around \( k_x = 0 \) defined similarly.

The structure of geometric phases in the Chern band is fully specified by the collection of the Wilson loops \( W_{\mathbf{k}}(\mathbf{k}) \) and \( W_\alpha = \alpha = x, y \). We now build a LLL basis in Bloch space, from which all properties of a Chern band with arbitrary Chern number can be translated \textit{mutatis mutandis}. Diagonalizing the Haldane pseudopotentials in this basis gives us the FCI model wavefunctions.

We consider electrons on a (continuum) torus \((L_x, L_y) \sim (N_x \mathbf{b}_x, N_y \mathbf{b}_y)\) with twist angle \( \theta \) in a magnetic field \( \mathbf{B} = B \mathbf{e}_z \). The magnetic transmutations are \( T(\mathbf{d}) = e^{-i \mathbf{d} \cdot \mathbf{k}} \), where \( \mathbf{K} = -i \hbar \mathbf{\nabla} - e \mathbf{A} + e \mathbf{B} \times \mathbf{r} \). We adopt the Landau gauge \( \mathbf{A}(\mathbf{r}) = B z \mathbf{e}_y \). The guiding-center periodic boundary conditions \( T(\mathbf{L}) = 1 \) quantize the number of flux quanta \( N_\phi = L_x L_y \sin \theta/(2\pi L_y^2) \) to an integer \([40]\), where \( L_y = \sqrt{\hbar/(eB)} \) is the magnetic length. We set \( N_\phi = N_x N_y \) in accordance with the Chern insulator \([3, 40]\) for \( C = 1 \). The usual basis \(|j\rangle\) in the LLL is

\[
\langle x, y | j \rangle = \frac{1}{(\sqrt{\pi} L_y)^{1/2}} \sum_n |2\pi(j + n N_\phi) x + iy \rangle L_y^{-1/2} - i \frac{\pi L_y e^{-i\theta}}{N_\phi L_y} (j + n N_\phi)^2 \rangle e^{-x^2 / (2 L_y^2)}. \quad (2)
\]

To make contact with the Bloch states, we introduce a new LLL basis that diagonalizes translations in both directions, \( T(L_\alpha/N_\alpha) | \mathbf{k} \rangle = e^{-i 2\pi k_\alpha/N_\alpha} | \mathbf{k} \rangle \),

\[
| \mathbf{k} \rangle = \frac{1}{\sqrt{N_\alpha}} \sum_{m=0}^{N_\alpha-1} e^{2\pi m k_x/N_\alpha} | j = m N_\phi + k_y \rangle, \quad (3)
\]

where \( \mathbf{k} = \sum_b k_b \mathbf{g}_b \) lives on the lattice reciprocal to \((L_x, L_y)\). These states are periodic in \( k_x, |k_x + N_x, k_y| = |k_x, k_y| \), but \textit{quasi}-periodic \([50]\) in \( k_y \), \( k_x, k_y + N_y = e^{-i 2\pi k_x/N_\alpha} | k_x, k_y \rangle \). Each \(| \mathbf{k} \rangle \) satisfies \( T(L_\alpha) = 1 \). We find the LLL-projected density in the \(| \mathbf{k} \rangle \) basis,

\[
\rho_q = e^{-q^2 \xi_z^2 / 4} \sum_{\mathbf{k}}^{BZ} e^{-i 2 \pi q_x (k_x + q_x)/2} \rho_\mathbf{q}|\mathbf{k}\rangle \langle \mathbf{k}|, \quad (4)
\]

with \( q = \sum_b q_b \mathbf{g}_b, q_b \in \mathbb{Z} \). The Wilson loops are \( W_\mathbf{q}(\mathbf{k}) = e^{i 2 \pi k_\alpha/N_\alpha} \), \( W_x = e^{-i 2 \pi k_x/N_\alpha} \), and \( W_y = e^{i 2 \pi k_y/N_\alpha} \).

Using Eq. (4), one can diagonalize any FQH Hamiltonian \( \sum_q V_q \rho_{q-B} \) (including pseudopotential and even higher-body Hamiltonians), directly in the \(| \mathbf{k} \rangle \) basis, and then translate the resulting wavefunction to the FCI by replacing \(| \mathbf{k} \rangle \) with the lattice Bloch states. The advantage of the new LLL basis \([\text{Eq. } (4)]\) is many-fold. The conditions for the relevance of the FQH state to FCI are explicit in this basis \([\text{Eq. } (4)]\): the Berry curvature must not fluctuate wildly \([8, 12]\) and the quantum distance \([8, 12]\) over the Chern band must fall off with \( q \) rapidly, similar to \( e^{-q^2 \xi_z^2 / 4} \). \( \text{Eq. } (4) \) also allows a much simpler and more effective treatment of the curvature fluctuations in gauge fixing (see below). The most practical advantage of working directly in Bloch basis is the avoidance of the \textit{many-body} Fourier transform in the Wannier prescription. This greatly simplifies the numerical implementation and nearly \textit{squares} the largest Hilbert space dimension that we can study in numerics.

We now turn to the case of \( C > 1 \) and construct a Bloch-like basis in the \( C \)-component LLL with \( N_\phi = N_x N_y / C \) fluxes that forms an \( N_x \times N_y \) BZ with flat curvatures and Chern number \( C \). The starting point is to look for two commuting translation operators that resolve an \( N_x \times N_y \) BZ. The finite magnetic translations \( T_\alpha = T(L_\alpha/N_\alpha) \) seem natural, but they do not commute, \( T_x T_y = T_y T_x e^{2\pi i / C} \). The cure must come from the color structure of the multi-component system. We assume a \textit{color-neutral} Hamiltonian \( H \). Two color operators \( P, Q \) (diagonal in real space) commute with the Hamiltonian,

\[
P|\sigma\rangle = |\sigma + 1 \text{ (mod } C)\rangle, \quad Q|\sigma\rangle = e^{i 2\pi \sigma / C}|\sigma\rangle. \quad (5)
\]
|σ⟩, with σ ∈ ZC, are color eigenstates. Their commutation relation \( PQ = QPe^{-i2π/C} \) is complementary to that of \( T_x, T_y \). The two color-entangled operators \( \tilde{T}_x = T_x P \) and \( \tilde{T}_y = T_y Q \) commute with each other and \( H \). We define the eigenstates \( |k⟩ \) with \( \tilde{T}_α|k⟩ = e^{-i2πk_x/N} |k⟩ \),

\[
\langle x, y, σ|k⟩ = \frac{1}{(\sqrt{π}N_x L_y l_B)^{1/2}} \sum_n e^{i2π(nC+σ)k_x/N} \exp\left[ 2\pi i \left( k_y + nN_y + \frac{σ}{C}N_y \right) \frac{x + iy}{L_y} \right] e^{-x^2/(2l_B^2)} \, . \tag{6}
\]

Due to \( [T(L_α), \tilde{T}_β] \neq 0 \), generically we have to abandon the boundary condition \( T(L_α) = 1 \), and adopt the color-entangled generalization \( \tilde{T}_α^{N_o} = 1 \), i.e.

\[
T(L_x)P^{N_o} = T(L_y)Q^{N_o} = 1 \, . \tag{7}
\]

This quantizes \( k_x \) to integers. Since \( \tilde{T}_α^{N_o} \) commute with each other by construction, \( N_o \) is not restricted to an integer any more, unlike \[29\]. We only require \( N_x, N_y, N_o \in Z \). The \( |k⟩ \) states are periodic in \( k_x \), but quasi-periodic in \( k_y \).

\[
|k_x, k_y + N_y⟩ = e^{-i2πk_x/C} |k_x, k_y⟩ \, . \tag{8}
\]

There are \( N_x \times N_y \) independent \( |k_x, k_y⟩ \) states, which form a BZ of the same size as the lattice and with the same Chern number \( C \).

After summing over colors, the LLL-projected density operator \( ρ_q = \sum_{σ} ρ_{qσ} \) in the color-entangled basis \( |k⟩ \) takes identical form as in Eq. [1] except for the generalization \( N_o = N_x N_y/C \). The color-entangled BZ has flat curvature \( f_k = 1/N_o \), as inferred from \( W_q(k) = e^{i2π/N} \). The matrix elements of \( ρ_q \) in the C-component LLL, which are the building blocks of the interacting Hamiltonian, are exactly equal to the \( C \)-th power of those in the single component LLL. Model wavefunctions of pseudopotential Hamiltonians in the \( |k⟩ \) basis can immediately be translated to the FCI with arbitrary \( C \). Further, we can generalize the color-entangled boundary conditions in the LLL to \( \tilde{T}_α^{N_o} = e^{-i2π/N_o} \), where the twist angle \( γ_o ∈ R \) corresponds to flux insertions. This shifts the momentum \( k → k + γ \) with \( γ = \sum_α γ_o g_α \). The connections become \( A_α(k + γ) \), while the large Wilson loop around \( k_o = 0 \) are \( W_x(γ_y) = e^{-i2πCγ_o/N_o} \) and \( W_y(γ_x) = e^{i2πCγ_x/N_o} \).

Linking together the LLL \( |k⟩ \) and the lattice \( |k⟩ \) bases requires one additional step of gauge fixing, \( |k⟩ \to e^{i\psi}|k⟩ \). After that, any many-body state \( |Ψ⟩ \) over our colorful LLL can be transcribed to the FCI [33].

\[
|Ψ⟩ = \sum_{\{k\}} e^{i\sum_{k} ψ_k}|\{k\}⟩ × γ_{\{k\}}|Ψ⟩_L \, , \tag{8}
\]

where \( γ_{\{k\}} \) is the color-entangled occupation-number basis in the LLL with twist \( γ \). See Supplemental Material [17] for the explicit construction of \( e^{i\psi_k} \) and \( γ \).

For FCI with \( C > 1 \), previous studies suggested that the equivalent FQH states are the SU(C) color-singlet Halperin states \[29\] [33] [31] [48]. They are the exact zero modes of the color-neutral LLL-projected Hamiltonian \( H_{\text{FQH}} = \sum_q V_q ρ_{qσ} ρ_{qσ}^\dagger \), where \( q \) is summed over the infinite lattice reciprocal to \( (L_x, L_y) \) and the interaction between color-neutral densities \( ρ_q = \sum_{σ} ρ_{qσ} \equiv V_q = V_0 \) for bosons and \( V_q = V_0 + (1 - q^2/2)|V_1| \) for fermions, with pseudopotential \( V_n > 0 \). For the FQH effect in 2D electron gas, the boundary conditions \( T(L_α) = 1 \) are imposed separately on different color components. In the LLL description of a FCI, however, we require the system to be periodic under the color-entangled translations \( \tilde{T}_α^{N_o} \). This breaks the SU(C) symmetry. To compare with the Halperin SU(C)-singlet states, we examine the commensurate case \( N_x/N_o ∈ Z \). The boundary conditions in Eq. (7) thread \( Φ_σ = σ N_y/C \) (color-dependent) magnetic fluxes along the \( y \) direction into the \( σ \)-component of the LLL \[55\]. In the one-dimensional localized basis for LLL [Eq. (2)], this shifts the Landau orbitals of color \( σ \) by \( ω_{σ}|L_x⟩/N_o \) in real space. Hence we propose that the Wannier mapping \[29\] be modified to identify the hybrid Wannier states with our shifted LLL orbitals. In the generic, non-commensurate case, translation \( T(L_x) \) changes the color of the particle, due to \( T(L_x)P^{N_o} = 1 \). Our construction thus provides a finite-size realization of the “worm-hole” connecting different color components \[29\].

We demonstrate the Bloch construction using the ruby lattice model \( (C = 1) \) and the two-orbital triangular lattice model \( (C = 3) \). We construct the FCI model states through Eq. (7) from the exact-diagonalization ground states of \( H_{\text{FQH}} \) with color-entangled boundaries. We find high overlaps (Fig. 1a) and identical low-lying Halperin states \[29\] [33] [34] [48]. They are the exact zero ground states \[10\] [34]. The 12-fermion Laughlin state on the ruby lattice model has a Hilbert space of dimension \( 3.4 \times 10^7 \). This state is well captured by the model wave function obtained from our construction (overlap \( ≈ 0.99 \)). The triangular lattice model has decent overlaps, albeit lower than the ruby lattice model. The model we propose has the particle-hole symmetry, which is generally absent in the FCI models \[27\] [35]. When the lattice model exhibits such an emergent symmetry, our construction can also capture it \[27\].

To further examine our construction for \( C > 1 \), we study the interpolation Hamiltonian \( H_λ = (1 - λ)H_{\text{FCI}} + λH_{\text{FQH}}, 0 ≤ λ ≤ 1 \). For bosonic on-site density-density interaction on the triangular lattice, \( H_{\text{FCI}} = \mathop{\sum}_{k} \mathop{\sum}_{σ} \mathop{\sum}_{l} \mathop{\sum}_{a} |k⟩σ_a k_bσ_b k_cσ_c a⟩ ⟨lσ_a k_bσ_b k_cσ_c a| \), where \( k_4 = k_1 + k_2 - k_3 \mod (N_o g_α) \), and \( ψ_kσ = e^{i\psi_kσ}|k⟩ \) is gauge-fixed by \( e^{i\psi_kσ} \), with \( |k⟩ = ω_k^0 |0⟩ \). For \( H_{\text{FQH}} \), we use color-entanglement boundary conditions \( γ \). We find that the FCI model states are adiabatically connected to the actual ground states: \( H_λ \) remains gapped for \( λ ∈ [0, 1] \) and
its ground states retain the characters of the FCI model states as seen in both overlaps and particle entanglement spectrum (Fig. 1). As observed in \[15\], the 6-boson state on 6 × 4 lattice has clear deviations from the usual Halperin state in the entanglement spectrum. Our FCI model state exactly reproduces these novel features. Note that the 8 × 4 lattice is closer to the thin-torus limit \[49\], resulting in smaller overlaps and Δξ values.

In this Letter, we introduce a Bloch basis for multicomponent LLL with rational number of fluxes that entangles real and internal spaces on the one-body level. We establish a Bloch-basis mapping between a Chern band with an arbitrary Chern number C on an arbitrary \(N_x \times N_y\) lattice and a C-component LLL with \(N_a = N_x N_y / C\) in \(\mathbb{Q}\) fluxes. This mapping leads to a novel scheme, which we call Bloch construction, to build FCI model states from color-neutral FQH Hamiltonians. It treats bosonic/fermionic FCI with arbitrary \(N_x, N_y, C \in \mathbb{Z}\) in a wholesale fashion, and can handle large system sizes. The new gauge fixing in our basis significantly improves the overlaps with the actual ground states when curvature strongly fluctuates.

We refer to the constructed FCI model states as the color-entangled Halperin states. They are distinct from the SU(C)-singlet Halperin states due to the color-entangled boundary conditions. When the lattice size is commensurate with \(C\), the color-entangled states are the generalization of the usual Halperin states to color-dependent twisted boundaries. More generally, the lattice setup opens up access to the color-entangled, unphysical sectors of a multicomponent FQH system in a physical way. Our new formalism can be applied to the NASS states, and can be used to extract the exclusion principle for the counting of low-lying levels in the energy and the entanglement spectra.

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[50] The non-periodicity signals an topological obstruction to a periodic smooth gauge (Chern number $C = 1$) in the continuum limit.

[51] To be precise, one minus the quantum distance as usually defined.

[52] Alternatively, we can also use the operator pair $(T_x Q, T_y P^\dagger)$ to define the momentum eigenstates. This amounts to substituting the color-eigenstate $|\sigma\rangle$ in $|k\rangle$ to $|\tau\rangle \equiv \frac{1}{\sqrt{C}} \sum_{\sigma=0}^{C-1} e^{i2\pi t\sigma/C} |\sigma\rangle$. For our purpose of obtaining a FCI model state, this change is just a trivial unitary transform that leaves the color-neutral Hamiltonian intact.

[53] For actual lattice calculations, it is desirable to use periodic gauge with $|k\rangle = |k + N_x g_x\rangle$ (no sum implied). Simply restricting $k$ to a single BZ would achieve this, as long as the BZ choice for the lattice system is consistent with that for the LLL.

[54] We focus only on the color-singlet states as observed in numerics [34].

[55] We have verified by numerical diagonalization that the eigenstates of $H_{\text{FQH}}$ with color-entangled boundary conditions indeed coincide with the usual Halperin states with $\Phi_\sigma$ flux insertion, when $N_x/C \in \mathbb{Z}$. 