Chern Insulators and Topological Flat-bands in Magic-angle Twisted Bilayer Graphene

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Magic-angle twisted bilayer graphene (MA-TBG) features intriguing quantum phase transitions between strongly correlated states with superconducting, ferromagnetic or nematic order\textsuperscript{1-7}. Their emergence is triggered by enhanced electron-electron interactions when the flat bands in MA-TBG are partially filled by electrostatic doping. To date however, questions concerning the nature of these states and their connection to the putative non-trivial topology of the flat bands\textsuperscript{8,9} in MA-TBG are largely unanswered. Here we report on magneto-transport and Hall density measurements that reveal a succession of doping-induced Lifshitz transitions where discontinuous changes in the Fermi surface topology are accompanied by van Hove singularity (VHS) peaks\textsuperscript{10} in the density of states (DOS). The VHSs facilitate gapping-out the highly degenerate flat bands of MA-TBG\textsuperscript{11}, allowing to uncover the topological nature of the emerging minibands at doping levels corresponding to filled minibands. In the presence of a magnetic field the non-trivial topology of the minibands is revealed through well quantized Hall plateaus which signal the appearance of Chern insulators with integer Chern numbers, C=1,2,3. Surprisingly, for magnetic fields exceeding 5T we observe a new Lifshitz transition at a doping level of 3.5 electrons per moiré cell, suggesting the emergence in higher fields of a topological miniband at a fractional moiré filling.
The band structure of twisted bilayer graphene is strongly renormalized by the moiré super-structure that forms in the presence of a small twist angle between the crystal orientations of the two layers (Fig. 1a)\textsuperscript{10,12,13}. As a result the superstructure is characterized by two inequivalent hexagonal mini-Brillouin zones, “valleys”, originating from the inequivalent corners K and K’ of the single layer Brillouin zone. Close to the “magic” twist-angle, $\theta \approx 1.1$°, the low energy electronic structure of MA-TBG consists of two four-fold degenerate nearly-flat bands\textsuperscript{11,14}, one per valley (including physical spin), that straddle the charge neutrality point (CNP) and are separated from higher energy bands by spectral gaps. Owing to this degeneracy, the flat bands in MA-TBG can accommodate a total of eight electrons per moiré cell. We define the number of carriers per moiré cell (filling factor) as $\frac{n}{n_0}$, where $n$ is the carrier density, $n_0 = 1/A_0$ corresponds to one carrier per moiré cell, and $A = \sqrt{3}L_M^2/2$ is the cell area (Fig. 1a). As the Fermi level is swept through these bands, their quenched kinetic energy facilitates interaction-induced instabilities leading to strongly correlated behavior such as superconductivity, ferromagnetism and charge nematicity\textsuperscript{1-7,15-17}. Beyond many-body interactions, the existence of non-trivial band-topology is believed to play a crucial role in shaping the correlated phases in this system. Recent theoretical work has shown that the two flat bands in MA-TBG can be understood in terms of zeroth pseudo Landau levels (pLL) generated by Dirac fermions coupled with opposite sign pseudomagnetic fields in each band\textsuperscript{8}. These bands have a non-trivial topology characterized by opposite Chern numbers, $C = \pm 1$, and opposite sublattice polarizations, A or B. In the absence of broken $\mathcal{C}_{2z}T$ symmetry ($\mathcal{C}_{2z} = 180^\circ$ in plane rotation; $T$ -time reversal), the bands are degenerate resulting in eight unique bands that can be labeled as: $\{C = +1,A,K,s\}$, $\{C = +1,B,K',s\}$, $\{C = -1,B,K,s\}$, $\{C = -1,A,K',s\}$ where $K$ and $K'$ is the valley index and $s = \uparrow,\downarrow$ represents the spin orientation (Extended Data Figure 1). Lifting the degeneracy by explicitly breaking time reversal or sublattice symmetry is expected to reveal the topological nature of these bands, but thus far the experimental evidence is limited. Here we uncover the interplay between the emergence of correlated insulating phases at integer fillings of the pLLs and the non-trivial topology of the flat bands as revealed by the observation of their finite Chern numbers in magneto-transport measurements.
The results described here were obtained on a MA-TBG sample (Fig. 1b), prepared by the “tear and stack” technique \(^{18}\) (Methods), with twist angle \(\theta \approx 1.17^\circ \pm 0.02\), \(n_0 = 0.8 \times 10^{12}\text{cm}^{-2}\). Using 4-terminal measurements of the Hall and longitudinal resistance, \(R_{xy}\) and \(R_{xx}\), we find that at low temperatures \(R_{xx}(n)\) develops strong peaks at \(|n/n_0| = 0, 2, 3\), and diverges at the band edges, \(|n/n_0| = 4\), (Fig. 1c) consistent with previous results\(^{1,3,19}\). Close to \(n/n_0 = -2\) the sample becomes superconducting with a critical temperature \(T_c \sim 3.5\text{K}\) (Extended Data Figure 2), consistent with previous reports for the highest-quality MA-TBG devices\(^{2-4}\). In order to better resolve the Lifshitz transitions revealed by the magneto-resistance measurements, we suppressed the superconductivity with driving currents exceeding the critical value, \(I_c = 12\text{nA}\). The density and magnetic field \((B)\) dependence of \(R_{xx}(n,B)\), shown in Fig. 1d, feature Shubnikov de Haas minima giving rise to Landau fans whose pleats (trajectories) can be parameterized according to: \(n/n_0 = s + v(\phi/\phi_0)\) with \(s, v \in \mathbb{Z}\). \(s = 0\) or \(s \cdot v < 0\). Here \(\phi\) is the magnetic flux per moiré unit cell, \(\phi_0 = h/e\) is the magnetic flux quantum, \(h\) is Planck’s constant, and \(s = n(B = 0)/n_0\) is the branch index.

Trajectories emanating from the CNP, \(s = 0\), form a bilateral (full) Landau fan, with indices \(v = \pm 1, \pm 2, \pm 3, \pm 4, \pm 8, \pm 12 \ldots\), which are characteristic of Landau levels in a system where both electron and hole carriers contribute to the fan. From \(R_{xx}\) and \(R_{xy}\), we obtain the corresponding conductivities,

\[
\sigma_{xy} = \frac{R_{xy}}{R_{xy}^2 + \left(\frac{w}{l}\right)^2 R_{xx}^2} \quad \text{and} \quad \sigma_{xx} = \frac{w/l}{R_{xy}^2 + \left(\frac{w}{l}\right)^2 R_{xx}^2}
\]

where \(w/l = 0.625\) is the sample aspect ratio (Fig. 1e and Extended Data Figure 3). The high quality of this sample is reflected in the appearance of well-quantized \(\sigma_{xy}\) plateaus and corresponding \(\sigma_{xx}\) minima. In the \(s = 0\) branch at \(B \sim 1.5\text{T}\), the fan develops a quantized Hall plateau sequence \(\sigma_{xy} = v e^2/h\), initially with \(v = \pm 4, \pm 8\) reflecting the 4-fold degeneracy of the bands (Extended Data Figure 3b). At higher fields, \(B > 5\text{T}\), the addition of all odd plateaus to the sequence \(v = 0, 1, \pm 2, \pm 3, \pm 4\) reflects the formation of insulating states with fully lifted spin and valley degeneracies (Fig. 1e inset). From this plateau sequence, as well as by fitting the \(1/B\) dependence of the Shubnikov de Haas oscillations (Extended Data Figure 5), we find that the Berry phase for the charge carriers at the CNP is zero,
indicating that they are not Dirac particles. This is contrary to non-interacting band structure calculations that find Dirac cones at the CNP\textsuperscript{11}, and is testimony to the important role of interactions in this system.

Unlike the full-Landau fans observed in the $s = 0$ branch, the trajectories emanating from the $s \neq 0$ branches form unilateral (half) Landau fans that slope away from the CNP, corresponding to $s \cdot v > 0$. We note that the trajectories of the $R_{xx}(n,B)$ minima are labeled by a partial Diophantine equation which resembles the recursive Hofstadter butterfly spectrum associated with the commensuration of the magnetic flux lattice and a periodic potential. However, the underlying physics is quite different. Whereas the Hofstadter butterfly describes a recursive spectrum associated with the commensuration of the magnetic flux lattice and a periodic potential\textsuperscript{20}, the $s \neq 0$ half-fan trajectories observed here reflect the appearance of correlation induced spectral gaps at integer moiré fillings, as discussed below.

We next discuss the Hall density measurements which we employed to detect changes in Fermi surface topology. Electron-electron interactions leading to complex quantum phases, can be significantly enhanced by DOS peaks, such as VHSs, where the Fermi surface area and its topology changes. Experimentally, changes in Fermi surface topology, known as Lifshitz transitions\textsuperscript{21-24}, can be inferred from the Hall density, $n_H = -B/(eR_{xy})$, ($e$ is the elementary charge). For a clean 2D system, in the low temperature limit, with closed Fermi pockets, $n_H = DA_{FS} = n$, ($D$ is the degeneracy) provides access to the net area enclosed by the Fermi surface, $A_{FS}$. Far from Lifshitz transitions, $n_H$ measures the free carrier density that determines transport properties\textsuperscript{25}. However, when the bands become malleable as may happen when the Fermi level approaches a VHS, this is no longer the case. If for example a gap opens at the VHS at some filling, $n_c$, then $n_H$ resets to zero in the newly created empty band. Beyond this point, $n_H$ still increases linearly with $n$, but with an offset: $n_H = n - n_c$. Thus, the evolution of $n_H$ with doping provides access to the Fermi surface reconstruction and to the emergence of broken symmetry states as the chemical potential is swept across the band\textsuperscript{26}.

We obtained the doping and field dependence of $n_H$ from the measured values of $R_{xx}$ and $R_{xy}$ (Fig. 2a). In low fields, $B < 2T$, for $|n/n_0| = 2, 3$, we observe pronounced peaks in $R_{xx}$ and simultaneously vanishing $R_{xy}$, while for
\[ \frac{n}{n_0} = 1, \] the curves are featureless. In the doping range \( 0 \leq \frac{n}{n_0} < 2 \) we find that \( n_H \approx n \) (Fig. 2b), which indicates that the Fermi surface consists of closed pockets, consistent with band structure calculations. Upon approaching \( \frac{n}{n_0} = 2 \) from the low-density side, the strong deviation from this simple relationship can be fitted with an expression describing the Lifshitz transition at a VHS in the low-field limit (Extended Data Figure 6)\(^{26} \),

\[ n_H \approx \alpha + \beta (n - n_{c2}) \ln |(n - n_{c2})/n_0|, \]

where \( \alpha, \beta \) are constants, and \( n_{c2} = \pm 2n_0 \). Surprisingly, on the high-density side of \( n_c \), the logarithmic divergence of \( n_H \) expected for a standard VHS is absent. Instead, \( n_H \) resets to zero and subsequently increases linearly, \( n_H = n \pm 2n_0 \), in both the conduction (−) and valence (+) bands. The fact that the value of \( n_H \) resets to zero shows that doping the system across the VHS, not only changes the Fermi surface topology but also reconstructs the band by inducing a correlation gap. Independently, we obtain the value of these gaps, from an Arrhenius fit of the temperature dependence of the longitudinal resistance discussed below (Fig. 3).

These results can be understood in terms of the theoretically predicted VHSs in the half-filled band of MA-TBG\(^{27} \), \( |n| = 2n_0 \). At this filling the Fermi surface consists of two pockets centered on \( \text{K}_s, \text{K}'_s \), that are separated by two VHSs from a higher energy single pocket Fermi-surface centered on the \( \Gamma_s \) point. Doping from the CNP towards these VHSs, the initially closed Fermi sheets around the \( \text{K}_s \) and \( \text{K}'_s \) points expand and start merging at the VHS (inset Fig. 2b)\(^{27} \). When the Fermi level reaches the VHS, the enhanced Coulomb interactions lead to a correlation induced gap. The initially four-fold degenerate band breaks up into two doubly degenerate minibands, one full and the other empty, with a reduced capacity of \( 2n_0 \) states in each. Doping the sample beyond this level starts filling the new miniband which again consists of closed Fermi pockets. This band reconstruction also explains the appearance of the half–Landau fan in the high-density side of the \( s = \pm 2 \) branches. As doping continues to increase towards \( |n/n_0| = 3 \) the Hall density starts deviating from \( n_H = n \pm 2n_0 \), and it again can be fit with the logarithmic divergence at a VHS that forms at \( |n_{c3}| \sim 3n_0 \) (solid line in Fig. 2b). At low fields, the divergence appears on both sides of \( n_{c3} \), and no Landau-fan is observed. This indicates that no gap opens when the Fermi level crosses this VHS in low fields. The VHS scenario is further supported by the appearance of strong
$R_{xx}$ peaks at $|n/n_0| \sim 3$ (Fig. 1c) which is consistent with the singular DOS and concomitant suppression of the Fermi velocity at a VHS. Further increasing the doping level towards the band edges at $|n/n_0| = 4$, we find that $n_H$ changes sign, indicating a crossover from electron-like to hole-like transport in the conduction band, and vice versa in the valence band (Fig. 2b). In this regime, $|n_H| = |n| - 4n_0$, consistent with the theoretical prediction of a single hole (electron) pocket Fermi surface centered on the $\Gamma$-point for the conduction (valence) band edge.

Turning to the $s = 3$ branch, we find that its transport properties change significantly with increasing magnetic field. This is illustrated in Fig. 2c by the field dependence of $R_{xy}$ measured at a constant density, $n/n_0 = 3.3$ (dashed line in Fig. 2d). At low fields, $R_{xy}$ grows linearly with field, and its slope corresponds to $n_H = -1.5n_0$, indicating hole carriers. This value differs from that expected for a closed Fermi surface at this filling, $n_H = n - 4n_0 = -0.7n_0$, because of the proximity to the VHS at $n = 3n_0$ where $n_H(n)$ diverges, as shown in Fig. 2b. Beyond $B \sim 3.5T$, a sharp change in the slope of $n_H$, signals the formation of a correlation induced gap, together with a sign change in $n_H$ as the charge carriers become electron-like near the bottom of the newly created miniband. In Fig. 2d, we compare the density of $n_H$ at low and high fields. At $n/n_0 = 3.3$, marked by the dashed line, the transition from the low field density dependence, $n_H = n - 4n_0$ to that at high field, $n_H = n - 3n_0$ after the gap opens is clearly resolved.

Interestingly, concomitant with the gap opening on the $s = 3$ branch, we observe a strong Lifshitz transition at half filling of the newly created miniband, $n/n_0 = 3.5$, signaled by the divergent $n_H$, shown in Fig. 2d and Extended Data Figure 7, 8. This divergence is consistent with the formation of a new VHS similar to the ones observed at integer moiré fillings. The interpretation of the divergence in terms of a VHS is supported by the appearance of a pronounced resistance peak at $n/n_0 \sim 3.5$ (Fig. 3f inset) which starts increasing rapidly with the in-plane field, $B_{||}$, as shown in Fig. 3f, once the gap at $n/n_0 = 3$ forms. Such a resistance peak is unusual for half-filled bands, but it is consistent with the singular DOS and simultaneous suppression of the Fermi velocity at a VHS.

The results described here suggest a phenomenological scenario for the evolution of the DOS with doping, where bringing the Fermi level to a VHS opens
a gap and creates a new miniband, which in turn generates a new VHS and so on. This sequence of transitions\textsuperscript{31,32}, which is depicted schematically in Fig. 2e, reflects the malleability of the partially filled bands in MA-TBGs. At low doping, we find \( n_H = n \), as expected for a rigid band. This rigidity is lost when the Fermi level approaches \( |n/n_0| = 2 \), where the large DOS of the VHS facilitates the emergence of a correlation induced gapped state. This gap defines a new miniband bracketed between \( |n/n_0| = 2 \) and \( |n/n_0| = 4 \) with a new VHS forming at its center, at \( |n/n_0| \sim 3 \). In high fields, \( B > 5T \), when the Fermi level crosses this VHS, a correlation induced gapped state forms, producing a new miniband bracketed between \( |n/n_0| = 3 \) and \( |n/n_0| = 4 \). The center of this miniband hosts a new VHS at \( |n/n_0| = 3.5 \), with 0.5 carriers per moiré cell, with weakly insulating behavior (Extended Data Figure 1). Having shown the creation of minibands we next address their topological nature and the emergence of Chern insulators, as characterized by their quantized Hall resistance. From the field and density dependence of \( d^2R_{xx}/dn^2 \) (Fig. 3a) we resolve the half-Landau fans emanating from the \( s = 2, 3 \) branches. On the \( s = 3 \) branch, following the appearance of the correlation gap at \( B \sim 3.5T \), a half fan appears with a single pleat corresponding to the \( \nu = 1 \) trajectory. With increasing field, the symmetrized Hall resistance \( \bar{R}_{xy}(B) = (R_{xy}(B) - R_{xy}(-B))/2 \) on this pleat approaches the quantized value, \( \bar{R}_{xy} = -\hbar/e^2 \) as shown in Fig. 3b and Extended Data Figure 7a. Similar behavior is observed on the \( s = -3 \) branch (Extended Data Figure 9). If this quantization was a signature of the typical quantum Hall effect, observed in translationally invariant 2D electron systems in external magnetic fields, it would have to be part of a sequence reflecting the degeneracy of the initial state, \( \nu = \pm 4, \pm 8 \ldots \), as in the case of bilayer graphene. But this is clearly not the case. We instead argue that the quantized Hall resistance observed for the \( s = \pm 3 \) branches signals the emergence of a \( C = \pm 1 \) Chern insulator, which reflects the topologically non-trivial miniband created by opening the gaps on the \( s = \pm 3 \) branches. This interpretation is supported by the theoretical scenario which, in the absence of broken sublattice or time reversal symmetry, describes the flat bands in MA-TBG as eightfold degenerate zeroth order pLLs\textsuperscript{8}. In this scenario the four spin-valley degenerate Chern bands with \( C= \)
carry orbital magnetization whose sign is opposite to that in the $C = -1$ Chern bands. As a result, an external magnetic field opens a single particle gap, due to the orbital Zeeman effect, which splits the $C = +1$ bands from the $C=-1$ bands. Bringing the Fermi level into these bands, the exchange part of the Coulomb interactions further lifts their degeneracy resulting in the emergence of correlated insulating states at integer band fillings, or equivalently, at integer moiré-cell fillings. Since each band carries a finite Chern number $C = \pm 1$, filling an odd number of these bands would naturally result in topological phases with nonzero total Chern number. In particular the $s = \pm 3$ states, where only one out of the eight pseudo-LLs is occupied (empty), must be ferromagnetic and carry a Chern number $C = \pm 1$, consistent with our observation. The evolution of the correlation gap with in-plane magnetic field discussed below further supports this scenario. It is worth comparing this result with recent reports of a $C=1$ Chern insulator observed at $n/n_0 = 3$, where the alignment with the hBN substrate, which breaks the $C_2$ symmetry, is responsible for opening the gap already at very low magnetic fields (150mT). By contrast, when the $C_2$ symmetry is not broken by the substrate as in the data reported here, breaking $C_2 T$ and opening a gap at $n/n_0 = 3$ requires breaking $T$ by applying a magnetic field. Once the field is large enough to induce a gap, the topological nature of this miniband becomes evident in the form of the quantized Hall plateau.

On the $s = \pm 2$ branches, the symmetrized Hall resistance on the $\nu = \pm 2$ trajectories, reaches the quantized values, $\bar{R}_{xy} = \mp h/2e^2$ (Fig. 3b and Extended Data Figure 2d). Interpreting this result as before in terms of the pLL scenario, the Chern number of these states, where two out of the eight pLLs are occupied (empty), would depend on how the 2 electrons (holes) are distributed within the bands. In the presence of the magnetic field, the four $C = +1$ Chern bands, which are lowest in energy due to the orbital Zeeman effect, will be occupied first. Therefore, regardless of which of these four bands are occupied by the 2 electrons (holes), the resulting state will have a Chern number $C = +2$ (-2). The final state could be either a valley polarized state or an inter-valley coherent state, depending on whether the two occupied bands are in the same valley (e.g. $\{ C = +1, K, A, \uparrow \}$ and $\{ C = +1, K, A, \downarrow \}$), or in opposite valleys (e.g. $\{ C = +1, K, A, s \}$ and $\{ C = +1, K', B, s' \}$) in which case the spin orientations, $s$ and $s'$, in the two valleys
can be either parallel or antiparallel (Extended Data Figure 1). The magneto-transport measurements are unable to distinguish between these scenarios.

We next discuss the \( s = -1 \) branch. This branch is featureless at low fields and shows no evidence of a Lifshitz transition or VHS-induced correlated state. The field and density dependence of \( d^2R_{xx}/dn^2 \) (Fig. 4a) reveals the appearance of a half fan with well-resolved pleats, \( \nu = 1, 3 \) appearing above \( B \sim 6T \). Their onset coincides with the field where the slope of \( n_H \) starts deviating from its low field value (Fig. 4b), signaling the opening of a correlation induced gap. As the field continues to increase the Hall resistance on the \( \nu = 3 \) pleat approaches the quantized value \( \bar{R}_{xy} = \hbar/3e^2 \) (Fig. 4c). Interpreting this result as before in terms of the pseudo-LL scenario, the three electrons in this state must occupy three of the four available lowest energy \( C = +1 \) Chern bands (Extended data Figure 1). This necessarily produces a ferromagnetic state with \( C = +3 \), consistent with the observed quantized Hall resistance, \( \bar{R}_{xy} = \hbar/3e^2 \).

The magnitude of the correlation-induced gaps, whose existence was inferred from the Hall density, can be obtained directly from the temperature dependence of the longitudinal resistance, \( R_{xx}(T) \). \( R_{xx}(T) \) includes a background with linear temperature dependence (Extended Data Figure 10), which must be subtracted in order to obtain the thermally activated part of the resistance, \( R^* \). This background has been attributed to either electron-phonon scattering\(^{19}\) or strange metal behavior\(^{33}\). The thermally activated gaps, \( \Delta \), are calculated from an Arrhenius analysis of the bare resistance, \( R^* \sim \exp(-\Delta/2k_BT) \), where \( k_B \) is Boltzmann’s constant. In zero field (Fig. 3c) we obtain \( \Delta^0 = 7.38 \pm 0.08 \) meV, \( \Delta^2 = 2.5 \pm 0.15 \) meV, and \( \Delta^{-2} = 1.7 \pm 0.15 \) meV, for the \( n/n_0 = 0, 2, -2 \) moiré fillings, respectively. The deviation of \( R^* \) at low temperatures from the exponential divergence expected for activated transport is attributed to variable range hopping\(^{34}\), which is most pronounced at \( n/n_0 = 0 \) where the carrier density is lowest.

Insights into the nature of the correlated gapped states can be obtained from their magnetic field dependence. We measured \( R^* \) for in plane (\( B_\parallel \)) and out of plane (\( B_\perp \)) fields in order to distinguish between spin and orbital effects. As shown in Fig. 3d, \( \Delta^2 \) and \( \Delta^{-2} \) decrease linearly with field, suggesting that the \( |n/n_0| = 2 \) insulating states are not spin polarized. The effective gyromagnetic ratios obtained from the slope of these curves, \( g_\perp = 2.1 \pm 0.3, g_\parallel = 2.4 \pm 0.1 \) for \( \Delta^2 \), and \( g_\parallel = \)
2.5 ± 0.3 for $\Delta^{-2}$, are close to the bare value, $g_0 = 2$, indicating that the field dependence is controlled by spin response. Turning to the field dependence of $\Delta^3$, Fig. 3e, we find that the gap increases linearly with field, with a slope corresponding to $g_{|\parallel|} = 1.7 ± 0.05$ and a finite field intercept $B_0 = 1.1 ± 0.1$T. This result suggests that the correlated state emerging at $n/n_0 = 3$ for $B > 2.5$T is a spin polarized insulator, consistent with the observed $C=1$ Chern number, and with the theoretically predicted stripe ferromagnetic insulator phase\textsuperscript{35}.

The results reported here demonstrate the creation of minbands with non-trivial topology and the concomitant emergence of correlated insulating states characterized by finite Chern numbers $C=3,2,1$ at integer fillings, $|n/n_0| = 1, 2, 3$, respectively. At $|n/n_0| = 2,3$, we find that the successive appearance of VHSs in the newly created minbands at half-filling, facilitates the emergence of the correlated states. In contrast, for $|n/n_0| = 1$, where a mid-band VHS is absent, a much higher field is required to induce the correlated state. Interestingly, we find that a new VHS develops at $|n/n_0| = 3.5$, suggesting the emergence of a topological miniband in the fractionally filled moiré cell and possibly a fractional Chern insulator - the lattice equivalent of an even denominator fractional quantum Hall state\textsuperscript{36} – at higher fields.

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**Author Contributions**

S.W., Z.Z. and E.A. conceived and designed the experiment, carried out low-temperature transport measurement, and analyzed the data. S.W., and Z.Z. fabricated the twisted bilayer graphene devices. K.W. and T.T. synthesized the hBN crystals. S.W., Z.Z., and E.A. wrote the manuscript.
Figure 1 | Emergence of correlated states and Chern insulators in magic-angle twisted bilayer graphene (a) A moiré pattern with period \( L_M \) forms by introducing a twist angle \( \theta \) between the crystallographic axes for two superposed graphene layers (left). The moiré mini-Brillouin zone is a hexagon with sides \( K_s = |\vec{K} - \vec{K}'| \) where \( \vec{K}, \vec{K}' \) are the wave-vectors of the single layer graphene Brillouin zone. (b) Optical micrograph of the device with schematic of multi-terminal measurements. Scale bar is \( 5 \mu m \). (c) Temperature dependence of the longitudinal resistance, \( R_{xx} \), versus moiré filling \( (n/n_0) \) at \( B = 0T \) from 60K down to 0.3K. The driving current is 100nA. (d) Diagram of \( R_{xx}(B, n/n_0) \). The Landau fans are parameterized according to the branch index, \( s \), and the pleat slope, \( \nu \), as discussed in the text. White labels mark the pleats of the \( s = 0 \) full-Landau fan, and black labels mark the \( s \neq 0 \) half-Landau fans. (e) Longitudinal (black) and Hall (red) conductivities at \( B = 7T, T = 0.3K \), as a function of filling. Cyan and grey bars label states with well-quantized Hall plateaus and concomitant longitudinal conductance minima in the \( s \neq 0 \) and \( s = 0 \) branches respectively. Inset, \( \sigma_{xy} \) as a function of Landau level filling in the \( s = 0 \) branch show well-defined integer quantum Hall plateaus \( \sigma_{xy} = \nu e^2/h \) (dashed red lines) with \( \nu = 0, 1, \pm 2, \pm 3, \pm 4 \).
Figure 2

Figure 2 | Lifshitz transitions and van Hove singularities (a) Doping dependence of longitudinal resistance ($R_{xx}$) and Hall resistance ($R_{xy}$) at $B = 0.8T$, $T = 0.3K$. (b) Doping dependence of the Hall density $n_H = -(1/e)(dR_{xy}/dB)^{-1}$ at $T = 0.3K$ (symbols) together with fits to the logarithmic divergence characteristic of VHS (solid lines) in the vicinity of $|n/n_0| = 2, 3$. Inset, schematic evolution of the Fermi surfaces (red lines) from separate pockets centered on the $K_s$ points in the mini-Brillouin zone for low doping (bottom) and their merging together near the VHS (top) close to $|n/n_0| = 2$. (c) $R_{xy}(B)$ for $n/n_0 = 3.3$ at $T = 0.3K$. The low field slope of $R_{xy}(B)$ (blue dashed line) abruptly changes sign at $~3.5T$ and saturates to a new slope (pink dashed line) indicating the emergence of a magnetically induced gap and the formation of a new miniband for $n/n_0 = 3$. (d) Doping dependence of Hall density ($n_H/n_0$) near $n/n_0 = 3$ at $B = 7.0T$ and $1.5T$ for $T = 0.3K$. Blue arrow marks the density for the data in panel (c). Slopes corresponding to the density dependence in each branch are marked by dashed lines. The divergent Hall density near $n/n_0 = 3.5$ which appears for $B > 5.0T$ signals the emergence of a new VHS. (e) Diagram depicting scenario for the evolution of the DOS with Fermi energy, $E_F$, as it is swept through the flat bands by electrostatic doping. When $E_F$ enters a VHS, a gap opens creating a new miniband with a new VHS at its center.
Figure 3 | Landau fans, Chern insulators and field dependent gaps at $n/n_0 = \pm 2, 3$. (a) Field and density dependence of $d^2R_{xx}/dn^2$, at $T = 0.3K$ reveals the half-Landau fans on the $s = 2, 3$ branches marked by black lines. (b) Evolution of the symmetrized Hall resistance $\bar{R}_{xy}(n/n_0)$ with magnetic field shows the emergence of well-quantized Hall plateaus on the $\nu = 2 (1)$ trajectories of the $s = 2 (s = 3)$ branches, indicative of $C = 2 (C = 1)$ Chern insulators. (c) Arrhenius fits of the temperature dependence of the net resistance, $R^*$ are used to calculate the thermal activation gaps at integer fillings and $B = 0T$. (d) In-plane and out-of-plane field dependence of the thermally activated gaps for states corresponding to $|n/n_0| = 2$ (symbols) as marked. Fits to the linear field dependence (dashed lines) indicate unpolarized insulating states at these fillings as detailed in the main text. (e) In-plane field dependence of the gap at $n/n_0 = 3$ (symbols) and its linear fit (dashed line) indicates a spin polarized insulating state. (f) Inplane field dependence of $R^*$ at $n/n_0 = 3.5$ and $T = 0.3K$ suggests the formation of a VHS as discussed in the text. Inset, doping dependence of resistance at $n/n_0 \sim 3.5, \ T = 0.3K$, for several values of the in-plane field.
Figure 4 | Landau fan and $C = 3$ Chern insulator at $n/n_0 = -1$. (a) Field and density dependence of $d^2R_{xx}/dn^2$, at $T = 0.3$K reveals the emergence for $B > 5.5$T of a half Landau fan on the $s = -1$ branch with well resolved pleats, $\nu = 1, 2, 3, 4$ marked by black lines. (b) $R_{xy}(B)$ at $n/n_0 = -1.55$ and $T = 0.3$K. The low field slope of $R_{xy}(B)$ (blue dashed line) corresponding to $n_H$, abruptly changes at $\sim 6$T and saturates to a new slope (pink dashed line) indicating the emergence of a magnetically induced gap at $n/n_0 = -1$. (c) Evolution of $R_{xy}(n/n_0)$ with magnetic field at $T = 0.3$K shows the emergence of a well quantized Hall plateau indicative of a $C = 3$ Chern insulator on the $s = -1$ branch, for $B > 7.2$T. (d) Evolution of doping dependence of the Hall density $n_H/n_0$ with magnetic field. The slope change from $n_H = n$ at low fields to $n_H = n + n_0$ for $B > 7.2$T reveals the emergence of a new miniband associated with a magnetically induced correlation gap on the $s = -1$ branch.
Extended Data

Methods

Sample preparation and transport measurements

The hBN/TBLG/hBN/gold stacks are prepared with the dry transfer method in a glove-box (Argon atmosphere), using a stamp consisting of polypropylene carbonate (PPC) film and polydimethylsiloxane (PDMS). Monolayer graphene, hBN flakes (30-50nm thick) were first exfoliated onto a Si substrate capped with 285nm of thermally oxidized chlorinated SiO$_2$. Half of a graphene flake is picked up by the hBN on the stamp. The substrate with the remaining part of the graphene flake is rotated by 1°~1.2° and picked up with the hBN/G stack. The hBN/TBLG stack is then deposited onto the bottom hBN flake that is prepared separately in advance. During the stack assembly the temperature is kept below 160°C. The bottom hBN flake is transferred in advance onto a gold electrode serving as a local gate and is annealed at 250°C in Ar/H$_2$ for 6 hours for surface cleaning. Atomic force microscopy (AFM) and electrostatic force microscopy (EFM) are subsequently used to identify a clean bubble-free region of the TBLG prior to depositing the electrical edge contacts (Cr/Au) for transport measurements.

Four-terminal resistance measurements are carried out in He-3 system with a base temperature of 0.3K. The measurements are acquired with an ac current excitation of 5-100nA, using standard lock-in technique at 13.7Hz as well as delta-mode of KE6221 ac current source.
Extended Data Figure 1 | Pseudo Landau Level occupation diagram and Chern insulating states at integer fillings in the presence of a perpendicular magnetic field.

The black and red columns represent the K and K' valley states respectively. In each row, the vertical axis indicates the energy of a state relative to the Fermi energy marked by a dashed blue line. The ±1, A/B, and ↑/↓ represent the Chern number, sublattice polarization and spin orientation of the flat bands respectively. Note that for \( C = \pm 2 \) and \( n/n_0 = \mp 2 \), only the case of valley polarized states is plotted in here. The case of inter-valley coherent state is still possible. Figure adapted from Jiapeng Liu et al.8.

Signatures of superconductivity near \( n/n_0 = -2 \)

Signatures of superconductivity emerge in this device below 5K. Here we focus on the moiré-filling range \( n/n_0 = -2.4 \). In Extended Data Figure 2a, a sharp resistance drop from 10kΩ to 200Ω is observed within the temperature range 8K-0.8K. The resistance then remains nearly constant from 0.8K to 0.3K. The temperature at which the resistance drops to half its value in the normal state,
defined here as the critical temperature, is $T_c \sim 3.5 K$. In Extended Data Figure 2b the nonlinear current-voltage ($I$-$V$) characteristics in zero field, indicates a critical current of $\sim 12nA$. In the presence of a 0.2T magnetic field at $T = 0.3K$, superconductivity is suppressed as shown by the linear IV. The finite resistance value ($\sim 200\Omega$) at base temperature (0.3K) and the voltage fluctuations are attributed to non-ideal electrical contacts which often affect four-terminal measurements of microscopic superconducting samples as previously reported.\(^3\)

From Extended Data Figure 2c the critical field is estimated at $B_c \sim 0.02T$.

![Extended Data Figure 2](image)

**Extended Data Figure 2 | Signature of superconductivity near $n/n_0 = -2$**

- **a**, $R(T)$ at $n/n_0 = -2.4$. The critical temperature, $T_c = 3.5K$ is marked. The driving current is 10nA.
- **b**, Comparison of $I$-$V$ curves at $n/n_0 = -2.4$ at zero and finite magnetic field shows suppression of critical current from 12nA down to zero.
- **c**, $R(B)$ curve measured with a 10nA current, indicates a critical field of $B_c \sim 0.02T$.

**Evolution of quantum Hall plateaus in a magnetic field**

Quantum Hall plateau sequences around the CNP and on the other integer filling branches, without an explicitly broken $C_{2z}$ symmetry, are observed here for the first time. The well-defined plateaus in $\sigma_{xy}$ and minima of $\sigma_{xx}$ indicate the high twist-angle homogeneity of this sample, which is key to probing the topology of the Fermi surface.
Extended Data Figure 3 | Quantum Hall plateaus.  a, $\sigma_{xy}(n/n_0)$ at 1.5T displays quantum Hall plateaus, $\sigma_{xy} = v e^2/h$, and concomitant minima in $\sigma_{xx}(n/n_0)$ (gray bars) near the CNP. The plateau sequence $v = \pm 4, \pm 8$ indicates the 4-fold degeneracy. b, Same as panel (a) at 4.5T shows a new sequence with $v = \pm 2, \pm 4$ and concomitant minima, indicating a that either spin or valley degeneracy is lifted by the field. c, $\sigma_{xy}$ and $\sigma_{xx}$ as a function of Landau level filling $v = \phi_0(n/B)$ in the $s = 0$ branch at 7.2T shows a new plateau sequence with $v = 0, +1, \pm 2, \pm 3, \pm 4$ and concomitant minima indicating that the spin and valley degeneracy is fully lifted. d, Filling $R_{xy}(B)$ shows the emergence of Chern insulators in the higher order branches. All data are taken at $T = 0.3K$.

Calculating the Hall density from Hall resistance measurements.

The Hall density, $n_H = -B/(eR_{xy})$ is calculated using the slope of $dR_{xy}/dB$ obtained from a linear fit of the measured $R_{xy}(B)$ curves at fixed $n/n_0$, as shown in Extended Data Figure 4a.
Extended Data Figure 4 | Calculating n_H. a, Linear fits of $R_{xy}(B)$ at fixed moiré fillings, $n/n_0$, as indicated in the legend. b, Filling dependence of $dR_{xy}/dB$ obtained by fitting $R_{xy}(B)$ curves as illustrated in panel (a).

Shubnikov-de Haas oscillations and Berry phase.

The Berry phase on the $s = 0$ and $s = 2$ branches was determined from Shubnikov-de Haas oscillations by plotting in Extended Data Figure 5b the inverse magnetic field ($1/B$) value at which the resistance minima, $\Delta R(B) = R(B) - R(0)$ obtained from Extended Data Figure 5a, occur as a function of Landau level (LL) index. Multiplying the LL index intercept of the curves in Extended Data Figure 5b, 5c by $2\pi$, gives the Berry phase for each branch, which is zero in both cases.
Extended Data Figure 5 | Berry phase obtained from Shubnikov-de Haas oscillations.

a, Shubnikov-de Haas oscillations near CNP and $n/n_0 = -2$. b, c 1/B-field location of Shubnikov-de Haas minima versus the Landau level index (LL index). The intercept of linear fits to the data points with the LL index axis multiplied by $2\pi$ gives the Berry phase. Insets: calculated Berry phase for both branches is zero.

Estimate of $\omega_c \tau$

The expression for the logarithmic divergence of $n_H$ near a VHS is valid in the low-field limit\textsuperscript{26}, $\omega_c \tau \ll 1$, where $\omega_c = \frac{eB}{m}$ is the cyclotron frequency and $\tau$ the scattering time. To ensure the validity of the fit in the main text we estimated the value of $\omega_c \tau$ as a function of density and field. Within the Drude model where, $\rho_{xx} = \frac{m}{ne^2\tau}$, $\rho_{xy} = \frac{B}{ne}$, we estimate $\omega_c \tau = |\rho_{xy}/\rho_{xx}|$ shown in Extended Data Figure 6. Clearly all the data taken near the putative VHSs is in the low field limit.
Extended Data Figure 6 | Estimate of $\omega_c \tau$. $|\rho_{xy}/\rho_{xx}| = \omega_c \tau$ as a function of $n/n_0$ at several fields as marked.

**Doping dependence of $R_{xy}$ in the $s = 3$ branch, and the divergent Hall density near $n/n_0 = 3.5$ in high fields.**

In a half-filled band, $n_H$ naturally diverges due to the vanishing Hall voltage at the point of particle-hole symmetry. Since $|n/n_0| = 3$ is the half-filling point of the new miniband that forms when the gap opens at $|n/n_0| = 2$, can one distinguish between the divergence due to a VHS and the one that reflects the particle-hole symmetry in half filled bands? To address this question we note appearance of strong $R_{xx}$ peaks at $|n/n_0| = 3$. This is unusual for half-filled bands, but is consistent with the singular DOS and concomitant suppression of Fermi velocity at a VHS.\(^{28-30}\) The VHS scenario is further bolstered by the fit to the logarithmic divergence expected for the VHS. (Fig 2b in main text). In addition, as we show below, the observation of a gap opening at higher magnetic fields is consistent with the existence of a VHS at $n/n_0 = 3$, as inferred from the slope of the Hall number $n_H = n - 3n_0$ (Extended Data Figure 7b), as well as from thermal activation measurements (Fig. 3e in main text). In high fields, the Hall resistance in the $s = 3$ branch saturates at $R_{xy} = -h/e^2$ indicating the emergence of $C = 1$ Chern insulator as shown in Extended Data Figure 7a.
Extended Data Figure 7| Doping dependence of $R_{xy}$ and $n_H$ near $n/n_0 = 3$

Doping dependence of $R_{xy}$ and Hall density ($n_H/n_0$) in the $s = 3$ branch for magnetic fields ranging from 5.6T to 8T. The quantized $R_{xy} = h/e^2$ indicates the emergence of a $C = 1$ Chern insulator. Divergent $n_H$ behavior around $n/n_0 = 3.5$ is clearly resolved after the gap opens at $n/n_0 = 3$ with $n_H = n - 3n_0$.

Divergent Hall density and VHS near $n/n_0 = 3.5$ in high fields.

With the gap opening at $n/n_0 = 3$, we observe a divergent dependence of $n_H$ on carrier density at $n/n_0 = 3.5$. Based on the estimate of $\omega_c\tau \ll 1$ around $n/n_0 = 3.5$ (Extended Data Figure 8a), the expression for the logarithmic divergence of VHS in the low-field limit, $n_H \approx \alpha + \beta|n - n_c|\ln(|n - n_c|/n_0)$ described in the main text was used in fitting the density dependence of $n_H$ in this regime, as shown in Extended Data Figure 8b.

Extended Data Figure 8| Divergent Hall density and VHS near $n/n_0 = 3.5$ a, $\omega_c\tau$ around $n/n_0 = 3.5$ obtained from $|\rho_{xy}/\rho_{xx}|$ at several $B$-fields shows that the low
field limit $\omega_c \tau \ll 1$ is valid in this regime. \textbf{b,} The Hall density dependence on carrier density around $n/n_0 = 3.5$ fits the logarithmic divergence expected for a VHS as discussed in the main text.

**Quantized Hall resistance $R_{xy} = \hbar/e^2$ in the $s = -3$ branch**

In the $s = -3$ branch, quantized $R_{xy} = \hbar/e^2$ is observed for fields above 7.2T indicating the emergence of a $C = 1$ Chern insulator as shown in Extended Data Figure 9.

![Extended Data Figure 9](image)

**Extended Data Figure 9| Quantized Hall resistance $R_{xy} = \hbar/e^2$ in the $s = -3$ branch**

\textbf{a,} Hall resistance in the $s = -3$ branch, saturates at a quantized value, $R_{xy} = \hbar/e^2$ indicating the emergence of a $C = 1$ Chern insulator. \textbf{b,} $R_{xy}$ at fixed carrier density ($n = -3.28n_0$) as a function of magnetic field shows the onset of the emergent Chern insulator at $\sim 6.5T$.

**Longitudinal resistivity and its dependence on temperature and moiré filling.**

The longitudinal resistivity displays linear in temperature dependence at all moiré fillings above $\sim 5K$ (Extended Data Figure 10(a-c)). The temperature derivative in the filling range $0.5 < |n/n_0| < 3.5$, is $d\rho/dT \approx 120 \pm 20(\Omega/K)$, which is comparable with the values reported by other groups.\textsuperscript{19,33} The origin of this contribution, which is still under debate, has been attributed to electron-phonon interaction\textsuperscript{19} as well as to strange metal behavior\textsuperscript{33}.  

Extended Data Figure 10 | Longitudinal resistivity and its dependence on behaviors a-c, \( \rho(T) \) curves at selected filling fractions. d, \( dp/dT \) extracted in the linear-temperature-resistivity regions in (a-c).

**Subtraction of the linear-temperature-resistivity background for the estimation of thermal activation gaps** \( \Delta_\alpha \) **at integer fillings.**

As shown in in Extended Data Figure 10 the longitudinal resistance has a linear in temperature- background that is observed at all temperatures and fillings. This background is unrelated to the thermally activated transport in the presence of the gaps opening at integer fillings, and was therefore subtracted. The thermal activation gap is estimated from the temperature dependence of the net resistance \( (R^*) \) by fitting the Arrhenius dependence \( R^* \sim \exp(-\Delta/2k_BT) \), where \( \Delta \) is the energy gap, \( k_B \) is Boltzmann’s constant. Extended Data Figure 10a, 10b shows the results at \( n/n_0 = 2 \) with and without background subtraction where the value of the calculated gap is \( \Delta^2 = 2.5\text{meV} \) and \( 0.1\text{meV} \), respectively. The value obtained after background subtraction, 2.5meV, matches the temperature range where the resistance peak starts showing up, and is consistent with the energy scale obtained from electron compressibility measurements.\(^{32,40} \) The inverse-temperature dependence of \( R^* \) at \( n/n_0 = 3 \) for a range of in plane fields, \( B_\parallel \) is
shown in Extended Data Figure 11c.

**Extended Data Figure 11** | Thermal activation gaps at integer fillings and in finite magnetic fields

**a,** Evolution of the resistance peak around $n/n_0 = 2$ with temperature measured at $B = 0T$. The subtracted background is marked as dashed line. The net resistance ($R^*$) is marked by a red line with arrows. **b,** Temperature dependence of resistance at $n/n_0 = 2$ with and without subtraction of the background. **c,** Evolution of temperature dependence of the net resistance, $R^*$, with in-plane field amplitude, $B_\parallel$, at $n/n_0 = 3$.

**Evolution with in-plane field amplitude of $R^*(T)$ at $n/n_0 = 3.5$;**

The miniband created by the gap opening for $B > 4T$ at moiré filling $n/n_0 = 3$ leads to a divergent Hall density at moiré filling $n/n_0 = 3.5$ that reflects the emergence of a VHS, as discussed in the main text. Another signature of this VHS is the appearance of a peak in the net resistance $R^*$. The initially positive slope of $R^*(T)$ at low temperatures, indicating metallic behavior, steadily decreases with increasing field, and becomes slightly insulating at 8T (Extended Data Figure 12).
Extended Data Figure 12] Evolution of $R^*(T)$ at $n/n_0 = 3.5$ with in-plane field amplitude, $B_y$.

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