Change of carrier density at the pseudogap critical point of a cuprate superconductor

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The pseudogap is a partial gap in the electronic density of states that opens in the normal (non-superconducting) state of cuprate superconductors and whose origin is a long-standing puzzle. Its connection to the Mott insulator phase at low doping (hole concentration, \( p \)) remains ambiguous and its relation to the charge order \( 2–4 \) that reconstructs the Fermi surface is still unclear. Here, we use measurements of the Hall coefficient in magnetic fields up to 88 tesla to show that Fermi-surface reconstruction by charge order in the cuprate \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) ends sharply at a critical doping \( p = 0.16 \) that is distinctly lower than the pseudogap critical point \( p^* \approx 0.19 \) (ref. 11). This shows that the pseudogap and charge order are separate phenomena. We find that the change in carrier density \( n \) from \( n = 1 + p \) in the conventional metal at high doping (ref. 12) to \( n = p \) at low doping (ref. 13) starts at the pseudogap critical point. This shows that the pseudogap and the antiferromagnetic Mott insulator are linked.

Electrons in cuprate materials go from a correlated metallic state at high doping to a Mott insulator at low doping, \( n = 1 + p \), as measured by the Hall effect. Prior Hall measurements in magnetic fields up to 60 T show that Fermi-surface reconstruction by charge order in the cuprate \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) contains conducting \( \text{CuO} \) chains along the \( c \)-axis, respectively (see Methods and Extended Data Fig. 1). While this has no impact on the Fermi signal coming from the \( \text{CuO}_2 \) planes, it does affect the signatures of the \( \text{CuO}_2 \) planes.

By contrast, at low doping, the CDW modulations in \( \text{YBa}_2\text{Cu}_3\text{O}_{6.8} \) (ref. 13) and \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) (YBCO) (ref. 16) yield \( n_{\text{Hall}} \approx p \), below \( p \approx 0.08 \). Having a carrier density equal to the hole concentration, \( n = p \), is known to be an experimental signature of the lightly doped cuprates. The question is: at what doping does the transition between those two limiting regimes take place? Specifically, does the transition from \( n = 1 + p \) to \( n = p \) occur at \( p^* \), the critical doping for the onset of the pseudogap phase? The pseudogap is a partial gap in the normal state of states that appears below \( p^* \approx 0.19 \) (ref. 11), and whose origin is a central puzzle in the physics of correlated electrons and the subject of much debate.

To answer this question using Hall measurements, one needs to reach low temperatures, which requires the use of large magnetic fields to suppress superconductivity. The only prior high-field study of cuprates that goes across \( p^* \) was performed on LSCO (ref. 17), a cuprate superconductor with a relatively low critical temperature (\( T_c < 40 \) K) and critical field (\( H_{c2} < 60 \) T). For mainly two reasons, studies on LSCO were inconclusive on the transition from \( n = 1 + p \) to \( n = p \). First, the Fermi surface of overdoped LSCO undergoes a Lifshitz transition from a hole-like to an electron-like surface as its band structure crosses a saddle-point van Hove singularity at \( p \approx 0.2 \) (ref. 18). This transition causes large changes in \( R_{\text{Hall}}(T) \) (ref. 15) that can mask the effect of the pseudogap onset at \( p^* \approx 0.19 \). The second reason is the ill-defined impact of the charge-density-wave (CDW) modulations that develop at low temperature in a doping range near \( p \approx 0.12 \) (ref. 19). Such CDW modulations should cause a reconstruction of the Fermi surface, and hence change \( R_{\text{Hall}} \) at low temperature. Therefore, the anomalies in \( n_{\text{Hall}} \) versus \( p \) observed below 60 K in LSCO (ref. 17)—and in \( \text{Bi}_2\text{La}_{1−x}\text{Sr}_{x}\text{CuO}_6+\delta \) (ref. 20)—between \( p \approx 0.1 \) and \( p \approx 0.2 \) are most likely to be the combined result of three effects that have yet to be disentangled: Lifshitz transition, Fermi-surface reconstruction (FSR) and pseudogap.

Here we turn to YBCO, a cuprate material with several advantages. First, it is one of the cleanest and best ordered of all cuprates, thereby ensuring a homogeneous doping ideal for distinguishing nearby critical points. Second, the location of the pseudogap critical point is well established in YBCO, at \( p^* = 0.19 \pm 0.01 \) (ref. 11). Third, the Lifshitz transition in YBCO occurs at \( p > 0.29 \) (ref. 21), well above \( p^* \). Fourth, the CDW modulations in YBCO have been thoroughly characterized. They are detected by X-ray diffraction (XRD) between \( p \approx 0.08 \) and \( p \approx 0.16 \) (refs 22, 23), below a temperature \( T_{\text{XRD}} \) (Fig. 1a). Above a threshold magnetic field, CDW order is detected by NMR (refs 24, 25) below a temperature \( T_{\text{NMR}} \) (Fig. 1b). Fifth, the FSR caused by the CDW modulations has a well-defined signature in the Hall effect of YBCO: \( R_{\text{Hall}}(T) \) decreases smoothly to become negative at low temperature—a signature of an electron pocket in the reconstructed Fermi surface. Prior Hall measurements in magnetic fields up to 60 T show that the CDW-induced FSR begins sharply at \( p = 0.08 \) and persists up to \( p = 0.15 \), the highest doping reached so far.

YBCO has one disadvantage, however. Its orthorhombic structure contains conducting \( \text{CuO} \) chains along the \( b \)-axis, which reduce the Hall signal coming from the \( \text{CuO}_2 \) planes. While this has no impact on the qualitative features of \( R_{\text{Hall}}(T) \) (such as its sign or its qualitative \( T \)-dependence), it does modify the quantitative relation between the measured Hall number \( n_{\text{Hall}} \) and the inferred carrier density \( n \). Specifically, \( n = \rho_{\text{Hall}} \rho_{\text{c}} n_{\text{Hall}} \) (ref. 16), where \( \rho_{\text{Hall}} \) and \( \rho_{\text{c}} \) are the in-plane resistivities parallel and perpendicular to the \( b \)-axis, respectively (see Methods and Extended Data Fig. 1).

We have performed Hall measurements in YBCO up to 88 T, allowing us to extend the doping range upwards, and hence track the normal-state properties across \( p^* \), down to at least \( T = 40 \) K. Our complete data on four YBCO samples with dopings \( p = 0.16, 0.177, 0.19 \) and 0.205 are displayed in Extended Data Figs 2, 3, 4 and 5, respectively. In Fig. 2, we compare field sweeps of \( R_{\text{Hall}} \) versus \( H \) at \( p = 0.15 \) (Fig. 2a; from ref. 6) and \( p = 0.16 \) (Fig. 2b), at various temperatures down to 25 K. The difference is striking. At \( p = 0.15 \), the high-field isotherms \( R_{\text{Hall}}(H) \) drop monotonically with decreasing \( T \) until they become negative at low \( T \).

1 Département de physique, Regroupement Québécois sur les Matériaux de Pointe, Université de Sherbrooke, Sherbrooke, Québec J1K 2R1, Canada. 2Laboratoire National des Champs Magnétiques Intenses (CNRS, EMFL, INSA, UGA, UPS), Toulouse 31400, France. 3AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, 30-059 Krakow, Poland. 4Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada. 5Canadian Institute for Advanced Research, Toronto, Ontario M5G 1Z8, Canada.
At $p = 0.16$, $R_H(H)$ never drops. Figure 3 compares the temperature evolution of the normal-state $R_H$ at different dopings. In Fig. 3a, we see that $R_H(T)$ at $p = 0.16$ shows no sign of the drop to negative values displayed at $p = 0.12$, 0.135 and 0.15, at least down to $T = 40$ K. Having said this, and although the isotherms at $T = 25$ K and 30 K are consistent with a constant $R_H$ below $T = 50$ K (Fig. 2), we cannot exclude that $R_H(T)$ might drop below 40 K. However, even if it did, the onset temperature for FSR would have to be much lower than it is at $p = 0.16$, and it would extrapolate to zero at $p < 0.165$ (Extended Data Fig. 6). We therefore find that the critical doping above which there is no FSR in the normal state of YBCO at $T = 0$ is $p_{FSR} = 0.16 \pm 0.005$. Because this is in excellent agreement with the maximal doping at which short-range CDW modulations have been detected by XRD, namely $p_{XRD} = 0.16 \pm 0.005$ (refs 22, 23), and it is consistent with the region of CDW order seen by NMR (ref. 24) (Fig. 1b), we conclude that the critical doping where CDW order ends in YBCO is $p_{CDW} = 0.16 \pm 0.005$. This is consistent with the highest doping at which quantum oscillations from the CDW-induced electron pocket have been detected, namely $p = 0.152$ (ref. 9).

An onset of CDW order at $p_{CDW} = 0.16$ is distinctly lower than the onset of the pseudogap. Indeed, extensive analysis of the normal-state properties of YBCO above $T_c$ yields $p^* = 0.19 \pm 0.01$ (ref. 11). The critical point $p^*$ can also be located by suppressing superconductivity with 6% Zn impurities25, which shrinks the $T_c$ dome to a small region centred around $p^* = 0.19$ (Fig. 1a). This robustness of $p^*$ confirms that CDW order and pseudogap are distinct phenomena, since CDW modulations are rapidly weakened by Zn substitution26. Applying a field of 50 T produces a small $T_c$ dome peak at exactly the same doping, showing that $p^* = 0.19 \pm 0.01$ is the normal state, whether induced by Zn or by field (Fig. 1).

We have arrived at our first main finding: the onset of pseudogap and CDW order occurs at two distinct and well-separated critical dopings. Just as $\Delta_{XRD} < T^*$ (and $T_{XRD} < T_c^*$) (Fig. 1), we now find that $p_{CDW} < p^*$, in the normal state of YBCO. This contrasts with the simultaneous onset of pseudogap and short-range CDW modulations observed in the zero-field superconducting state of Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212) by scanning tunnelling microscopy (ref. 8).

Having established that the FSR due to CDW order ends at $p_{FSR} = 0.16$, we now see what happens at higher $p$. At $p = 0.205$, the temperature dependence of $R_H$ in YBCO is similar to that of Tl-2201 (refs 12, 15) at dopings where the Fermi surface is known to be a single large hole-like cylinder with carrier density $n = 1 + p$ (refs 14, 15) (Extended Data Fig. 7). In particular, as $T$ increases from zero, $R_H(T)$ rises initially, because of the growth in inelastic scattering, which is anisotropic around the large Fermi surface15. This yields a characteristic

**Figure 1** | Temperature–doping phase diagram of YBCO. a, Phase diagram in zero magnetic field ($H = 0$). The superconducting phase (grey dome) lies below $T_c$ (solid black line) and the antiferromagnetic phase lies below $T_N$ (brown line). The small (dark grey) dome shows how $T_c$ is suppressed by substituting 6% of the Cu atoms for Zn (white circles from ref. 25). Short-range charge-density-wave (CDW) modulations are detected by X-ray diffraction below $T_{XRD}$ (upward-pointing open triangles and error bars from ref. 22; downward-pointing open triangles and error bars from ref. 23). Note that unlike $T_{XRD}$, the amplitude of the CDW modulations decreases monotonically to zero as doping goes from $p = 0.12$ to $p_{CDW} = 0.16 \pm 0.005$ (refs 22, 23). Short-range spin-density-wave (SDW) modulations are detected by neutron diffraction below $T_{SDW}$ (blue triangles and error bars23). The red dashed line marks the approximate location of the pseudogap temperature $T^*$, while $p^* = 0.19 \pm 0.01$ marks the critical doping below which the pseudogap is known to appear11 (red diamond). b, Phase diagram in a magnetic field of $H = 50$ T. Above a threshold magnetic field, CDW order is detected by NMR (ref. 2) below a transition temperature $T_{NMR}$ (green squares and error bars24). The green region is where the Hall coefficient $R_H$ is negative (from ref. 6 and this work), starting above $p = 0.08$ (left green diamond). Our Hall data show that Fermi-surface reconstruction, and hence CDW order, ends at $p_{FSR} = 0.16 \pm 0.005$ (right green diamond). The red dashed line is the same as in a. The zero-field SDW phase is reproduced from a (blue region). The black and green solid lines and the blue dashed line are guides to the eye.

**Figure 2** | Field dependence of the Hall coefficient in YBCO. a, b, Hall coefficient ($R_H$) of YBCO at various fixed temperatures, as indicated, plotted as $R_H$ versus $H/H_{c2}$, where $H_{c2}(T)$ is the vortex-solid melting field above which $R_H$ becomes non-zero, for two dopings: $p = 0.15$ (a) and $p = 0.16$ (b). Upon cooling, we see that $R_H$ decreases and eventually becomes negative at $p = 0.15$, while it never drops at $p = 0.16$. The red dashed line marks the approximate location of the pseudogap temperature $T^*$, while $p^* = 0.19 \pm 0.01$ marks the critical doping below which the pseudogap is known to appear11 (red diamond). b, Phase diagram in a magnetic field of $H = 50$ T. Above a threshold magnetic field, CDW order is detected by NMR (ref. 2) below a transition temperature $T_{NMR}$ (green squares and error bars24). The green region is where the Hall coefficient $R_H$ is negative (from ref. 6 and this work), starting above $p = 0.08$ (left green diamond). Our Hall data show that Fermi-surface reconstruction, and hence CDW order, ends at $p_{FSR} = 0.16 \pm 0.005$ (right green diamond). The red dashed line is the same as in a. The zero-field SDW phase is reproduced from a (blue region). The black and green solid lines and the blue dashed line are guides to the eye.

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such that doping at the measured resistivity of YBCO, which is essentially independent of the Fermi surface are lost and a qualitative change: the magnitude of a decrease as upon crossing (sign of a decrease as) a qualitative change has taken place (peak in $R_H$ at $T = 150\,\text{K}$). The arrow marks the location of the peak in $R_H$ versus $T$, for $p = 0.12$ ($T_{\text{max}}$). The drop in $R_H(T)$ at low temperature is the signature of Fermi-surface reconstruction (FSR), caused by charge-density-wave (CDW) order. At $p = 0.16$, no such drop occurs, at least down to 40 K. This reveals that the critical doping for the end of FSR in the doping phase diagram (Fig. 1b) is $p_{\text{FSR}} = 0.16 \pm 0.005$ (Extended Data Fig. 6). $R_H$ versus $T$ at $p = 0.16$ (and higher, measured at (or extrapolated to) $H = 80\,\text{T}$ filled circles), from isotherms in Extended Data Figs 2, 3, 4 and 5. The curves are temperature sweeps at $H = 16\,\text{T}$, above $T = 100\,\text{K}$ (red), 100 K (green), 120 K (yellow). The dashed line is a flat extrapolation below 40 K. The data points for $p = 0.16$ (red) are taken at (or extrapolated to) $H = 80\,\text{T}$, from the $R_H$ versus $H$ isotherms in Extended Data Fig. 2. The data points for $p = 0.15$ (blue) and $p = 0.135$ (yellow) are not shown from the $R_H$ versus $T$ sweeps at $H = 80\,\text{T}$, above $100\,\text{K}$ (red and blue) and 120 K (yellow). The extrapolated $T = 0$ value, $R_H(0)$, doubles upon crossing $p^*$. Moving to still lower doping, we see that there is also a major quantitative change: the magnitude of $R_H$ at low $T$ undergoes a nearly sixfold increase between $p = 0.205$ and $p = 0.16$ (Fig. 3b), seen directly in the raw data at $T = 50\,\text{K}$ (Fig. 4a). We attribute this huge increase in $R_H$ to a corresponding decrease in carrier density. In other words, states at the Fermi surface are lost and $R_H(T = 0)$ increases. One may argue that for $p < 0.2 R_H(T)$ could decrease below 50 K and reach a value at $T = 0$ such that $n_{\text{H}} = 1 + p$ for all dopings down to $p = 0.16$. In this scenario, the peak in $R_H(T)$ at $T = 50\,\text{K}$ would be due to an anisotropic inelastic scattering that grows rapidly with underdoping. In Methods and Extended Data Fig. 9, we show that this mechanism is inconsistent with the measured resistivity of YBCO, which is essentially independent of doping at $T = 50\,\text{K}$ (Extended Data Fig. 9).

Colour-coded lines are a guide to the eye through the data points. The dashed lines are a linear extrapolation below the lowest data point. Open circles are low-field data from ref. 16 for the normal-state $R_H(T)$ of YBCO above $T_c$, for $p = 0.16$ (red, $y = 6.95, T_c = 93\,\text{K}$) and $p = 0.178$ (green, $y = 7.00, T_c = 91\,\text{K}$). These data are in excellent quantitative agreement with our own data. The error bars reflect the relative uncertainty in determining the change in $R_H$ versus $T$ for a given doping (see Methods). Shown only for one data point per doping, the colour-coded error bar is the same for all points on the corresponding curve (doping). c. Same as b showing the two highest dopings only, but with $R_H$ normalized at $T = 150\,\text{K}$. The curve at $p = 0.19$ is qualitatively different from the curve at $p = 0.205$, showing no sign of a drop at low $T$ (Extended Data Fig. 8). We attribute the twofold increase in the magnitude of $R_H$ at $T = 0$ to a decrease in carrier density as the pseudogap opens at $p^*$, with $p^*$ located between $p = 0.205$ and $p = 0.19$. Same as b but over a wider range of doping and temperature. For the three curves in the interval $0.09 < p < 0.15$, the dotted lines show how the normal-state $R_H(T)$ might extend down to $T = 0$ in the absence of the FSR caused by CDW order.
Figure 4 | Doping evolution of the normal-state carrier density. 

**a**, Isotherms of \( R_b \) versus \( H \) in YBCO at \( p = 0.16, 0.177, 0.19 \) and 0.205, measured at \( T = 50 \) K. Note the huge increase in the value of \( R_b \) at \( H = 80 \) T (or extrapolated to \( H = 80 \) T; dashed lines), by a factor 5.7, when going from \( p = 0.205 \) to \( p = 0.16 \). **b**, Doping dependence of the Hall number, \( n_H = \frac{V}{eR_b} \), in hole-doped cuprates, measured in the normal state at \( T = 50 \) K for LSCO (circles, ref. 13) and YBCO \( (p < 0.08, \) grey squares, ref. 16). For YBCO at \( p > 0.15 \) (red squares), we use \( R_b \) at \( H = 80 \) T from **a**. The white diamond (with its error bar) is obtained from the \( T = 0 \) limit of \( R_b(T) \) in strongly overdoped Ti-2201 (ref. 12). The solid black line is a guide to the eye. The red line is \( n_H = p \); the blue line is \( n_H = 1 + p \). The region where Fermi-surface reconstruction due to CDW order occurs in YBCO is marked as a green band; in that band, \( R_b < 0 \) at \( T \to 0 \). The error bars (±15%) for our four samples (red squares) reflect the uncertainty

\[ k = (0, \pm \pi) \text{ and } (\pm \pi, 0), \]

where the electronic states at the Fermi level must lie near \( k = (\pm \pi/2, \pm \pi/2) \), where the four nodes of the \( d \)-wave superconducting gap are located. This is indeed what is observed, in the form of nodal Fermi arcs, for example by ARPES (angle-resolved photoemission spectroscopy) in YBCO (ref. 21) and by scanning tunnelling microscopy in Bi-2212 (ref. 8), below \( p \approx 0.2 \). Given that the relation \( n_H = p \) extends down to the lowest dopings (Fig. 4b), two scenarios for these nodal states come to mind. One is associated with the antiferromagnetic order, the other is associated with the Mott insulator.

In the first scenario, antiferromagnetic order with a commensurate wavevector \( \mathbf{Q} = (\pi, \pi) \)—the order that prevails in YBCO below \( p = 0.05 \) (Fig. 1a)—would reconstruct the large Fermi surface into four small hole-like nodal pockets whose total volume would contain \( p \) carriers, so that \( n_H = p \) (see sketch in Fig. 4b). In electron-doped cuprates, an antiferromagnetic quantum critical point is believed to account for the abrupt drop in carrier density detected in the normal-state Hall coefficient\(^{22} \). The question is whether in YBCO magnetic order—present at low temperature up to \( p \approx 0.08 \) in zero field\(^{28} \) (Fig. 1b)—could extend up to \( p^* \approx 0.19 \) when superconductivity is suppressed by a magnetic field of the order of 100 T. An antiferromagnetic quantum critical point at \( p^* \) in YBCO could account for the linear temperature dependence of the resistivity\(^{29} \) and possibly also the divergent effective mass\(^{9} \).

In the second scenario, the pseudogap phase is a consequence of strong correlations associated with Mott physics. Numerical solutions of the Hubbard model find nodal Fermi arcs at low doping and intermediate temperatures\(^{30,31} \). It has been argued that at \( T \to 0 \), the Fermi surface could in fact consist of four hole-like nodal pockets\(^{32,33} \), whose total volume would contain \( p \) carriers. These arcs/pockets develop even though translational symmetry is not broken. The question is whether such a Mott-based pseudogap can appear at a doping as high as \( p = 0.19 \).

Overall, the fact that the normal-state carrier density—measured directly in the archetypal cuprate YBCO at low temperature—drops sharply from \( n = 1 + p \) to \( n = p \) precisely at \( p^* \) reveals a robust and fundamental new fact about the pseudogap phase: it causes a transformation of the Fermi surface such that its volume suddenly shrinks by one hole per Cu atom. We expect that a microscopic understanding of this transformation will elucidate the enigmatic behaviour of electrons in cuprate superconductors.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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**Author Contributions**


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Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to L.T. (louis.taillefer@usherbrooke.ca) or C.P. (cyril.proust@lncmi.cnrs.fr).
METHODS

Samples. Single crystals of YBa$_2$Cu$_3$O$_y$ (YBCO) were obtained by flux growth at UBC (ref. 34). The superconducting transition temperature $T_c$ was determined as the temperature below which the zero-field resistance $R = 0$. The hole doping $p$ is obtained from $T_c$ (ref. 35). In order to access dopings above $p = 0.18$, Ca substitution was used, at the level of 1.4% (giving $p = 0.19$) and 5% (giving $p = 0.205$). The samples are rectangular platelets with six contacts applied in the standard geometry, using diffused gold pads.

Measurement of the longitudinal and transverse resistances. The longitudinal resistance $R_L$ and transverse (Hall) resistance $R_H$ of our YBCO samples were measured in Sherbrooke in steady fields up to 16 T and in Toulouse in pulsed fields up to 88 T, using a dual coil magnet developed at the LNCFMI-Toulouse to produce non-destructive magnetic fields up to 90 T. The magnetic field profile is shown in Extended Data Fig. 10.

The pulsed-field measurements were performed using a conventional six-point configuration with a current excitation between 5 mA and 10 mA at a frequency of ~60 kHz. A high-speed acquisition system was used to digitize the reference signal (current) and the voltage drop across the sample at a frequency of 500 kHz. The data were post-analysed with software to perform the phase comparison. Data for the rise and fall of the field pulse were in good agreement, thus excluding any heating due to eddy currents. Tests at different frequencies showed excellent reproducibility.

Error bars. Note that the resistance of the samples was small due to their geometric factor and their high conductivity in this doping range — typically a few milliohms in the normal state at high fields. Despite the fact that $R_L$ was obtained by anti-symmetrizing the signals measured for a field parallel and anti-parallel to the $c$ axis, a slight negative slope was observed in the Hall coefficient $R_H$ versus $H$, similar to that found in prior high-field studies. This slope, which may be intrinsically present, has no impact on any of our conclusions, since they do not depend on the precise absolute value of $R_H$. Indeed, our conclusions depend on two results: (1) the temperature dependence of $R_H$ at low $T$, in a given sample; (2) the doping dependence of $R_H$ at low $T$, at a given temperature. In both cases, what matters is to measure $R_H$ at the same value of $H$, namely $H = 80$ T. So in Fig. 3c, and Extended Data Figs 7 and 8, where we compare the detailed temperature dependence of $R_H(T)$ in two samples ($p = 0.19$ and $p = 0.205$), the relevant uncertainty is the relative error bar associated with a change of temperature in one sample. That error is defined as the standard deviation of the value of $R_H$ at $H = 80$ T given by the linear fit in Extended Data Fig. 8. The maximum such error bar is shown in Fig. 3 for each of our four samples.

In Fig. 4a, we simply compare the magnitude of $R_H$ in our four samples when measured at $H = 80$ T and $T = 50$ K. As can be seen from the raw data, the negative slope of $R_H$ versus $H$ does not really affect this comparison. What is involved is the error bar on the absolute value of $R_H$ (in mm$^2$ C$^{-1}$), which involves geometric factors and which we estimate to be at most ±15%. This error bar is shown in Fig. 4b. Note the excellent quantitative agreement between our data and the data of ref. 16 at $p = 0.16$ and 0.177 (Fig. 3b).

Sample size. No statistical methods were used to predetermine sample size.

Relation between Hall number and carrier density in YBCO. In Fig. 4b, we plot the Hall number $n_H = V/(R_H e)$ in YBCO, the relation between $n_H$ and the carrier density $n$ involves a correction factor, the in-plane anisotropy of transport, so that $n = n_H/(p_\rho_\rho)$, where $p_\rho$ and $\rho_\rho$ are the resistivities along the $\alpha$ and $\beta$ directions of the orthorhombic structure, respectively. This is because the conducting CuO chains that run along the $\beta$ axis short-circuit the transverse (Hall) voltage when a current is sent along the $\alpha$ axis.

In Extended Data Fig. 1, we show the chain resistivity $\rho_{chain}$ of our YBCO sample at $p = 0.177$, defined as $\rho_{chain} = 1/(4\pi p_\rho/\rho_\rho)$. It displays the known $T^2$ behaviour of chain conduction, with $\rho_{chain} = 50 \mu$m cm at $T = 50$ K. Combined with the $p_\rho(T)$ data plotted in Extended Data Fig. 9, where $p_\rho = 2.5 \mu$m cm at $T = 50$ K, we get $p_\rho/\rho_\rho = 1.5$ at $T = 50$ K. We expect a similar anisotropy for the four samples used in our study.

Therefore, if in Fig. 4b we wanted to plot $n$ instead of $n_H$, we would need to divide $n_H$ by 1.5. The red squares at $p = 0.16$, 0.177 and 0.19 would move down by a factor of 1.5. For $p = 0.16$, this means that $n \approx p$, since $n_0 \approx 0.24$. So our claim that $n \approx p$ below $p^*$ remains correct. For $p = 0.205$, we get $n \approx 0.9$, significantly below 1 + $p = 1.205$. However, at $p = 0.205$, the value of $n_H$ at $T = 0$ is larger than at $T = 50$ K (Fig. 3c), by a factor of 1.3 or so, giving $n(T=0) \approx 1.2$.

Calculation of the Hall coefficient and resistivity in cuprates. Assuming a single large hole-like Fermi surface, as measured in strongly overdoped Tl-2201, Hussey has shown that one can calculate the resistivity and Hall coefficient using the Jones-Zener expansion. The model calculates directly the longitudinal and transverse electrical conductivities $\sigma_{xx}$ and $\sigma_{xy}$.
the experimental $\rho_a$, which are essentially independent of doping at $T = 50$ K. In other words, if inelastic scattering were responsible for the increase in $R_H$ at 50 K with underdoping, it would necessarily show up as a comparable (even larger) increase in the resistivity $\rho_a$ at 50 K. The fact that it does not show up in this way rules out inelastic scattering as a mechanism for the sixfold increase in $R_H$.

We conclude that the large rise in $R_H$ versus doping is due to a loss of carrier density, and it is a property of the normal-state Fermi surface at $T = 0$.


Extended Data Figure 1 | Temperature dependence of resistivity of CuO chains in YBCO at $p = 0.177$. Shown is the chain resistivity in YBCO at $p = 0.177$ (red), defined as $\rho_{\text{chain}} = \frac{1}{(1/\rho_a) - (1/\rho_b)}$, where $\rho_a$ and $\rho_b$ are the in-plane resistivities along the $a$ and $b$ directions of the orthorhombic structure, respectively, plotted versus $T^2$. The black line is a linear fit that extrapolates to $\rho_{\text{chain}} = 50 \mu\Omega \text{ cm}$ at $T = 50$ K.
Extended Data Figure 2 | Isotherms of $R_H$ versus $H$ in YBCO at $p = 0.16$. Shown is the magnetic field dependence of the Hall coefficient $R_H$ in our YBCO sample with $y = 6.92$ ($T_c = 93.5$ K; $p = 0.161$) at various temperatures, as indicated (key at right).
Extended Data Figure 3 | Isotherms of $R_H$ versus $H$ in YBCO at $p = 0.177$. As for Extended Data Fig. 2 but for our YBCO sample with $y = 6.97$ ($T_c = 91$ K, $p = 0.177$).
Extended Data Figure 4 | Isotherms of $R_H$ versus $H$ in YBCO at $p = 0.19$. As for Extended Data Fig. 2 but for our YBCO sample with $y = 6.99$ and 1.4% Ca doping ($T_c = 87$ K; $p = 0.19$).
Extended Data Figure 5 | Isotherms of $R_H$ versus $H$ in YBCO at $p = 0.205$. As for Extended Data Fig. 2 but for our YBCO sample with $y = 6.99$ and 5% Ca doping ($T_c = 77$ K; $p = 0.205$).
Extended Data Figure 6 | Doping dependence of $T_{\text{max}}$. Shown is the temperature $T_{\text{max}}$ at which $R_H$ versus $T$ peaks in YBCO (Fig. 3a), plotted versus doping $p$. At $p = 0.16$, there is no downturn in the normal-state $R_H(T)$ down to 40 K. The $p = 0.16$ data are consistent with $T_{\text{max}} = 0$ (lower bound), with an upper bound at $T_{\text{max}} = 40$ K (shown as black vertical segment). The width of the grey band marks the upper and lower limits for $T_{\text{max}}$ versus $p$. The green diamond defines the critical doping above which FSR is no longer present, at $p_{\text{FSR}} = 0.16 \pm 0.005$, with an error bar defined from the minimal and maximal possible values of $T_{\text{max}}$. Error bars on the three data points (black dots) represent the uncertainty in defining the peak position of the $R_H(T)$ curves in Fig. 3a.
Extended Data Figure 7 | Zoom on $R_H$ versus $T$ in Tl-2201 and YBCO at high doping. 

**a**, Temperature dependence of $R_H$ in Tl-2201 (squares) at $p = 0.3$ (blue, $T_c = 10\,\text{K}$; ref. 38) and $p = 0.27$ (green, $T_c = 25\,\text{K}$; ref. 39). 

**b**, $R_H$ versus $T$ in YBCO (circles, from Extended Data Figs 4, 5 and 8) at $p = 0.205$ (yellow) and $p = 0.19$ (blue). The dashed lines are an extrapolation of the low-$T$ data to $T = 0$. The YBCO curve at $p = 0.205$ is qualitatively similar to the two Tl-2201 curves, all exhibiting an initial rise with increasing temperature from $T = 0$, and a characteristic peak at $T \approx 100\,\text{K}$—two features attributed to inelastic scattering on a large hole-like Fermi surface\(^\text{15}\). The YBCO curve at $p = 0.19$ is qualitatively different, showing no sign of a drop at low $T$ (see Extended Data Fig. 8). We attribute the twofold increase in the magnitude of $R_H$ at $T \rightarrow 0$ to a decrease in carrier density as the pseudogap opens at $p^*$, with $p^*$ located between $p = 0.205$ and $p = 0.19$. The error bars are defined in the legend of Fig. 3.
Extended Data Figure 8 | Comparison between $p = 0.205$ and $p = 0.19$.
a, b, The field dependence of the Hall coefficient $R_H$ in YBCO at $p = 0.205$ (a) and $p = 0.19$ (b), for different temperatures as indicated. The colour-coded lines are parallel linear fits to the high-field data. They show that at low temperature $R_H$ decreases upon cooling at $p = 0.205$, while it saturates at $p = 0.19$. The value of $R_H$ given by the fit line, at $H = 80$ T, is plotted in Fig. 3 and in Extended Data Fig. 7b. Similar fits are used to extract $R_H(80 \text{ T})$ for $p = 0.16$ and $p = 0.177$ (from data in Extended Data Figs 2 and 3).
Extended Data Figure 9 | Scenario of inelastic scattering. a, $R_H$ versus $T$ in YBCO at four dopings $p$, as indicated (Fig. 3b). b, Electrical resistivity $\rho_a$ versus $T$ in YBCO at four dopings, as indicated. Lines are at $H = 0$; dots are in the normal state at high field. c, $R_H$ versus $T$ calculated for five values of inelastic scattering, with $\Gamma_1 = 0, 1, 5, 15$ and 25 $\text{THz K}^{-1}$, showing that $R_H(T)$ grows with increasing $\Gamma_1$ (see Methods). Dots are from a.

d, Corresponding calculated values of the electrical resistivity $\rho_a$ plotted versus $T$, using the same parameters and values of $\Gamma_1$ as for the colour-coded curves of c. The vertical grey lines mark $T = 50$ K, the temperature at which we see a sixfold increase in $R_H$ (a), yet no increase in $\rho_a$ (b). The calculation can reproduce the large increase in $R_H$ (c), but it is accompanied by a tenfold increase in $\rho_a$ (d).
Extended Data Figure 10 | Magnetic field profile. Time dependence of the magnetic field pulse in the 90 T dual-coil magnet at the LNCMI in Toulouse. Inset, zoom around maximum field.