Two-particle time-domain interferometry in the Fractional Quantum Hall Effect regime.

Imen Taktak

CEA Saclay

Maelle Kapfer

CEA Saclay

Jayshankar Nath

IQM Germany GmbH <https://orcid.org/0000-0001-6780-3842>

Preden Roulleau

CEA <https://orcid.org/0000-0002-8397-5019>

Matteo Acciai

Chalmers University of Technology <https://orcid.org/0000-0001-9739-9289>

Janine Splettstoesser

Chalmers University of Technology

Ian Farrer

The University of Sheffield <https://orcid.org/0000-0002-3033-4306>

David Ritchie

University of Cambridge <https://orcid.org/0000-0002-9844-8350>

Denis Glattli (✉ christian.glattli@cea.fr)

CEA Saclay <https://orcid.org/0000-0002-1457-0915>

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Authors:

I. Taktak¹, M. Kapfer¹, J. Nath¹, P. Roulleau¹, M. Acciai², J. Splettstoesser², I. Farrer³,
D. A. Ritchie⁴ and D.C. Glatli^{1*},

Affiliations:

10 ¹ SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif sur Yvette Cedex France

²Department of Microtechnology and Nanoscience - MC2, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

³Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, S1 3JD, UK

15 ⁴Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK.

Abstract:

As with like particles in ordinary vacuum, quasi-particles are elementary excitations of the ground state of condensed matter quantum phases. Demonstrating that they keep quantum coherence while propagating is a fundamental issue and an important challenge for their manipulation for quantum information tasks. This is particularly the case for the quasi-particles called anyons of the Fractional Quantum Hall Effect (FQHE), a quantum phase displayed by two-dimensional electronic conductors in high magnetic fields. These fractionally charged quasi-particles obey anyonic statistics intermediate between fermionic and bosonic. Their quantum coherence has been observed by their transmission through the discrete localized states of electronic Fabry-Pérot interferometers [1-5]. Surprisingly, no quantum interference of anyons was observed in electronic Mach-Zehnder interferometers [6-8] for which the quasi-particle transmission occurs via propagating states forming a continuum of states. Here we address this puzzle by demonstrating that FQHE anyons do keep a finite quantum coherence while propagating along extended states by using a different kind of interferometry, namely two-particle time-domain interference [9] using an electronic beam-splitter. By varying the time delay between photo-created electron-hole pairs and measuring cross-correlated noise sensitive to the two-particle Hanbury Brown Twiss (HBT) phase [9], we observe strong quasi-particle interference. Visibilities as high as 53% and 60% are observed for $e/5$ and $e/3$ charged anyons propagating on the FQHE chiral edges modes. Our results give a positive message for the challenge of performing controlled quantum coherent braiding of anyons and call for a better understanding of the absence of interference in Mach-Zehnder interferometers.

Main Text:

The Quantum Hall Effect appears in high perpendicular magnetic field for electrons confined to a plane. The quantization of cyclotron orbits leads to the formation of Landau levels. For integer or fractional filling of the Landau levels, a topological insulator with a gap forms. Chiral gapless modes appear on the conductor edges on which the carriers propagate allowing a current to flow. For integer filling factor, the quantum coherence of edge channels is large. For fractional filling, the carriers are anyons whose quantum coherence is puzzling [10]: coherence is observed on Fabry-Pérot interferometers but not on Mach-Zender interferometers. In this work we use another type of interferometry, based on two-quasiparticle interference, which demonstrates the quantum coherence of propagating anyons.

Fabry-Pérot Interferometers (FPI), based on quantum dots or antidots, showed quasi-particle interference in FQHE as early as the 1990s through the periodic oscillations of the transmitted current versus magnetic flux or gate voltage [2]. Recently, discrete phase shifts of the interference pattern of a FPI have been reliably ascribed to the statistic angle of anyons trapped in the dot, providing, together with an independent noise experiment [11], definitive proof of anyonic statistics [1]. In an electronic Fabry-Pérot interferometer, two separate Quantum Point Contacts (QPCs) form beam-splitters which connect a Quantum Dot (QD) to right and left leads. By appropriate tuning of their transmission, the paths of carriers going straight through the two QPCs, or performing several turns inside the dot, interfere before exiting. The interference leads to the periodic oscillation of the transmission versus the magnetic flux or versus the gate voltage used to change the dot size, attesting to the quantum coherence. The resonant character of the transmission gives quasiparticle states localized in the dot with quasi-discrete spectrum. The separation between energy levels is believed to help preserve the quantum coherence needed to observe interference.

The Mach-Zehnder Interferometer (MZI) is a different kind of interferometer, also made using two beam-splitters. Its realization in electronic systems in the Integer Quantum Hall regime has been a breakthrough as the chiral edge channel propagation imposes a topology requiring delicate fabrication [12]. In contrast to FPIs, only two distinct paths interfere in a MZI. MZIs have been used to quantify the quantum coherence of carriers propagating along edge channels of the IQHE, in particular the loss of coherence due to the noisy environment [12,13]. Surprisingly and contrasting with measurements using FPIs, a full disappearance of interference was observed [6-8] when entering the FQHE regime (filling factor $\nu < 1$). One possible reason for the different behavior could be ascribed to the nature of states involved in the two interferometers: discrete versus continuous spectrum, the latter being more fragile with respect to environmental fluctuations. Counter-propagating neutral modes are also believed to degrade the coherence. Checking these hypothesis requires searching for quantum interference using a different kind of interferometer, also based on delocalized propagating states.

This is the aim of this work. We use a single beam-splitter to perform time-controlled quantum interference of propagating quasi-particles in the IQHE and FQHE regime. While FPI and MZI interferometers, based on DC conductance measurements, are sensitive to single-quasi-particle interference, our measurements detect current fluctuations (quantum shot noise) which is known to reveal two-particle interference, see [14,17,18]. The experiment is inspired from the seminal work of V. Rychkoff, Polianski, and M. Büttiker [9], see also [15,16], who proposed a new kind of interferometry based on the measurement of the so-called Hanbury Brown Twiss (HBT) quantum phase. They showed that, when applying two out-of-phase ac potentials of equal magnitude and frequency on two different contacts of a four probe conductor, the current noise reveals a two-particle interference resulting from particle indistinguishability. Here, we use the simplest four-terminal

conductor: a QPC which mixes and partitions two incoming chiral edge channels into two transmitted and reflected edge channels. Figure 1(a) shows the principle of the measurement and figure 1(f) is a sketch of the experimental set-up used. The experiments are first done in the IQHE regime at filling factor $\nu=2$, as a benchmark situation, and then in the FQHE regime at filling factor $\nu=2/5$ allowing us to probe anyons with charges... $e^*=e/5$ and $e/3$. Note that, the $\nu=2/5$ FQHE state maps to the $\nu=2$ IQHE state in the composite fermion picture [19] as both filling factors have two co-propagating edge channels.

Two AC sinewave voltages $V(t)=V_{ac}\cos(2\pi ft)$ and $V(t-\tau)=V_{ac}\cos(2\pi ft-\Delta\Phi)$ are applied to contacts (1) and (2) respectively to inject photo-created electron-hole pairs in the beam-splitter input leads, see figure 1. $\Delta\Phi=2\pi f\tau$ is the relative phase due the time-delay τ between the sources. The scattering amplitudes relating input leads (1) and (2) to output leads (3) and (4), see figure 1(a), are $s_{3,1}=s_{4,2}=t$ and $s_{3,2}=s_{4,1}=ir$ (to make expressions simpler, in the main text we disregard in the scattering amplitudes the phase factors $e^{i\varphi_{\beta\alpha}}$ describing the phase $\varphi_{\beta\alpha}$ accumulated by electrons propagating from input contact (α) to output contacts (β)). $|t|^2=D$ and $|r|^2=1-D$ are the transmission and reflection probabilities of the QPC beam-splitter. Electron and hole interferences are detected through the cross-correlated current fluctuations of leads (3) and (4). According to [9], the magnitude of the current cross-correlation is shown to depend on the Hanbury Brown Twiss phase $\chi = \arg(s_{13}^*s_{32}s_{24}^*s_{41})$ resulting from the indistinguishability of photo-created electron-hole pairs. Contrasting with pure DC transport and noise experiments, the creation of photo-assisted electron-hole pairs allows us to probe the HBT phase, providing a new type of interferometry to test for the quantum coherence of carriers. This is done by varying the time delay between the AC sources and measuring the cross-correlation noise whose expression, in the limit of single photon excitation $eV_{ac} \ll hf$, is [9]:

$$S_{I_3 I_4} = -e^2 f \left(\frac{eV_{ac}}{2hf} \right)^2 |s_{13}^*s_{41}e^{-i\Delta\phi} + s_{23}^*s_{42}|^2 \quad (1)$$

Figure 1 : (a) electron-holes pairs emitted by the AC biased contact (1) and (2) are scattered into leads (3) and (4) by a tunable QPC which forms an electronic beam splitter. In the IQHE regime, the two scattering processes, where (b) an electron-hole pair is created in lead (1) and where (c) the electron-hole pair is created in lead (2), lead to an electron in (3) and a hole in (4). Indistinguishability leads to a probability for occurrence of process (b) and (c) whose variation with the relative time delay τ reveals two-particle interference. Similar interfering scattering processes (not shown) lead to a hole in (3) and an electron in (4). This generates the cross-correlated current noise $S_{I_3 I_4}$ which is measured in the set-up sketched in (f). In the FQHE regime, the scattered process involve e/m

fractionally charged anyons ($m=3$ or 5). Photo-created electron-hole pairs give rise to scattering of two indistinguishable particles where in process (d) ((e)) an electron (hole) is transmitted while a hole (electron) is backscattered as a charge $-e/m$ (e/m) and transmitted as charge $-(m-1)e/m$ ($(m-1)e/m$) respectively.

5 Expression (1) contains the square of the sum of two two-particle probability amplitudes corresponding to the two possible electron-hole paths shown in figure 1(b) and (c) whose indistinguishability is controlled by the time delay τ . The process where an electron arrives in lead (4) and a hole in lead (3), not shown, gives similar interference and these two processes lead to current fluctuations, hence the noise given by (1).

10 The time-delay between AC voltages provides the knob to modulate the interference between the two paths. This plays the role of the magnetic flux or the gate voltage control used to vary the interference in FP and MZ interferometers. The complete expression, based on photo-assisted shot noise calculation and including finite temperature and multi-photon absorption/emission of electrons and holes is:

$$15 \quad S_{I_3 I_4} = -2e^2 f D(1 - D) \sum_{l=-\infty}^{+\infty} l \left[J_l \left(\frac{eV_{ac}}{hf} 2 \sin \left(\frac{\Delta\Phi}{2} \right) \right) \right]^2 \left(\coth \left(\frac{hf}{2k_B T} \right) - 2k_B T / hf \right) \quad (2)$$

For small V_{ac} and zero temperature, this expression is equivalent to equation (1).

IQHE regime:

The measurements are performed on a two-dimensional electron gas made in high mobility GaAs/Ga(Al)As heterojunction with electron density $n_s = 1.11 \cdot 10^{15} \text{m}^{-2}$ and zero field mobility
 20 mobility $\mu = 300 \text{ Vm}^{-2}\text{s}^{-1}$. The filling factor $\nu=2$ occurs at field $B=2.3$ Tesla. Low frequency conductance measurements, done while varying the QPC gate voltage V_G , are first performed to measure the transmitted and reflected differential conductance by applying a small (few μV) amplitude 270Hz frequency AC voltage on contact (1). The conductance traces are shown in figure 2(a). The e^2/h conductance plateau for $V_G < -0.37$ volts signals the full reflection of the $\nu=2$ inner
 25 edge channel. We choose to only partition the inner edge channel while the outer edge channel is fully transmitted. Similar observations can be obtained when fully reflecting the inner edge and partitioning the outer edge. We therefore concentrate on two working points at $V_G = -0.2\text{V}$ and -0.27V respectively corresponding to partial transmissions $D=0.89$ and 0.84 of the inner edge channel.

Figure 2. (a) DC conductance at filling factor $\nu=2$ versus gate voltage used to measure the transmission and reflection of the inner edge channel while the outer edge channel is transmitted. The vertical dashed lines denote the working points used here. (b): DC Cross-correlated noise ($-S_{I_3 I_4}$) data (blue circles) and comparison with the equation (4) for transmission $D=0.89$ and $T_{el}=40mK$ (dashed red line). (c) and (d): (black circles) Shot noise versus time-delay measured for 14.15GHz microwave excitation and RF source powers 5 and 8 dB respectively and comparison (red dashed curves) with the heuristic model given by equation (3) including the noise offset S_M .

Figure 2(c) and (d) show two-particle interference noise measurements for a microwave frequency of 14.15 GHz at $V_G=-0.2V$ for two microwave excitations differing in power by 3dB power of the sources. For the chosen frequency and 25mK temperature, the photon energy is $hf \approx 26k_B T$ so that thermal effects are small. Clear two-particle interference is observed when varying the time delay. The visibility calculated by the ratio of the difference between the maximum and the minimum noise over the sum of the maximum and minimum, is found to be 43% and 44% for both microwave excitations. Measurements at smaller QPC transmission, $V_G=-0.27V$, for two different AC excitations also differing in power by 3dB give similar 38 and 40% visibility, see the supplementary material.

The above measurements demonstrate two-particle quantum interference in the IQHE regime. The electron-hole pair interference can be put in perspective with electronic Hong Ou Mandel experiments where, instead of electron-hole pairs, single electrons are periodically emitted by on-demand single electron sources. In Ref.[20], a driven quantum dot in the IQHE regime (also $\nu=2$) injecting single electrons in the outer edge of a QPC beam-splitter gave the first evidence of two-particle dynamical interference. Later, Hong Ou Mandel interference with 100% visibility was observed at zero magnetic field in Ref.[21] using a different on-demand single electron source generating single particle states called levitons. In Ref.[20] electrons were injected on the outer

edge only and the low visibility was attributed to the Coulomb interaction between inner and outer co-propagating edge channels giving spin-charge separation. In the present experiment, a 100% visibility may have been expected from equation (2). Indeed, as theoretically shown in [22-25], no loss of visibility is expected when including Coulomb interaction between co-propagating edge channels as the AC voltages generates coherent states which do not suffer from decoherence. To understand the finite but reduced 40% visibility observed here, we suggest that this may be due to the weak elastic mixing of co-propagating channels resulting from local impurities combined with spin-orbit coupling. Indeed, for different inner and outer edge channel velocity, the HBT phase for electrons injected in the inner edge and reaching the QPC in the outer edge differs from the HBT phase of electrons emitted in the outer edge channel and remaining in this channel. One can also say that the tunneling between the outer and inner edge input leads allows the inner edge channel to gain information on “which-path” the incoming electron-hole pairs are taking, thus breaking indistinguishability. The loss of coherence can be brought in correspondence with the one observed in “which-path” experiments done with standard MZ interferometer [29]. We leave this issue for further studies where a systematic study of visibility versus edge channel length should confirm this conjecture.

In order to perform a quantitative analysis, one can remark that equation (2) can be expressed as a sum of DC shot noise, i.e. shot noise without microwave excitation, where V_{DC} is replaced in the expression by $h\nu/e$ and weighted by the term $\left[J_l \left(\frac{eV_{ac}}{h\nu} 2 \sin \left(\frac{\Delta\Phi}{2} \right) \right) \right]^2$

$$S_{I_3 I_4} = S_M + \sum_{l=-\infty}^{+\infty} \left[J_l \left(\frac{eV_{ac}}{h\nu} 2 \sin \left(\frac{\Delta\Phi}{2} \right) \right) \right]^2 S_{I_3 I_4}^{DC} (V_{DC} = \frac{h\nu}{e}, T) \quad (3)$$

with:

$$S_{I_3 I_4}^{DC} (V_{DC}, T) = -2e^2 D(1-D) eV_{DC} \left(\coth \left(\frac{eV_{DC}}{2k_B T} \right) - 2k_B T / eV_{DC} \right) \quad (4)$$

In equation (3) we have added an extra noise term S_M which may account for a possible mixing of co-propagating edge channels, see below. This heuristic approach provides the best fit of data. As explained in the supplementary material, it is supported, by channel mixing hypothesis [24] which leads to a close expression, equation S6, where a mixing noise contribution is found not to depend on τ , like the heuristic term S_M in equation (3). Elastic tunneling between co-propagating edge channels is likely to occur. Indeed, typical scattering lengths ranging from few ten of μm to 100 μm has been reported at filling factor 2 [26-28].

To analyze the noise interference data, we use the DC Shot noise measurements versus V_{DC} applied on contact (1) for the gate voltage $V_G = -0.2V$ are shown in figure 2(b). The red dashed line compares the data to equation (4) using the known transmission. Knowing the DC shot noise parameters extracted from the dashed red curve fit of figure 2(b), microwave frequency and phase difference, we are left with only two unknown parameters, V_{ac} and S_M , to analyze and fit the two-particle noise interference using the heuristic model (3).

The red dashed curves in figures 2(c) and 2(d) are best fits using equation (3). One finds $V_{ac} = 31 \mu V$, $S_M = 2.1 \cdot 10^{-29}$, and $40 \mu V$, $S_M = 3.2 \cdot 10^{-29} A^2/Hz$, respectively for the two different excitations differing by a 3dB power increment. Similar fits for $V_G = -0.27V$ gives $V_{ac} = 33.5 \mu V$ and $41 \mu V$ respectively using the heuristic formula (3). Slightly higher amplitudes are found using the complete channel mixing model of ref.[24] (see Suppl. Mat.). For both gate voltages, the ratio of the microwave amplitudes for 3dB power increment is close to $\sqrt{2}$, albeit slightly lower, giving confidence in the

analysis. We now turn to the investigation of two-particle dynamical interference in the FQHE regime.

FQHE regime

We concentrate on the so-called weak backscattering regime $1 - D \ll 1$ for which the quasi-particle scattering is best understood. Consider, for simplicity, a single edge channel in the Laughlin state at $\nu=1/3$. Electrons in the $1/3$ edge channel form a correlated one-dimensional quantum liquid, densely occupying one state over three. To the weakest order in scattering, an electron can be either transmitted as a whole, charge e , with amplitude of probability $t \approx 1$, or be split as a backscattered charge $e/3$ and a transmitted charge $2e/3$ with amplitude of probability ir . The same can occur for a hole, with respective charges $-e$, $-e/3$ and $-2e/3$ and amplitude $(ir)^*$. Now consider an electron-hole pair created in input lead (1). Consider the event where the hole is backscattered. After scattering, we are left with a charge e transmitted to output lead (3) and a split hole transmitted as charge $-2e/3$ in lead (3) and reflected as hole of charge $-e/3$ in lead (4), see figure 1(d). This process leads to a total charge $e/3$ in lead (3) and $-e/3$ in lead (4). The same set of charge in the output contacts is also obtained for the process where an electron-hole pair is created in input lead (2) and the electron is backscattered. After scattering, the electron is split as a charge $e/3$ in lead (3) and transmitted as a charge $2e/3$ in lead (4) while the hole is transmitted as charge $-e$ in lead (4) as shown in figure 1(e). When only charge is considered, the two events of figure 1(d) and (e) are not distinguishable and interfere.

Another process, leading to charge $-e/3$ and $e/3$ in the output leads (3) and (4) respectively, gives similar interference. The anti-correlated fluctuations of $\pm e/3$ charges give rise to a noise whose expression is similar to equation (1). When written to first order in reflection probability $1-D$, it yields, disregarding propagation phase accumulated in the leads:

$$S_{I_3 I_4} = -4(e^*)^2 f(1-D) \left(\frac{e^* V_{ac}}{2hf} \right)^2 |1 - e^{-i\Delta\Phi}|^2 \quad (5)$$

This expression agrees with the low V_{ac} limit of a full multiphoton expression which has been theoretically obtained using perturbative approaches, including interaction [30-32]:

$$S_{I_3 I_4} = \sum_{l=-\infty}^{+\infty} \left[J_l \left(\frac{e^* V_{ac}}{hf} 2 \sin \left(\frac{\Delta\Phi}{2} \right) \right) \right]^2 S_{I_3 I_4}^{DC} (V_{DC} = \frac{hf}{e^*}, T) \quad (6)$$

where:

$$S_{I_3 I_4}^{DC} (V_{DC}, T) \approx -2(e^*)^2 (1-D) e^* V_{DC} \left(\coth \left(\frac{e^* V_{DC}}{2k_B T} \right) - 2k_B T / e^* V_{DC} \right) \quad (7)$$

The expressions are similar to those of the integer regime Eq.(4), except for the quasi-particle charge e^* and the limit $1-D \ll 1$.

Figure 3. QPC conductance versus gate voltage V_G at $B=11.3$ Tesla ($\nu=2/5$). (b): DC Cross-correlated noise ($-S_{I_3 I_4}$) data (blue circles) and comparison with equation (7) for constant transmission $D=0.984$ and $T_{el}=15$ mK and $e^*=e/3$ (red dashed curve). (c) Shot noise versus time-delay measured for 14.15 GHz microwave excitation and two RF source powers differing by 3 dB and comparison with equation (6) including a noise offset.

Figure 3(a) shows the conductance of the QPC for filling factor $\nu=2/5$ in the bulk ($B=11.3$ Tesla). Starting at $\frac{2}{5}e^2/h$ for $V_G=0.2$ V, the conductance decreases to reach a plateau at $\frac{1}{3}e^2/h$ for $V_G < -0.1$ V signaling the reflection of the $2/5$ inner edge channel and the formation of a region of filling factor $\nu_G=1/3$ inside the QPC. For $V_G < -0.38$ V, the last edge channel starts to be reflected. We choose two working points A and B at $V_G=-0.42$ V and -0.0 Volts corresponding to the weak backscattering of anyons with charge $e^*=e/3$ and $e^*=e/5$ respectively. These fractional charges have been previously confirmed through the measurements of their Josephson relation in a previous work in a similar regime, see [33]. For the weak backscattering regime of the $\nu_G=1/3$ state, at working point A, figure 3 (c) shows the shot noise data versus time delay for microwave powers differing by 3 dB measurements and microwave frequency $f=14.15$ GHz. Clear oscillations with 55% and 60% visibility are observed.

To analyze the data, we introduce a constant noise offset S_M to take into account a possible mixing noise, as done for the IQHE study. The fits calculated from equation (6), to which a noise offset S_M has been added, with $e^*=e/3$ and using the measured DC shot noise data taken in the same conditions are shown as red dashed curves. They provide an excellent agreement with each experimental trace with $V_{ac}=650 \pm 20$ μ V and $V_{ac}=870 \pm 10$ μ V and $S_M=0.11 \cdot 10^{-28}$ A^2/Hz . For a 3 dB microwave power difference, the ratio of the V_{ac} values is 1.34 ± 0.05 , close to $\sqrt{2}$.

Figure 4: (a) DC Cross-correlated noise ($(-S_{I_3 I_4})$ data (blue circles) and comparison with equation (7) for transmission $D=0.94$ and $T_{el}=20\text{mK}$ (green solid curve) and $e^*=e/5$. (c) Shot noise versus time-delay measured for 14.15GHz microwave excitation and two RF source powers differing by 3dB and comparison with equation (6) including a noise offset.

Similar measurements performed for $\nu_G=2/5$, at working point B, are displayed in figure 4(b) for the same 14.15GHz frequency and two microwave powers differing by 3dB. Visibilities of 53% and 51% are observed. The fits done using $e^*=e/5$ and experimental DC shot noise traces give $V_{ac}=740\pm 50 \mu\text{V}$ and $V_{ac}=940\pm 40 \mu\text{V}$, with a V_{ac} ratio 1.27 ± 0.15 weaker but still close to $\sqrt{2}$ for 3dB power difference. Here the weaker noise due to the one fifth charge leads to larger uncertainty due to lower signal to noise ratio.

To conclude, the present demonstration of two-particle dynamical interference in the FQHE regime shows that the propagating edge channels do keep significant quantum coherence over several tens of microns (our sample dimension), contrasting with the experiments performed using MZIs. The work also provides the first example of a new kind of interferometry based on the HBT phase. This work helps resolve the issue of diverging results previously reported on quantum coherence in the FQHE regime, at the same time highlighting the work needed on MZI to understand the prior results better. The current demonstration also highlights the possibility of performing anyon braiding in FQHE systems, which is a crucial step towards the realization of topologically protected qubits for quantum computing.

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5 **Author contributions:**

D.C.G. designed and supervised the project.

I.T. & performed the experiment with help from D.C.G. and J.N.;

M.K. fabricated the sample on heterojunctions grown by I.F. and D.R.

I.T., D.C.G., J.S., M.A. and P.R. analyzed and discussed the data

10 I.T. & D.C.G. wrote the manuscript with inputs from all coauthors;

* main corresponding author

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Supplementary Information:

A. Experimental Methods

1. Sample characteristics and fabrication

20

2. Measurement set-up

3. Visibility optimization

4. IQHE measurements at $V_G = -0.27V$

B. Electron-hole pair Interferometry

1. The Hanbury Brown Twiss phase

25

2. Channel mixing modeling

30 **A1. Sample characteristics and fabrication:** samples are 2DEGs with electrons confined at the interface of high mobility epitaxially grown GaAs/GaAlAs heterojunctions at 90 nm below the surface. The low temperature zero field mobility is $2 \cdot 10^6 \text{cm}^2 \text{s}^{-1} \text{V}^{-1}$ and the electron density is $n_s = 1.1 \cdot 10^{15} \text{m}^{-2}$. For this density, the bulk filling factor $\nu_B = 2/5$ corresponds to a magnetic field of ≈ 11.2 Tesla. Ohmic contacts are realized by evaporating 125 nm Au, 60 nm Ge, 4 nm Ni followed by annealing at 470°C. A shallow mesa etching (H3PO4 phosphoric acid, time 4 minutes) defines the sample. The QPC gates are realized by e-beam lithography, see Fig.S1 for a SEM image of the

sample used. The edge channel length between each contacts and the center of the QPC is about $18\mu\text{m}$.

Figure S1: SEM view of the sample used. Yellow areas are ohmic contacts, blue areas denotes the unetched part of 2DEG mesa. A 10um black bar indicates the scale.

A2. Measurement set-up: an ultra-low temperature cryo-free dilution refrigerator with a 22 mK base temperature from CryoConcept is used as in [33,21]. It is equipped with a dry superconducting coil able to reach 14.5 Tesla. Ultra-low-loss dc-40GHz microwave cables, same as in ref. [21,33], bring the room temperature microwave excitation from an Agilent N5183A RF source to a PCB. The RF power of the microwave source, given in the main text is attenuated by fixed 63dB cold attenuators and extra losses in the cryogenic coaxial cables. Coplanar waveguides designed by CST microwave Studio^R etched on the Printed Circuit Board (PCB) bring the two radiofrequency excitations to ohmic contact (1) and (2) of the sample, see Fig.1(f) and Fig.S1. Noise measurements are obtained by separately converting the transmitted and reflected current fluctuations into voltage fluctuations at contact (3) and (4) respectively in parallel to a R-L-C resonant circuit tuned to 2.2 MHz frequency and bandwidth ≈ 150 kHz, with $R=20\text{k}\Omega$. Note that an effective resonant circuit resistance $R_{\text{eff}} = RR_L/(R + R_L) \approx 6.5\text{k}\Omega$ is found instead of $20\text{k}\Omega$ due to inductance loss, giving a shunt resistance $R_L = (L2\pi f_0)^2/r$ in parallel to R , where $r=15$ Ω is the series resistance of the inductance. Finally, the Q factor of the RLC resonant circuit is given by the ratio of the parallel resistance $R_{\text{eff}}/R_{\text{Hall}}$ to the characteristic impedance $\sqrt{\frac{L}{C}}$, where R_{Hall} is the Hall resistance of the sample. The voltage fluctuations are amplified by two home-made cryogenic amplifiers with $0.22 \text{ nV/Hz}^{1/2}$ input noise at low temperature, followed by low noise room temperature amplifiers. The amplified fluctuations are passed through Chebyshev filters and then sent to a fast 20Ms/s digital acquisition card (ADLink 9826) while a PC provides real-time computation of the cross-correlation spectrum. Absolute

Noise calibration is done by recording the equilibrium Johnson Nyquist noise when varying the temperature from 20mK to 200mK. Differential Conductance measurements giving the transmission and reflection are made by applying an low frequency AC voltage, frequency 270Hz, and μV amplitude voltage to contact (1) and sending the amplified AC voltage from contacts (3) and (4) to two Lock-in amplifiers. The low frequency measurement accuracy is mostly limited by the large $1/f$ noise of the cryogenic HEMT (white noise cross-over at $\approx 1\text{MHz}$). The shot noise accuracy is limited by the input white noise of the amplifier and time averaging. For $v_B=2/5$, the 20kOhm resistor and the $\approx 5\text{kOhm}$ inductance the effective RLC parallel resistance $R_{\text{eff}}=6.5\text{kOhms}$ in parallel with the bulk Hall resistance converts the input noise of $220\text{pV/Hz}^{1/2}$ into $1.4 \cdot 10^{-27} \text{A}^2/\text{Hz}$ equivalent current noise power. Using cross-correlation and noise averaging during the measurement time $\tau_m=3\text{s}$ with $\approx 150\text{kHz}$ effective detection bandwidth, the accuracy of a raw noise data point is $\sim 2 \cdot 10^{-30} \text{A}^2/\text{Hz}$.

A3. Visibility optimization:

Figure S2: Visibility optimization. The left graph shows noise measurements versus time-delay for various RF source powers P_2 sent to contact (2) while the power sent to contact (1) is $P_1=12\text{dBm}$. The equality of the actual V_{ac} amplitudes transmitted on contacts (1) and (2) is obtained for the maximum of the visibility. Right graph: visibility versus power P_2 in dBm.

In the main text, all noise interference formulas are given for equal RF amplitudes applied on the injecting contact. As the microwave transmission of the RF-lines is not accurately known at low temperature and may suffer from unwanted microwave reflection in connectors linking different temperature stages or suffer from uncontrolled dissipation, it is best to find a way to determine in situ the equality of the RF amplitudes. This is done by fixing the microwave amplitude on contact (1) and varying the amplitude on contact (2) while measuring the noise versus time-delay. The maximum of visibility signals equal RF amplitudes and allows to fix P_2 , here about -0.5dB lower than P_1 to ensure perfect equality of the amplitudes on the sample.

A4. IQHE measurements at $V_G = -0.27V$

Figure S3: right: transmission and reflection probability for the partial transmission of the inner edge channel versus bias voltage at $V_G = -0.27V$ and filling factor 2. Left: DC shot noise measured in the same conditions. The red dashed curve is calculated using the DC shot noise theoretical expression (4) in which a weak energy dependent transmission deduced from the right graph is included.

Here we present measurements which are complementary to the ones presented in the main text. The mean inner edge channel reflection is $R=0.3$ for $V_G = -0.27V$. Figure S3 shows a slight non-linearity of the transmission versus DC voltage bias. The DC shot noise trace (blue filled circles) is well described by the standard DC shot noise formula, equation (4) using the measured transmission.

Figure S4 shows the two-particle noise interference shot noise for 5dBm and 8dBm RF source power at frequency 14.15GHz (blue filled circles). The red dashed line is a fit using the heuristic equation (3) for a constant transmission $D=0.7$ and AC voltage amplitude $V_{ac}=33.5$ and $41 \mu V$ for respectively 5 and 8 dBm. The extracted values are close to the ones deduced with similar RF power at the other gate voltage $-0.20V$. The black dashed line is a fit using a model of channel mixing, see equation (S6) below.

Figure S4: Shot noise versus time-delay measured for 14.15GHz microwave excitation and RF source powers 5dBm (a) and 8 dBm (b) respectively at $V_G=-0.27V$ (blue filled circles). The comparison with the heuristic equation (3) including a noise offset $S_M=0.63$ and $0.86 \cdot 10^{-28} A^2/Hz$ is shown as a red dashed curve. Comparison with equation (S6) for a model of two symmetric mixing points (strength $R_A=R_B=0.10$, $\Delta\tau=\tau_i-\tau_o=44ps$) placed on both input channels is shown as a black dashed curve. A constant QPC transmission 0.7 and a 25mK temperature are used to fit the data.

B1. The Hanbury Brown Twiss phase:

We consider zero temperature for simplicity and no channel mixing such that the scattering of a single channel by the QPC only occurs. Electrons emitted by the reservoir at energy ε and experiencing the AC voltage in contacts (1) and (2) are put in a quantum superposition of states with energies $\varepsilon_{+/-} = \varepsilon \pm hf$. For low AC amplitude, the amplitude of probability to absorb/emit a single photon is $p_{\pm 1} = \pm \left(\frac{eV_{ac}}{2hf}\right)^2$ for contact (1) and $p_{\pm 1}e^{i\Delta\phi} = \pm \left(\frac{eV_{ac}}{2hf}\right)^2 e^{i\Delta\phi}$ for contact (2) where $\Delta\phi=2\pi f\tau$ is the voltage phase shift. Higher photon number processes are discarded for $\left(\frac{eV_{ac}}{2hf}\right)^2 \ll 1$. The many-particle state incident on the scattering region is then [9]:

$$|in\rangle = |F\rangle + \int_0^{hf} d\varepsilon p_1 \left(\hat{a}_1^\dagger(\varepsilon)\hat{a}_1(\varepsilon_-) + e^{i\Delta\phi}\hat{a}_2^\dagger(\varepsilon)\hat{a}_2(\varepsilon_-) \right) |F\rangle \quad (S1)$$

where $|F\rangle = \prod_{\varepsilon < E_F, \alpha=1-4} \hat{a}_\alpha^\dagger(\varepsilon)|0\rangle_\alpha$ is the ground state formed by the filled Fermi sea of all leads and $\hat{a}_\alpha^\dagger(\varepsilon)$ the fermionic creation operator acting on the occupation states of contacts $\alpha=1,2$.

Denoting $\widetilde{\hat{a}}_\alpha(\varepsilon) = \hat{a}_\alpha(\varepsilon) + p_1\hat{a}_\alpha(\varepsilon - hf) + p_{-1}\hat{a}_\alpha(\varepsilon + hf)$ the annihilation operator describing, to lowest order in single photon absorption/emission probability, the electrons emitted by lead (α) and scattered in energy by the AC potential, the operators describing the states of electrons entering in contacts (3) and (4) are:

$$\hat{b}_3(\varepsilon) = s_{31}\widetilde{\hat{a}}_1(\varepsilon) + s_{32}\widetilde{\hat{a}}_2(\varepsilon) \quad (S2a)$$

$$\hat{b}_4(\varepsilon) = s_{41}\widetilde{\hat{a}}_1(\varepsilon) + s_{42}\widetilde{\hat{a}}_2(\varepsilon) \quad (S2b)$$

The many-particle outgoing state is then:

$$|out\rangle = |0\rangle + \int_0^{hf} d\varepsilon p_1 \left[s_{31}s_{31}^*\hat{b}_3^\dagger(\varepsilon)\hat{b}_3(\varepsilon_-) + s_{41}s_{41}^*\hat{b}_4^\dagger(\varepsilon)\hat{b}_4(\varepsilon_-) + s_{31}s_{41}^*\hat{b}_3^\dagger(\varepsilon)\hat{b}_4(\varepsilon_-) + s_{41}s_{31}^*\hat{b}_4^\dagger(\varepsilon)\hat{b}_3(\varepsilon_-) + e^{i\Delta\phi} \left(s_{32}s_{32}^*\hat{b}_3^\dagger(\varepsilon)\hat{b}_3(\varepsilon_-) + s_{42}s_{42}^*\hat{b}_4^\dagger(\varepsilon)\hat{b}_4(\varepsilon_-) + s_{32}s_{42}^*\hat{b}_3^\dagger(\varepsilon)\hat{b}_4(\varepsilon_-) + s_{42}s_{32}^*\hat{b}_4^\dagger(\varepsilon)\hat{b}_3(\varepsilon_-) \right) \right] |0\rangle \quad (S3)$$

The terms of the form $\hat{b}_\alpha^\dagger(\varepsilon)\hat{b}_\alpha(\varepsilon_-)$ describe neutral excitations in the output leads and do not contribute to current noise at zero frequency. The only terms contributing to the zero frequency cross-correlated fluctuations of leads (3) and (4) are of the form $\hat{b}_\alpha^\dagger(\varepsilon)\hat{b}_{\beta \neq \alpha}(\varepsilon_-)$. Namely:

$$p_1[s_{31}s_{41}^* + e^{i\Delta\phi}s_{32}s_{42}^*] \hat{b}_3^\dagger(\varepsilon)\hat{b}_4(\varepsilon_-) + p_1[s_{41}s_{31}^* + e^{i\Delta\phi}s_{42}s_{32}^*] \hat{b}_4^\dagger(\varepsilon)\hat{b}_3(\varepsilon_-) \quad (S4)$$

The first term corresponds to the interference of electron-hole pairs separately created in lead (1) and (2) and scattered as an electron in lead (3) and a hole in lead (4), as shown in figure 1(b) and (c) of the main text. The second term describes the interference leading to an electron created in lead (4) and a hole in lead (3) or vice versa. These terms leads to equation (1) of the main text.

Defining $s_{31} = te^{i\varphi_{31}}$, $s_{42} = te^{i\varphi_{42}}$, $s_{41} = (ir)e^{i\varphi_{41}}$, $s_{32} = (ir)e^{i\varphi_{32}}$, with $\varphi_{\beta\alpha}$ denoting the electronic phase accumulated while propagating from contact (α) to contact (β) and using the local transmission and reflection amplitudes t and (ir) for the QPC, we see that the interference allows us to probe the so-called HBT phase [9] $\chi = \arg(S_{13}^* S_{32} S_{24}^* S_{41}) = \pi + (\varphi_{32} + \varphi_{41}) - (\varphi_{31} + \varphi_{42})$ using the controlled time-delay of the sinewave sources. Expression (S4) vanishes for $\Delta\Phi = \chi - \pi$. The phase χ , not accessible to DC transport and DC noise measurement, is the relevant phase of the two-particle dynamical interferometer and plays a role similar to the phase of single particle interferometers.

Let us discuss in more details the interference process. One can interpret the first term in bracket in equation (S4) in the following way: when an electron-hole pair is created in lead (1) the 2-particle amplitude of probability to have an electron in lead (3) and hole in lead (4) is $p_1 s_{31} s_{41}^*$. Similarly, when an electron-hole pair is created in lead (2) the 2-particle amplitude of probability to have an electron transmitted in lead (3) and hole backscattered in lead (4) due to a is $p_1 e^{i\Delta\Phi} s_{32} s_{42}^*$. As these two processes are not distinguishable, one has to add the amplitude of probabilities of each process, hence the term in brackets. The second term in brackets is (S4) and represents a similar two-particle interference but with a hole in lead (3) and an electron in lead (4). The $\pm e$ charge fluctuations generated in output leads by these two processes have equal probability. This leads to the noise power density given by equation (1).

One can extend the two-particle interference processes to the FQHE regime. When an electron-hole pair is created, the transmitted electron (hole) is transmitted as a whole, charge e ($-e$) while, in contrast to the IQHE regime, the standard backscattering is replaced by a partial backscattering of the incoming charge. One finds a split hole (electron) transmitted as a charge $(m-1)/me$ ($-(m-1)/me$) and backscattered as a charge e/m ($-e/m$). This lead to equation (7) using the weak backscattering of the scattering amplitudes. Equation (7) quantitatively agrees, in this limit, with a more involved interacting electron theory.

B2. Channel mixing modeling:

Figure S5: elastic channel mixing. The QPC beam splitter is aimed at partitioning the outer edge channel only, transmission D . However, a localized scatterer situated at distance L from the injecting contact (1) allows tunneling between the outer and inner edges. The probability of inter-edge tunneling is R_A . $T_A=1-R_A$ is the probability of no mixing. For different outer and inner edge channel propagation velocities V_o and V_i , electrons on the outer and inner edge have different dynamical phase $\phi_o=2\pi f\tau_o$ and $\phi_i=2\pi f\tau_i$. This generates photo-assisted shot noise making electrons arriving at the upper left of the QPC beam splitter noisy, reducing the visibility of the two-particle interference. In other words, the mixing point allows the inner edge channel to know “which path” the interfering electron-hole pairs are coming from, spoiling quantum coherence. Similar physics holds when the QPC partitions the inner edge while transmitting the outer edge.

Figure S5 schematically shows how one can model the effect of channel mixing. We consider only a single mixing point along one input edge channel (the left input). Generalization to more mixing points both on the left and right side of the central QPC beam-splitter is straightforward and gives similar qualitative effects, see Ref.[25]. Being interested in bulk filling factors $\nu=2$ and $2/5$, we consider only co-propagating edge channels.

In the absence of mixing, the inner edge channel is spectator and the noise of lead (3) or (4) measures the two-particle interference of indistinguishable electron-hole pairs photo-created in the outer at input leads (1) and (2). The visibility is expected to be 100%. However a finite mixing allows the inner edge to acquire information on which path an electron-hole pair comes from and the visibility is reduced. Note this requires that the wavefunction of particles propagating on channel (o) and (i) can be distinguished. This is indeed so if the propagation time $\tau_{i,o}$ in the inner and outer edge are different such that the dynamical phases $\phi_{i/o}$ are different. A full calculation using standard Floquet scattering theory can be found in [25]. For a single scattering point, as considered in figure S5, one finds the shot noise S_I :

$$-S_{I_3 I_4}(\tau) = 2 \frac{e^2}{h} h f D^2 (T_A R_A) \left(\frac{e V_{ac} 2 \sin(2\pi f(\Delta\tau))}{h f} \right)^2 + T_A 2 (e^*)^2 f D (1 - D) \left(\frac{e^* V_{ac}}{2 h f} \right)^2 (1 - \cos(2\pi f(\tau - \tau_i))) + R_A 2 (e^*)^2 f D (1 - D) \left(\frac{e^* V_{ac}}{2 h f} \right)^2 (1 - \cos(2\pi f(\tau - \tau_o))) \quad (S5)$$

Where $\Delta\tau=\tau_o - \tau_i$ and we have assumed for simplicity that the propagation time from the scatter to the QPC is negligible. Including finite propagation time towards the QPC can be taken into account by a proper redefinition of the time delay τ .

The effect of mixing is twofold: -1) the generation of an extra noise given by the first term of equation (S5) ; -2) the smearing of the interference as τ cannot make the last two terms simultaneously vanish unless $\tau_o=\tau_i=\tau$.

Figure S6: multiple inter edge channel tunneling points. $\tau_{0,k}$ and $\tau_{i,k}$ denote the propagation time between point (k) and (k-1). For weak inter-tunneling, $R_{k=1,N} \ll 1$, and, now, the inner channel partitioned by the QPC, one can add in the HBT interference noise the independent contribution of each tunneling point (k) weighted by the probability R_k and using the time delay $\tau_k = \sum_{q \leq k} \tau_{o,q} + \sum_{q > k} \tau_{i,q}$ corresponding to the propagation along the dashed green path describing the tunneling from the outer edge to the inner edge at point (k). These contributions lead to the smearing of the HBT interference and loss of visibility.

The model can be extended to two mixing points of strength R_A and R_B placed on both input channels at a distance L from the injecting contacts, see [25]. Here we give the expression for symmetrically placed mixing points of equal strength. This expression is used to fit the data of figure S4 (black dashed curves).

$$-S_{I_3 I_4} = 2 \frac{e^2}{h} hf \left[D(1-D) \left((T_A^2 + R_A^2) S(\tau) + T_A R_A (S(\tau + \Delta\tau) + S(\tau - \Delta\tau)) \right) + 2D^2 T_A R_A S(\Delta\tau) \right] \quad (S6)$$

Here, τ is the controlled time delay between the AC sources, $\Delta\tau = |\tau_i - \tau_o| = \left| \frac{L}{V_i} - \frac{L}{V_o} \right|$ is the propagation time difference for particles travelling from the contact to the mixing point with velocity V_i and V_o for respectively the inner and outer edge, $T_A = 1 - R_A$ and $S(\tau) = \sum_l l J_l^2 \left(\frac{e^* V_{ac}}{hf} 2 \sin \left(\frac{\Delta\Phi}{2} \right) \left(\coth \left(\frac{hf}{2k_B T} \right) - \frac{2k_B T}{hf} \right) \right)$. The last term in (S6), independent of τ , originates from the noise generated at each mixing point and plays the role of S_M in the heuristic formula, the first three terms are interference terms. The shift by $\pm \Delta\tau$ with respect to τ in the argument of $S(\tau)$ contributes to the smearing of the HBT interference. Figure S4 uses equation (S6) to fit the experimental data. A moderate 10% mixing strength ($R_A = 0.1$) is found. This is consistent with a channel mixing length observed in the literature [26-28]. For L necessarily smaller than the $18 \mu\text{m}$ input channel length, a propagation time difference of 44ps suggests an outer edge channel velocity $> 2.4 \cdot 10^5 \text{ m/s}$ dominating the inner edge velocity. This is consistent with the outer and inner edge channel velocities reported in [34] for filling factor 2. A fit the data of similar quality is obtained using two different mixing parameters $T_A = 0.92$ and $T_B = 0.86$ while keeping same V_{ac} and $\Delta\tau$ values.

The smearing of the interference pattern is probably the most serious loss of visibility if multiple tunneling points occur. For example, let us consider multiple mixing points in one arm, say the left, as suggested in Fig S6, where we choose to partition the inner edge. To first order of inter-edge tunneling probabilities $\{R_p\}$, we are left with a sum of terms corresponding to tunneling paths (k) where an electron emitted from (o) has been transferred to the input edge (i) at the k^{th} tunneling point corresponding to the propagation time $\tau_k = \sum_{q \leq k} \tau_{o,q} + \sum_{q > k} \tau_{i,q}$ and

contributing by $R_k 2(e^*)^2 f D (1 - D) \left(\frac{e^* V_{ac}}{2\hbar f} \right)^2 (1 - \cos(2\pi f(\tau - \tau_k)))$ to the two-particle noise.

For stronger mixing $R_{k=1,N}$, second order inter-tunneling probabilities (like the case where an electron emitted in lead (i) visit once lead (o) and returns back to lead (i) to contribute to the interference) add more paths with different propagation times. This further smears the original interference pattern. In a more realistic description one has to consider multiple mixing points in both left and right input leads. This contributes to more loss of visibility [25].

5