Anyonic and Fermionic Statistics in a Mesoscopic Collider

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Abstract

The concept of anyon [1,2], non-fermionic non-bosonic particles, has raised a lot of interest after the discovery of the fractional quantum Hall effect (FQHE): for some value of the filling factor, and due to the strong coulomb interactions, electrons condense into a strongly correlated quantum phase in which the elementary excitations of the system are described by quasi-particles with fractional charge, and fractional exchange statistics.

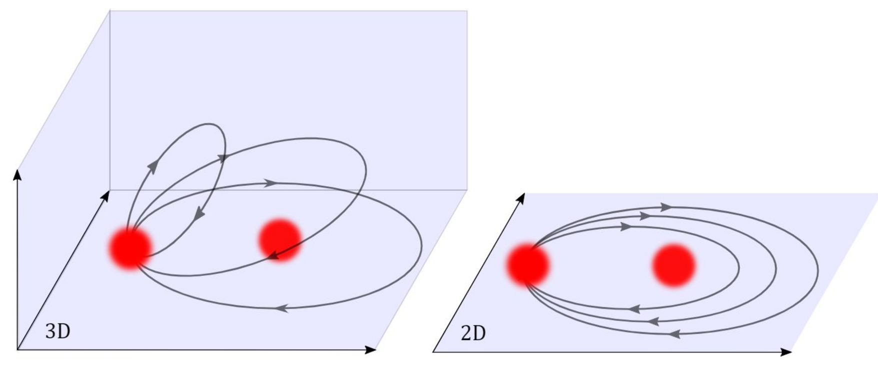
This work introduces the mesoscopic collider geometry [3,4,5] in both integer and fractional Quantum Hall regimes. By measuring the cross-correlations of current fluctuations resulting from the collisions between two dilute currents of fractional particles, we are able to extract the statistical exchange phase $\pi/3$ of anyons in the Laughlin state $\nu = 1/3$, providing strong evidence of the "anyonic" nature of the charge carriers in FQH systems.

Quantum statistics

What happen to the many body wave function when two particles are exchanged/braided ?

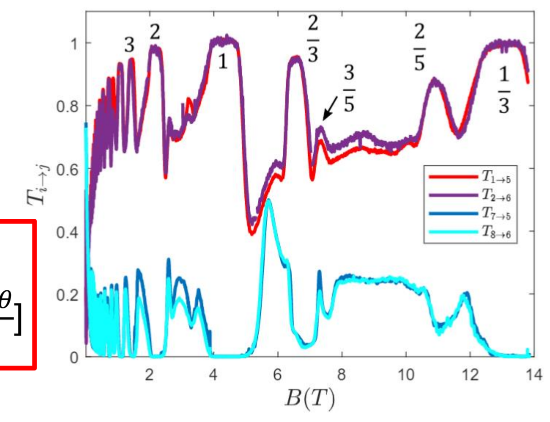
$$P_{ij}\Psi(r_1,\dots,r_i,\dots,r_j,\dots,r_N) = e^{i\varphi}\,\Psi(r_1,\dots,r_i,\dots,r_j,\dots,r_N)$$

- Abelian particles: an exchange phase φ is accumulated
- 3D case = braiding is trivial : $\varphi = 0$ (Bosons) $\varphi = \pi$ (Fermions)
- 2D case = braiding non trivial : φ takes any values (Anyons)



Shot noise in FQHE systems

- AlGaAs/GaAs two dimensional electron gas under strong perpendicular magnetic field => Quantum Hall effects
- Shot noise: low freq. current noise arising from tunneling at a quantum point contact (QPC): **charge q measurement**



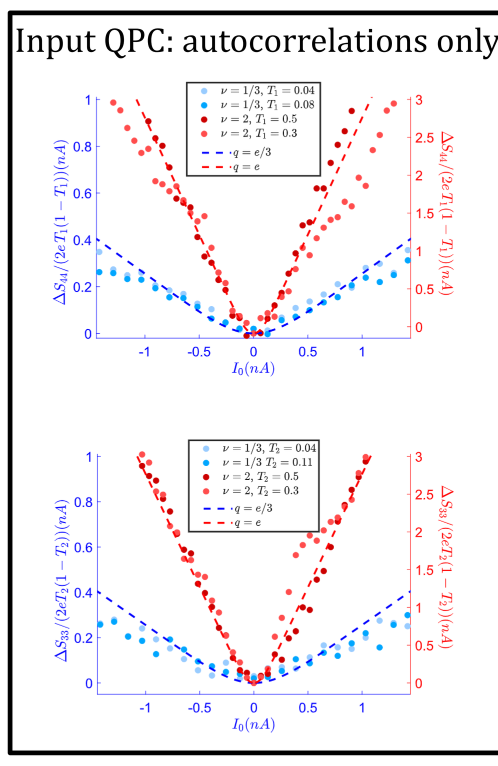
$$S_{ij} = \int d\tau < \delta I_i(\tau)\delta I_j(0) >$$
$$= \pm 2qT(1-T)G_0V[coth\left(\frac{qV}{2k_B\theta}\right) - \frac{2k_B\theta}{qV}]$$

- Current conservation for cQPC, and excess noises relations:

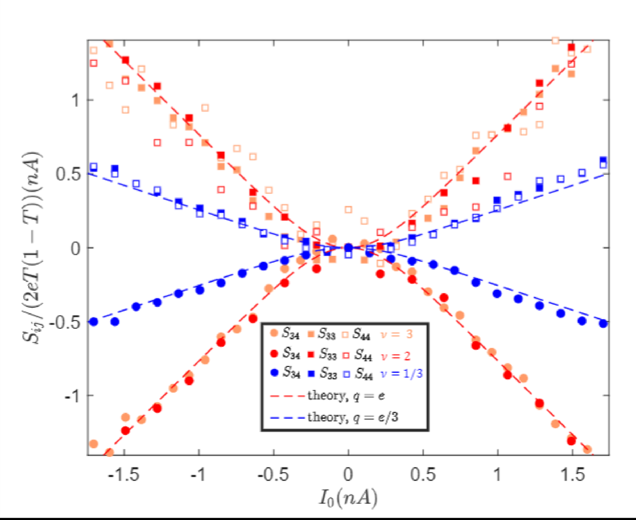
$$I_1 + I_2 = I_3 + I_4 \quad \Rightarrow \quad \delta S_{33} + \delta S_{44} + 2\delta S_{34} = \delta S_{11} + \delta S_{22} = 0$$
$$\Rightarrow \quad \delta S_{33} = \delta S_{44} = -\delta S_{34}$$

- Single QPC charge characterization for $\nu = 2\,;3\,;\frac{1}{3}$

Input QPC: autocorrelations only

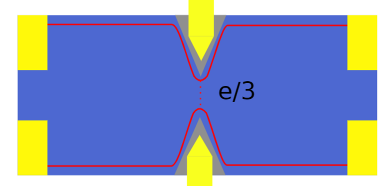


cQPC: auto and cross-correlations



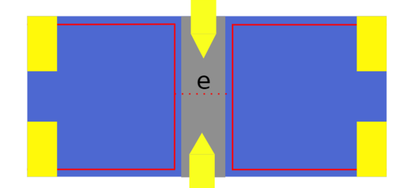
- The two regimes of particles tunneling in FQHE:

Weak backscattering $T \ll 1$



Anyons through correlated bulk

Strong backscattering $1 - T \ll 1$

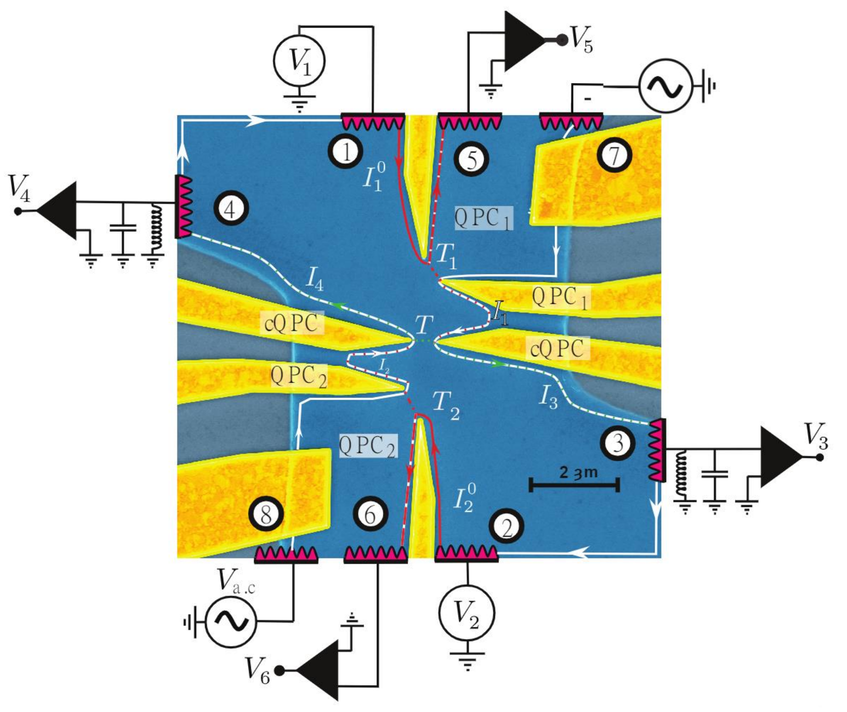


Electron through insulating bulk

The collider experiment

The collider geometry has three QPC

- QPC1/2 are random particles emitters
- Emitted particles collide at CQPC
- Cross-correlations at CQPC output probe the result of collisions



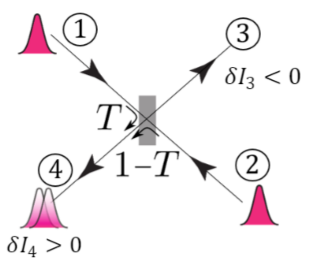
Collider = HOM [6,7,8] experiment with random sources

- Definition of the generalized Fano factor [3]

$$S_{34} = P \times 2qT(1-T)I_+$$

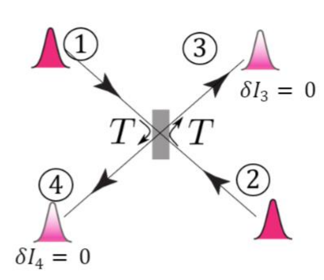
With $I_+ = I_1 + I_2$ and $I_- = I_1 - I_2$

Bunching



$S_{I_3I_4} < 0$

Pauli exclusion



$S_{I_3I_4} = 0$

- Expectations for P:

IQHE: Electrons=exclusion $P = 0$
FQHE (WBS): Anyons=bunching $P < 0$
FQHE (SBS): Electrons=exclusion $P = 0$

Electrons at $\nu = 2$ and 3

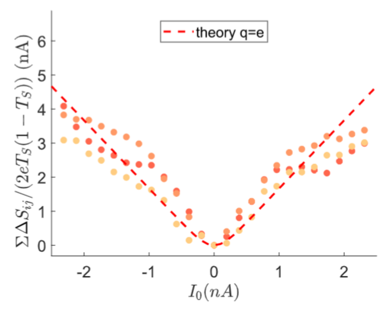
Collisions for integer states $\nu = 3$ and $\nu = 2 \Rightarrow$ electrons

- Balanced collider: both input emit the same average current

$$I_1 = I_2 \text{ and } I_- = 0$$

➡ Noise conservation allows to characterize the "colliding charge" q

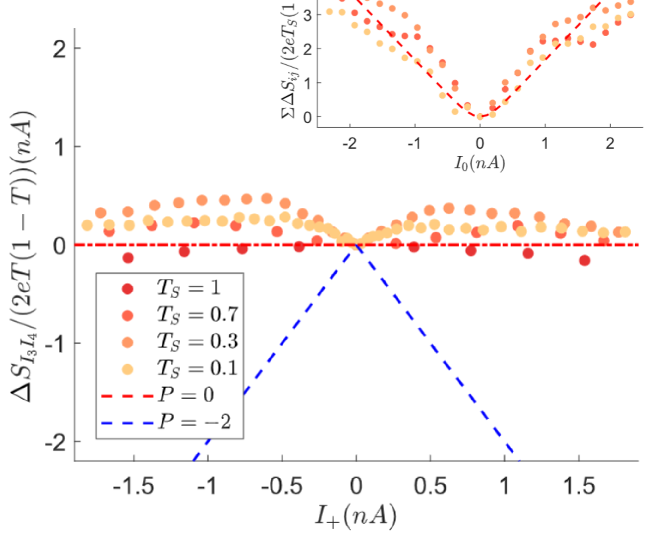
$$\Rightarrow \quad \delta S_{33} + \delta S_{44} + 2\delta S_{34} \simeq 2 \times \delta S_0 \propto 4qT_S(1-T_S)I_0$$



- Result of the collision for $\nu = 2$, with $T = 0{,}4$ and different T_S

➡ Slightly positive cross-correlations, with slope giving $P \simeq 0$

IQHE electrons = Fermions

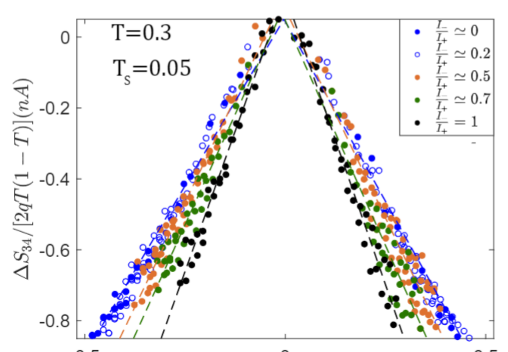


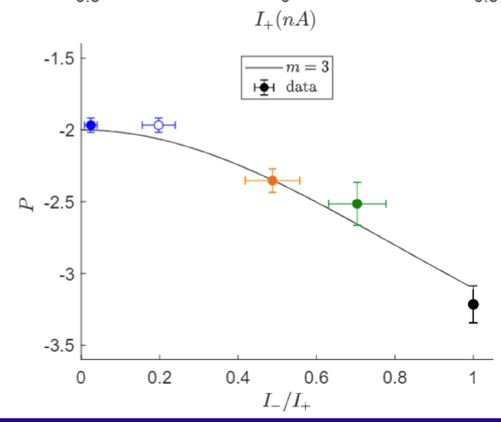
Unbalanced collider

Unbalanced collisions for $\nu = 1/3$ in weak back-scattering regime WBS

➡ $V_1 \neq V_2 \Rightarrow I_1 \neq I_2$ and $I_- \neq 0$ (Same input QPC transmissions)

➡ Measure the evolution of $P(\frac{I_+}{I_-})$ and compare to the Luttinger model from [3] for anyon with phase $\varphi = \pi/m$





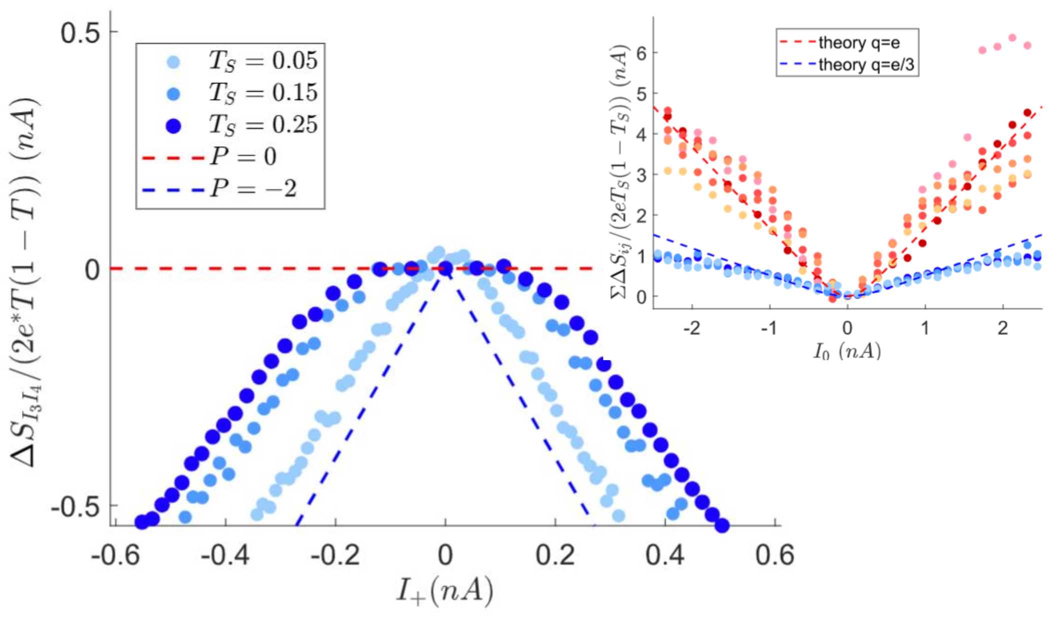
Excellent agreement with $\varphi = \pi/3$!

Anyons and electrons at $\nu = \frac{1}{3}$

Balanced collisions for the Laughlin fractional state $\nu = 1/3$ in WBS $\Rightarrow$ Anyons

- Results for $T = 0{,}2$ and different T_S in diluted regime

➡ Strong negative cross-correlations, with slope giving $P = -2$



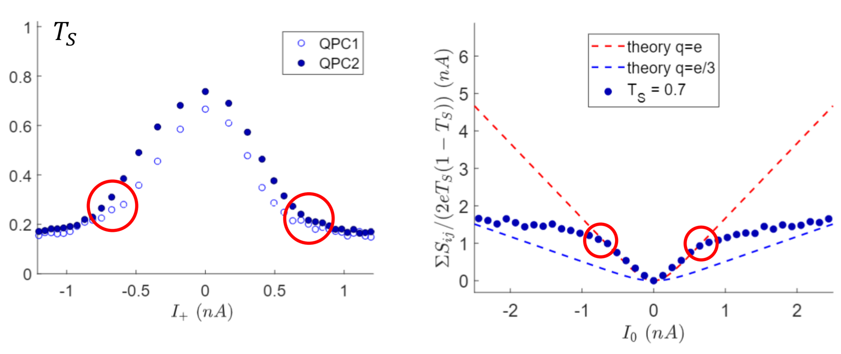
Anyons with exchange phase $\varphi = \pi/3$

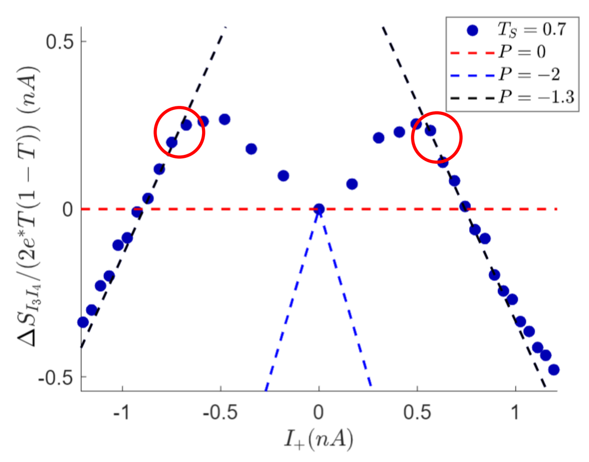
Case of the balanced collisions $\nu = 1/3$ in SBS $\Rightarrow$ Electrons

- Results for $T =$ and $T_S = 0{,}7$

➡ Non linear transmission with input current: switching from SBS to WBS

➡ Switching from electrons ($P = 0$) to anyons ($P = -1{,}3$) !





References

[1] J. Leinaas and J. Myrheim, Nuovo Cimento Soc. Ital. Fis.B (1977)
[2] F. Wilczek, Phys. Rev. Lett. (1982)
[3] B. Rosenow, I. P. Levkivskyi, and B. I. Halperin, Phys. Rev. Lett. (2016)
[4] H. Bartolomei, M. Kumar, R. Bisognin, A. Marguerite, J.-M. Berroir, E. Bocquillon,B. Plaçais, A. Cavanna, Q. Dong, U. Gennser, Y. Jin, and G. Fève , Science(2020)
[5] H Bartolomei, M Kumar, M Ruelle, G Fève, F. Wilczek: 50 Years of Theoretical Physics (2022)
[6] C. K. Hong, Z. Y. Ou, and L. Mandel, PRL59 (1987)
[7] R. C. Liu, B. Odom, Y. Yamamoto, and S. Tarucha, Nature (1998)
[8] E. Bocquillon, V. Freulon, J.-M. Berroir, P. Degiovanni, B. Plaçais, A. Cavanna, Y. Jin, and G. Fève, Science (2013)