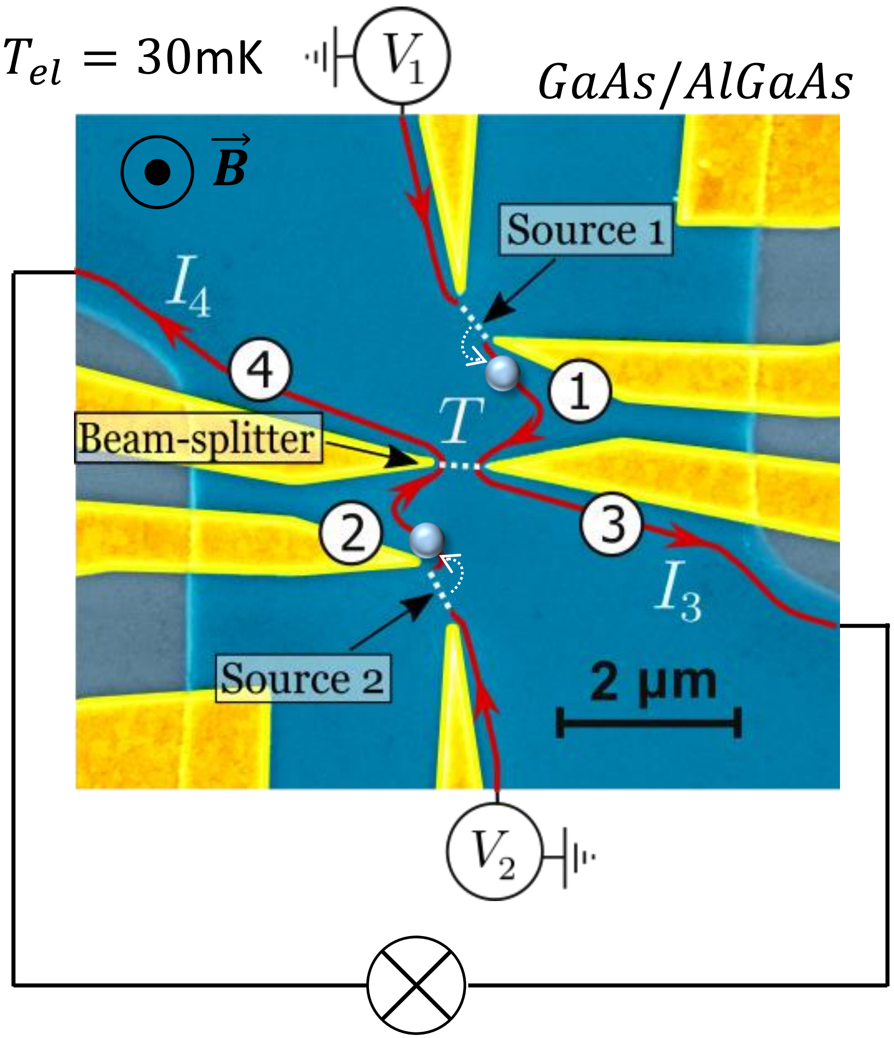
Fractional statistics of anyons in a mesoscopic collider

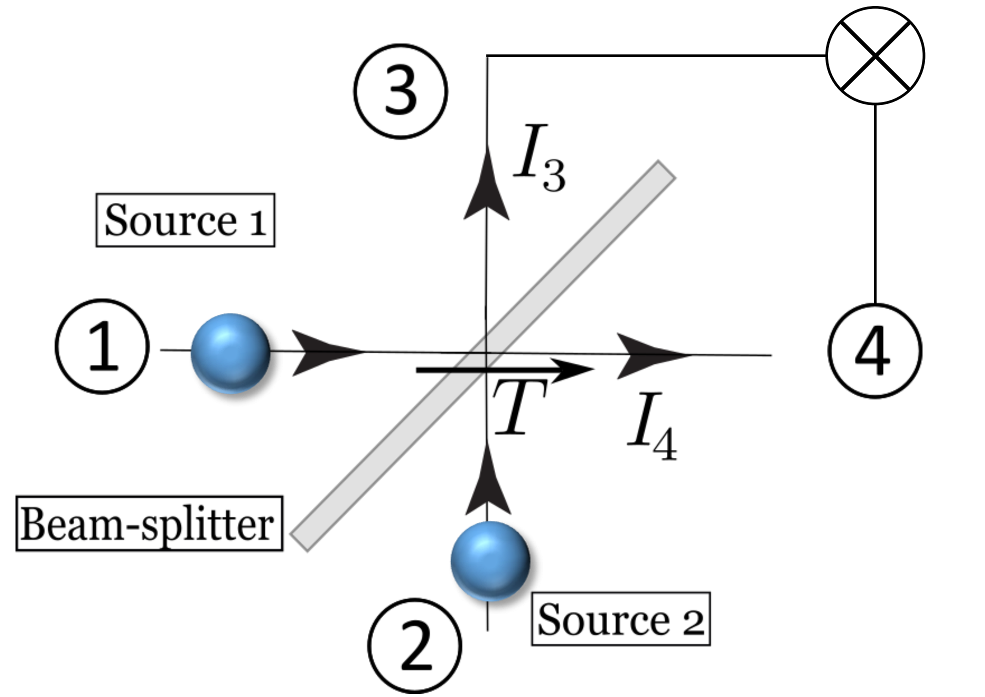
Electron optics experiments in quantum Hall conductors

$T_{el} = 30\text{mK}$



Current correlations $\langle \Delta I_3 \Delta I_4 \rangle$

Current correlations $\langle \Delta I_3 \Delta I_4 \rangle$



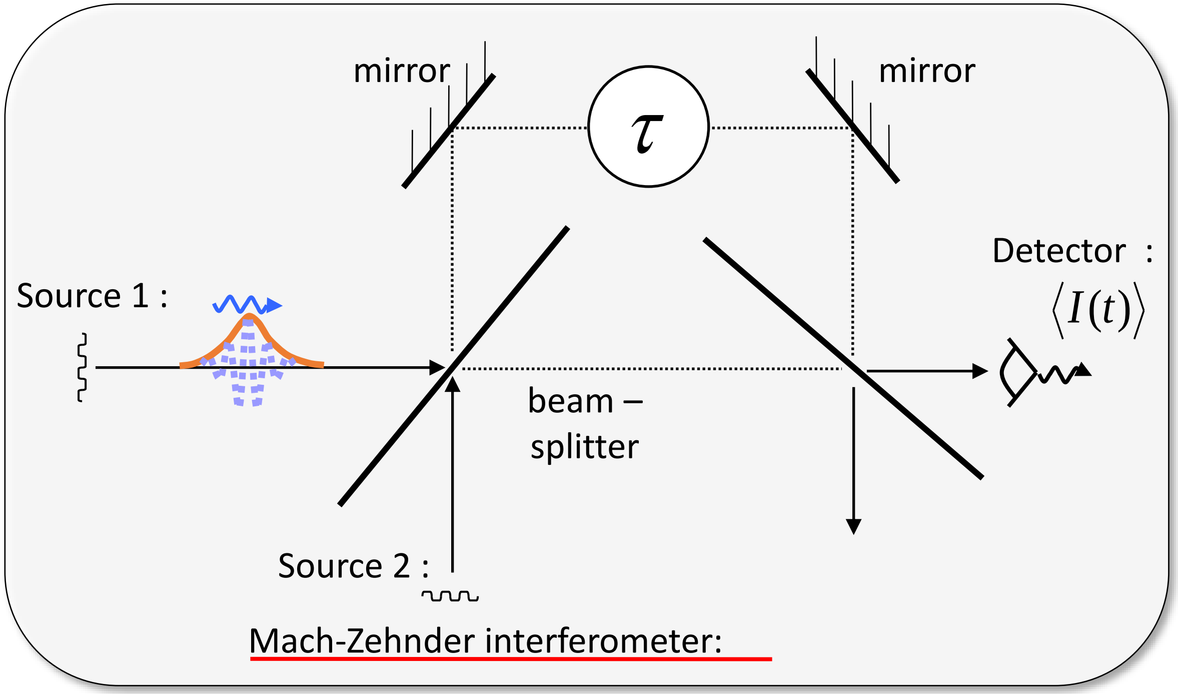
Single-particle vs two-particle interferometry

Optics: $E(t)$

Single particle interferometer

$$G^{(1)}(t+\tau,t) \propto \langle E(t+\tau)E(t)\rangle$$

Coherence of electric field



Two-particle interferometer

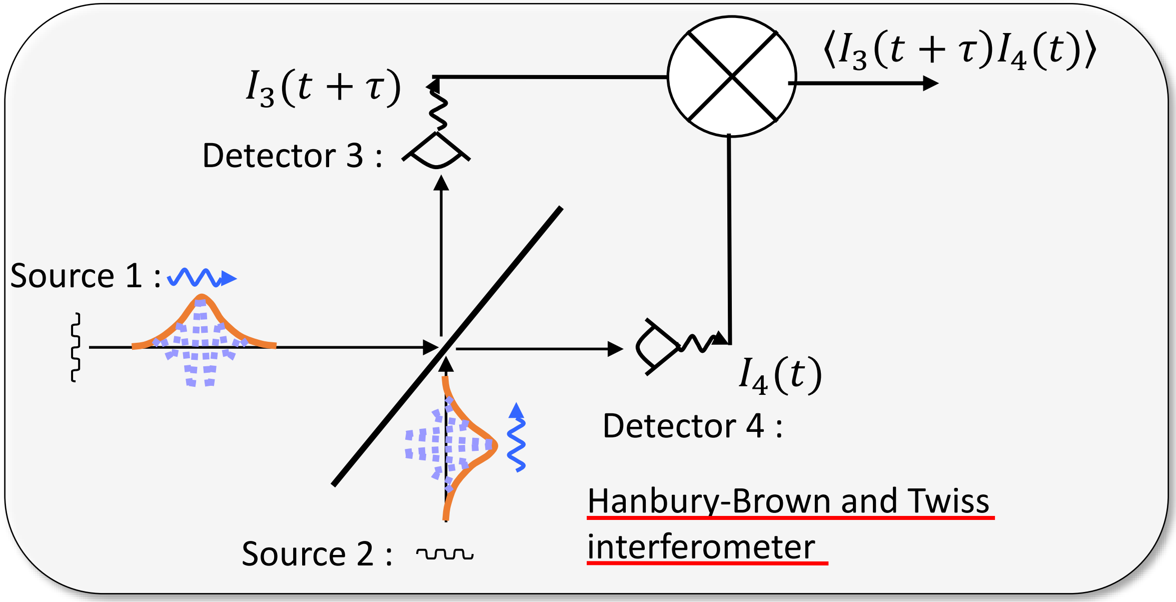
$$\langle I_3(t+\tau)I_4(t)\rangle$$

$$\propto \langle E_1(t+\tau)E_1(t)\rangle\langle E_2(t+\tau)E_2(t)\rangle$$

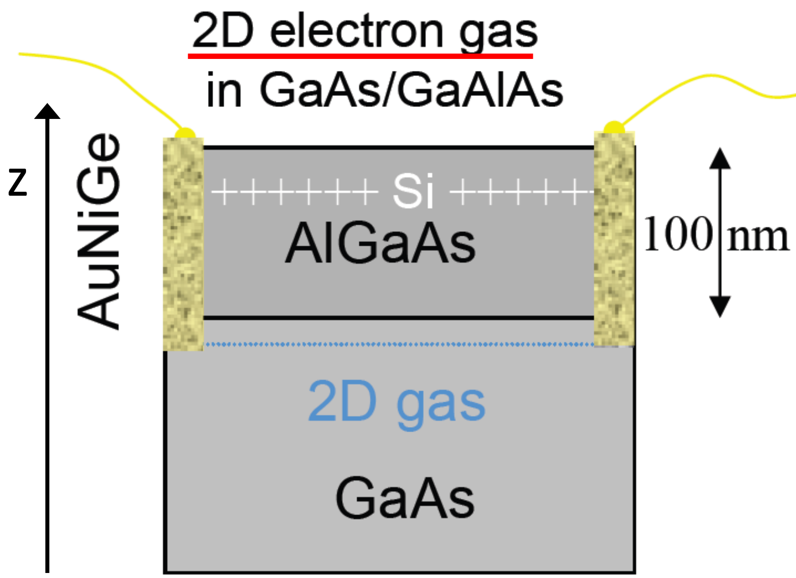
Product of coherences

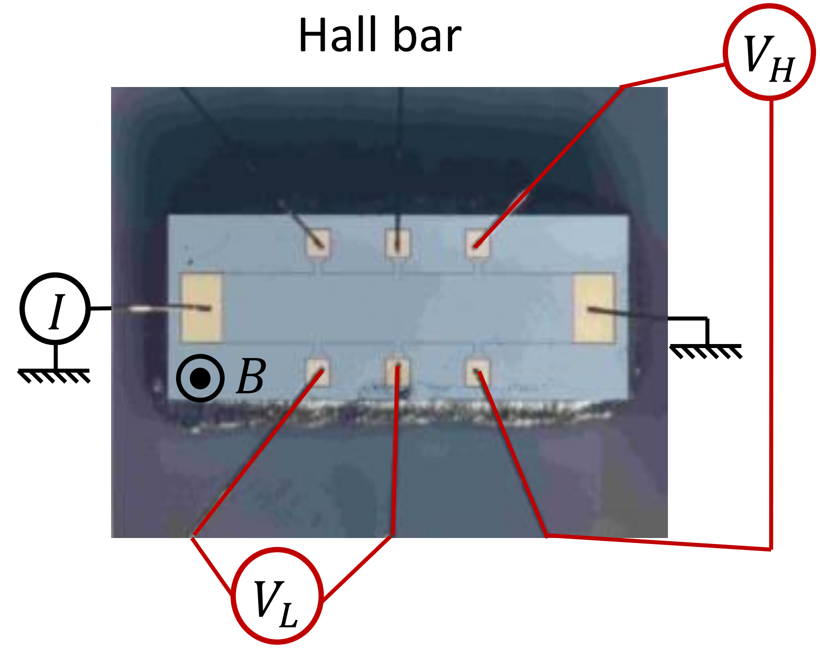
HBT interferometry

(no correlations between sources)

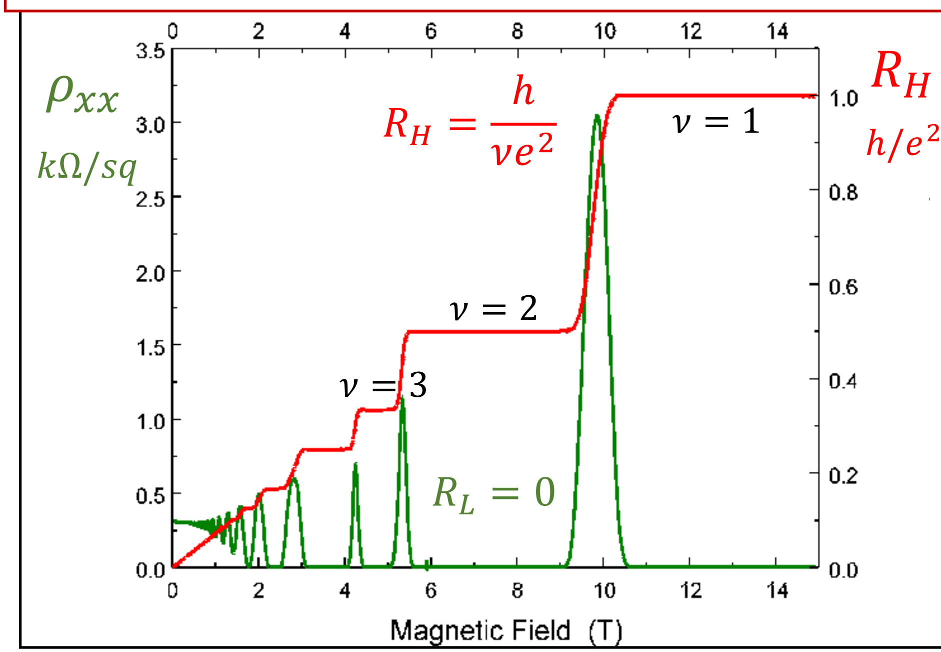


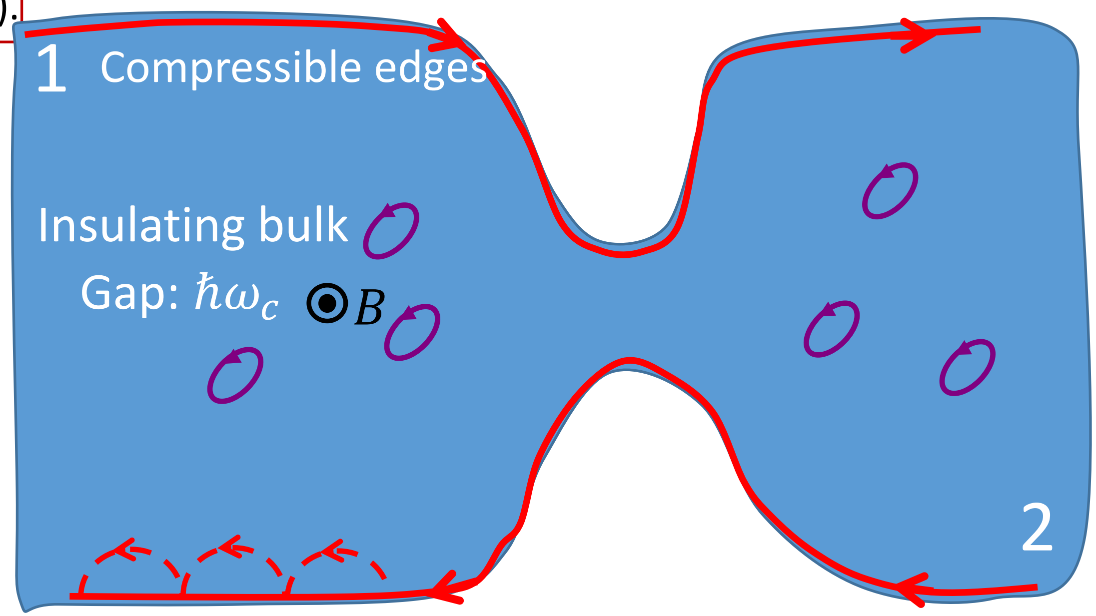
The quantum Hall effect





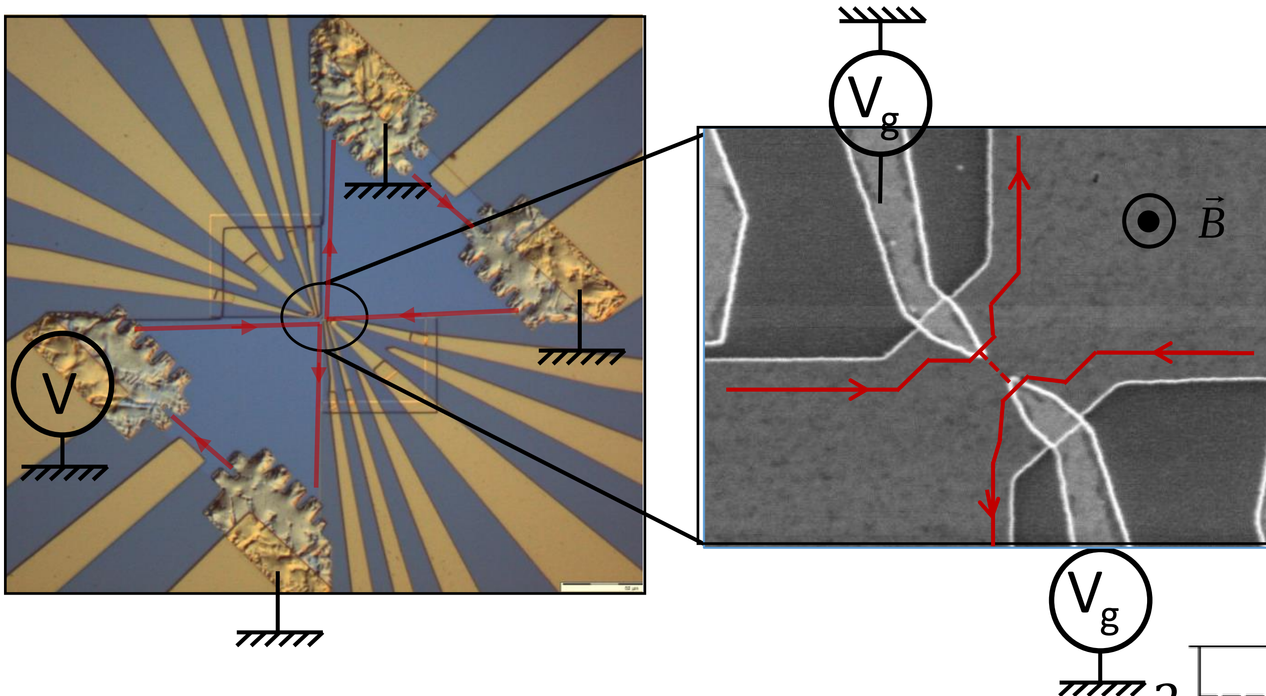
K. v. Klitzing, G. Dorda, and M. Pepper, PRL **45**, 494 (1980).

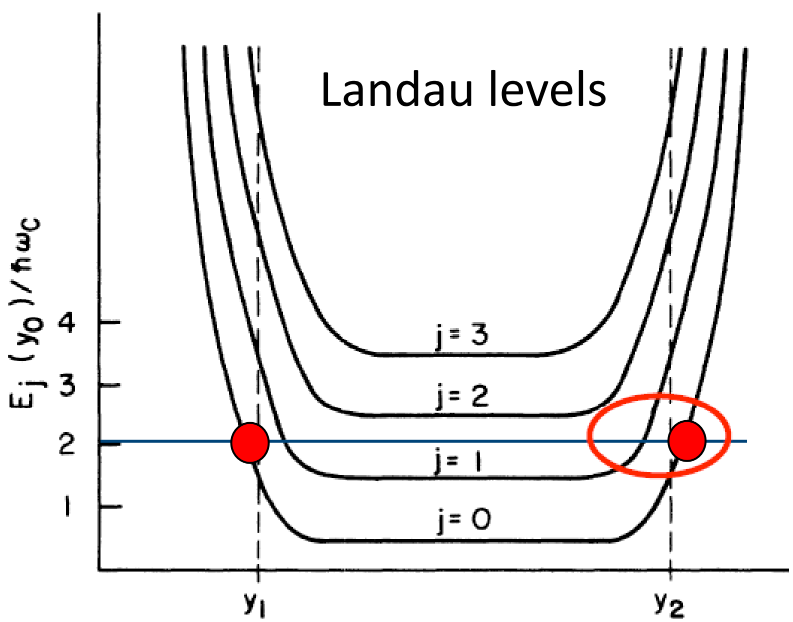


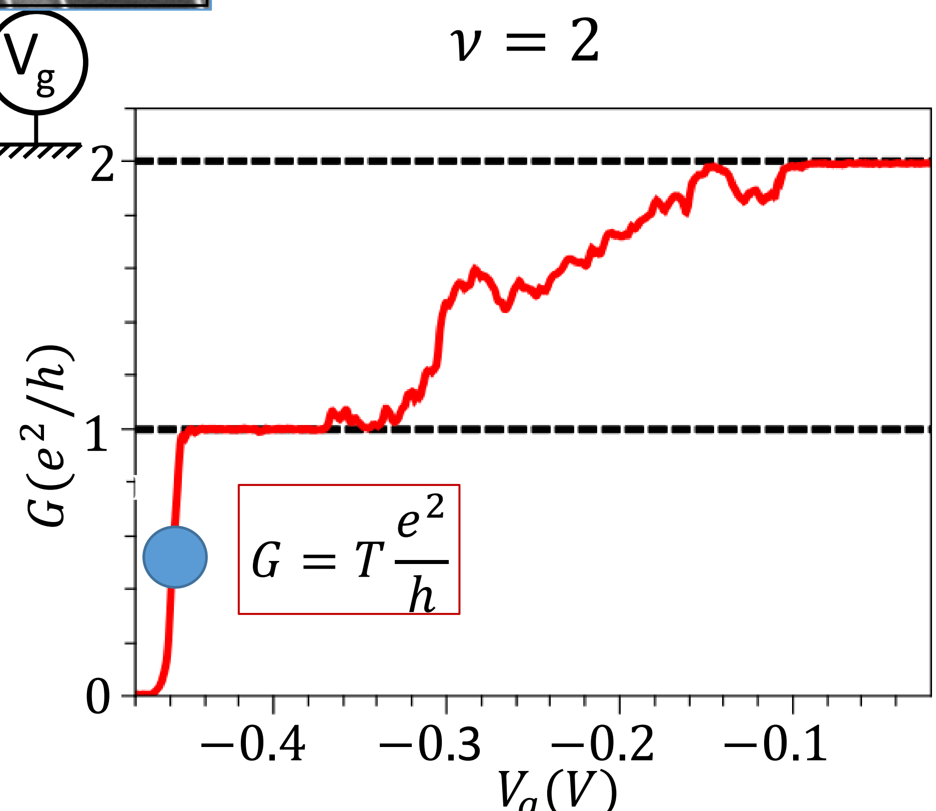


Ballistic propagation along the edges

The Quantum Point Contact (QPC):a tunable beam-splitter

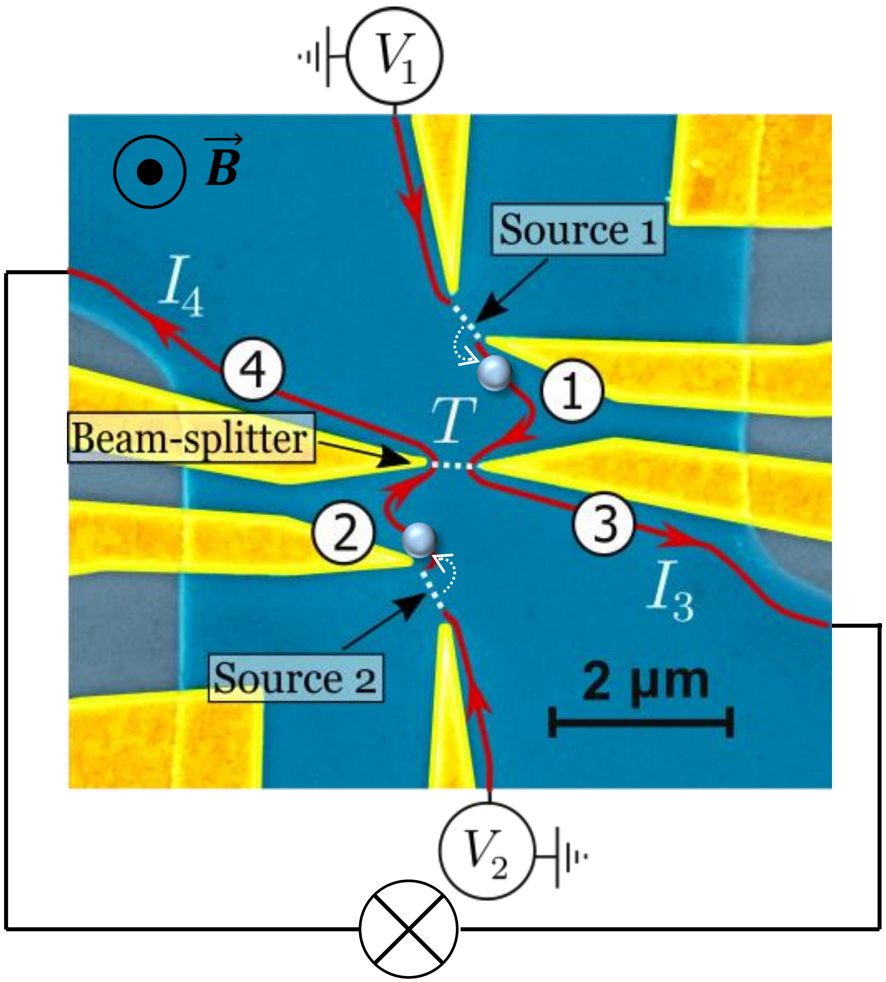






Single and two particle interferometers in quantum Hall conductors

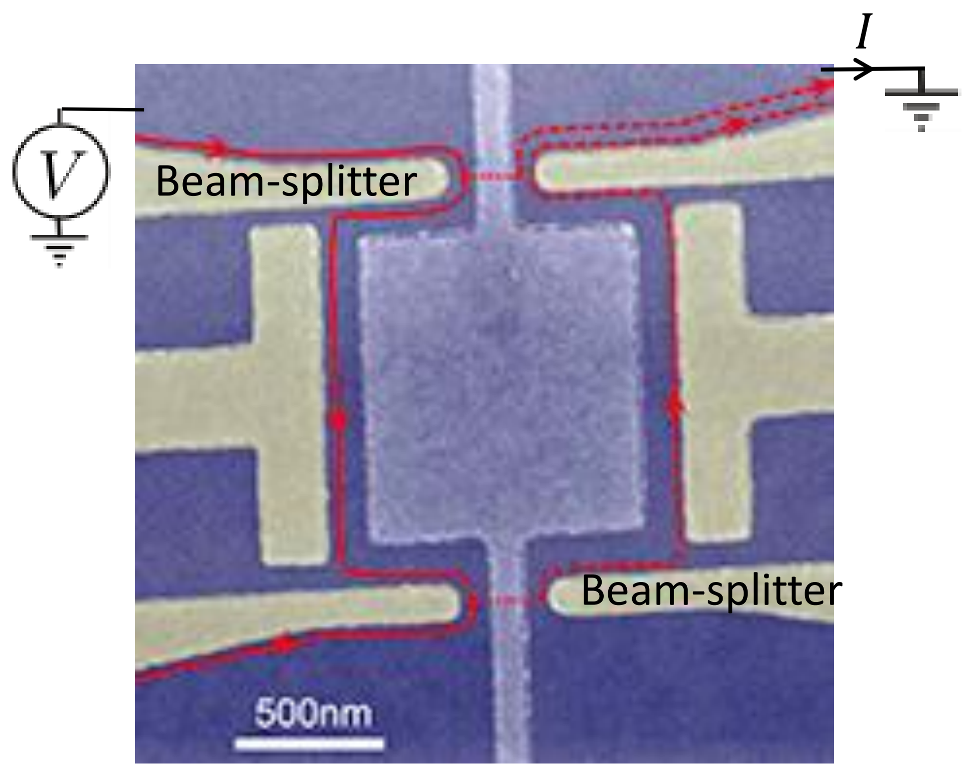
<u>***Electron optics experiments in quantum Hall conductors***</u>



Current correlations $\langle \delta I_3(t) \delta I_4(t') \rangle$

Two-particle interferometry

H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

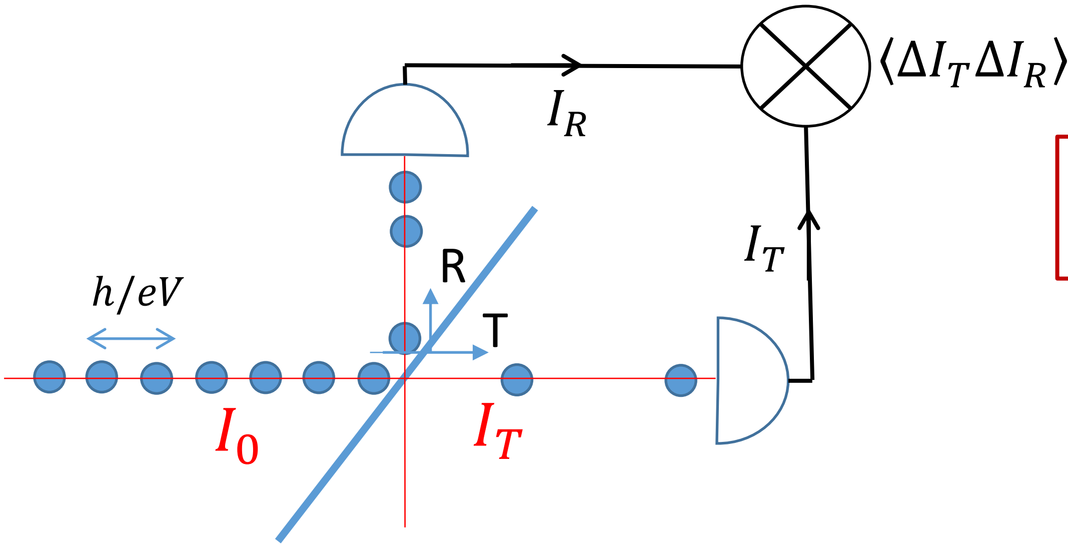


Electrical current $\langle I\ (t)\ \rangle$

Single-particle interferometry

J. Nakamura, S. Liang, G.C. Gardner, M.J. Manfra, Nature Physics **16** 931 (2020).

Electron beam splitters: random partition noise and charge measurement

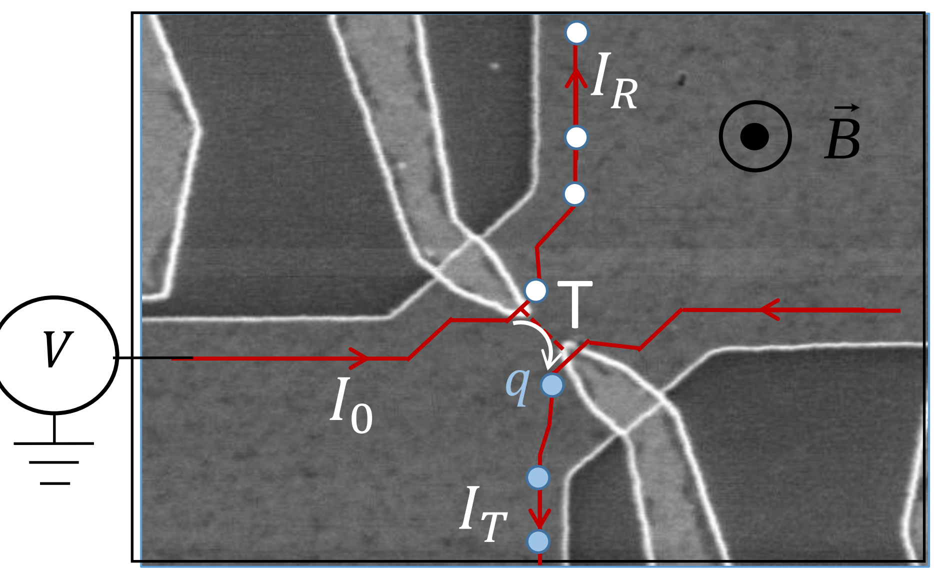


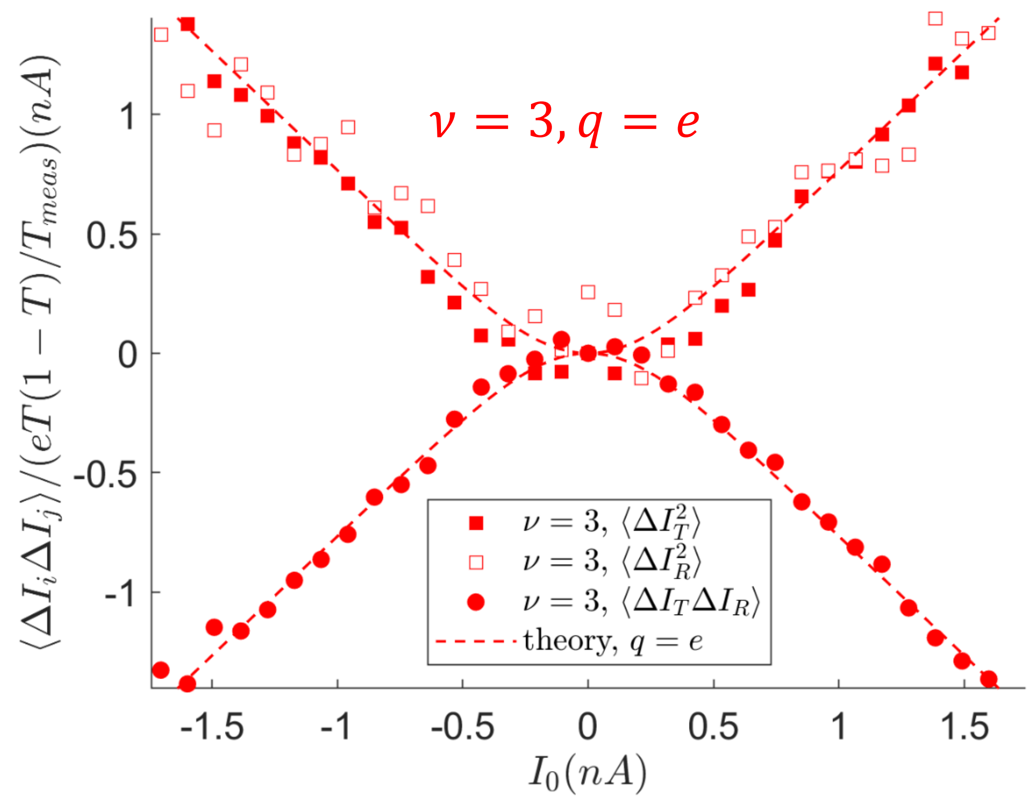
Binomial law: $\langle \Delta N_T^2 \rangle = T(1-T)\, N_0$

$$\langle \Delta I_T^2 \rangle = \frac{q^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{qT(1-T)I_0}{T_{meas}} \equiv \langle \Delta I_{RP}^2 \rangle$$

Current conservation: $I_T + I_R = I_0$

$$\langle \Delta I_T \Delta I_R \rangle = -\langle \Delta I_T^2 \rangle$$

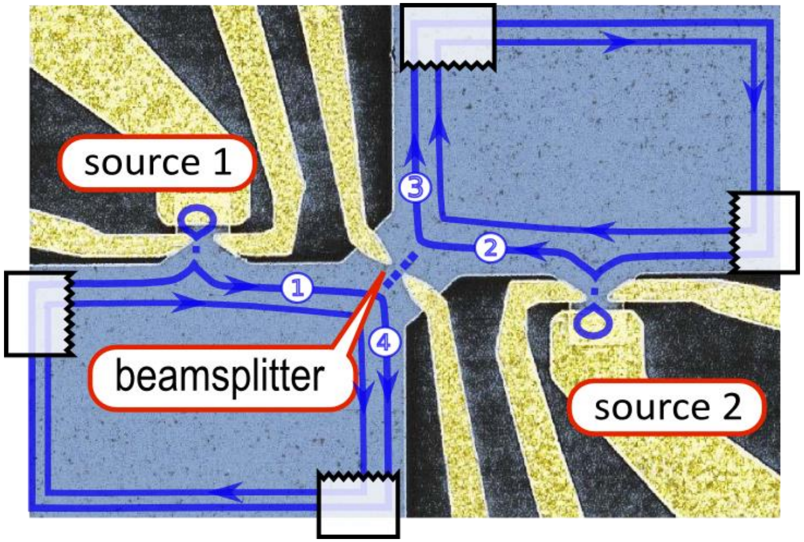


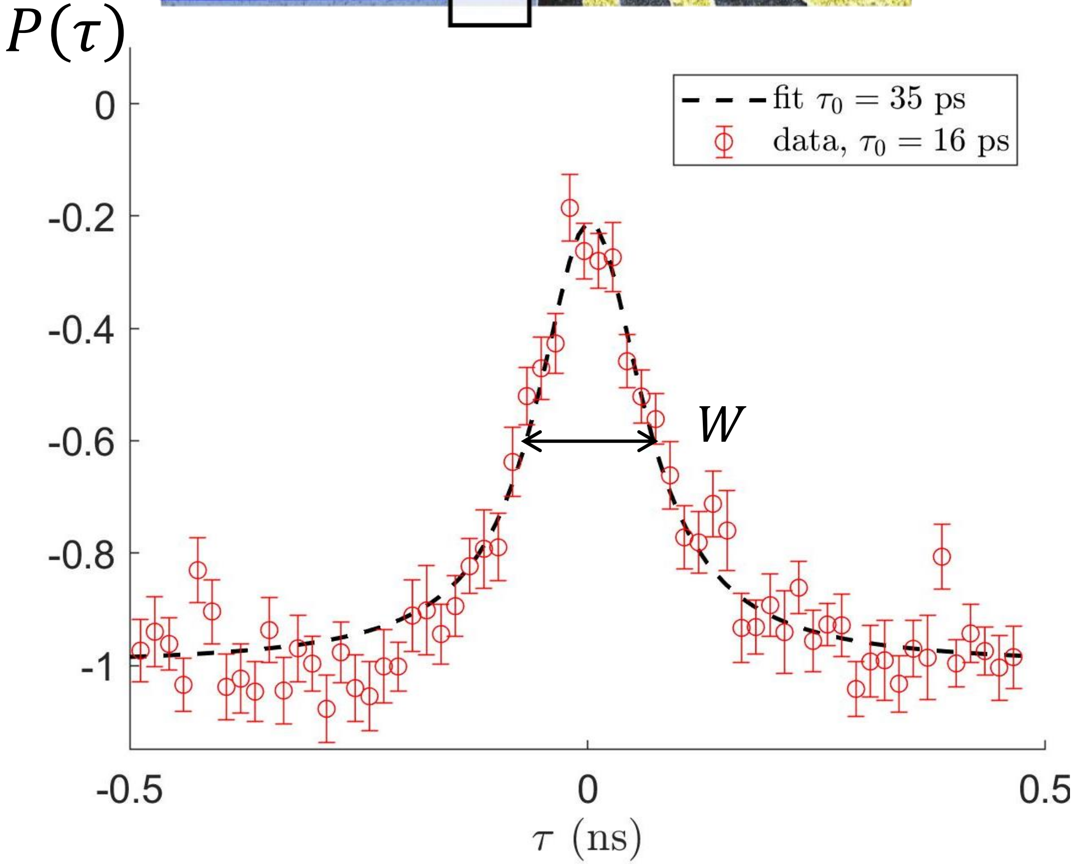


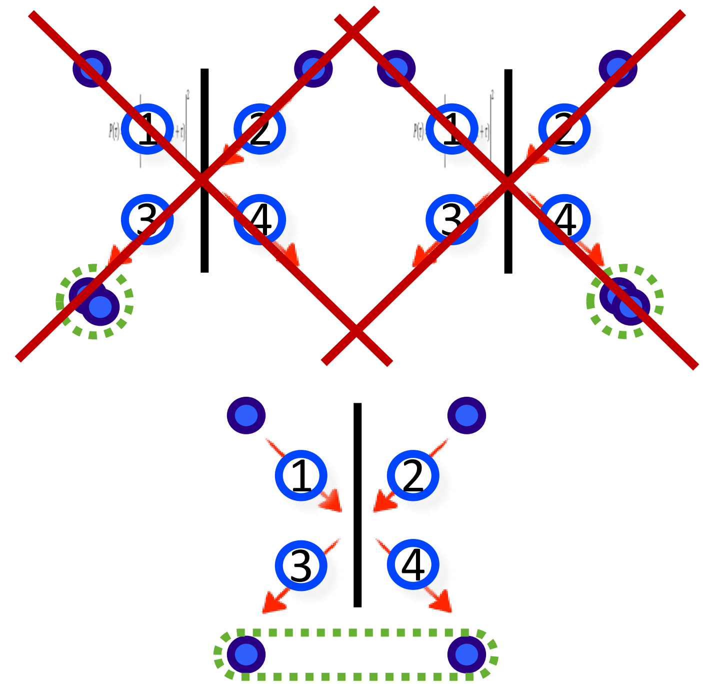
M. Reznikov et al., Phys. Rev. Lett. **75**, 3340 (1995).

A. Kumar et al., Phys. Rev. Lett. **76**, 2778 (1996).

$\nu = 2$: Two-particle interferometry with electrons







- $\tau \gg W$ Classical random partitioning

$$P(\tau) = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{\langle \Delta I_{RP}^2 \rangle} = -1$$

- $\tau \ll W$ Fermion antibunching

$$P(\tau) \approx 0$$

S. Ol'khovskaya et al., PRL **101**, 166802, (2008).
E. Bocquillon et al., Science **339**, 1054 (2013).

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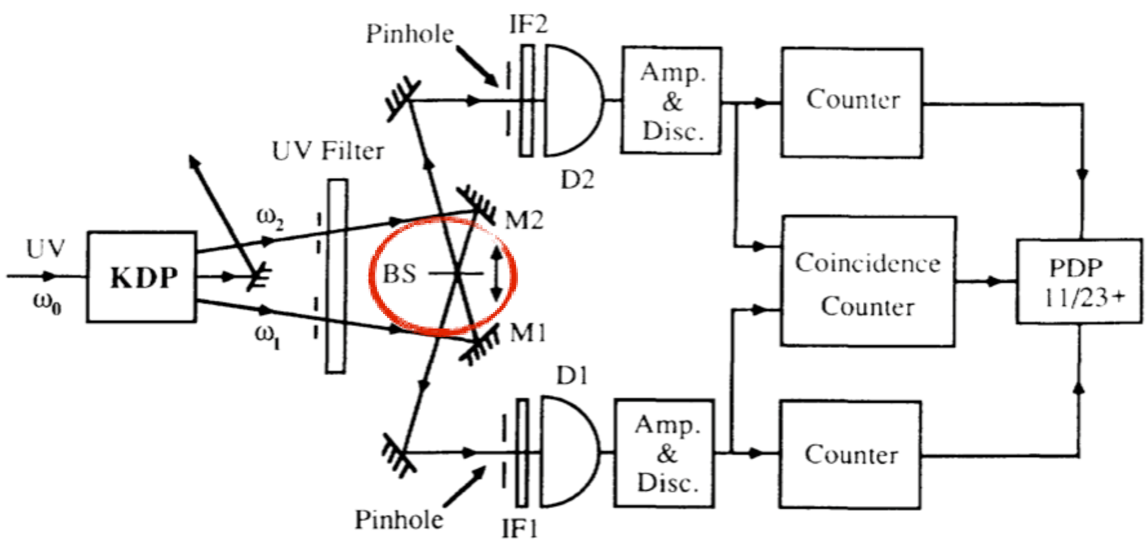
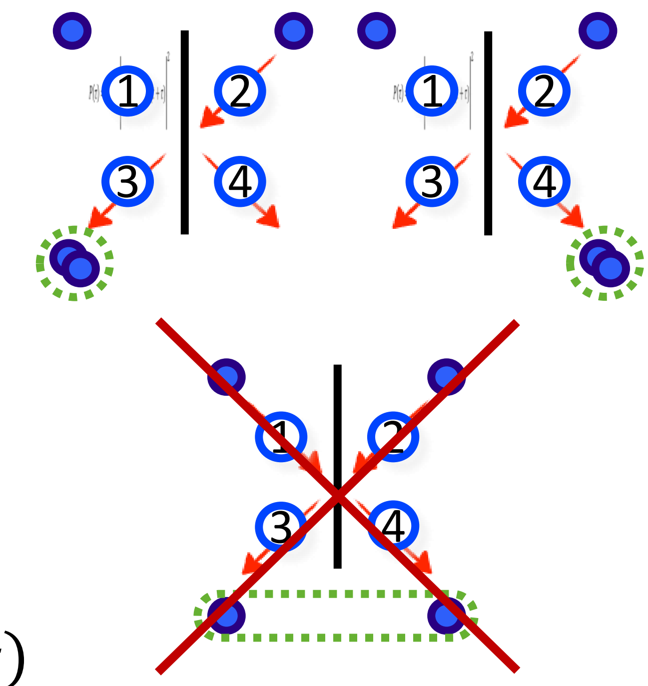
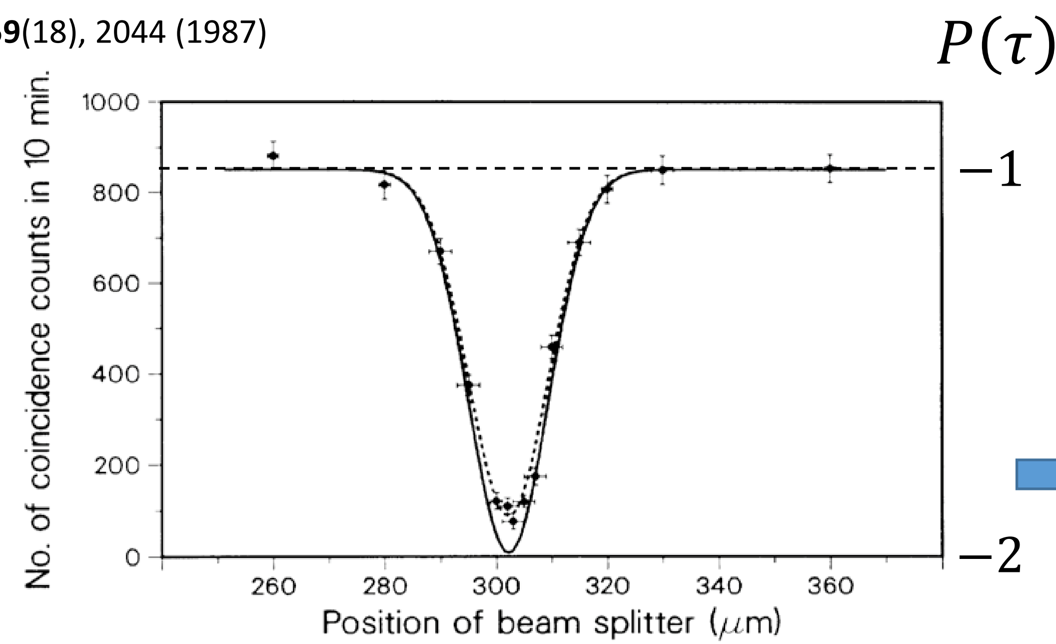
Bosonic case: the Hong-Ou-Mandel experiment





Photons pairs :
C. Hong *et al.,* PRL **59**(18), 2044 (1987)



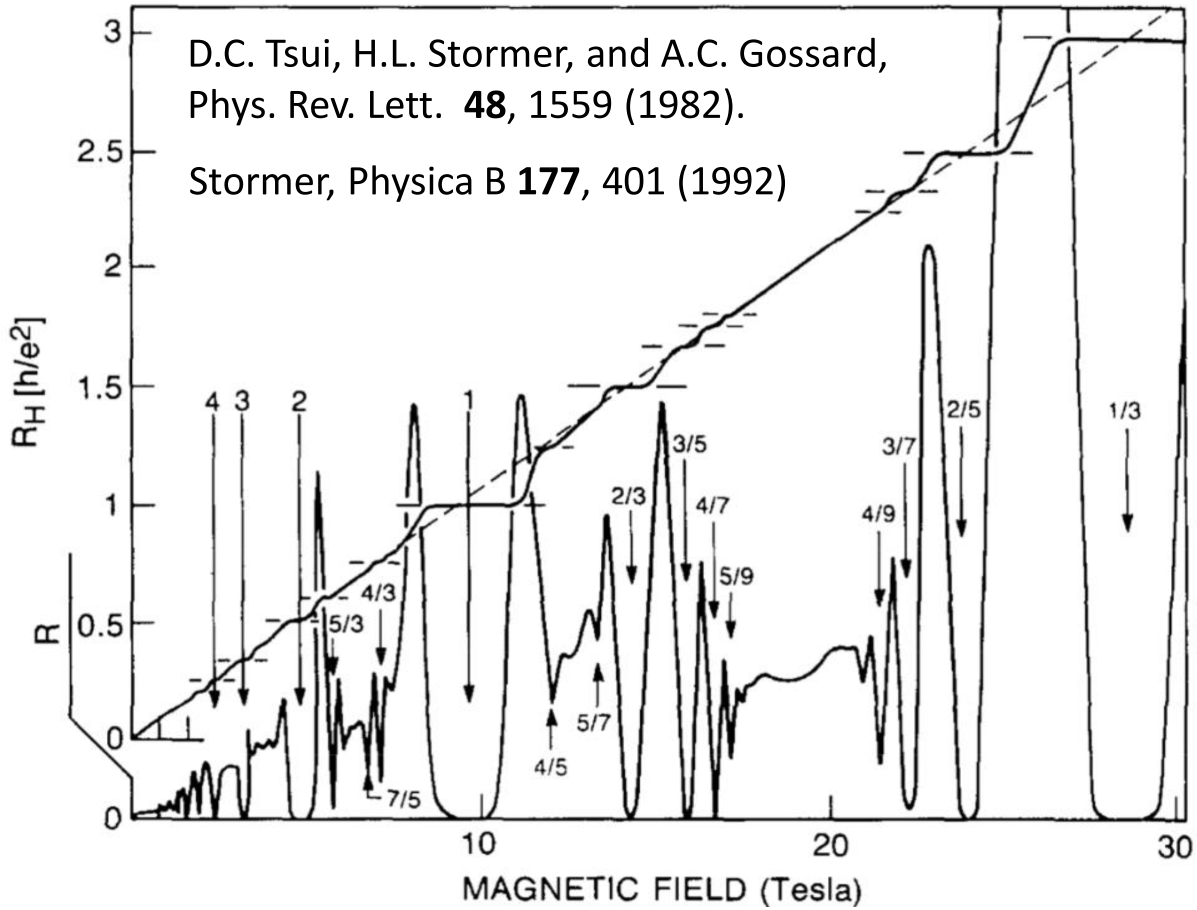
Undistinguishable photons

Bunching:

more negative cross-correlations

Anyons and the Fractional Quantum Hall Effect (FQHE)

$T_{el} \approx 30\ mK$



Each FQHE phase hosts a specific variety of anyons characterized by their fractional charge q and their fractional statistics φ

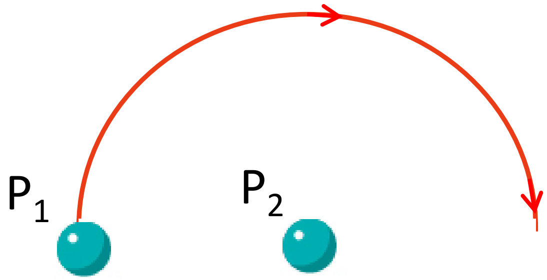
Halperin, PRL **52** 1583 (1984)

Arovas, Schrieffer, Wilczek PRL **53** 722 (1984)

Review: Stern, Annals of Physics **323** 204 (2008)

Fermions, bosons and anyons

Symmetry of the wavefunction ψ under the exchange of two particles:



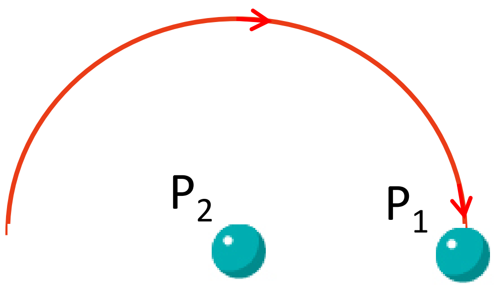
J.M.Leinaas, and J.Myrheim, Nuovo Cimento **B37**, 1-23 (1977).

G. A. Goldin, R. Menikoff, and D. H. Sharp, J. Math. Phys., **21** 650 (1980).

F. Wilczek, PRL **49**, 957 (1982).

Fermions, bosons and anyons

Symmetry of the wavefunction ψ under the exchange of two particles:



$$P_{1\to 2}\psi = e^{i\varphi}\,\psi$$

J.M.Leinaas, and J.Myrheim, Nuovo Cimento **B37**, 1-23 (1977).

G. A. Goldin, R. Menikoff, and D. H. Sharp, J. Math. Phys., **21** 650 (1980).

F. Wilczek, PRL **49**, 957 (1982).

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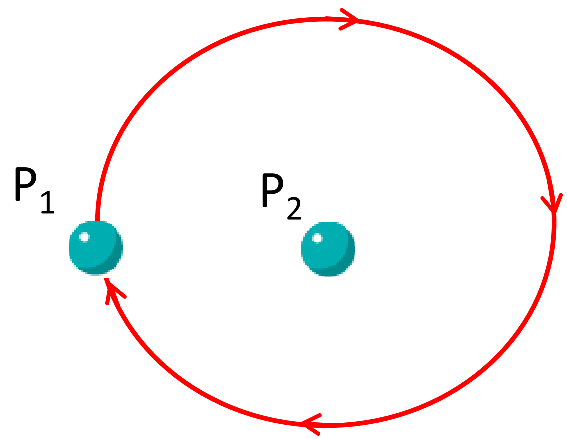
Fermions and bosons

Symmetry of the wavefunction ψ under the exchange of two particles:



Braiding operation

$$B = P_{1\to2}P_{1\to2} = e^{2i\varphi}\mathbb{I}$$

$$P_{1\to2}P_{1\to2}\psi = e^{2i\varphi}\psi$$

If $P_{1\to2}P_{1\to2} = \mathbb{I}$ ⇒ $2\varphi = \theta = 2n\pi$ ⇒

- $\varphi=0$ bosons *bunching*
- $\varphi=\pi$ fermions *antibunching*

J.M.Leinaas, and J.Myrheim, Nuovo Cimento **B37**, 1-23 (1977).

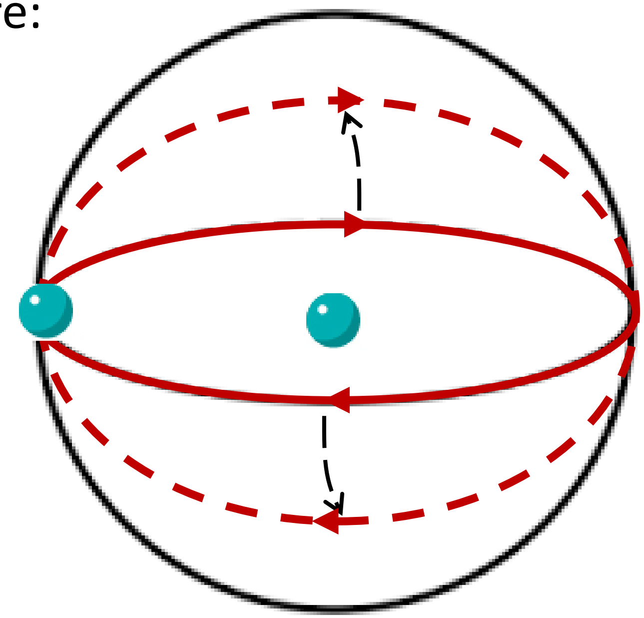
G. A. Goldin, R. Menikoff, and D. H. Sharp, J. Math. Phys., **21** 650 (1980).

F. Wilczek, PRL **49**, 957 (1982).

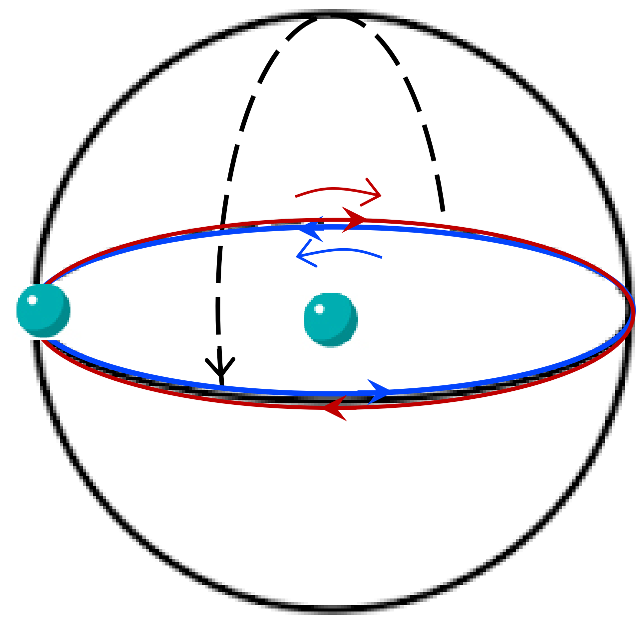
3D: Fermions and bosons

Path of particle 1 can be continuously deformed on the sphere to the reversed path : these two paths are topologically equivalent

3D sphere:



$$P_{1\to2}P_{1\to2}\psi = e^{i\theta}\psi$$



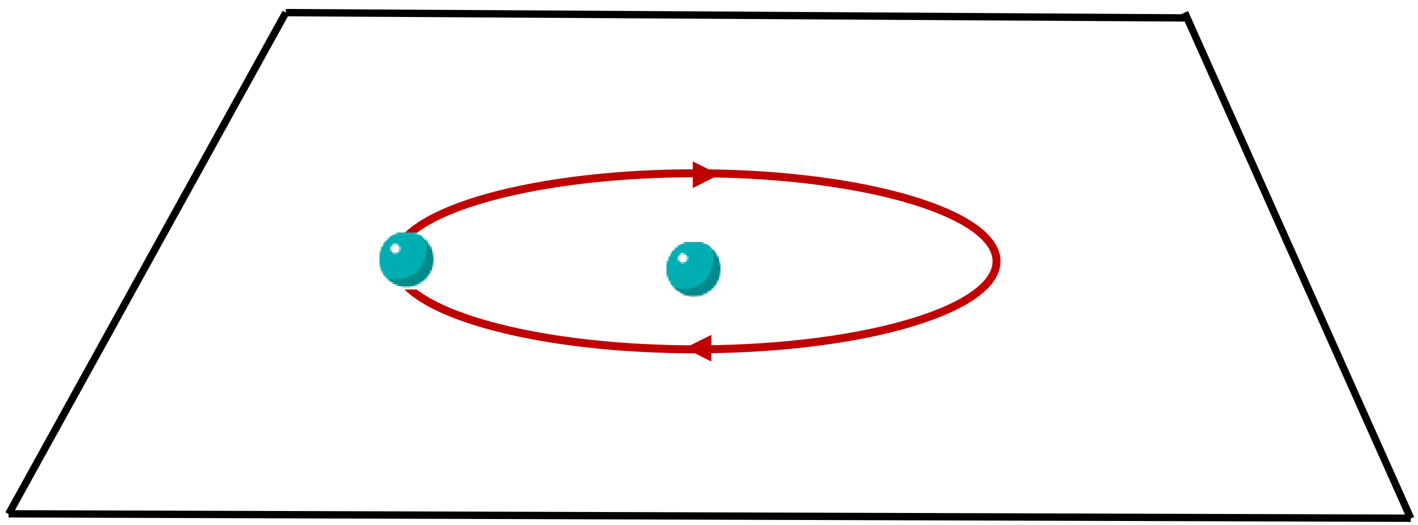
$$P_{1\to2}P_{1\to2}\psi = e^{-i\theta}\psi$$

$$e^{i\theta} = 1$$

- $\varphi=0$ bosons
- $\varphi=\pi$ fermions

2D: Fermions and bosons and anyons

2D plane:



In 2D, the trajectory of P_1 cannot be continuously deformed to the reversed path

$$P_{1\to 2}P_{1\to 2} = e^{i\theta}\,\mathbb{I}$$

φ can take any value: anyons

anyons keep a memory of braiding operations

J.M.Leinaas, and J.Myrheim, Nuovo Cimento **B37**, 1-23 (1977).

G. A. Goldin, R. Menikoff, and D. H. Sharp, J. Math. Phys., **21** 650 (1980).

F. Wilczek, PRL **49**, 957 (1982).

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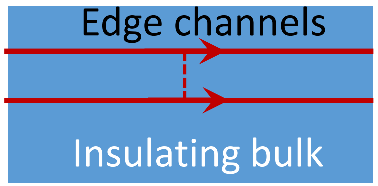
Anyons and the Fractional Quantum Hall Effect (FQHE)

$T_{el} \approx 30\ mK$

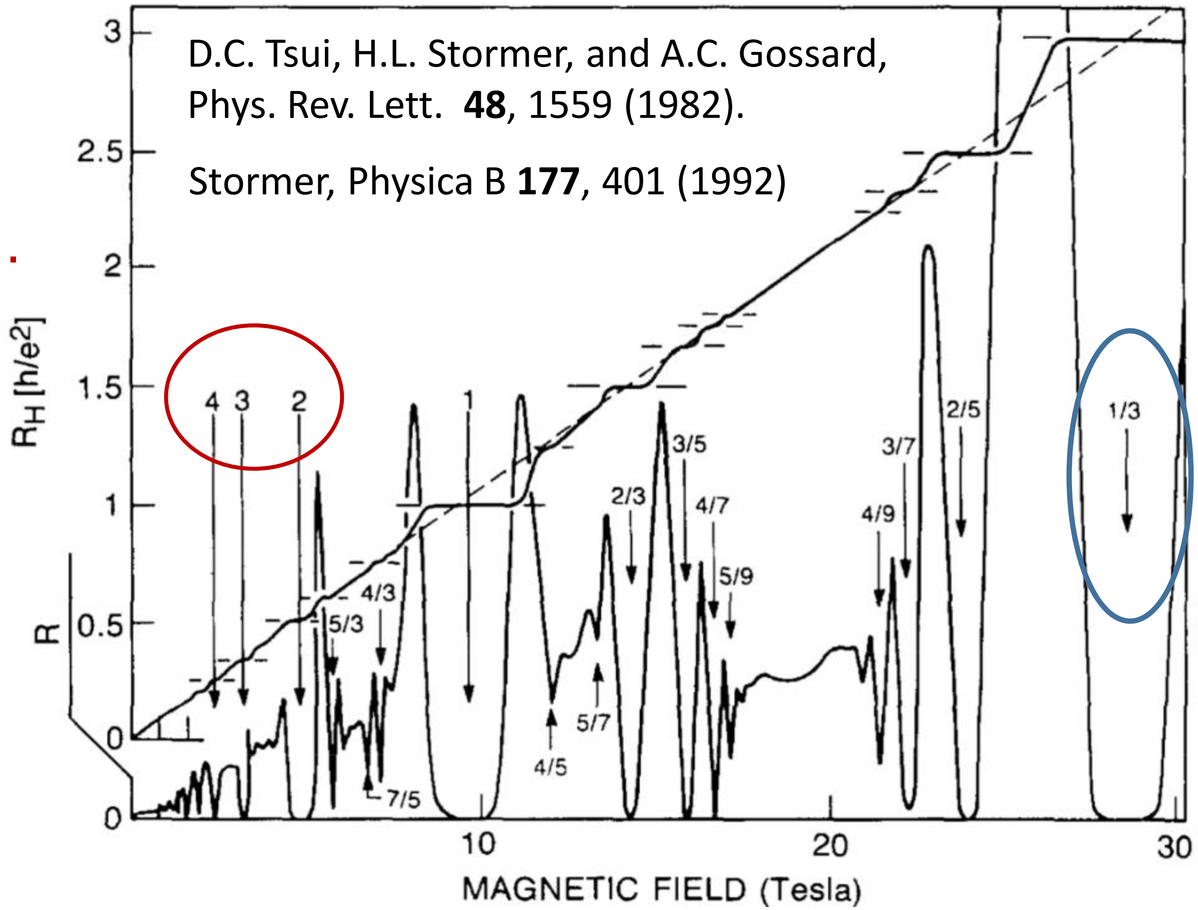
IQHE, $\nu = 1, 2\ , 3..$



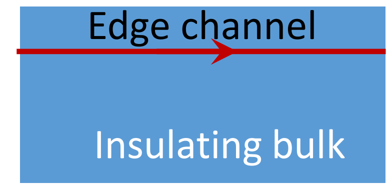
$G_0 = N\frac{e^2}{h}$

$e^* = e$

$\varphi = \pi$



FQHE, $\nu = 1/3$



$G_0 = \frac{1}{3}\frac{e^2}{h}$

$e^* = e/3$

$\varphi = \pi/3$

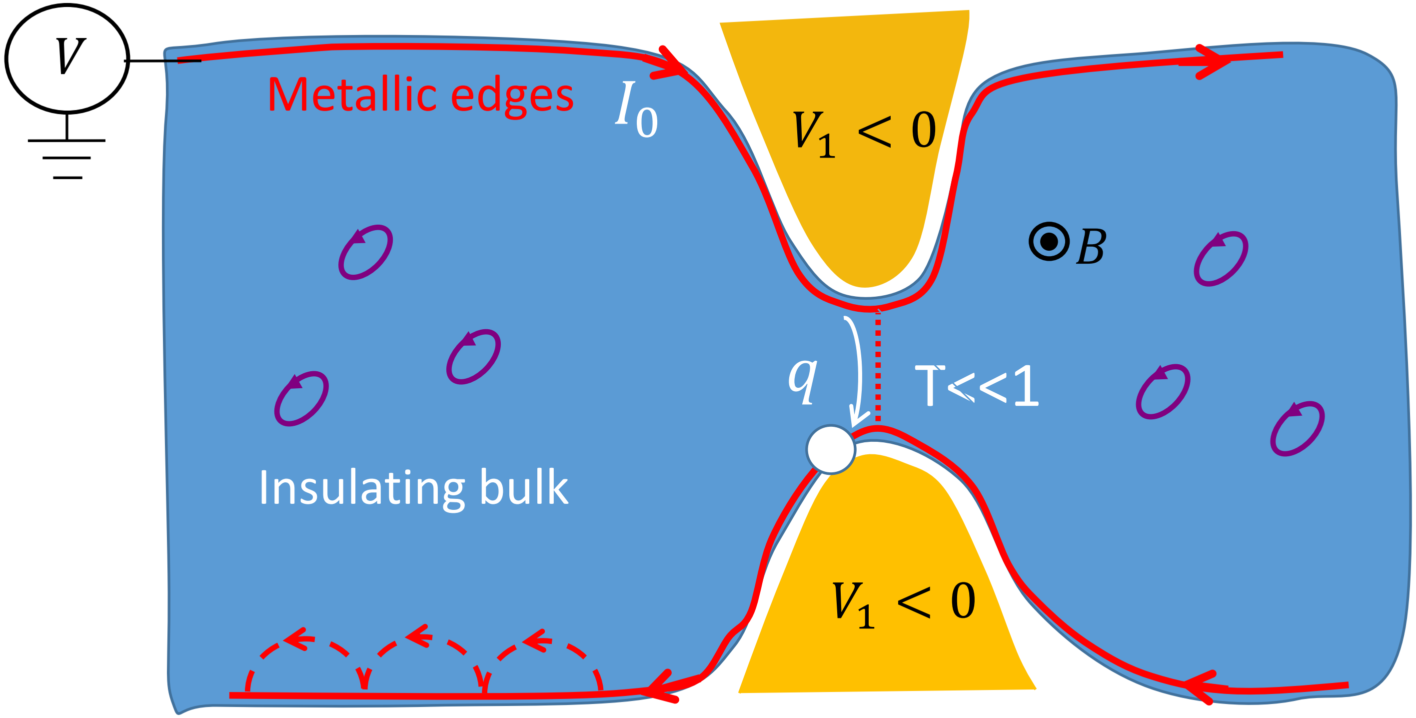
Each FQHE phase hosts a specific variety of anyons characterized by their fractional charge q and their fractional statistics φ

Halperin, PRL **52** 1583 (1984)

Arovas, Schrieffer, Wilczek PRL **53** 722 (1984)

Review: Stern, Annals of Physics **323** 204 (2008)

Transfer of electrons and anyons at the edge: the quantum point contact



Integer case: random transmission of electrons

$$\nu = 2, \nu = 3 \quad q = e$$

$$H_T = \zeta \psi^+_{1,e} \psi_{2,e} + \zeta^* \psi^+_{2,e} \psi_{1,e}$$

Electron creation operator

$$\psi^+_{1,e}(x)\psi^+_{1,e}(x') = e^{-i\pi} \psi^+_{1,e}(x')\psi^+_{1,e}(x)$$

$\varphi = \pi$ Electrons=fermions

Fractional case: random transmission of anyons

$$\nu = 1/3, \; q = e/3$$

$$H_T = \zeta \psi^+_{1,a} \psi_{2,a} + \zeta^* \psi^+_{2,a} \psi_{1,a}$$

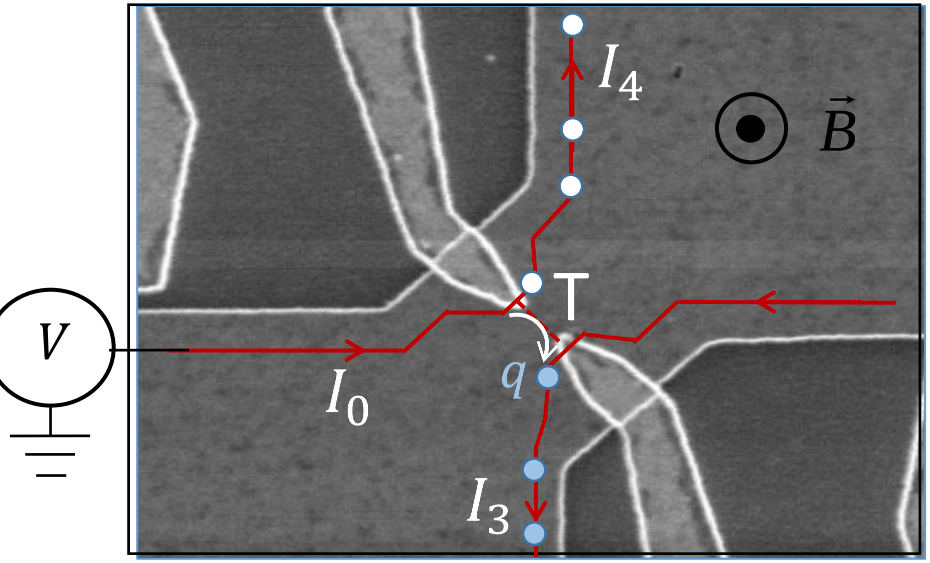
anyon creation operator

$$\psi^+_{1,a}(x)\psi^+_{1,a}(x') = e^{-i\frac{\pi}{3}\,\mathrm{sgn}(x-x')} \psi^+_{1,a}(x')\psi^+_{1,a}(x)$$

$\varphi = \pi/3$ Anyon excitations at $\nu = 1/3$

C.L. Kane, M.P.A Fisher, edge state transport (1996)

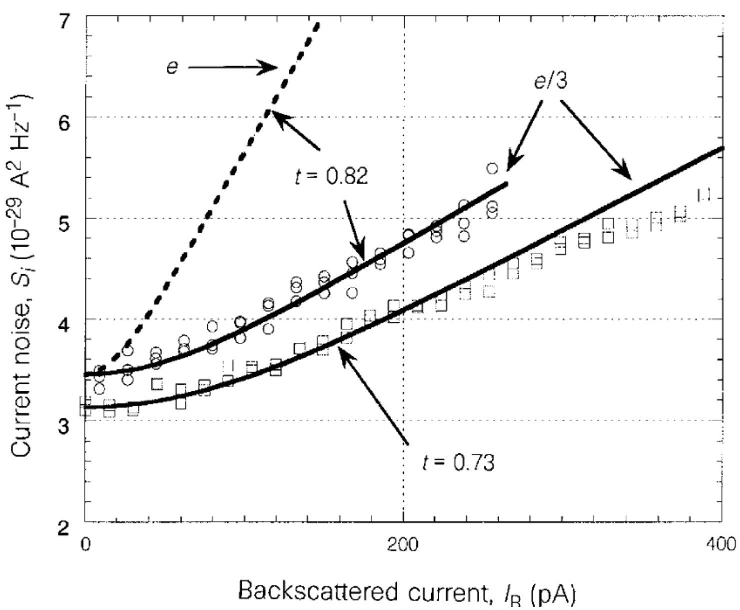
Electron/anyon beam splitters: random partition noise and charge measurement



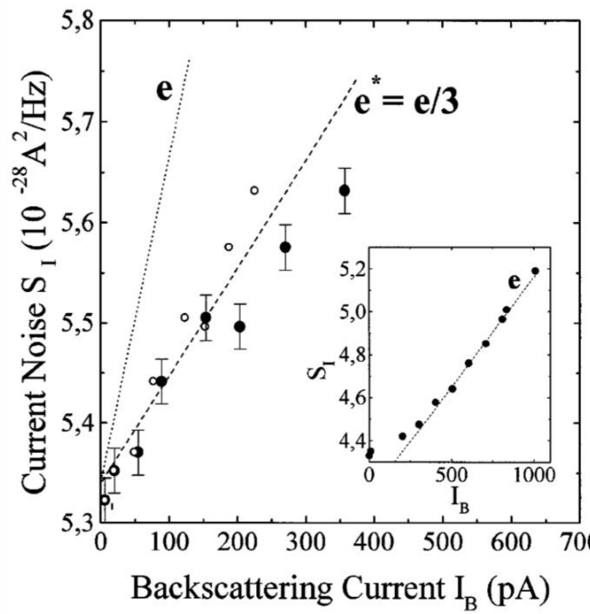
Binomial law: $\langle \Delta N_T^2 \rangle = T(1-T)\, N_0$

$$\langle \Delta I_T^2 \rangle = \frac{q^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{qT(1-T)I_0}{T_{meas}} \equiv \langle \Delta I_{RP}^2 \rangle$$

Fractional case: $q = e/3$

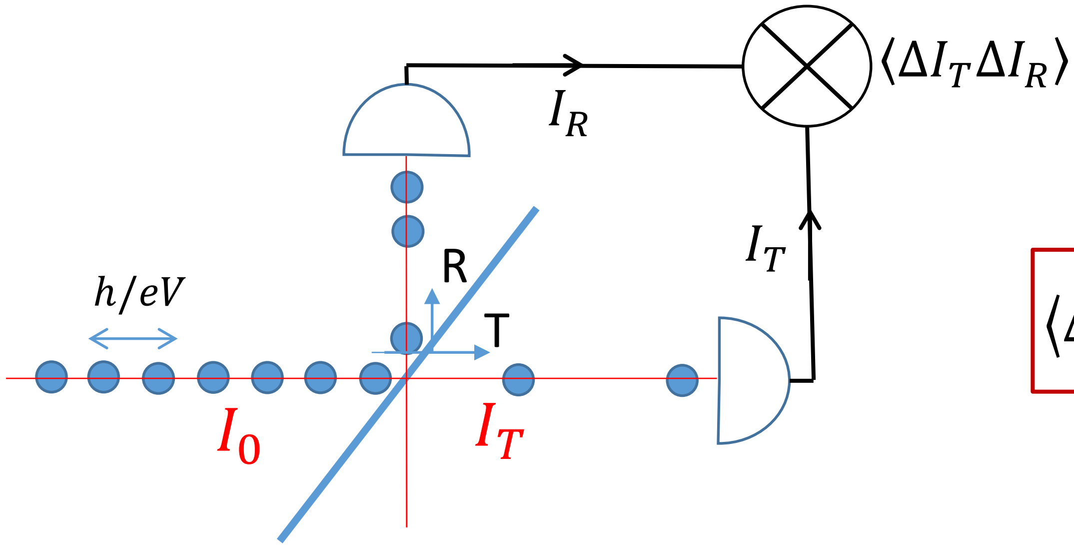


R. de Picciotto et al., Nature **389**, 162 (1997).



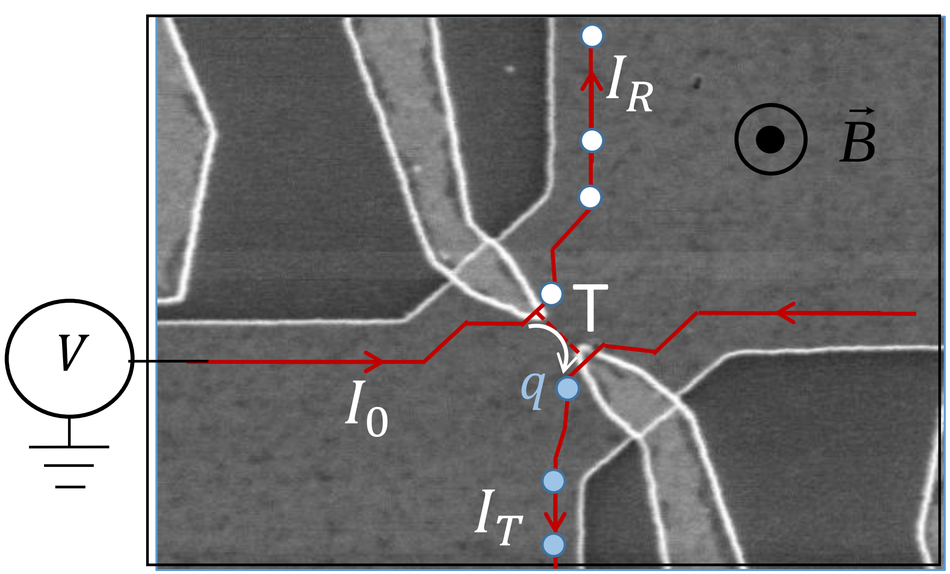
L. Saminadayar et al., Phys. Rev. Lett. **79**, 2526 (1997).

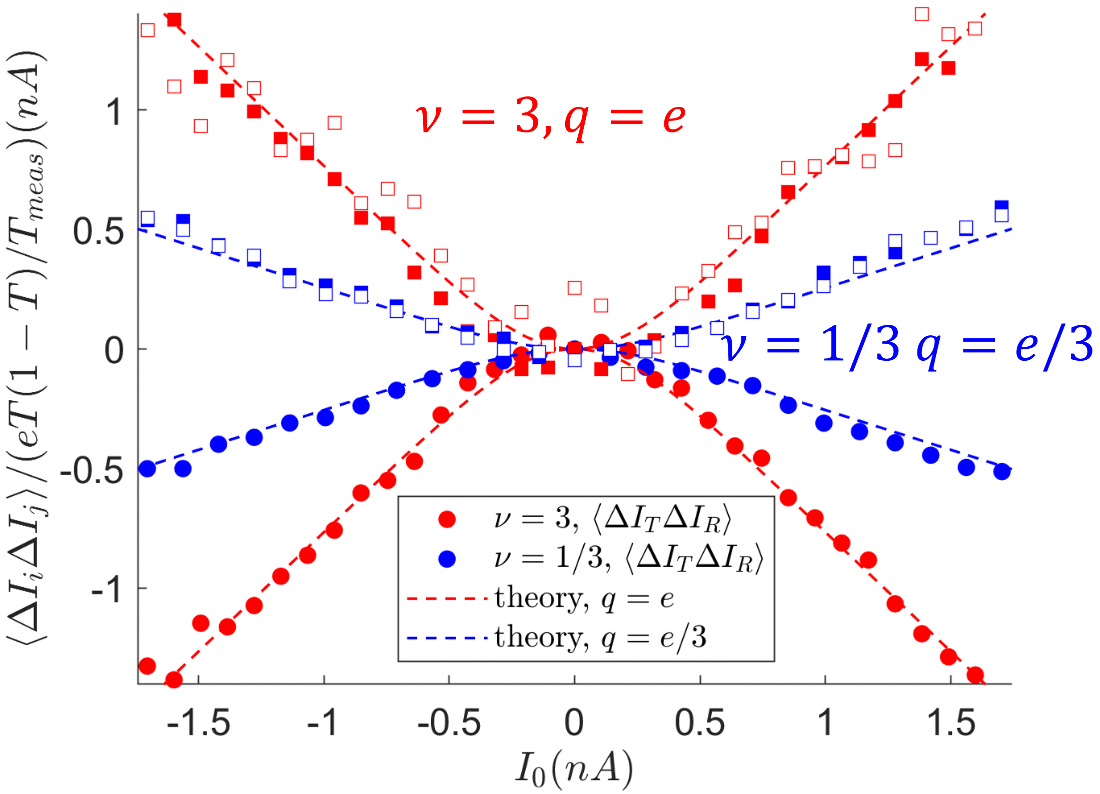
Electron/anyon beam splitters: random partition noise and charge measurement



Binomial law: $\langle \Delta N_T^2 \rangle = T(1-T)\, N_0$

$$\langle \Delta I_T^2 \rangle = \frac{q^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{qT(1-T)I_0}{T_{meas}} \equiv \langle \Delta I_{RP}^2 \rangle$$

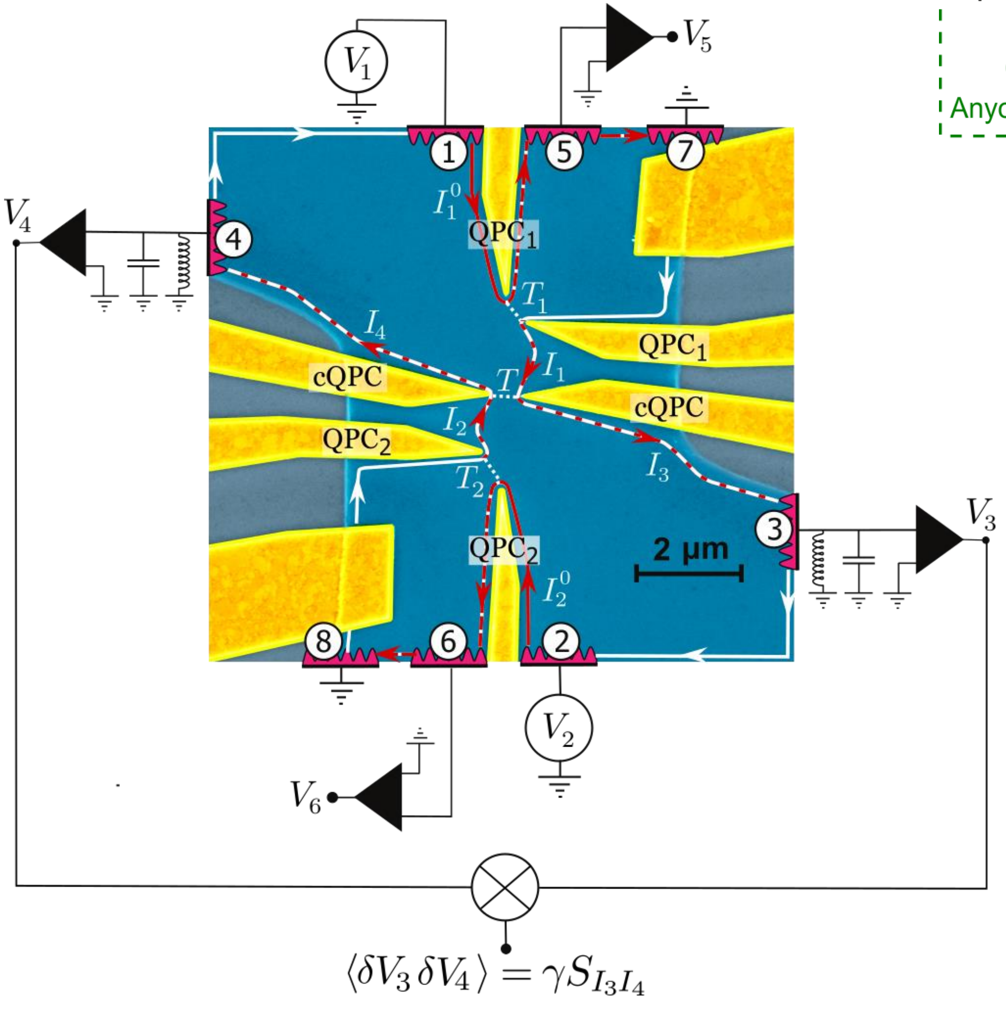


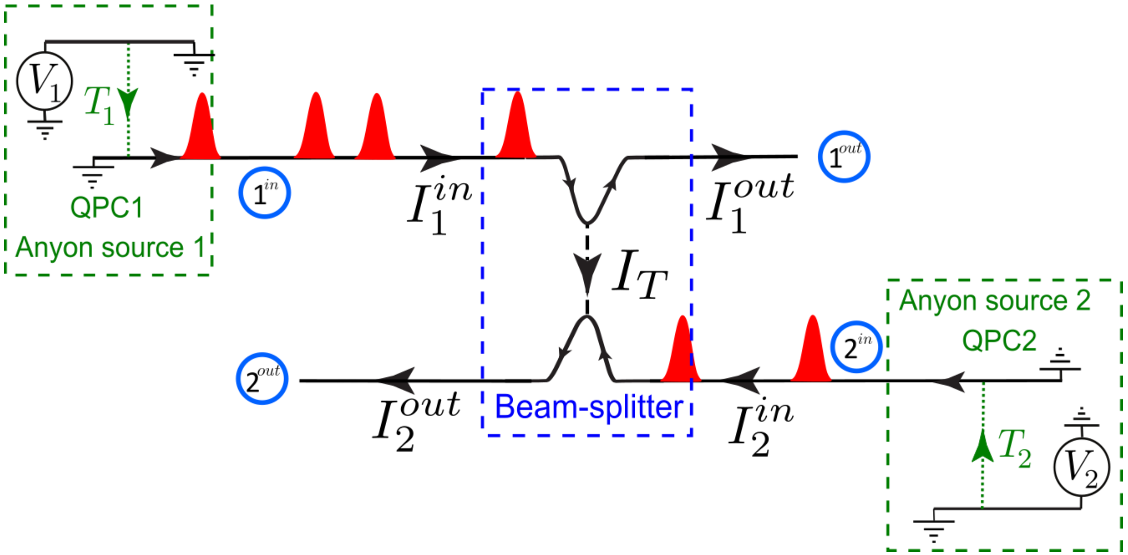


The anyon collider

B. Rosenow, I.P. Levkivskyi, B. Halperin PRL **116**, 156802 (2016)

H. Bartolomei et al., Science **368**, 173 (2020)





Random emission of particles: probabilities $T_1 = T_2 = T_S$

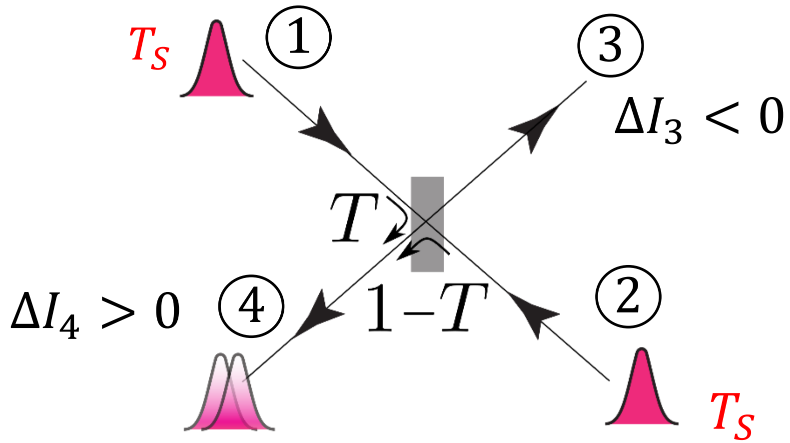
Poissonian limit, $T_S \ll 1$

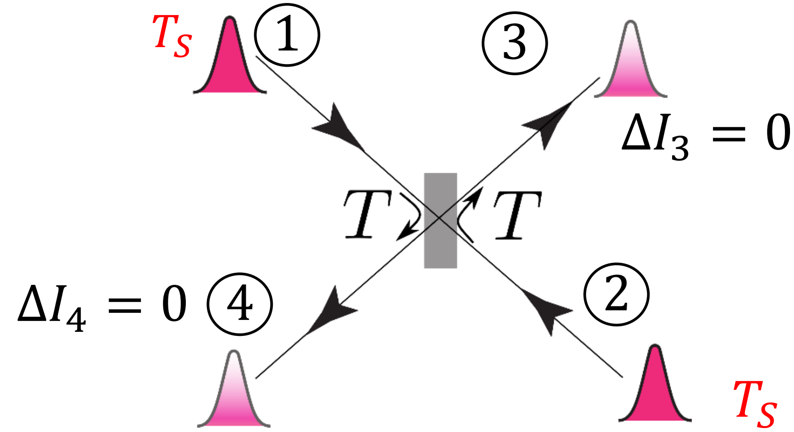
Fano factor: $P = \dfrac{\langle \Delta I_3 \Delta I_4 \rangle}{\langle \Delta I_{RP}^2 \rangle}$

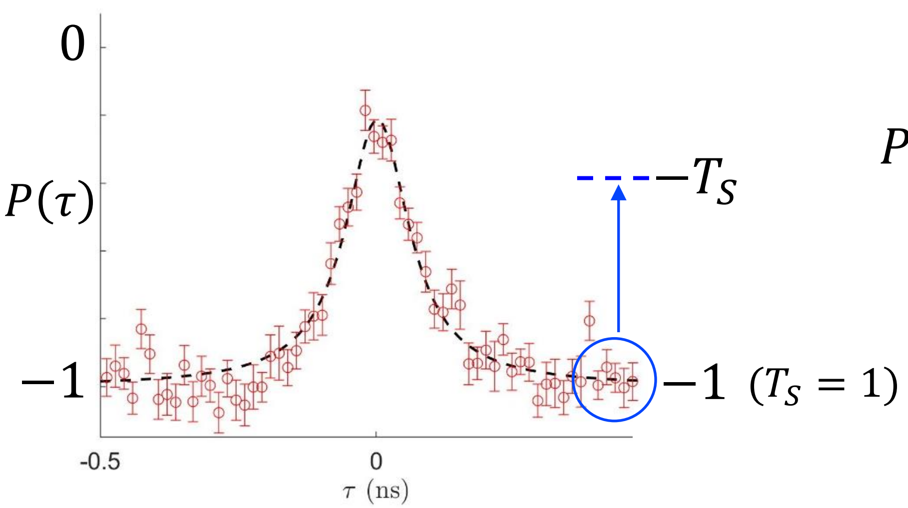
$\langle \Delta I_{RP}^2 \rangle = qT(1-T)I_+/T_{meas}$

Total input current: $I_+ = I_1^{in} + I_2^{in}$

Collider with random poissonian sources: classical model



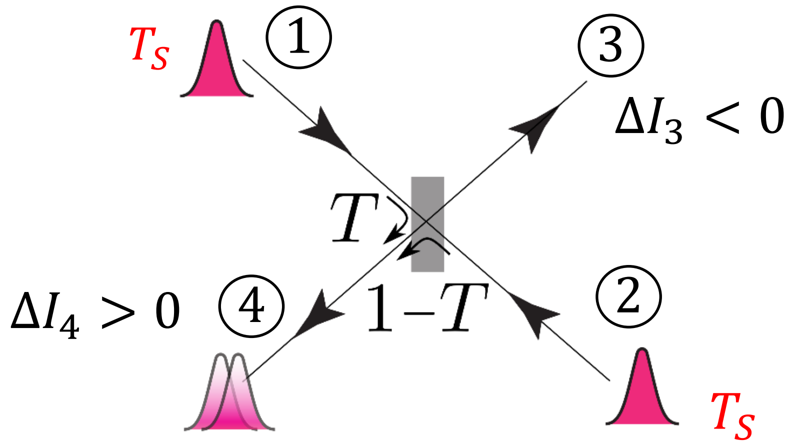




$$P_{cl} = \frac{\langle \Delta I_3 \Delta I_4 \rangle_{cl}}{\langle \Delta I_{RP}^2 \rangle} = -T_S \Rightarrow P_{cl} \approx 0 \text{ for, } T_S \ll 1$$

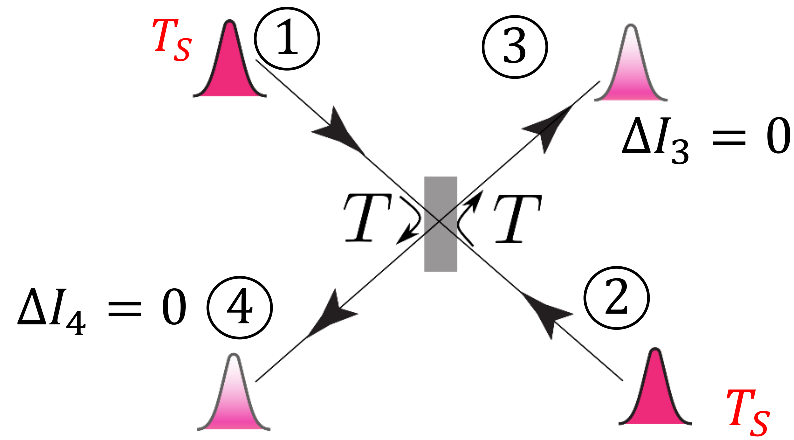
No cross-correlations for
classical Poissonian sources

Collider with random poissonian sources: fermions/bosons



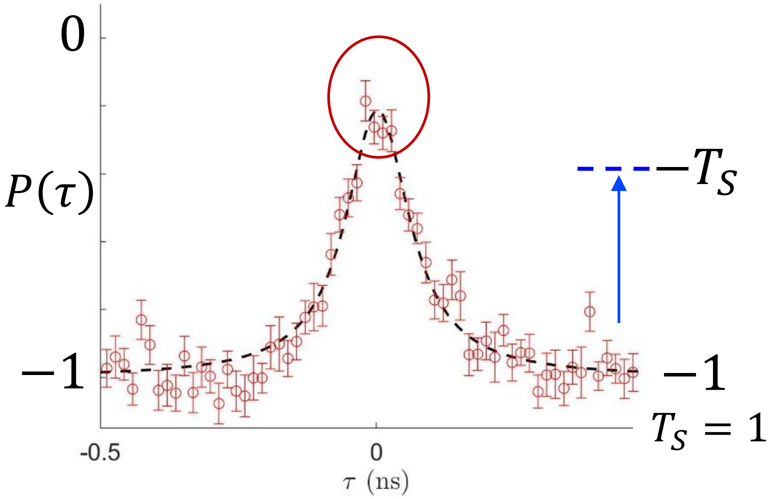
Boson bunching

$$\langle \Delta I_3 \Delta I_4 \rangle_B = \langle \Delta I_3 \Delta I_4 \rangle_{cl} - \alpha T_S^2$$



Fermion antibunching

$$\langle \Delta I_3 \Delta I_4 \rangle_F = \langle \Delta I_3 \Delta I_4 \rangle_{cl} + \alpha T_S^2$$



Fermions: $\langle \Delta I_3 \Delta I_4 \rangle_F = 0 \longrightarrow P_F(I_- = 0)$

fermion antibunching

Fermions and bosons in the poissonian limit, $T_S \ll 1$: $P_{F/B} \approx P_{cl} = 0$

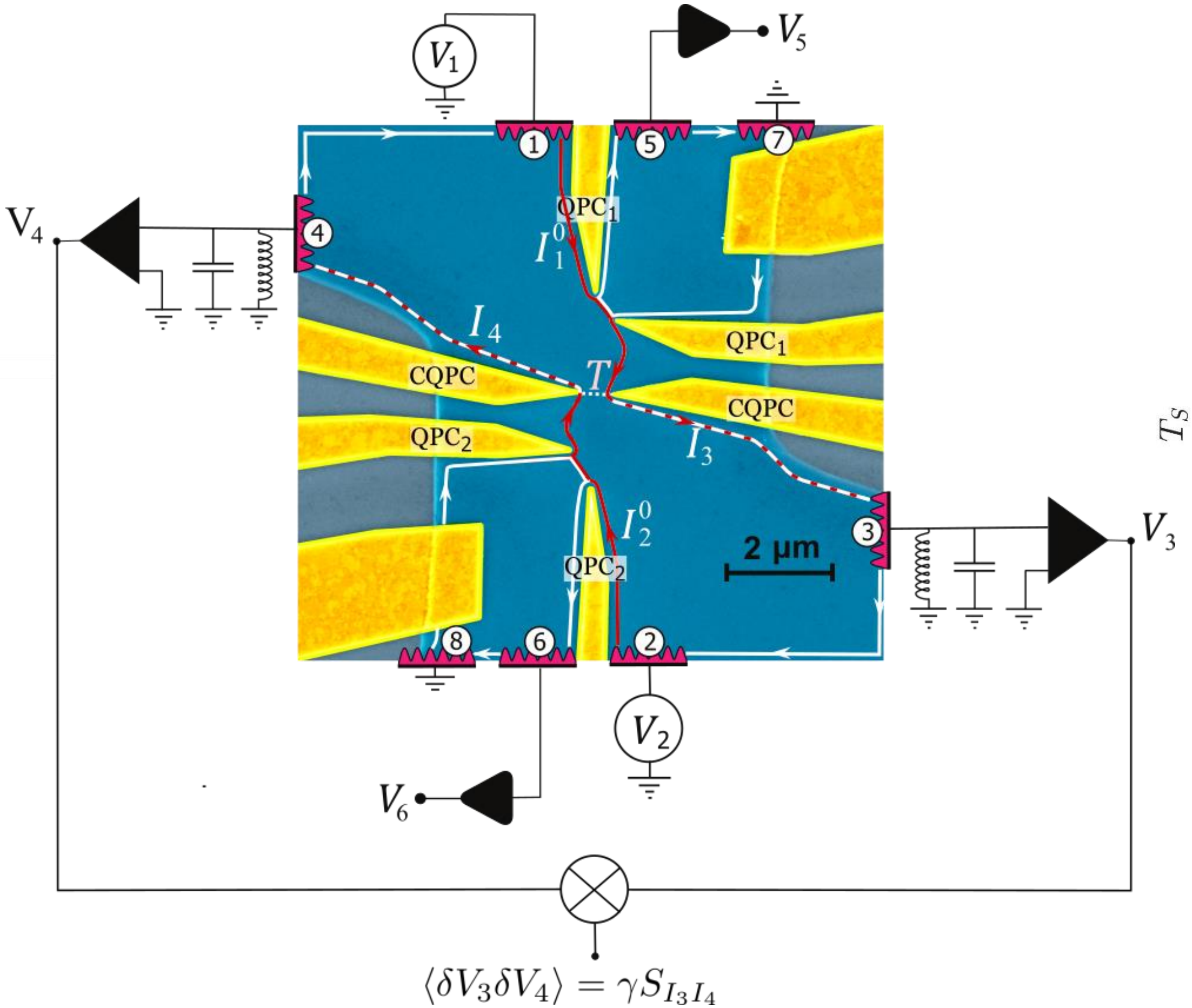
Boson bunching and fermion antibunching vanish for $T_S \ll 1$

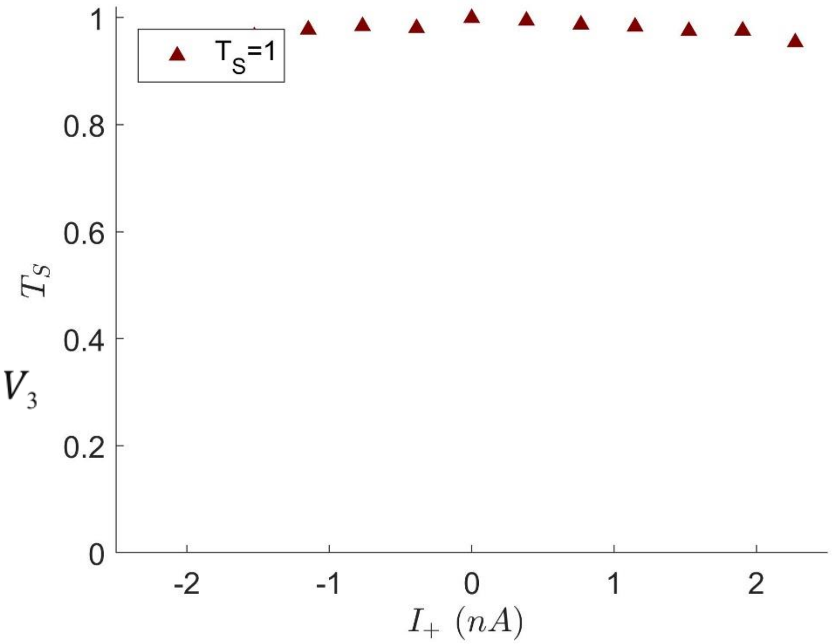
Balanced collider, $I_- = 0$, electron case, $\nu = 2$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: $q = e$, fermions

$\nu = 2, T = 0.4, T_S = 1$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

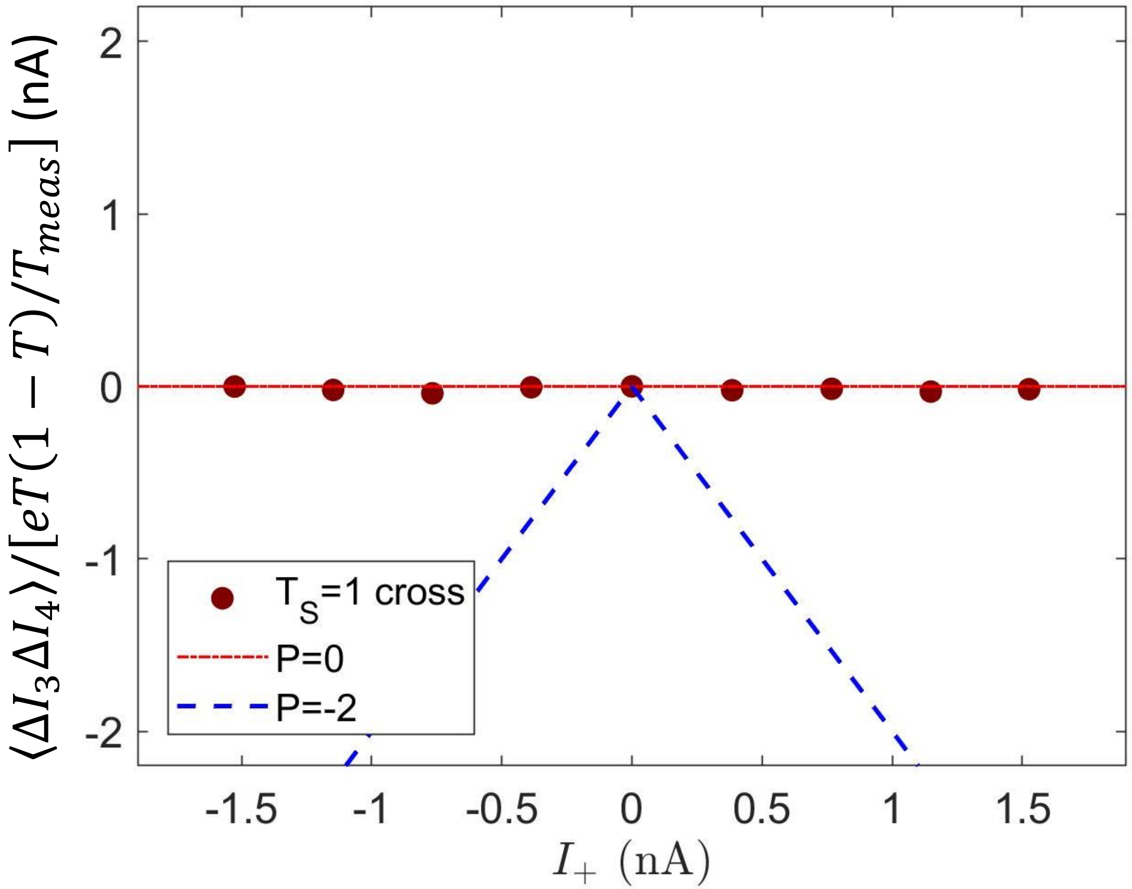
M. Ruelle et al., PRX **13**, 011031 (2023)

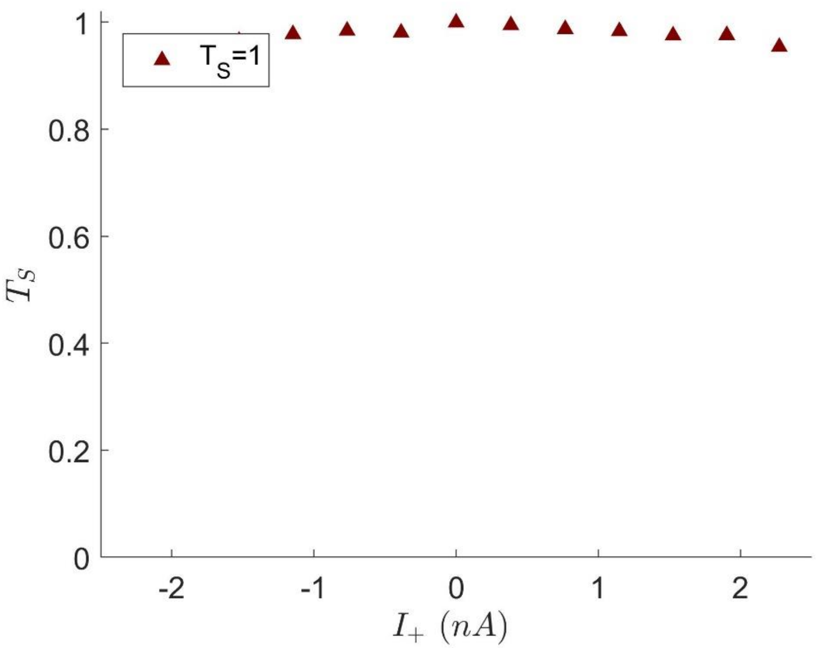
Balanced collider, $I_- = 0$, electron case, $\nu = 2$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: q $= e$, fermions

$\nu = 2, T = 0.4, T_S = 1$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

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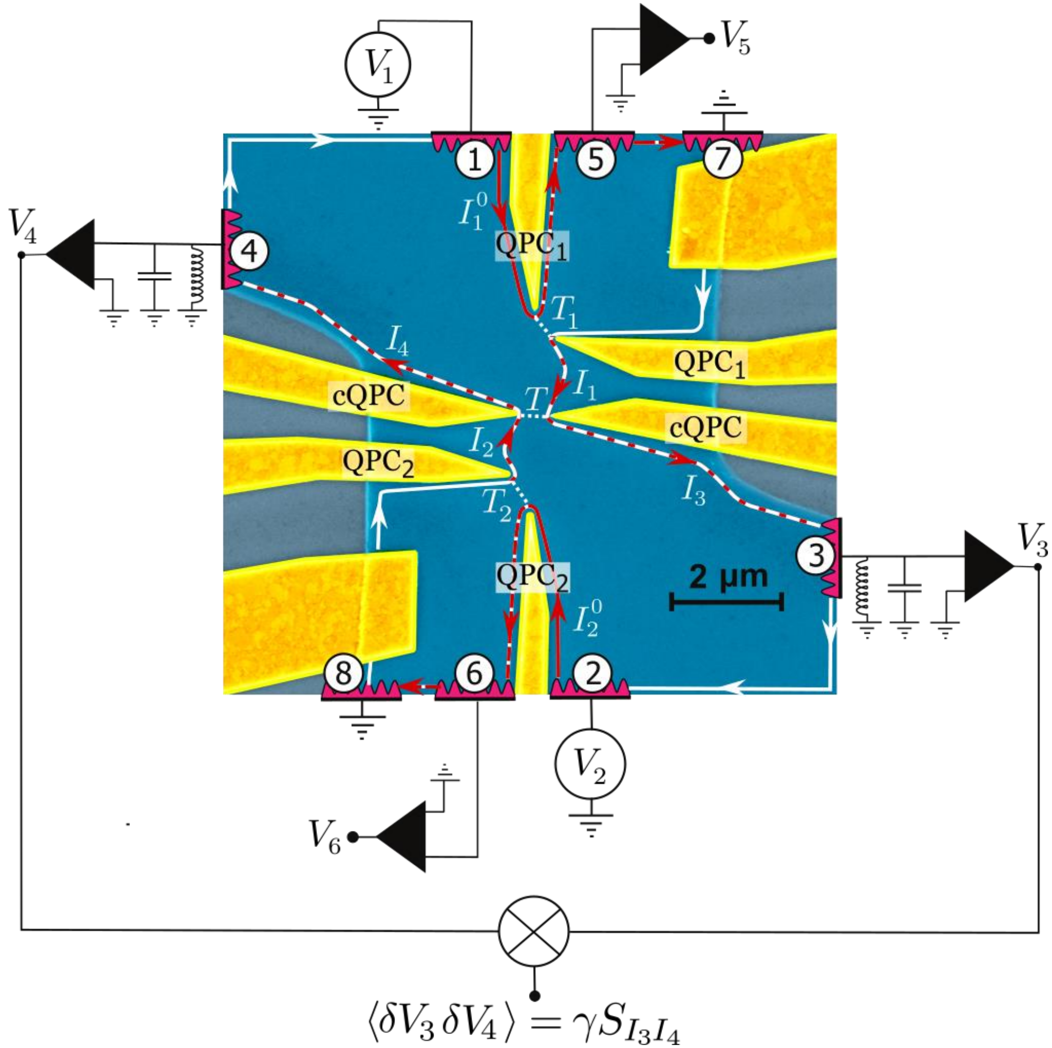
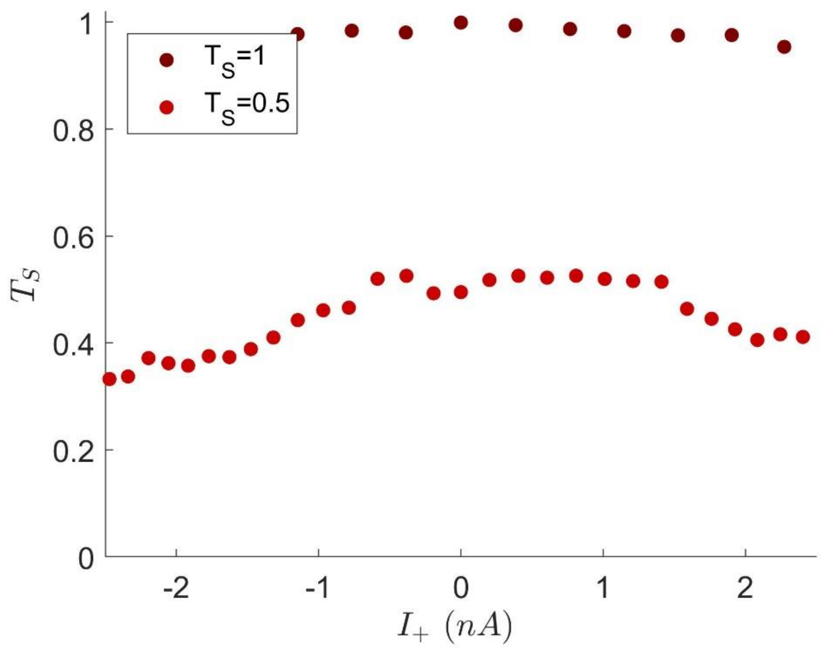
Balanced collider, $I_- = 0$, electron case, $\nu = 2$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: $q = e$, fermions

$\nu = 2, T = 0.4, T_S = 0.5$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

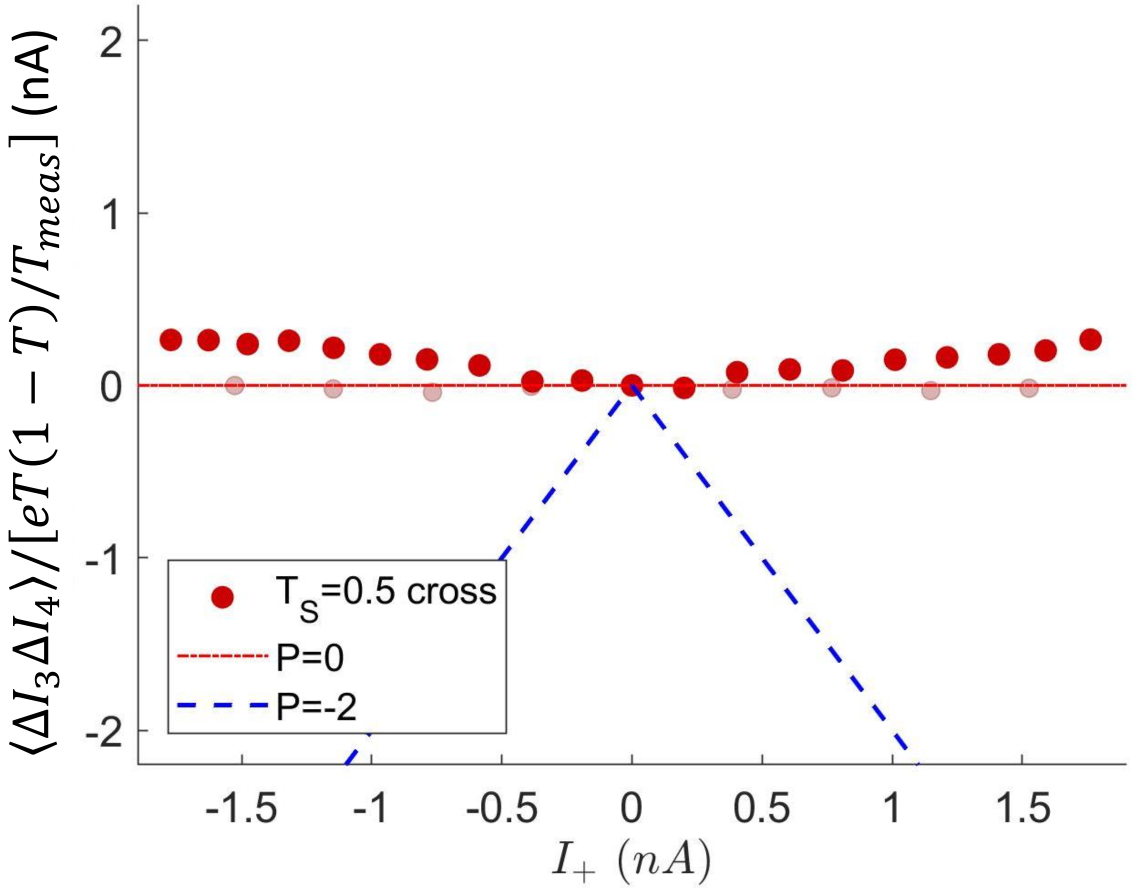
M. Ruelle et al., PRX **13**, 011031 (2023)

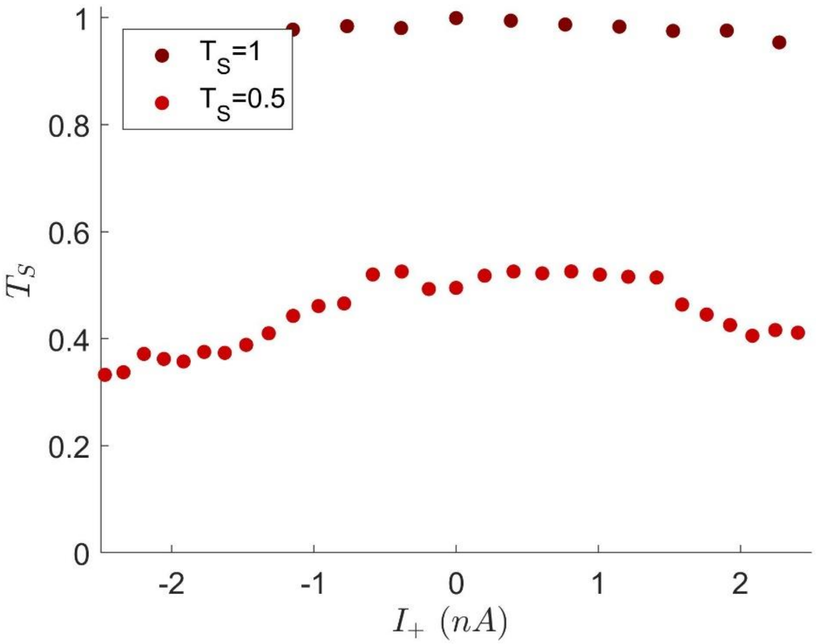
Balanced collider, $I_- = 0$, electron case, $\nu = 2$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: $q = e$, fermions

$\nu = 2, T = 0.4, T_S = 0.5$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

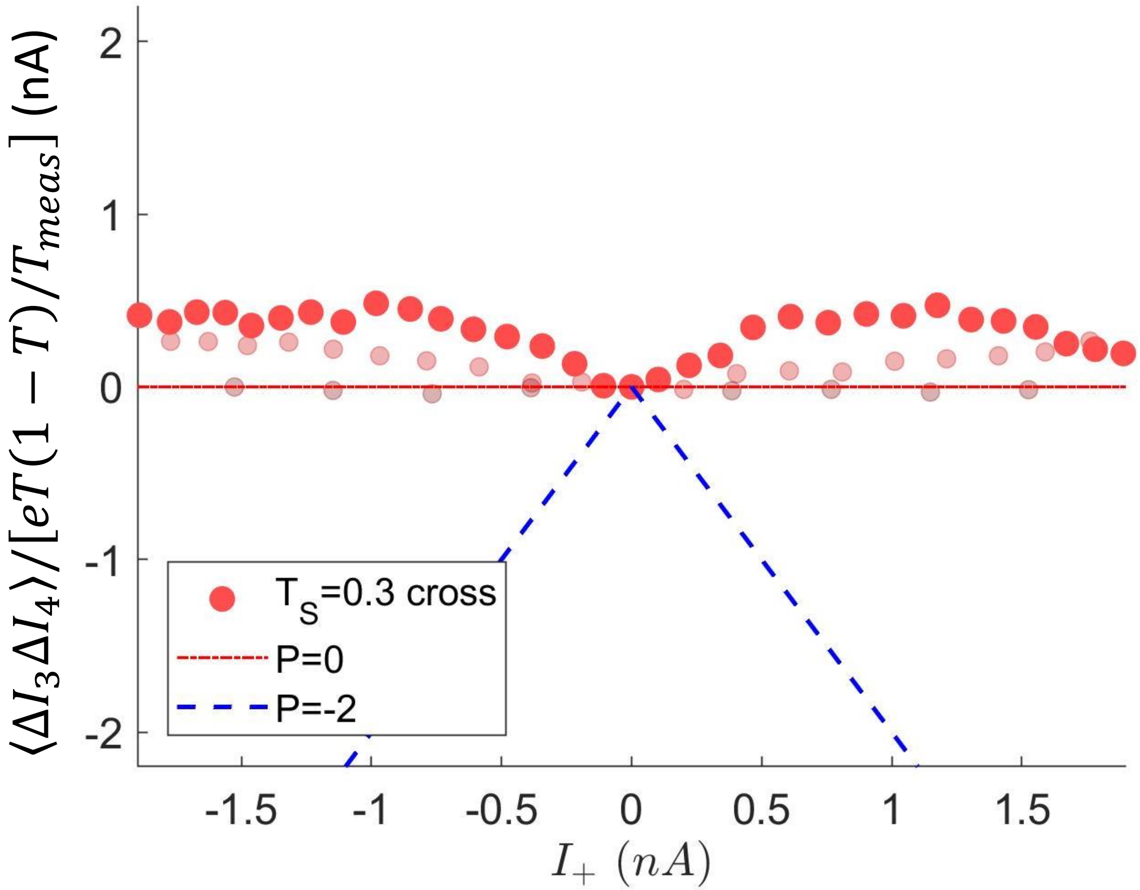
M. Ruelle et al., PRX **13**, 011031 (2023)

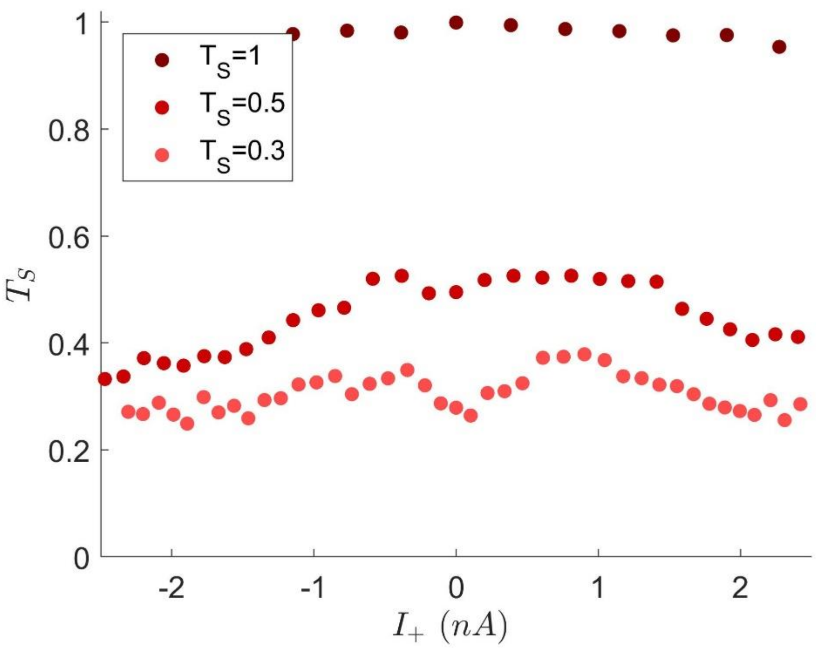
Balanced collider, $I_- = 0$, electron case, $\nu = 2$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: q $= e$, fermions

$\nu = 2, T = 0.4, T_S = 0.3$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

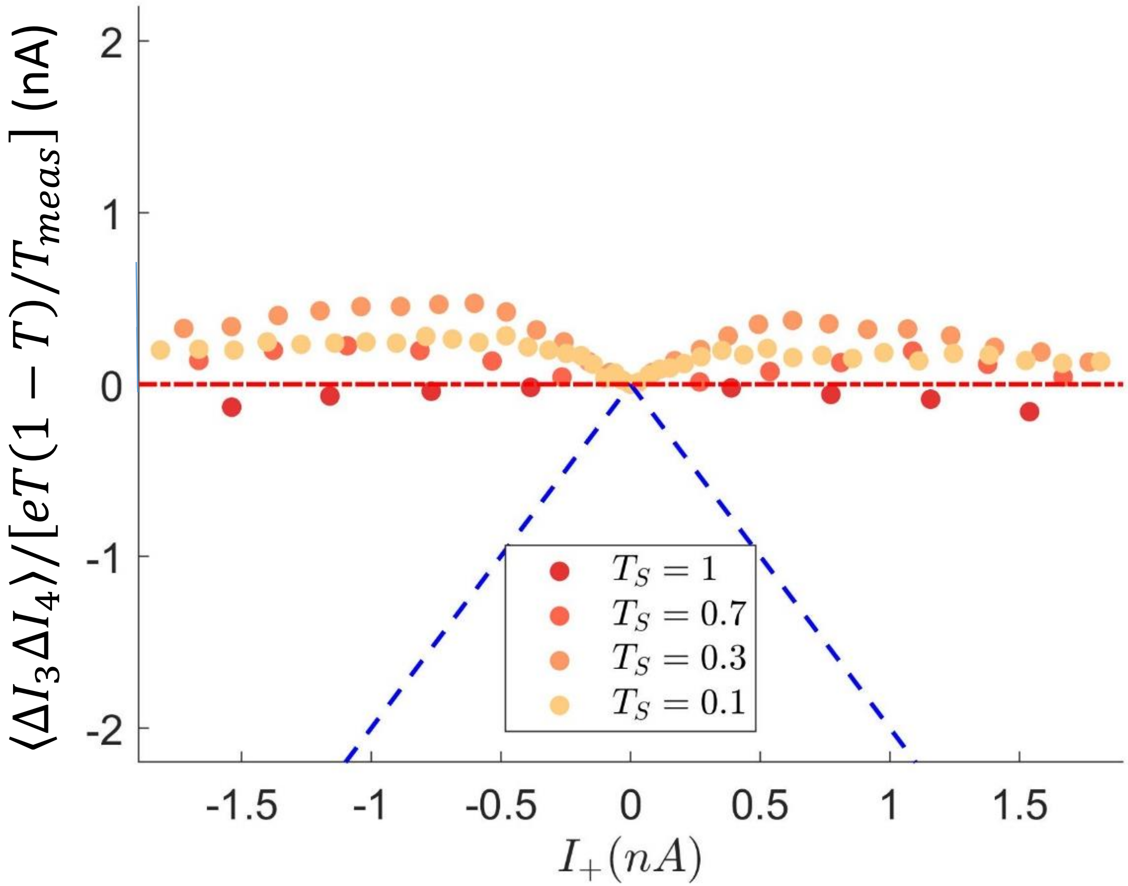
M. Ruelle et al., PRX **13**, 011031 (2023)

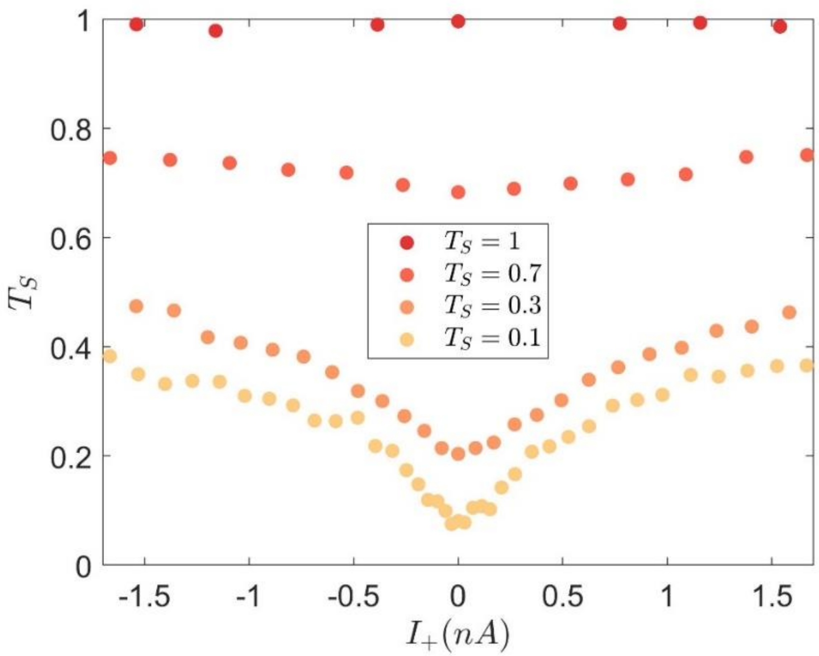
Balanced collider, $I_- = 0$, electron case, $\nu = 3$

Balanced case: $I_1^{in} = I_2^{in}$

Integer case: $q = e$, fermions

$\nu = 3, T = 0.4, T_S = \{1; 0.7; 0.3; 0.1\}$





$P(I_- = 0) = 0^+$ fermions

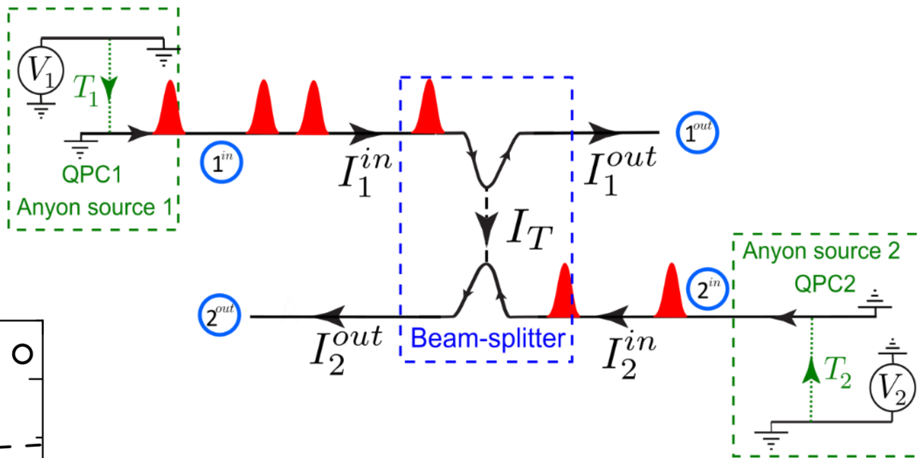
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

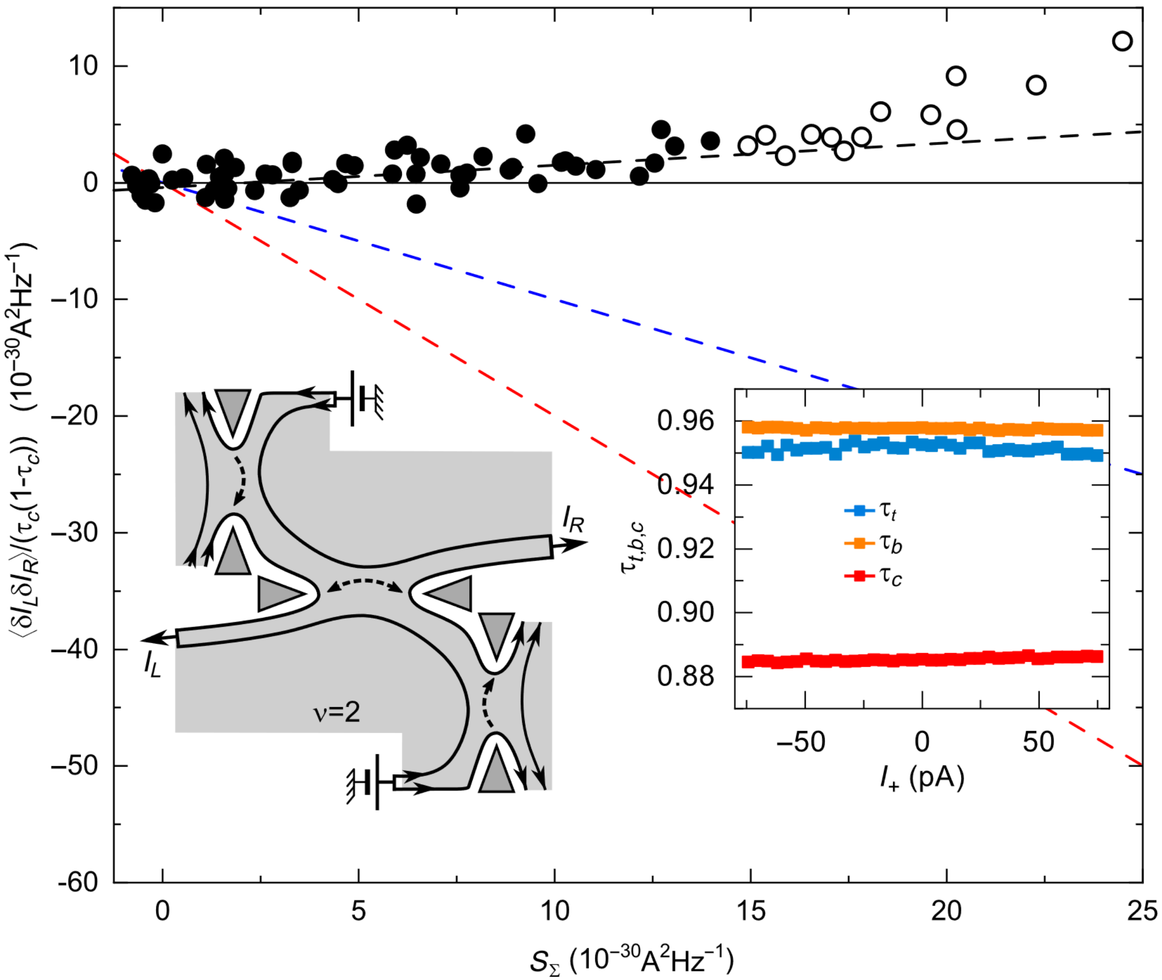
M. Ruelle et al., PRX **13**, 011031 (2023)

Balanced collider, $I_1^{in} = I_2^{in}$, electron case, $\nu = 2$

Integer case: q $= e$, electrons

$\nu = 2, \nu = 3$





$$P\left(I_1^{in} = I_2^{in}\right) = 0^+ \text{ fermions}$$

Other experiment in
F. Pierre and A. Anthore group

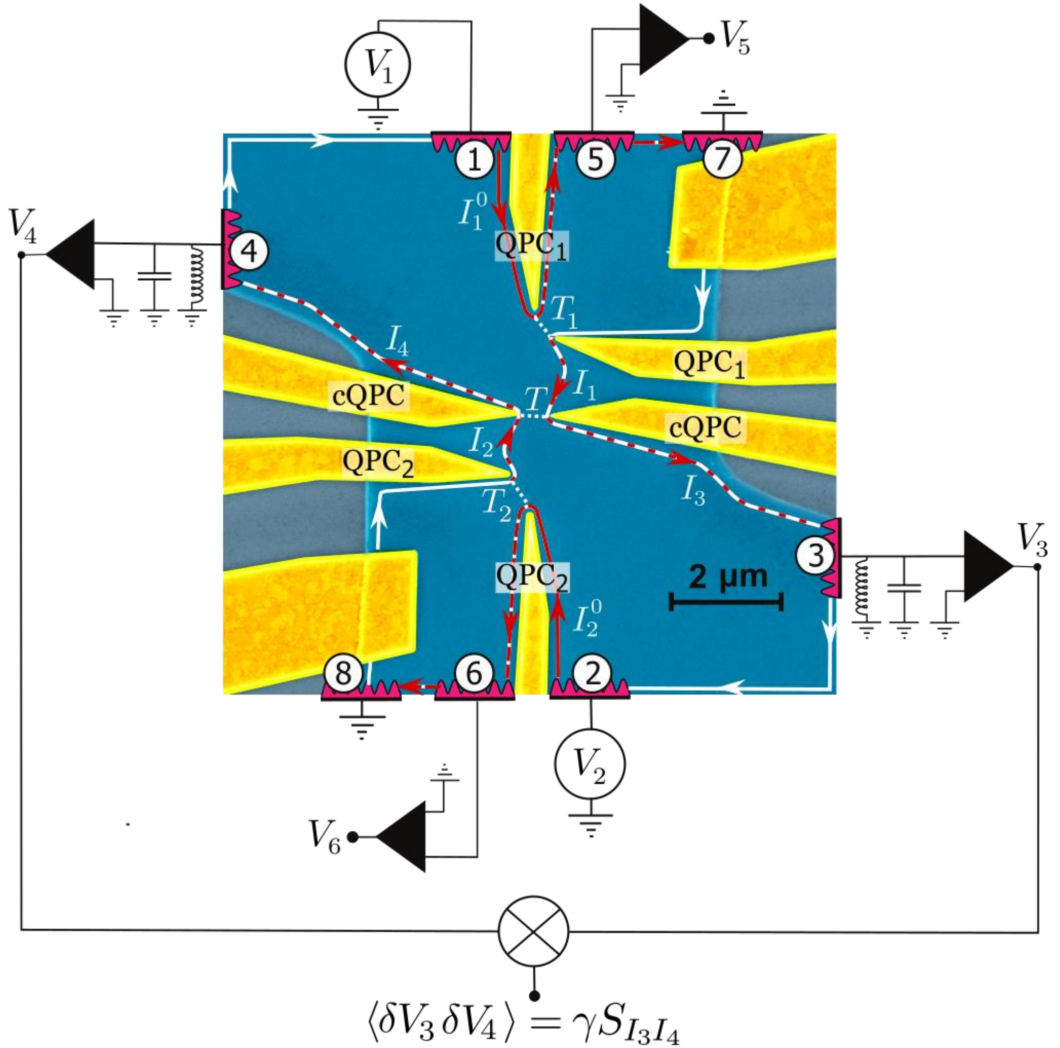
P. Glidic et al., Phys. Rev. X **13**, 011030 (2023).

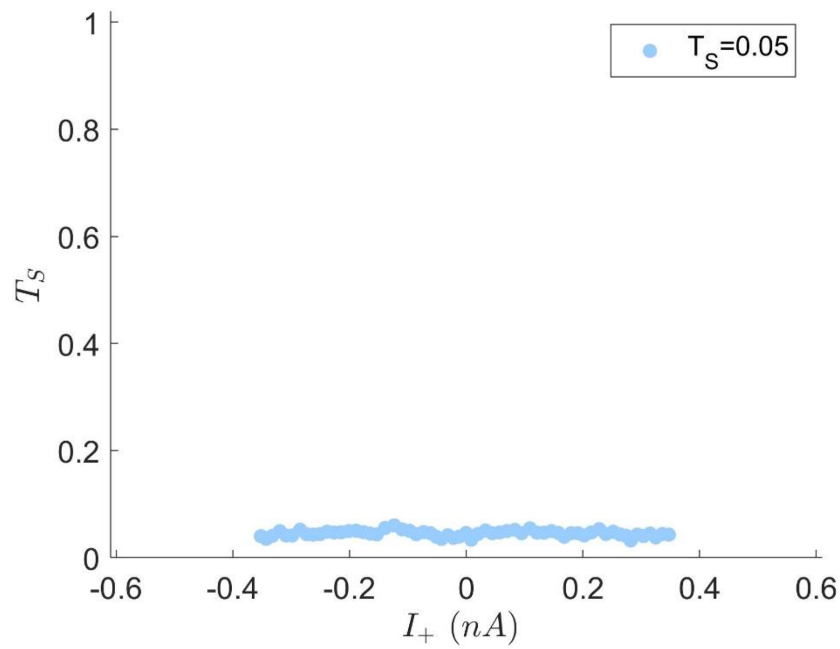
Balanced collider, $I_- = 0$, anyon case, $\nu = 1/3$

Balanced case: $I_1^{in} = I_2^{in}$

Fractional case: q $= e/3$, anyons

$\nu = 1/3, T = 0.3, T_S = 0.05$





H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

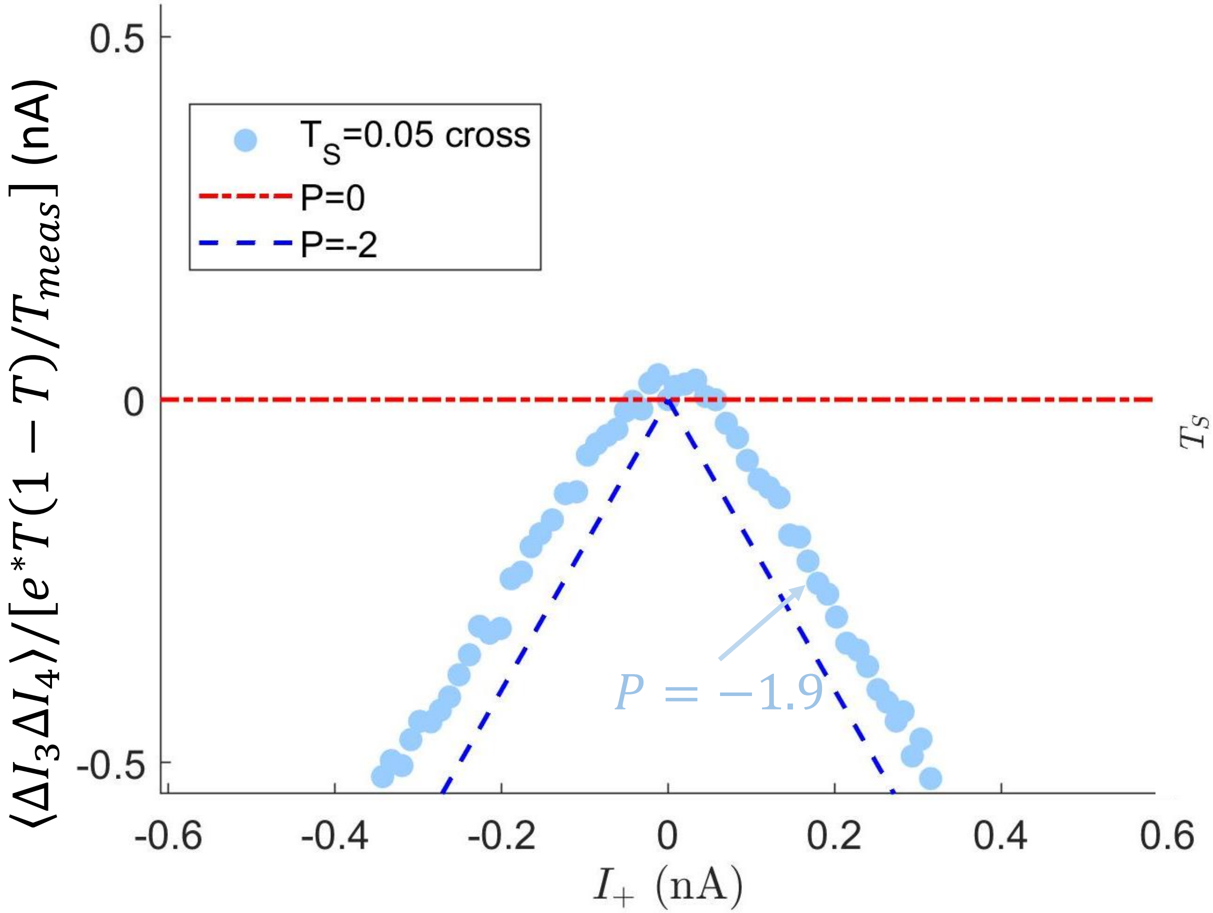
M. Ruelle et al., PRX **13**, 011031 (2023)

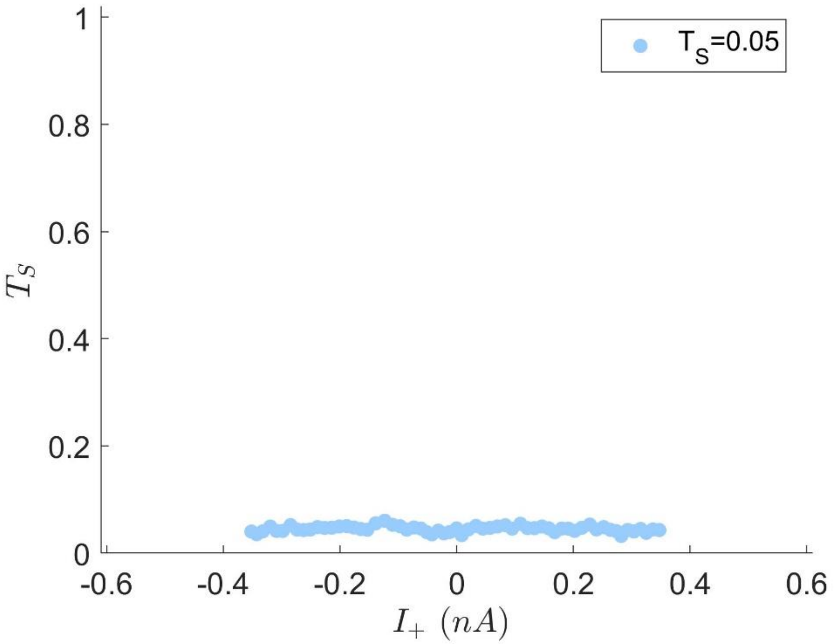
Balanced collider, $I_- = 0$, anyon case, $\nu = 1/3$

Balanced case: $I_1^{in} = I_2^{in}$

Fractional case: $q = e/3$, anyons

$\nu = 1/3, T = 0.3, T_S = 0.05$





$P(I_- = 0) \approx -2$ anyons ($T_S \ll 1$)

H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

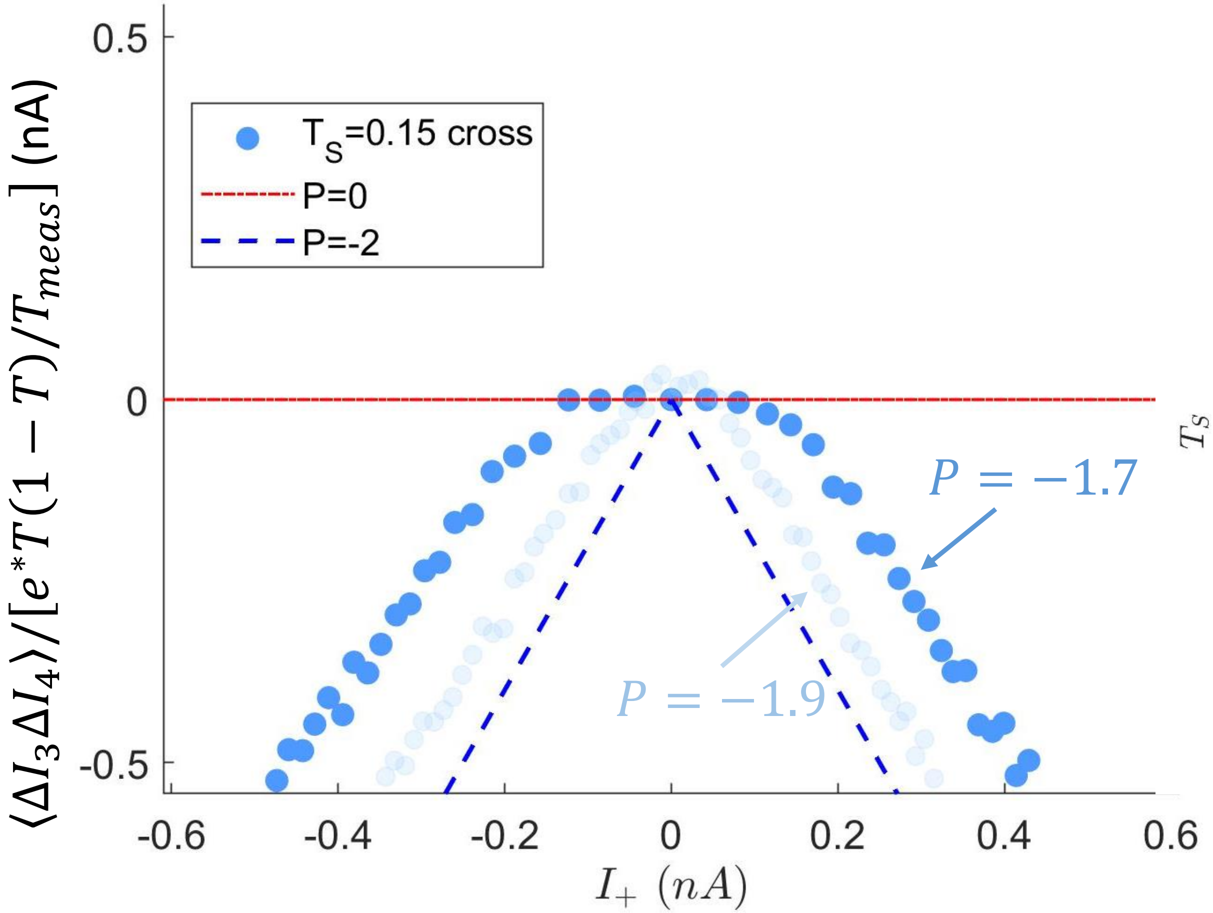
M. Ruelle et al., PRX **13**, 011031 (2023)

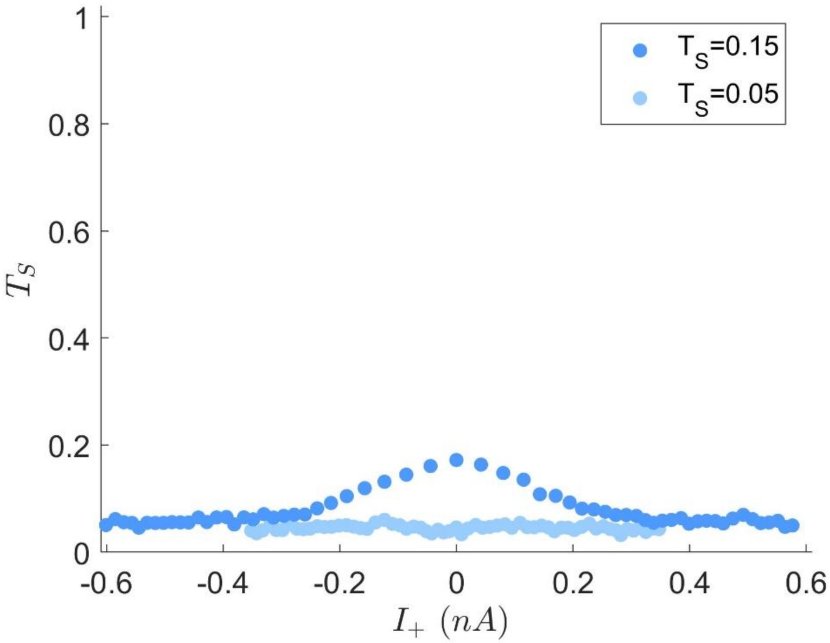
Balanced collider, $I_- = 0$, anyon case, $\nu = 1/3$

Balanced case: $I_1^{in} = I_2^{in}$

Fractional case: $q = e/3$, anyons

$\nu = 1/3, T = 0.3, T_S = 0.15$





$P(I_- = 0) \approx -2$ anyons ($T_S \ll 1$)

H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

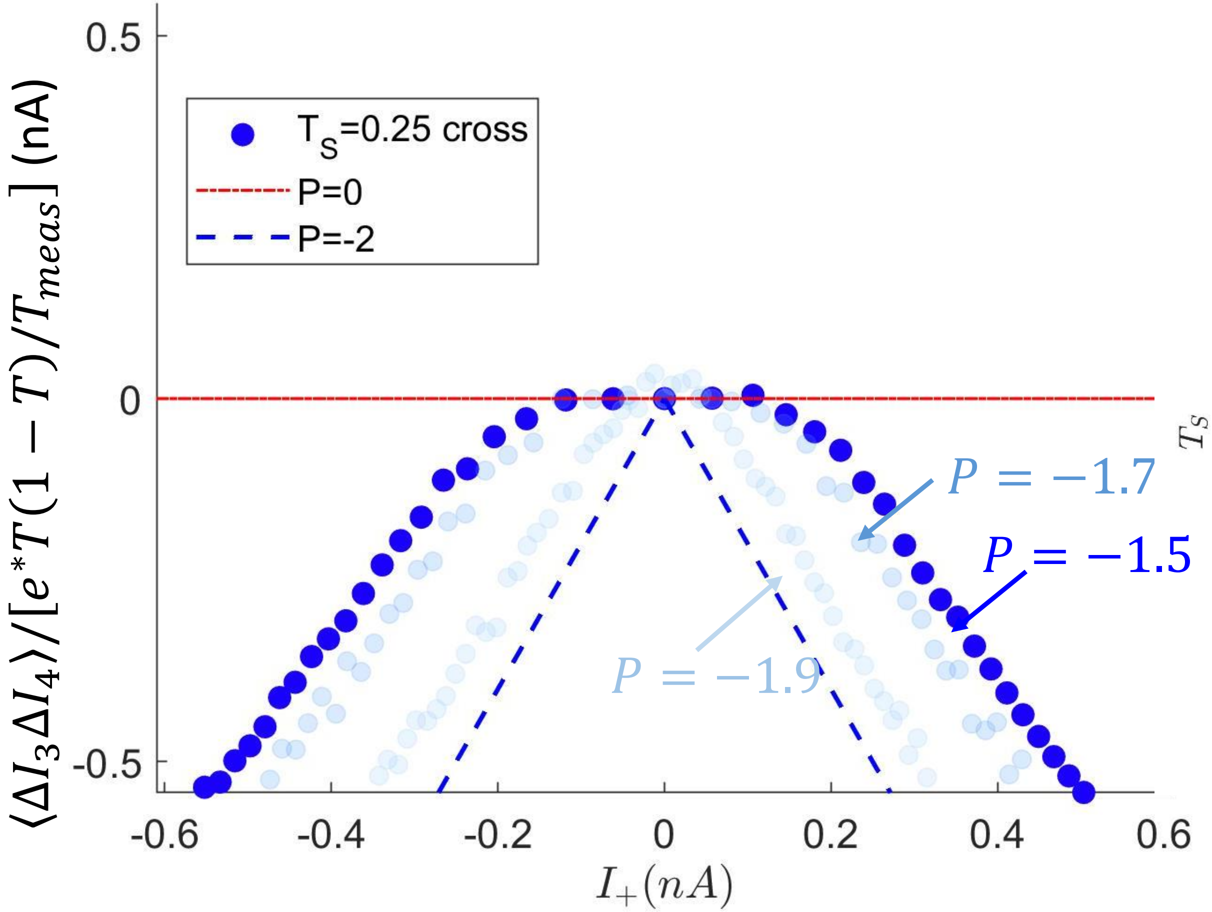
M. Ruelle et al., PRX **13**, 011031 (2023)

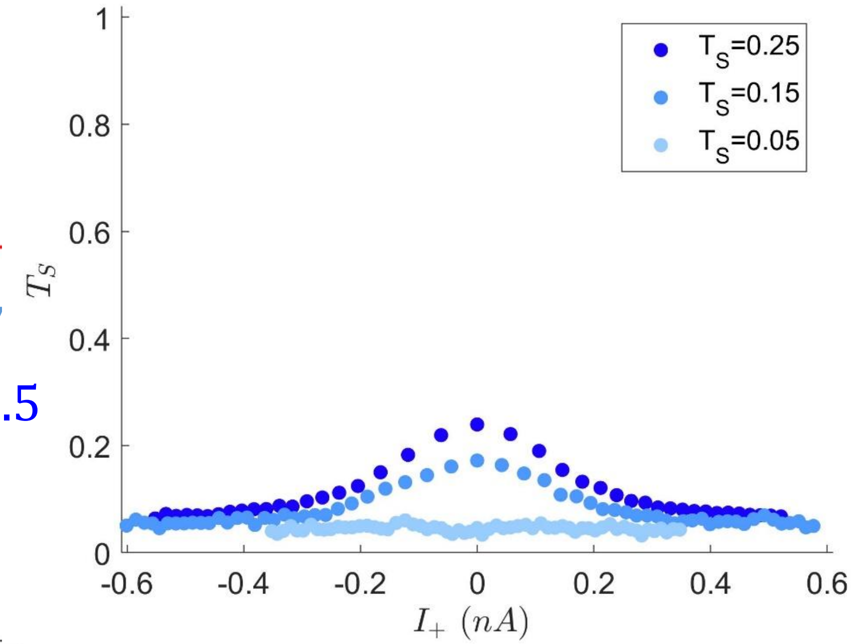
Balanced collider, $I_- = 0$, anyon case, $\nu = 1/3$

Balanced case: $I_1^{in} = I_2^{in}$

Fractional case: q $= e/3$, anyons

$\nu = 1/3, T = 0.3, T_S = 0.25$





$P(I_- = 0) \approx -2$ anyons ($T_S \ll 1$)

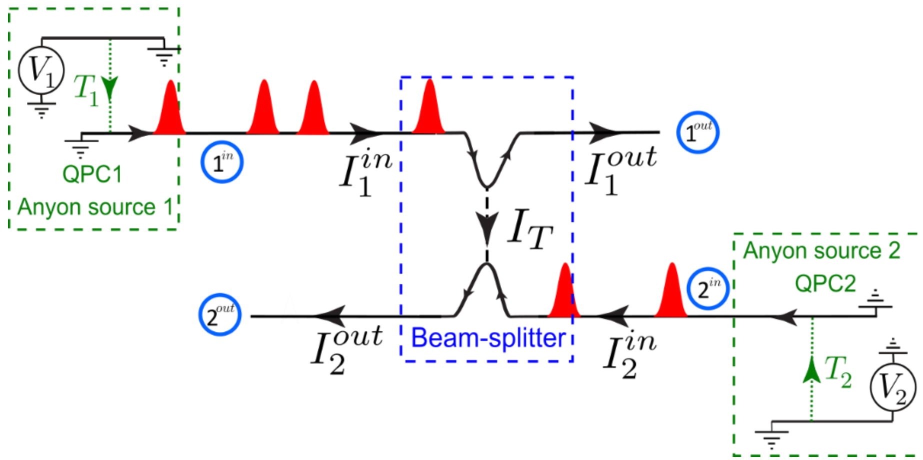
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

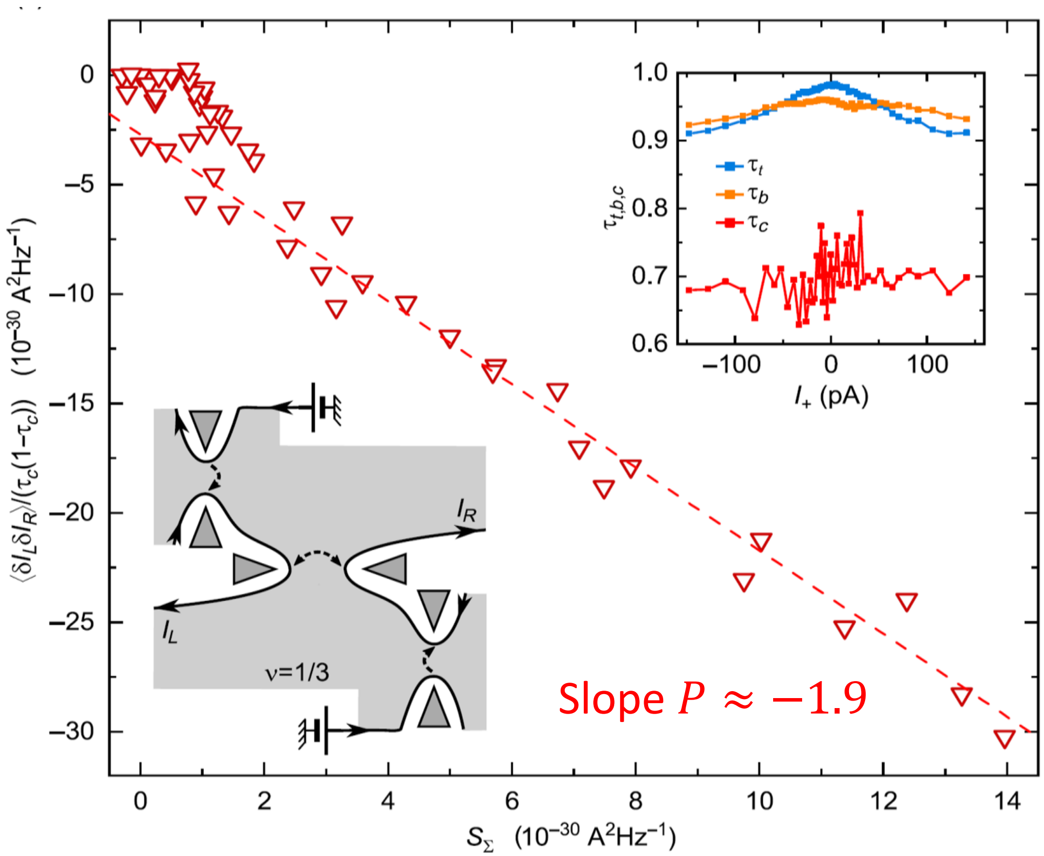
M. Ruelle et al., PRX **13**, 011031 (2023)

Balanced collider, $I_1^{in} = I_2^{in}$, anyon case, $\nu = 1/3$

Fractional case: q $= e/3$, anyons

$\nu = 1/3, T = 0.3, T_S = 0.05$





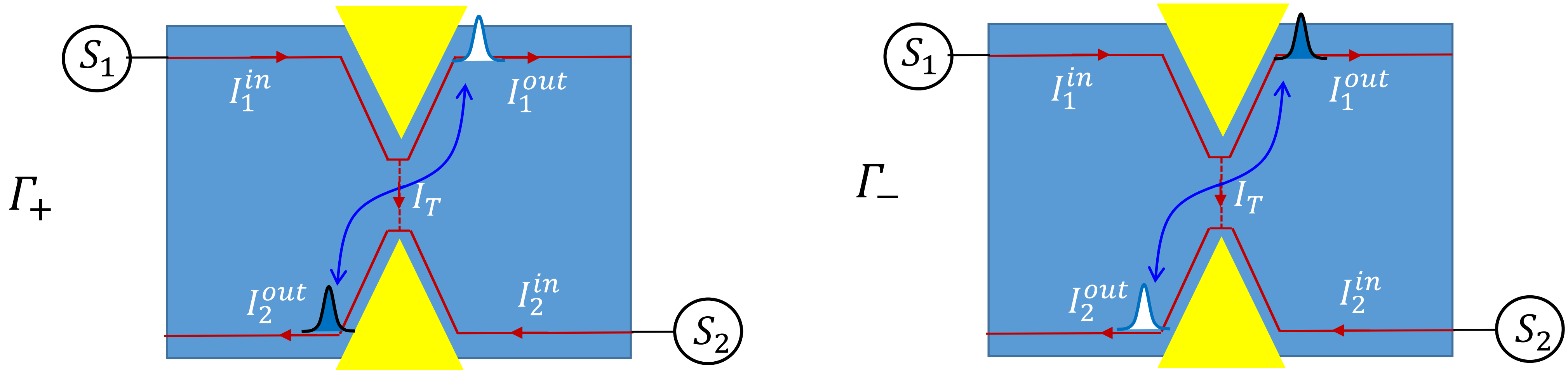
Other experiment in
F. Pierre and A. Anthore group

P. Glidic et al., Phys. Rev. X **13**, 011030 (2023).

$$P\left(I_1^{in} = I_2^{in}\right) \approx -2 \text{ anyons } (T_S \ll 1)$$

Two-particle interferometry and anyon tunneling

Weak backscattering regime: lowest order in tunneling $H_T = \zeta\psi_1^\dagger\psi_2 + \zeta^*\psi_2^\dagger\psi_1$

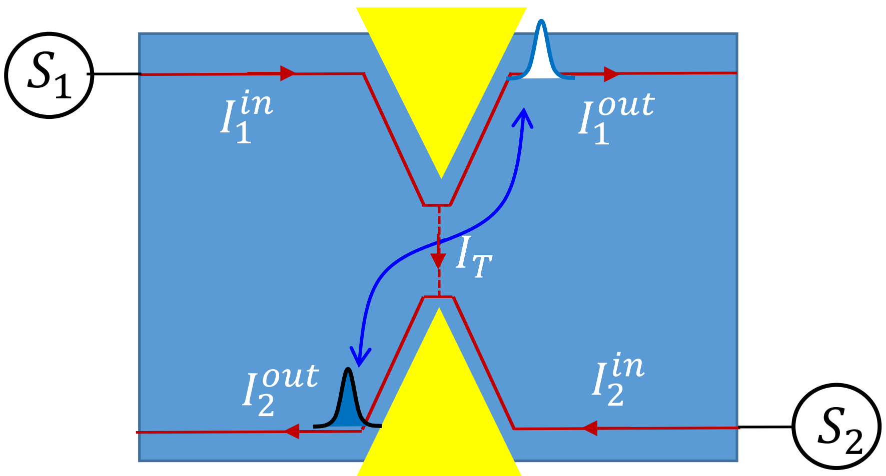


$I_T = q(\Gamma_+ - \Gamma_-)$	Tunneling current
$\langle \Delta I_T^2 \rangle = q^2(\Gamma_+ + \Gamma_-)/T_{meas}$	Noise of tunneling current

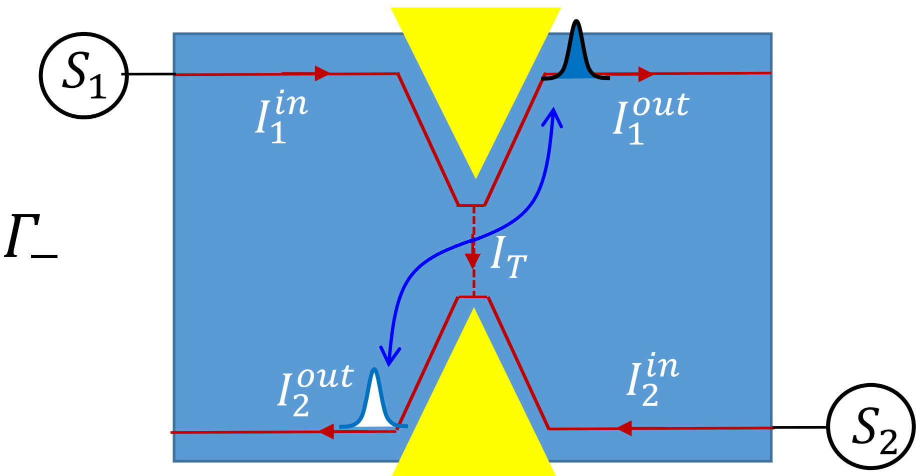
Two-particle interferometry and anyon tunneling

Weak backscattering regime: lowest order in tunneling $H_T = \zeta \psi_1^{+} \psi_2 + \zeta^* \psi_2^{+} \psi_1$

Γ_+



Γ_-



$I_T = q(\Gamma_+ - \Gamma_-)$	Tunneling current
$\langle \Delta I_T^2 \rangle = q^2 (\Gamma_+ + \Gamma_-)/T_{meas}$	Noise of tunneling current

$$\Gamma_+ \propto \int_{-\infty}^{+\infty} d\tau \underbrace{\langle \psi_1^{+,in}(\tau) \psi_1^{in}(0) \rangle}_{G^{(1)}(\tau)} \langle \psi_2^{in}(\tau) \psi_2^{+,in}(0) \rangle$$

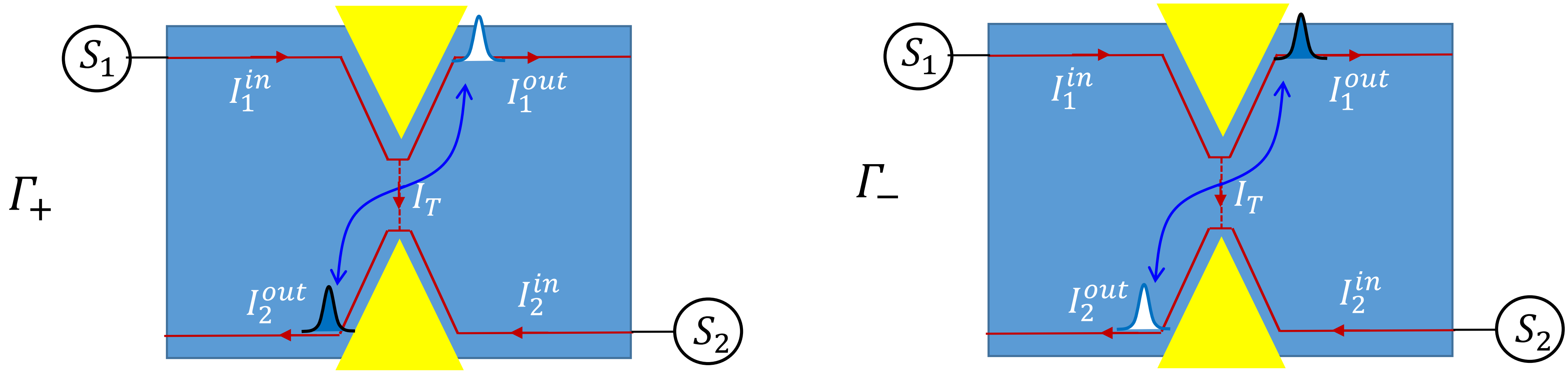
2 particle interferometry
Product of coherence/correlation functions

$G^{(1)}(\tau)$ (optics, $G^{(1)}(\tau) = \langle E(\tau) E(0) \rangle$)

$$\Gamma_- \propto \int_{-\infty}^{+\infty} d\tau \langle \psi_1^{in}(\tau) \psi_1^{+,in}(0) \rangle \langle \psi_2^{+,in}(\tau) \psi_2^{in}(0) \rangle$$

Two-particle interferometry and anyon tunneling

Weak backscattering regime: lowest order in tunneling $H_T = \zeta\psi_1^+\psi_2 + \zeta^*\psi_2^+\psi_1$



$I_T = q(\Gamma_+ - \Gamma_-)$	Tunneling current
$\langle \Delta I_T^2 \rangle = q^2(\Gamma_+ + \Gamma_-)/T_{meas}$	Noise of tunneling current

$$\Gamma_+ \propto \int_{-\infty}^{+\infty} d\tau \langle \psi_1^{+,in}(\tau)\psi_1^{in}(0)\rangle\langle \psi_2^{in}(\tau)\psi_2^{+,in}(0)\rangle$$

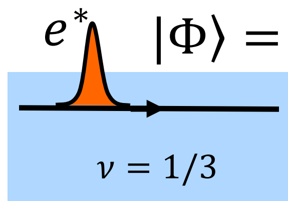
$$\Gamma_- \propto \int_{-\infty}^{+\infty} d\tau \langle \psi_1^{in}(\tau)\psi_1^{+,in}(0)\rangle\langle \psi_2^{+,in}(\tau)\psi_2^{in}(0)\rangle$$

Fourier space and fermions:

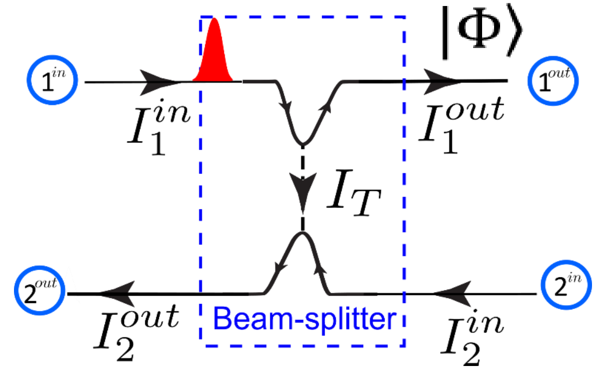
$$\Gamma_+ \propto \int_{-\infty}^{+\infty} d\varepsilon f_1(\varepsilon)[1 - f_2(\varepsilon)] \qquad \Gamma_- \propto \int_{-\infty}^{+\infty} d\varepsilon f_2(\varepsilon)[1 - f_1(\varepsilon)]$$

Anyon tunneling at a QPC, single anyon emitted

Single anyon incoming on the QPC at time t_0:



$$|\Phi\rangle = \psi_1^{+}(t_0)|GS\rangle$$



Tunneling rate: $\Gamma_{-} \propto \int_{-\infty}^{+\infty} d\tau \langle \Phi|\psi_1^{in}(\tau)\psi_1^{+,in}(0)|\Phi\rangle\langle GS|\psi_2^{+,in}(\tau)\psi_2^{in}(0)|GS\rangle$

Non-equilibrium: 1 anyon emitted

Equilibrium: $G_{eq,\delta}(t-t')$

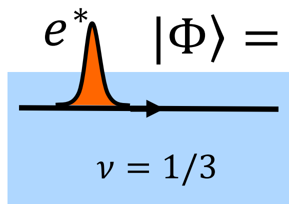
Morel et al., PRB **105**, 075433 (2022),
Lee et al., Nat. Commun. **13**, 6660 (2022)

Mora, arXiv:2212.05123 (2022)
Schiller et al., PRL **131** 186601 (2023)

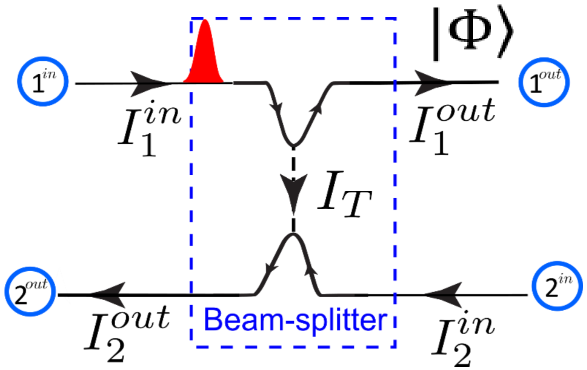
LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

Anyon tunneling at a QPC, single anyon emitted

Single anyon incoming on the QPC at time t_0:



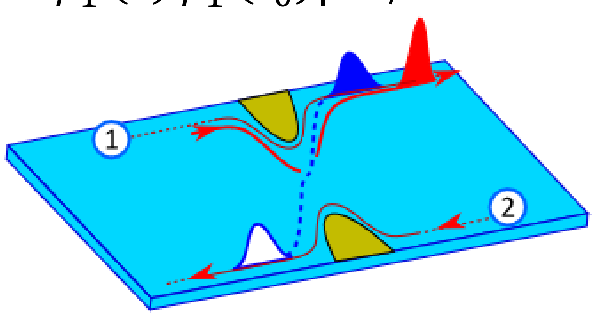
$$|\Phi\rangle = \psi_1^+(t_0)|GS\rangle$$



Tunneling rate: $$\Gamma_- \propto \int_{-\infty}^{+\infty} d\tau \langle GS|\psi_1(t_0)\psi_1(\tau)\psi_1^+(0)\psi_1^+(t_0)|GS\rangle\langle GS|\psi_2^{+,in}(\tau)\psi_2^{in}(0)|GS\rangle$$

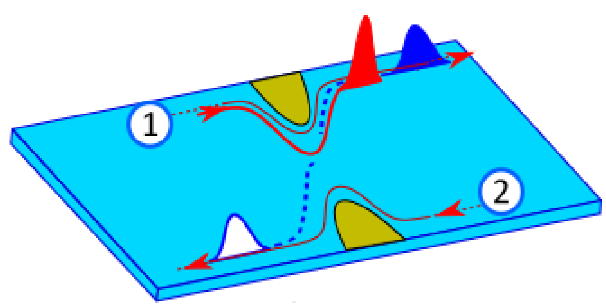
$$0 \le t_0 \le \tau$$

$$\psi_1^+(\tau)\psi_1^+(t_0)|GS\rangle$$



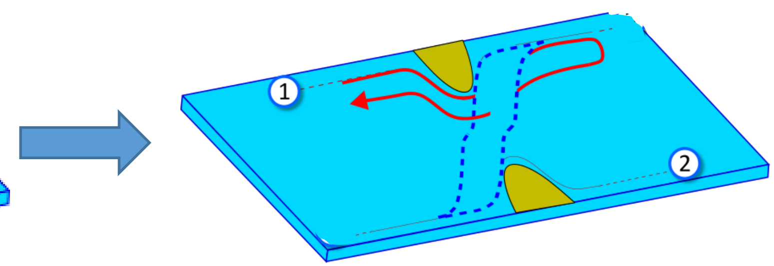
emitted at $\tau > t_0$

$$\psi_1^+(0)\psi_1^+(t_0)|GS\rangle$$



emitted at $t = 0 < t_0$

$$\langle\Phi|\psi_1^{in}(\tau)\psi_1^{+,in}(0)|\Phi\rangle = e^{-i\theta}G_{eq,\delta}(\tau)$$



θ: mutual braiding phase between blue and red anyons

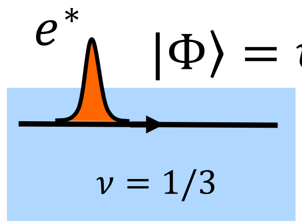
$\nu = 1/3 \qquad \theta = 2\pi/3$

Morel et al., PRB **105**, 075433 (2022),
Lee et al., Nat. Commun. **13**, 6660 (2022)

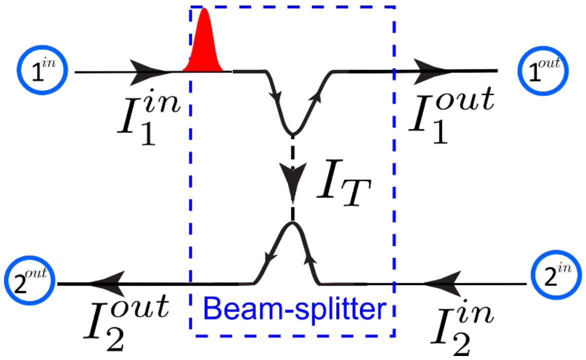
Mora, arXiv:2212.05123 (2022)
Schiller et al., PRL **131** 186601 (2023)

Anyon tunneling at a QPC, single anyon emitted

Single anyon incoming on the QPC at time t_0:

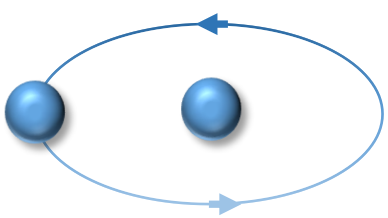


$$|\Phi\rangle = \psi_r^+(t_0)|GS\rangle$$



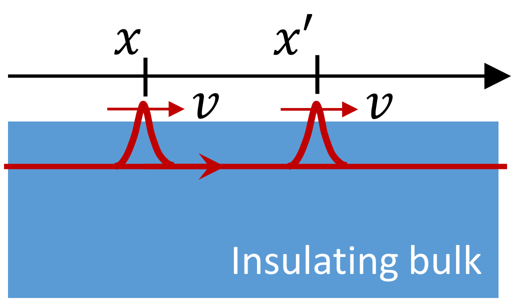
Tunneling rate: $\Gamma_- \propto 2Re\left[\int_0^{+\infty} dt' \langle GS|\psi_r(t_0)\psi_b(\tau)\,\psi_b^+(0)\psi_r^+(t_0)|GS\rangle\langle GS|\psi_{2,a}^+(\tau)\psi_{2,a}(0)|GS\rangle\right]$

Anyons in the bulk:



$$\hat{B}\psi = e^{i\theta}\psi$$

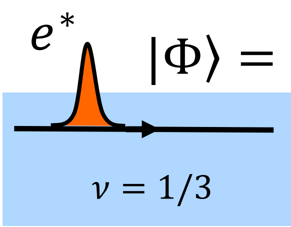
Anyons at the edge:



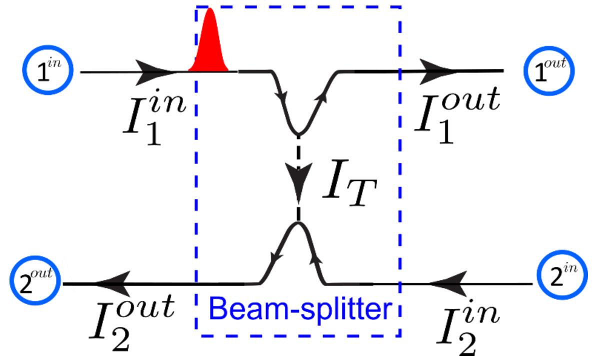
$$\psi_a^+(x)\psi_a^+(x') = e^{i\frac{\theta}{2}\mathrm{Sign}(x'-x)}\psi_a^+(x')\psi_a^+(x)$$

Anyon tunneling at a QPC, single anyon emitted

Single anyon incoming on the QPC at time t_0:

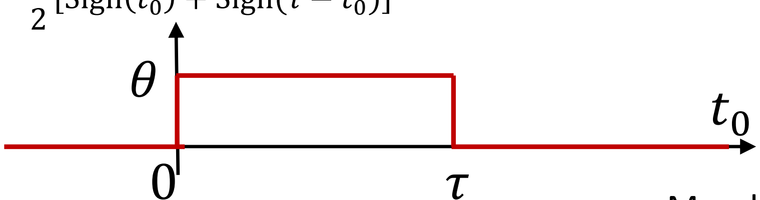


$$|\Phi\rangle = \psi_r^+(t_0)|GS\rangle$$



Tunneling rate: $$\Gamma_- \propto 2Re\left[\int_0^{+\infty} dt' \langle GS|\psi_r(t_0)\psi_b(\tau)\,\psi_b^+(0)\psi_r^+(t_0)|GS\rangle\langle GS|\psi_{2,a}^+(\tau)\psi_{2,a}(0)|GS\rangle\right]$$

$$\Gamma_- \propto 2Re\left[\int_0^{+\infty} d\tau\, e^{-i\frac{\theta}{2}[\mathrm{Sign}(t_0)+\mathrm{Sign}(\tau-t_0)]}\langle GS|\psi_b(\tau)\,\psi_b^+(0)|GS\rangle\langle GS|\psi_{2,a}^+(\tau)\psi_{2,a}(0)|GS\rangle\right]$$



$$\Gamma_- \propto 2Re\left[\int_0^{+\infty} e^{-i\theta N_1(\tau)} G_\delta(\tau)^2 d\tau\right]$$

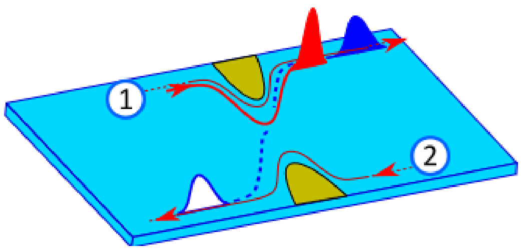
Morel et al., PRB **105**, 075433 (2022),
Lee et al., Nat. Commun. **13**, 6660 (2022)

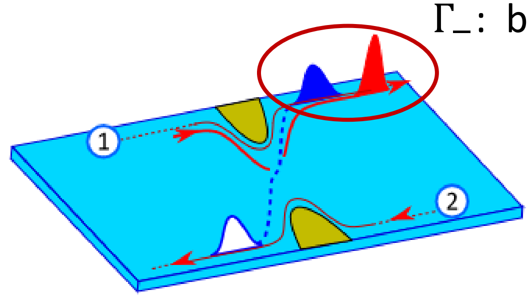
Mora, arXiv:2212.05123 (2022)
Schiller et al., PRL **131** 186601 (2023)

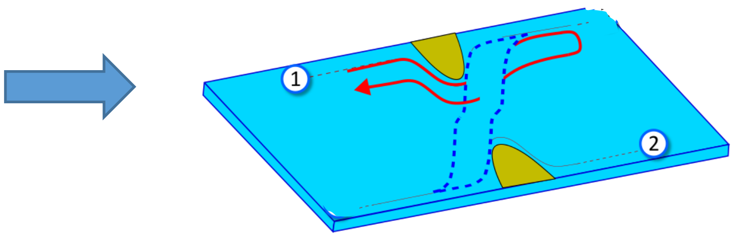
Anyon tunneling at a QPC, random anyon source

$N(t,t')$ anyons incoming on the QPC between times t' and t

Γ_-: bunching mechanism ⇨ $P < 0$







▲/△ emitted at $t = 0 < t_0$ ▲/△ emitted at $\tau > t_0$

mutual braiding phase

$$\Gamma_{\pm} \propto Re\left[\int_0^{+\infty} e^{\pm i\theta N_1(\tau)} G_\delta(\tau)^2 d\tau\right]$$

number of anyons emitted at input 1 reaching the QPC

equilibrium Green's function, long-time decay governed by δ

N_1 is a random Poissonian variable: $\left\langle e^{\pm i\theta N_1}\right\rangle = e^{-\langle N_1\rangle(1-e^{\pm i\theta})}$

Morel et al., PRB **105**, 075433 (2022),
Lee et al., Nat. Commun. **13**, 6660 (2022)
Mora, arXiv:2212.05123 (2022)
Schiller et al., PRL **131** 186601 (2023)

$$P = 1 - \frac{\tan\theta/2}{\tan\pi\delta}\frac{1}{1-2\delta} = -2 \qquad \theta = 2\pi\delta = \frac{2\pi}{3}$$

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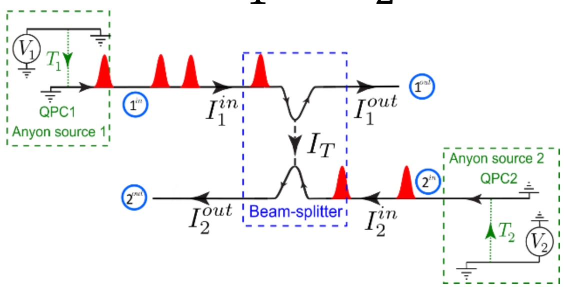
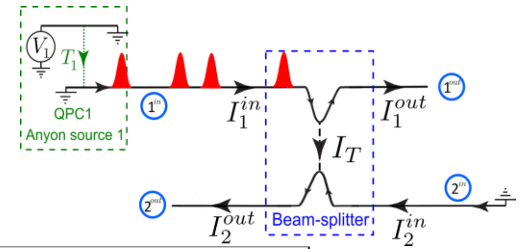
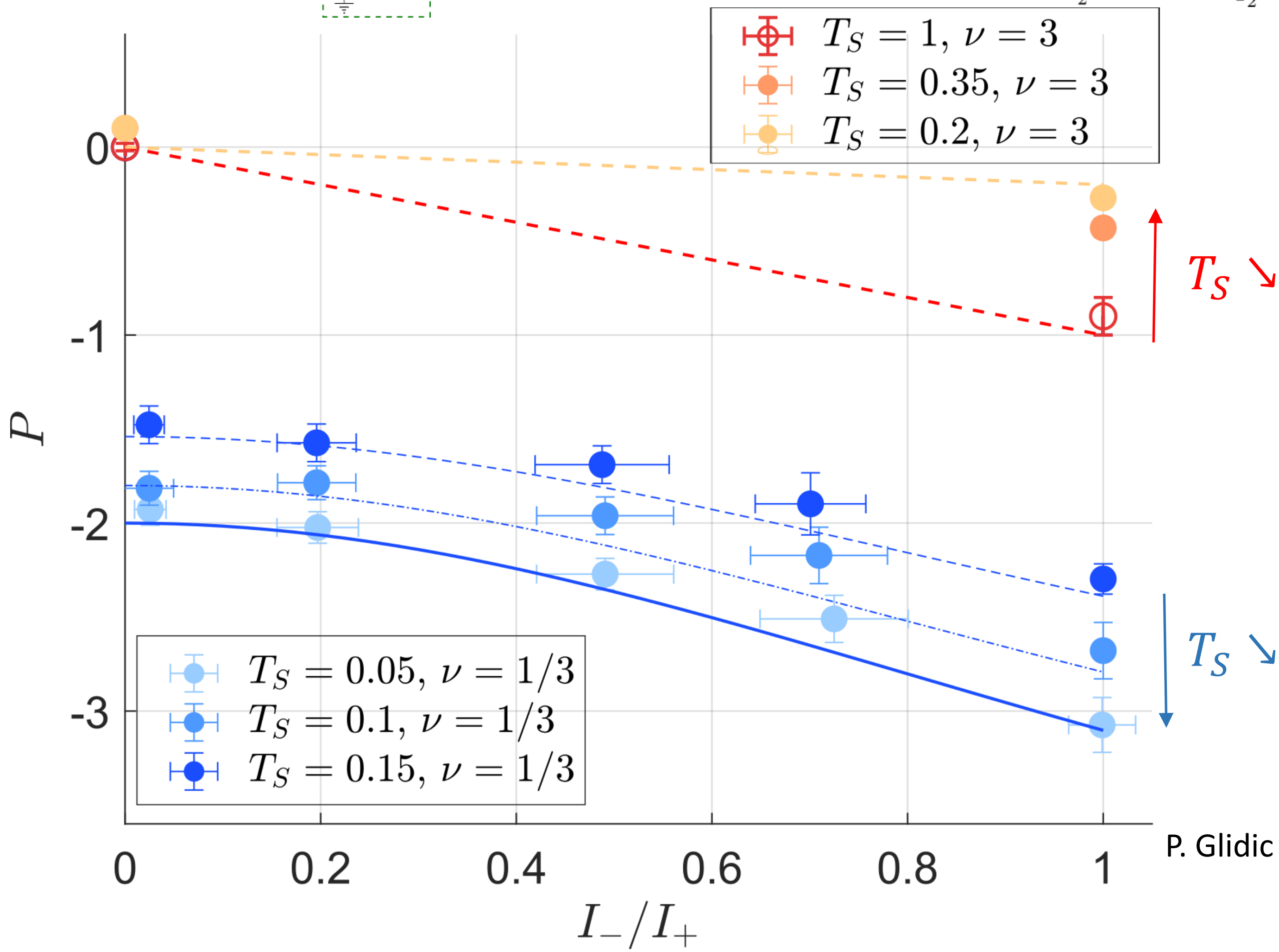
Anyon/Fermion collisions, $I_-/I_+ \neq 0$

$I_- = I_1^{in} - I_2^{in} = 0$



$I_- = I_1^{in} - I_2^{in} = I_1^{in} = I_+$





See also

P. Glidic et al., PRX **13**, 011030 (2023).

Single source, anyon case, $\nu = 1/3$

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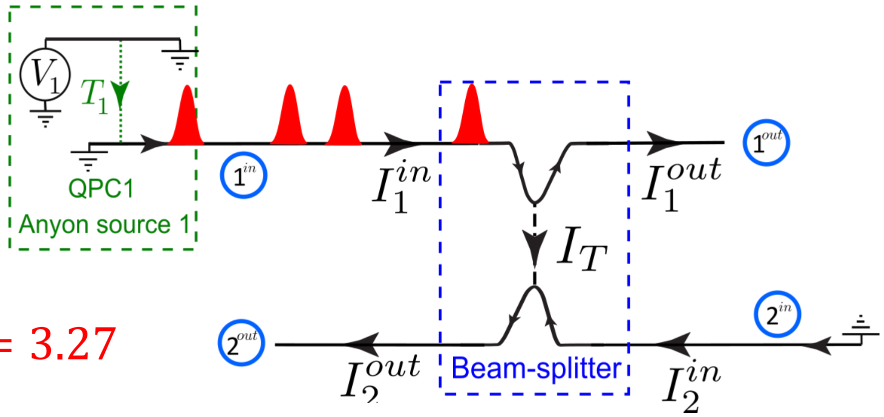
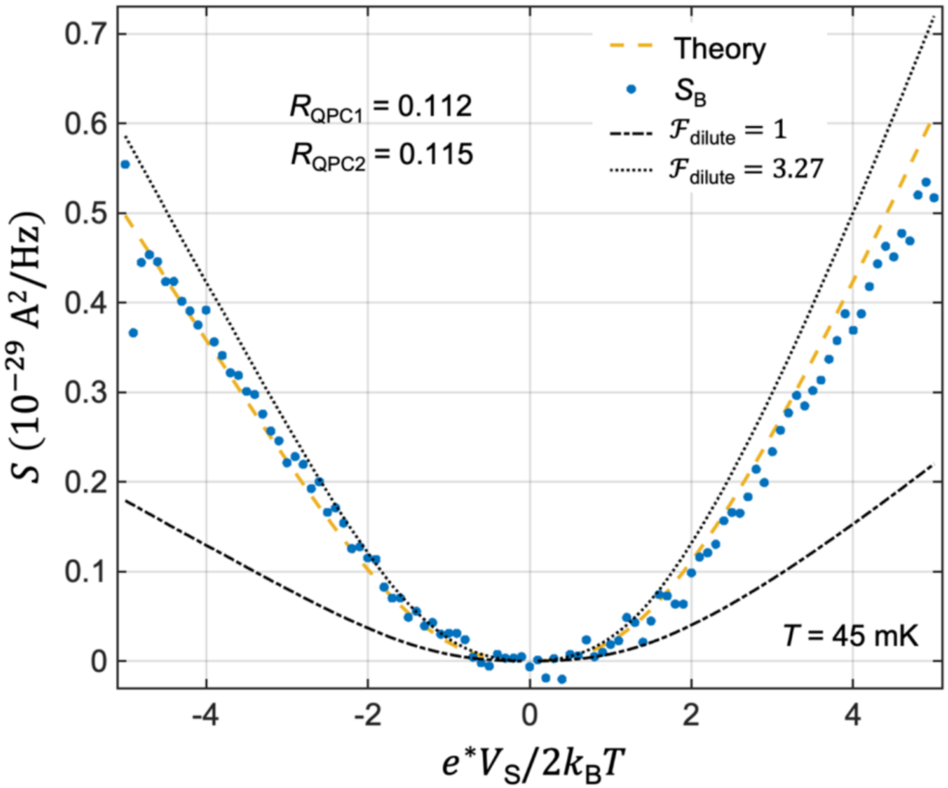
Anyons, $\theta = 2\pi/3$

$$F = \frac{\langle \Delta I_T^2 \rangle}{q I_T / T_{meas}} = -\cot(\pi\delta)\cot\left[\left(\frac{\pi}{2} - \theta/2\right)(2\delta - 1)\right] = 3.27$$

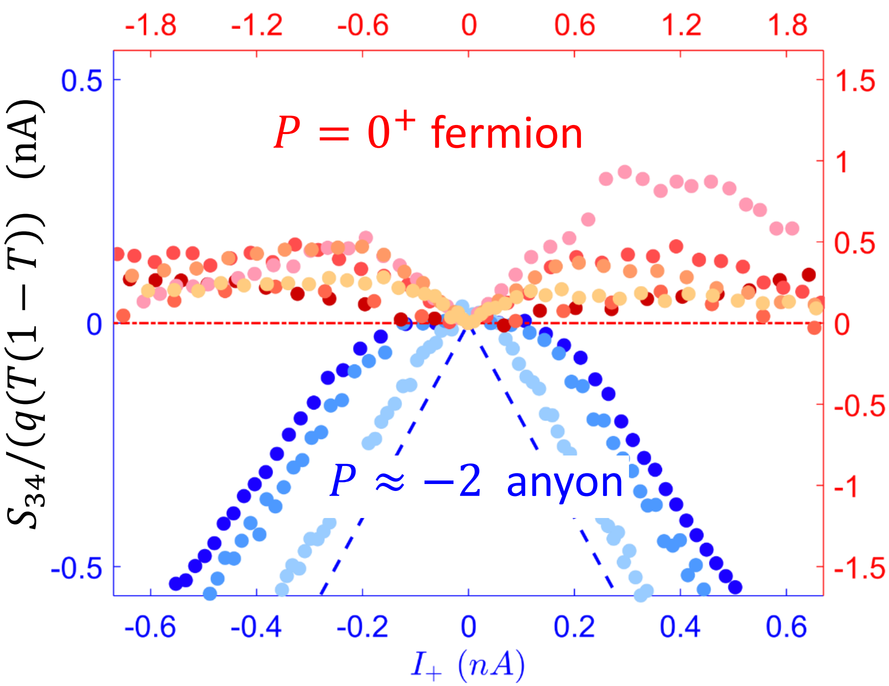




Lee et al., Nature **617**, 277–281 (2023)

Conclusion 1

- Two-particle interferometry

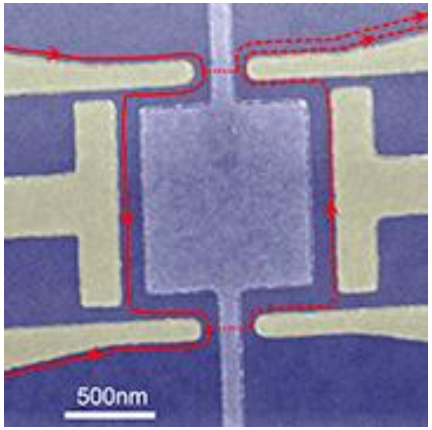


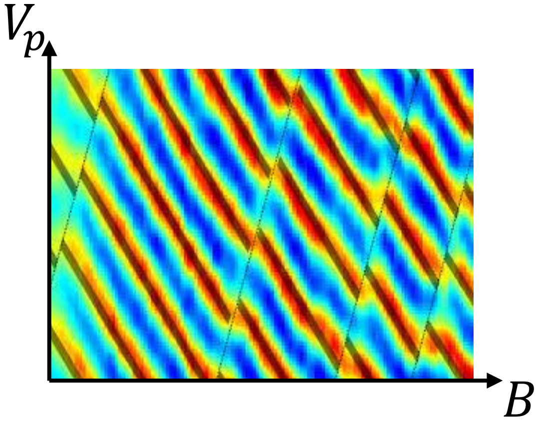
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

P. Glidic et al., Phys. Rev. X **13**, 011030 (2023).

J.-Y.M. Lee et al., Nature **617**, 277–281 (2023).

- Single particle interferometry





Fabry-Perot interferometer

J. Nakamura, S. Liang, G.C. Gardner, M.J. Manfra, Nature Physics **16** 931 (2020).

Mach-Zehnder interferometer

H.K. Kundu, S. Biswas, N. Ofek, V. Umansky, and M. Heiblum, Nature physics **19**, 515 (2023).

Experiments LPENS

M. Ruelle, H. Bartolomei, E. Frigerio, M. Kumar,

A. Marguerite, J.M Berroir, B. Plaçais, G. Ménard, G. Fève

Samples Fab,C2N Palaiseau

Y. Jin, Q. Dong, A. Cavanna, U. Gennser