LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

Electronique quantique dans les nanoconducteurs

Experiences LPENS

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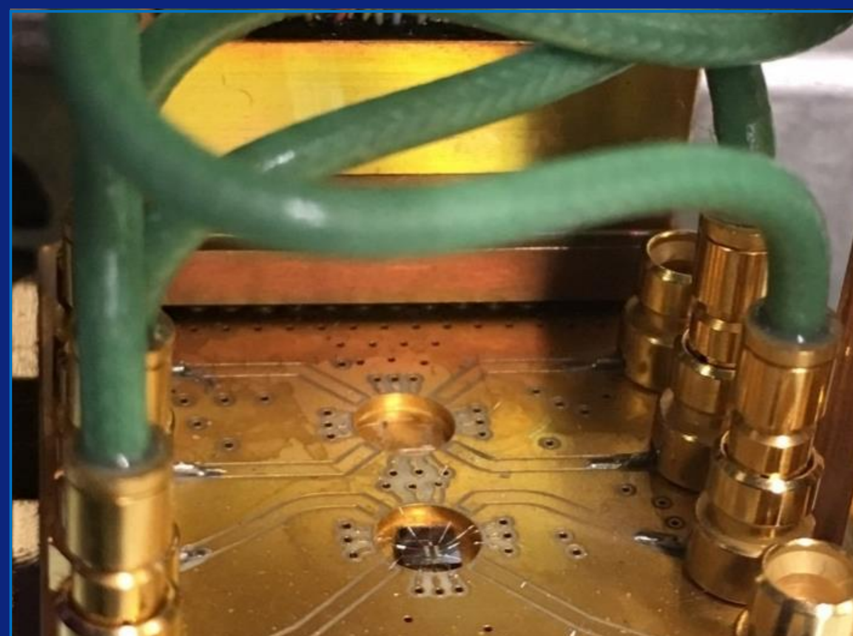
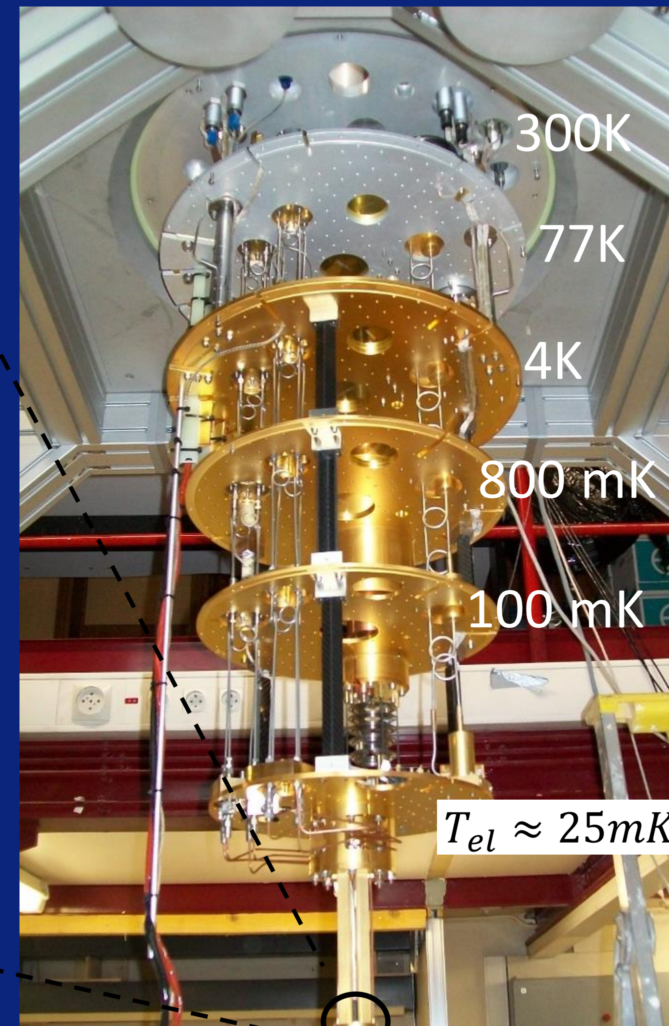
LPS Orsay





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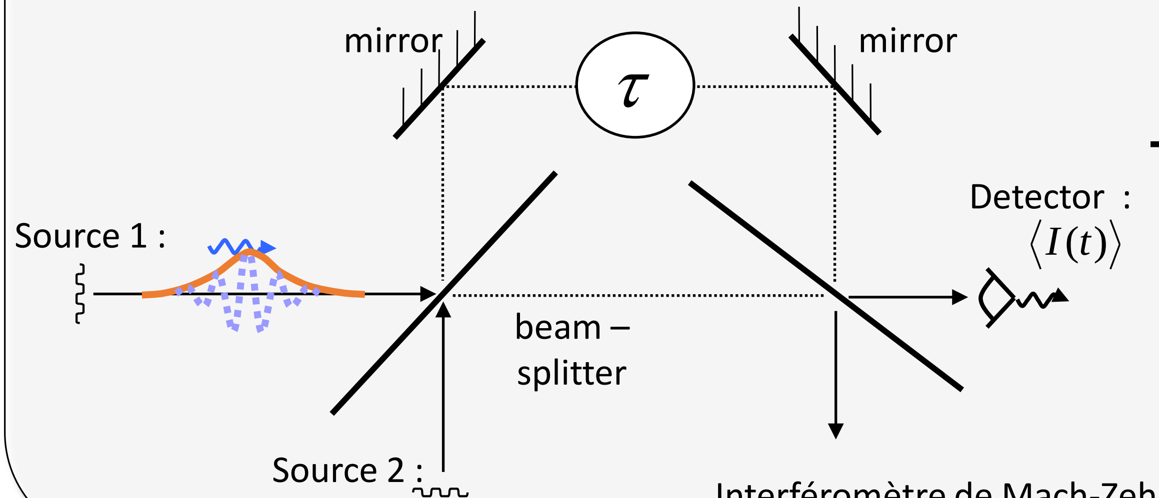
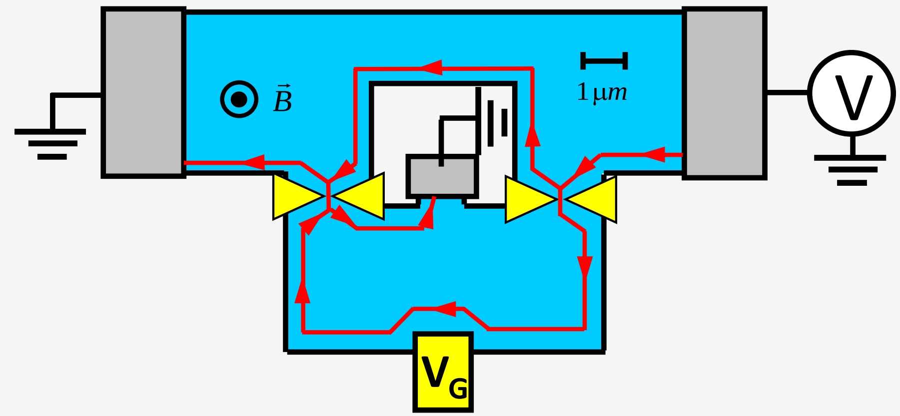
Optique électronique dans les conducteurs de Hall quantique

Interférométrie à 1 particule

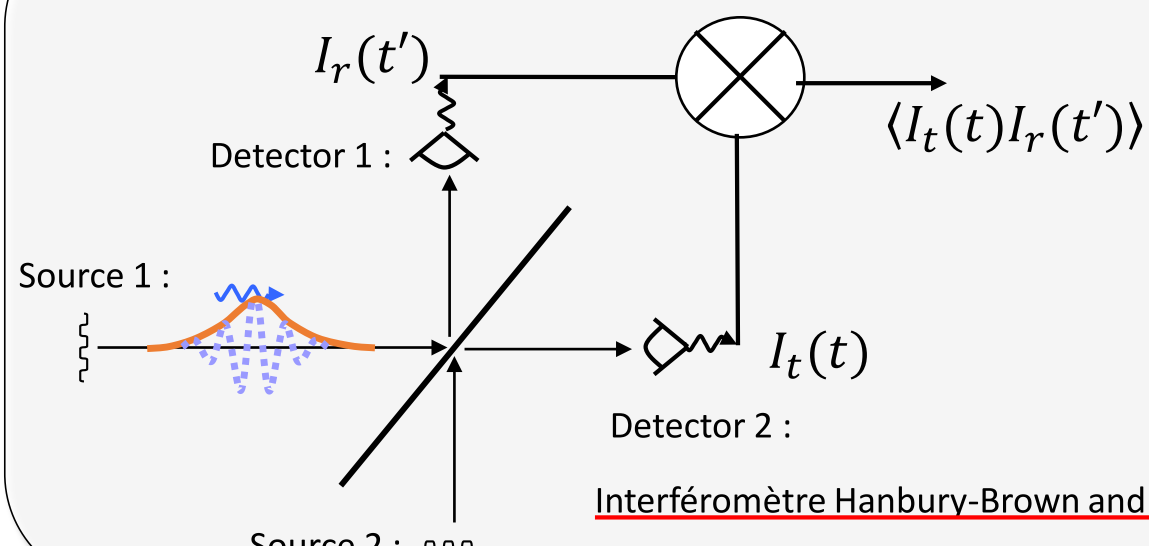


Interféromètre de Mach-Zehnder

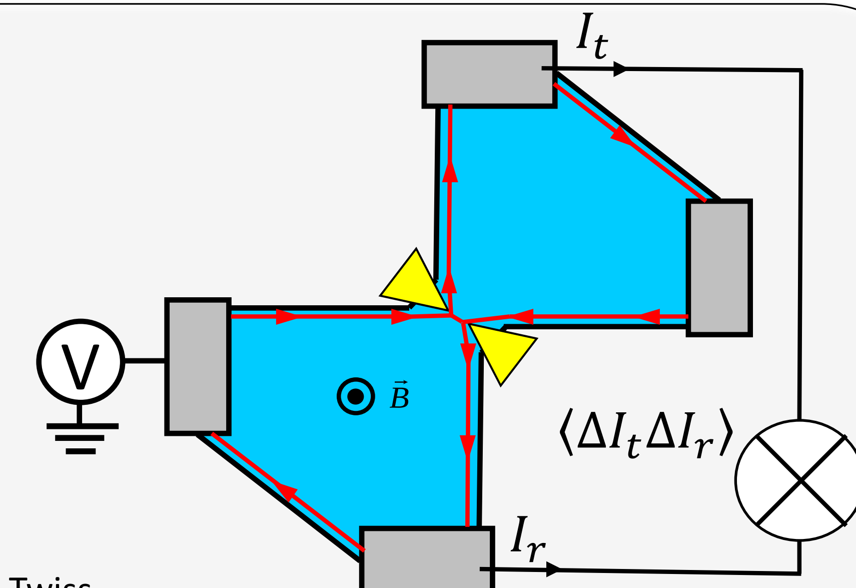


Y. Ji et al., Nature **422**, 415 (2003)

Interférométrie à 2 particules



Interféromètre Hanbury-Brown and Twiss

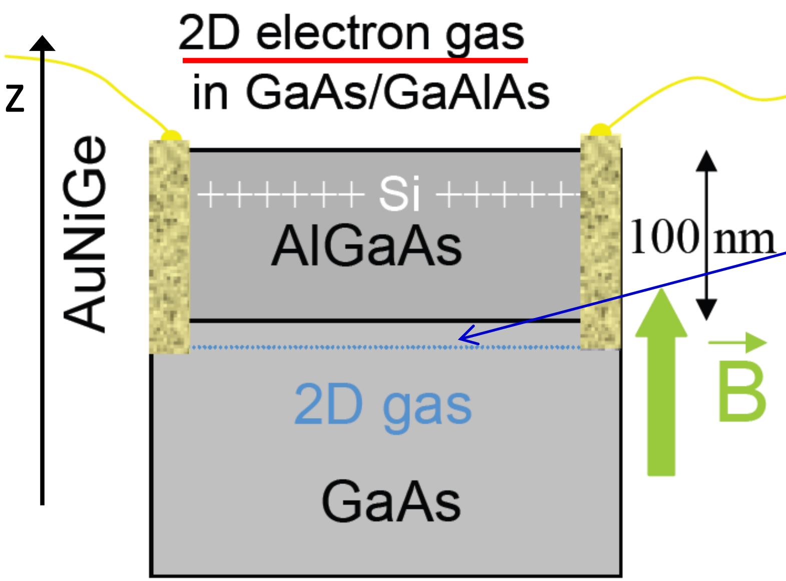


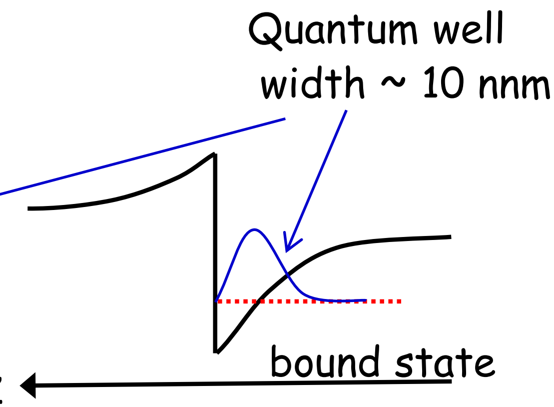
M. Henny et al., Science **284**, 296 (1999)

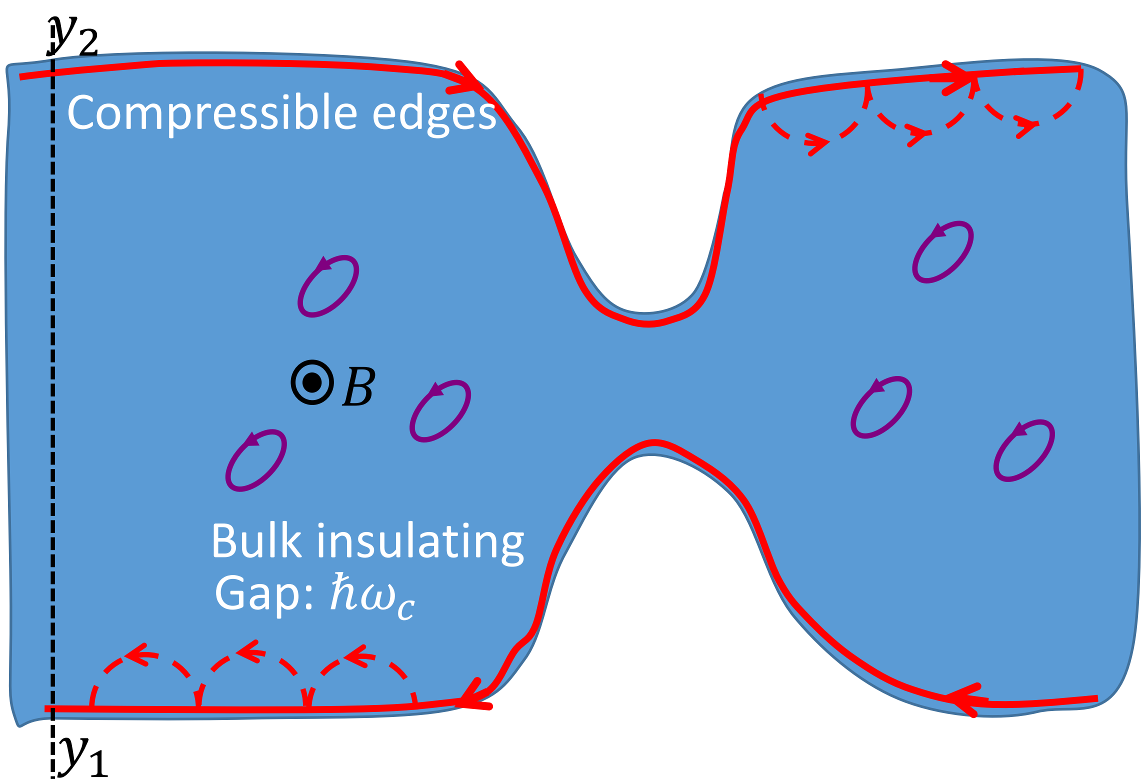
I Electrons dans le régime d’effet Hall quantique entier

II Anyons dans le régime d’effet Hall quantique fractionnaire

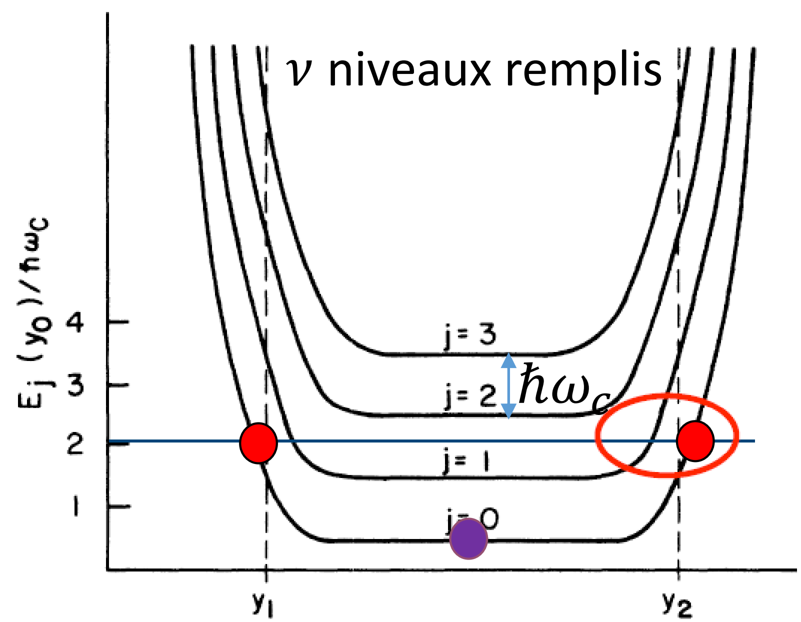
Matériaux 2D et fort champ magnétique: l'effet Hall quantique



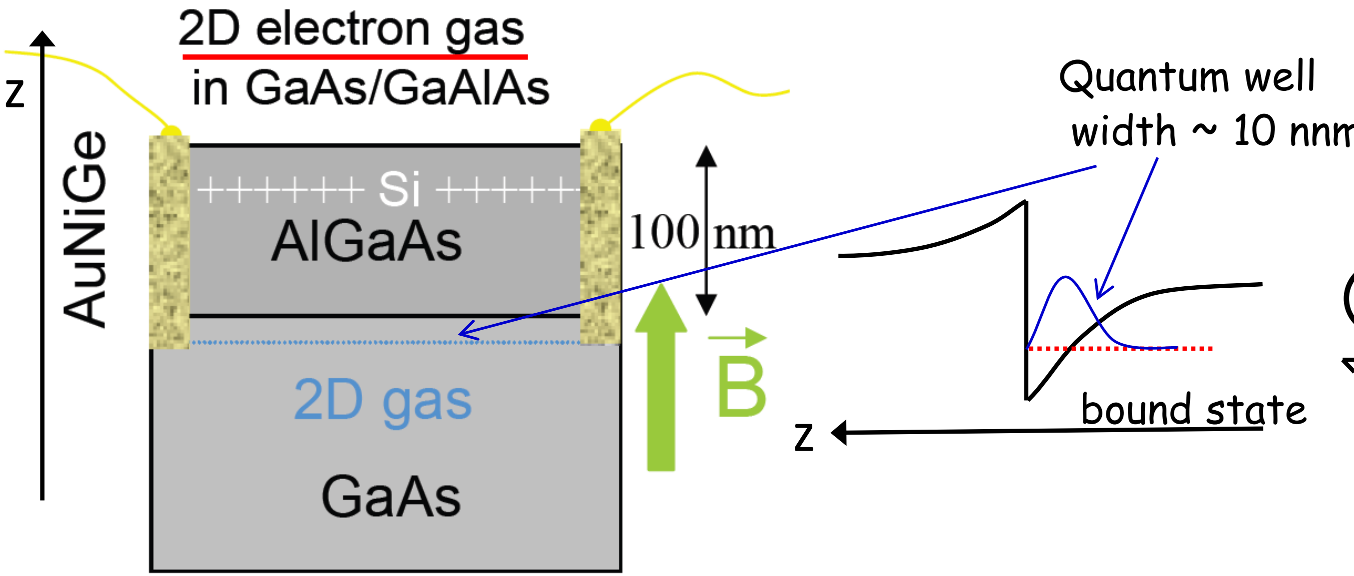


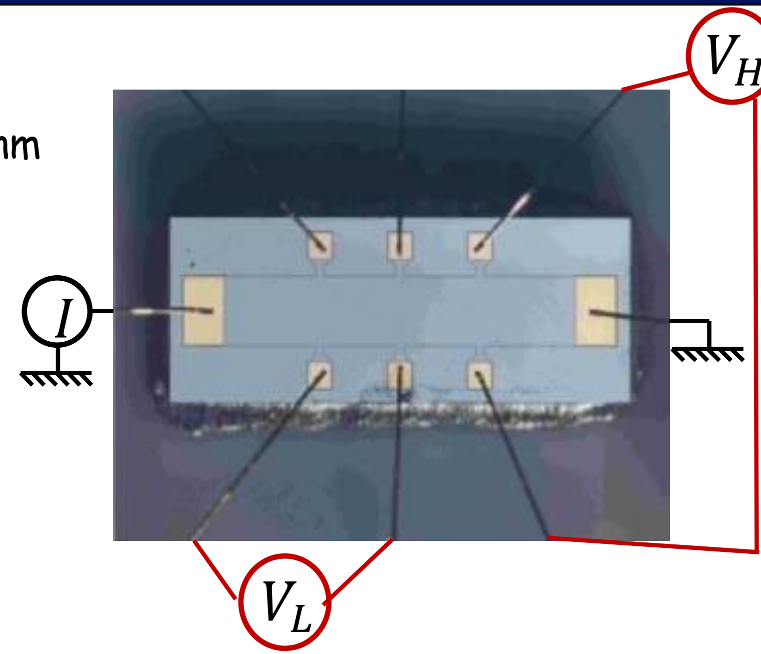


Niveaux de Landau

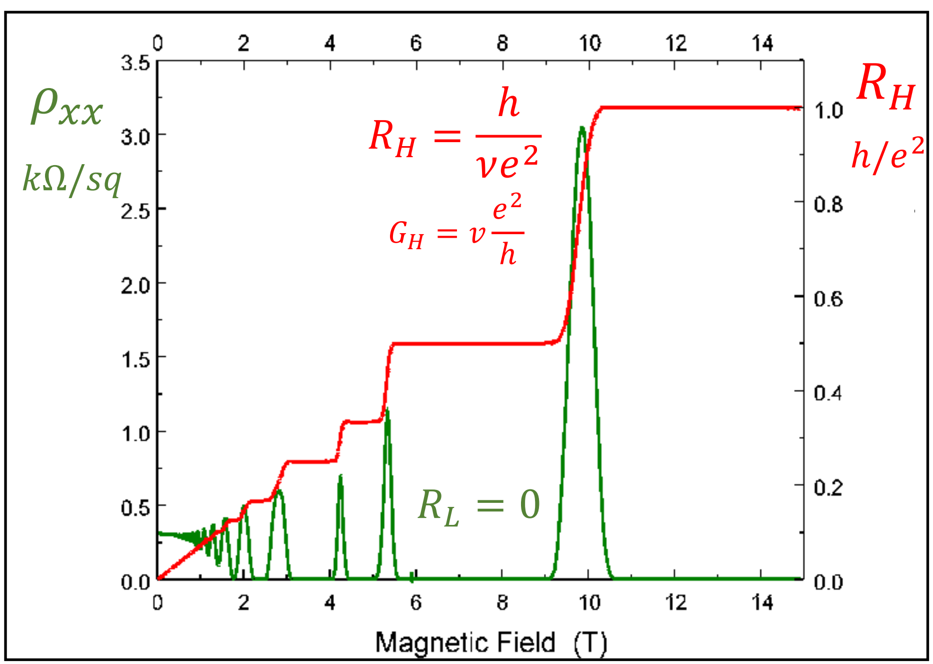


Matériaux 2D et fort champ magnétique: l'effet Hall quantique





y_2



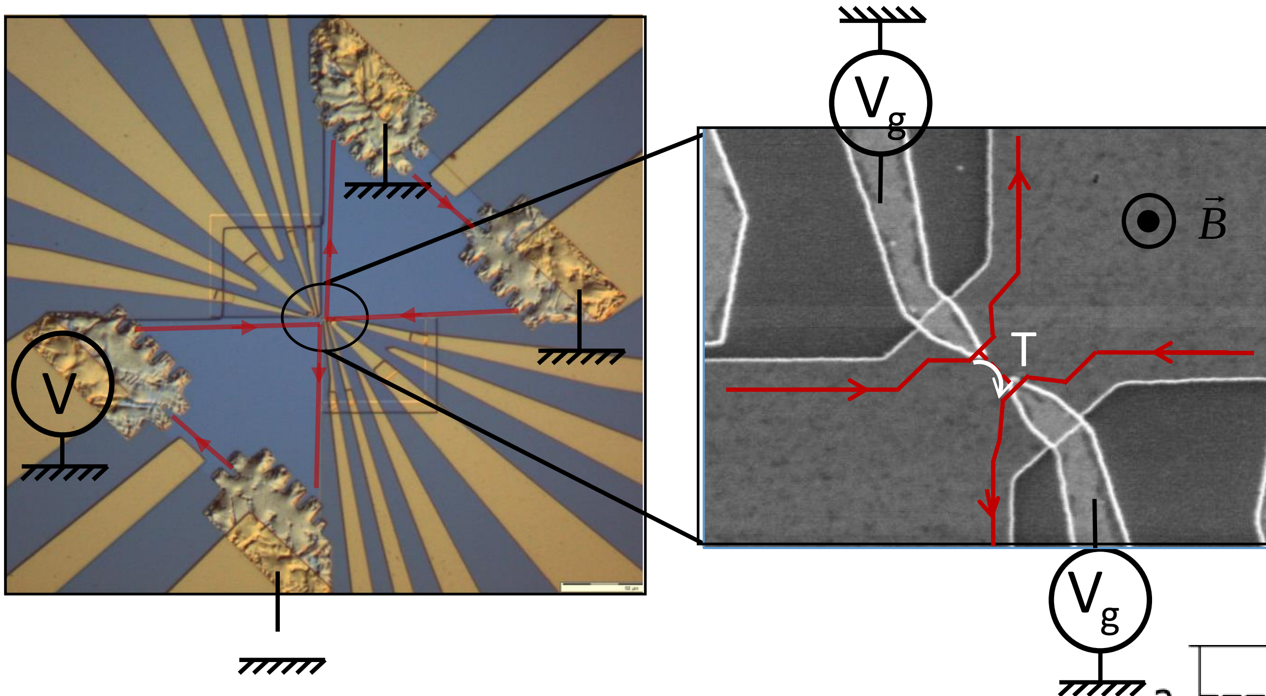
Effet Hall quantique:

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

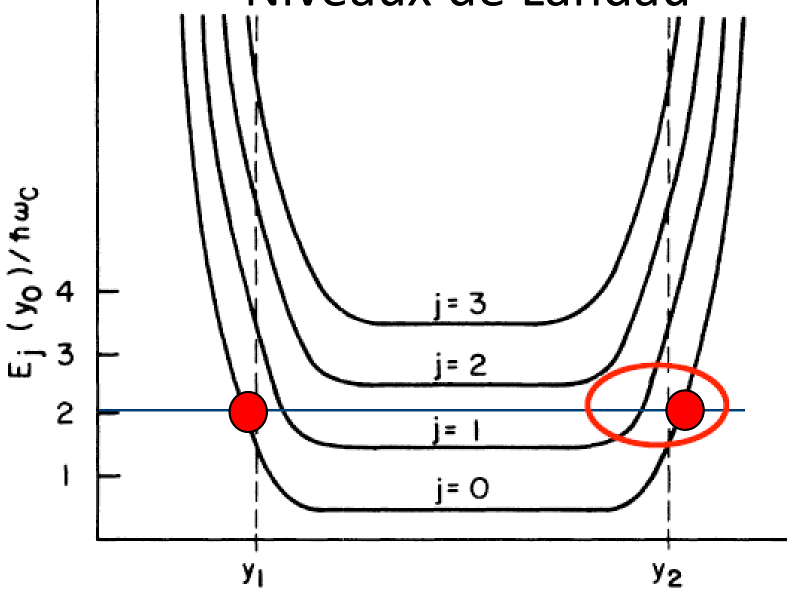
Quantification robuste de la résistance Hall

ν fils 1D transportant le courant sans rétrodiffusion

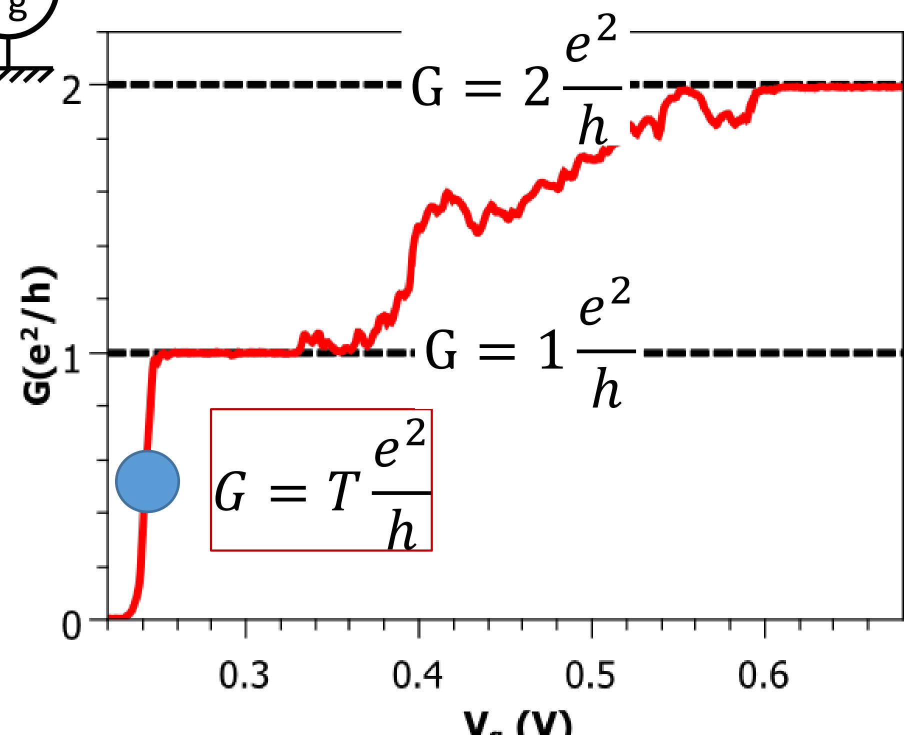
Le contact ponctuel quantique: une lame semi-réfléchissante réglable



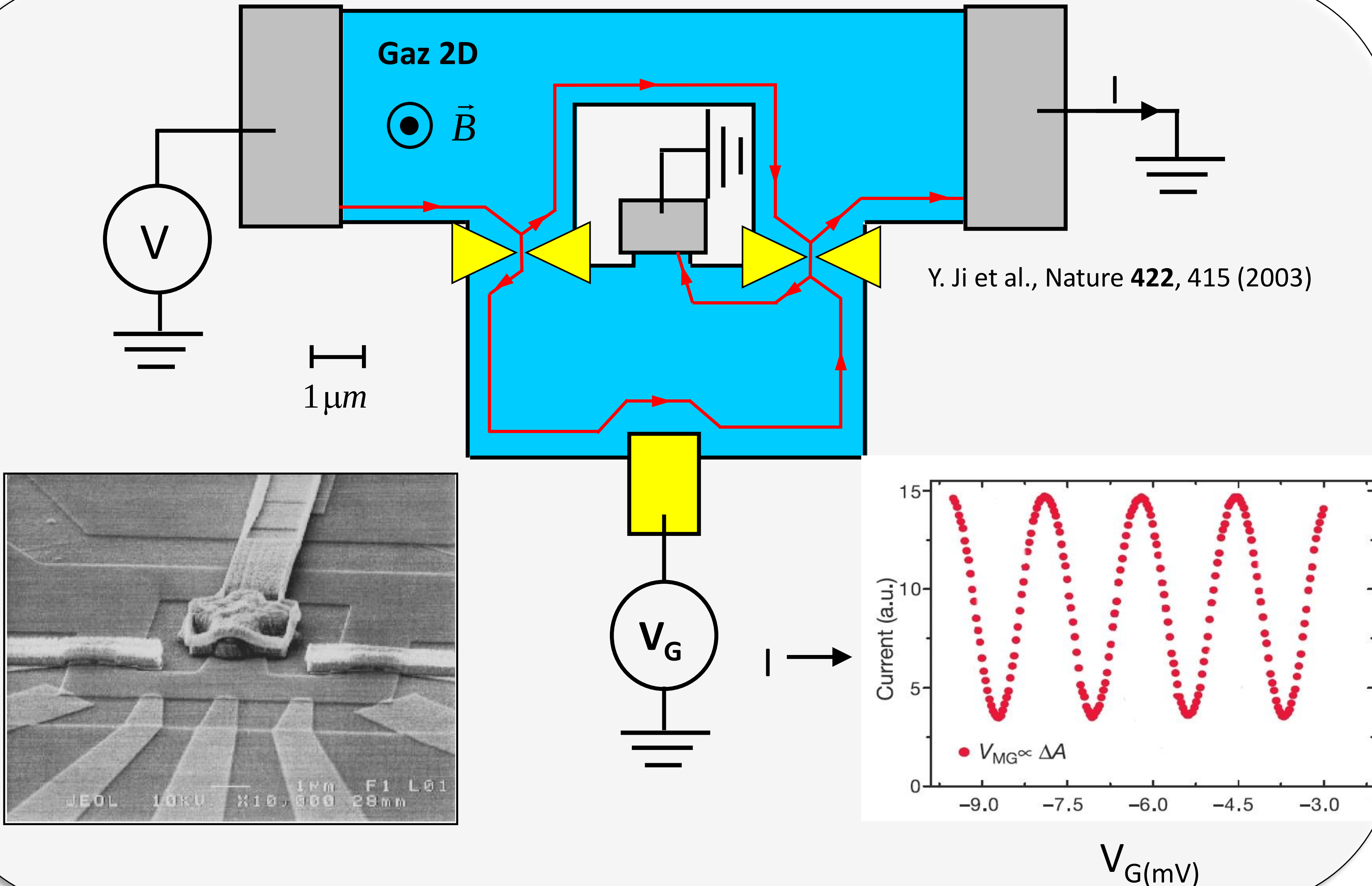
Niveaux de Landau



Example, $\nu = 2$

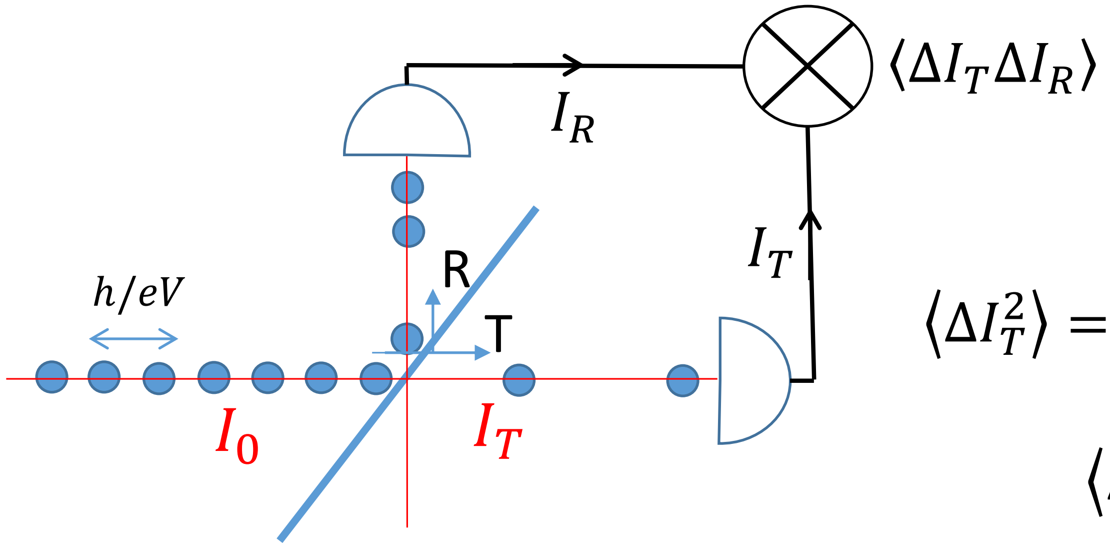


Un interféromètre de Mach-Zehnder électronique



Y. Ji et al., Nature **422**, 415 (2003)

Interféromètre à deux particules: mesures de bruit



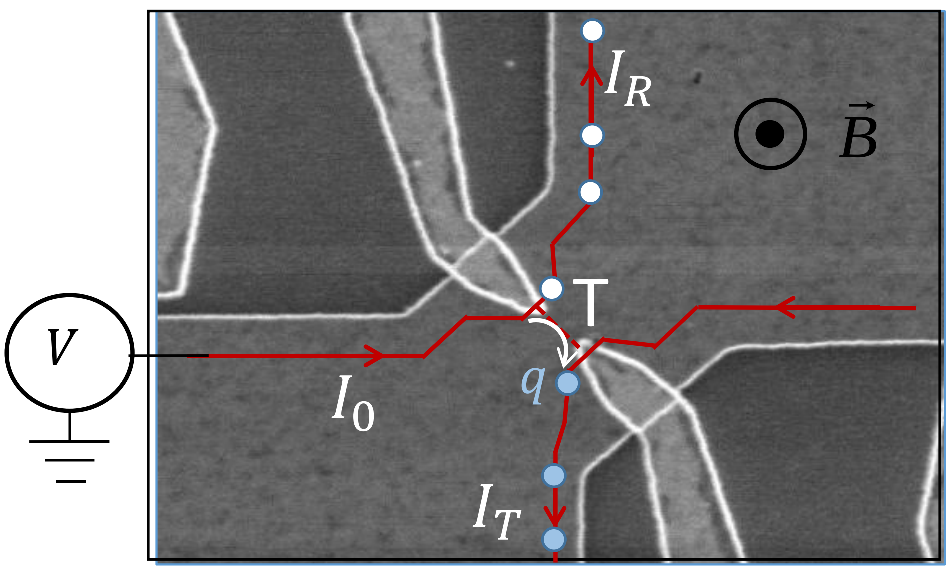
T<<1: processus de Poisson

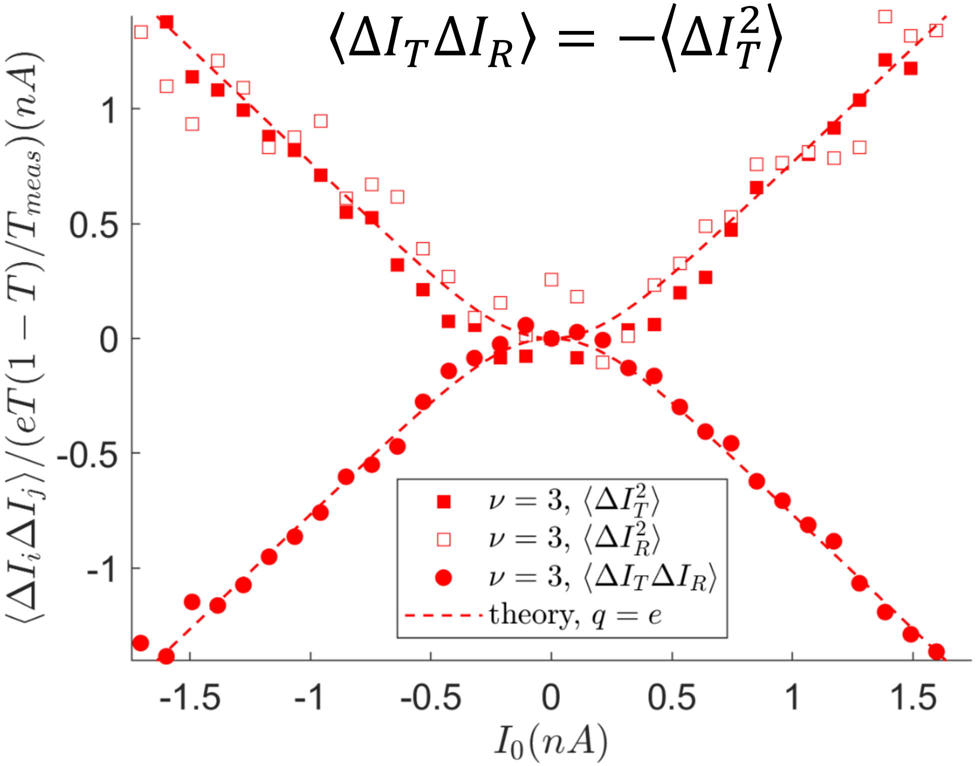
$$\langle \Delta N_T^2 \rangle = \langle N_T \rangle = T N_0$$

$$\langle \Delta I_T^2 \rangle = \frac{e^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{eT}{T_{meas}} \frac{eN_0}{T_{meas}} = \frac{eT}{T_{meas}} I_0$$

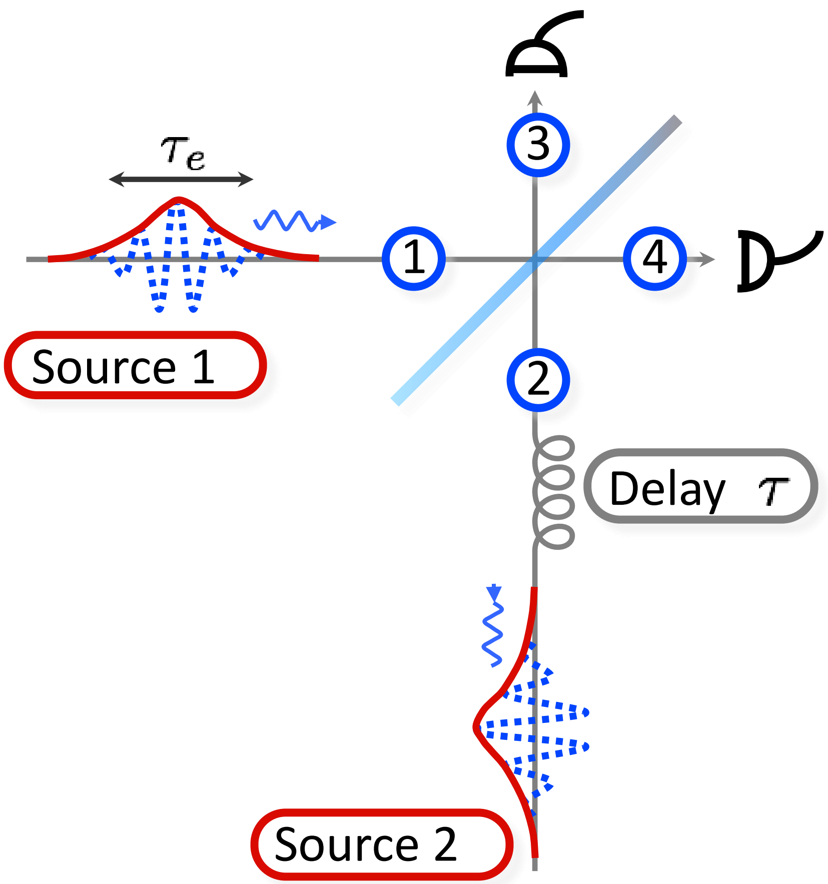
$$\langle \Delta I_T^2 \rangle + \langle \Delta I_R^2 \rangle + 2\langle \Delta I_T \Delta I_R \rangle = \langle \Delta I_0^2 \rangle = 0$$

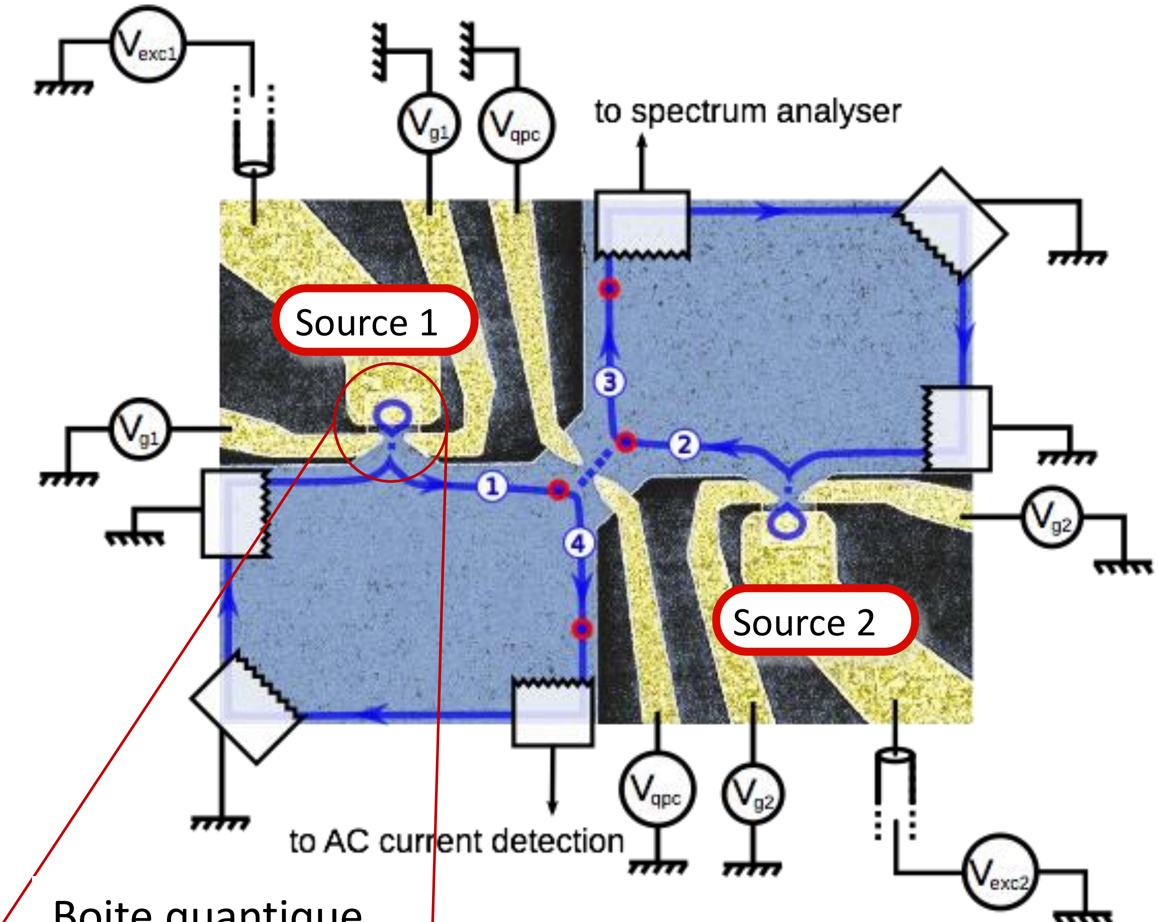
$$\langle \Delta I_T \Delta I_R \rangle = -\langle \Delta I_T^2 \rangle$$

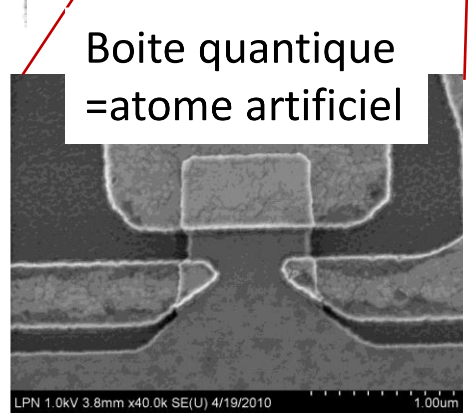


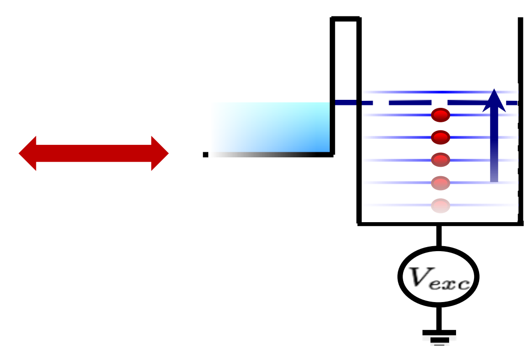


Interféromètre à deux particules: l’experience HOM électronique





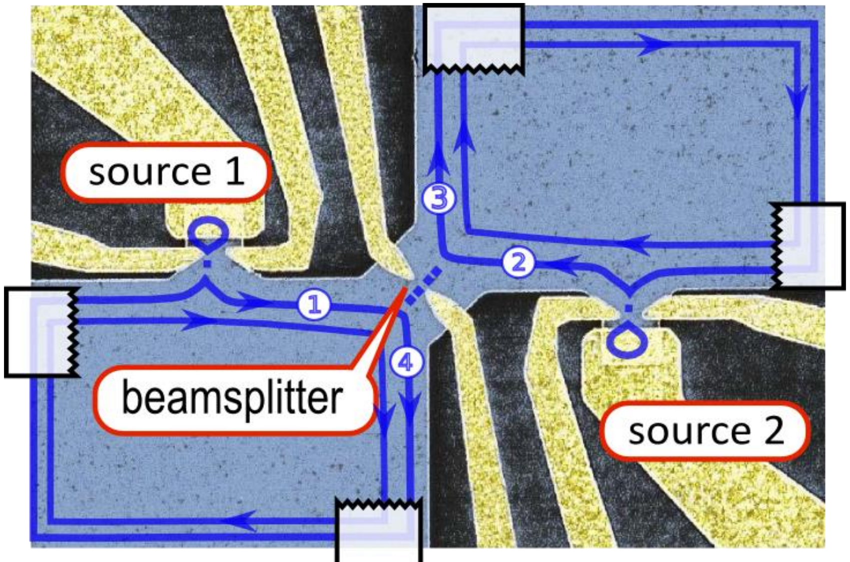


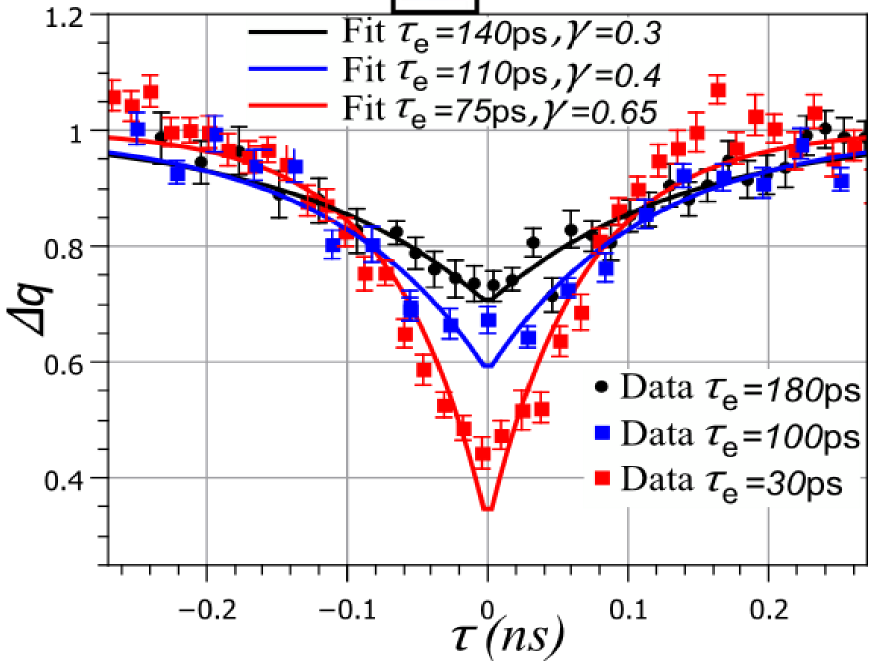


Photons :

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

Noise measurements and two electron interferences

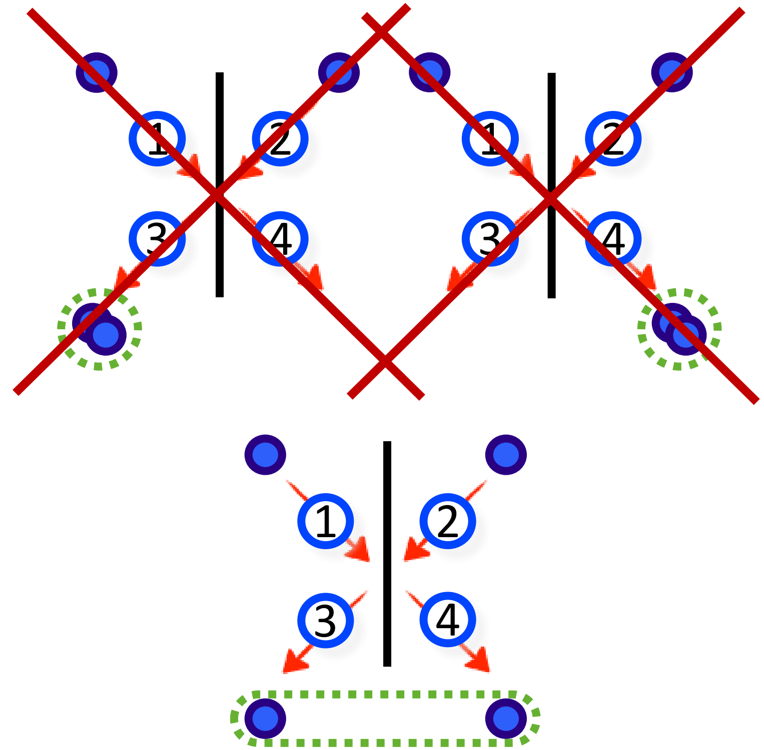




S. Ol'khovskaya et al., PRL **101**, 166802, (2008).

E. Bocquillon et al., Science **339**, 1054 (2013).

A. Marguerite et al., PRB **94**, 115311 (2016).



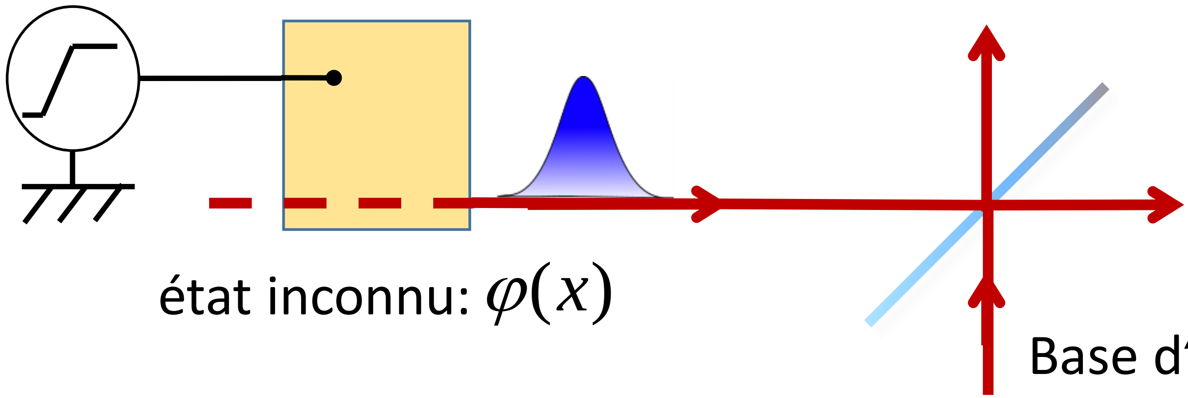
$$\frac{\langle \Delta N^2 \rangle}{\langle \Delta N^2_{class} \rangle} = 1 - \left| \int dt \varphi_1(t) \varphi_2^*(t+\tau) \right|^2$$

Fluctuations classiques (bruit de partition)

Signe – pour les fermions

Recouvrement entre états

Extraction des fonctions d'onde d'électrons



état inconnu: $\varphi(x)$

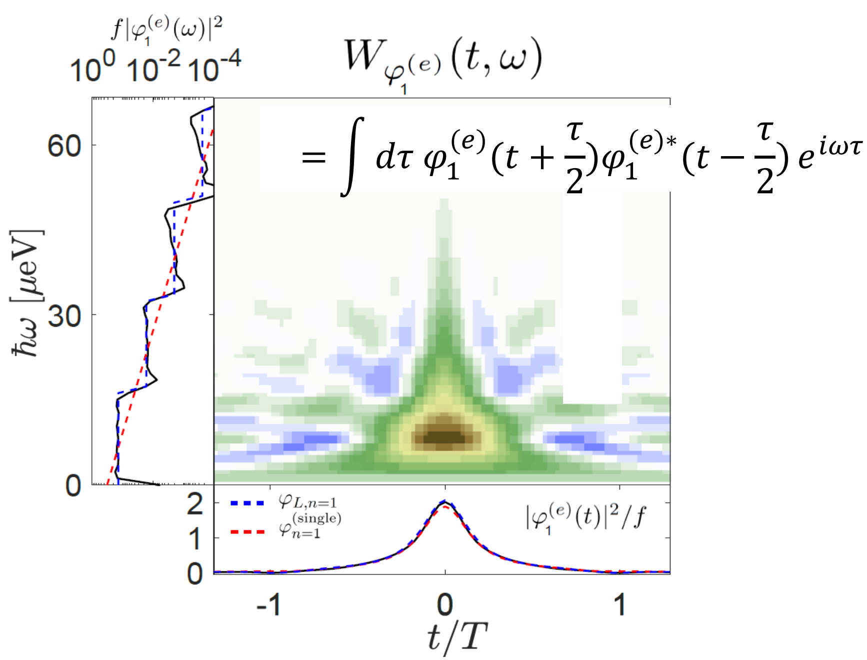
Base d'états. $\varphi_{ref}(x)$

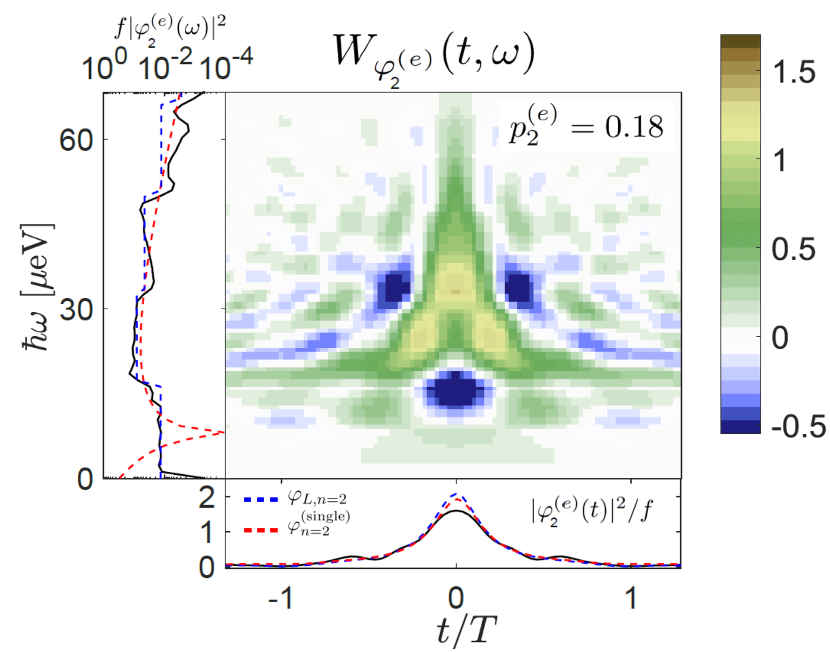
$$\frac{\langle \Delta N^2 \rangle}{\langle \Delta N^2_{class} \rangle} = 1 - \left| \vec{\varphi} . \vec{\varphi}_{ref} \right|^2$$

Mélange:

$\varphi_1(t), P_1 = 0.8$

$\varphi_2(t), P_2 = 0.2$





T. Jullien et al., Nature **514**, 603–607 (2014)
R Bisognin, A Marguerite, B Roussel, et al. Nature communications **10**, 1-12 (2019)

I Electrons dans le régime d’effet Hall quantique entier

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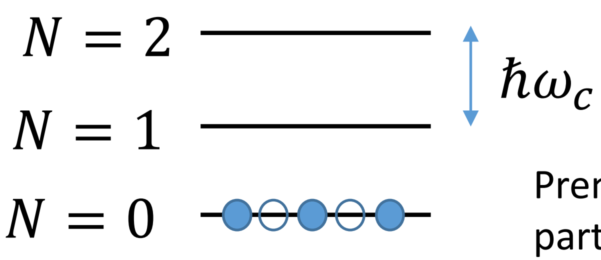
L'effet Hall quantique fractionnaire

High field, ν<1



Premier niveau de Landau partiellement rempli

La seule échelle d'énergie restante est l'interaction de Coulomb $H = E_c$

On retrouve un système isolant au cœur (incompressible) pour des remplissages spécifiques: $\nu = \frac{1}{m} \; (\frac{1}{3}, \ldots)$

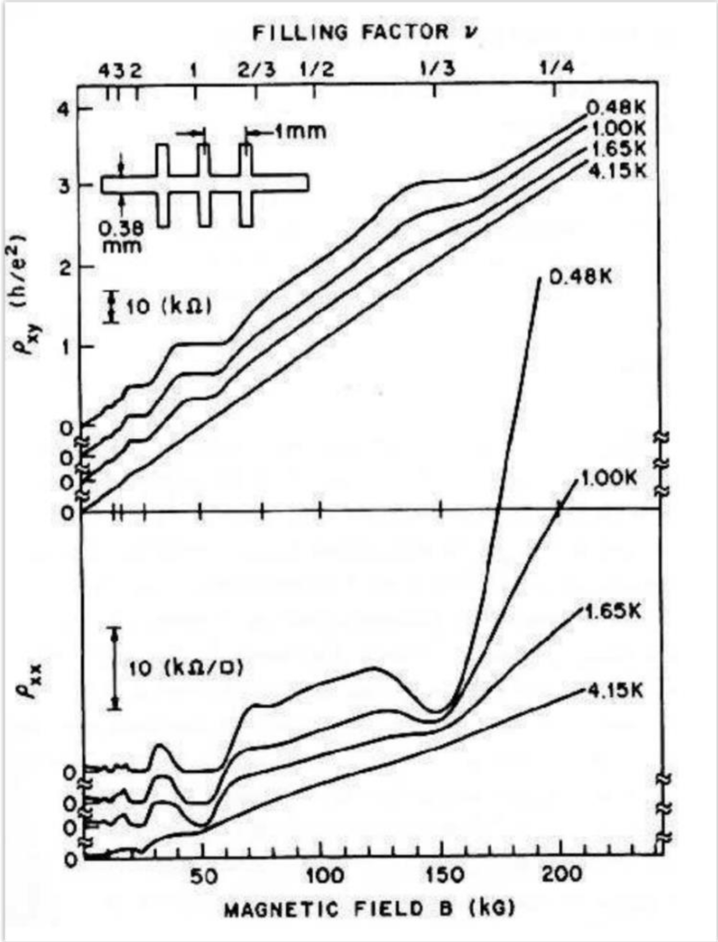
R. Laughlin, Phys. Rev. Lett.**50**, 1395 (1983).

Résistance/ conductance Hall quantifiée $G_H = \frac{1}{m}\frac{e^2}{h}$

Excitations élémentaires= anyons: charge et statistique fractionnaires

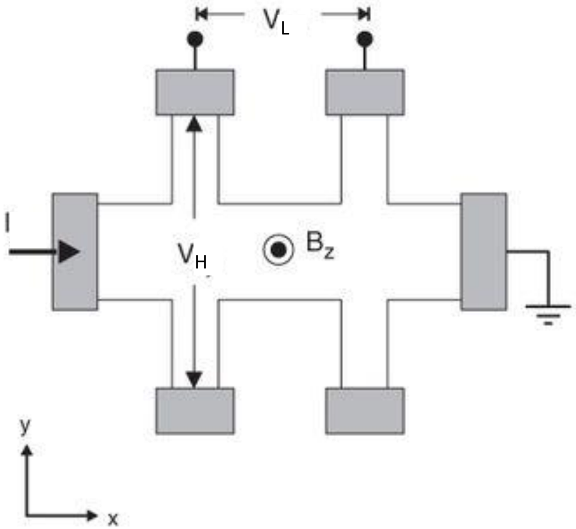
$$\nu = \frac{1}{m}, \quad e^* = \frac{e}{m}, \quad \varphi = \frac{\pi}{m}$$

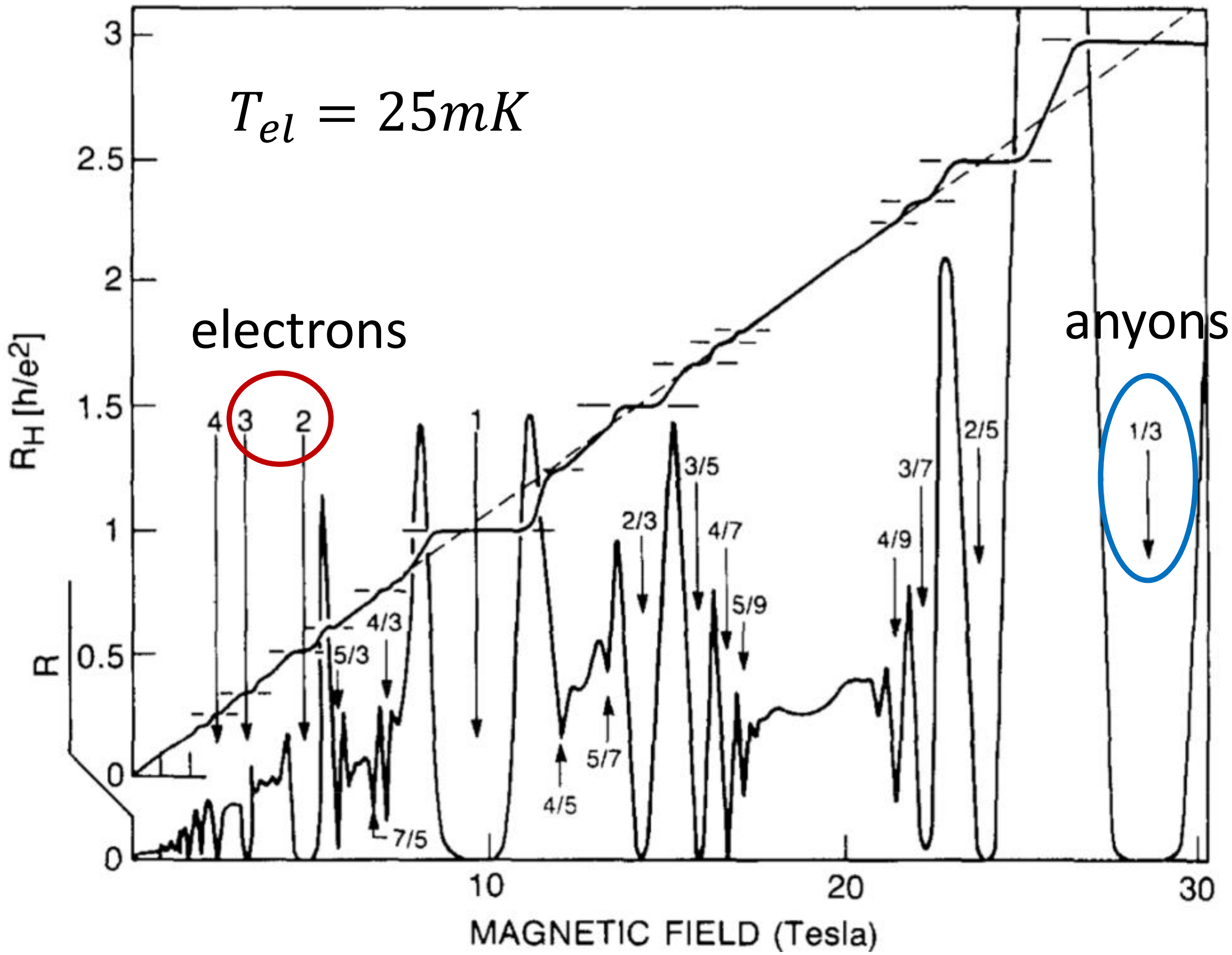
Halperin, PRL **52** 1583 (1984)



D.C. Tsui, H.L. Stormer, and A.C. Gossard, Phys. Rev. Lett.48, 1559 (1982).

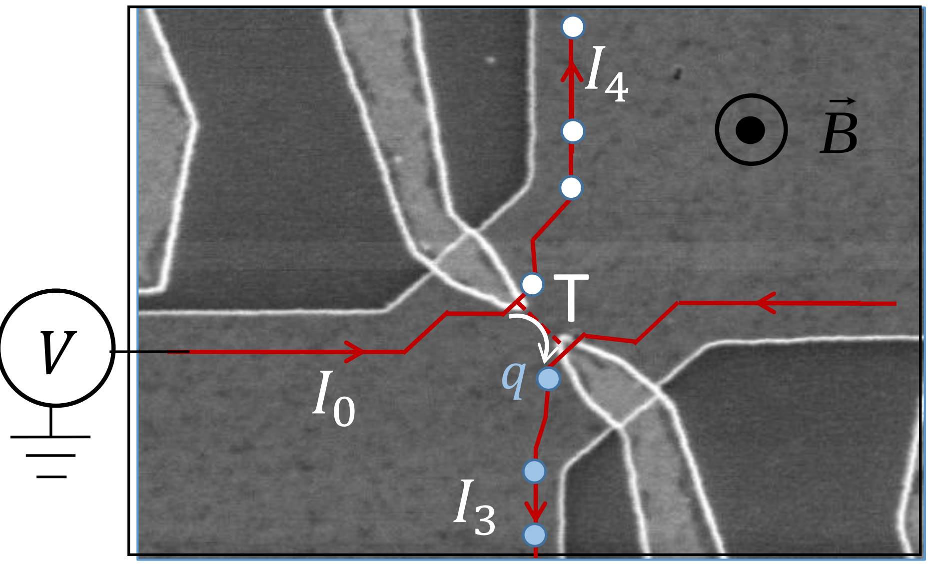
L'effet Hall quantique fractionnaire





H.L. Stormer, Physica B **177**, 401 (1992).

Bruit et charges fractionnaires, ν=1/3



T<<1: processus de Poisson

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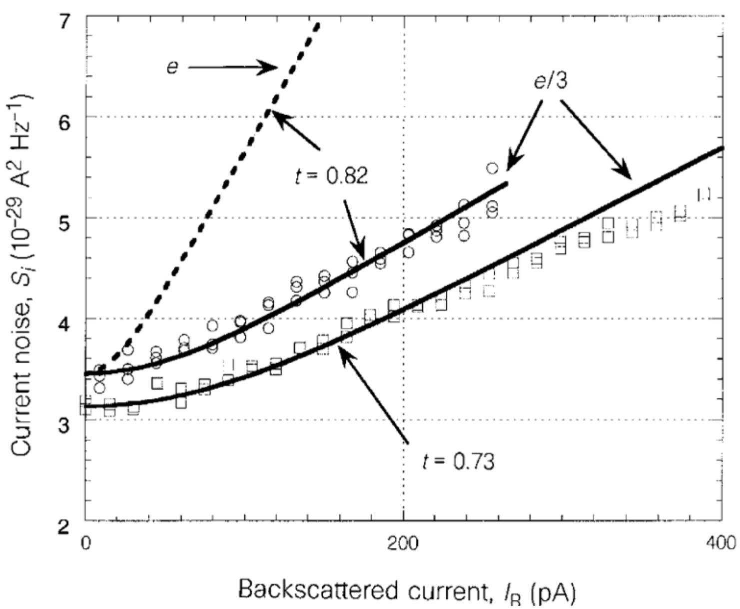
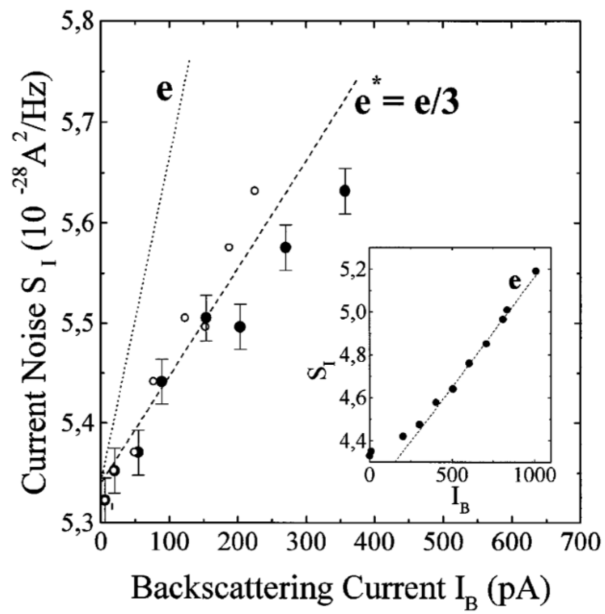
Fractional case: $\nu = 1/3, q = e/3$

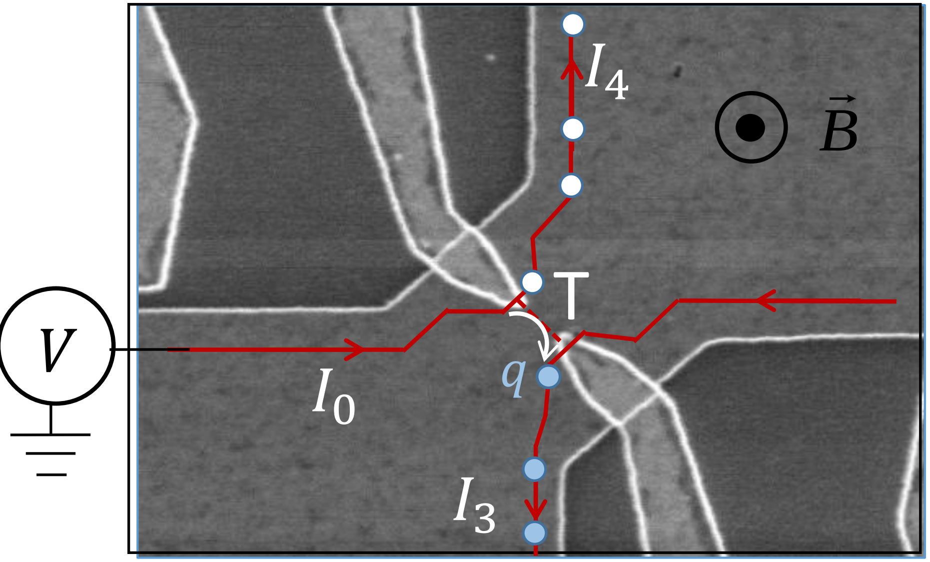


R. de Picciotto et al., Nature **389**, 162 (1997).



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

Bruit et charges fractionnaires, ν=1/3



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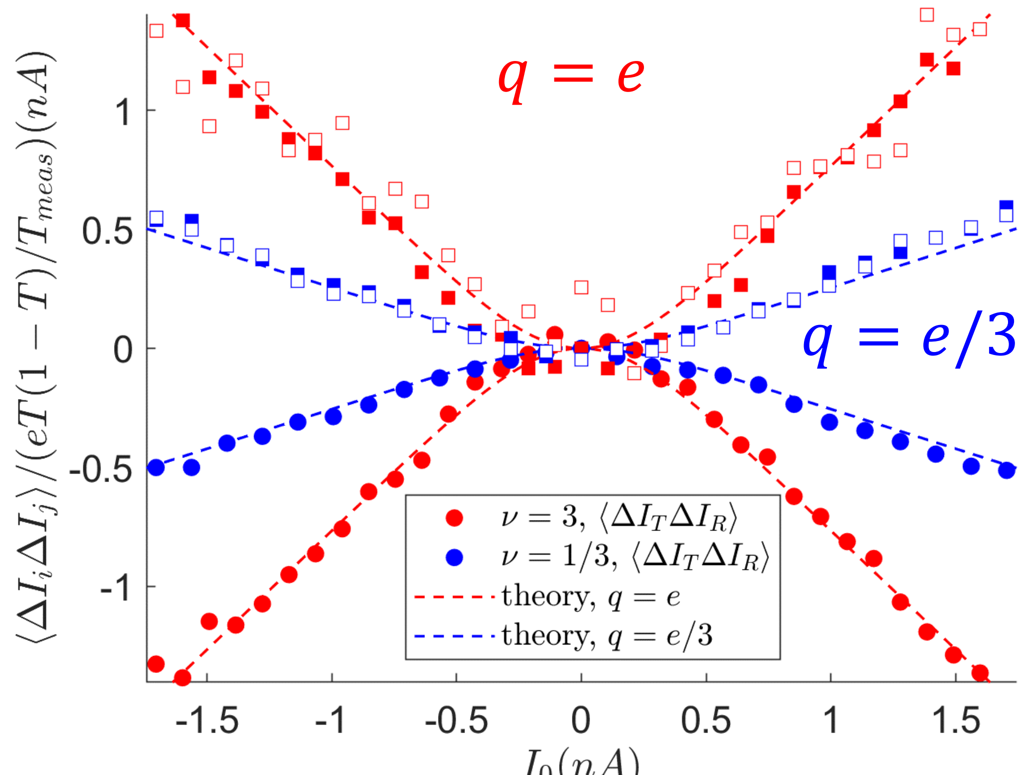
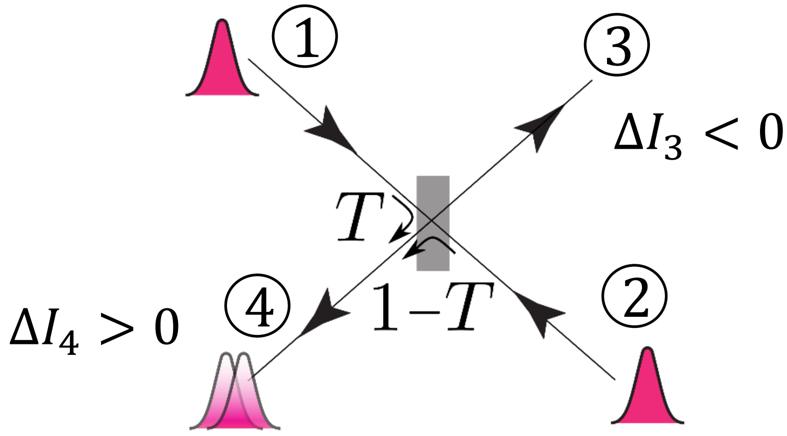
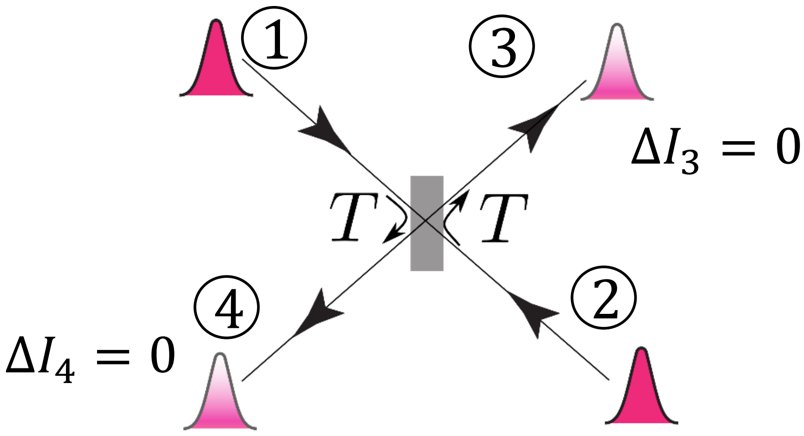


Collisionneurs : groupement et dégroupement



Groupement

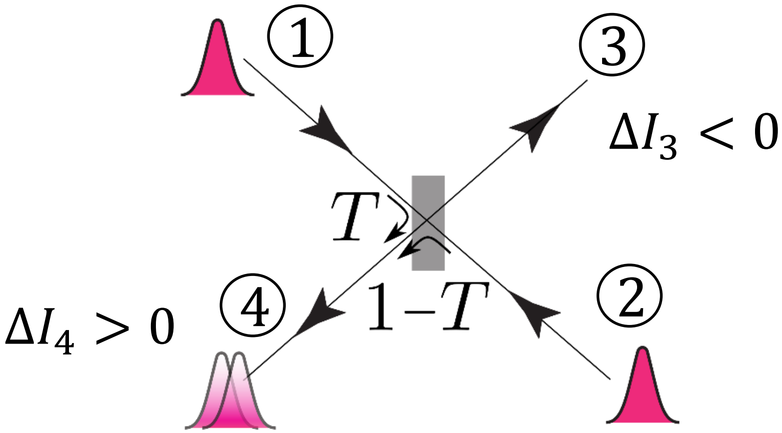
$\langle \Delta I_3 \Delta I_4 \rangle < 0$

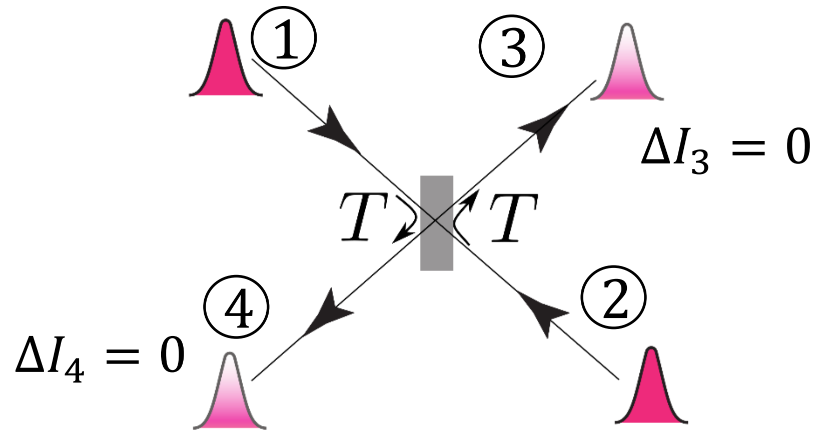


Dégroupement

$\langle \Delta I_3 \Delta I_4 \rangle = 0$

Collisionneurs : groupement et dégroupement





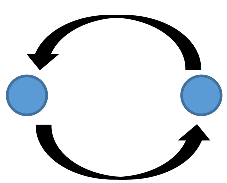
Groupement

$\langle \Delta I_3 \Delta I_4 \rangle < 0$

Dégroupement

$\langle \Delta I_3 \Delta I_4 \rangle = 0$

Anyons



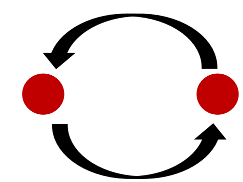
$\varphi = \pi/3 \ \ (\nu = 1/3)$

Peuvent se regrouper en paquets

$\nu = 1/3$, 3 anyons pour 1 état inaccessible

Haldane PRL **67** 937 (1991)

Electrons: fermions

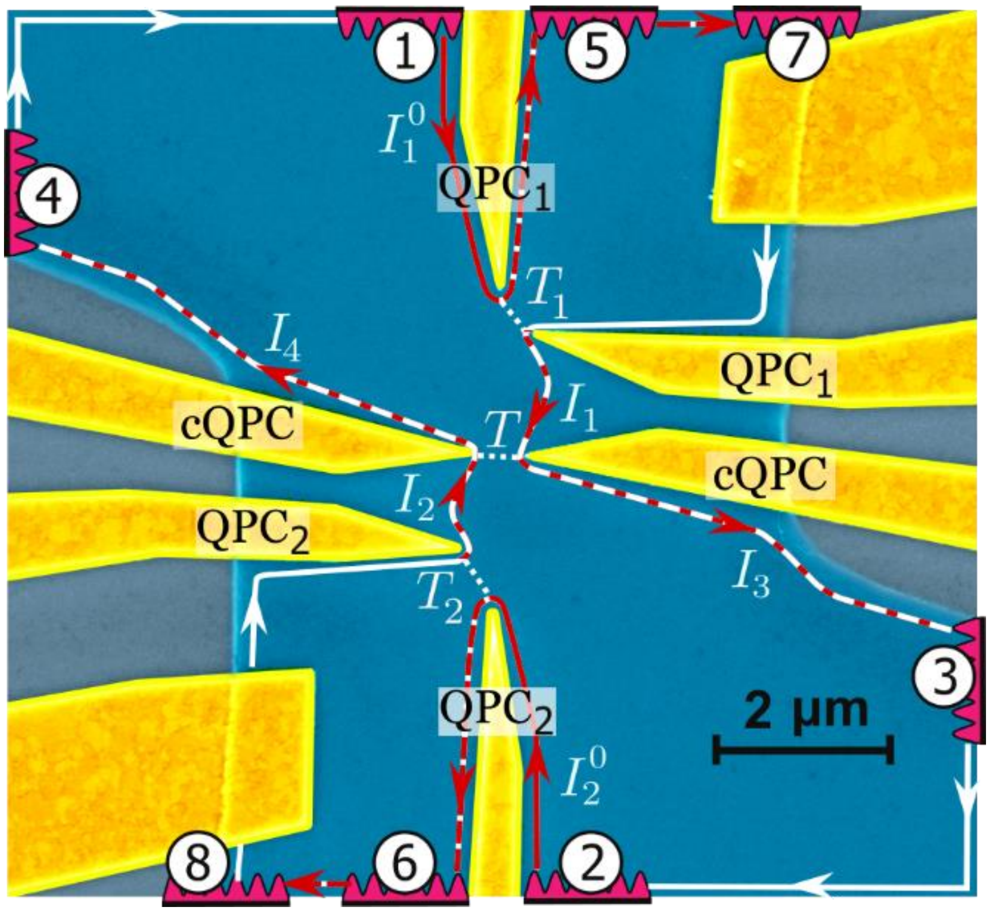


$\varphi = \pi$

Dégroupement complet

Principe d'exclusion de Pauli

Le collisionneur à anyons



Particules émises dans les bras d'entrées avec une probabilité: $T_1 = T_2 = T_S$

Courant total $I_+ = I_1 + I_2$

Différence de courant $I_- = I_1 - I_2 = 0$

Pseudo-facteur de Fano

$$\langle \Delta I_3 \Delta I_4 \rangle = P\ 2qT(1-T)I_+/T_{meas}$$

Prédictions:

Electrons (fermions), $P = 0$

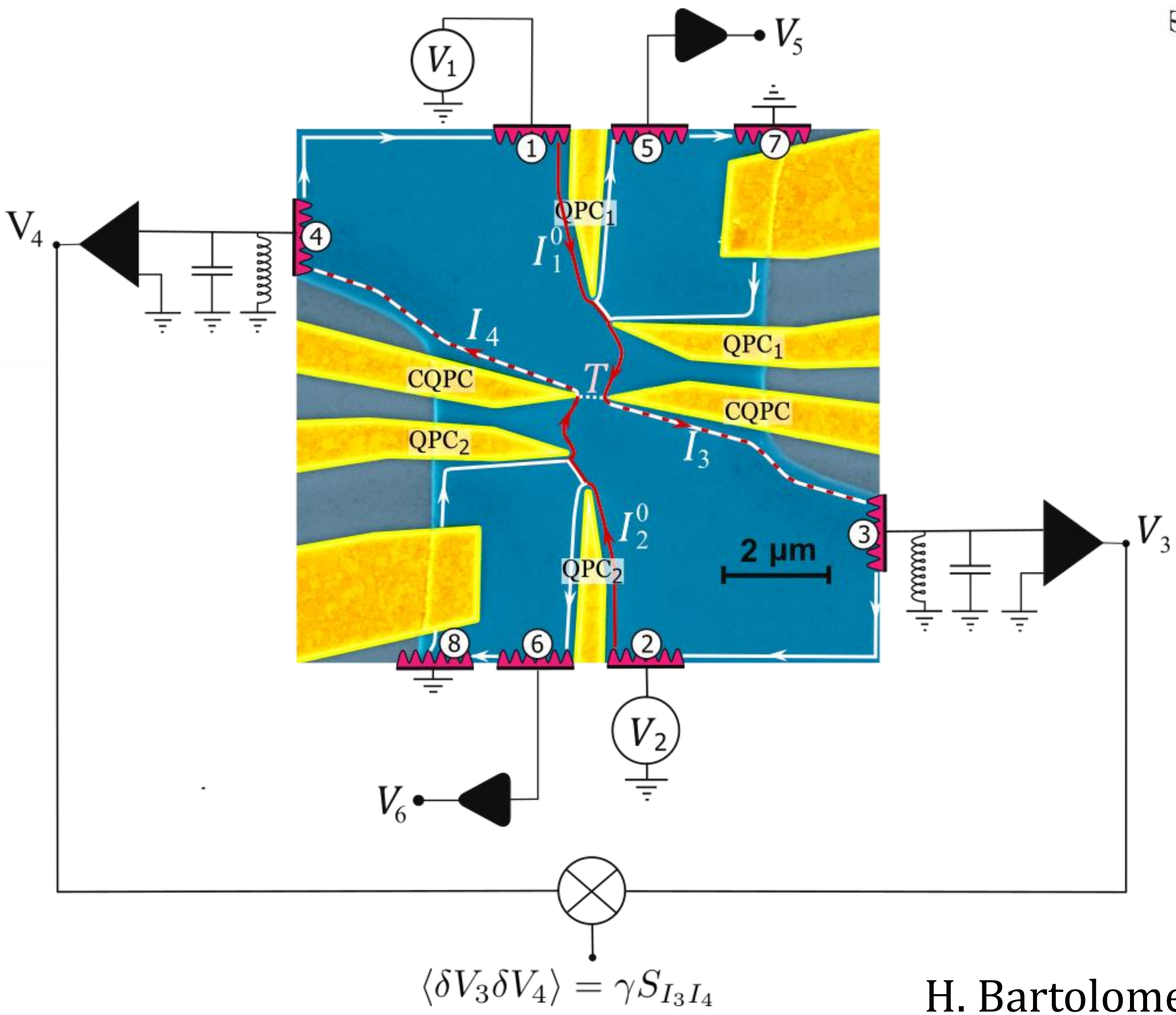
Anyons ($\upsilon = 1/3$), $P = -2$ (for $\varphi = \frac{\pi}{3}$)

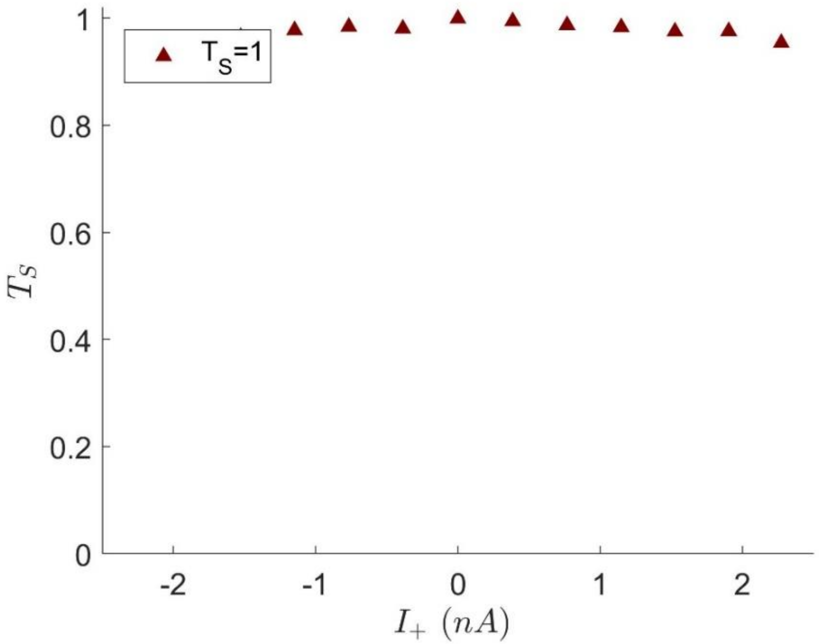
B. Rosenow et al., PRL 116, 156802 (2016)

Collisions d'électrons, $\nu = 2$

Cas entier:

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



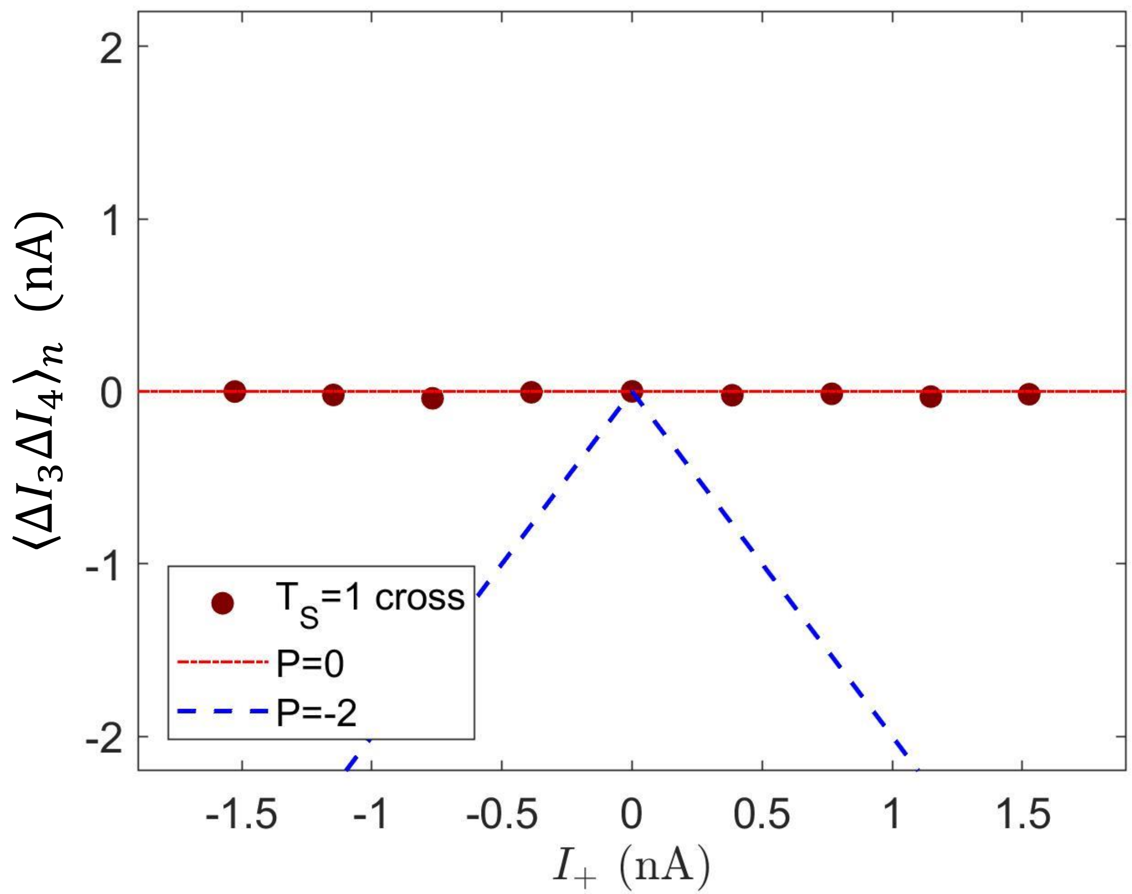


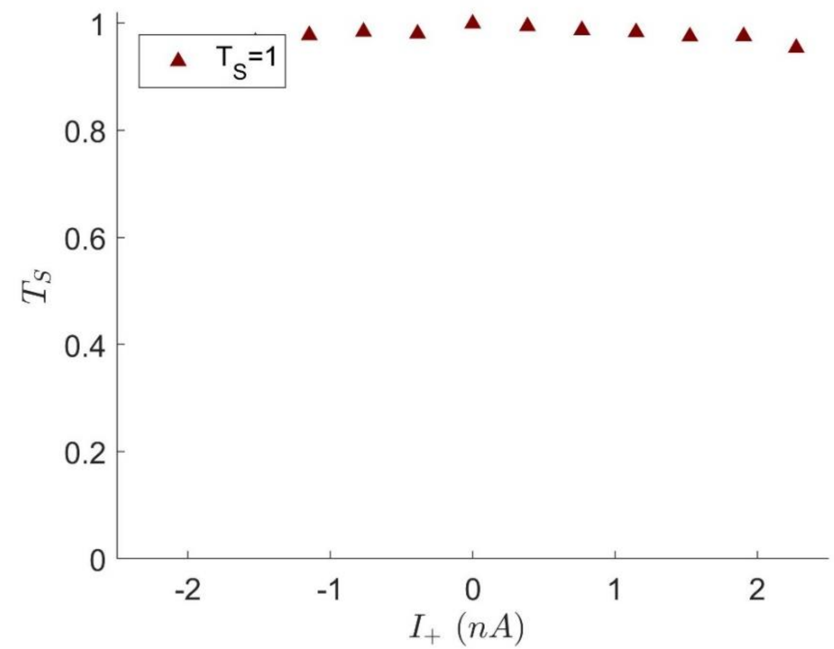
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'électrons, $\nu = 2$

Cas entier:

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





$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

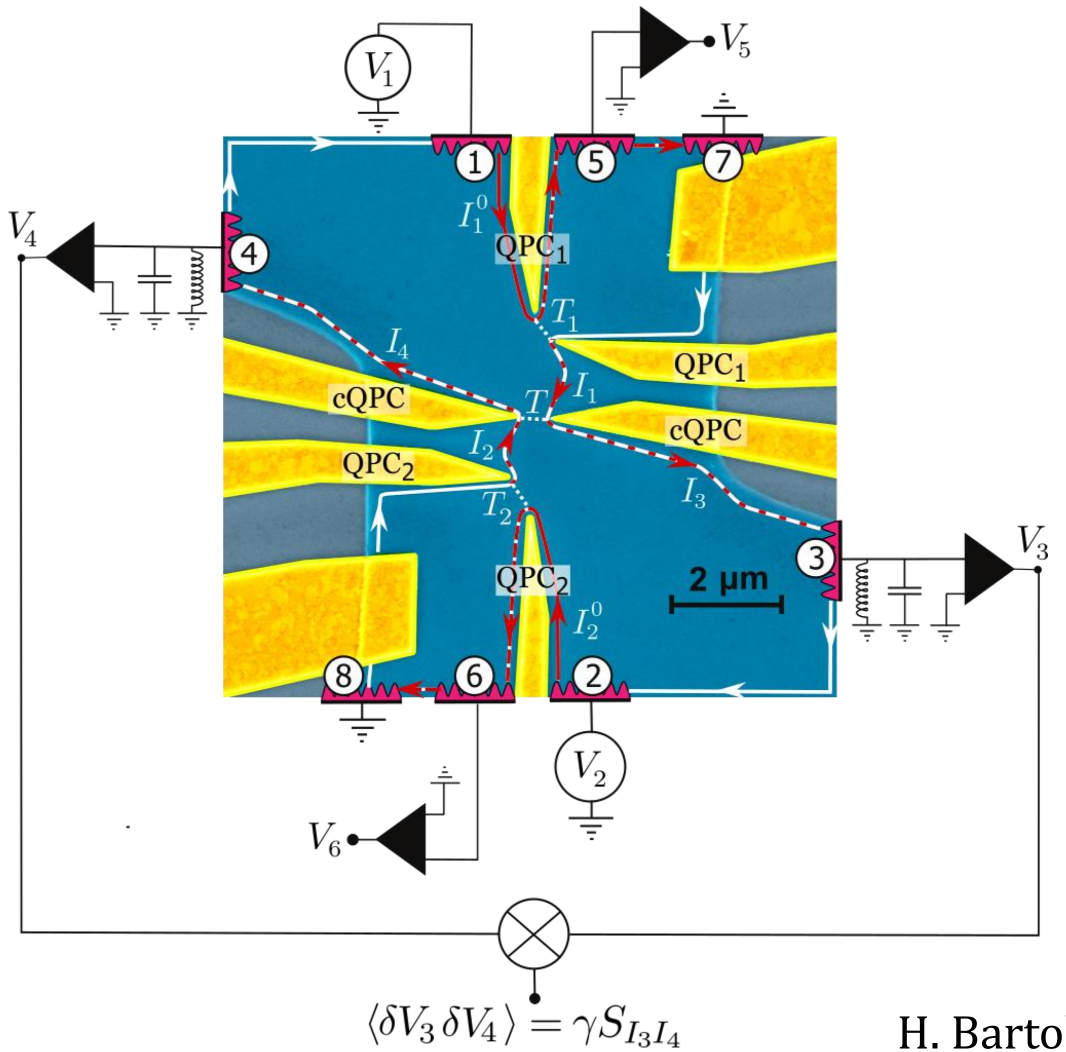
$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

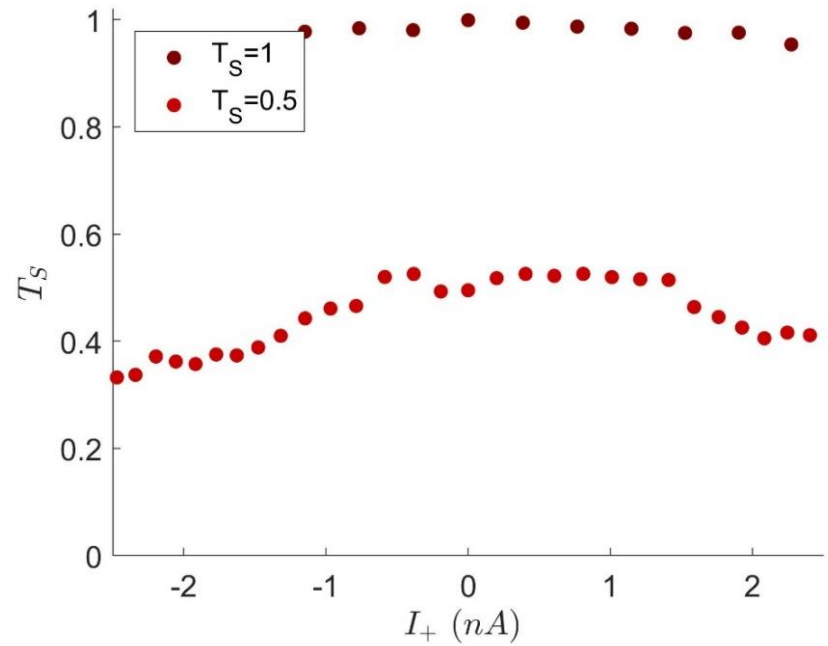
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'électrons, $\nu = 2$

Cas entier:

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



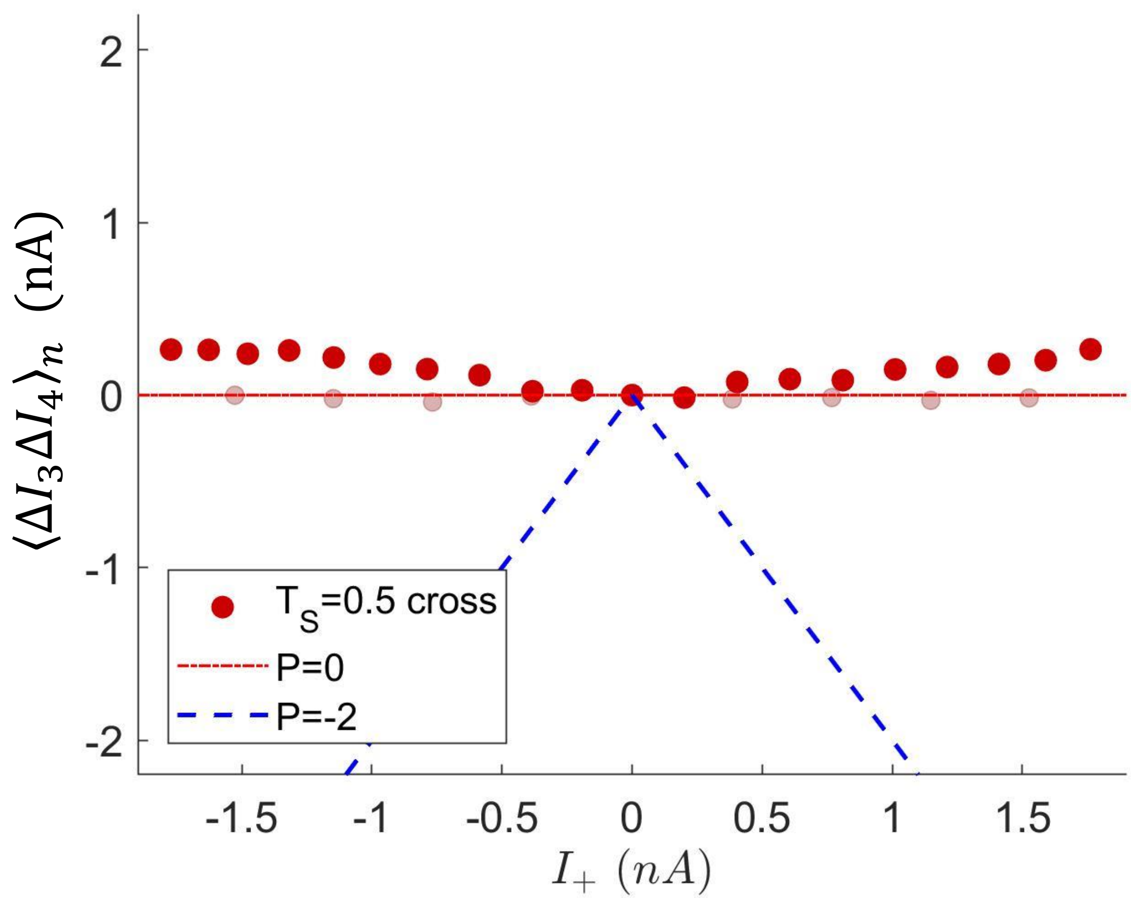


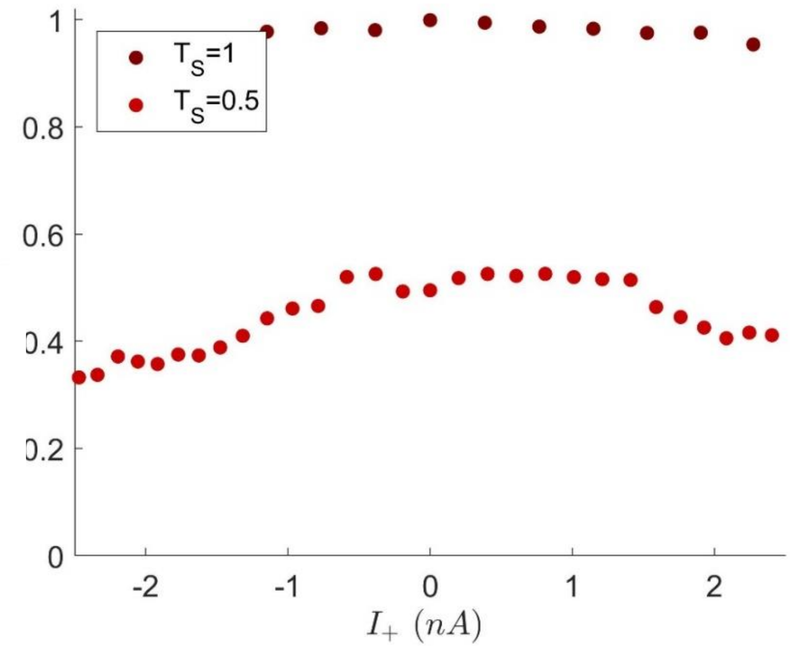
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'électrons, $\nu = 2$

Cas entier:

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





$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

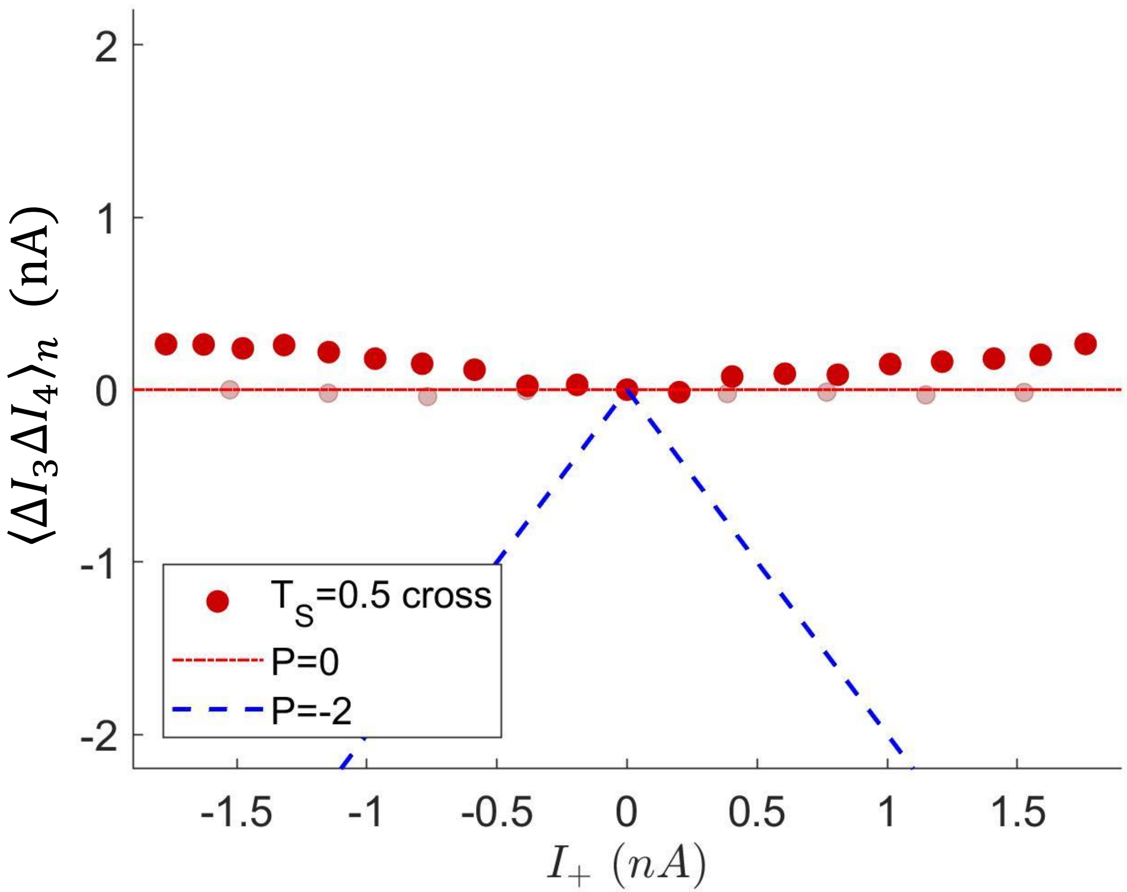
$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

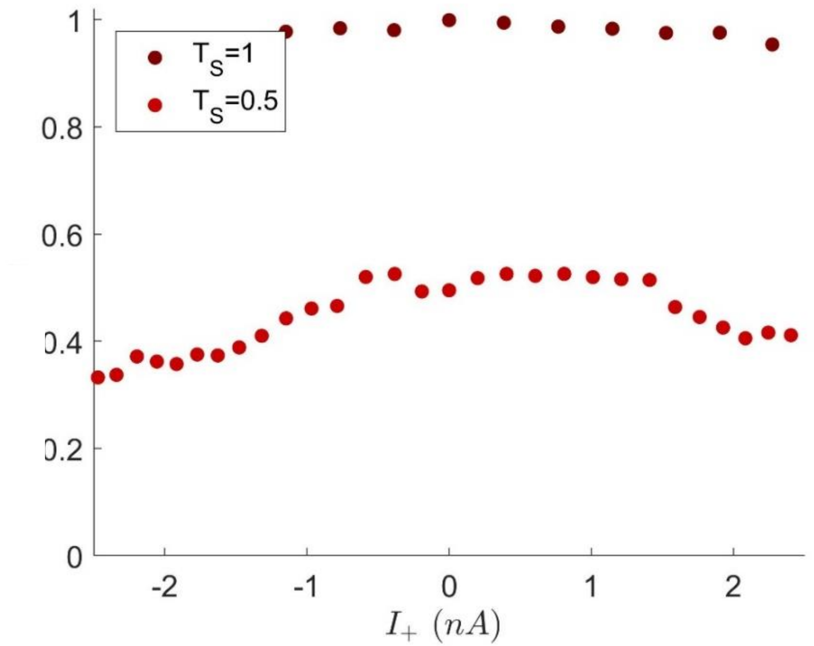
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'électrons, $\nu = 2$

Cas entier:

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





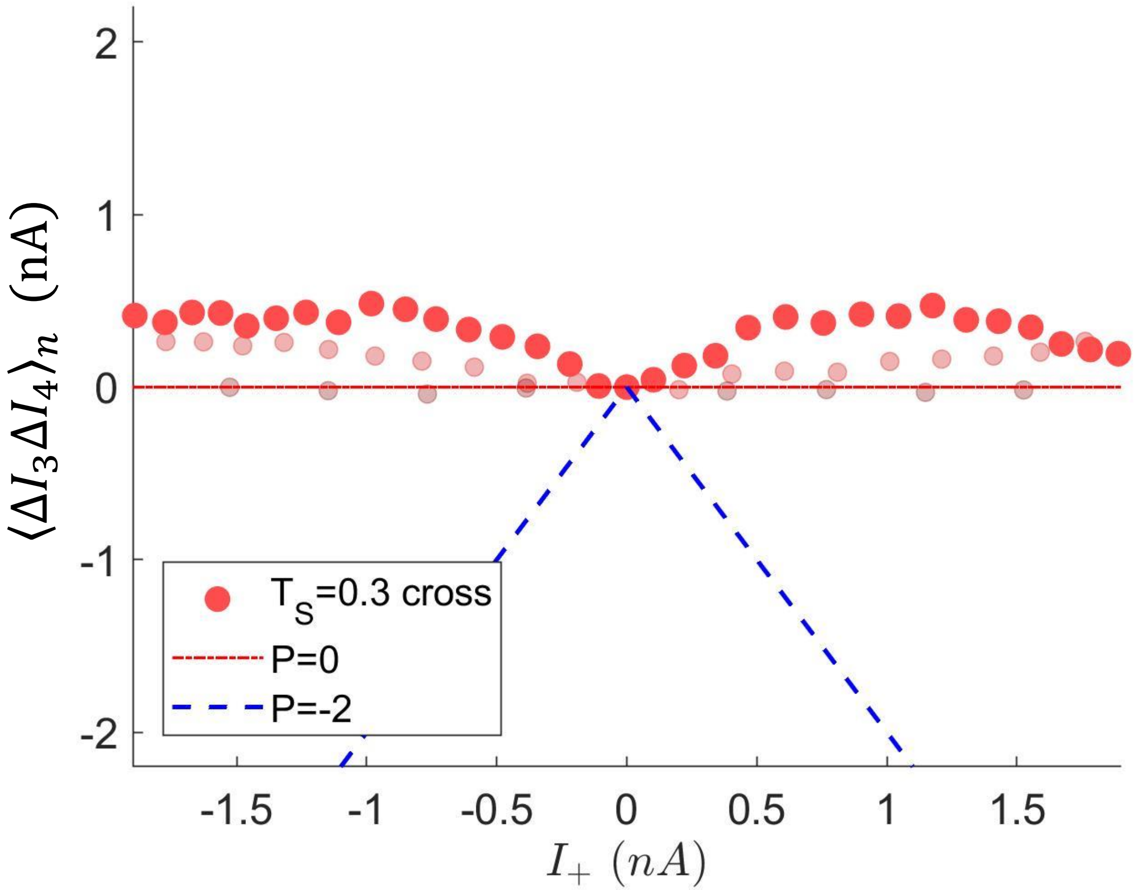
$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

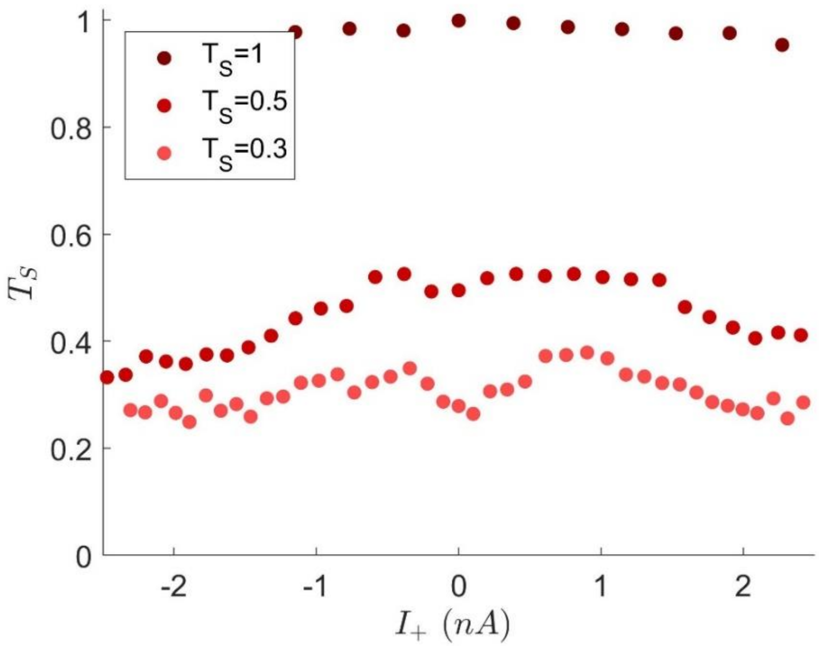
$$\langle \Delta I_3 \Delta I_4 \rangle_n = PI_+$$

Collisions d'électrons, $\nu = 2$

Cas entier:

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





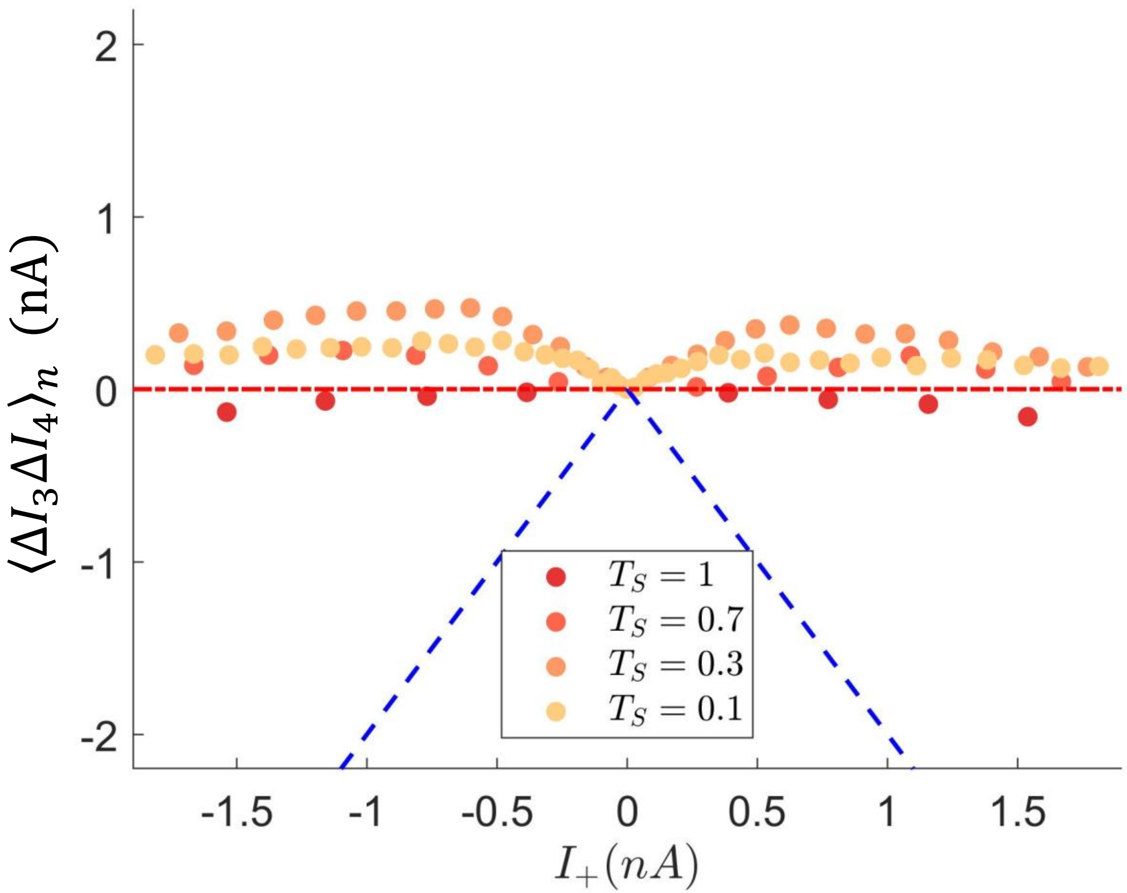
$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

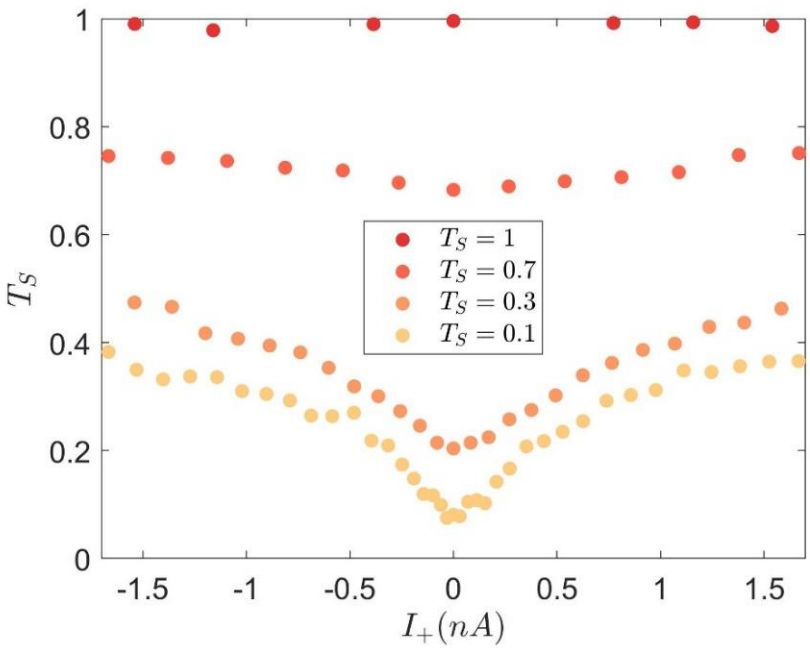
$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

Collisions d'électrons, $\nu = 3$

Cas entier:

$\nu = 3, T = 0.5$





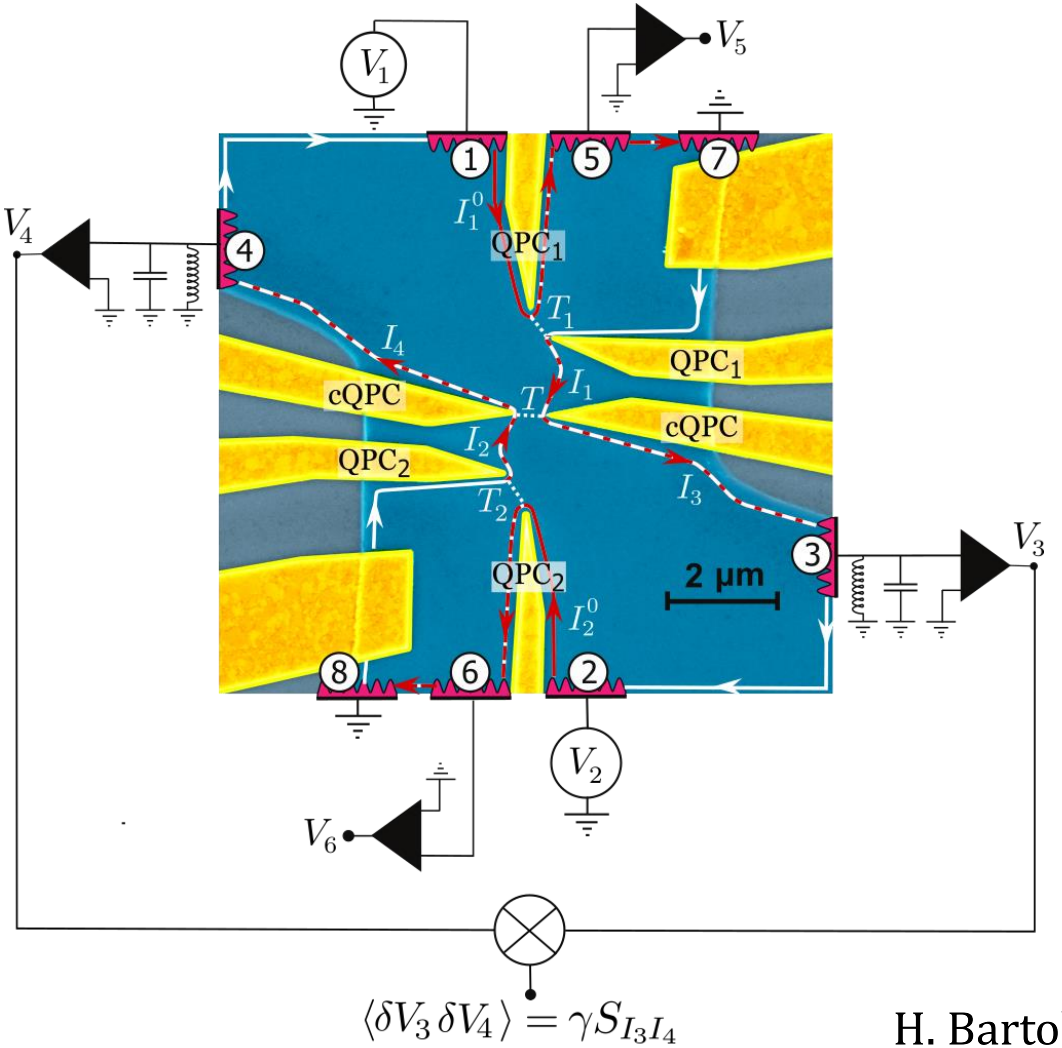
$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

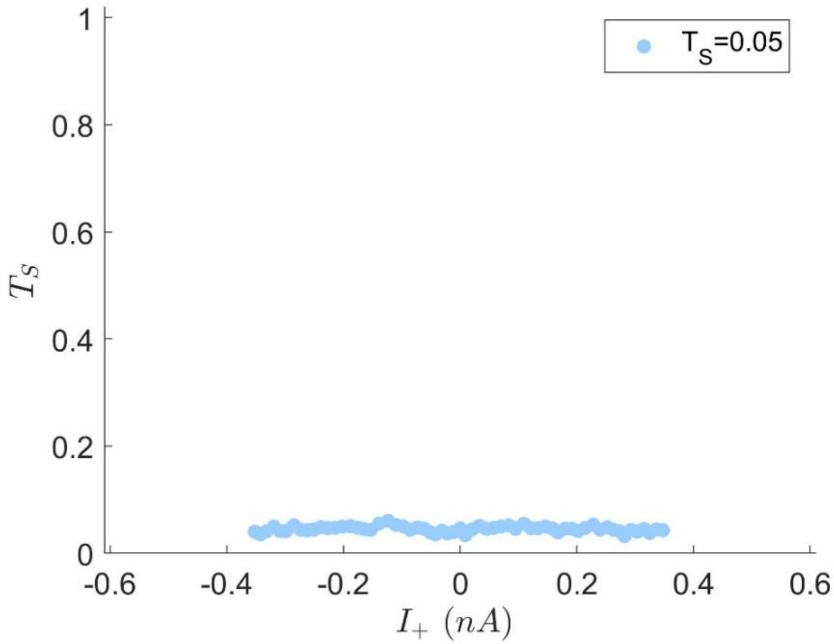
$$\langle \Delta I_3 \Delta I_4 \rangle_n = PI_+$$

Collisions d'anyons, $\nu = 1/3$

Cas fractionnaire:

$$\nu = \frac{1}{3}, T = 0.3, T_S = 0.05 \ll 1$$



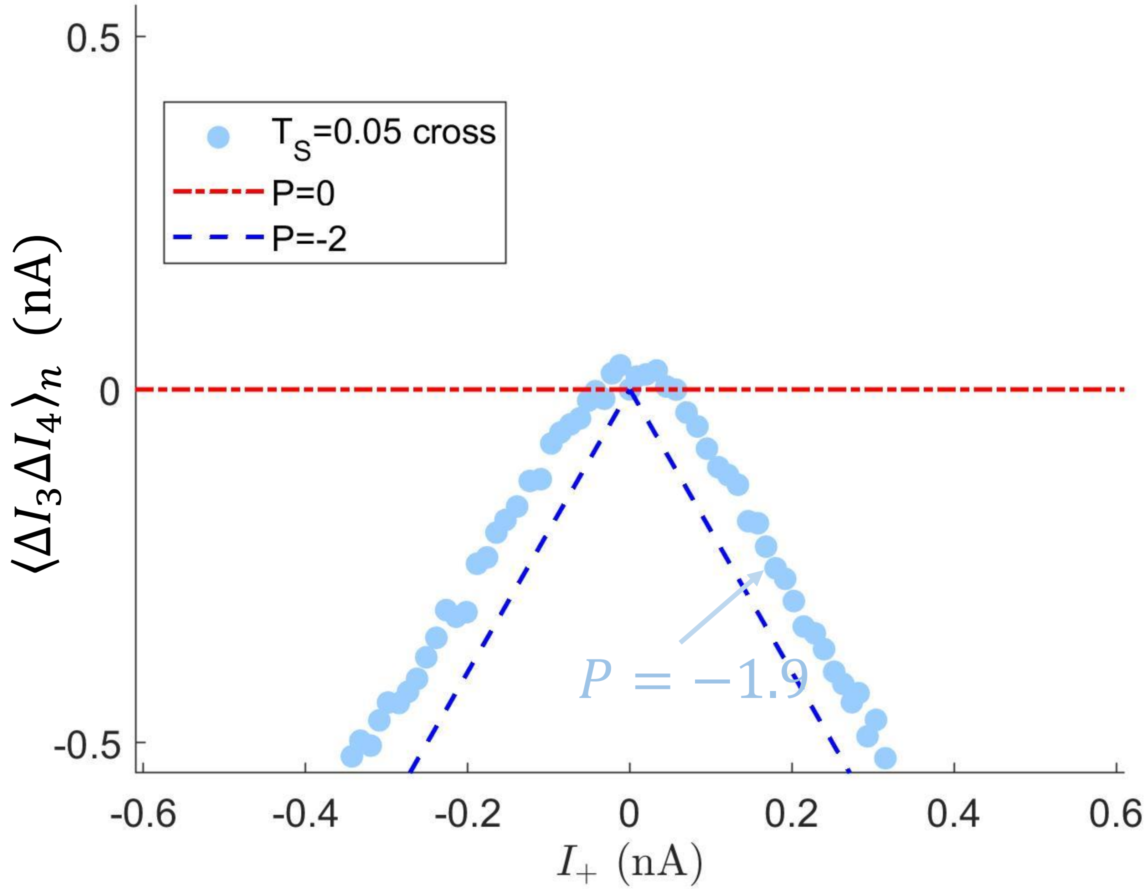


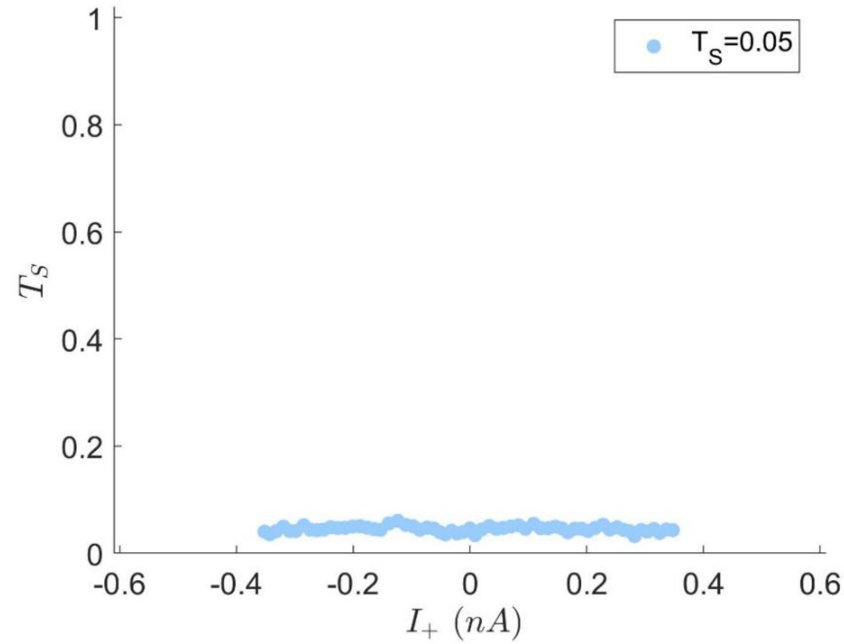
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'anyons, $\nu = 1/3$

Cas fractionnaire:

$$\nu = \frac{1}{3}, T = 0.3, T_S = 0.05 \ll 1$$





$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

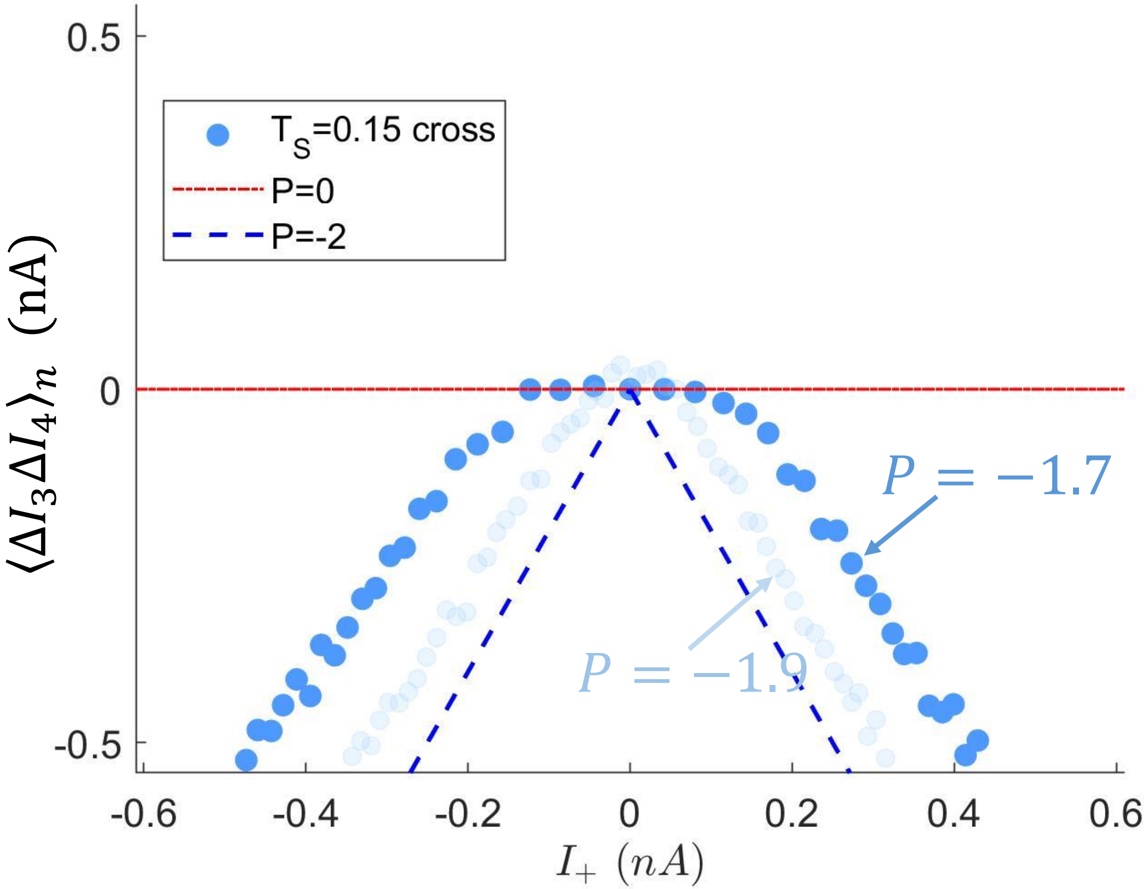
$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

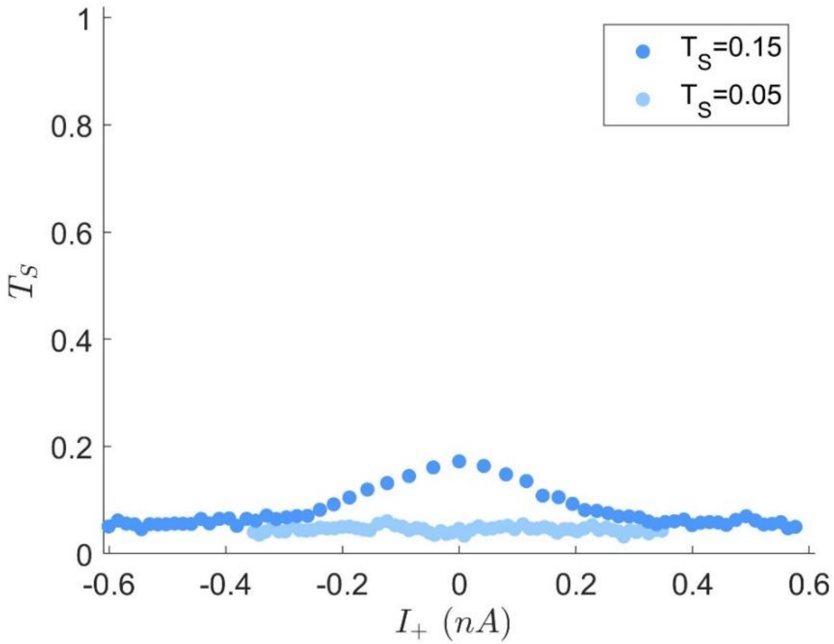
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'anyons, $\nu = 1/3$

Cas fractionnaire:

$$\nu = \frac{1}{3}, T = 0.3, T_S = 0.15$$





$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

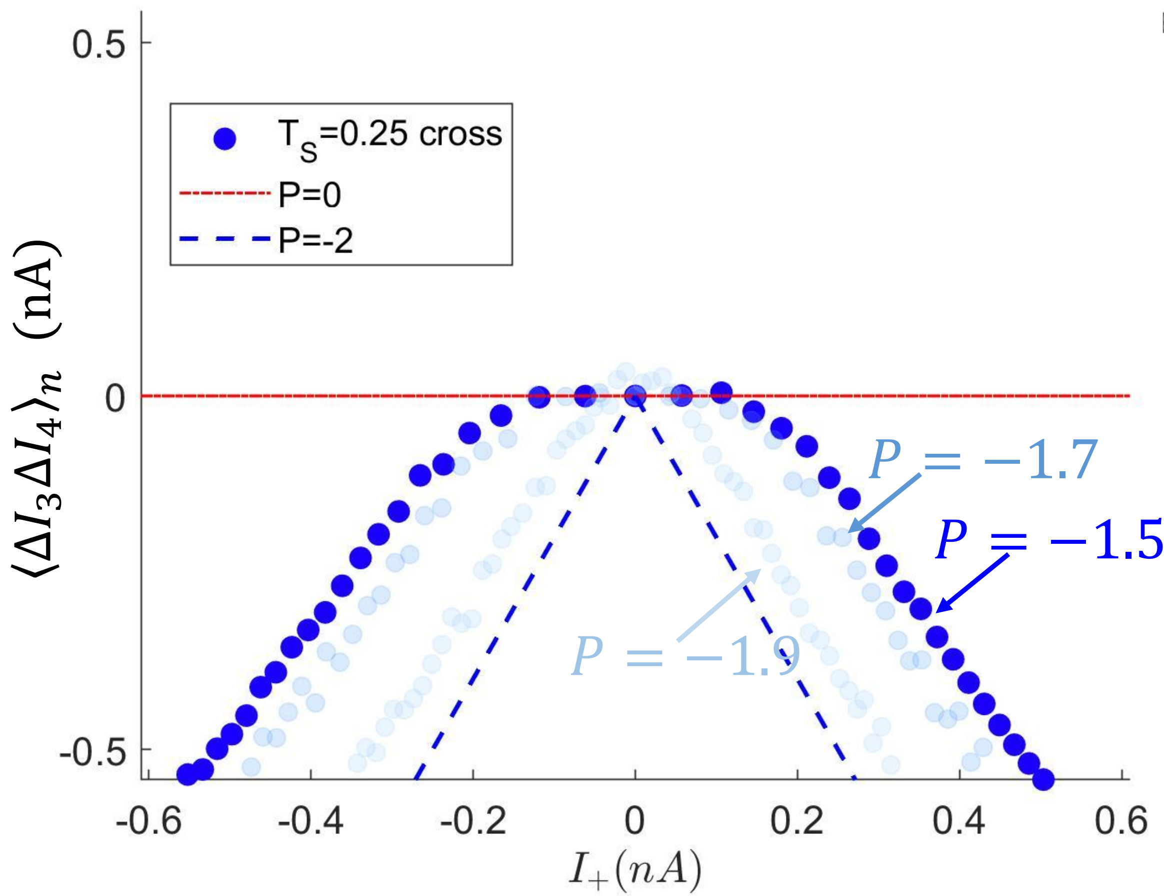
$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

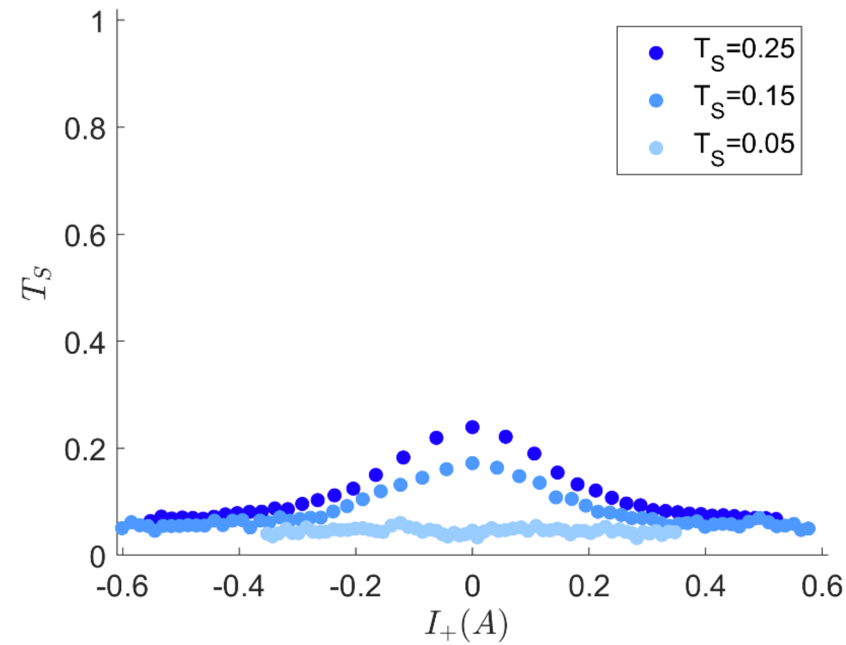
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

Collisions d'anyons, $\nu = 1/3$

Cas fractionnaire:

$$\nu = \frac{1}{3}, T = 0.3, T_S = 0.25$$





$$\langle \Delta I_3 \Delta I_4 \rangle_n = \frac{\langle \Delta I_3 \Delta I_4 \rangle}{2qT(1-T)/T_{meas}}$$

$$\langle \Delta I_3 \Delta I_4 \rangle_n = P I_+$$

$P \approx -2$ anyon

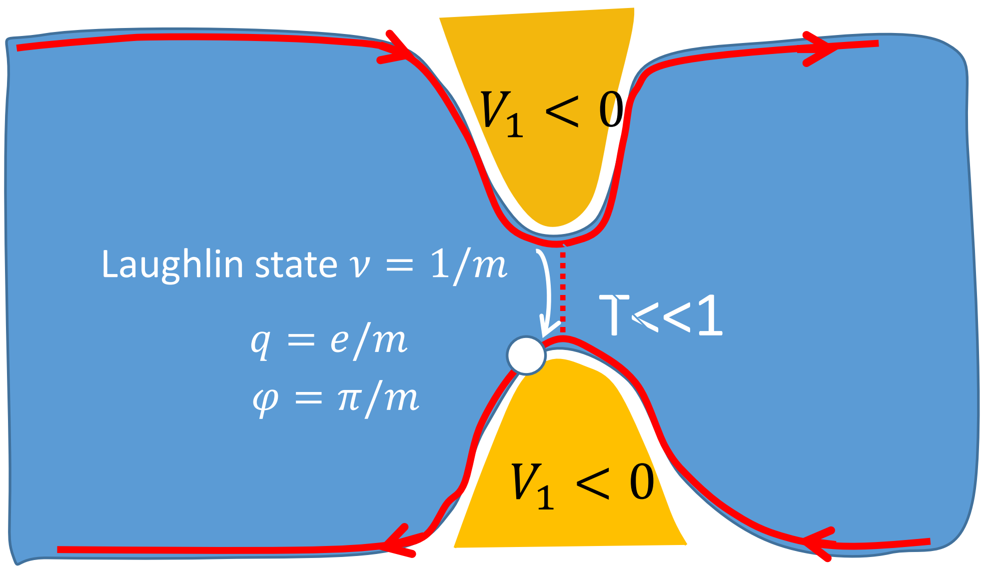
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

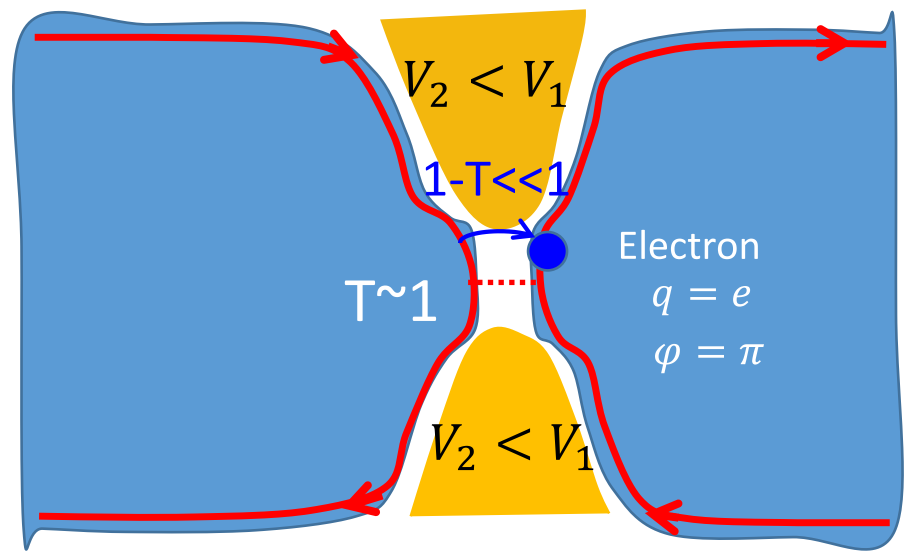
LPENS
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

Régime de forte rétrodiffusion

Faible rétrodiffusion:
Trasnfert d'anyons

Forte rétrodiffusion:
Transfert d'électrons

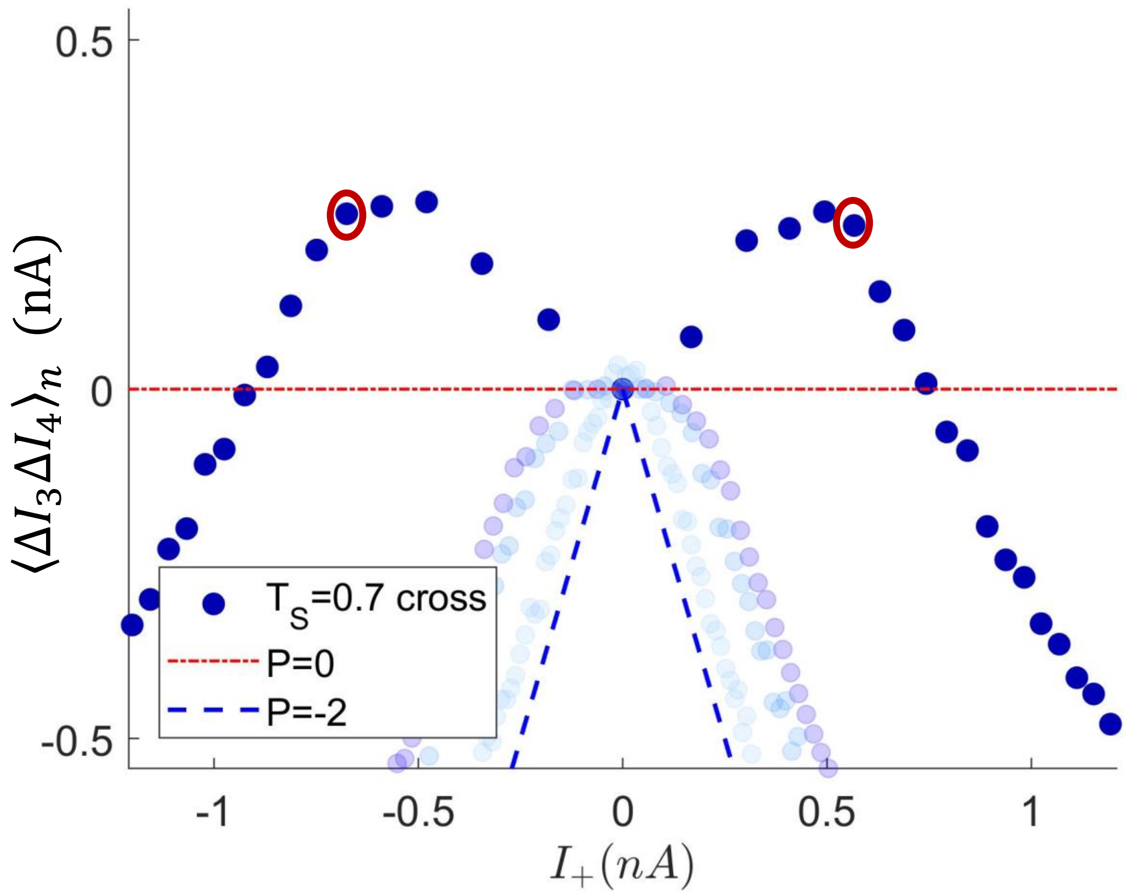




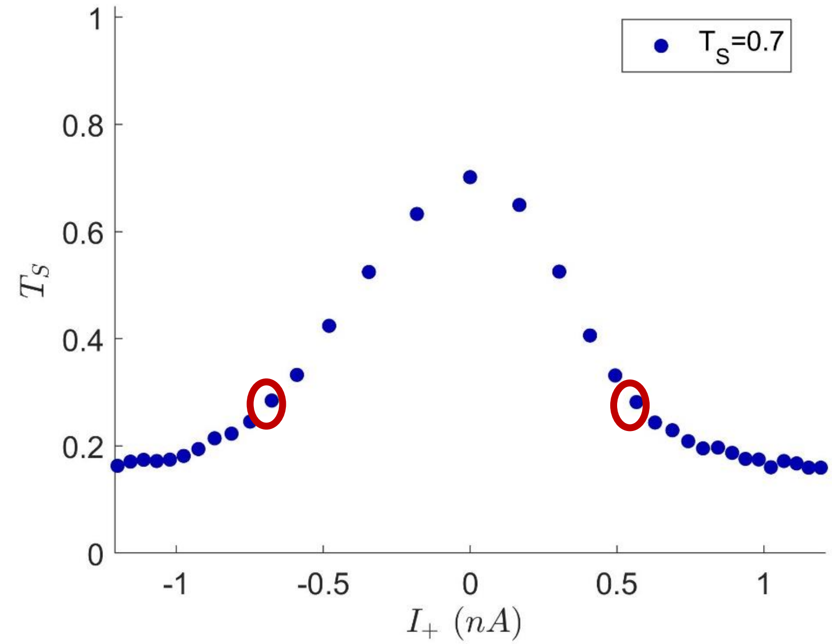
Collision d'electrons/anyons à $\nu = 1/3$

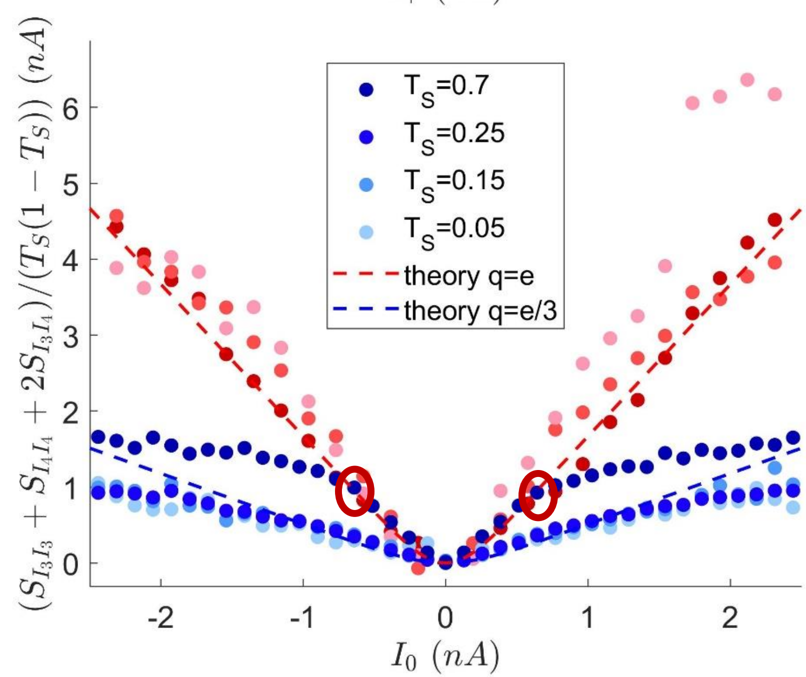
Cas fractionnaire:

$$\nu = \frac{1}{3}, T = 0.3, T_S = 0.7$$



Strong backscattering, tunneling charge q=e

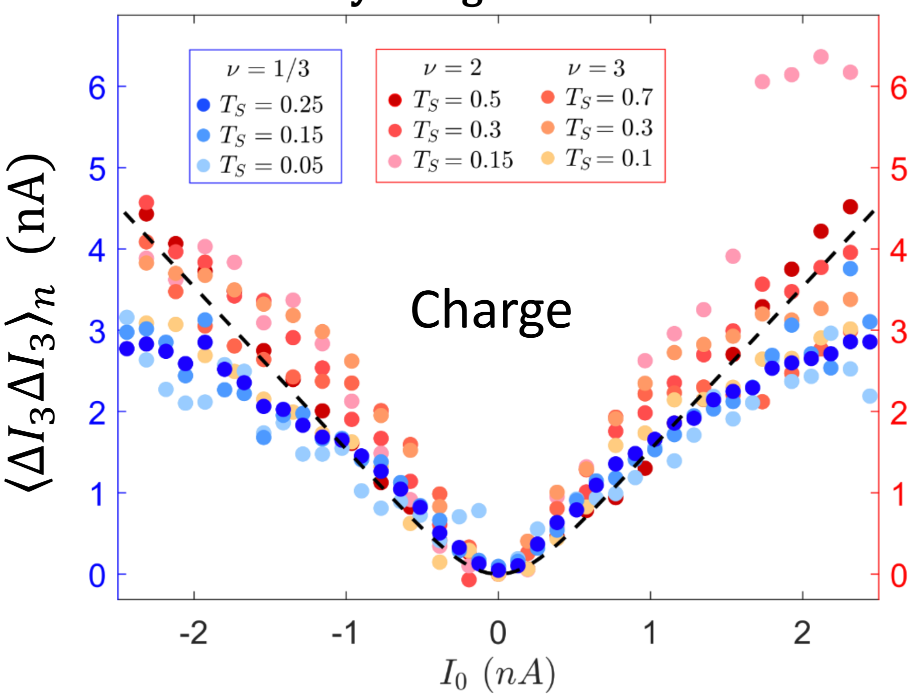




Conclusion

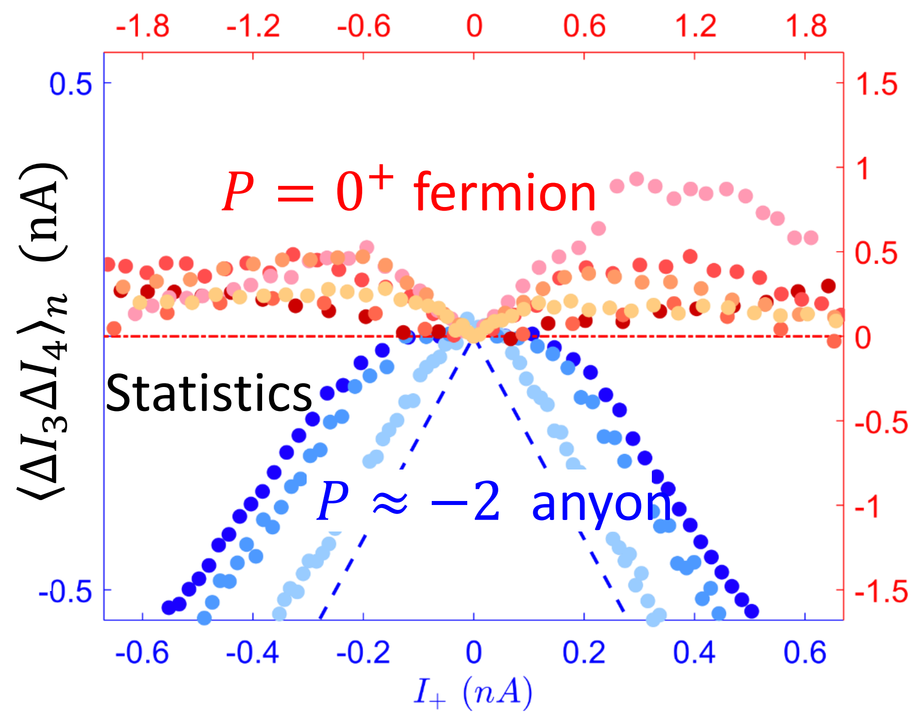
- Colliders can be used to highlight fermionic/fractional statistics independently of charge

Single QPC autocorrelation shot noise normalized by charge



$$\frac{S_{I_3 I_3}}{2qT(1-T)} = I_0$$

Collision crosscorrelations normalized by charge



$$\frac{S_{I_3 I_4}}{2qT(1-T)} = \boldsymbol{P}\, I_+$$

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

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

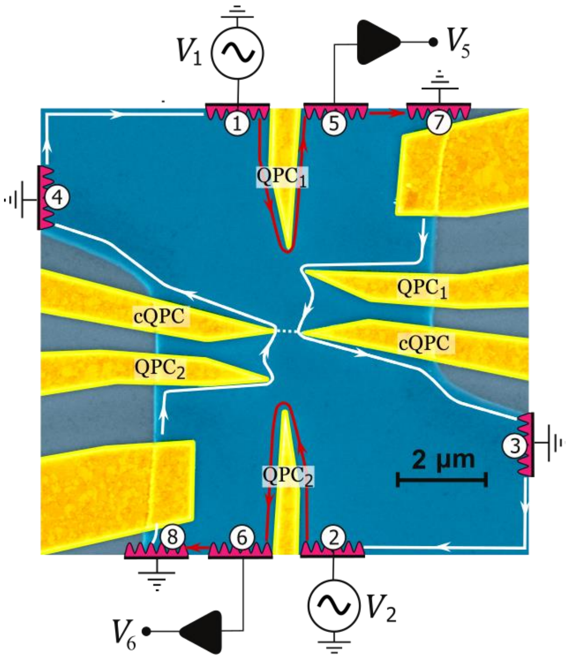
B. Rosenow, I. Levkivskyi and B. Halperin, PRL **116** 156802 (2016)

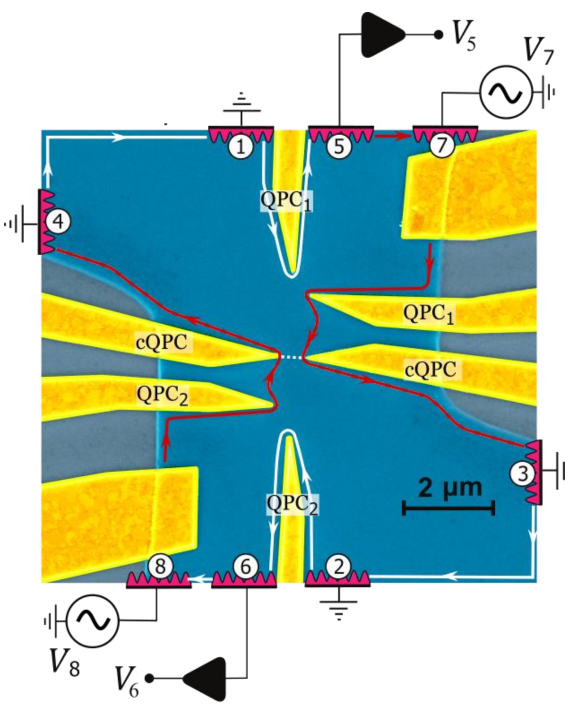
H. Bartolomei, M. Kumar et al., Science **368** 173 (2020)

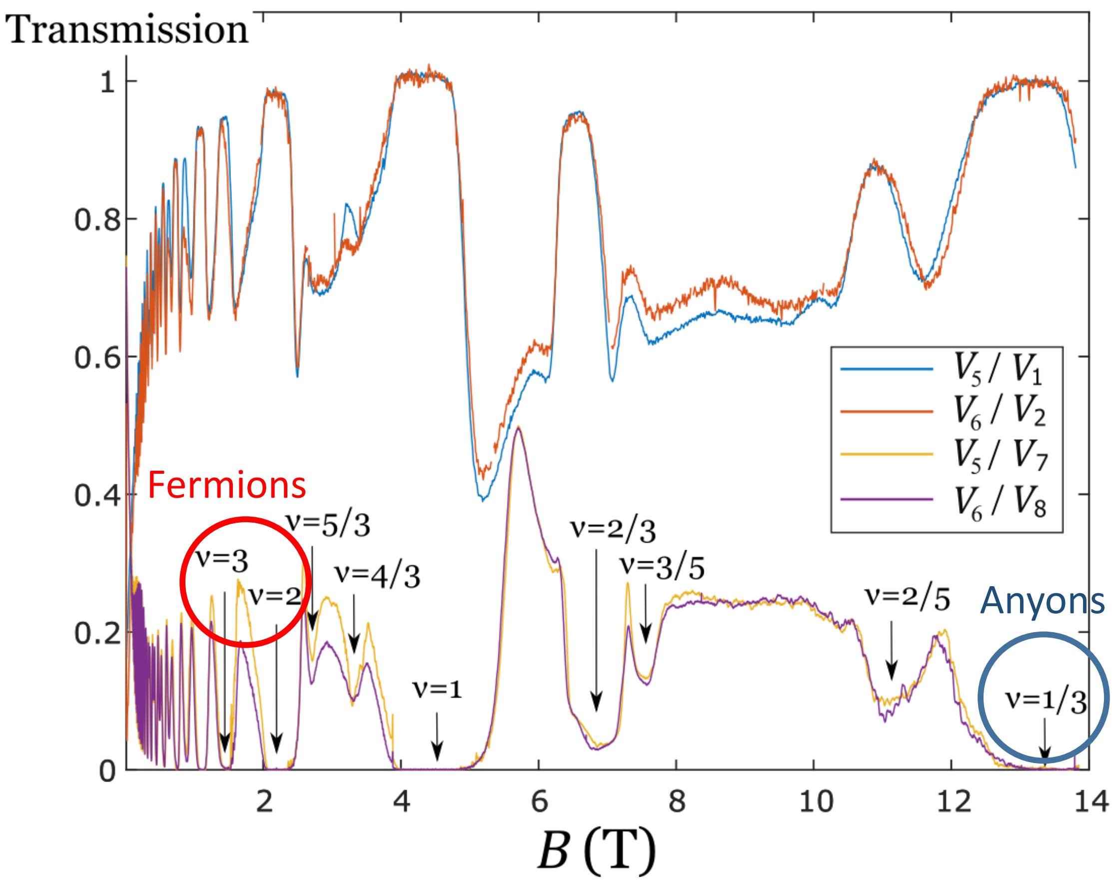
- Fractional statistics can also be measured in interferometers (Fabry-Perot)

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

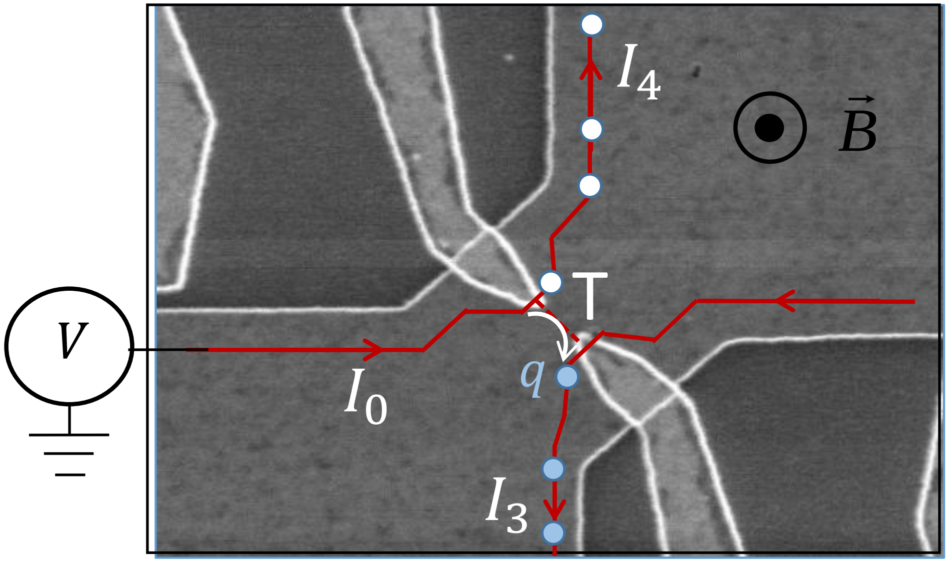
The collider: sample





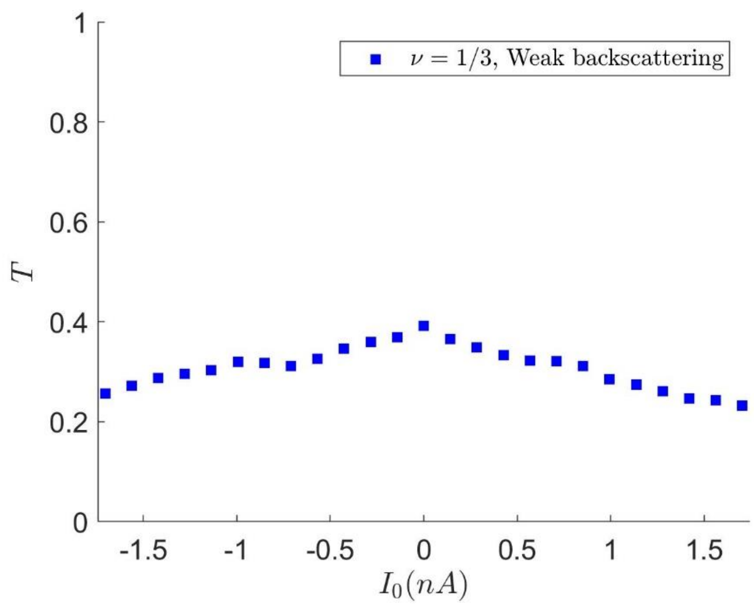


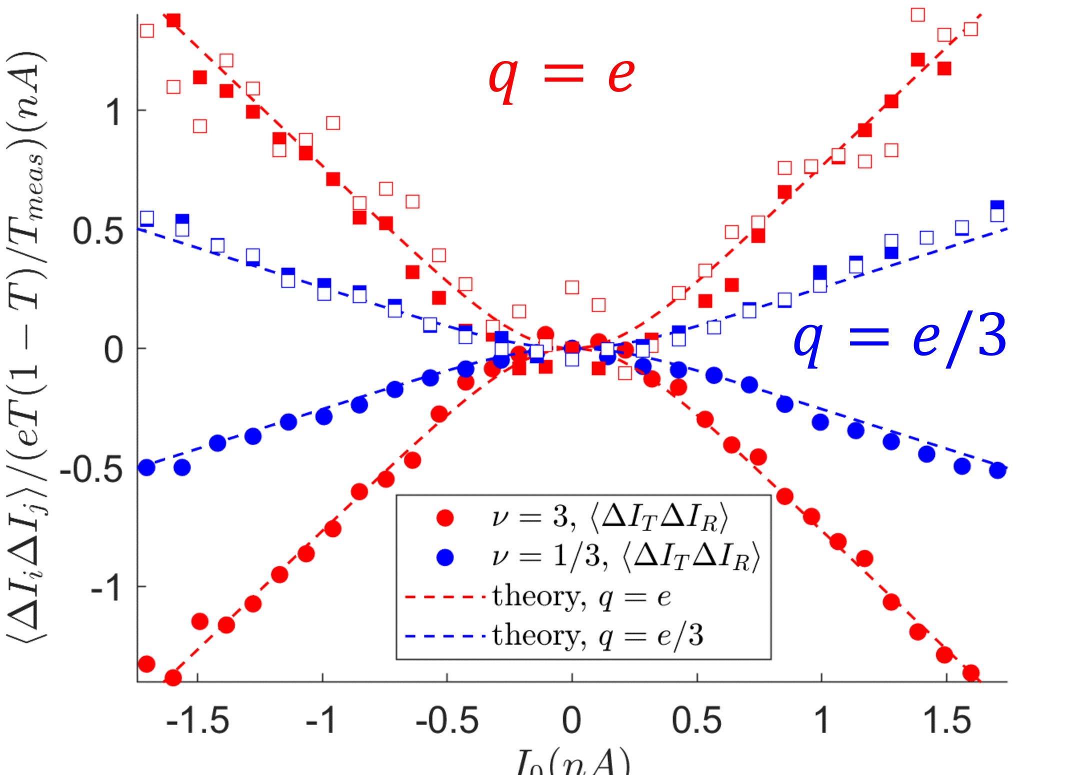
Fractional charges and noise, ν=1/3



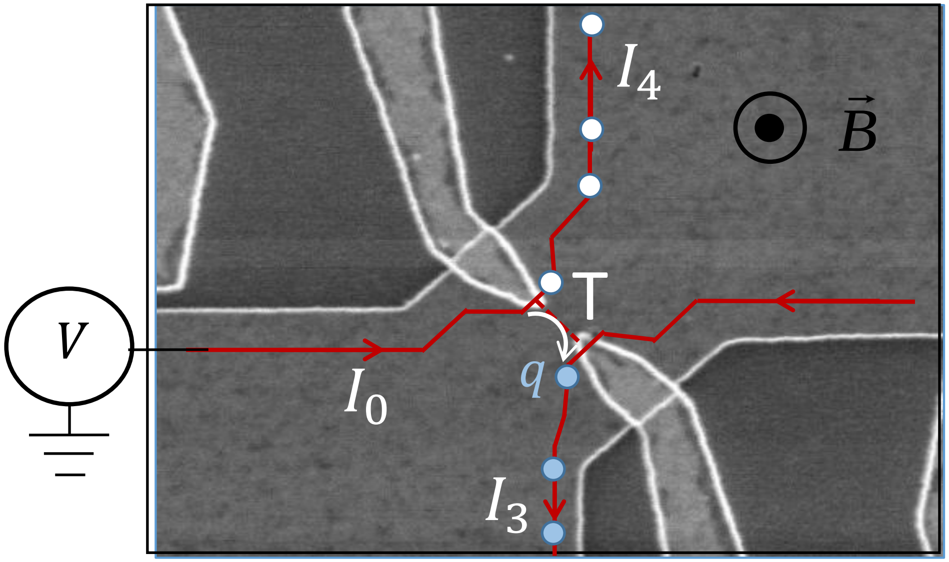
T<<1:quasiparticle transfer is a poissonian process: $\langle \Delta N_T^2 \rangle = \langle N_T \rangle = T N_0$

$$\langle \Delta I_T^2 \rangle = \frac{q^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{qT}{T_{meas}} \frac{qN_0}{T_{meas}} = \frac{qT}{T_{meas}} I_0$$



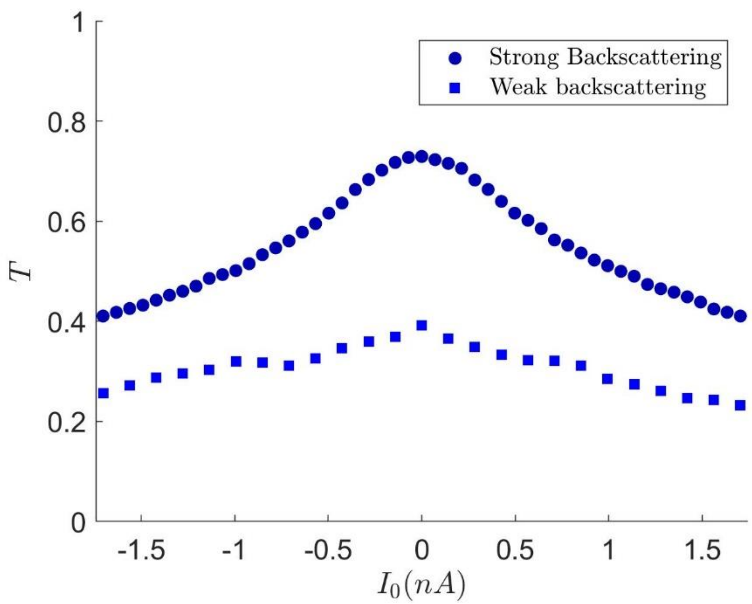


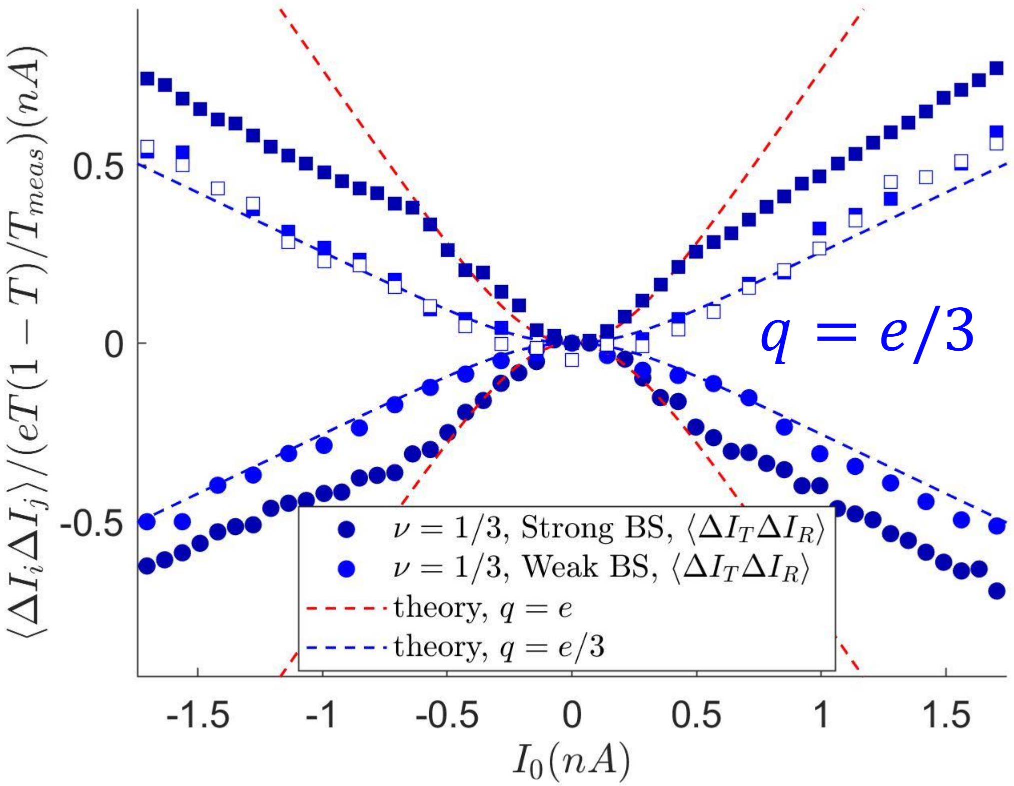
Fractional charges and noise, ν=1/3



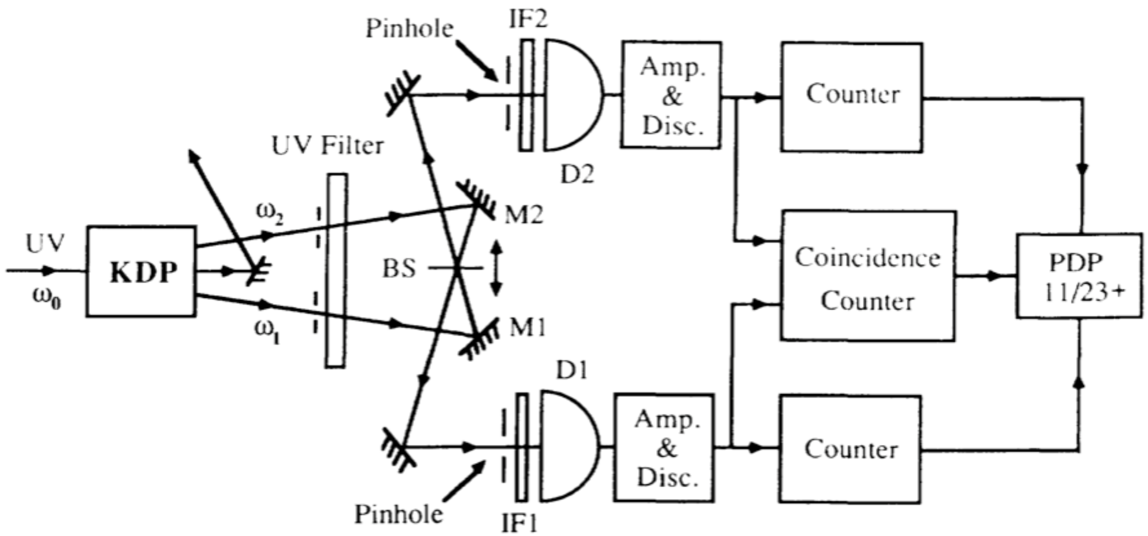
T<<1:quasiparticle transfer is a poissonian process: $\langle \Delta N_T^2 \rangle = \langle N_T \rangle = T N_0$

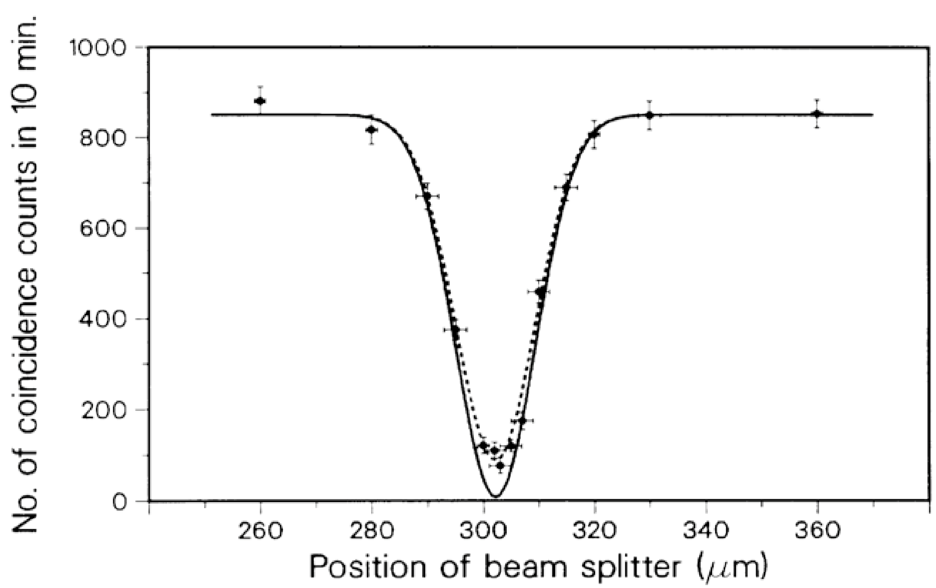
$$\langle \Delta I_T^2 \rangle = \frac{q^2}{T_{meas}^2} \langle \Delta N_T^2 \rangle = \frac{qT}{T_{meas}} \frac{qN_0}{T_{meas}} = \frac{qT}{T_{meas}} I_0$$



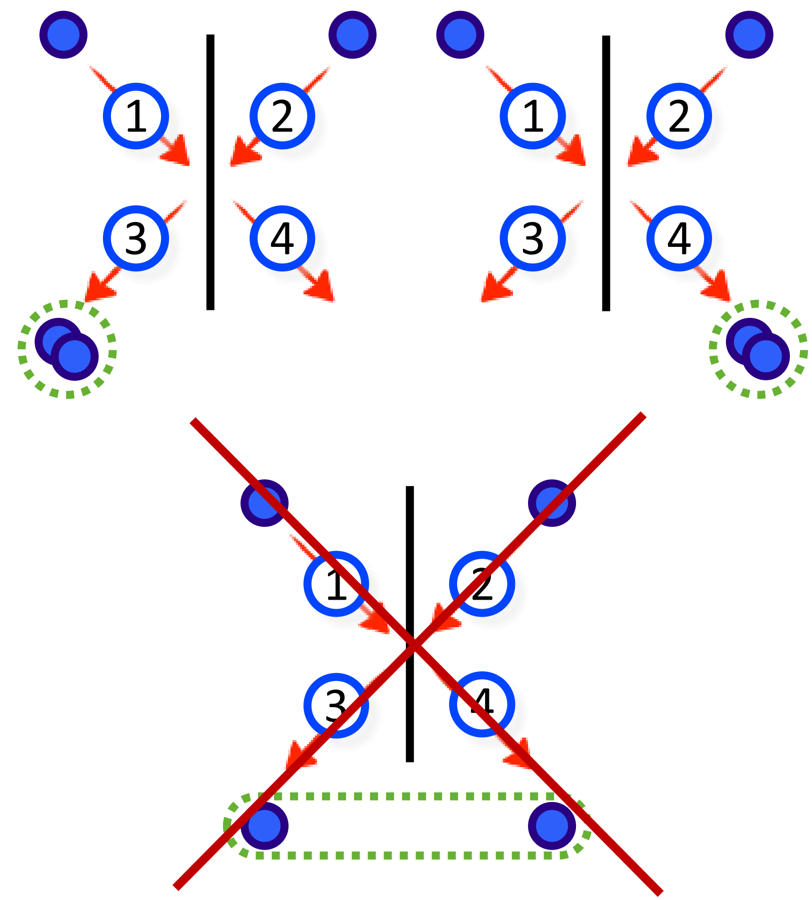


Inteférences quantiques de 2 photons





Interférences quantiques à 2 particules



Photons pairs :

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

Different emitters :

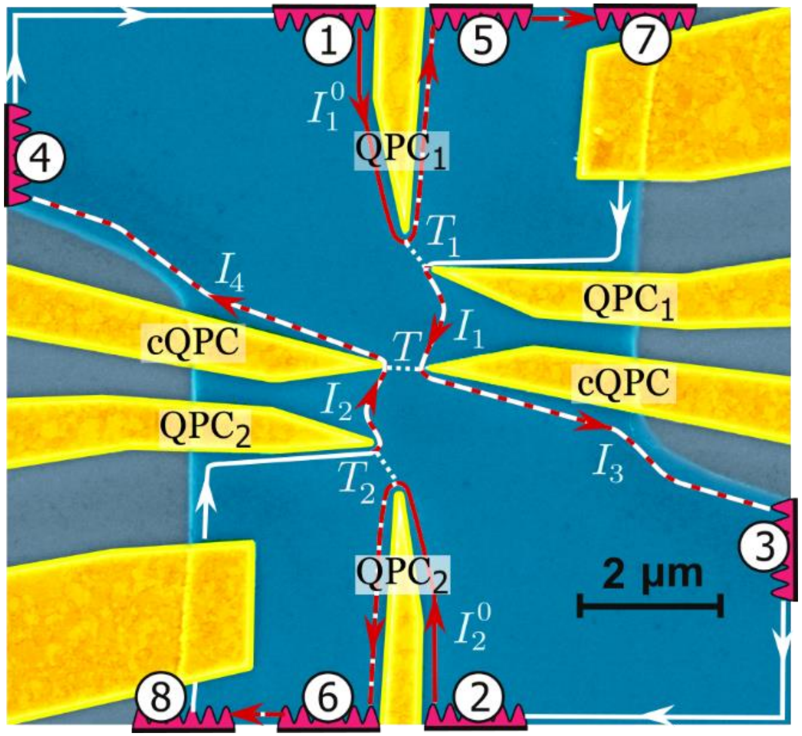
J. Beugnon *et al.*, Nature **440**, 779 (2006)

P. Maunz *et al.*, Nature Physics **3**, 538 (2007)

E. B. Flagg *et al.*, PRL **104,** 137401 (2010)

The anyon collider, Rosenow et al., Phys. Rev. Lett **116**, 156802 (2016)

Chiral Luttinger liquid description: bosonic fields describe charge fluctuatoins at the input of the collider



$$[\phi_i(0,t), \phi_j(0,t')] = i\pi\delta\, \delta_{ij}\, sgn(t-t')$$

φ

$$H_T = \zeta e^{i\phi_1(0,t) - i\phi_2(0,t)} + h.c.$$

Poissonian emission of quasiparticles at inputs 1 and 2:

$$\phi_i(0,t) = \phi_i^{(0)}(0,t) + 2\pi\lambda\, N_i(t)$$

$N_i(t)$: random (poissonian) variable, number of quasiparticles emitted in time t

Laughlin case: $\lambda = 1/m$

but λ can be renormalized by interactions

$$V_1 = V_2 = V_S$$

$$T_1 = T_2 = T_S \ll 1$$

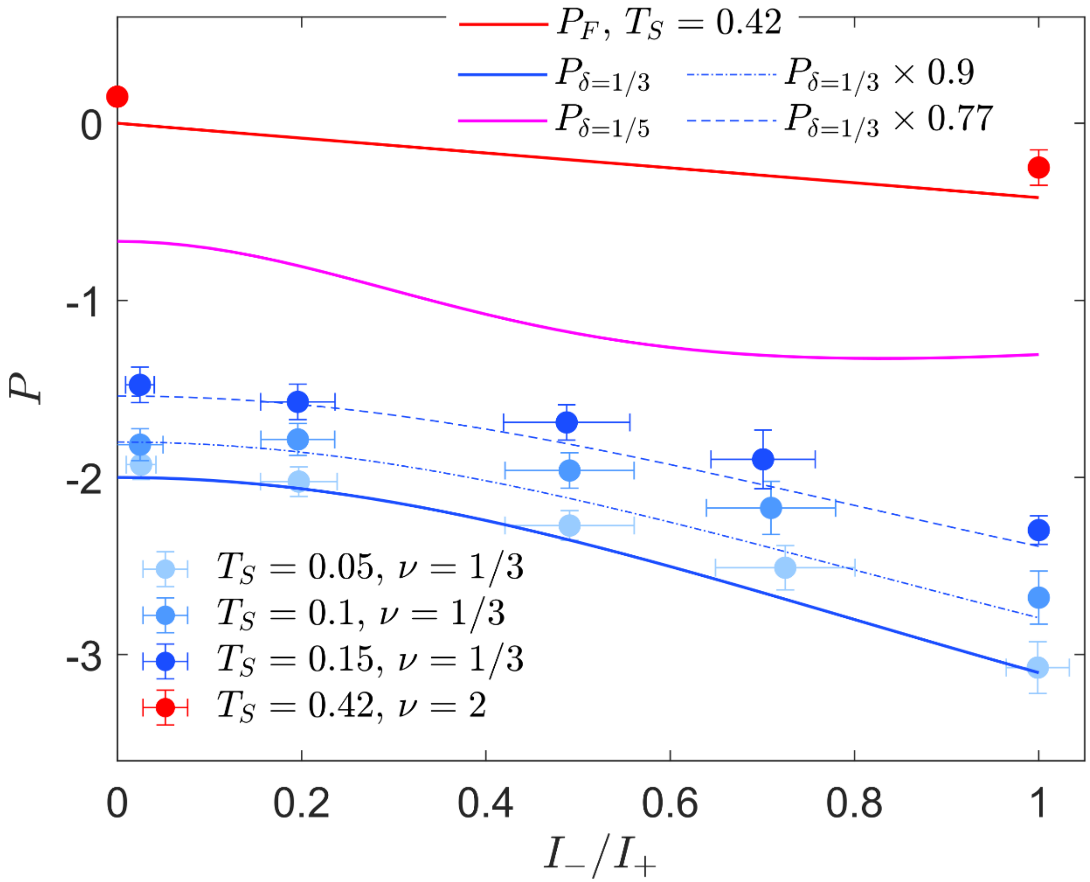
$$I_+ = I_1 + I_2 \neq 0$$

$$I_- = I_1 - I_2 = 0$$

$$S_{I_3 I_4} = P\; 2qT\; I_+, \qquad P = 1 - \frac{\tan(\pi\lambda)}{\tan(\pi\delta)} \frac{1}{1-2\delta} = -2 \quad (\lambda = \delta = \nu = 1/3)$$

Anyon collisions, $I_- \neq 0$

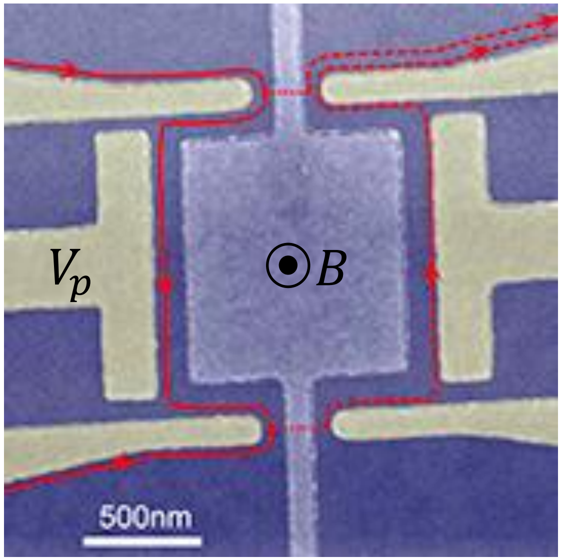
$T_1 = T_2 = T_S$ $\quad V_1 \neq V_2$ $\quad \begin{cases} I_+ = I_1 + I_2 \neq 0 \\ I_- = I_1 - I_2 \neq 0 \end{cases} \Rightarrow P(I_-/I_+)$

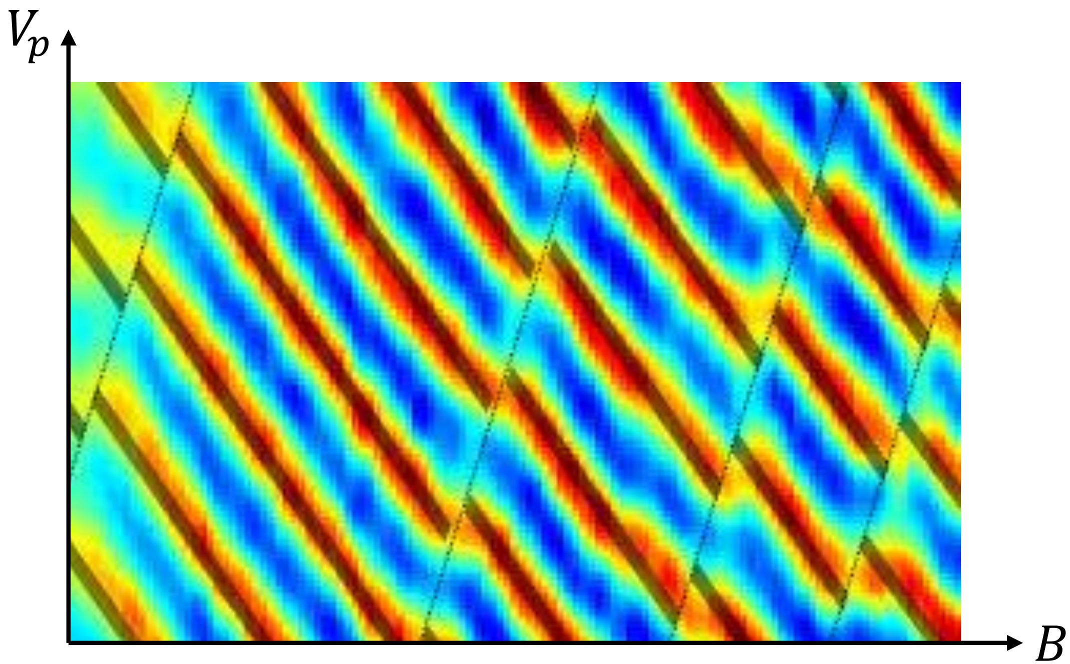


Very good agreement with predictions for anyon collisions with $\varphi = \frac{\pi}{3}$

B. Rosenow et al., Phys. Rev. Lett **116**, 156802 (2016)

Conclusion 2: Fabry-Perot experiments





C. de C. Chamon, et al., PRB **55**, 2331 (1997)

K.T. Law, D.E. Feldman, Y. Gefen, PRB **74**, 045319 (2006)

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

$$\theta = 2\pi \frac{q}{h} BA + N_{qp} 2\varphi$$

AB phase: $2\pi \frac{q}{h} BA$

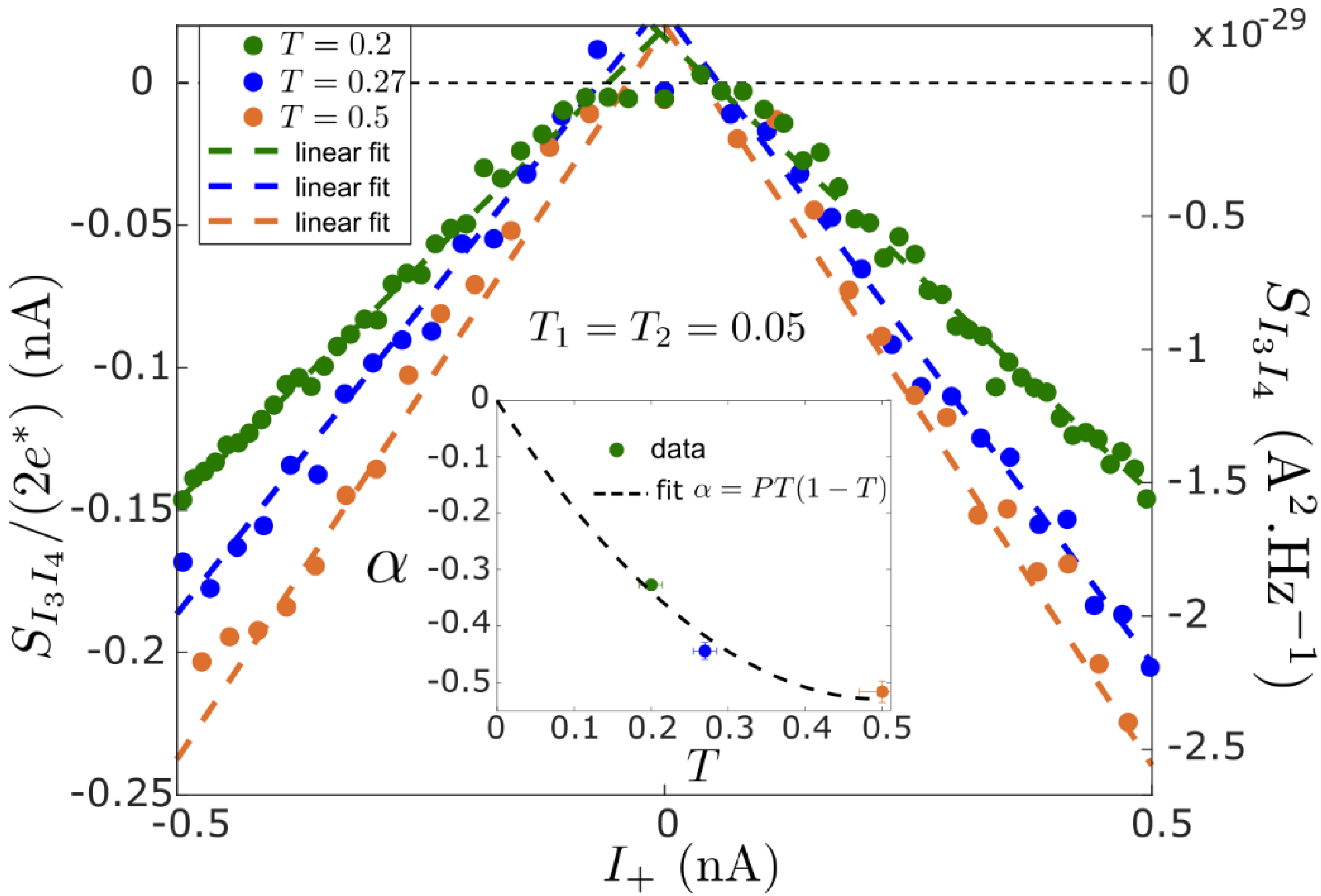
Braiding phase: $N_{qp} 2\varphi$

$\nu = 1/3$

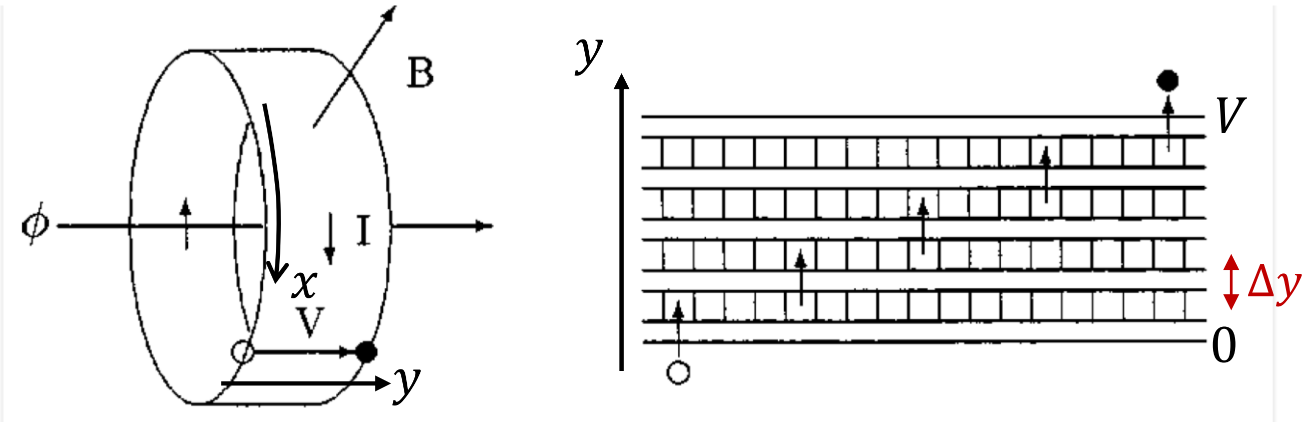
$2\varphi = 2\pi/3$

Important: coulomb interactions can be neglected

Anyon collision : different transmission for cQPC



Laughlin's argument for quantized Hall conductance



$$\vec{A} = By\overrightarrow{e_x}$$

$$H = \sum_{j=1}^{N} \frac{(\vec{p_j} - e\vec{A}(\vec{r_j}))^2}{2m} + eEy_j$$

$$\psi_{k,n}(x,y) = e^{ik_p x}\phi_n\left(y + y_0 - \frac{\hbar k_p}{eB}\right) \qquad y_0 = \frac{Em}{eB^2} \qquad k_p = p\frac{2\pi}{L_x} \longrightarrow \Delta y = \frac{h}{eBL_x}$$

$$\vec{A} \longrightarrow \vec{A} + A_0\overrightarrow{e_x}$$

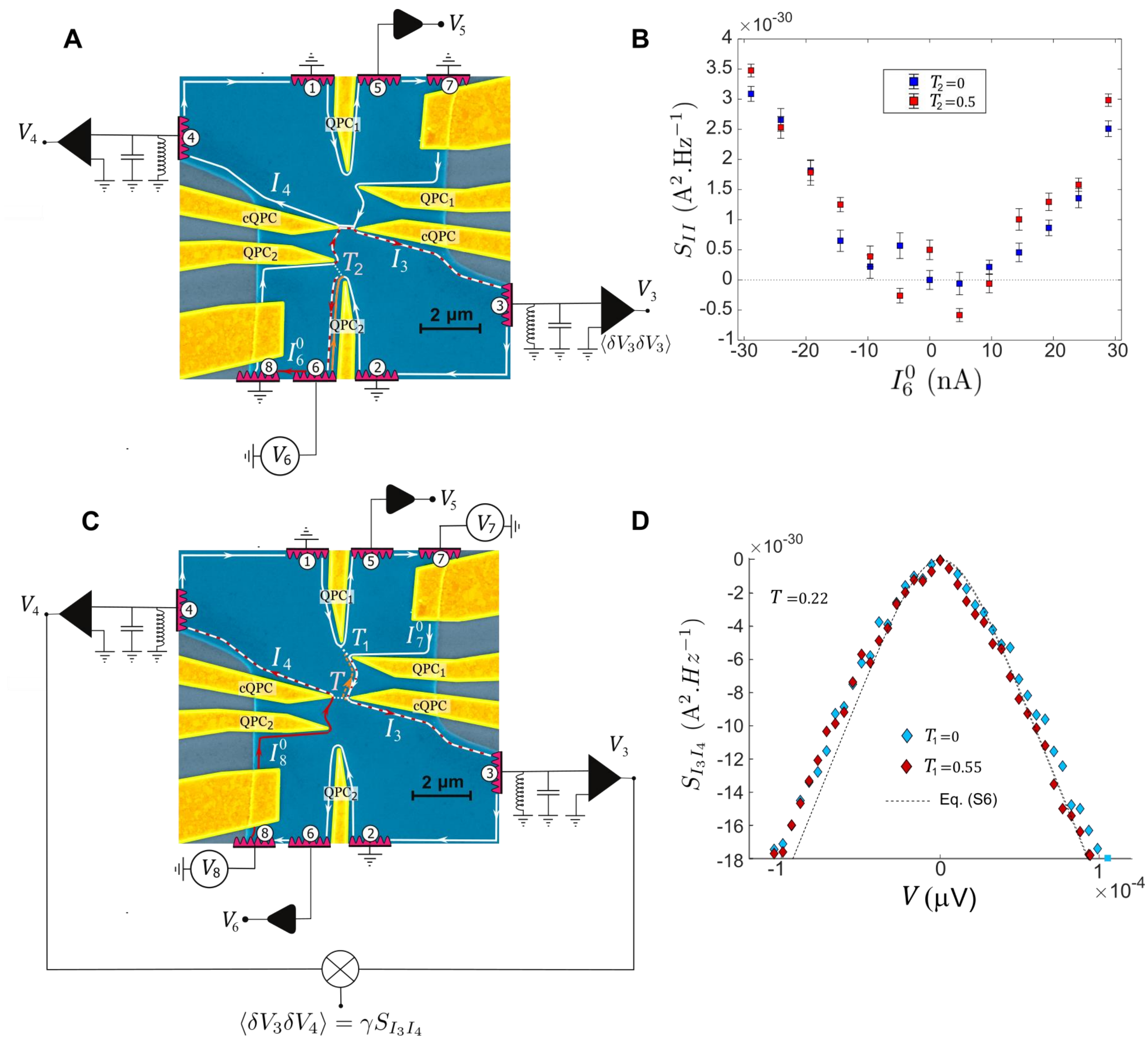
$$\Delta\phi = A_0 L_x$$

$$\psi_{k,n}(x,y) \longrightarrow e^{ik_p x}\phi_n\left(y + y_0 - \frac{\hbar k_p}{eB} - \alpha\right) \qquad \alpha = \frac{A_0}{B}$$

For $\alpha = \Delta y, \Delta\phi = h/e$ wavefunctions shifted to another: one electron is transferred

$$I = \frac{\Delta H}{\Delta\phi} = \frac{qV\nu}{h/e} \longrightarrow \begin{cases} q = e, G = \upsilon\dfrac{e^2}{h} \\ q = e/3, G = \dfrac{e^2}{3h} \end{cases}$$

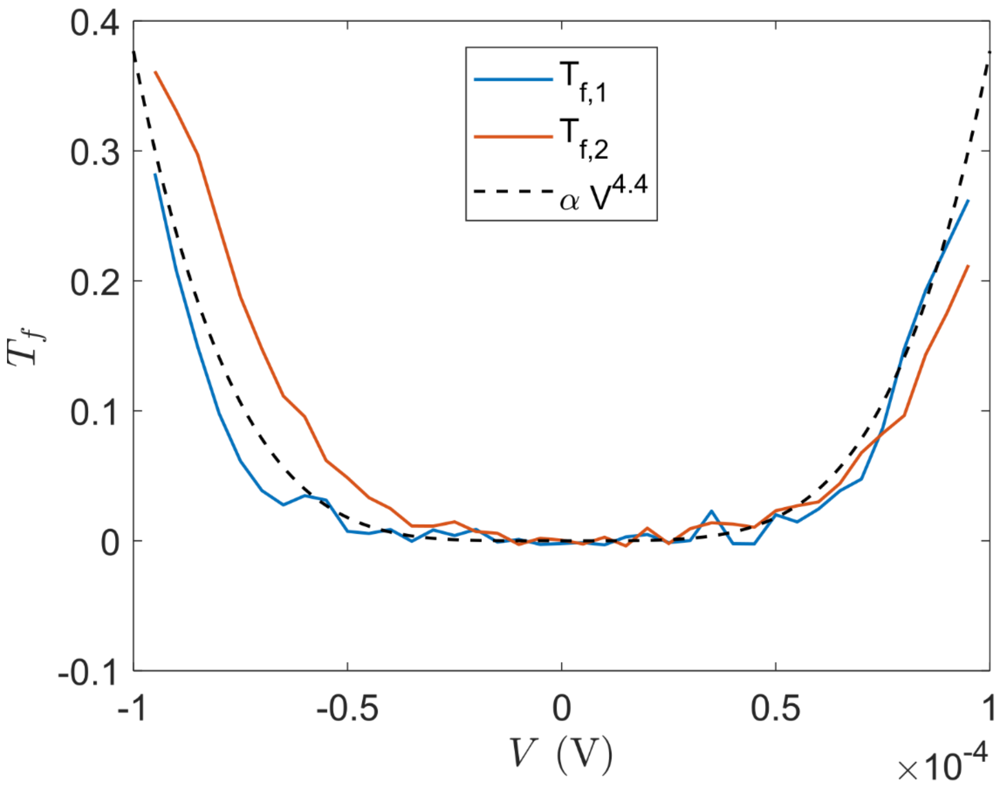
Looking for neutral modes?

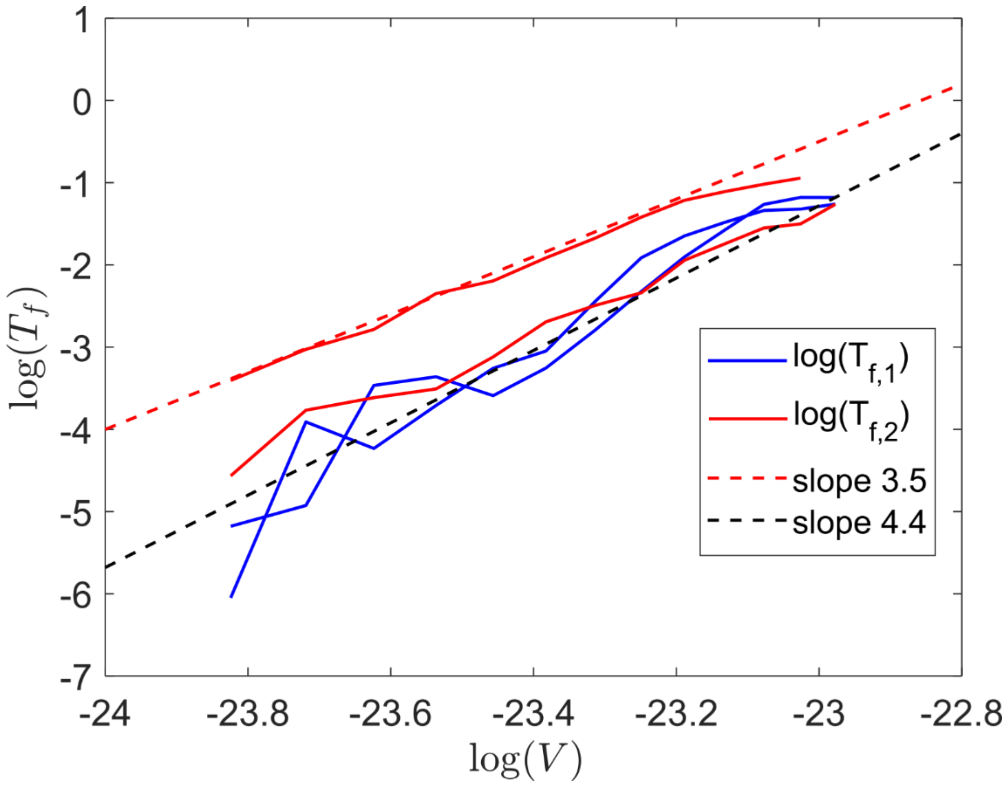


Non-linearities, weak tunneling limit

Weak tunneling limit: $T_f = 1 - T \ll 1$

Pinched QPC





$$T_f = \frac{\partial I_f}{\partial V} \frac{3h}{e^2} \propto V^{\frac{2}{\delta} - 2}$$

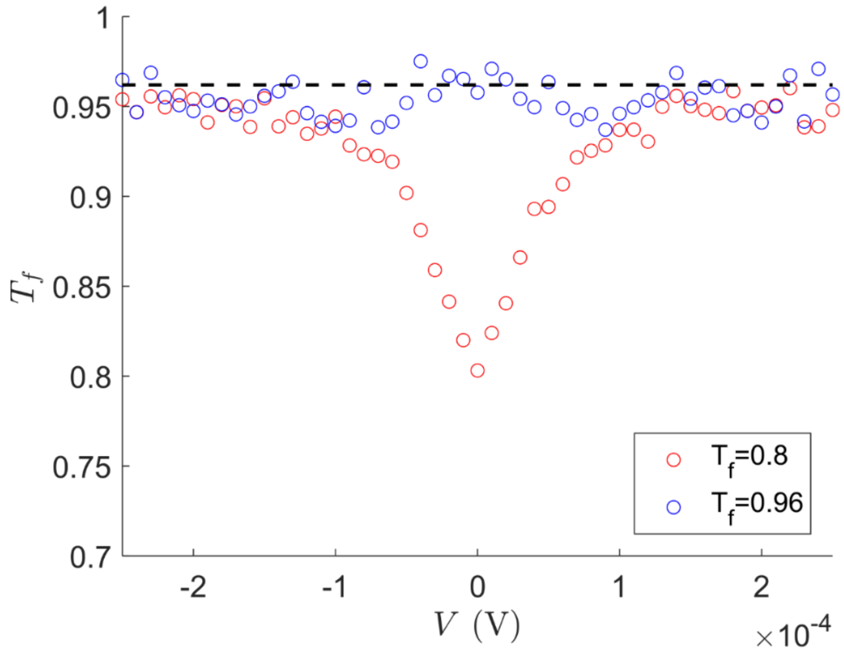
$$3.5 \leq \frac{2}{\delta} - 2 \leq 4.5$$

$$0.36 \leq \delta \leq 0.31$$

Non-linearities, weak backscattering limit

Weak backscattering limit: Open QPC

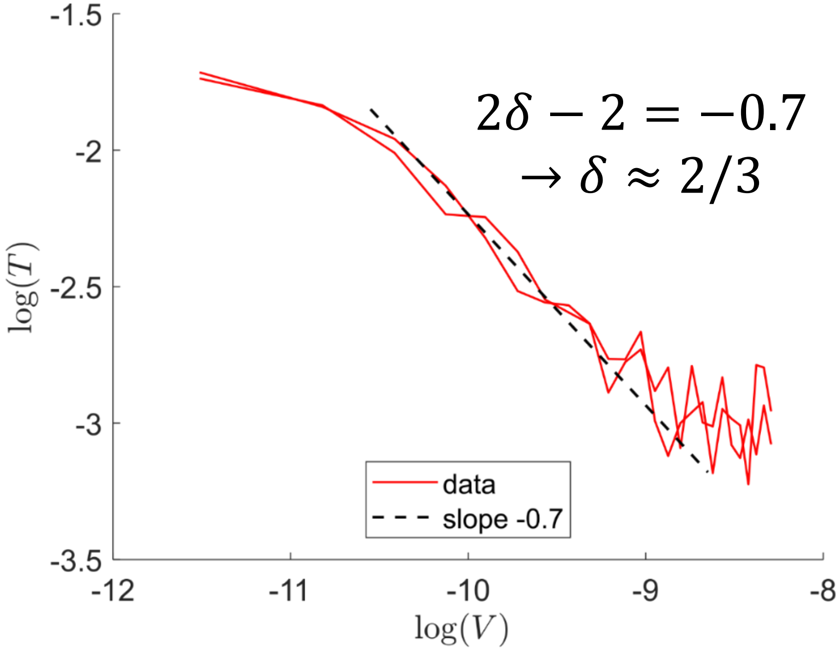
$$T = 1 - T_f \ll 1$$

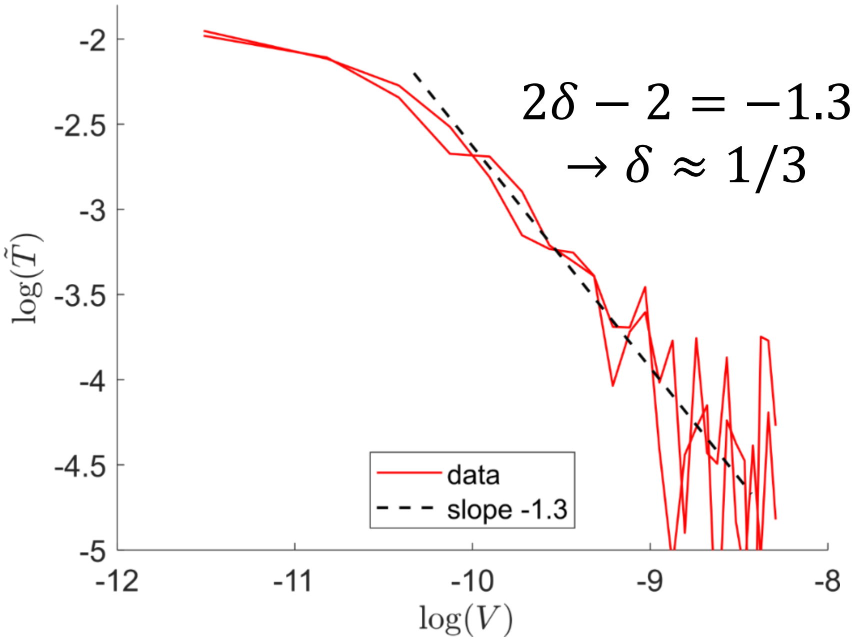


$$T = \frac{\partial I_b}{\partial V}\frac{3h}{e^2} \propto V^{2\delta-2}$$

$$\tilde{T} = 0.96 - T_f$$

$$\tilde{T} \propto V^{2\delta-2}$$

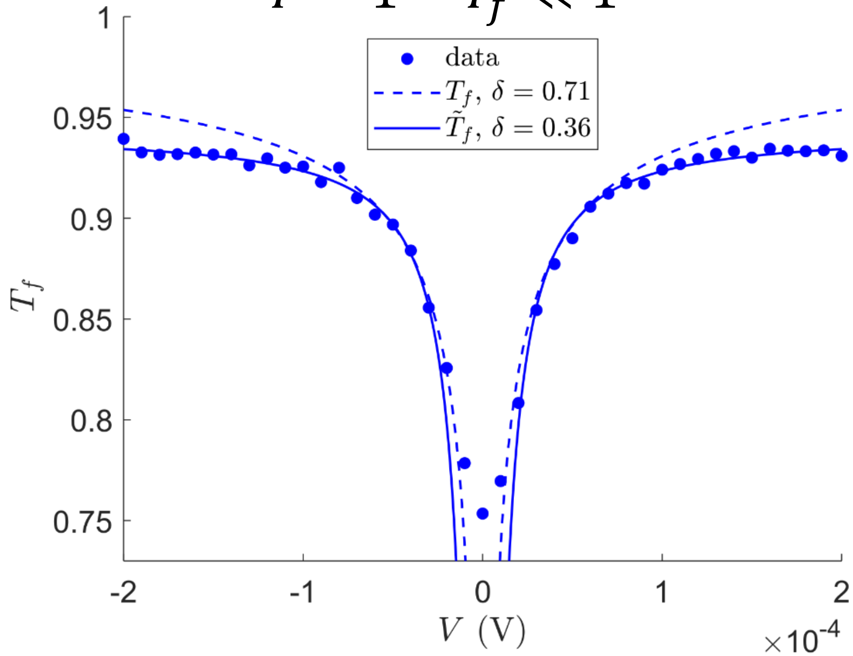




Non-linearities, weak backscattering limit

Weak backscattering limit:

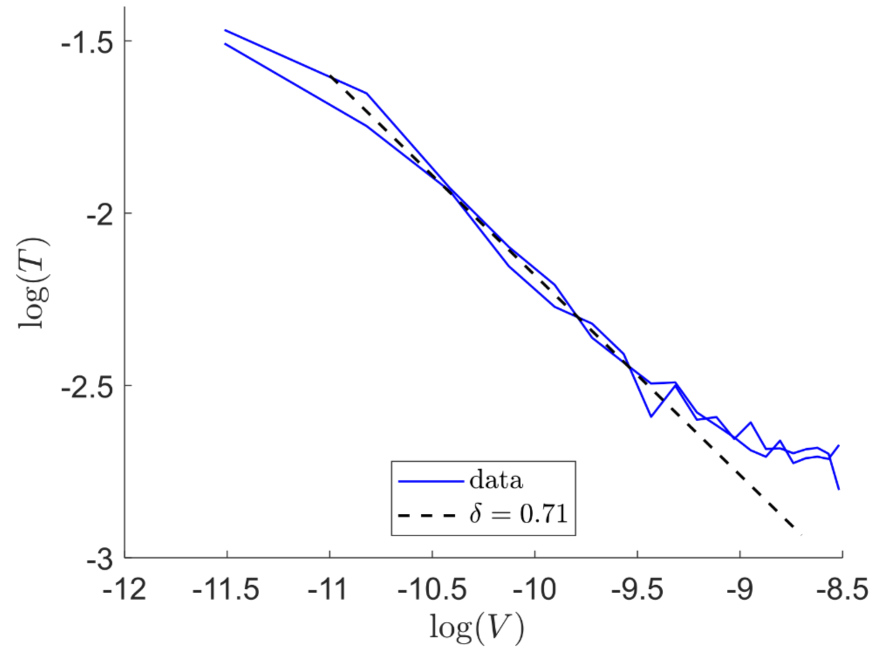
$$T = 1 - T_f \ll 1$$

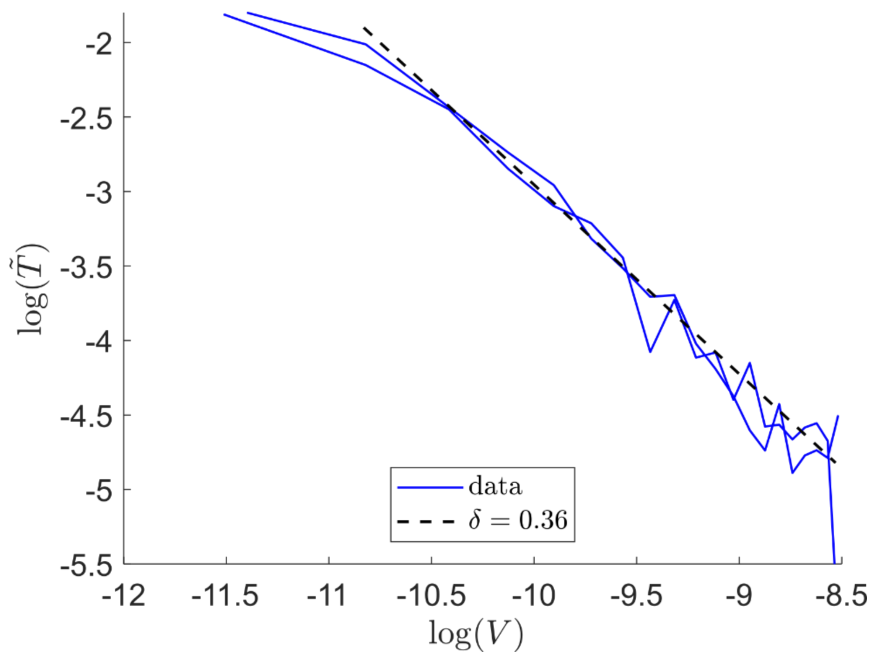


$$T = \frac{\partial I_b}{\partial V}\frac{3h}{e^2} \propto V^{2\delta-2}$$

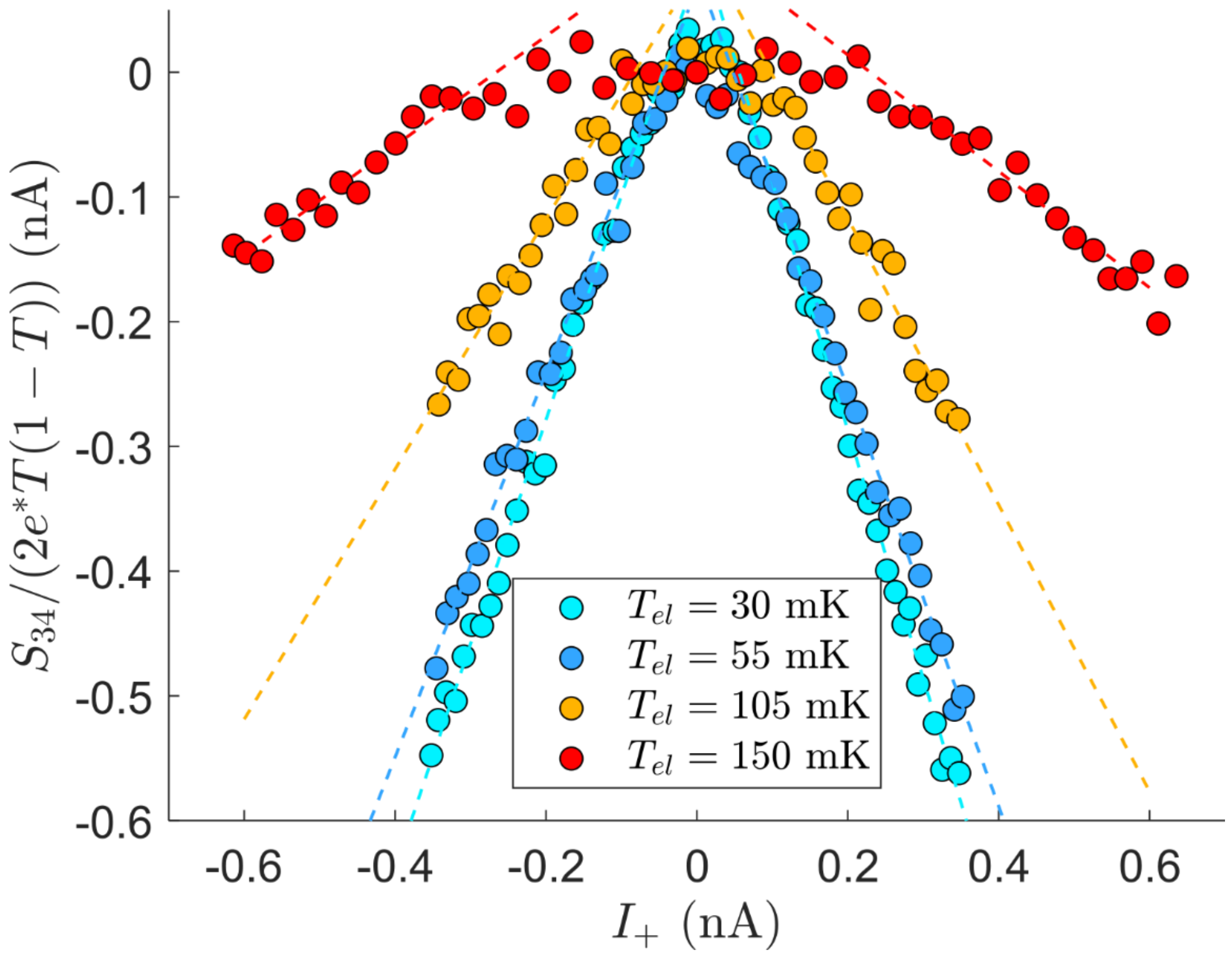
$$\tilde{T} = 0.942 - T_f$$

$$\tilde{T} \propto V^{2\delta-2}$$





Temperature dependence



The collider: sample