Electron interferometry in quantum Hall edge channels

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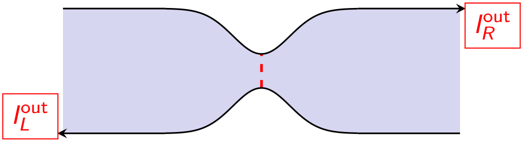
in collaboration with

C. Wahl, T. Jonckheere and T. Martin



Electronic quantum optics

Quantum optics analogs with electrons, i.e. the controlled preparation, manipulation and measurement of single excitations in ballistic conductors

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- Ingredient list

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Electrons	Chiral edge QHE	Point contact	?!

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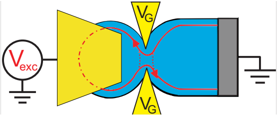

Emits single electrons on-demand

→ opens the way to all sorts of interference experiments!

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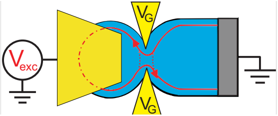

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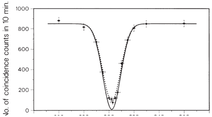
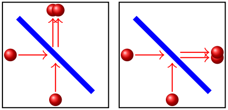
- Hong-Ou-Mandel setup in quantum optics

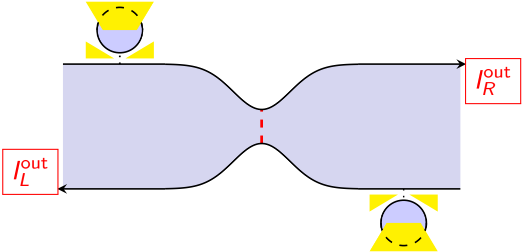




- pairs of identical photons sent on a beam-splitter
- dip in the coincidence rate ➜ bosonic statistics

Hong-Ou-Mandel interference experiment

- Setup
  - 2 single electron sources
  - counter-propagating channels coupled at QPC
  - measure output currents



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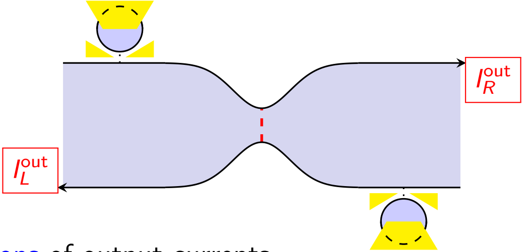

- Zero-frequency cross-correlations of output currents

$$S_{RL}^{\text{out}} = \int dtdt' \left[\langle I_R^{\text{out}}(x,t) I_L^{\text{out}}(x',t')\rangle - \langle I_R^{\text{out}}(x,t)\rangle\langle I_L^{\text{out}}(x',t')\rangle\right]$$

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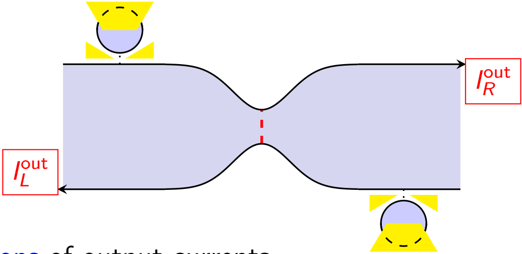

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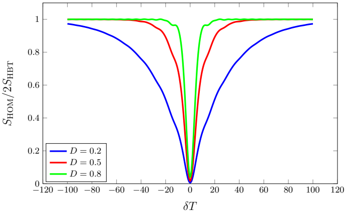
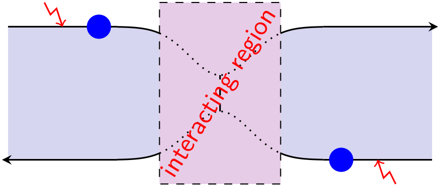
- Results at $\nu = 1$ for $|S_{RL}^{\text{out}}|$



- flat background contribution
  ➙ Hanbury-Brown and Twiss
- HOM/Fermi/Pauli dip down to 0
- signatures of injected object

Beyond $\nu = 1$: interactions!

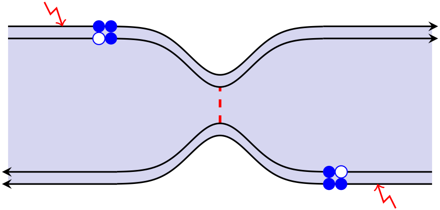
- Different possible types of interactions
  - between counter-propagating channels, near the QPC



(work in progress)

Beyond $\nu = 1$: interactions!

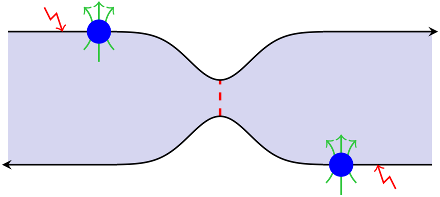
- Different possible types of interactions
  - between counter-propagating channels, near the QPC
  - between co-propagating channels at filling $\nu = 2$



(go listen to talk by C. Wahl)

Beyond $\nu = 1$: interactions!

- Different possible types of interactions
  - between counter-propagating channels, near the QPC
  - between co-propagating channels at filling $\nu = 2$
  - strong interactions within a channel: Fractional QHE



(this talk)

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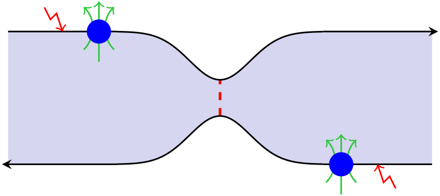

(this talk)

- Formalism and methods

	FQHE	$\nu = 2$ (go listen to talk by C. Wahl)
injection	prepared state $\lvert\varphi\rangle$	prepared state $\lvert\varphi\rangle$
propagation	bosonized H	bosonized H + diagonalization
tunneling	perturbative expansion	scattering matrix

Beyond $\nu = 1$: interactions!

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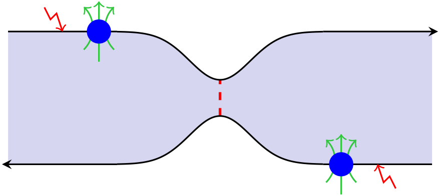

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	FQHE
• injection	prepared state $\vert\varphi\rangle$
• propagation	bosonized H
• tunneling	perturbative expansion

Model

- Hall bar in the Laughlin series $\nu = \dfrac{1}{2m+1}$

  ➞ edge quasi-particles with fractional statistics

- Bosonization:

$$\psi_{R,L}(x) = \frac{U_{R,L}}{\sqrt{2\pi a}} \exp\left(-i\sqrt{\nu}\phi_{R,L}(x)\right)$$

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Klein factor

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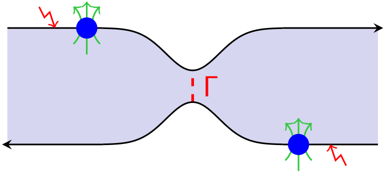
- Hamiltonian



$$H = H_0 + H_T$$

$$H_0 = \frac{\hbar v_F}{4\pi} \int dx \left[(\partial_x \phi_R)^2 + (\partial_x \phi_L)^2\right]$$

$$H_T = \sum_{\epsilon=\pm} \left[\Gamma \psi_R^\dagger(0) \psi_L(0)\right]^\epsilon$$

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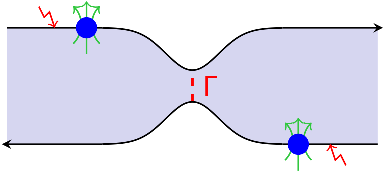

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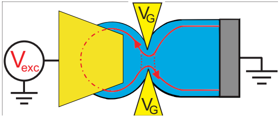
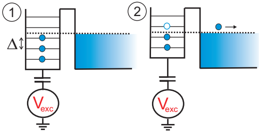
Problem!

Tunneling Hamiltonian is not quadratic ➞ perturbative expansion in Γ

Mimicking the source: injection

- Experimental single electron source in the IQHE





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- tunable dot transmission via V_g
- control via V_{exc}

➞ well described through Floquet scattering theory

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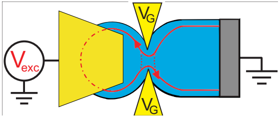

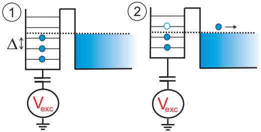

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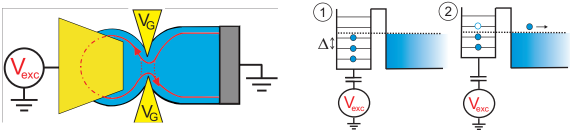

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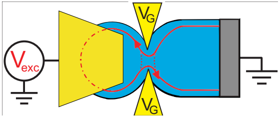

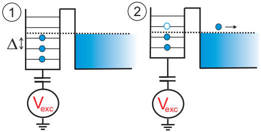

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- Simplified model of injection: prepared state
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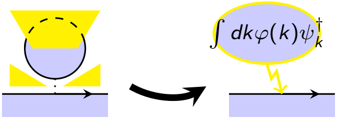
  - preparation operator $\mathcal{O}^\dagger = \mathcal{O}_R^\dagger \mathcal{O}_L^\dagger$ with

ground-state

preparation operator

$$\mathcal{O}_{R,L}^\dagger = \int dk \varphi_{R,L}(k) \left[\psi_{R,L}^\dagger(k; t = -T_0)\right]^{n_{R,L}}$$



- Exponential wave-packets

$$\varphi_{R,L}(x) = \sqrt{\frac{2\Gamma}{v_F}}\, e^{\pm(i\epsilon+\Gamma)x/v_F}$$

- Versatile: any paquet or number of qp

4-branch Keldysh contour

Problem!

Average not taken over the ground-state but over some prepared state $|\varphi\rangle$

4-branch Keldysh contour

Problem!

Average not taken over the ground-state but over some prepared state $|\varphi\rangle$

- Interaction representation and Keldysh contour
  - Usual case

$$
\begin{aligned}
C_{RL}(t,t') &= \langle 0| I_R(t) I_L(t') |0\rangle \\
&= \langle 0| S(-\infty,t)\tilde{I}_R(t) S(t,t')\tilde{I}_L(t') S(t',-\infty)|0\rangle
\end{aligned}
$$

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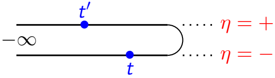
$$C_{RL}(t,t') = \langle 0|I_R(t)I_L(t')|0\rangle$$
$$= \langle 0|\,T_K \tilde{I}_R(t^-)\tilde{I}_L(t'^+)\,\tilde{S}_K\,|0\rangle$$

$$T_K \exp\left(\frac{-i}{\hbar}\int_K dt_1 \tilde{H}_T(t_1)\right)$$



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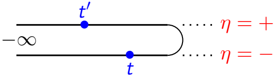

  - Present case

$$C_{RL}(t,t') = \langle \varphi|I_R(t)I_L(t')|\varphi\rangle$$
$$= \langle 0|S(-\infty,-T_0)\tilde{\mathcal{O}}(-T_0)S(-T_0,t)\tilde{I}_R(t)S(t,t')$$
$$\times\, \tilde{I}_L(t')S(t',-T_0)\tilde{\mathcal{O}}^\dagger(-T_0)S(-T_0,-\infty)|0\rangle$$

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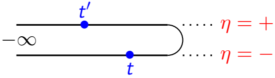
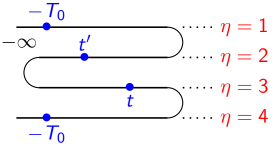


  - Present case

$$C_{RL}(t,t') = \langle\varphi|I_R(t)I_L(t')|\varphi\rangle$$
$$= \langle 0|\, T_{K_4}\tilde{\mathcal{O}}(-T_0^{4})\tilde{I}_R(t^{3})$$
$$\times\ \tilde{I}_L(t'^{2})\tilde{\mathcal{O}}^{\dagger}(-T_0^{1})\ \tilde{S}_{K_4}\ |0\rangle$$
$$\tilde{S}_{K_4} = T_{K_4} \exp\left(\frac{-i}{\hbar}\int_{K_4} dt_1 \tilde{H}_T(t_1)\right)$$



A few more technical details

- Second order perturbation in tunneling $\tilde{H}_T$

$$\langle I_R(x^+,t) I_L(x^-,t')\rangle \to \frac{-1}{2\hbar^2}\int dt_1 dt_2 \sum_{\eta_1\eta_2}(-1)^{\eta_1+\eta_2}\sum_{\epsilon_1,\epsilon_2}\Gamma^{\epsilon_1}\Gamma^{\epsilon_2}$$
$$\times \langle T_{K_4}\mathcal{O}_R\left(-T_0^4\right) I_R\left(x^+,t^3\right)\mathcal{O}_R^\dagger\left(-T_0^1\right)\psi_R^\dagger\left(0,t_1^{\eta_1}\right)^{\epsilon_1}\psi_R^\dagger\left(0,t_2^{\eta_2}\right)^{\epsilon_2}\rangle_R$$
$$\times \langle T_{K_4}\mathcal{O}_L\left(-T_0^4\right) I_L\left(x^-,t'^2\right)\mathcal{O}_L^\dagger\left(-T_0^1\right)\psi_L\left(0,t_1^{\eta_1}\right)^{\epsilon_1}\psi_L\left(0,t_2^{\eta_2}\right)^{\epsilon_2}\rangle_L$$

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- Current in terms of chiral bosonic fields

$$I_{R,L}(x) = \pm\frac{e^* v_F}{2\pi\sqrt{\nu}}\partial_x\phi_{R,L}(x)$$

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- Current in terms of chiral bosonic fields

$$I_{R,L}(x) = \pm\frac{e^* v_F}{2\pi\sqrt{\nu}}\partial_x\phi_{R,L}(x)$$

- Average of bosonic operators

$$\langle T_{K_4}\prod_{n=1}^{N} e^{\alpha_n\phi_{R,L}(x_n,t_n)}\rangle_{R,L} = \exp\left[\sum_{n=1}^{N}\sum_{m=n+1}^{N}\alpha_n\alpha_m\mathcal{G}\left(\sigma_{\eta_n\eta_m}^{t_n t_m}\left\{t_n - t_m \mp \frac{x_n - x_m}{v_F}\right\}\right)\right]$$

with $\sigma_{\eta_n\eta_m}^{t_n t_m} = \delta_{\eta_n\eta_m}(-1)^{\eta_n}\mathrm{Sgn}(t_n - t_m) + (1-\delta_{\eta_n\eta_m})\mathrm{Sgn}(\eta_n - \eta_m)$

Final expression

- Current cross-correlations

$$S_{RL}(x^+, x^-; t, t') = \frac{\langle\varphi|I_R(x^+, t)I_L(x^-, t')|\varphi\rangle}{\langle\varphi|\varphi\rangle} - \frac{\langle\varphi|I_R(x^+, t)|\varphi\rangle}{\langle\varphi|\varphi\rangle}\frac{\langle\varphi|I_L(x^-, t')|\varphi\rangle}{\langle\varphi|\varphi\rangle}$$

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- Zero-frequency, finite temperature expression

$$\mathcal{S}_{RL} = \int dtdt' S_{RL}(x^+,x^-;t,t')$$

$$= -\mathrm{Re}\left\{ \left(\frac{e^*\Gamma}{2\pi a}\right)^2 \int d\tau \left[\sum_{\epsilon=\pm 1}\left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} - \epsilon\pi\frac{v_F\tau}{\beta v_F}\right)}\right)^{2\nu}\right] \int dy_R dz_R dy_L dz_L \int dt \right.$$

$$\times \frac{\varphi_R(y_R)\varphi_R^*(z_R)}{(2\pi a)^{n_R}\mathcal{N}_R}\left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{y_R - z_R}{\beta v_F}\right)}\right)^{\nu n_R^2} \frac{\varphi_L(y_L)\varphi_L^*(z_L)}{(2\pi a)^{n_L}\mathcal{N}_L}\left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{z_L - y_L}{\beta v_F}\right)}\right)^{\nu n_L^2}$$

$$\times \left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F} + \pi\frac{v_F t + z_R}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} + \pi\frac{v_F(t+\tau) + z_R}{\beta v_F}\right)}\right)^{\nu n_R} \left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{v_F(t+\tau) + y_R}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{v_F t + y_R}{\beta v_F}\right)}\right)^{\nu n_R}$$

$$\left.\times \left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F} + \pi\frac{v_F(t+\tau+\delta T) - z_L - \delta L}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} + \pi\frac{v_F(t+\delta T) - z_L - \delta L}{\beta v_F}\right)}\right)^{\nu n_L} \left(\frac{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{v_F(t+\delta T) - y_L - \delta L}{\beta v_F}\right)}{\sinh\left(\frac{i\pi a}{\beta v_F} - \pi\frac{v_F(t+\tau+\delta T) - y_L - \delta L}{\beta v_F}\right)}\right)^{\nu n_L} \right\}$$

Benchmarking against $\nu = 1$

- Vacuum contribution (no injection)

$$\mathcal{S}^{\text{vac}}(\omega = 0) = -\frac{(e^*\Gamma)^2\Gamma(\nu)^2}{2\pi^2 a v_F \Gamma(2\nu)} \left(\frac{2\pi a}{\beta v_F}\right)^{2\nu-1}$$

Noise from Fermi sea at finite T
[T. Martin, Les Houches LXXXI]

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- Hanbury-Brown and Twiss setup at $\nu = 1$: noise reduction!

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➡ antibunching with thermal excitations [Bocquillon et al., PRL 108, 196803 (2012)]

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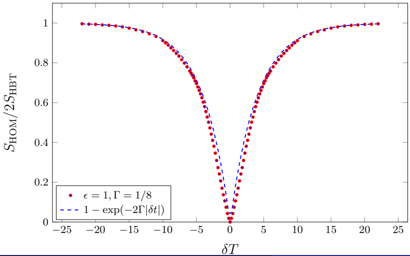
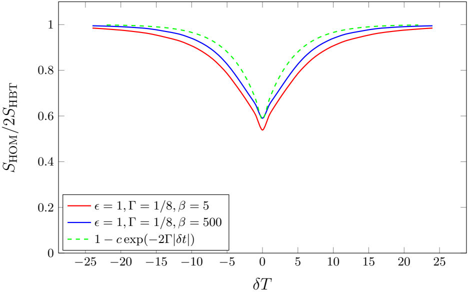
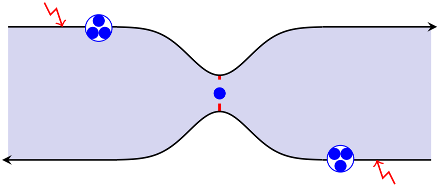
- Hong-Ou-Mandel setup at $\nu = 1$

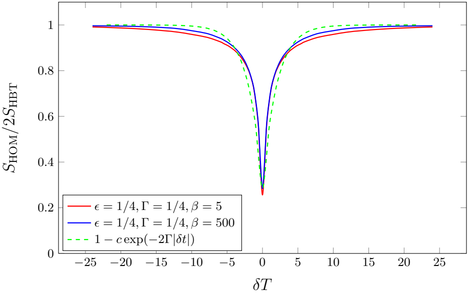


- well-defined dip reflecting indistinguishability
- reaches 0 for synchronized injections
- in agreement with expected exponential [Ol'khovskaya et al., PRL 101, 166802 (2008)]

Injecting single electrons ($\nu = 1/3$)



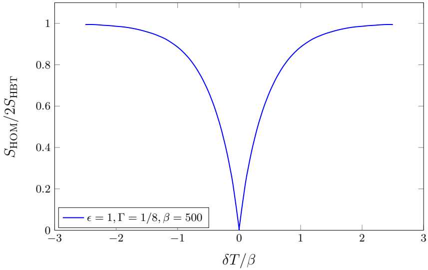




- dip does not reach 0
- contrast smaller for resolved packets
- shape is not simply given by the wave-packet
- weak temperature dependence

Injecting single quasi-particles

- At filling factor $\nu = 1/3$



- presence of a dip
- approaches 0 at $\delta T = 0$
- striking temperature dep.
- intriguing wave-packet (in)dependence

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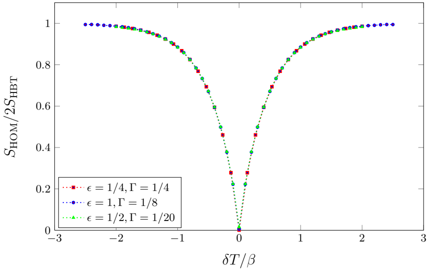

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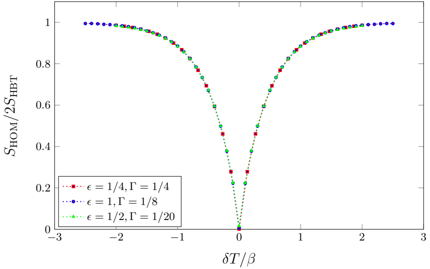

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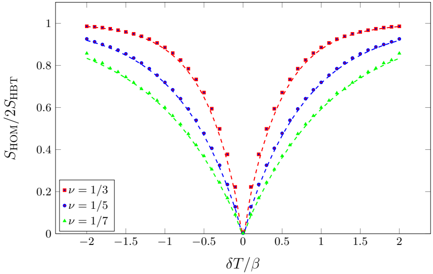
- Other filling fractions



- similar behavior $\forall \nu$
- surprisingly good fit

$$\frac{\mathcal{S}_{\mathrm{HOM}}}{2\mathcal{S}_{\mathrm{HBT}}} = 1 - \exp\left(-2\nu \frac{\pi|\delta T|}{\beta}\right)$$

Conclusions

- A general formalism for the computation of noise correlations for electron quantum optics setups in the quantum Hall regime
- When injecting electrons, the current cross-correlations show a dip, with less than optimal contrast
- When injecting single quasi-particles, an exponential dip appears, like nothing seen in the IQHE