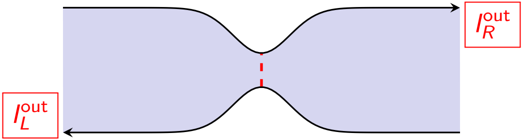
Electron interferometry in quantum Hall edge channels

Jérôme Rech

Centre de Physique Théorique, Marseille

in collaboration with
C. Wahl, D. Ferraro, T. Jonckheere and
T. Martin



Electronic quantum optics in quantum Hall systems

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

Photons

↓

Electrons

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INGREDIENT LIST

Photons
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Light beam
↓

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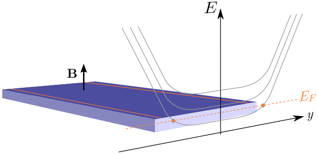
Chiral edge QHE



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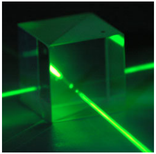

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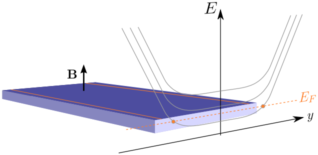

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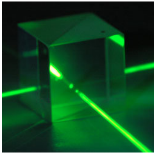

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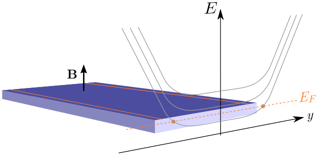

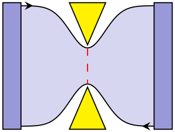

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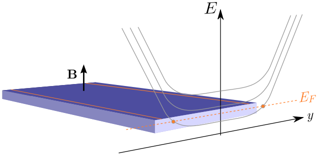

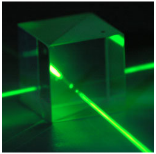

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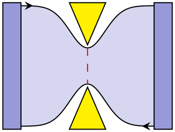

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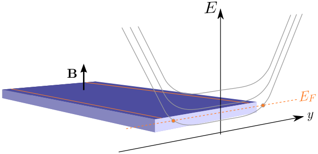

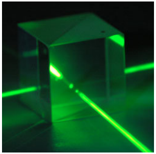

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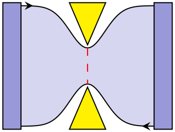

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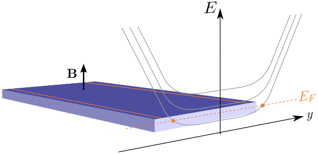

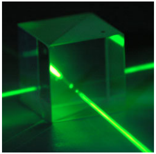

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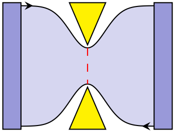

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Mesoscopic capacitor
[Fève et al., Science ('07)]

Surface acoustic waves
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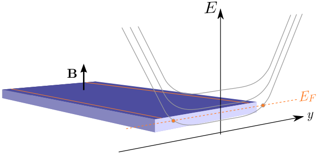

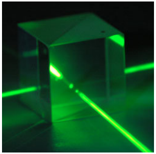

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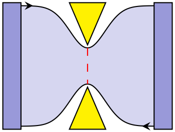

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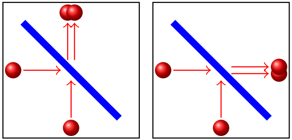
➙ opens the way to all sorts of interference experiments!

Hong-Ou-Mandel interference experiment

- Two-photon interferences



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- necessarily exit by the same output channel

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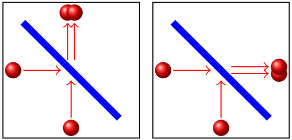

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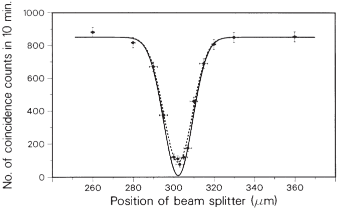

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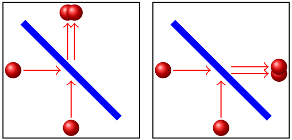

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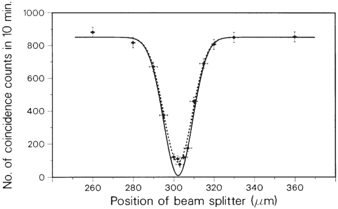

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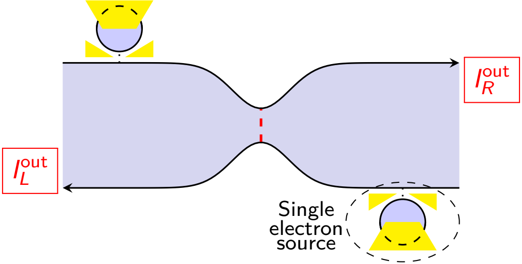
- Why would it be so different with electrons?
  - they obey fermionic statistics ➙ Fermi sea, hole excitations, ...
  - thermal effects do matter
  - they interact via Coulomb interaction

HOM with electrons: general principle and first results

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



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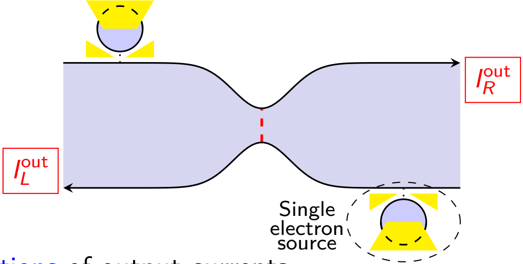

- Zero-frequency cross-correlations of output currents

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

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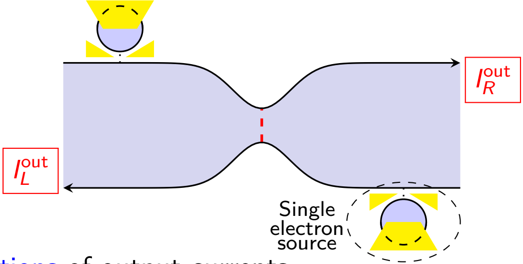

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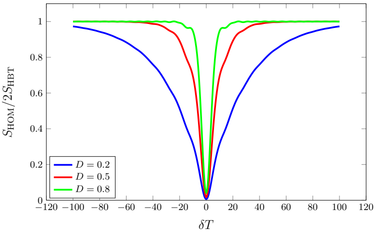
- Theory at $\nu = 1$ [Jonckheere et al. Phys. Rev. B 86, 125425 ('12)]



When electrons arrive independently

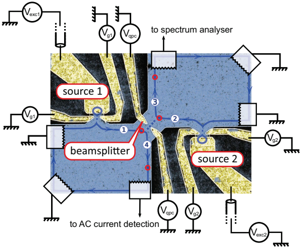
- S_{RL} : sum of the partition noise
- flat contrib. ➞ random partitioning

When electrons arrive simultaneously

- $S_{RL} = 0$ ➞ HOM/Pauli dip
- signatures of injected object (overlap)

HOM with electrons: experimental results

- Main experimental results [Bocquillon et al., Science 339, 1054 ('13)]



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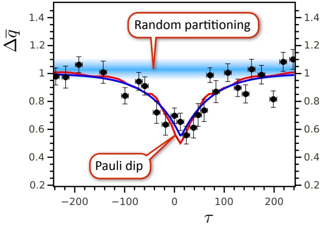
As expected

✓ Flat background contribution

✓ dip for simultaneous injection

But... How come it does not reach 0?

➙ decoherence effect



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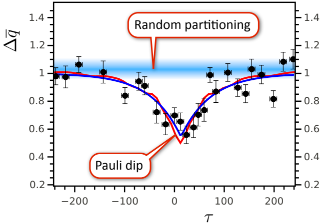

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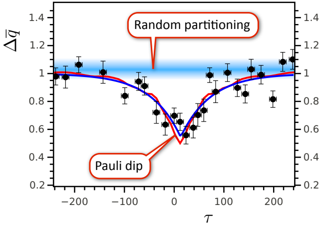

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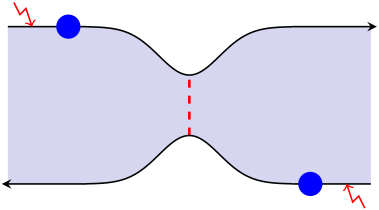

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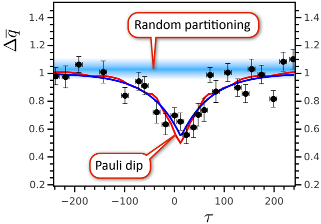

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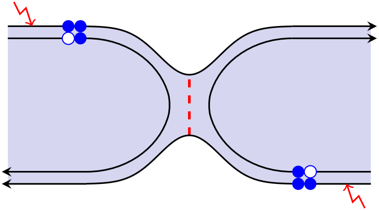

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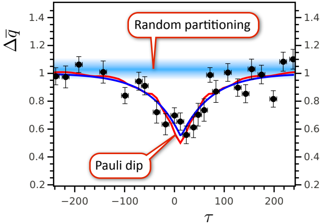

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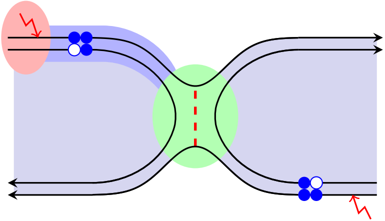

- $\cancel{\nu = 1}$ ➜ $\nu = 2$
- interactions between co-propagating channels
- injection, propagation, tunneling

1 - Injection

- Simplified model of injection: prepared state
  - injection in the past at $t = -T_0$:

$$|\varphi\rangle = \underbrace{\mathcal{O}^\dagger(-T_0)}_{\text{preparation operator}} \overset{\text{ground-state}}{|0\rangle}$$

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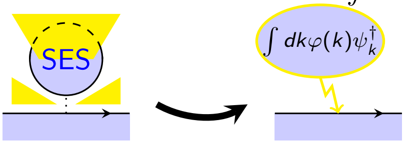

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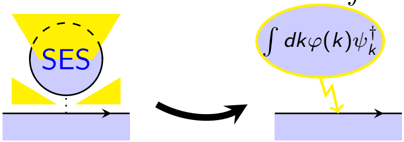

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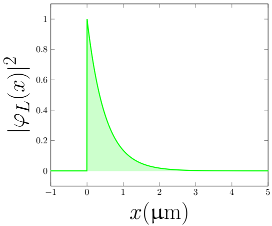

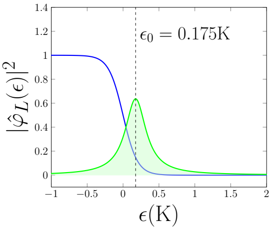

Tunable resolution $\gamma = \epsilon_0/\Gamma$
[emission time $\tau_e = \hbar/(2\Gamma)$]

$$\left.\begin{array}{l}\epsilon_0 = 0.175\mathrm{K}\\ \Gamma = 0.175\mathrm{K}\end{array}\right\} \longrightarrow \gamma = 1$$

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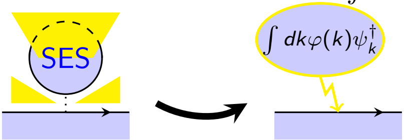

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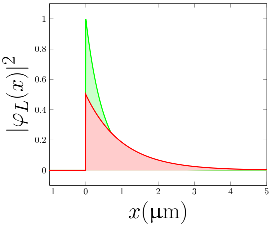

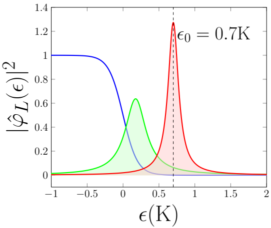

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$$\left.\begin{array}{l}\epsilon_0 = 0.7\mathrm{K} \\ \Gamma = 0.0875\mathrm{K}\end{array}\right\} \longrightarrow \gamma = 8$$

2 - Propagation

- Bosonization identity: $\psi_{j,r}(x) = \frac{U_{j,r}}{\sqrt{2\pi a}} \exp\left(i\, \phi_{j,r}(x)\right)$

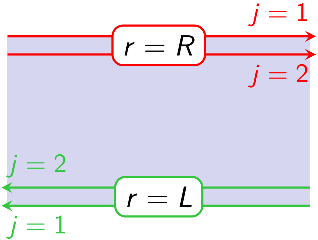
Klein factor

cutoff

chiral bosonic field

2 - Propagation

- Bosonization identity: $\psi_{j,r}(x) = \frac{U_{j,r}}{\sqrt{2\pi a}} \exp\left(i\ \phi_{j,r}(x)\right)$
- Hamiltonian $H = H_0 + H_{\text{inter}}$



- Propagation + intra-channel interaction

$$H_0 = \frac{\hbar}{\pi} \sum_{j=1,2} \left(v_j^{(0)} + U \right) \sum_{r=R,L} \int dx \left(\partial_x \phi_{j,r}\right)^2$$

edge velocities

interaction strength

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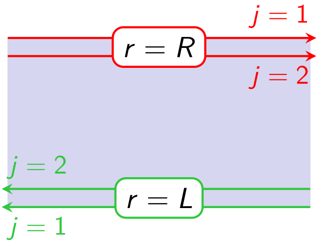

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$$H_{\text{inter}} = 2\frac{\hbar}{\pi}\, u \sum_{r=R,L} \int dx \left(\partial_x \phi_{1,r}\right) \left(\partial_x \phi_{2,r}\right)$$

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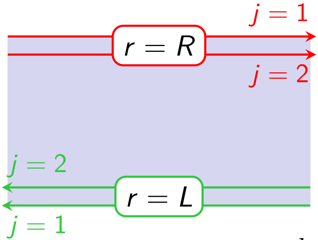

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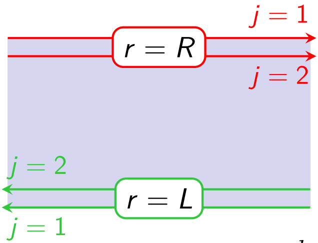

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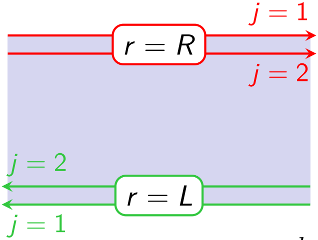

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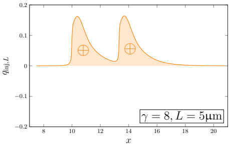
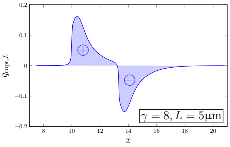
- Charge fractionalization: fast charged ϕ_+, slow neutral ϕ_-



injection channel



co-propagating channel

- Average charge density $q_{s,r}(x,t) = \frac{e}{\pi}\langle \partial_x \phi_{s,r}(x,t)\rangle_{\varphi}$
- Excitations characterized by the charge they carry ⊕/⊖

3 - Tunneling

- QPC couples counter-propagating channels ➙ two possibilities

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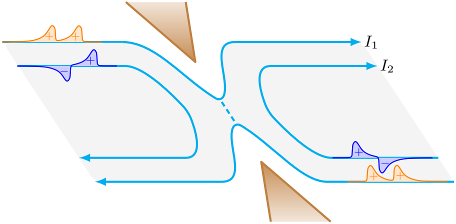
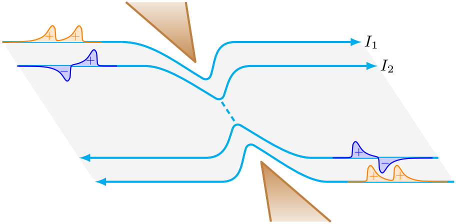


SETUP 1



SETUP 2

3 - Tunneling

- QPC couples counter-propagating channels ➞ two possibilities
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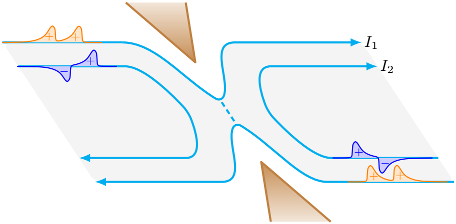
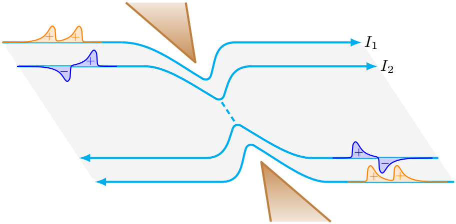


SETUP 1



SETUP 2

- Tunneling Hamiltonian $H_{\text{tun}} = \Gamma \left[\psi^\dagger_{s,R}(0)\psi_{s,L}(0) + \psi^\dagger_{s,L}(0)\psi_{s,R}(0) \right]$

tunnel amplitude

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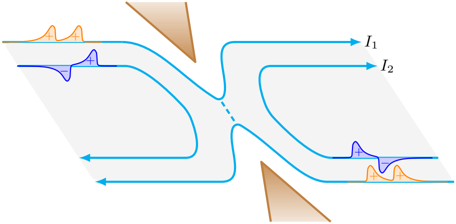

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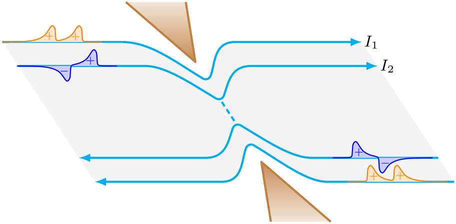

SETUP 2

- Tunneling Hamiltonian $H_{\text{tun}} = \Gamma \left[\psi^\dagger_{s,R}(0)\psi_{s,L}(0) + \psi^\dagger_{s,L}(0)\psi_{s,R}(0) \right]$
- Scattering matrix:

$$\begin{pmatrix} \psi_{s,R} \\ \psi_{s,L} \end{pmatrix}^{\text{outgoing}} = \begin{pmatrix} \sqrt{\mathcal{T}} & i\sqrt{\mathcal{R}} \\ i\sqrt{\mathcal{R}} & \sqrt{\mathcal{T}} \end{pmatrix} \begin{pmatrix} \psi_{s,R} \\ \psi_{s,L} \end{pmatrix}^{\text{incoming}}$$

$\mathcal{T}$ is the transmission and $\mathcal{R}$ the reflexion probability

Performing the calculation: final expression

- Quantity of interest: $S_{RL}^{\text{out}}\left[I_{s,r}^{\text{out}}(x,t)\right] \longrightarrow S_{RL}^{\text{out}}\left[\phi_{\pm,r}^{\text{in}}(0,t)\right]$

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- Final expression of noise for the Hong-Ou-Mandel experiment

$$
\begin{aligned}
S_{RL}^{\text{HOM}} &= -2S_0\mathrm{Re}\left\{\int d\tau \mathrm{Re}\left[g(\tau,0)^2\right]\right. \\
&\quad \times \int dy_R dz_R \frac{\varphi_R(y_R)\varphi_R^*(z_R)}{(2\pi a)^2\mathcal{N}_R} g(0, y_R - z_R) \int dy_L dz_L \frac{\varphi_L(y_L)\varphi_L^*(z_L)}{(2\pi a)^2\mathcal{N}_L} g(0, z_L - y_L) \\
&\quad \left. \times \int dt \left[\frac{h_s(t; y_L + L, z_L + L)h_s(t + \tau - \delta T; L - y_R, L - z_R)}{h_s(t + \tau; y_L + L, z_L + L)h_s(t - \delta T; L - y_R, L - z_R)} - 1\right]\right\}
\end{aligned}
$$

$$
g(t,x) = \left[\frac{\sinh\left(i\frac{\pi a}{\beta v_+}\right)\sinh\left(i\frac{\pi a}{\beta v_-}\right)}{\sinh\left(\frac{ia + v_+ t - x}{\beta v_+/\pi}\right)\sinh\left(\frac{ia + v_- t - x}{\beta v_-/\pi}\right)}\right]^{\frac{1}{2}} \quad h_s(t; x, y) = \left[\frac{\sinh\left(\frac{ia - v_+ t + x}{\beta v_+/\pi}\right)}{\sinh\left(\frac{ia + v_+ t - y}{\beta v_+/\pi}\right)}\right]^{\frac{1}{2}} \left[\frac{\sinh\left(\frac{ia - v_- t + x}{\beta v_-/\pi}\right)}{\sinh\left(\frac{ia + v_- t - y}{\beta v_-/\pi}\right)}\right]^{s - \frac{3}{2}}
$$

Performing the calculation: final expression

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$$\left.\times \int dt \left[\frac{h_s(t; y_L + L, z_L + L) h_s(t + \tau - \delta T; L - y_R, L - z_R)}{h_s(t + \tau; y_L + L, z_L + L) h_s(t - \delta T; L - y_R, L - z_R)} - 1\right]\right\}$$

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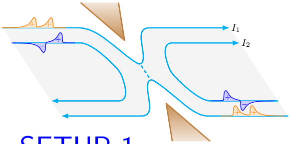
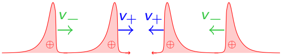
- Focus on the most experimentally relevant situation



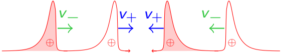
SETUP 1

time delay $\delta T = 0$



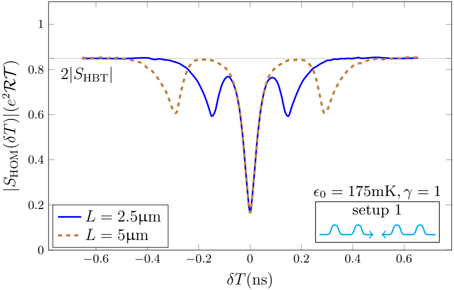
interference of ⊕ excitations
with same velocity

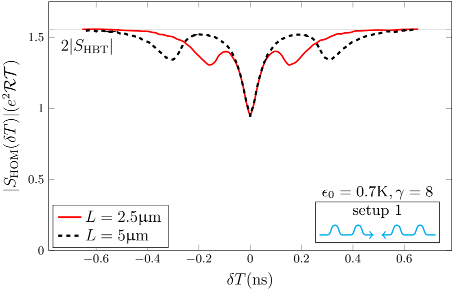
time delay $\delta T = \pm L\frac{v_+ - v_-}{v_+ v_-}$



interference of ⊕ excitations
with different velocity

Main results





3-dip structure + flat background contribution (no interference)

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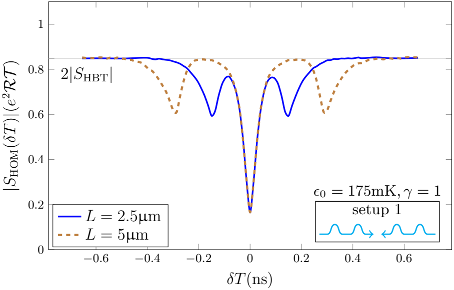
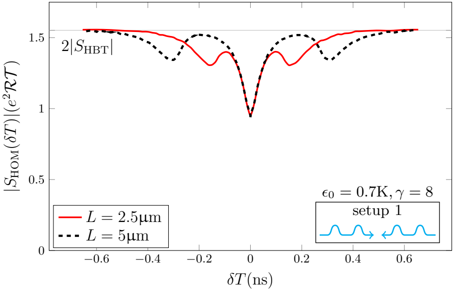


Central dip

- noise reduction → destructive interference of $\oplus/\oplus$ excitations
- loss of contrast due to interactions, strong dependence on resolution



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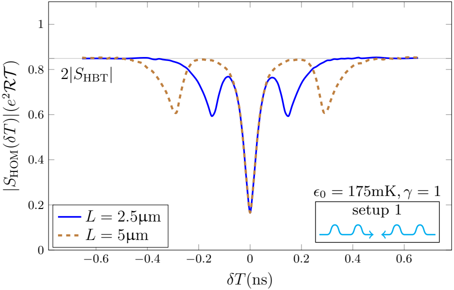

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Side dips

- $\oplus$-excitations with different velocities
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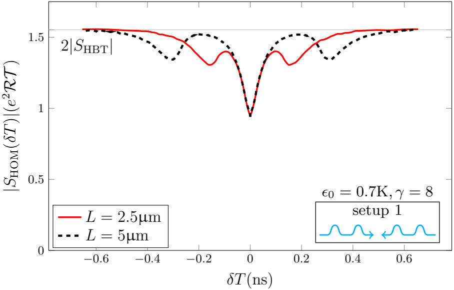
- velocity mismatch : asymmetry + smaller than half central dip



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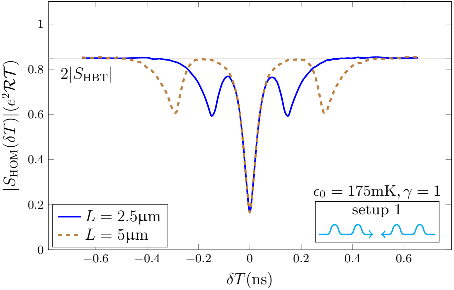

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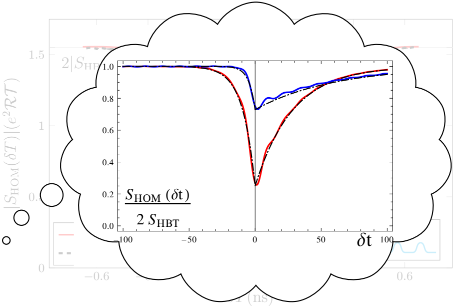

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Towards a more quantitative agreement

- Results are functions of 4 parameters $\epsilon_0, \tau_e, \beta, \tau_s$ all given by the experiment ➞ No adjustable parameters!

$$L\left(\frac{1}{v_-} - \frac{1}{v_+}\right)$$

Towards a more quantitative agreement

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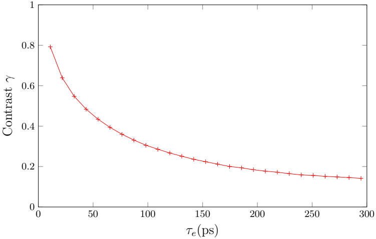
- Contrast $\eta = 1 - \frac{S_{\text{HOM}}(\delta T=0)}{2S_{\text{HBT}}}$



- Dramatic loss of contrast with energy resolution/emission time
- Experimental values:

  $\epsilon_0 = 0.7$ K $\quad \tau_s = 70$ ps

  $1/(k_B\beta) = 100$ mK

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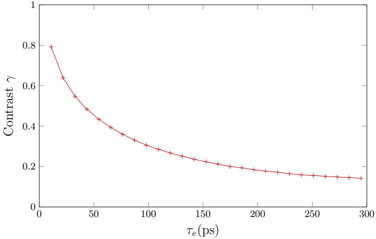

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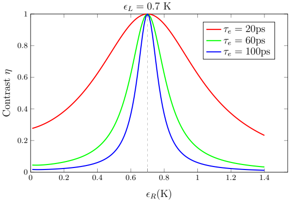
  - $\nu = 1$: rapid decrease

    consistent with packet overlap



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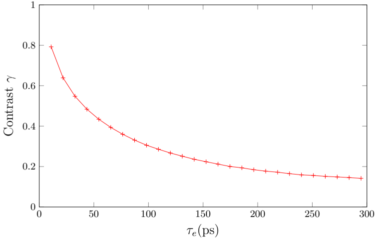

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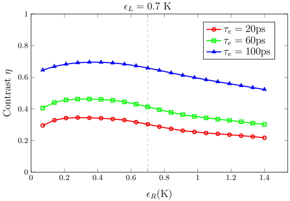

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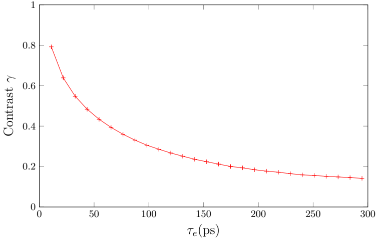

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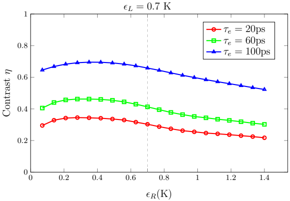

➡ interactions dramatically affect the nature of excitations

Fractional case

- Taking interactions to the next level: Fractional Quantum Hall effect

IQHE	FQHE
electrons e	quasiparticles e^*
fermionic	anyonic
Fermi sea	non-trivial vacuum

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- This raises tons of new and exciting open questions!
  - Can we emit controlled single quasiparticles in the system?
  - Is a perturbative treatment in tunneling sufficient?
  - Do quasiparticles show bunching?
  - Are there signatures of non-trivial statistics in the HOM noise signal?
  - How to extend the idea of minimal excitations?

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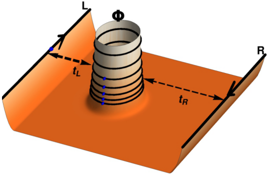
  - Are there signatures of non-trivial statistics in the HOM noise signal?
  - How to extend the idea of minimal excitations?
- On-demand source of single quasiparticles



- driven antidot as a QP source
- quantization of the emitted charge
- fluctuations? ➞ jitter noise

Conclusions

- Strong coupling between channels accounts for a sensible loss of contrast of the HOM central dip

- The contrast strongly depends on the energy resolution of the injected wave-packet

- Fast and slow modes interfere and produce, depending on the charge carried by the colliding excitations, smaller asymmetric dips or peaks

- Our interacting model recovers the main experimental features
  ➙ Detailed quantitative comparison is under way!

Interactions and charge fractionalization in an electronic HOM interferometer
C. Wahl, J. Rech, T. Jonckheere, T. Martin, Phys. Rev. Lett. 112, 046802 (2014)
Single quasiparticle and electron emitter in the fractional quantum Hall regime
D. Ferraro, J. Rech, T. Jonckheere, T. Martin, Phys. Rev. B 91, 205409 (2015)