Minimal excitations in the fractional quantum Hall regime

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in collaboration with
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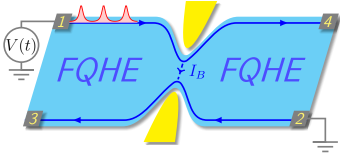
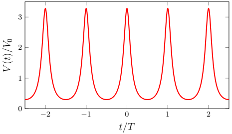
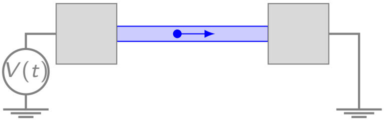
M. Sassetti and T. Martin





What are minimal excitations?

- Simply posed problem



- single-mode 1d conductor (quantum wire) with time-dependent voltage $V(t)$ across

  ➡ $q = \frac{e}{h} \int dt V(t)$ charges injected

- how to make it a reliable qp injector?

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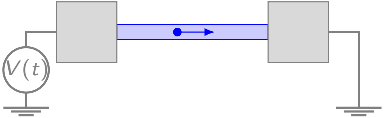

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  - engineer $V(t)$ so that $N_{\text{exc}} = N_e + N_h$ minimal
  - acquired phase $\phi(t)$ such that $e^{i\phi(t)}$ has special pole structure

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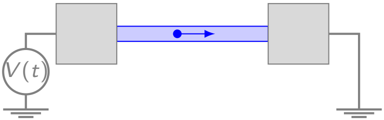

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$\frac{e}{\hbar} \int_{-\infty}^{t} dt' V(t')$

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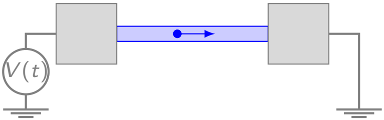

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$$V(t) = \frac{\hbar}{e} \sum_{i=1}^{n} \frac{2\tau_i}{(t - t_i)^2 + \tau_i^2} \implies N_{\text{exc}} = n + 0 \text{ is minimal}$$

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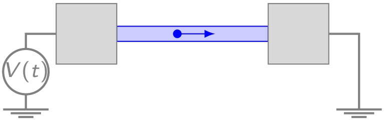

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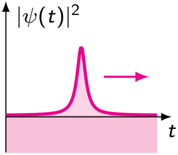
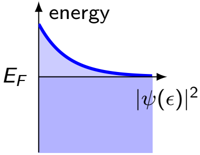
- Profiles of a leviton [Keeling et al., PRL 97, 116403 ('06)]



Time space



Energy space

- particle excited above E_F

  + undisturbed Fermi sea
- many-body excitation conspiring to behave like a single particle

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

$\downarrow$

Electrons

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INGREDIENT LIST

Photons	Light beam
↓	↓
Electrons	

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Photons	Light beam
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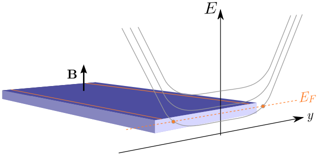
Electrons	Chiral edge QHE



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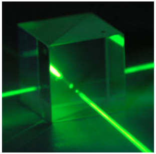
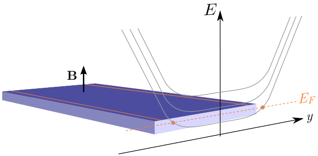


Photons	Light beam	Beam-splitter
↓	↓	↓
Electrons	Chiral edge QHE	



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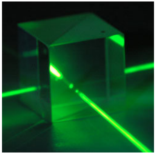
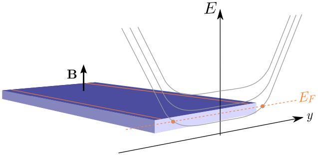
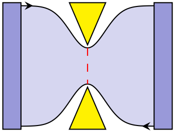


Photons ↓ Electrons

Light beam ↓ Chiral edge QHE

Beam-splitter ↓ Point contact





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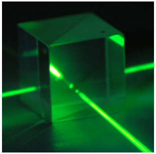

Photons	Light beam	Beam-splitter	Coherent light source
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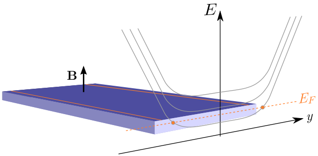
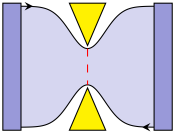
Electrons	Chiral edge QHE	Point contact	





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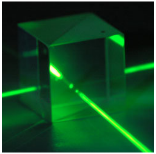

Photons	Light beam	Beam-splitter	Coherent light source
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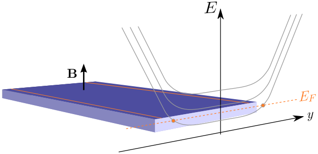

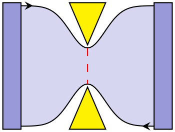

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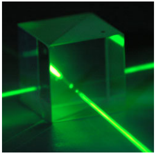

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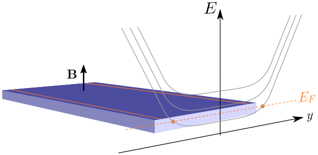

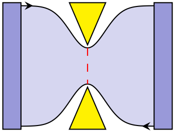

Mesoscopic capacitor
[Fève et al., Science ('07)]

Surface acoustic waves
[Hermelin et al., Nature ('11)]
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Quantum turnstiles
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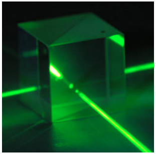

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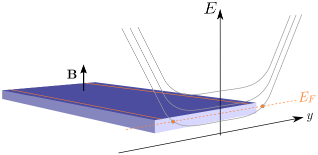

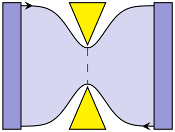

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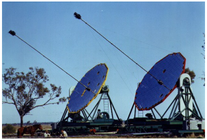
➡ opens the way to all sorts of interference experiments!

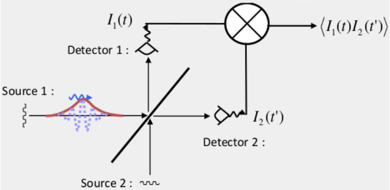
Hanbury-Brown and Twiss interferometry

- From astronomy... [Hanbury-Brown and Twiss, Nature 178, 1046 ('56)]



- two spatially separated detectors
- interference signal used to measure the angular size of Sirius

- intensity interferometry $\langle I_1(t) I_2(t') \rangle$
- access the statistical properties of a light source



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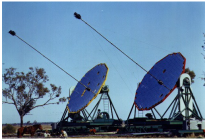

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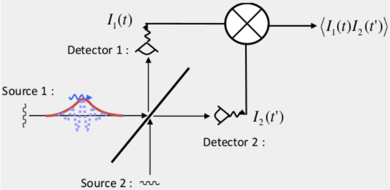
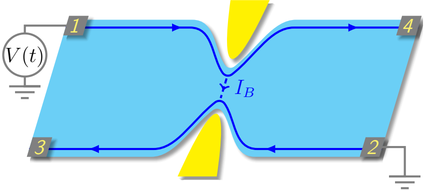


- ... to electron quantum optics



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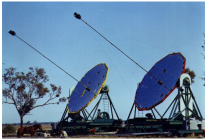

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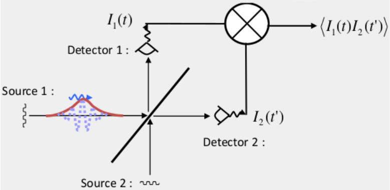

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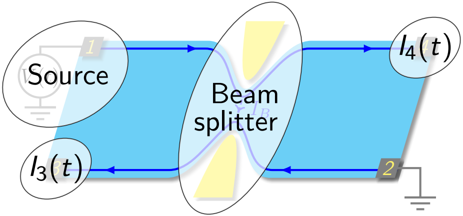

Measure $\langle I_3(t) I_4(t') \rangle$

Detecting minimal excitations

Recall Levitov's argument

Quantized Lorentzian pulses: $V(t) = \frac{\hbar}{e} \frac{2W}{(t-t_0)^2+W^2} \Rightarrow N_{\text{exc}}$ minimal

- How can one measure N_{exc}?

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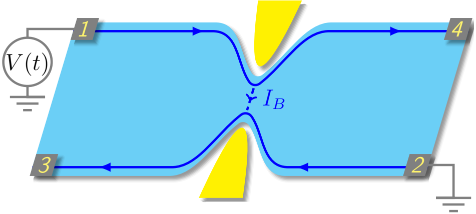

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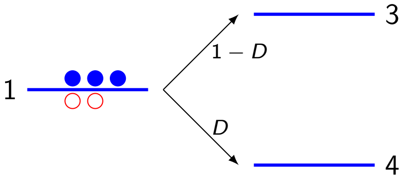

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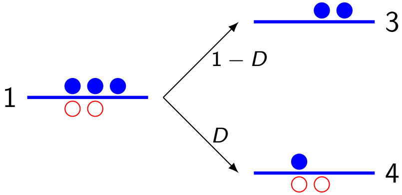

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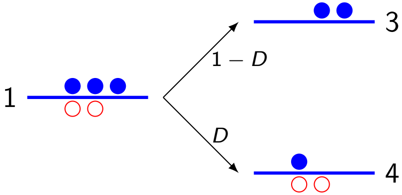

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- Zero-frequency current noise at zero temperature (periodic drive)

$$\mathcal{S} = 2\int d\tau \int_0^T \frac{d\bar{t}}{T}\, S\left(\bar{t}+\frac{\tau}{2};\bar{t}-\frac{\tau}{2}\right) = 2\frac{e^2}{T}D(1-D)\left(N_e+N_h\right)$$

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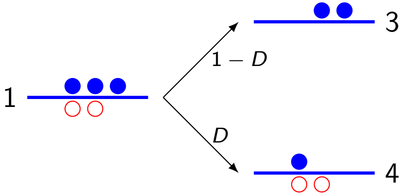

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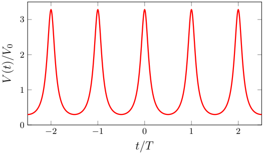
QPC transmission

$S(t,t') = \langle \delta I_B(t)\delta I_B(t')\rangle$

driving period

Levitons in the language of PASN

- Decompose the voltage bias $V(t) = V_{dc} + V_{ac}(t)$ (with $\int_0^T dt V_{ac}(t) = 0$)



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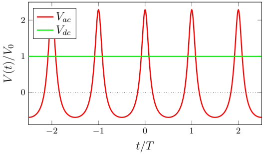
  - $V_{ac}(t)$ ➡ energy is not conserved

    e$^-$ scattered into a superposition of states



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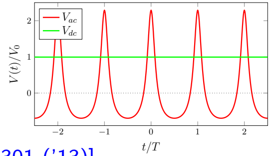

- Photo-assisted transport [Dubois et al. PRB 88, 085301 ('13)]
  - Acquired phase shift $\phi(t) = \frac{e}{\hbar} \int_{-\infty}^{t} dt' V_{ac}(t')$: $e^{-i\phi(t)} = \sum_{l=-\infty}^{+\infty} p_l e^{-il\Omega t}$

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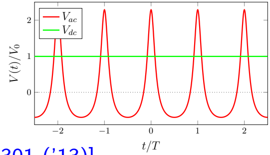

- Photo-assisted transport [Dubois et al. PRB 88, 085301 ('13)]
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proba. amplitude to absorb/emit photons

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- Decompose the voltage bias $V(t) = V_{dc} + V_{ac}(t)$ (with $\int_0^T dt V_{ac}(t) = 0$)
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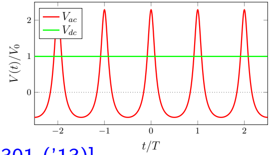

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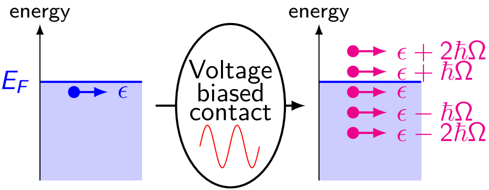

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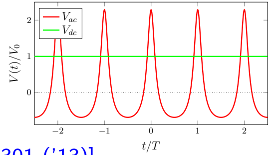

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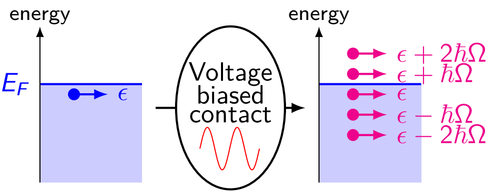

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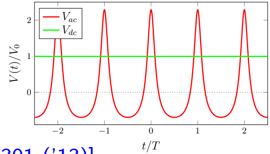

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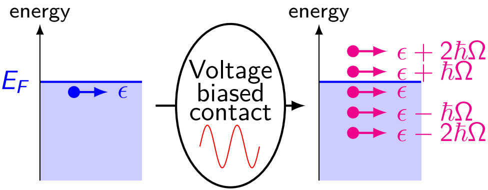

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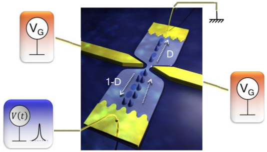
$|p_l|^2$

Experimental results

[Dubois et al., Nature 502, 659 ('13) - Dubois et al., PRB 88, 085301 ('13)]

- Setup: 2DEG with single-channel constriction



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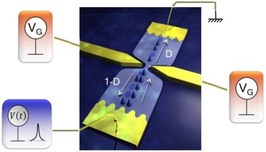

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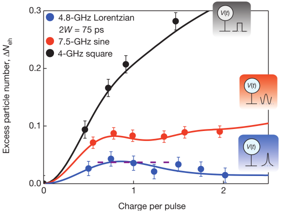

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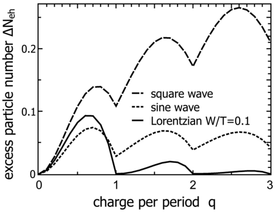

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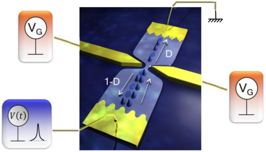

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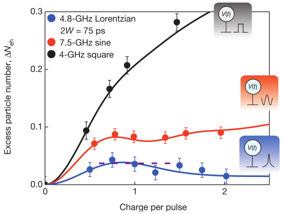

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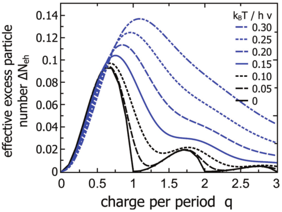

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➙ Important finite temperature effects

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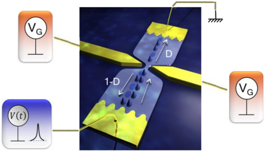

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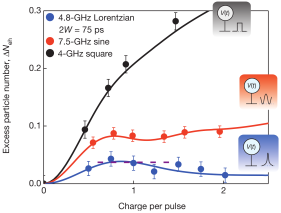

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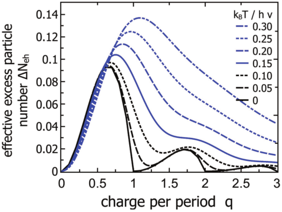


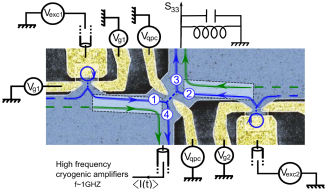
Theoretical prediction

➞ Important finite temperature effects

- Further characterization in energy and time domain

Adding interactions to the mix

- Interactions in EQO [Marguerite et al., PRB 94, 115311 ('16)]



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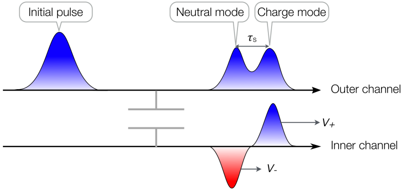

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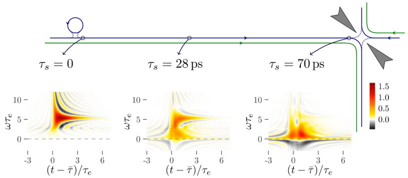

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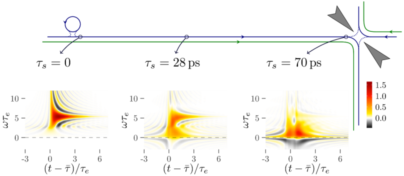

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  - 2DEG in even higher magnetic field
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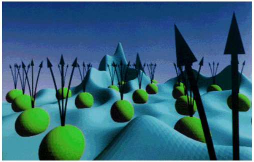

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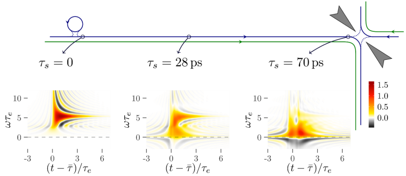

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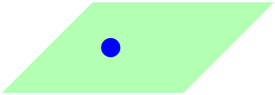

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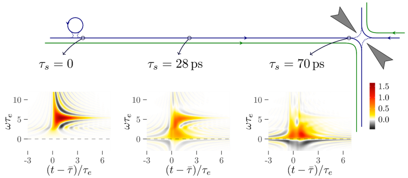

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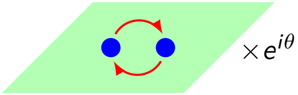

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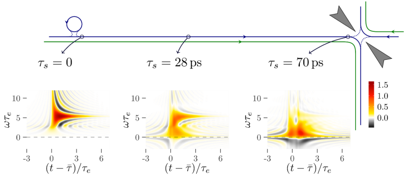

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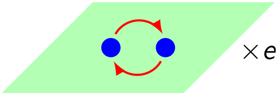


$\times e^{i\theta}$

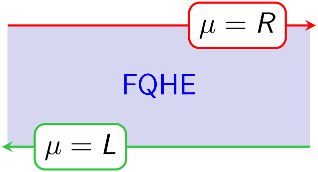
$e^* = \nu e$

Motivations for minimal excitations

- manipulation at the level of single anyons
- studying the exchange properties of anyons
- combining quasiparticles through interferometric setups

Model and derivation

- FQH bar at Laughlin filling $\nu = \frac{1}{2n+1}$ with Hamiltonian



- Propagation $H_0 = \frac{1}{4\pi} \sum_{\mu=R,L} \int dx \, v_F \, (\partial_x \phi_\mu)^2$

propagation velocity

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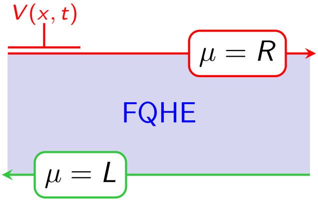

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$V(x,t)$: $\theta(-x-d)V(t)$

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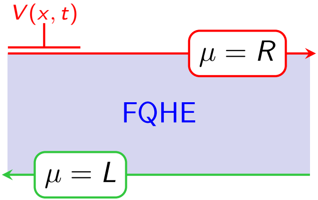

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- Accounting for the voltage drive $V(t)$

Bosonization id.

$$\psi_R(x,t) = \frac{U_R}{\sqrt{2\pi a}} e^{-i\sqrt{\nu}\phi_R(x,t)}$$

$+$ equations of motion

$$\Longrightarrow \quad \psi_R(x,t) \longrightarrow \psi_R(x,t) \, e^{-i\nu e \int_{-\infty}^{t} dt' \, V(t')}$$

acquired phase shift

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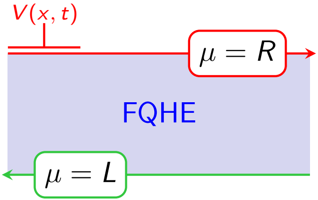

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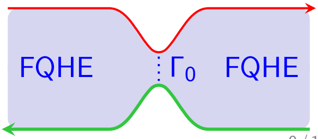
- HBT geometry in the weak backscattering regime
  - tunneling $H_T = \Gamma_0 \psi_R^\dagger(0)\psi_L(0) + H.c.$



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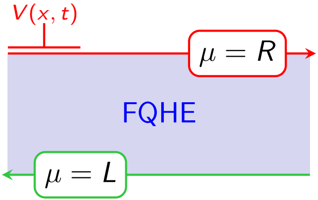

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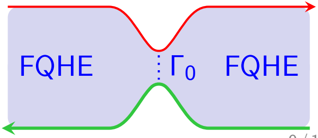
  - backscattering current

$\Gamma_0 e^{-i\nu e \int_{-\infty}^{t} dt' V(t')}$

$$I_B(t) = ie^* \left[\Gamma(t) \psi_R^\dagger(0,t) \psi_L(0,t) - \text{H.c.}\right]$$



Main results in the WB regime at $\nu = 1/3$

- Minimal excitations $\Leftrightarrow$ Poissonian noise
  ➡ search for vanishing excess noise $\Delta\mathcal{S} = \mathcal{S} - 2e^*\overline{\langle I_B(t)\rangle}$

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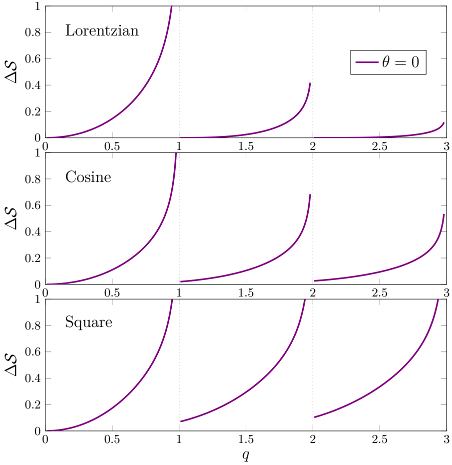

Zero temperature

- Expression

$$\Delta\mathcal{S} = \frac{2}{T}\left(\frac{e^*\Gamma_0}{v_F}\right)^2 \frac{1}{\Gamma(2\nu)}\left(\frac{\Omega}{\Lambda}\right)^{2\nu-2}$$
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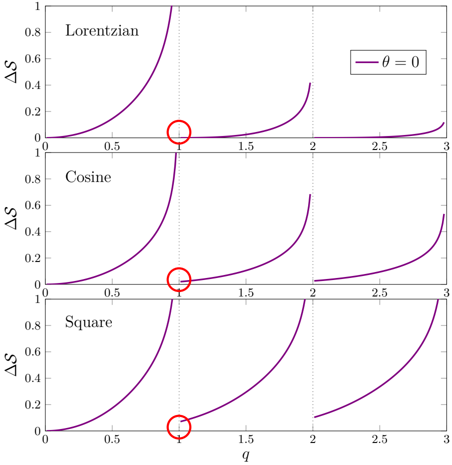

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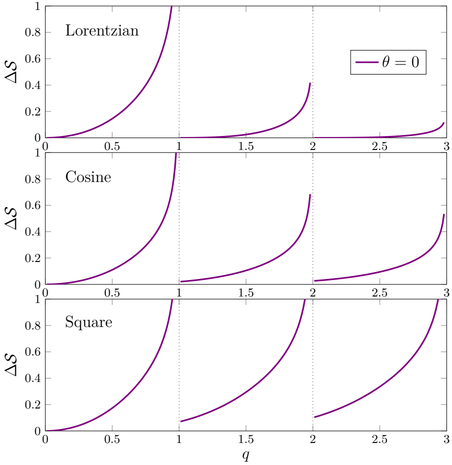

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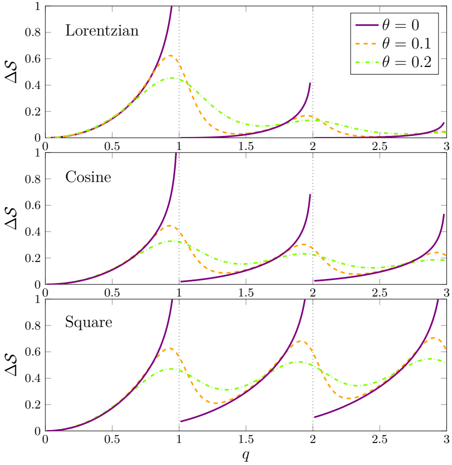

Zero temperature

- Expression

$$\Delta\mathcal{S} = \frac{2}{T}\left(\frac{e^*\Gamma_0}{v_F}\right)^2 \frac{1}{\Gamma(2\nu)}\left(\frac{\Omega}{\Lambda}\right)^{2\nu-2}$$
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- minimal excitations associated with quantized Lorentzian drive
- with charge $Q = \int_0^T dt\langle I(t)\rangle = qe$

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- strong asymmetry at $q \in \mathbb{N}$

Finite temperature $\theta = \frac{k_B\Theta}{\hbar\Omega}$

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Main results in the WB regime at $\nu = 1/3$

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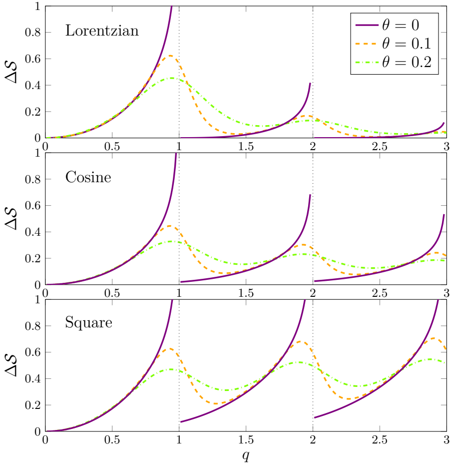

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- Is a perturbative treatment of the QPC sufficient?

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$\psi_a(t)$: after the QPC

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$\psi_b(t')$: before the QPC

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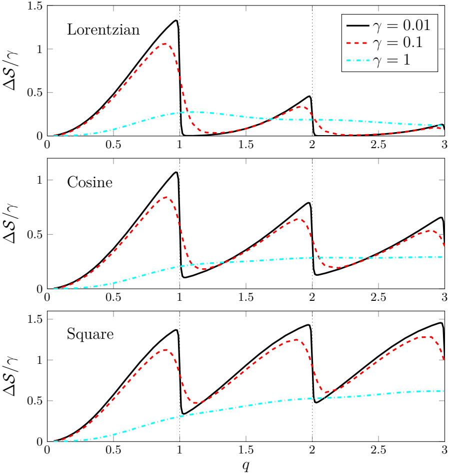
$$\mathcal{S} = \frac{e^2}{T} 4\gamma^2 \sum_{klm} \frac{\text{Re}\left(p_k^* p_l p_{l+m}^* p_{k+m}\right)}{m^2 + 4\gamma^2} \text{Re}\left[\left(\frac{\frac{2\gamma^2}{m} - i\gamma}{\tanh\left(\frac{l-k}{2\theta}\right)} - \frac{m + i\gamma + \frac{2\gamma^2}{m}}{\tanh\left(\frac{k+l+m+2q}{2\theta}\right)} \right) \Psi\left(\frac{1}{2} + \frac{\gamma - i(k+q)}{2\pi\theta}\right) \right]$$

Excess noise and main results

- Zero-temperature results



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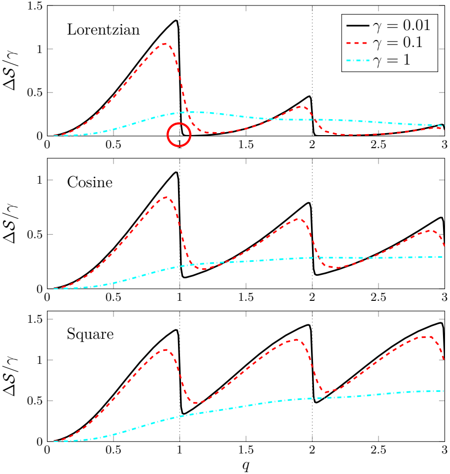

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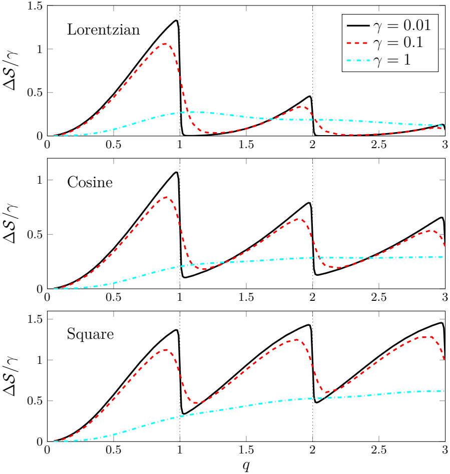

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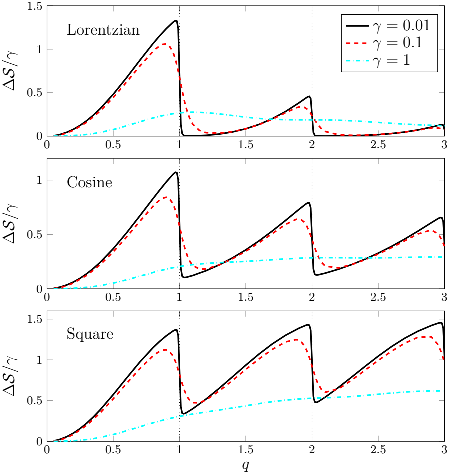

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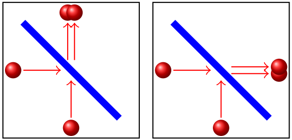
- Finite temperature effects
  - $\theta \lesssim \gamma$ excess noise almost unaffected
  - larger θ variations in q are completely smeared out

Hong-Ou-Mandel interferometry

- Tool to probe two-photon interferences



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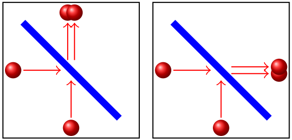

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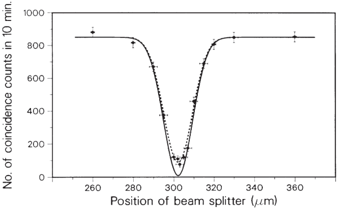

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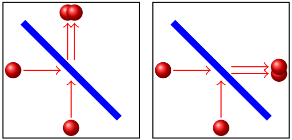

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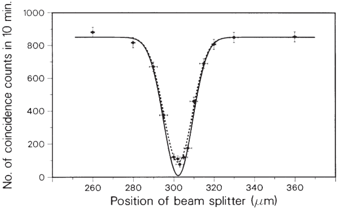

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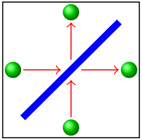
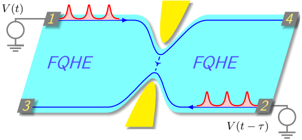
- Electronic equivalent?
  - variation on the HBT geometry
  - 2 sources with tunable delay
  - reveals fermionic statistics



Levitons in the time domain

- Setup and quantity of interest



- HOM to HBT ratio

$$\Delta Q(\tau) = \frac{\mathcal{S}_{V(t)-V(t-\tau)} - \mathcal{S}_{\text{vac}}}{\mathcal{S}_{V(t)} + \mathcal{S}_{V(t-\tau)} - 2\mathcal{S}_{\text{vac}}}$$

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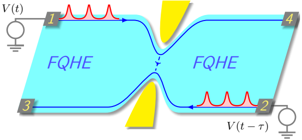

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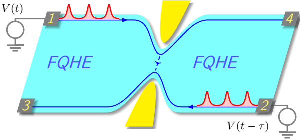

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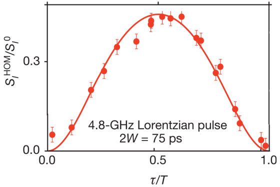
- Experimental Fermi liquid results



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- decoupling of time-delay and temperature variations
- interpretation in terms of wavepacket overlap

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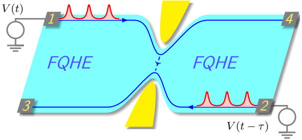

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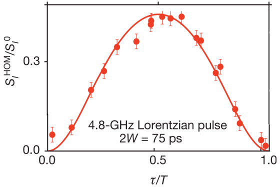

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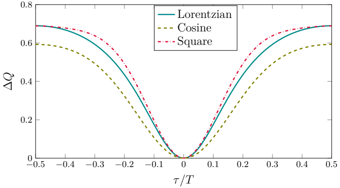
- HOM collisions in the FQHE ($\nu = 1/3$)



- not a diagnosis for minimal excitations
- universal form, $\forall \Theta$, $\forall \nu$

$$\Delta Q(\tau) = \frac{\sin^2\left(\frac{\pi\tau}{T}\right)}{\sin^2\left(\frac{\pi\tau}{T}\right) + \sinh^2(2\pi\eta)}$$

Conclusions

- Minimal excitations exist in the fractional quantum Hall regime
  - correspond to a periodic Lorentzian drive with quantized flux
  - can be detected in an HBT setup
  - bear an *integer* electron charge

- results confirmed for arbitrary tunneling via exact refermionization at $\nu = 1/2$

- leviton collisions bear a universal HOM signature, identical to the Fermi liquid case

Minimal excitations in the fractional quantum Hall regime
J. Rech, D. Ferraro, T. Jonckheere, L. Vannucci, M. Sassetti, T. Martin,
arXiv:1606.01122

From excitation number to excess noise

- Number of excitations in the Fermi liquid case

$$N_e = \sum_k n_F(-k)\langle\psi_k^\dagger\psi_k\rangle \qquad N_h = \sum_k n_F(k)\langle\psi_k\psi_k^\dagger\rangle$$

- Using the bosonized description, this becomes

$$N_{e/h} = v_F^2 \int \frac{dtdt'}{(2\pi a)^2} \exp\left[2\mathcal{G}(t'-t) \mp ie\int_{t'}^{t} d\tau V(\tau)\right]$$

- Generalizing to the FQHE: minimal excitation $\Longrightarrow$ vanishing of

$$\mathcal{N} = v_F^2 \int \frac{dtdt'}{(2\pi a)^2} \exp\left[2\nu\mathcal{G}(t'-t) + ie^*\int_{t'}^{t} d\tau V(\tau)\right]$$

- Direct correspondence with excess noise $\Delta\mathcal{S} = \mathcal{S} - 2e^*\overline{\langle I_B(t)\rangle}$

$$\Delta\mathcal{S} = \left(\frac{e^*\Gamma_0}{\pi a}\right)^2 \int d\tau \int_0^T \frac{d\bar{t}}{T} \exp\left[2\nu\mathcal{G}\left(-\tau\right) + ie^*\int_{\bar{t}-\frac{\tau}{2}}^{\bar{t}+\frac{\tau}{2}} dt'' V(t'')\right]$$

Back to main