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The Ensslin Group
nanophysics @ ETH

Tunneling between Landau levels in a quantum dot in the integer and fractional quantum Hall regimes

Ensslin group, ETH Zürich:
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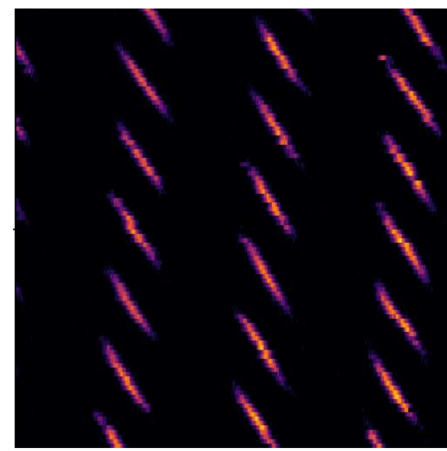
B. A. Braem, S. Hennel, A. Kurzmann, T. Ihn, K. Ensslin

Wegscheider group, ETH Zürich:
M. Berl, C. Reichl, W. Wegscheider



QSIT Quantum Science and Technology
National Centre of Competence in Research

FNSNF
Schweizerischer Nationalfonds
zur Förderung der wissenschaftlichen Forschung

[…] the fractional quantum Hall effect, and new interaction phenomena will be more important, not to mention that a microscopic picture of the quantum Hall effect for real devices […] is still missing.

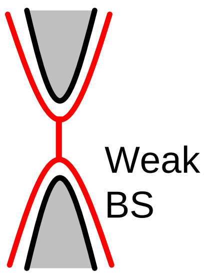
--- Klaus von Klitzing, 2019

K. von Klitzing, Phys. Rev. Lett. ***122****, 200001 (2019)*

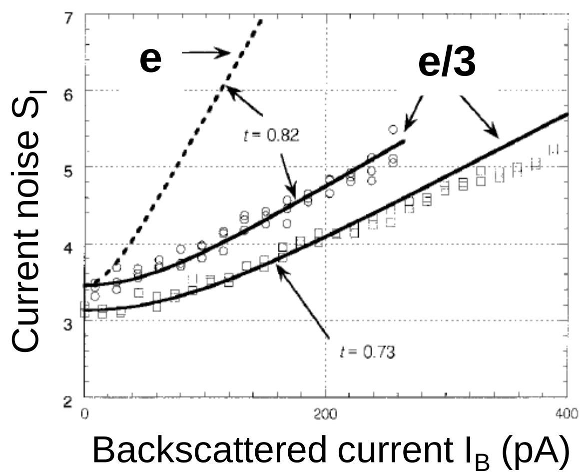
Fractional quantum Hall effect – quasi-particles

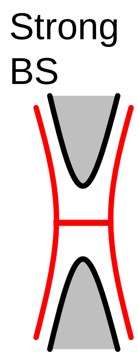
Laughlin (1983) → fractionally charged quasiparticles

Shot noise:

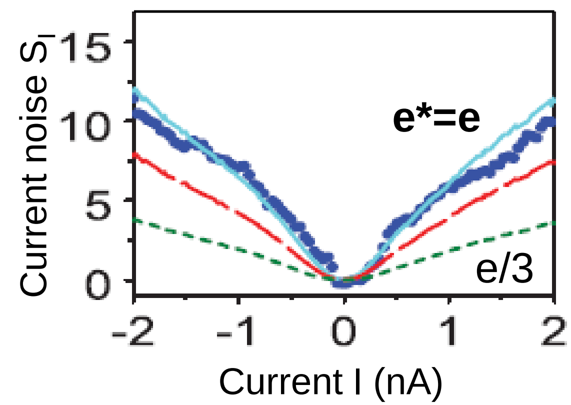


$\nu = 1/3$





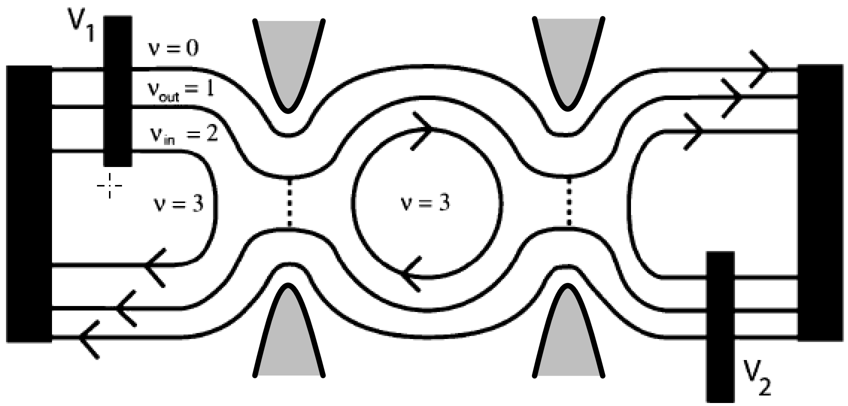
$\nu = 1/3$



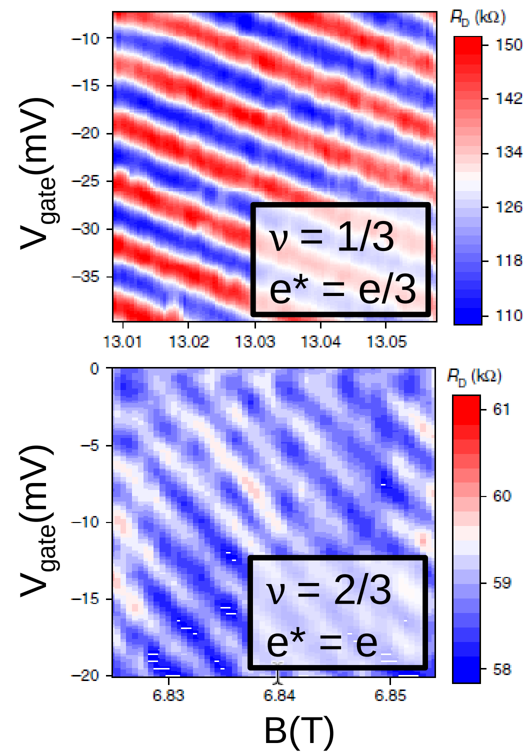
*R. de-Picciotto, et al., Nature **389**, 162 (1997)*
*L. Saminadayar et al., Phys. Rev. Lett. **79**, 2526 (1997)*
*M. Reznikov et al., Nature **399**, 238 (1999)*
*A. Bid et al., Phys. Rev. Lett. **103**, 236802 (2009)*

S. Hennel et al., Phys. Rev. B 97, 245305 (2018)

Interferometry of quantum Hall states



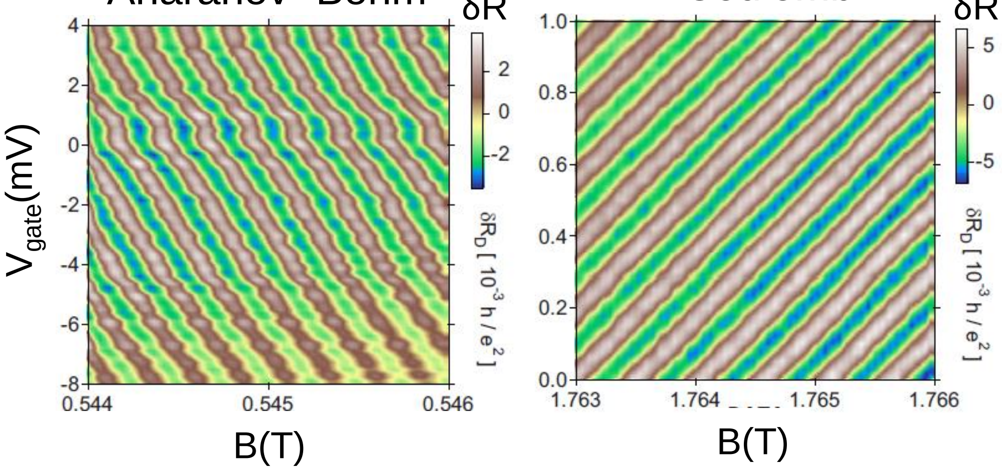
Fractional QH regime



Integer QH regime

Aharanov- Bohm

Coulomb



Y. Zhang et al., Phys. Rev. B ***79****, 241304 (2009)*
B. I. Halperin et al., Phys. Rev. B ***83****, 155440 (2011)*
Y. Ji et al., Nature ***422****, 415 (2003)*
J. Nakamura et al., Nature Physics ***15****, 563 (2019).*
R. L. Willett et al., arXiv:1905.10248 (2019).
…and more…

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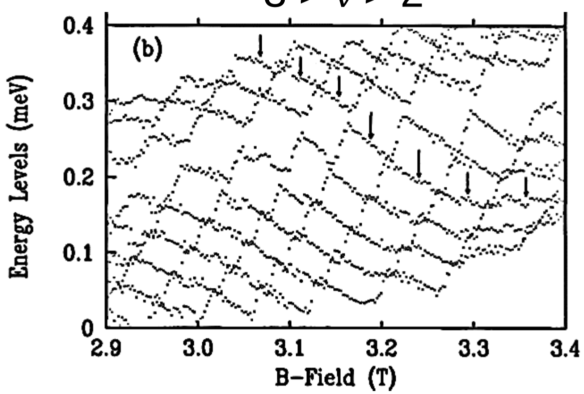
Quantum dots in the quantum Hall regime

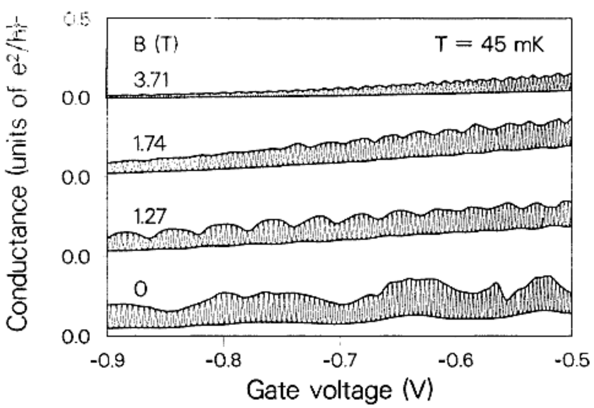
Single particle spectrum

$3 > \nu > 2$



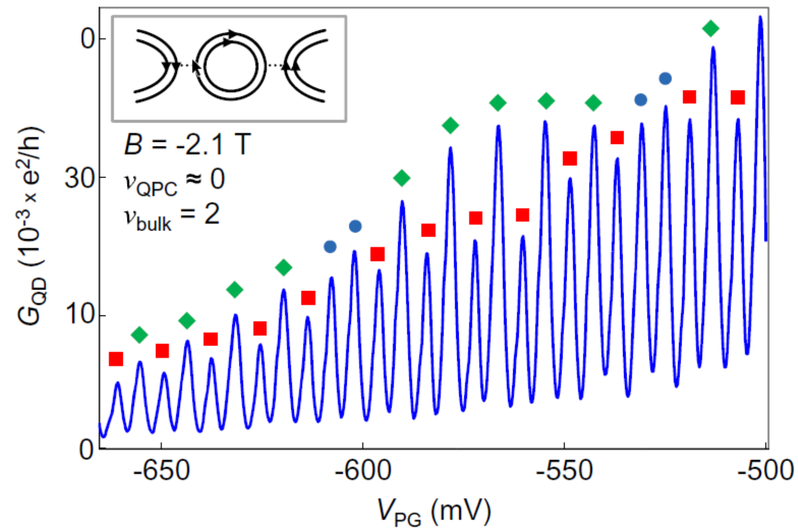
P. L. McEuen et al., Physica B: Cond. Mat. ***189****, 70 (1993)*

Modified Coulomb oscillations



A. A. M. Staring et al., Phys. Rev. B ***46****, 12869 (1992)*

Cyclic depopulation



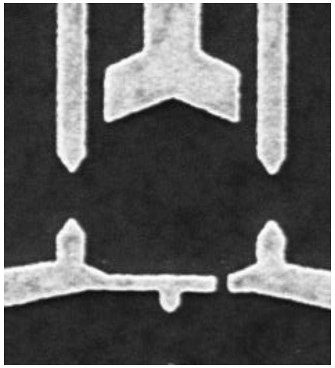
T. Heinzel et al., Phys. Rev. B ***50****, 15113 (1994)*
S. Baer et al., New J. Phys. ***15****, 023035 (2013)*

Interaction and spin important

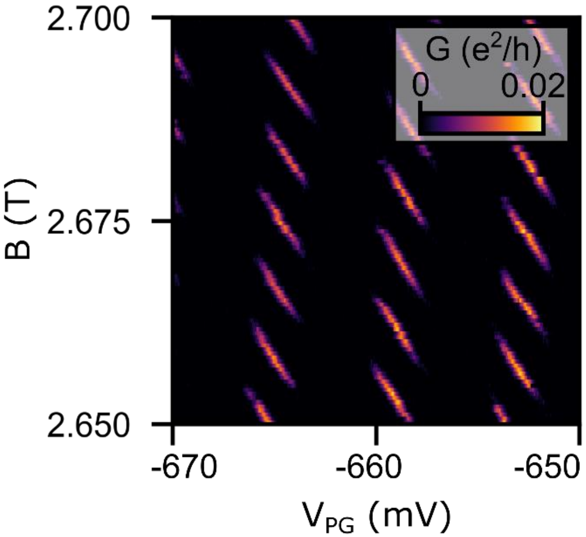
O. Klein et al., Phys. Rev. B ***53****, R4221 (1996)*
P. Hawrylak et al., Phys. Rev. B ***59****, 2801 (1999)*

Idea

Goal: (time-resolved) tunneling of fractional quasiparticles



- large quantum dot → energy quantization
- Quantum dot as charge detector for charging processes in the dot itself
  → (time-resolved) detection of tunneling between Landau levels

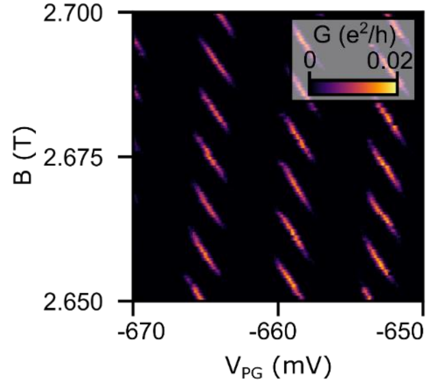


Previous work:

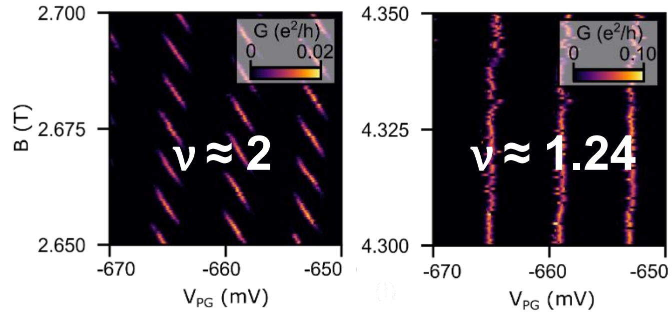
Van der Vaart et al.(1997),TU Delft;
Baer et al. (2014), ETH Zürich

Overview

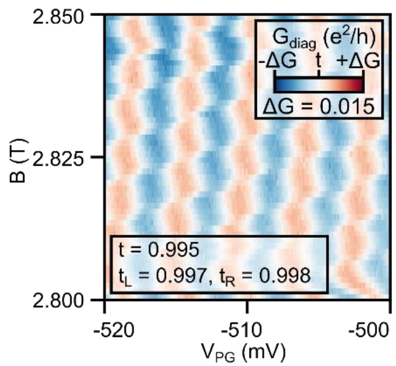
Gate voltage and magnetic field dependence



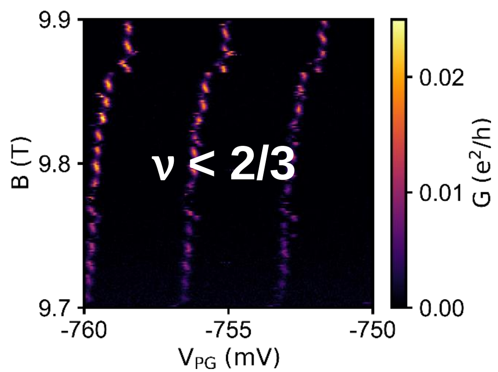
Evolution for different filling factor ν = 2 to ν = 1



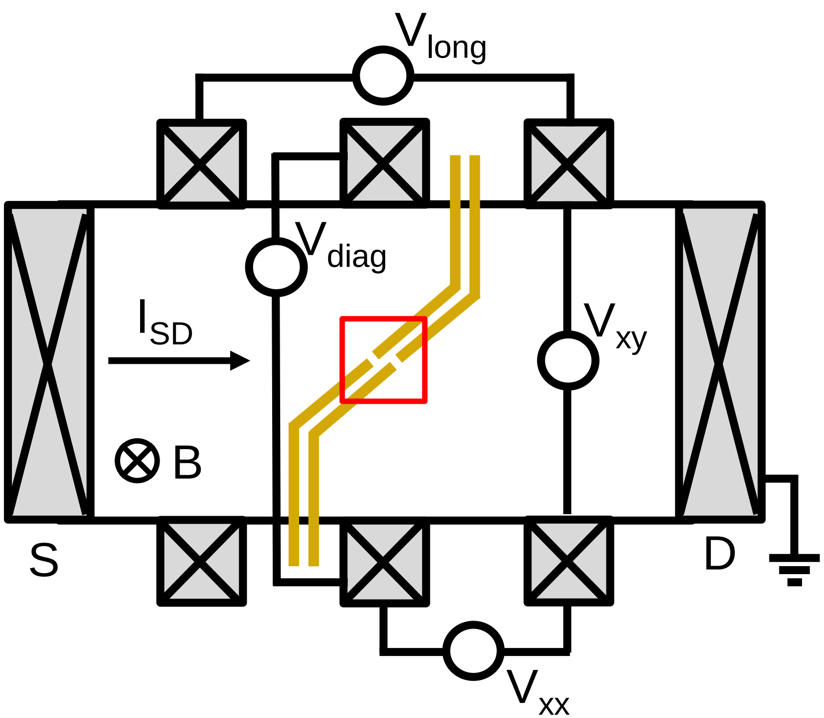
Interferometer: open QD barriers

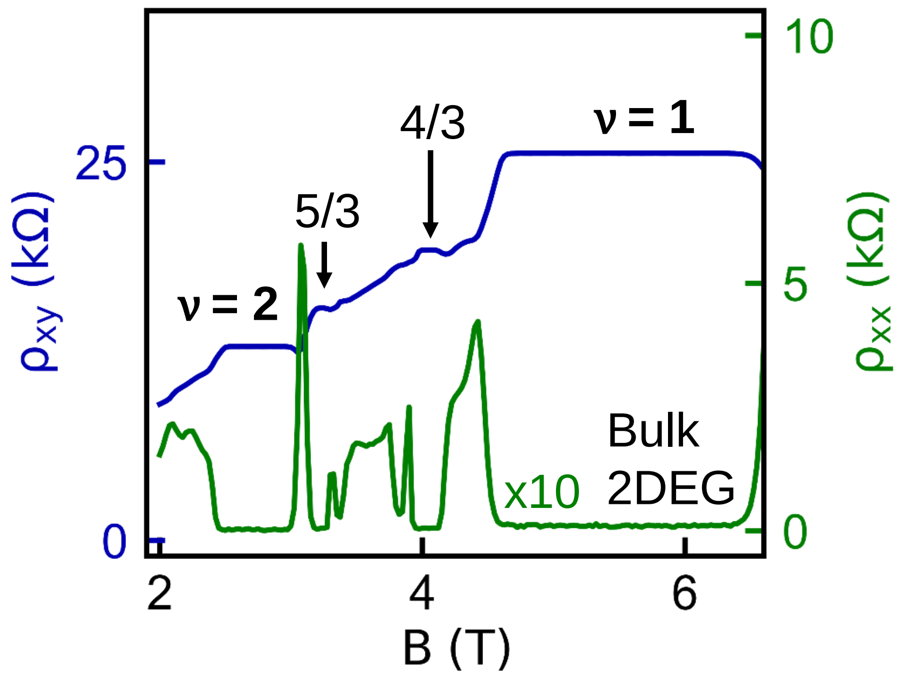


QD in fractional QH regime



Sample





Hall bar with nanostructure on AlGaAs/GaAs heterostructure

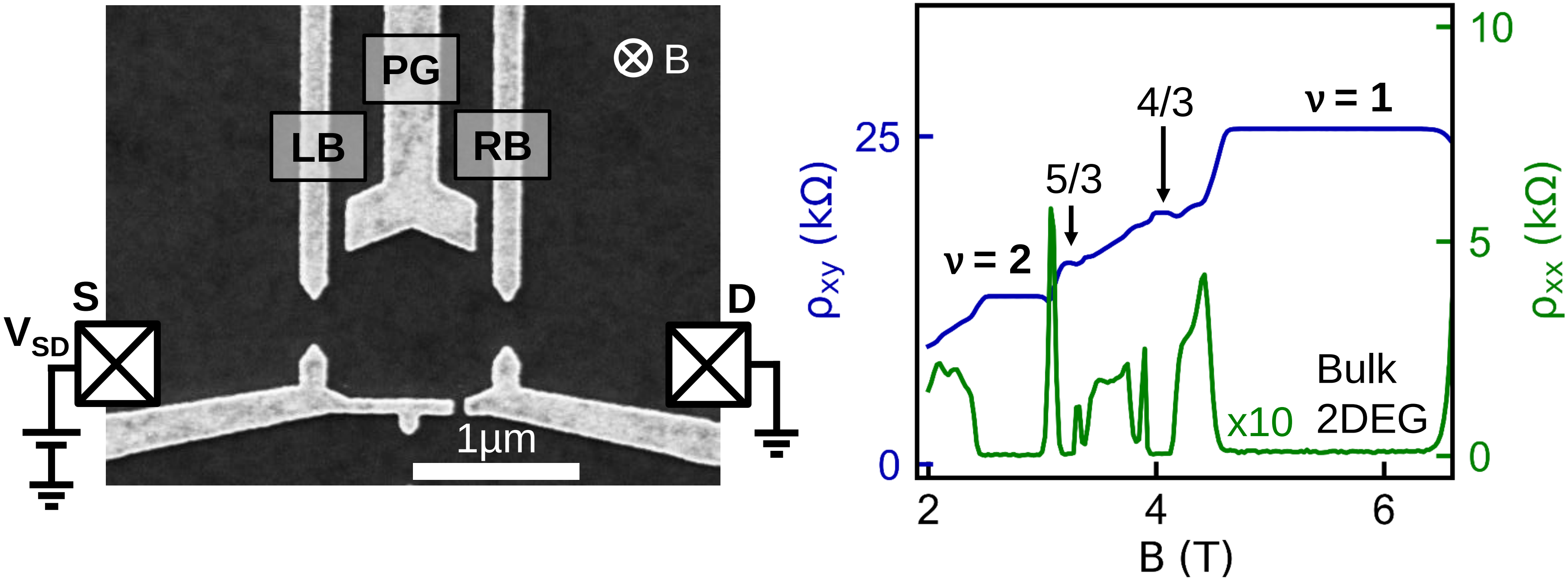
$n = 1.3 \times 10^{11}\ \mathrm{cm}^{-2}$

$\mu = 5.3 \times 10^{6}\ \mathrm{cm}^{2}/(\mathrm{Vs})$

2DEG depth: 130 nm

$T_e \approx 25$ mK

Sample



1x1 µm² quantum dot on AlGaAs/GaAs heterostructure

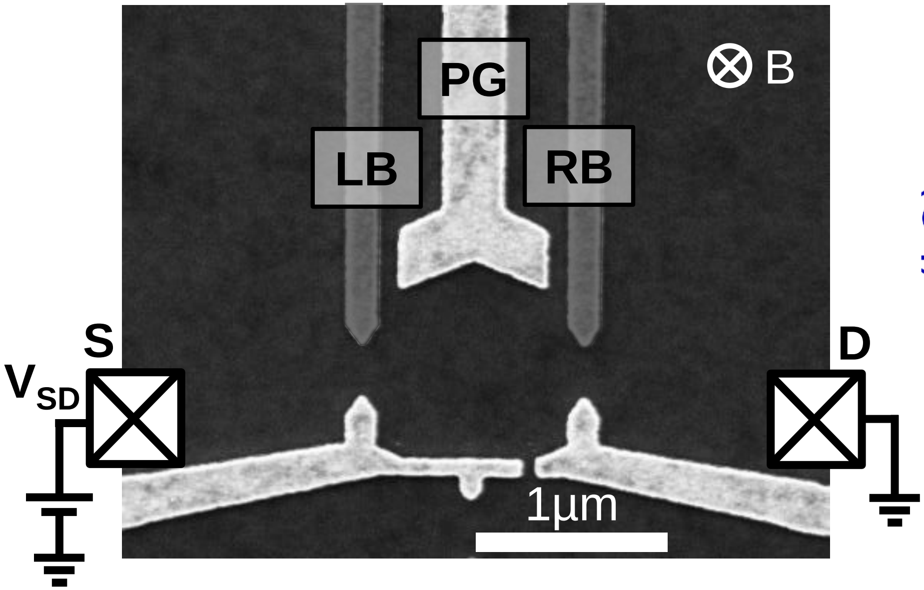
$n = 1.3 \times 10^{11}\ \mathrm{cm}^{-2}$

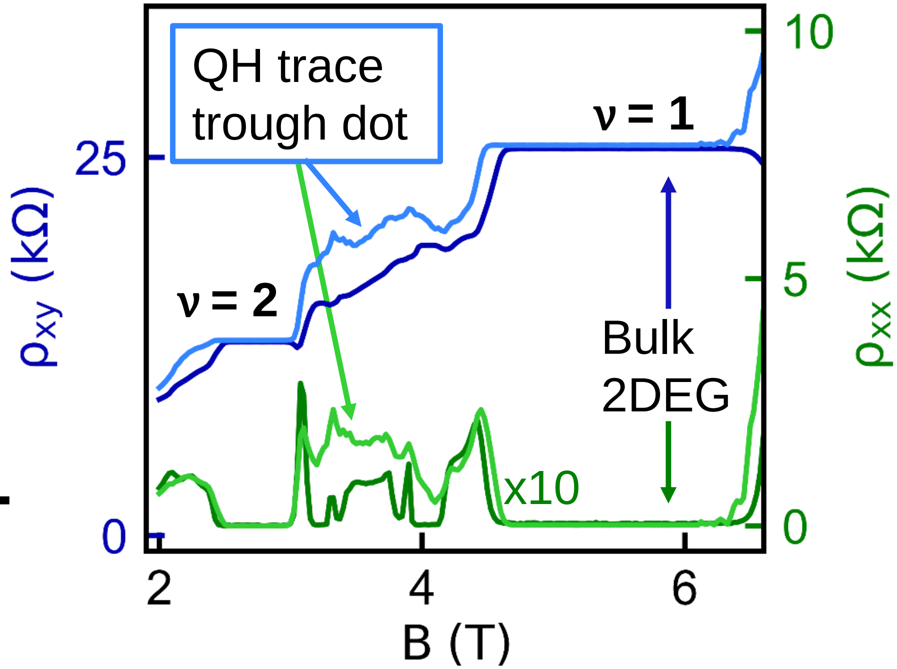
$\mu = 5.3 \times 10^{6}\ \mathrm{cm}^{2}/(\mathrm{Vs})$

2DEG depth: 130 nm

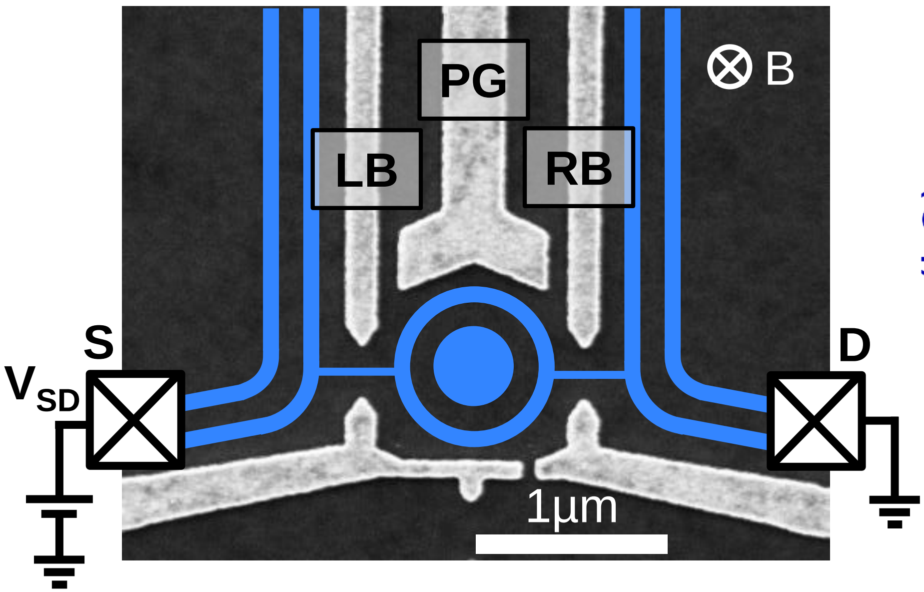
$T_e \approx 25$ mK

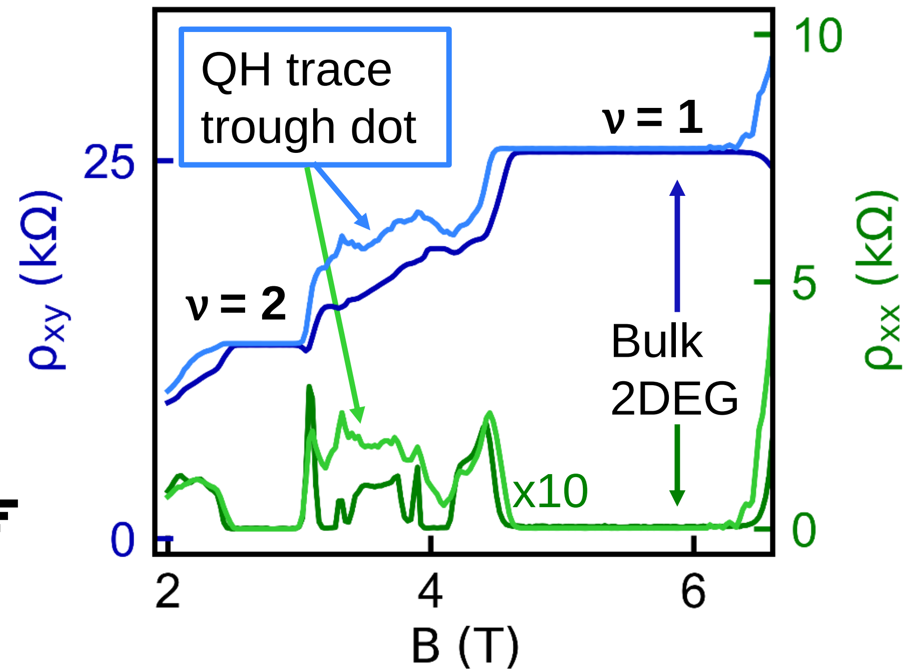
Sample


PG
LB
RB
⊗ B
S
D
V_{SD}
1µm


QH trace
trough dot
ν = 1
ν = 2
Bulk
2DEG
x10
25
0
10
5
0
2
4
6
B (T)
ρxy (kΩ)
ρxx (kΩ)

Sample



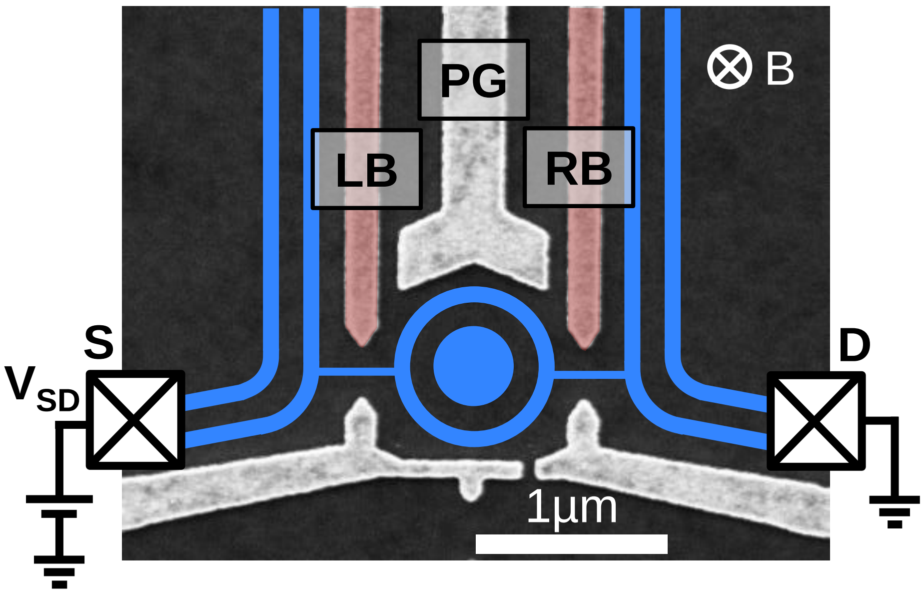


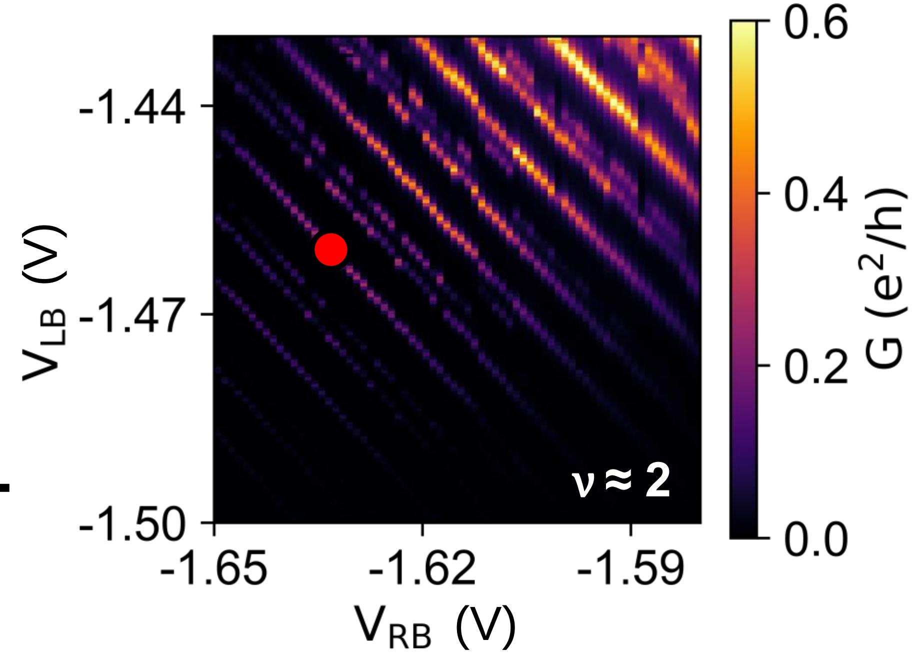
Quantum Hall regime 2 > ν > 1:

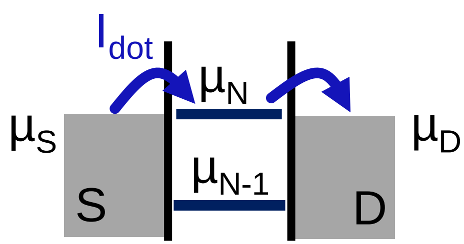
two compressible regions separated by incompressible stripe

➡ Quantum Hall states exist in the QD

Forming a single quantum dot

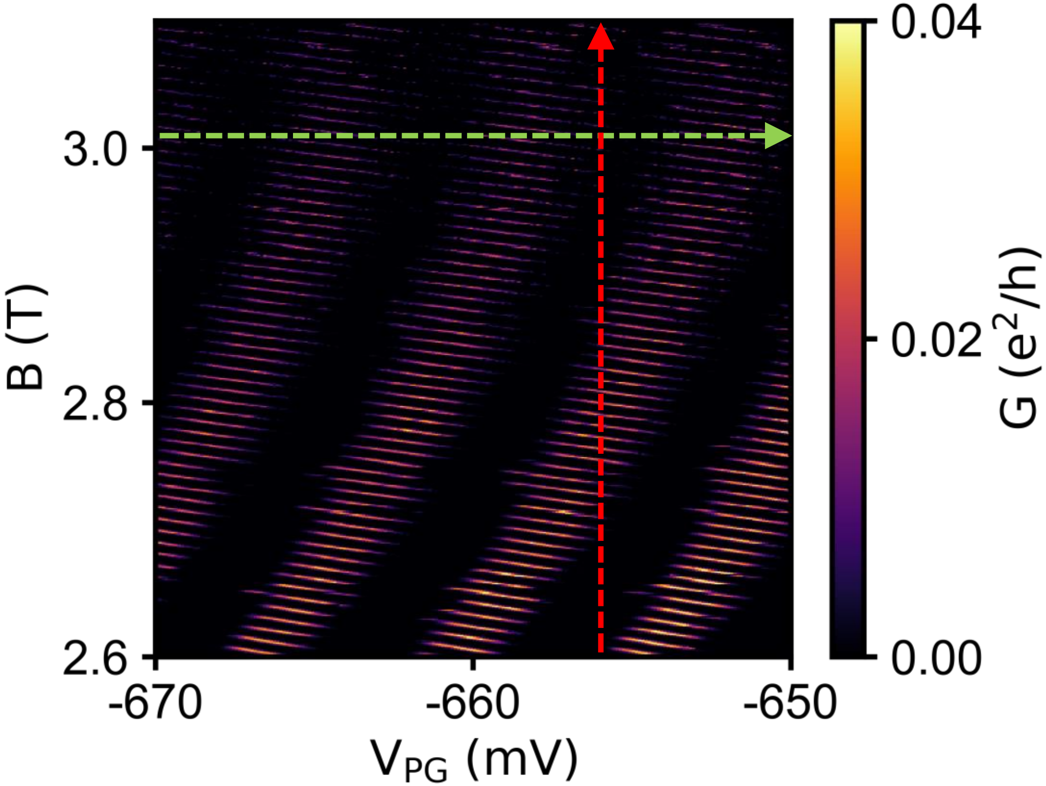


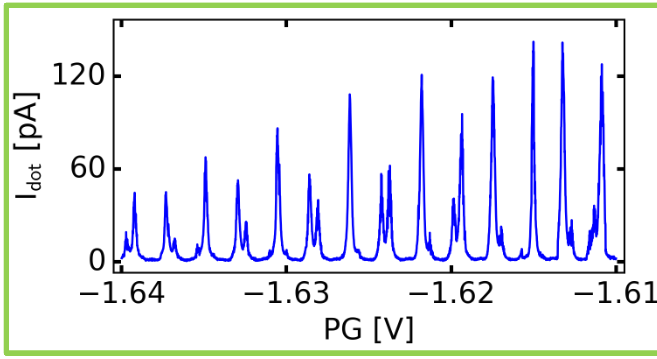


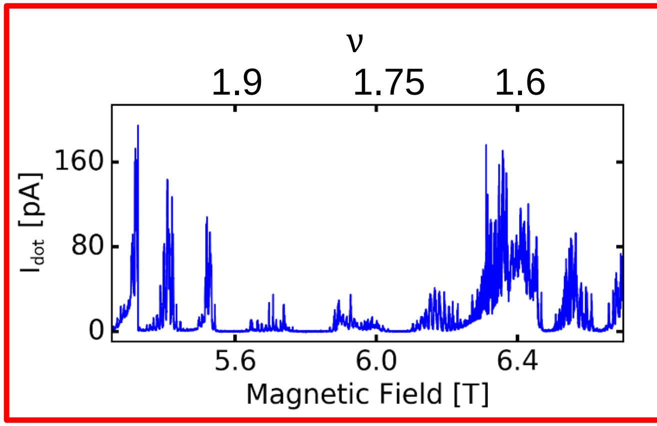


➡ stable 1x1 μm^2 quantum dot in the quantum Hall regime

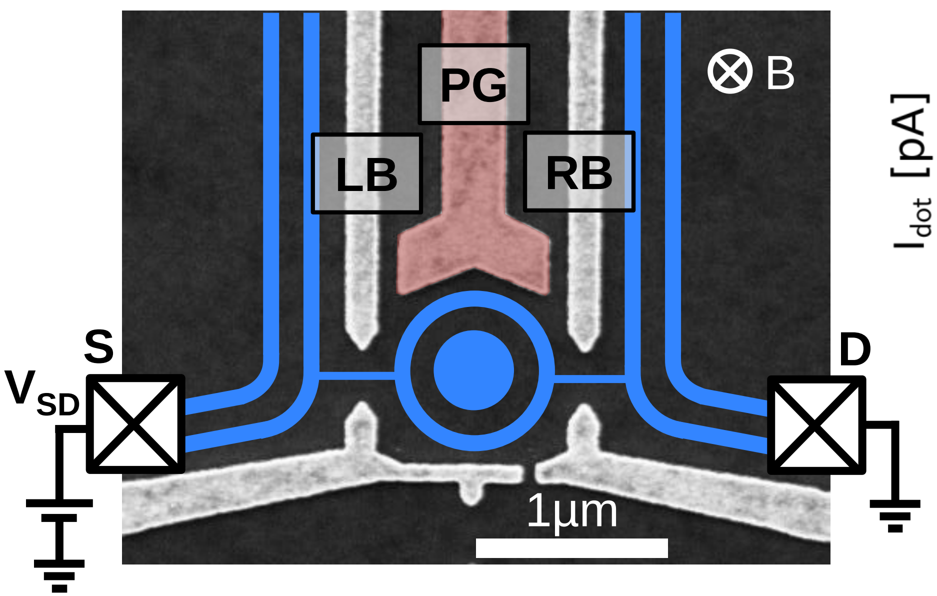
Magnetic field vs plunger gate

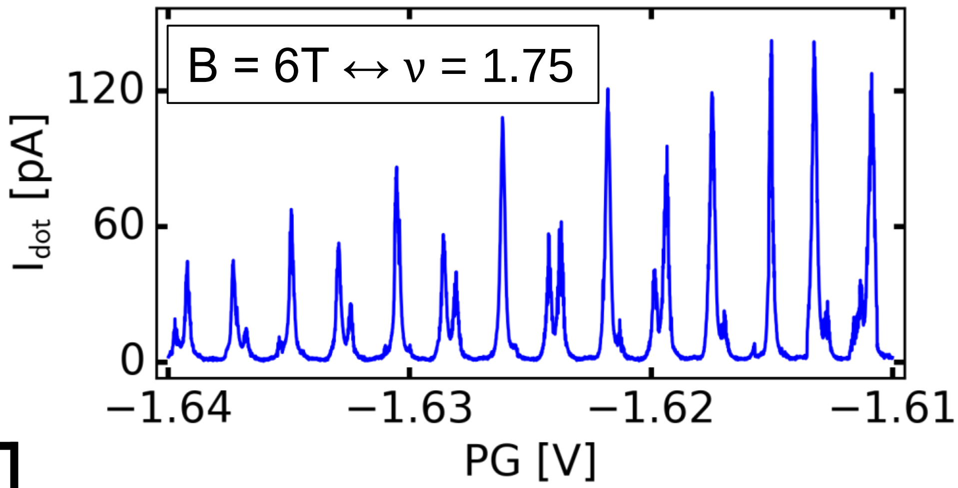


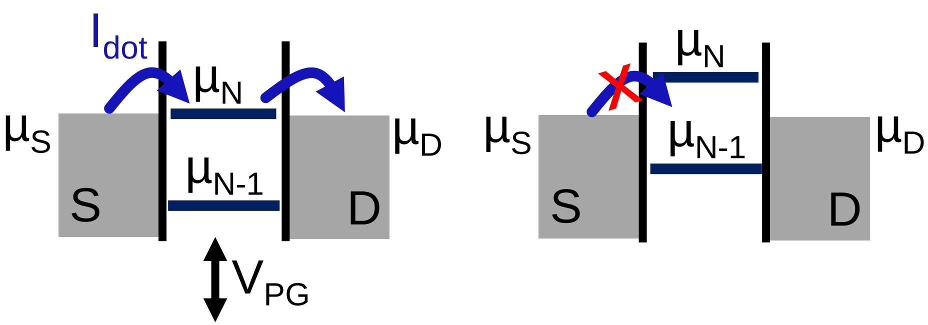


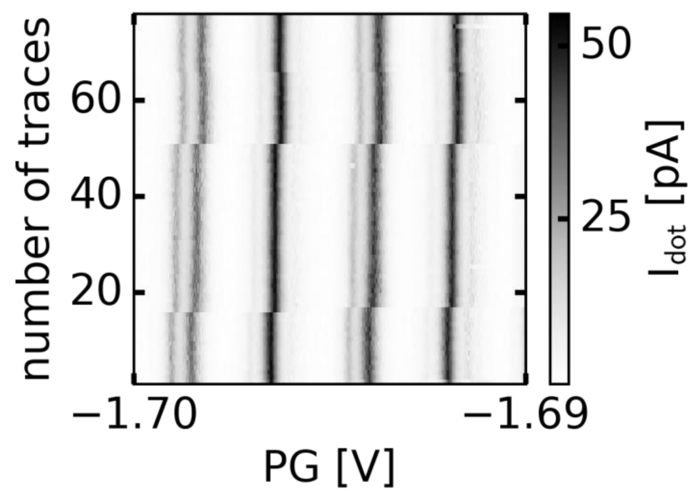


Split Coulomb oscillations









Split Coulomb resonances

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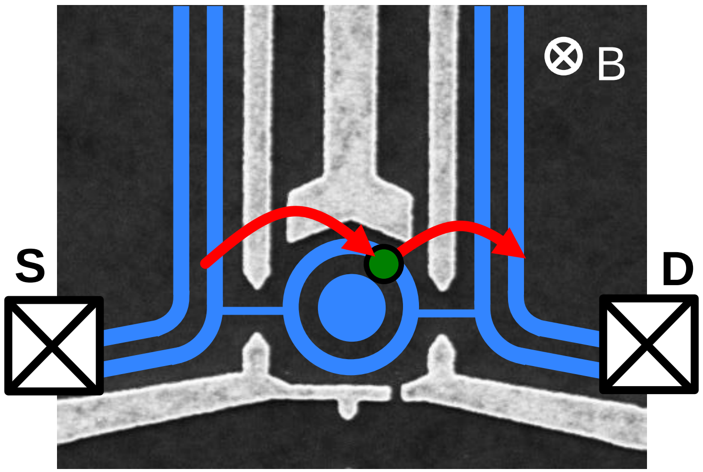
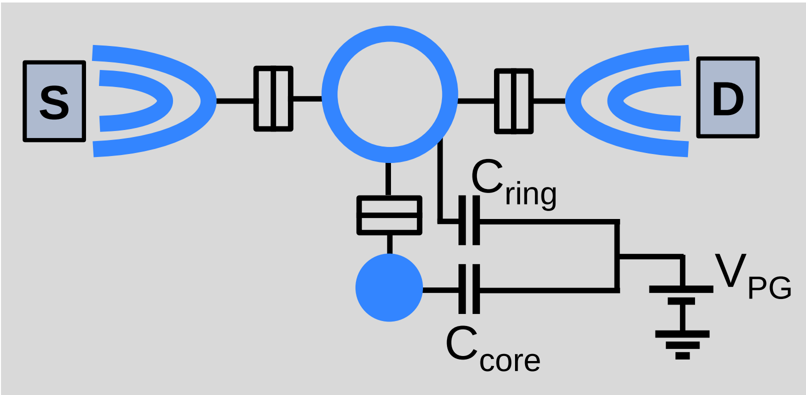
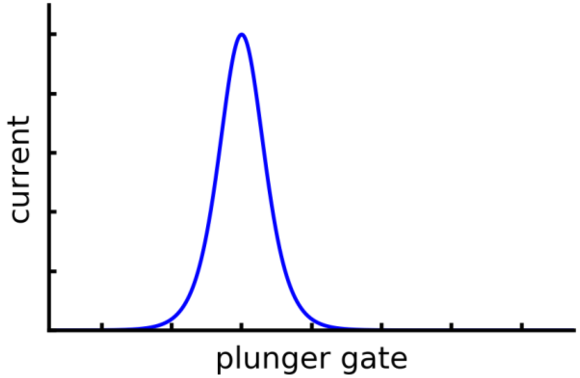
Split Coulomb oscillations



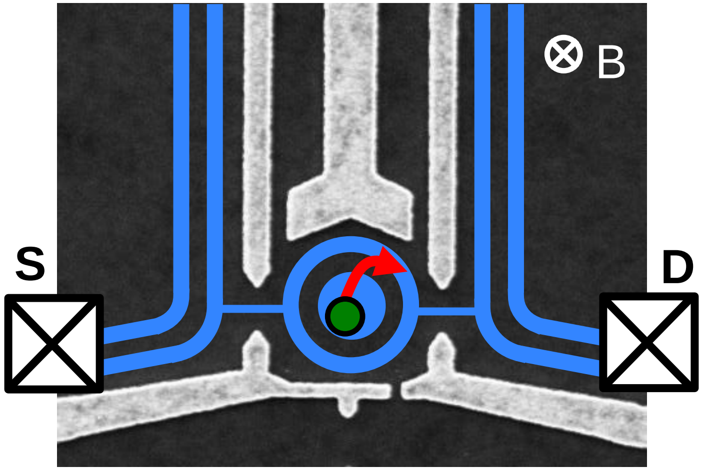


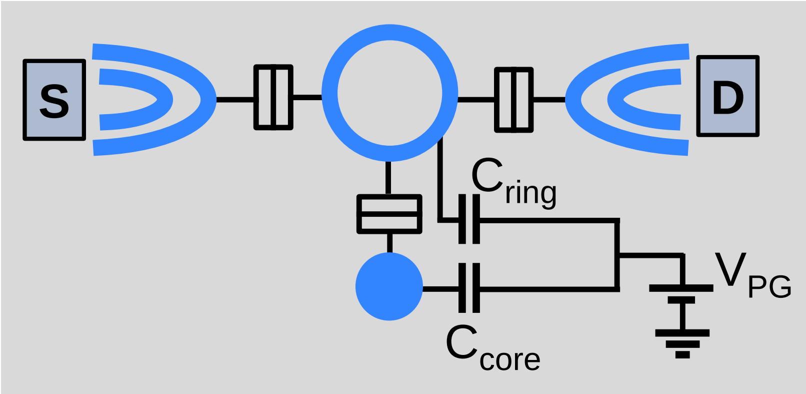


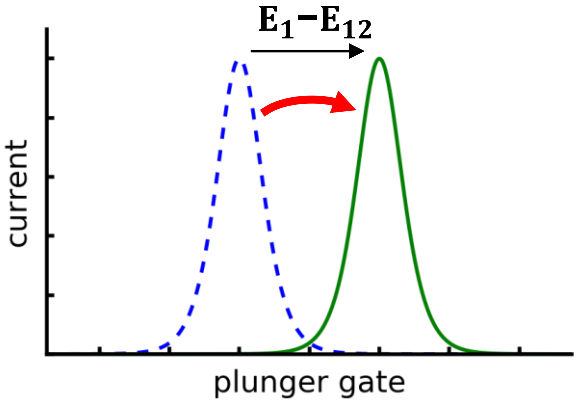
- Each Landau level forms quantum dot
- Capacitive coupling
- Double dot system
- Charge rearangement → shift of Coulomb resonance

N. C. van der Vaart et al. Phys. Rev. B ***55****, 9746 (1997)*

Split Coulomb oscillations







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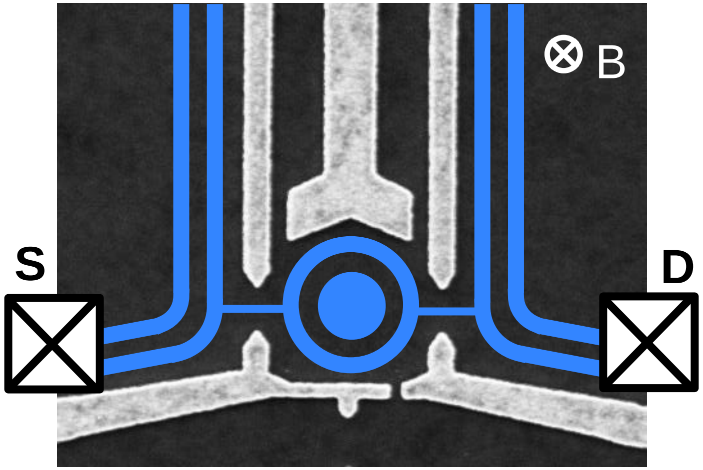

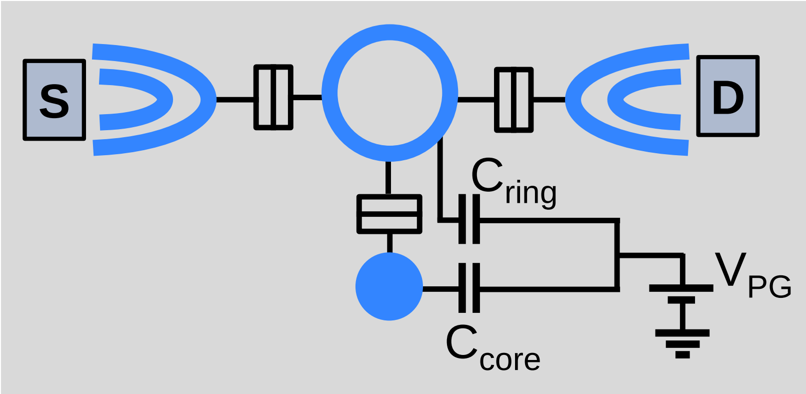

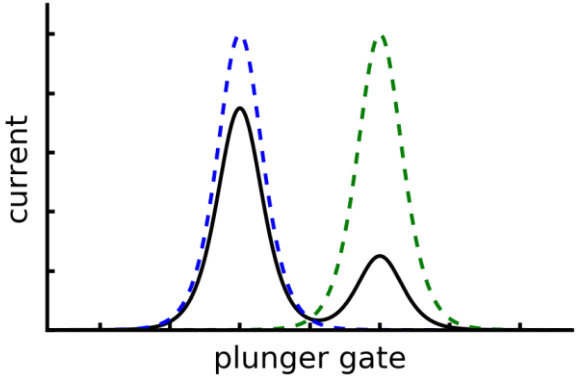

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➡ Split peaks due to capacitive coupling of the edge channels in a double dot picture

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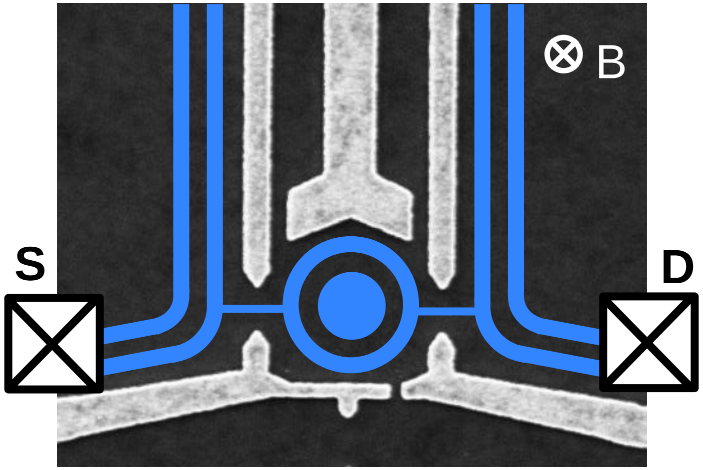
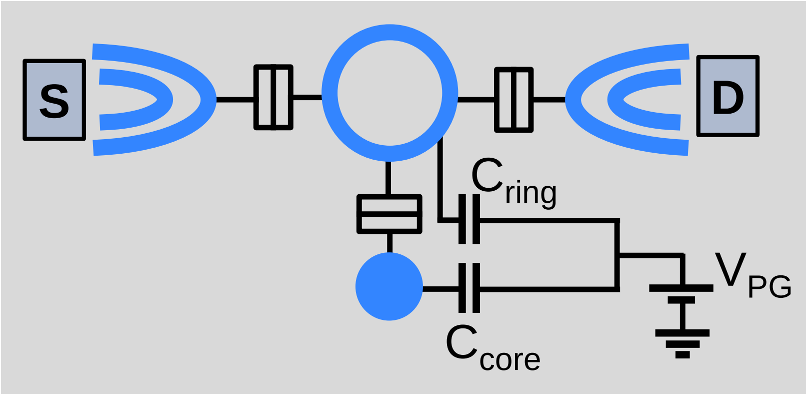
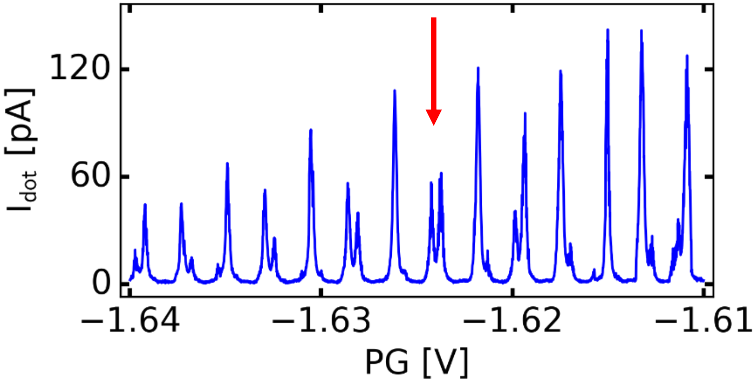
Split Coulomb oscillations







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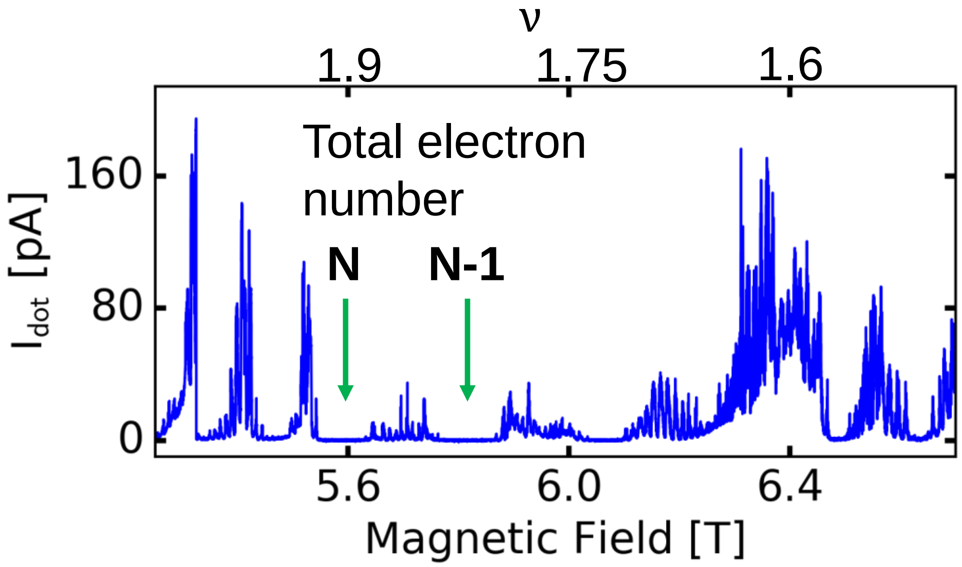
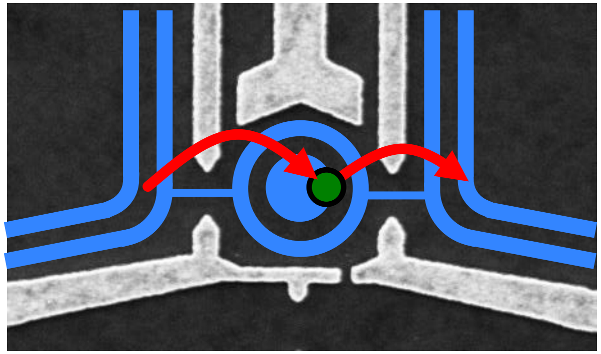
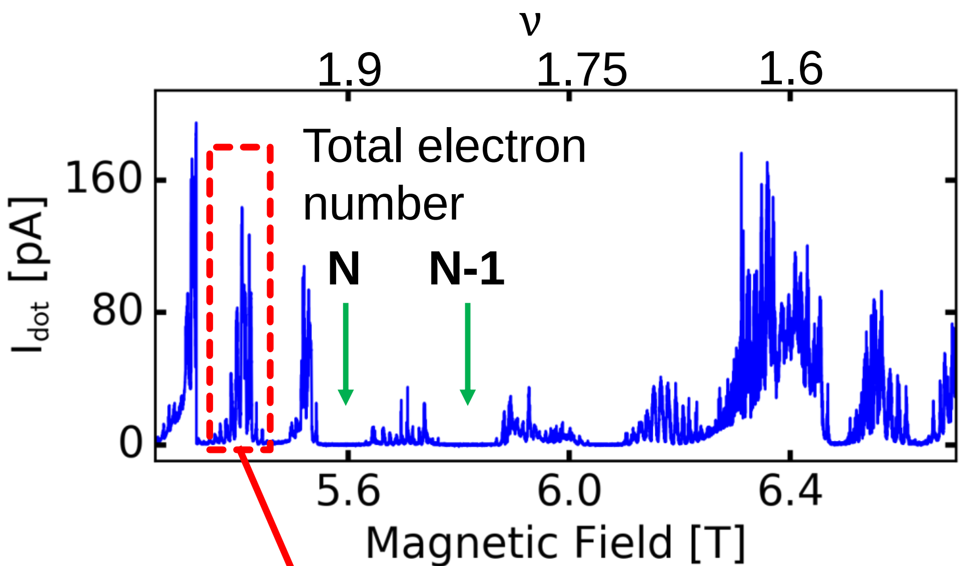
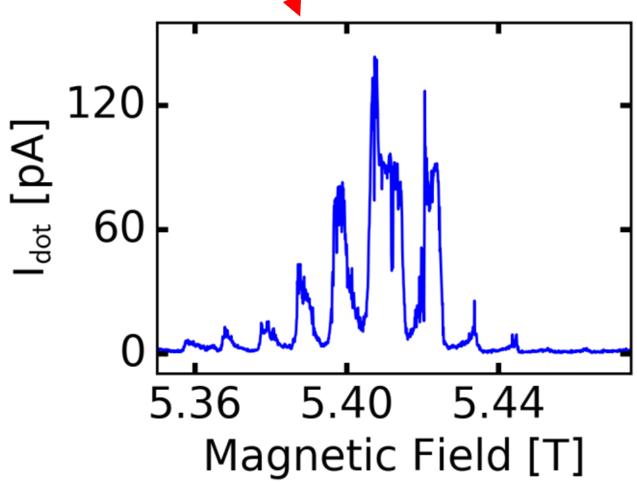
Magnetotransport

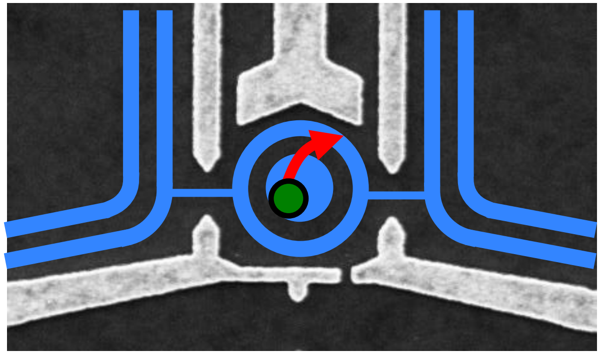


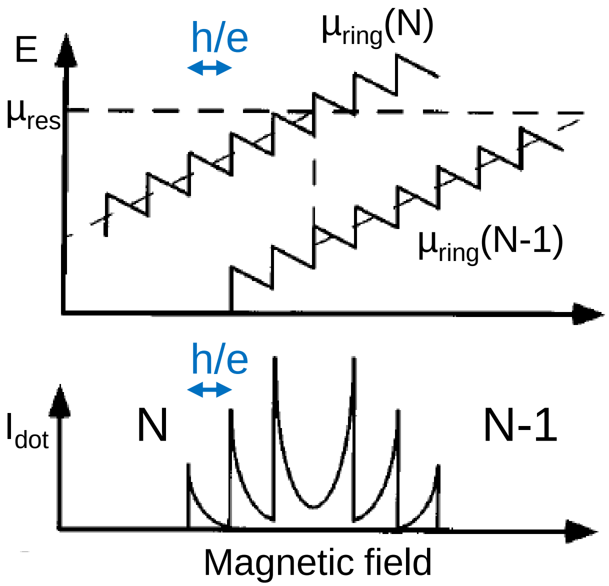


Magnetotransport



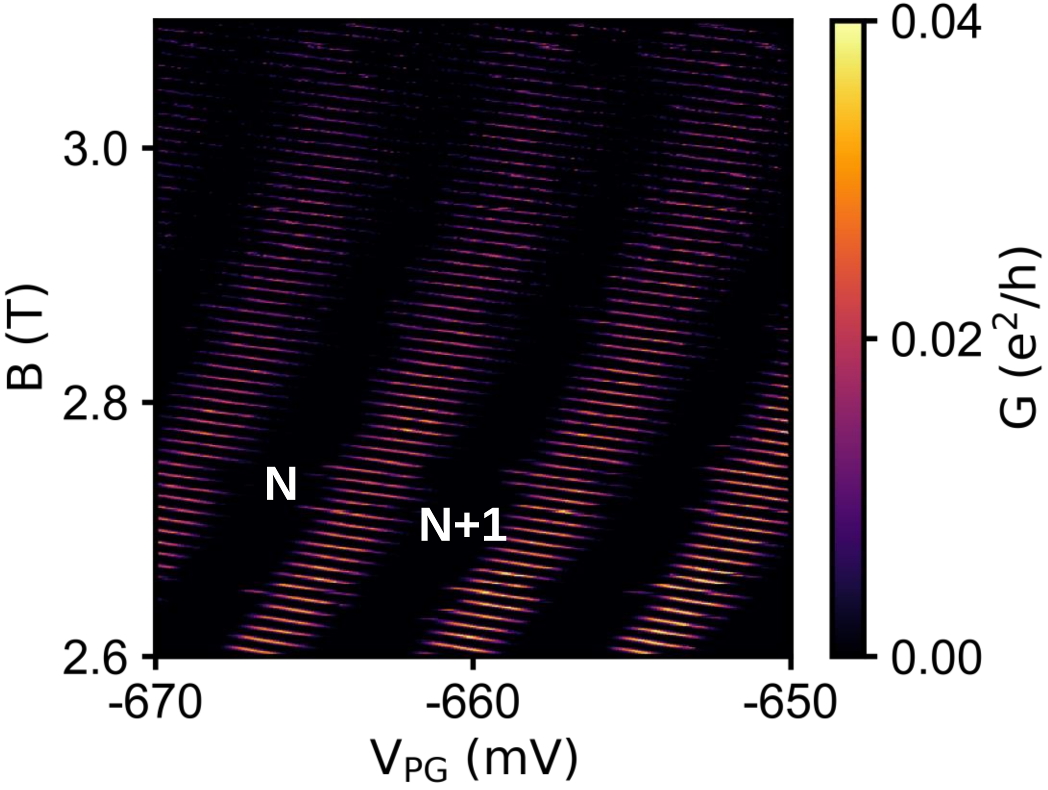


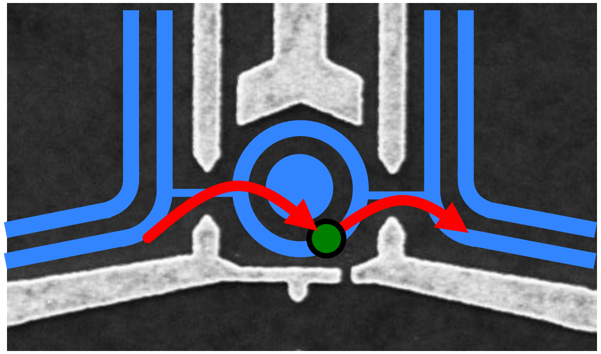




*N. C. van der Vaart et al. Phys. Rev. B **55**, 9746 (1997)*

Magnetic field vs plunger gate





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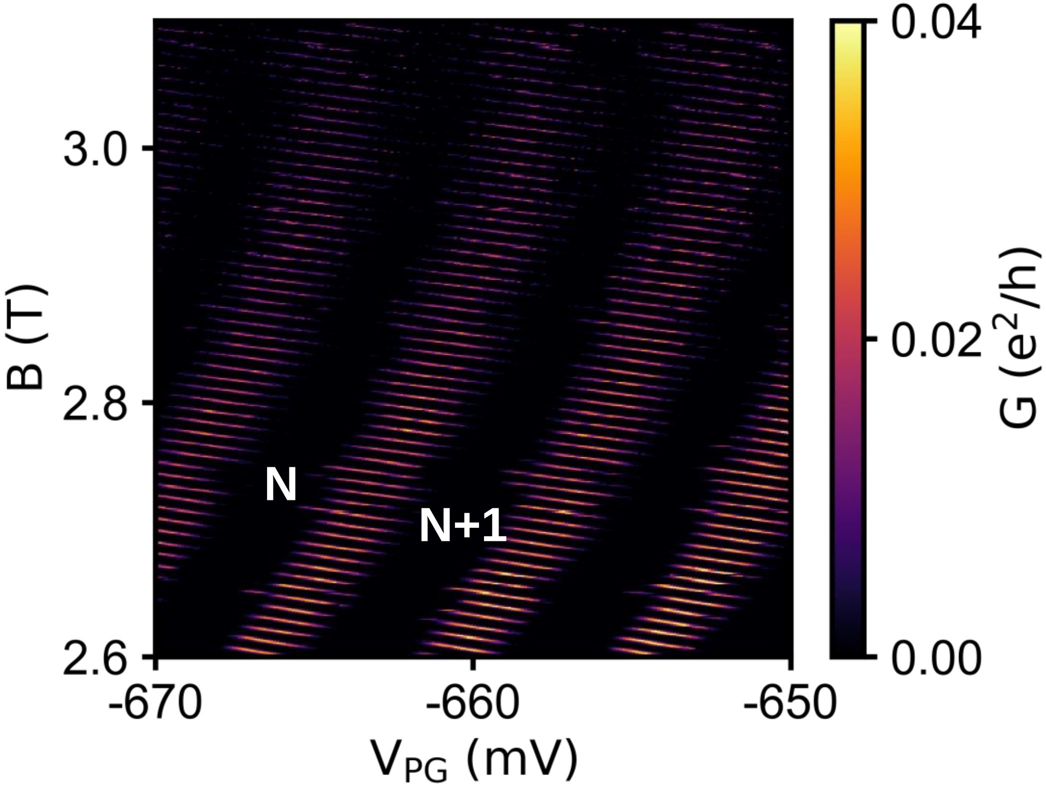

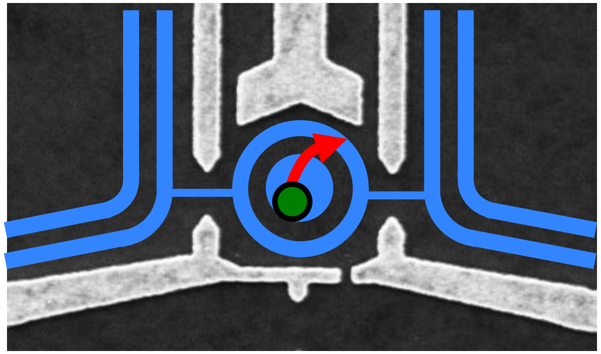

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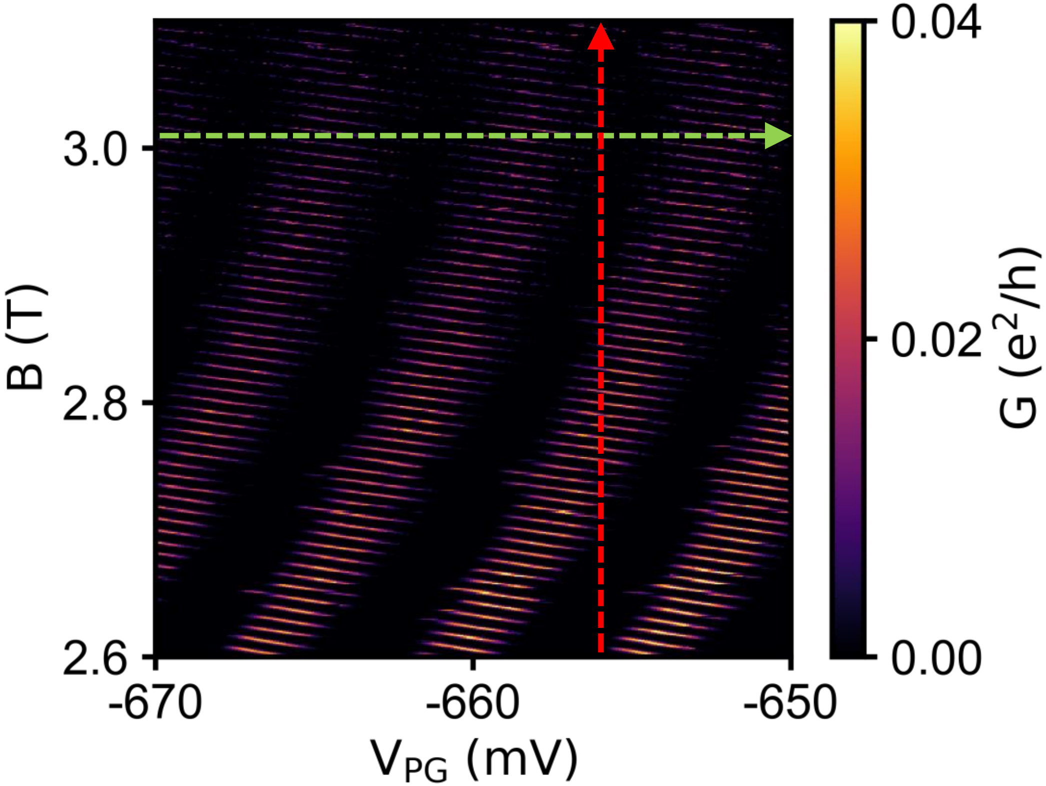

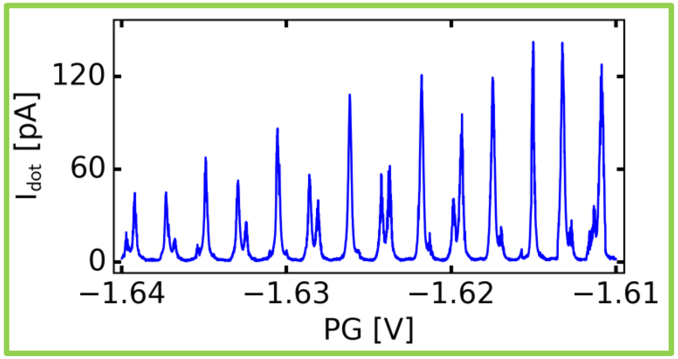

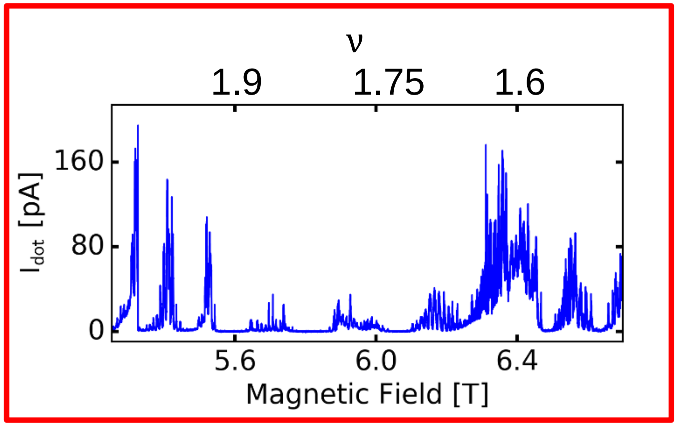

Tunneling between Landau levels over a large regime

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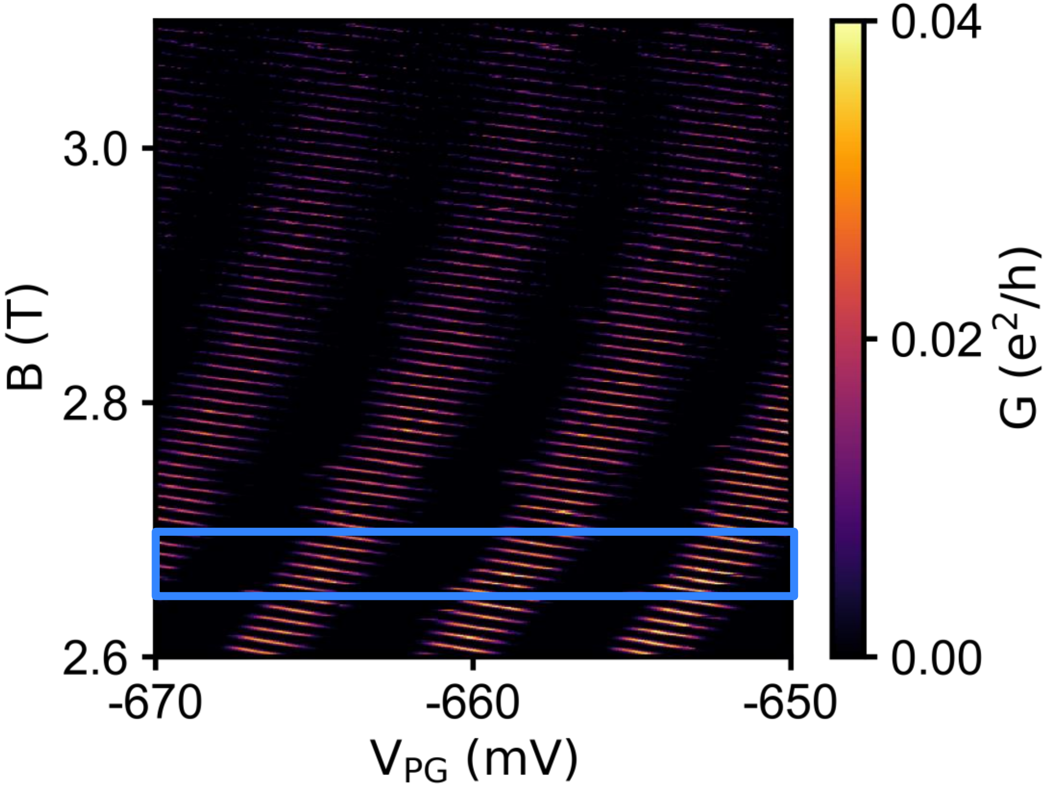
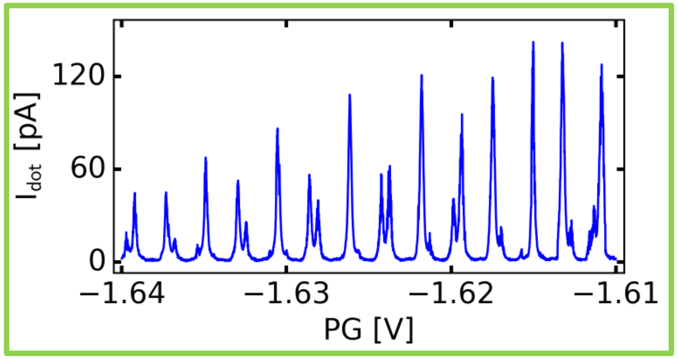
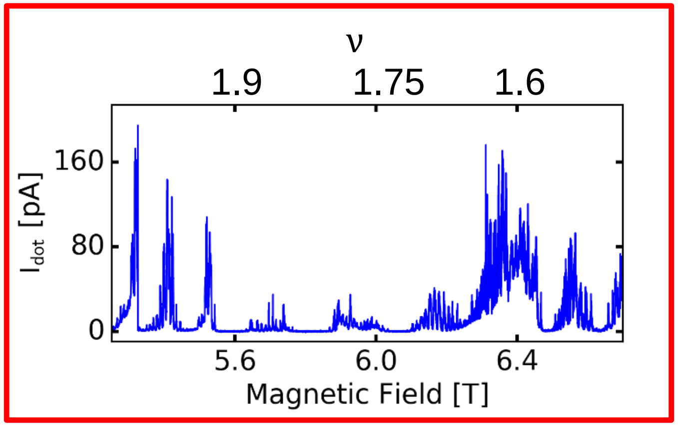
Magnetic field vs plunger gate

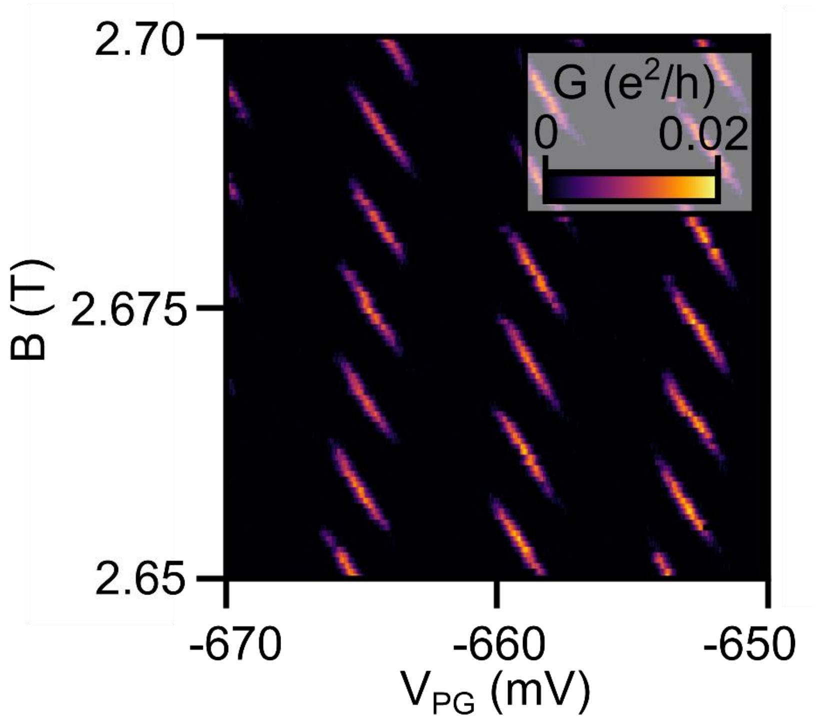




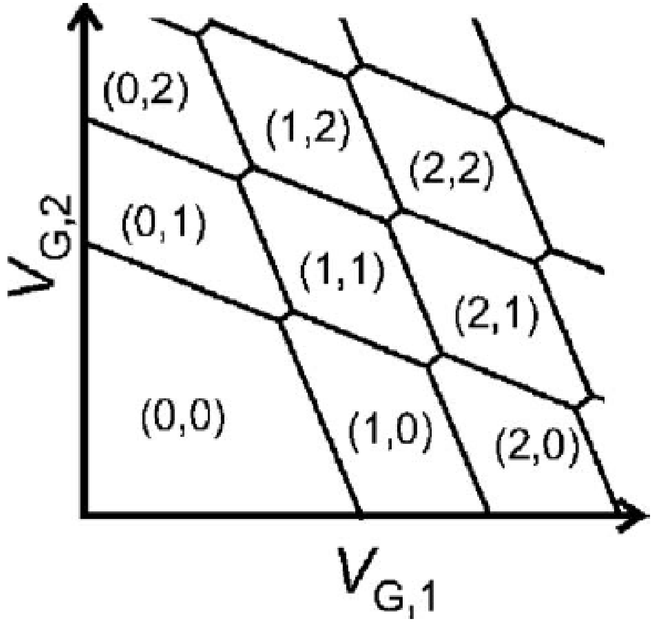


➡ Tunneling between Landau levels over a large regime

Charge stability diagram

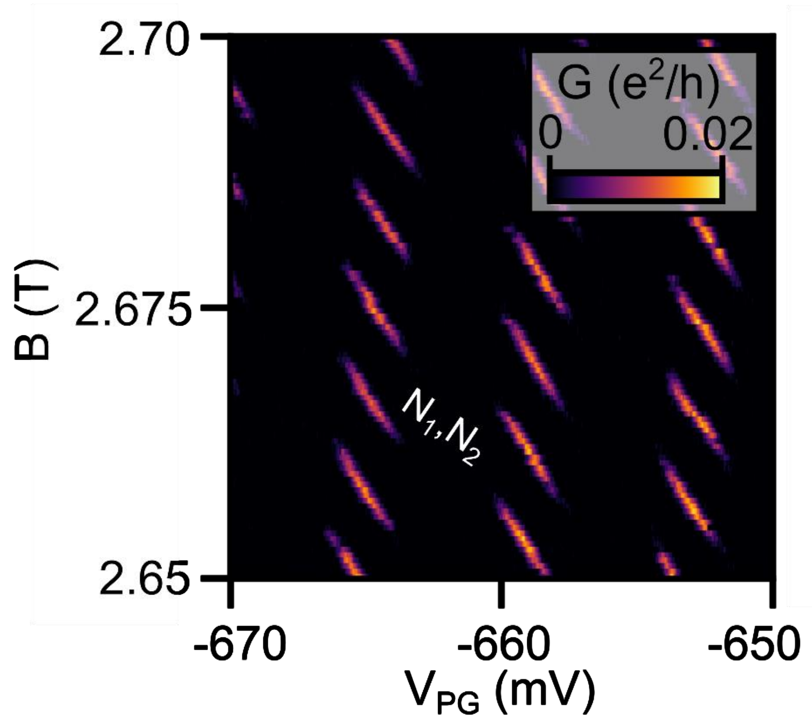


Standard
double quantum dot

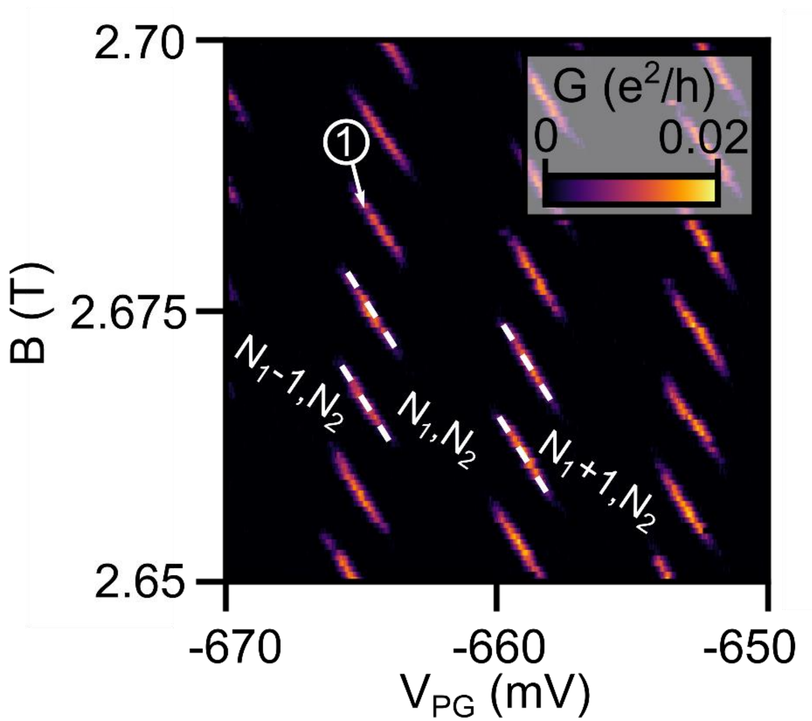


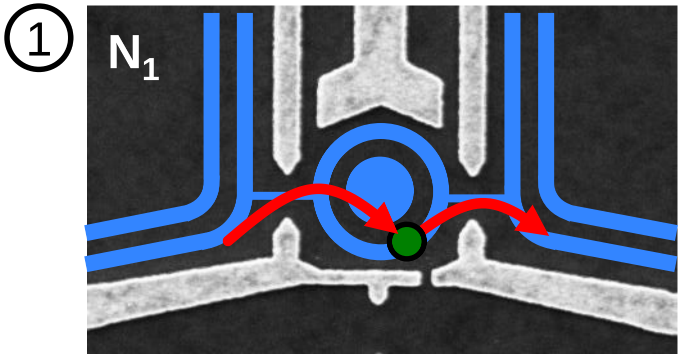
R. Hanson et al., Rev. Mod. Phys. ***79****, 1217 (2007)*

Charge stability diagram

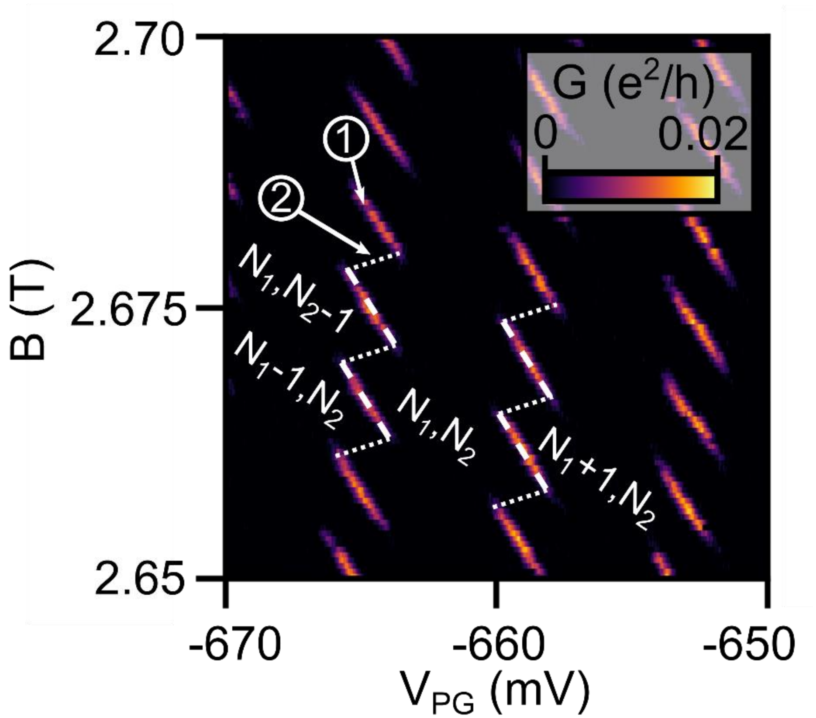


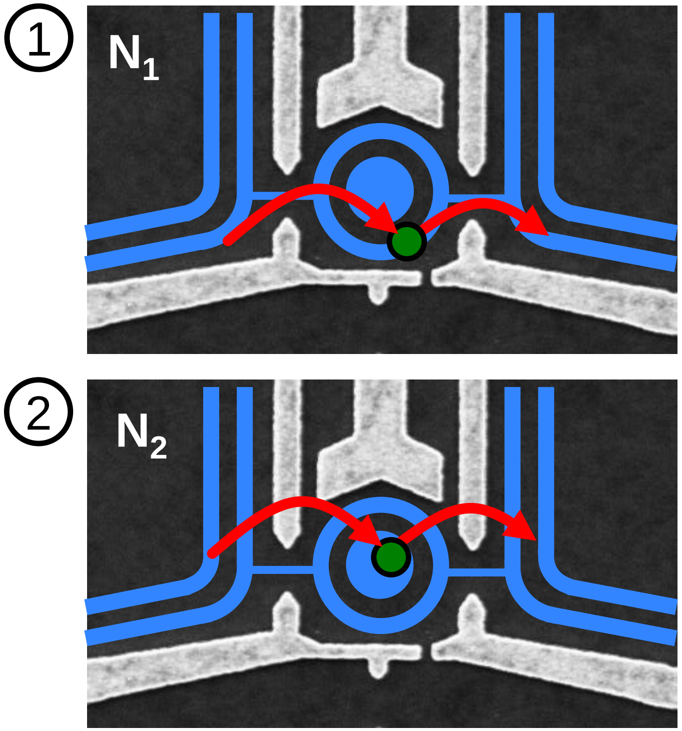
Charge stability diagram





Charge stability diagram





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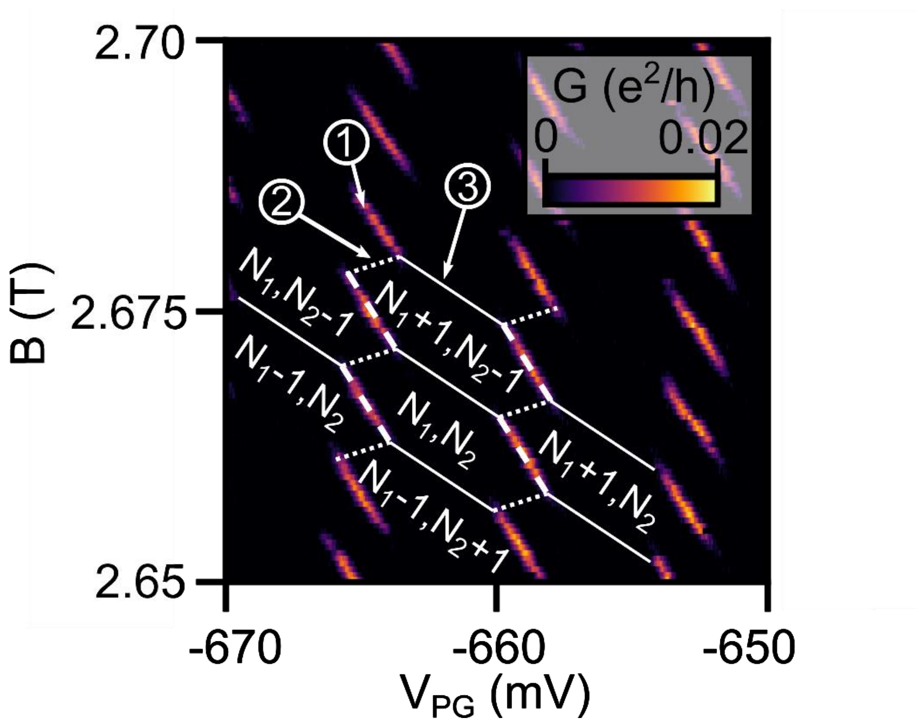
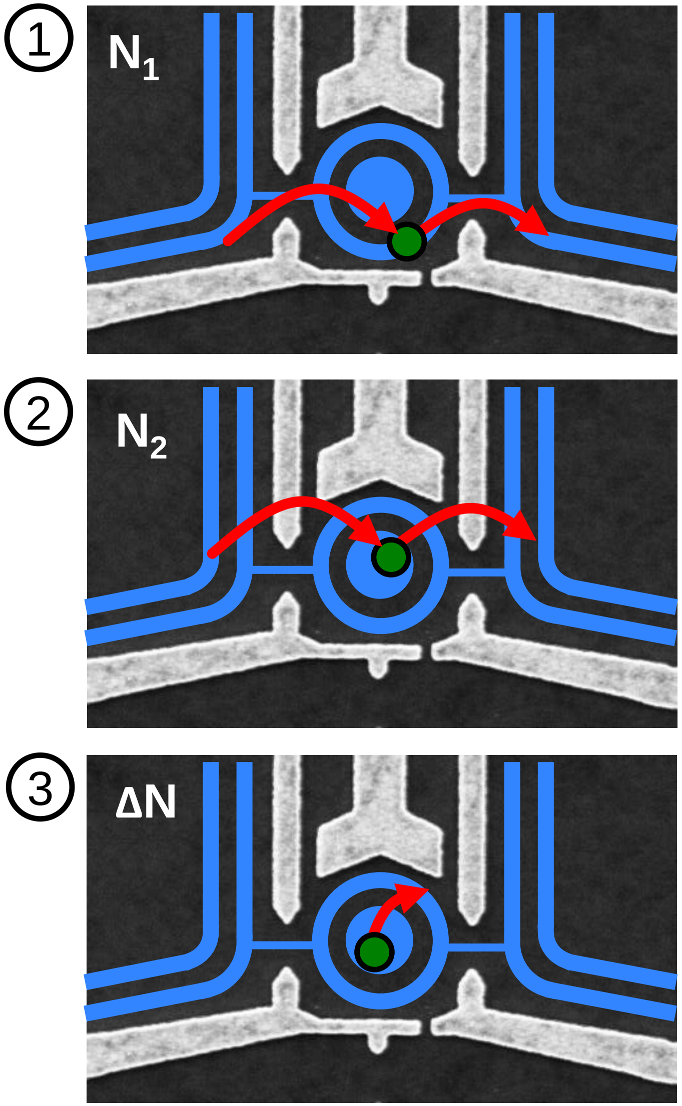
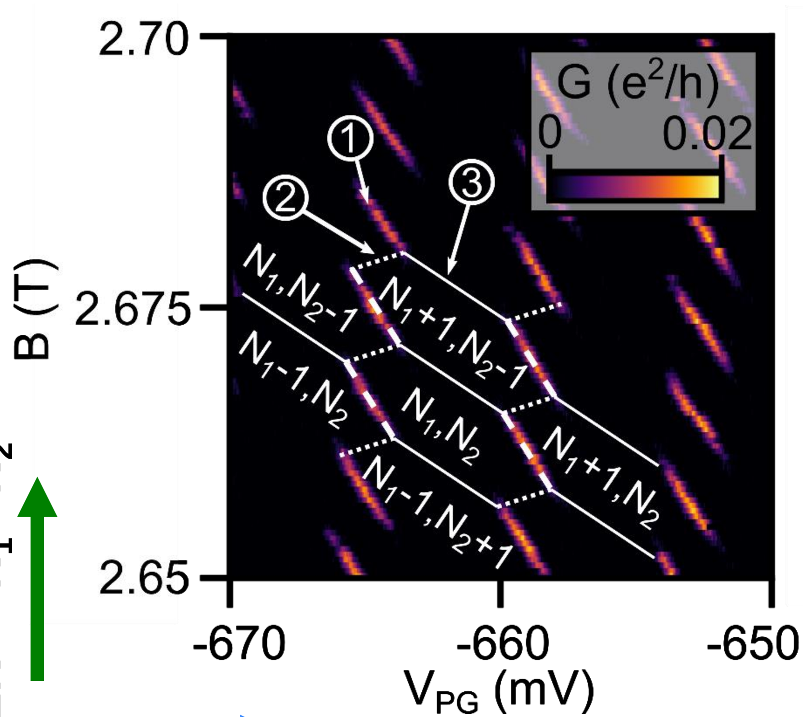
Charge stability diagram





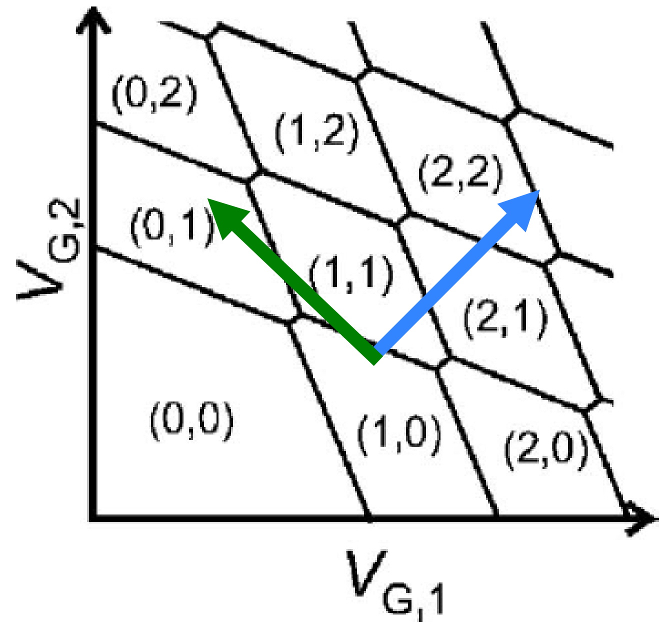
Charge stability diagram



$\Delta N = N_1 - N_2$

$N_{tot} = N_1 + N_2$

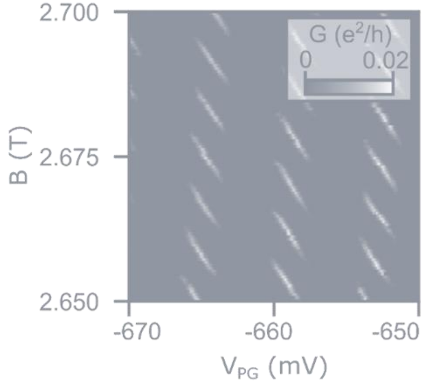
Standard
double quantum dot



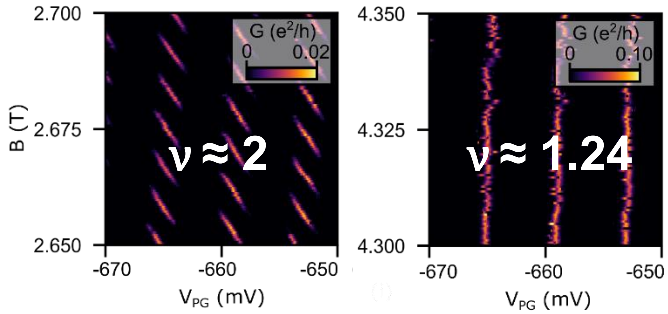
*R. Hanson et al., Rev. Mod. Phys. **79**, 1217 (2007)*

Overview

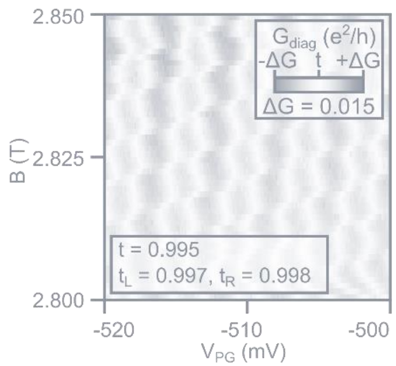
Gate voltage and magnetic field dependence



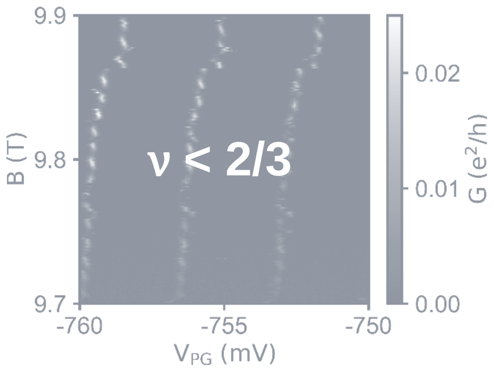
Evolution for different filling factor ν = 2 to ν = 1



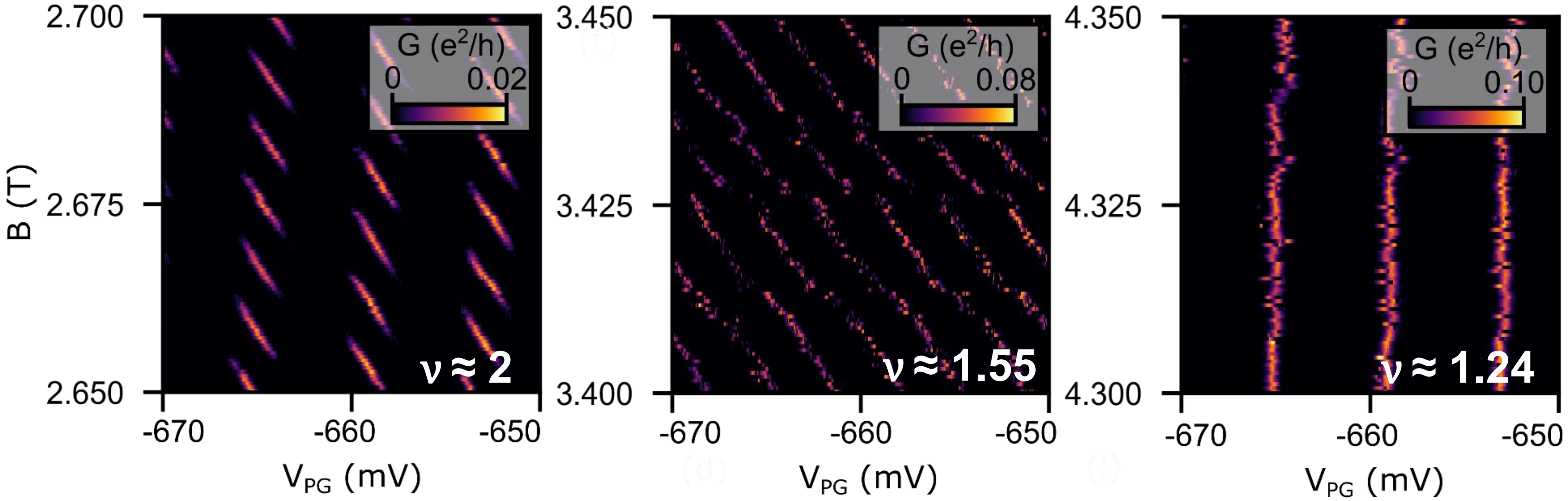
Interferometer: open QD barriers



QD in fractional QH regime

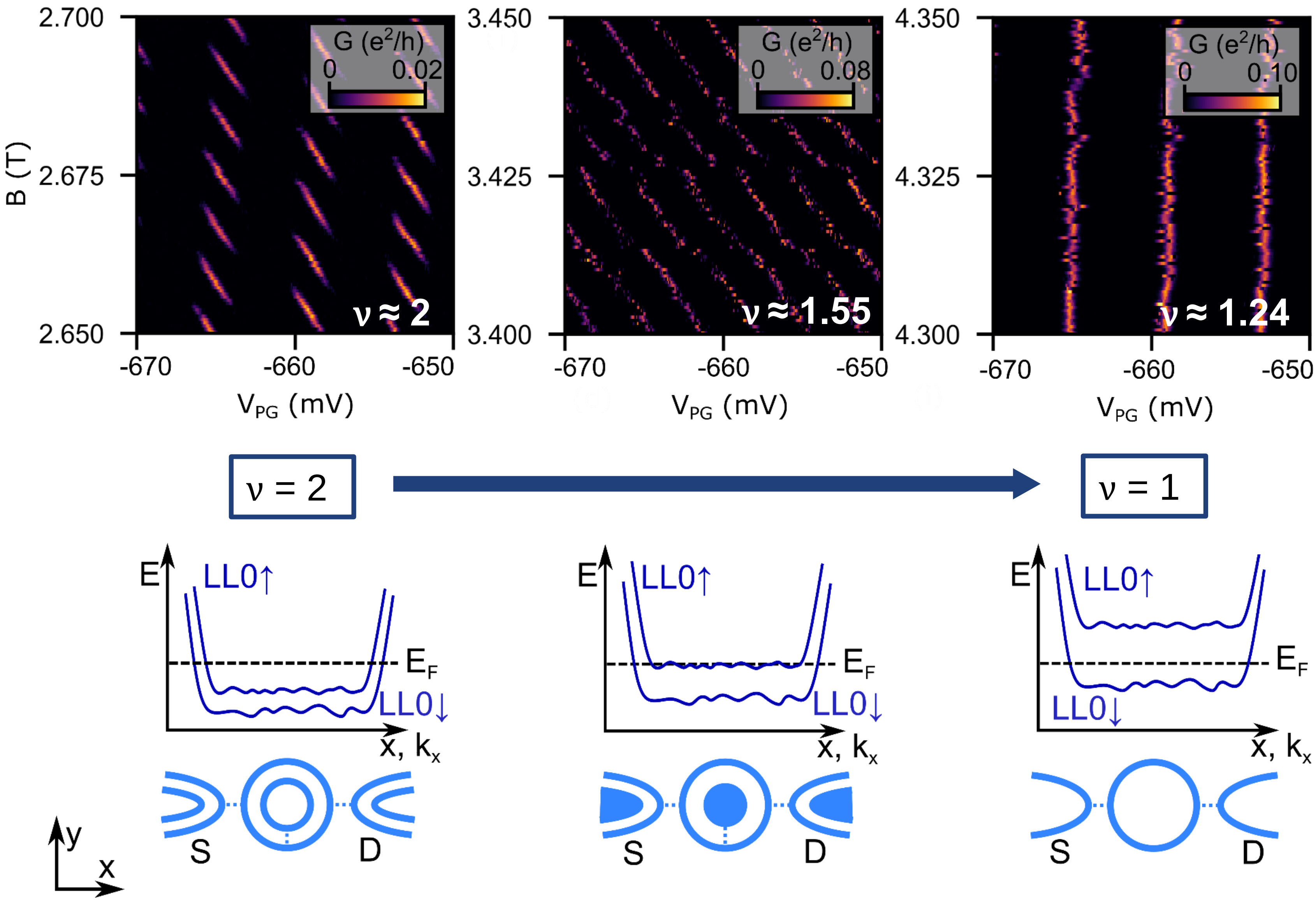


Evolution from ν = 2 to ν = 1

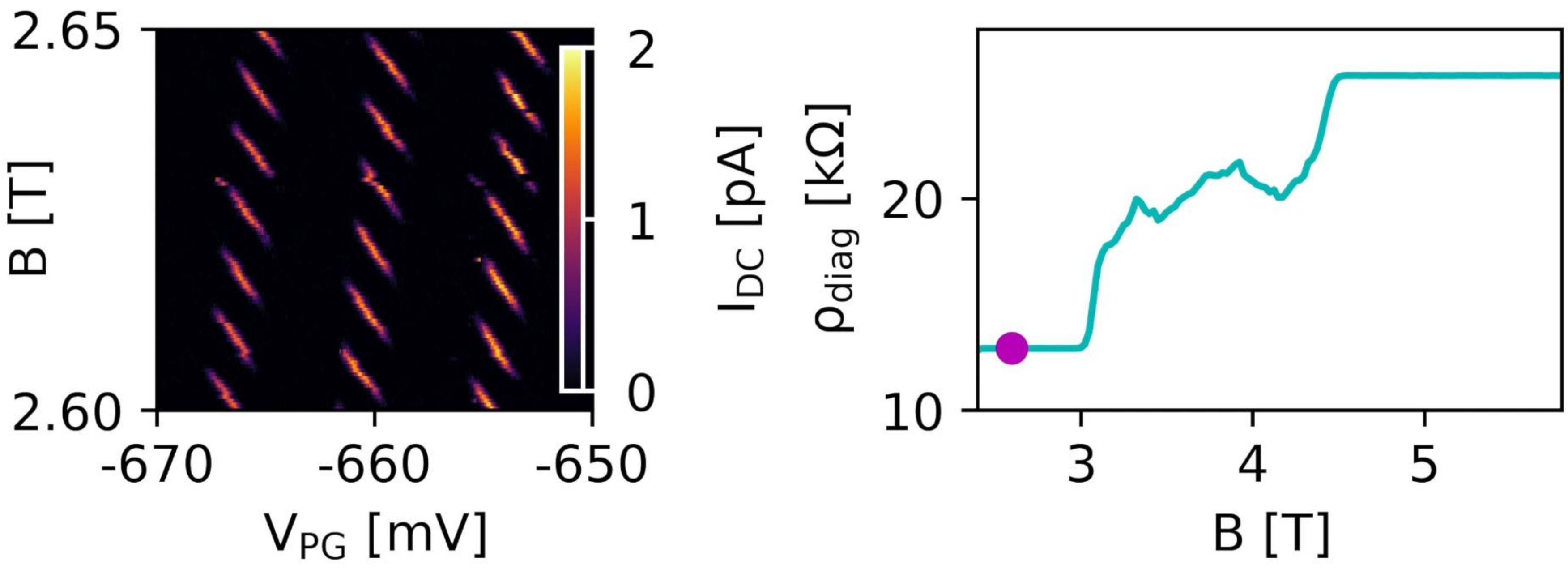


ν = 2 → ν = 1

Evolution from ν = 2 to ν = 1

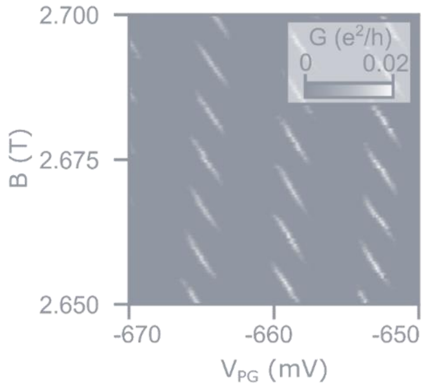


Evolution from ν = 2 to ν = 1

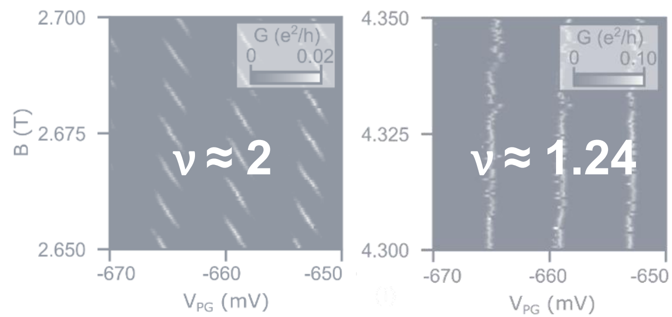


Overview

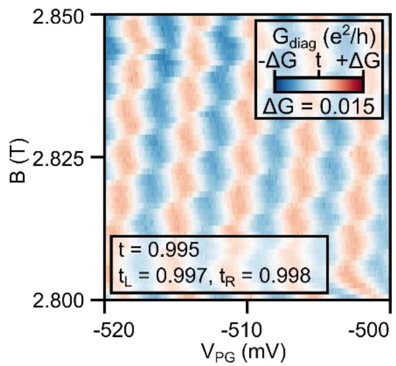
Gate voltage and magnetic field dependence



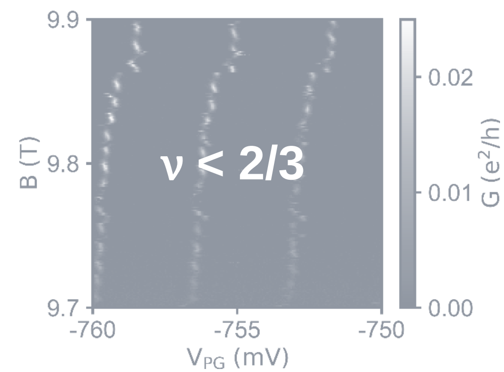
Evolution for different filling factor ν = 2 to ν = 1



Interferometer: open QD barriers

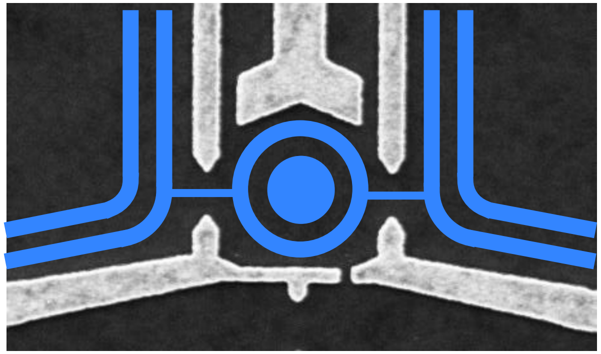


QD in fractional QH regime

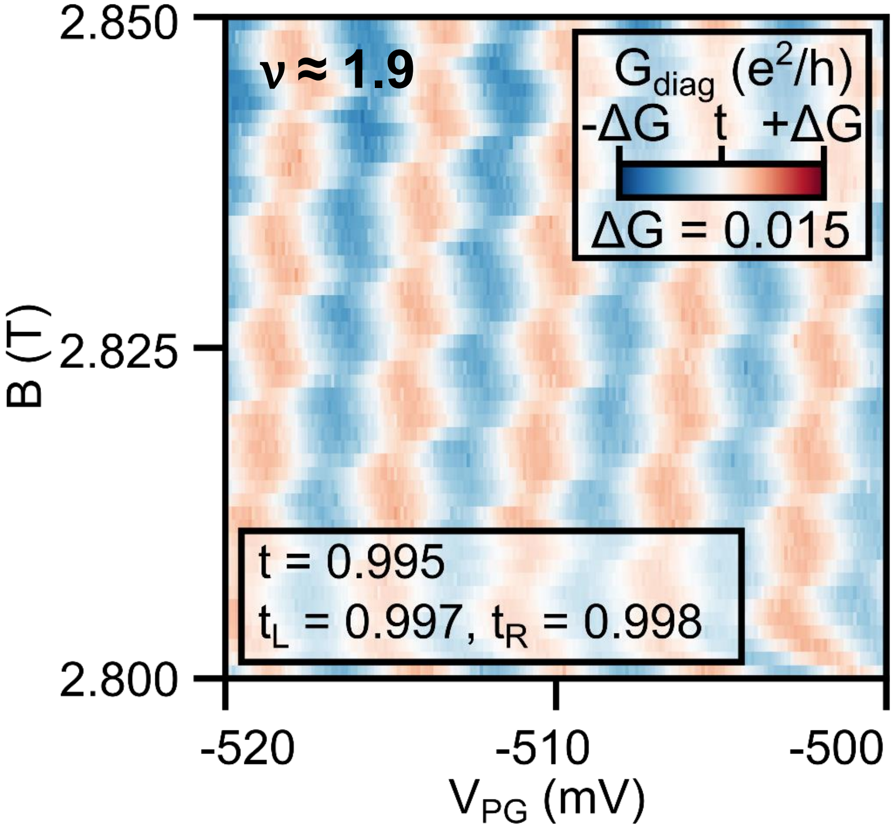


Quantum dot as an interferometer

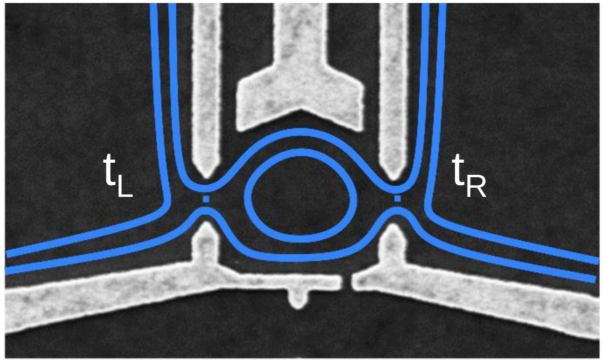
$\nu_{bulk} = 2, \nu_{QPC} \approx 0$



Quantum dot as an interferometer



$\nu_{bulk} = 2$, $\nu_{QPC} \approx 1$

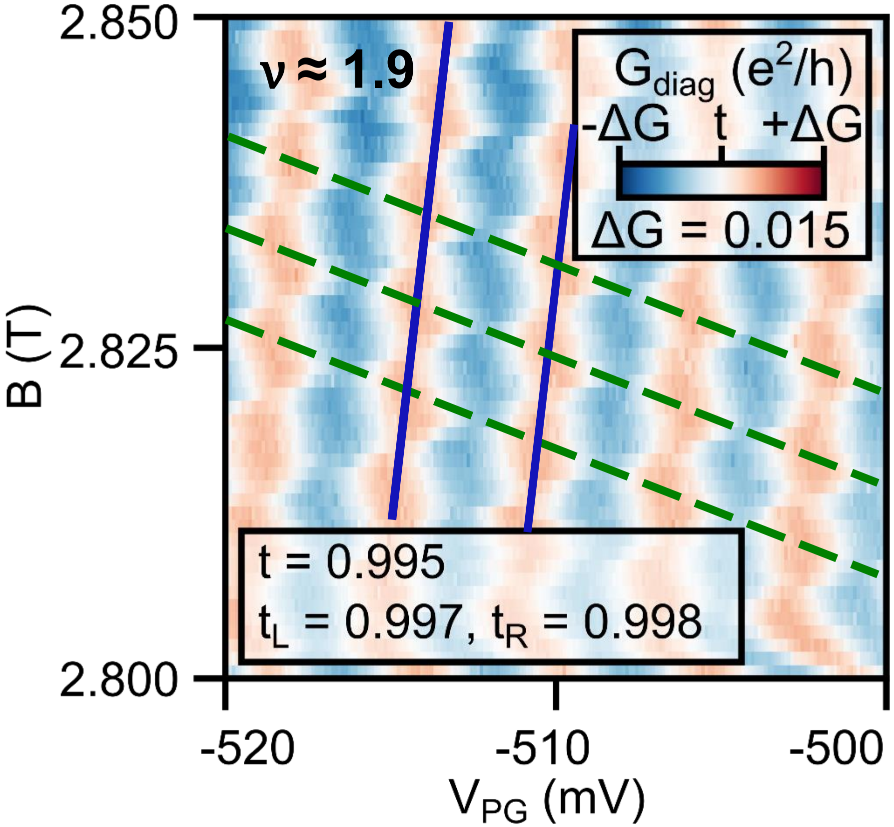


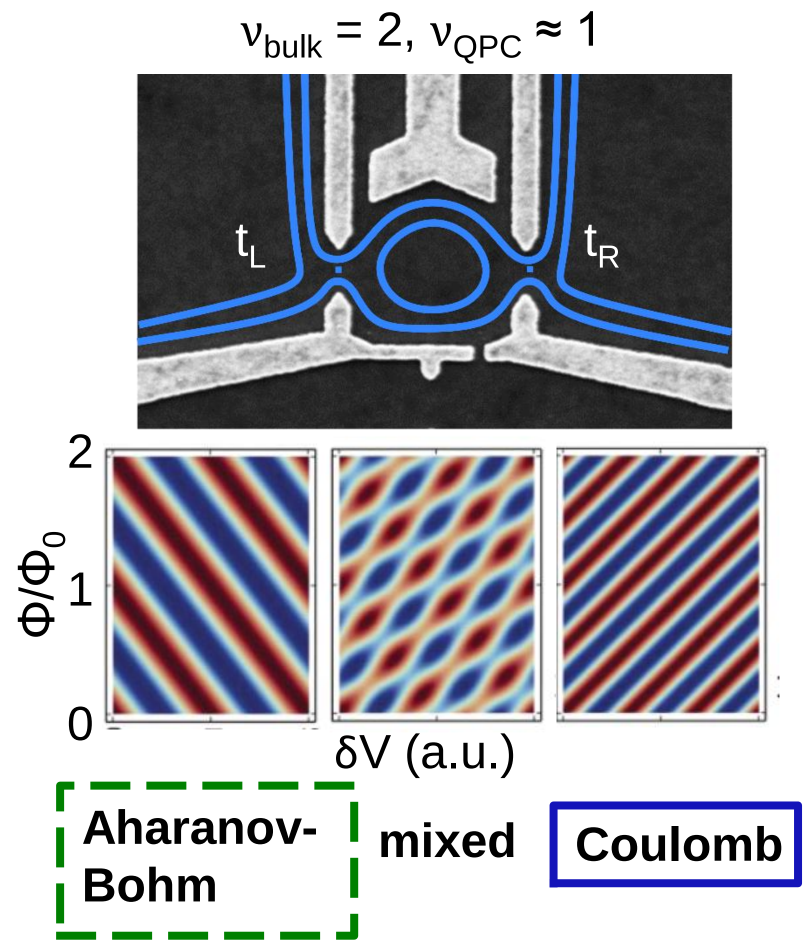
Expected classical transmission t through interferometer:

$$t = \frac{t_L t_R}{1 - (1 - t_L)(1 - t_R)}$$

➡ Interference pattern around classically expected transmission

Quantum dot as an interferometer

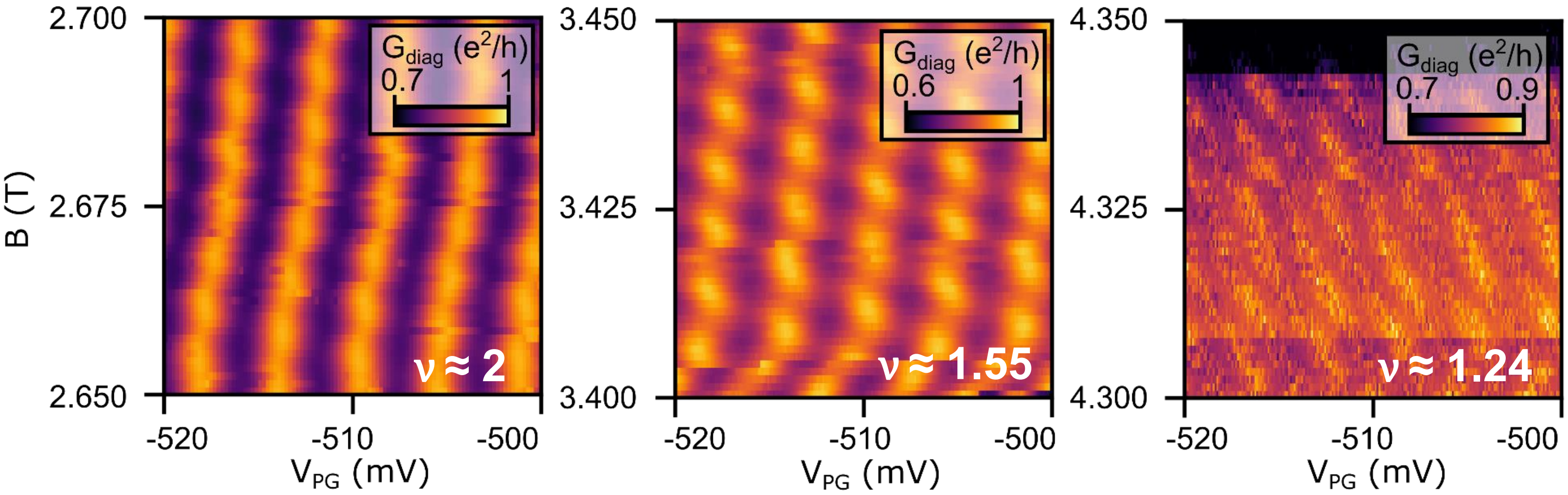


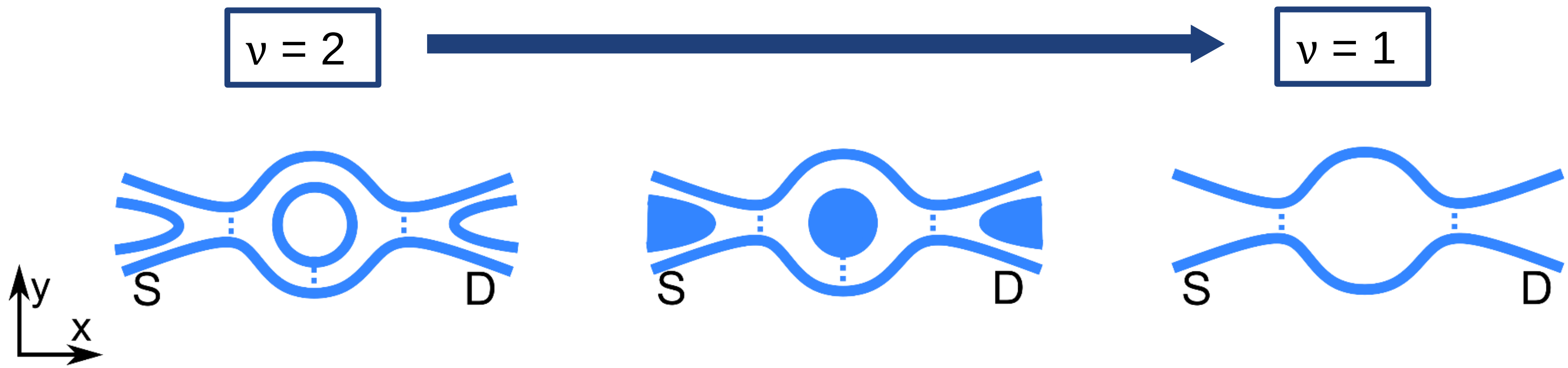


➡ Aharanov-Bohm interference mixed with Coulomb effects

Adapted from B. I. Halperin et al., Phys. Rev. B 83, 155440 (2011)

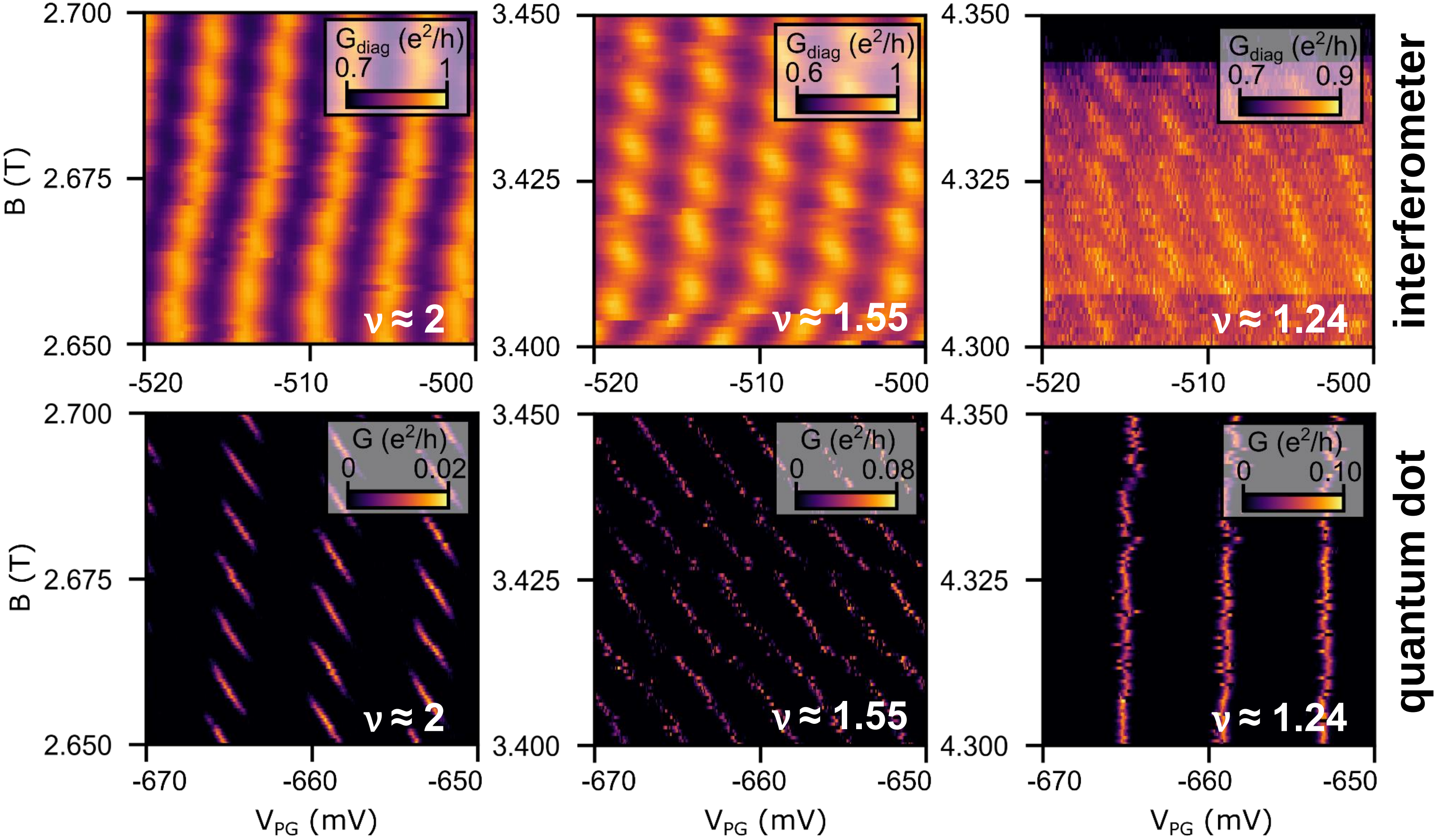
Interferometry: from ν = 2 to ν = 1





Charging of the inner QD changes interference

Interferometry: comparison to QD



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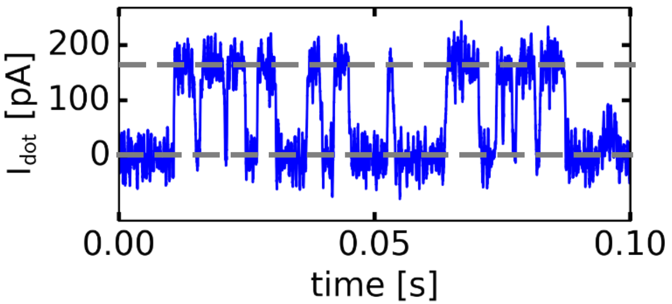
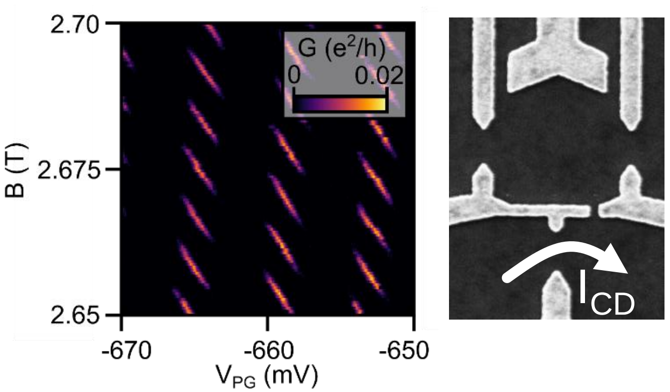
Integer Landau level tunneling - some remarks

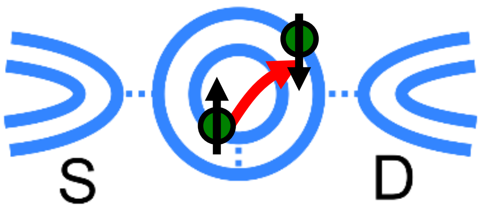
- **Time-resolved Landau level tunneling**
  → counting statistics



- **Additional charge detector:**
  → different charging lines in CSD

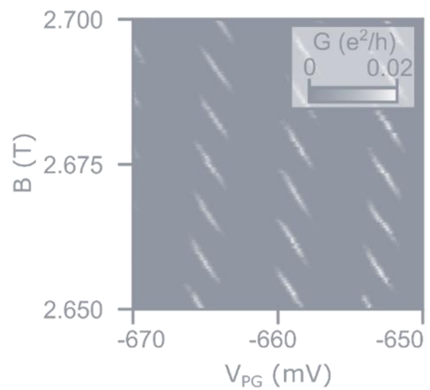


- **Influence of Spin ?**
  → each tunneling event flips spin

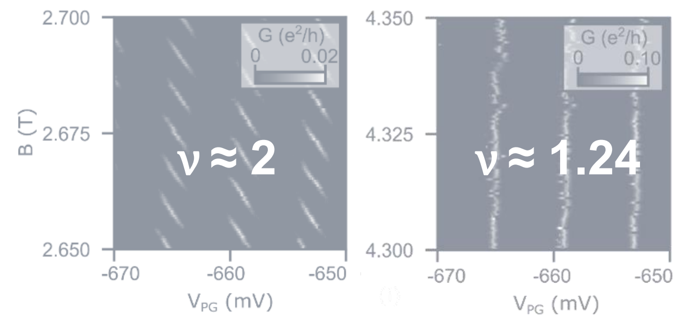


Overview

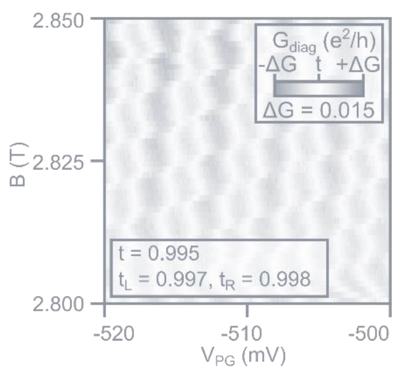
Gate voltage and magnetic field dependence



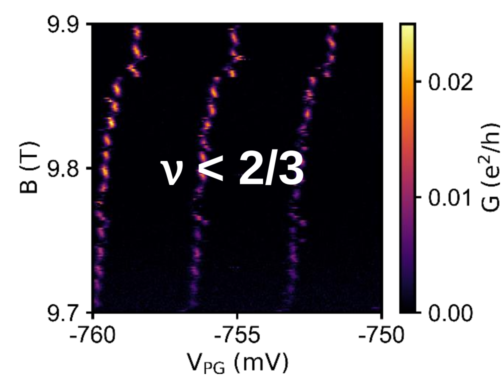
Evolution for different filling factor ν = 2 to ν = 1



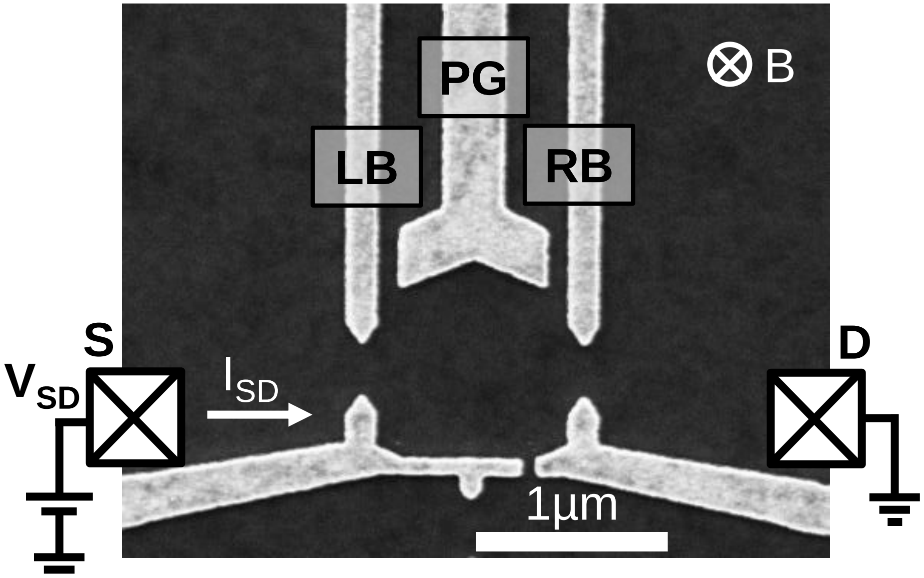
Interferometer: open QD barriers

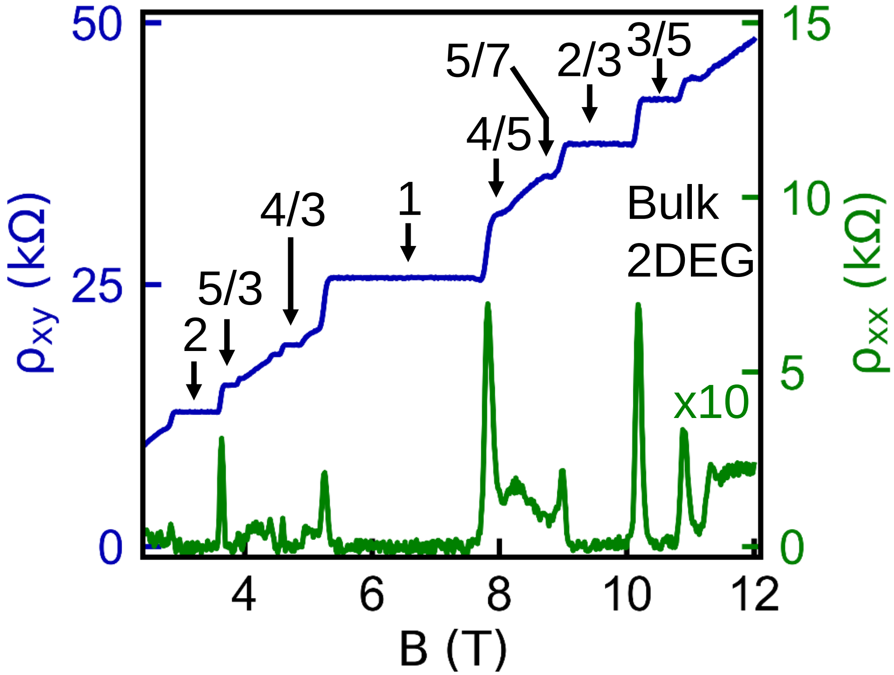


QD in fractional QH regime



Quantum dot in the fractional QH regime





$n = 1.3 \times 10^{11}\ \mathrm{cm}^{-2}$

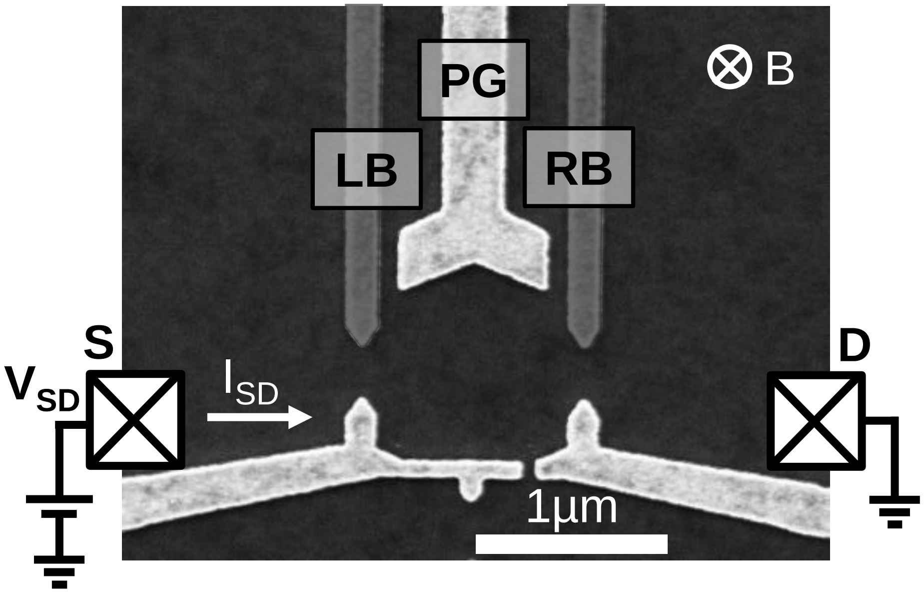
$\mu = 5.3 \times 10^{6}\ \mathrm{cm}^{2}/(\mathrm{Vs})$

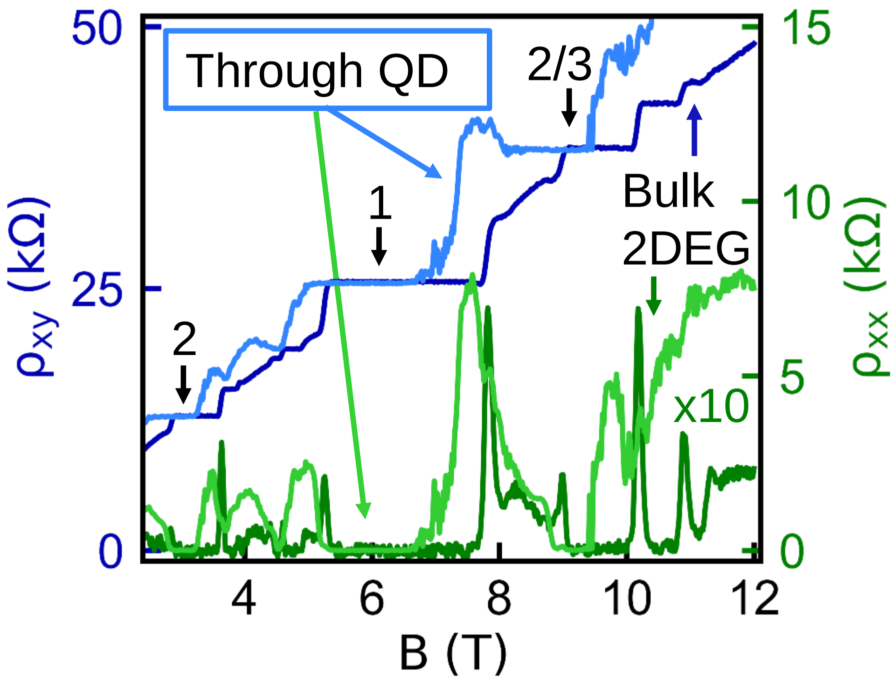
2DEG depth: 120 nm

$T_e \approx 25$ mK

➡ Fractional QH states $\nu < 1$ exist and are reachable

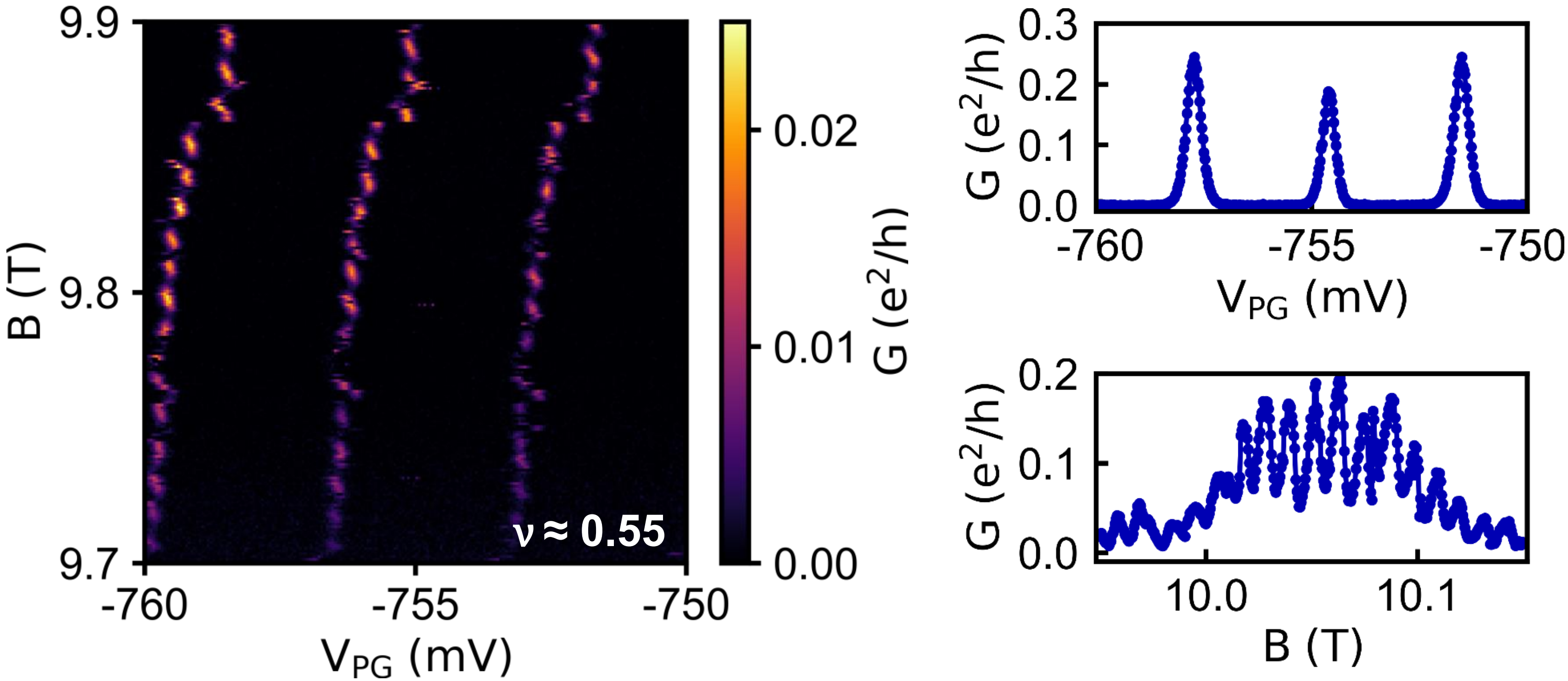
Quantum dot in the fractional QH regime





➡ 2/3 fractional QH states exist in the QD

Modulated Coulomb peaks for ν < 2/3

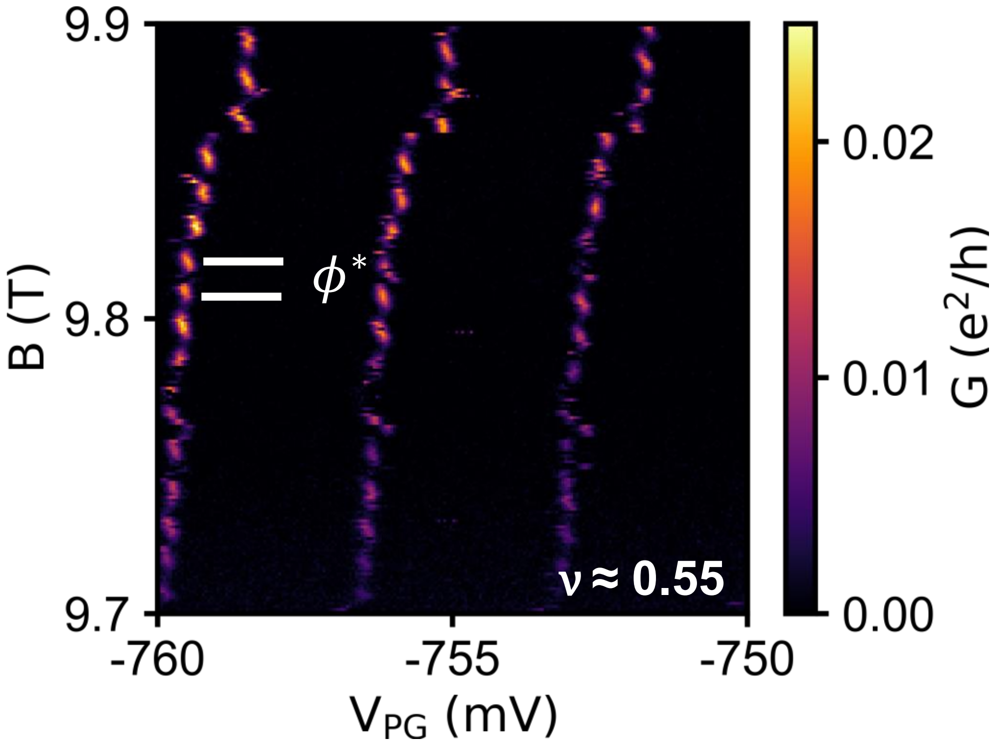


- Coulomb peaks modulated similarly to integer QH regime

- No split Coulomb peaks in V_{PG}
- Sawtooth pattern in B

➡ Non-trivial fractional QH state in the quantum dot

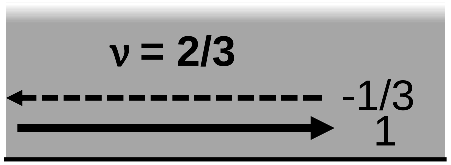
Fractional quasi-particle charge?



ΔB ≈ 11.8 mT
A = 0.36 μm^2 (a = 600nm)

$$\frac{e^*}{e} = \frac{\phi_0}{\phi^*} = \frac{h/e}{h/e^*} = \frac{h/e}{\Delta B\ A} = \mathbf{0.97}$$

- Consistent with MacDonald edge state picture:



- Previous results:

*A. H. MacDonald, Phys. Rev. Lett. **64**, 220 (1990)*
*J. Nakamura et al., Nature Physics **15**, 563 (2019)*
*A. Bid et al., Phys. Rev. Lett. **103**, 236802 (2009)*

➡ Magnetic field period suggests electron charge

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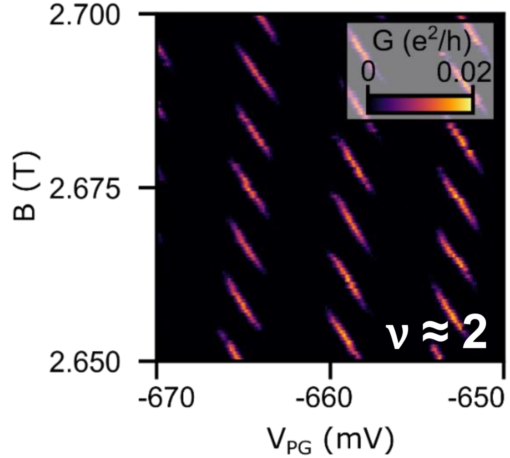
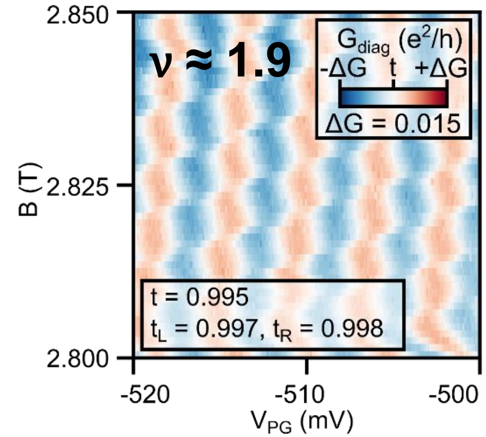
Conclusion / Outlook

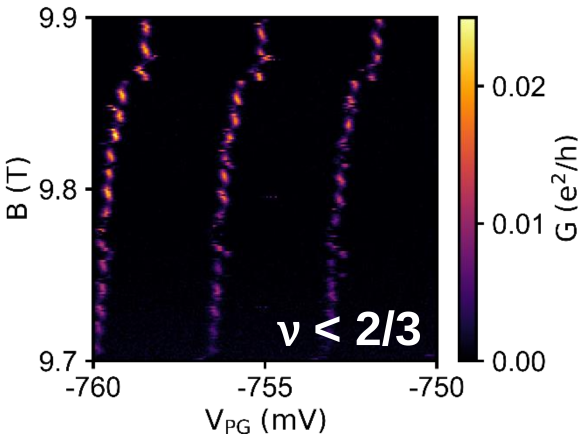
Marc P. Röösli, marcro@phys.ethz.ch

Tunneling between Landau levels in the integer QH regime

- Evolution for different regimes
- Transition to interferometer







First observation of modulated Coulomb blockade in the fractional QH regime

➡ Better understanding of fractional effect