Optical Detection of Quantum Dot Single-Electron Tunneling

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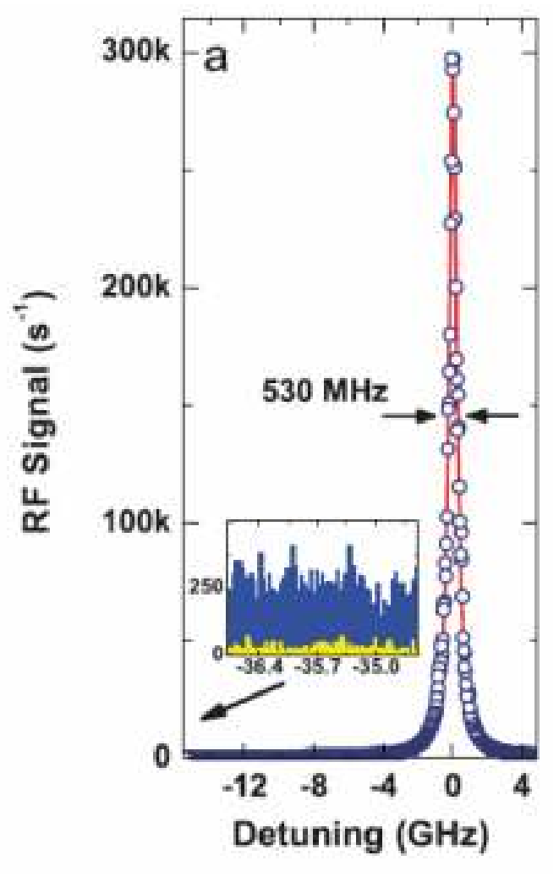
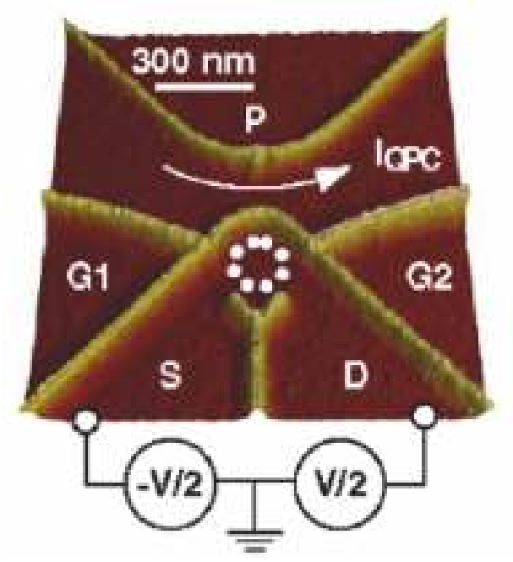
1. Motivation

Optical measurements
- Resonance fluorescence (RF) of a single quantum dot (QD)

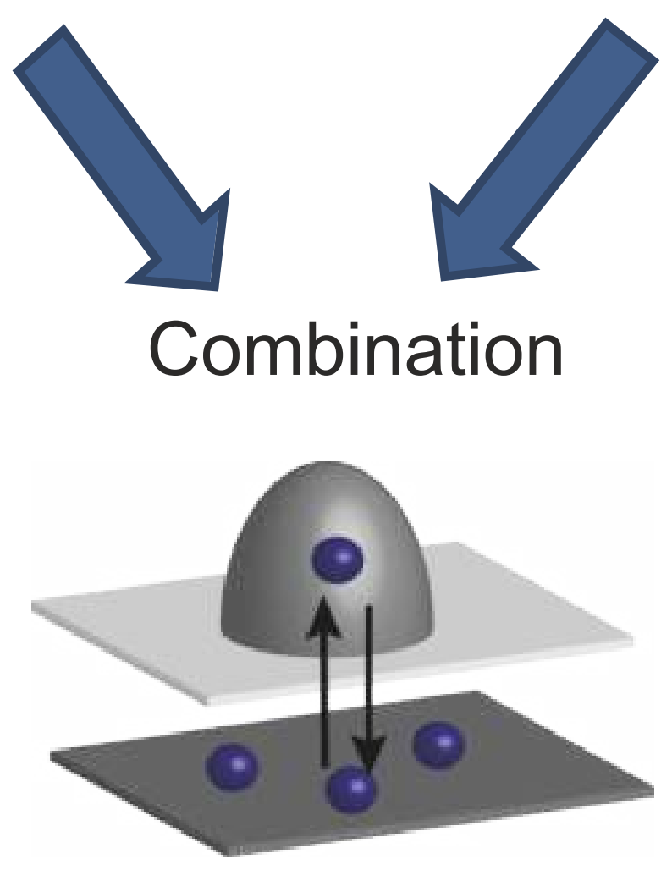


[1]

Transport measurements
- Characterization of tunneling processes in a single QD
- Full counting statistics (FCS)



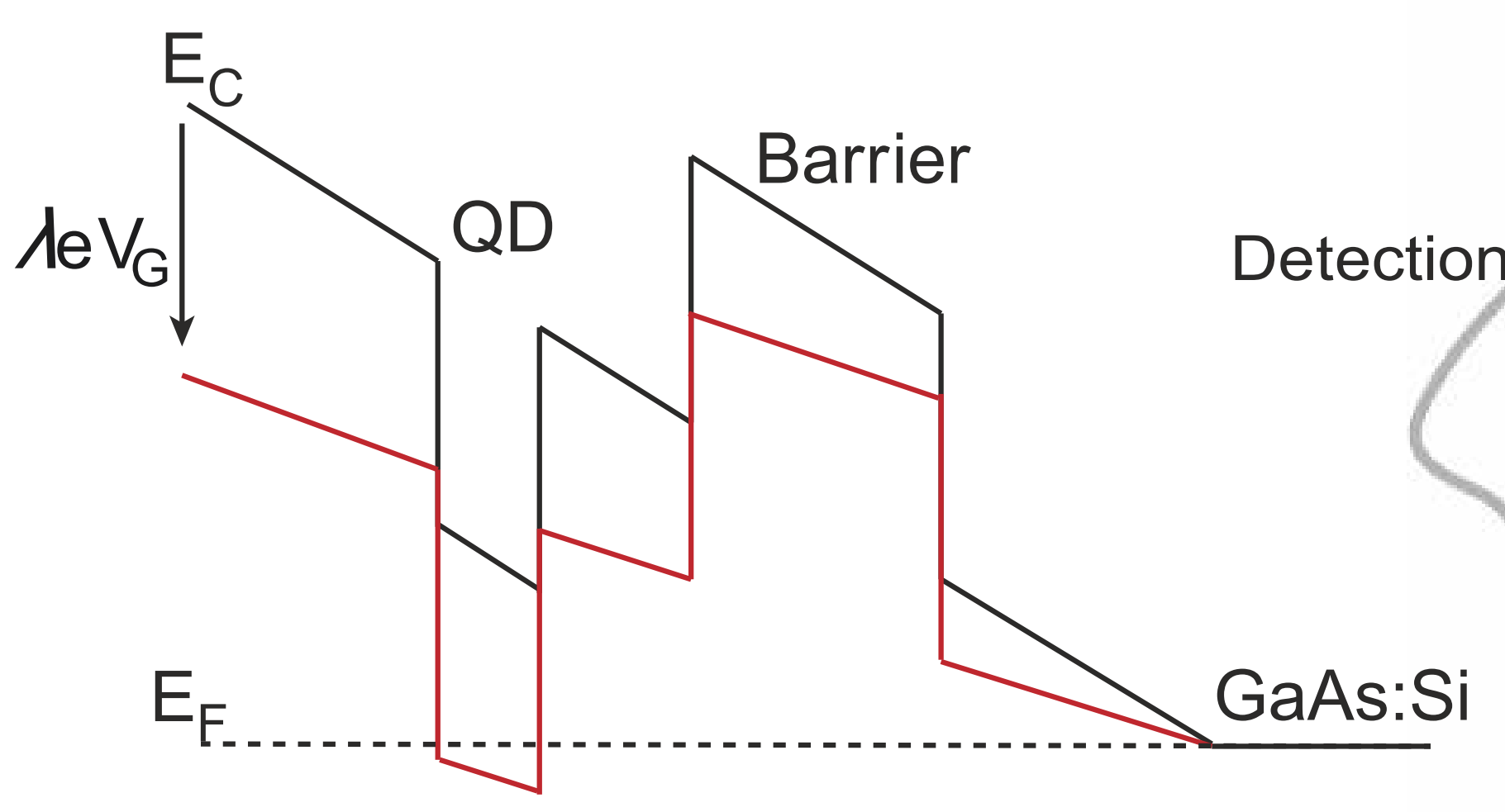
[2]



Is it possible to observe every tunneling event into a single self-assembled QD?
- Correlation and interaction in full counting statistics (FCS) with factorial cumulants [3]

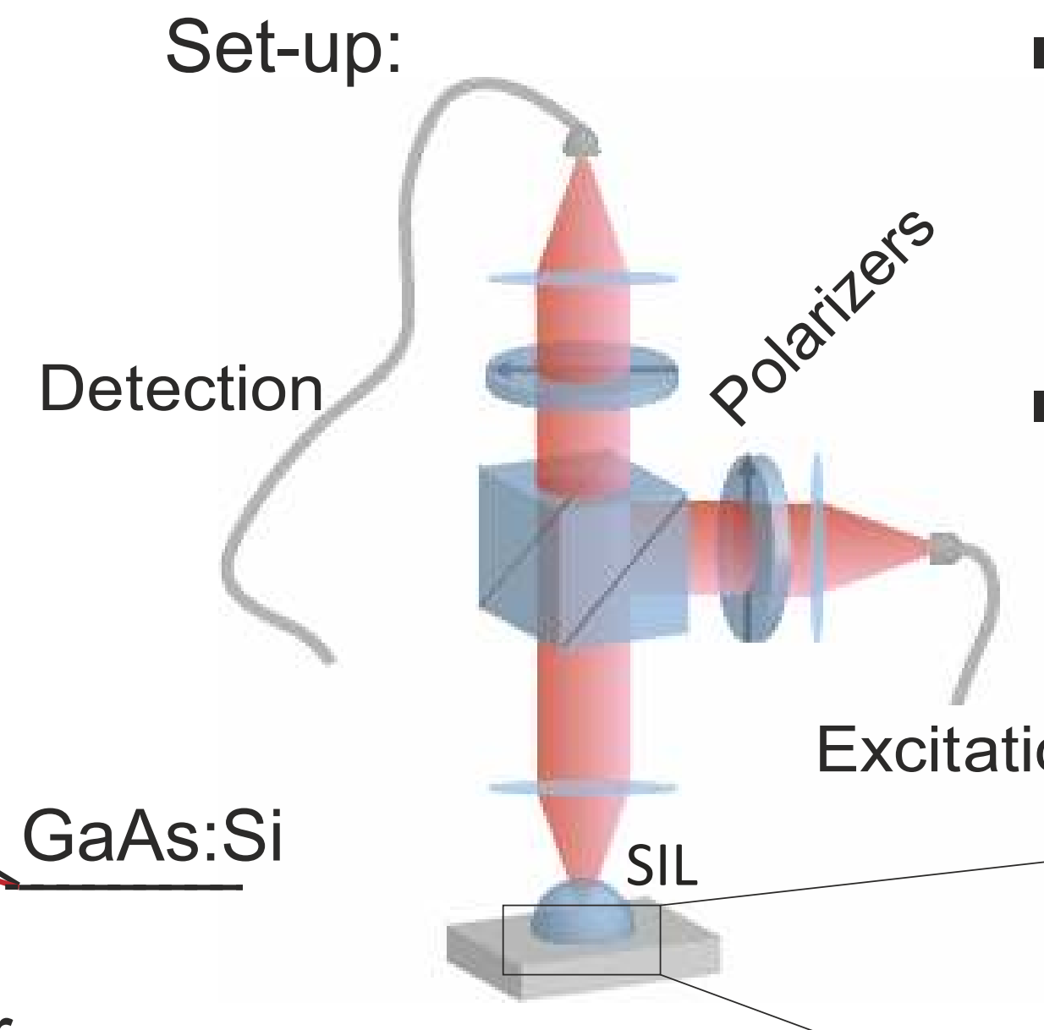
2. Sample and set-up

Conduction band structure

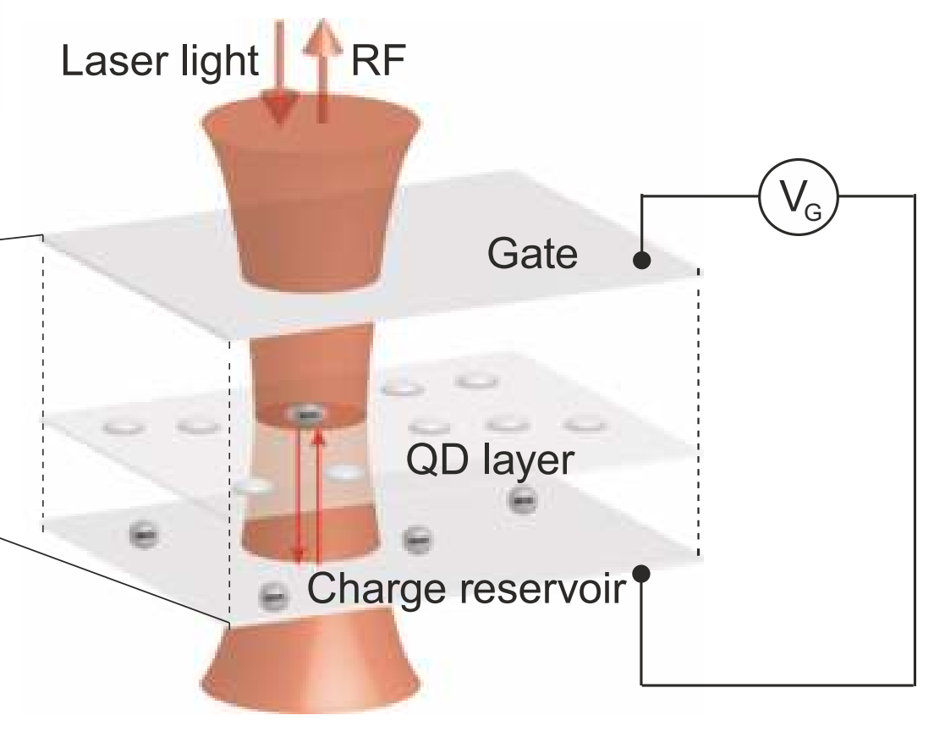


- Si-doped GaAs as charge reservoir
- 45 nm AlGaAs/GaAs tunneling barrier
- QD can be charged with single charge resolution

Set-up:

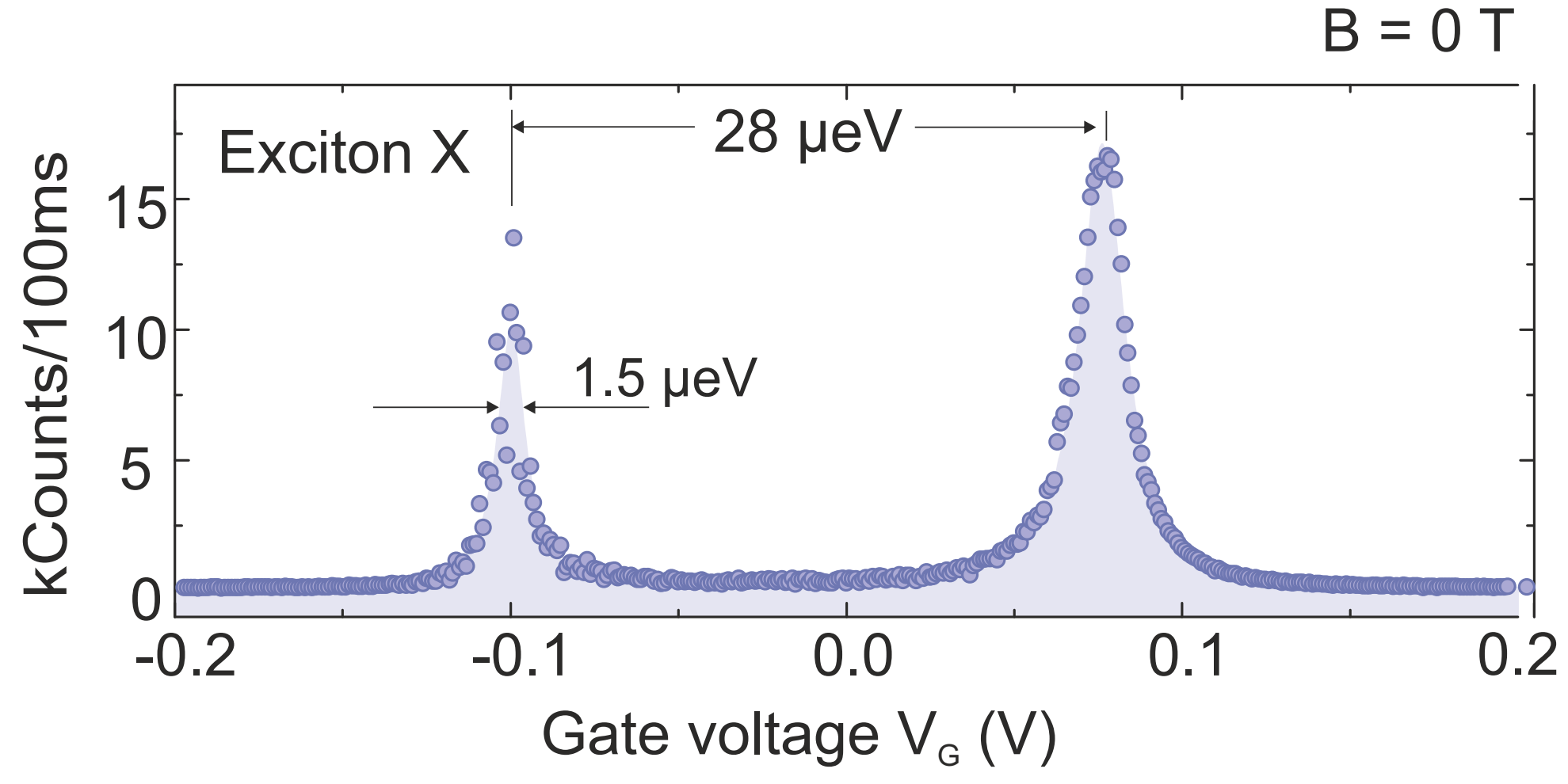


- Resonance fluorescence set-up with linear polarizers to separate laser excitation and QD emission
- 10^7 laser background suppression

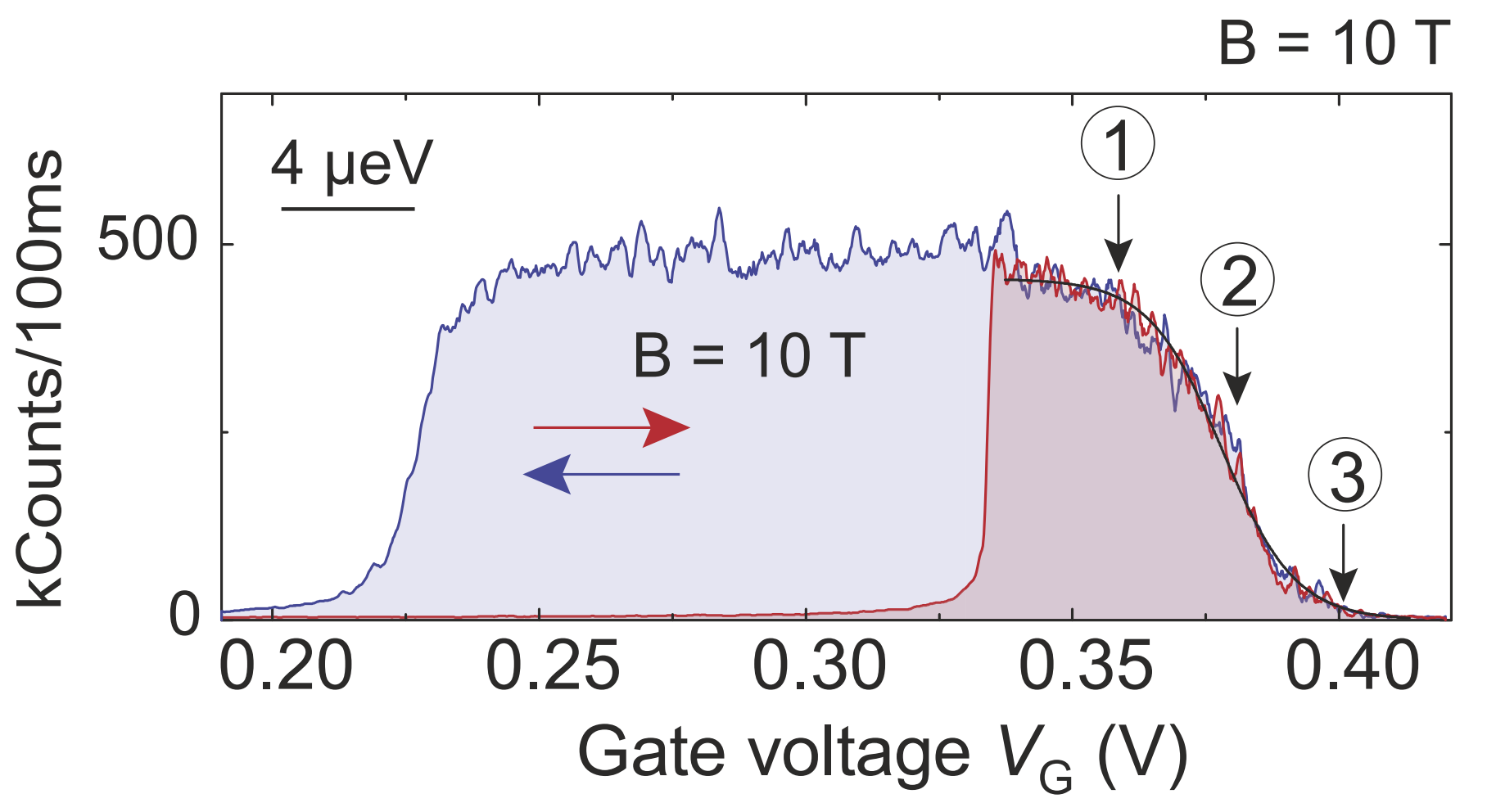


3. Quantum jumps of single electron tunneling

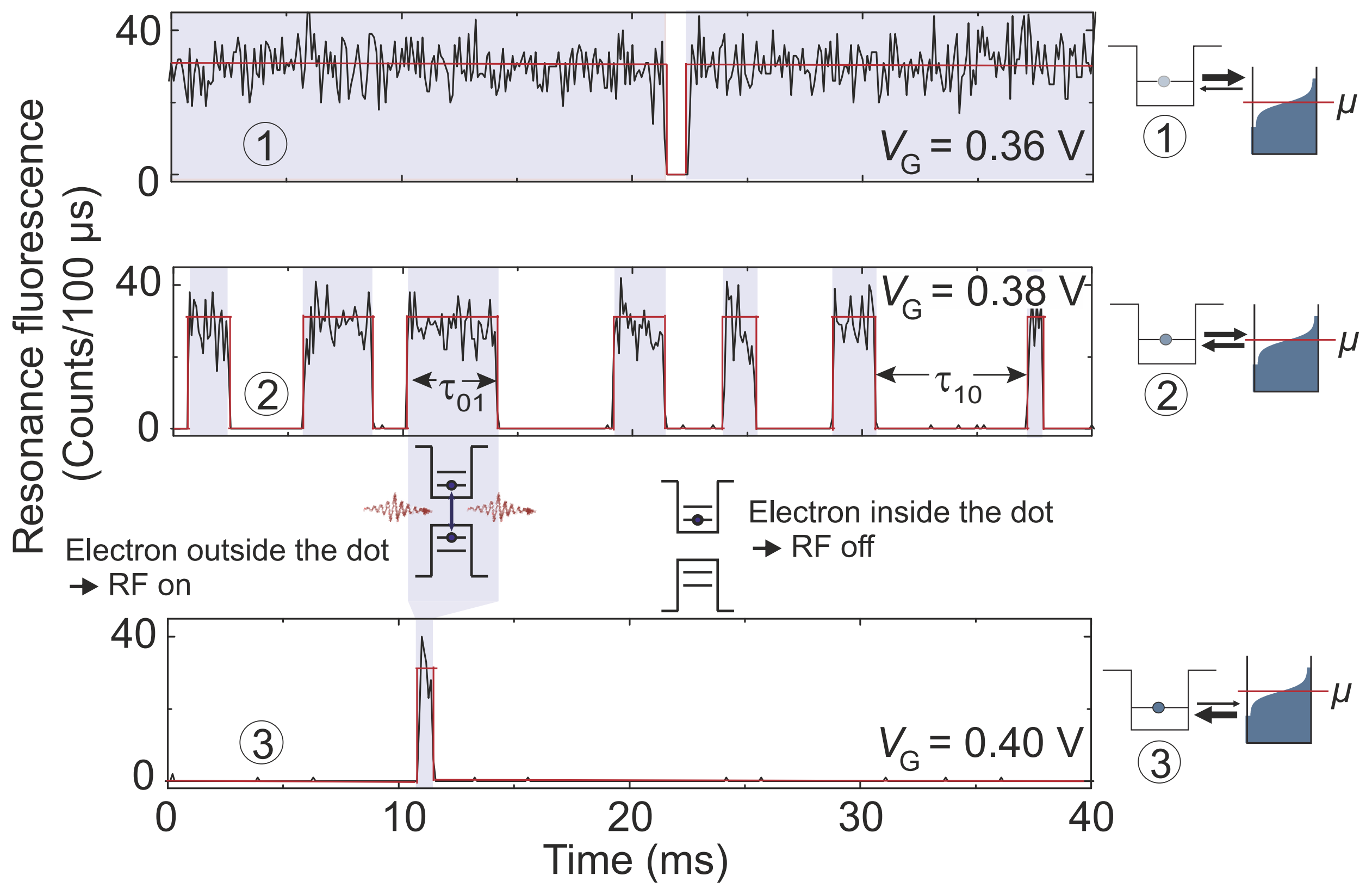
- Resonance fluorescence of the fine-structure splitted exciton



- Nuclear spin polarization in an magnetic field
- Stabilization of the resonant excitation on the exciton transition



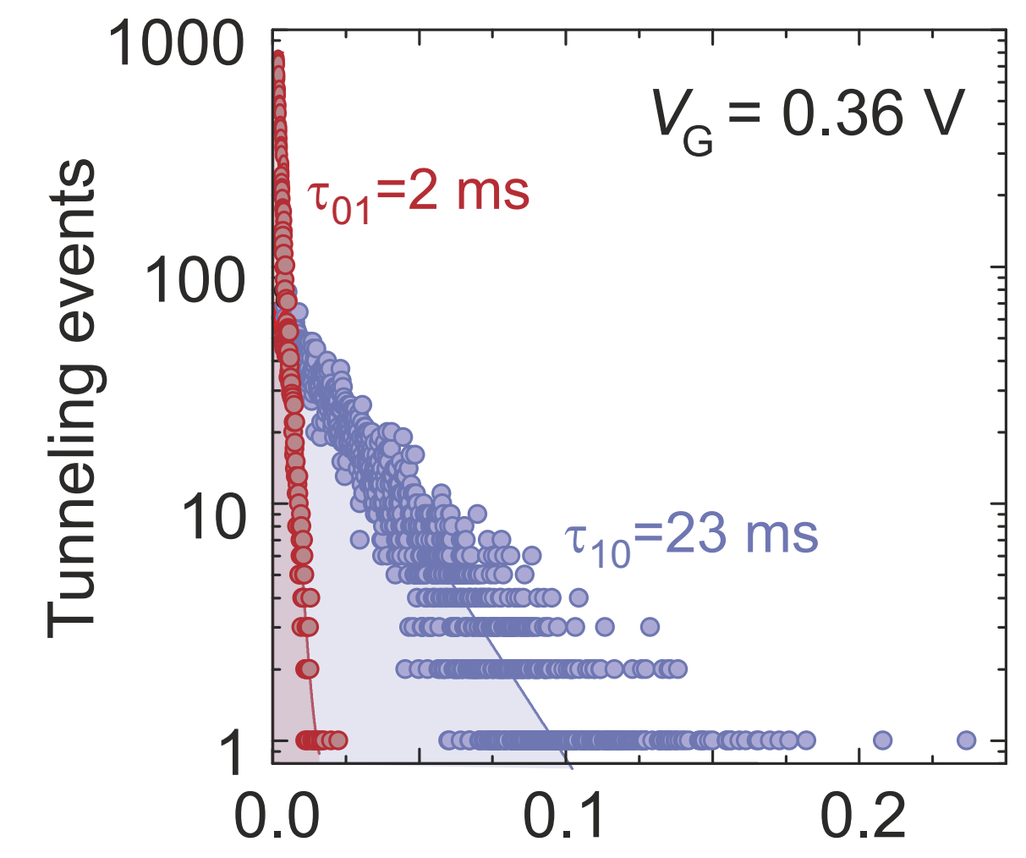
- Time-resolved RF of the Exciton (X) while an electron tunnels into the QD



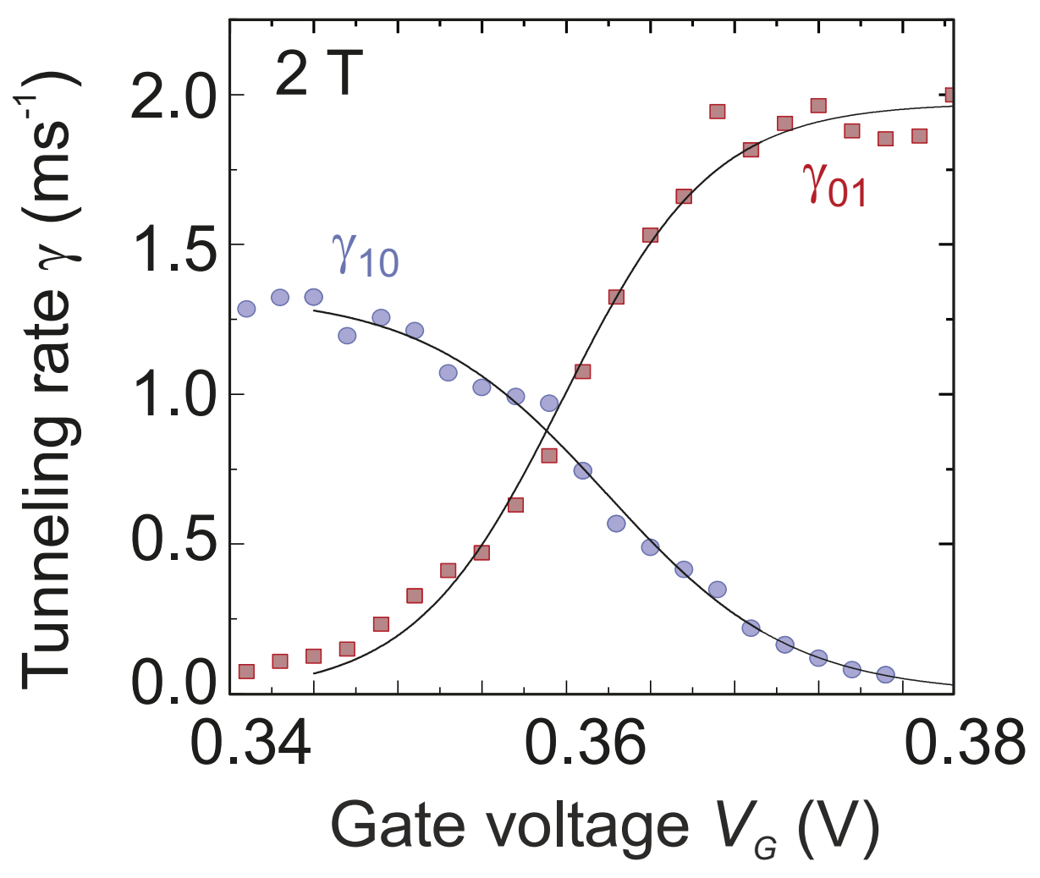
- The electron in the QD switches the resonance fluorescence signal off and on
- We observe quantum jumps of the electron tunneling into and out of the dot
- Time-resolution: 100 µs

4. Tunneling rates

Tunneling rates as probability distribution in a 100 ms time interval (from the telegraph signal)

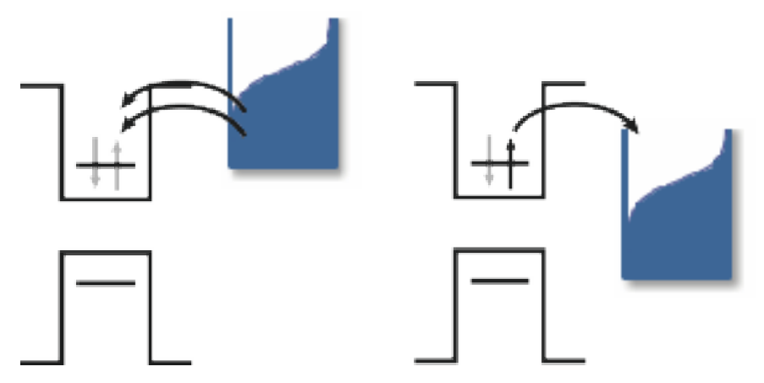


- Tunneling rates for tunneling into γ_{01} and out of the dot γ_{10}



- Tunneling rates γ_{01} and γ_{10} show a Fermi-distribution at T= 8 K:

$\gamma_{In} = \gamma_{10} = 2\,\Gamma f(E)$
$\gamma_{Out} = \gamma_{01} = \Gamma(1-f(E))$
$\Gamma \approx$ 1 ms



- Tunneling rate into the QD exceeds the tunneling rate for electron tunneling out of the dot by a factor of two, due to spin degeneracy [4]

5. Counting statistics and spin relaxation

- Probability from the number of tunneling events in a 100 ms time-interval
- Cumulants:

$$C_m(t) = \langle N^m(t) \rangle = \partial z^m M(z,t)\big|_{z=0}$$

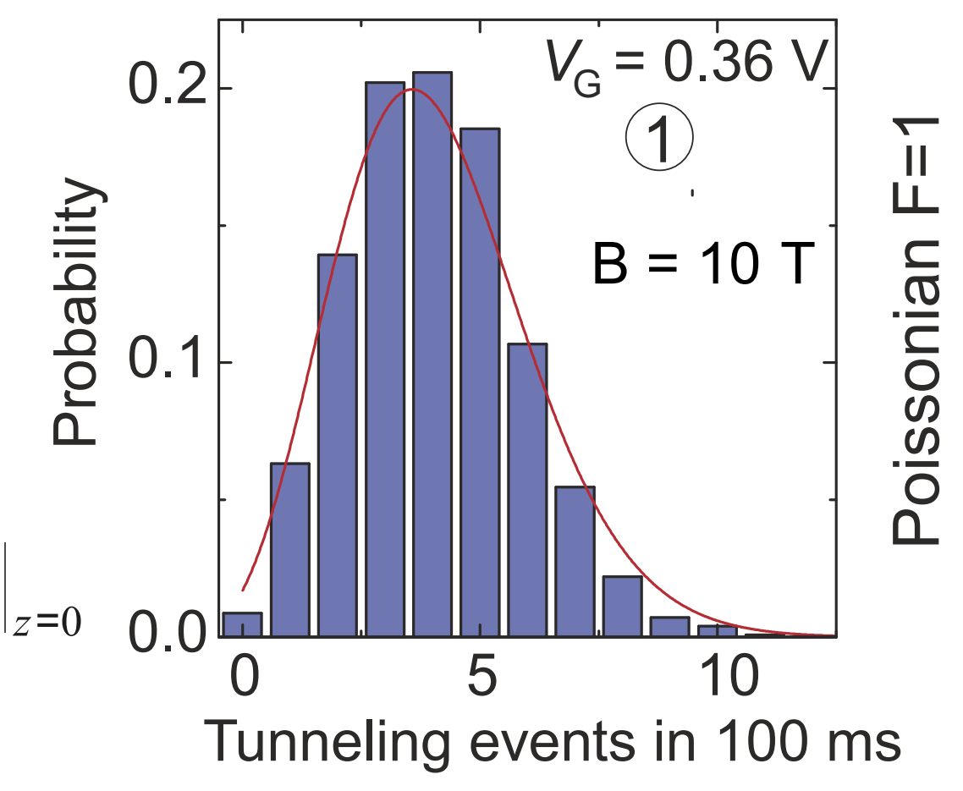
- with the cumulant generating function:

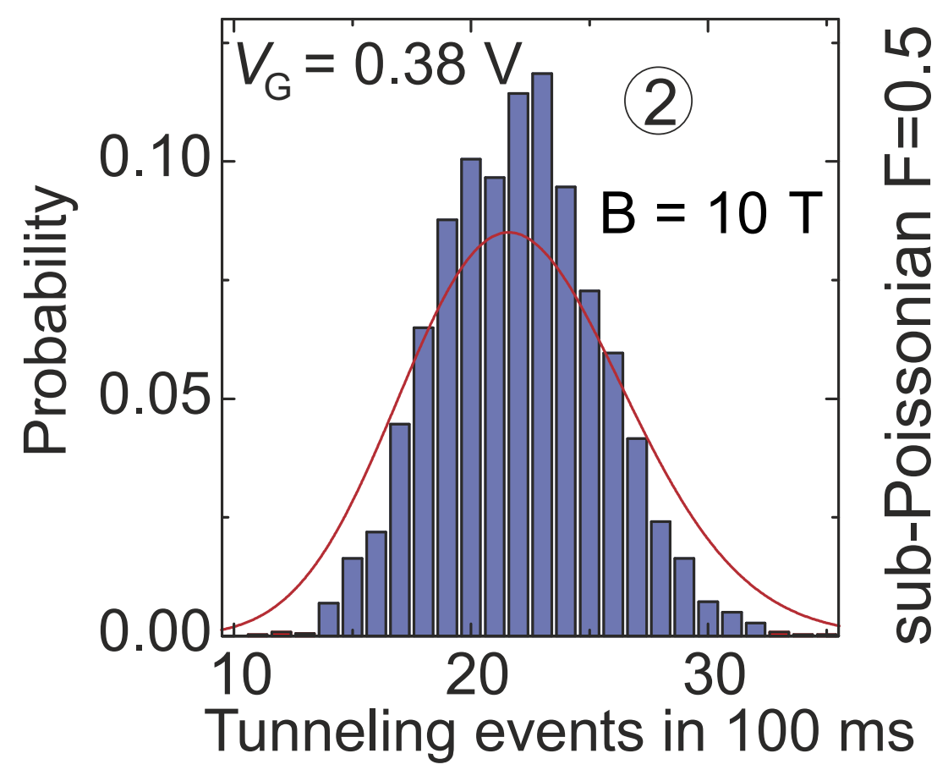
$$M(z,t) = \sum_N e^{zN} P_N(t)$$

- Fano-Factor:

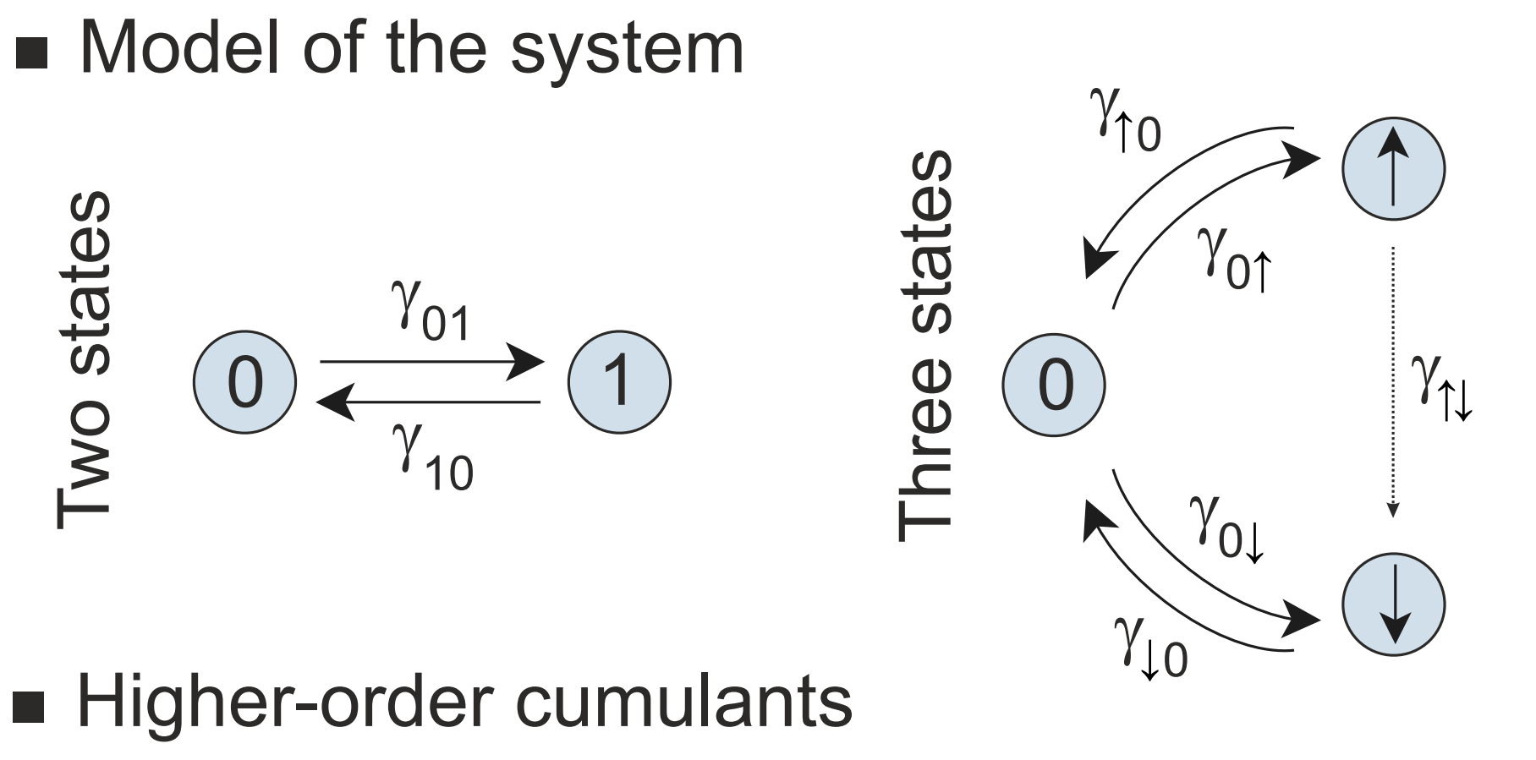
$$F = C_2/C_1$$

- Fano-Faktor <1: Electron transport is correlated due to Coulomb repulsion

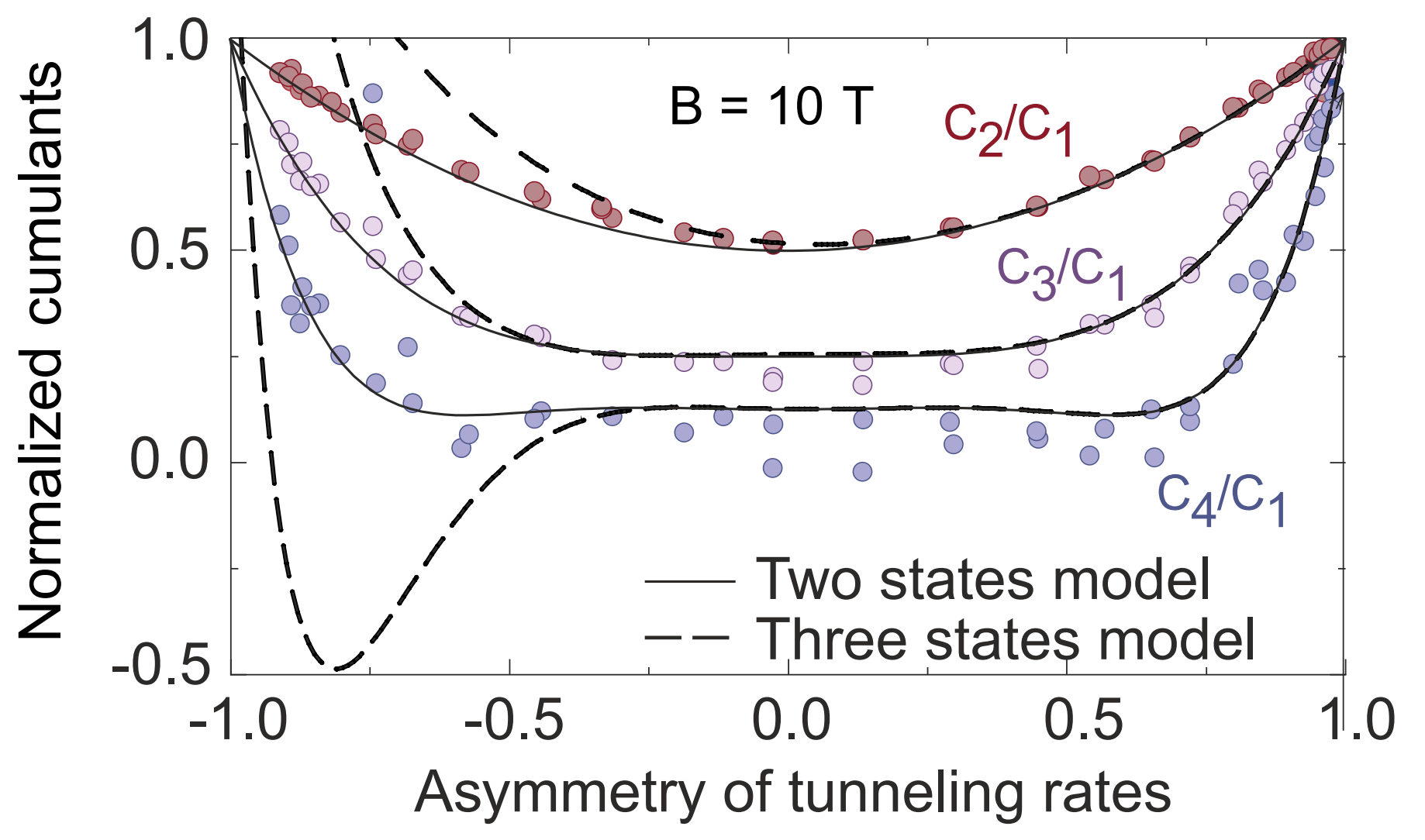




- Model of the system



- Higher-order cumulants

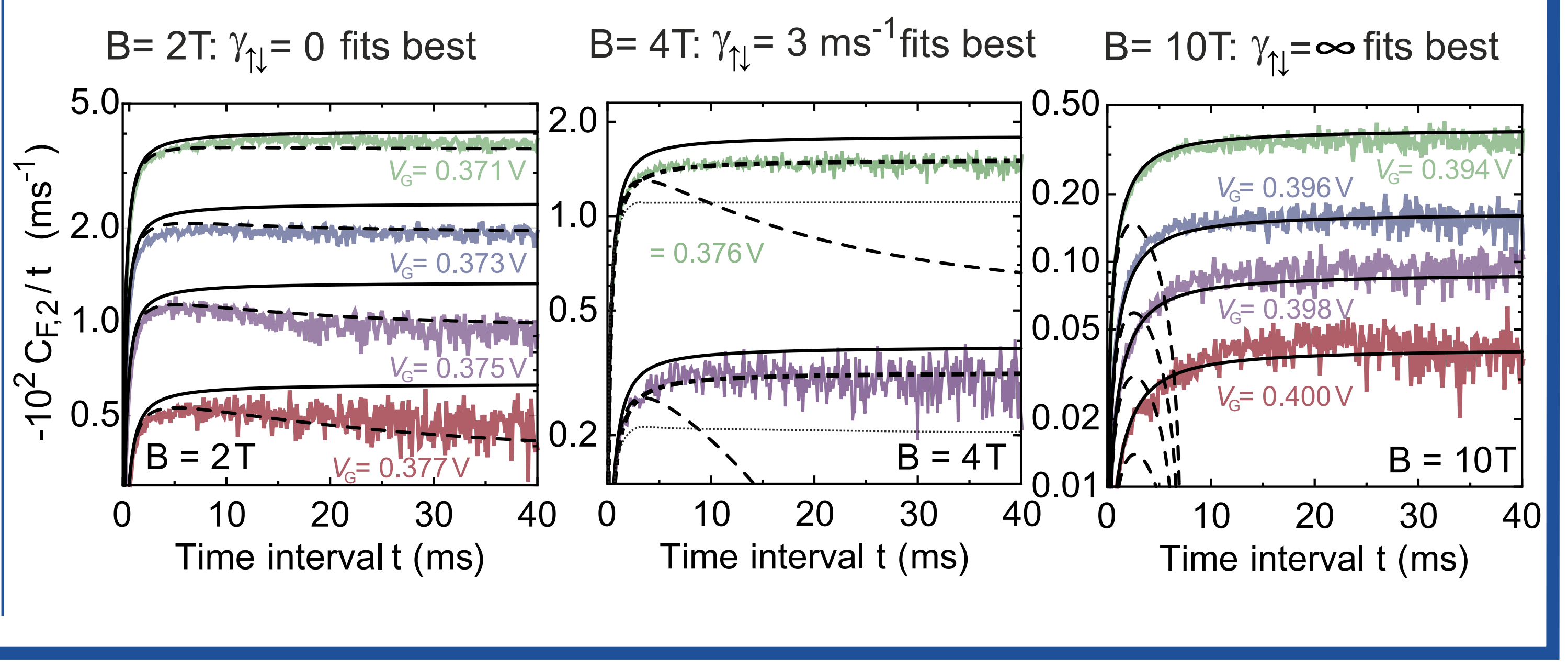


Factorial cumulants [5,6]

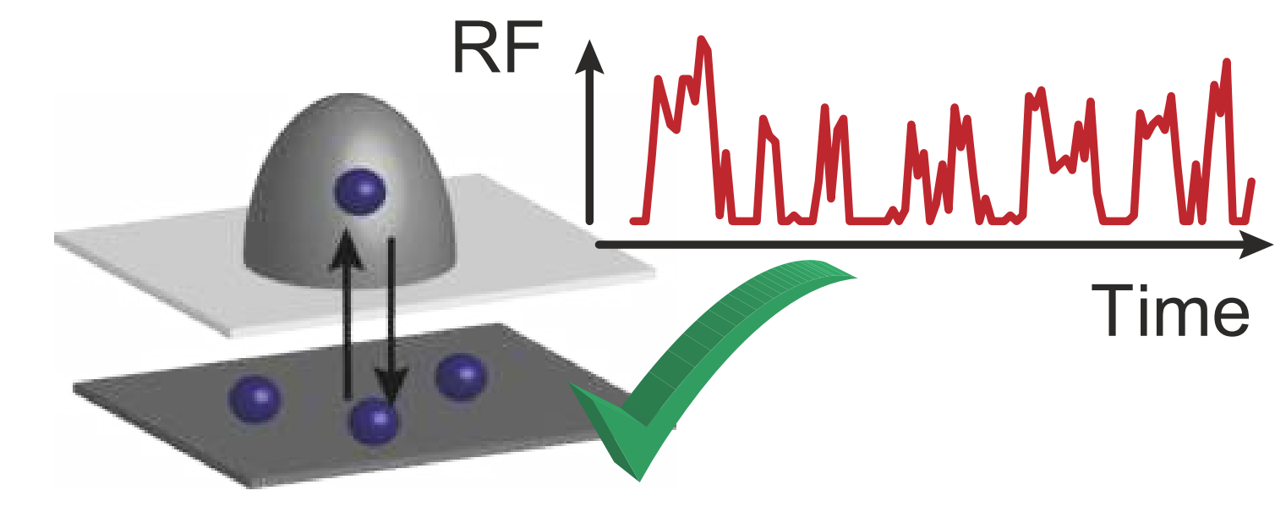
$$C_{F,m}(t) = \partial z^m \ln M_F(z,t)\big|_{z=0} \quad \text{with} \quad M_F(z,t) = \sum_N (z+1)^N P_N(t)$$

- ... are more sensitive to interactions between the charge carriers
- Factorial cumulants in a three-state model with spin relaxation $\gamma_{\uparrow\downarrow}$

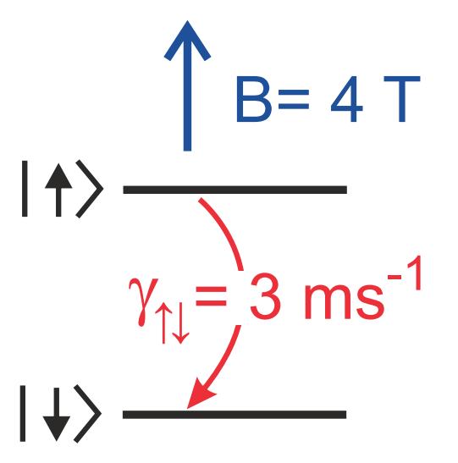
— $\gamma_{\uparrow\downarrow} = \infty$ – · – $\gamma_{\uparrow\downarrow} = 3\ \mathrm{ms}^{-1}$ ····· $\gamma_{\uparrow\downarrow} = 1\ \mathrm{ms}^{-1}$ – – $\gamma_{\uparrow\downarrow} = 0$


B= 2T: $\gamma_{\uparrow\downarrow} = 0$ fits best
B= 4T: $\gamma_{\uparrow\downarrow} = 3\ \mathrm{ms}^{-1}$ fits best
B= 10T: $\gamma_{\uparrow\downarrow} = \infty$ fits best

6. Conclusion



Optical measurements of the electron tunneling dynamics
- Single-electron tunneling events (quantum jumps) in a RF telegraph signal
- Full counting statistics demonstrates Sub-Poissonian distribution for equal tunneling rates
- Factorial cumulants enable to observe the **spin dynamics** in an **equilibrium charge** measurement



Further reading

[1] Matthiesen et al., Phys. Rev. Lett. **108**, 093602 (2012).
[2] Gustavsson et al., Phys. Rev. Lett. **96**, 076605 (2006).
[3] Kurzmann et al., Phys. Rev. Lett. **122**, 247403 (2019).
[4] Kurzmann et al, Phys. Rev. Lett. **117**, 017401 (2016).
[5] Stegmann et al., Phys. Rev. B **92**, 155413 (2015).
[6] Stegmann et al., Phys. Rev. B **94**, 125433 (2016).

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