Shot noise in disordered graphene samples

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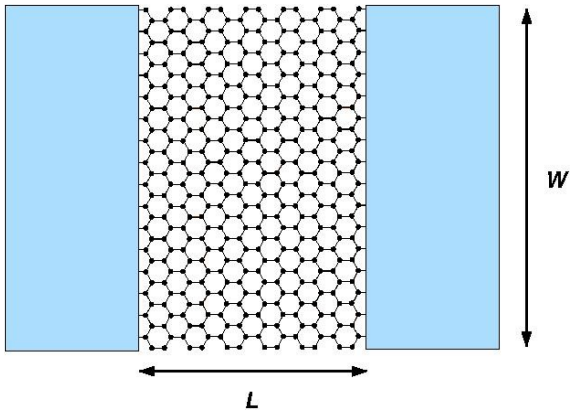
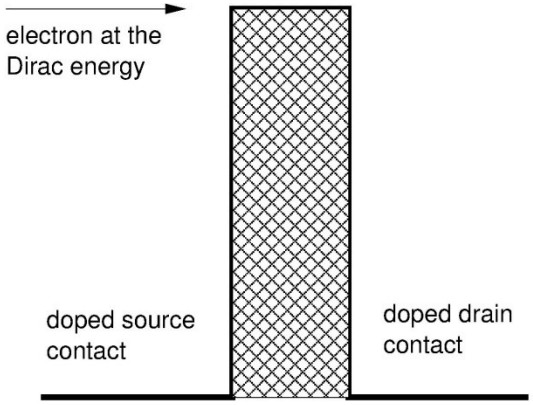
Summary

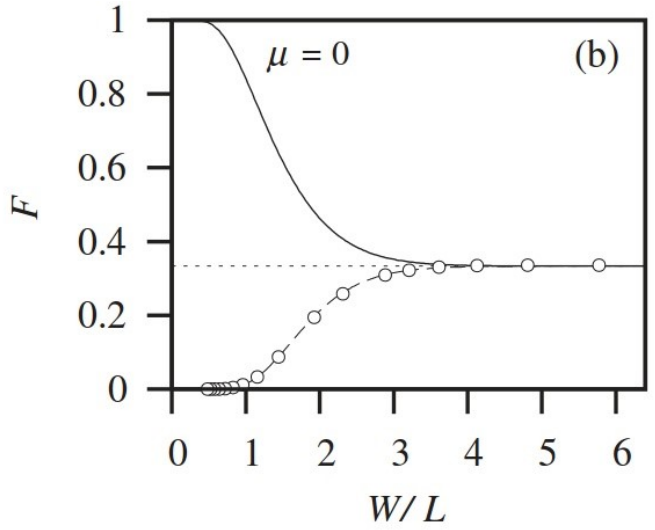
- Prediction on the shot noise behavior in graphene by Tworzydlo *et al.*
- Attempts at the experimental verification
- Our simulation approach
- Comparison between simulations and experimental data
- Interpretation of the experimental data
- Suggestions for future attempts at the experimental verification of the effect predicted by Tworzydlo *et al.*

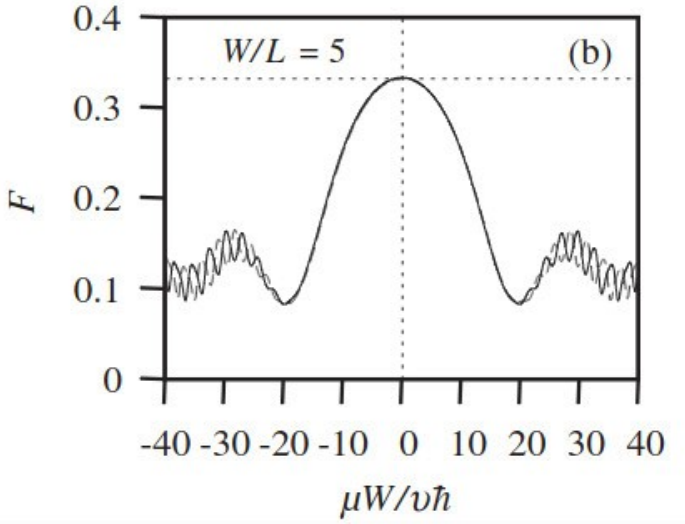
Shot noise in graphene flakes with high aspect ratios



In a seminal paper in 2006 Tworzydlo *et al.* predicted that in very short and wide graphene samples shot noise exhibits a 1/3 suppression for injection at the Dirac energy

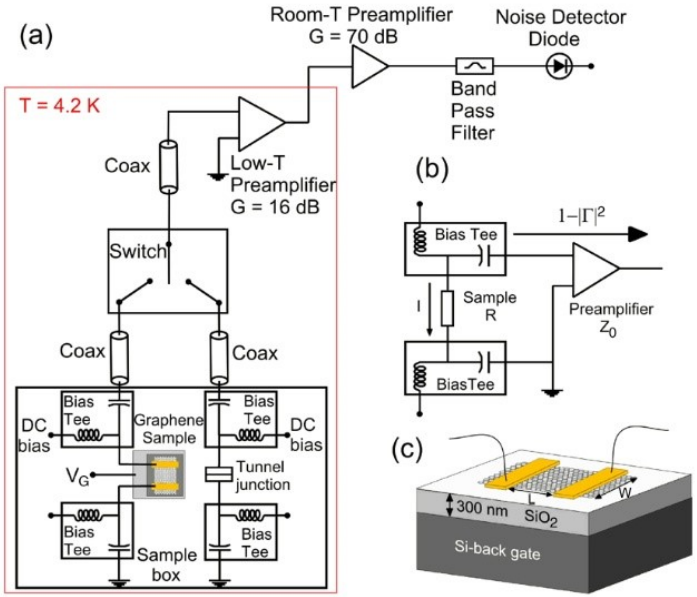


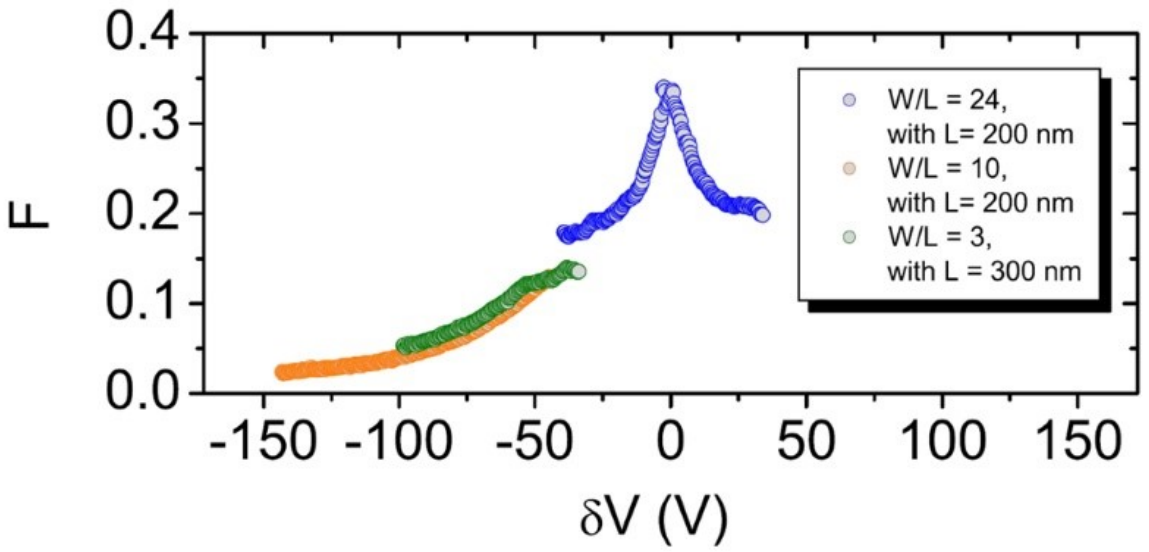




J Tworzydlo, B. Trauzettel, M. Titov, A. Rycerz, and C. W. J. Beenakker, PRL **96**, 246802 (2006)

Published experimental results (I)



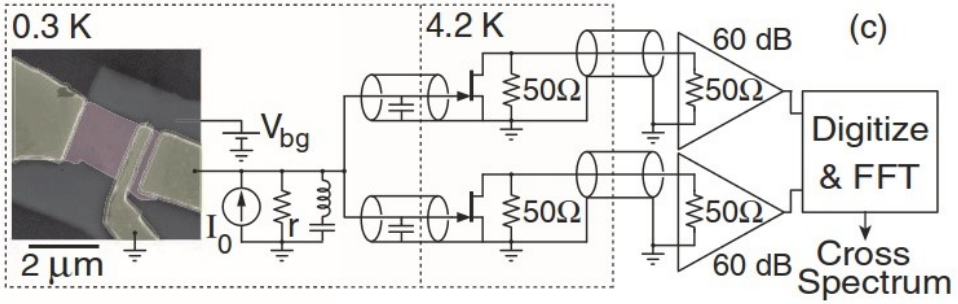


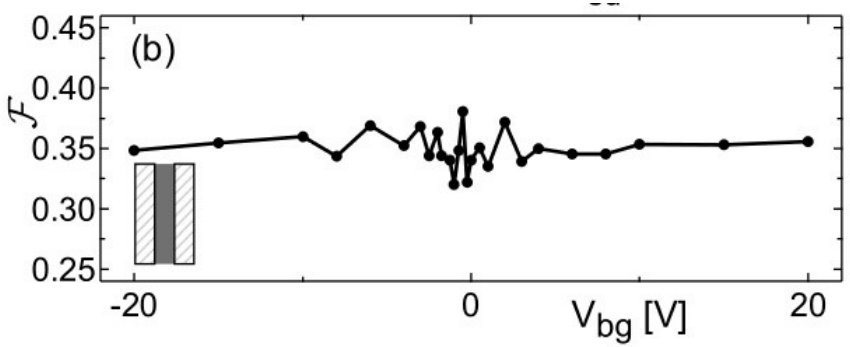
R. Danneau, F. Wu, M. F. Craciun, S. Russo, M. Y. Tomi, M. Salmilehto, A. F. Morpurgo, and P. J. Hakonen , PRL **100**, 196802 (2008)

This experiment was performed at a temperature around 8.5 K and with an applied bias up to 40 mV. Considering that at 8.5 K kT/q=0.732 mV, the transport window is much wider than kT/q.

Due to the relatively large current, the corner frequency of *1/f* noise is high, and shot noise measurements need to be performed above 600 MHz

Published experimental results (II)





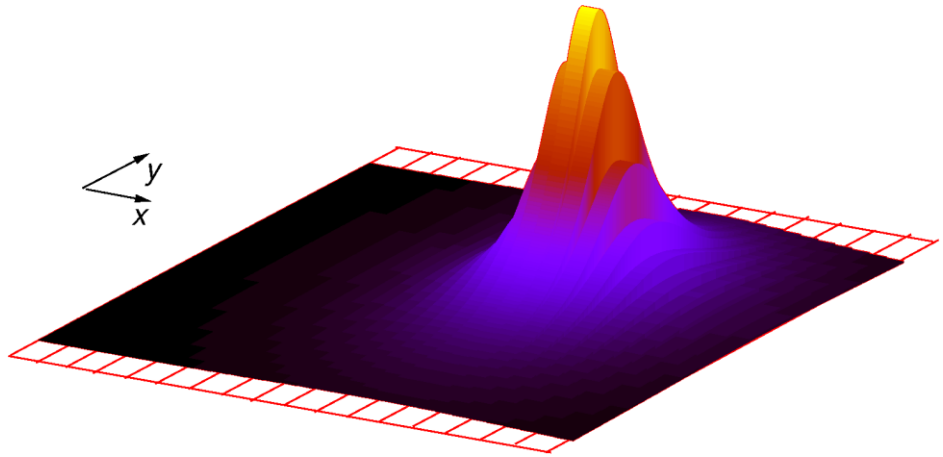
Di Carlo et al. measured shot noise in graphene samples at 0.3 K, with an applied bias up to 0.3 mV, operating at a frequency of 1.5 MHz. In this case kT/q=25.85 µV, about 1/10 of the transport window.

They observed a substantially constant Fano factor as a function of gate bias.

L. DiCarlo, J. R. Williams, Y. Zhang, D. T. McClure, C. M. Marcus, PRL **100**, 156801 (2008)

Dirac equation

The problem can be partitioned into a collection of one-dimensional subproblems



within a single section:

$$F^{\vec{K}(\vec{K}')}_{A(B)}(x,y) = e^{i\kappa_x x}\Phi^{\vec{K}(\vec{K}')}_{A(B)}(y)$$

$$\Rightarrow \begin{cases} -\frac{d}{dy}\Phi^{\vec{K}}_{A}(y) + \frac{E-V(y)}{\gamma}\Phi^{\vec{K}}_{B}(y) = \kappa_x \Phi^{\vec{K}}_{A}(y) \\ \frac{E-V(y)}{\gamma}\Phi^{\vec{K}}_{A}(y) + \frac{d}{dy}\Phi^{\vec{K}}_{B}(y) = \kappa_x \Phi^{\vec{K}}_{B}(y) \\ \frac{d}{dy}\Phi^{\vec{K}'}_{A}(y) + \frac{E-V(y)}{\gamma}\Phi^{\vec{K}'}_{B}(y) = \kappa_x \Phi^{\vec{K}'}_{A}(y) \\ \frac{E-V(y)}{\gamma}\Phi^{\vec{K}'}_{A}(y) - \frac{d}{dy}\Phi^{\vec{K}'}_{B}(y) = \kappa_x \Phi^{\vec{K}'}_{B}(y) \end{cases}$$

$$\begin{cases} \Phi^{\vec{K}}_{A(B)}(0) = i\vec{\Phi}^{\vec{K}'}_{A(B)}(0) \\ \Phi^{\vec{K}}_{A(B)}(W) = ie^{i2KW}\vec{\Phi}^{\vec{K}'}_{A(B)}(W) \end{cases}$$

Fourier approach for the solution of the Dirac equation

We define

$$f(y) \equiv \frac{E - U(y)}{\gamma} \qquad \vec{\varphi}(y) = \begin{cases} e^{-iKy} \begin{pmatrix} \Phi_A^{\vec{K}}(y) \\ \Phi_B^{\vec{K}}(y) \end{pmatrix} & y \in [0, W] \\ ie^{iK(2W-y)} \begin{pmatrix} \Phi_A^{\vec{K}'}(2W-y) \\ \Phi_B^{\vec{K}'}(2W-y) \end{pmatrix} & y \in [W, 2W] \end{cases}$$

The original problem is proven to be equivalent to

$$\begin{cases} \sigma_z \left[\frac{\mathrm{d}}{\mathrm{d}y} + iK \right] \vec{\varphi}(y) + f(W - |W - y|)\sigma_x \vec{\varphi}(y) = -\kappa_x \vec{\varphi}(y) \\ \vec{\varphi}(2W) = \vec{\varphi}(0) \end{cases}$$

If we extend by periodicity $\vec{\varphi}(y)$ and $f(W - |W - y|)$ outside $[0, 2W]$ and we reformulate in terms of Fourier coefficients $\vec{a}_n$, f_n, we obtain:

$$\sum_{l=-\infty}^{\infty} \left[i \left(\frac{\pi n}{W} + K \right) \sigma_z \delta_{ln} + f_{|n-l|} \sigma_x \right] \vec{a}_l = -\kappa_x \vec{a}_n$$

Noise calculation and representation

- The overall scattering matrix is obtained with a recursive combination procedure.
- The Fano factor can be expressed as a function of the transmission eigenvalues, with an average performed over a range of energy determined on the basis of the applied voltage

$$\gamma = \frac{\sum_i T_i(1-T_i)}{\sum_i T_i}$$

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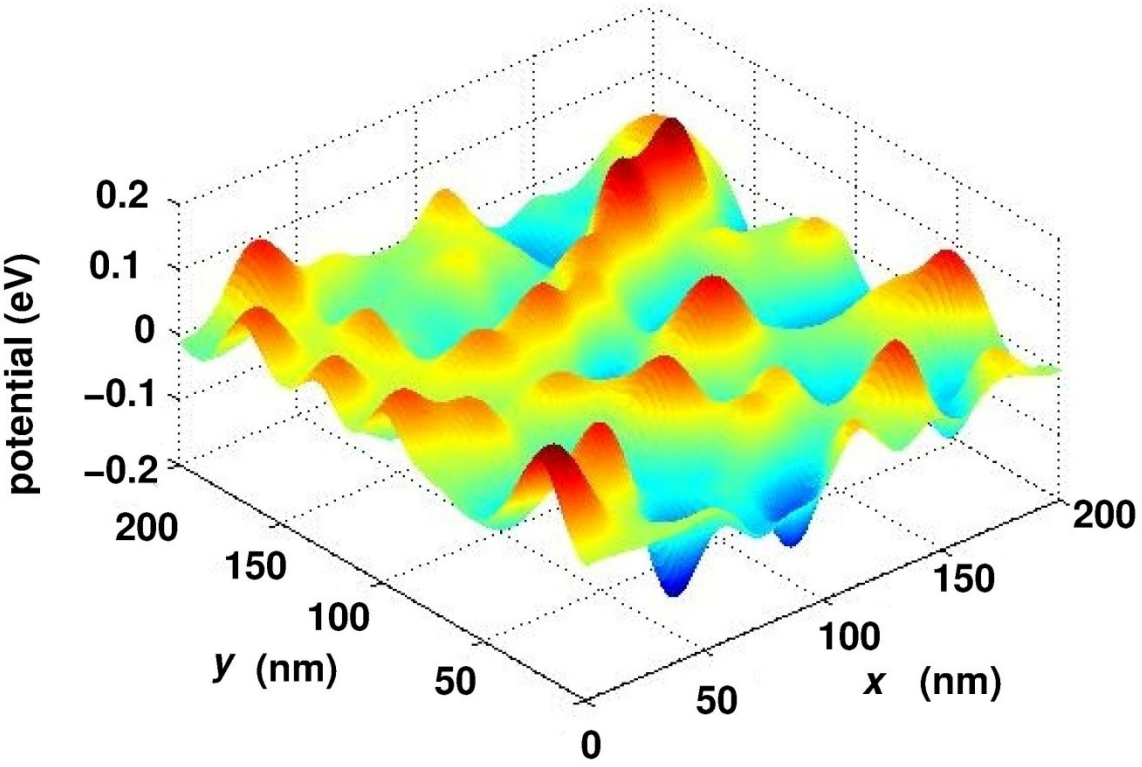
- To plot the Fano factor as a function of the gate voltage, instead of the chemical potential, we use the relationship

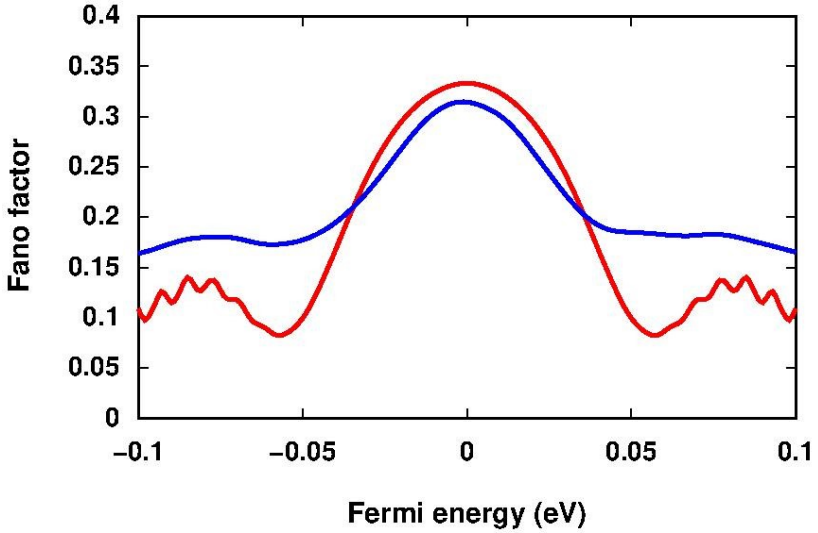
$$\left| \frac{\Delta\mu}{-e} \right| = \sqrt{\frac{\pi(\hbar\nu_F)^2 C_G}{e^3}} \sqrt{|\Delta V_G|}$$

Disorder

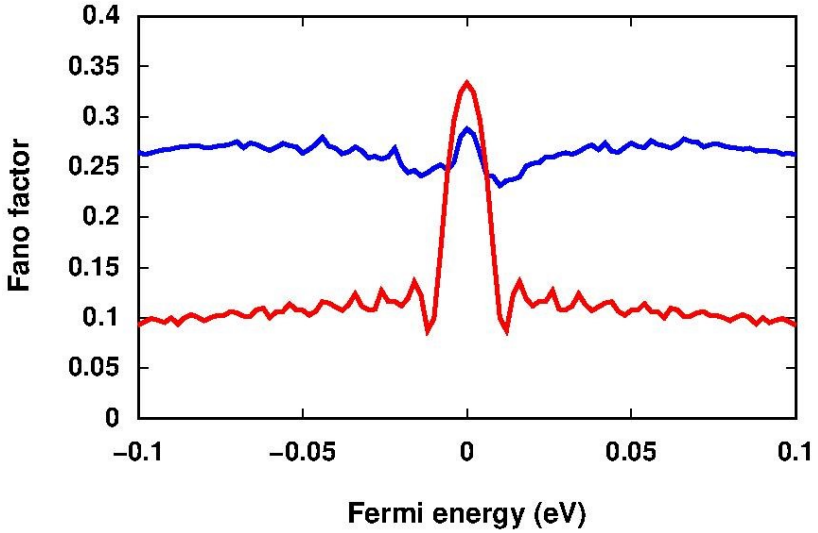


Disorder is reproduced with a superposition of Gaussians that are randomly located across the device, with an amplitude that is uniformly distributed in an interval [-δ,+δ]. Both δ and the half width at half maximum are computed on the basis of the distance of the impurities from the graphene sheet

In the presence of disorder results do not scale

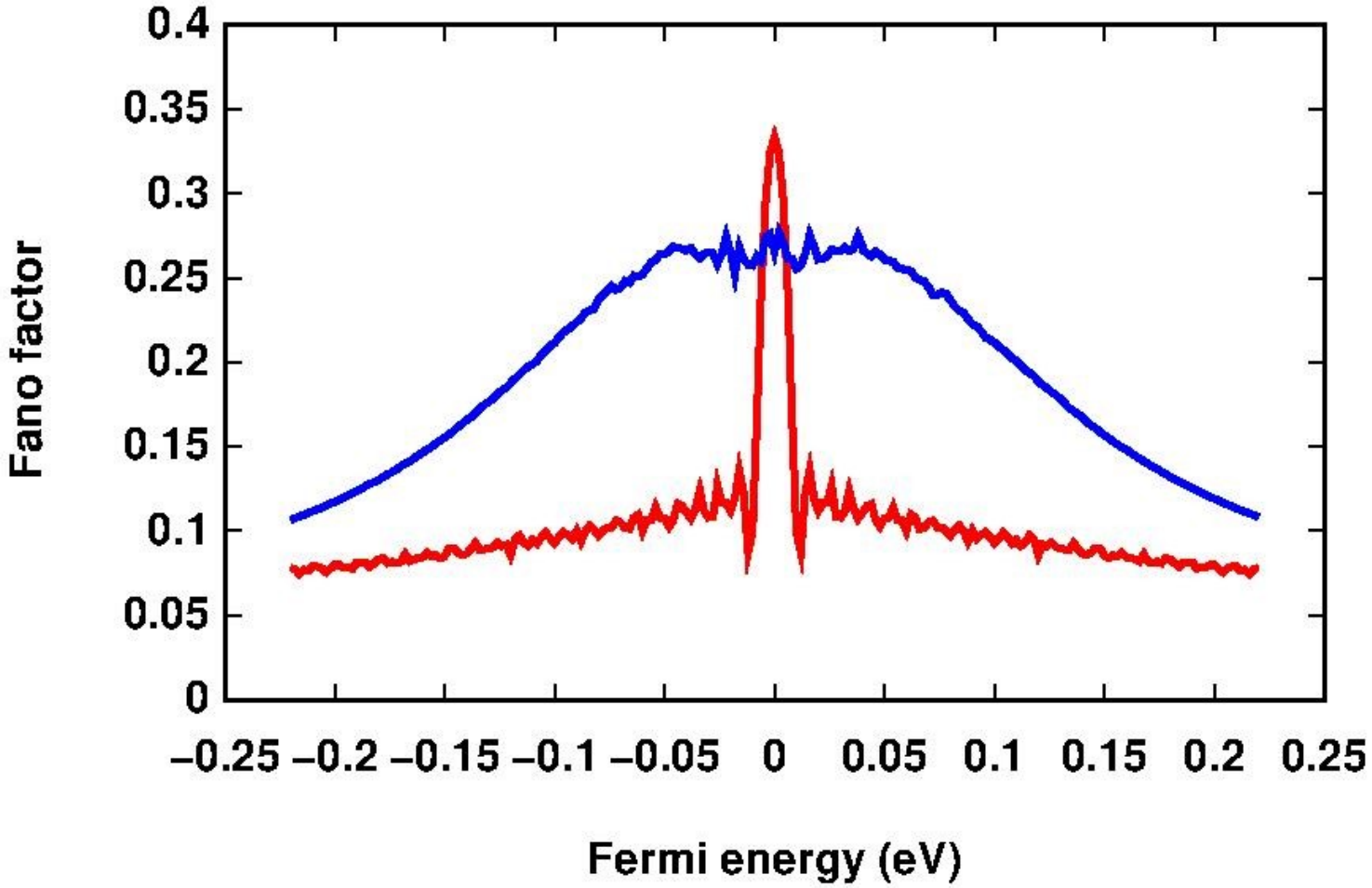


Fano factor for a sample with W=200 nm and W/L=5, in ideal graphene and in the presence of disorder with a concentration of 5 x 10^{11} cm^{-2} located 1 nm away



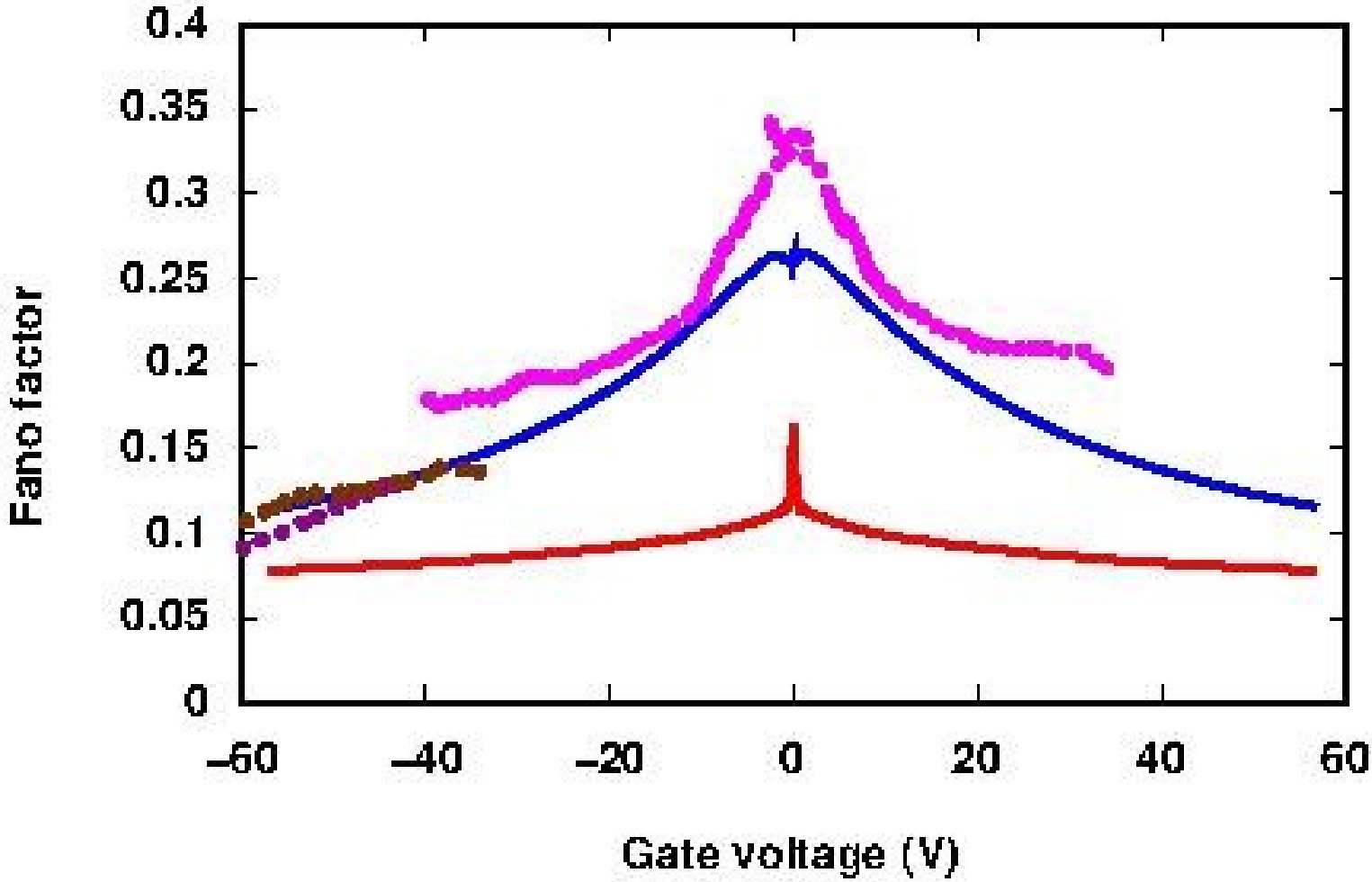
Fano factor for a sample with W=1000 nm and W/L=5 in ideal graphene and in the presence of disorder with a concentration of 5 x 10^{11} cm^{-2} located 1 nm away

Weaker disorder



Fano factor for a sample with W=1000 nm and W/L=5, in ideal graphene and in the presence of disorder with a concentration of 5 x 10^{11} cm^{-2} located 2.15 nm away

Comparison with the experiment by Danneau *et al.*



Comparison with the data by Danneau *et al.*: conversion from chemical potential to gate voltage and averaging over the transport window have been performed

Interpretation

- **Our model provides a reasonable approximation of the results by Danneau *et al.*, which can be interpreted as the consequence of the action of the disorder on the transmission coefficients: as the Fermi energy grows, the effect of the disorder is reduced, and the Fano factor decreases as well. However, the variation of the Fano factor is more than an order of magnitude slower, as a function of the gate voltage, than in the effect predicted by Tworzydlo *et al.*, as already pointed out by Lewenkopf *et al.* [PRB 77,081410(R) (2008)]**
- **We notice an important difference between the resistance data for the samples measured by Danneau *et al.* and those measured by DiCarlo *et al.*: the former have a conductivity at the Dirac point (obtained dividing the conductance by the aspect ratio) close to $4e^2/(\pi h)$ (which is close to the value obtained by Tworzydlo for large aspect ratio samples), while the latter exhibit a conductivity close to $4e^2/h$, the value predicted in the presence of strong disorder (while away from the Dirac point disorder lowers the conductivity, it increases it at the Dirac point)**
- **Therefore it is possible that DiCarlo *et al.* have observed a constant Fano factor either because their samples are affected by a stronger disorder or because their actual aspect ratio is indeed smaller than the nominal value**

Conclusions

- Tworzydlo *et al.* predicted an interesting behavior of the Fano factor for shot noise in graphene, in particular for samples with a large aspect ratio
- Some experiments were performed trying to validate such predictions, but obtained results that were not conclusive
- We have tried to explain the experimental results with simulations based on our envelope-function technique, which allows treatment of graphene samples of realistic size with proper inclusion of disorder
- By tuning the strength of the disorder, we are able to reproduce the experimental results by Danneau *et al.*, but we conclude the effect they observe is not the one predicted by Tworzydlo *et al.*
- On the basis of our results we suggest that, in order to observe the effect predicted by Tworzydlo *et al.*, new experimental efforts should focus on very high mobility suspended graphene and low bias voltages