The Ensslin Group
Nanophysics @ ETH

Nonlocal transport in InAs/GaSb composite quantum well: A candidate for 2D topological insulator

Collaborators:
Fabrizio Nichele
Patrick Pietsch
Susanne Müller
Matija Karalic
Thomas Ihn
Klaus Ensslin

Wafers:
C. Charpentier
T. Tschirky
W. Wegscheider

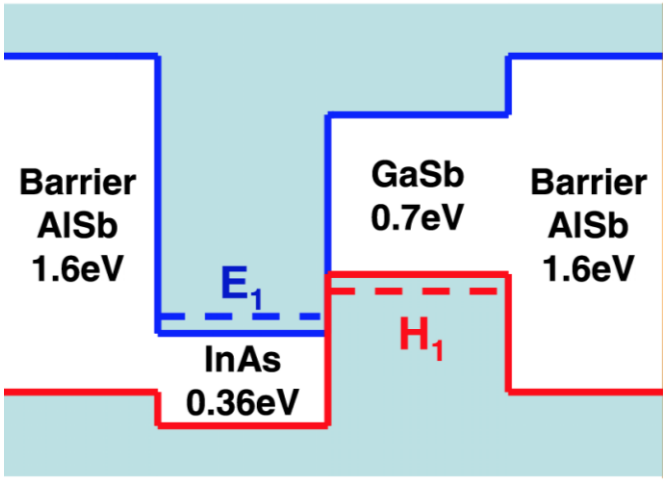
Solid State Physics Laboratory, ETH Zurich

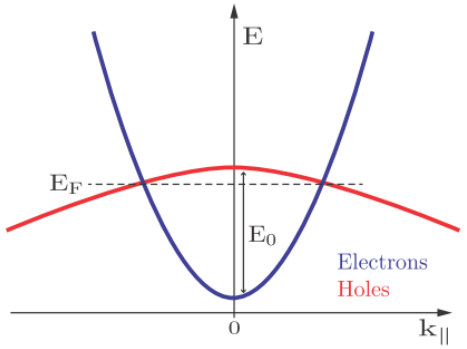
Atindra Nath Pal

Department of Physics, IIT Kharagpur

ISPCM - 2017, ICTS, Bangalore

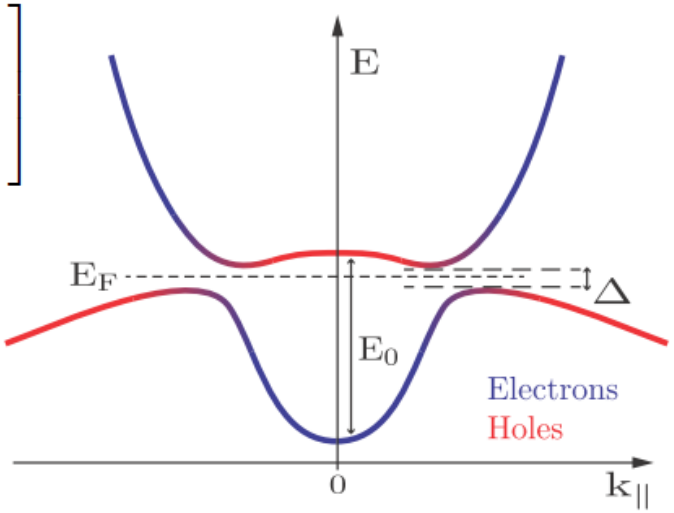
InAs/GaSb Composite Quantum Well





Inverted

$$H = \begin{bmatrix} E_e & V(k) \\ V(k)^\star & E_h \end{bmatrix}$$



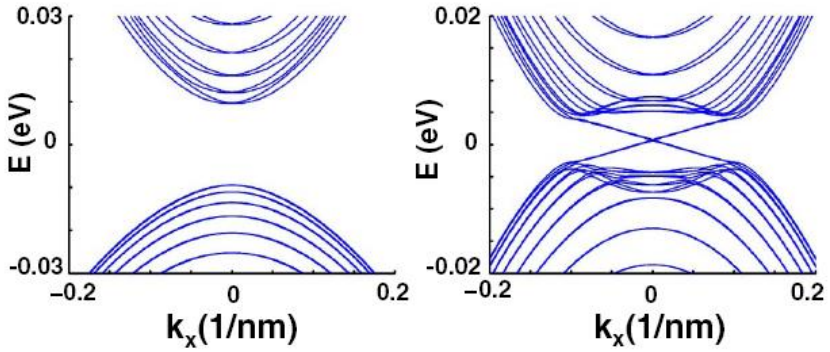
- Peculiar type-III band alignement
- Electron and holes in separate layers
- Hybridization gap due to coupling between layers

Naveh & Laikhtman, APL 66, 1980 (1995)

Prediction of Quantum Spin Hall Effect

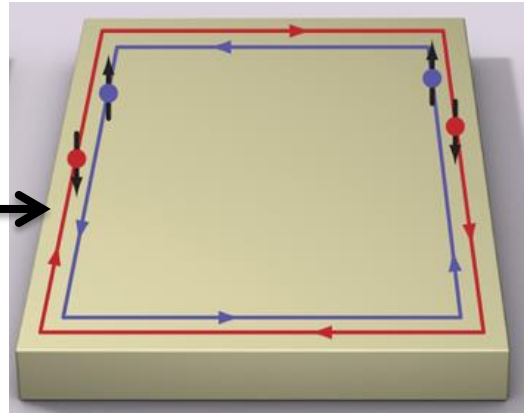
Normal regime

Inverted regime

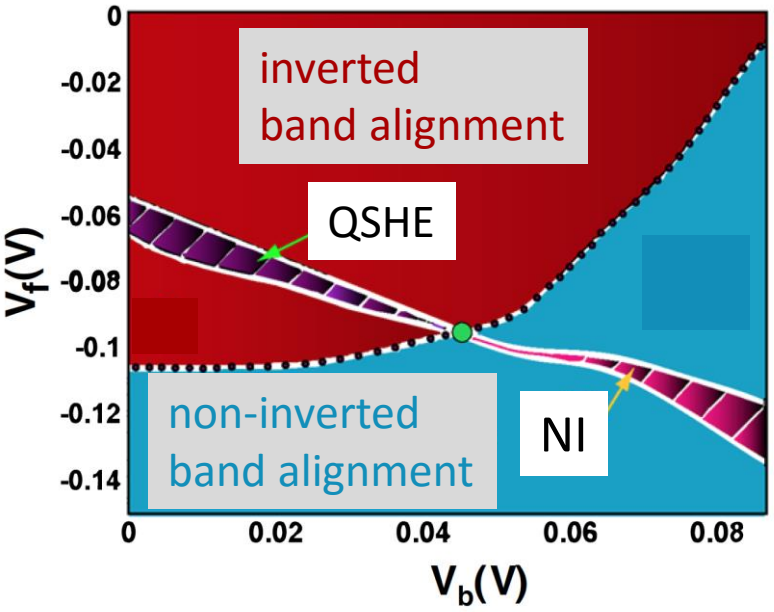


Liu *et al.* Phys. Rev. Lett. 100 236601 (2008)

Helical edge channels



Electrically tunable



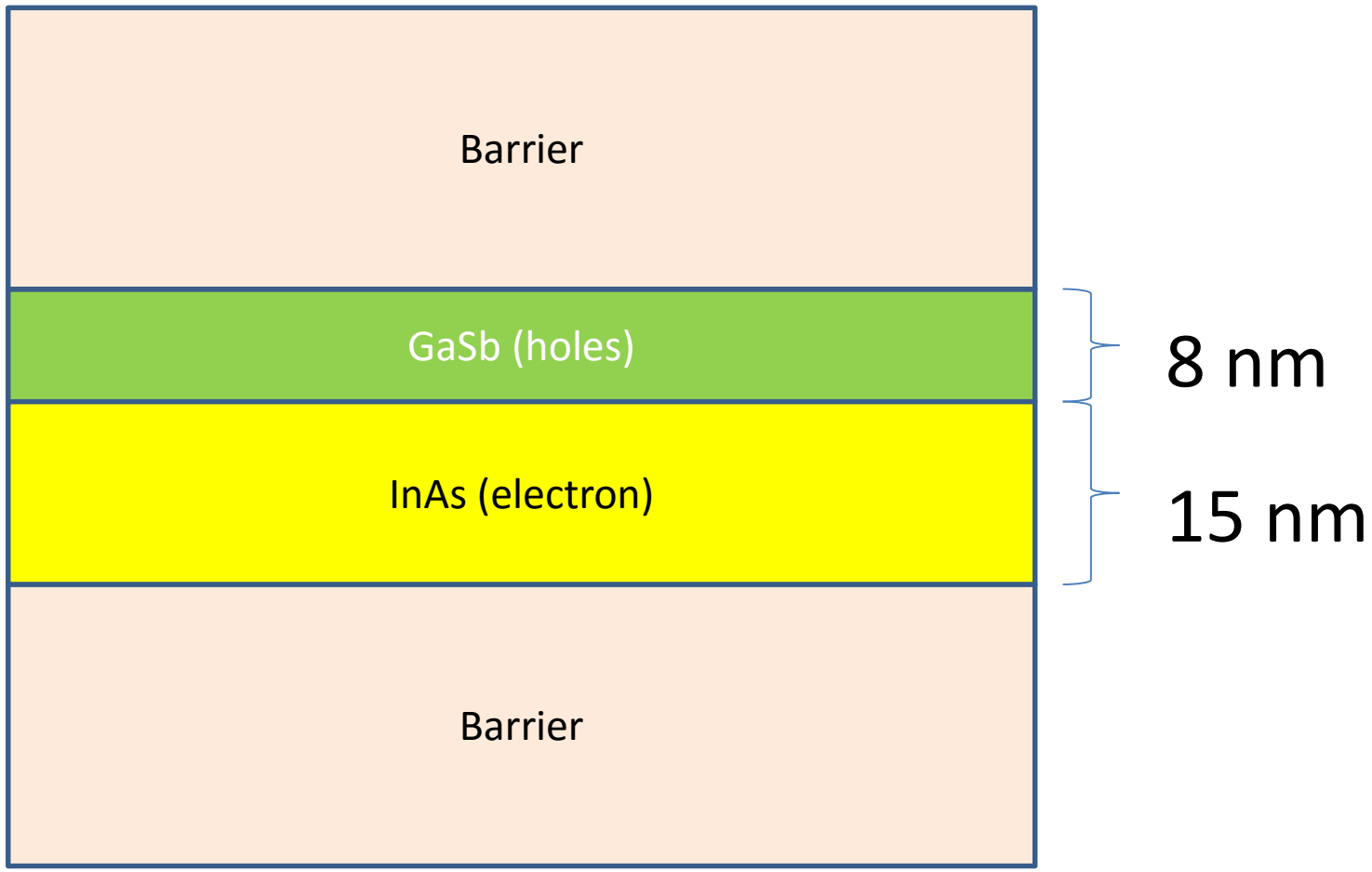
- Band inversion and Hybridization gap
- Spin-orbit coupling
- Time reversal symmetry
- gap-modes at the sample edge form a Kramers-pair in k-space.

Liu *et al.* PRL 100 236601 (2008)

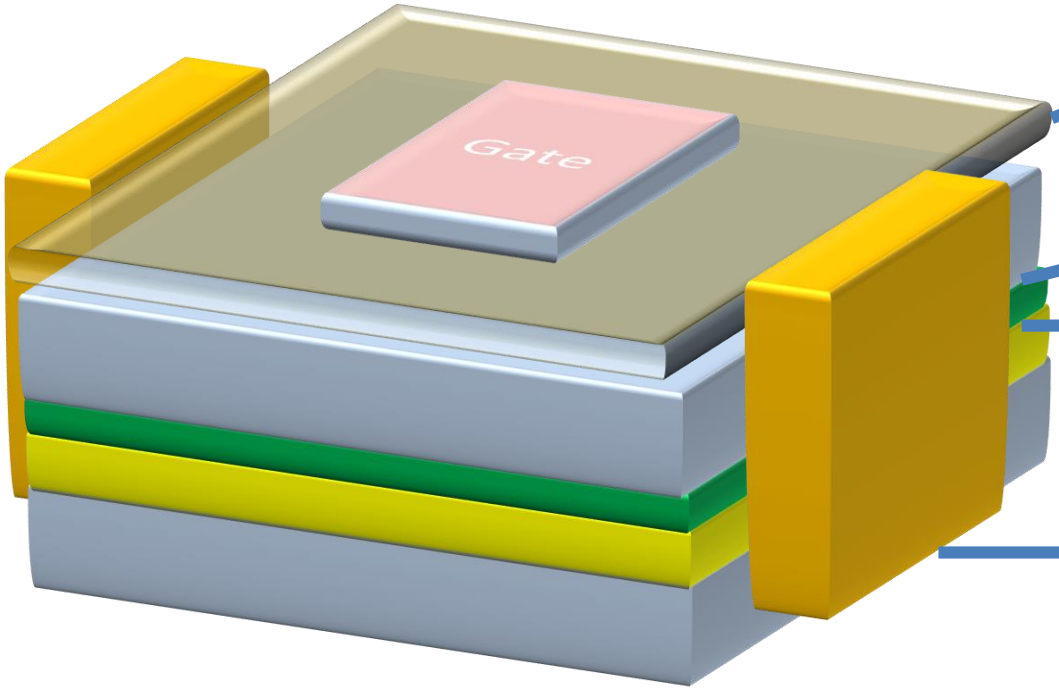
Questions……

- **Electron-hole transport and their hybridization?**
- **What is effect of disorder?**
- **What is effect of magnetic field?**
- **Can we observe Quantum spin Hall edge states?**

Layer by layer growth by MBE



Basic device structure



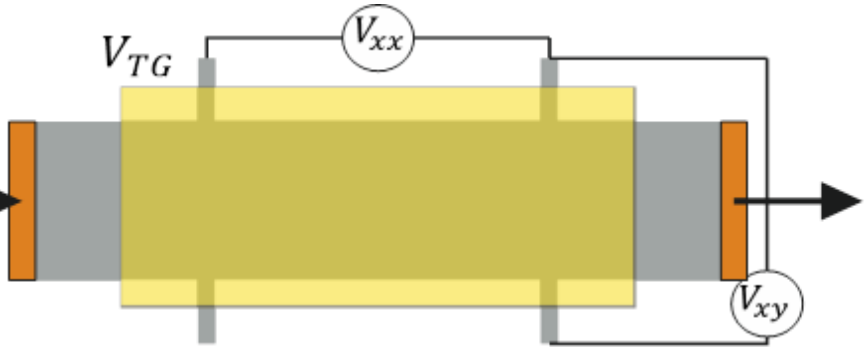
Dielectric

GaSb (hole layer)

InAs (electron layer)

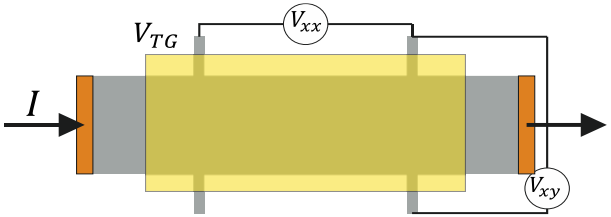
Metal Contacts

Hall bar structure

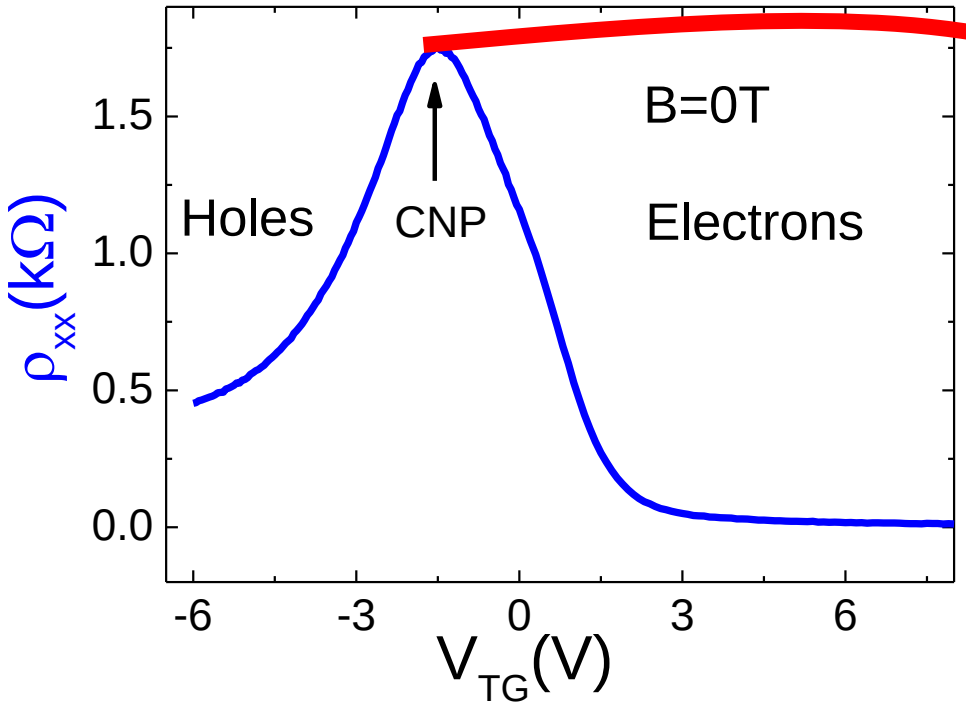


Electron-hole transport: Pseudographene!!

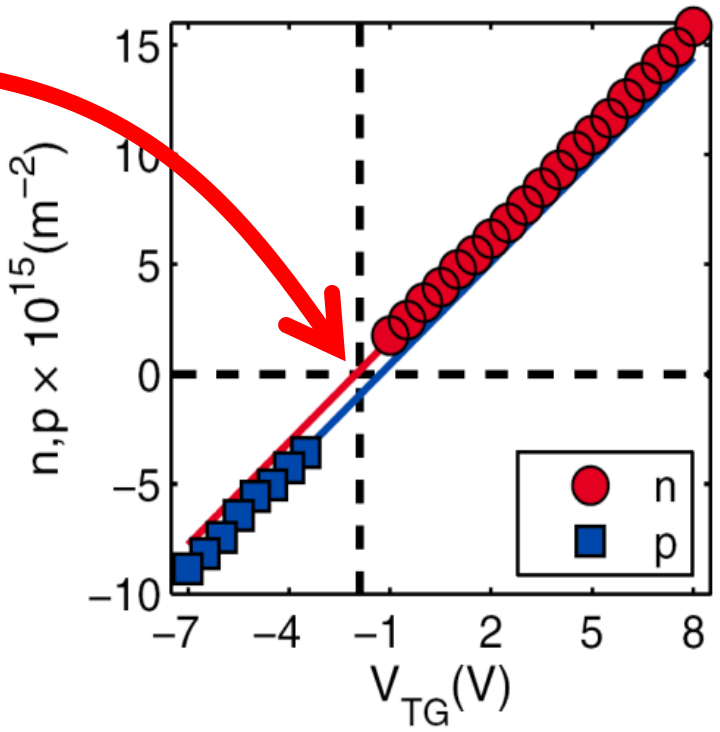
25 μmx50 μm Hall bar



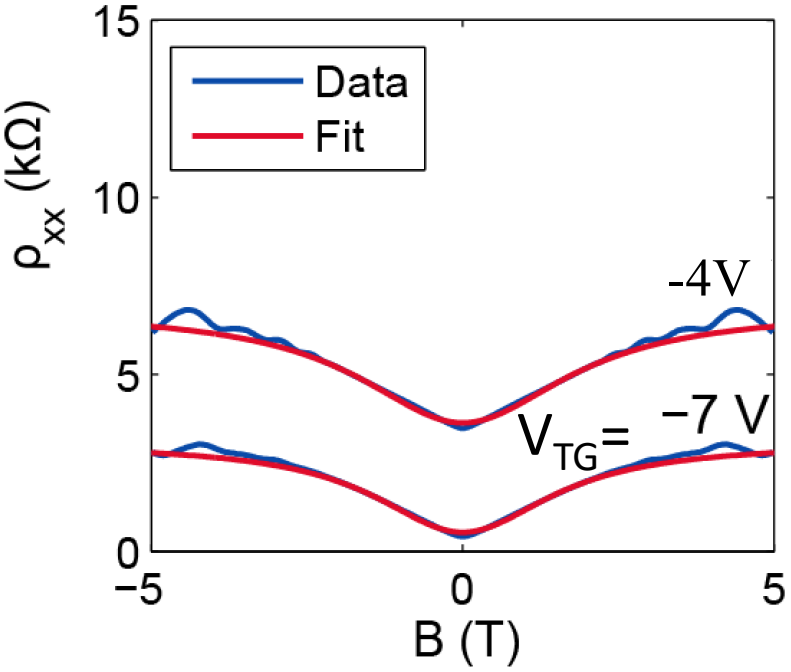
Longitudinal resistivity

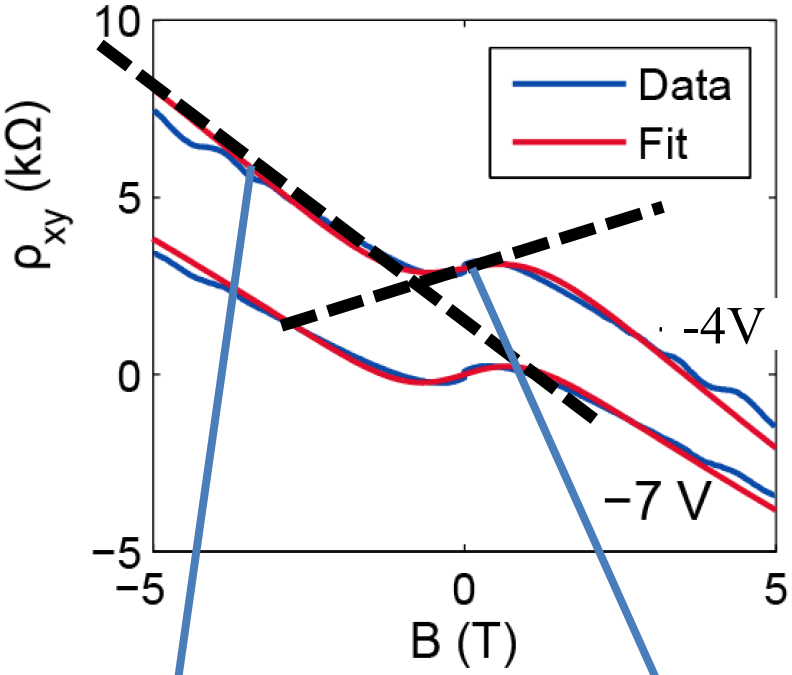


Hall Density



Low-field magnetoresistivity in perpendicular magnetic field





Classical two-band model works

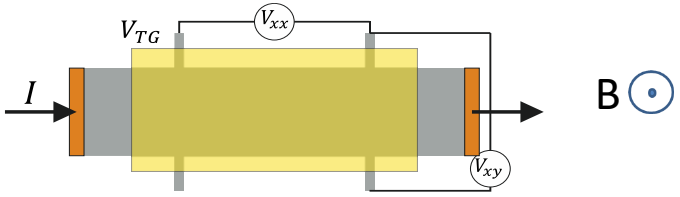
Electrons and holes coexist

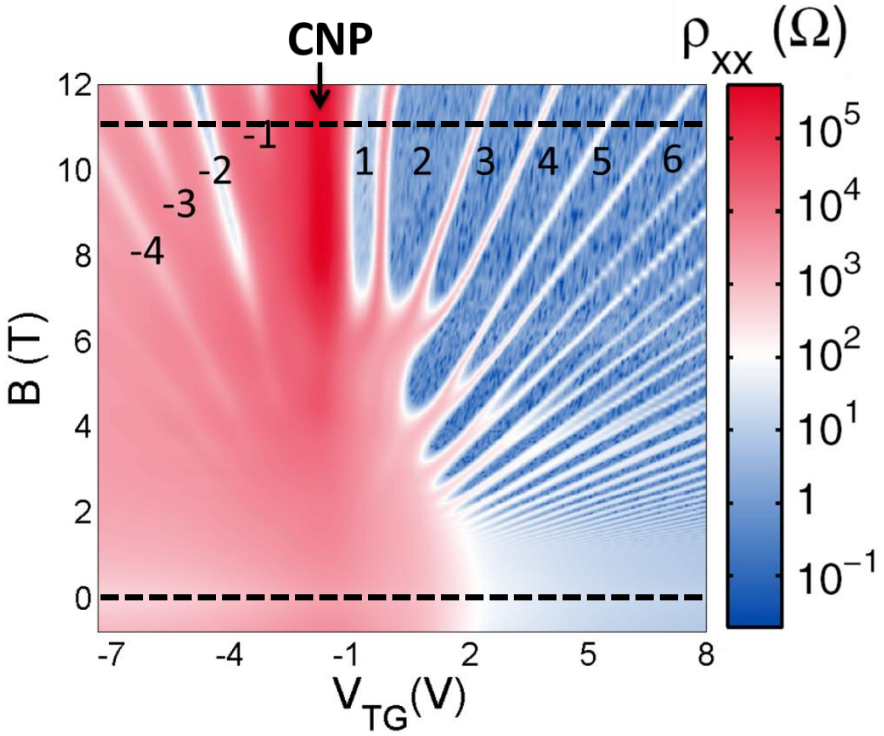
holes

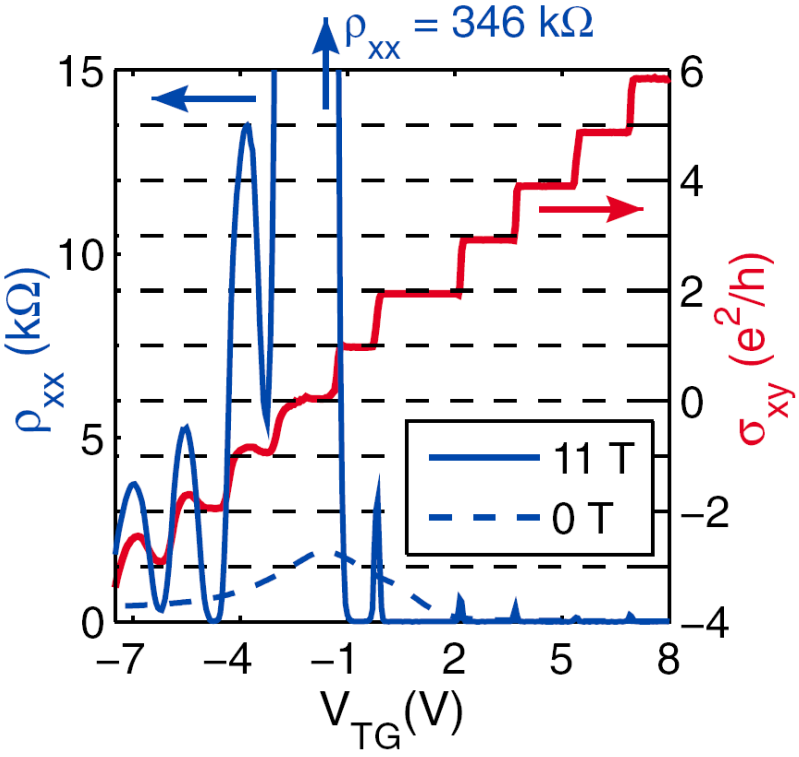
electrons

E Zaremba, Phys. Rev. B 45, 14143 (1992).

Quantum Hall Effect of Electrons and Holes



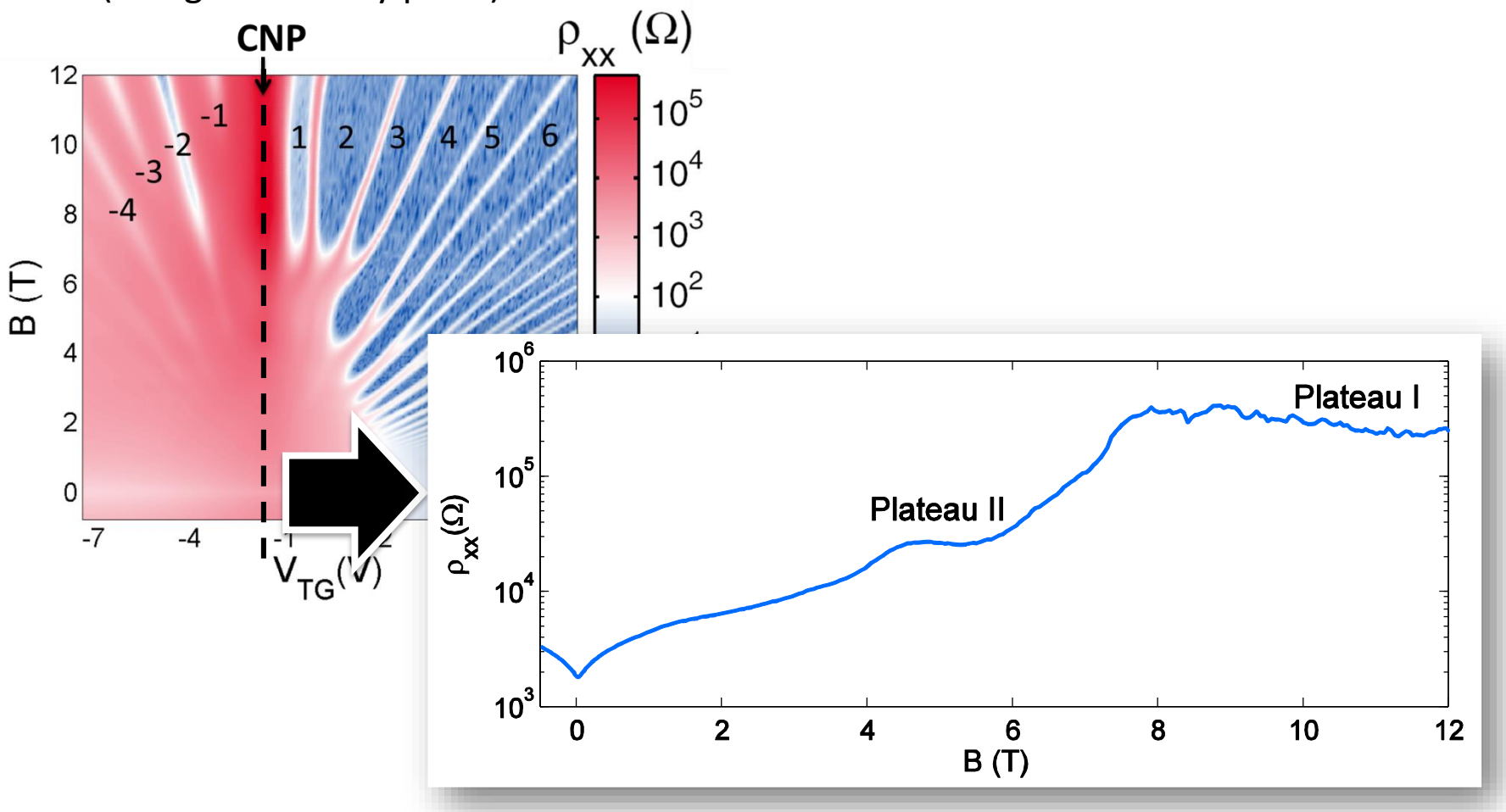




- Resistance peak and $\upsilon = 0$ plateau at the CNP : more than 10 times higher than resistance quantum (**h/e^2=25.8 kΩ**)

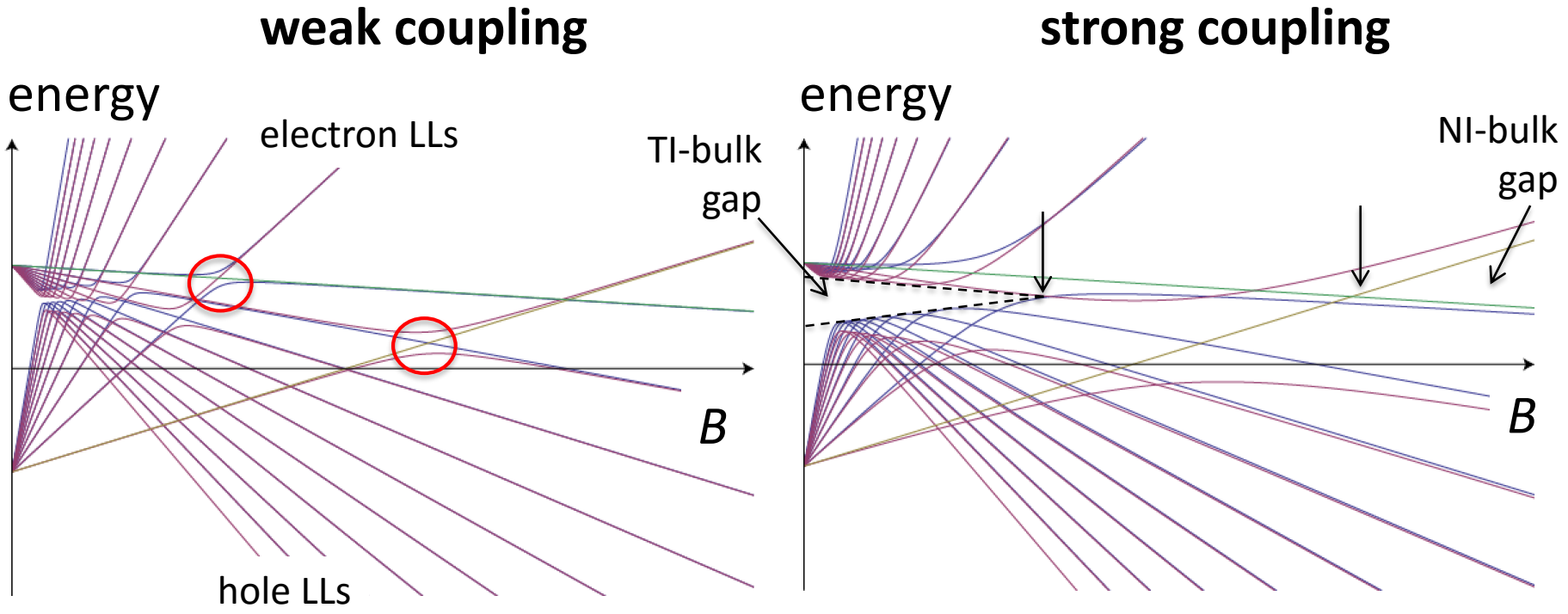
Resistance Peak at CNP

(charge neutrality point)



- Resistance peak and $\upsilon = 0$ plateau at the CNP
- Plateaus in ρ_{xx} at the CNP as a function of magnetic field

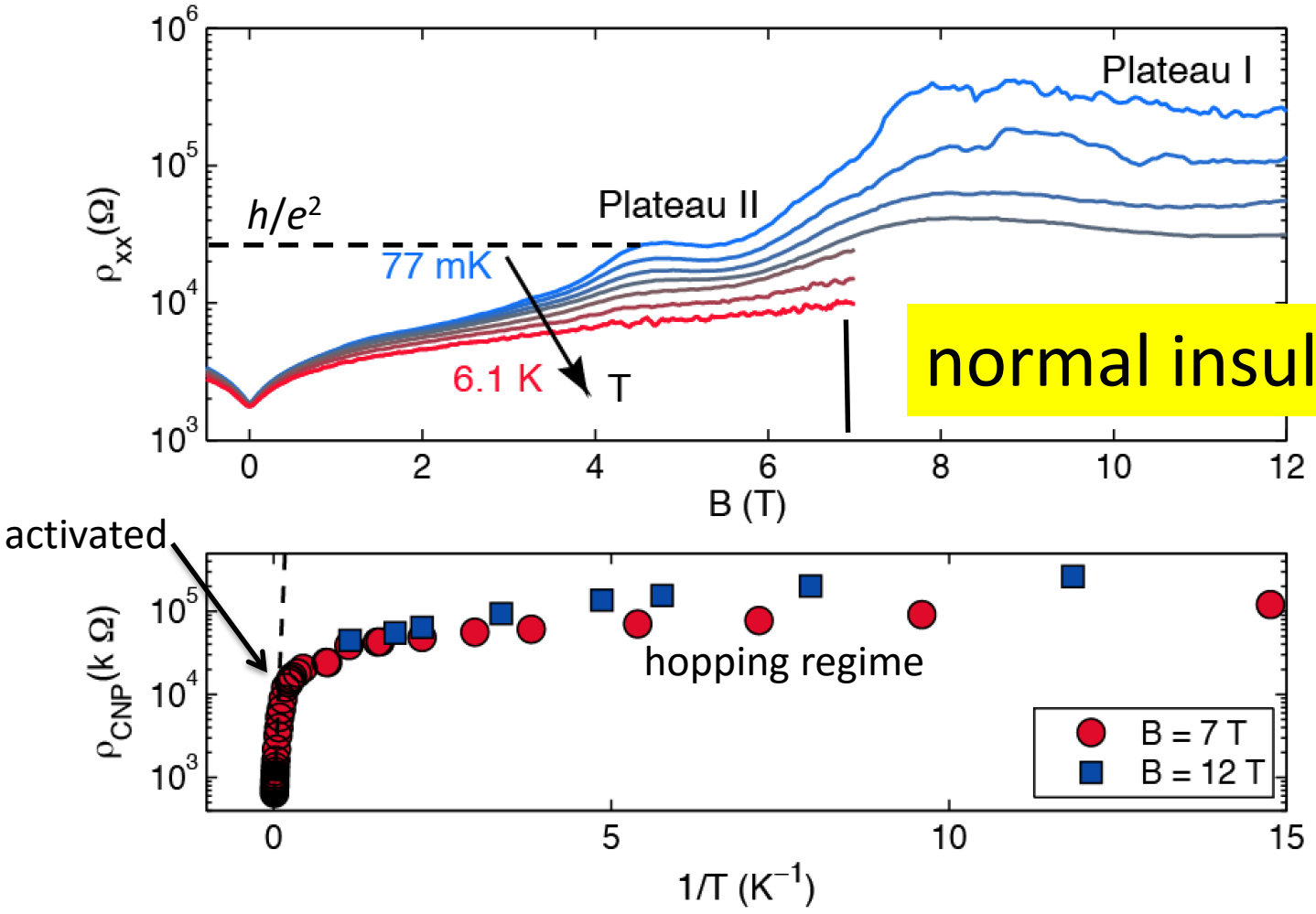
Landau-level coupling



Interlayer tunneling and spin-orbit interaction couple electron- and hole-Landau levels

e.g. Wagner *et al*, Superlattices and Microstructures **21**, 95 (1997).
D. I. Pikulin *et al*, Phys. Rev. B **89**, 161403 (2014).

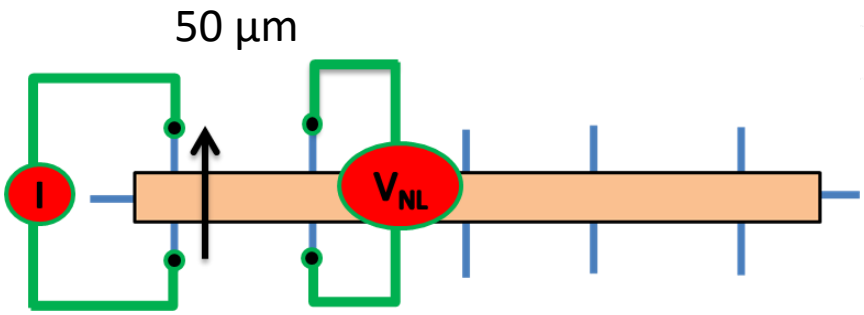
Resistance Peak at CNP



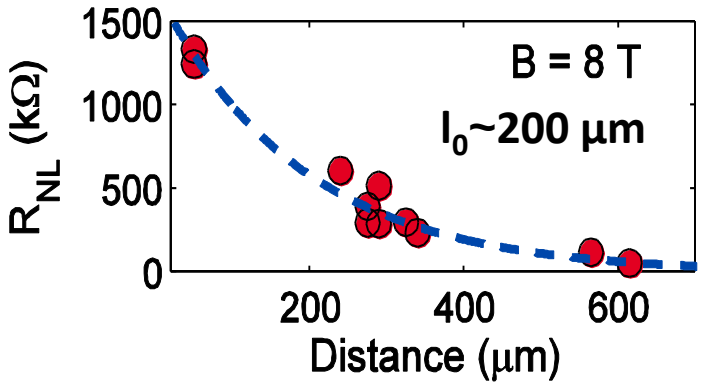
normal insulator ?

Magnetic field perpendicular to the plane of the quantum well

Non-local Transport at the CNP



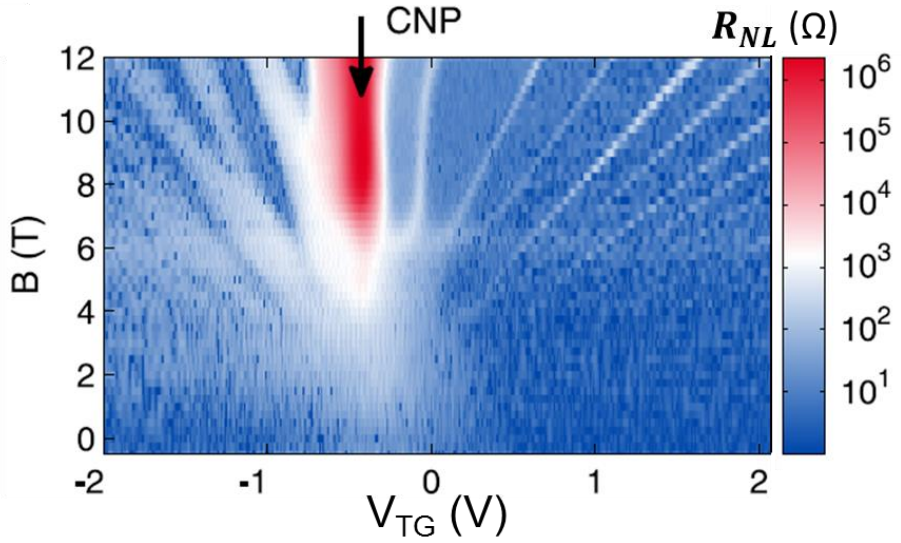
$$R_{NL} = \frac{V_{NL}}{I}$$



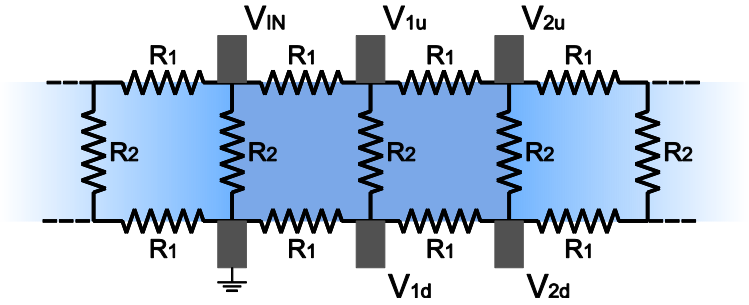
- The non-local resistance follows an exponential decay:

$$R_{NL}(x) = R_0 e^{-x/l_0}$$

- Diffusive transport : $l_0 = W/\pi = 8\ \mu m$



- Simple resistive network model



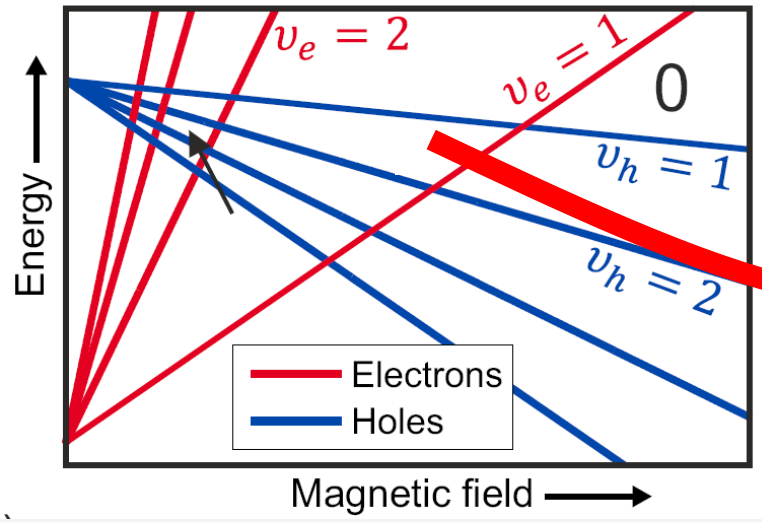
$$\frac{R_1}{R_2} = \frac{1}{100}$$

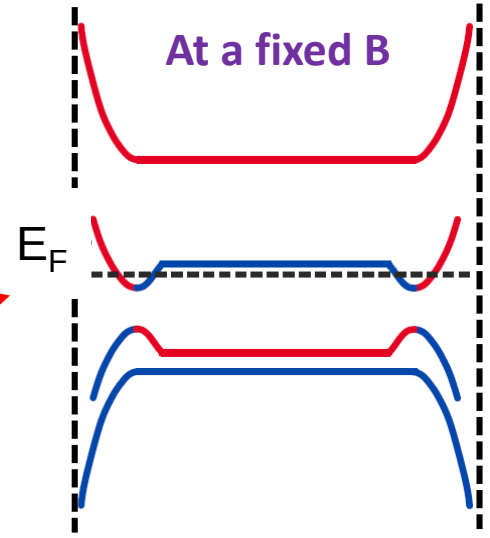
R_1: Edge channel resistance

R_2: Bulk resistance

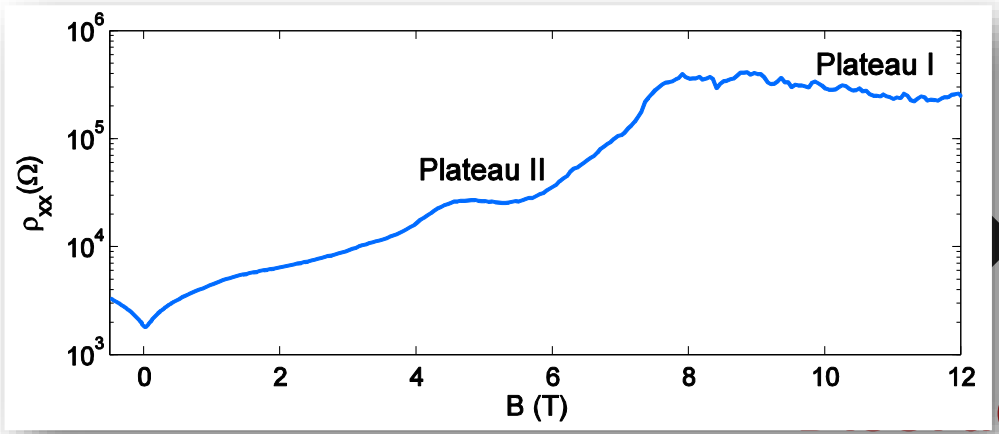
A qualitative model

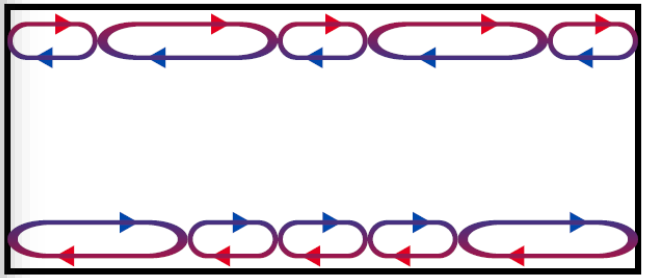
- At finite field, electron and hole Landau levels can hybridize
- The formation of energy gaps is masked by disorder potential





Sample Edge





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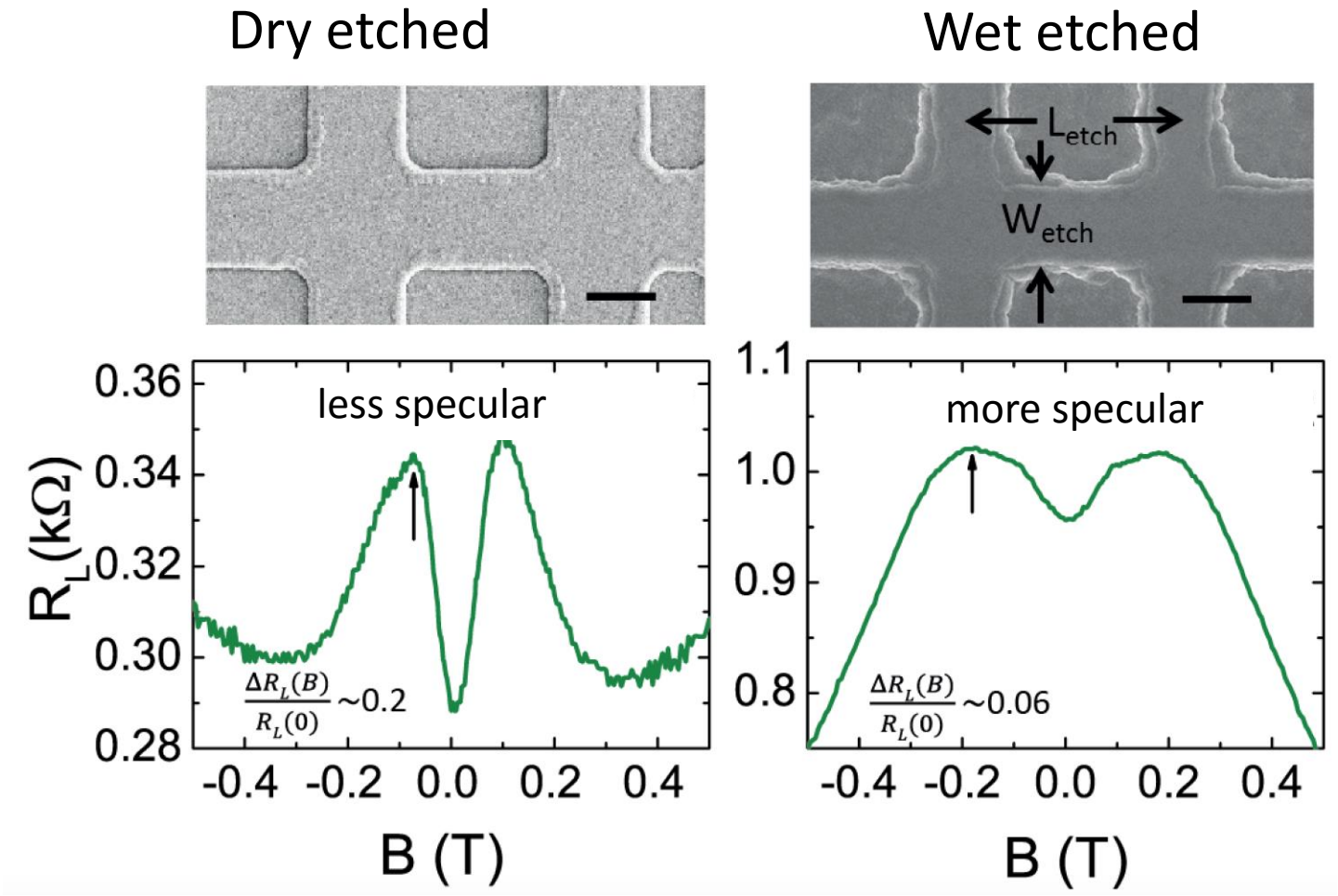
Part II:
Towards quantum spin Hall effect

Fabrication of mesoscopic Hall bars

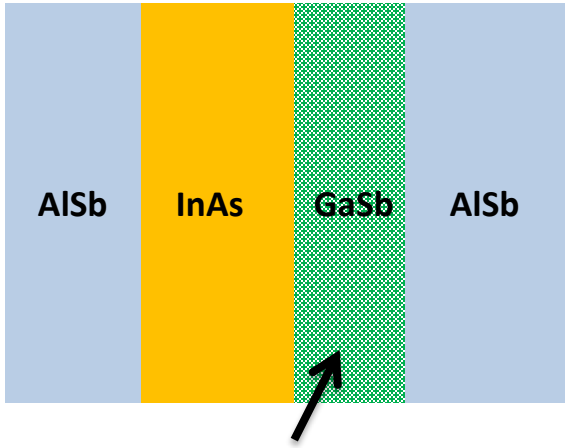


devices passivated by 200 nm of Si_3N_4

A N Pal *et al* AIP ADVANCES 5, 077106 (2015), arXiv:1502.06697

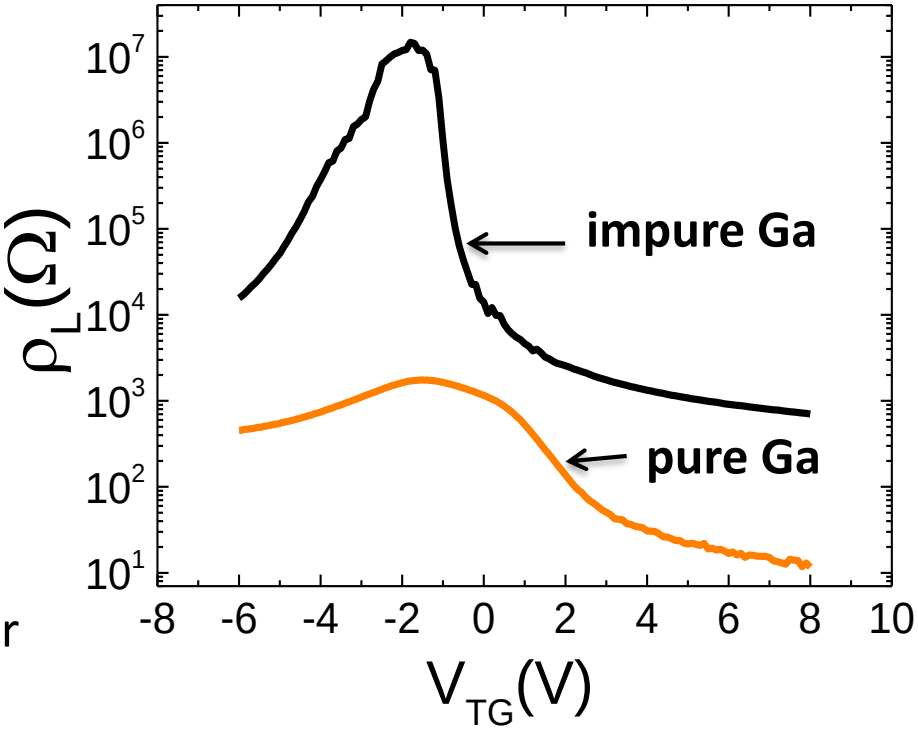
Reducing bulk conduction in InAs/GaSb

- Small hybridization gap (few meV).
- Wave functions do not 100% overlap: Residual e and h



Introducing impure **Ga** in the **GaSb** layer

D1: 25 µm x 50 µm Hall bar



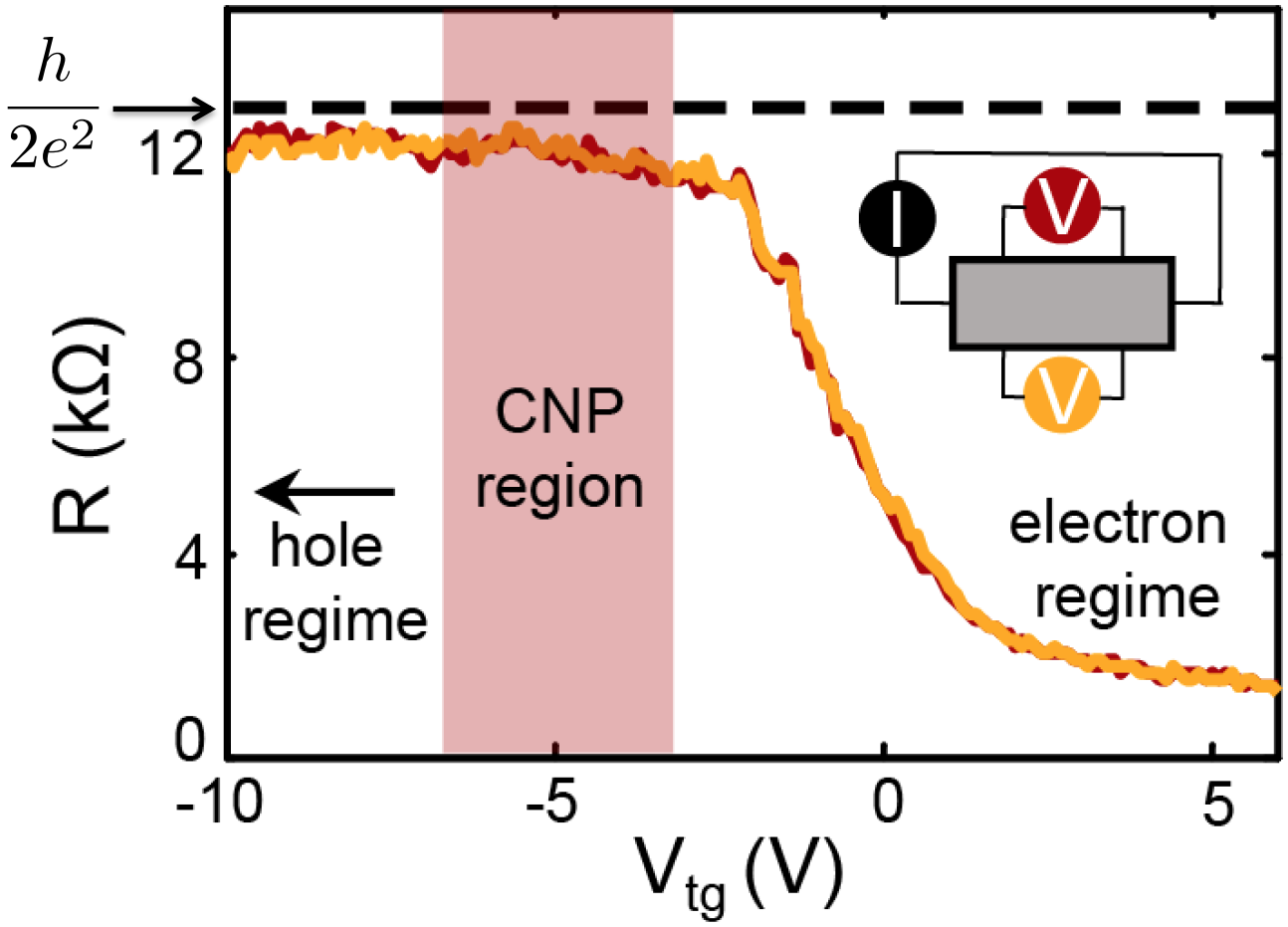
Charpentier *et al.* APL 103, 112102 (2013)

Du *et al.* PRL 114, 096802 (2015)

Dong-Hui Xu et al., PRB 89, 195104 (2014)

Suzuki *et al.* PRB 87, 235311 (2013)

Small devices – four-terminal resistance

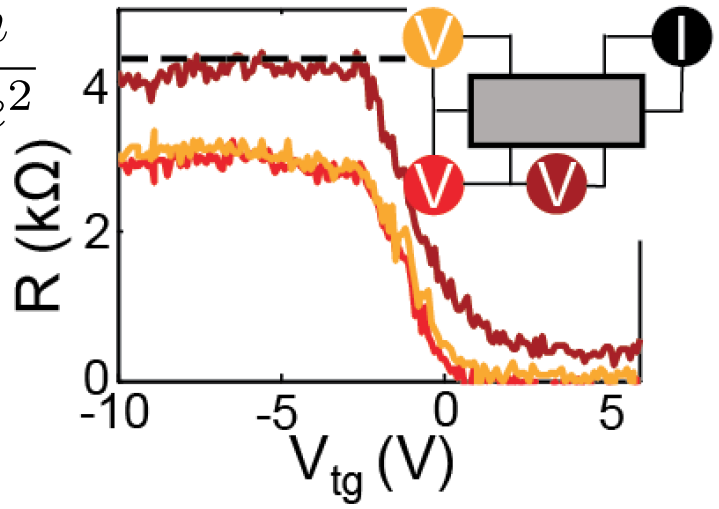


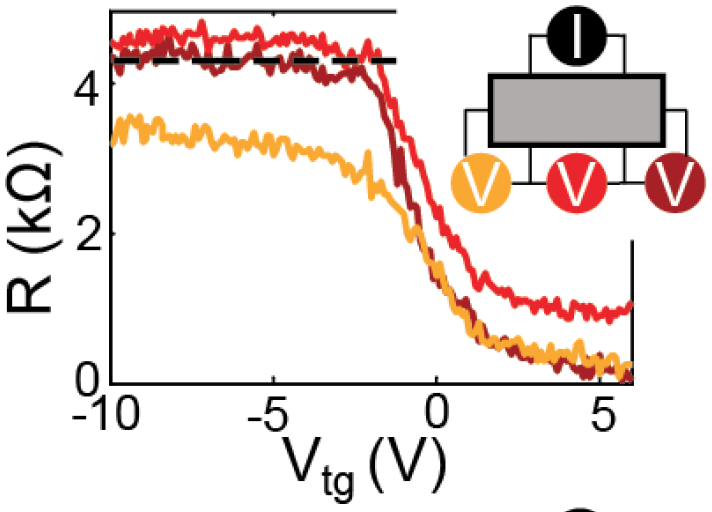
➔ Plateau value close to expected $h/2e^2$: helical edge transport?

Non-local resistance – systematics

$R_{\mathrm{nl}} = \dfrac{h}{6e^2}$

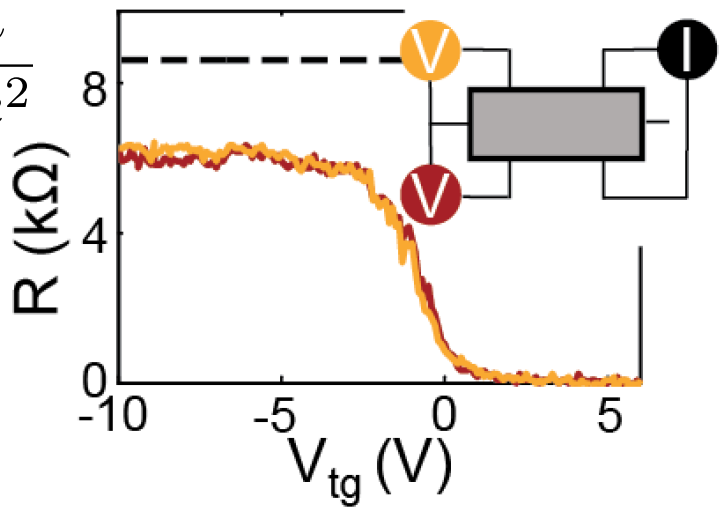
70%

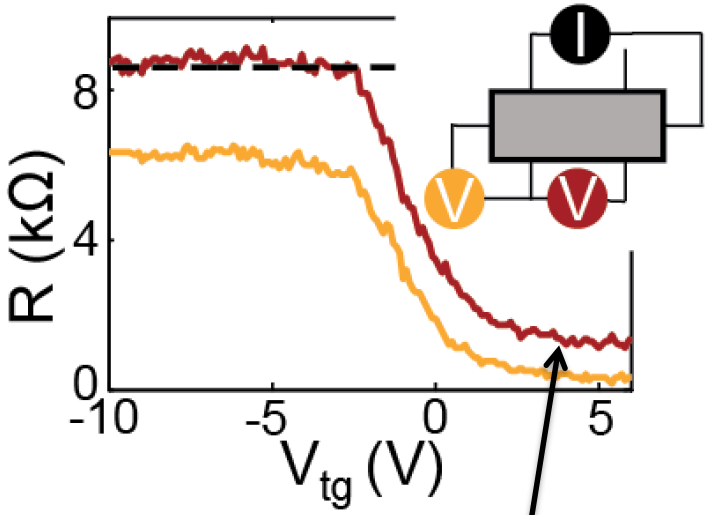




$R_{\mathrm{nl}} = \dfrac{h}{3e^2}$

70%

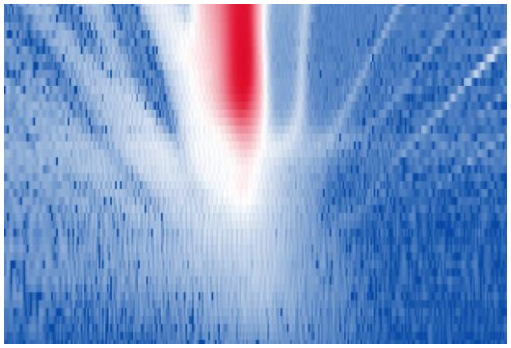




local contribution

Conclusion

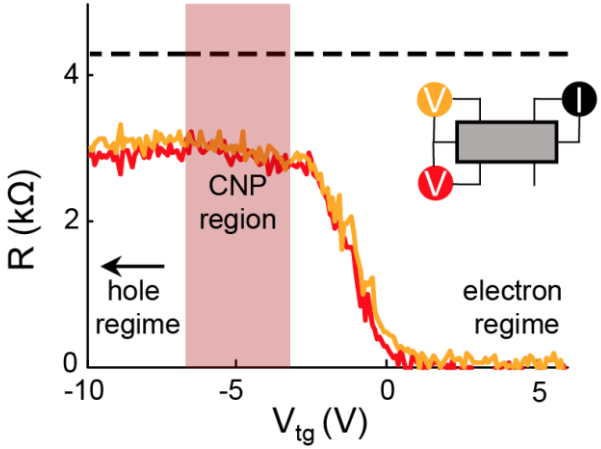
Magnetotransport in high-mobility InAs/GaSb quantum wells



Giant non-local response at the CNP at high magnetic fields mimicking helical edge channels

F. Nichele, A N Pal *et al*, PRL **112**, (2014).

Hunting topological insulator behavior in lower mobility samples



A glimpse of helical edge channel transport at zero magnetic field

Non-local resistivities are systematically low

S. Mueller, A N Pal *et al* PRB (R) 92, 081303(R) (2015)

Thank you for your attention!

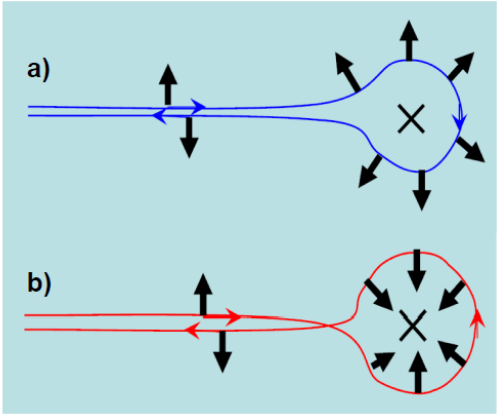


Figure 2.7 : Scattering of a quantum spin Hall edge state around a non-magnetic impurity. Due to time reversal symmetry the spin rotates by π in the clockwise direction and $-\pi$ in the counterclockwise direction, with a total change in phase of 2π. Upon 2π spin rotation the wavefunction changes sign and the two paths interfere destructively [5].

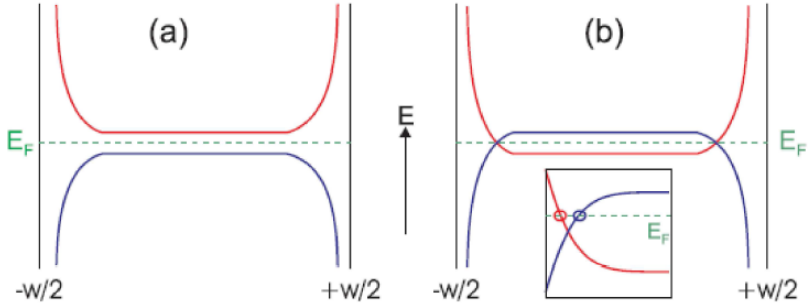
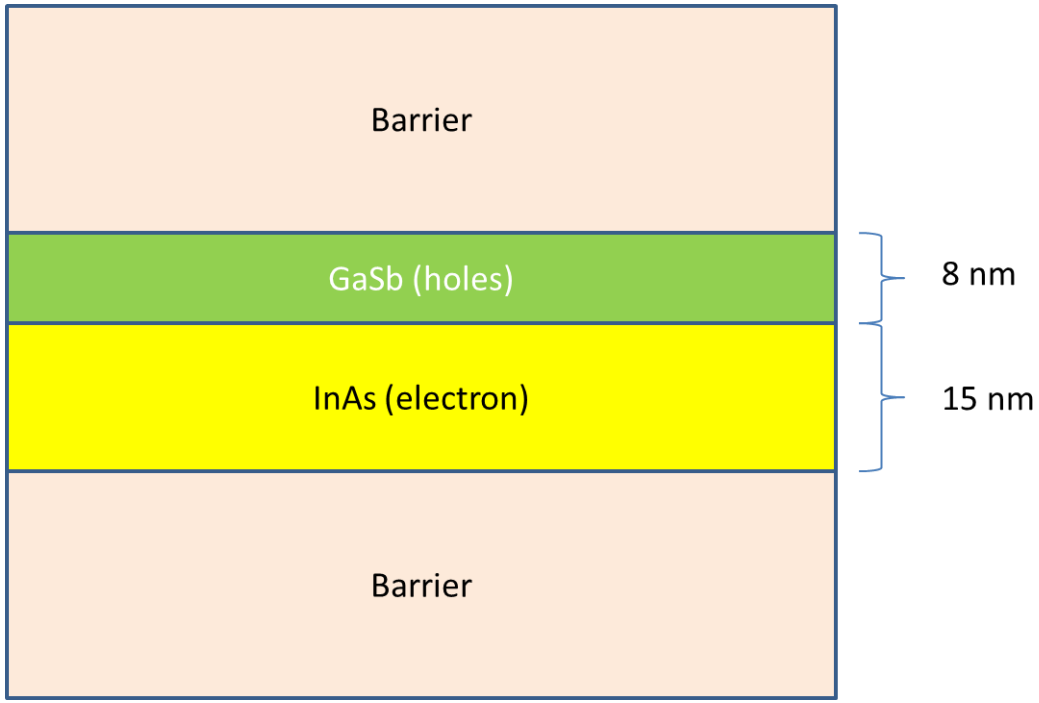
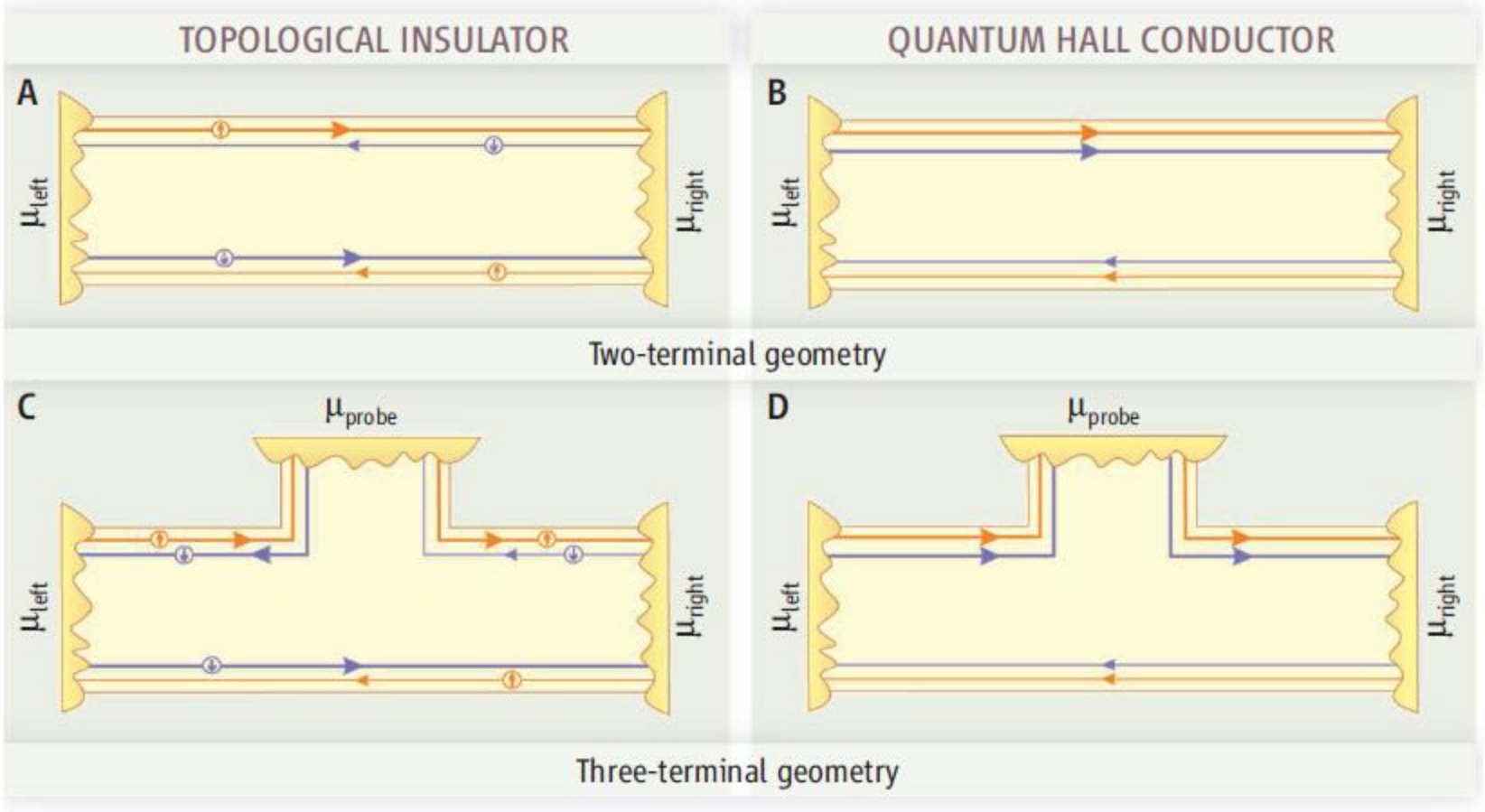


Figure 2.6 : Energy spectrum in real space for normal regime in a) and inverted regime in b). The confinement potential for electrons and holes has opposite direction. For the inverted structure and Fermi level E_F in the gap, E_F crosses energy states at edges, while for the normal regime E_F stays in the gap for the entire width of the sample [58].


Barrier
GaSb (holes)
InAs (electron)
Barrier
8 nm
15 nm

QHE and QSHE



Markus Büttiker, Science, 325, 278 (2013)