Recent Results from Single and Double Layer Quantum Hall Systems

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Division of Materials Sciences

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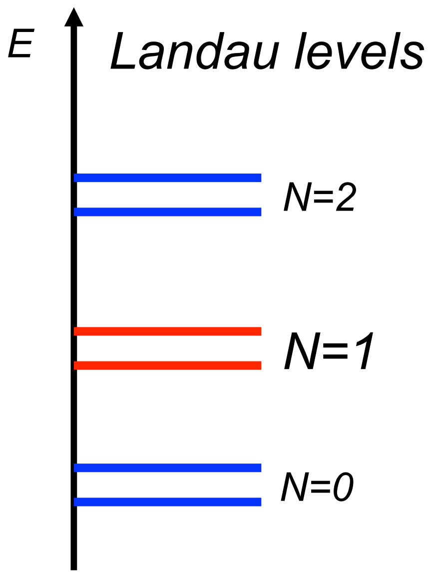
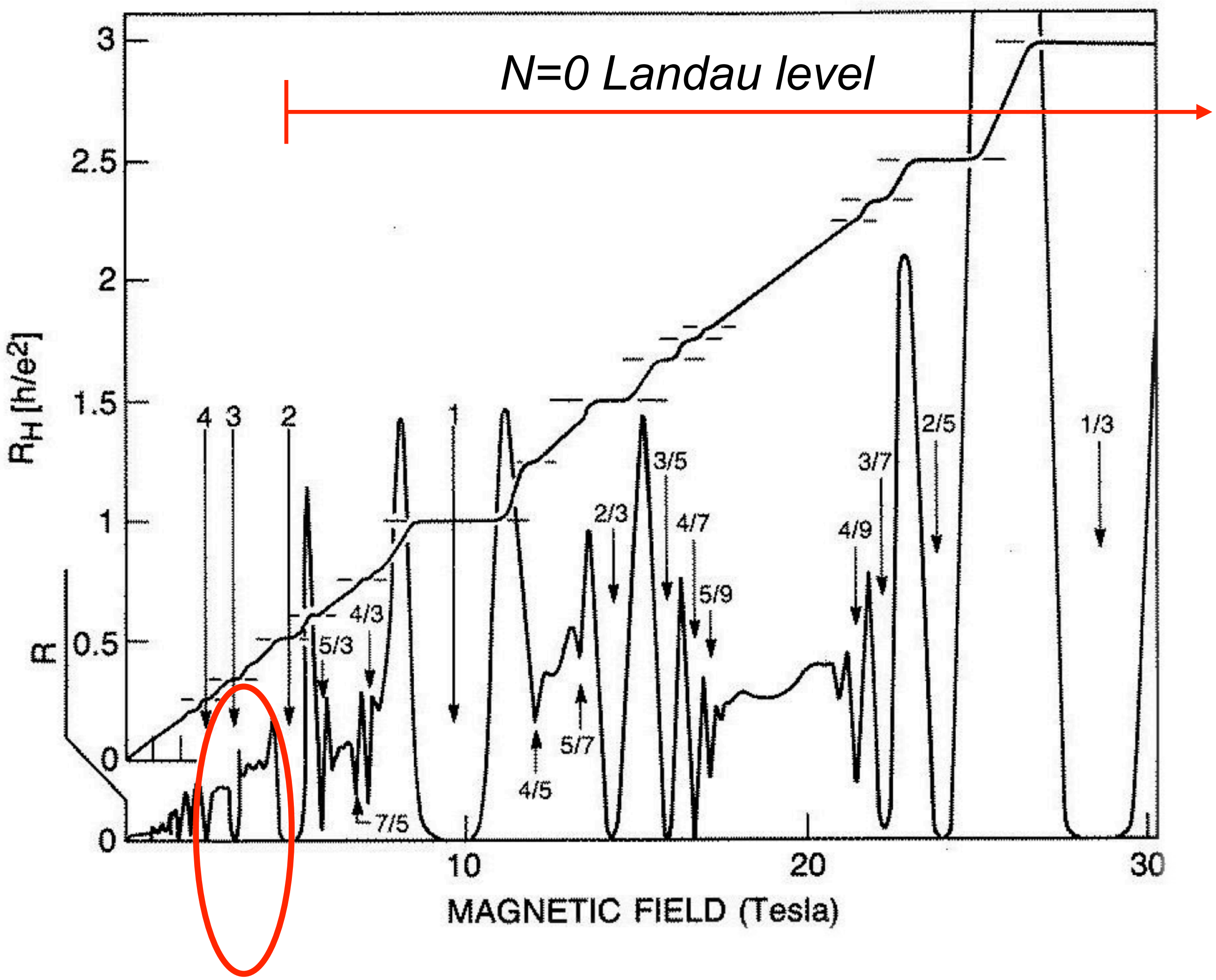
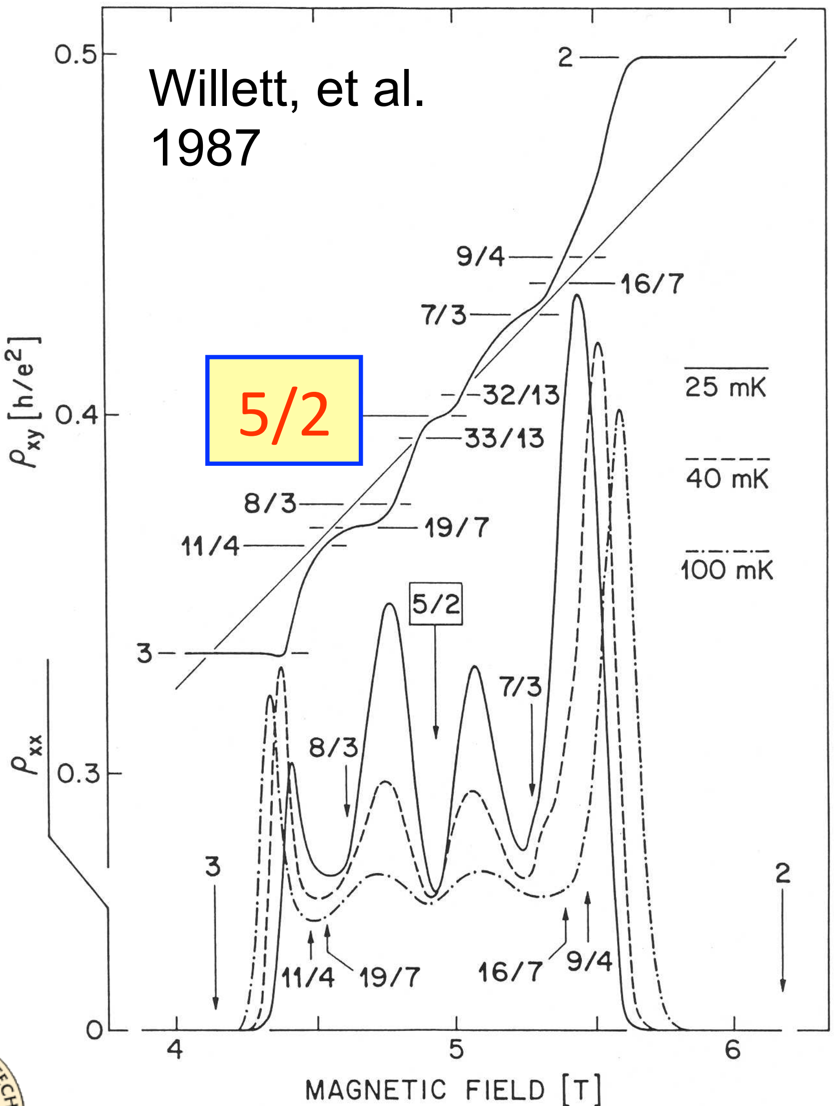
Single layer FQHE systems

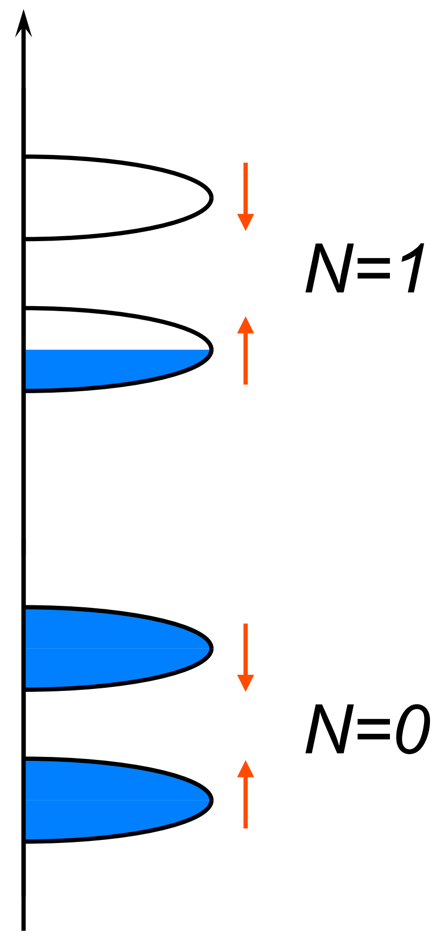
N=1 Landau level



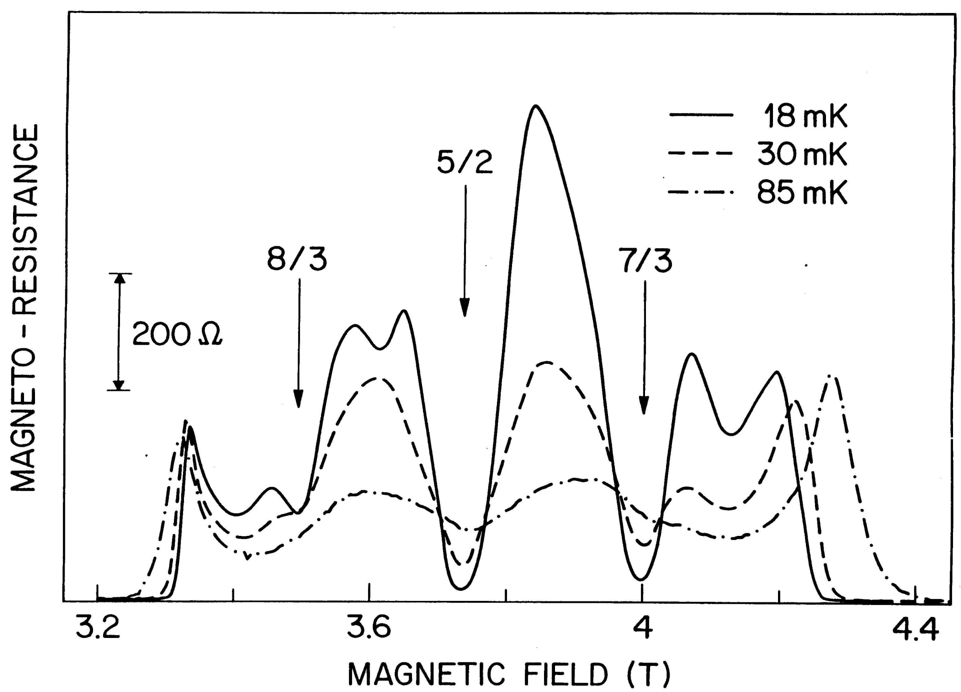


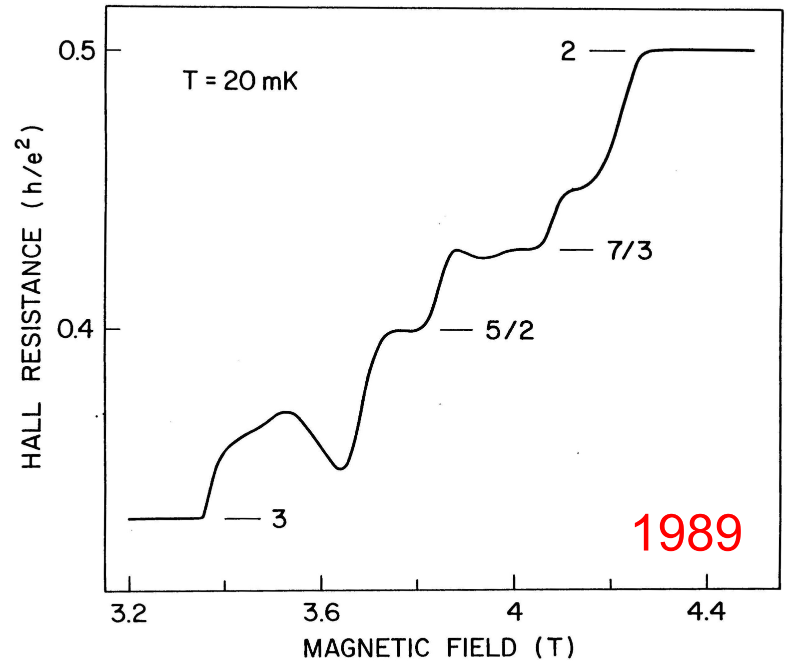
Even-denominator FQHE





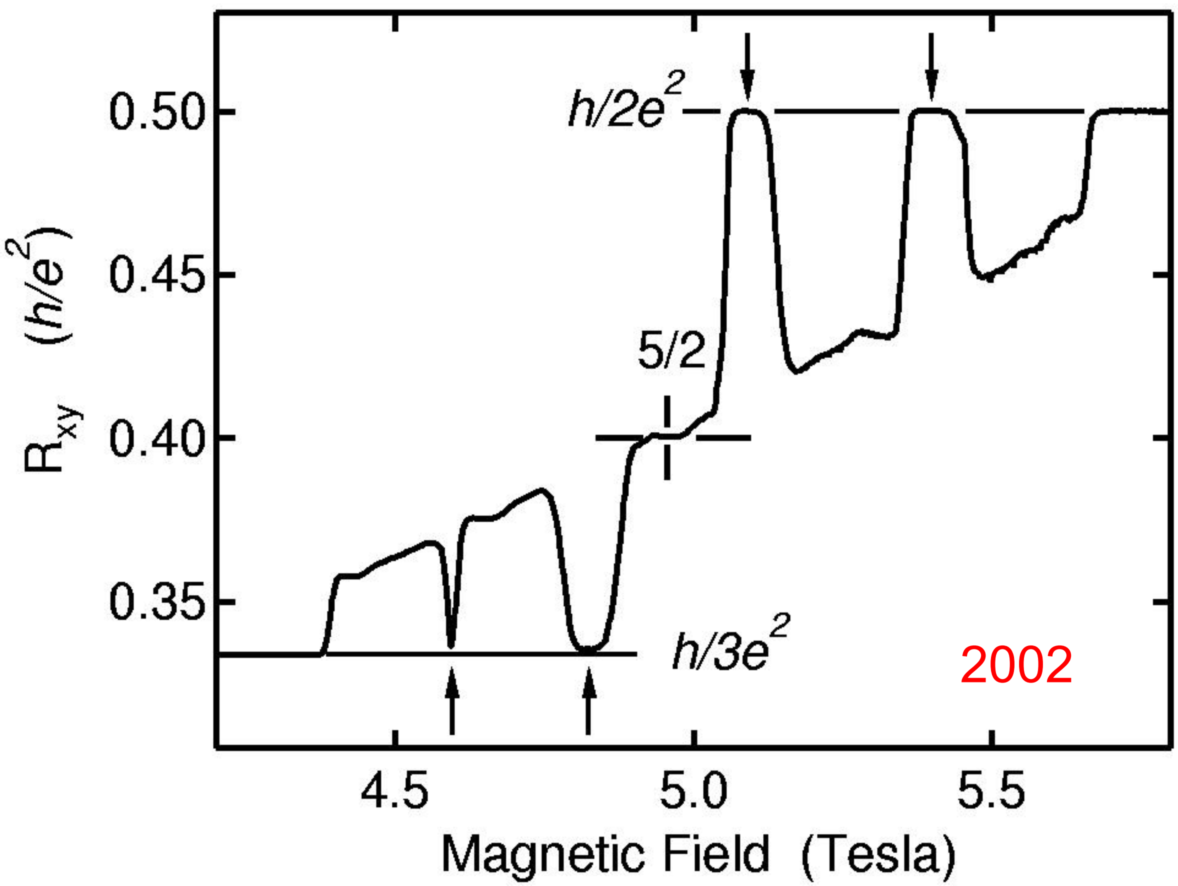
Better sample





Vanishing R_{xx} and good Hall plateau

Re-entrant integer QHE states

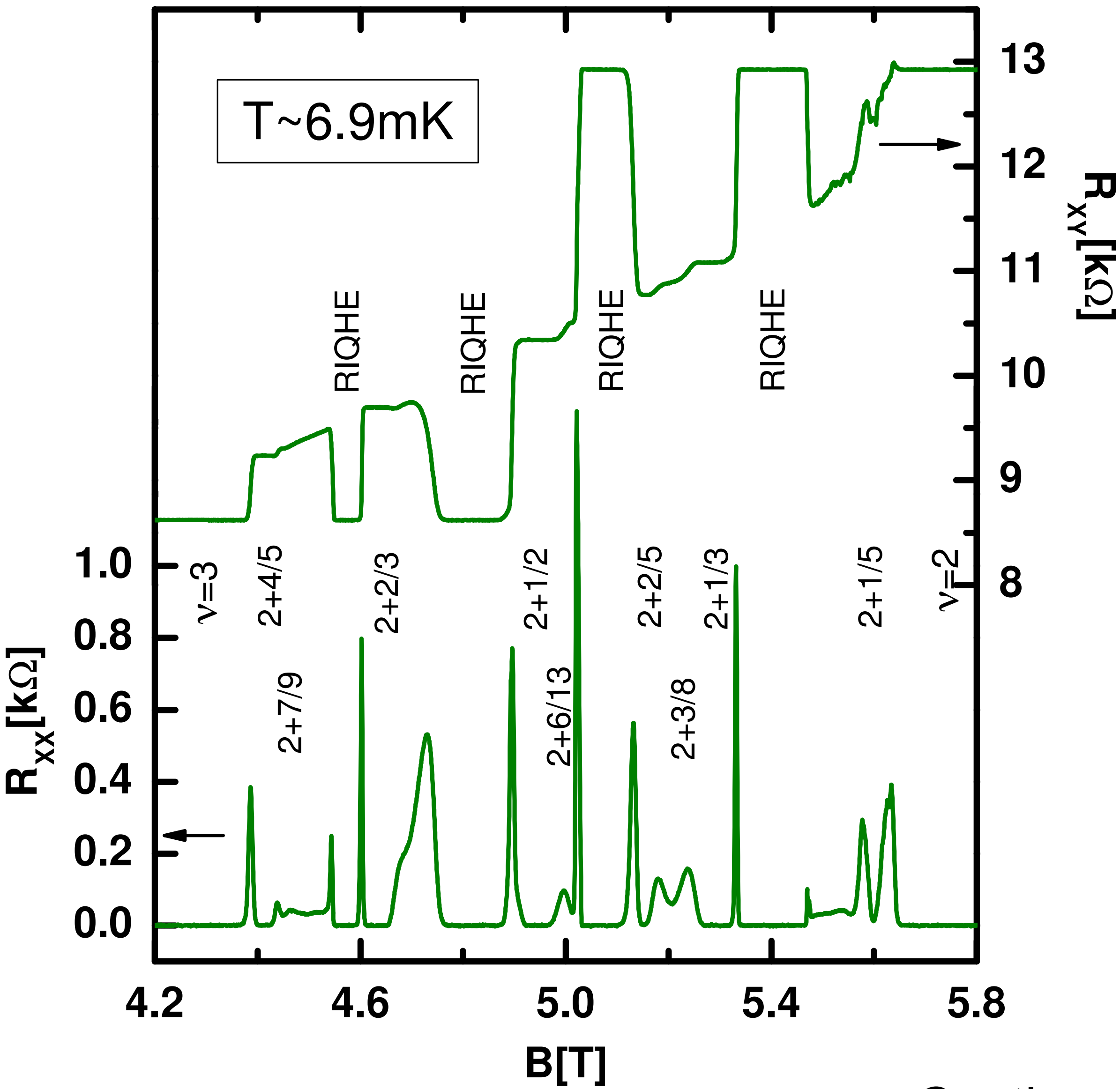


Integer Hall quantization near

$\nu - 2 \approx 2/7, 3/7, 4/7,$ and $5/7$

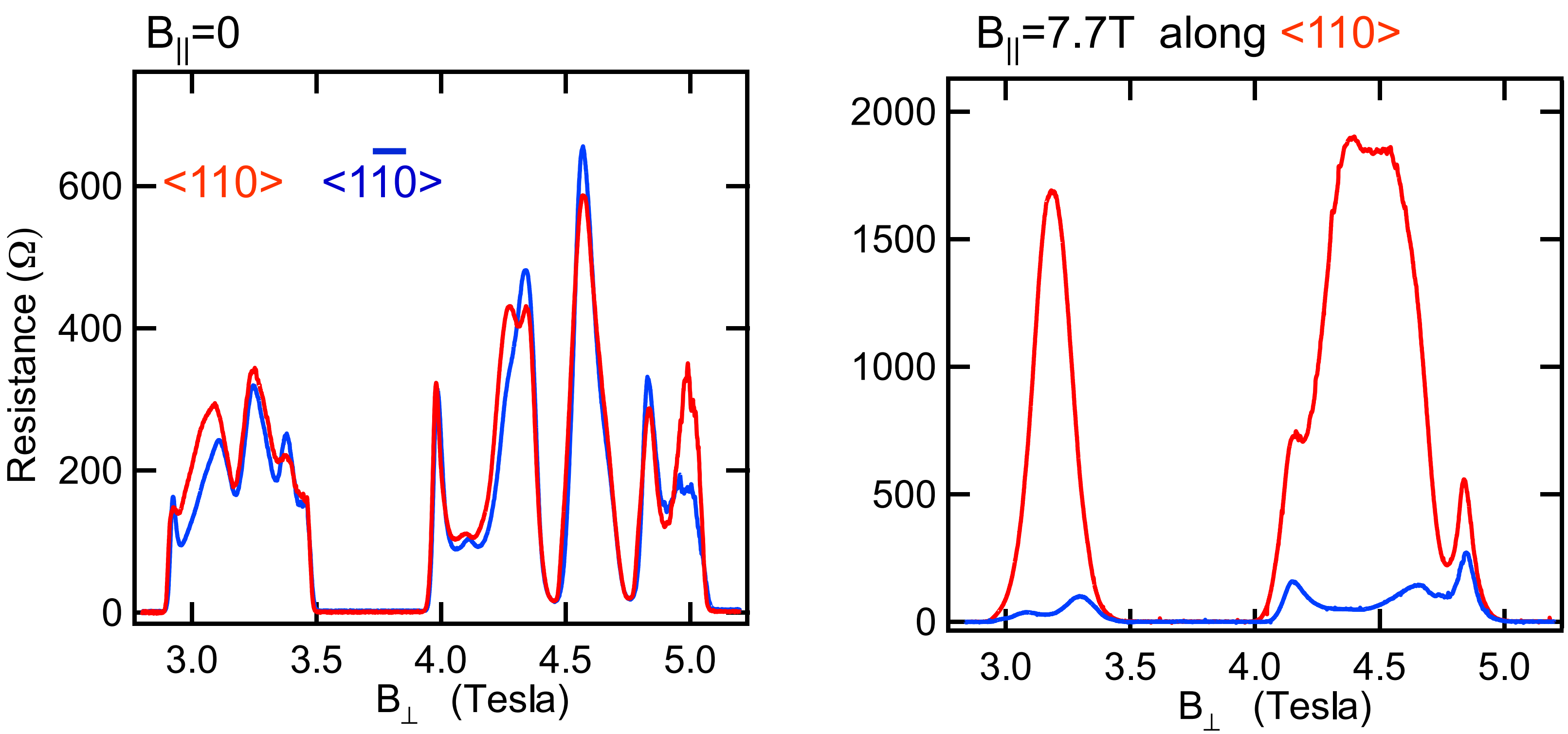
New Collective Insulators

Best data yet?



Csathy, et al PRL 2010

5/2 State in tilted fields



Tilting destroys 5/2 and 7/2 FQHE states and produces strongly anisotropic transport. Competing phases must be nearby.

Nearly degenerate phases at 5/2

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Incompressible Paired Hall State, Stripe Order, and the Composite Fermion Liquid Phase in Half-Filled Landau Levels

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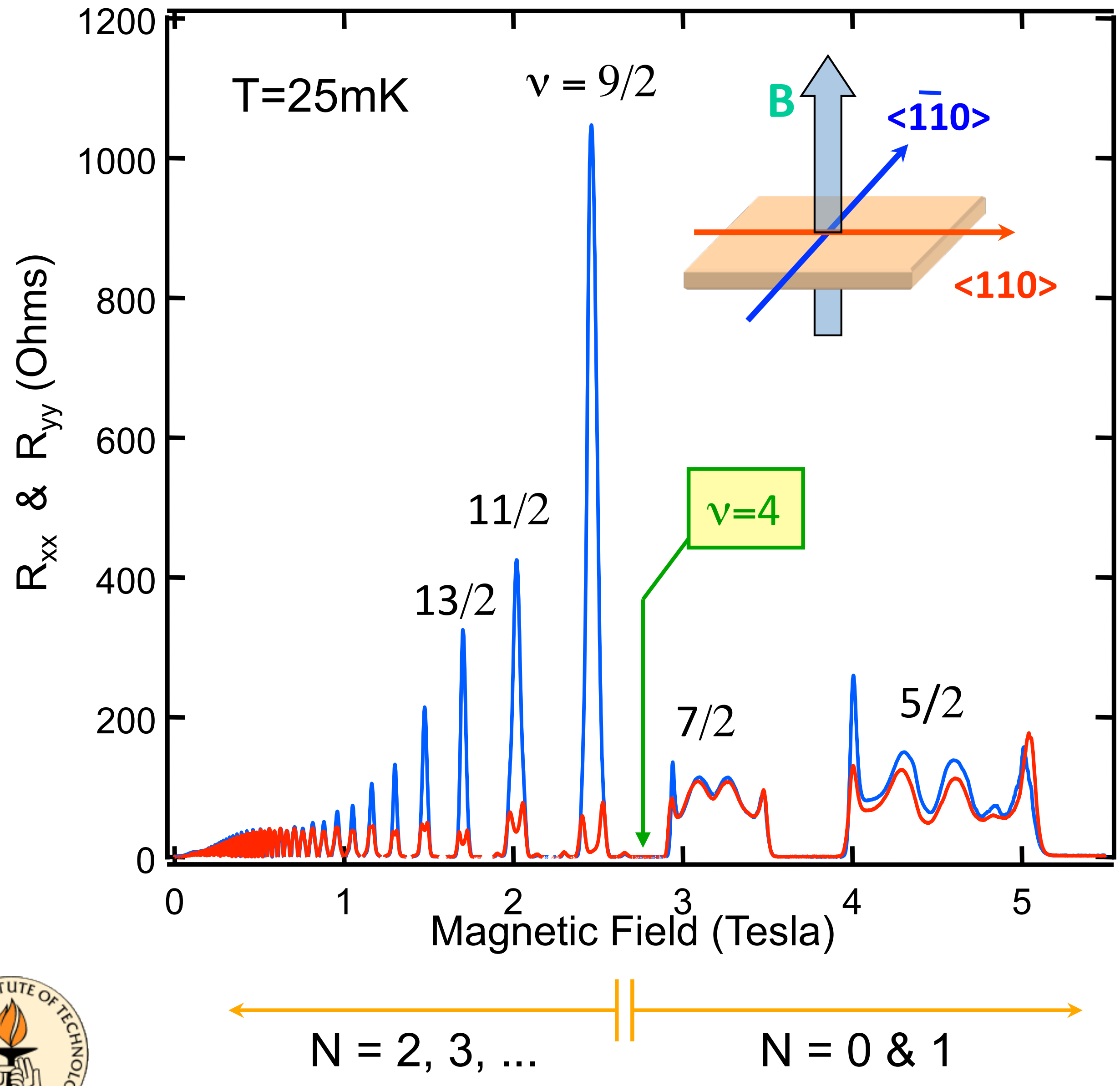
We consider the two lowest Landau levels at half filling. In the higher Landau level ($\nu = 5/2$), we find a first-order phase transition separating a compressible striped phase from a paired quantum Hall state, which is identified as the Moore-Read state. The critical point is very near the Coulomb potential and the transition can be driven by increasing the width of the electron layer. We find a much weaker transition (either second-order or a crossover) from pairing to the composite fermion Fermi-liquid behavior. A very similar picture is obtained for the lowest Landau level, but the transition point is not near the Coulomb potential.

Wider wells stabilize FQHE at 5/2.
Narrowing well drives transition to stripe phase.
Tilting narrows wavefunction?

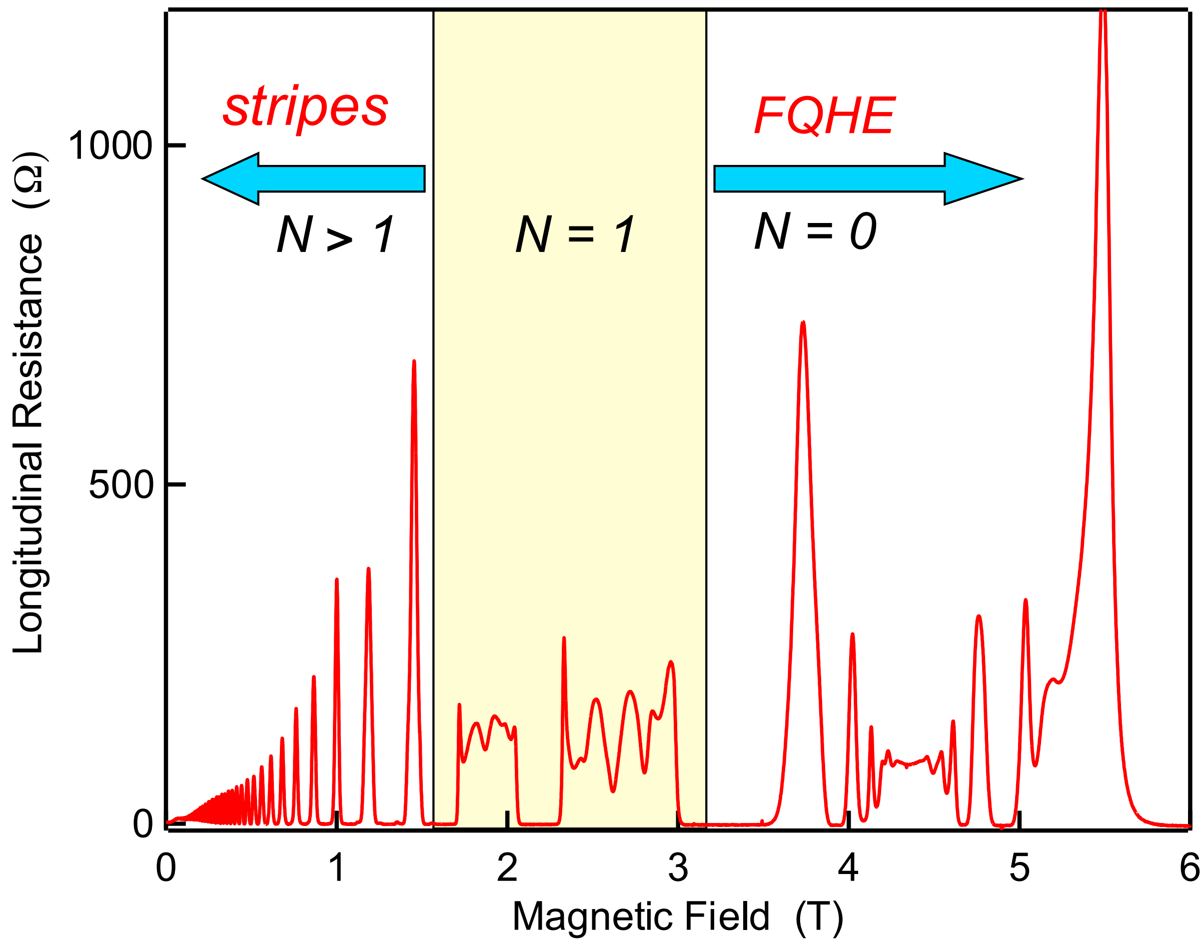
cf. Peterson, Jolicoeur, and Das Sarma, 2008

Transport anisotropy in N ≥ 2 Landau levels

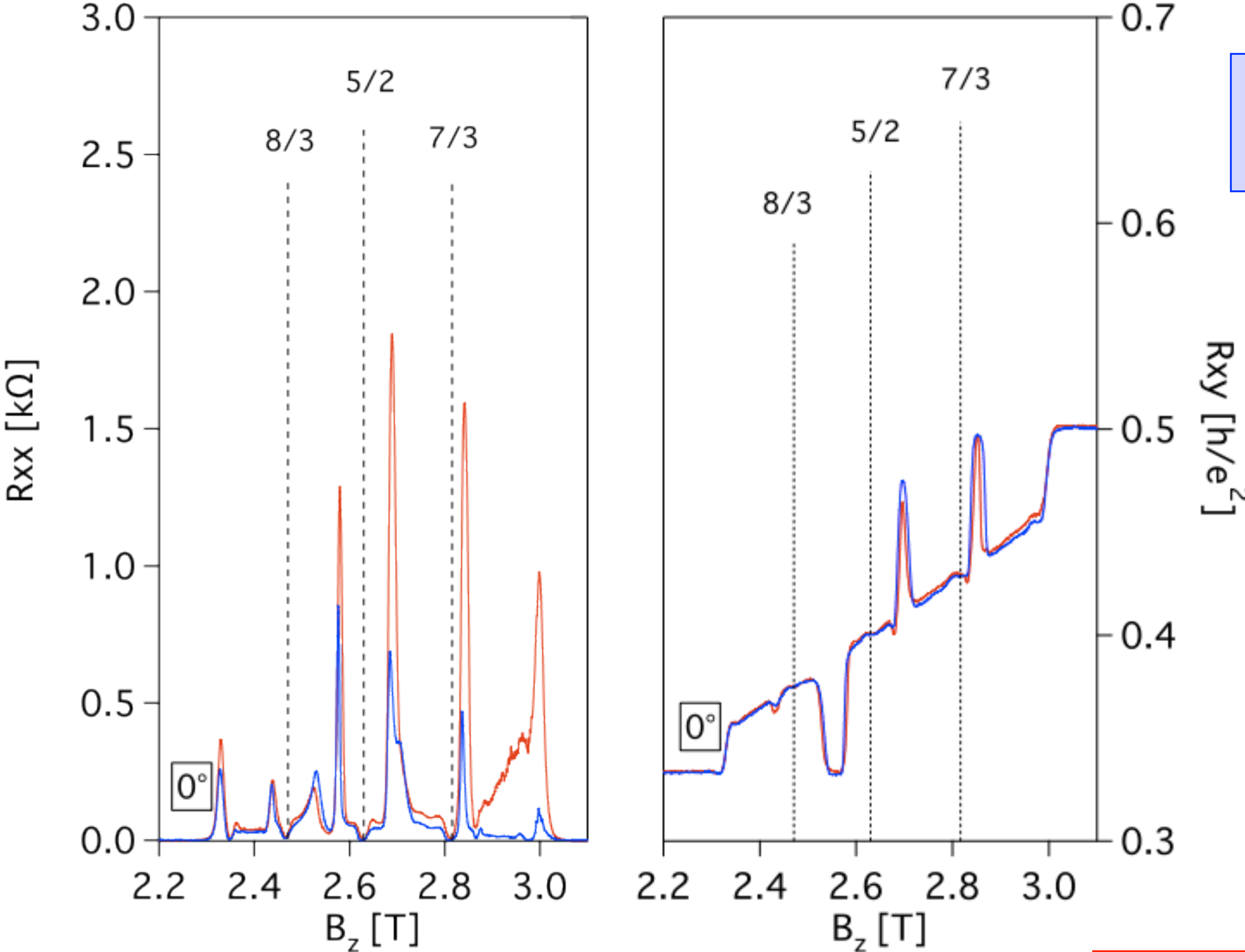


Evidence for electron stripe phases.

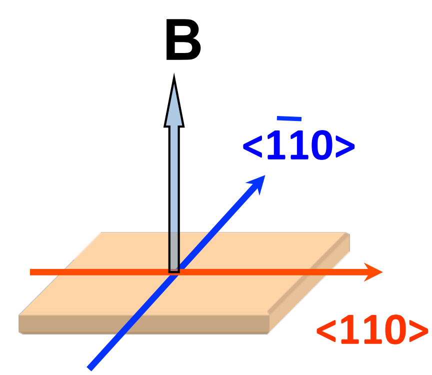
N=1 LL: Land of many phases!



400 Å quantum well

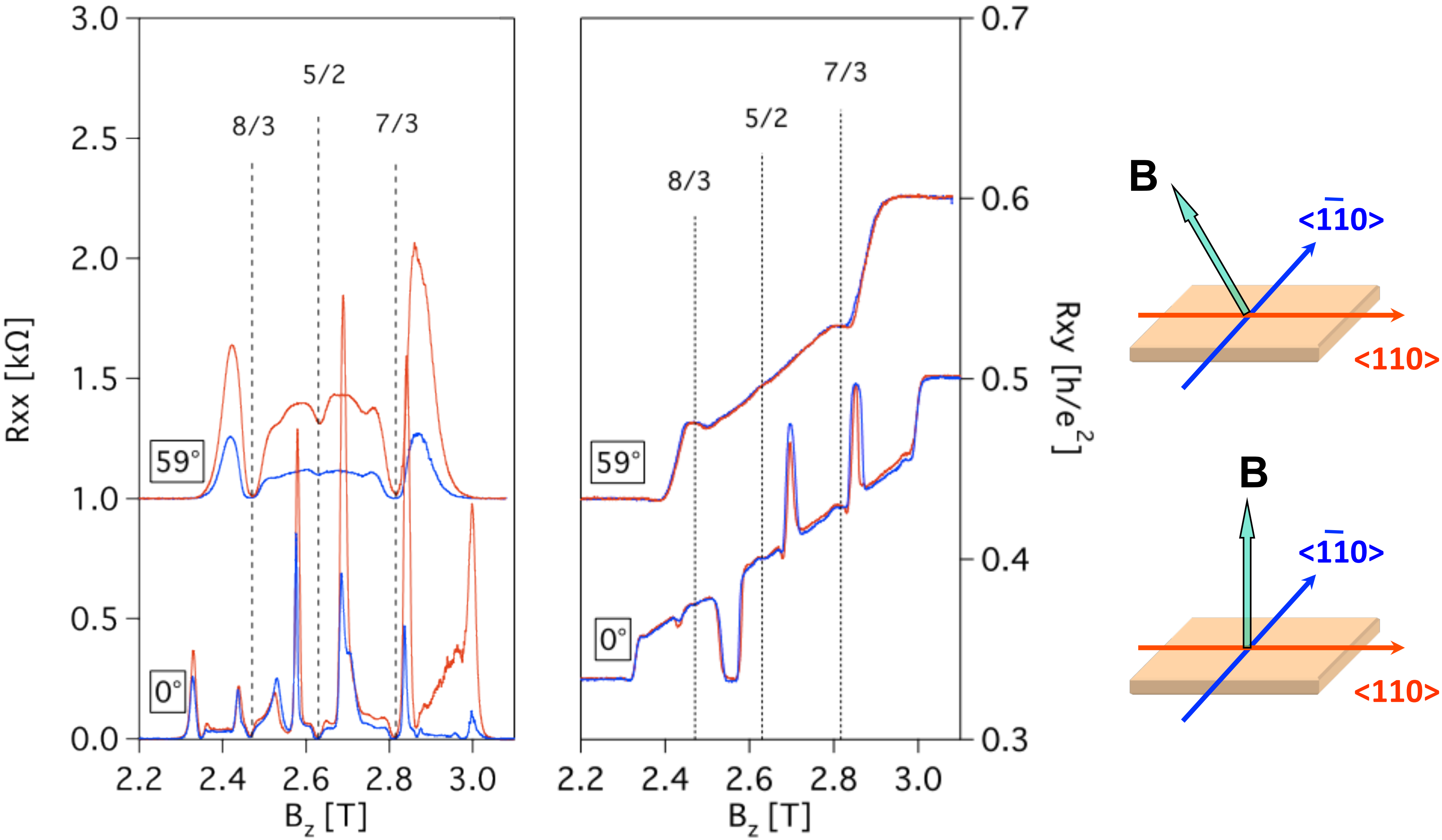


n = 1.6 x 10^{11} cm^{-2}
μ = 16 M



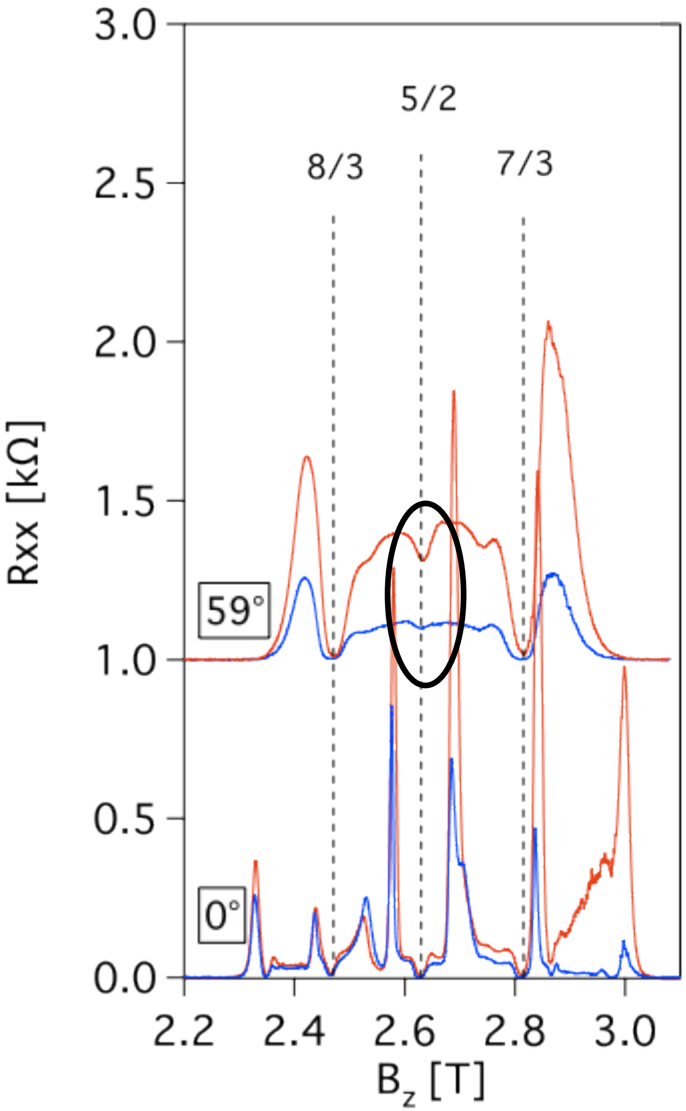
Familiar phenomenology

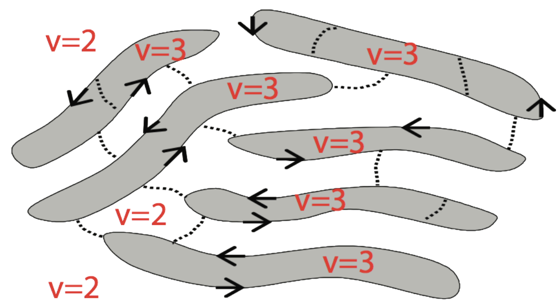
400 Å quantum well

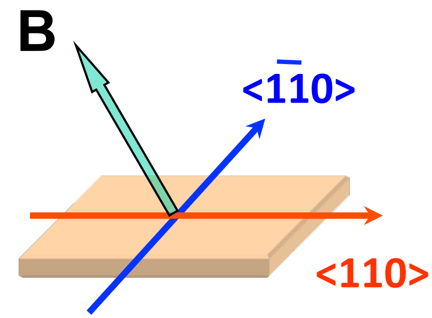


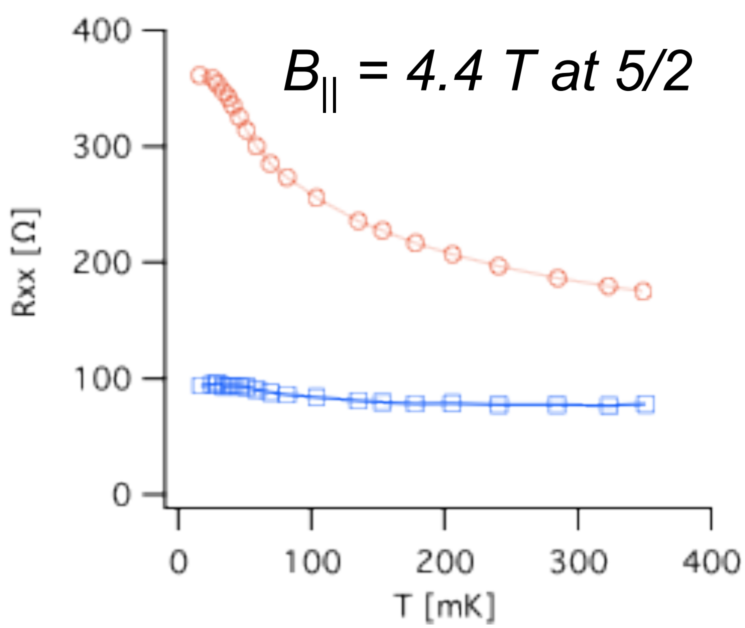
5/2 FQHE and RIQHE destroyed

400 Å quantum well



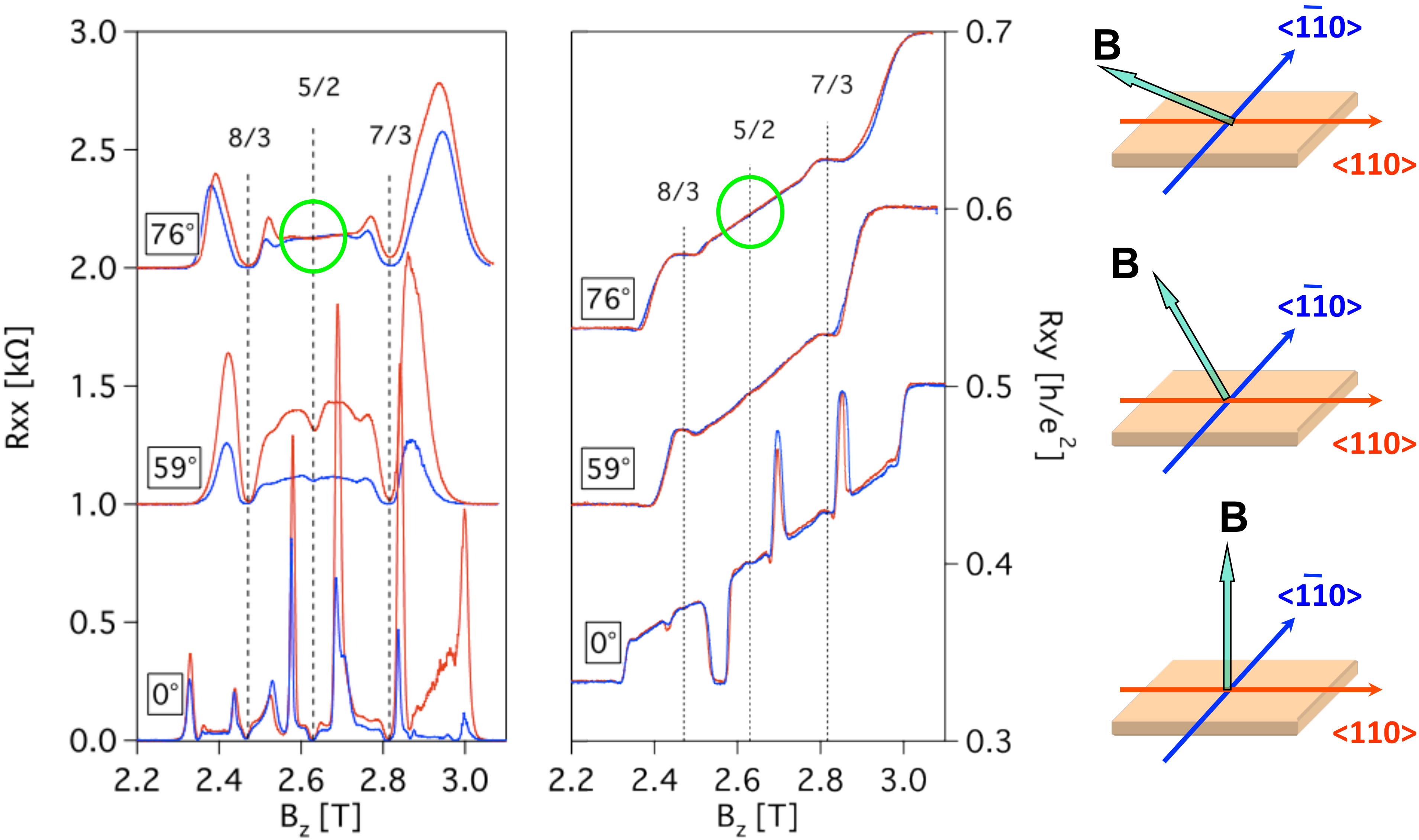






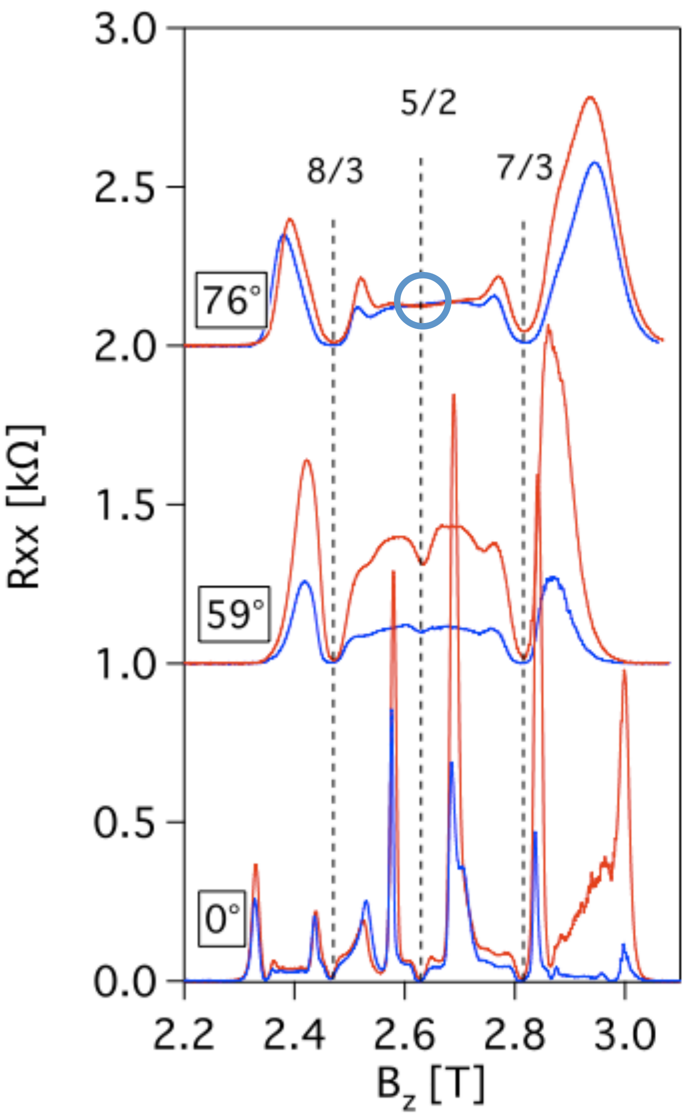
Stripe or Nematic at 5/2

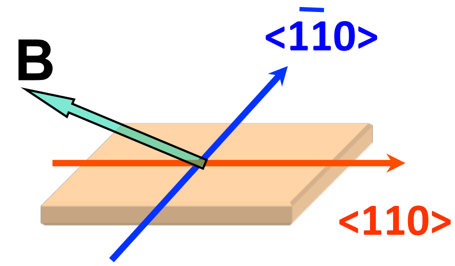
400 Å quantum well

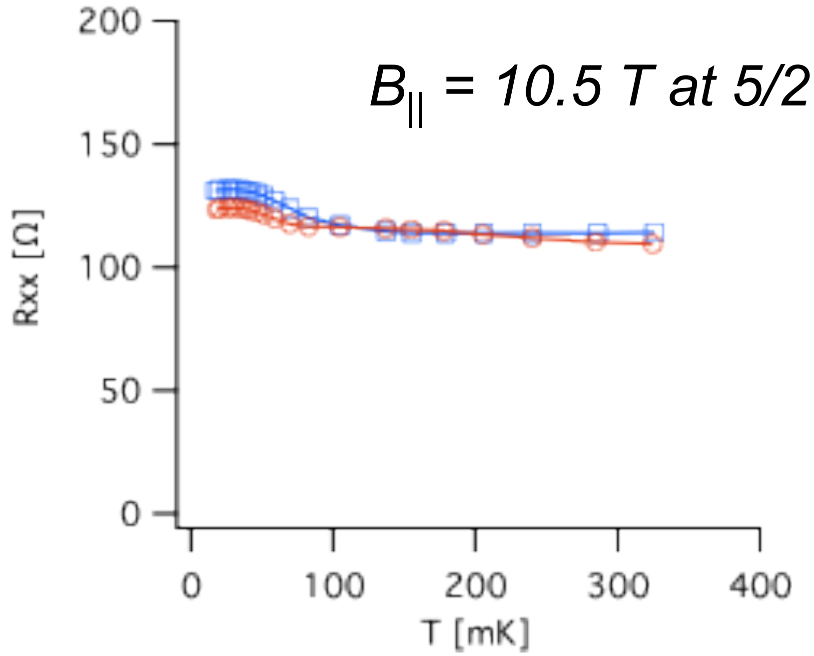


Re-entrant Isotropic Compressible (RIC) Phase at 5/2!

400 Å quantum well

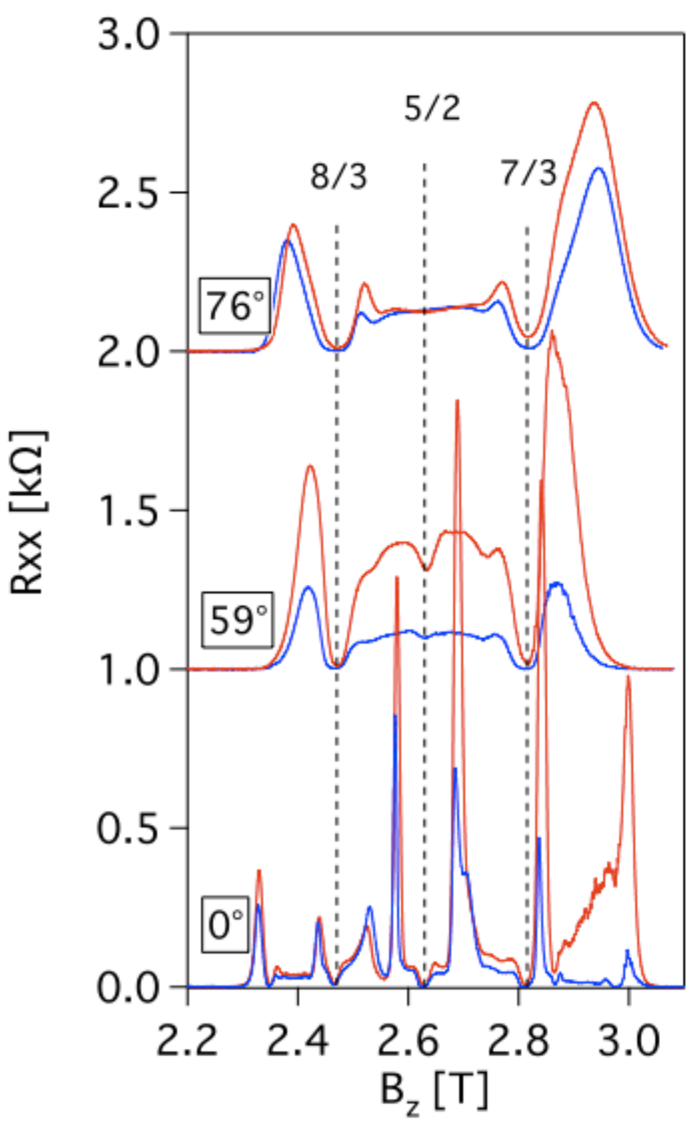


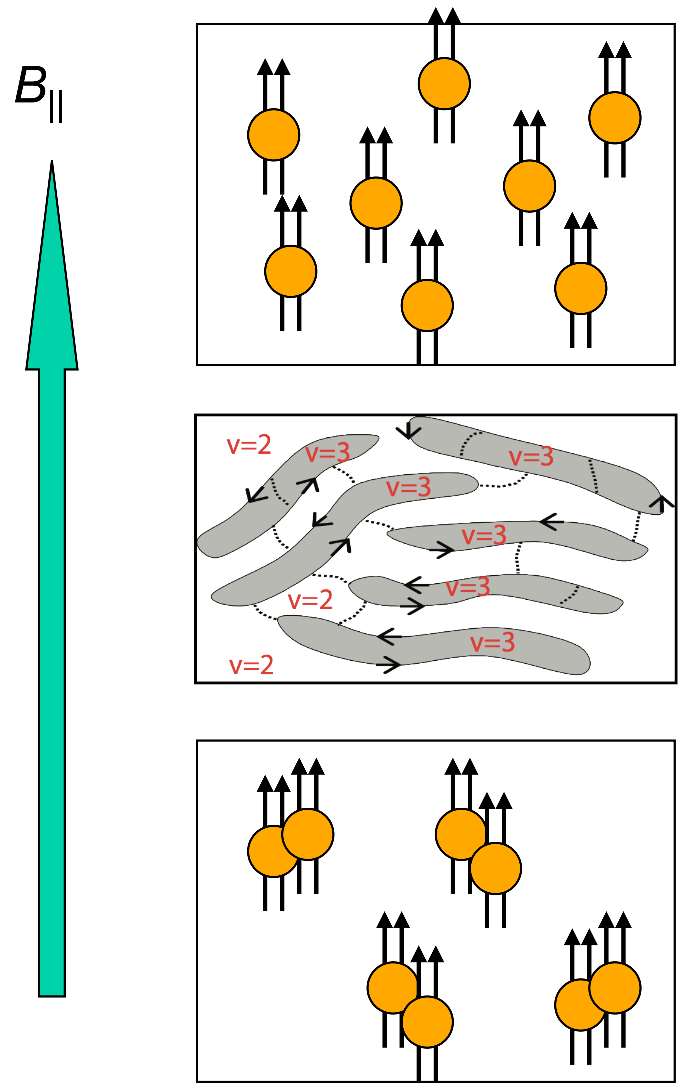




Composite Fermi Sea at 5/2?

Quantum zoology at ν = 5/2





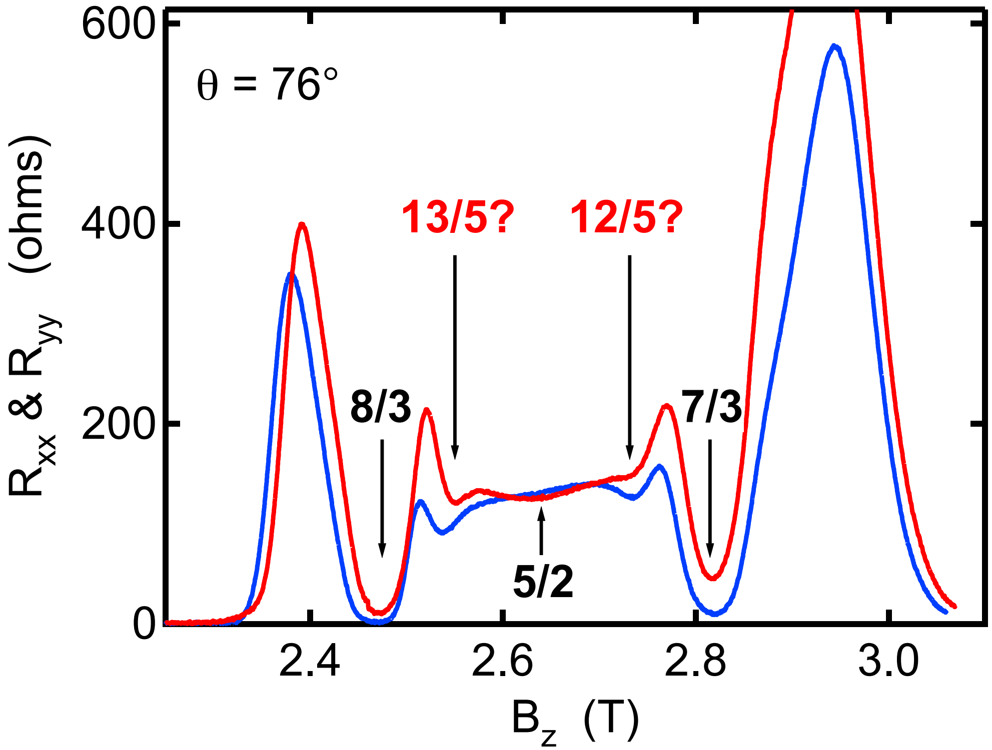
CF Fermi Liquid

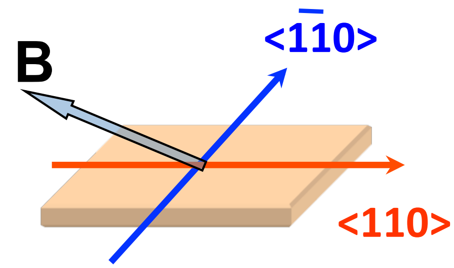
Stripes or Nematic

Paired CF FQHE

What drives these transitions?

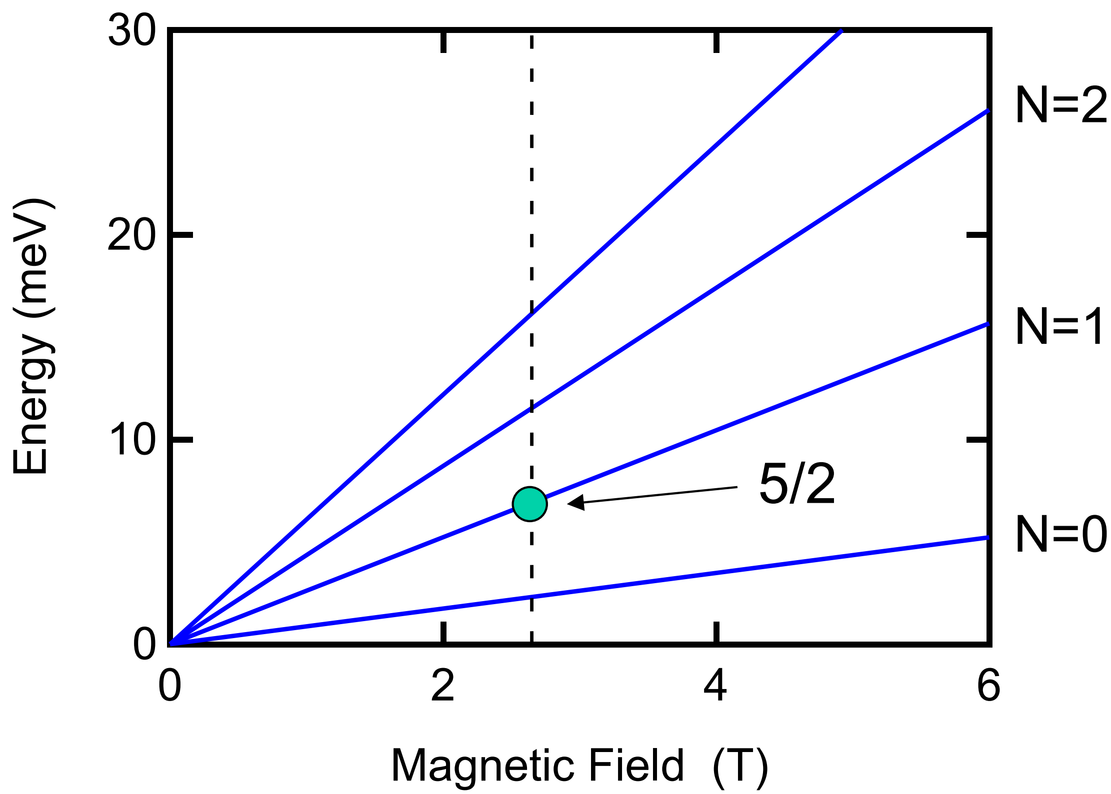
400 Å Quantum Well



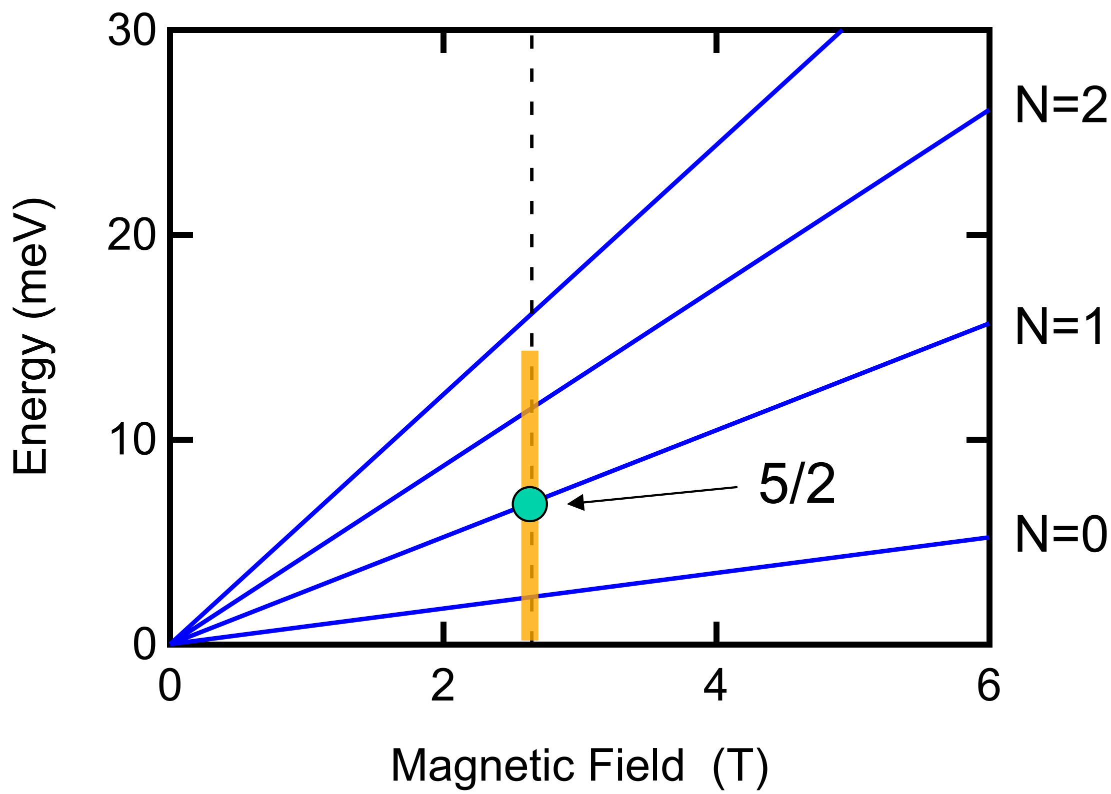


Looks like the lowest Landau level

Landau level mixing

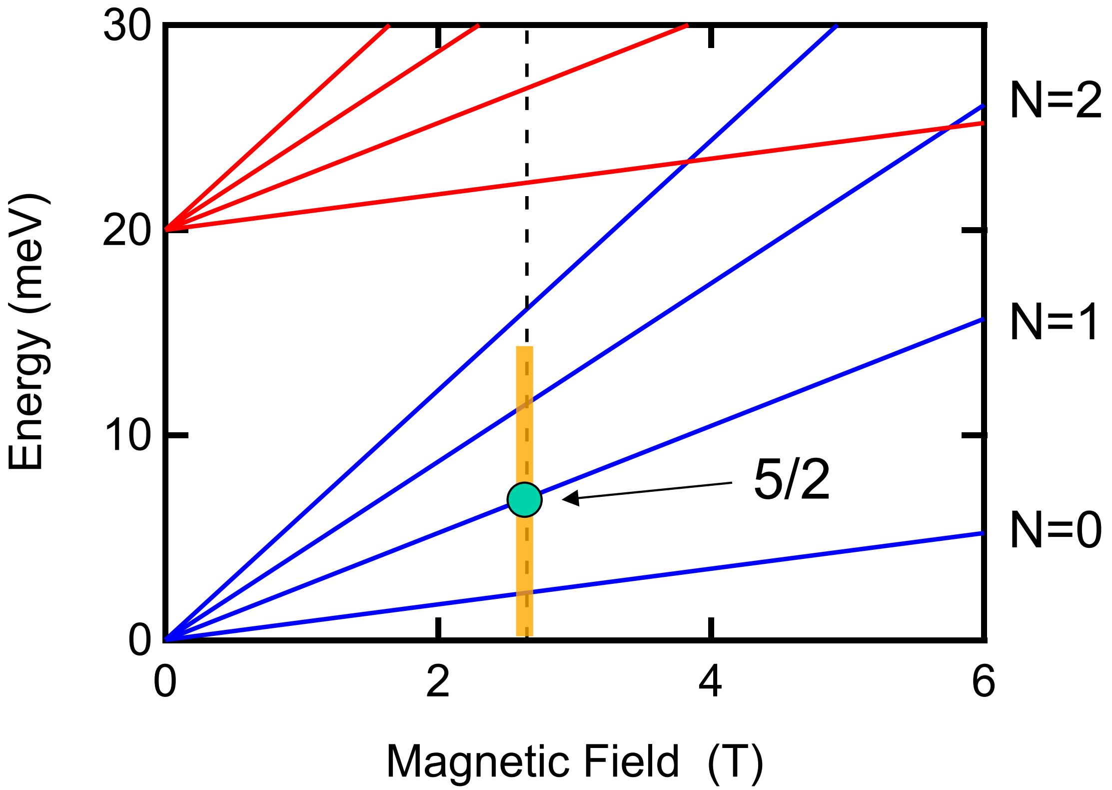


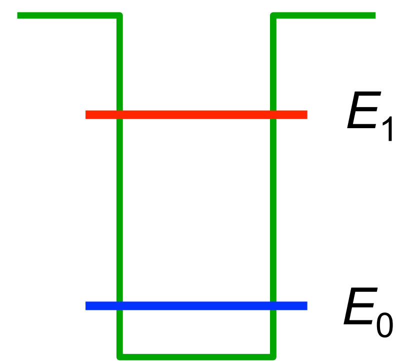
Landau level mixing



$$\frac{e^2}{\varepsilon \ell} \approx 1.5\,\hbar\omega_c \quad @\, B = 2.65\ \mathrm{T}$$

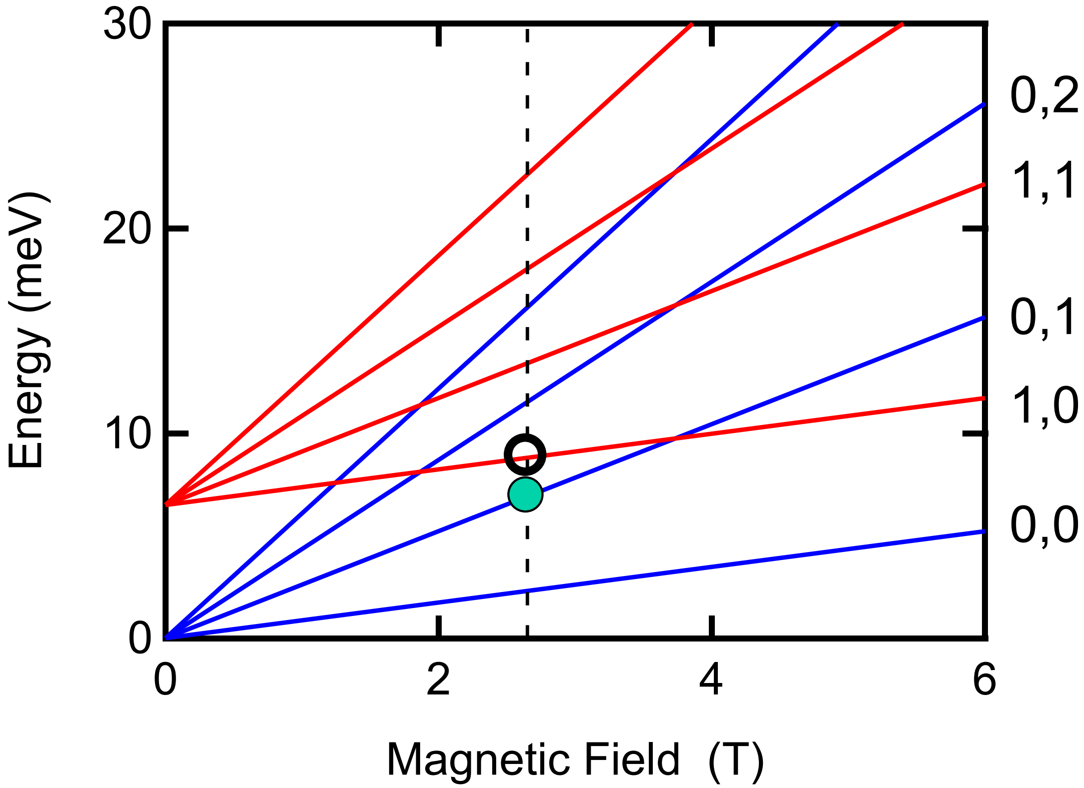
Landau level mixing

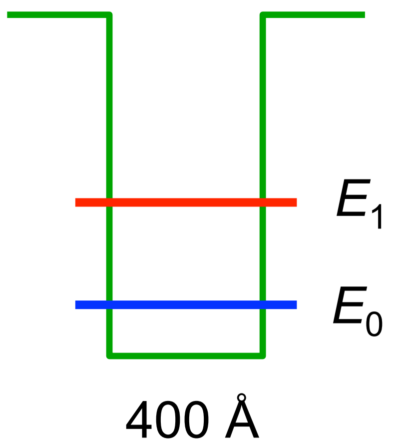




Second subband usually ignored.

Subband – Landau level mixing

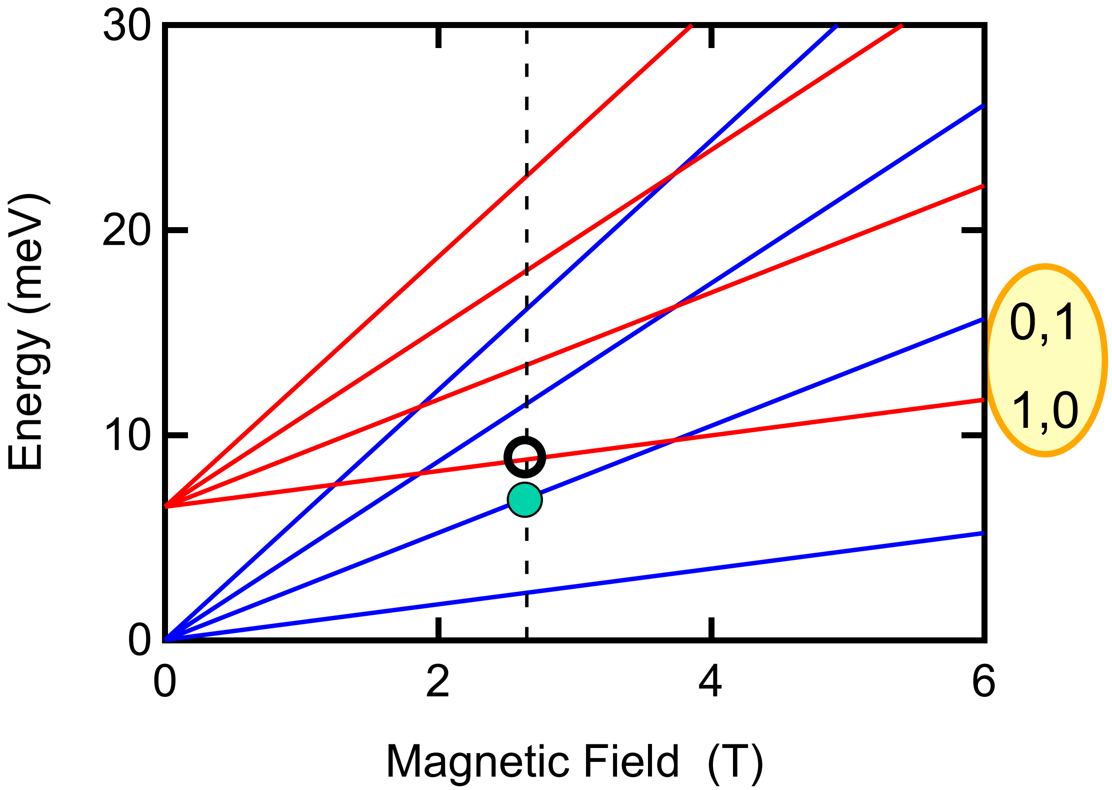


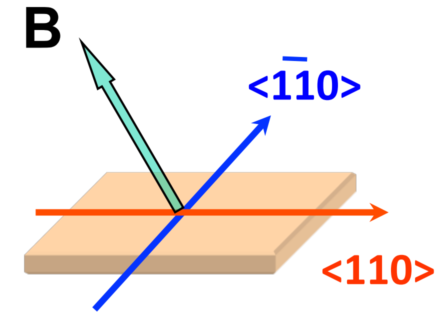


ΔE_{10} = 6.5 meV

Nearest empty level is N=0 LL in second subband

Subband – Landau level mixing

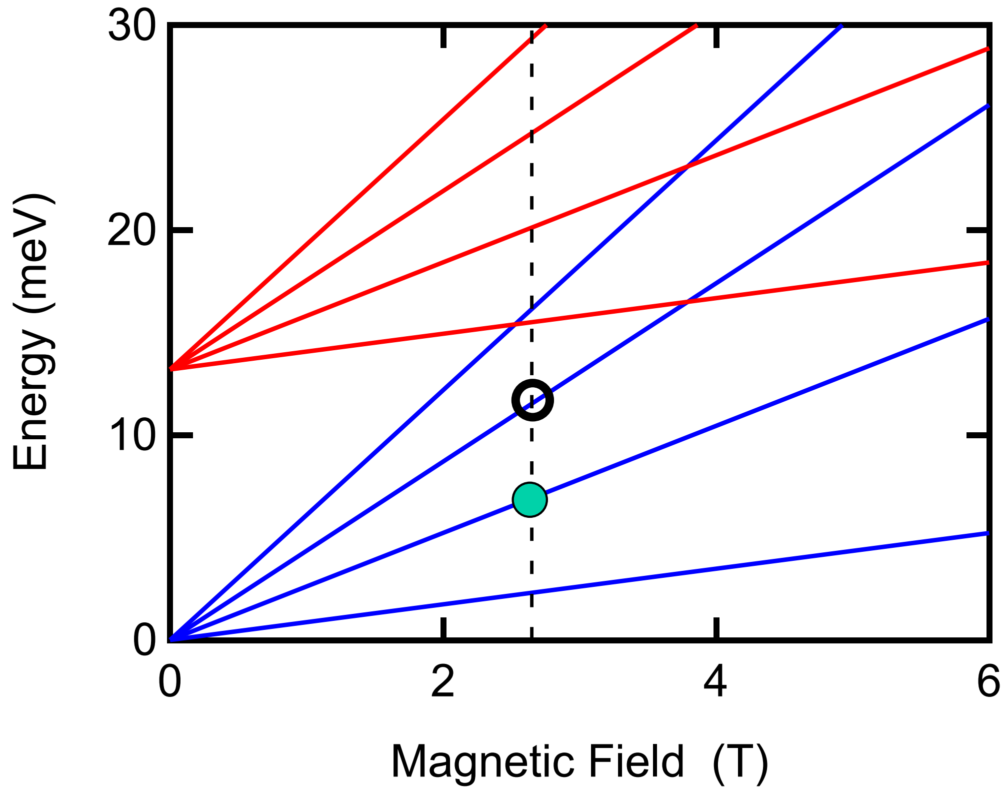


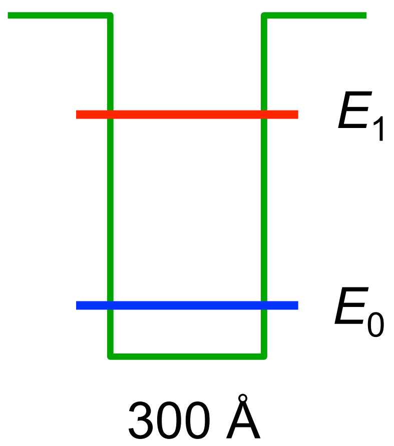


$$H' \sim B_{\parallel}\, z\, p_y$$

Tilting induces SB-LL coupling at the single particle level

Test: Narrower quantum well sample



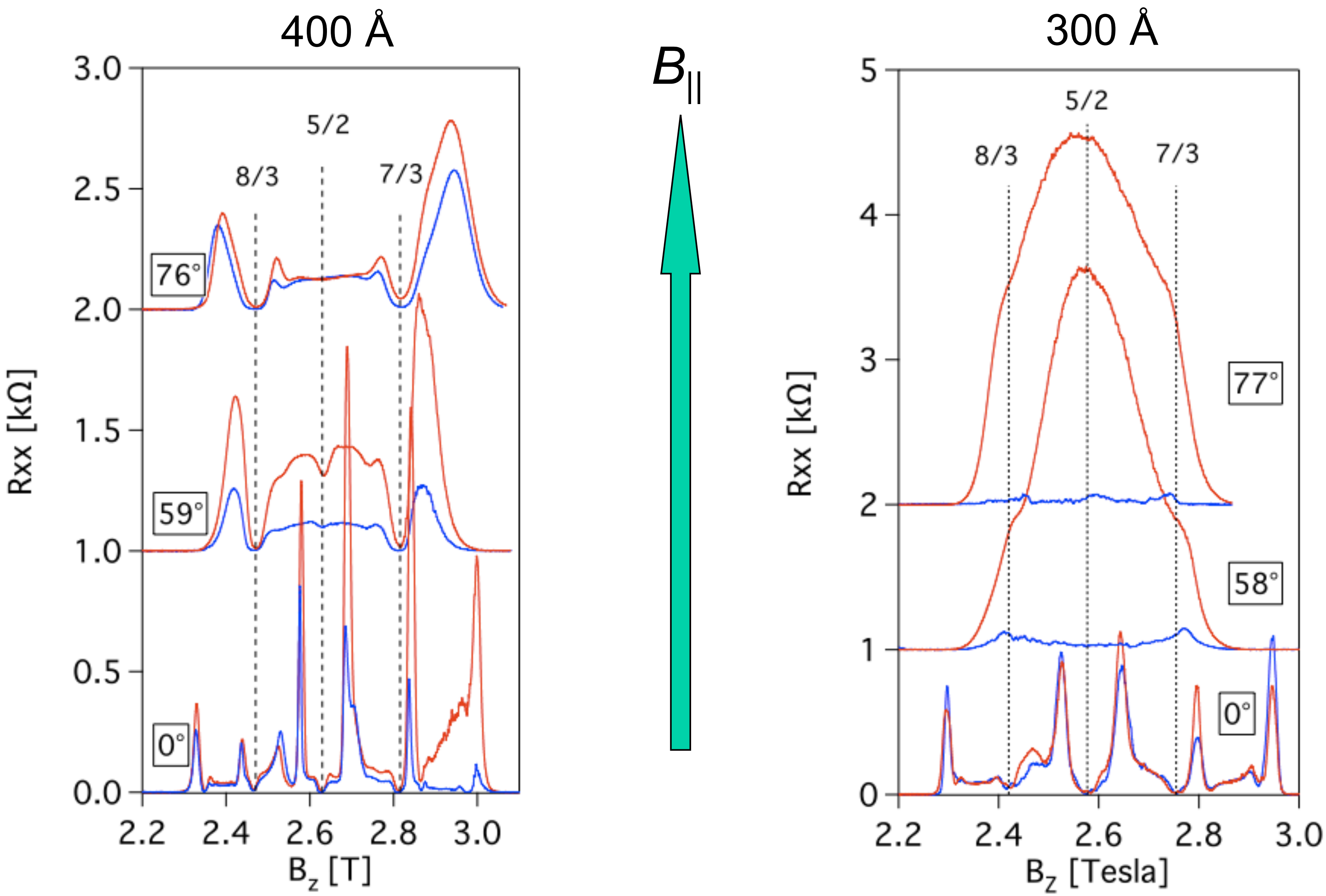


ΔE_{10} = 13.2 meV

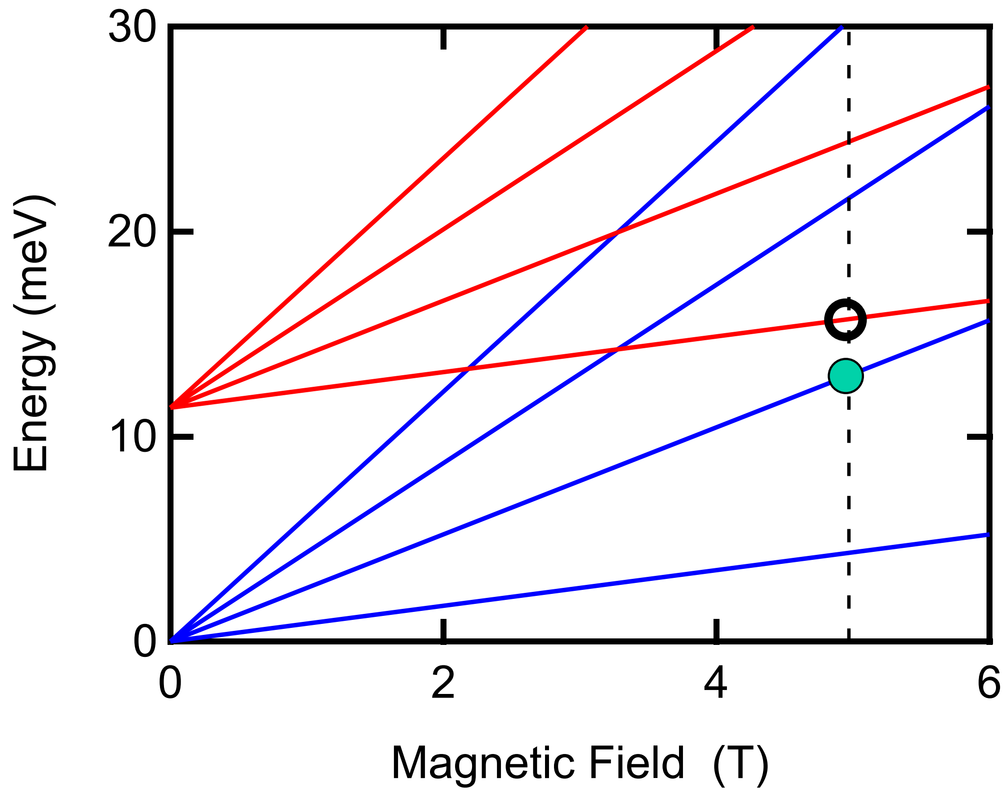
n = 1.6 x 10^{11} cm^{-2}
μ = 16 M

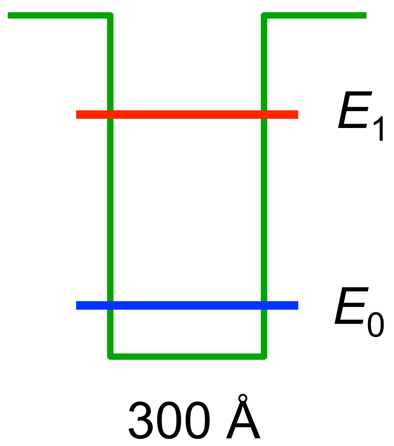
Nearest empty level is N=2 LL in ground subband

Dramatic difference between samples



Is well width the key difference?



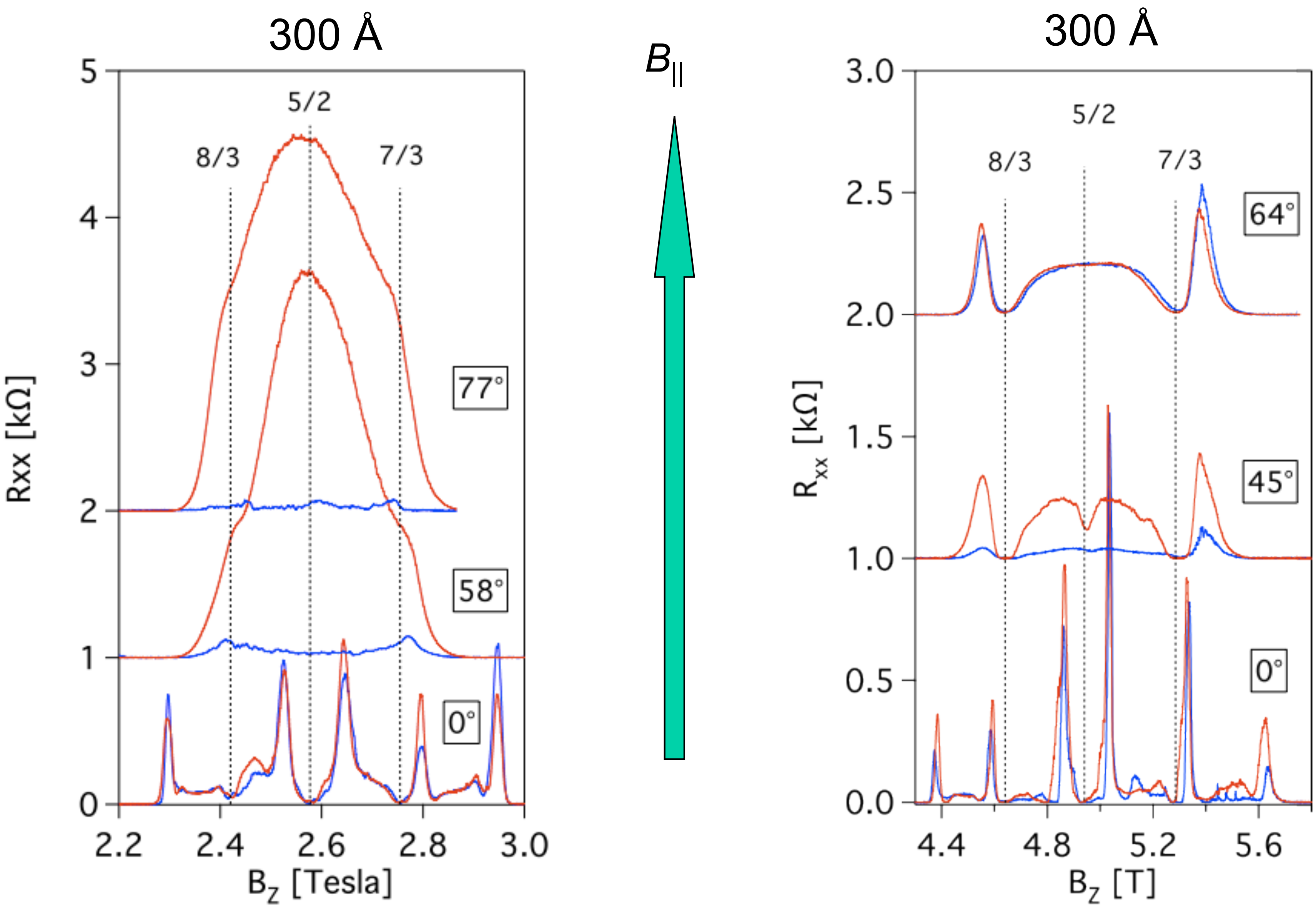


ΔE_{10} = 11.4 meV

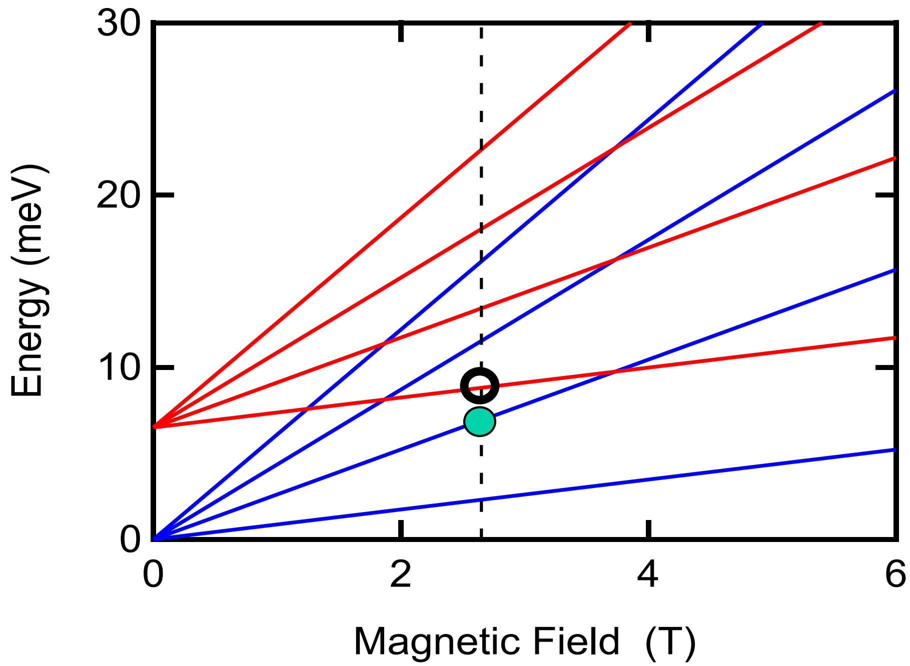
n = 3.0 x 10^{11} cm^{-2}
μ = 30 M

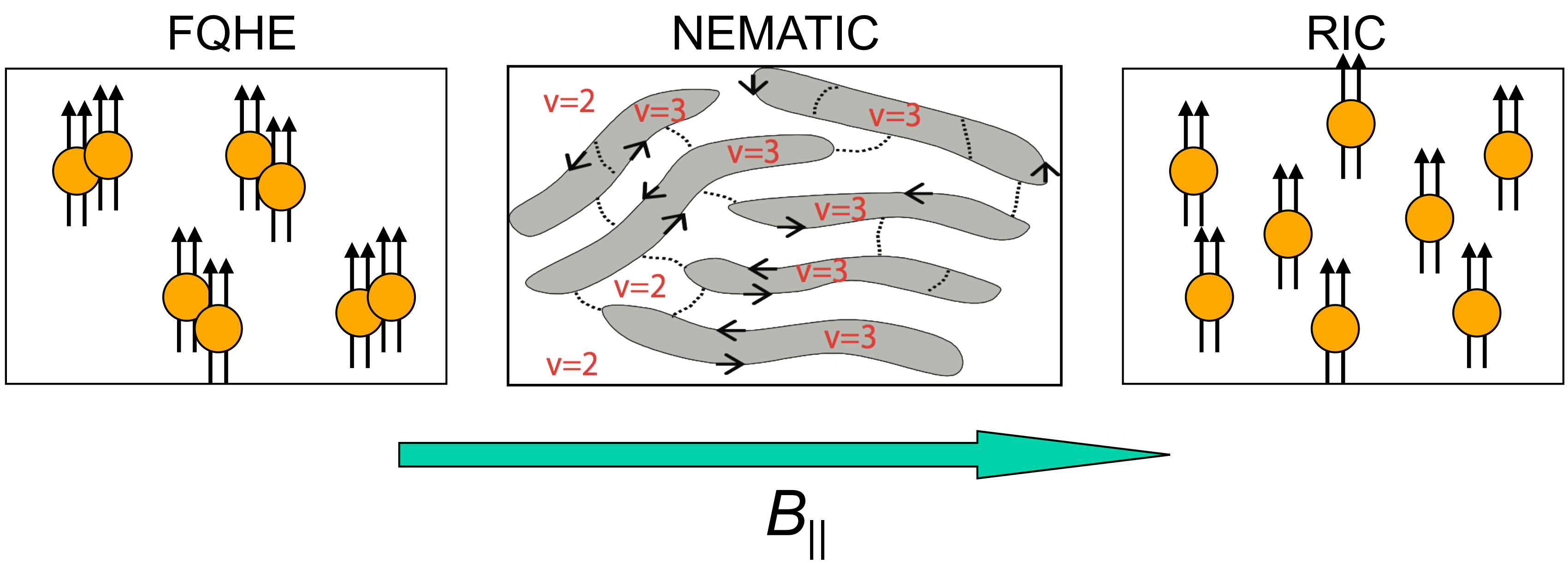
Higher density: Again the nearest empty level is N=1 LL in second subband

The RIC returns!

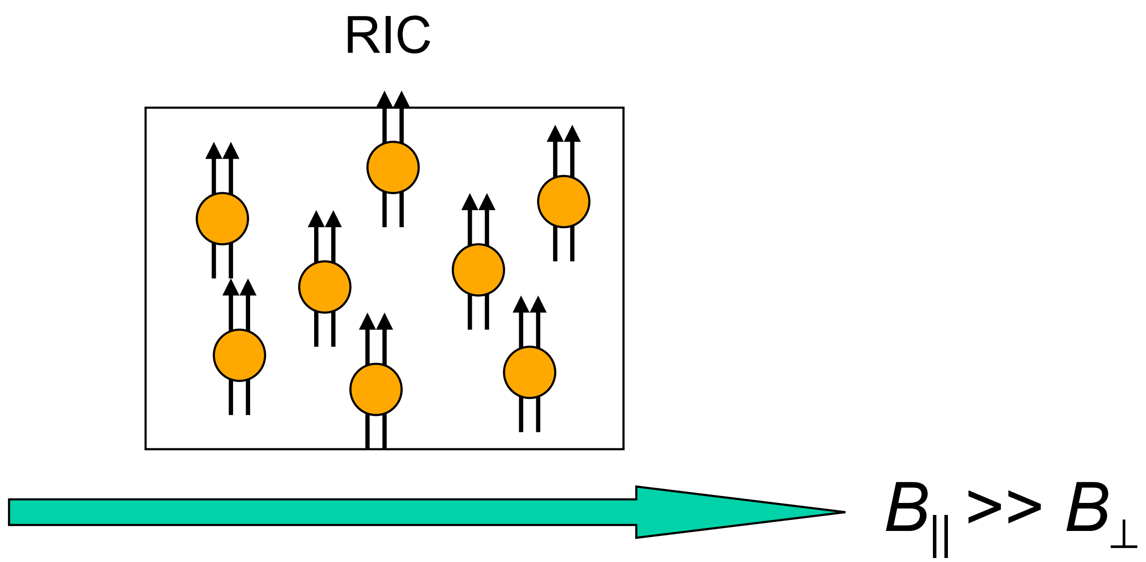


Subband-LL alignment is the key to RIC at 5/2



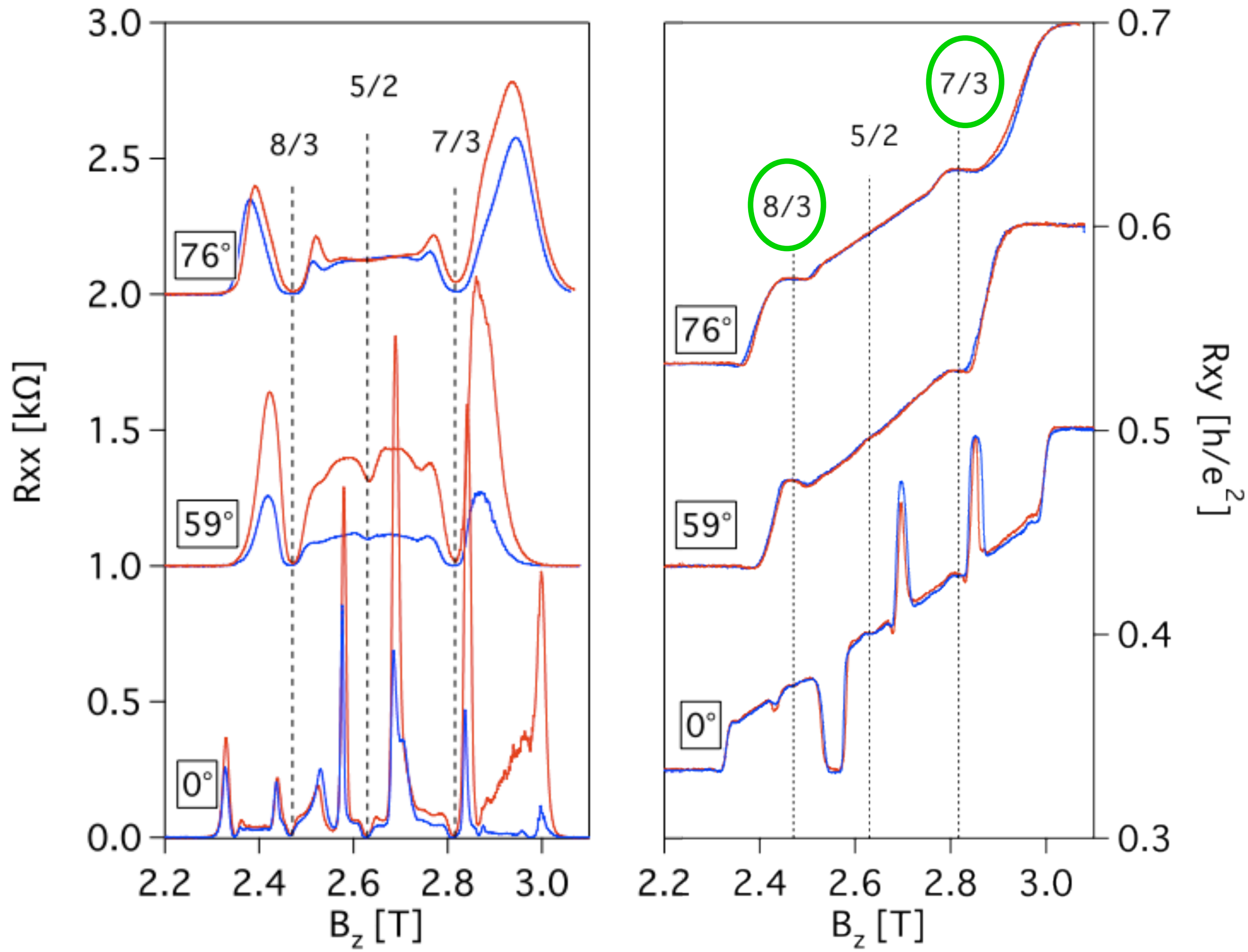


What is the nature of the RIC phase?

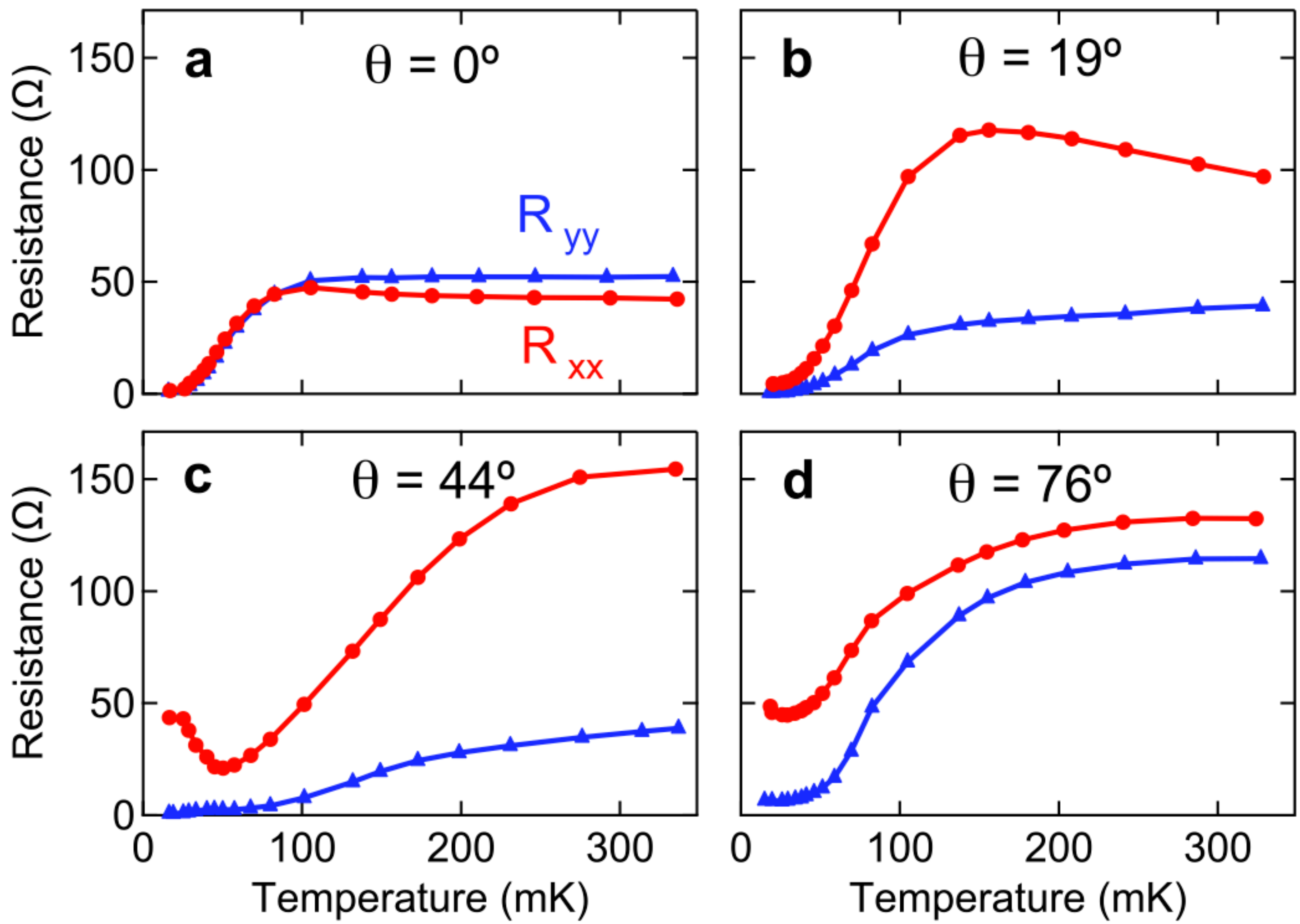


- *Is it a CF Fermi liquid?*
- *If so, is the Fermi surface elliptical?*
- *Why is the transport so isotropic?*

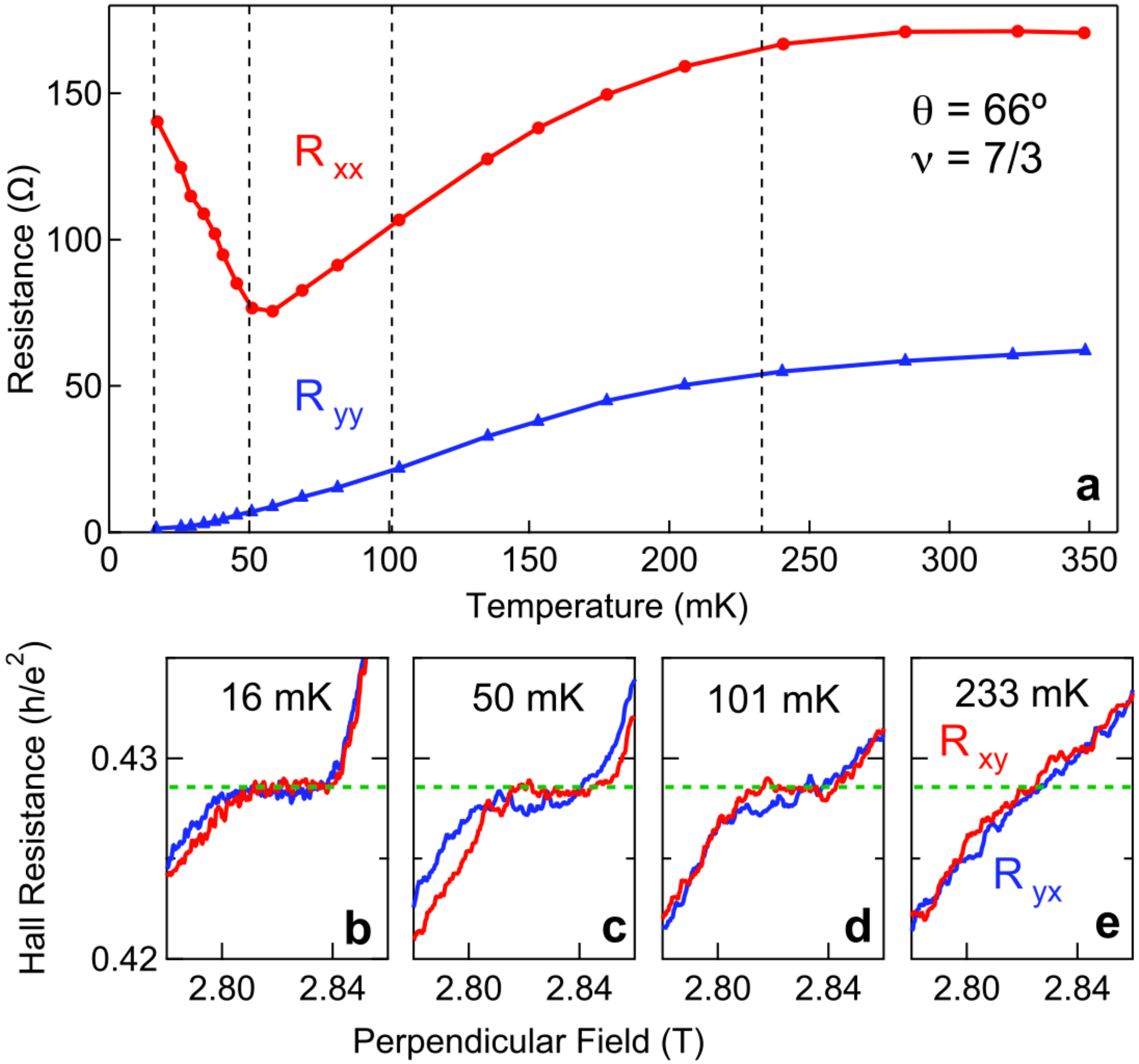
Robust 7/3 & 8/3 FQHE at high tilt in 400Å sample



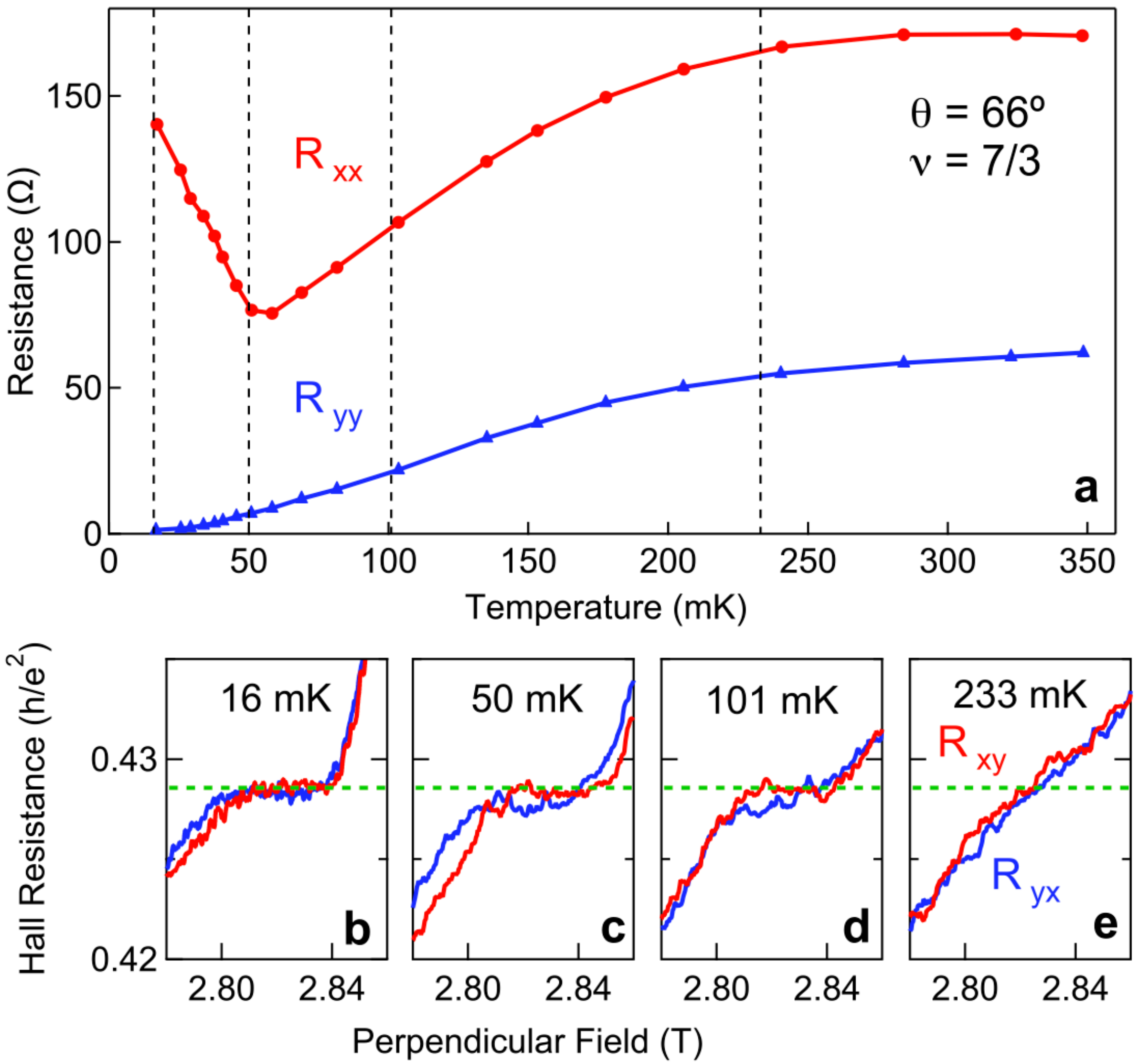
Anisotropic resistivity at 7/3



Competing orders at ν = 7/3 in 40 nm sample?



Competing orders at ν = 7/3 in 40 nm sample?



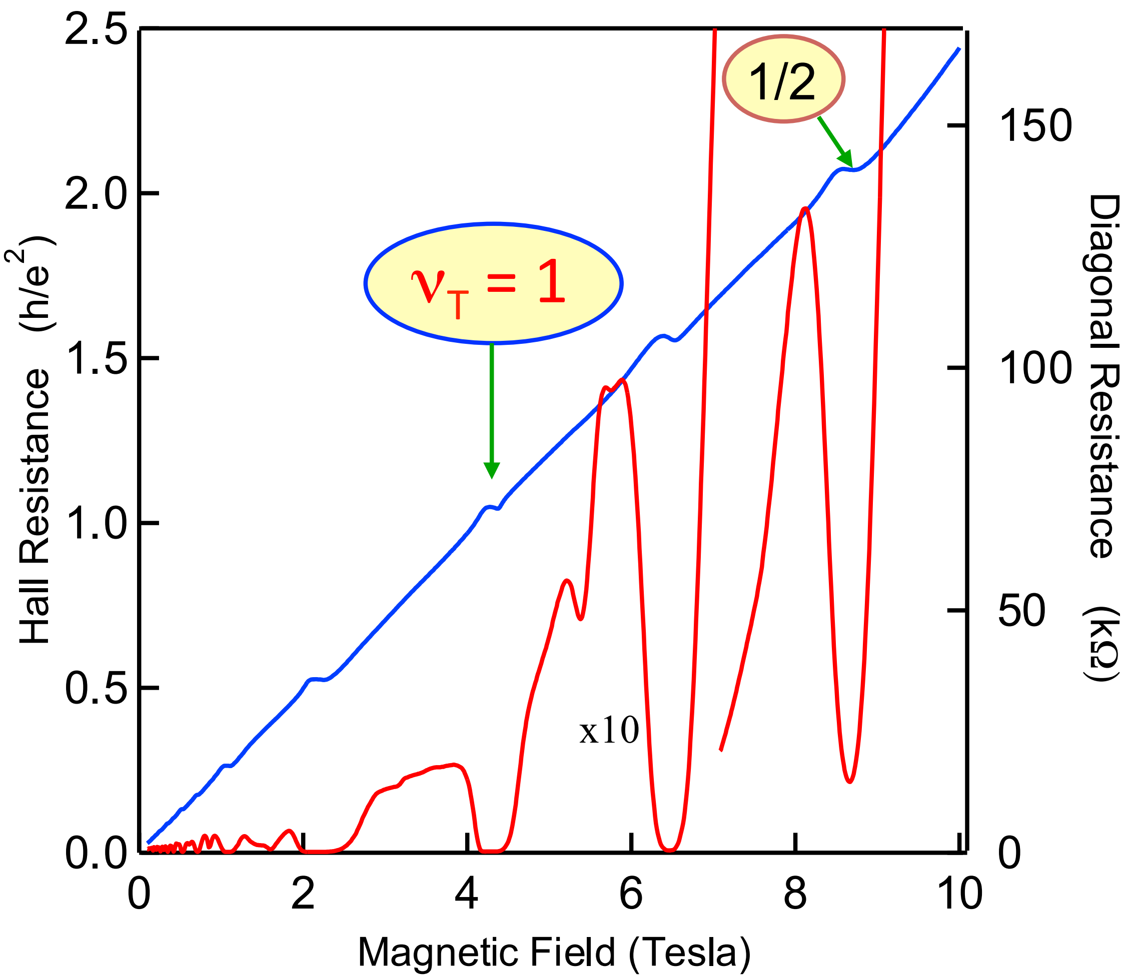
Musaelian & Joynt,
J. Phys. Cond. Matt. 8, L105 (1996).

Mulligan, Nayak, and Kachru
PRB 82, 085102 (2010).

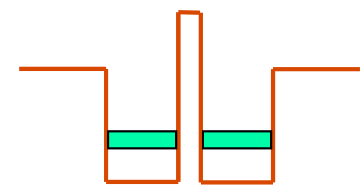
Hall plateau with stripe-like temperature dependence:
A quantum Hall nematic phase?

Double layer FQHE systems

QHE in double layer 2D systems

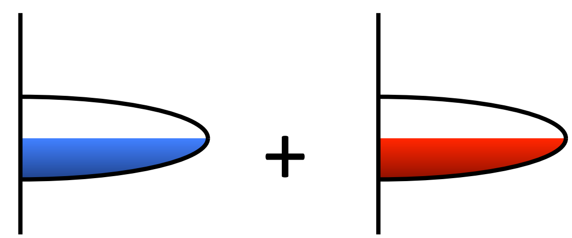


$\nu_T = \nu_1 + \nu_2$

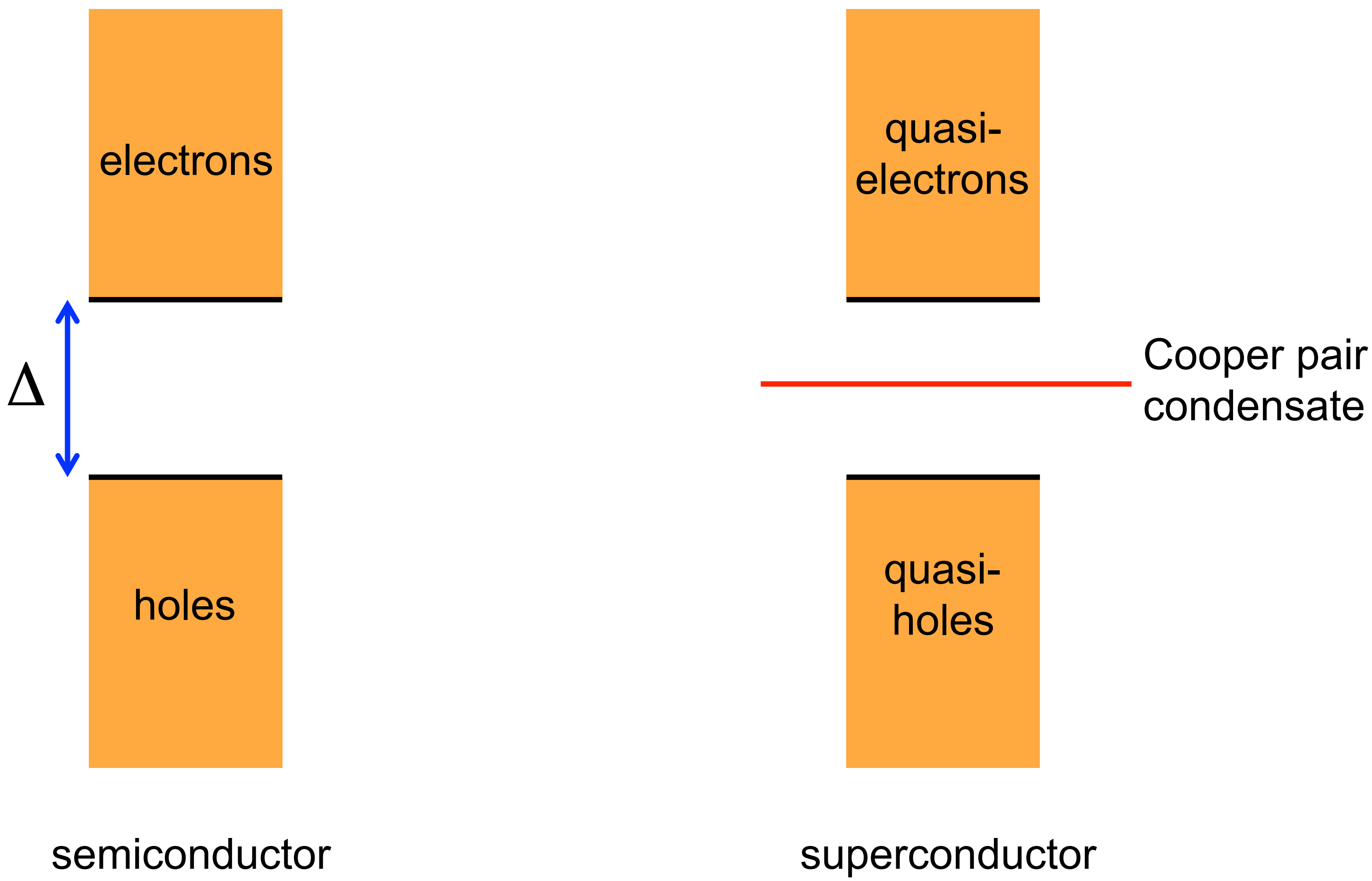


$\nu_T = \frac{1}{2} = \frac{1}{4} + \frac{1}{4}$

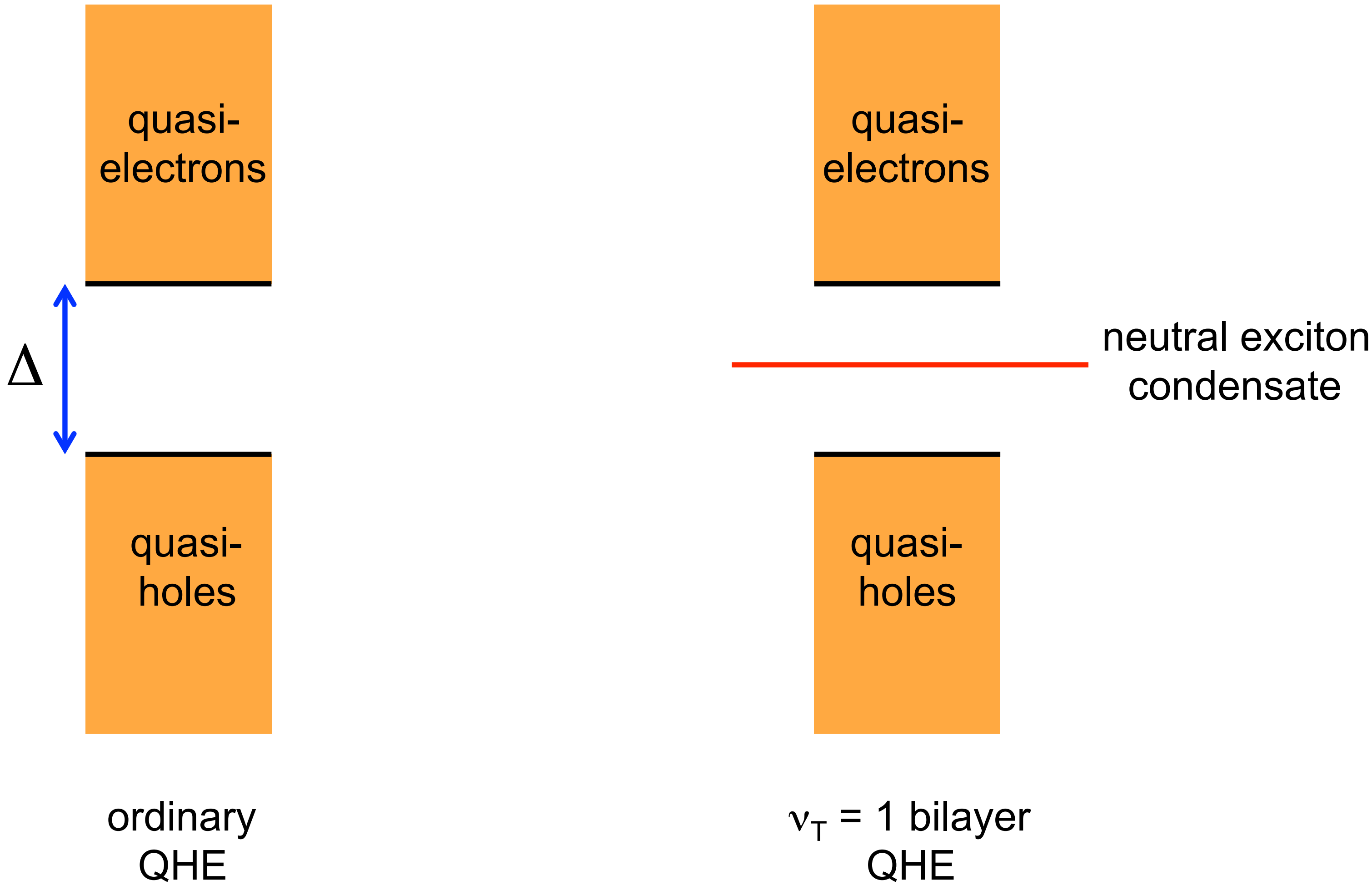
$\nu_T = 1 = \frac{1}{2} + \frac{1}{2}$



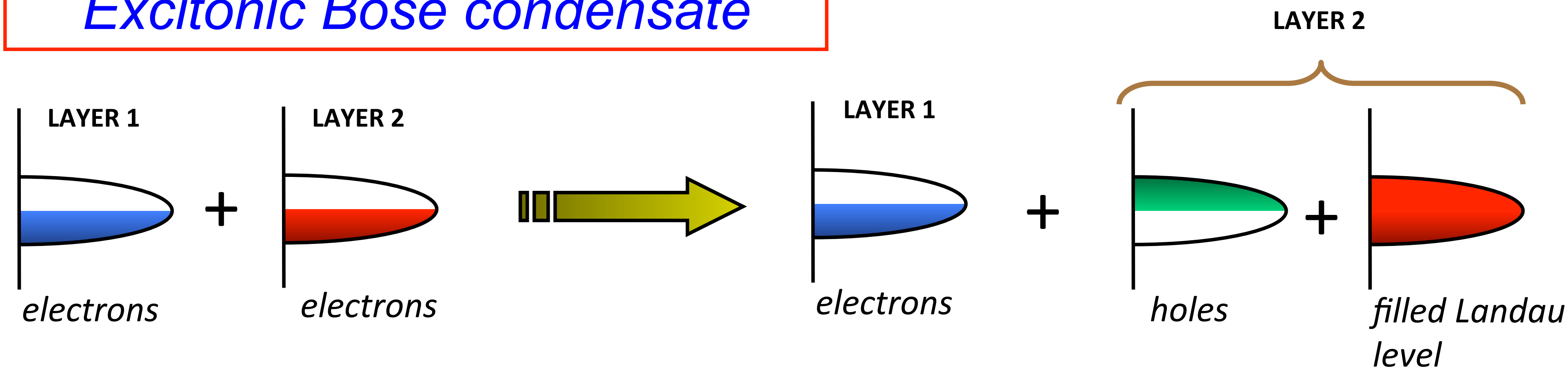
What's special about ν_T = 1 bilayers?



What's special about ν_T = 1 bilayers?

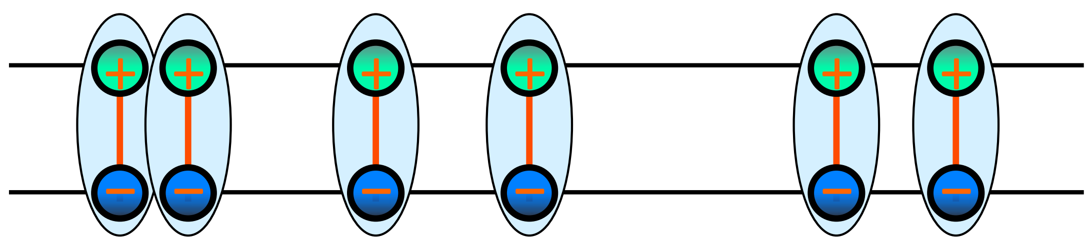


Excitonic Bose condensate



$$|\Psi\rangle = \prod_k \frac{1}{\sqrt{2}}\left[1 + e^{i\phi}\underbrace{c^{\dagger}_{k,1}\, c_{k,2}}\right]|vac'\rangle$$

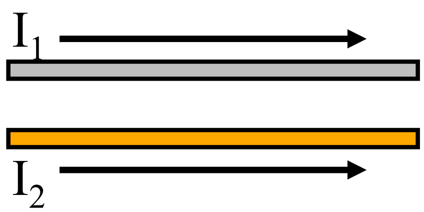
exciton creation operator



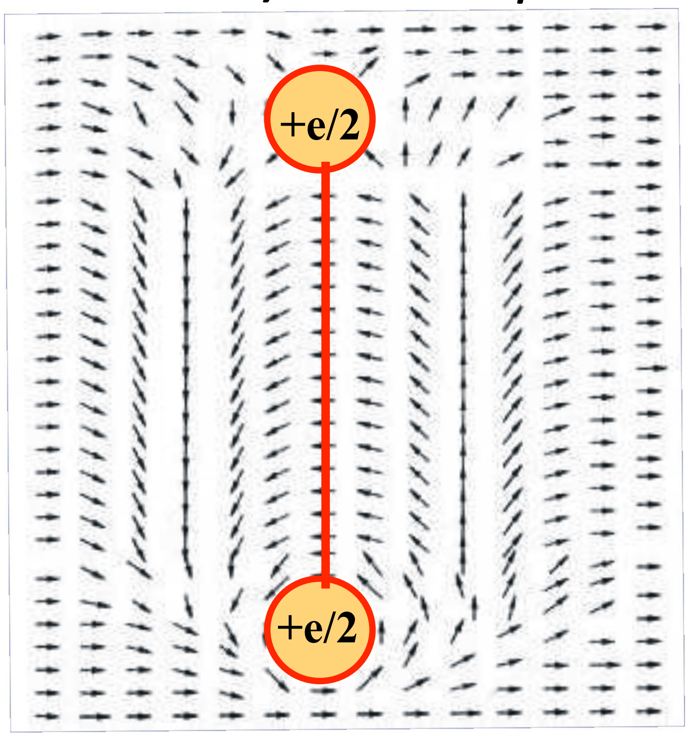
$\nabla\phi \longrightarrow$ *excitonic supercurrents*

Two transport channels

1. Parallel Transport



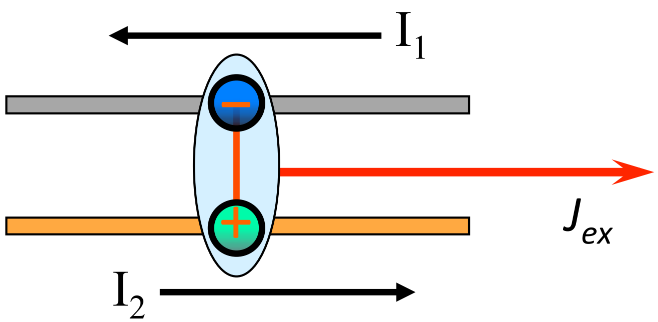
meron / anti-meron pair

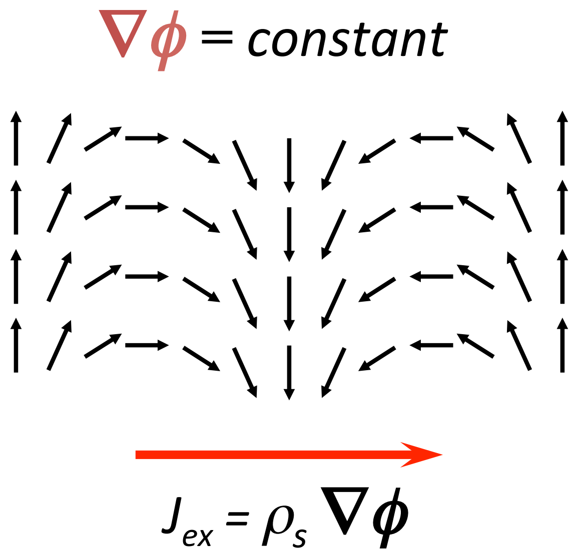


quantized Hall effect

Two transport channels

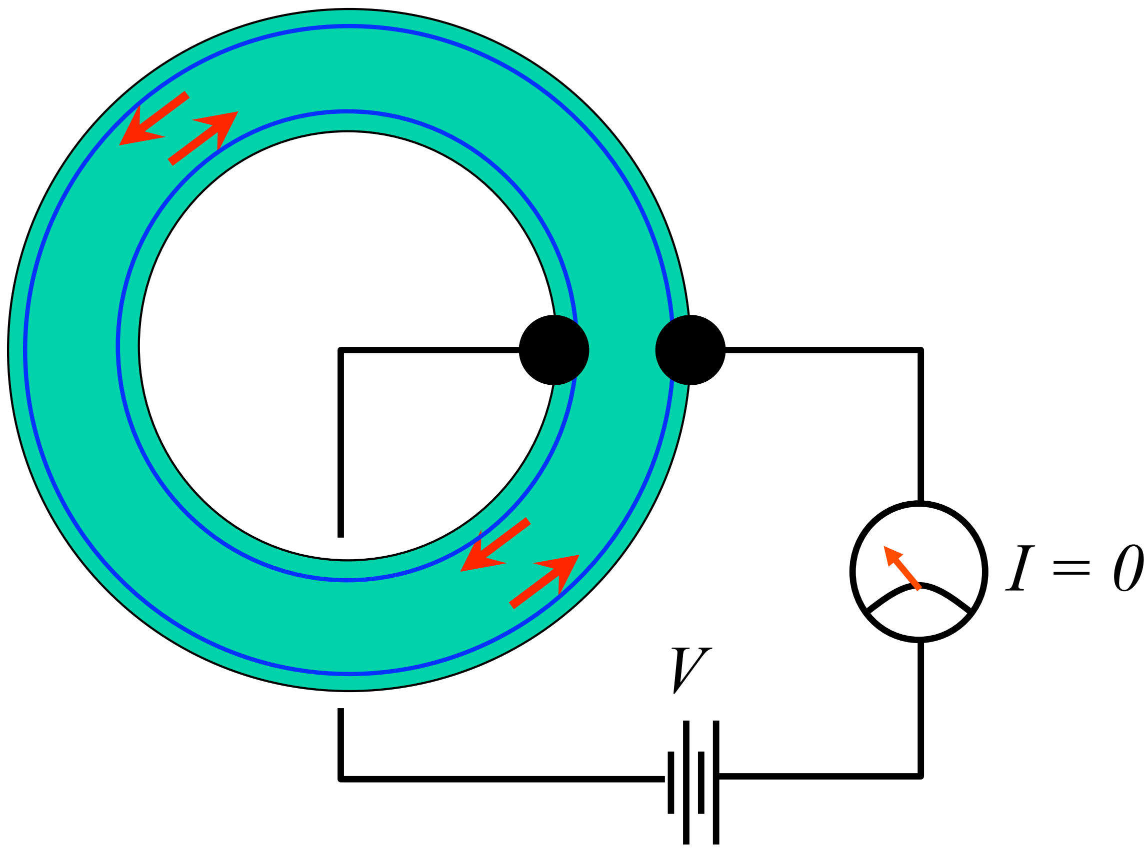
2. Counterflow Transport





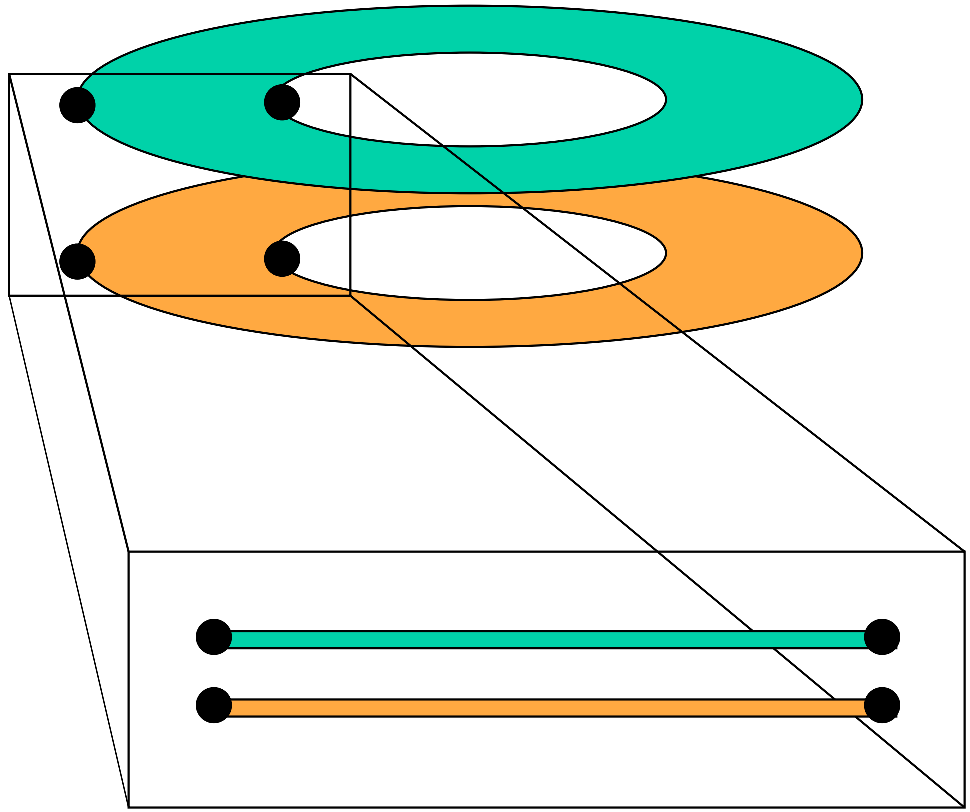
collective exciton transport in condensate

Quantum Hall systems are topological insulators

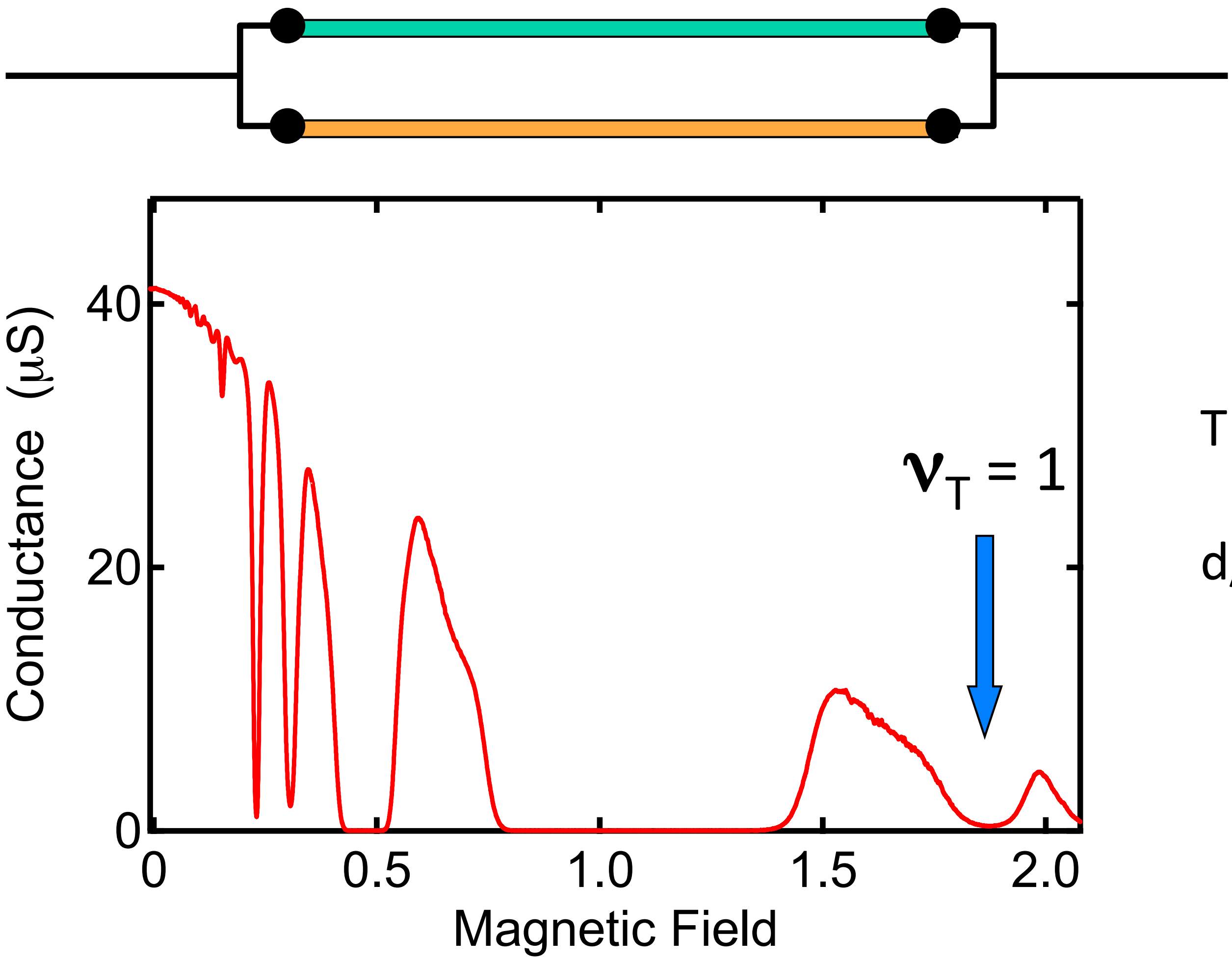


Bulk is opaque to charge transport.

Bilayer Corbino geometry



QHE suppresses parallel charge transport across the bulk

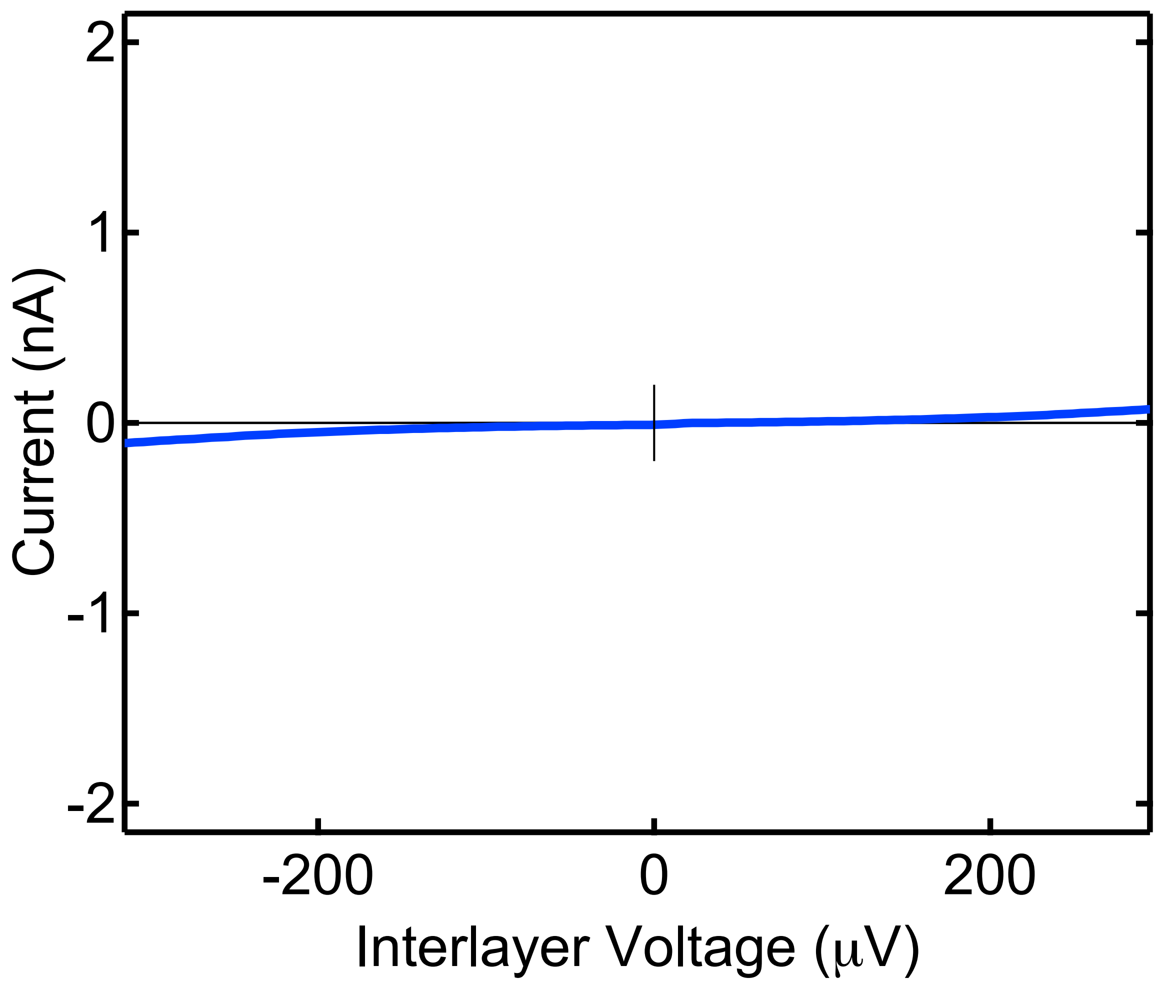


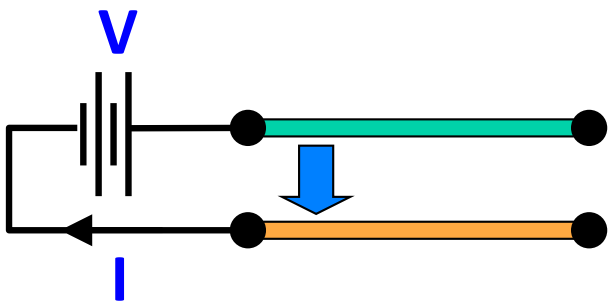
T = 25 mK

d/ℓ = 1.5

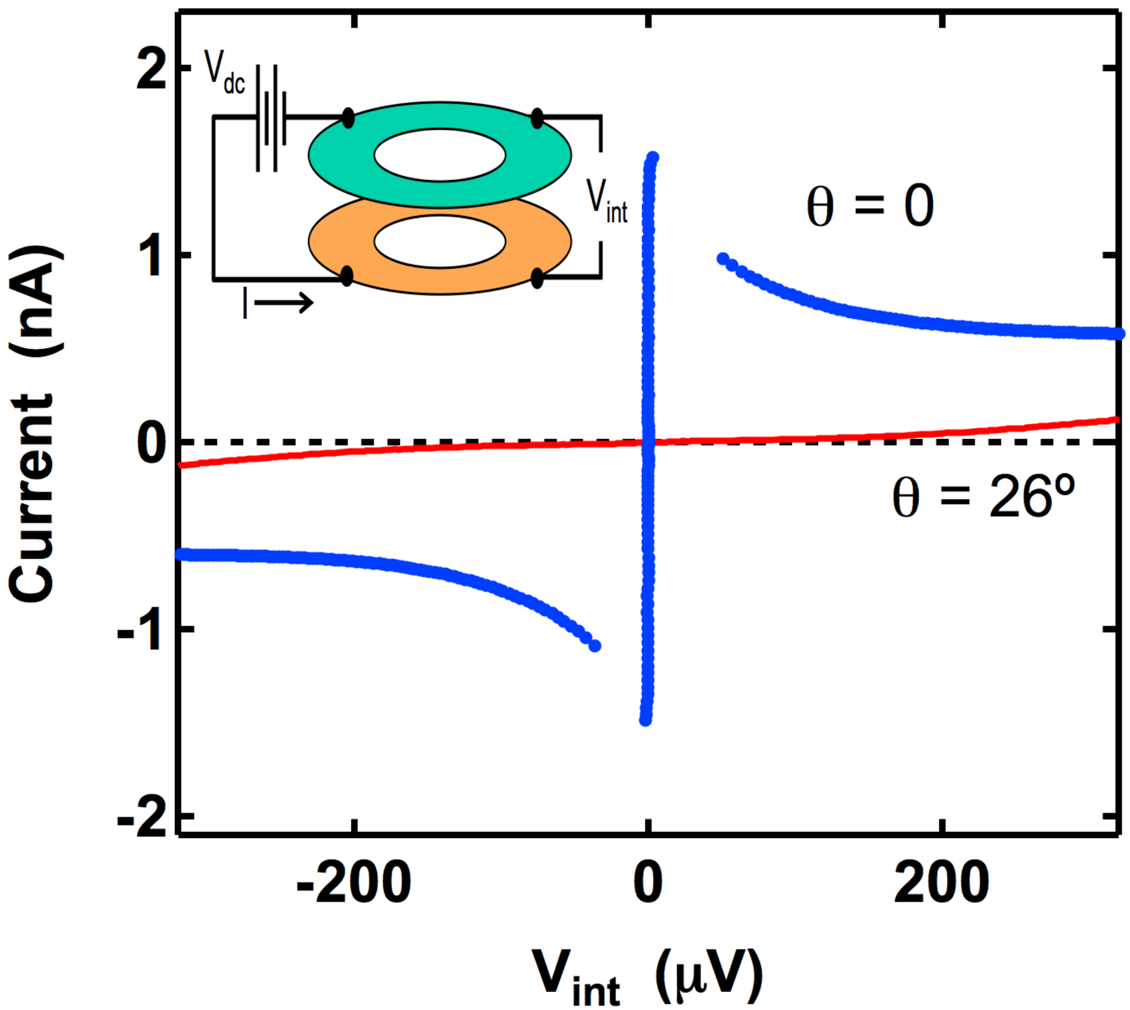
No surprise here.

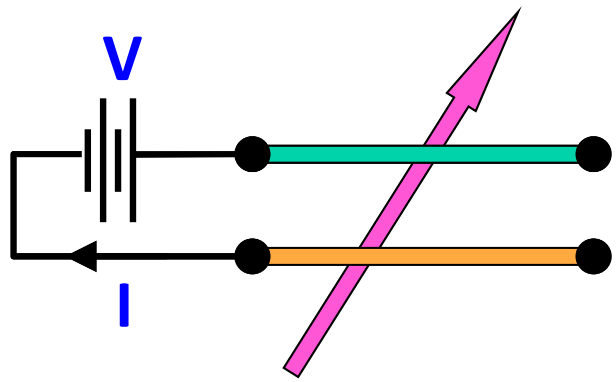
Tunneling configuration





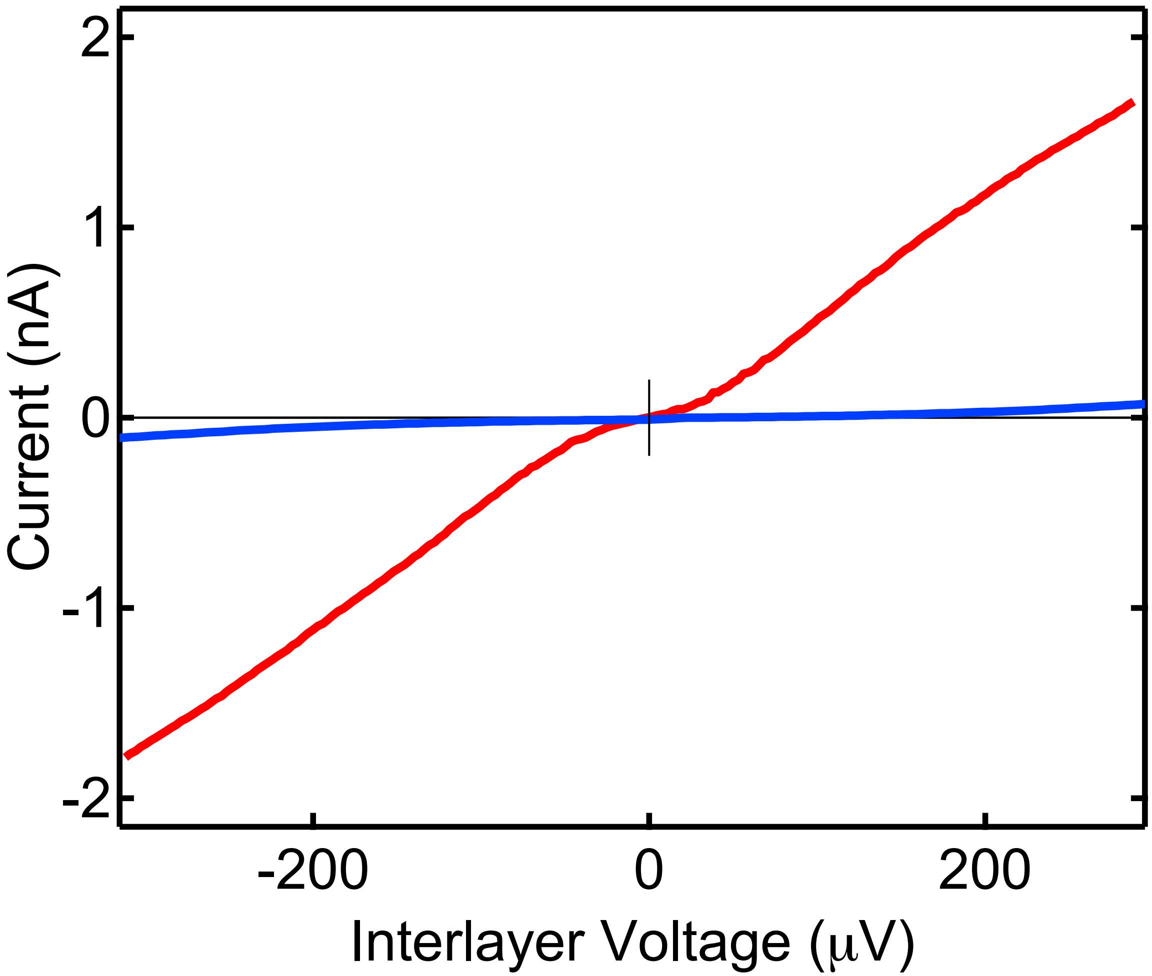
Tunneling configuration

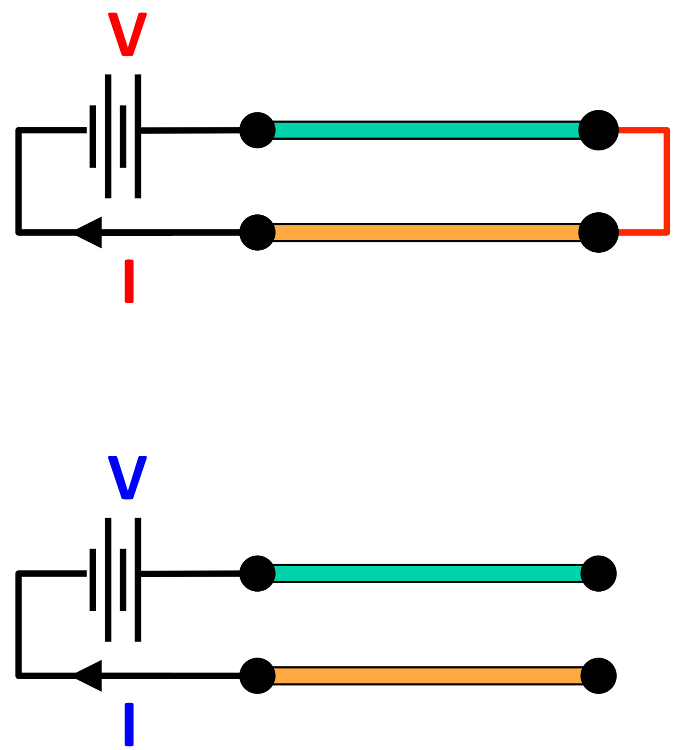




Tunneling intentionally suppressed by tilting.

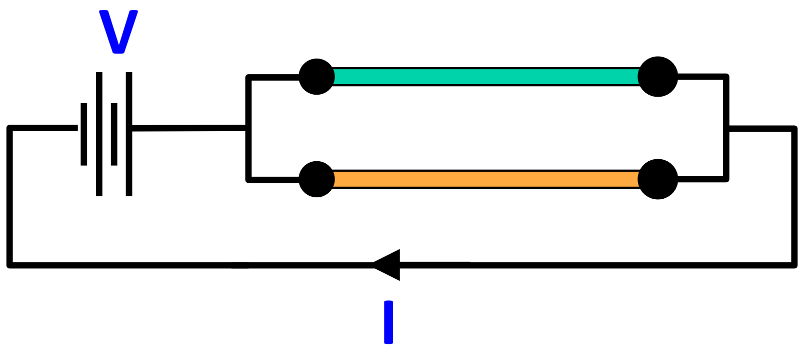
Tunneling vs. Corbino counterflow



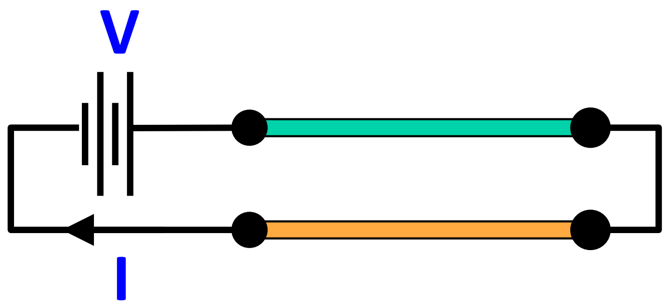


Remote short vastly enhances current.

A paradox?

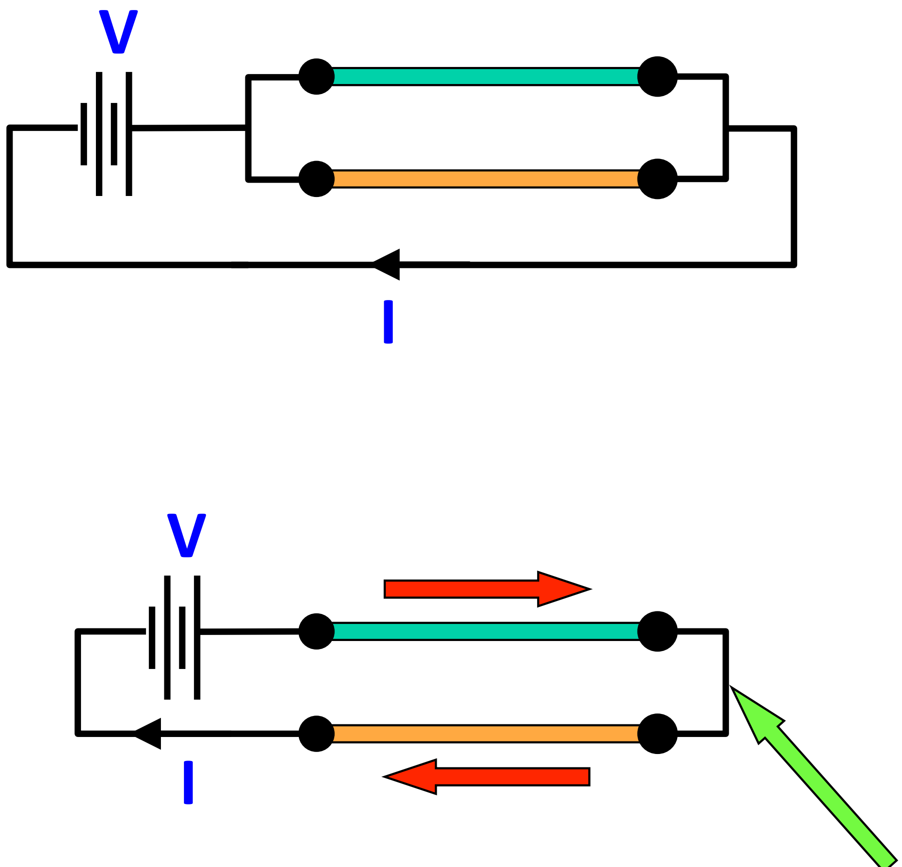


No current



Lots of current

A paradox?



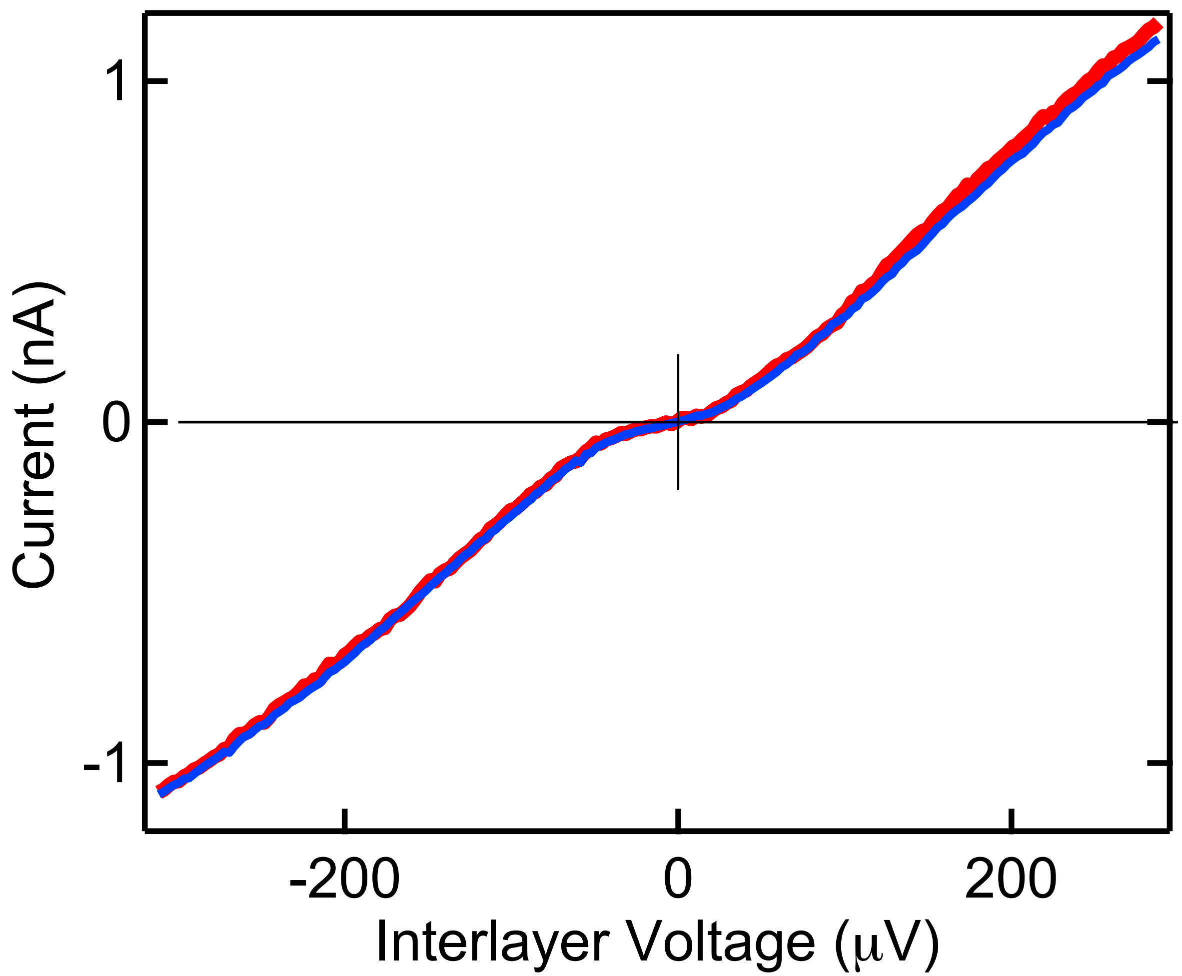
No current

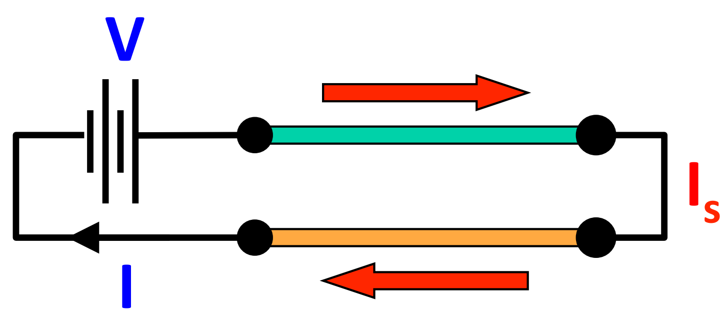
Lots of current

Counterflow?

Measure current here!

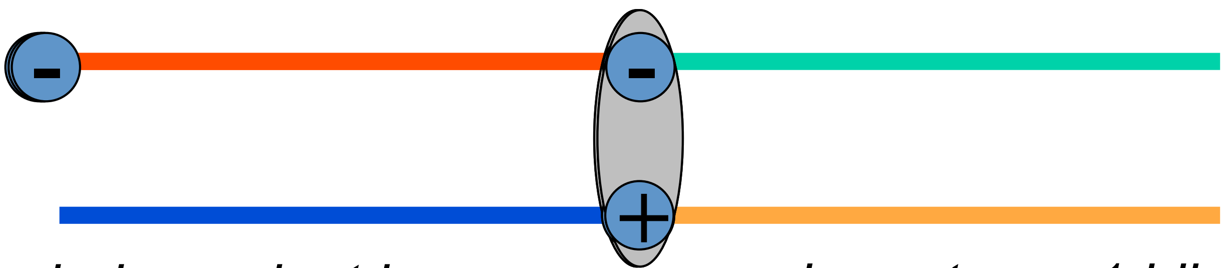
Measuring the shunt current





It IS counterflow.

The mechanism

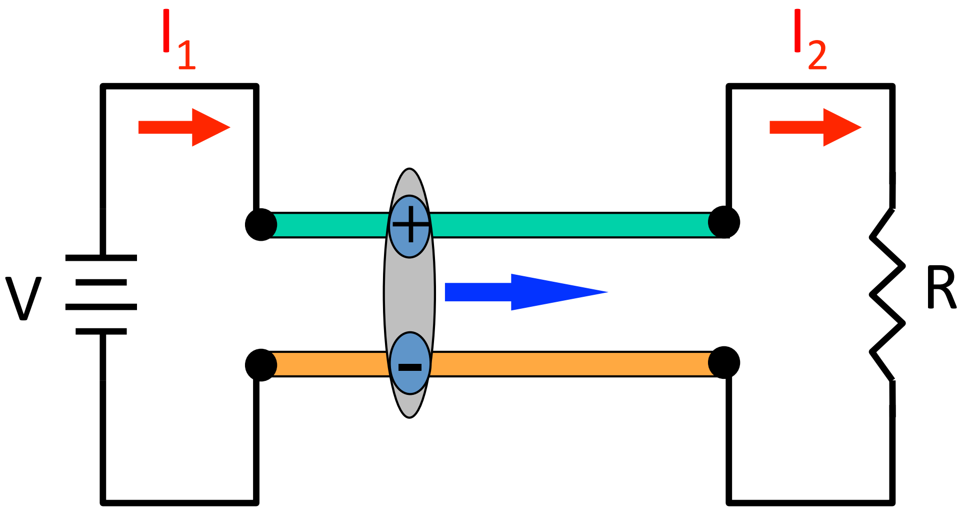


independent layers

coherent ν_T *= 1 bilayer*

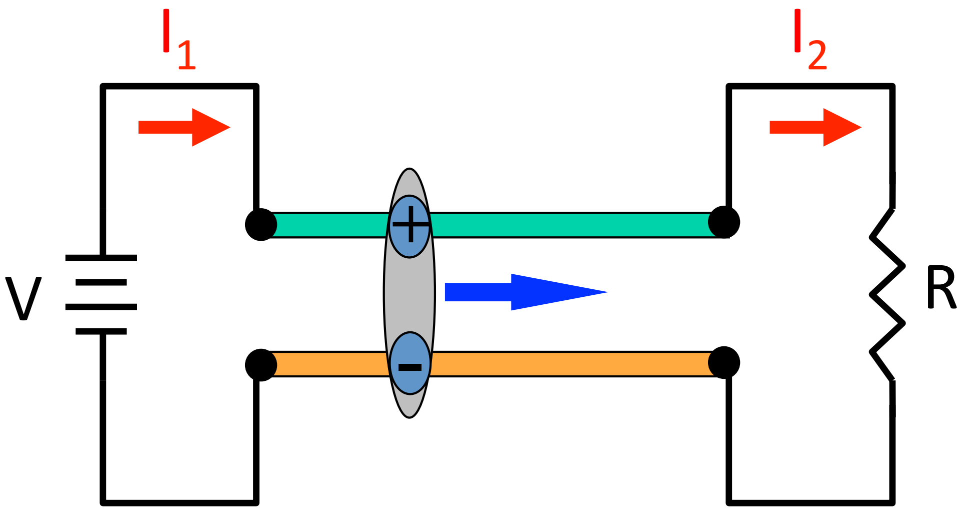
Excitons are launched and absorbed via Andreev reflection.
Excitons transport energy but not charge.

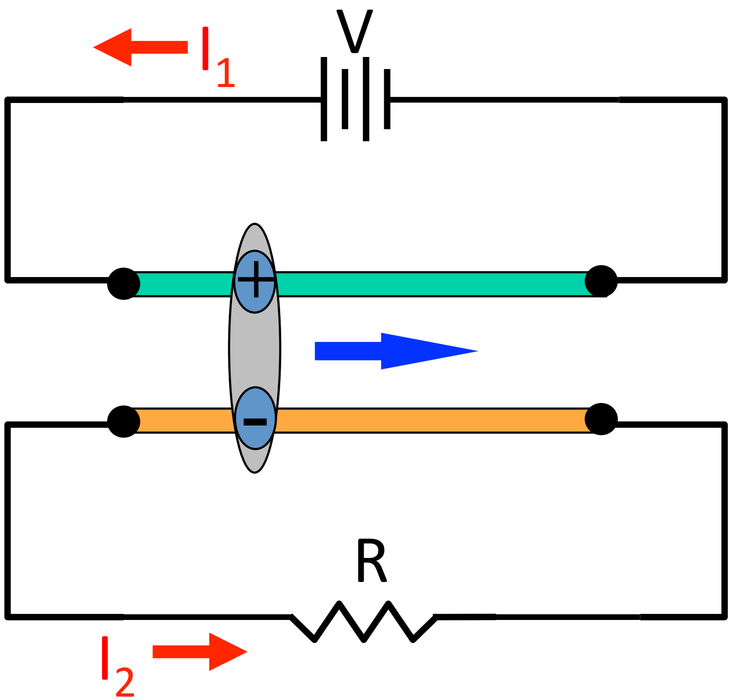
Inducing exciton transport



Ideally, $I_1 = I_2$

Inducing exciton transport

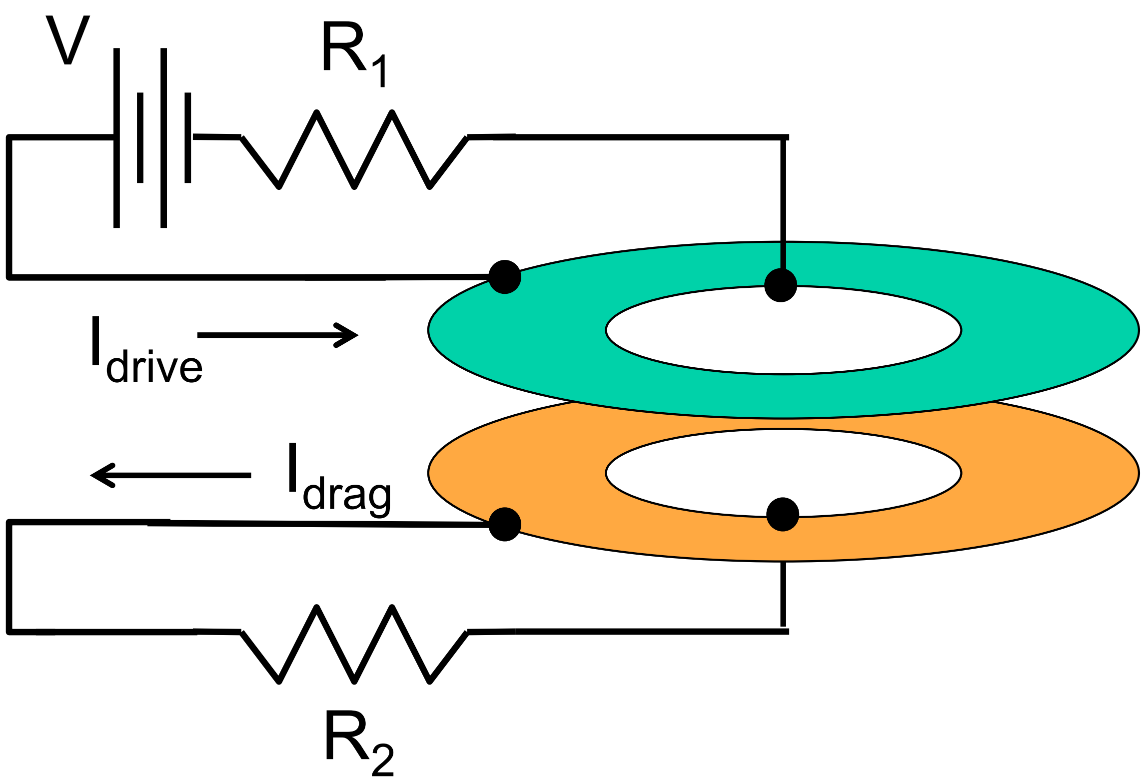




Ideally, $I_1 = I_2$

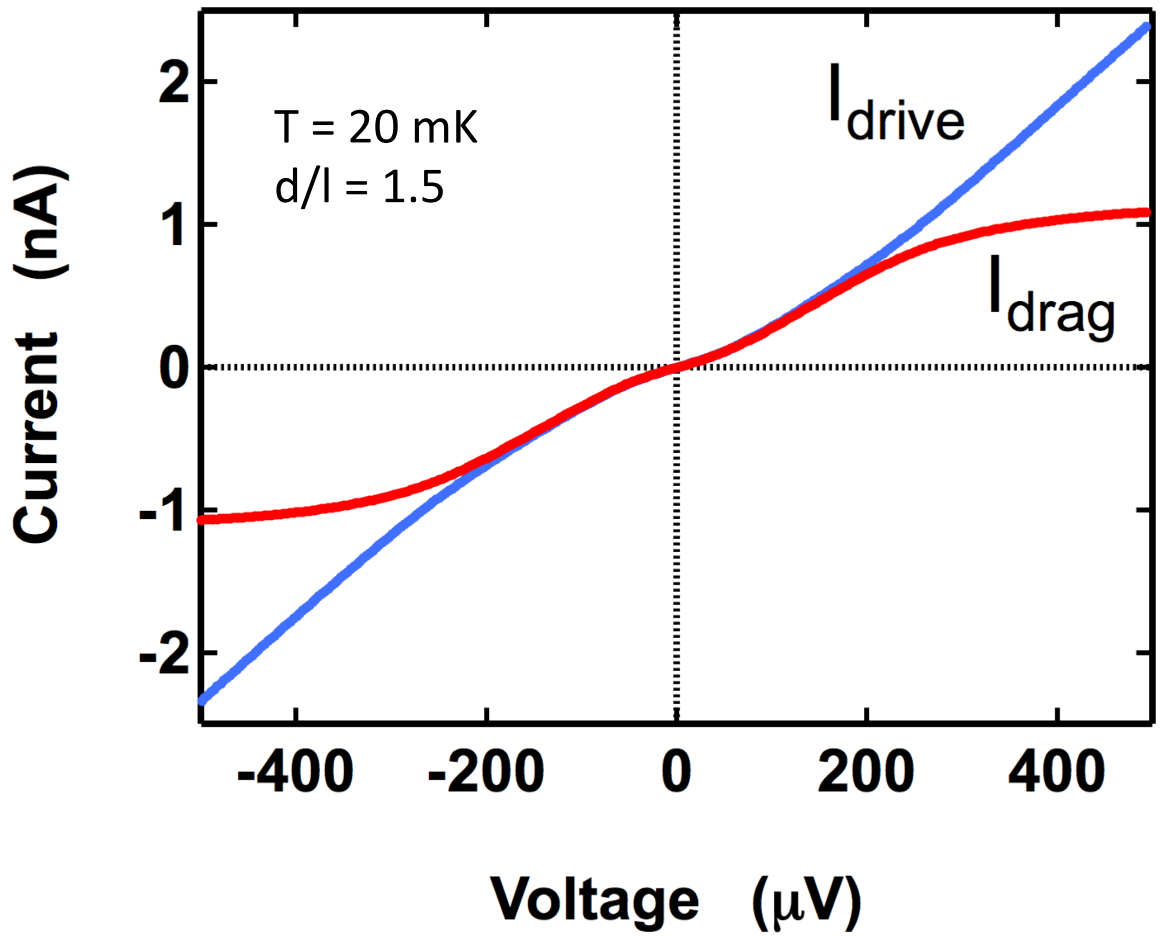
Su & MacDonald 2008

Corbino Coulomb drag



cf. Tiemann et al. PRB 2008

Perfect Coulomb drag



Drag and drive currents equal at small V.
"Perfect" Coulomb Drag

Conclusions

Single layer 2D systems

- *Competing phases at ν = 5/2 in the N=1 Landau level.*
- *Details of quantum confinement can be qualitatively important.*
- *Evidence for an anisotropic FQHE state.*

Double layer 2D systems

- *Direct observation of exciton transport across insulating bulk of the bilayer ν_T = 1 QHE state.*
- *Energy transport without charge transport.*
- *"Perfect" Coulomb drag at low T, d/l, and V.*