SAND2013-8931P

Spin Transition in the Second Landau Level

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Sandia National Laboratories

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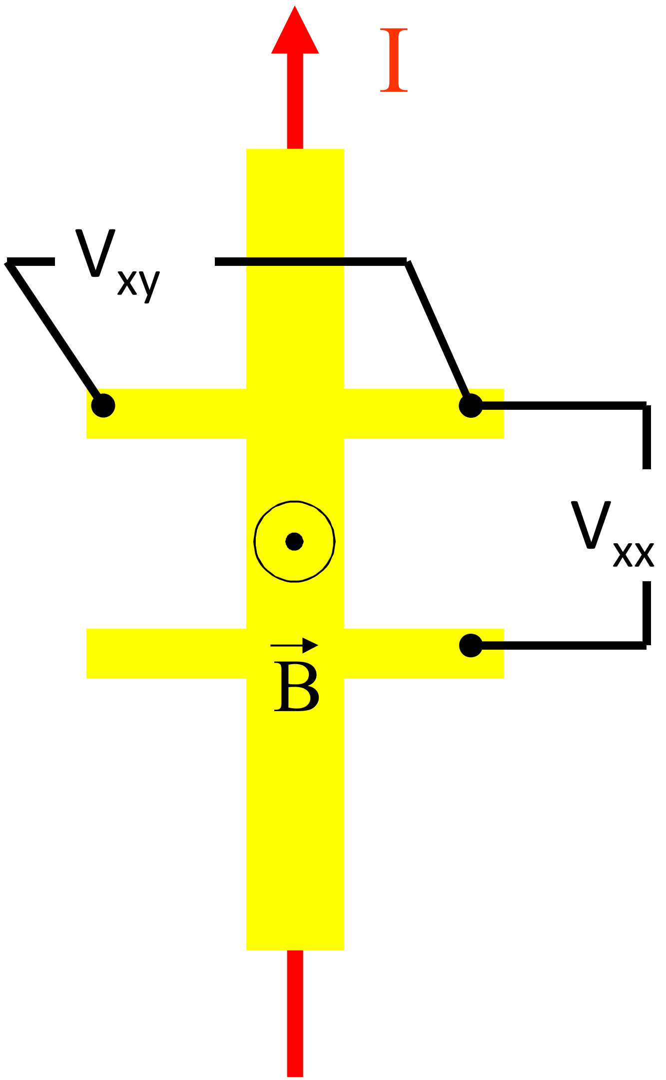
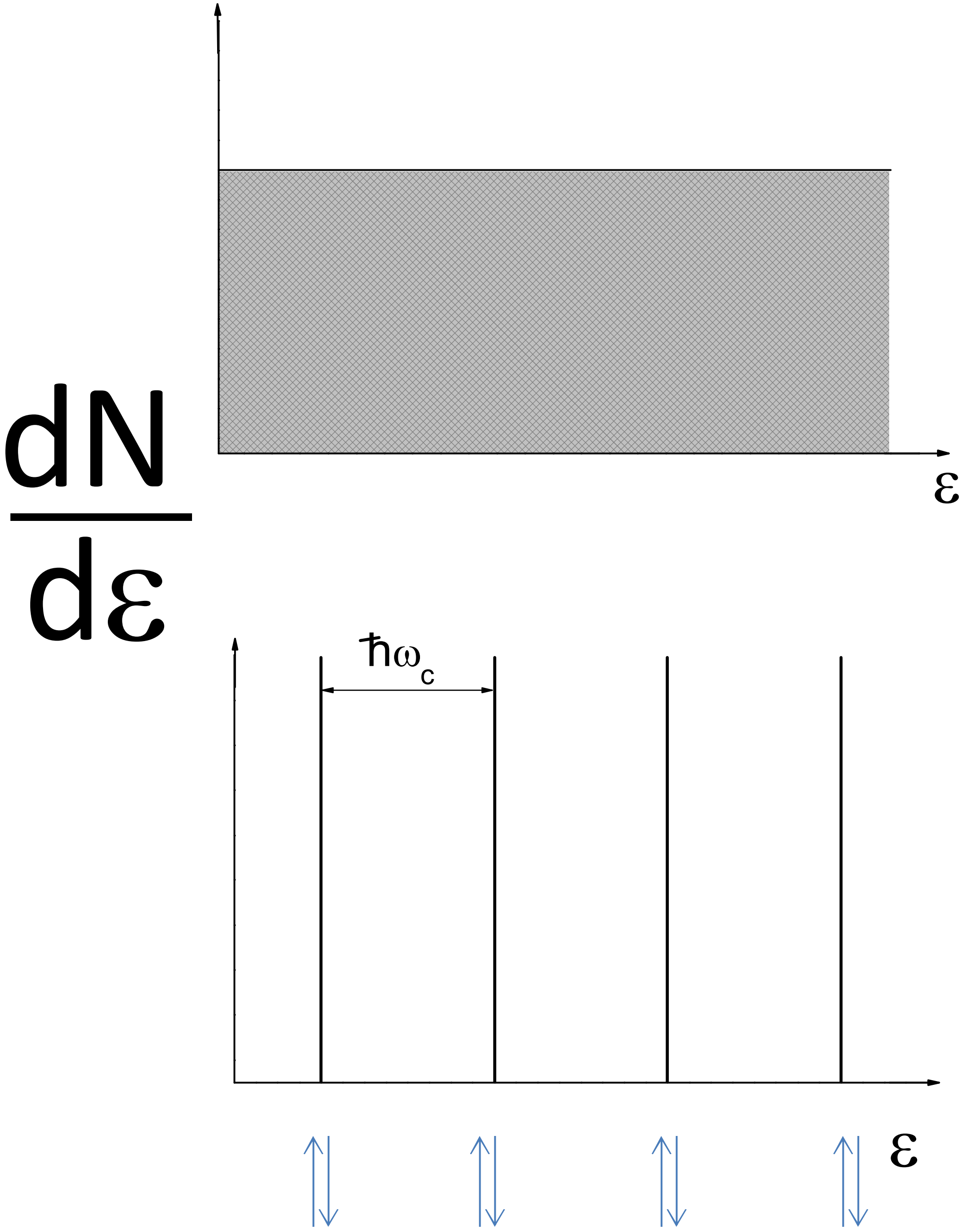
Outline:

- Introduction of quantum Hall effects
- Spin transition in the second Landau level
  - 12/5
  - 8/3
- Tunneling measurements at 8/3 and 7/3



transport coefficients:

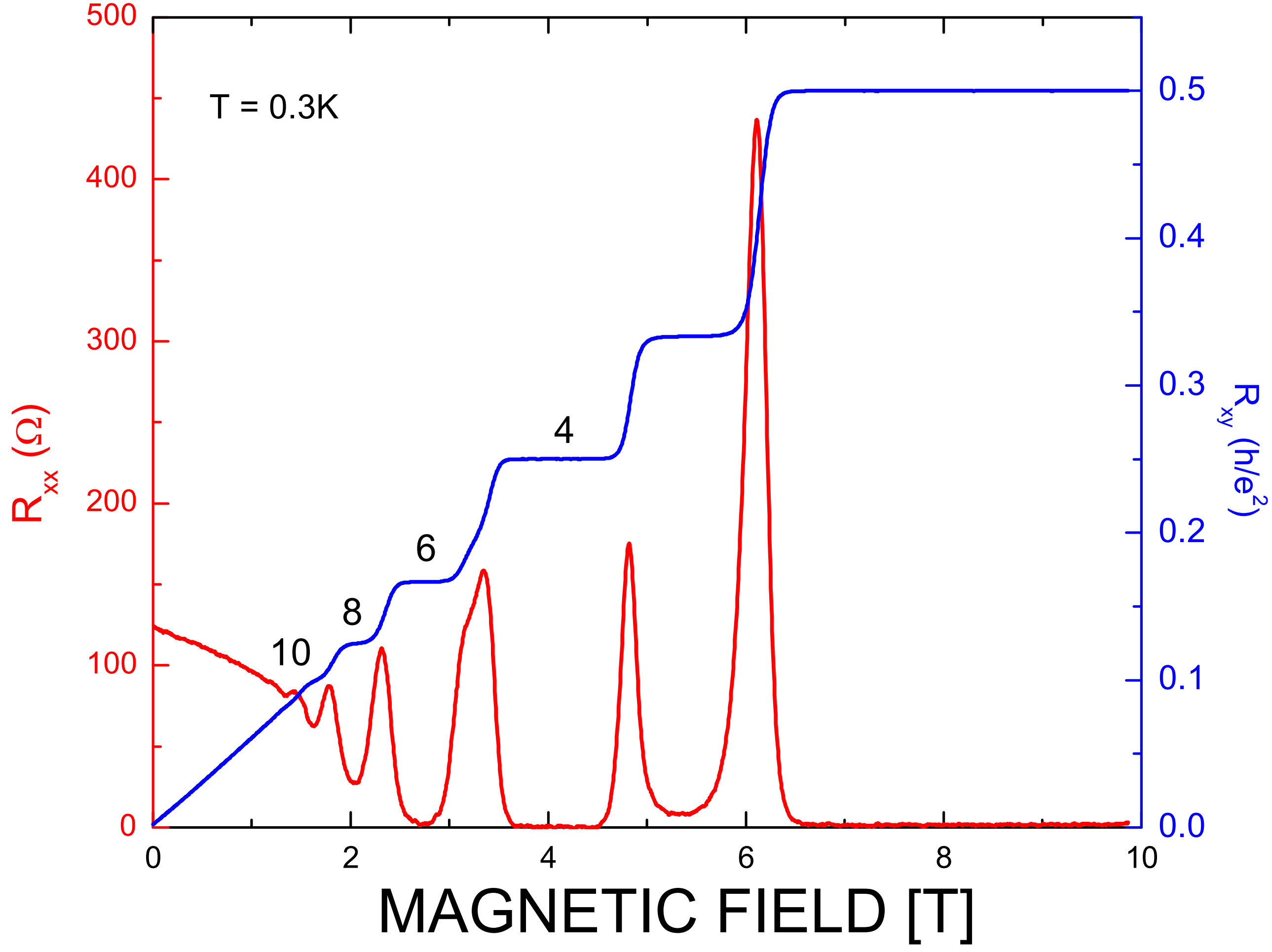
$$R_{xx} = V_{xx}/I; \; R_{xy} = V_{xy}/I$$



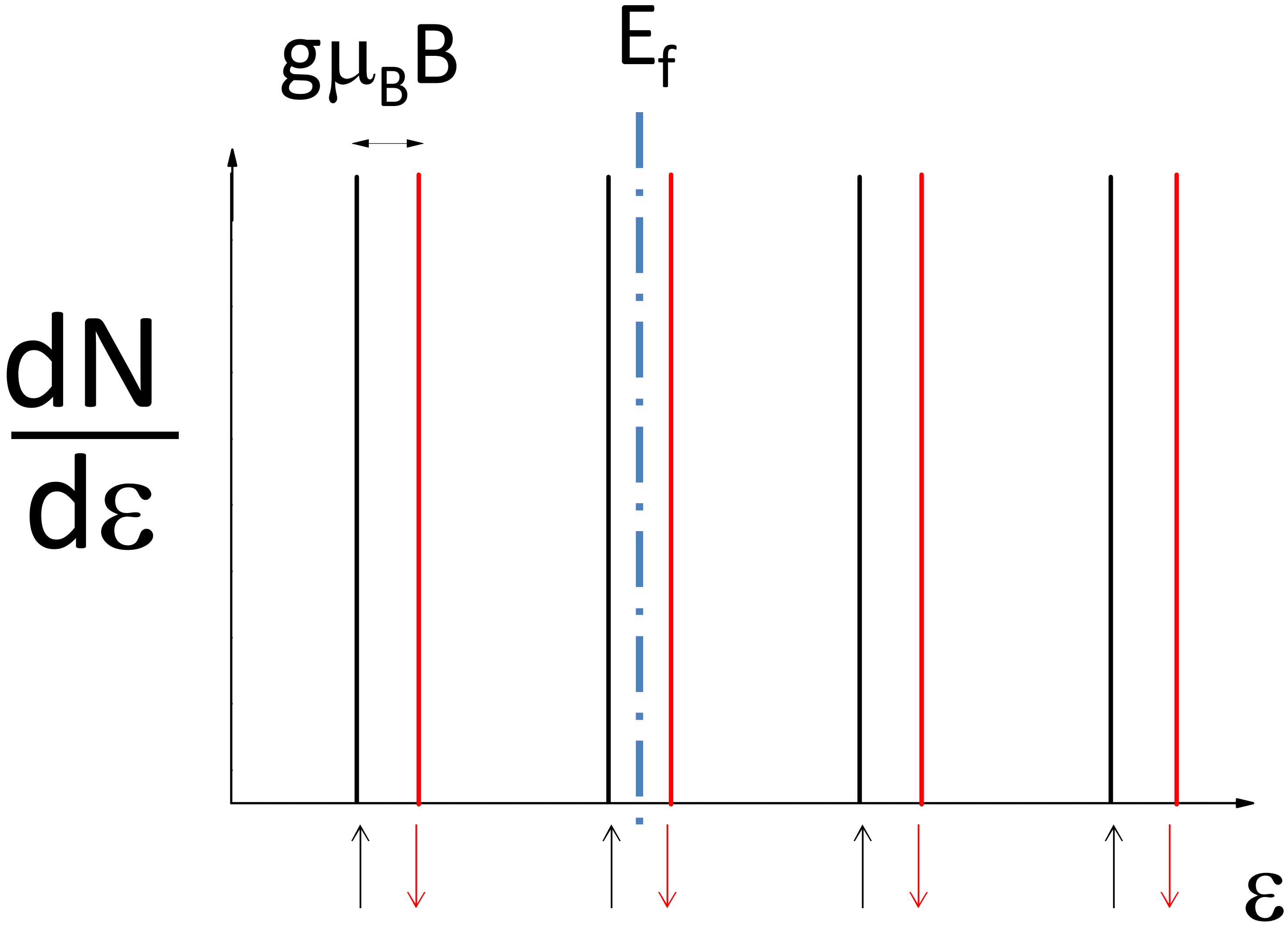
B=0

quantized B field

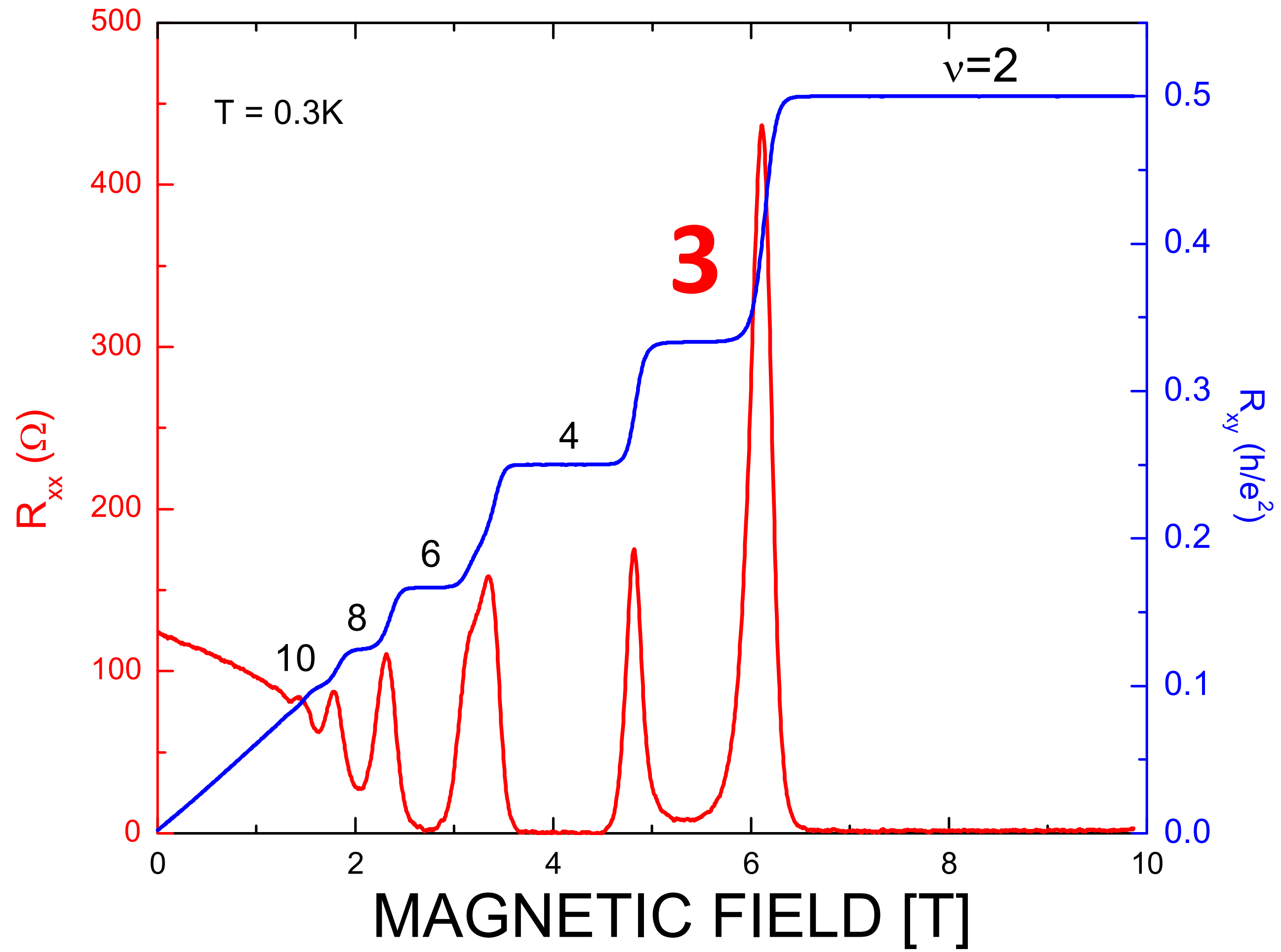
Landau levels



T = 0.3K
10
8
6
4
R_{xx} (Ω)
R_{xy} (h/e^2)
MAGNETIC FIELD [T]
0
100
200
300
400
500
0.0
0.1
0.2
0.3
0.4
0.5
0
2
4
6
8
10



$g\mu_B B$
E_f
$\frac{dN}{d\varepsilon}$
ε

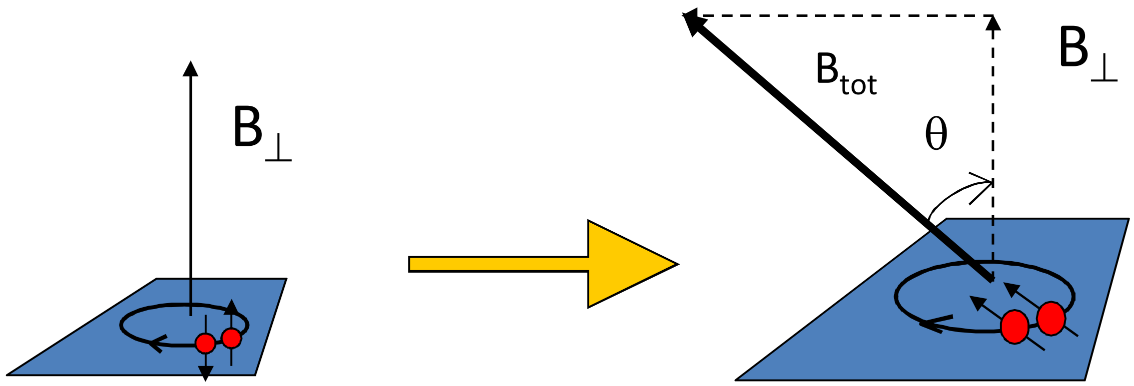


T = 0.3K
ν=2
3
4
6
8
10
R_{xx} (Ω)
R_{xy} (h/e^2)
500
400
300
200
100
0
0.5
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
10
MAGNETIC FIELD [T]

tilt magnetic field technique

$$B_{tot} = B_{\perp}/\cos(\theta)$$

$$\hbar\omega_c \propto B_{\perp},\ E_z = g\mu_B B_{tot} \propto B_{tot}$$



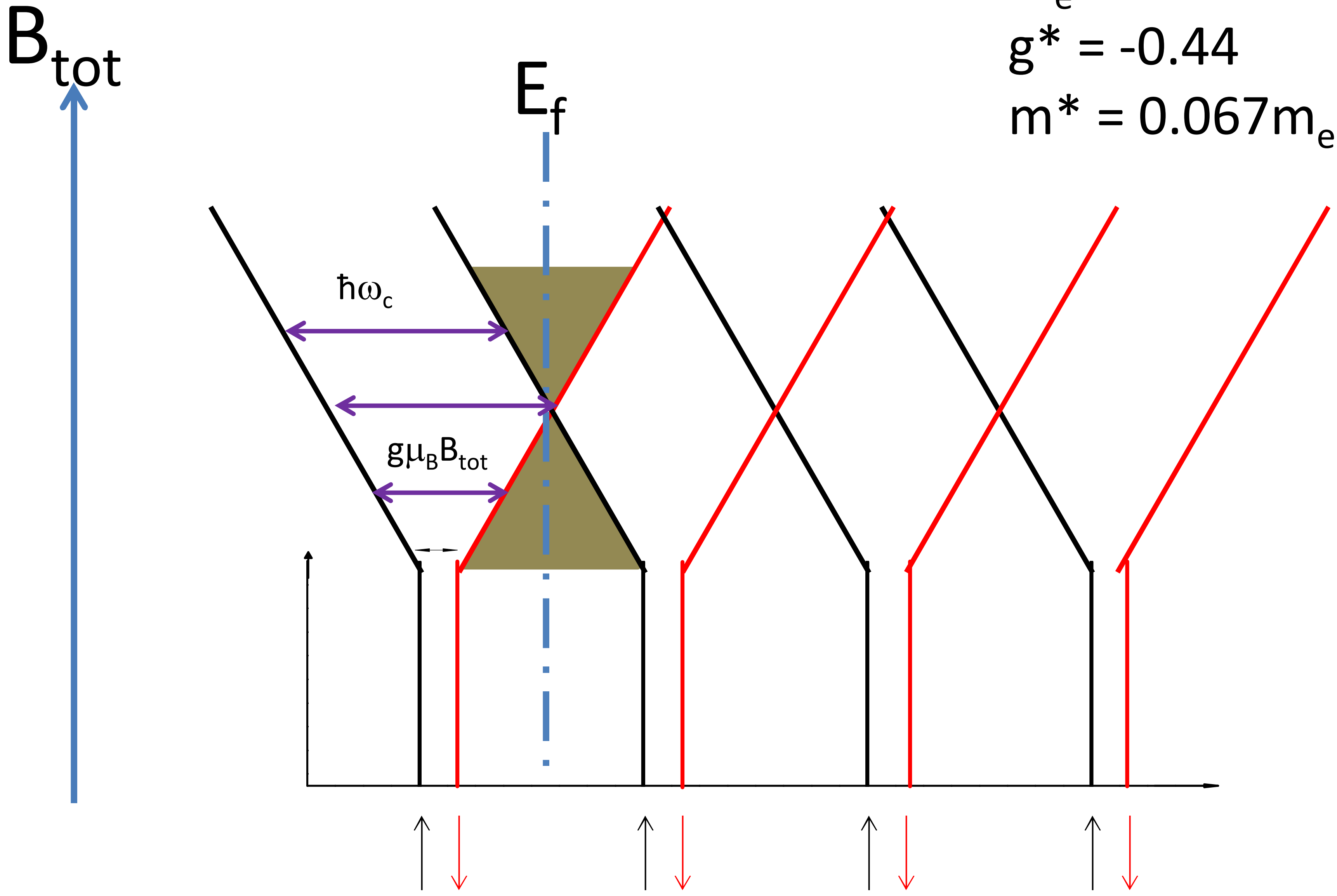
$$\hbar\omega_c = g\mu_B B_{tot} \rightarrow B_{tot}/B_{\perp} = 2m_e/(g^*m^*)$$

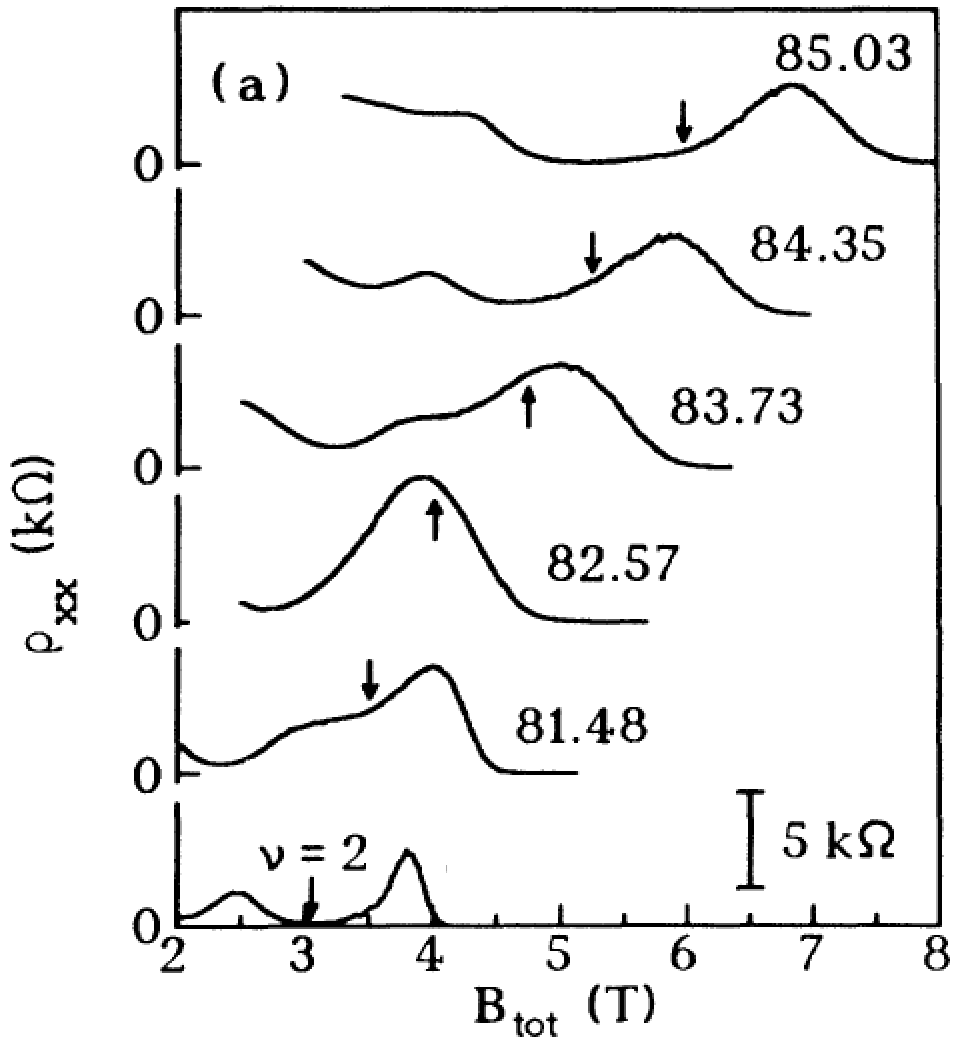
Spin up and down levels cross

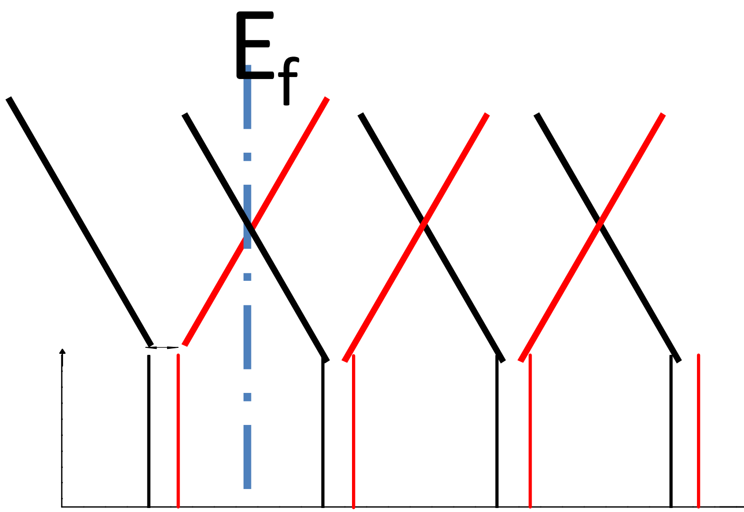
m_e– electron mass

$g^* = -0.44$

$m^* = 0.067m_e$





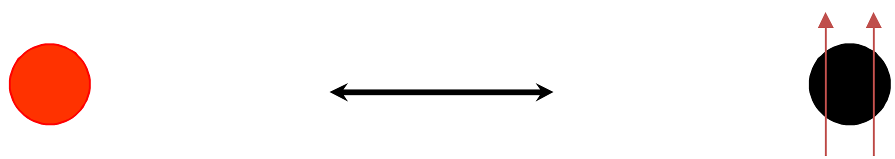


Koch et al, PRB (1993)

Composite Fermion (CF) Model

J.K. Jain, 1989
B.I. Halperin, P.A. Lee, and N.Read,1993

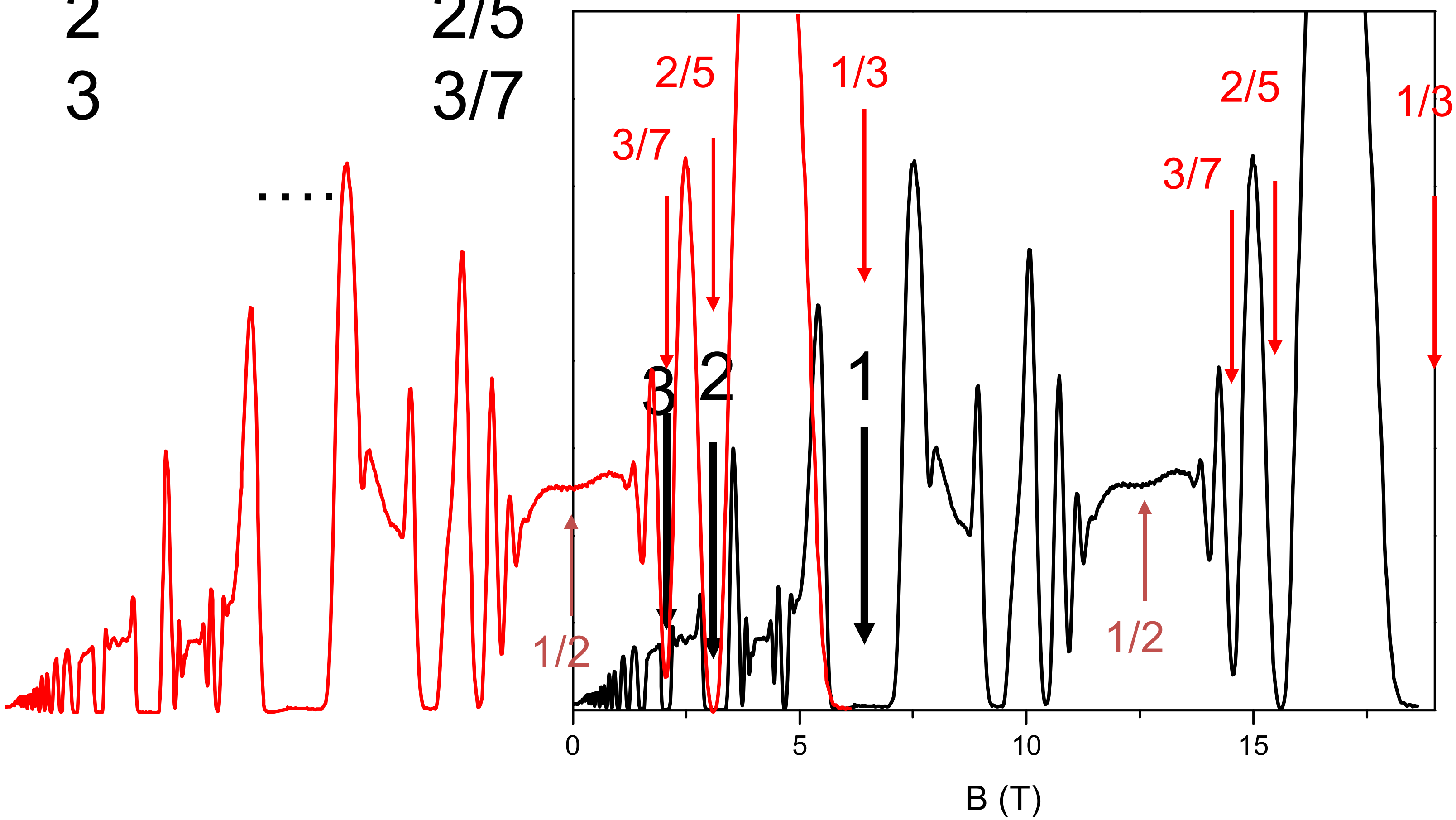
one composite fermion = one electron + 2 flux quanta

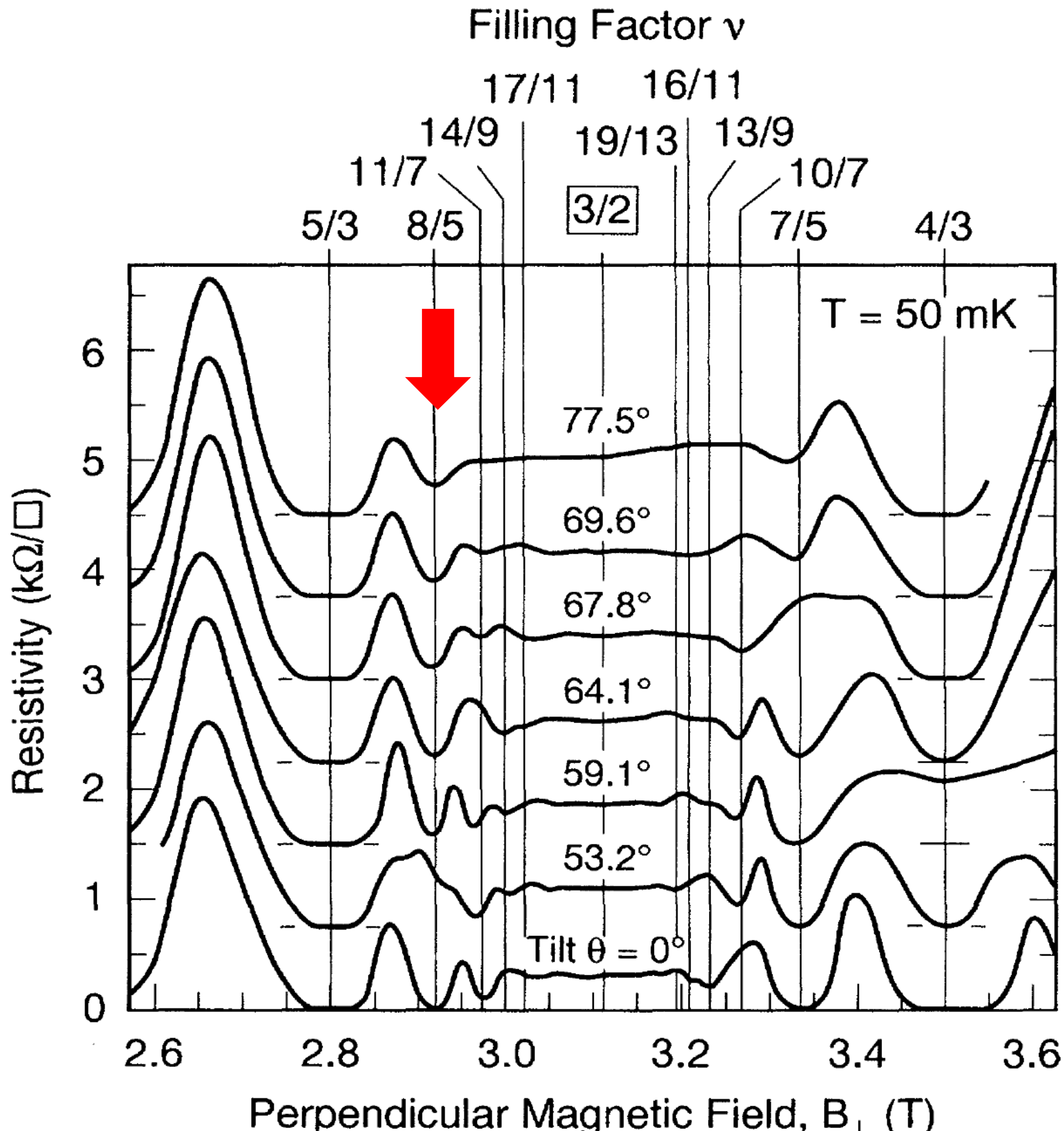


$$B_{eff} = B - 2\Phi_0 \times n = B - 2nh/e$$

IQHE of CF FQHE of e^-

p	$\nu = p/(2p+1)$
1	1/3
2	2/5
3	3/7
….	



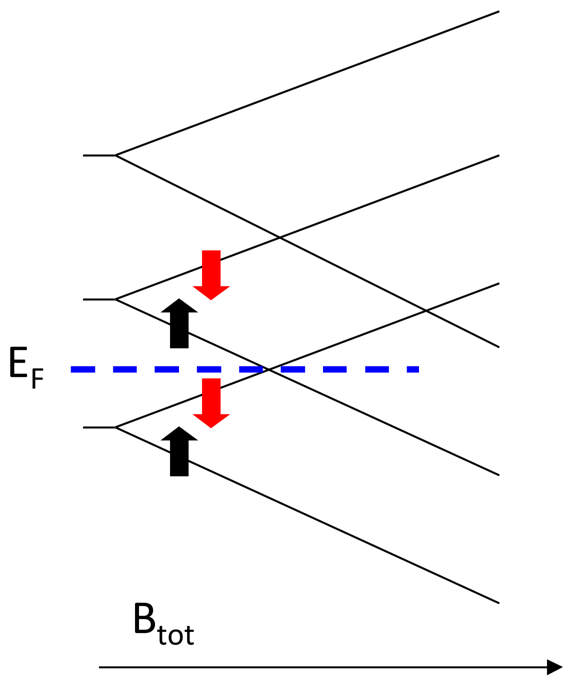


R. R. Du et al, **PRL** (1995)

8/5 state under Composite Fermion model

Jain, PRL (1989)
Halperin, Read, and Lee, PRB (1993)

$\nu=8/5 = 2\text{-}2/5 \longleftrightarrow \nu^*=2$
(electron) (CF)



Spin up and down CF Landau levels crossing at

$B_{tot}/B_{eff} = 2m_e/(g^*m^*)$

m_e – electron mass
g^* – g-factor of CFs
m^* – effective mass of CFs

R. R. Du et al, **PRL** (1995)

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    - 12/5
    - 12/5
- Summary

Pergamon

Solid State Communications, Vol. 94, No. 2, pp. 107–112, 1995
Elsevier Science Ltd
Printed in Great Britain
0038-1098/95 $9.50+.00

0038-1098(95)00034-8

FRACTIONAL QUANTUM HALL EFFECT IN HIGHER LANDAU LEVELS

Lotfi Belkhir* and J. K. Jain

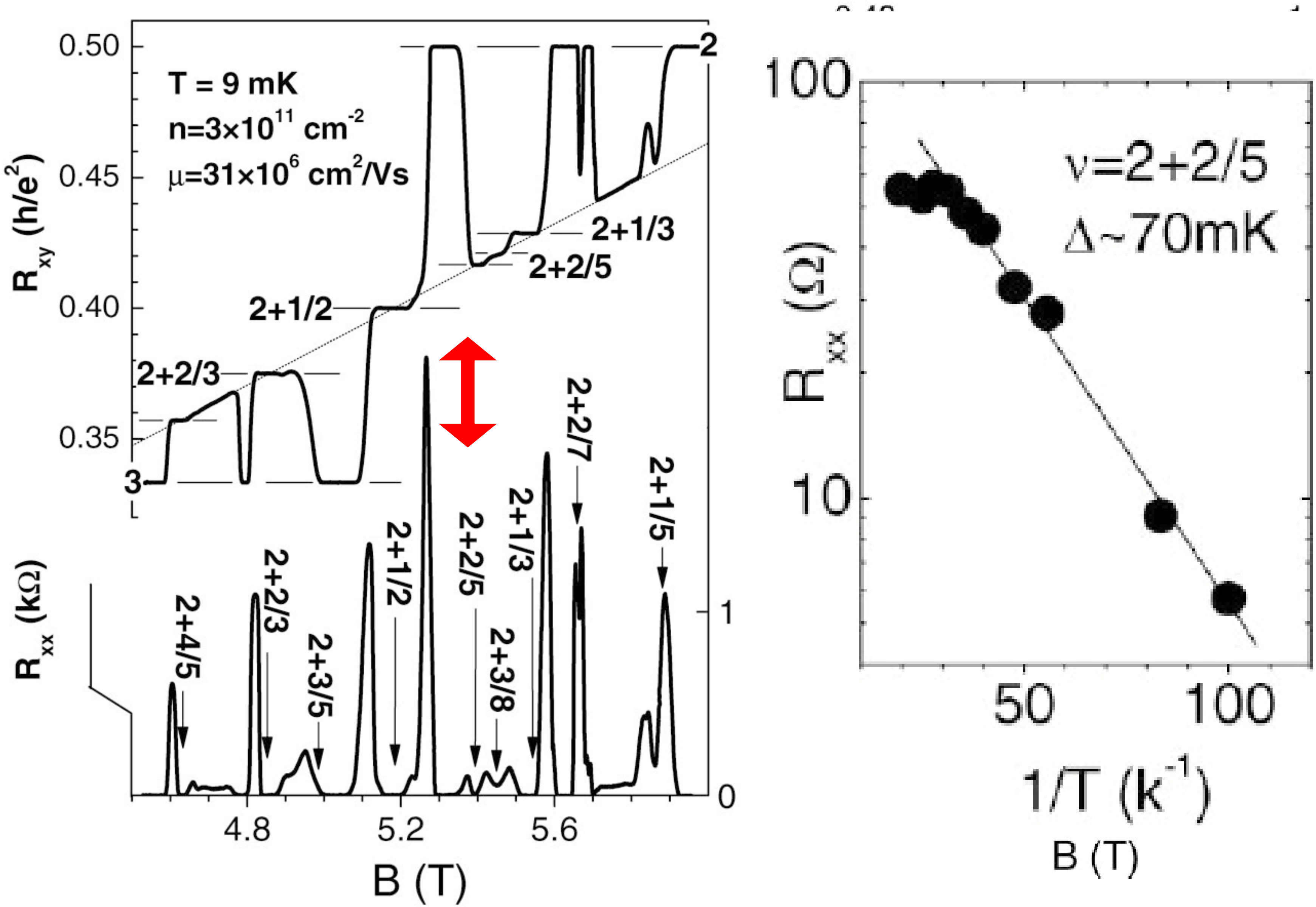
conventional

a finite size effect, and that there is, in fact, no FQHE at 12/5 in the thermodynamic limit.

theoretical proposals for the 12/5 state

- N. Read and E. Rezayi, Phys. Rev. B 59, 8084 (1999).
- E. Ardonne and K. Schoutens Phys. Rev. Lett. 82, 5096 (1999).
- M. Freedman, M. Larsen, and Z. Wang, Comm. Math. Phys. **227**, 105 (2002).
- S.H. Simon, E.H. Rezayi, N.R. Cooper, and I. Berdikov, Phys. Rev. B 75, 075317 (2007).
- W. Bishara, G.A. Fiete, and C. Nayak, Phys. Rev. B 77, 241306 (2008).
- P. Bonderson and J.K. Slingerland, Phys. Rev. B 78, 125323 (2008).
- B.A. Bernevig and F.D.M. Haldane, Phys. Rev. Lett. 101, 246806 (2008).
- E.H. Rezayi and N. Read, Phys. Rev. B 79, 075306 (2009).
- M. Levin and B.I. Halperin, Phys. Rev. B 79, 205301 (2009).
- M.V. Milovanović, Th. Jolicoeur, and I. Vidanović, Phys. Rev. B 80, 155324 (2009).
- L. Hormozi, N.E. Bonesteel, S.H. Simon, Phys. Rev. Lett. **103**, 160501 (2009).
- Z. Papić, N. Regnault, and S. Das Sarma, Phys. Rev. B 80, 201303 (2009).
- M. Barkeshli and X.G. Wen, Phys. Rev. B 84, 115121 (2011).
- G.J. Sreejith, C. Tőke, A. Wójs, and J.K. Jain, Phys. Rev. Lett. 107, 086806 (2011).
- P. Bonderson, A.E. Feiguin, G. Möller, and J. K. Slingerland, Phys. Rev. Lett. 108, 036806 (2012).
- ….

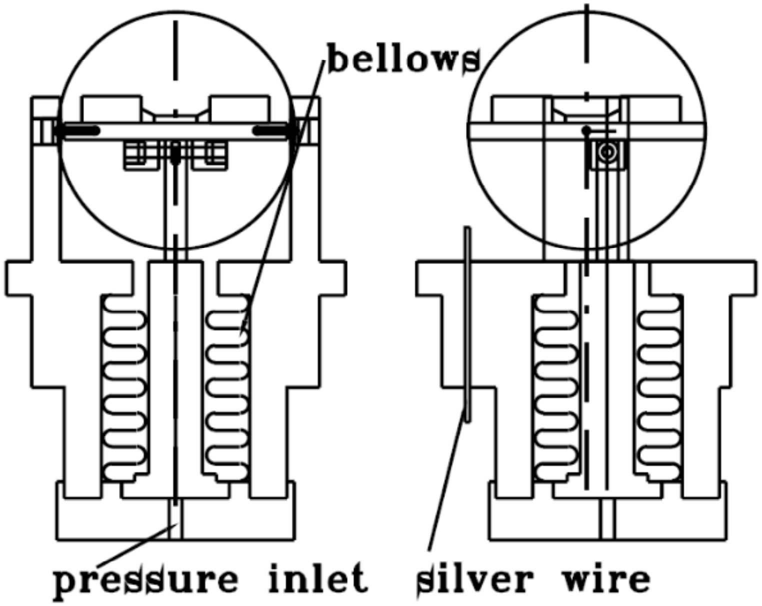
the 12/5 fractional quantum Hall state



tilt at de-mag temperatures

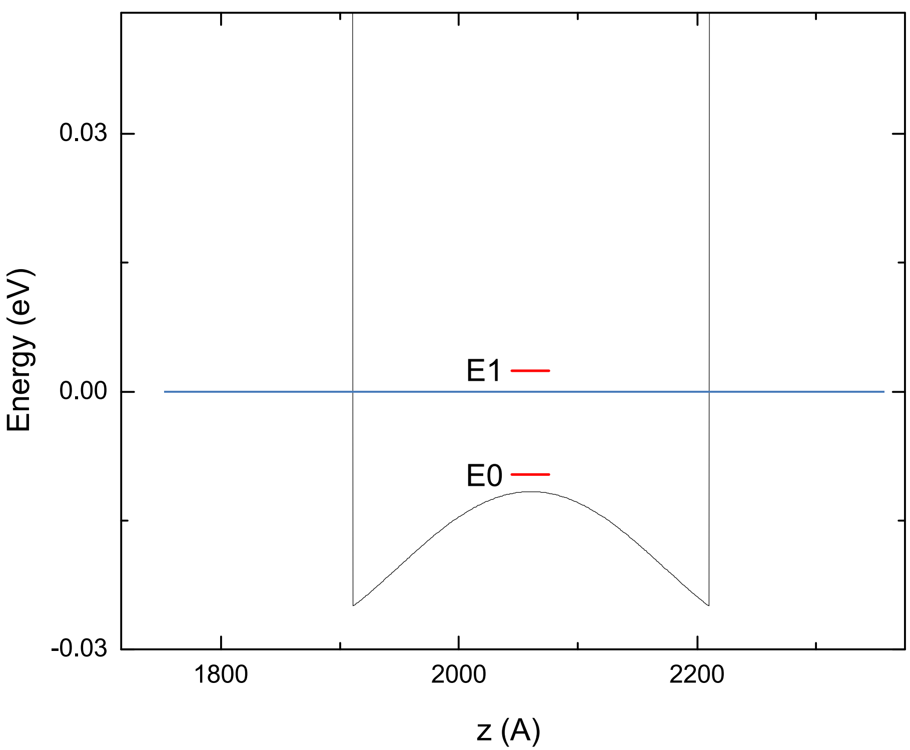
- tilting done by tuning liquid 3He pressure. Almost no heating at de-mag temperatures.

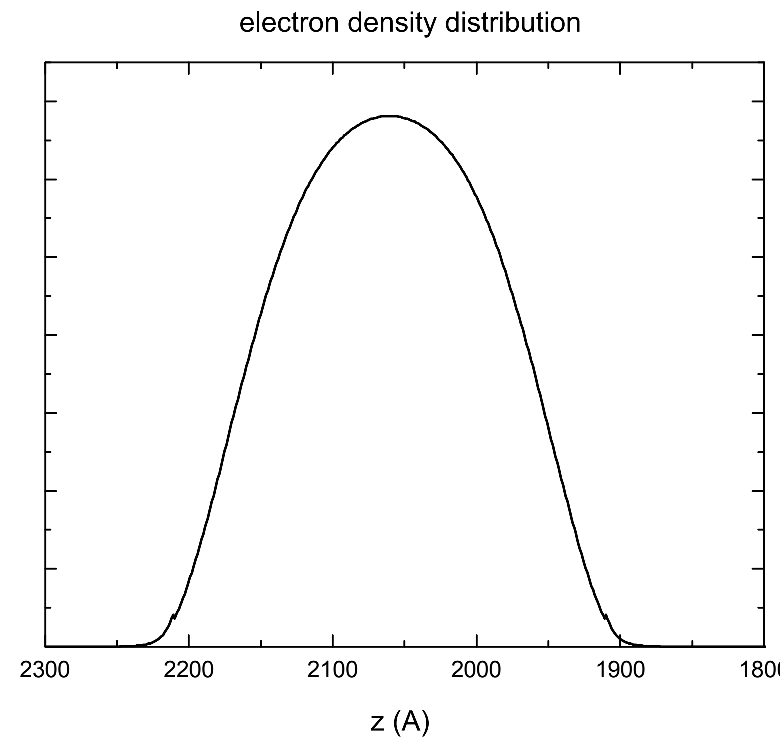
- sintered silver powder heat exchangers for electron cooling.



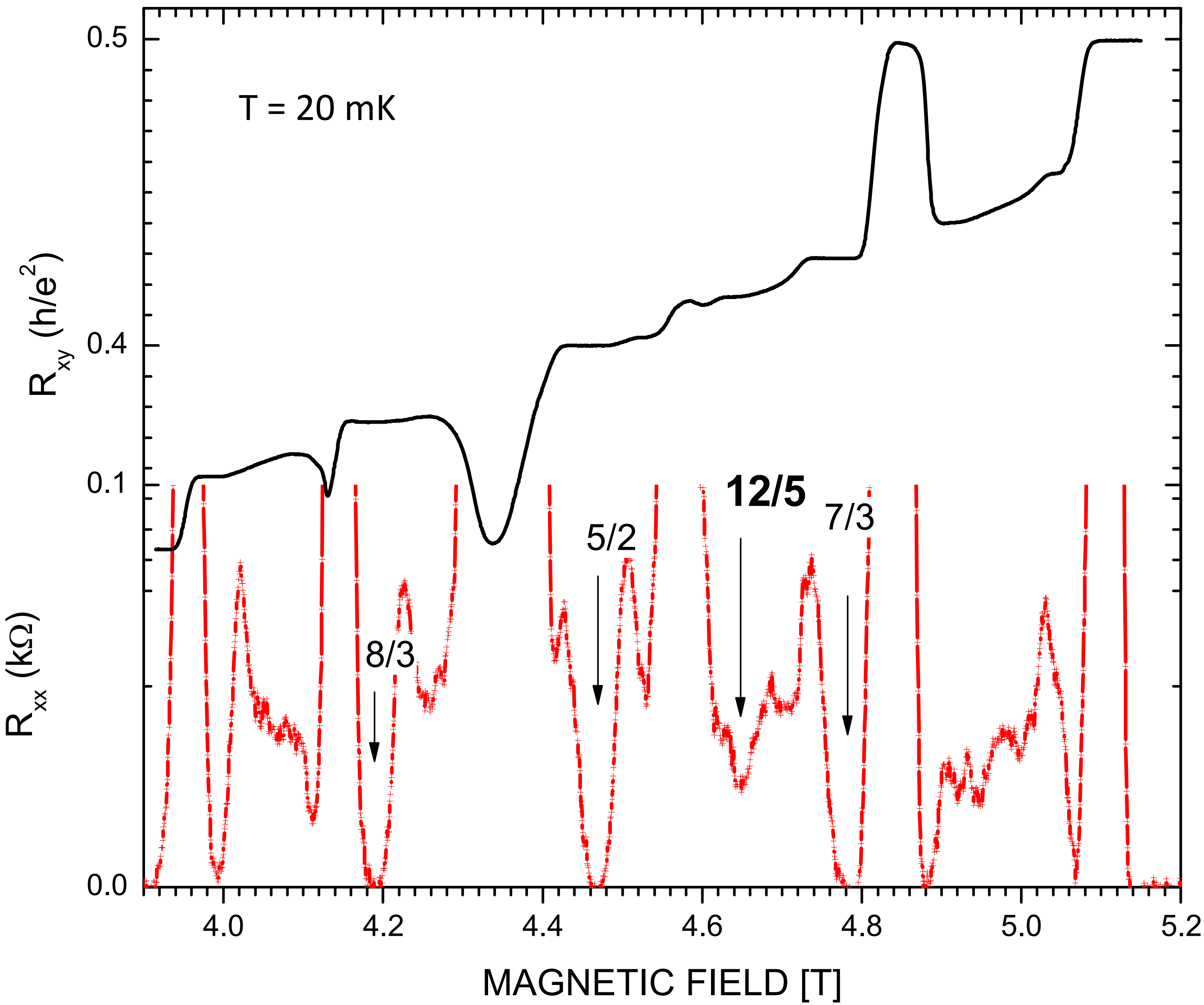
- sample immersed in 3He liquid.

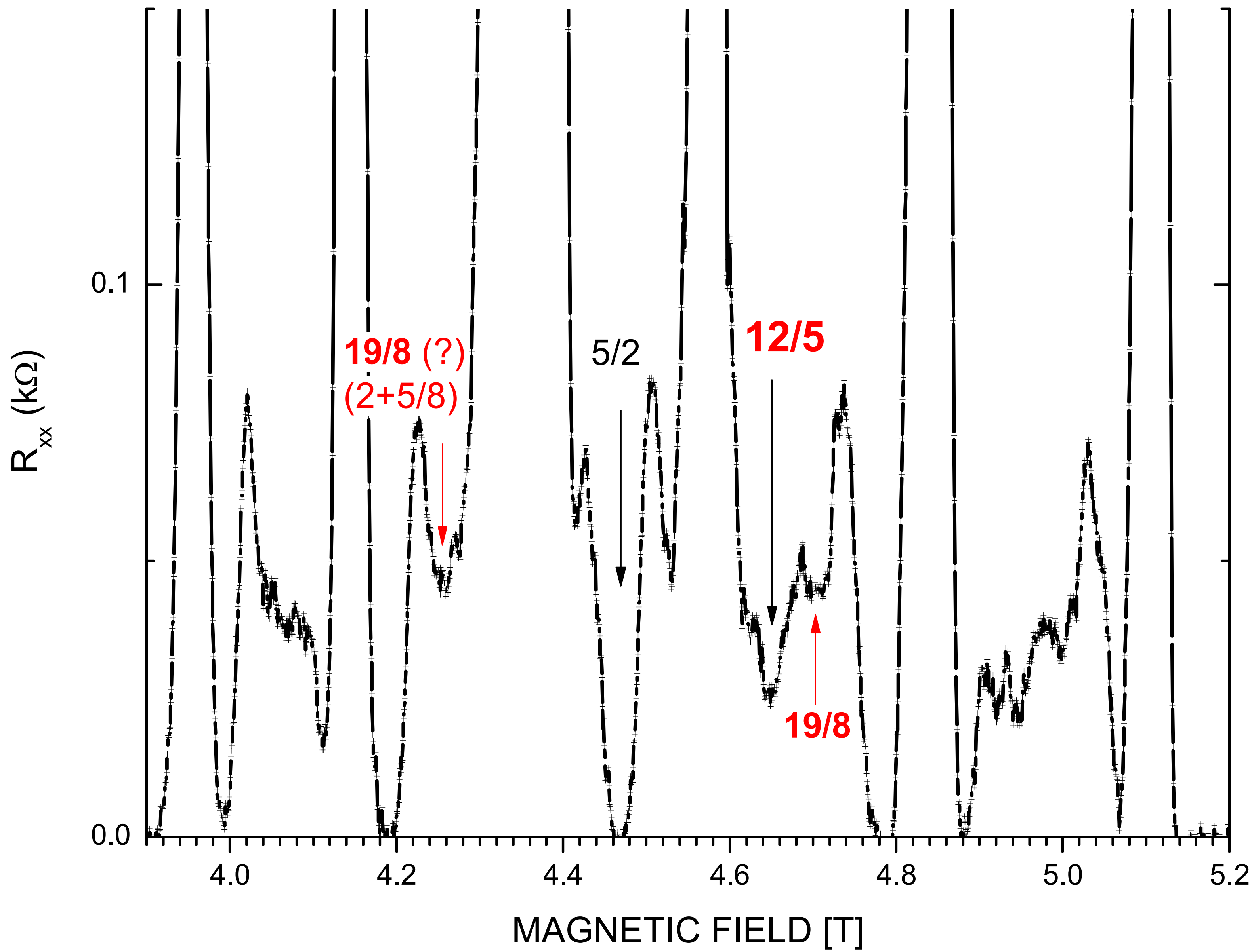
- 30 nm wide, $Al_{0.24}Ga_{0.76}As/GaAs/Al_{0.24}Ga_{0.76}As$ QW
- Low T, n=2.7×10^{11} cm^{-2} and μ= 31×10^{6} cm^{2}/Vs





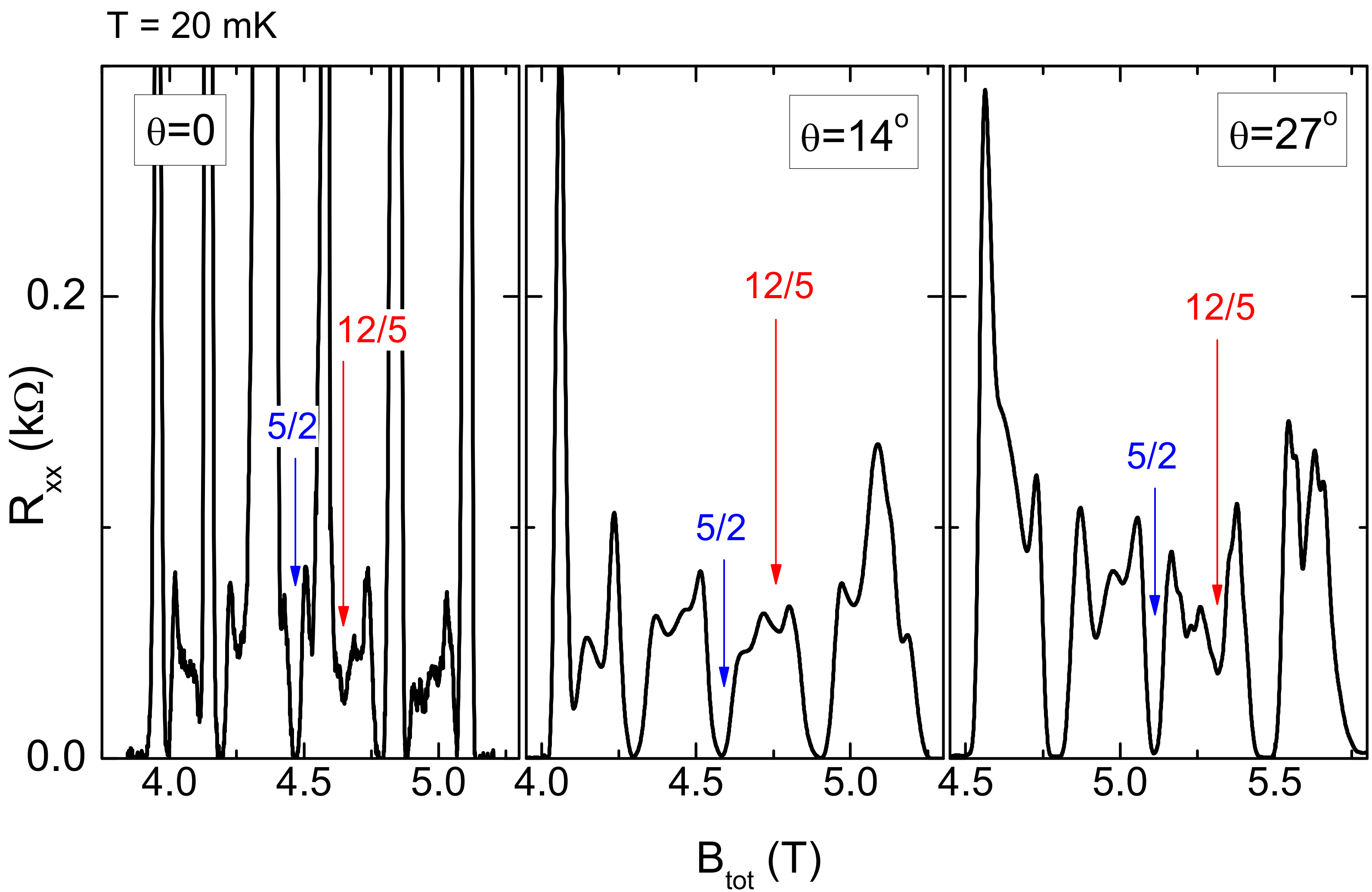
R_{xx} and R_{xy} data



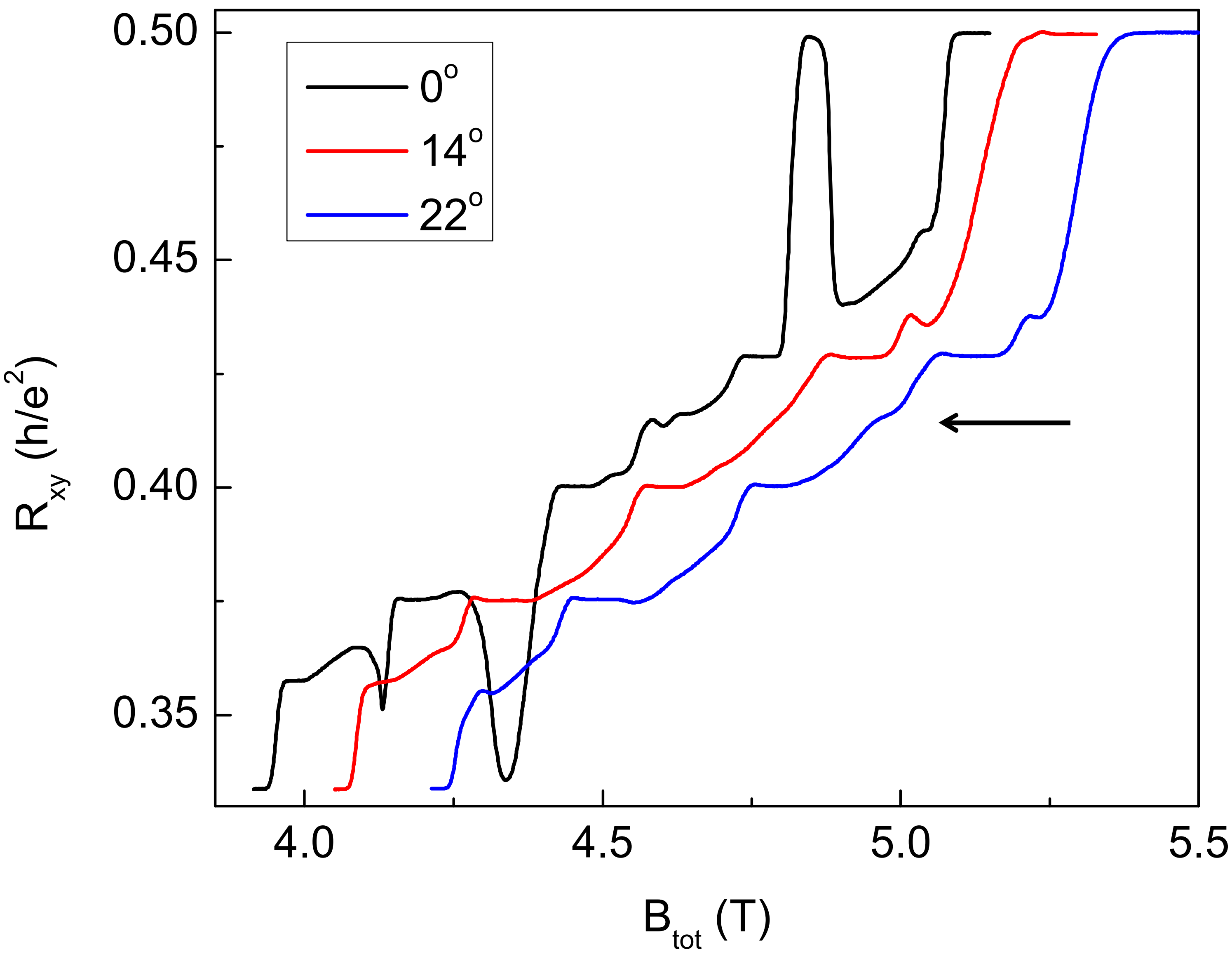


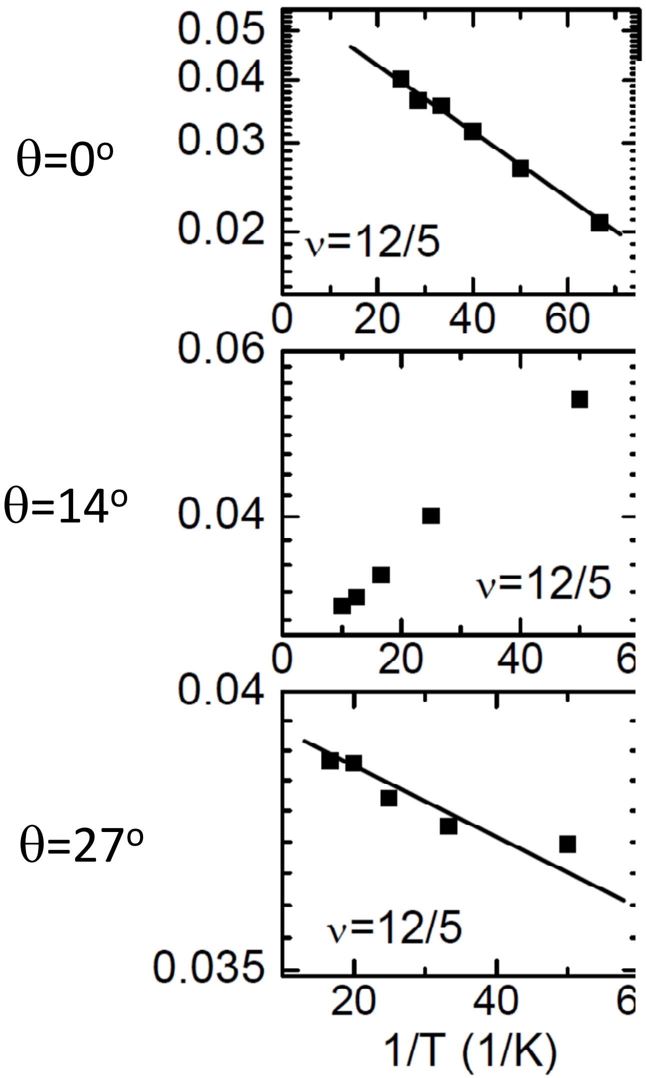
0.1
0.0
R_{xx} (kΩ)
19/8 (?)
(2+5/8)
5/2
12/5
19/8
4.0
4.2
4.4
4.6
4.8
5.0
5.2
MAGNETIC FIELD [T]

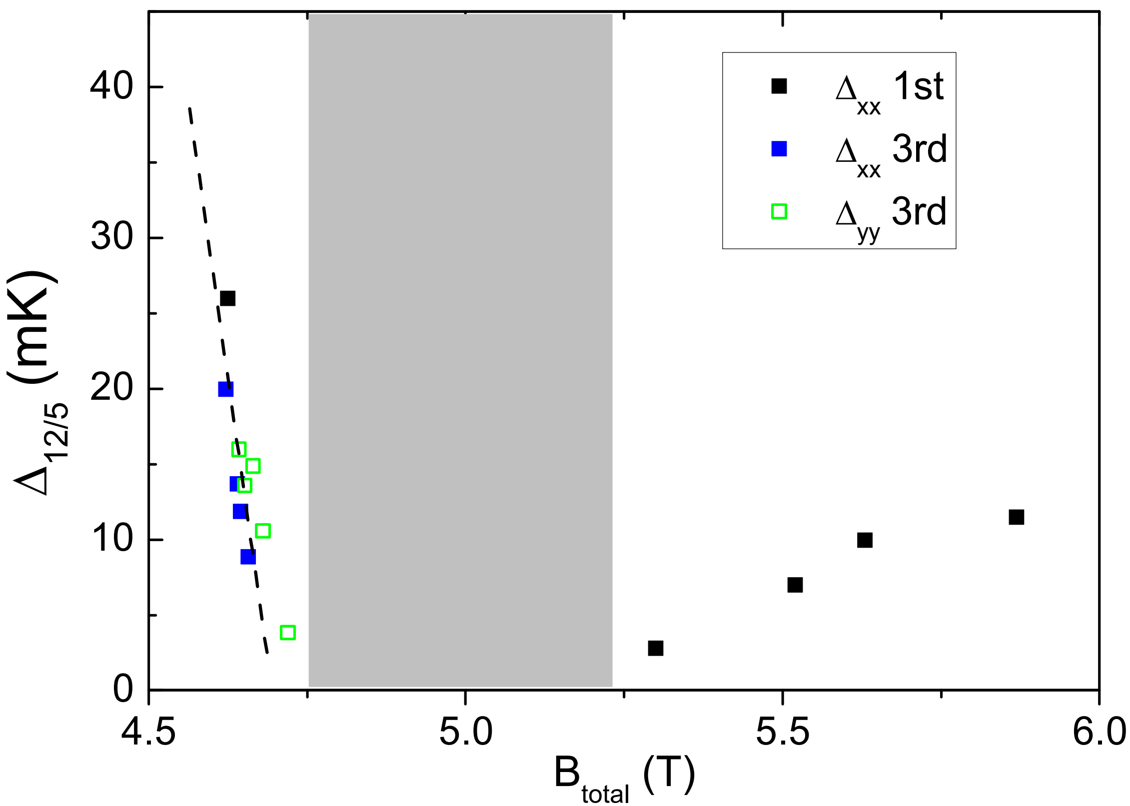
R_{xx} under tilt



Rxy data for tilted angles



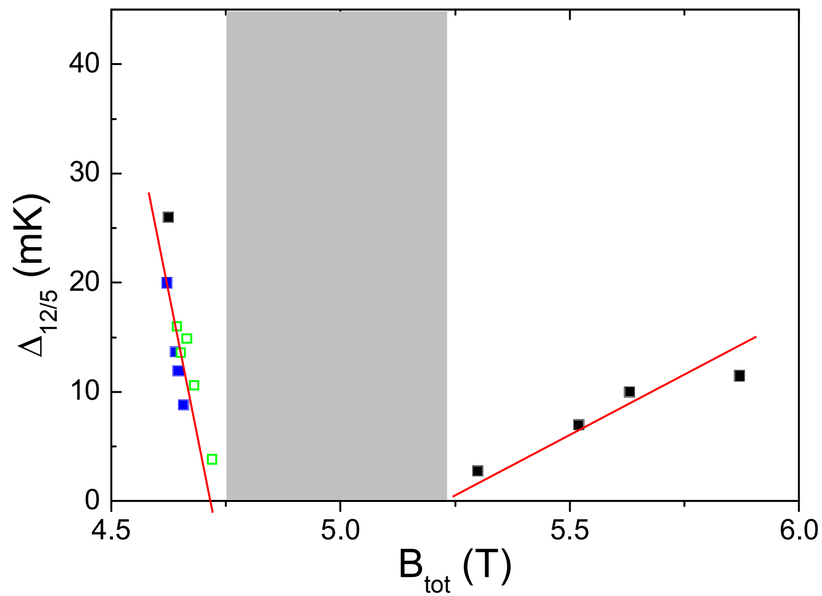




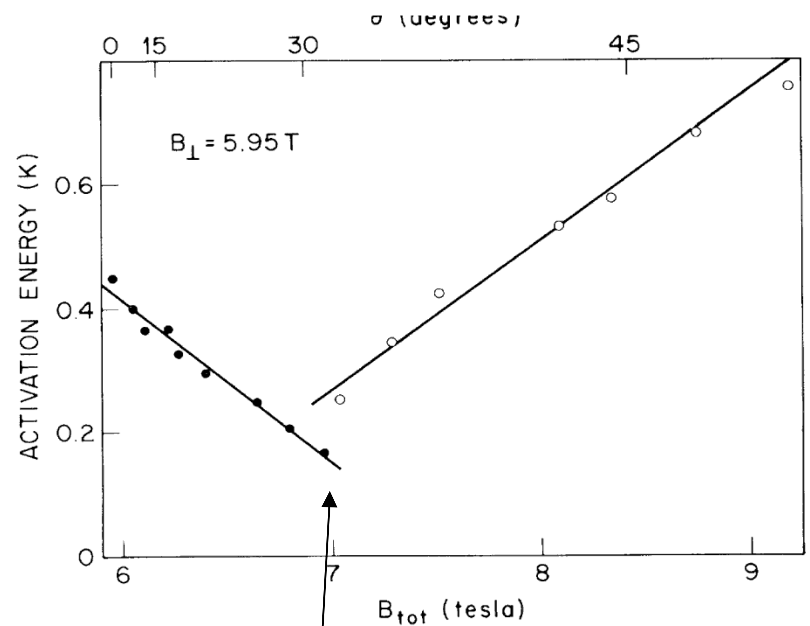
$$R_{xx} \propto \exp(-\Delta/2k_BT)$$

activation energy versus B_{tot}

ν=12/5



ν=8/5

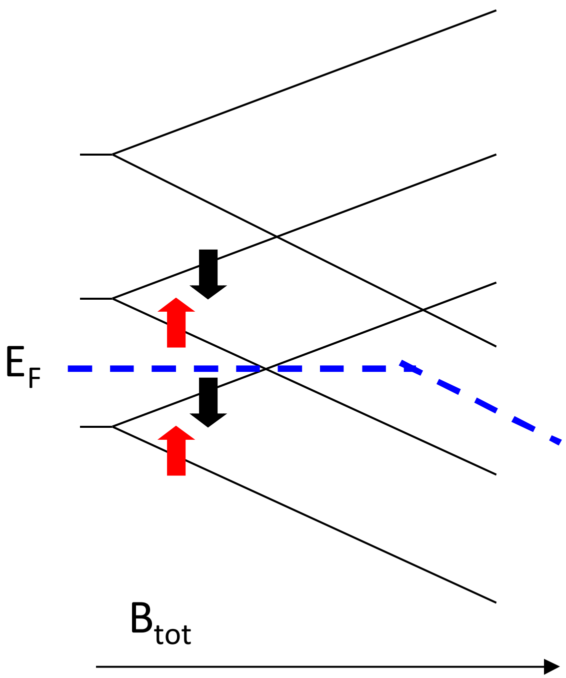


Eisenstein et al, PRL (1989)

spin transition at 8/5

8/5 state under Composite Fermion model

ν=8/5 (electron) ⟷ ν^*=2 (CF)



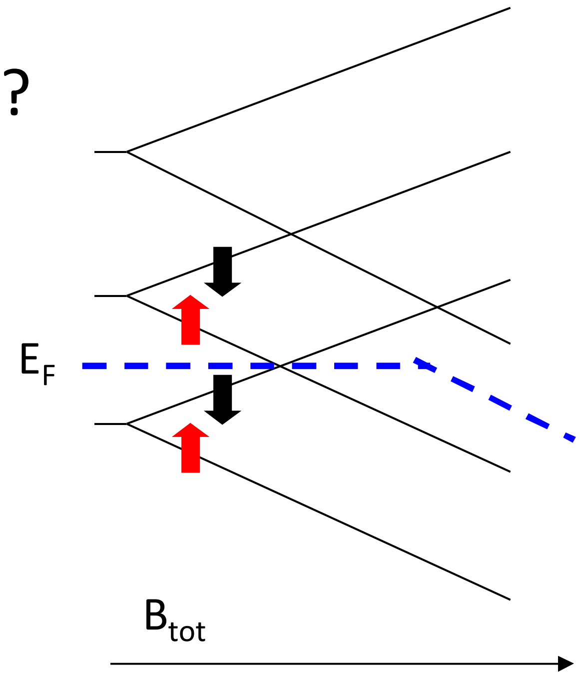
Spin up and down CF levels crossing at

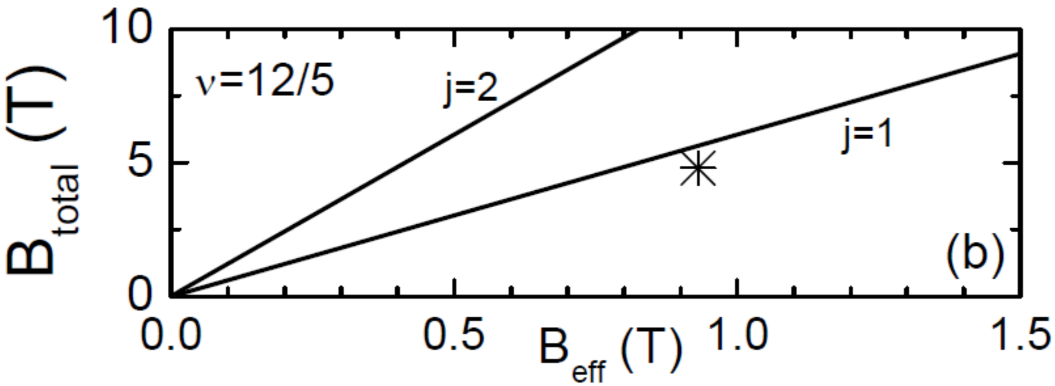
$B_{tot}/B_{eff} = j \times 2m_e/(g^*m^*)$, $j = 1$

R. R. Du et al, **PRL** (1995)

What about the 12/5 state?

ν=12/5 (electron) $\leftrightarrow$ ν^*=2 in the second LL ? (CF)



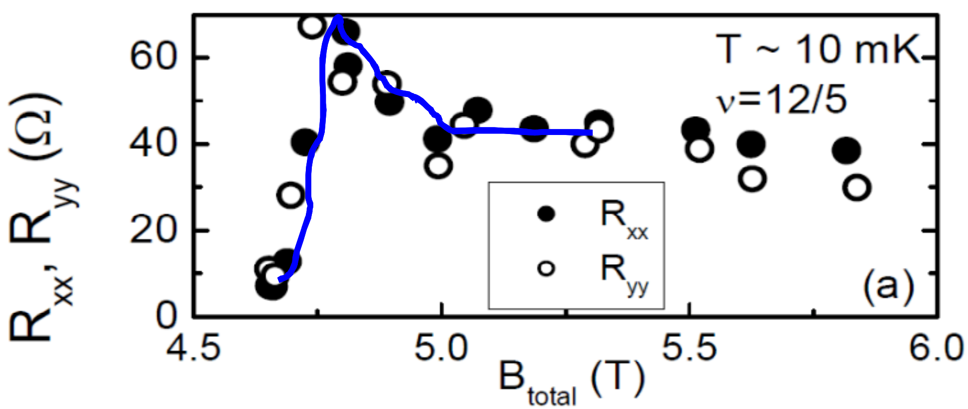


$B_{tot}/B_{eff} = j \times 2m_e/(g^* m^*)$

$j = 1, 2, \ldots$

$m^*/m_e \sim 0.26\, B_\nu^{1/2} \sim 0.55$

W. Pan et al, **PRB** (2000)



$g^* \sim 0.6$

R. R. Du et al, **PRL** (1995)

A. S. Yeh et al, **PRL** (1999)

Is the 12/5 state a CF state?

Is it non-Abelian spin-singlet QH state?

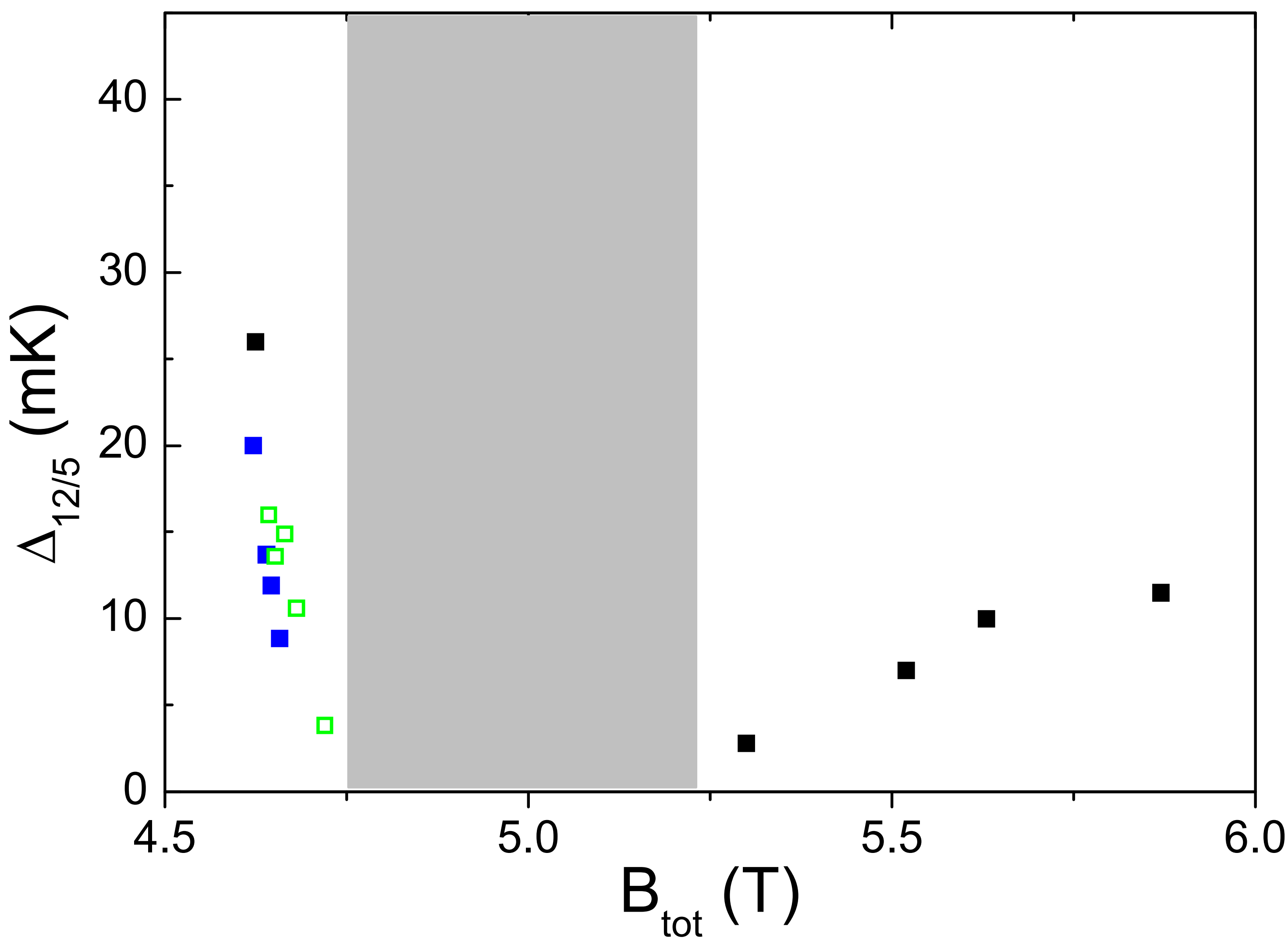
Ardonne and Schoutens, PRL (1999)

$$\nu=2k/(2kM+3)$$

if k=3, M=2,

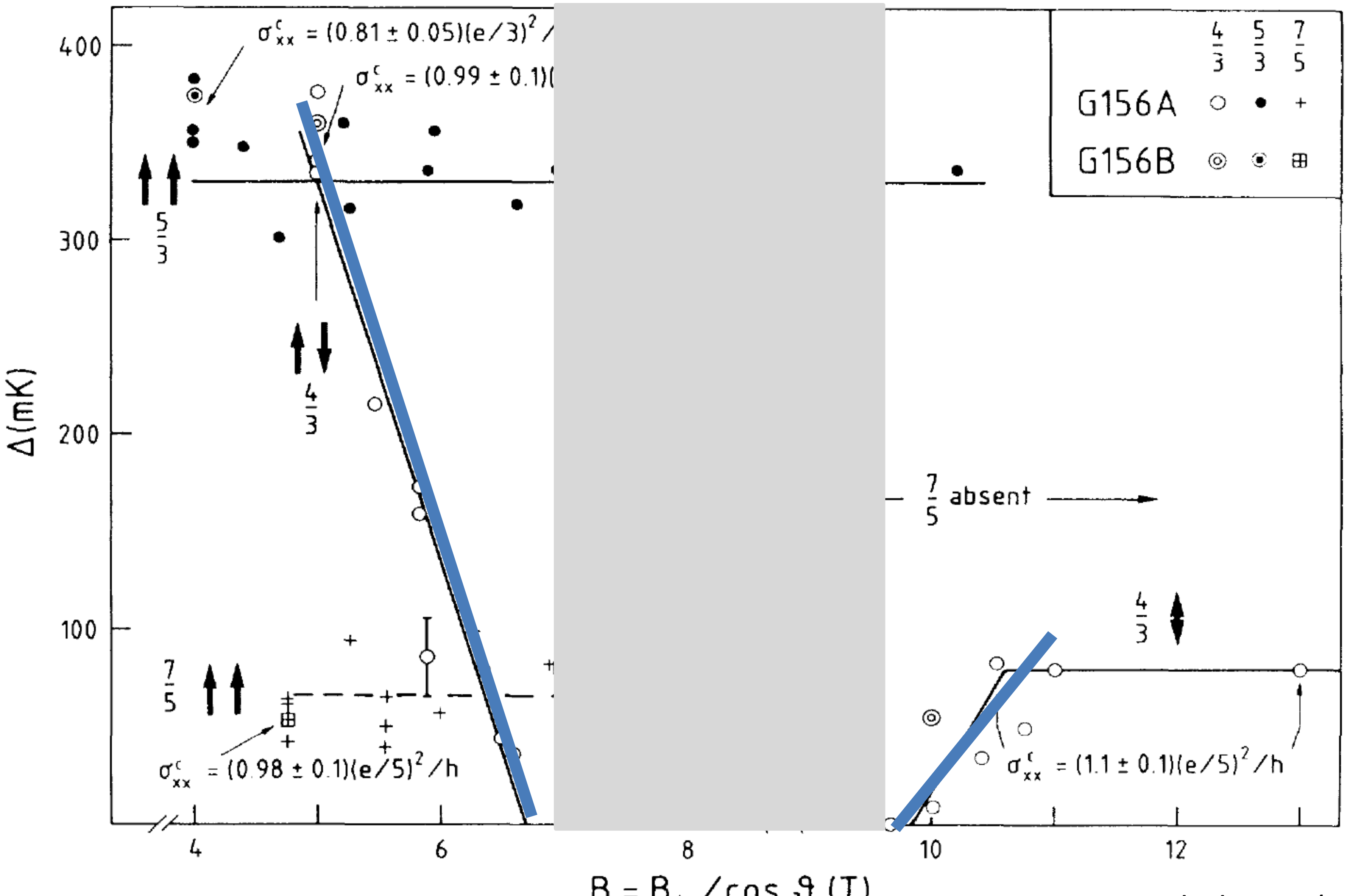
$$\nu=3/5 \rightarrow 2/5$$

Is it a spin unpolarized Bonderson and Slingerland state?



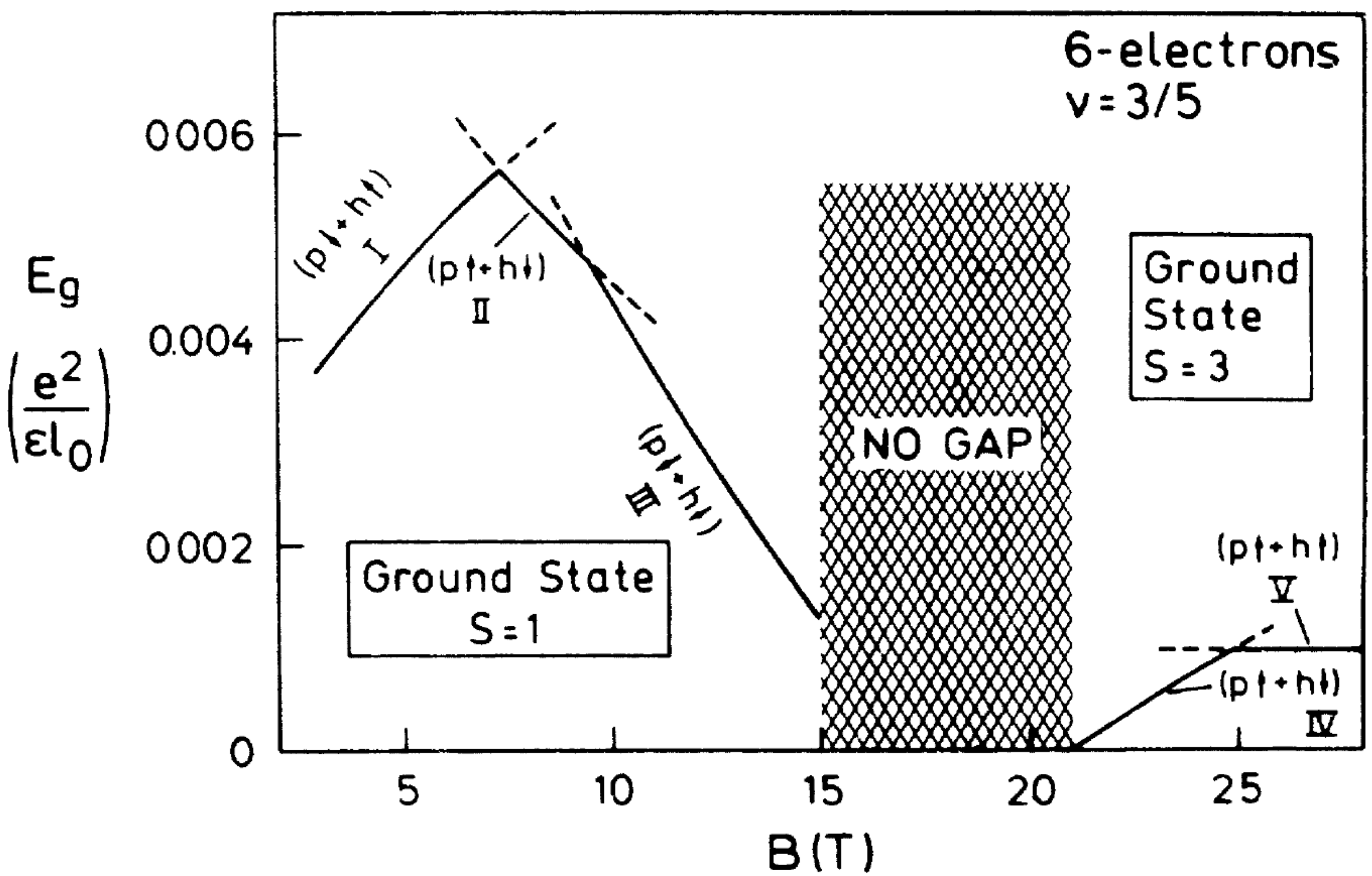
40
30
20
10
0
$\Delta_{12/5}$ (mK)
4.5
5.0
5.5
6.0
B_{tot} (T)

4/3 state under tilt

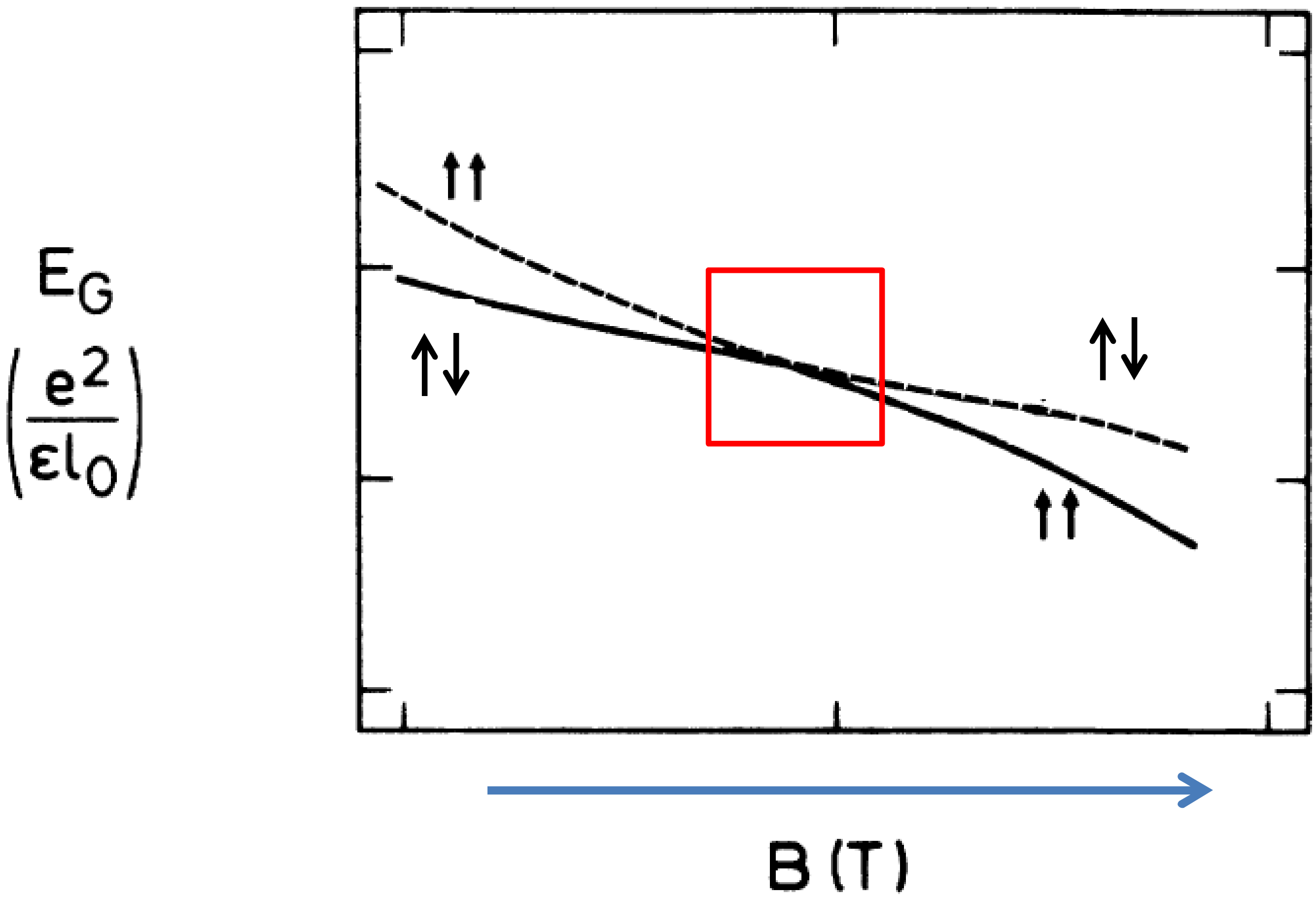


R.G. Clark, PRL (1989)

Numerical calculation for the 3/5 state



T. Chakraborty and P. Pietilainen, Phys. Rev. B 41, 10862 (1990)



E_G
$\left(\frac{e^2}{\varepsilon l_0}\right)$
↑↑
↑↓
↑↓
↑↑
B (T)

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    - 8/3
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- Summary

PHYSICAL REVIEW B VOLUME 33, NUMBER 6 15 MARCH 1986

Collective excitations of fractional Hall states and Wigner crystallization in higher Landau levels

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Surface Science Division, National Bureau of Standards, Gaithersburg, Maryland 20899

(Received 29 August 1985; revised manuscript received 2 December 1985)

An expression has been derived for the collective-excitation dispersion for fractional Hall states which occur in higher orbital Landau levels in terms of the electron pair-correlation function in these states. Explicit results for the $n=1$ Landau level have been obtained at fractional filling factors $\nu=\frac{1}{3}$ and $\nu=\frac{1}{5}$ based on Laughlin's trial wave functions for the ground state. The results at $\nu=\frac{1}{3}$ are qualitatively different from those in the lowest Landau level and are consistent with a weak quantum Hall effect at this fraction for $n=1$. The results for $\nu=\frac{1}{5}$ are similar to those in the $n=0$ Landau level but the collective excitations have a higher energy. We associate this increase

$\nu=\frac{1}{3}$ are qualitatively different from those in the lowest Landau level

Pergamon

Solid State Communications, Vol. 94, No. 2, pp. 107–112, 1995
Elsevier Science Ltd
Printed in Great Britain
0038-1098/95 $9.50+.00

0038-1098(95)00034-8

FRACTIONAL QUANTUM HALL EFFECT IN HIGHER LANDAU LEVELS

Lotfi Belkhir* and J. K. Jain

at this fraction. Our calculations confirm this result for strictly two-dimensional (2D) systems. However, we find the surprising result that for wider quantum wells, the exact ground state becomes closer to the Laughlin state, and the FQHE at 7/3 becomes stronger; the energy gap acquires its maximum value when the thickeness is roughly equal to twice the magnetic length. This is in contrast to the situation in the lowest LL, where the FQHE is in general the strongest at zero thickness.

theoretical proposals for the 8/3 and 7/3 states

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- S.H. Simon, E.H. Rezayi, N.R. Cooper, and I. Berdikov, Phys. Rev. B **75**, 075317 (2007).
- W. Bishara, G.A. Fiete, and C. Nayak, Phys. Rev. B **77**, 241306 (2008).
- P. Bonderson and J.K. Slingerland, Phys. Rev. B **78**, 125323 (2008).
- N. Regnault, M.O. Goerbig, and Th. Jolicoeur, Phys. Rev. Lett. **101**, 066803 (2008).
- B.A. Bernevig and F.D.M. Haldane, Phys. Rev. Lett. **101**, 246806 (2008).
- M. Levin and B.I. Halperin, Phys. Rev. B **79**, 205301 (2009).
- A. Wojs, Phys. Rev. B **80**, 041104 (2009).
- M. Barkeshli and X.G. Wen, Phys. Rev. B **82**, 233301 (2010).
- G.J. Sreejith, C. Toke, A. Wojs, and J.K. Jain, Phys. Rev. Lett. **107**, 086806 (2011).
- ….

Experimentally:

- 7/3 and 8/3 are true FQHE states

- $\Delta_{7/3} \approx 2\,\Delta_{8/3}$

$$\Delta \propto \sqrt{B} \rightarrow \Delta_{7/3}/\Delta_{8/3} = \sqrt{B_{7/3}/B_{8/3}} \sim 1$$

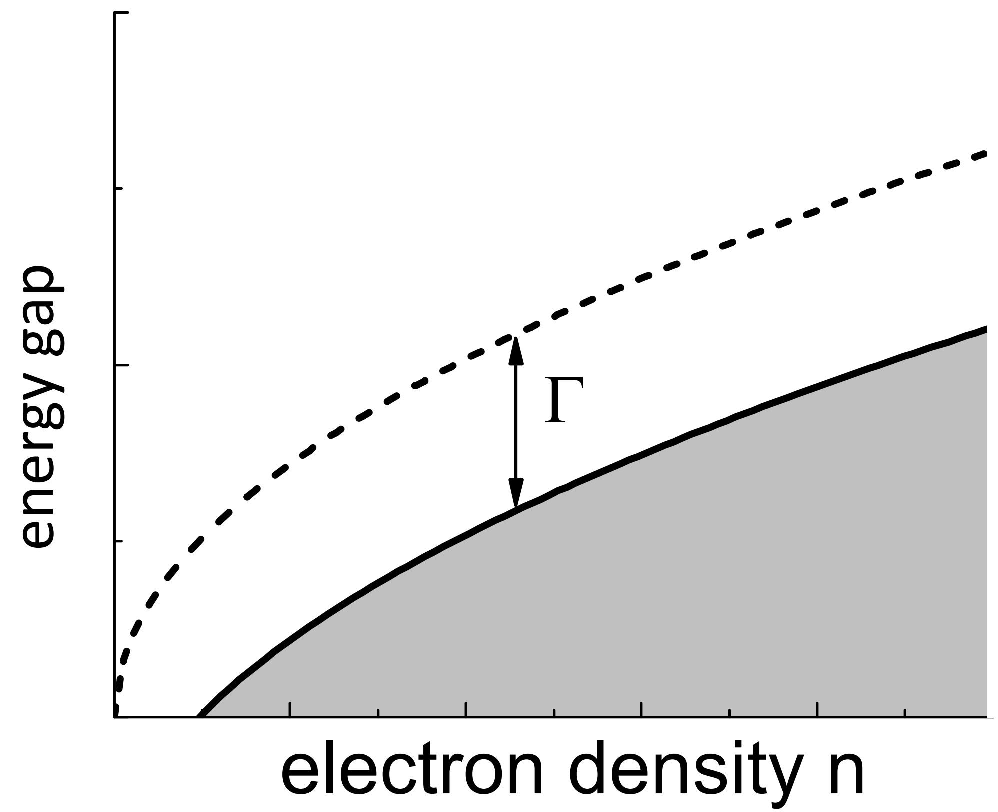
Density dependence of the 8/3 state

E_c (Coulomb energy) = $e^2/\varepsilon r \propto n^{1/2}$

E_z (Zeeman energy) $\propto n$

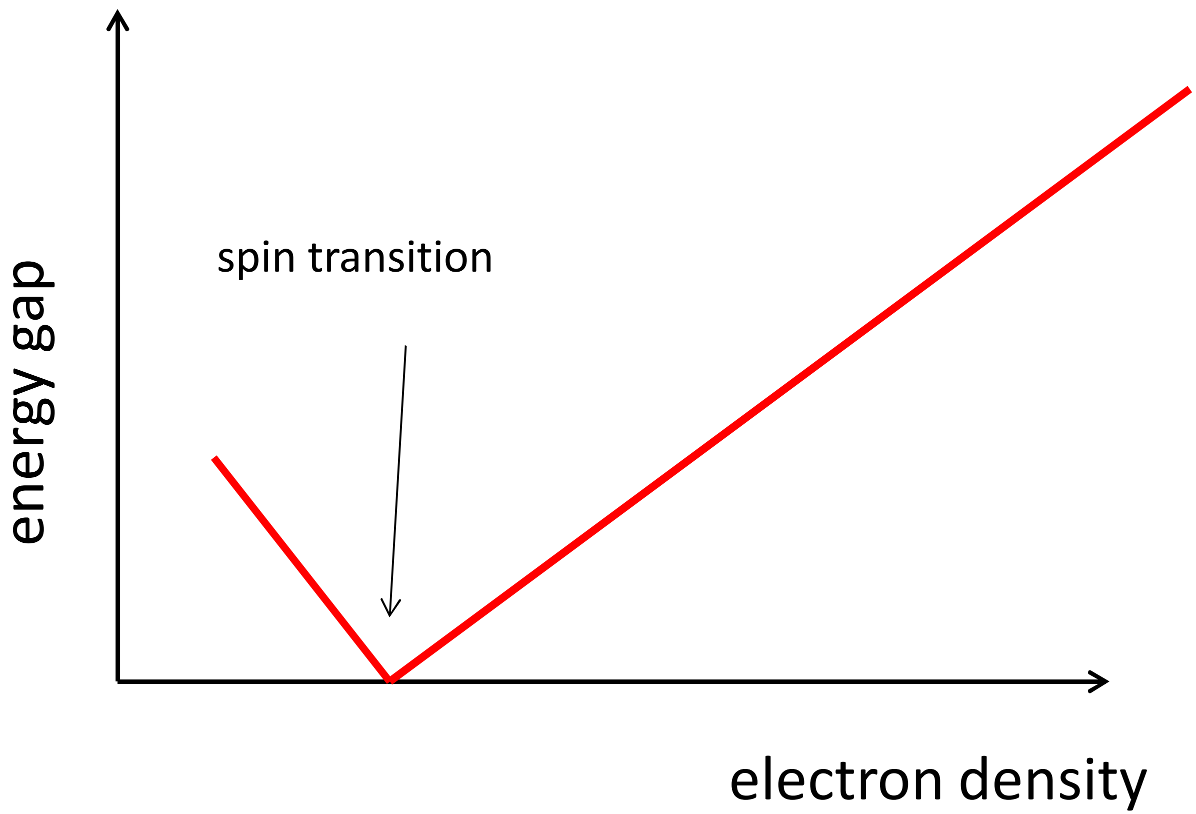
$\Delta \propto E_c$ (Coulomb energy) = $e^2/\varepsilon r \propto n^{1/2}$

spin polarized ground state: $\Delta = \alpha\sqrt{n} - \Gamma$



$E_c \propto n^{1/2}$, E_z(Zeeman energy) $\propto n$

spin unpolarized ground state: $\Delta = \alpha\sqrt{n} - \beta n - \Gamma$

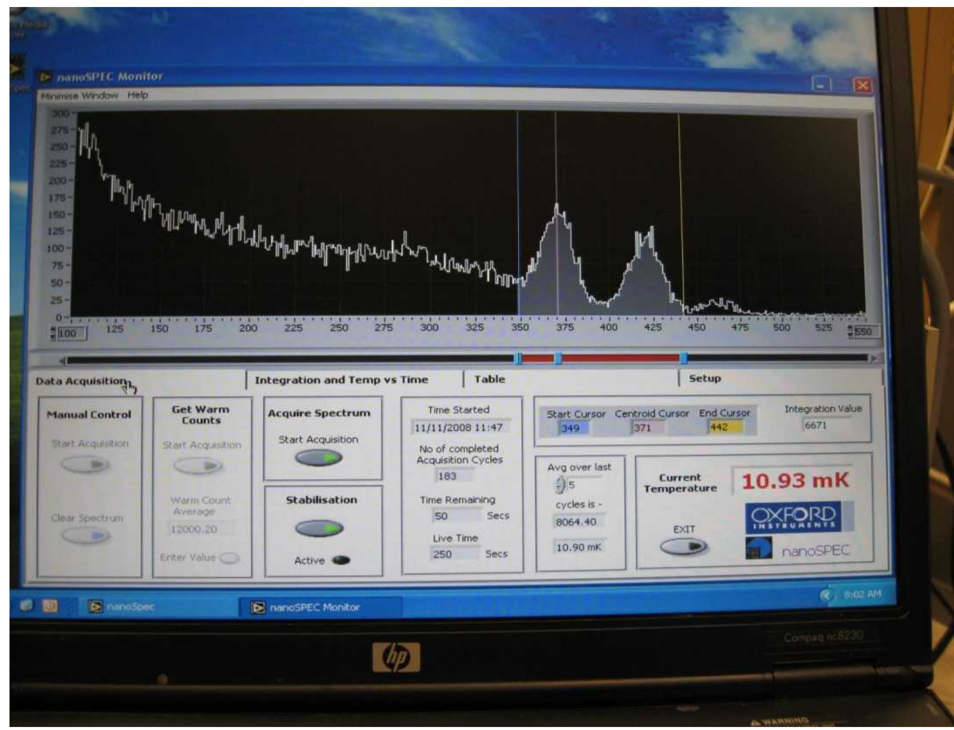


samples	well width (nm)	density (10^{11} cm^{-2})	mobility (10^6/V s)	l_B at ν=8/3 (nm)	W/l_B
A	60	0.5	10	29.2	2.1
B	60	0.6	9.1	26.7	2.2
C	56	0.77	13	23.6	2.4
D	45	1.15	13.8	19.3	2.3
E	33	2.1	23	14.3	2.3
F	30	2.6	24	12.9	2.3
G	30	3.1	31	11.8	2.5

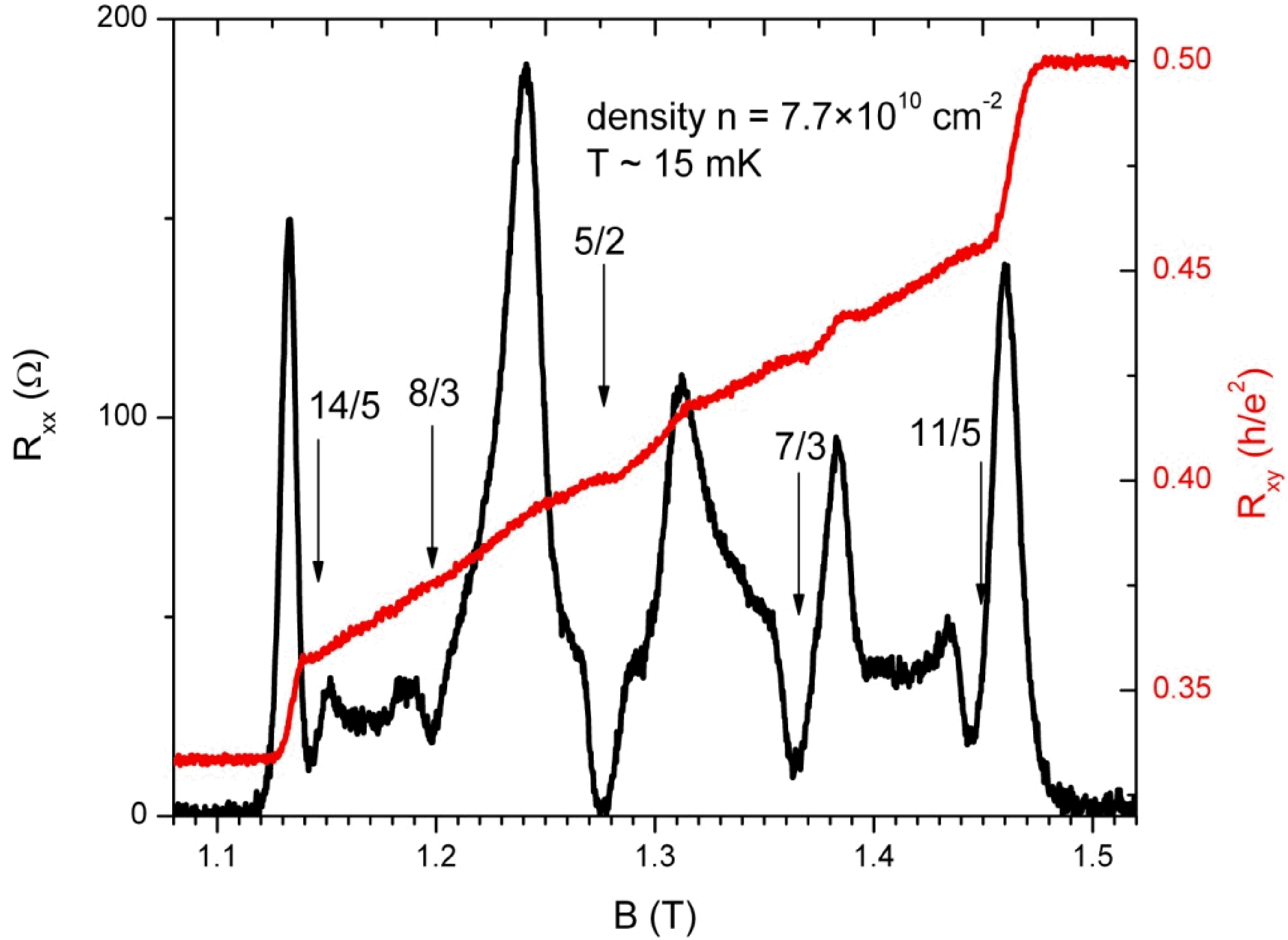
Top Loading Dilution Refrigerator

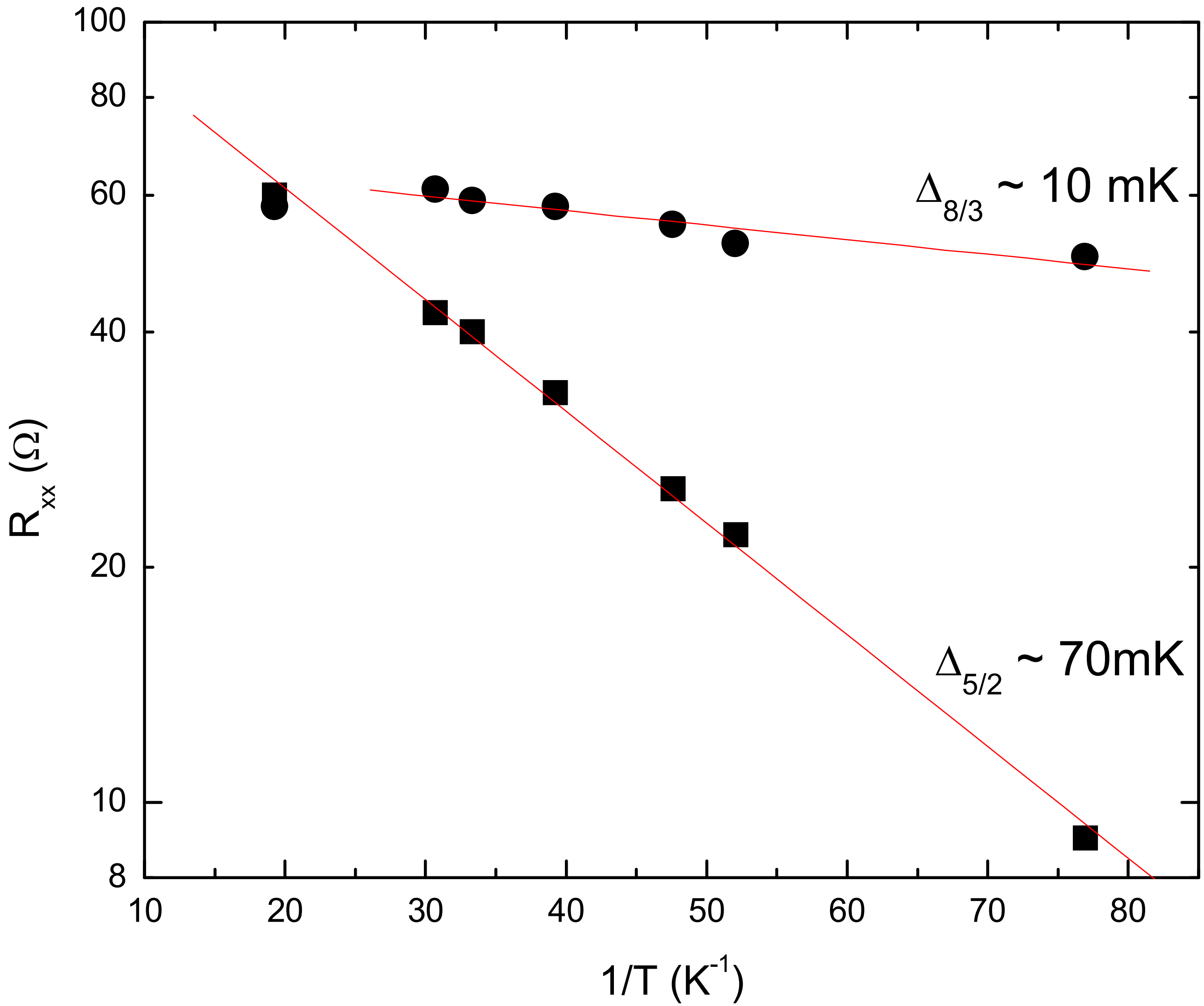
base temperature ~ 10 mK

magnetic field 14/16T

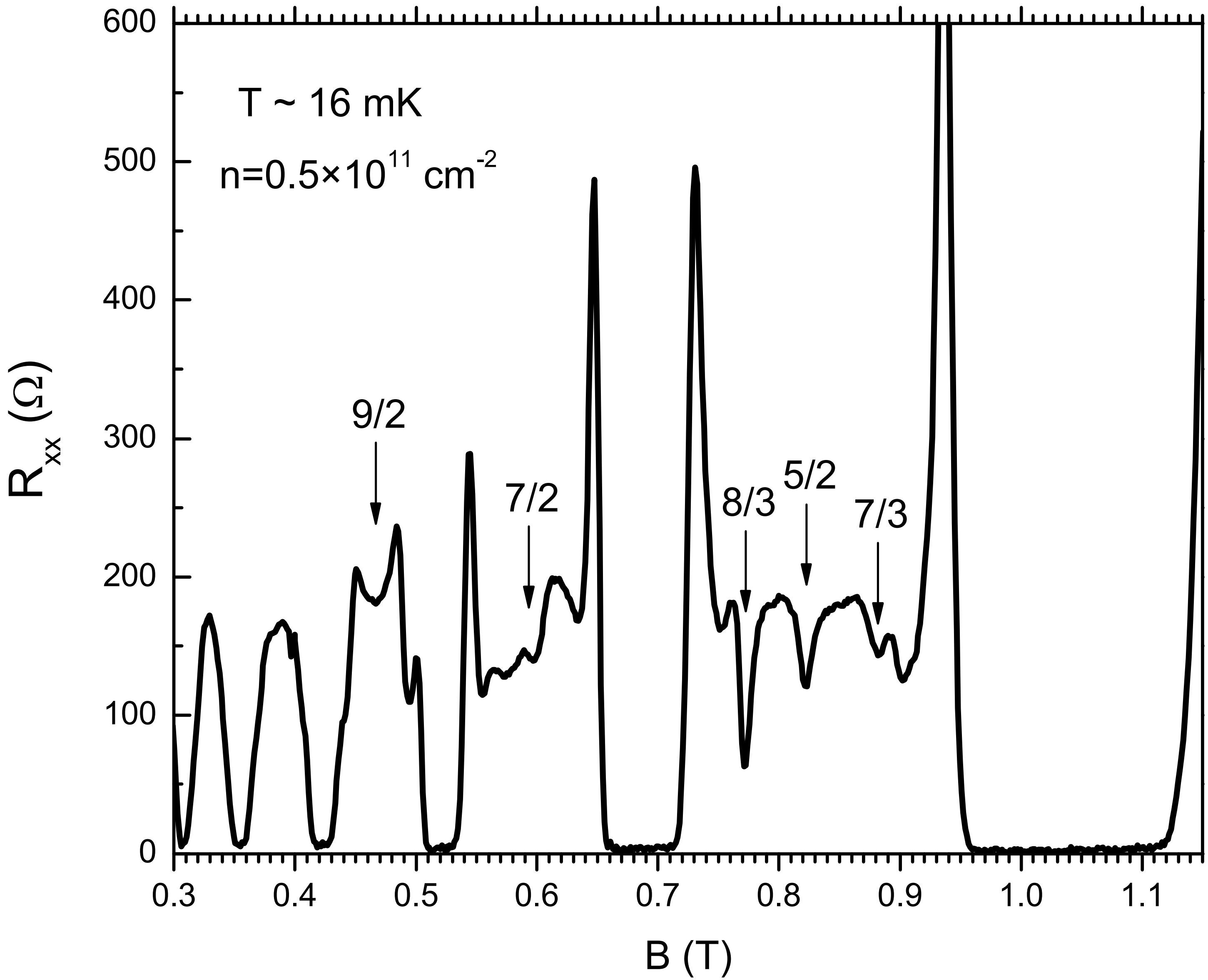


FQHE states in the second LL at low densities

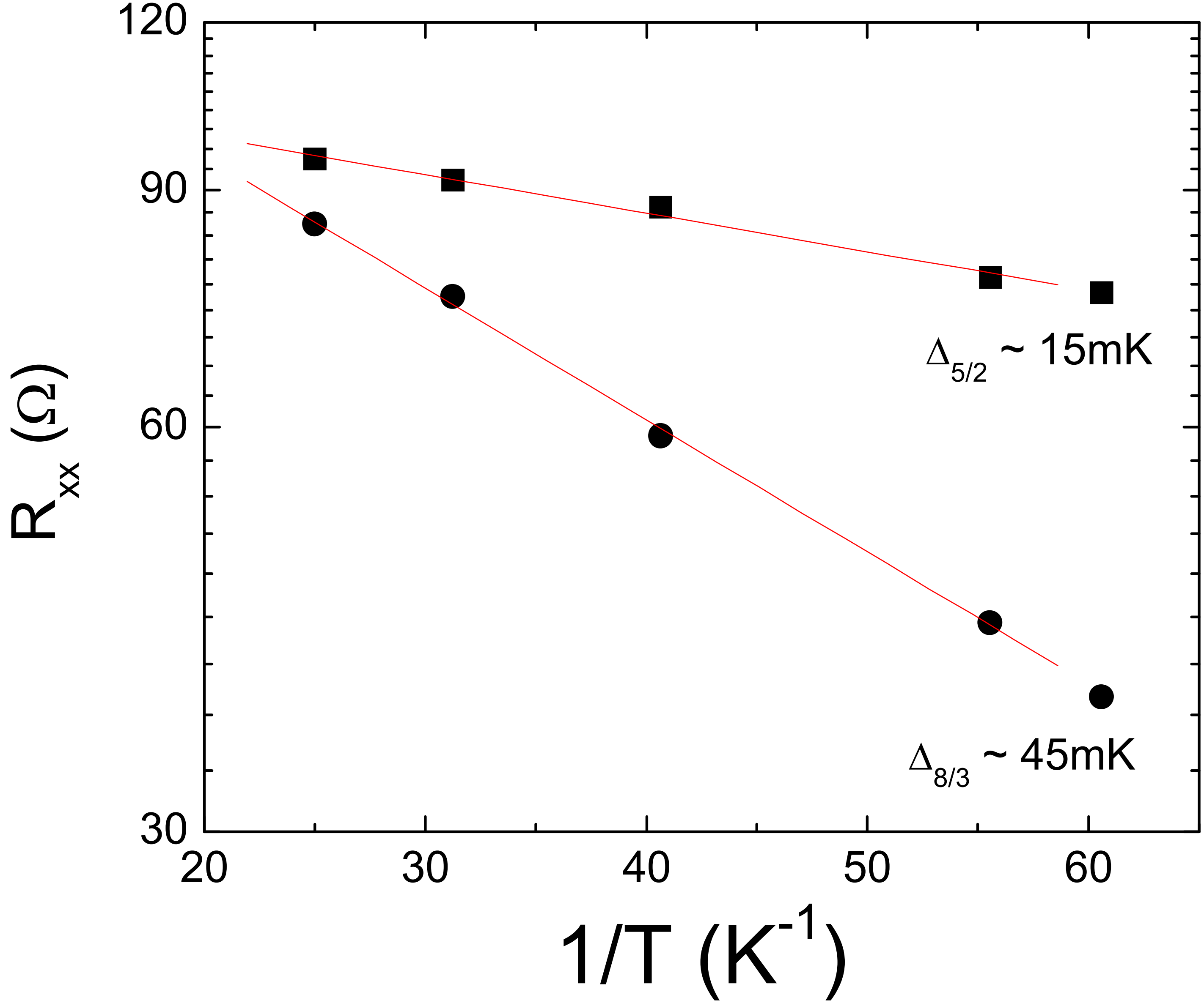




100
80
60
40
20
10
8
10
20
30
40
50
60
70
80
R_{xx} (Ω)
1/T (K^{-1})
$\Delta_{8/3}$ ~ 10 mK
$\Delta_{5/2}$ ~ 70mK

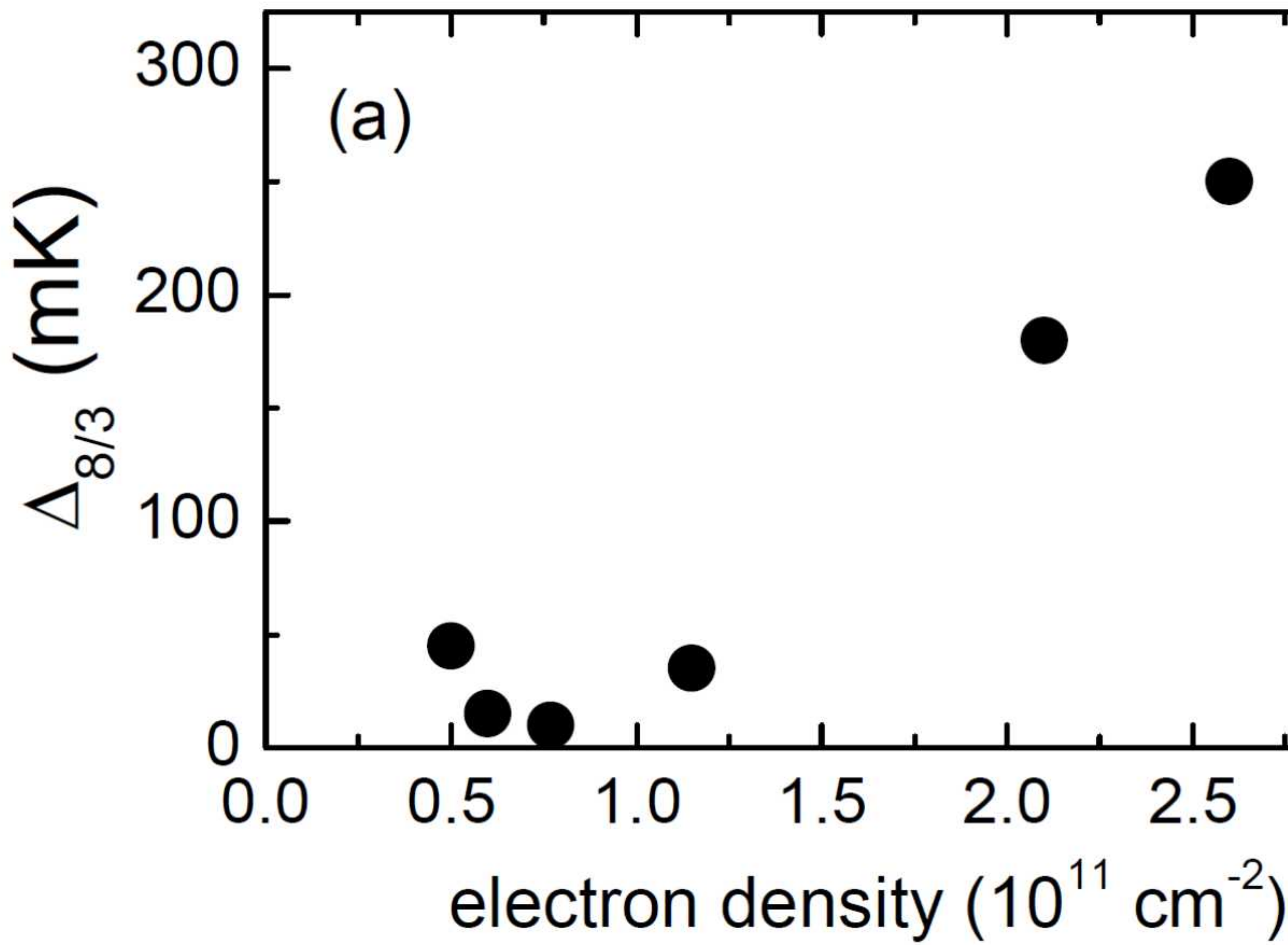


T ~ 16 mK
n=0.5×10^11 cm^-2
9/2
7/2
8/3
5/2
7/3
R_xx (Ω)
B (T)
0
100
200
300
400
500
600
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1



120
90
60
30
20
30
40
50
60
R_{xx} (Ω)
1/T (K^{-1})
$\Delta_{5/2}$ ~ 15mK
$\Delta_{8/3}$ ~ 45mK

spin transition at ν=8/3



The apparent transition is

- a spin transition under CF picture?

- a spin transition, but from, for example, a spin unpolarized interlayer pfaffian state (Barkeshli and Wen, PRB 2010) to a spin polarized pfaffian state?

- not a spin transition?

For the 8/3 state:
at the transition
$E_z/E_c \sim 0.006$

E_z zeeman energy
E_c Coulomb energy

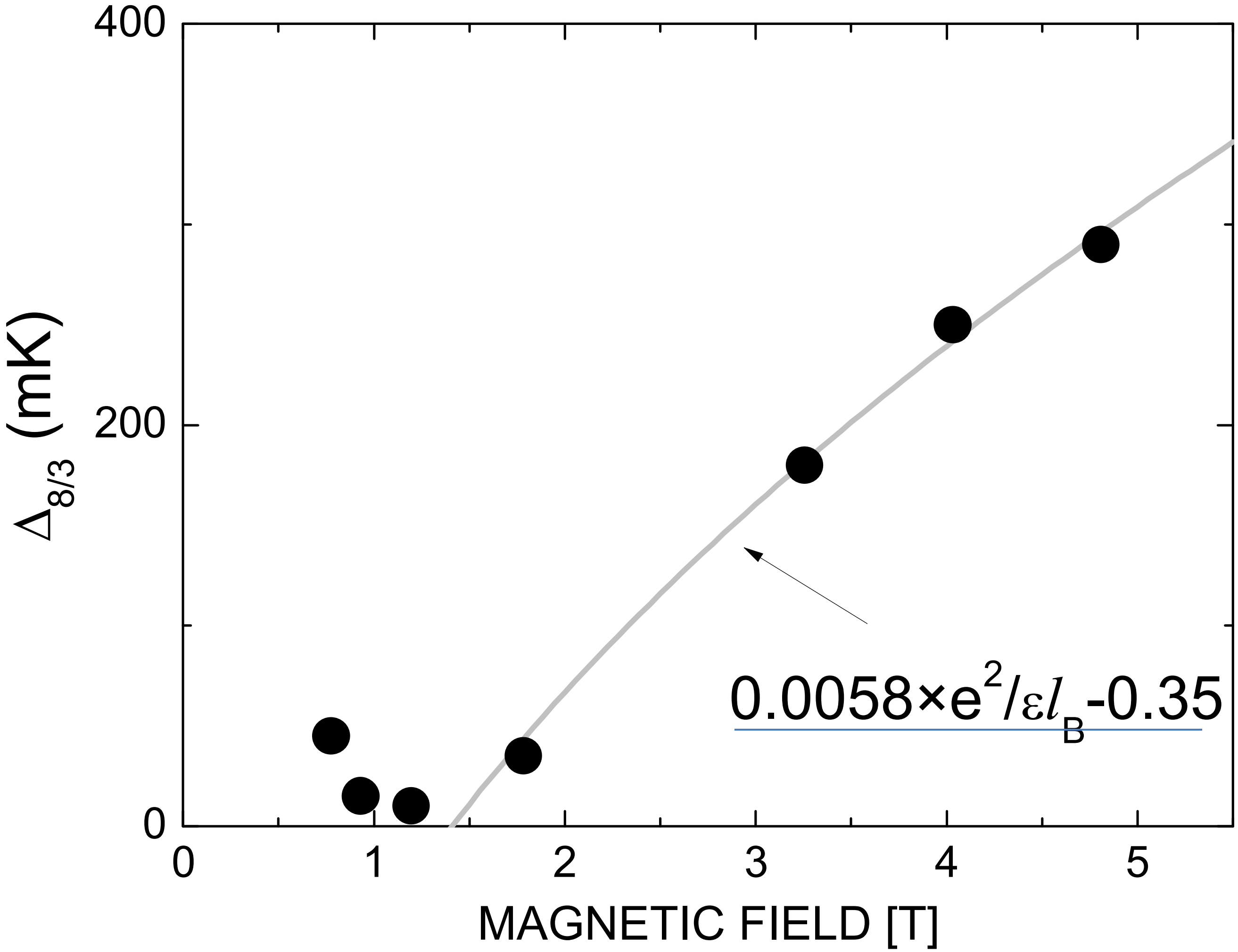
For the 2/3 state:
$E_z/E_c \sim 0.01$ (from density and tilt magnetic field)

Eisenstein et al; Engel et al

For the 4/3 state:
$E_z/E_c \sim 0.02$ (from tilt magnetic field)

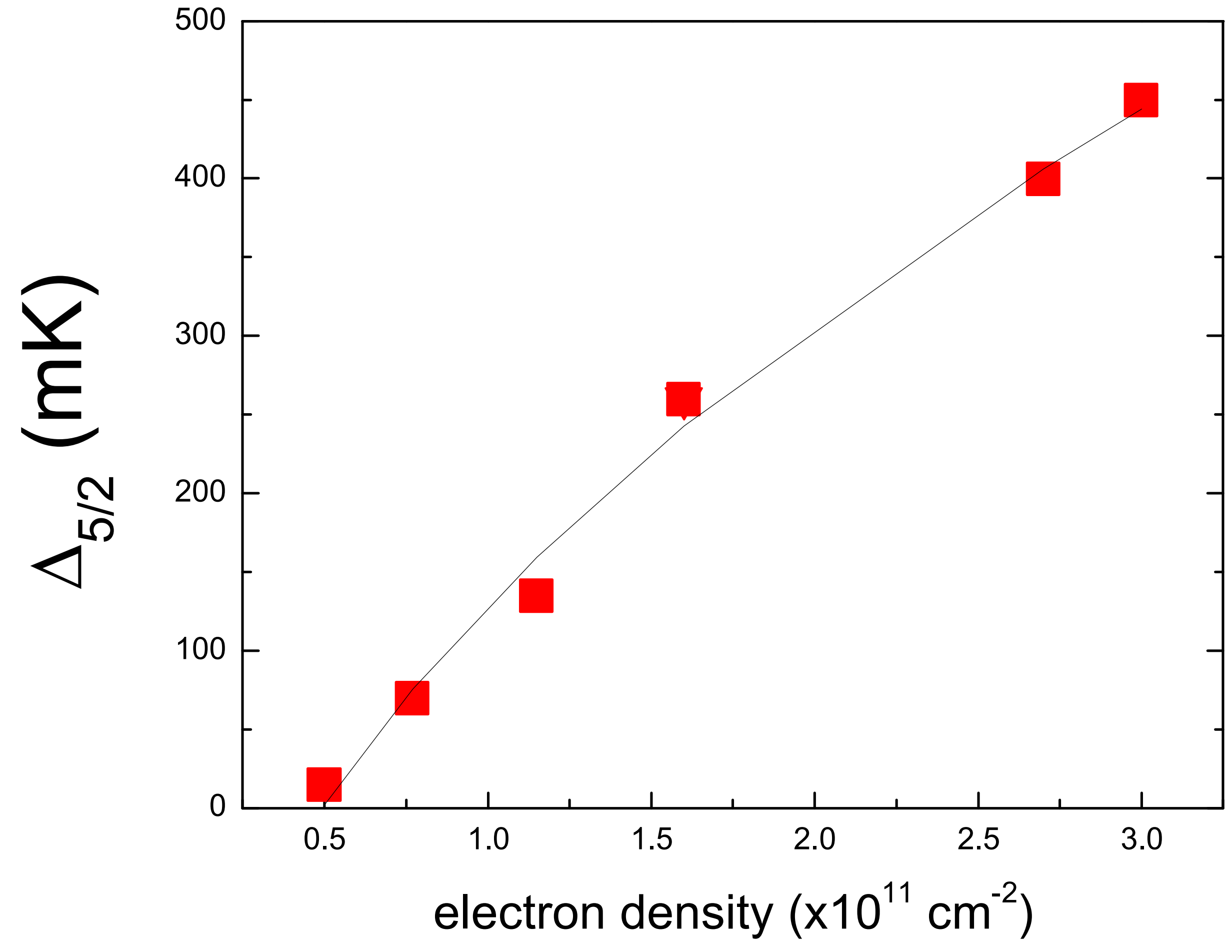
Du et al

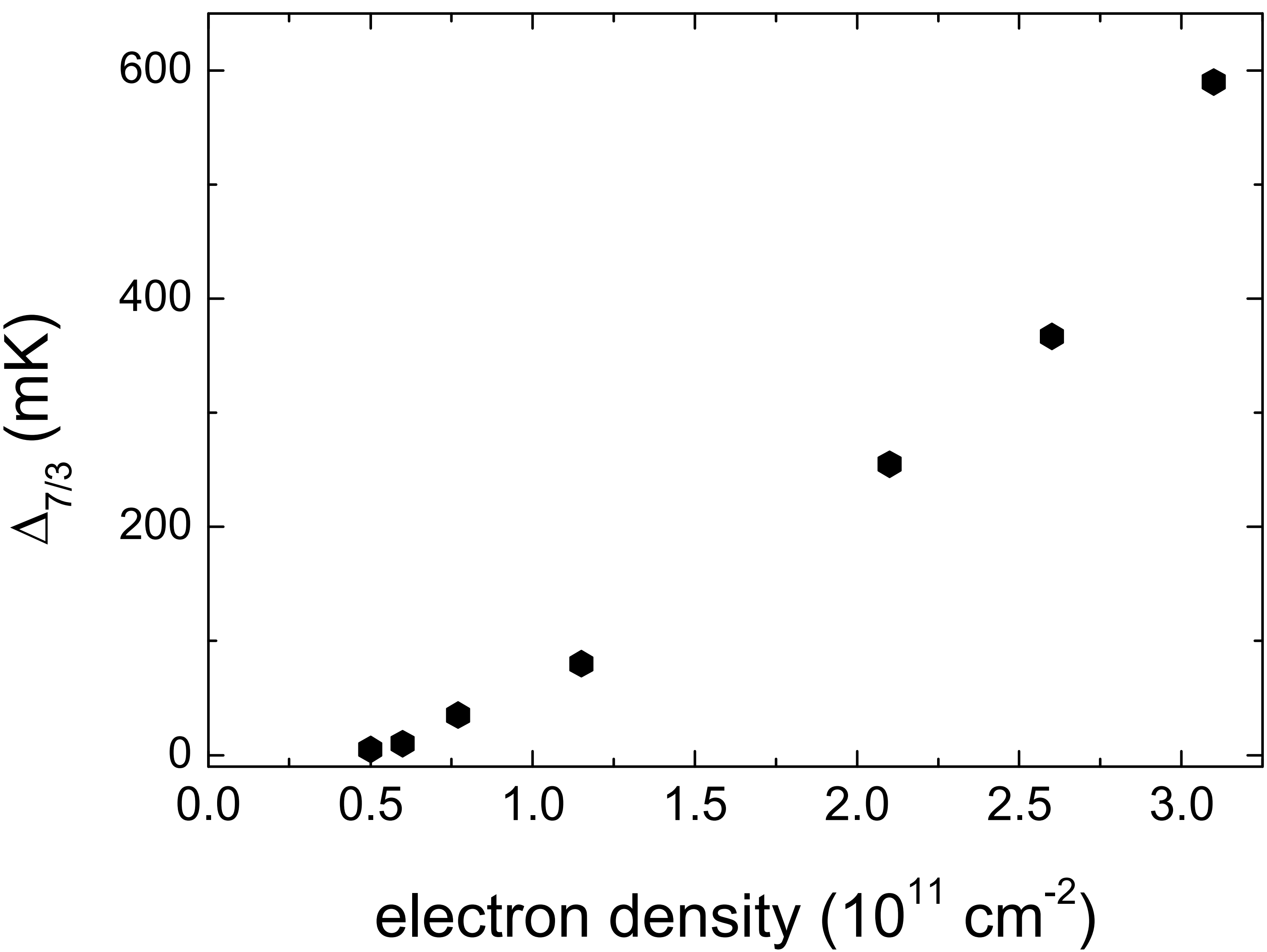
spin polarized $\Delta = \alpha\sqrt{n} - \Gamma$



$$\Delta_{5/2} = 0.0066\times e^2/\varepsilon l_B - 0.3$$

$$\Delta_{8/3} = 0.0058\times e^2/\varepsilon l_B - 0.35$$





600
400
200
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
$\Delta_{7/3}$ (mK)
electron density (10^{11} cm^{-2})

Temperature Dependence of Spin Polarizations at Higher Landau Levels

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(Received 16 June 1999)

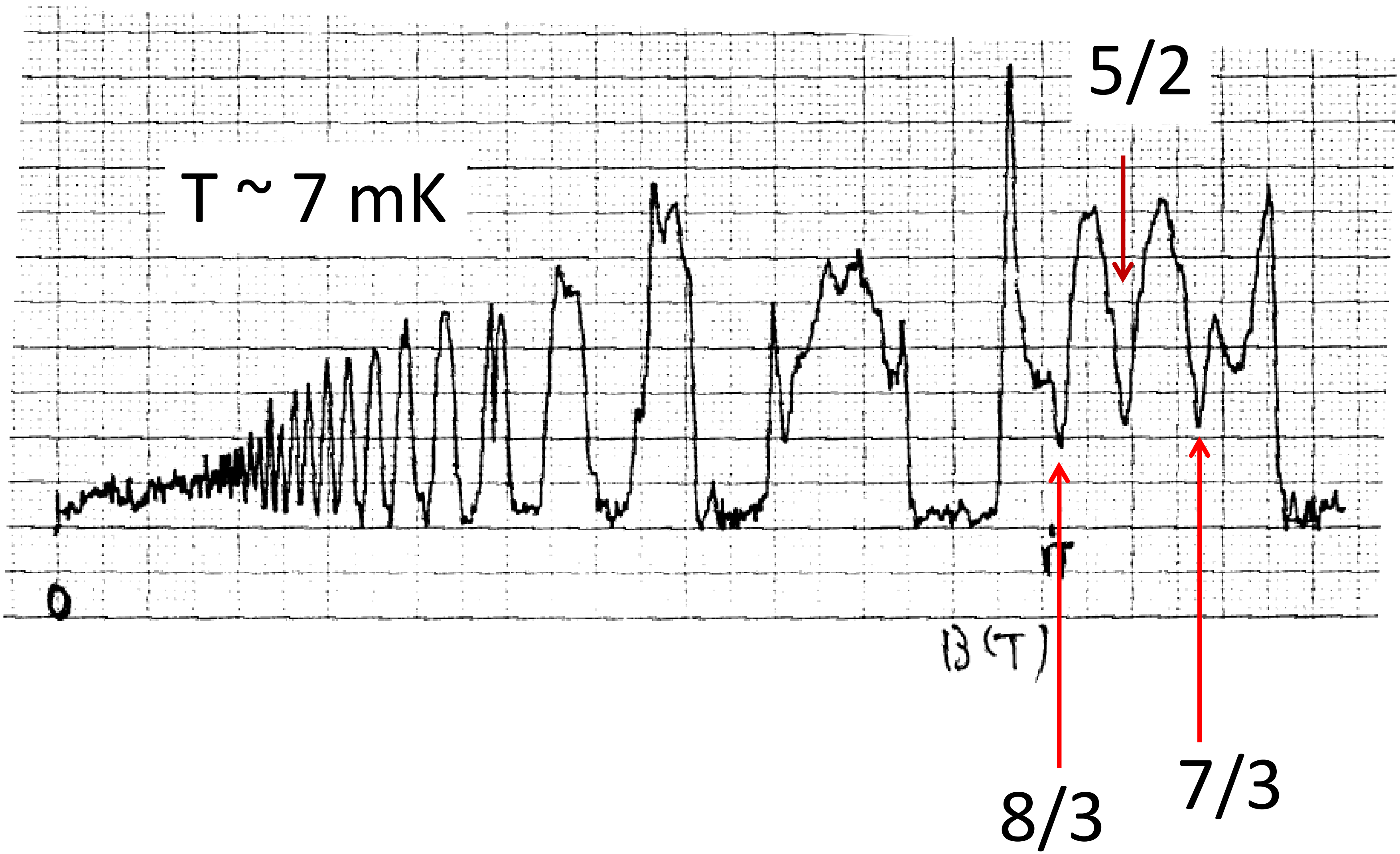
We report our results on the temperature dependence of spin polarizations at $\nu = 1$ in the lowest as well as in the next higher Landau level. They compare well with recent experimental results. At $\nu = 3$, spin polarization has a smaller magnitude but is not much influenced by higher Landau levels. In sharp contrast, for filling factor $\nu = \frac{8}{3}$ we predict that, unlike in the case of $\nu = \frac{2}{3}$, the system remains fully spin polarized even at vanishingly small Zeeman energies.

Zeeman energy is important in the 8/3 and 12/5 ground states

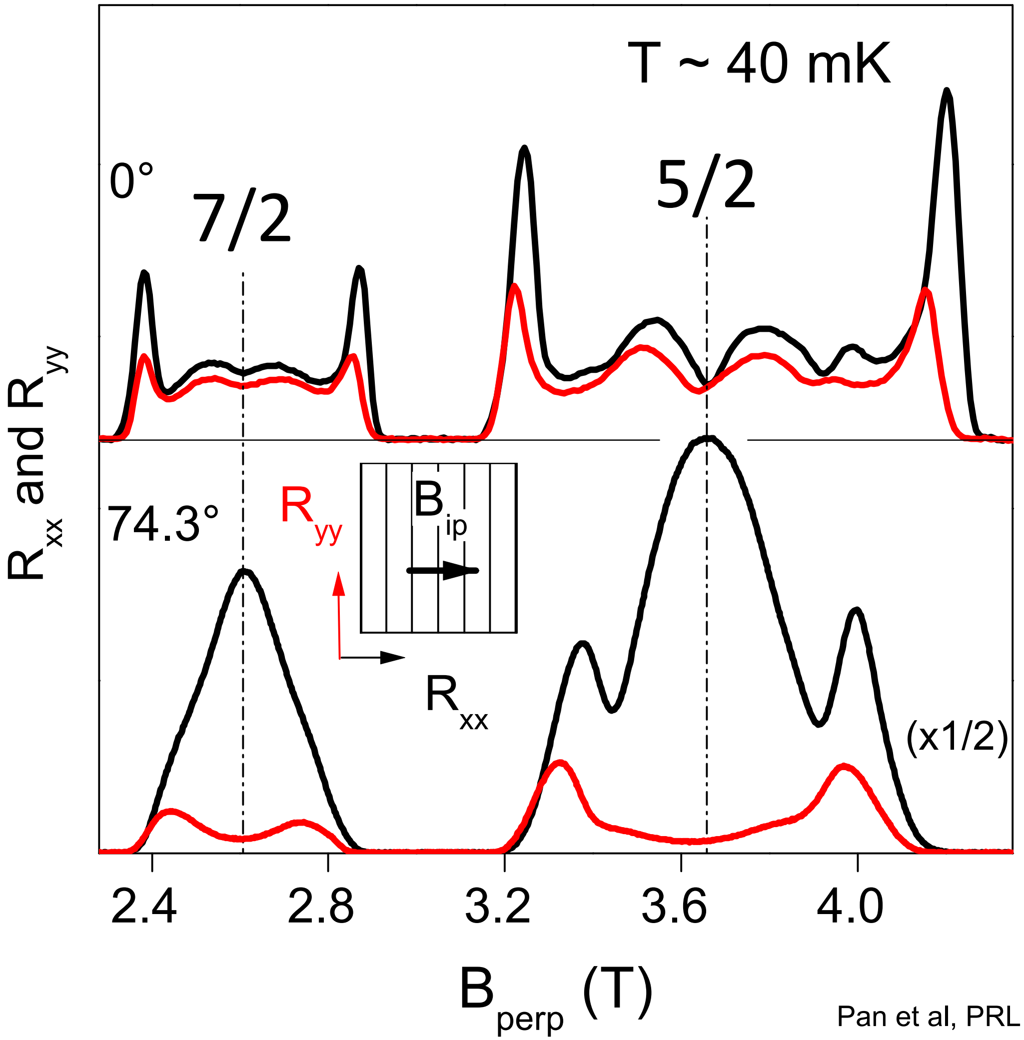
Work done in collaboration with:

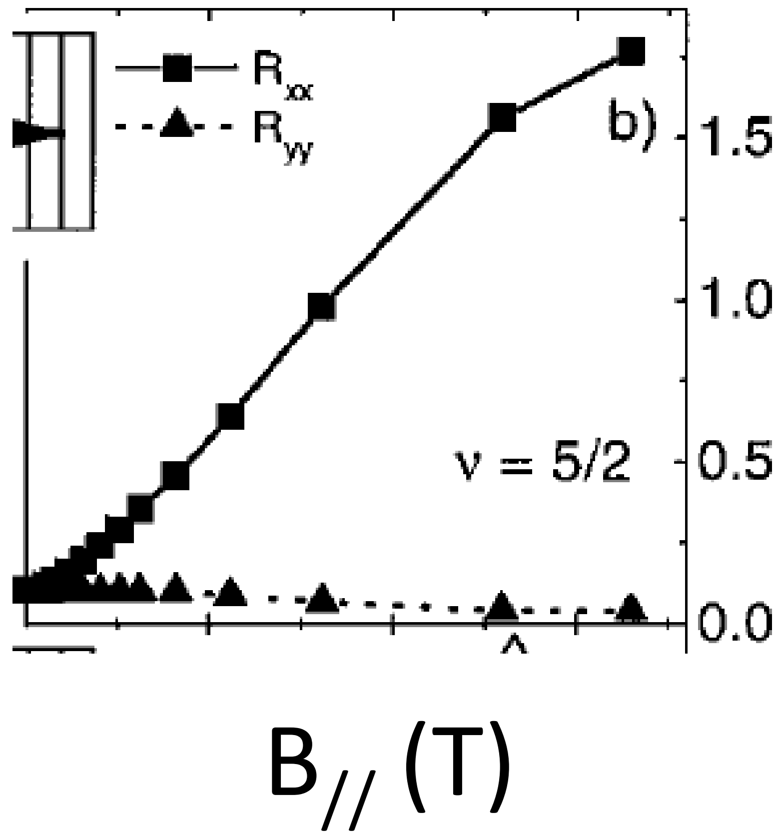
Loren Pfeiffer
Ken West
Kirk Baldwin
Dan Tsui
Chi Zhang
Chao Huan
Jian-Sheng Xia
Neil Sullivan
Madhu Thalakulam

Single heterojunction ($n=6.5 \times 10^{10}$ cm^{-2})

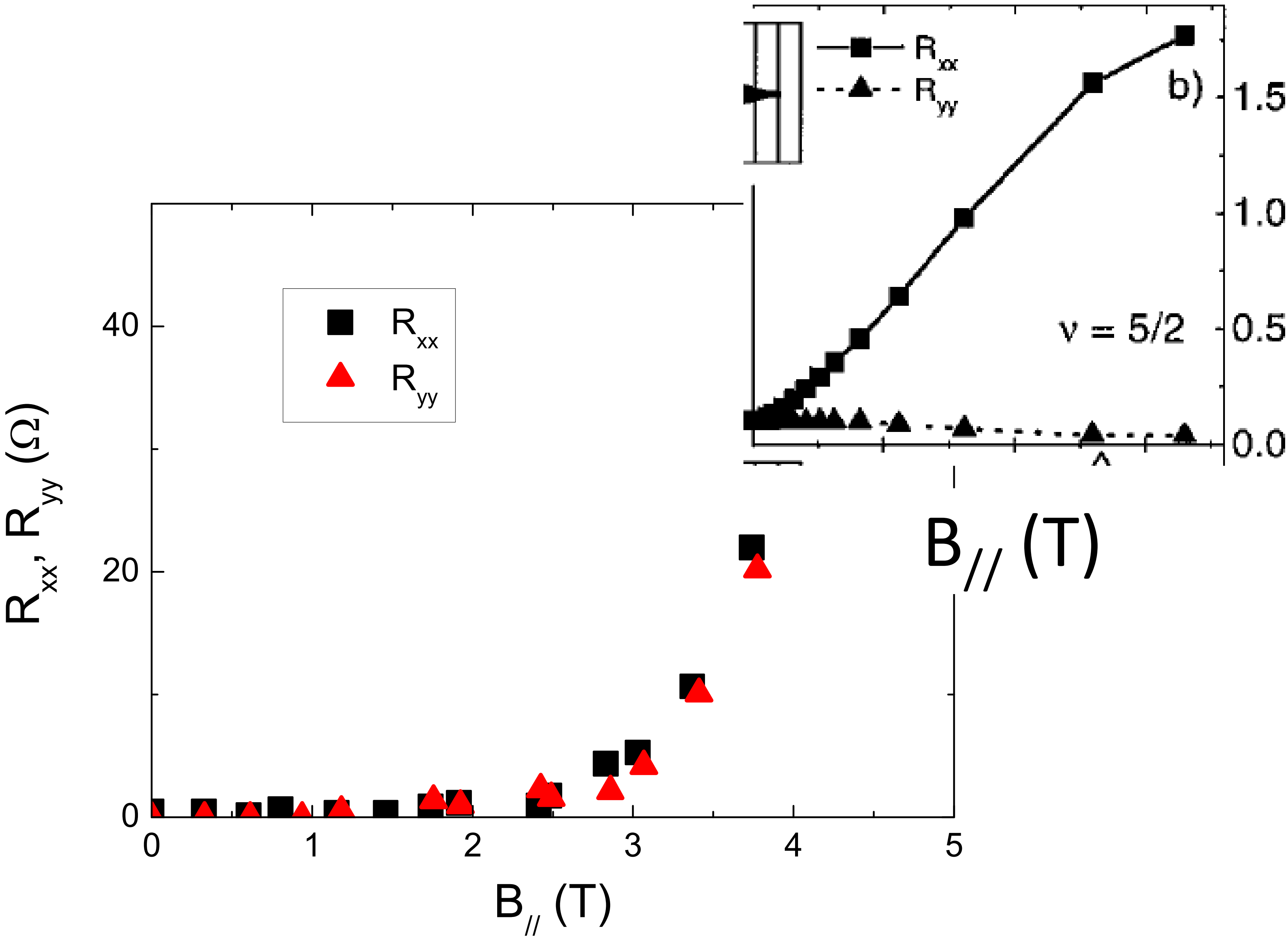


5/2 under tilt



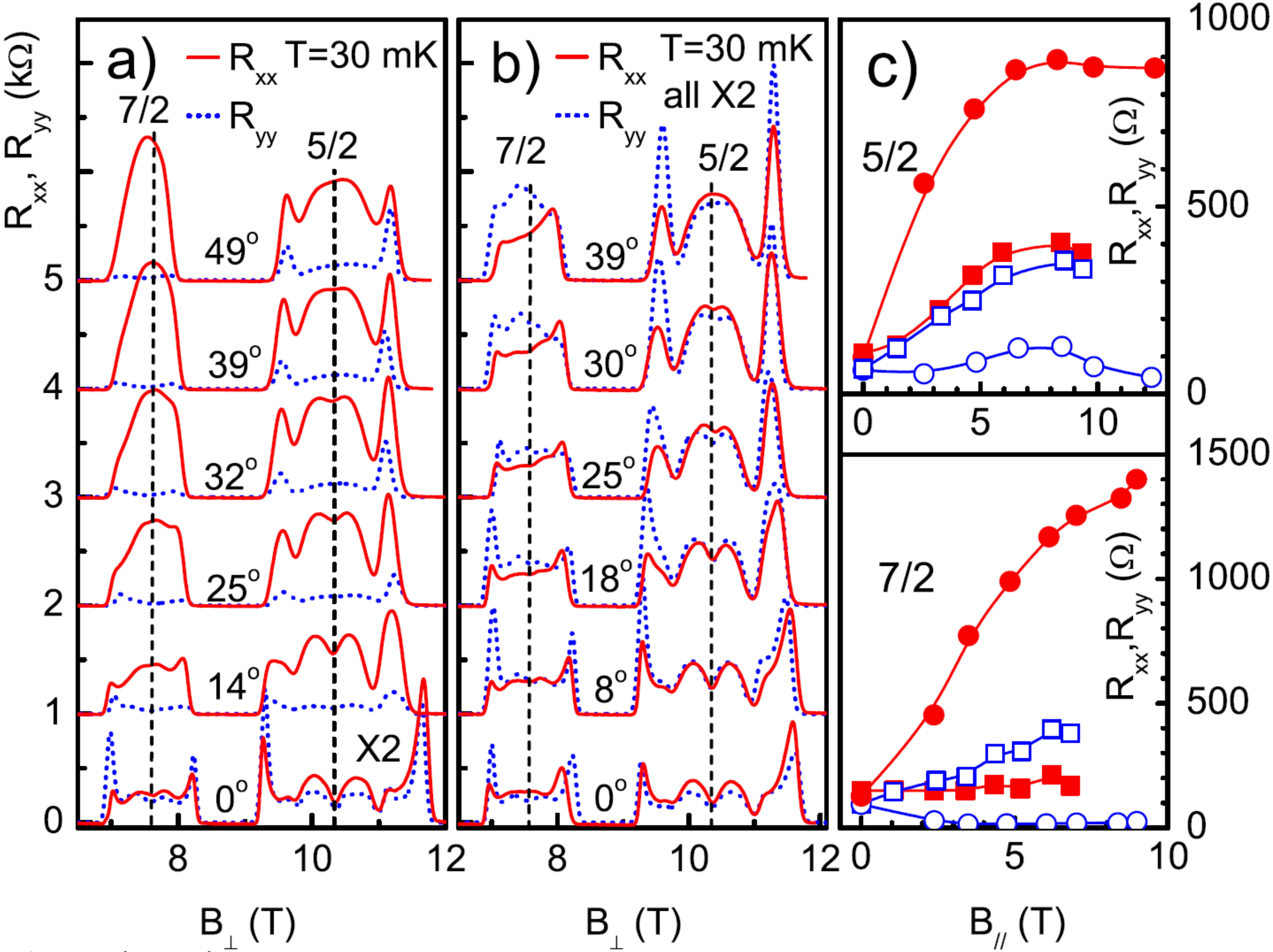


Pan et al, PRL (1999)
Lilly et al, PRL (1999)

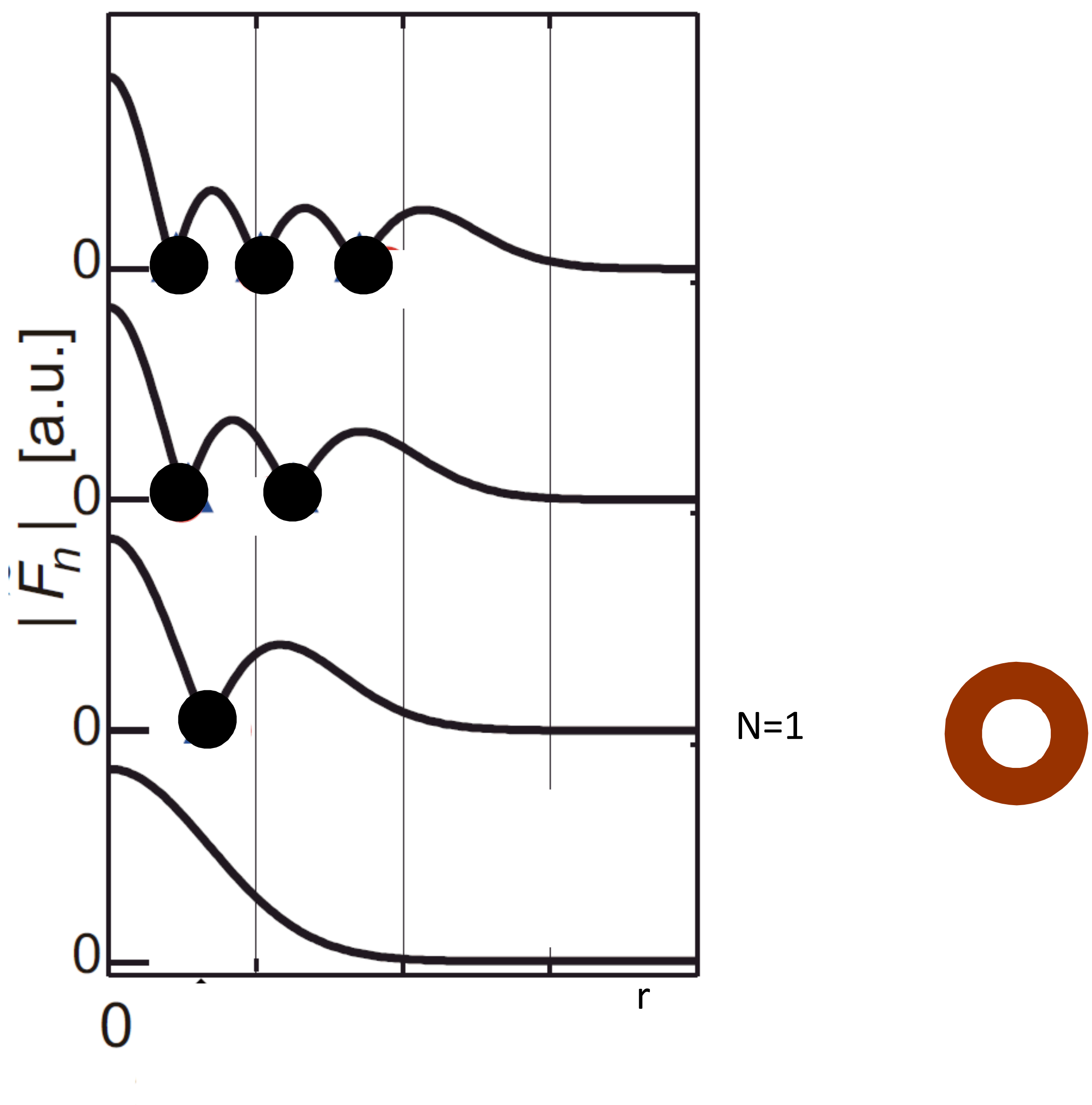


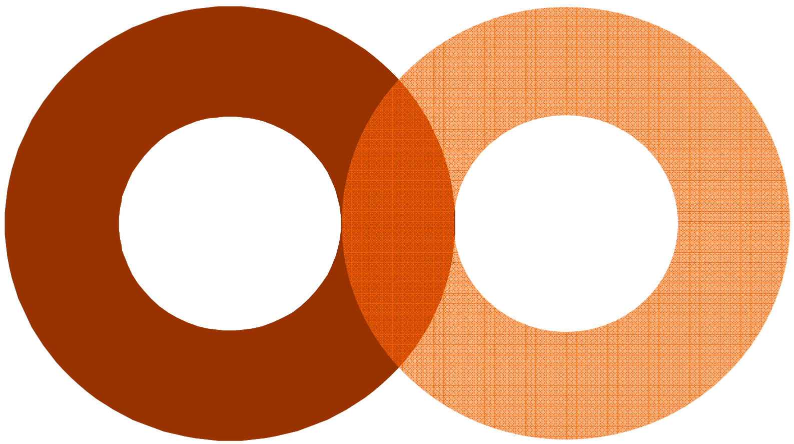
R_{xx}, R_{yy} (Ω)
0
20
40
0
1
2
3
4
5
$B_{//}$ (T)
R_{xx}
R_{yy}
b)
1.5
1.0
0.5
0.0
ν = 5/2
$B_{//}$ (T)

$B_{//}$ along $[\bar{1}10]$ $B_{//}$ along $[110]$

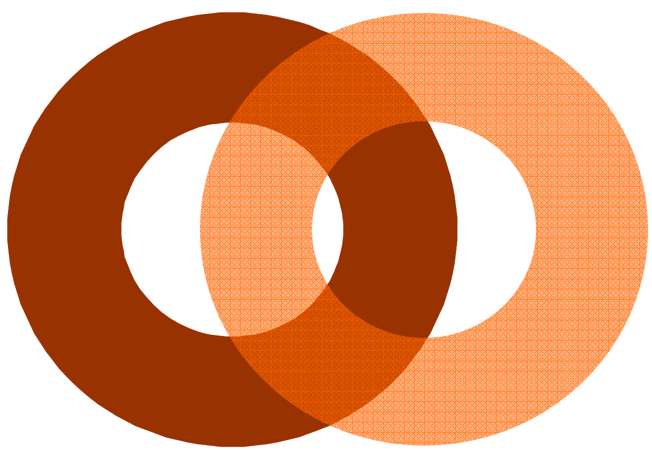


Zhang et al, PRL (2010)

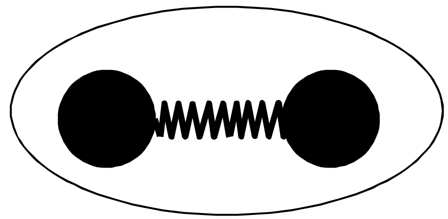

0
0
0
0
$|\tilde{F}_n|$ [a.u.]
0
r
N=1



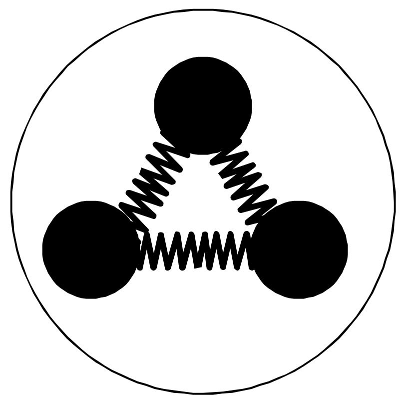
N=1



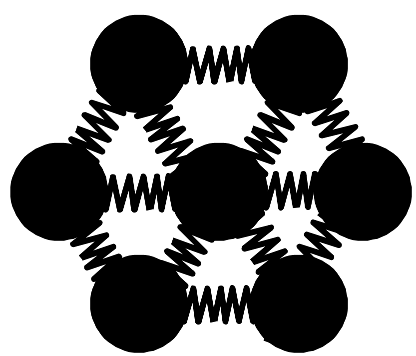
short range interactions softened



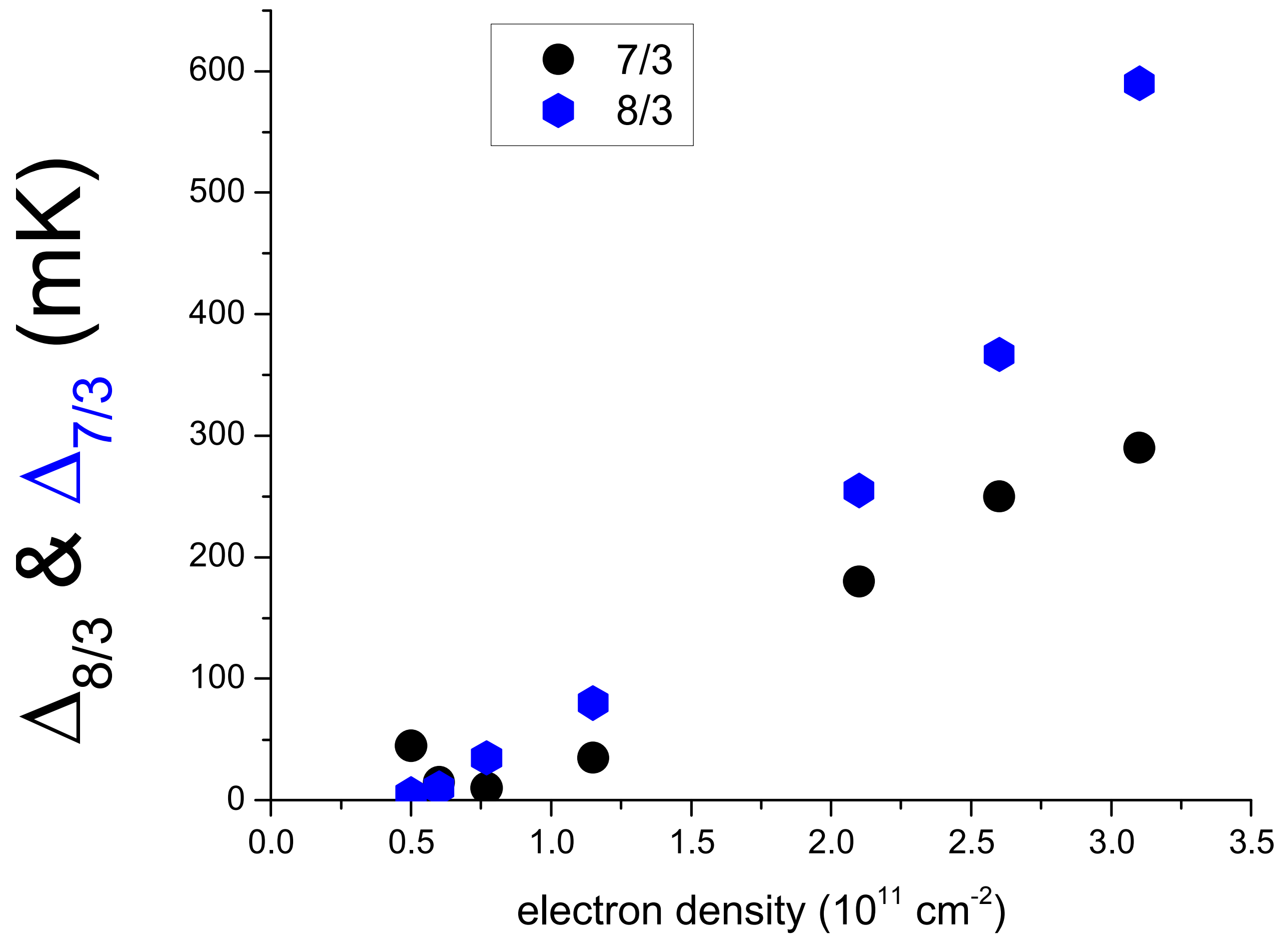
pair

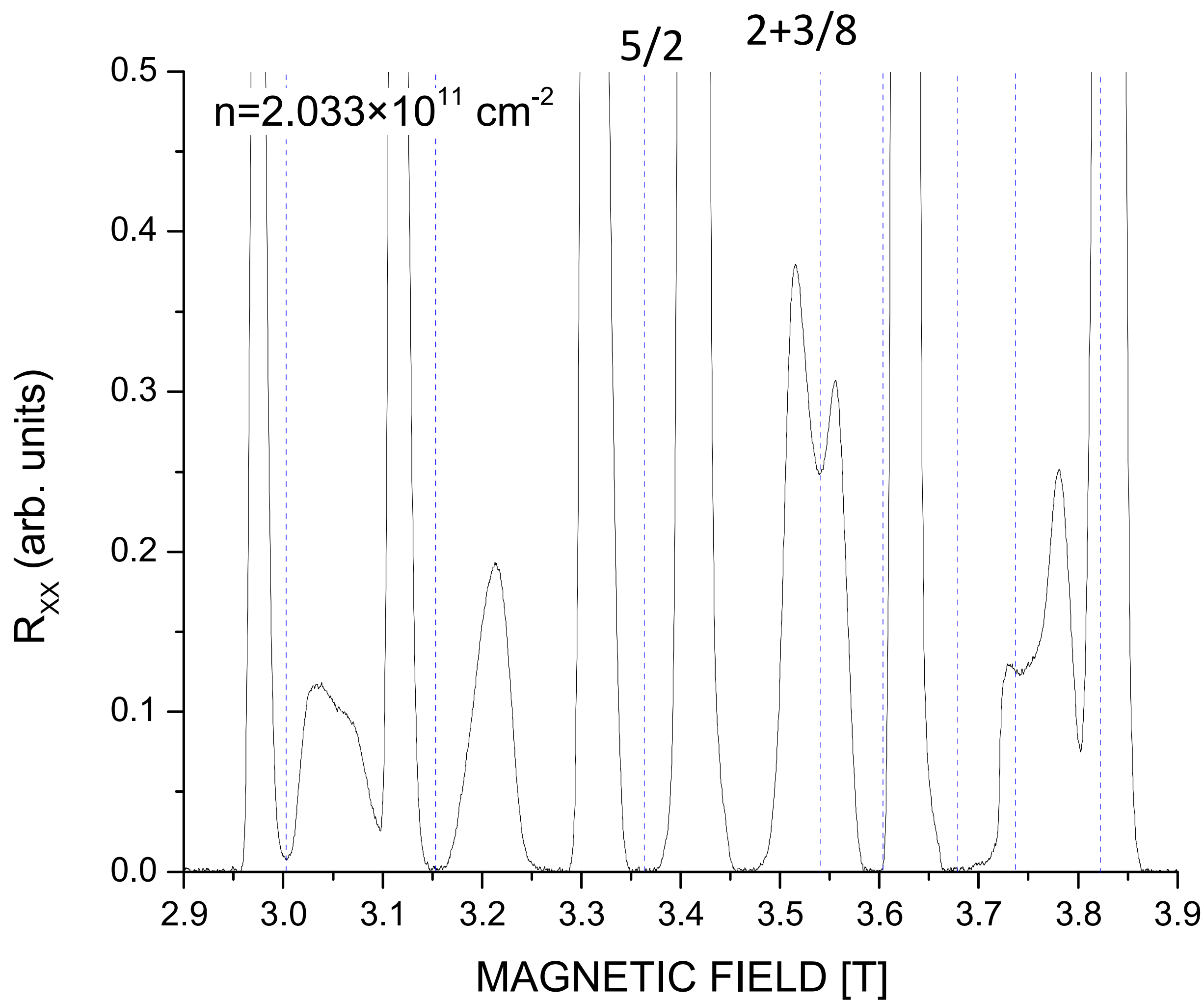


three-particle
cluster



or more exotic


7/3
8/3
600
500
400
300
200
100
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
electron density (10^{11} cm^{-2})
$\Delta_{8/3}$ & $\Delta_{7/3}$ (mK)



5/2
2+3/8
n=2.033×10^11 cm^-2
R_XX (arb. units)
0.0
0.1
0.2
0.3
0.4
0.5
2.9
3.0
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
MAGNETIC FIELD [T]

At the spin transition:

E_z zeeman energy
E_c Coulomb energy

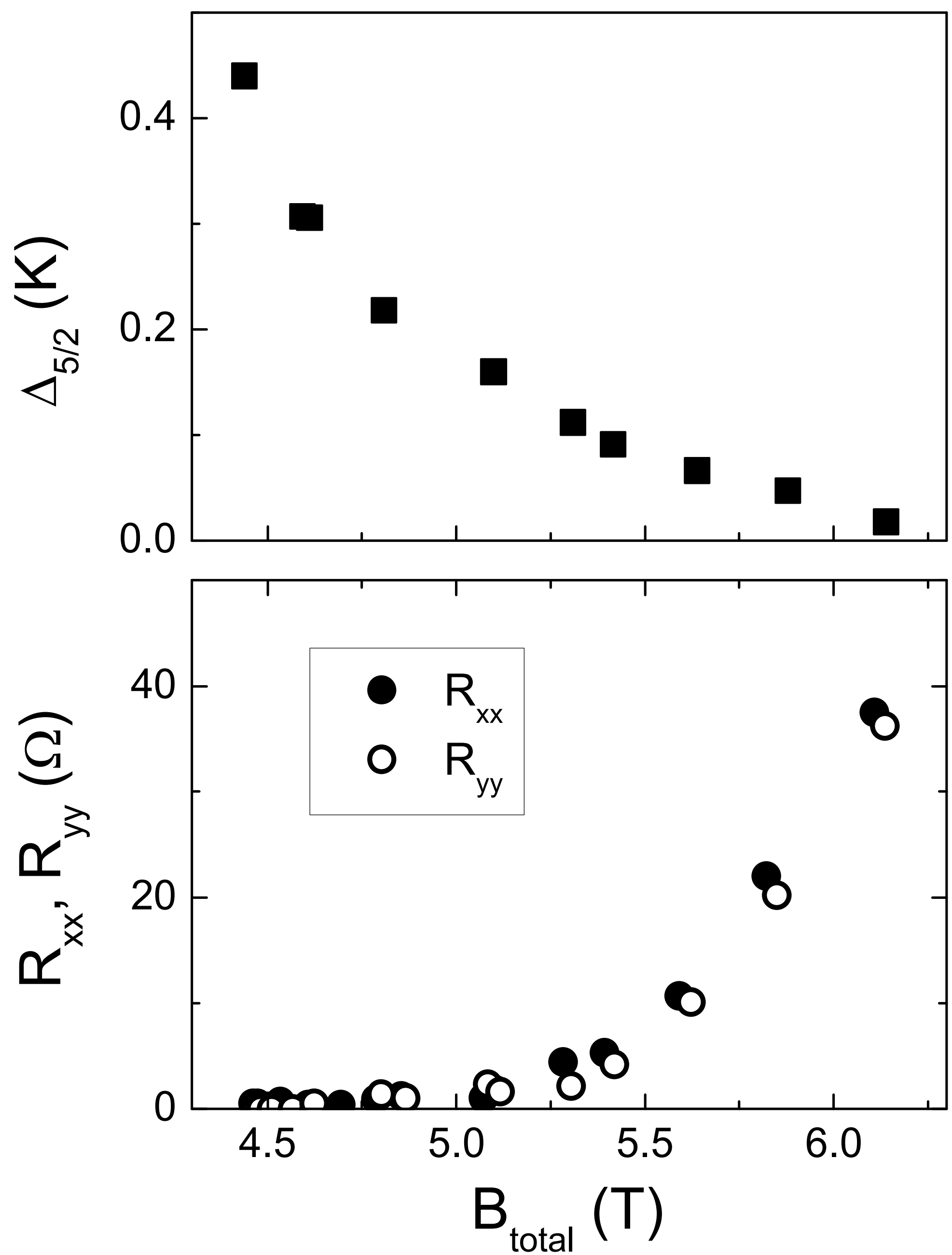
$E_z/E_c \sim 0.013$

For the 8/5 state:
$E_z/E_c \sim 0.017$ (from tilt magnetic field)

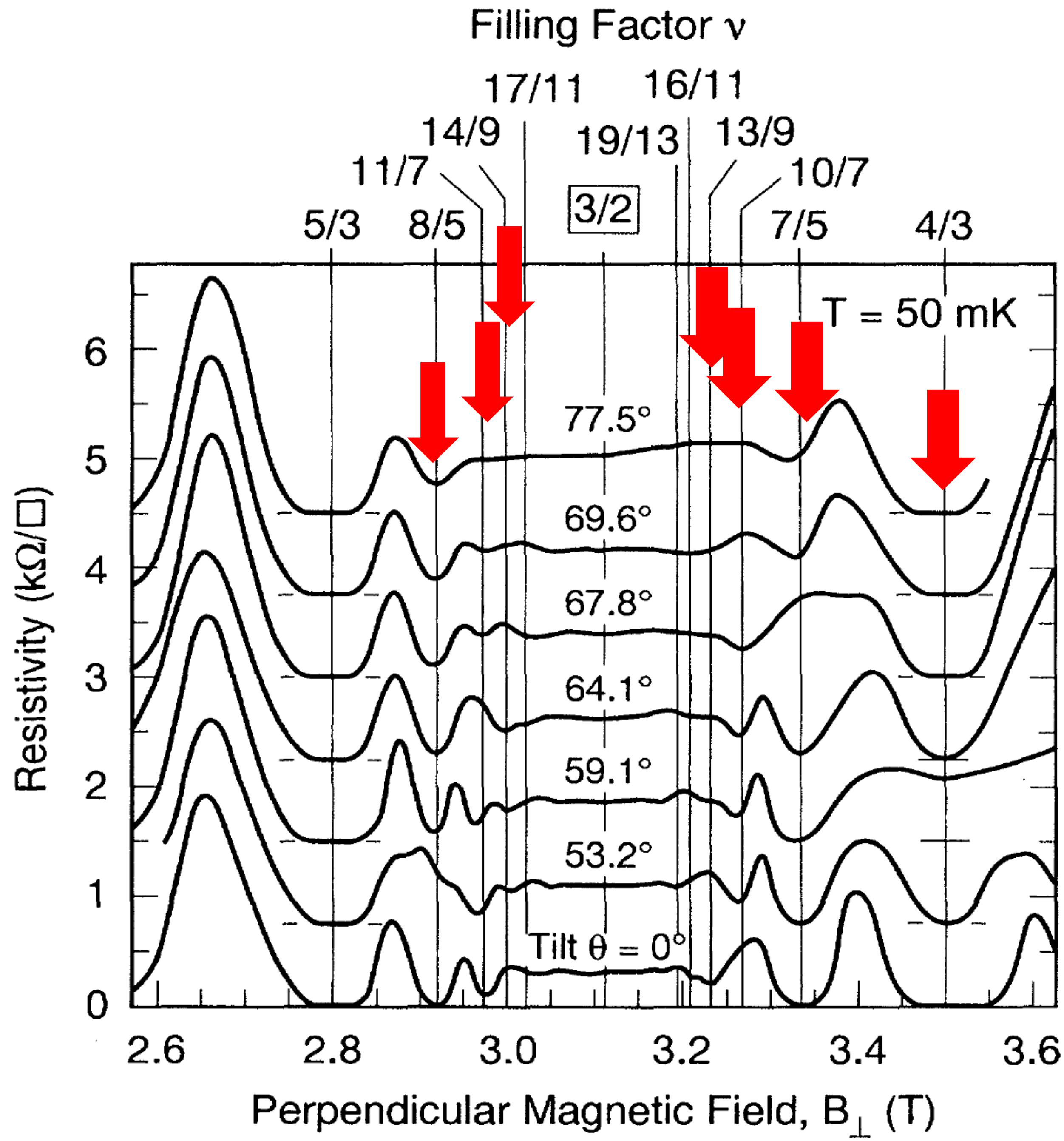
Eisenstein et al; Du et al

For the 3/5 state:
$E_z/E_c \sim 0.009$ (from tilt magnetic field)

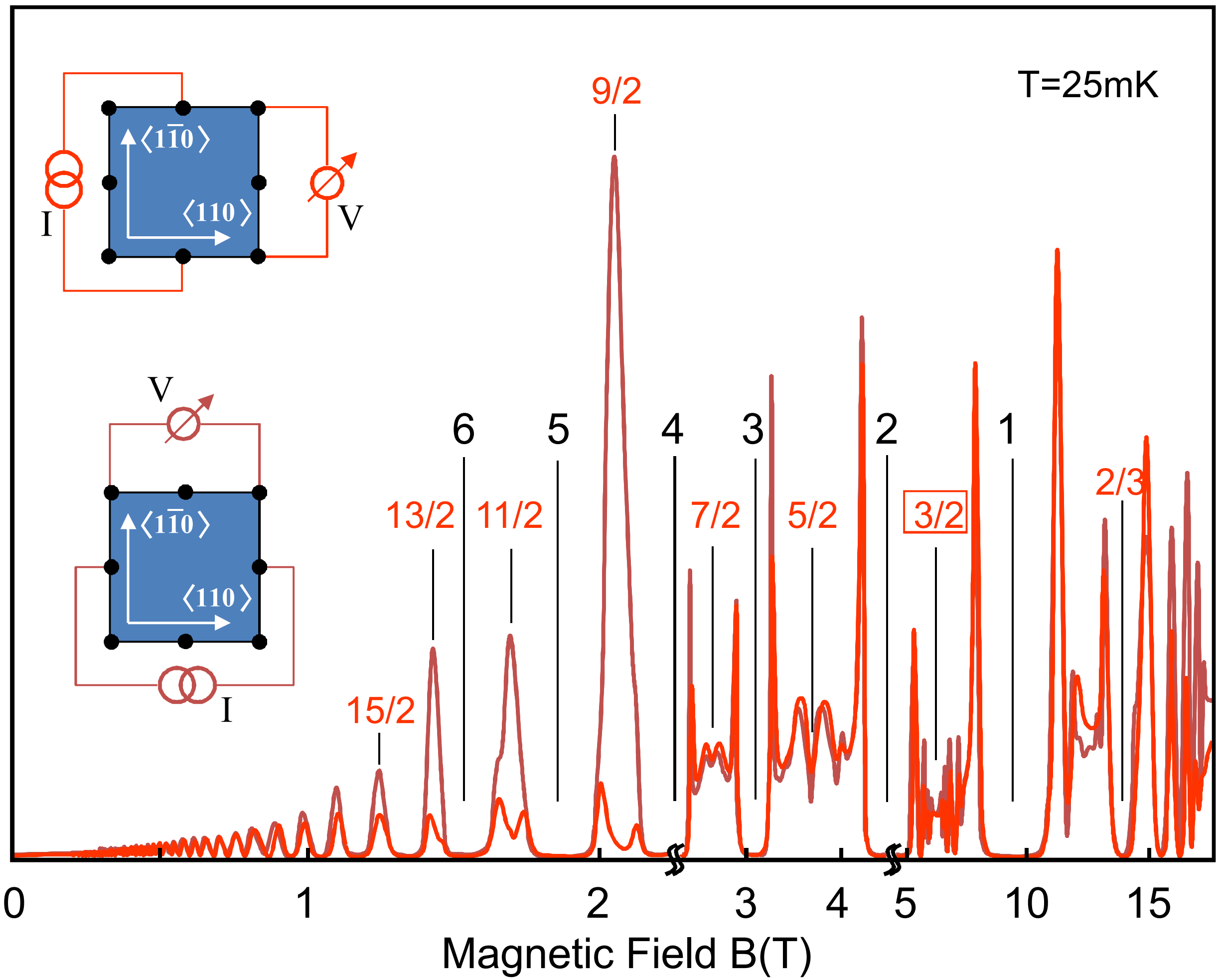
Engel et al

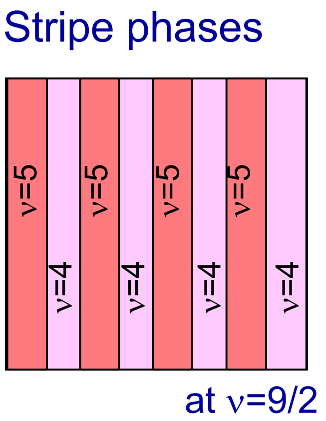


0.0
0.2
0.4
Δ5/2 (K)
0
20
40
Rxx, Ryy (Ω)
Rxx
Ryy
4.5
5.0
5.5
6.0
Btotal (T)



Filling Factor ν
17/11
16/11
14/9
19/13
13/9
11/7
10/7
3/2
5/3
8/5
7/5
4/3
T = 50 mK
77.5°
69.6°
67.8°
64.1°
59.1°
53.2°
Tilt θ = 0°
Resistivity (kΩ/□)
0
1
2
3
4
5
6
2.6
2.8
3.0
3.2
3.4
3.6
Perpendicular Magnetic Field, B⊥ (T)

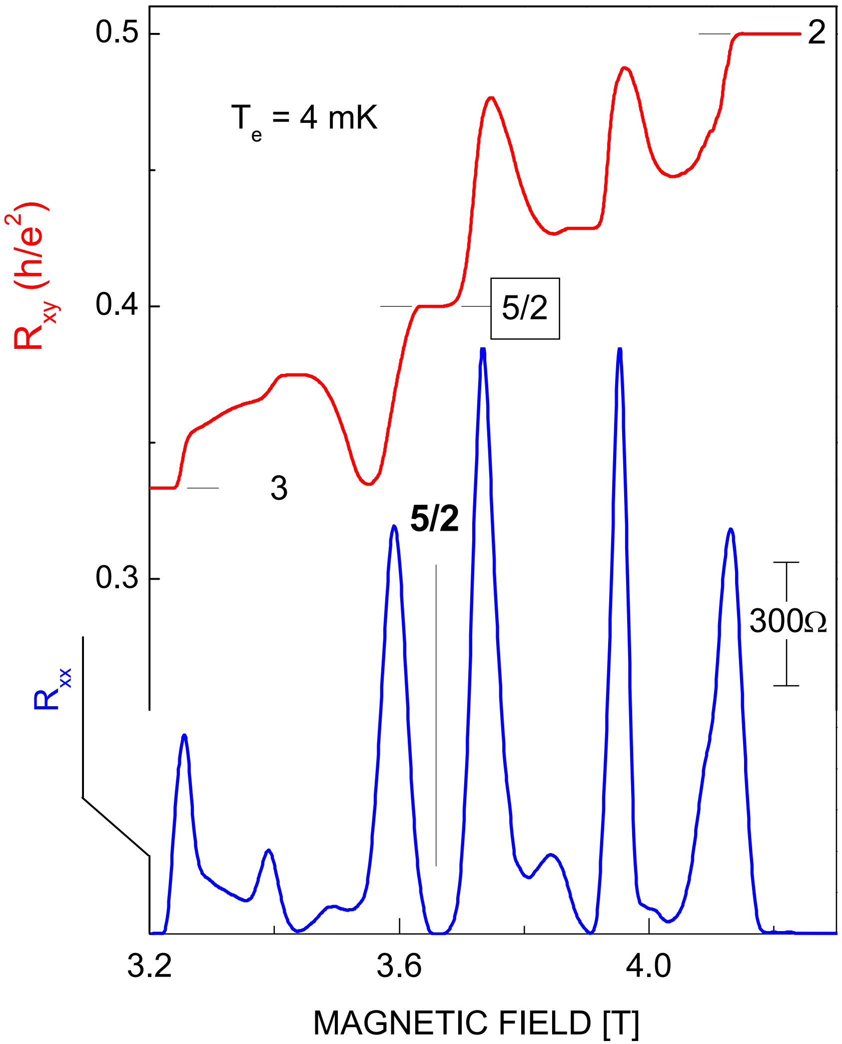




Theory: Fogler et al '96

Exp.: Lilly et al, Du et al '99

true FQHE at ν=5/2



Pan et al, PRL (1999)

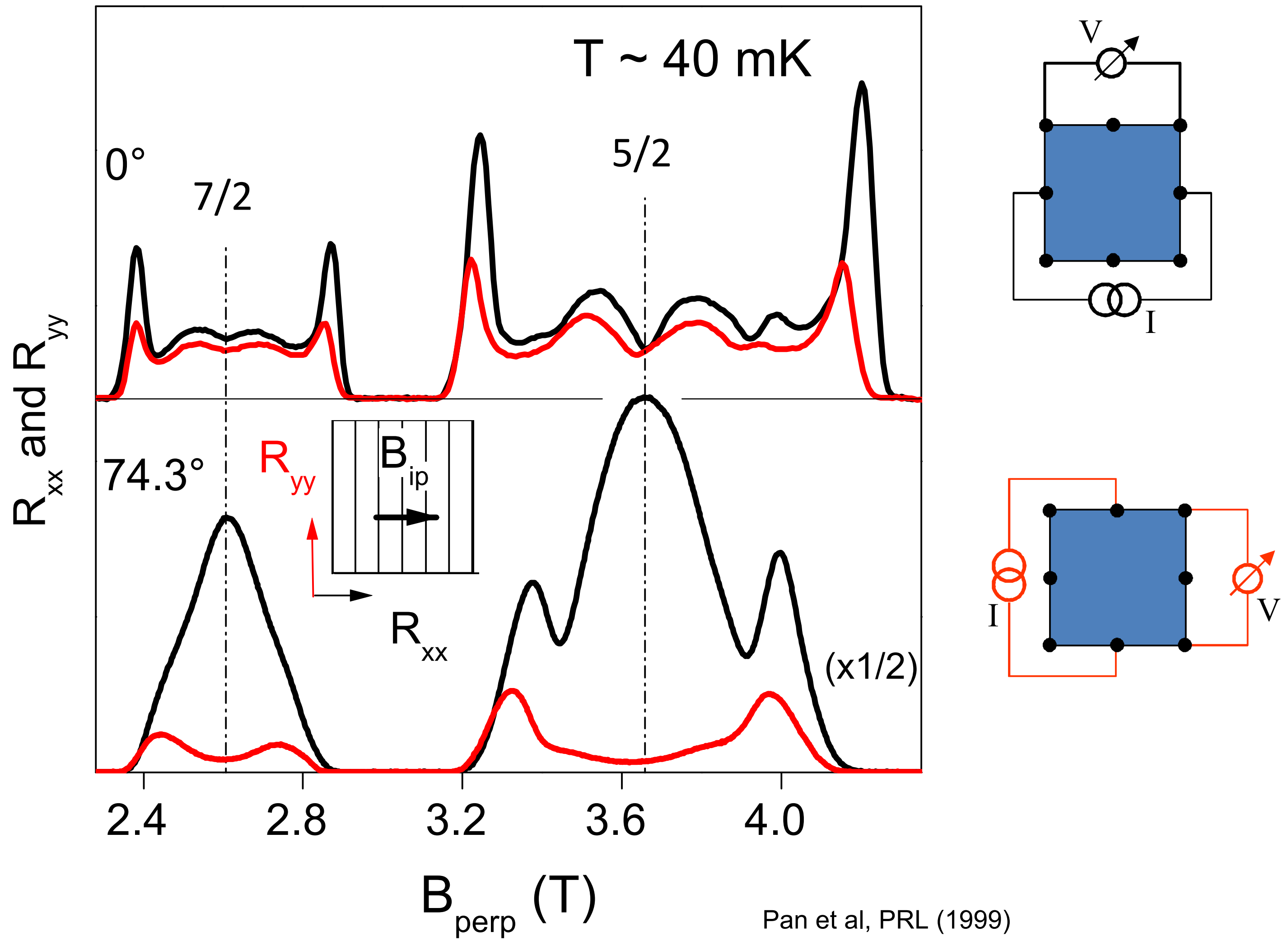
electron mobility
$\mu \approx 17 \times 10^6$ cm^2/Vs

5/2-state is a true FQHE state with even-denominator

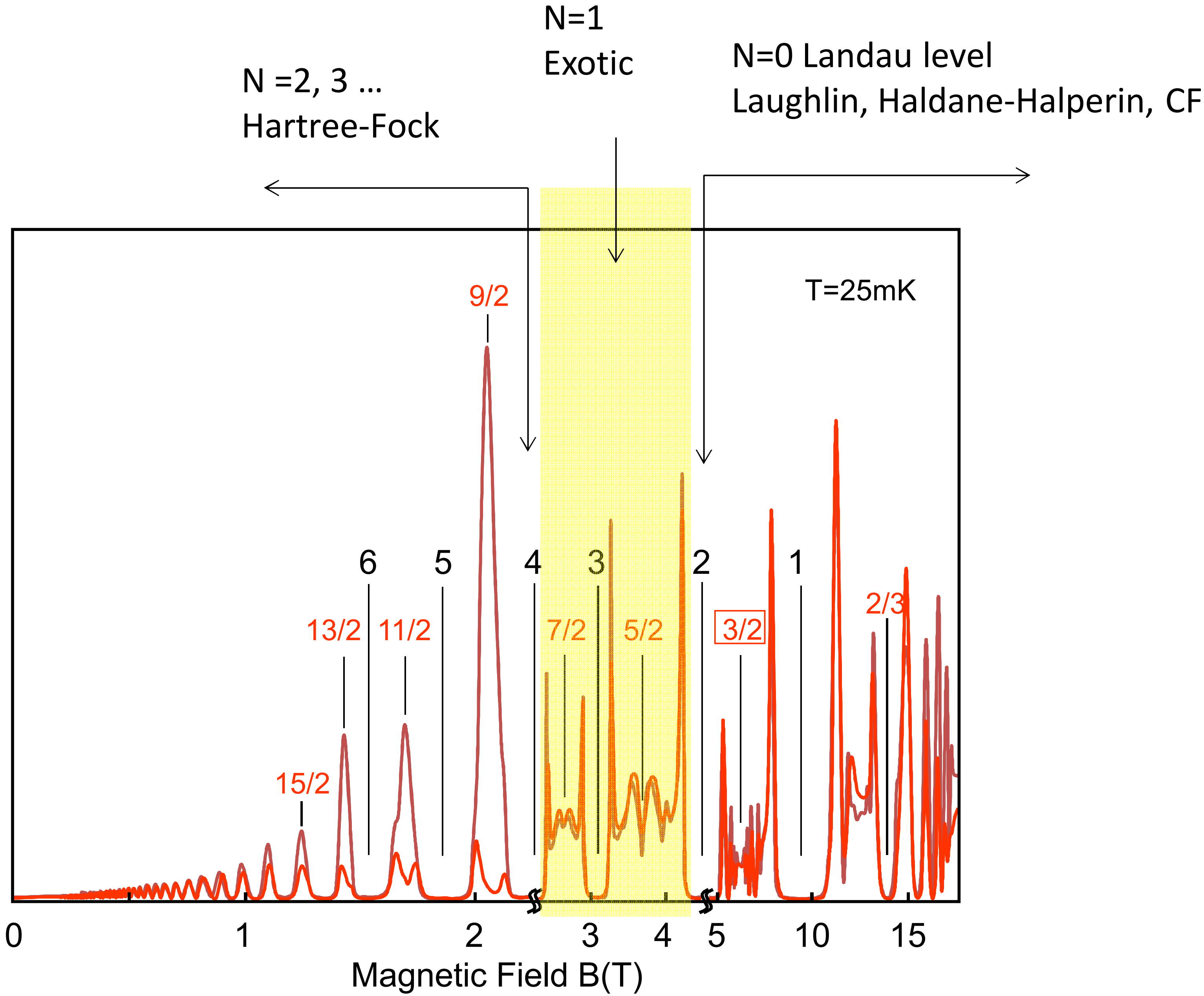
- R_{xx} is vanishingly small
- quantized Hall plateau

- Can't be explained by Laughlin's theory
- Can't be explained by CF model
- Due to pairing of CF's

Tilt magnetic field induced anisotropy in second Landau level



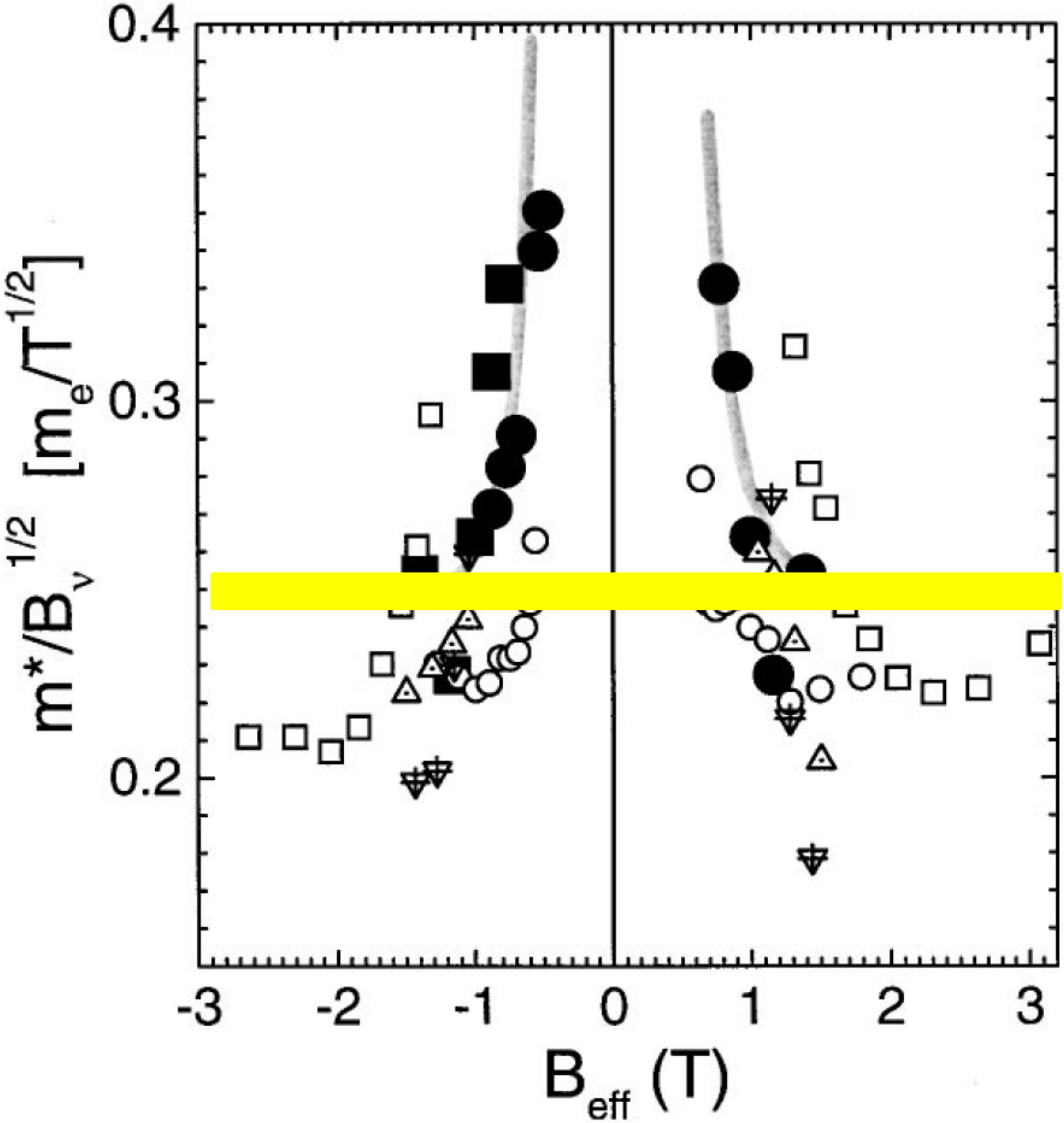
Pan et al, PRL (1999)
Lilly et al, PRL (1999)



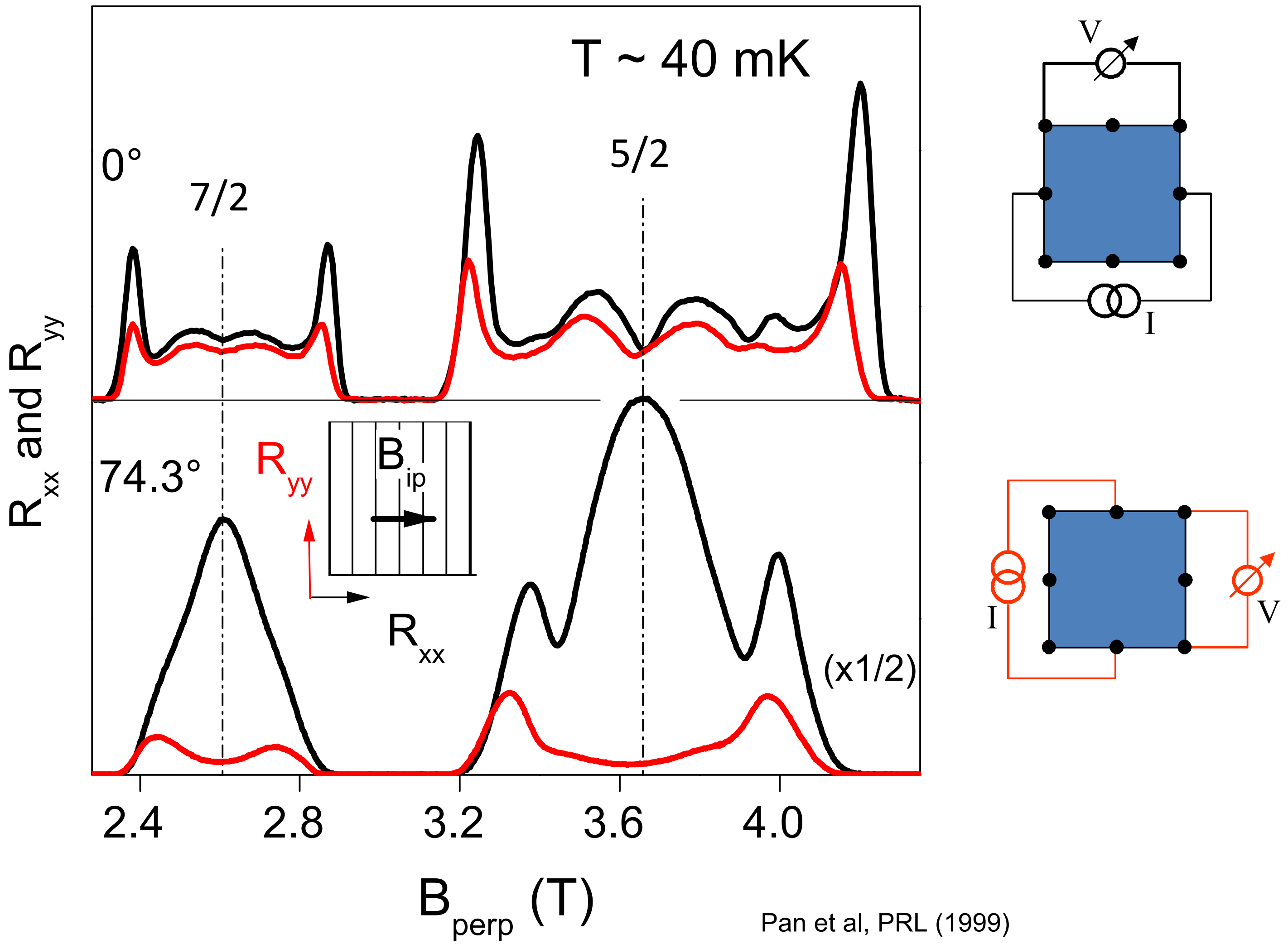
N=1
Exotic
N =2, 3 ...
Hartree-Fock
N=0 Landau level
Laughlin, Haldane-Halperin, CF
T=25mK
9/2
6
5
4
3
2
1
13/2
11/2
7/2
5/2
3/2
2/3
15/2
0
1
2
3
4
5
10
15
Magnetic Field B(T)

CF activation mass around ν=1/2, 3/2, ¼, ¾

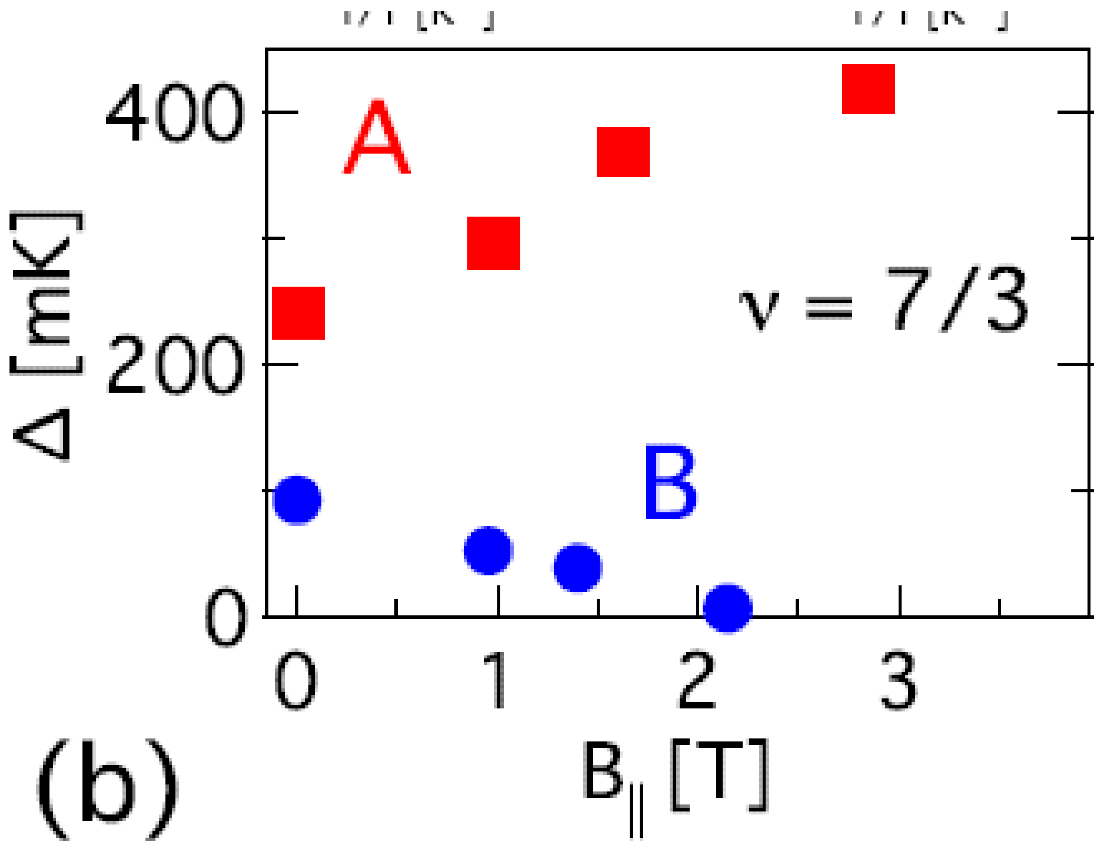
$$m^*/m_e \sim 0.26\, B_\nu^{1/2}$$



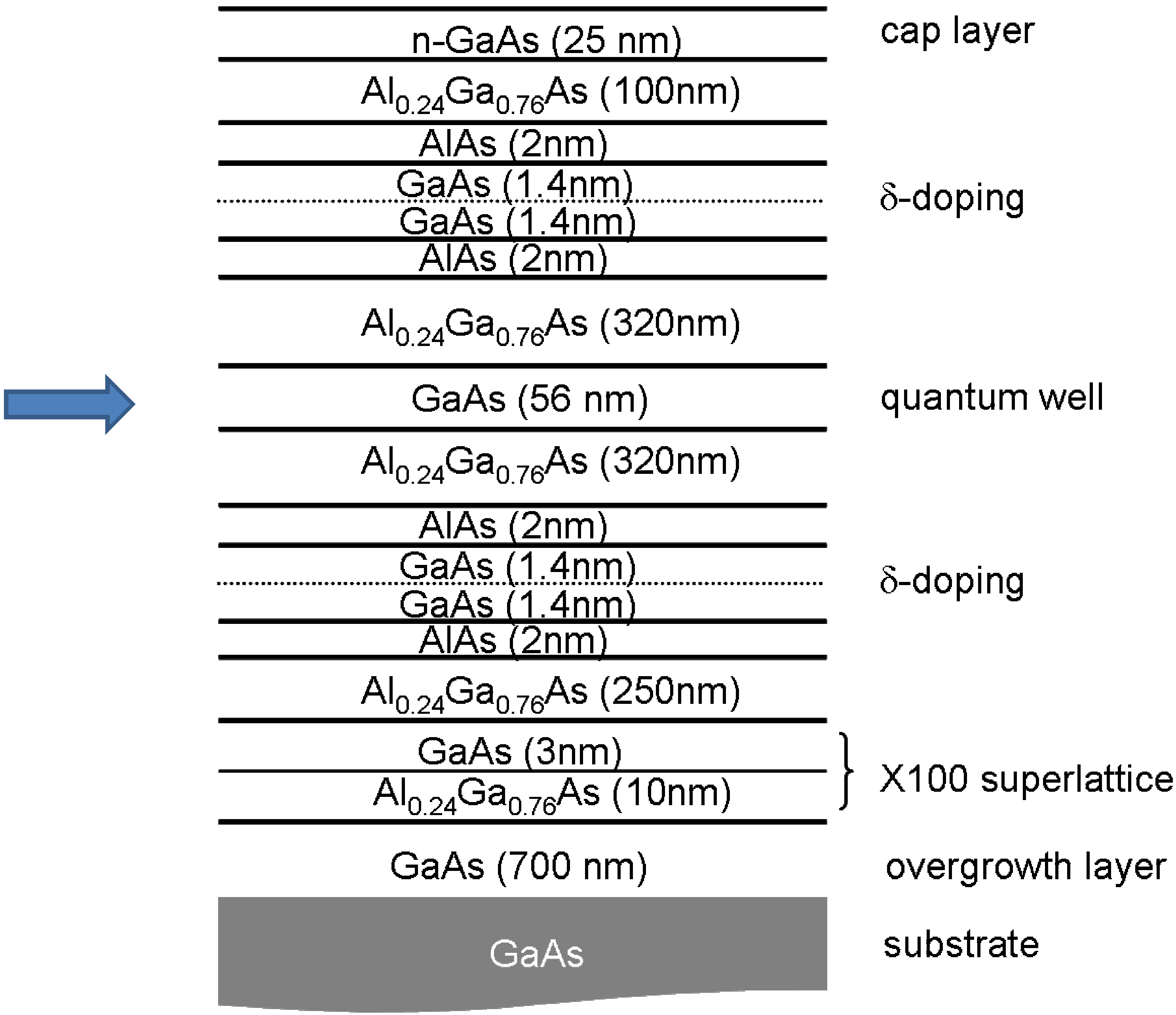
Tilt magnetic field induced anisotropy in second Landau level

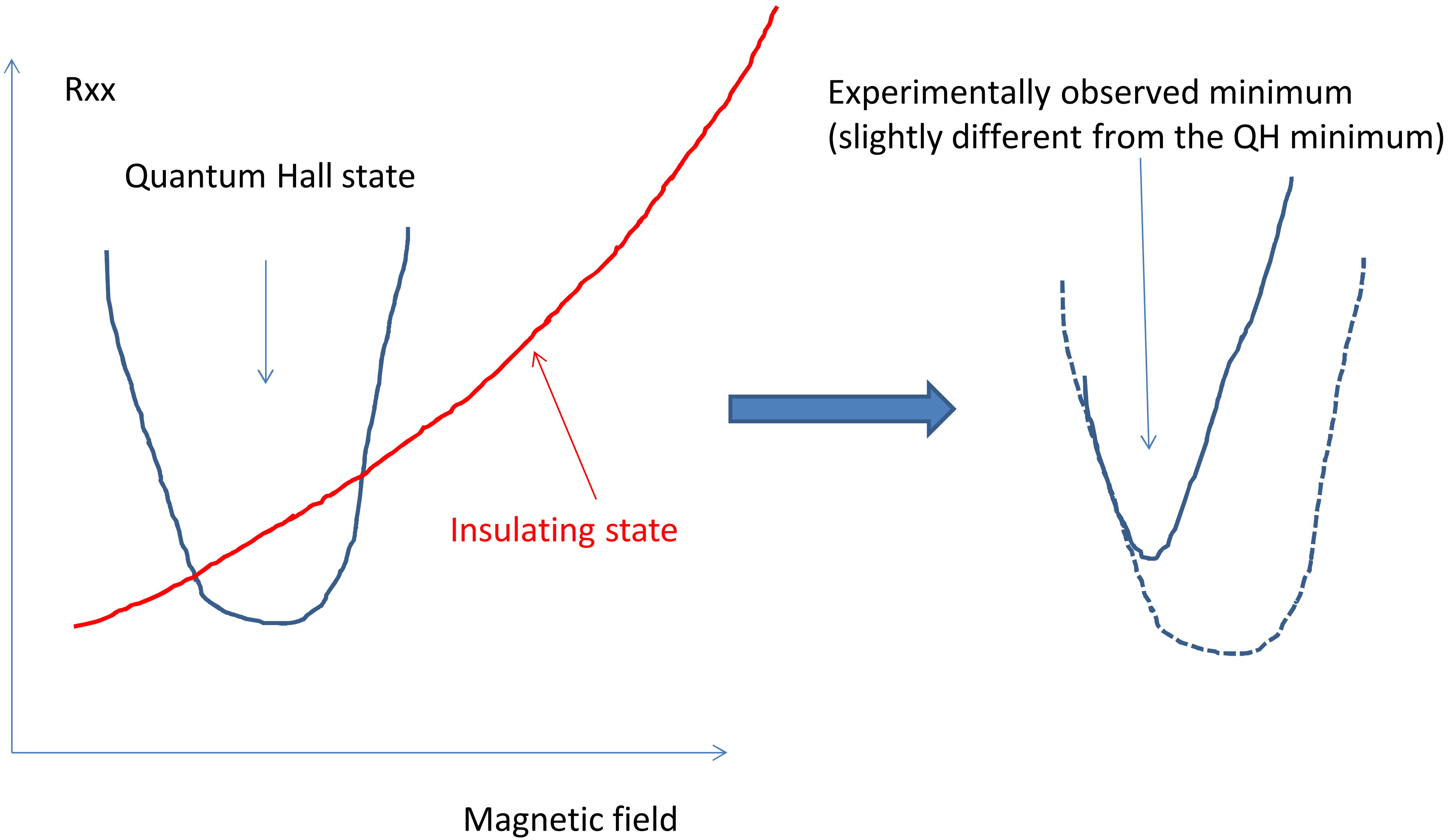


Pan et al, PRL (1999)
Lilly et al, PRL (1999)



Xia et al, PRL


n-GaAs (25 nm)
cap layer
Al0.24Ga0.76As (100nm)
AlAs (2nm)
GaAs (1.4nm)
GaAs (1.4nm)
AlAs (2nm)
δ-doping
Al0.24Ga0.76As (320nm)
GaAs (56 nm)
quantum well
Al0.24Ga0.76As (320nm)
AlAs (2nm)
GaAs (1.4nm)
GaAs (1.4nm)
AlAs (2nm)
δ-doping
Al0.24Ga0.76As (250nm)
GaAs (3nm)
Al0.24Ga0.76As (10nm)
X100 superlattice
GaAs (700 nm)
overgrowth layer
GaAs
substrate


Rxx
Quantum Hall state
Insulating state
Magnetic field
Experimentally observed minimum
(slightly different from the QH minimum)