SAND2015-20724C

Disorder Matters in the 5/2 Fractional Quantum Hall Effect

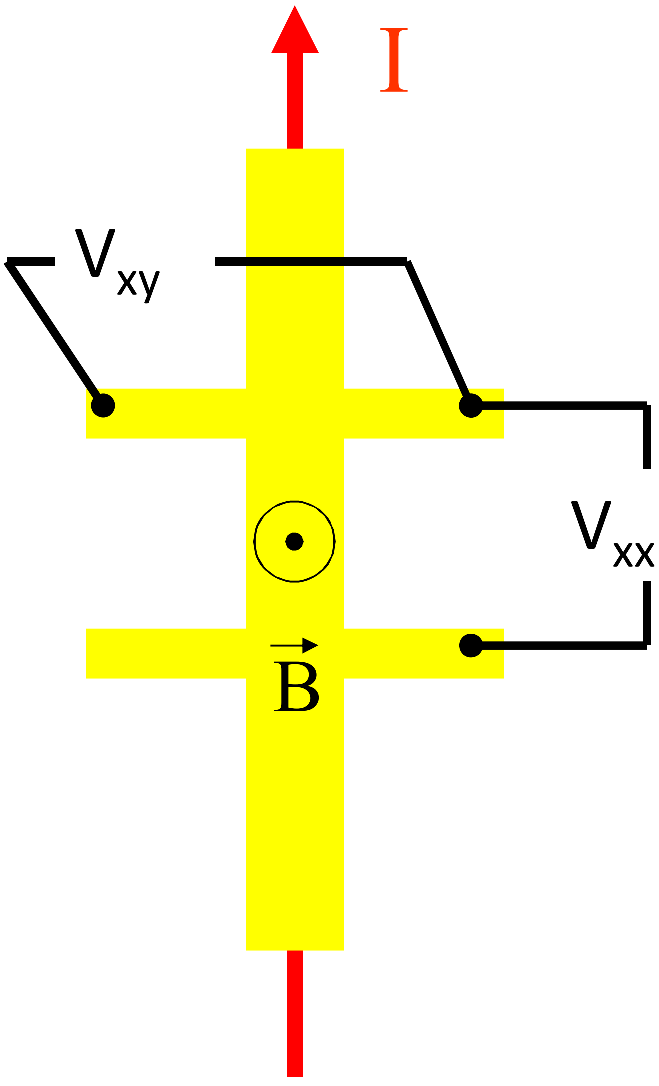
Wei Pan

Sandia National Laboratories

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline:

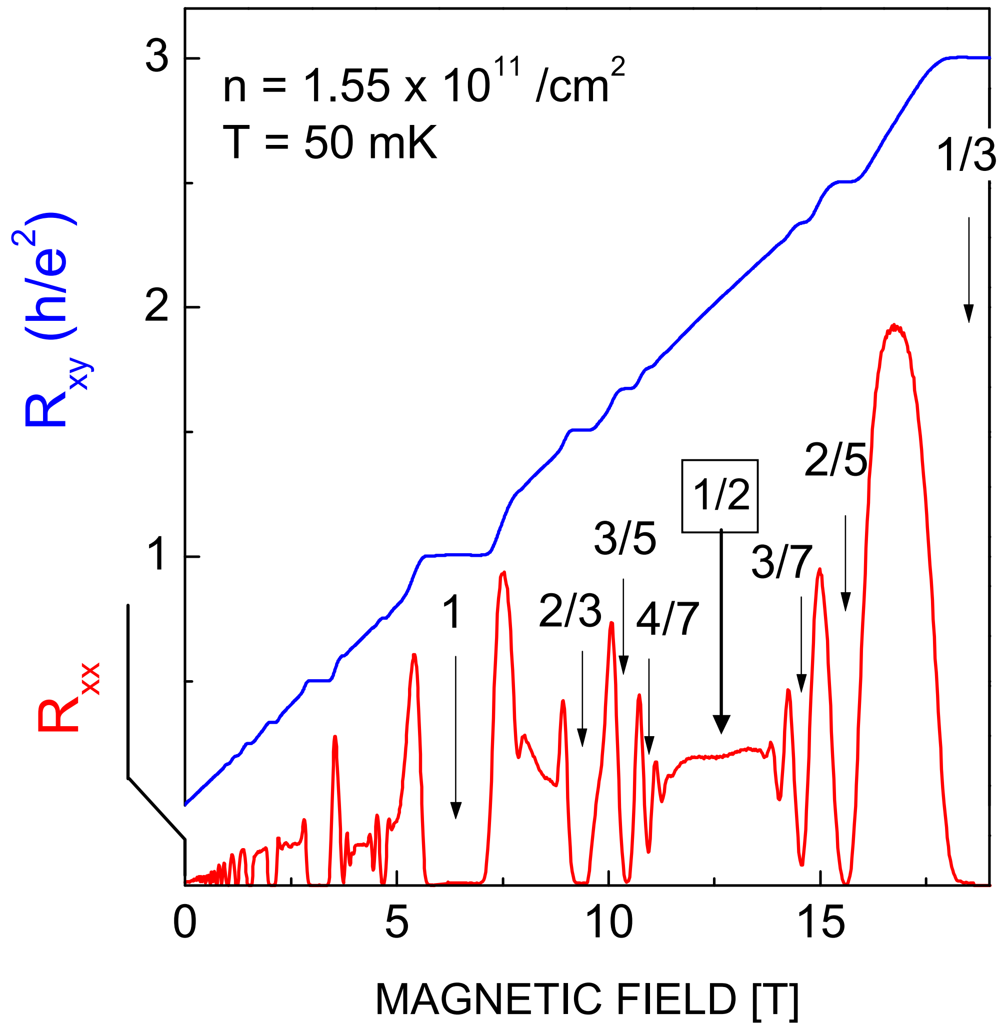
- Introduction
- Spin transition in the 5/2 fractional quantum Hall effect
- Impact of disorder in tilt induced 5/2 anisotropy
- Anisotropic 7/2 state in the low density limit



transport coefficients:

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

More fractions



$R_{xy}=(h/e^2)/\nu$

ν= 1/3, 2/5, 3/7 ...
2/3, 3/5, 4/7 ...

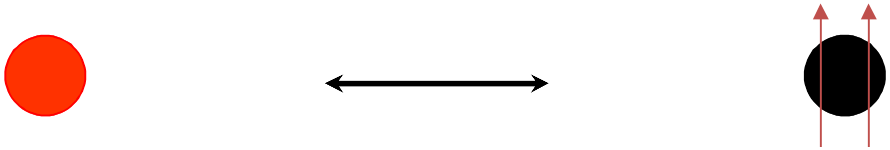
Lots of Fractions Observed

1/3	1/5	1/7	1/9	2/11	2/13	2/15	2/17	3/19	5/21	6/23
2/3	2/5	2/7	2/9	3/11	3/13	4/15	3/17	5/19	10/21	6/25
4/3	3/5	3/7	4/9	4/11	4/13	7/15	4/17	9/19		
5/3	4/5	4/7	5/9	5/11	5/13	8/15	5/17	10/19		
7/3	6/5	5/7	7/9	6/11	6/13	11/15	6/17			
8/3	7/5	9/7	11/9	7/11	7/13	22/15	8/17			
	8/5	10/7	13/9	8/11	10/13	23/15	9/17			
	9/5	11/7	14/9	16/11	19/13					
	11/5	12/7		17/11	20/13					
	12/5									
	13/5									
	14/5									

Composite Fermion (CF) Model

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

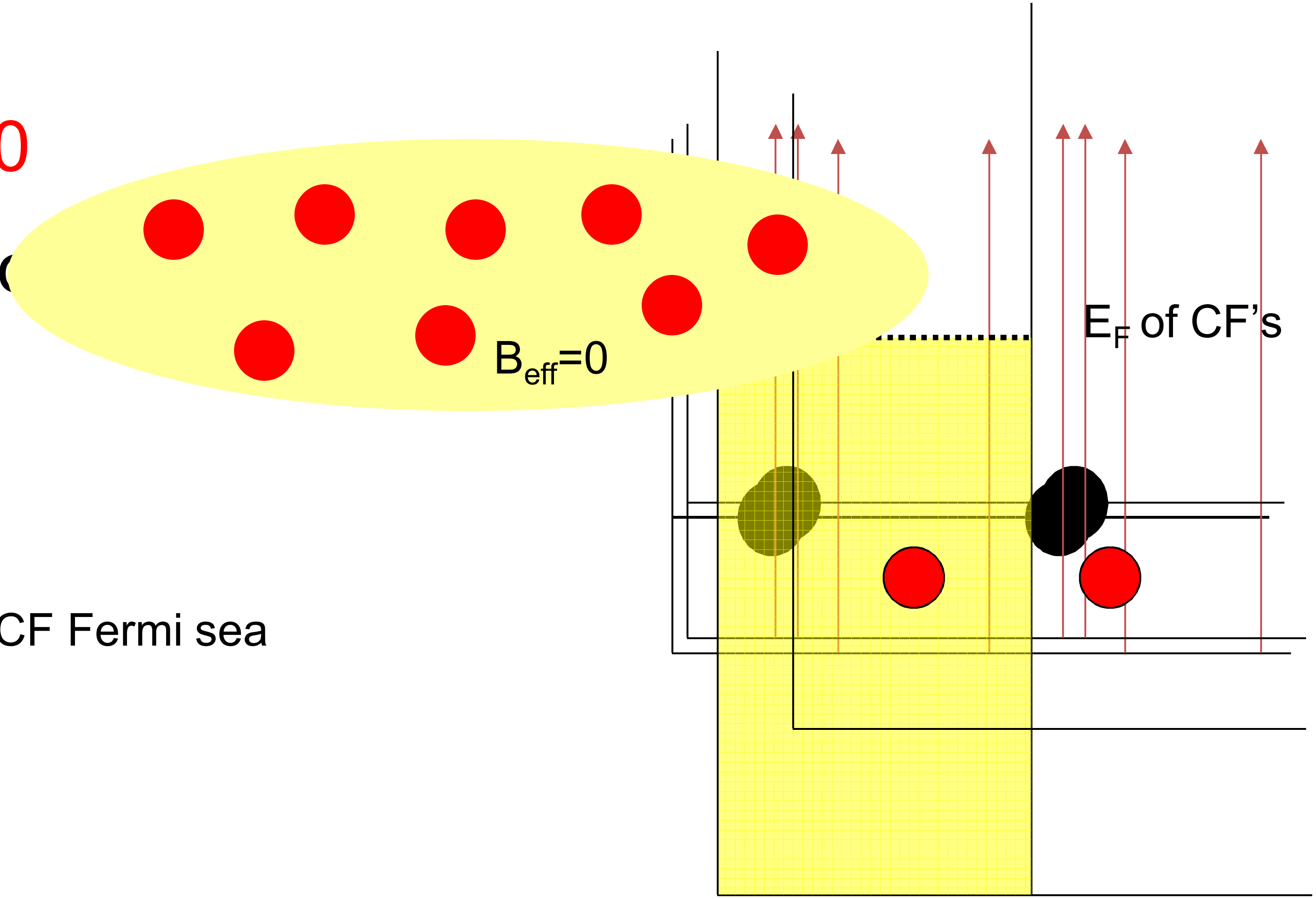
one composite fermion = one electron + 2 flux quanta



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

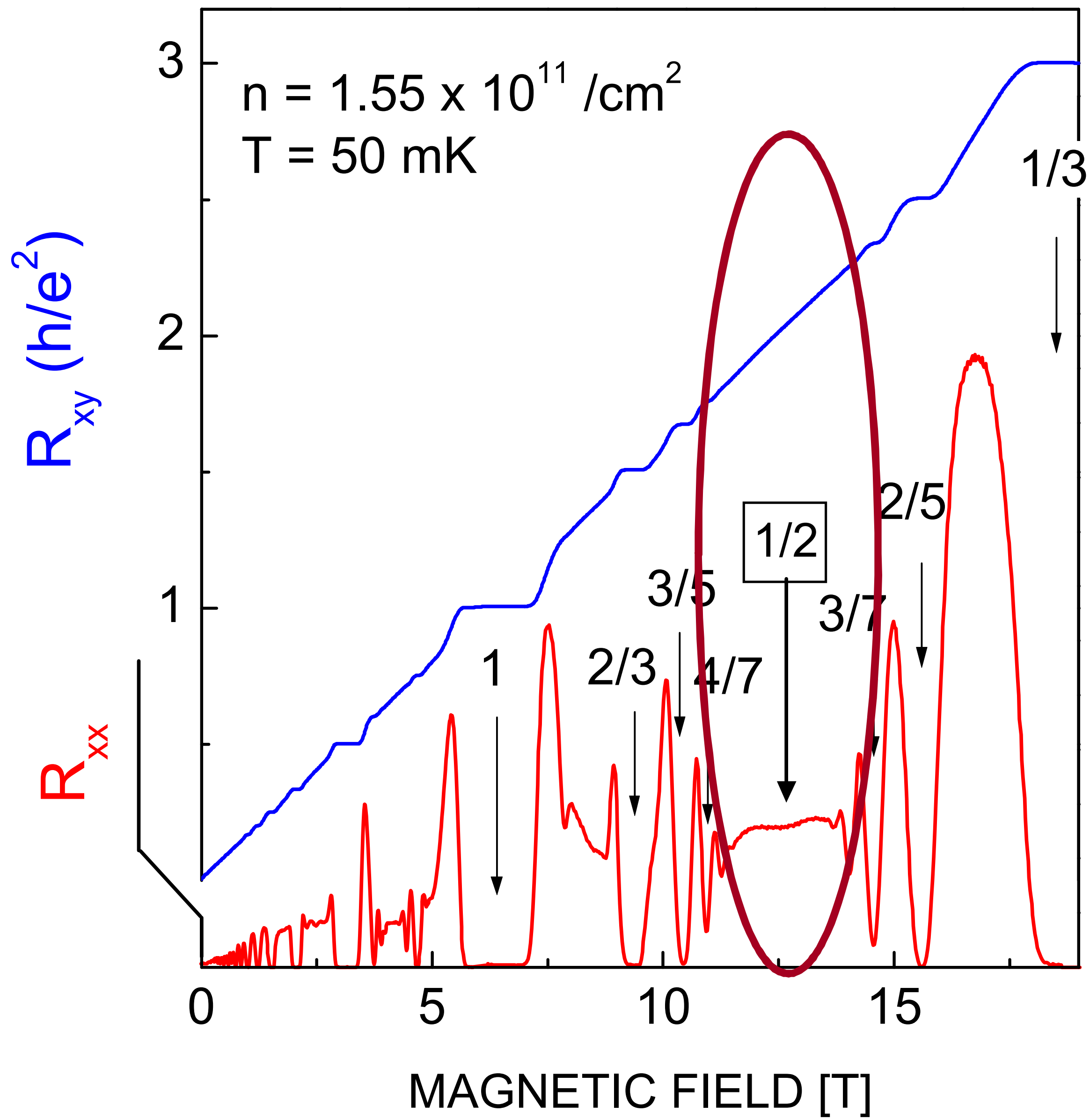
At $\nu = 1/2$

- $B_{eff} = 0$
- CF’s fo



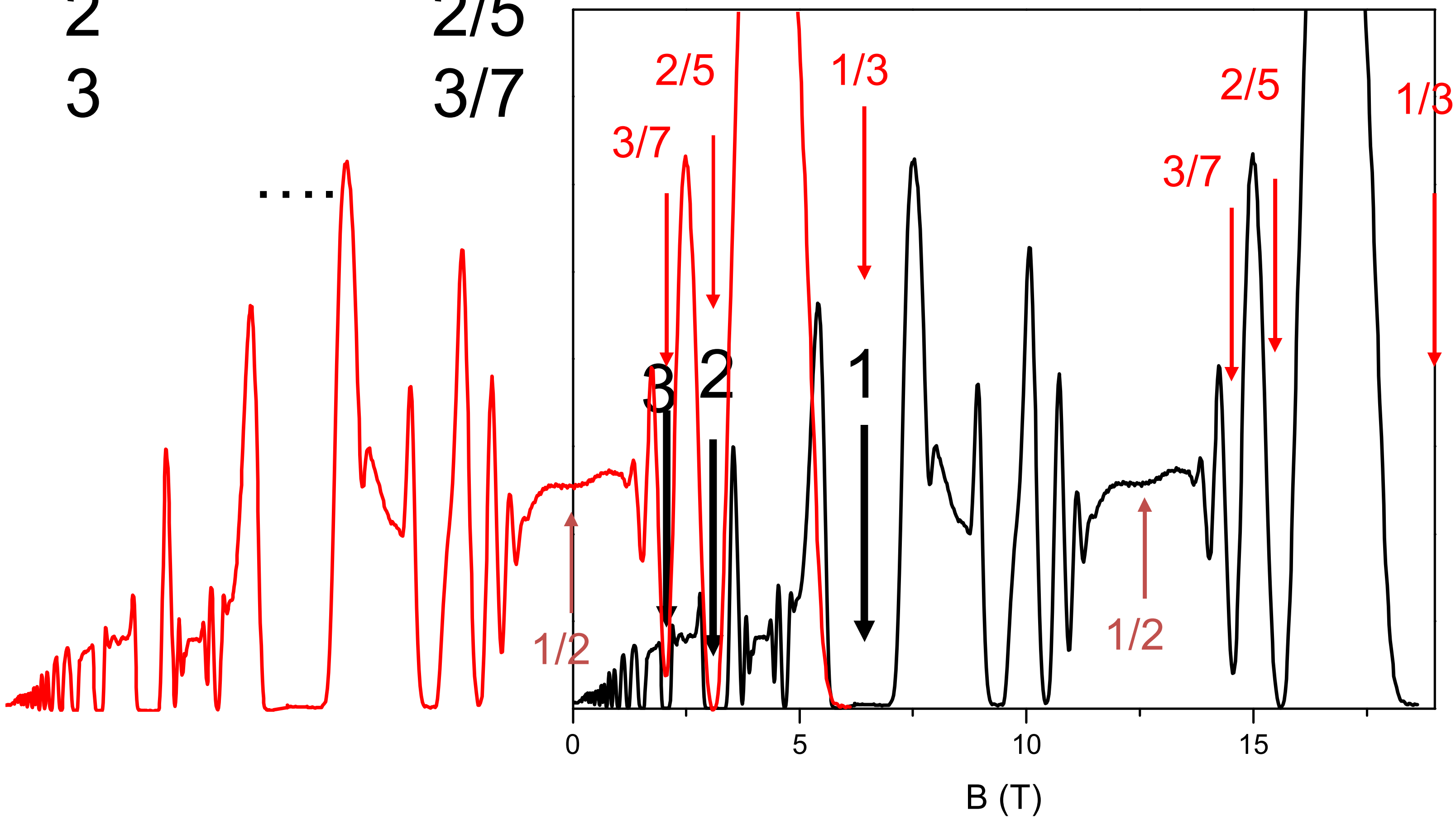
- CF Fermi sea

Featureless transport around ν=1/2 – Fermi sea state

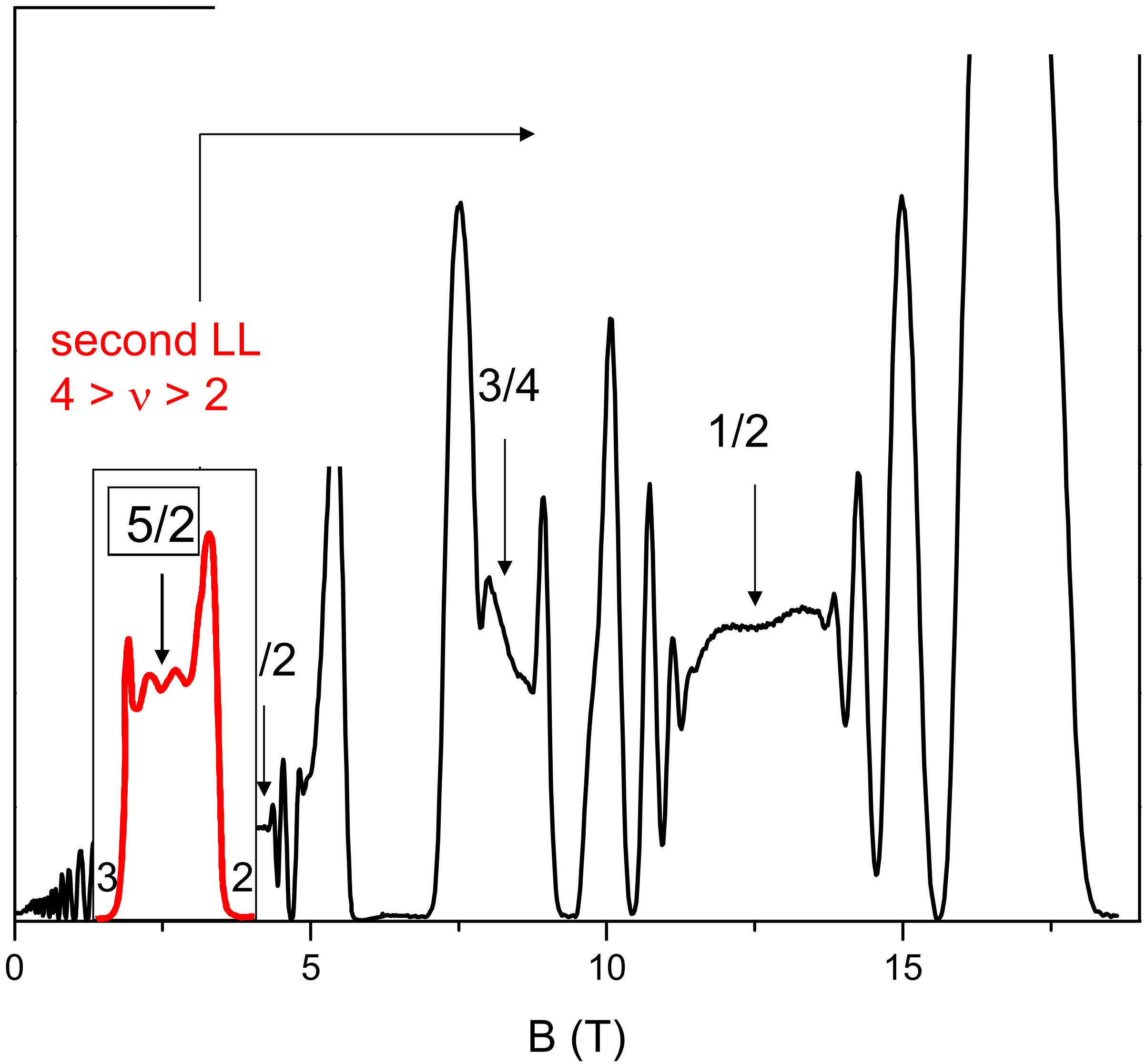


IQHE of CF   FQHE of e^-

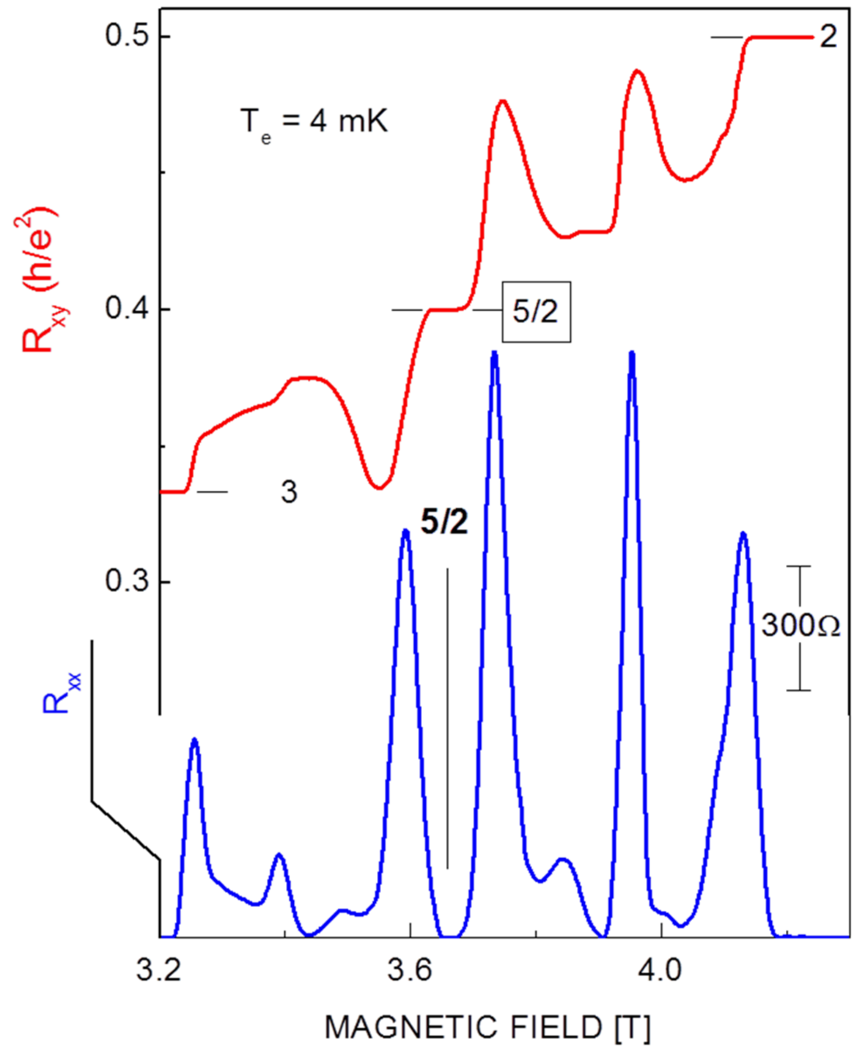
p	$\nu=p/(2p+1)$
1	1/3
2	2/5
3	3/7



in the lowest Landau level, the
CF model applies to almost all the FQHE
states and the even-denominator fractions



True FQHE at ν=5/2



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

Pan, Xia, and et al, PRL (1999)

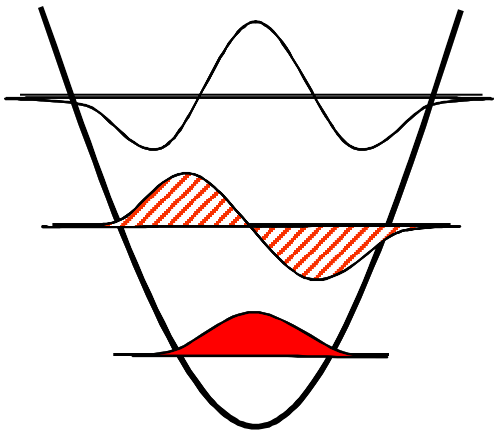
5/2-state is a true FQHE state with even-denominator

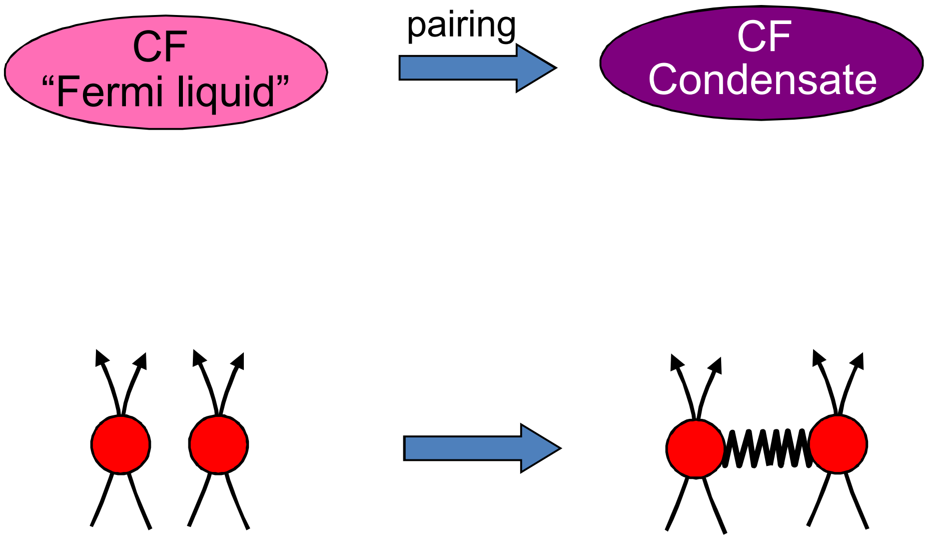
- R_{xx} is vanishingly small
- quantized Hall plateau

- Can't be explained by Laughlin's theory
- Can't be explained by hierarchical model
- Doesn't belong to any CF sequences
- Due to pairing of CF's

Origin of 5/2-state: BCS pairing of CF's

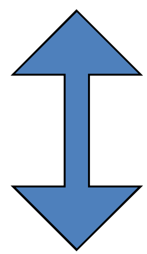
$\nu=5/2$





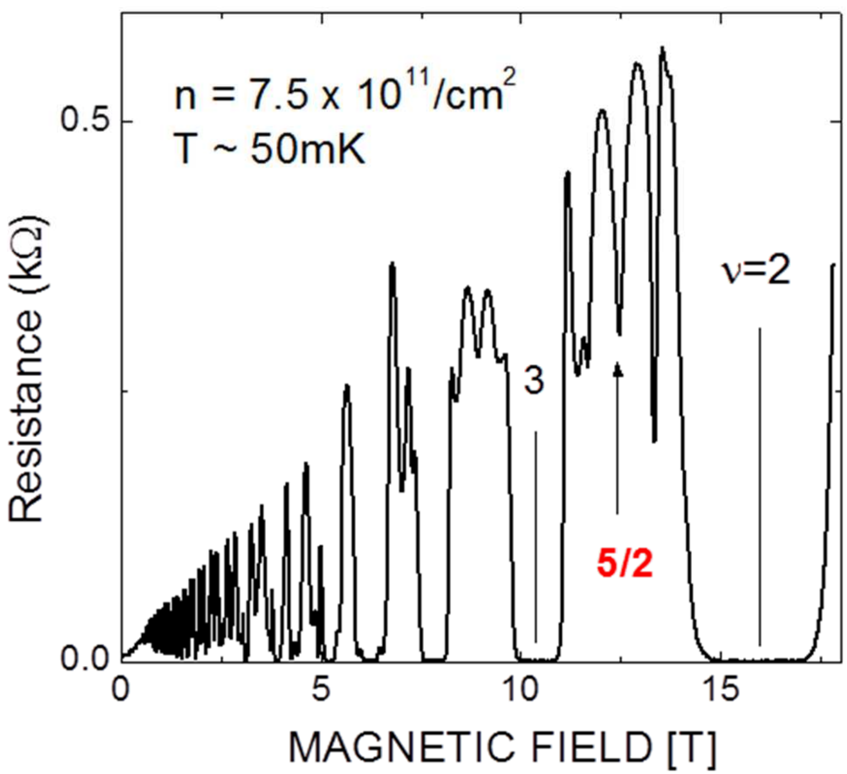
Spin Polarization of the 5/2 Fractional Quantum Hall Effect

Non-abelian quantum Hall state



Spin polarized

5/2 state at very high magnetic field



At high B,

$E_z = g\mu_B B \sim 4K >> \Delta_{5/2}$

Spin-singlet state should no longer exist

5/2-state probably is spin-polarized

Density dependence of the 5/2 energy gap

Work done in collaboration with:

Dan Tsui
Loren Pfeiffer
Ken West
Kirk Baldwin

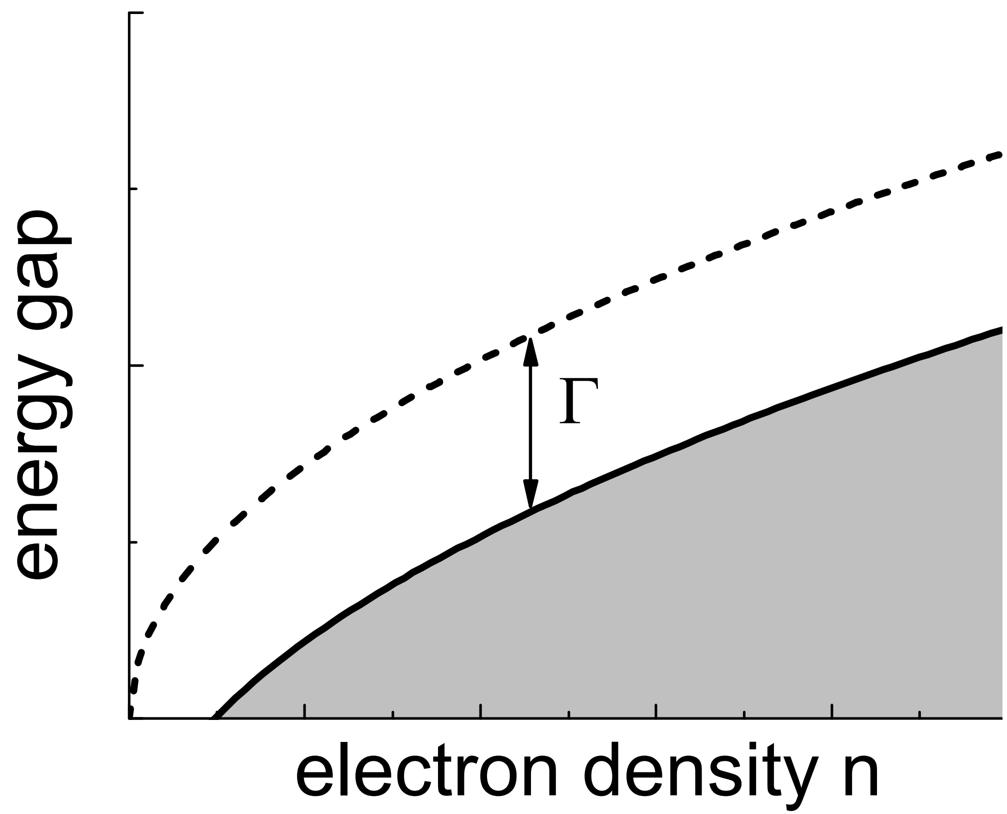
} Princeton

Jian-Sheng Xia
Alex Serafin
Liang Yin
Neil Sullivan

} High B/T of NHMFL in Gainesville, FL

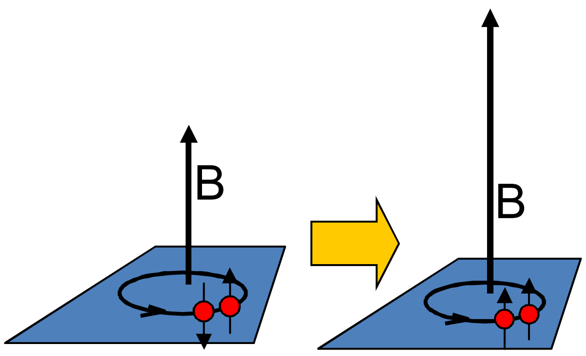
$\Delta \propto E_c$ (Coulomb energy) = $e^2/\varepsilon r \propto n^{1/2}$

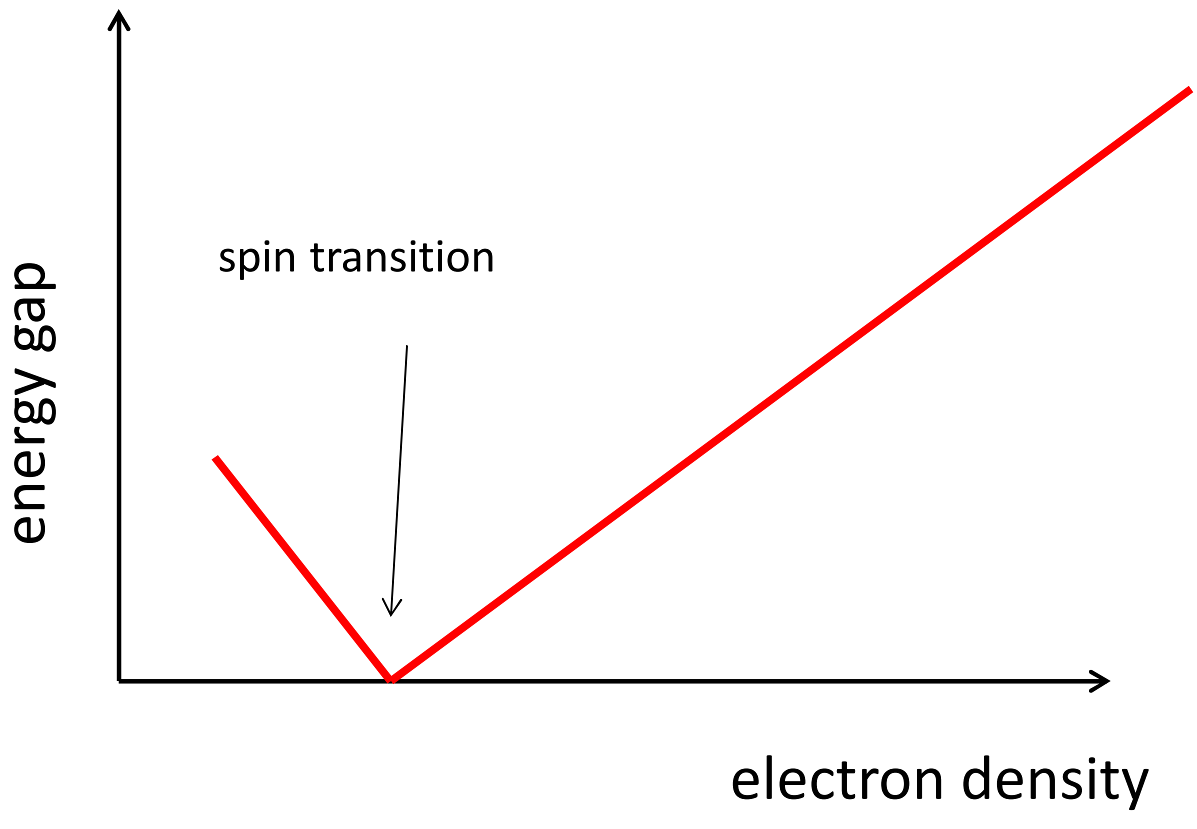
spin polarized ground state: $\Delta = \alpha\sqrt{n} - \Gamma$



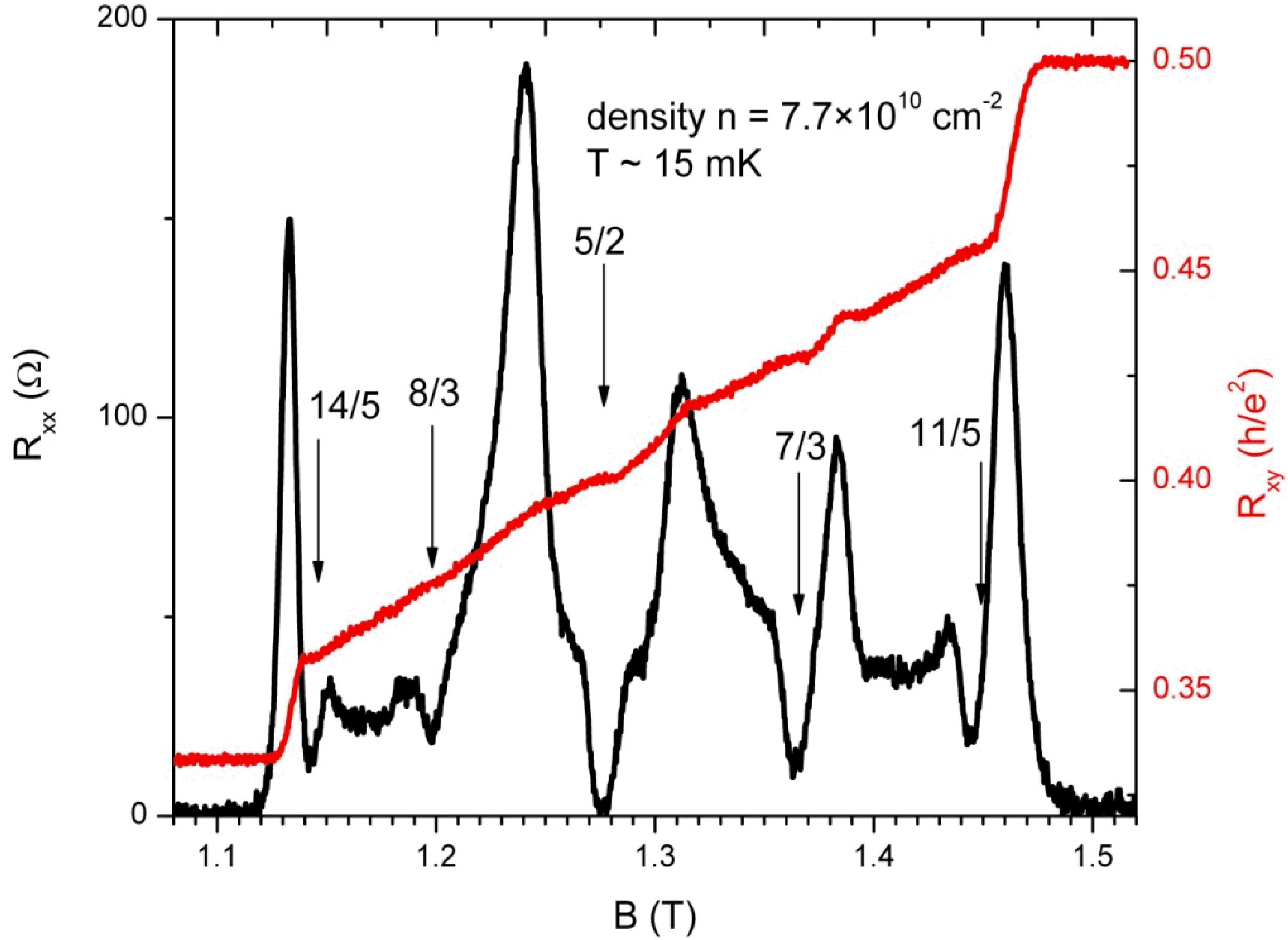
$E_c \propto n^{1/2}$, E_z(Zeeman energy) $\propto n$

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

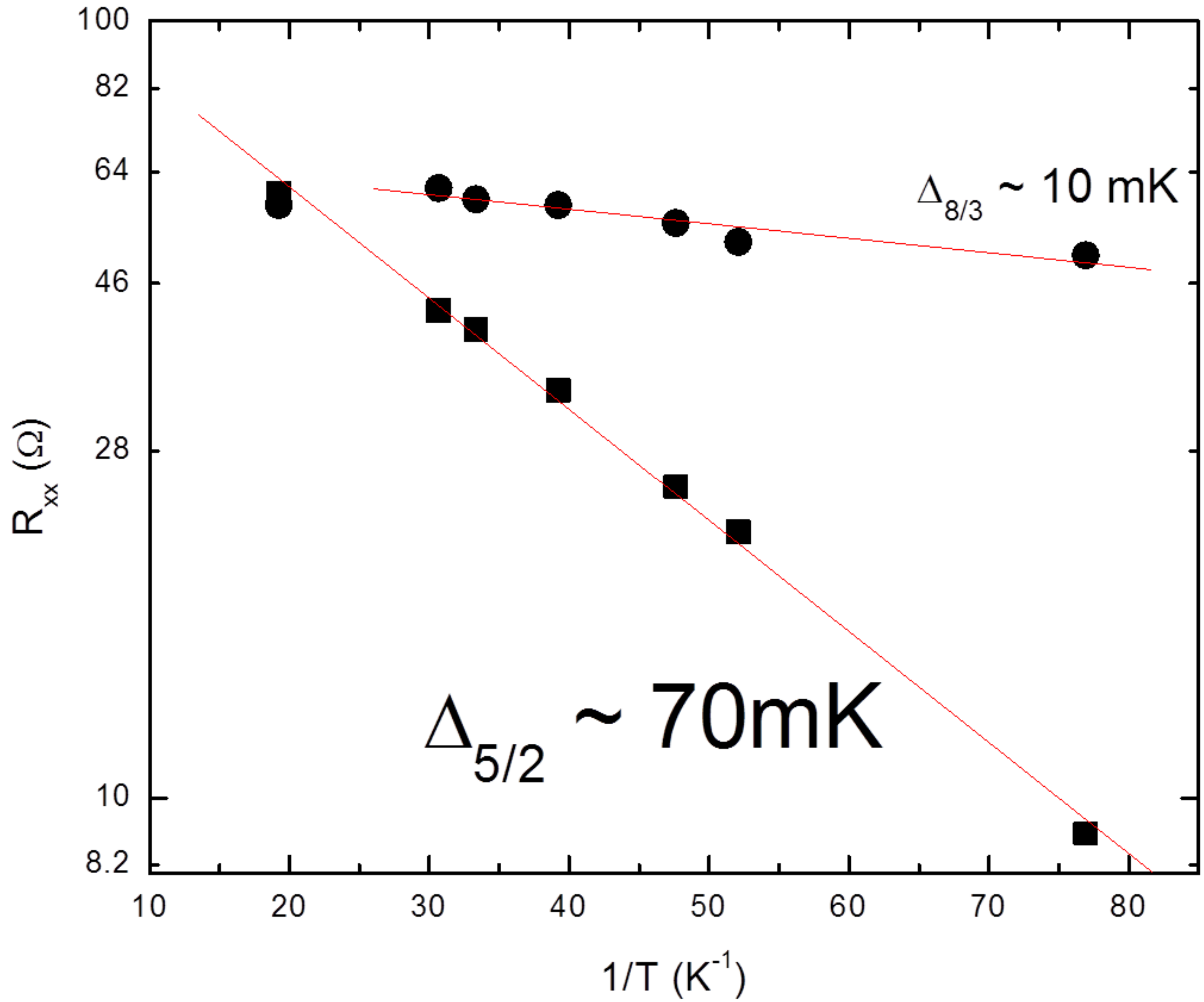




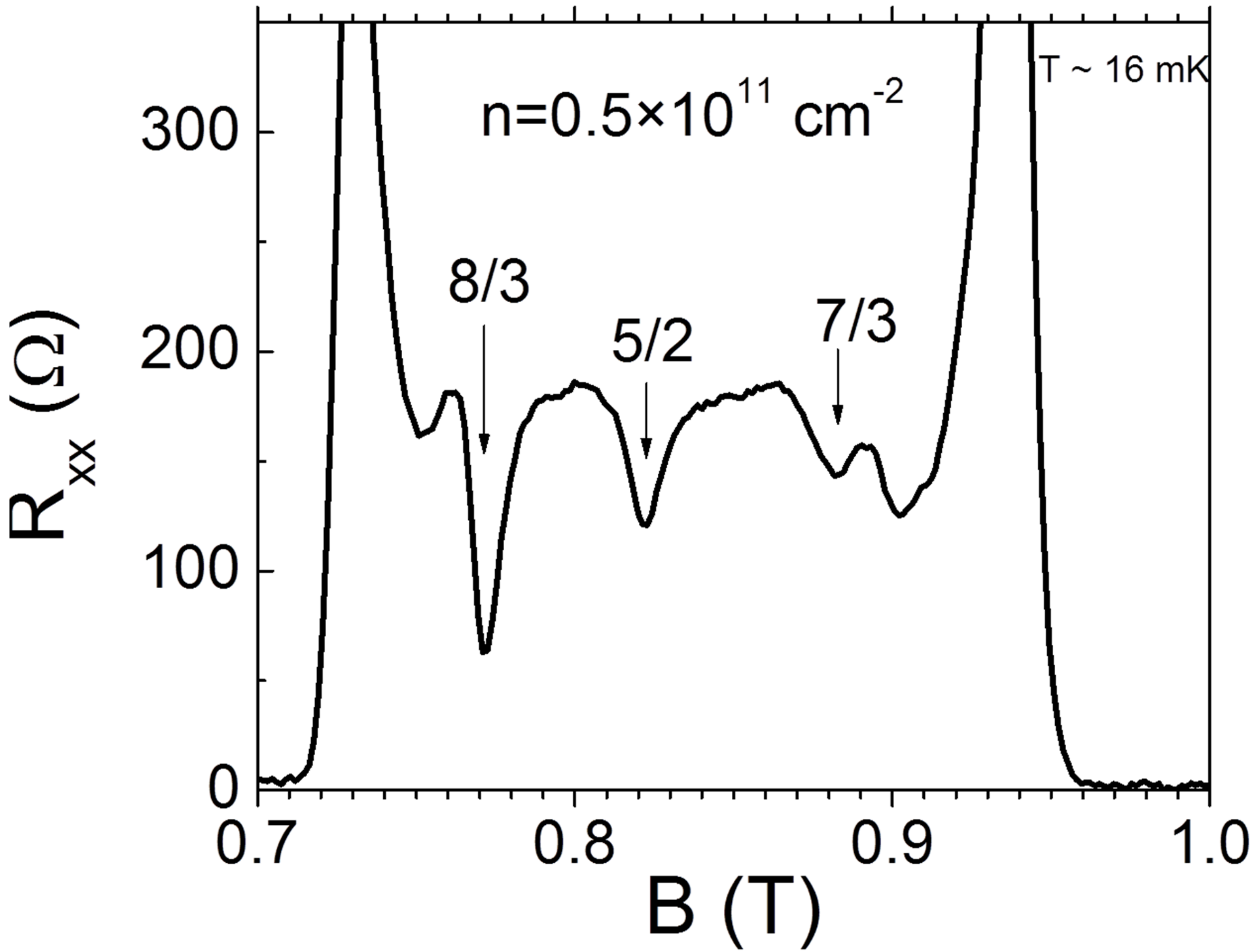
samples	well width (nm)	density (10^{11} cm^{-2})	mobility (10^6/V s)	l_B at ν=5/2 (nm)	W/l_B
A	65	0.41	10	31.1	2.1
B	60	0.5	10	28.2	2.1
C	56	0.77	13	22.7	2.4
D	45	1.15	13.8	18.6	2.4
E	33	2.1	23	13.8	2.4
F	30	2.6	24	12.4	2.4
G	30	3.1	31	11.3	2.6



density n = 7.7×10^10 cm^-2
T ~ 15 mK
14/5
8/3
5/2
7/3
11/5
R_xx (Ω)
R_xy (h/e^2)
B (T)
200
100
0
0.50
0.45
0.40
0.35
1.1
1.2
1.3
1.4
1.5



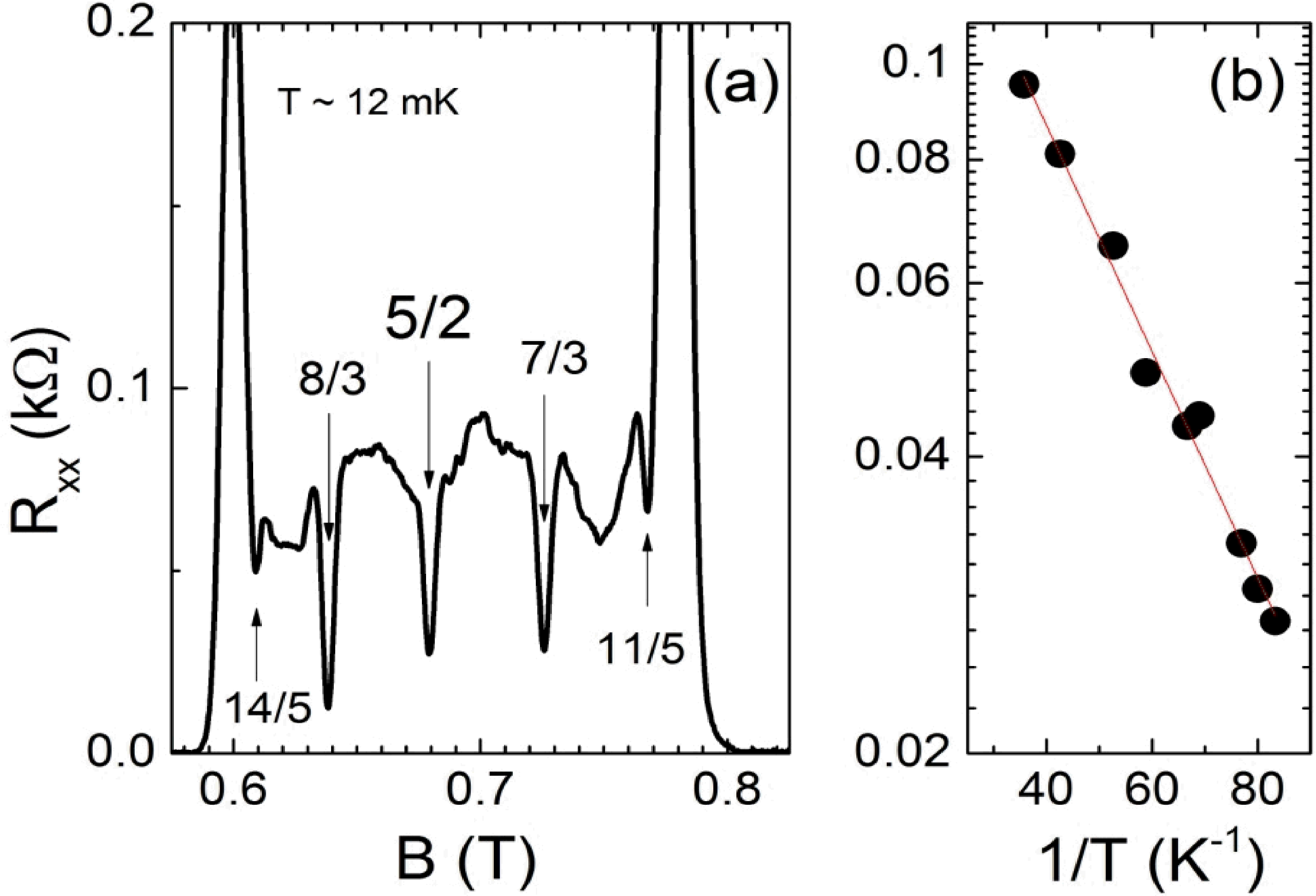
100
82
64
46
28
10
8.2
10
20
30
40
50
60
70
80
R_{xx} (Ω)
1/T (K^{-1})
$\Delta_{8/3}$ ~ 10 mK
$\Delta_{5/2}$ ~ 70mK



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

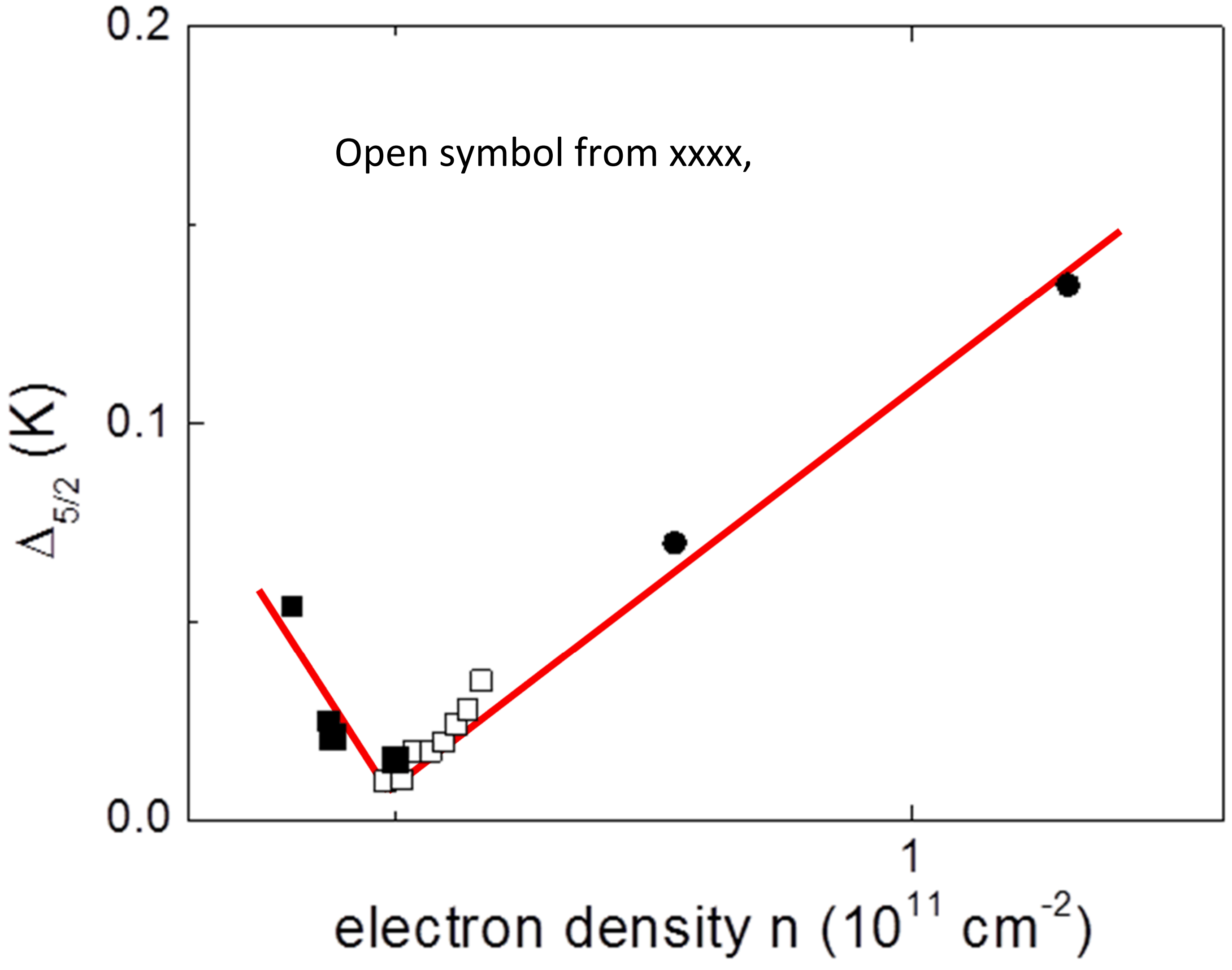
$n = 0.41 \times 10^{11}$ cm^{-2}

$\Delta_{5/2} \sim 55$ mK



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

Spin transition in the 5/2 state



The spin transition is

- a spin transition from an Abelian state to a non-Abelian state?

- a spin transition from a non-Abelian spin-singlet state to a non-Abelian spin-polarized state

- the Landau level mixing effect?

$$\kappa = e^2/\varepsilon l_B/\hbar\omega_c \sim 3 \text{ at } \nu=5/2 \text{ at } n=0.41\text{x}10^{11}\ \text{cm}^{-2}$$

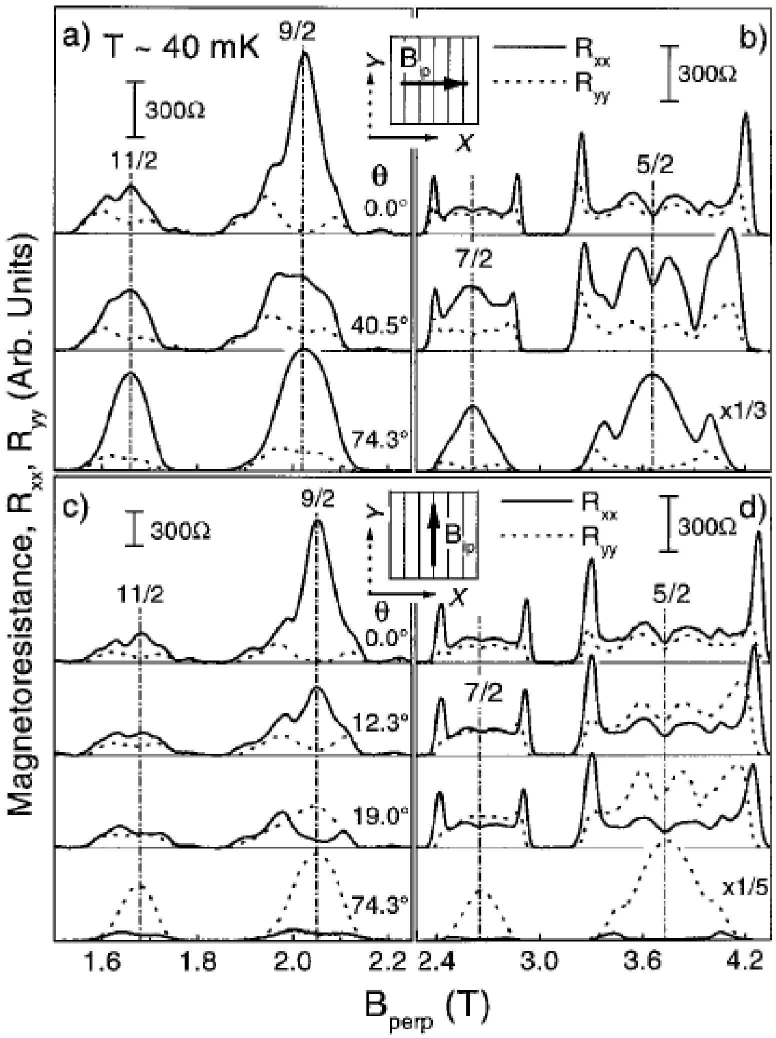
Disorder matters in tilt magnetic field induced anisotropy at 5/2

Work done in collaboration with:

Xiaoyan Shi } Sandia Labs

Loren Pfeiffer
Ken West
Kirk Baldwin
Dan Tsui
} Princeton

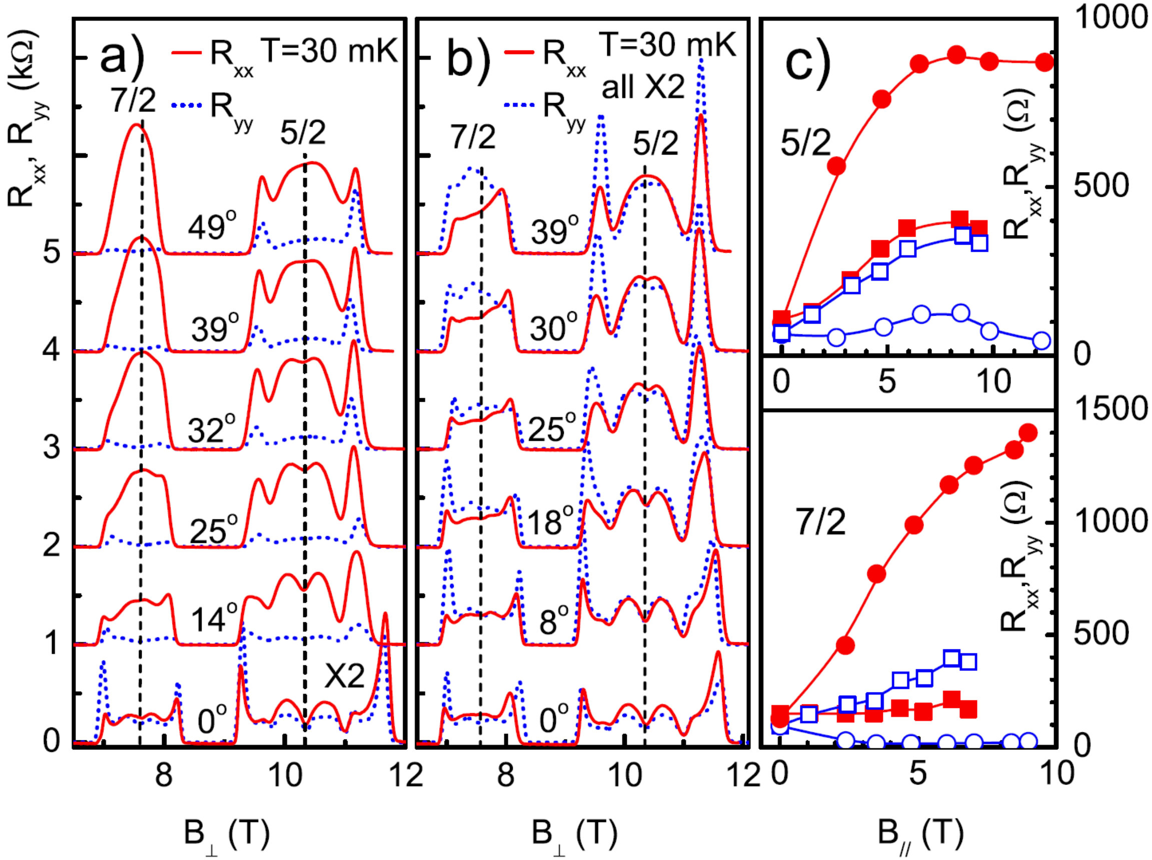
5/2 under tilt



- **Isotropic without tilt**
- **Strong electrical anisotropy under tilt**
- **Hard (higher R) axis is always along in-plane B direction**
- ***n*=2.2×10¹¹ cm⁻² *μ* = 1.7×10⁷ cm²/Vs**

W. Pan et al., PRL 83, 820, (1999)
M.P. Lilly et al., PRL 83, 824 (1999)

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



Zhang et al, PRL (2010)

Question:

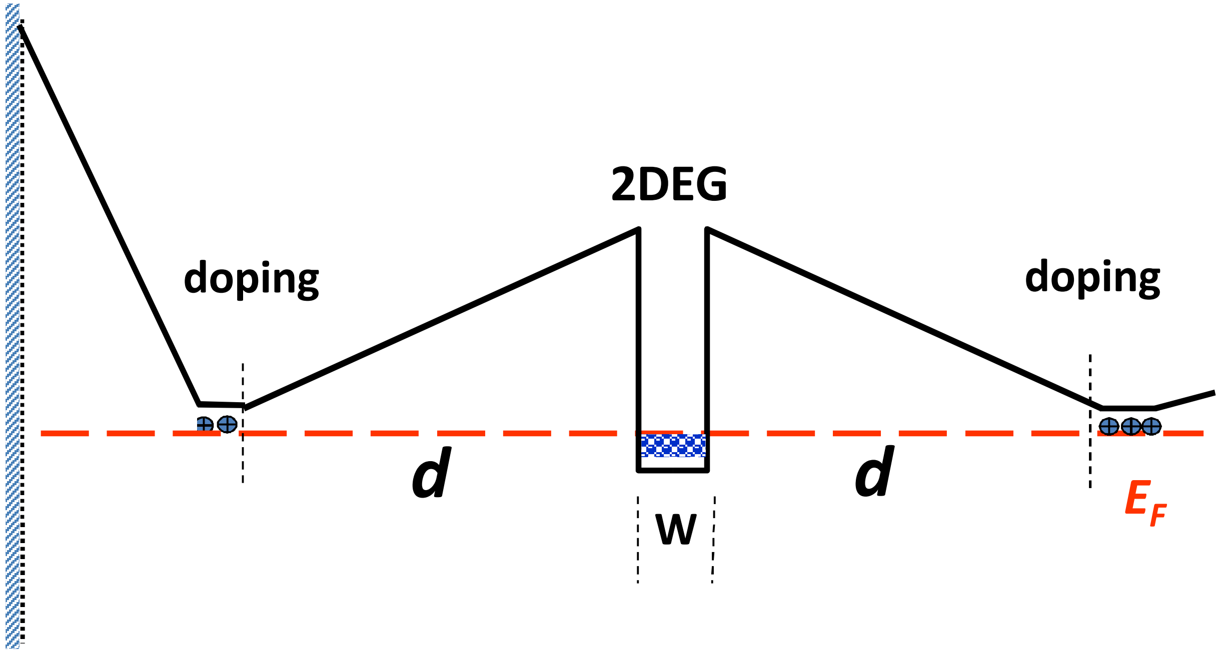
Is this anisotropy difference along crystalline directions due to disorders?

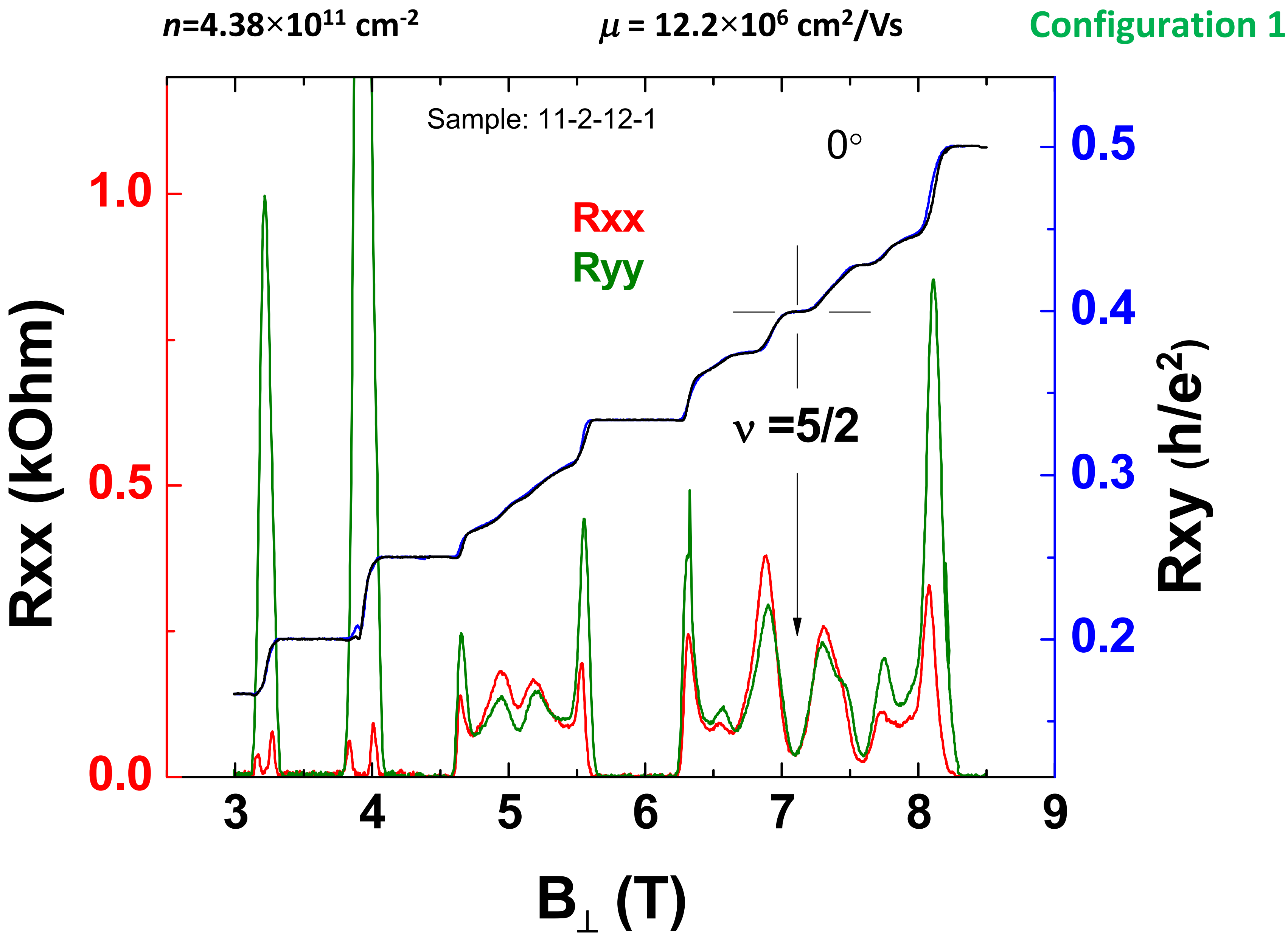
High electron density sample:

- **isotropic in one crystalline axis**
- **anisotropic in another axis**
- **n=6.3×10^{11} cm^{-2} μ = 1.0×10^{7} cm^{2}/Vs**

Samples

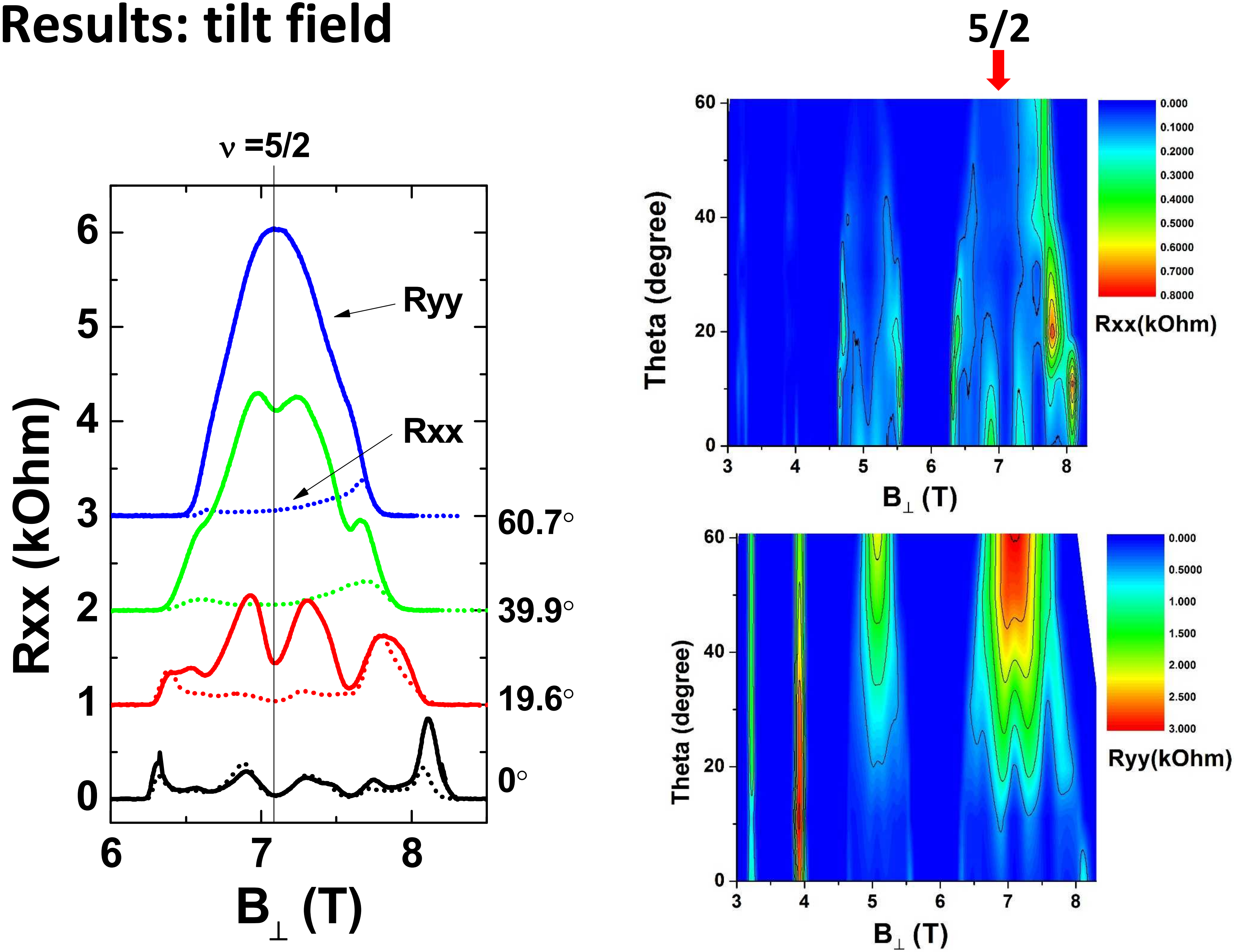
- Symmetrically doped $Al_xGa_{1-x}As/GaAs/Al_xGa_{1-x}As$ quantum well
- Well width: w = 20 nm
- Fix dopant concentration
- Vary set-back distance: d = 29-260 nm
- 2DES density: $n = 0.935\text{-}6.58\times10^{11}$ cm^{-2}
- Mobility: $\mu = 3.2\text{-}12.2\times10^{6}$ cm^2/Vs

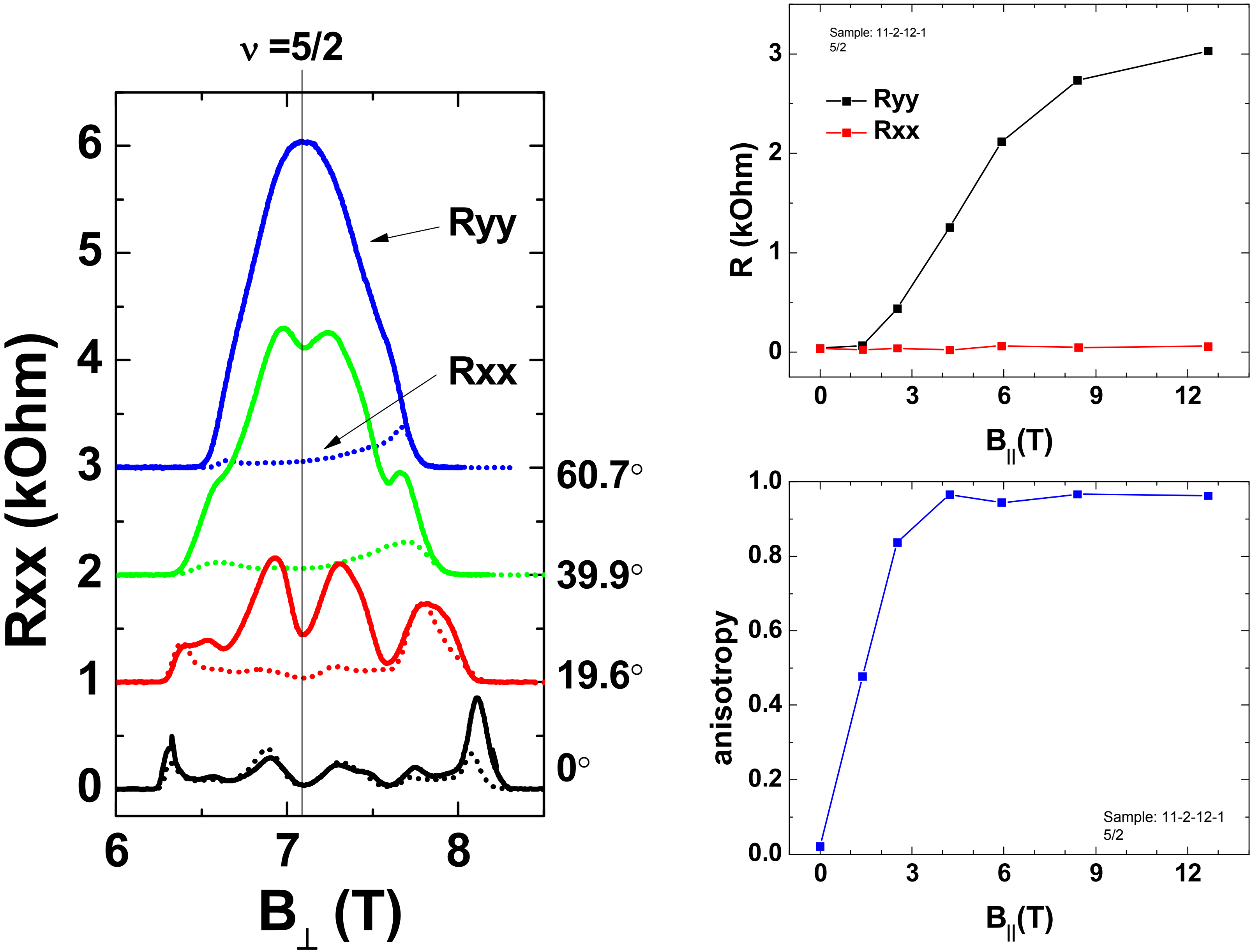


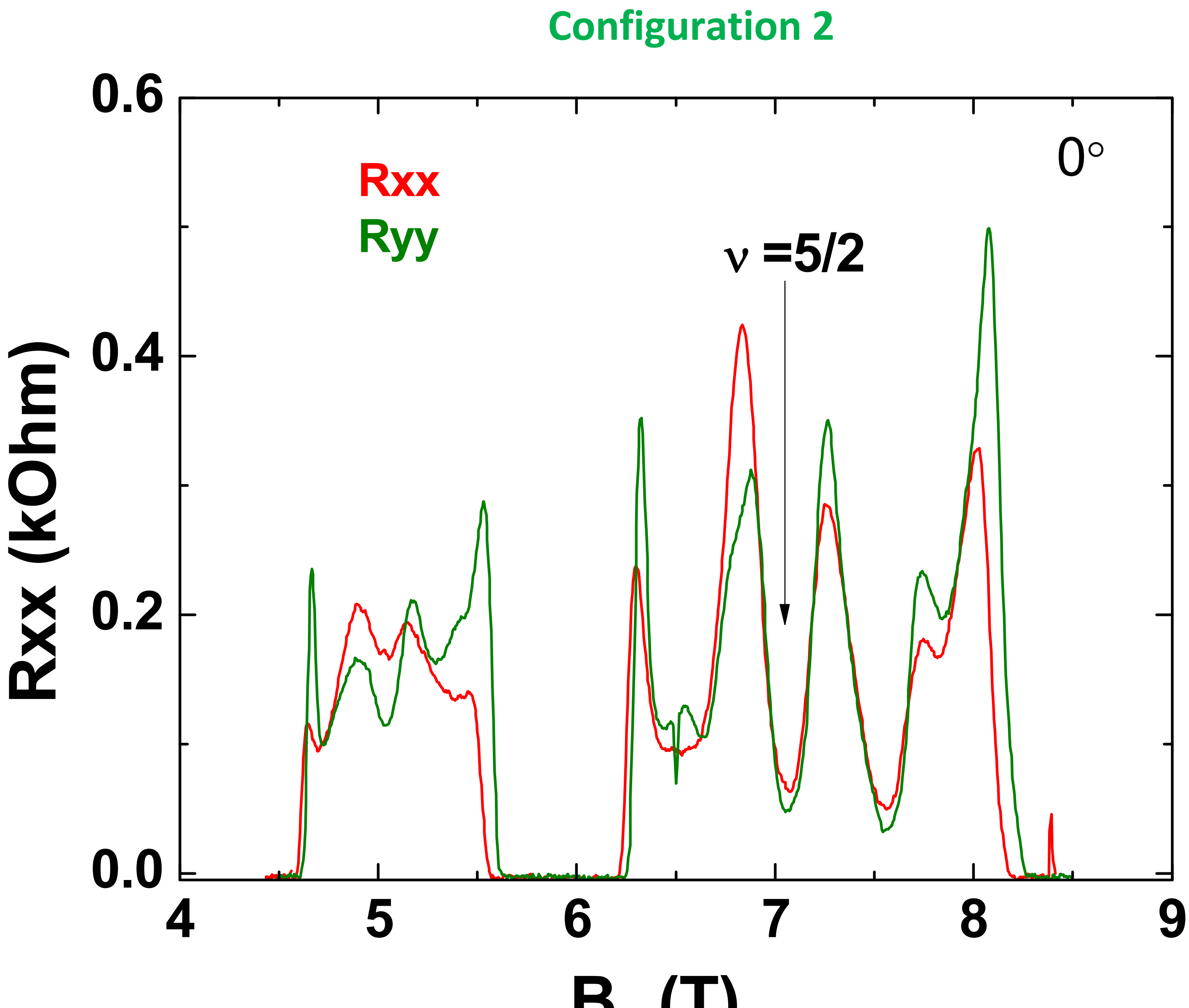


n=4.38×10^11 cm^-2
μ = 12.2×10^6 cm^2/Vs
Configuration 1
Sample: 11-2-12-1
0°
Rxx
Ryy
ν =5/2
Rxx (kOhm)
Rxy (h/e^2)
B⊥ (T)
1.0
0.5
0.0
0.5
0.4
0.3
0.2
3
4
5
6
7
8
9

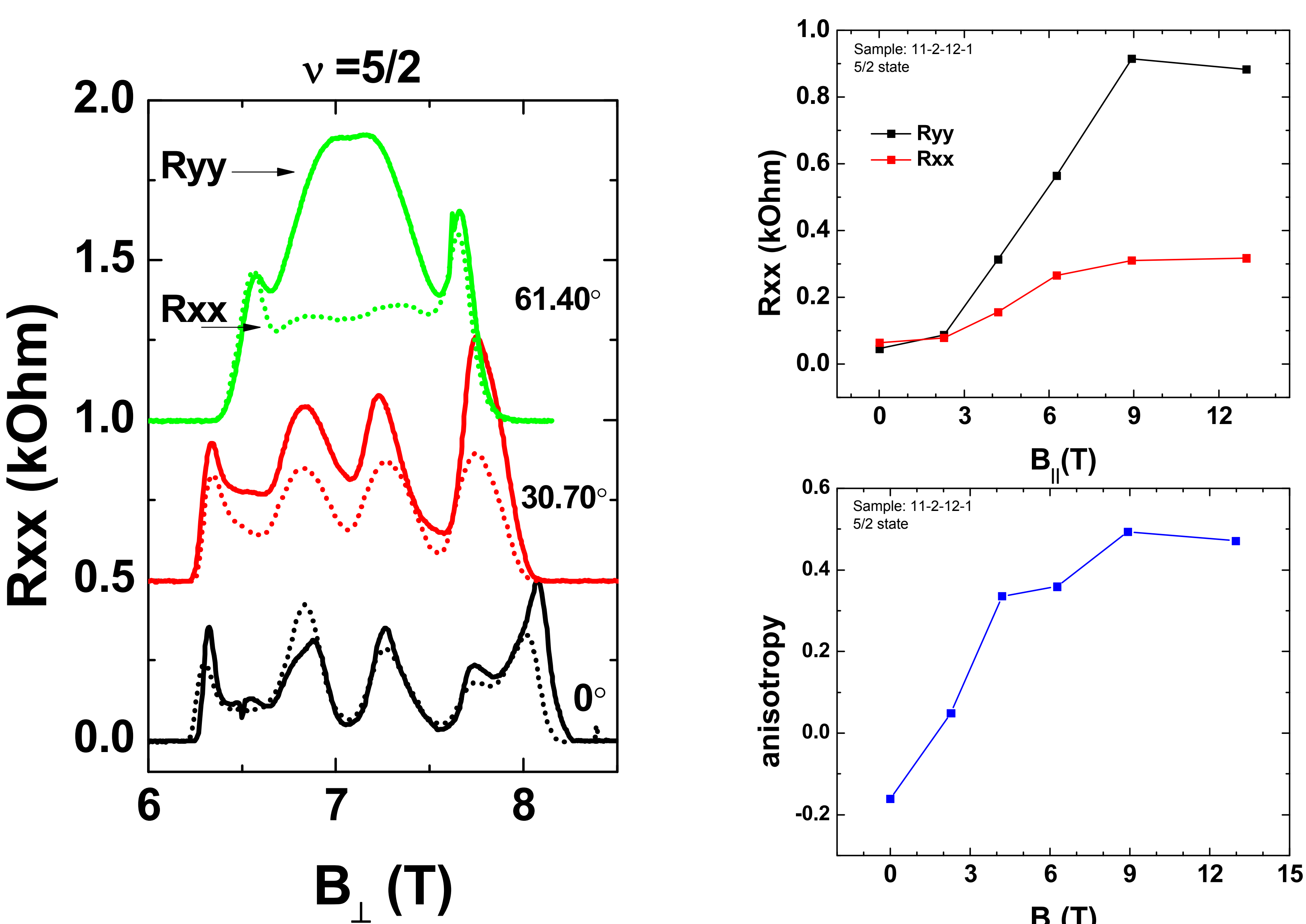
Results: tilt field




ν =5/2
Rxx (kOhm)
B⊥ (T)
Ryy
Rxx
60.7°
39.9°
19.6°
0°
Sample: 11-2-12-1
5/2
Ryy
Rxx
R (kOhm)
B||(T)
anisotropy
Sample: 11-2-12-1
5/2
B||(T)

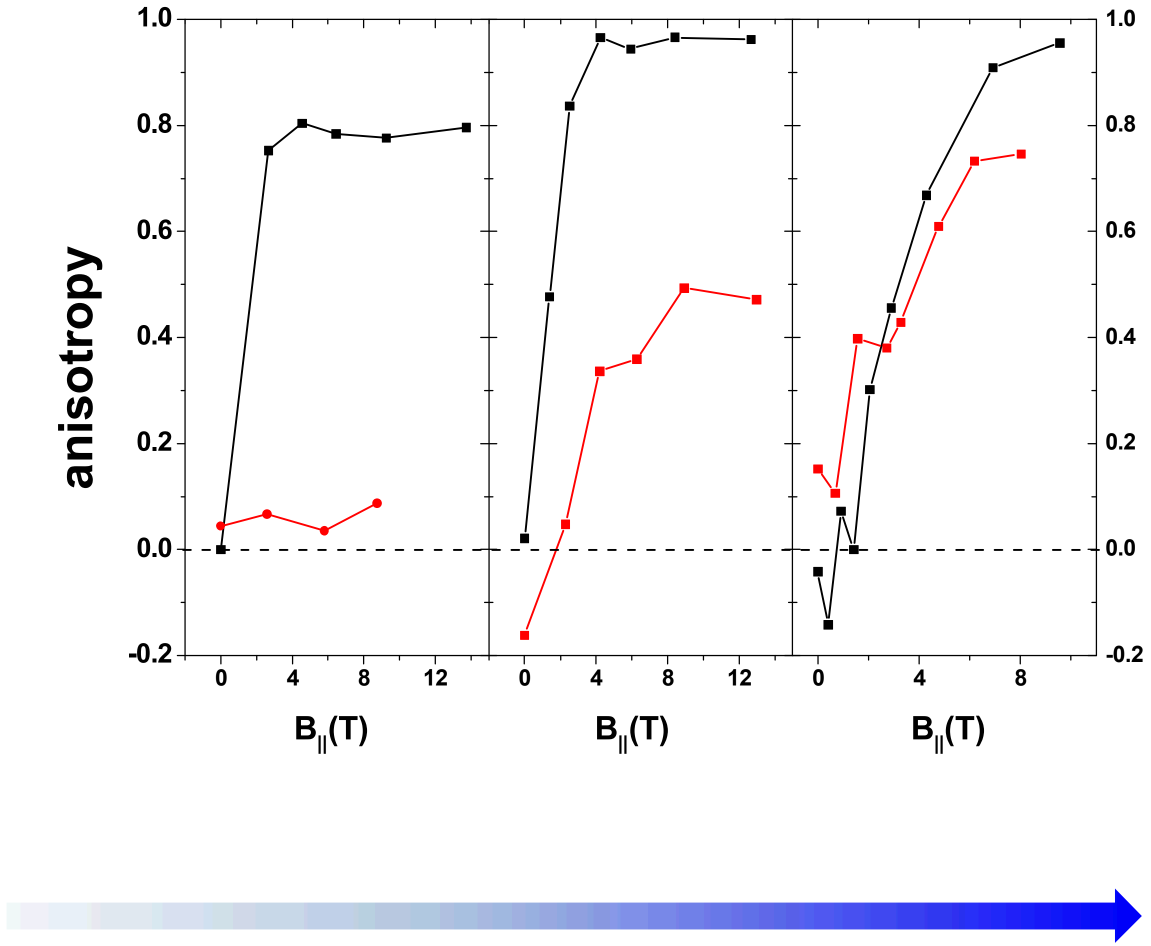


Configuration 2
0.6
0.4
0.2
0.0
Rxx (kOhm)
Rxx
Ryy
0°
ν =5/2
4
5
6
7
8
9
B⊥ (T)



ν =5/2
Ryy
Rxx
61.40°
30.70°
0°
Rxx (kOhm)
B⊥ (T)
Sample: 11-2-12-1
5/2 state
Ryy
Rxx
Rxx (kOhm)
B||(T)
Sample: 11-2-12-1
5/2 state
anisotropy
B||(T)

Results: *d* dependence



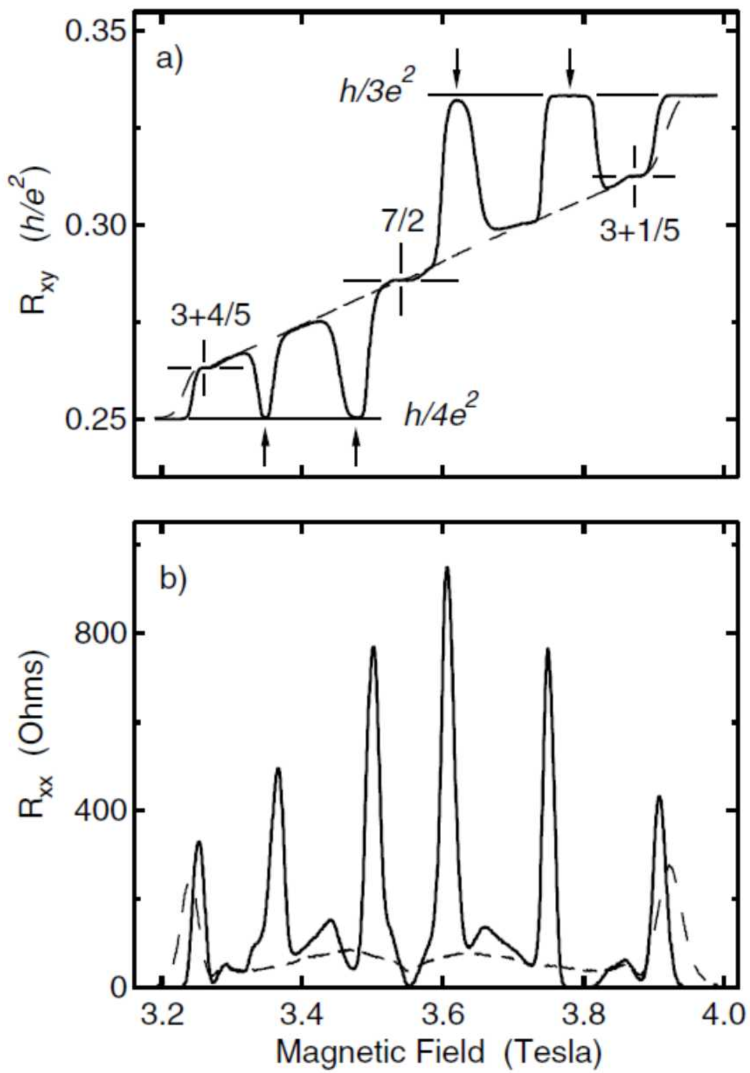
Increasing *d* (decreasing disorder)

- **highly disordered samples (small *d*): electronic transport is anisotropic in one crystallographic direction but remains more or less isotropic in the other direction**
- **less-disordered samples (large *d*): electronic transport is anisotropic in both crystallographic directions**

Anisotropic 7/2 state

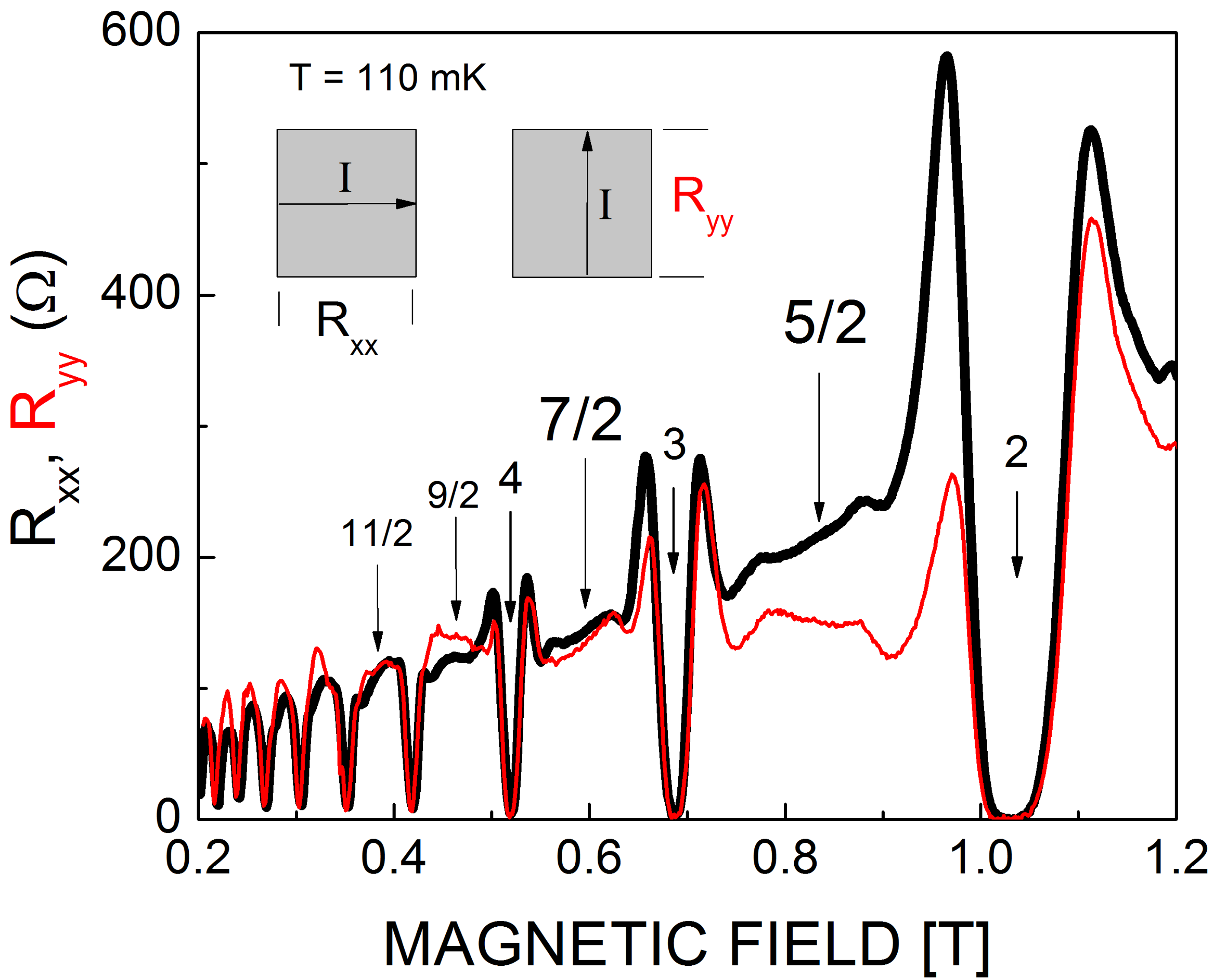
7/2 is a quantum Hall state at high densities

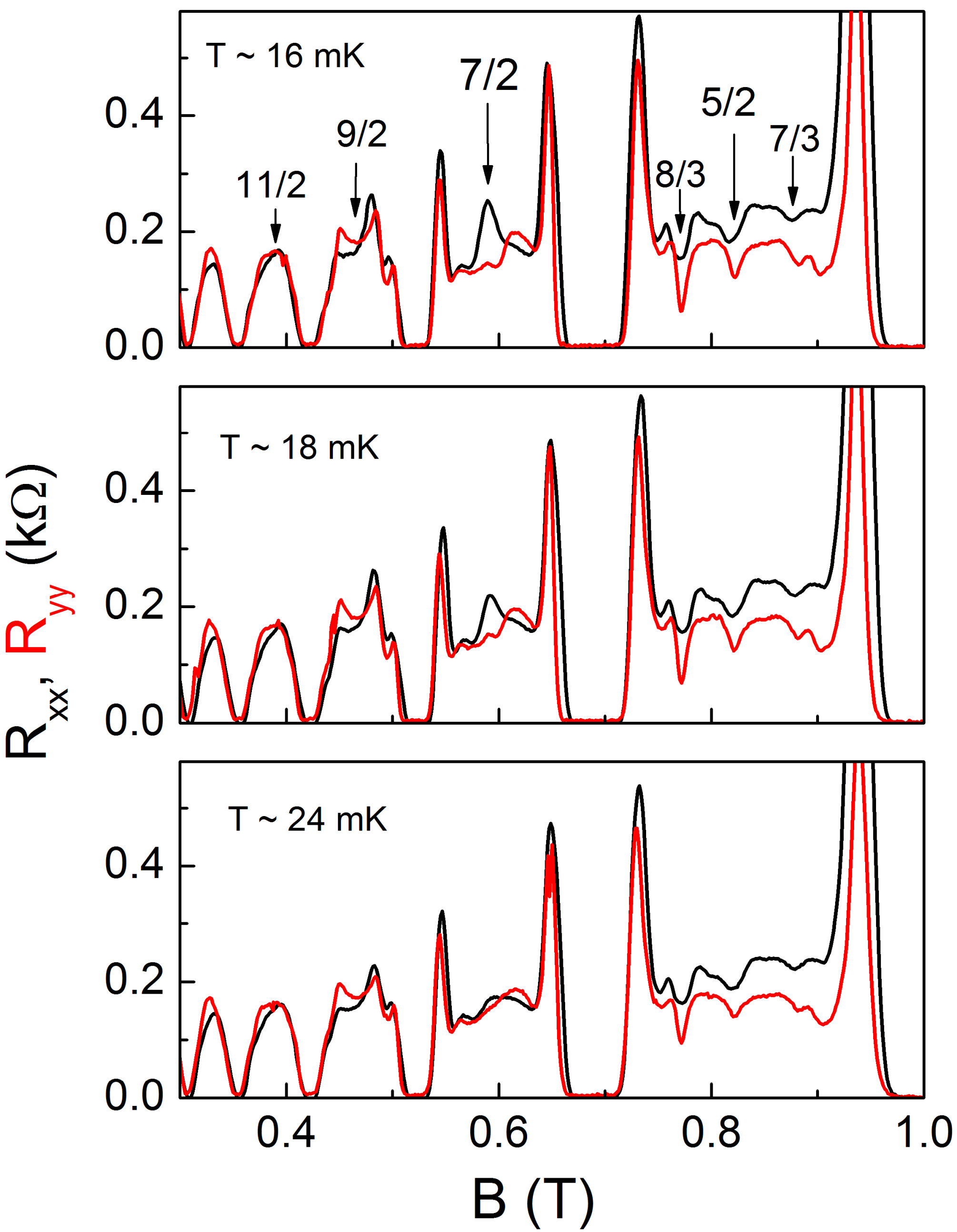
Particle hole conjugate state of the 5/2 state



Eisenstein et al, PRL 2002

In our low density sample, isotropic 7/2 state at high temperatures





7/2 is anisotropic at lower temperatures.

It becomes isotropic at 24mK!

More or less isotropic at 9/2, 11/2, 13/2, etc. in this sample

Landau level mixing effect?

Thank you for your attention!

- wide quantum well, thicker 2DES, Coulomb repulsion weakened – favor spin-singlet state, or formation of Skyrmions. [Wojs et al, PRL (2010)].

- a phase transition from a partially-polarized to a fully spin-polarized ground driven by Zeeman energy. [Liu et al, PRL (2012)]

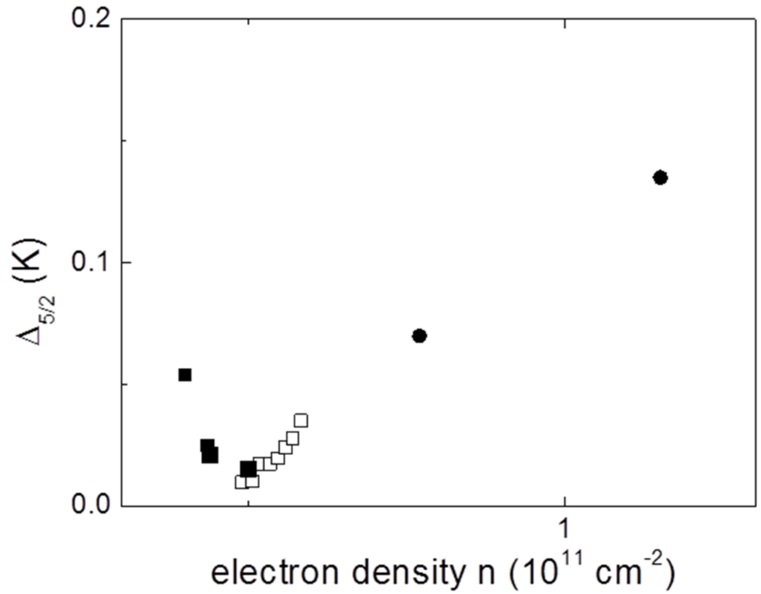
Or due to rotation of spin polarization?

Quantum Hall ferrom … in the fractional regime

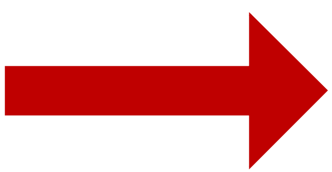
(PRL,2008)

Depar … itzerland

The competitio… …haus spin-orbit cou-
plings is studied f… …fects. A transition of
the direction of th… …ıan energy. We show
that these values … …d thus provide infor-
mation about the … …ıples of the Laughlin
wavefunctions and … …r bath.

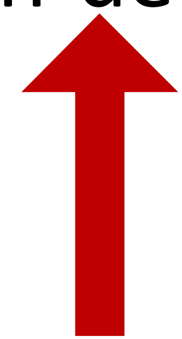


low-density



P=1

high-density



P=1