TheoryWinter School, NHMFL, Jan 2014

Transport Experiments on 3D Topological insulators

Part I

N. P. Ong, Princeton Univ.

1. **Transport in non-metallic Bi_2Se_3 and Bi_2Te_3**
2. **A TI with very large bulk ρ – Bi_2Te_2Se**
3. **SdH oscillations to 45 Tesla – Evidence for ½ shift from Dirac Spectrum**
4. **Tuning SdH oscillations by liquid gating**
5. **The Quantized Anomalous Hall Effect (Tsinghua, IOP)**

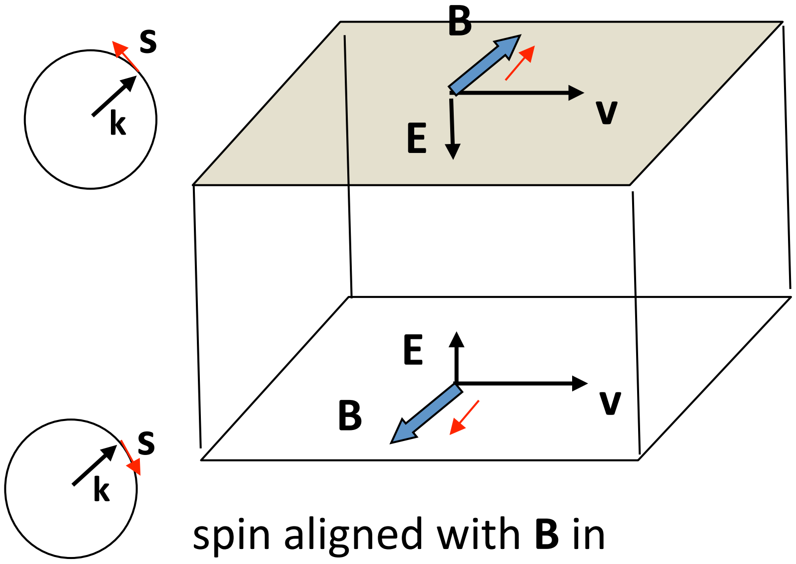
Support from
NSF DMR 0819860
DARPA
ARO, MURI

Helicity and large spin-orbit interaction

- **Surface electron feels surface E-field.**
  In its rest, sees field B = v × E
- **Large B (enhanced by SOI)**
  locks spin s ⊥ v
- **Rashba-like Hamiltonian**

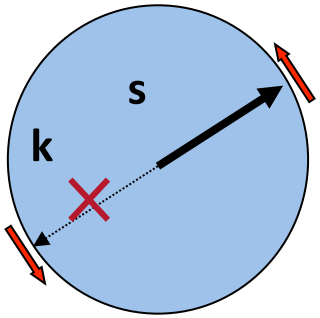
$$\boxed{H = v_F\, \hat{\mathbf{n}}\times\mathbf{k}\cdot\mathbf{s}}$$

Helical, massless Dirac states with opposite chirality on opp. surfaces of crystal



spin aligned with **B** in rest frame of moving electron

Suppression of $2k_F$ scattering



Surface conductance

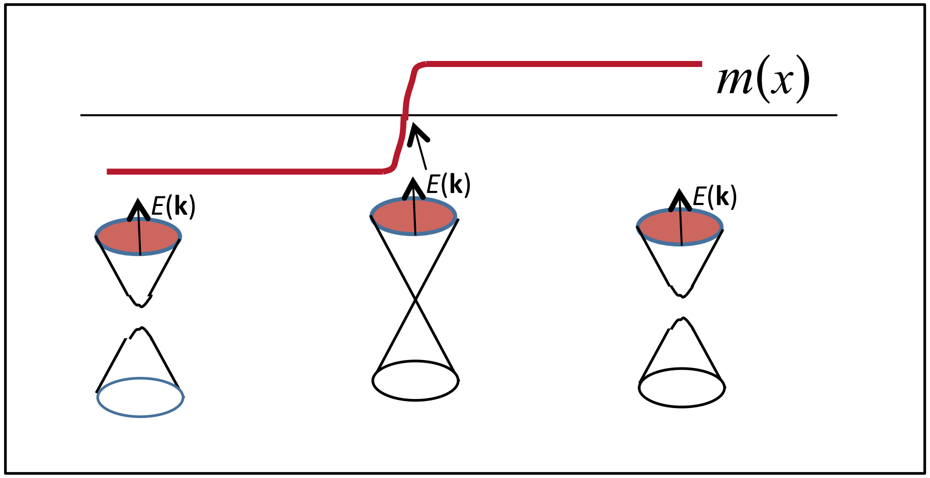
$G_s = (e^2/h)\, k_F l$

$R_s \sim 400$ Ohms if $k_F l = 100$

Topological Insulators: spin locking

1. Mass twist → helical state at zero mass

$$H = \begin{bmatrix} m(\mathbf{x}) & \mathrm{v}_F(k_x - ik_y) \\ \mathrm{v}_F(k_x + ik_y) & -m(\mathbf{x}) \end{bmatrix}$$

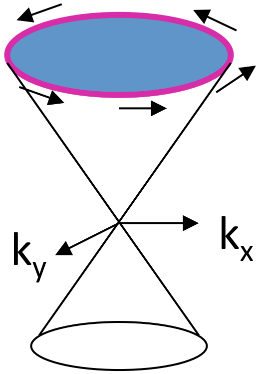


Twist is topologically stable

2. Strong spin-orbit int. → giant Rashba term
and spin-locking with opposite helicities

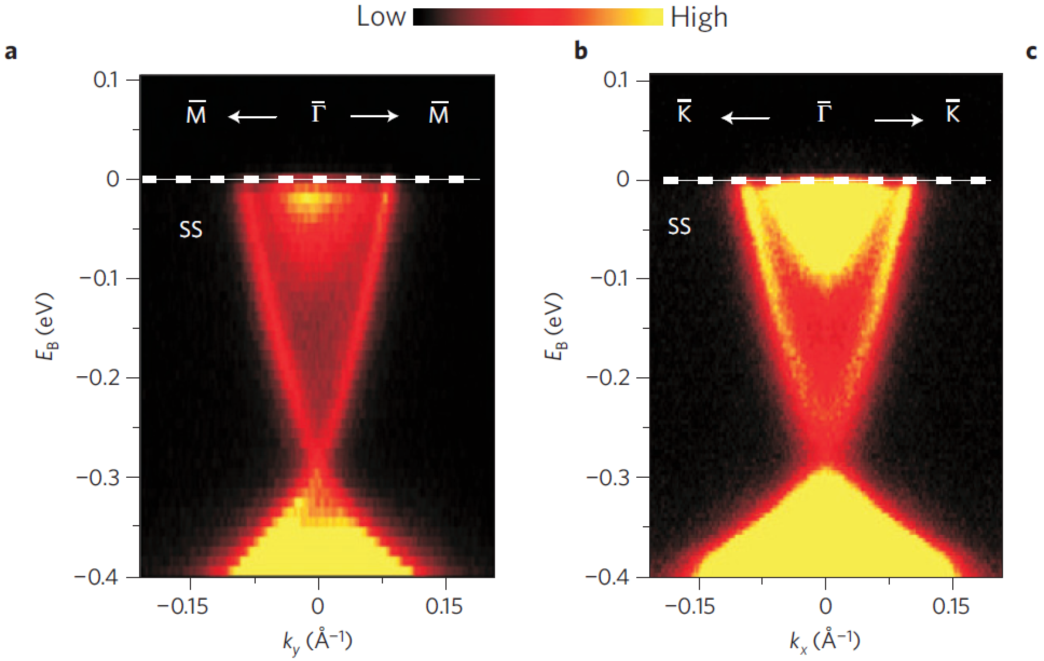
$$H_R = \mathrm{v}_F\, \hat{\mathbf{n}} . \vec{\sigma} \times \mathbf{k}$$

n = surface normal

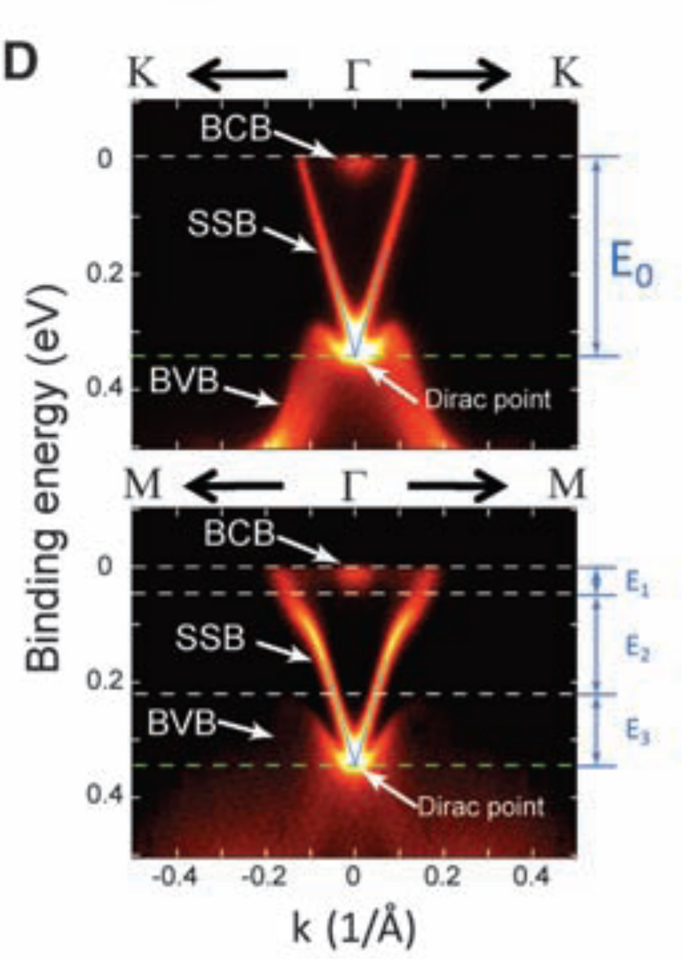


Surface Dirac states in Bi_2Se_3 and Bi_2Te_3 from ARPES

Xia, Hasan et al. *Nature Phys* ‘09



Chen, Shen et al. *Science* 2009



In Bi_2Se_3 and Bi_2Te_3

- **Only 1 surface state present**
- **Massless Dirac spectrum**
- **Large gaps -- 300 and 200 meV**

Detection of Dirac Surface States by transport

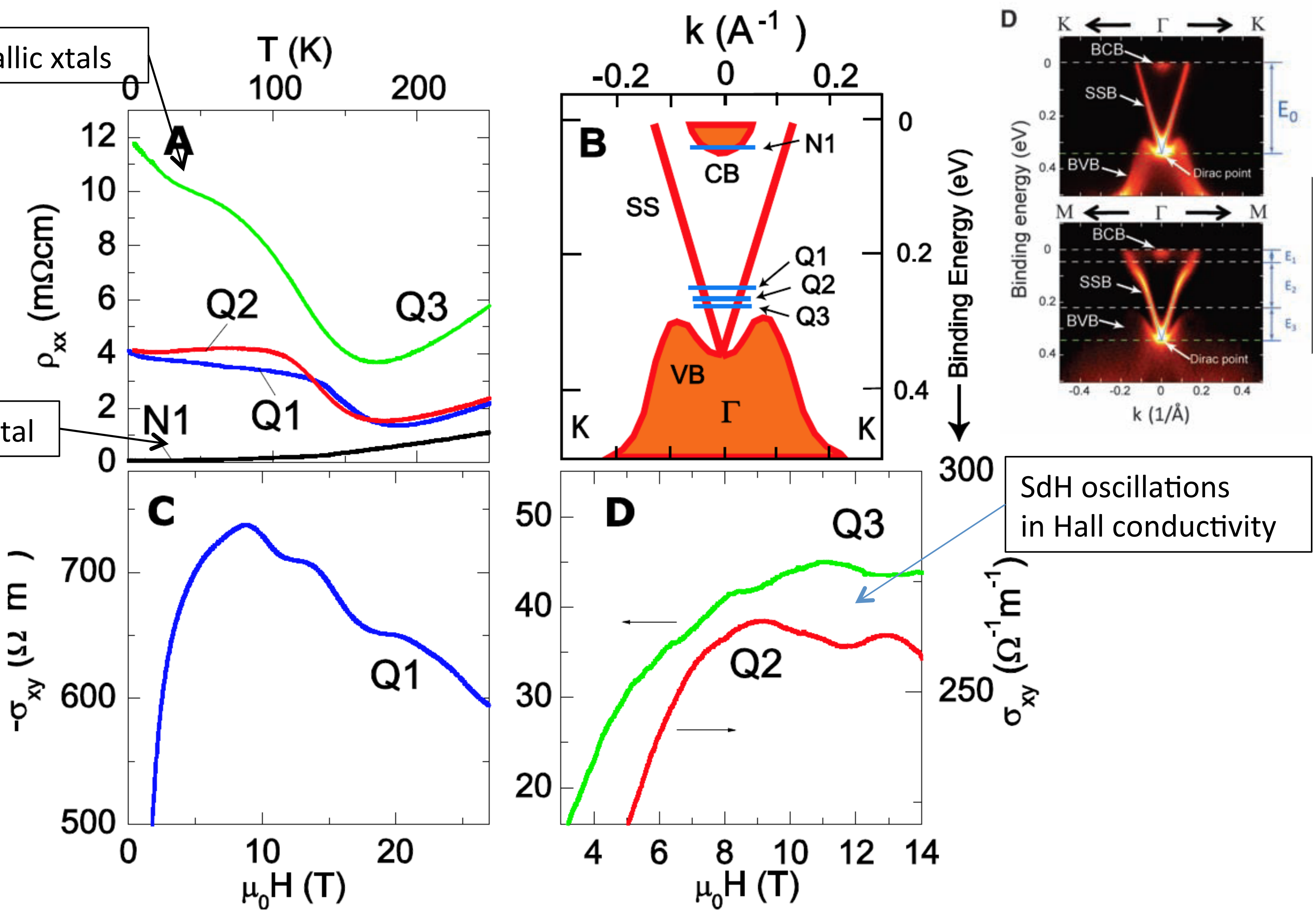
Shubnikov de Haas oscillations

Comparison of transport parameters

Material	R_{obs} (Ω)	ρ_b (mΩcm)	μ_s (cm^2/Vs)	$k_F l$	G_s/G_{bulk}	μ_s/μ_b
Bi_2Se_3 (Ca)	0.01 30-80	< 200 ?	?	?		
Bi_2Te_3	0.005	4-12	10,000 100	0.03	12	
Bi_2Te_2Se	300-400	6,000	2,800 40	~1	60	

Shubnikov de Haas Oscill. in non-metallic Bi_2Te_3

Qu, NPO et al. *Science*, 2010



Non-metallic xtals

Metallic xtal

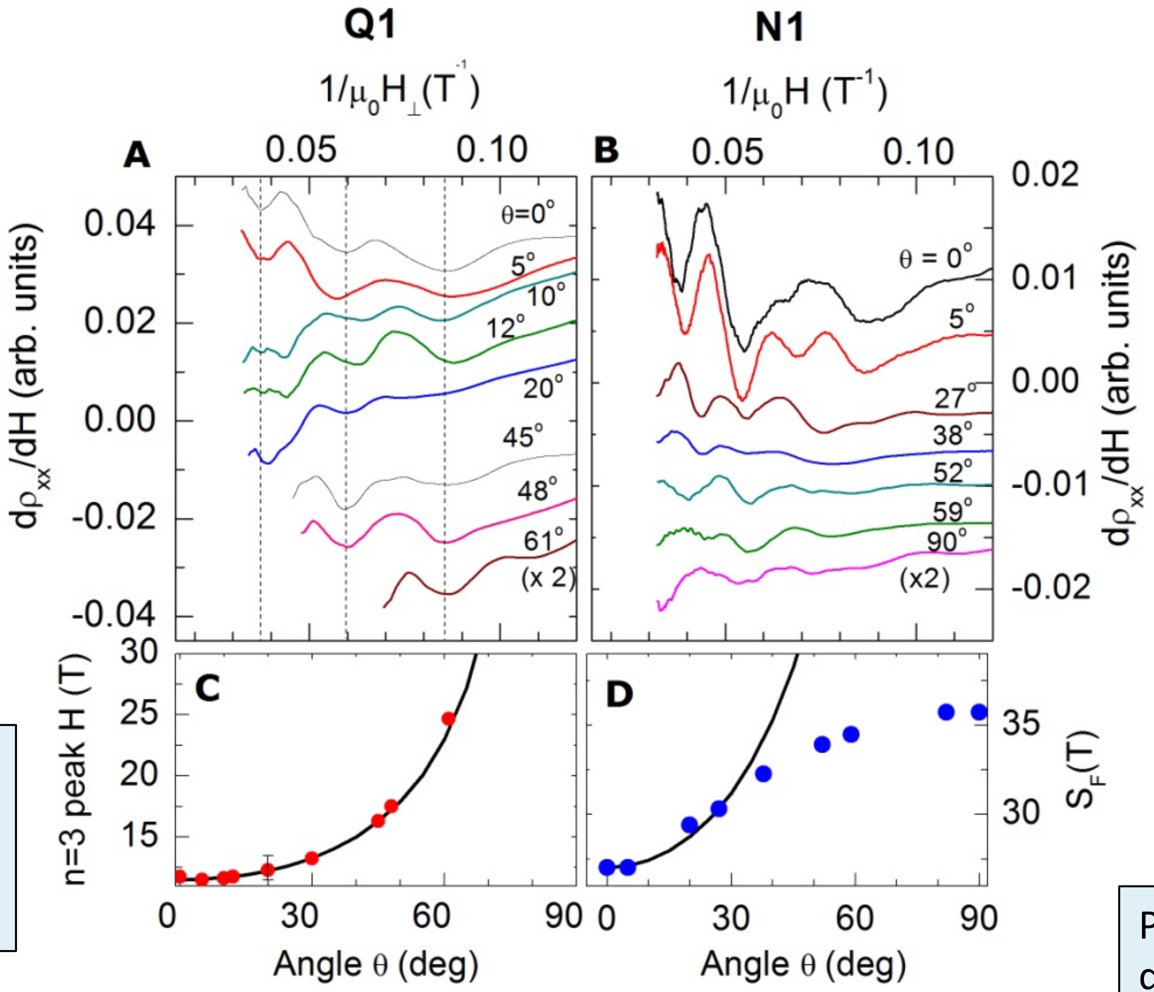
SdH oscillations in Hall conductivity

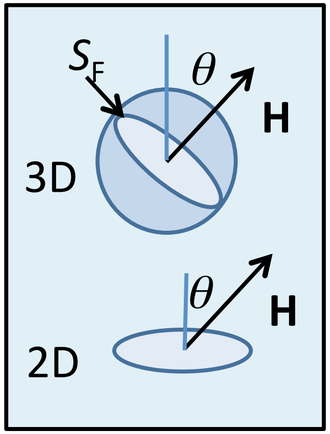
2D vs 3D Shubnikov de Haas period in bulk Bi_2Te_3

Qu, NPO et al. *Science* 2010

Non-metallic sample

Metallic sample



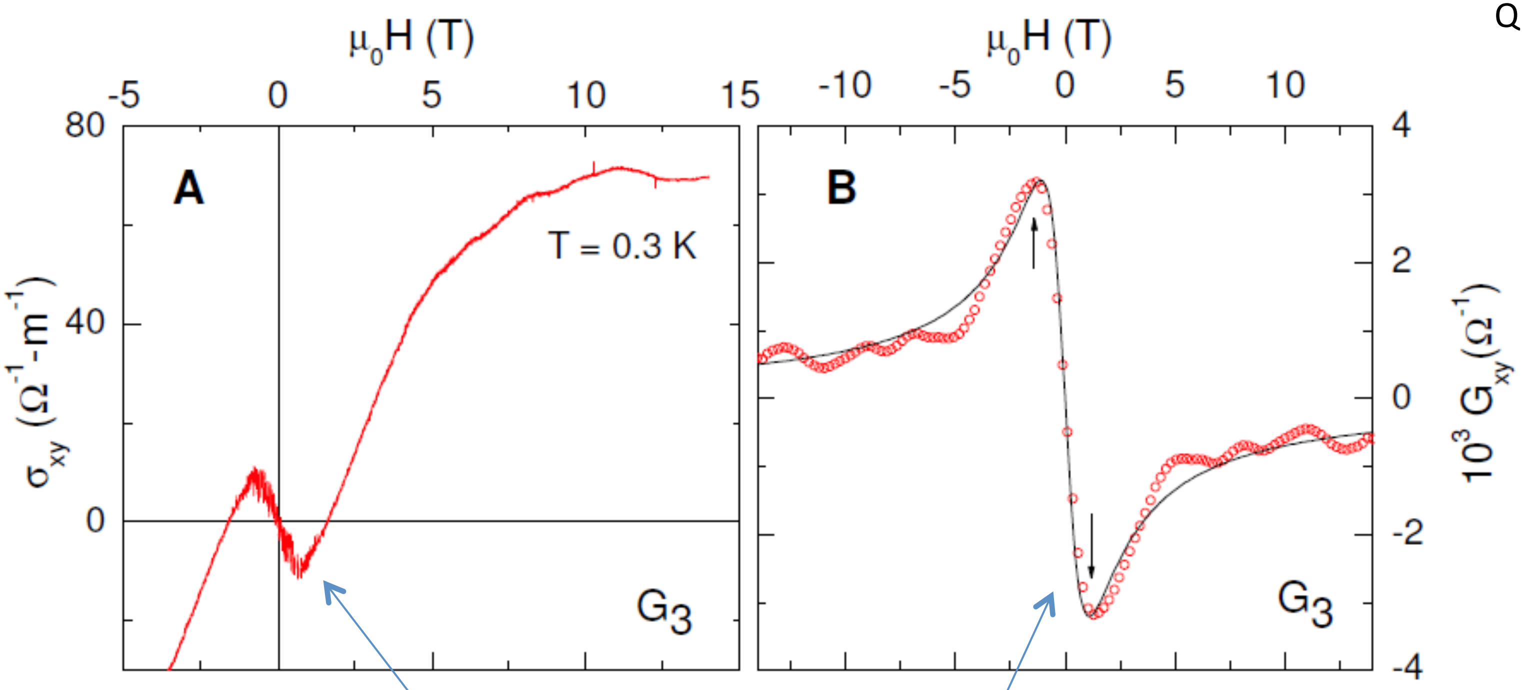


SdH period
S_F scales
as $\cos\theta$
Hence, 2D

Period S_F
deviates from 2D
Hence, 3D
ellipsoidal

Seeing surface conduction directly in Hall channel

Qu, NPO et al. 2010



1. (Panel A) Hall conductivity σ_{xy} shows a "resonance" anomaly in weak *H*

2. (Panel B) After subtracting bulk contribution, the resonance is the isolated surface Hall conductivity G_{xy}. Peak position yield mobility μ (~9,000 cm^2/Vs) and peak height yields metallicity $k_F\ell = 80$.

Panel B is a "snap shot" that gives mobility and $k_F\ell$ by inspection.

Fit (semiclassical)

$$\sigma_{xy} = \sigma^{b}{}_{xy} + G_{xy}/t$$

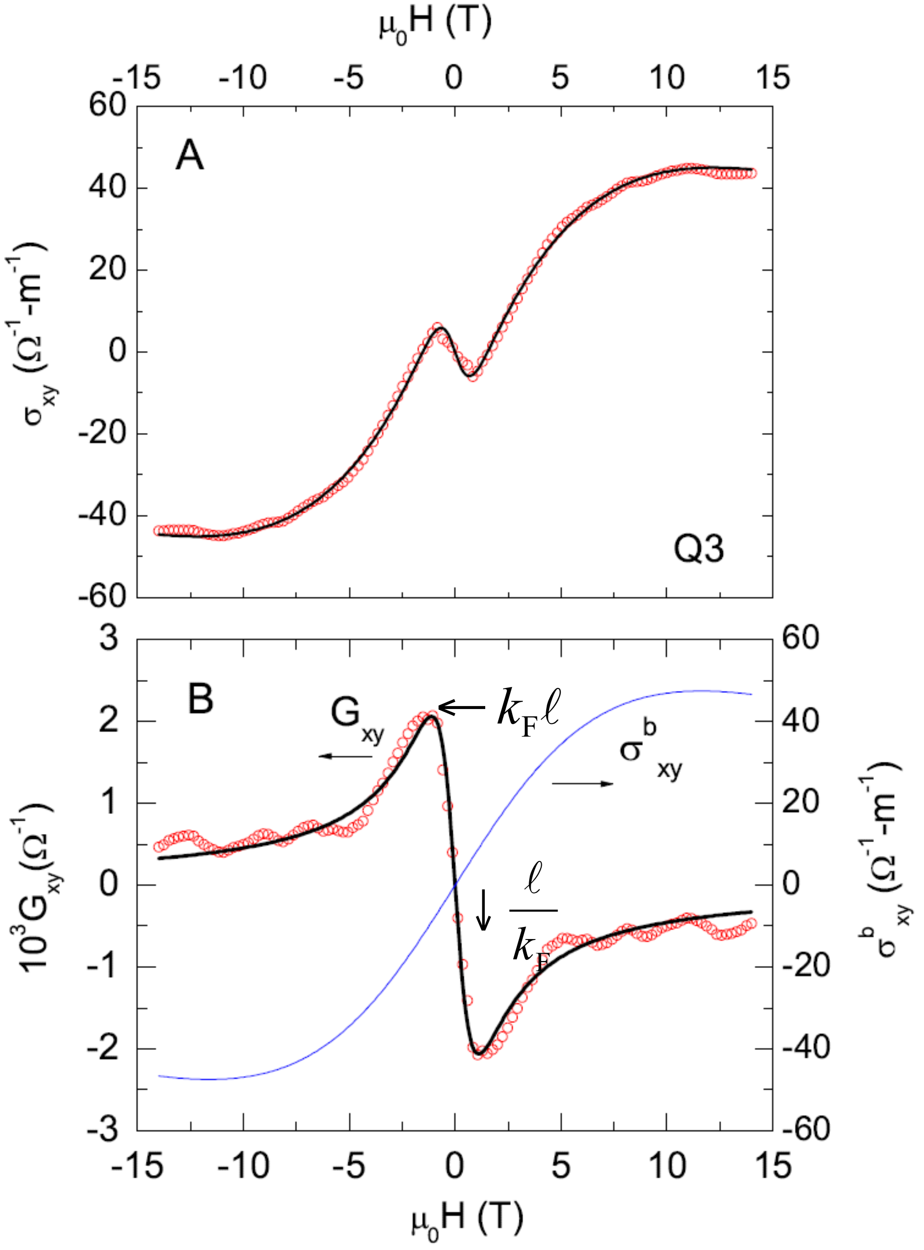
$$\sigma^{b}{}_{xy} = n_b e \mu_b \frac{\mu_b H}{[1+(\mu_b H)^2]}$$

$$G_{xy} = \frac{e^2}{h} k_F \ell \frac{\mu_s H}{[1+(\mu_s H)^2]}$$

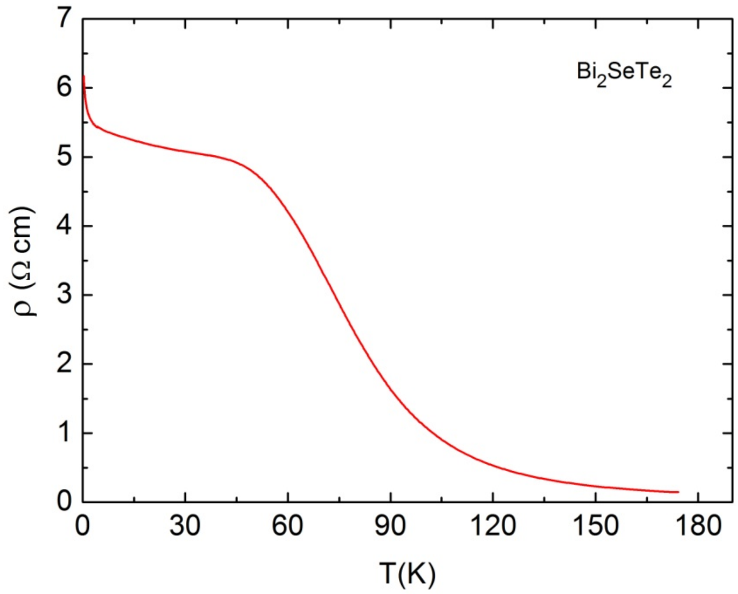
$$\mu_s = \frac{e}{\hbar}\frac{\ell}{k_{\mathrm{F}}}$$

$\ell = 240\ \mathrm{nm}$ $\mu_s = 8{,}000\ \mathrm{cm}^2/\mathrm{Vs}$

- Good agreemt w Dingle analysis & 2D massless Dirac state.
- Numbers rule out G_{xy} as 3D bulk term.

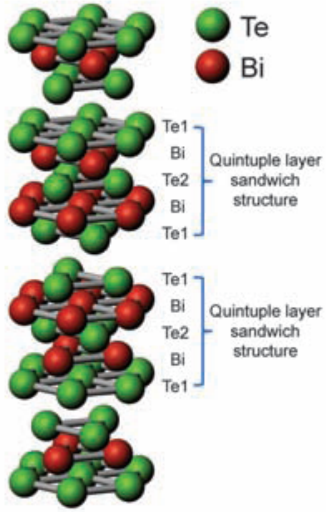


Topological Insulator with sharply reduced bulk cond. --- Bi_2Te_2Se



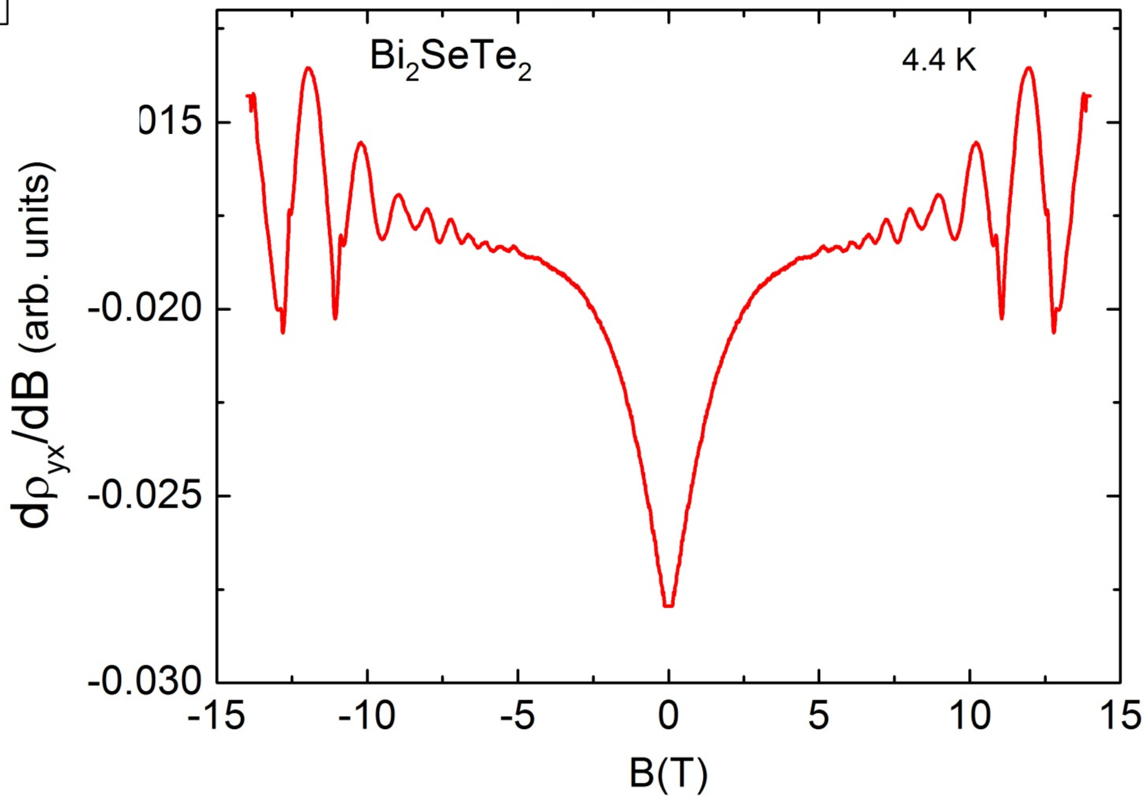
Xiong, Cava, NPO
cond-mat/1011.1315

Also,
Y. Ando et al., PRB ‘11

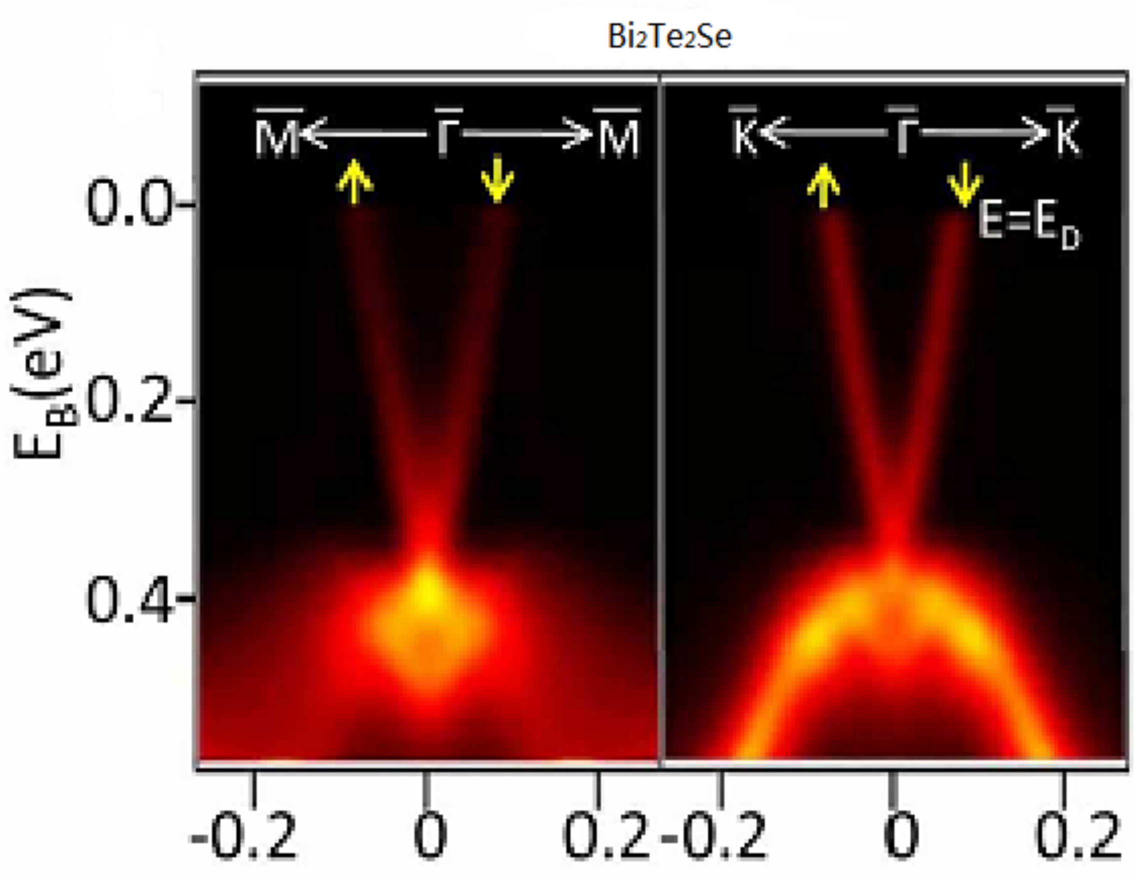


Bulk mobility $\mu_b \sim 50\ cm^2/Vs$

Bulk carrier density
$n_b \sim 2.6 \times 10^{16}\ cm^{-3}$



Band Structure of Bi_2Te_2Se



S.-Y. Xu, M.Z. Hasan *et al.*, arXiv:1007.5111

Approaching the N = 0 Landau Level

Shubnikov de Haas oscillations in 45 T field

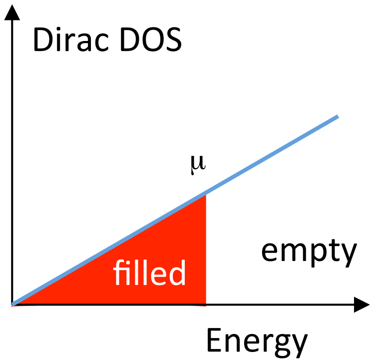
π phase shift from Berry term

Resistivity max or min?

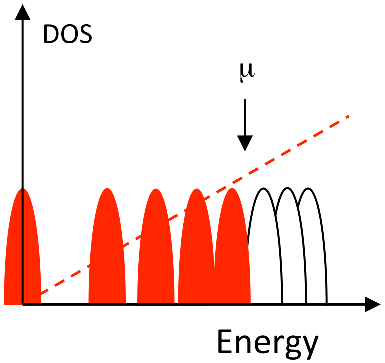
Is there a g-factor shift?

Indexing the Landau Levels (LLs)

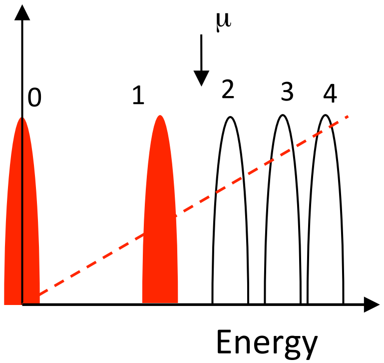
Applied magnetic field *B* quantizes density of states (DOS) into Landau Levels



B = 0



B = 10 Tesla



B = 45 Tesla

Dirac Landau Levels (LLs) spread out as *B* increases

Chemical potential μ approaches *n* = 0 level (Dirac Point)

μ falls between LLs when ρ_{xx} is a local maximum (at B_n)

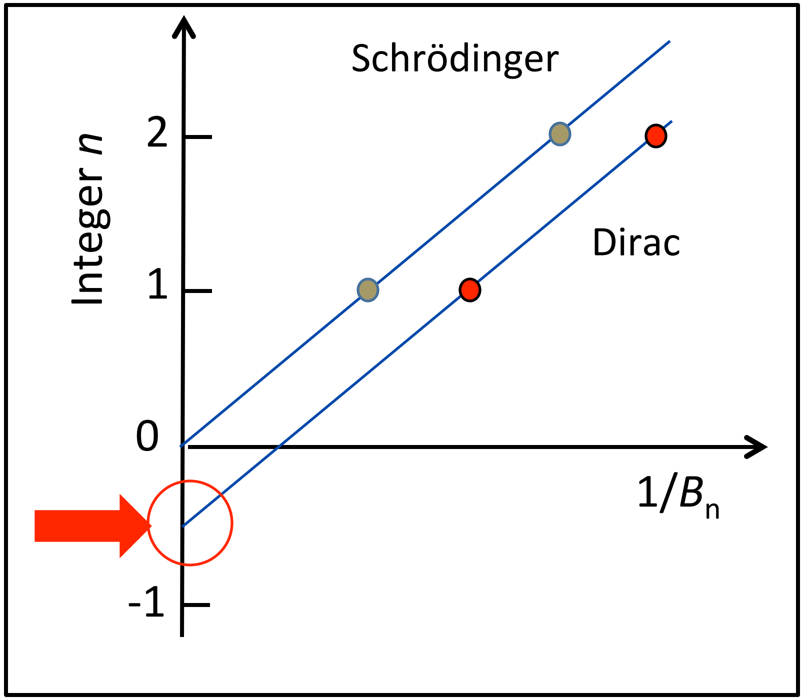
Landau Level Index *n* determined by plotting *n* vs. $1/B_n$

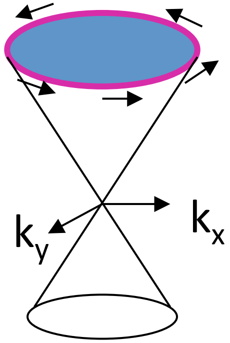
In index plot, must align n with maxima in Rxx
(n counts number of filled LLs)

Schrödinger *vs* Dirac spectrum

Check intercept of index plot in quantum limit 1/*B* → 0

$$\frac{1}{B_n} = (n+1/2)\frac{e}{hn_s} \quad \text{or} \quad \frac{1}{B_n} = \frac{e}{hn_s}n \quad ?$$





Dirac states have intercept at n = -1/2 because states at n = 0 LL come from both conduction and valence bands.

Equivalently, effect of Berry phase π-shift

Quantum Oscillations in Bi_2Te_2Se in high B

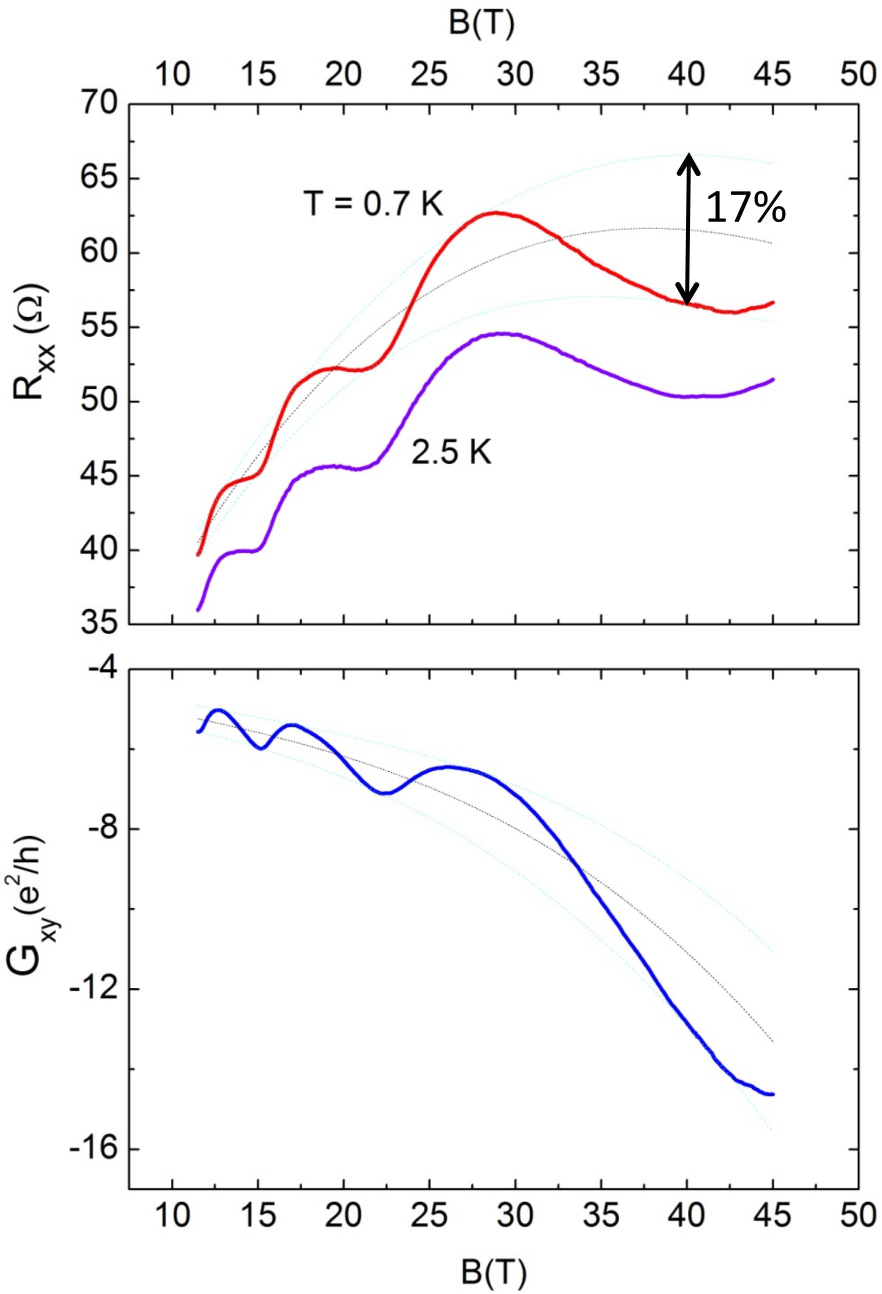
Xiong et al. PRB 2012

Amplitude of SdH oscillations is 17% of total conductance

Derivatives not needed to resolve SdH oscillations

Bulk resistivity ρ_b = 4 - 8 Ωcm (~4 K)

Oscillations seen in both G_{xx} and G_{xy}



High-field Quantum Oscillations in Bi_2Te_2Se

Xiong et al. PRB 2012

Isolate SdH oscill terms ΔG, ΔG_{xy}

Largest oscillations seen to date in Bi based TI's

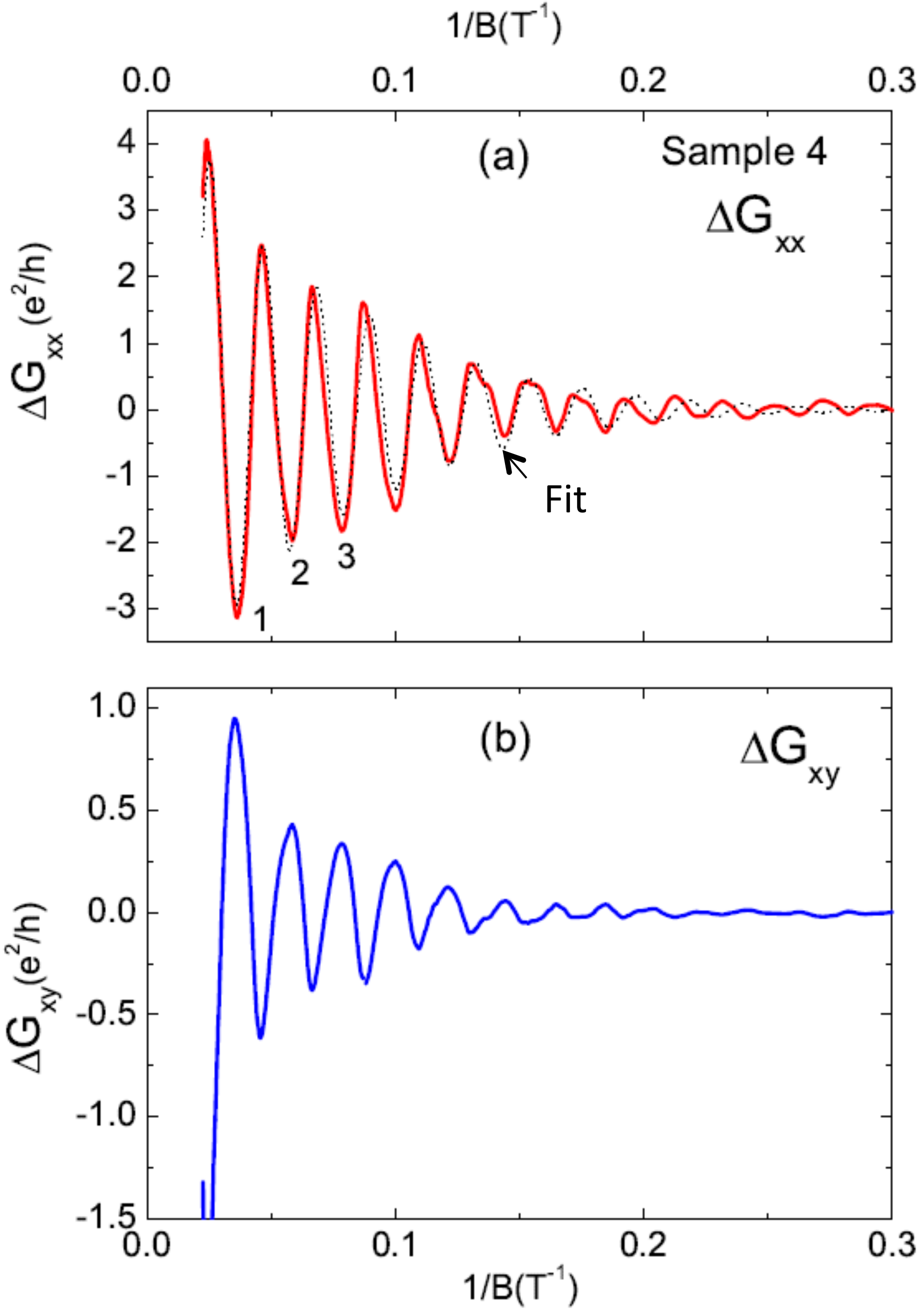
Peak-to-peak amplitudes

~ e^2/h in ΔG_{xy}

~ $4e^2/h$ in ΔG

Fit to Lifshitz expression yields

μ= 3,200 cm^2/Vs



Index Plot in Bi_2Te_2Se → The Quantum Limit

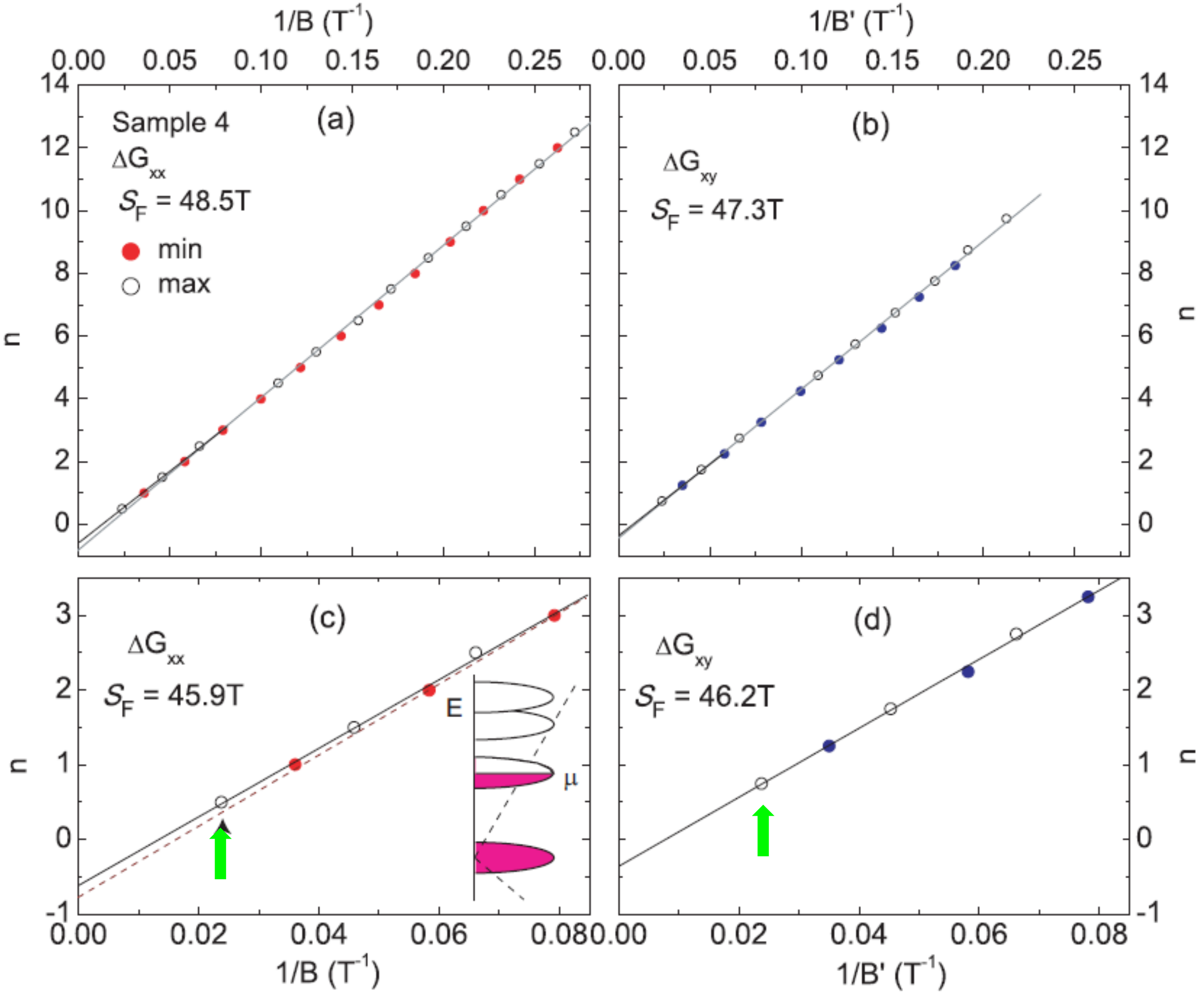
Xiong et al. PRB 2012

Limiting behavior
as $1/B_n \rightarrow 0$

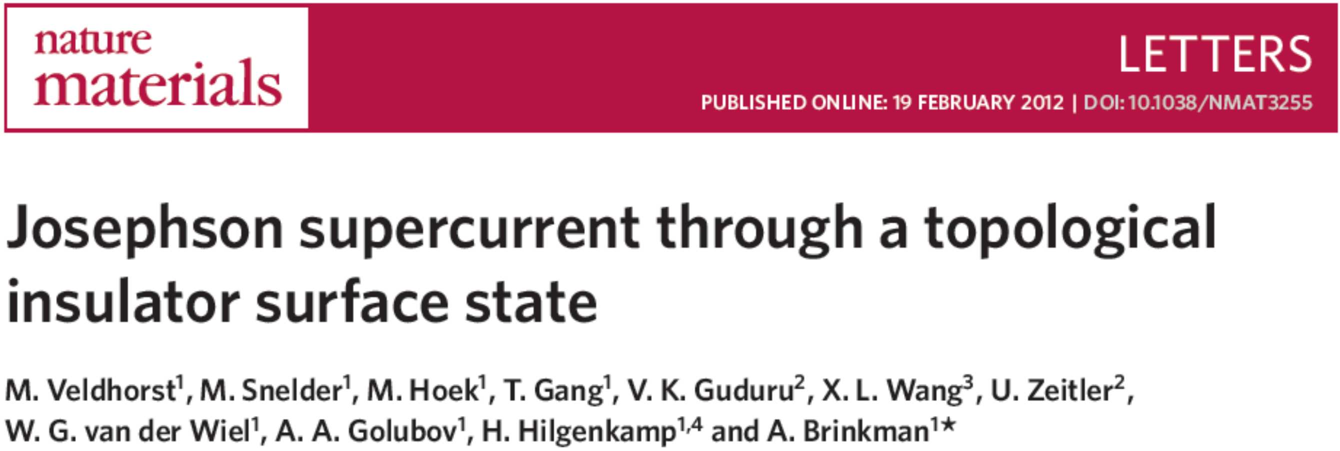
Intercept ($1/B \rightarrow 0$) at
$n = -0.40 \rightarrow -0.55$

High-field SdH
results support
Dirac dispersion

Crucial to plot *n* versus
maxima in Rxx,
Not minima



Oops

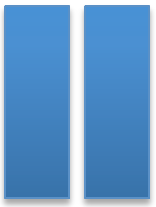


nature materials

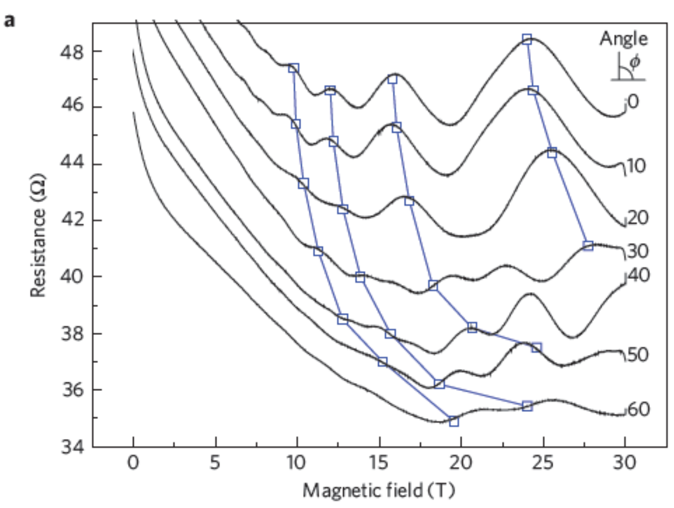
LETTERS

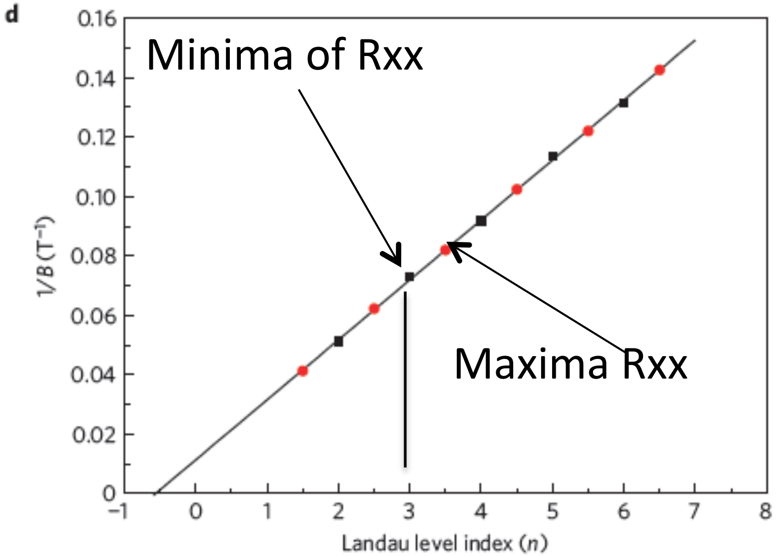
Josephson supercurrent through a topological insulator surface state

M. Veldhorst[1], M. Snelder[1], M. Hoek[1], T. Gang[1], V. K. Guduru[2], X. L. Wang[3], U. Zeitler[2], W. G. van der Wiel[1], A. A. Golubov[1], H. Hilgenkamp[1,4] and A. Brinkman[1]*



2-probe resistance of exfoliated Bi_2Te_3





Minima of Rxx

Maxima Rxx

Incorrect identification of index field B_n

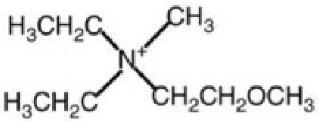
Oscillations are actually from bulk carriers

Tuning Shubnikov de Haas oscillations by

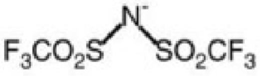
Ionic Liquid Gating

Ionic Liquid Gating

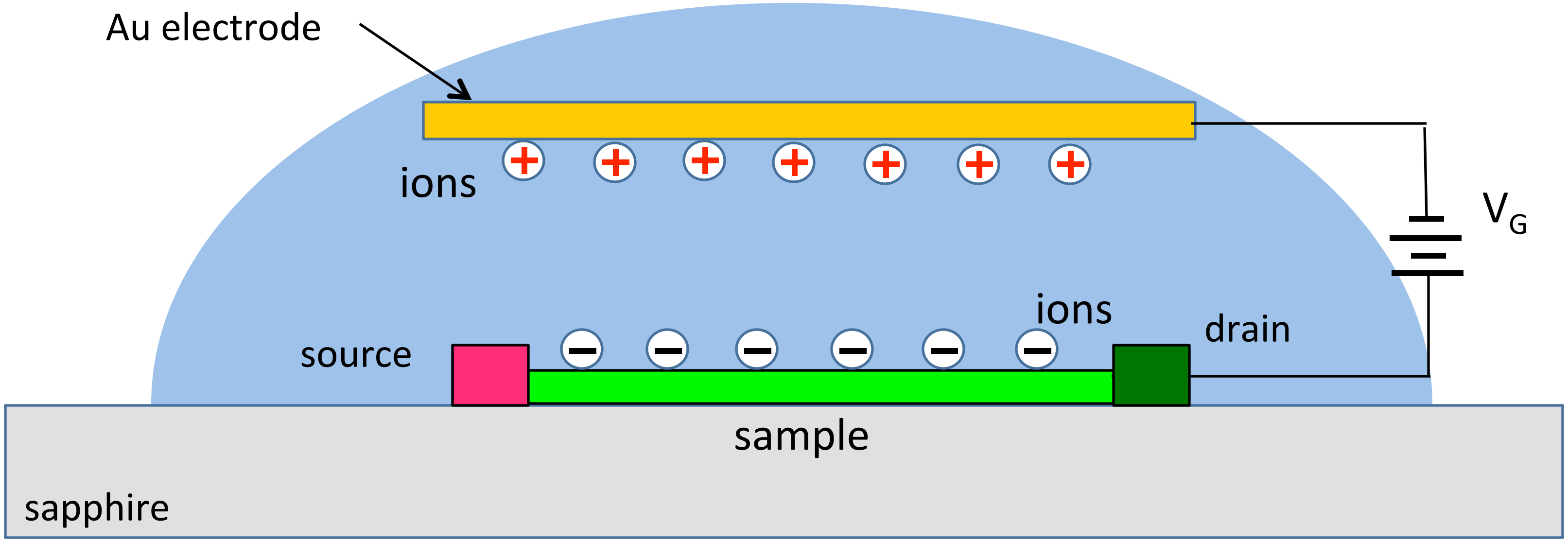
Cation



Anion



Ionic liquid DEME - TFSI



Au electrode

ions

V_G

ions

source

drain

sample

sapphire

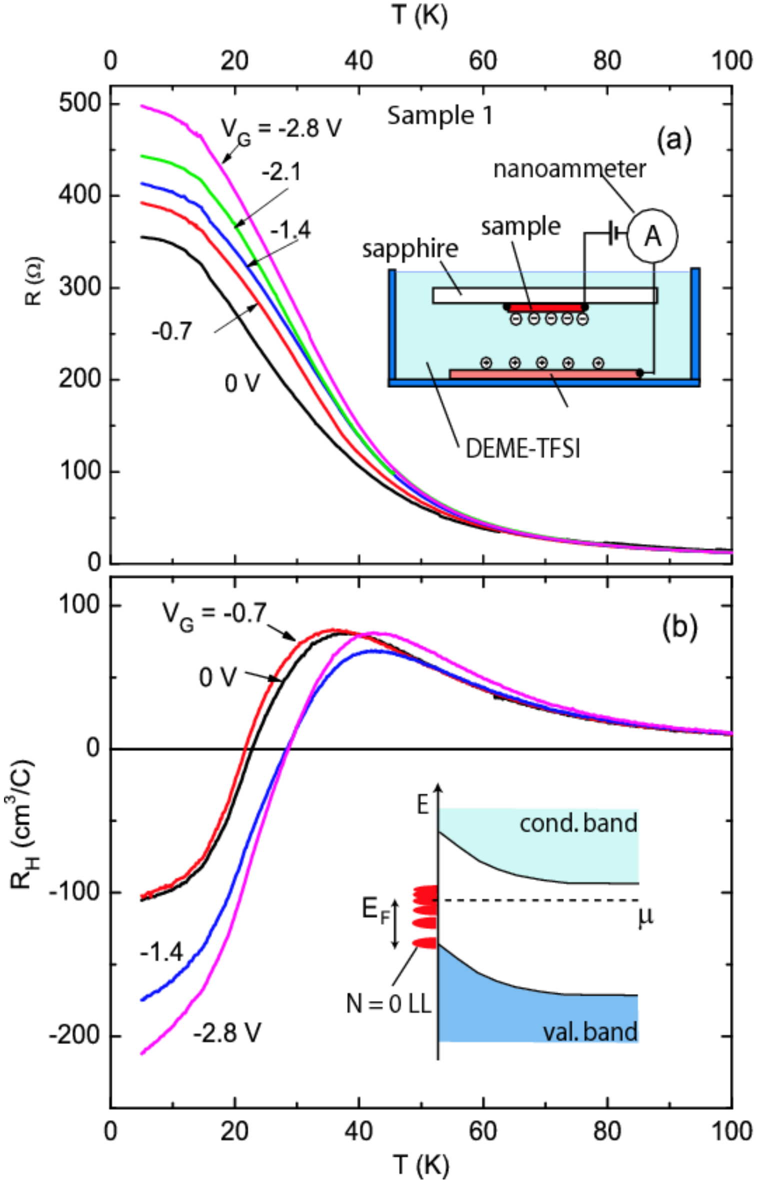
Intense *E* field applied to sample by ions

Liquid Gating Effect on Resistivity and Hall Coefficient

Xiong et al. PRB 2013

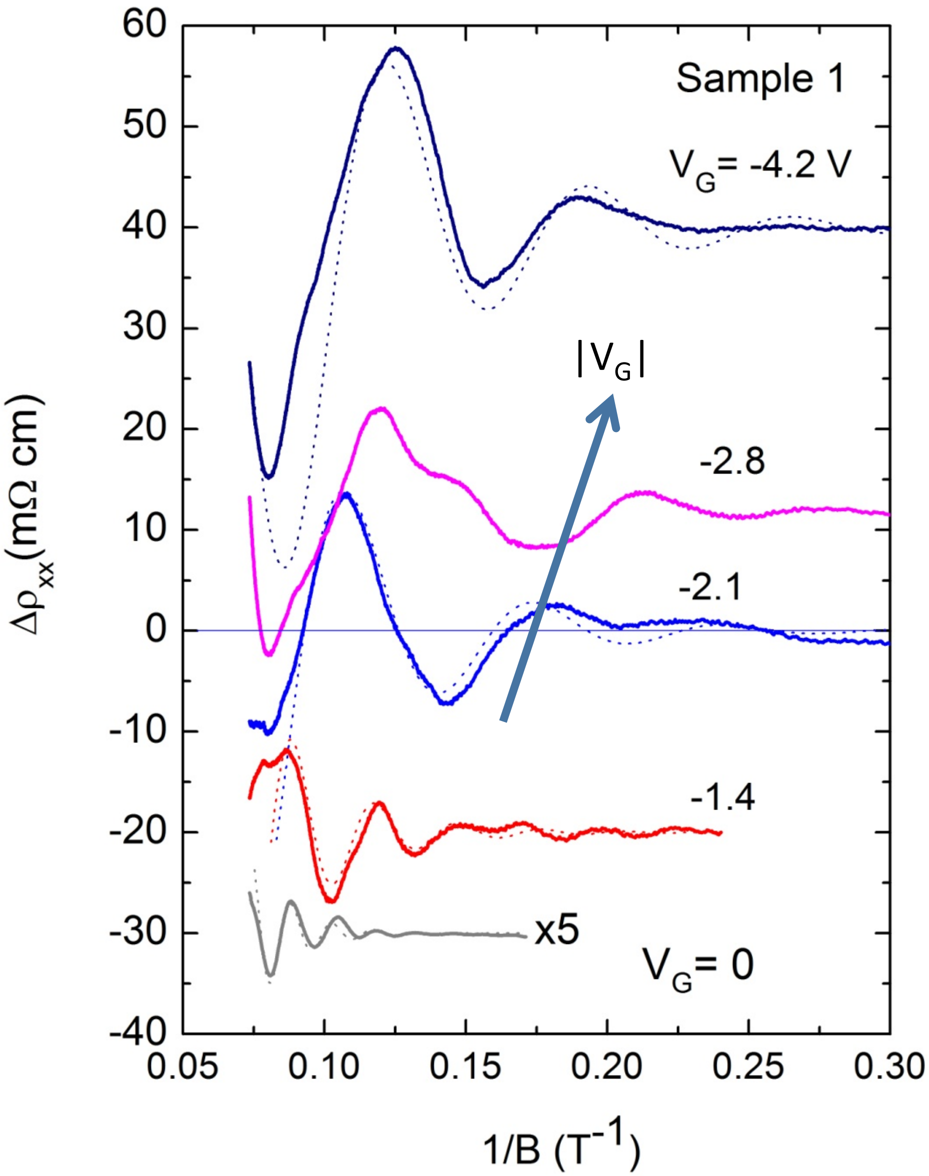
As V_G increases to more negative values, resistivity increases.

Hall density decreases. Implies surface density decreases



Liquid Gating Effect on Surface Quantum Oscillations

Xiong et al. PRB 2013



As $|V_G|$ increases,
period of oscillations increases
(Fermi Surface cross section decreases).

Also, amplitude of oscillations *increases* (more uniform density?)

Period increases 7-fold

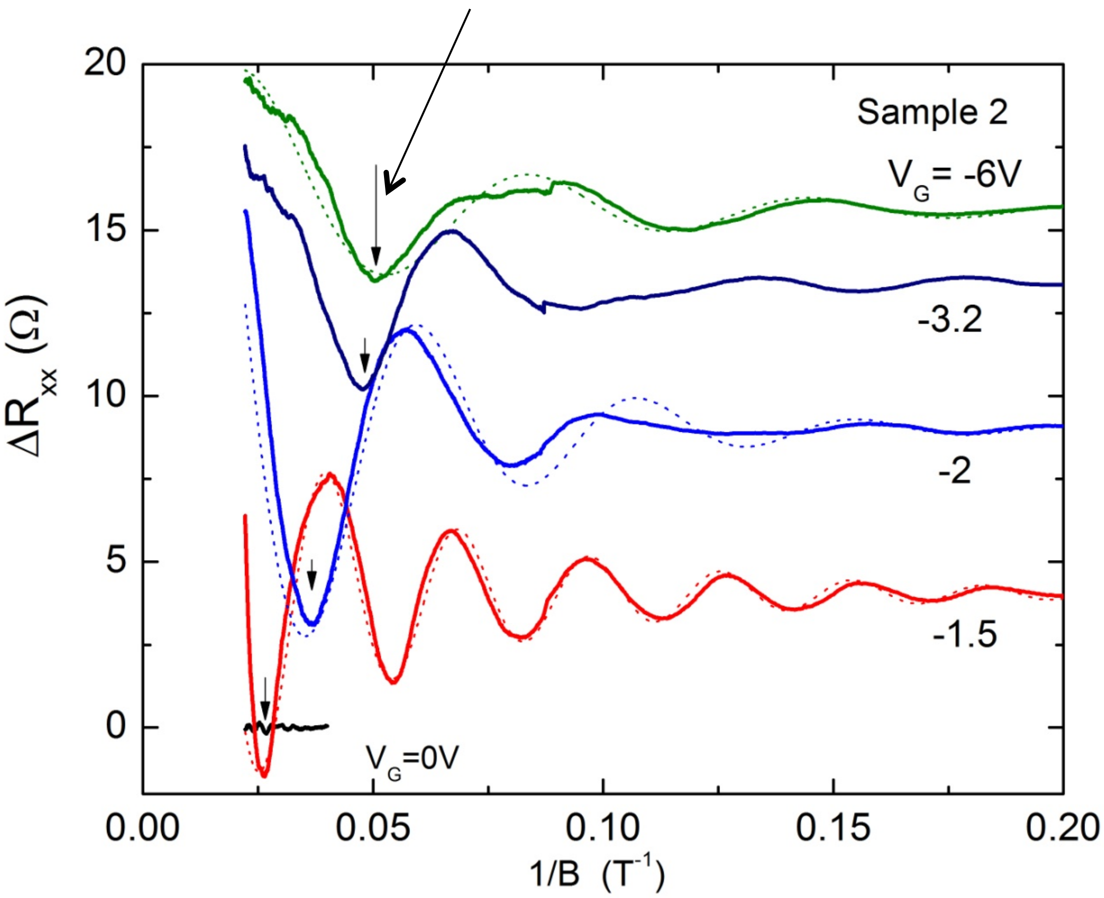
Energy decreases by 2.6

Tuning SdH oscillations by liquid gating in fields up to 45 Teslas

Sample 2

Xiong et al. PRB 2013

n = 1/2



Approaching the Dirac Point by Ionic Liquid Gating on Bi_2Te_2Se

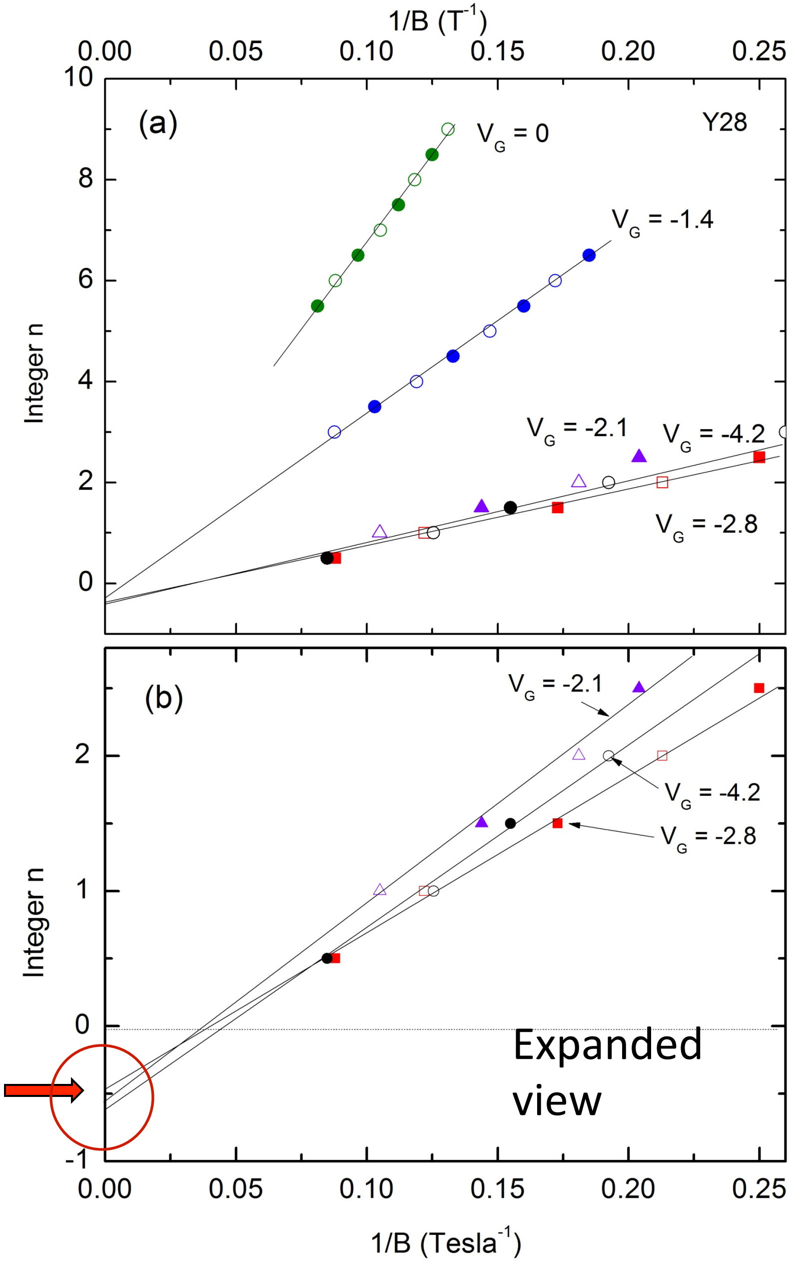
Sample 2
Tuning V_G from 0 → -3 V decreases FS area and n_s by ~7

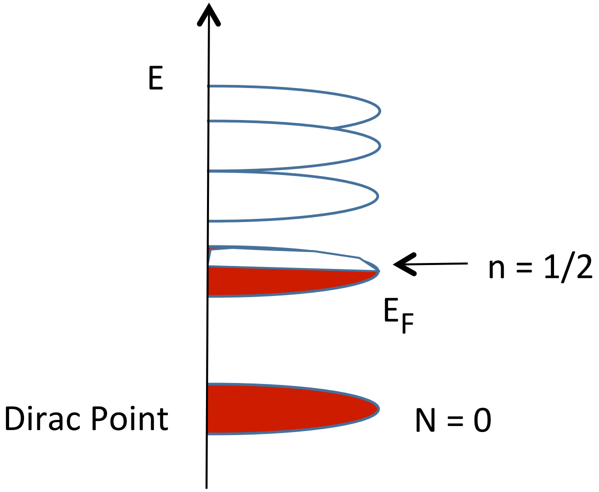
SdH amplitude increases

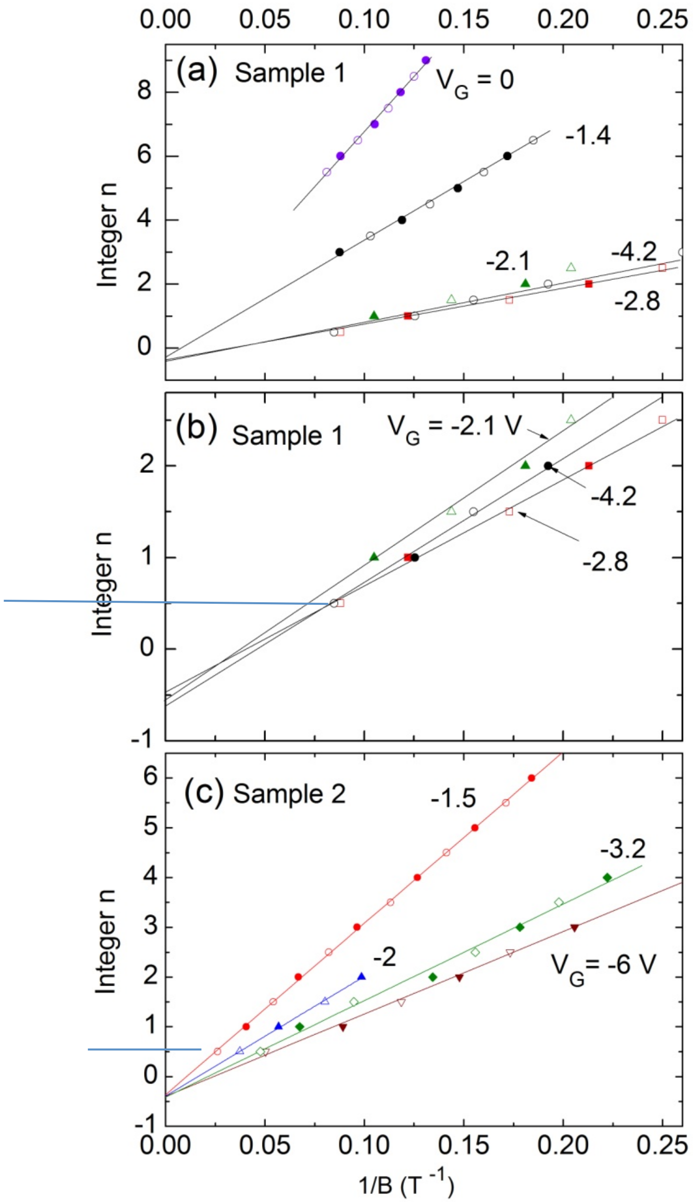
At 14 Tesla, Lowest Landau Level accessed is *n* = 1!

Intercept in quantum limit $1/B_n \rightarrow 0$ gives *n* = -1/2,
with much higher resolution.

Strong evidence for Dirac spectrum




E
n = 1/2
E_F
Dirac Point
N = 0


(a) Sample 1
V_G = 0
-1.4
-2.1
-4.2
-2.8
(b) Sample 1
V_G = -2.1 V
-4.2
-2.8
(c) Sample 2
-1.5
-2
-3.2
V_G= -6 V
Integer n
1/B (T^{-1})
0.00
0.05
0.10
0.15
0.20
0.25
0
2
4
6
8
-1
1
3
5

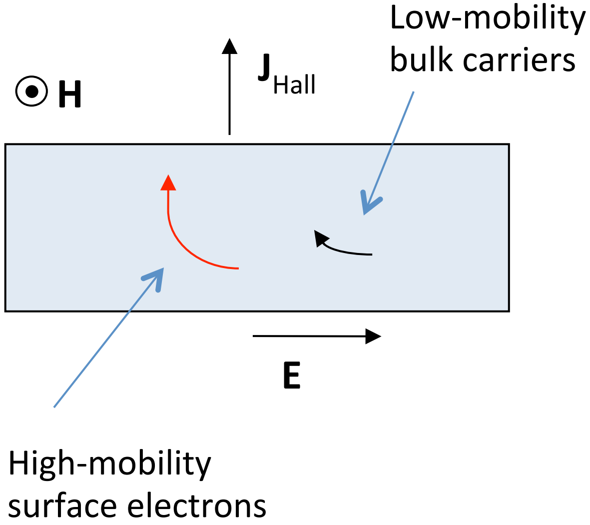
The importance of the weak-B Hall conductivity

Additivity of surface and bulk Hall conductivities

$$\sigma_{xy} = \sigma^{b}{}_{xy} + G^{s}{}_{xy} / t$$

The bulk term $$\sigma^{b}{}_{xy} = n_b e \mu_b{}^2 H$$

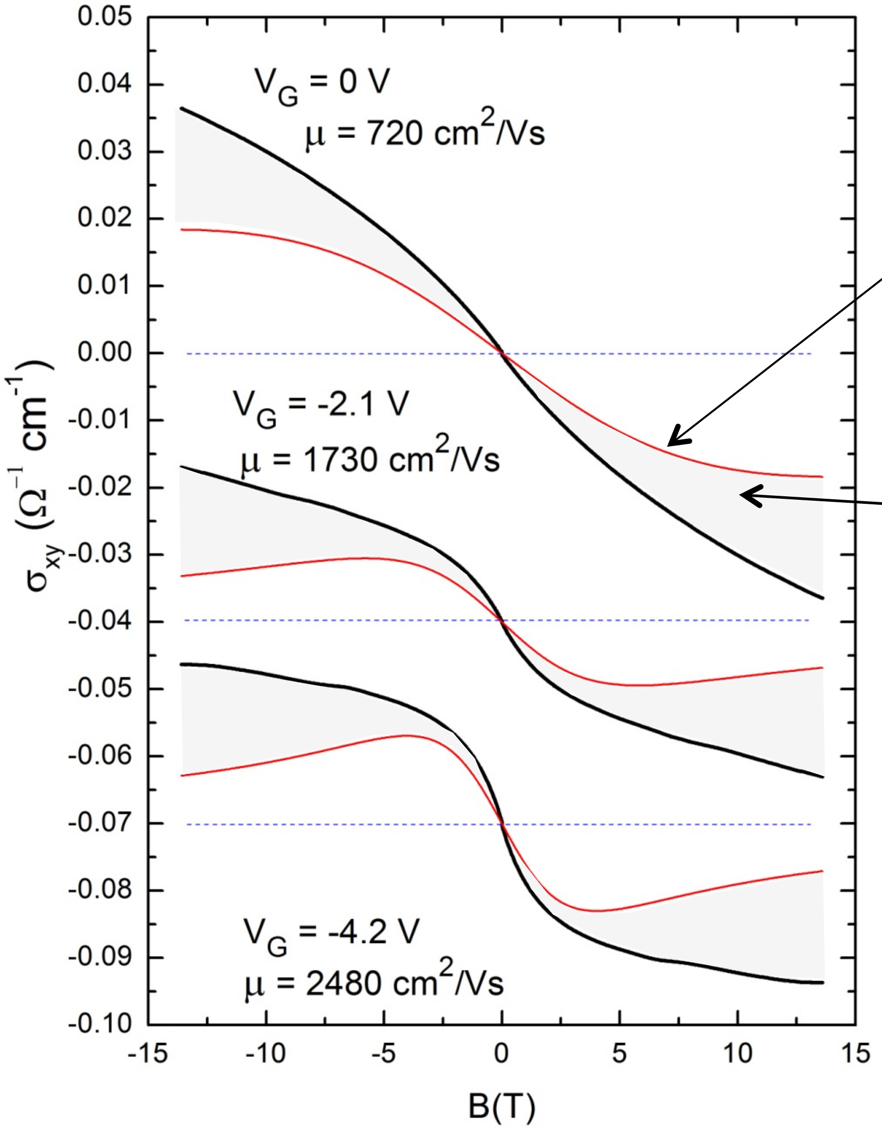
surface term $$G^{s}{}_{xy} / t = N_s e \mu \frac{\mu H}{[1 + (\mu H)^2]}$$



$n_b \gg N_s/t$, *but* the mobility ratio $\mu/\mu_b \gg 1$.

Since Hall currents ~ $(\text{mobility})^2$, could the surface Hall current $G^{s}{}_{xy}$ become dominant in low magnetic fields?

Separating surface and bulk Hall currents



Xiong et al. PRB 2013

Surface Hall current

$$G^{s}{}_{xy} / t = N_s e\mu \frac{\mu H}{[1+(\mu H)^2]}$$

Bulk Hall current

$$\sigma^{b}{}_{xy} = n_b e \mu_b{}^2 H$$

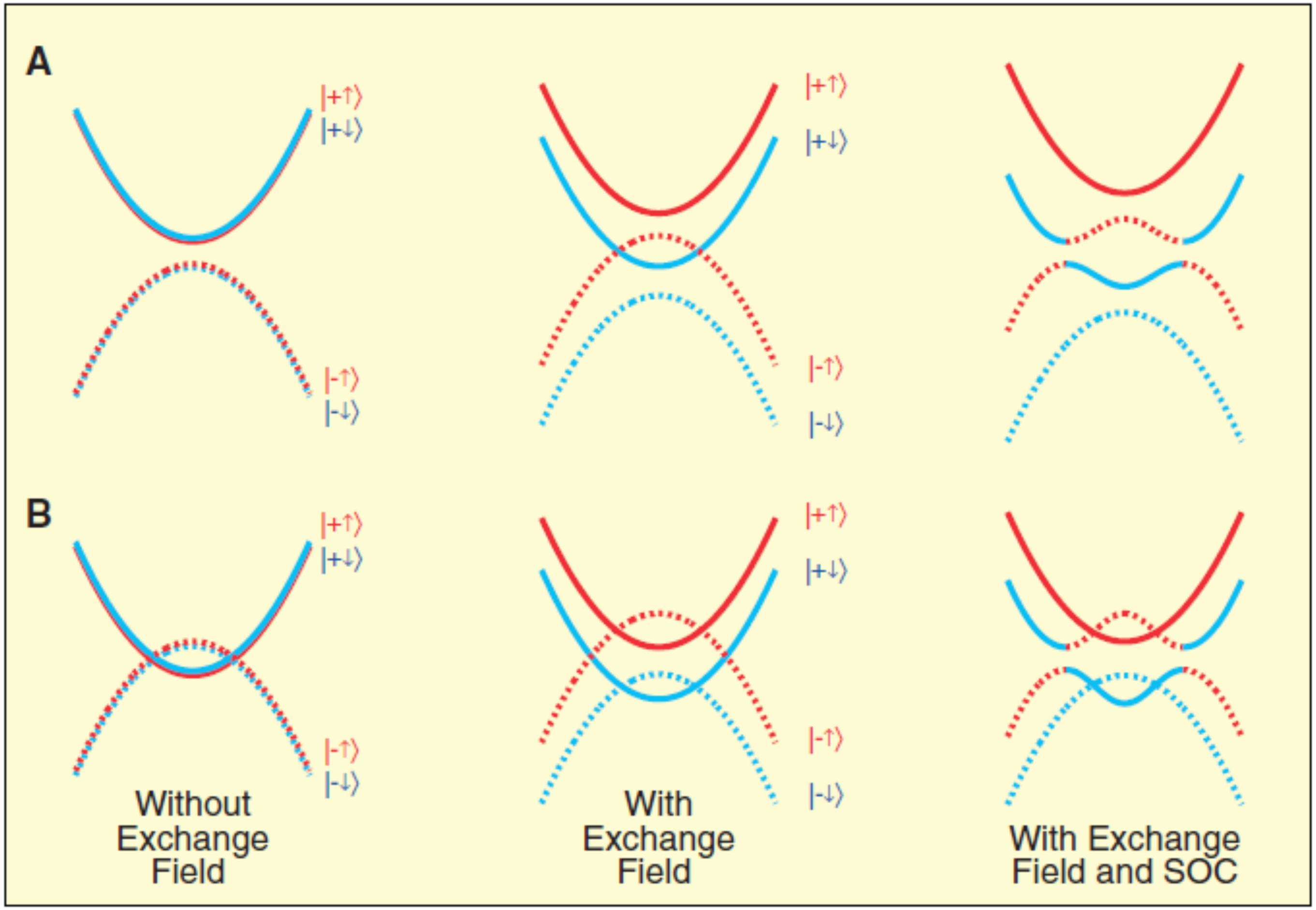
At large gate V_G,
Surface term dominates

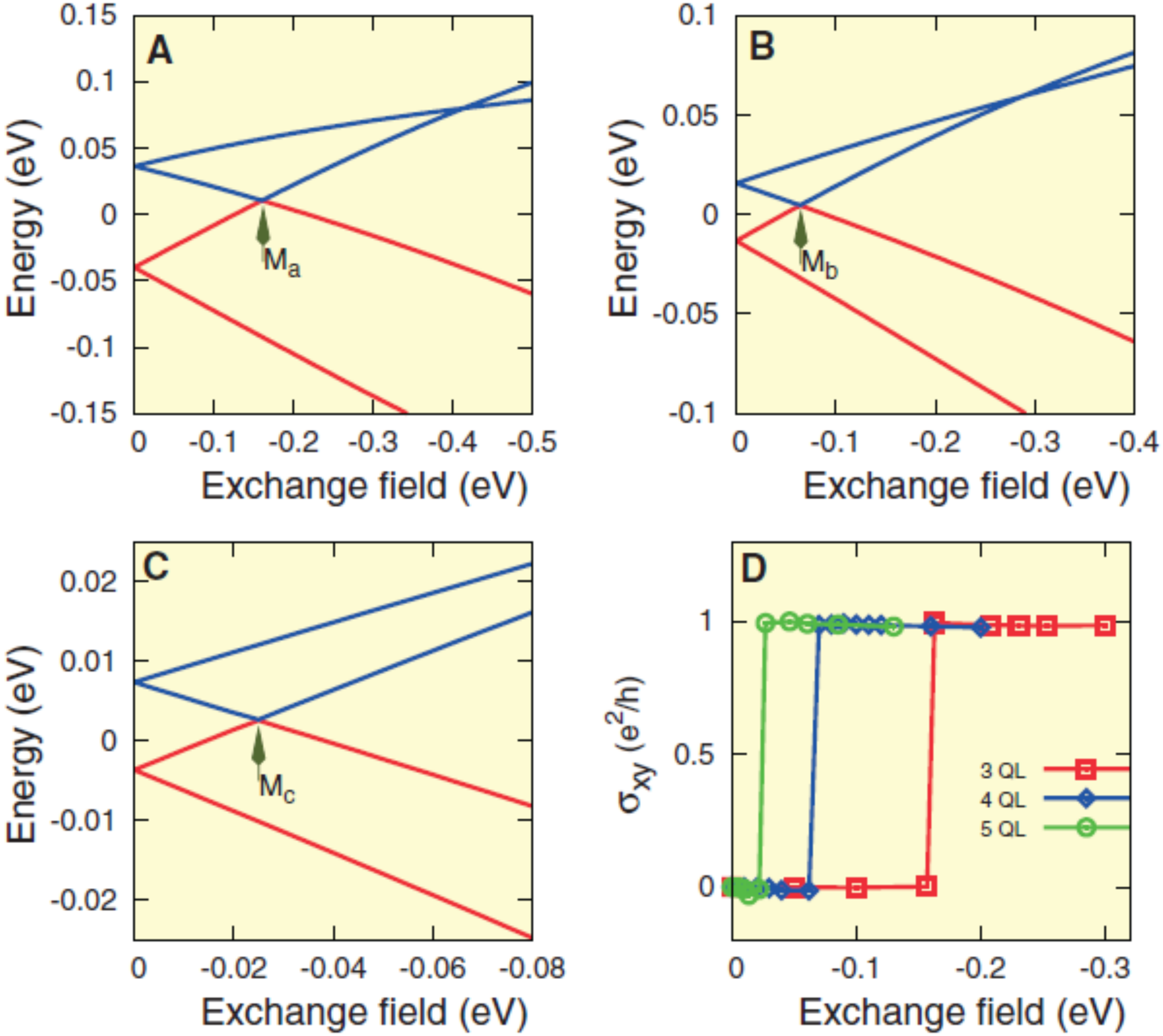
The Quantum Anomalous Hall Effect

Quantized Anomalous Hall Effect in Magnetic Topological Insulators

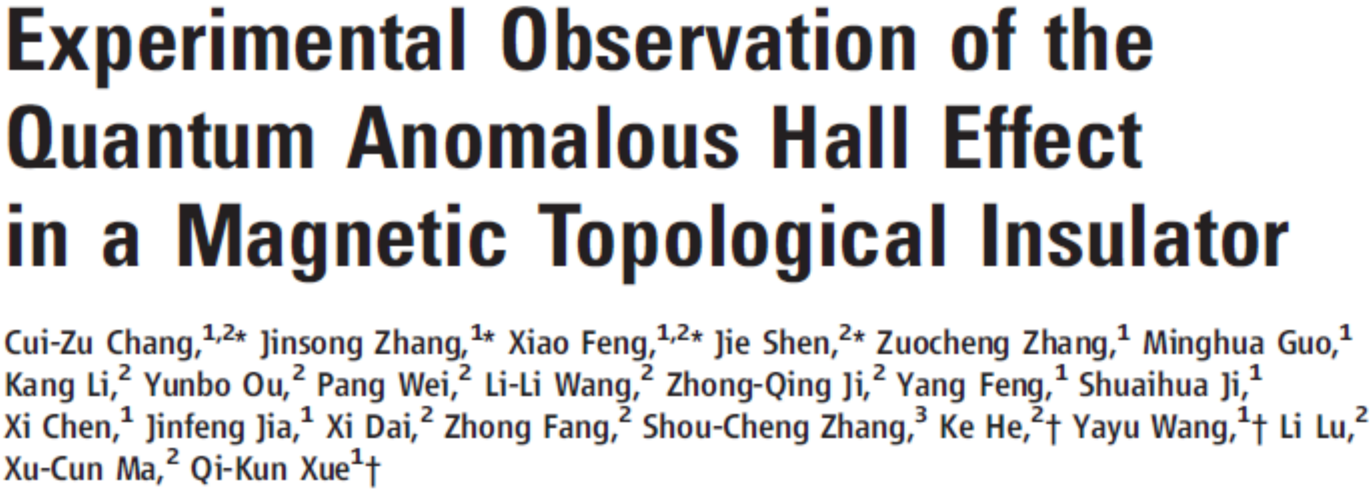
Science 2010

Rui Yu,[1] Wei Zhang,[1] Hai-Jun Zhang,[1,2] Shou-Cheng Zhang,[2,3] Xi Dai,[1]* Zhong Fang[1]*



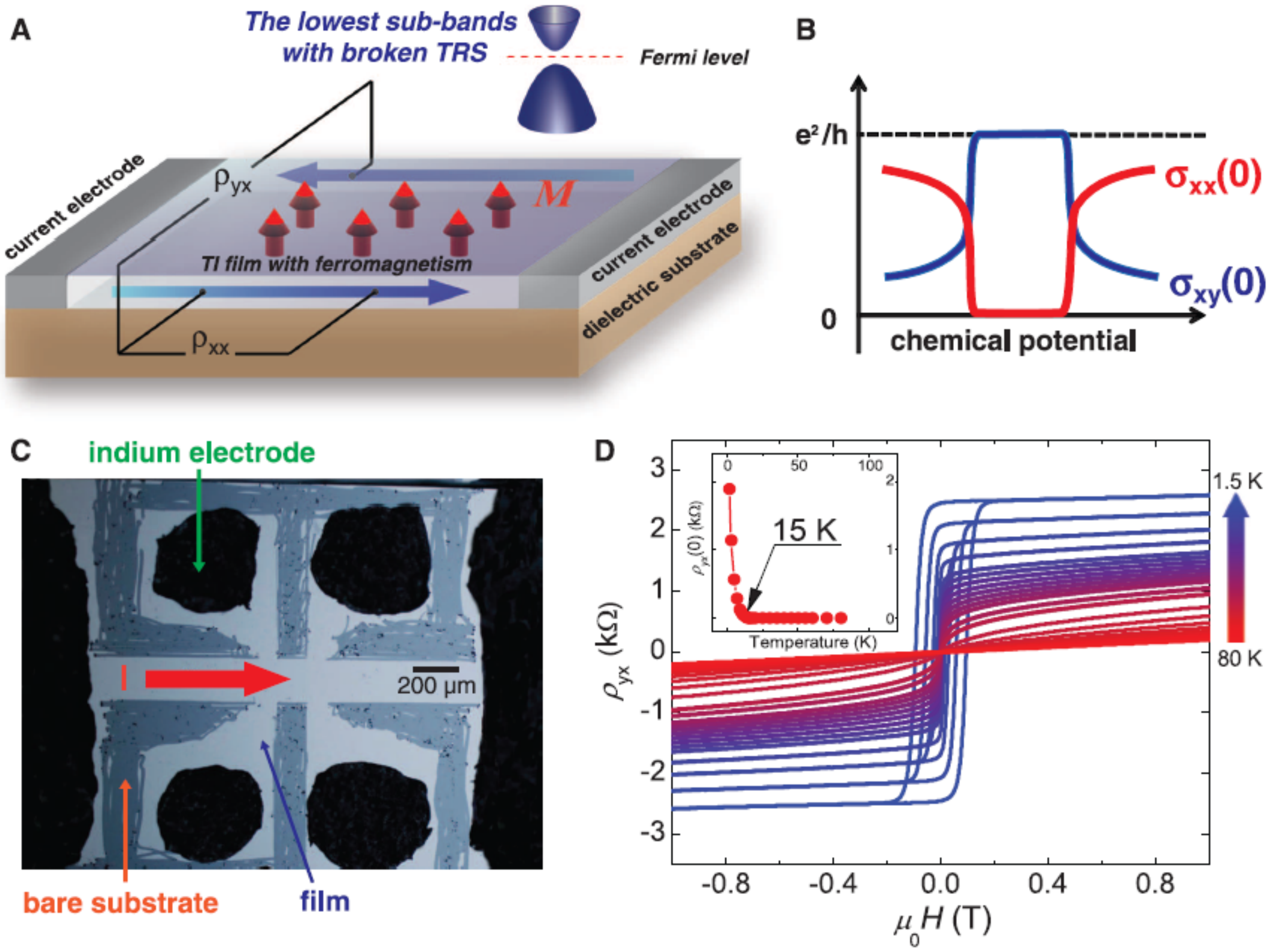

A
B
C
D
Ma
Mb
Mc
Energy (eV)
Exchange field (eV)
σxy (e²/h)
3 QL
4 QL
5 QL
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.3
-0.4
-0.5
0.02
0.01
-0.01
-0.02
-0.04
-0.06
-0.08
1
0.5

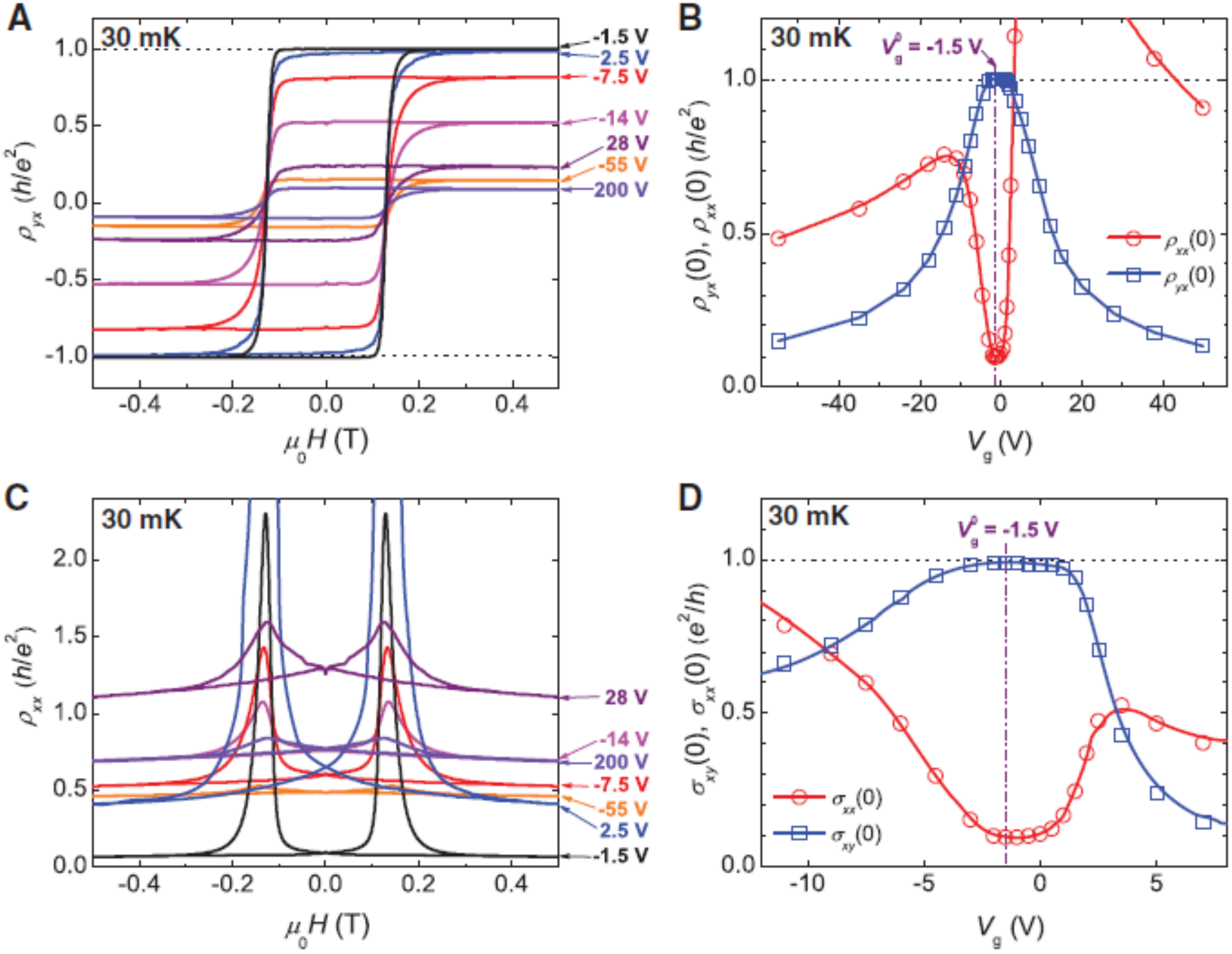
Science 2013

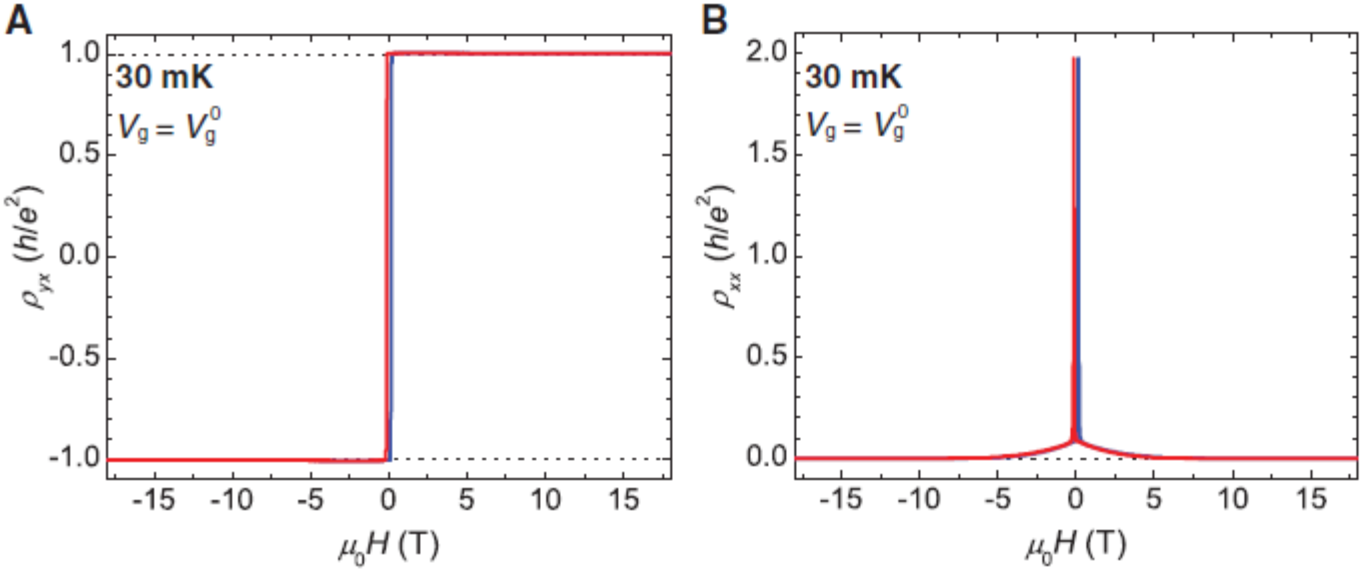


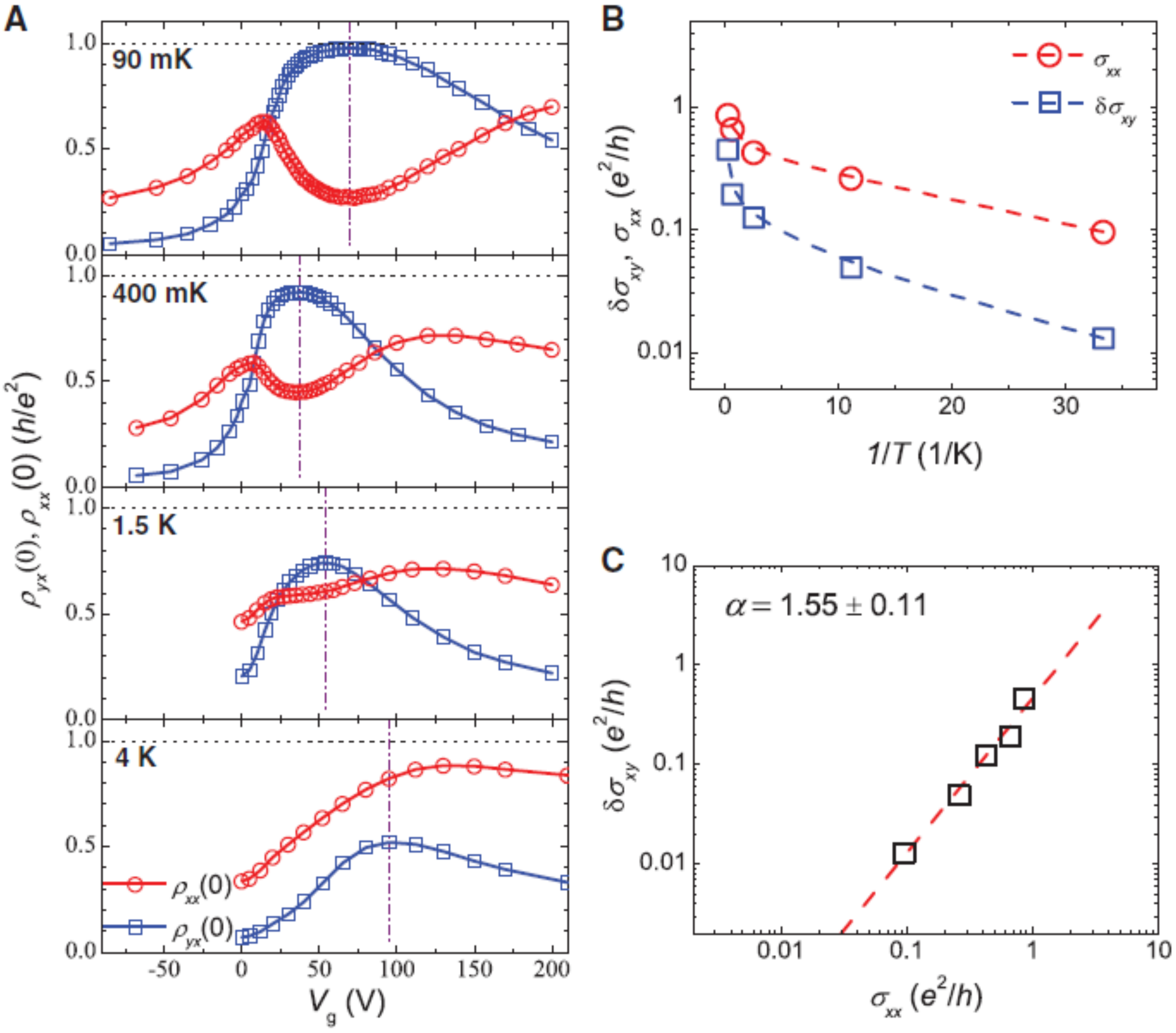
Experimental Observation of the Quantum Anomalous Hall Effect in a Magnetic Topological Insulator

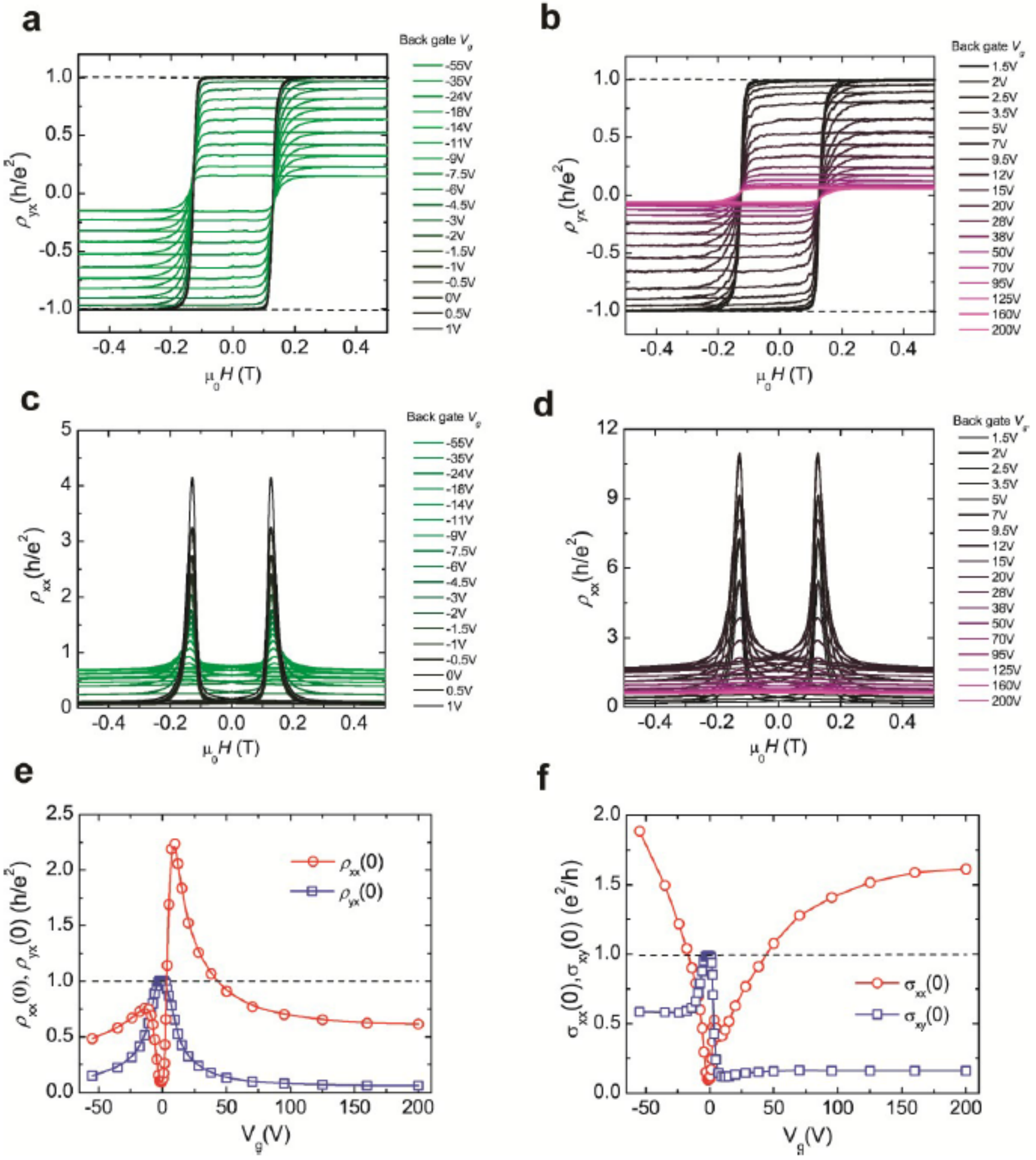
Cui-Zu Chang,[1,2]* Jinsong Zhang,[1]* Xiao Feng,[1,2]* Jie Shen,[2]* Zuocheng Zhang,[1] Minghua Guo,[1] Kang Li,[2] Yunbo Ou,[2] Pang Wei,[2] Li-Li Wang,[2] Zhong-Qing Ji,[2] Yang Feng,[1] Shuaihua Ji,[1] Xi Chen,[1] Jinfeng Jia,[1] Xi Dai,[2] Zhong Fang,[2] Shou-Cheng Zhang,[3] Ke He,[2]† Yayu Wang,[1]† Li Lu,[2] Xu-Cun Ma,[2] Qi-Kun Xue[1]†


A
The lowest sub-bands
with broken TRS
Fermi level
current electrode
ρyx
M
TI film with ferromagnetism
current electrode
dielectric substrate
ρxx
B
e²/h
0
σxx(0)
σxy(0)
chemical potential
C
indium electrode
I
200 μm
bare substrate
film
D
3
2
1
0
-1
-2
-3
ρyx (kΩ)
-0.8
-0.4
0.0
0.4
0.8
μ0H (T)
1.5 K
80 K
0
50
100
2
1
0
ρyx(0) (kΩ)
15 K
Temperature (K)


A
30 mK
ρ_yx (h/e²)
μ₀H (T)
-1.5 V
2.5 V
-7.5 V
-14 V
28 V
-55 V
200 V
B
30 mK
V_g⁰ = -1.5 V
ρ_yx(0), ρ_xx(0) (h/e²)
V_g (V)
ρ_xx(0)
ρ_yx(0)
C
30 mK
ρ_xx (h/e²)
μ₀H (T)
28 V
-14 V
200 V
-7.5 V
-55 V
2.5 V
-1.5 V
D
30 mK
V_g⁰ = -1.5 V
σ_xy(0), σ_xx(0) (e²/h)
V_g (V)
σ_xx(0)
σ_xy(0)

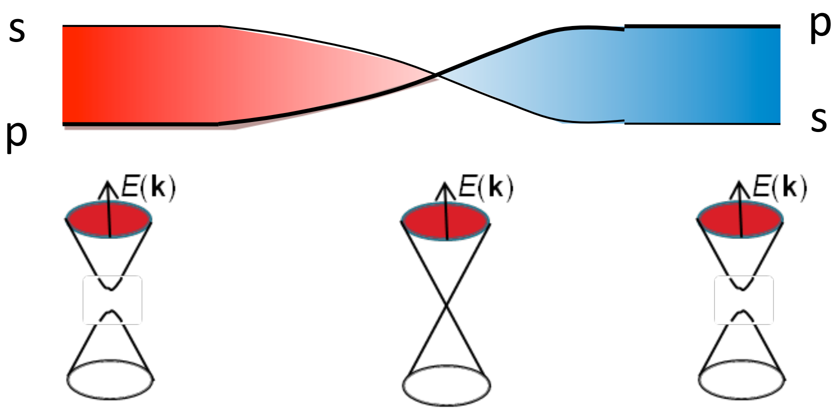

A
30 mK
$V_g = V_g^0$
ρ_{yx} (h/e^2)
1.0
0.5
0.0
-0.5
-1.0
-15
-10
-5
0
5
10
15
μ_0H (T)
B
30 mK
$V_g = V_g^0$
ρ_{xx} (h/e^2)
2.0
1.5
1.0
0.5
0.0
-15
-10
-5
0
5
10
15
μ_0H (T)

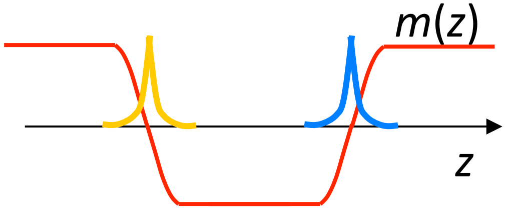

A
90 mK
400 mK
1.5 K
4 K
$\rho_{yx}(0), \rho_{xx}(0)$ (h/e^2)
0.0
0.5
1.0
-50
0
50
100
150
200
V_g (V)
$\rho_{xx}(0)$
$\rho_{yx}(0)$
B
σ_{xx}
$\delta\sigma_{xy}$
$\delta\sigma_{xy}$, σ_{xx} (e^2/h)
0.01
0.1
1
0
10
20
30
1/T (1/K)
C
$\alpha = 1.55 \pm 0.11$
$\delta\sigma_{xy}$ (e^2/h)
0.01
0.1
1
10
σ_{xx} (e^2/h)

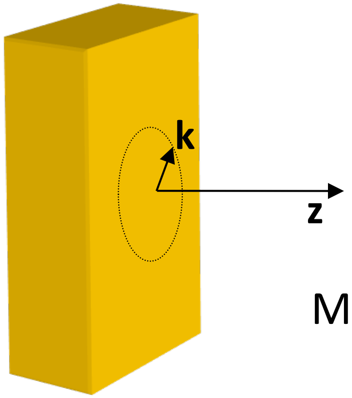

a
Back gate V_g
-55V
-35V
-24V
-18V
-14V
-11V
-9V
-7.5V
-6V
-4.5V
-3V
-2V
-1.5V
-1V
-0.5V
0V
0.5V
1V
ρ_{yx}(h/e^2)
μ_0H (T)
b
Back gate V_g
1.5V
2V
2.5V
3.5V
5V
7V
9.5V
12V
15V
20V
28V
38V
50V
70V
95V
125V
160V
200V
ρ_{yx}(h/e^2)
μ_0H (T)
c
Back gate V_g
-55V
-35V
-24V
-18V
-14V
-11V
-9V
-7.5V
-6V
-4.5V
-3V
-2V
-1.5V
-1V
-0.5V
0V
0.5V
1V
ρ_{xx}(h/e^2)
μ_0H (T)
d
Back gate V_g
1.5V
2V
2.5V
3.5V
5V
7V
9.5V
12V
15V
20V
28V
38V
50V
70V
95V
125V
160V
200V
ρ_{xx}(h/e^2)
μ_0H (T)
e
$\rho_{xx}(0)$
$\rho_{yx}(0)$
$\rho_{xx}(0)$, $\rho_{yx}(0)$ (h/e^2)
V_g(V)
f
$\sigma_{xx}(0)$
$\sigma_{xy}(0)$
$\sigma_{xx}(0)$,$\sigma_{xy}(0)$ (e^2/h)
V_g(V)

A twist of the gap leads to topological surface states

Gap (mass) twist







Mass twist traps surface helical fermions