Quantum Hall Effect and Electron-electron interaction in graphene

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Outlines

- Review of graphene Quantum Hall effect
  * Non-interacting picture
  * Interaction mediated SU (4) symmetry breaking of zero LL

- Bulk gap measurements
  * IR Spectroscopy
  * Transport measurement using Corbino geometry

- SU(8) Symmetry breaking in bilayer graphene sample

- Fractional Quantum Hall Effect in Suspended Graphene

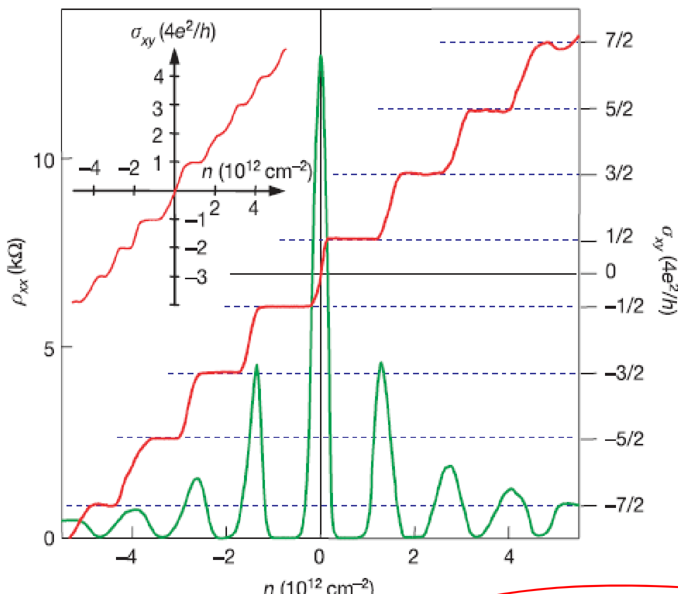
Quatum Hall Effect in Graphene (2005)

Vol 438|10 November 2005|doi:10.1038/nature04233 nature

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

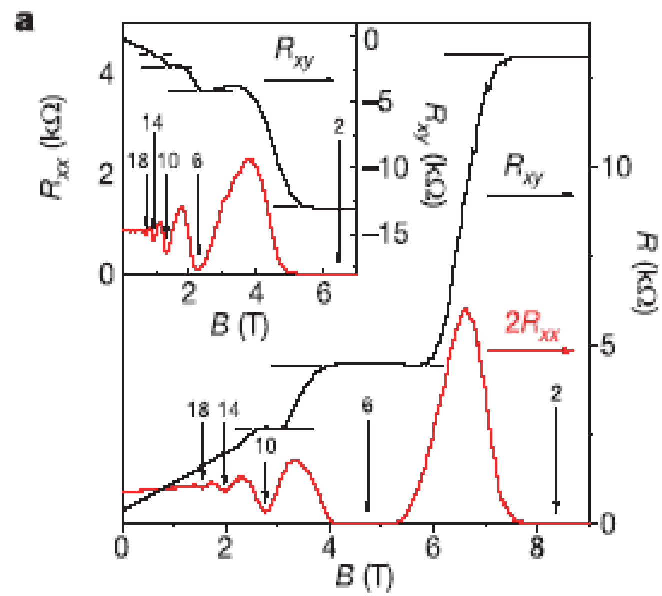


Vol 438|10 November 2005|doi:10.1038/nature04235 nature

LETTERS

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]



Quantization:

$$R_{xy}^{-1} = 4\left(n + \frac{1}{2}\right)\frac{e^2}{h}$$

spin (2) X valley (2)

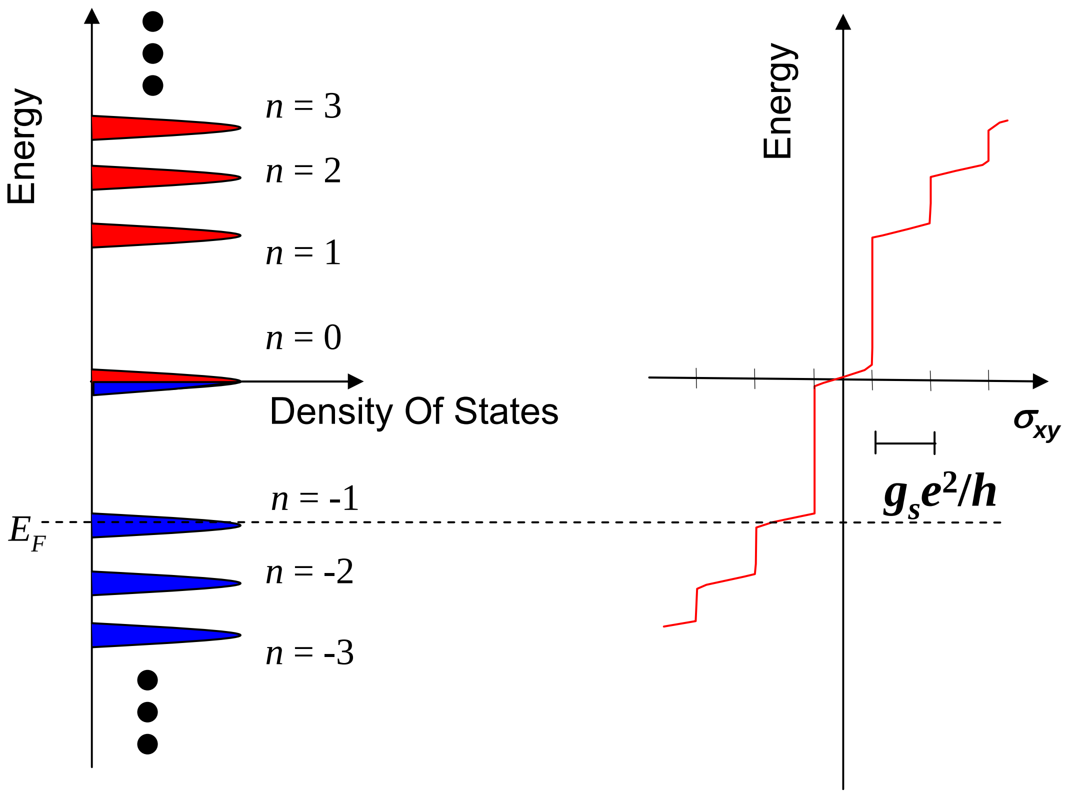
pseudo-spin origin

Graphene Landau Level and Half Integer QHE

I. I. Rabi, Z. Phys. 49, 507 (1928); McClure, Phys Rev. (1957), Haldane, Phys. Rev. Lett. (1988)

Landau Level $$E_n = \pm\sqrt{2e\hbar v_F^2 |n| B}$$

Landau Level Degeneracy
$g_s = 4$
2 for spin and 2 for sublattice



Quantized Condition

$$R_{xy}^{-1} = \pm g_s (n + \frac{1}{2}) \frac{e^2}{h}$$

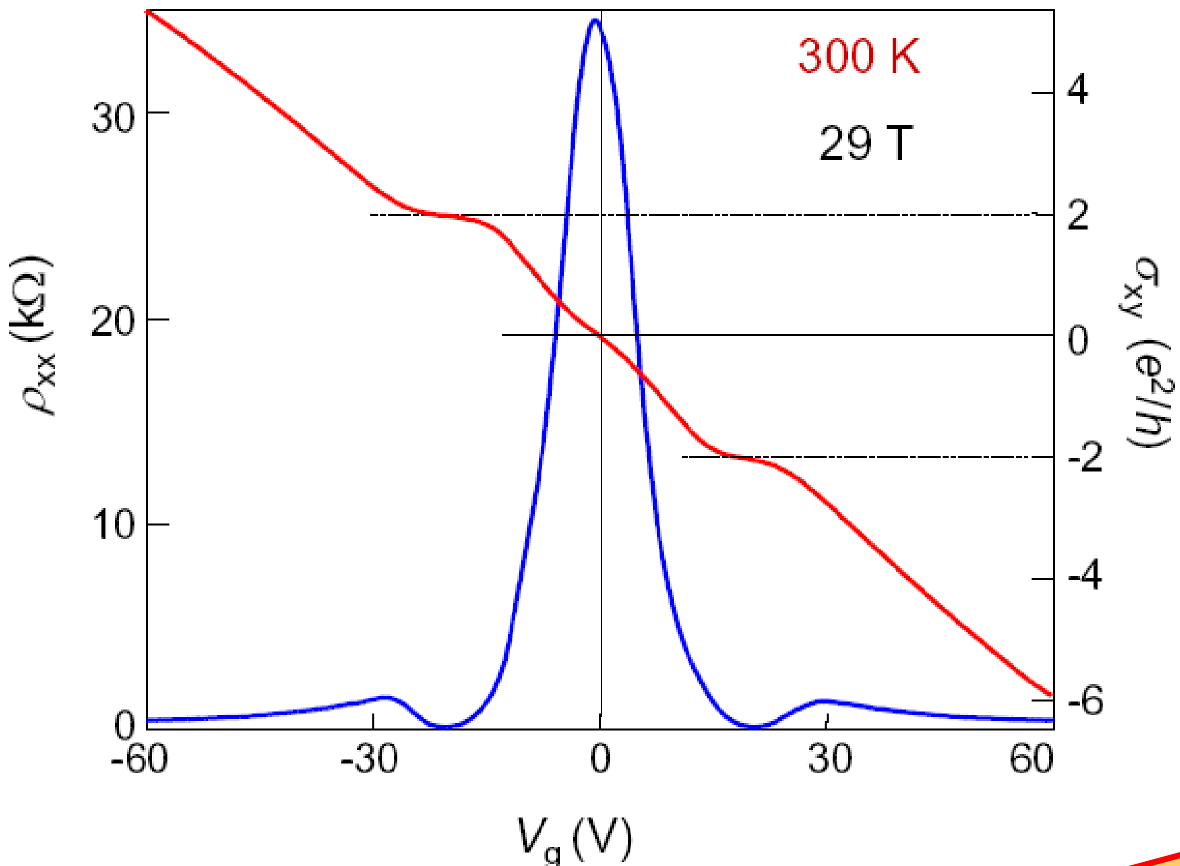
$$\nu = \pm g_s (n + 1/2)$$

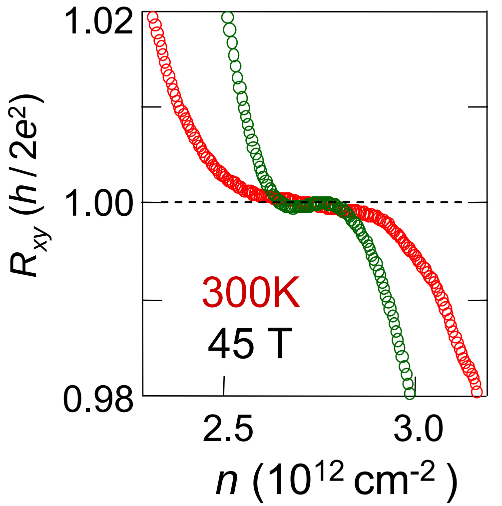
LL filing factor

T. Ando et al (2002)

$E_1 \sim 300\text{K}\ [\text{B(T)}]^{1/2}$

Room Temperature Quantum Hall Effect





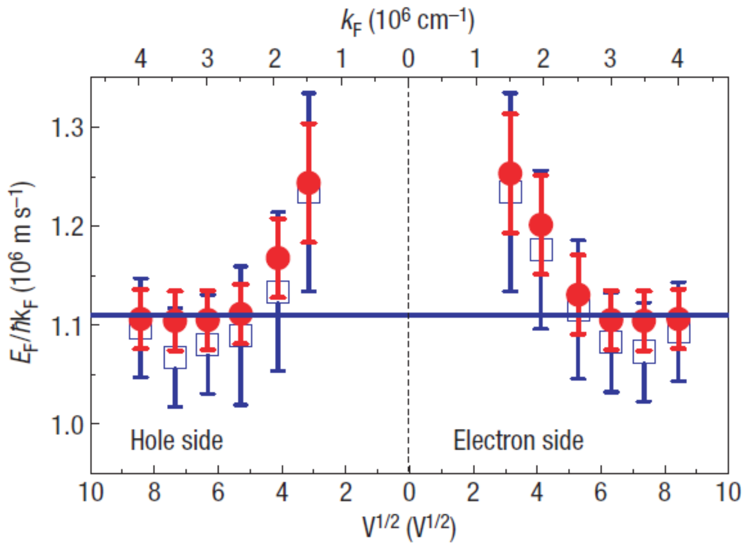
Deviation < 0.3%

Nice! But, all are described by the single particle picture!

Novoselov, Jiang, Kim and Geim et al. *Science* (2007)

What is the role of electron-electron interaction in graphene?

Fermi velocity renormalization

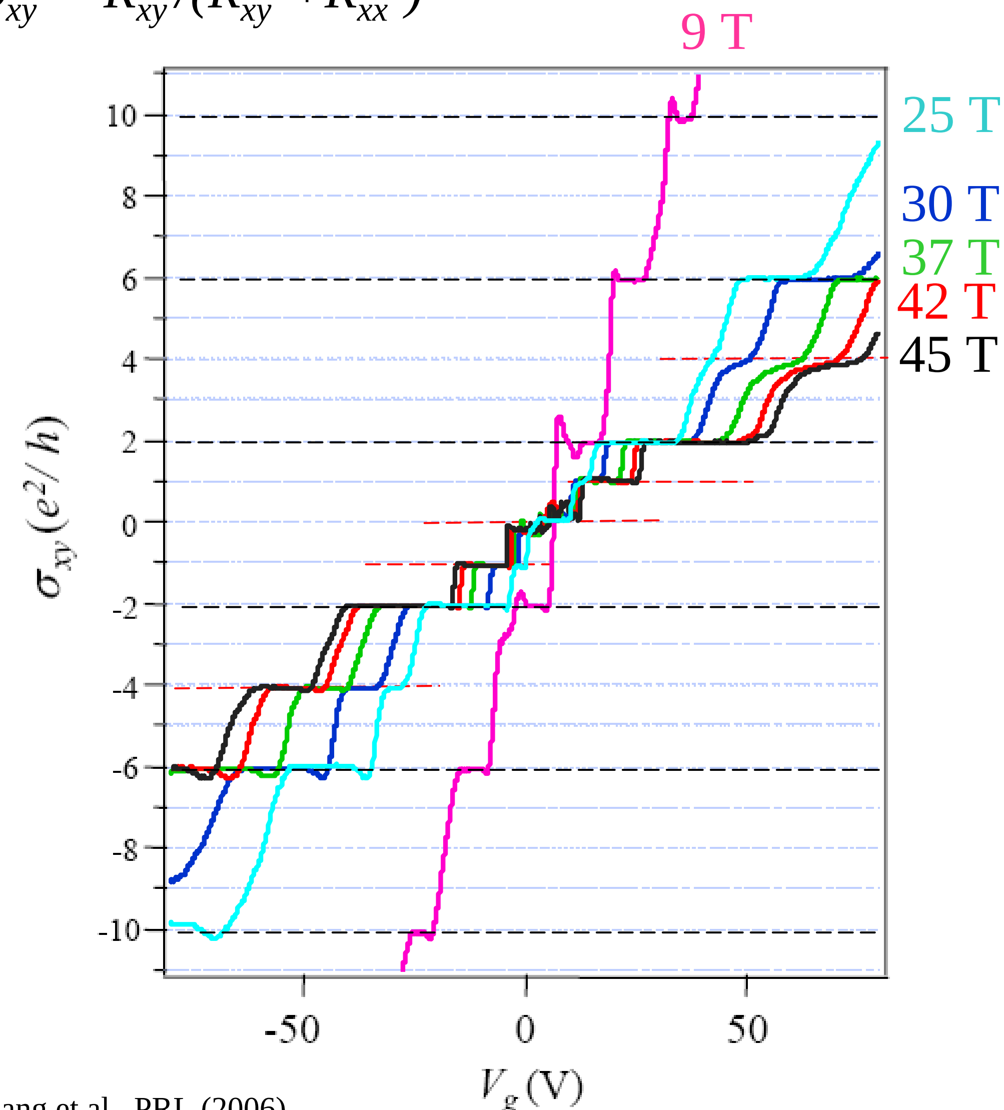


Dirac charge dysnmics in graphene by infrared spectroscopy
Z. Q. Li et al., *Nature Physics* **4**, 532-535 (2008)

In a Landau level: $E_{e-e} \sim \dfrac{e^2}{\varepsilon \ell_B}$

Splitting of Landau Levels in High Magnetic Fields

$\sigma_{xy} = -R_{xy}/(R_{xy}^2 + R_{xx}^2)$



Y. Zhang et al., PRL (2006)

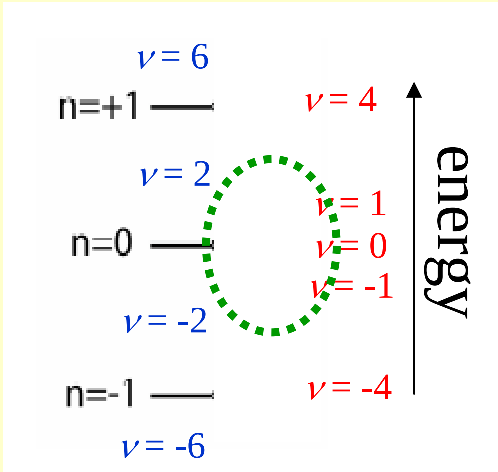
Low fields (B < 10 T)

$\nu = \pm 2,\ \pm 6,\ \pm 10,\ \ldots.$

High fields (B > 20 T)

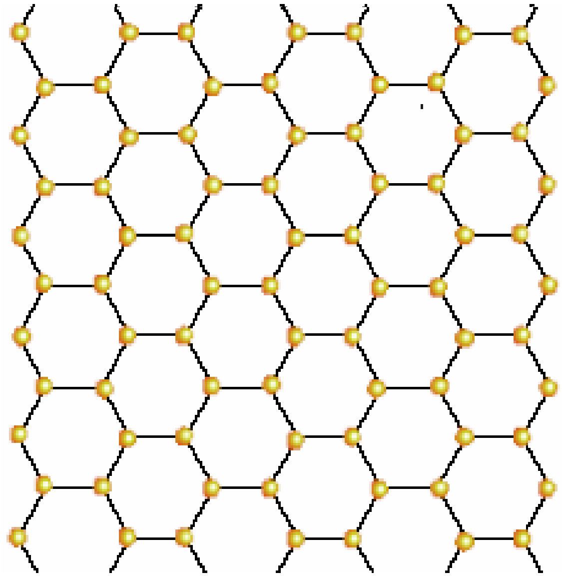
$\nu = 0,\ \pm 1,\ \pm 2,\ \pm 4,\ \pm 6,\ \ldots$

Landau Level $E_n = \mathrm{sgn}(n)\sqrt{2e\hbar v_F^2 |n| B}$



Spin & valley symmetry lifted!

How to break sub-lattice symmetry?



SU(4) Symmetry:
spin/pseudo spin

Spontaneous Symmetry Breaking

Charge density wave, Spin density wave, Skyrmions, excitons, and etc

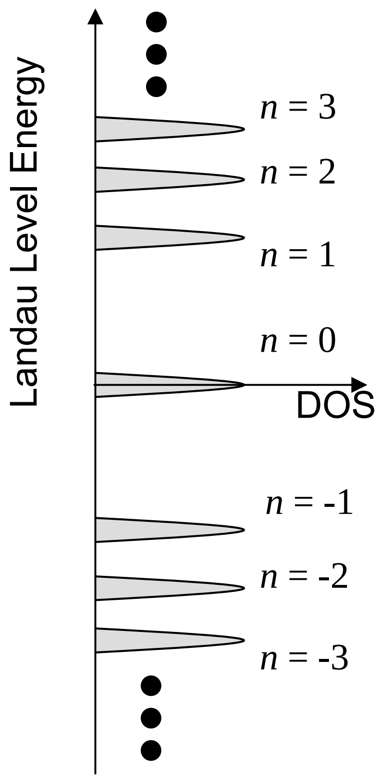
Theory Reference list (partial)

[13] K. Nomura, A.H. MacDonald, Phys. Rev. Lett. 96 (2006) 256602.
[14] M.O. Goerbig, R. Moessner, B. Doucot, Phys. Rev. B 74 (2006) 161407.
[15] J. Alicea, M.P.A. Fisher, Phys. Rev. B 74 (2006) 075422.
[16] Kun Yang, S. Das Sarma, A.H. MacDonald, Phys. Rev. B 74 (2006) 075423.
[17] Dmitry A. Abanin, Patrick A. Lee, Leonid S. Levitov. cond-mat/0611062.
[18] V.P. Gusynin, V.A. Miransky, S.G. Sharapov, I.A. Shovkovy, Phys. Rev. B 74 (2006) 195429.
[19] V.P. Gusynin, V.A. Miransky, S.G. Sharapov, I.A. Shovkovy. cond-mat/0612488.
[20] I.F. Herbut, Phys. Rev. B 75 (2007) 165411.
[21] M. Ezawa, cond-mat/0609612; cond-mat/0606084.
[22] D.V. Khveshchenko, Phys. Rev. Lett. 87 (2001) 206401.
[23] Jean-Noöl Fuchs, Pascal Lederer, Phys. Rev. Lett. 98 (2007) 016803; cond-mat/0612386.

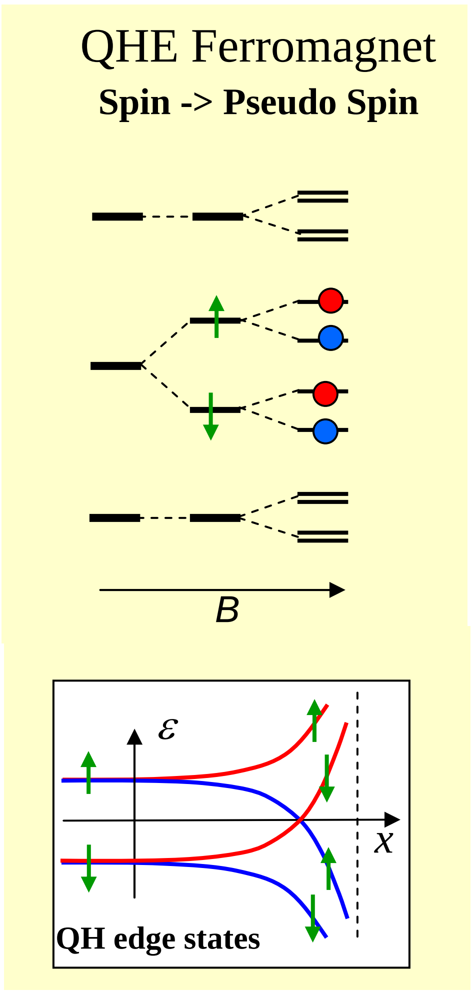
Quantum Hall Insulator OR Quantum Hall Ferromagnet?

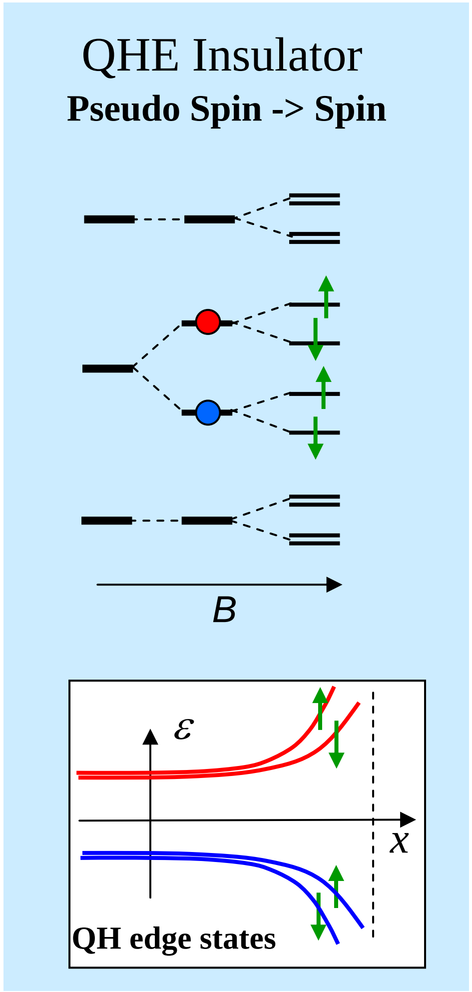
Low magnetic field

High magnetic field degeneracy break: two scenarios



Spin & Pseudo-spin degenerate

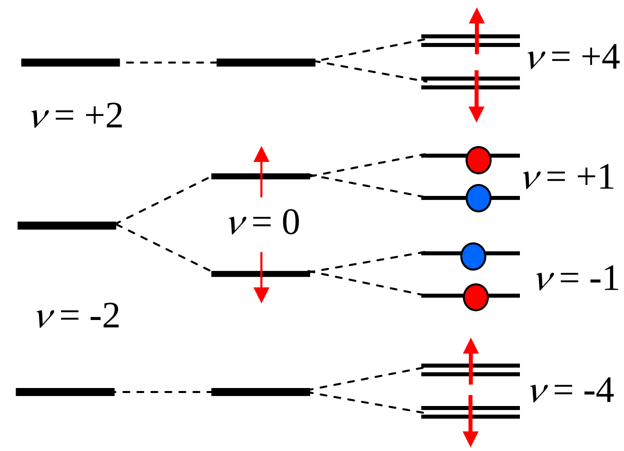




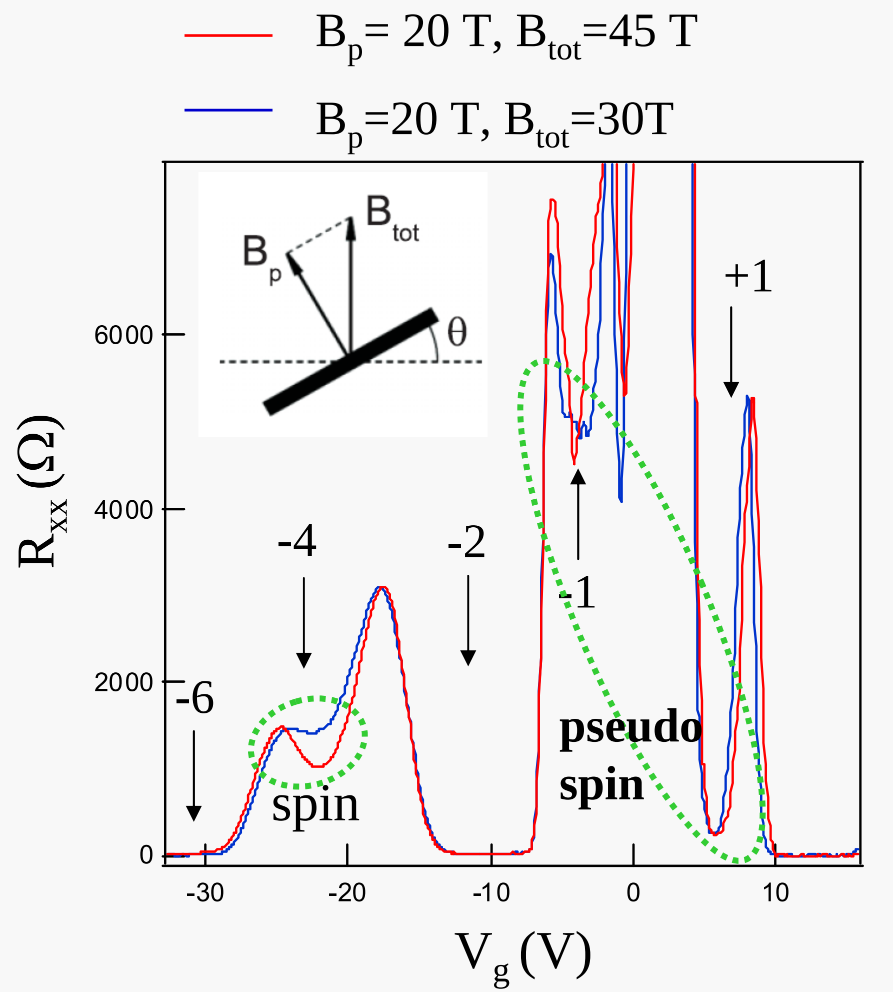
Normura & Macdonald, PRL 96, 256602 (2006); Abanin, Lee, & Levitov, PRL 98, 156801 (2007);

Spin or Pseudo Spin Splitting?

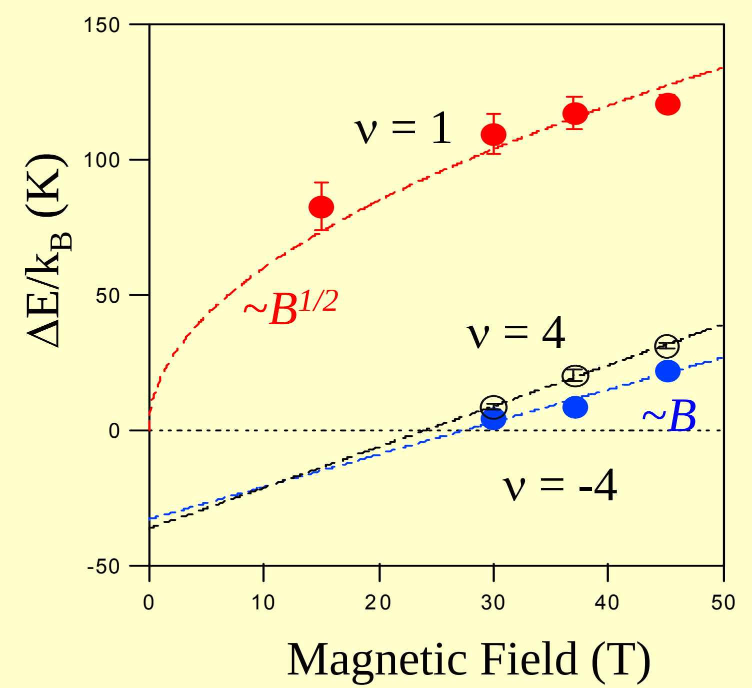
Quantum Hall Ferromaget!



Tilted Magnetic Field



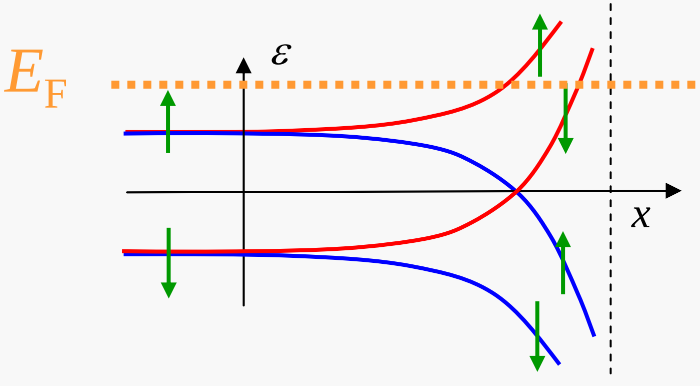
Activation Energy Gap Measurements



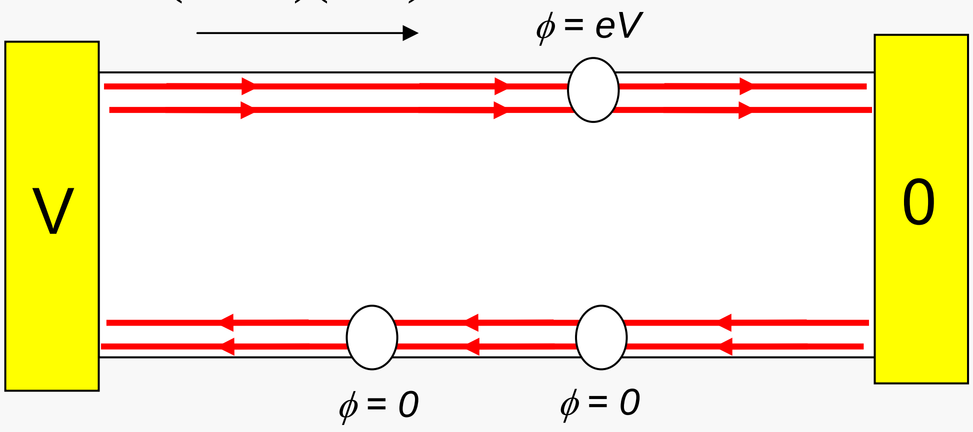
Zhang, et al, PRL (2007)

Graphene QH Edge States for Quantum Hall Ferromagnet

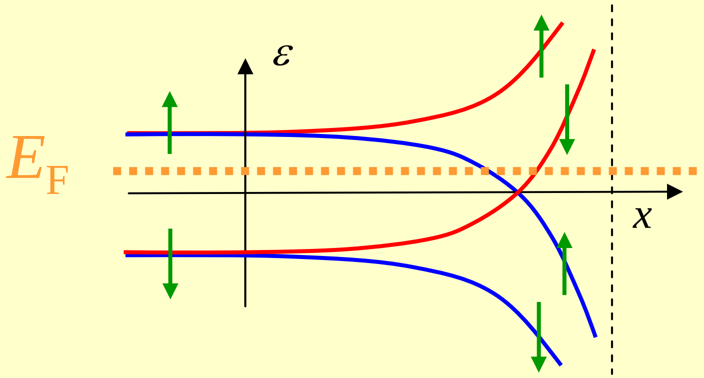
$\nu \neq 0$



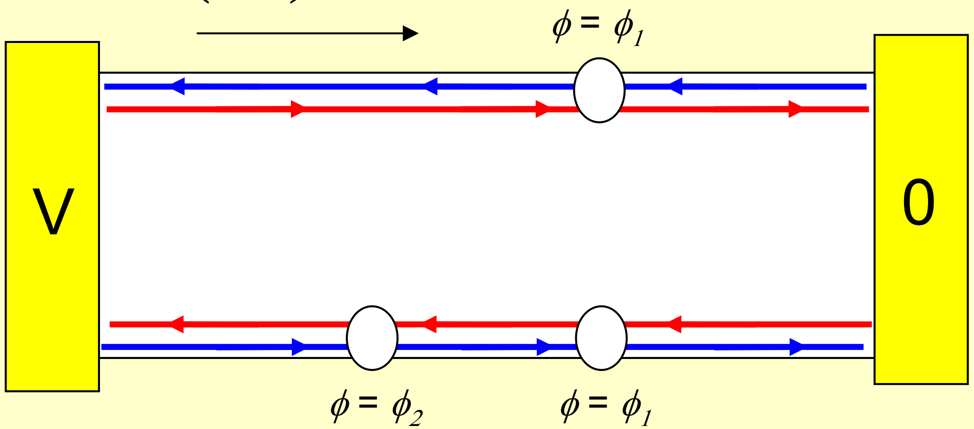
$I = (4n+2)(e^2/h)\,V$



$\nu = 0$



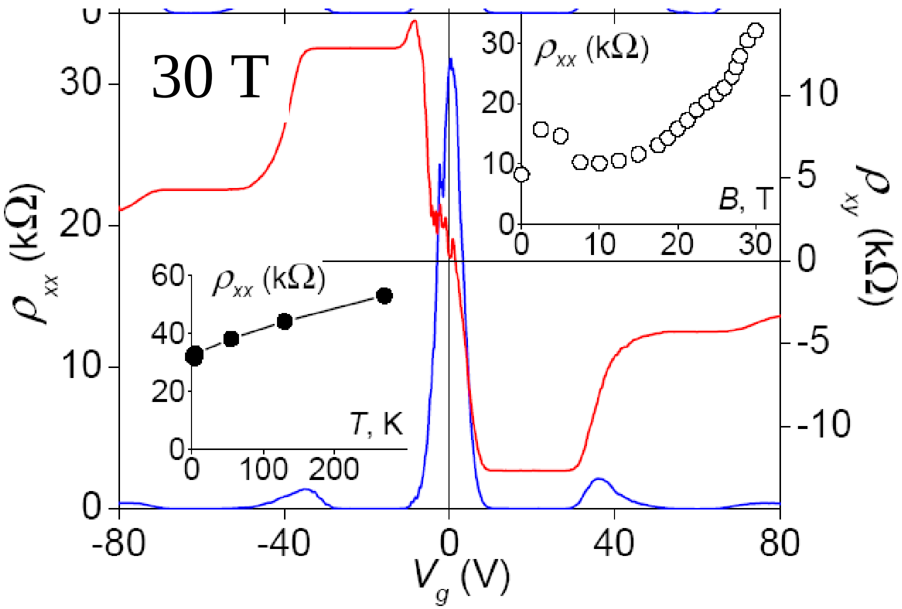
$I = 2(e^2/h)\,V$



We expect metallic states all gate voltages!

Abanin, et al., Phys. Rev. Lett. 98, 196806 (2007)

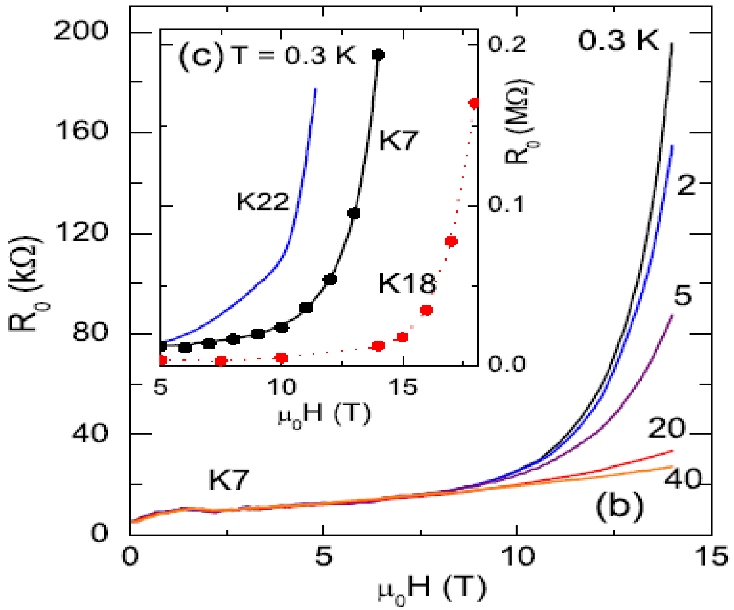
Resistance Maximum for $\nu = 0$ Quantum Hall State



Abanin, et al., Phys. Rev. Lett. 98, 196806 (2007)

Metallic temperature behavior

$\rho_{xx} < 40$ kΩ @ 30 T



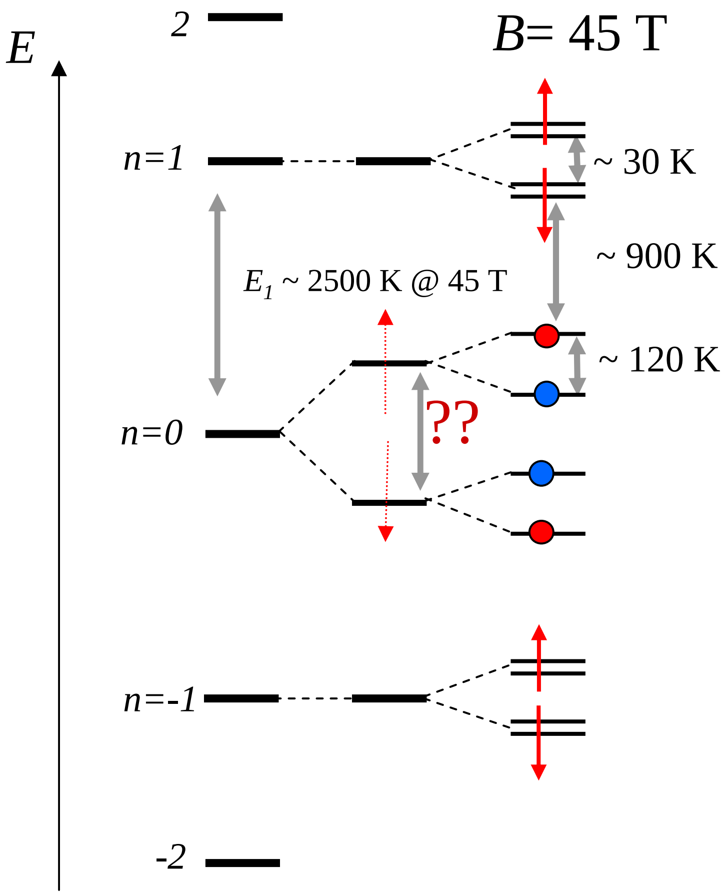
J. Chekelsky, L. Li, N. P. Ong, PRL (2007) PRB (2008)

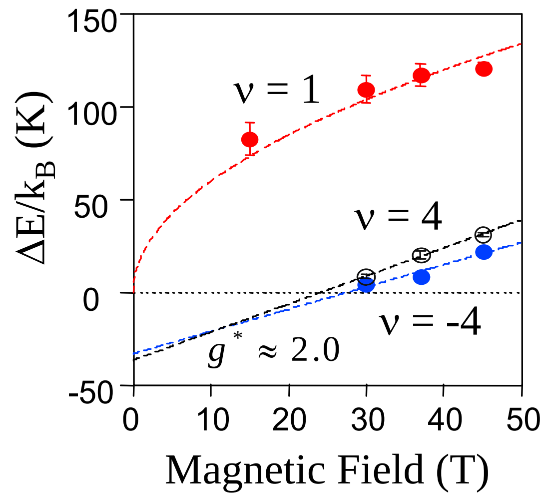
Insulator like behaviors for clean samples at high magnetic field 30 T.

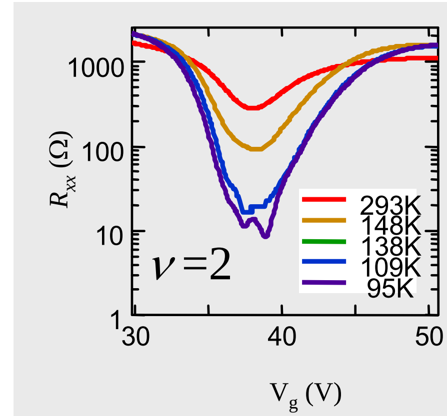
Probing the Nature of ν=0 QH state : Energy Gap

Activation Energy Measurement

Landau Level Hierarchy





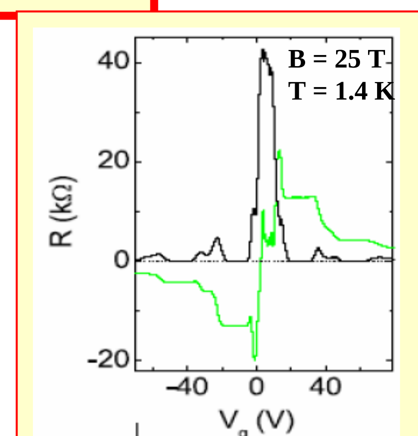


$\Delta E_{\nu=2}$ ~ 900 K *

* Giesbers *et al*. has ~2000 K

We expect $\Delta E_{\nu=0} > \Delta E_{\nu=1}$ ~ 100 K
→ Enhenced g^* at half filled n = 0??

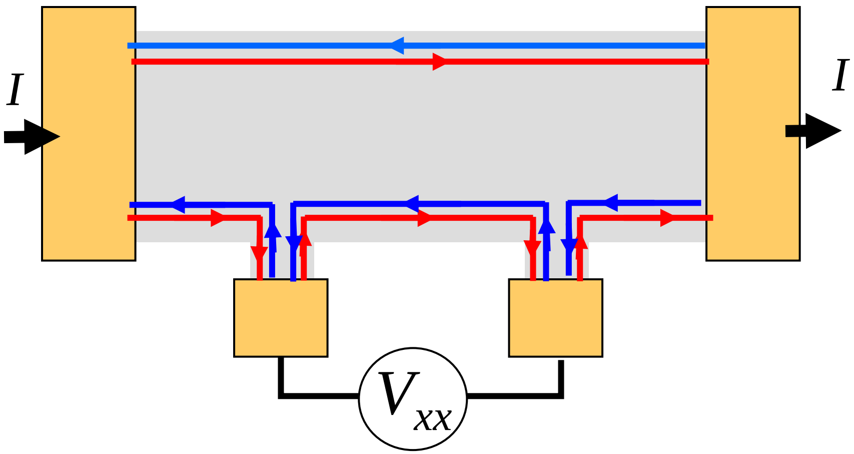
ν=0 state has no deep for an activation energy measurement…



Zhang, et al, PRL (2007)

Transport Gap Measurement at the Dirac Point

Hall Bar Measurement



In the Quantum Hall regime

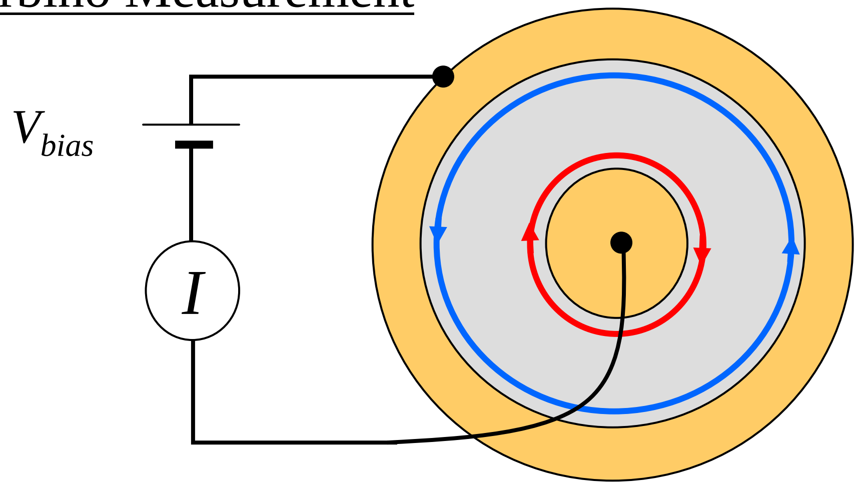
Filling factor

$\nu \neq 0 : \quad \boldsymbol{R_{xx} = V_{xx} / I = 0}$

$\nu = 0 : \quad \boldsymbol{R_{xx} \neq 0}$

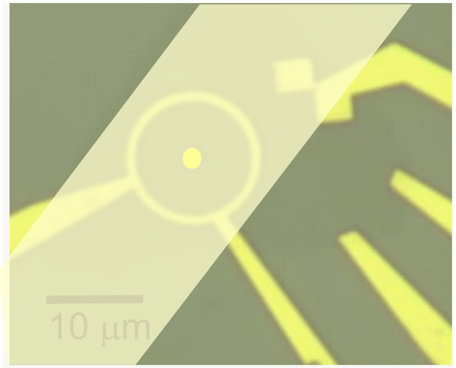
(only in graphene, see Abanin *et al.*)

Corbino Measurement



In the Quantum Hall regime

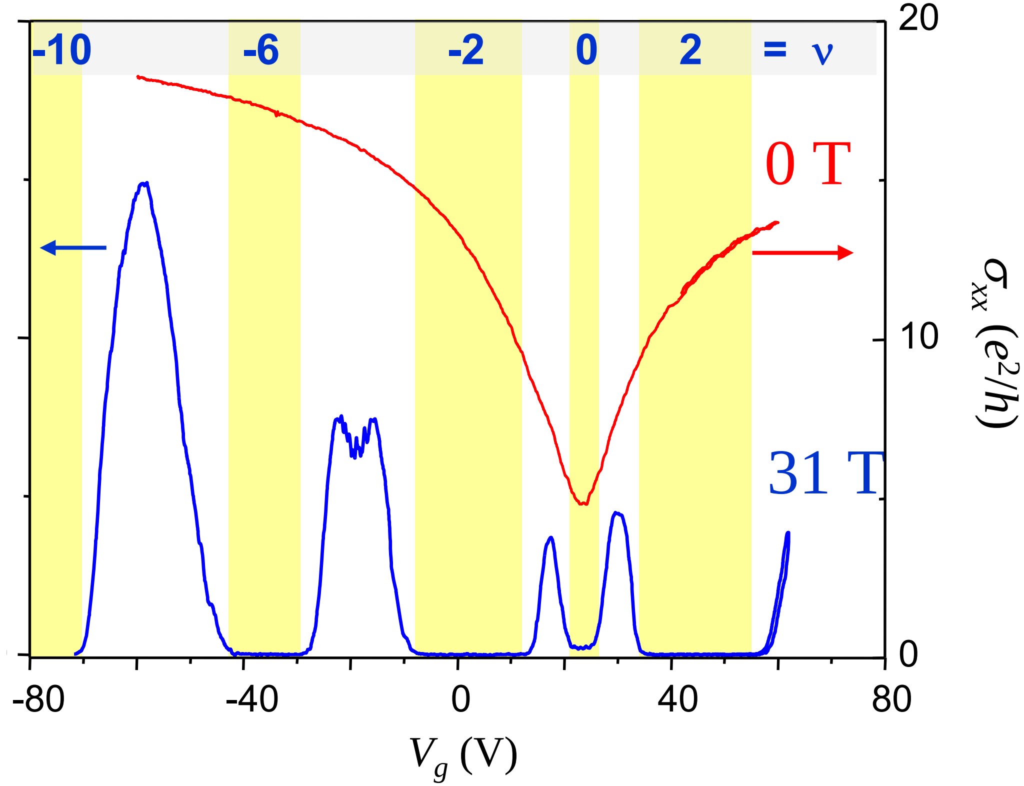
$$\sigma_{xx} = I / V_{bias} = 0$$

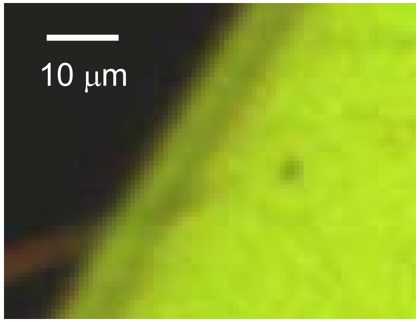


Graphene Corbino

- **Dielectric layer deposition**
- **Contact via fabrication**
- **Inner electrode contacted by a ground plane**

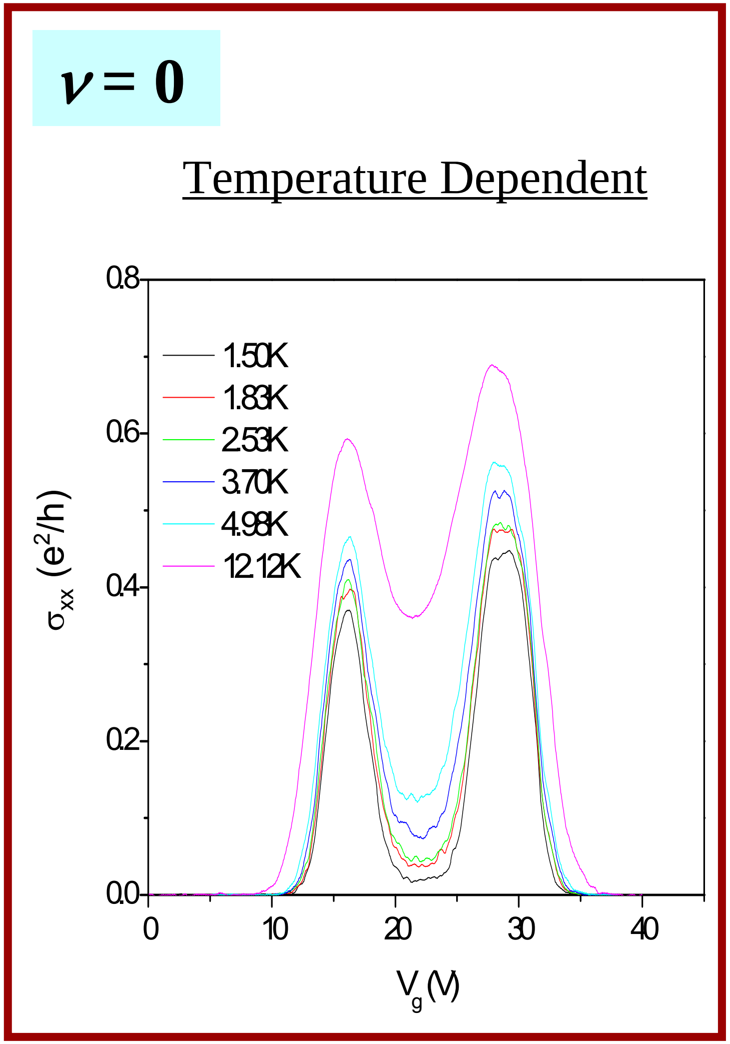
Quantum Hall Effect in Graphene Corbino Device





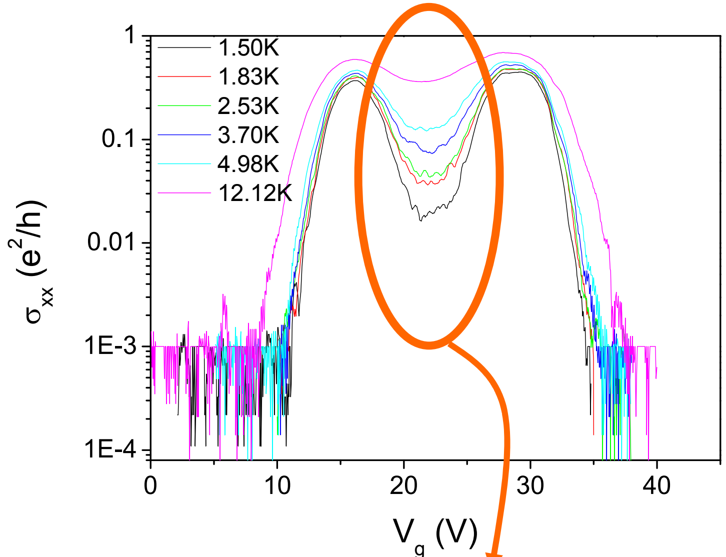
T = 1.5 K

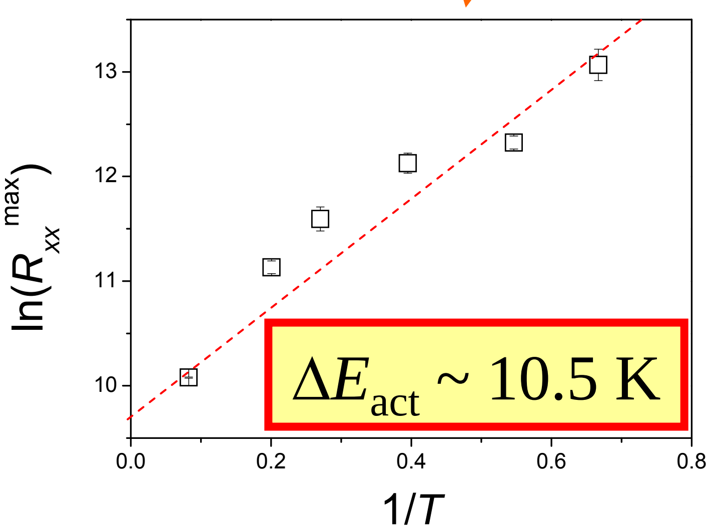
Mobility ~ 10,000 cm²/Vsec



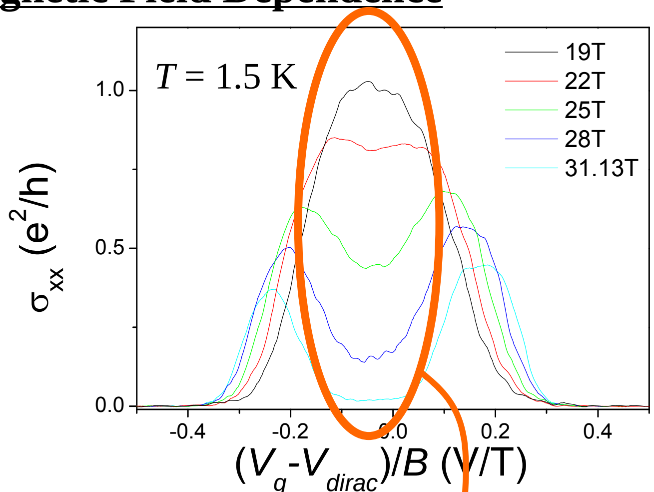
Transport Gap in $\nu = 0$ state

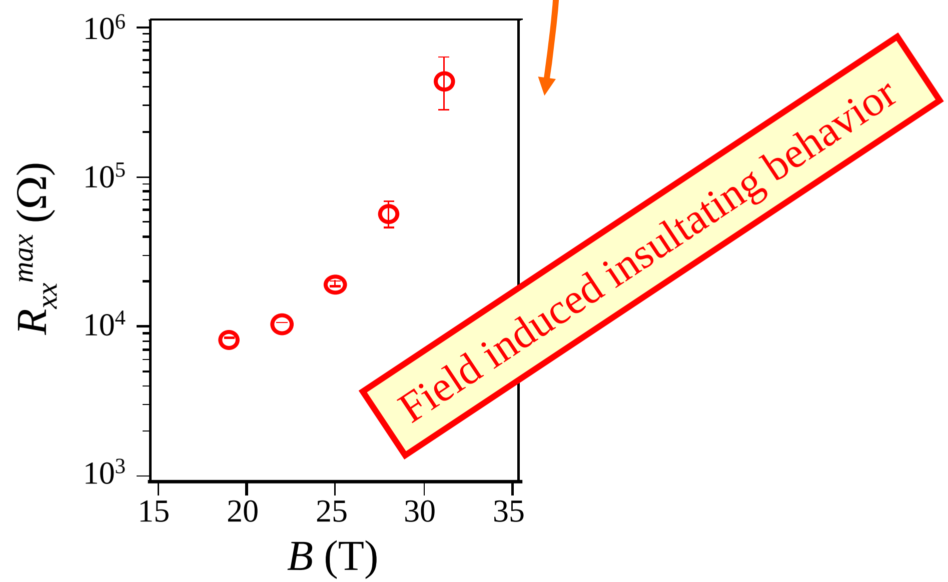
Activation Energy Gap at 31T





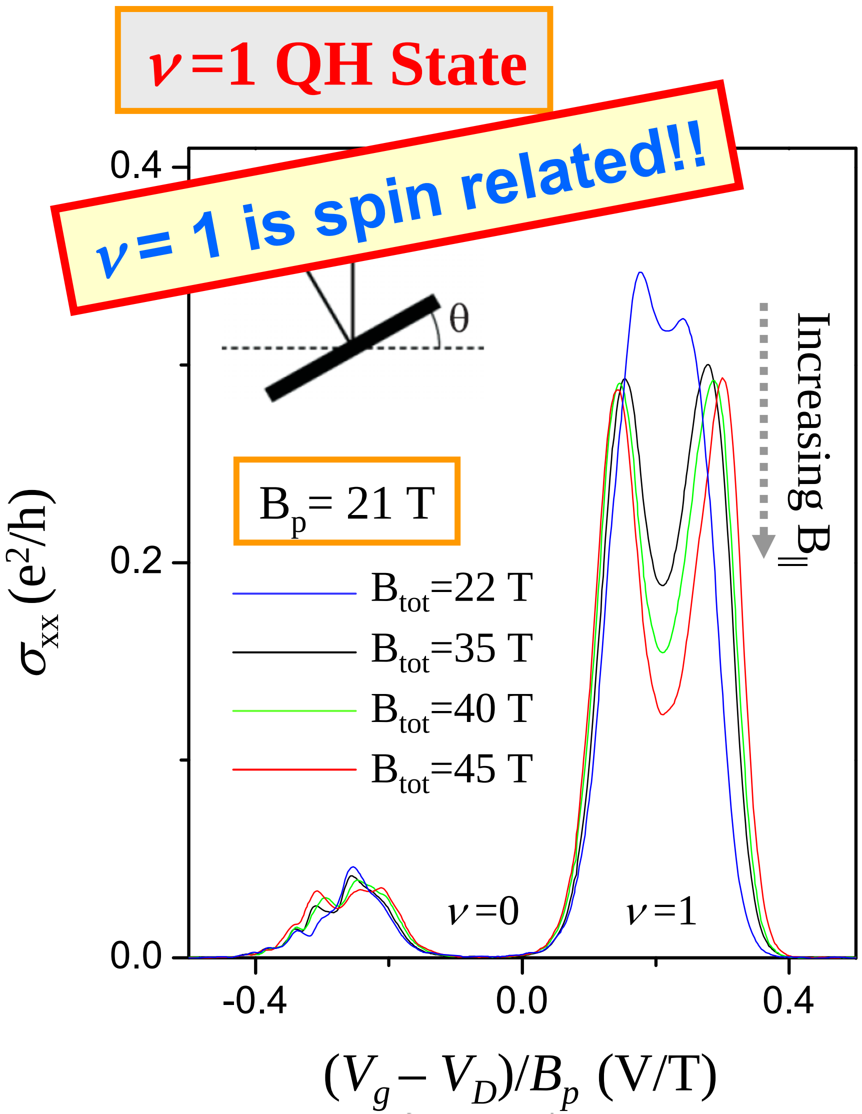
Magnetic Field Dependence

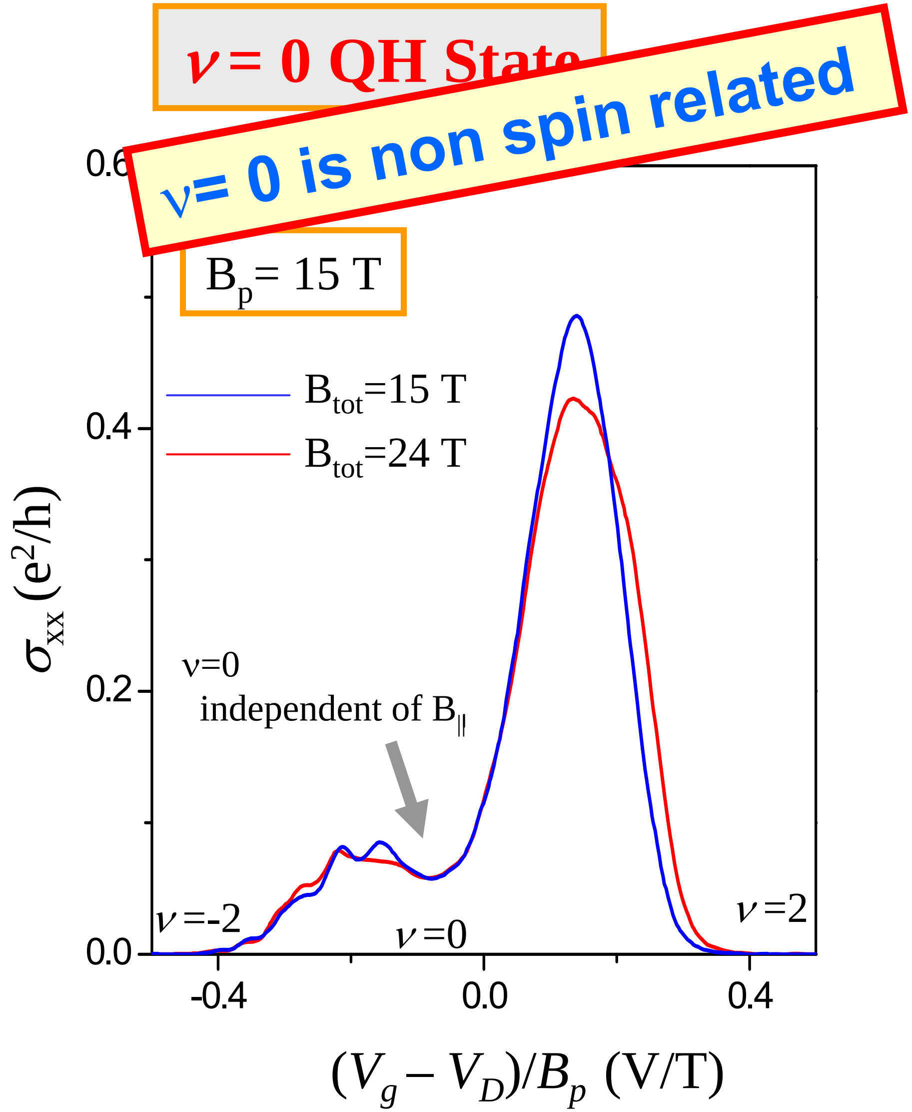




Similar to J. Chekelsky, L. Li, N. P. Ong, PRL (2007) PRB (2008)

Degeneracy Lifting: Spin or Pseudo Spin?



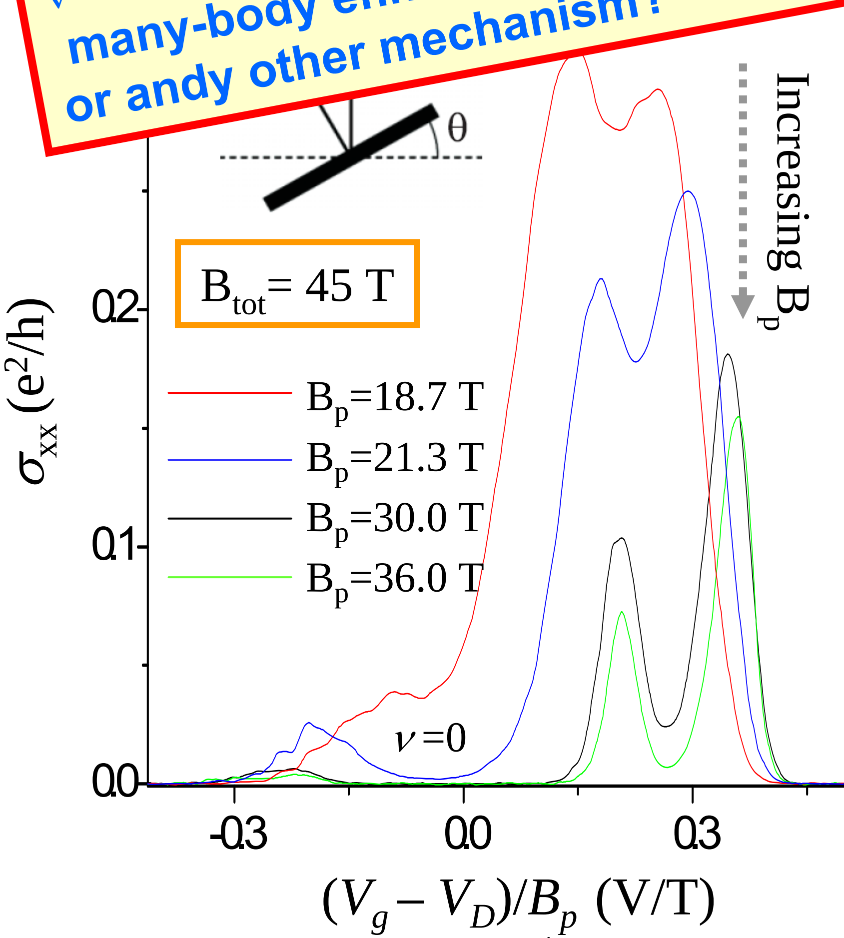


Caveats

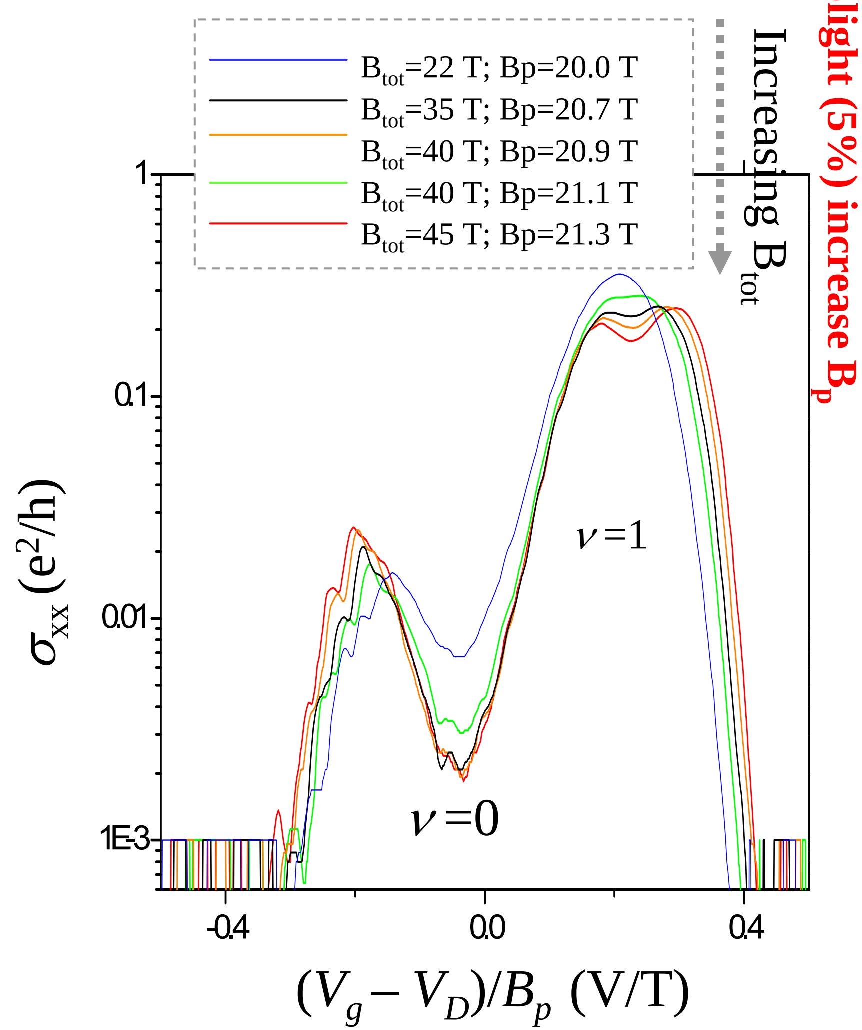
Require < 5% experimental accuracy in tilting angle adjustment…

$\nu = 1$ QH State

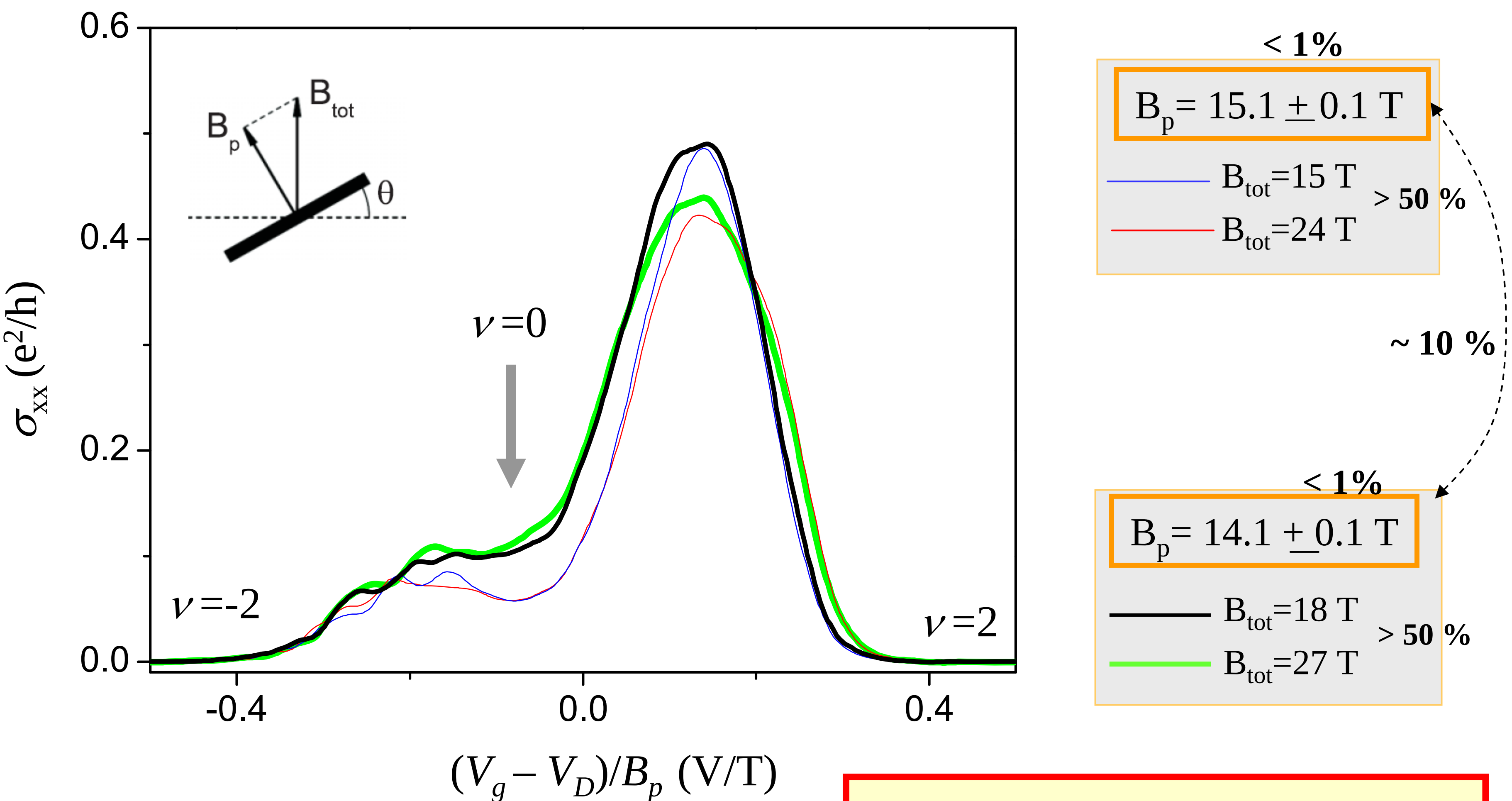
ν= 1 is not bare spin related: many-body enhanced spin effect? or andy other mechanism?



$\nu = 0$ QH State



ν =0 Quantum Hall Splitting: Tilting Angle Adjustment



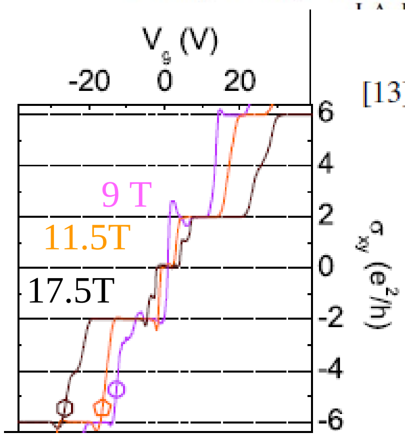
ν= 0 is non spin related

Brief History of LL Symmetry Breaking Hierarchy

PRL 96, 136806 (2006) PHYSICAL REVIEW LETTERS

Landau-Level Splitting in Graphene in High Magnetic Fields

Y. Zhang,[1] Z. Jiang,[1,3] J. P. Small,[1] M. S. Purewal,[1] Y.-W. Tan,[1] M. Fazlollahi,[1] J. D. Chu
...aszczak,[4] H. L. Stormer,[1,2] and P. Kim[1]



[13] The fact that the $\nu = \pm 1$ and $\nu = \pm 4$ ... solved at similar magnetic fields sugg... splitting responsible for these QH stat... same origin.

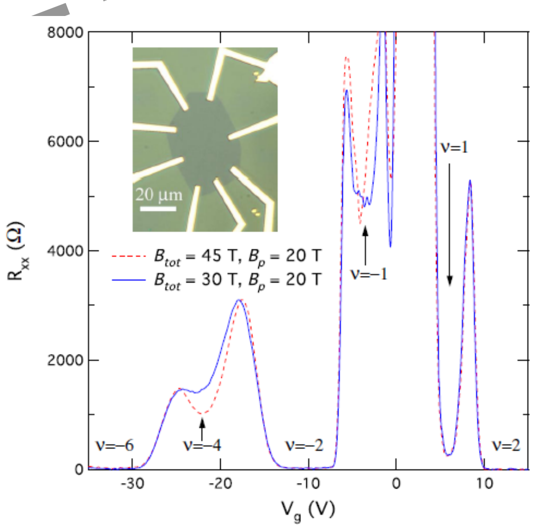
2009 New experimental findings in bulk (Corbino) measurements:

- ν=1 QH state
  -> spin (but manybody enhanced) related
- ν=0 QH state
  -> pseudo spin related

PRL 99, 106802 (2007) PHYSICAL REVIEW LETTERS week ending 7 SEPTEMBER 2007

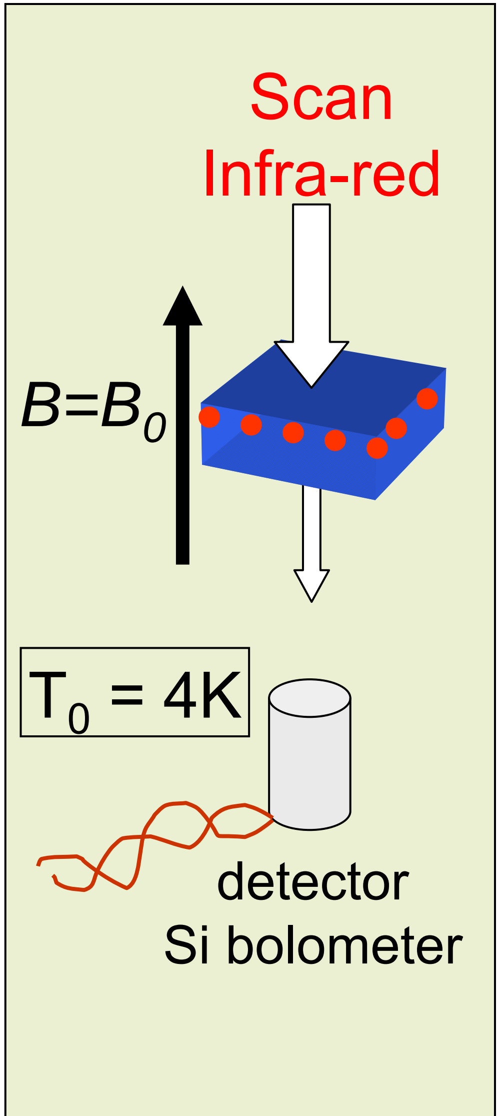
Quantum Hall States near the Charge-Neutral Dirac Point in Graphene

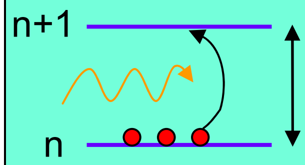
Z. Jiang,[1,2,*] Y. Zhang,[1,†] H. L. Stormer,[1,3,4] and P. Kim[1]



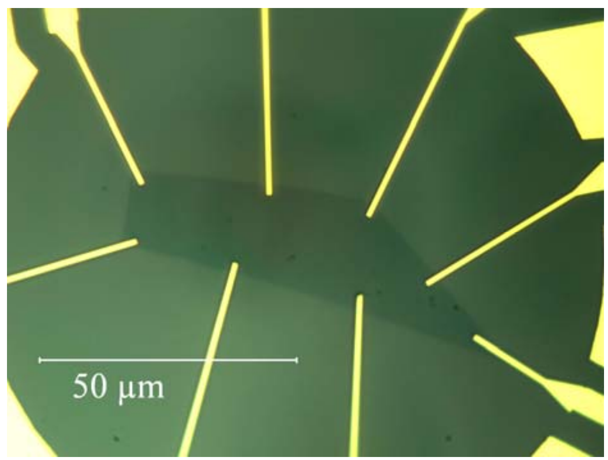
We investigate the quantum Hall (QH) states near the charge-neutral Dirac point of a high mobility graphene sample in high magnetic fields. We find that the QH states at filling factors $\nu = \pm 1$ depend only on the perpendicular component of the field with respect to the graphene plane, indicating that they are not spin related. A nonlinear magnetic field dependence of the activation energy gap at filling factor $\nu = 1$ suggests a many-body origin. We therefore propose that the $\nu = 0$ and ± 1 states arise from the lifting of the spin and sublattice degeneracy of the $n = 0$ Landau level, respectively.

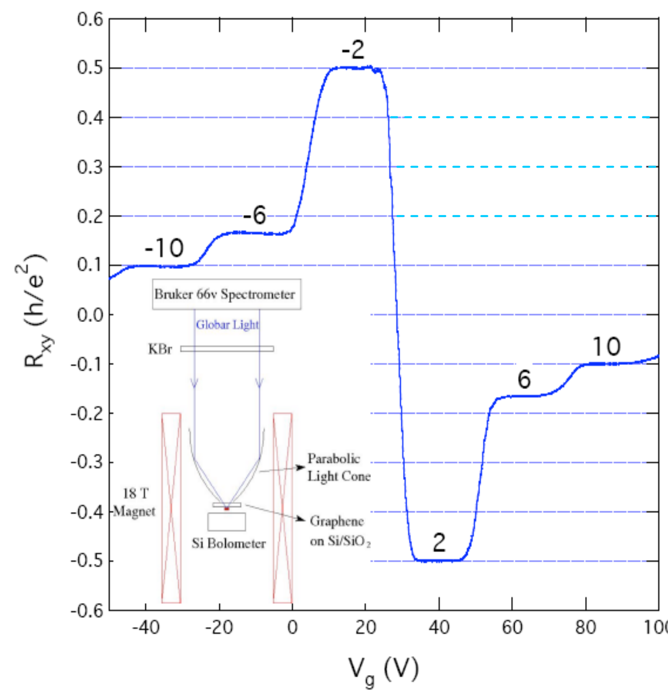
Energy Gap Measurement: Cyclotron Resonance





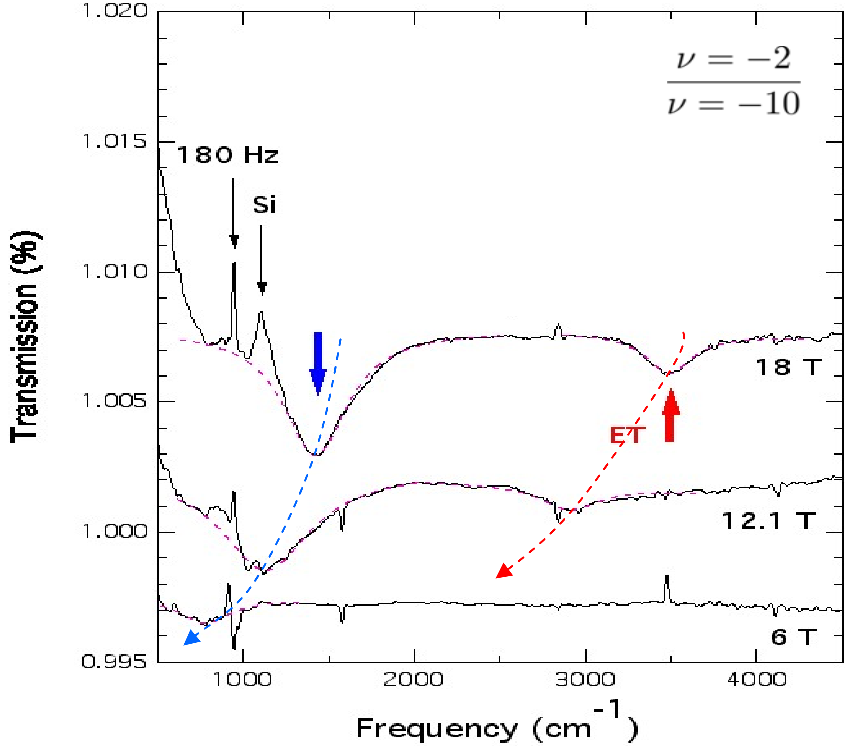
$$\hbar\omega_C = \sqrt{2e\hbar v_F B}\left(\sqrt{n+1}-\sqrt{n}\right)$$

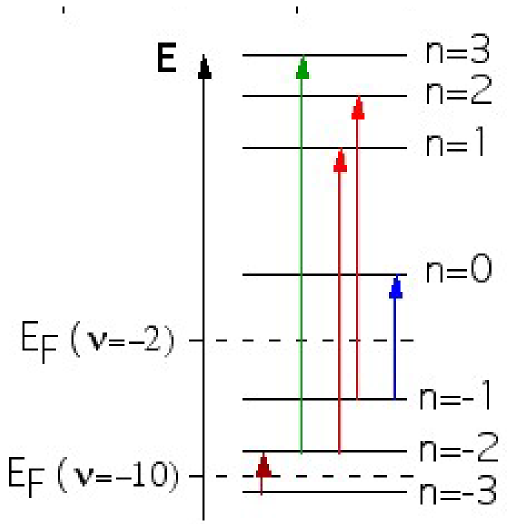




large size: 1000-4000 μm^2
high quality: 7000~17,000 cm^2/Vs

Landau Level Spectroscopy with IR Measurement





R. S. Deacon, K.-C. Chuang, R. J. Nicholas, K. S. Novoselov, and A. K. Geim, Phys. Rev. B **76**, 081406(R) (2007).

Z. Jiang, E. A. Henriksen, L.-C. Tung, Y.-J. Wang, M. E. Schwartz, M. Y. Han, P. Kim, and H. L. Stormer, Phys. Rev. Lett. **98**, 197403 (2007).

E. A. Henriksen, Z. Jiang, L.-C. Tung, M. E. Schwartz, M. Takita, Y.-J. Wang, P. Kim, and H. Stormer, Phys. Rev. Lett **100**, 087403 (2008).

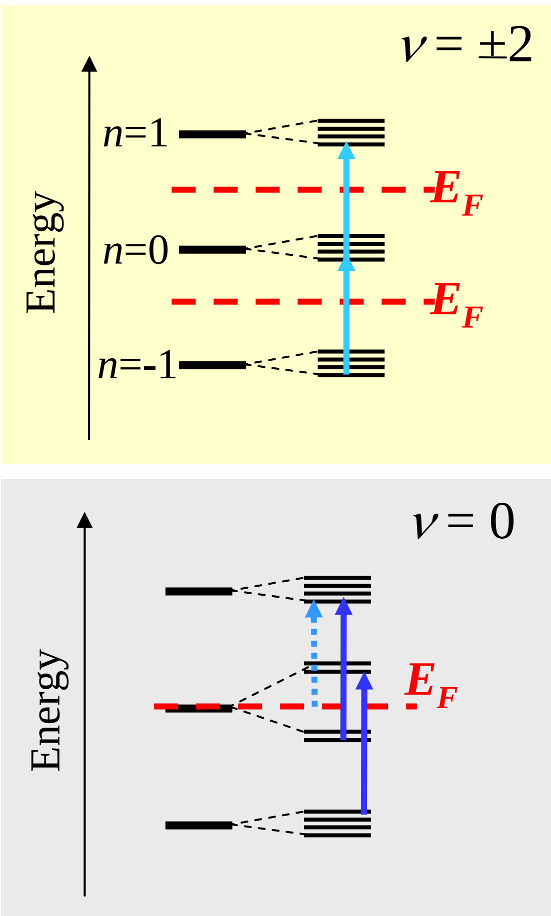
M. L. Sadowski, G. Martinez, M. Potemski, C. Berger, and W. A. de Heer, Phys. Rev. Lett. **97**, 26640? (2006).

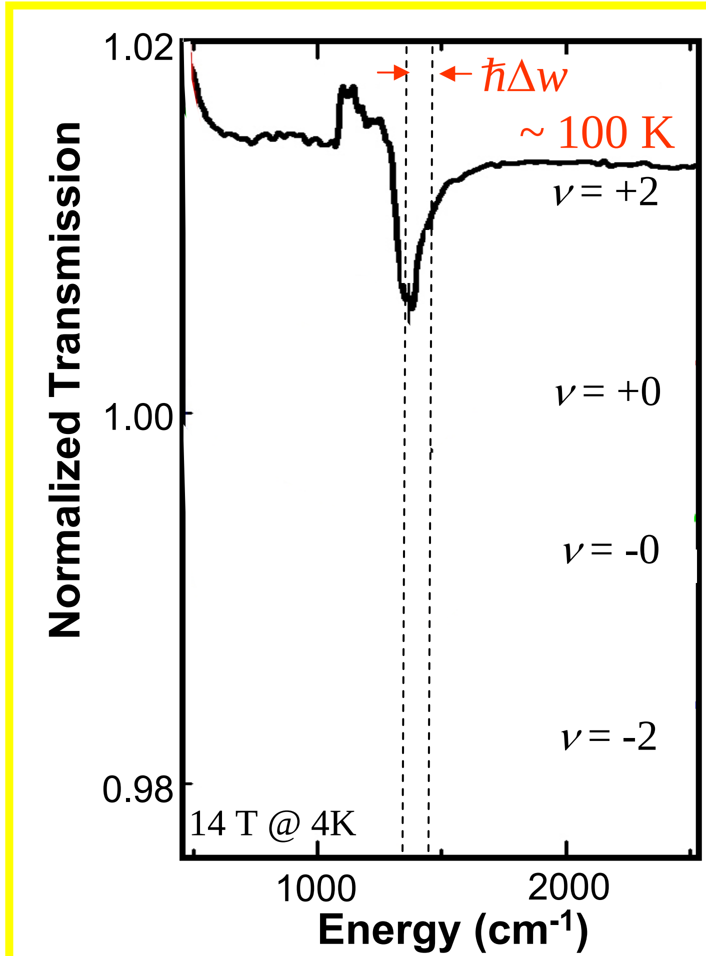
■ ■ ■ ■ ■

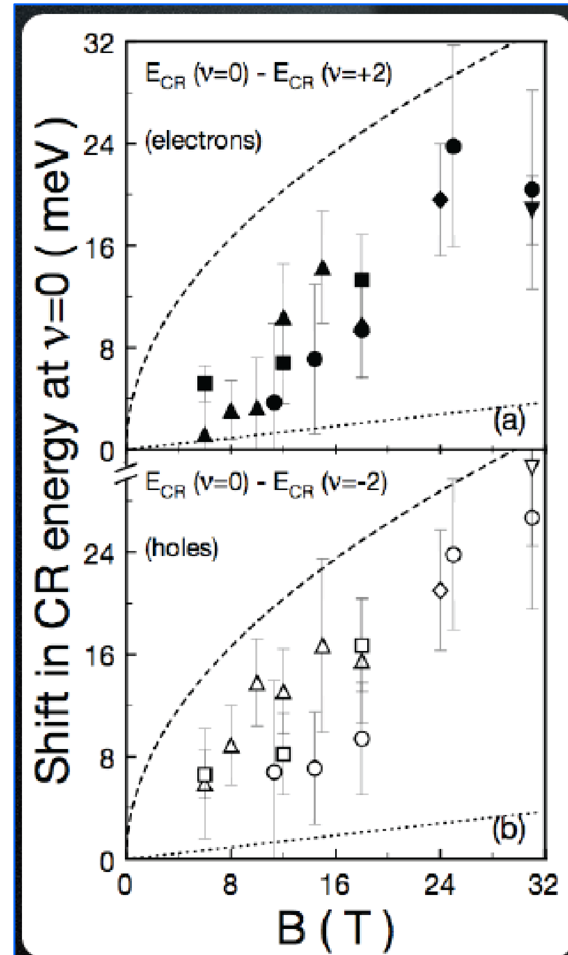
Measuring energy between LL centers in bulk

$\nu = 0$ Gap Measurement by IR Spectroscopy

Landau Level Hierarchy





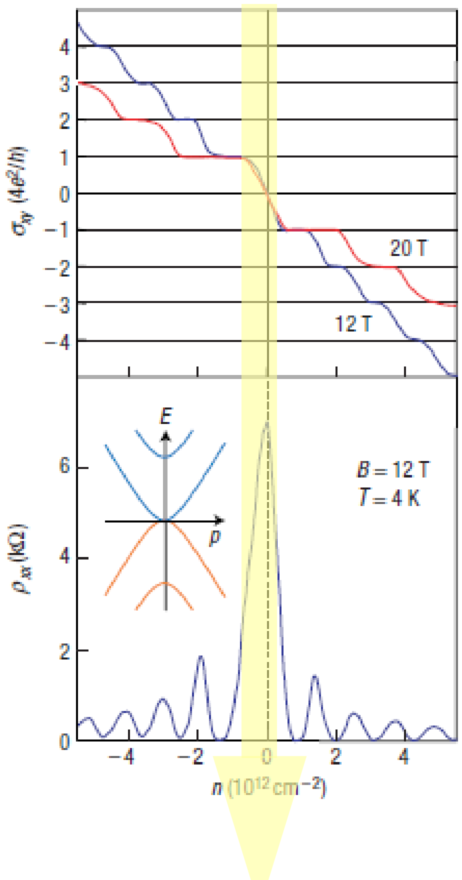


$$\hbar w_{\nu=0} - \hbar w_{\nu=2} = \frac{1}{2}\Delta E_{n=0}$$

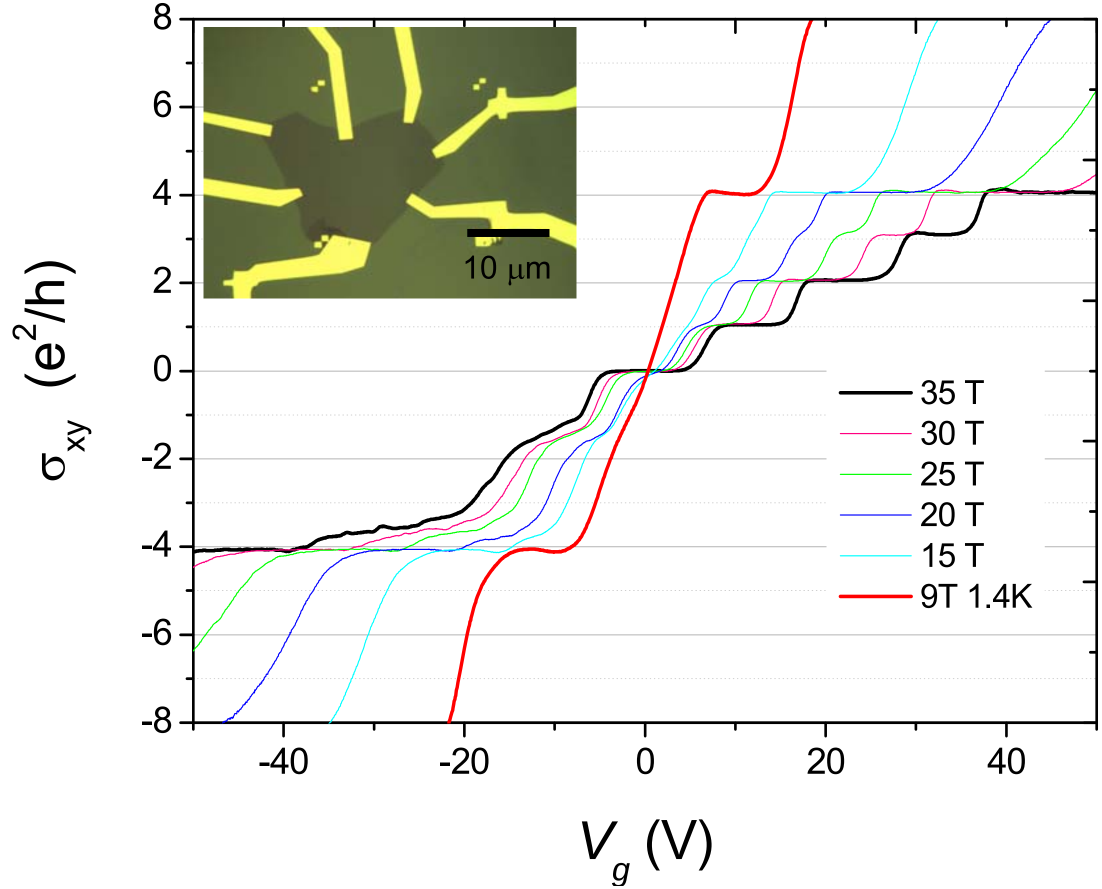
Energy Gap at Dirac Point ~ 300K @ 31 T

Symmetry Breaking of $\nu = 0$ QH state in Bilayer graphene

Bilayer QHE: Novoselov *et al.*, ***Nature Physics* 2,** 177-180 (2006).



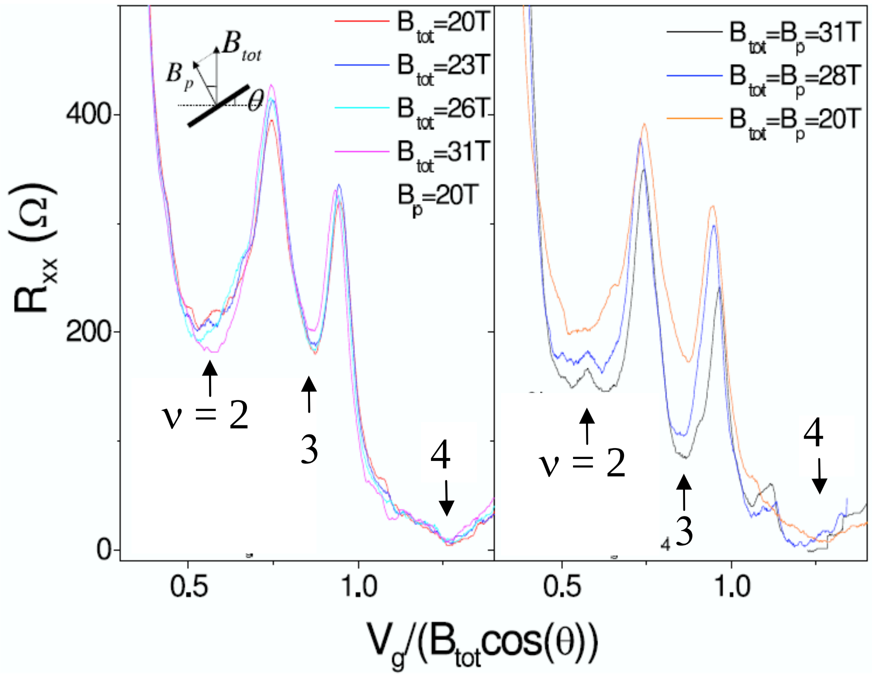
Degeneracy # = 8



- New QH states at higher field:
  ν = 0, ± 1, ±2, ±3, ±4, ±8, …
- All 8 degeneracy of n=0 LL lifted at high magnetic fields

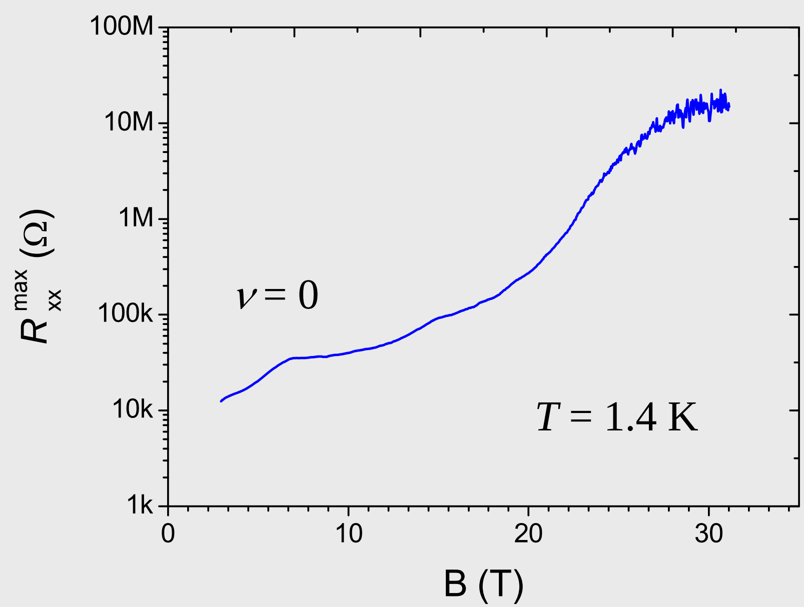
Nature of Symmetry Breaking

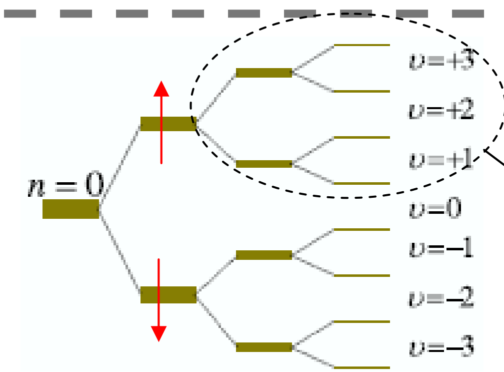
Tilted Field Measurement



Activation Energy Gap

Field induced 'insulating' state at ν=0

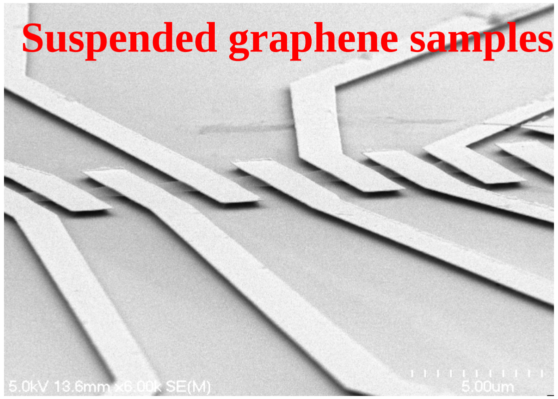




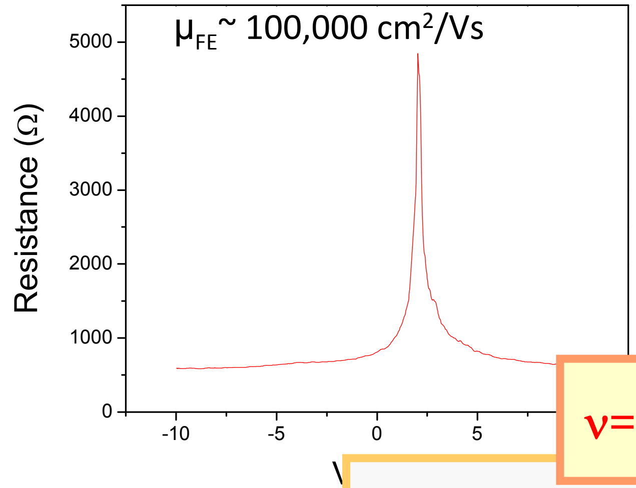
Non spin related symmetry breaking

Theory Yafis Barlas, R. Côté, K. Nomura, and A. H. MacDonald, Phys. Rev. Lett. 101, 097601 (2008).

Quantum Hall Effect in Suspended Graphene



Bolotin et al., (2008); Du et al., (2008)

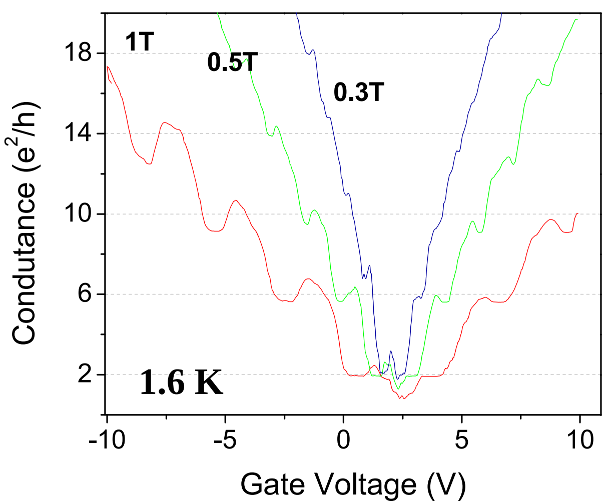


- Cleaning: current annealing
  Bachtold et al. (2007)
- Mechanical stability
  J. Lau et al. (2009)

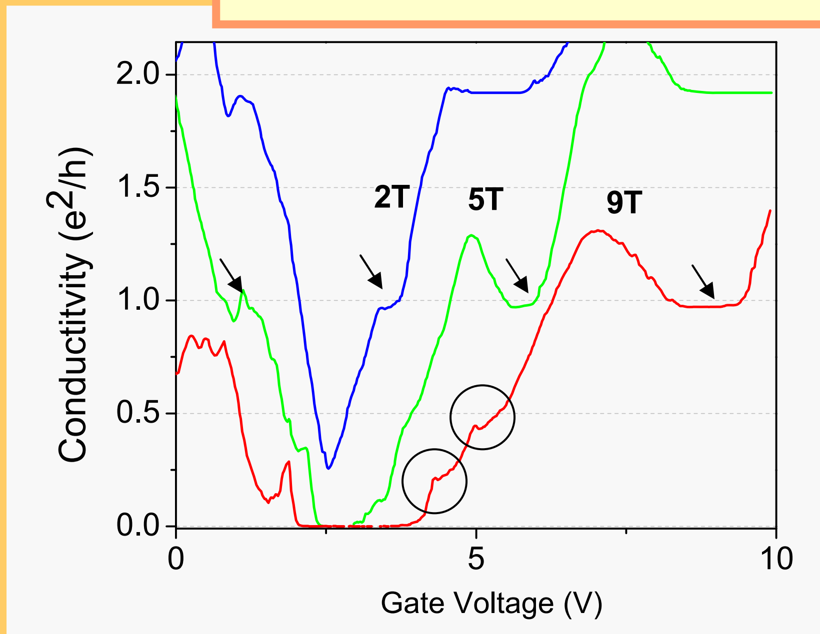
New features for ν < 1

ν=1 states appeared at 2 T !!

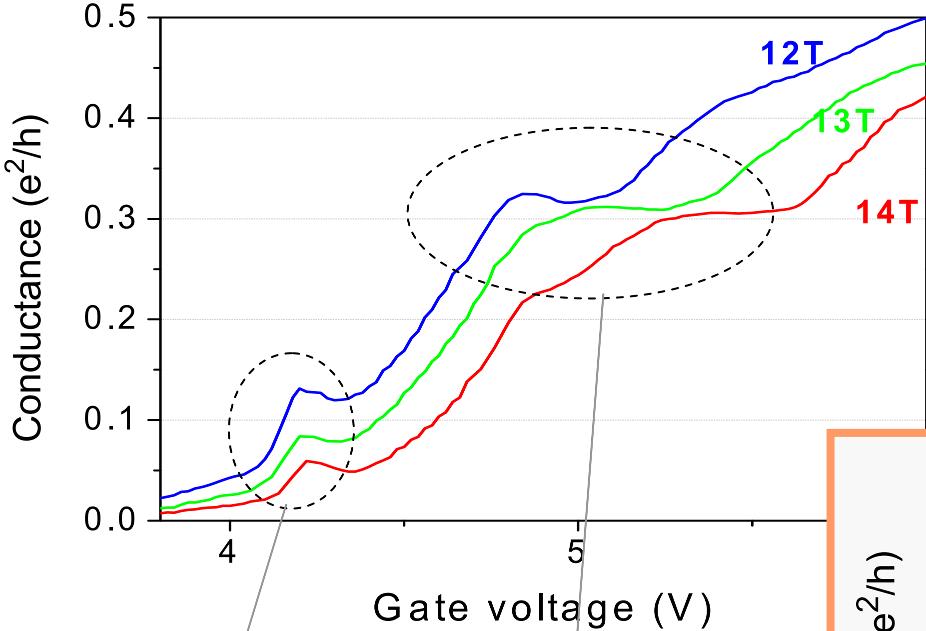
Low Field QHE



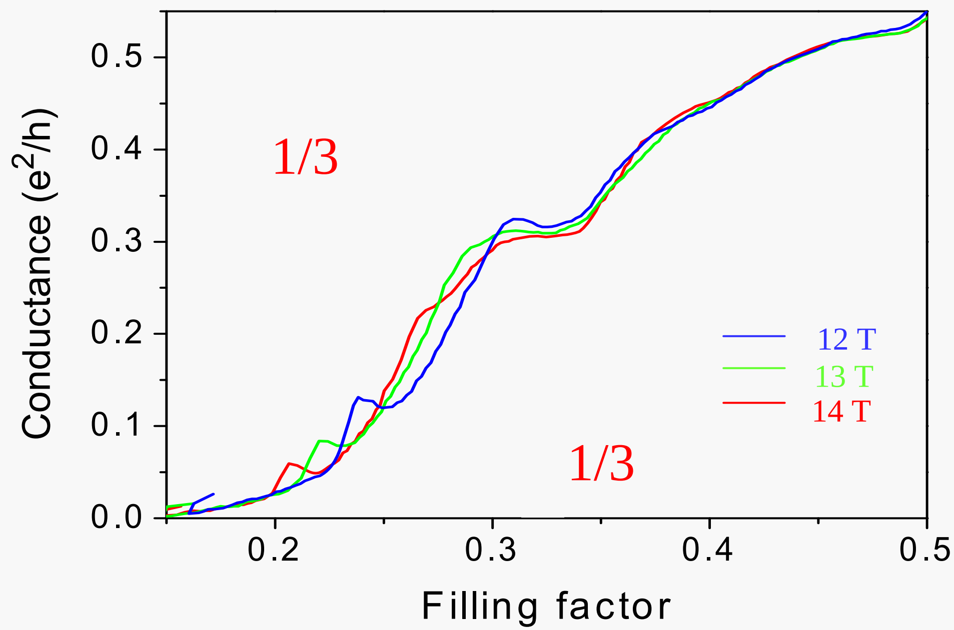
Increasing B



Fractional Quantum Hall State in graphene



ν = 1/3 FQHE observed!

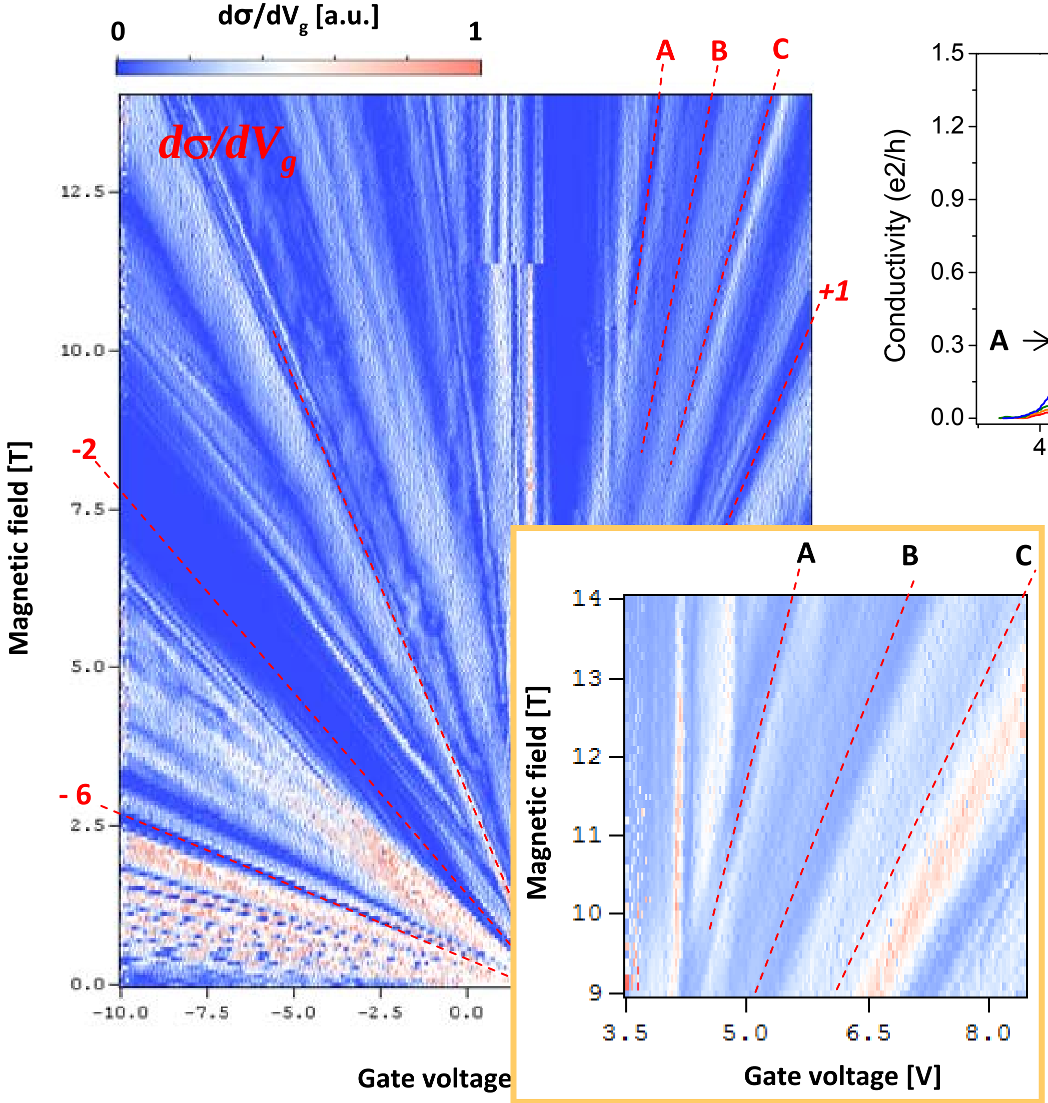


UCF from localized states

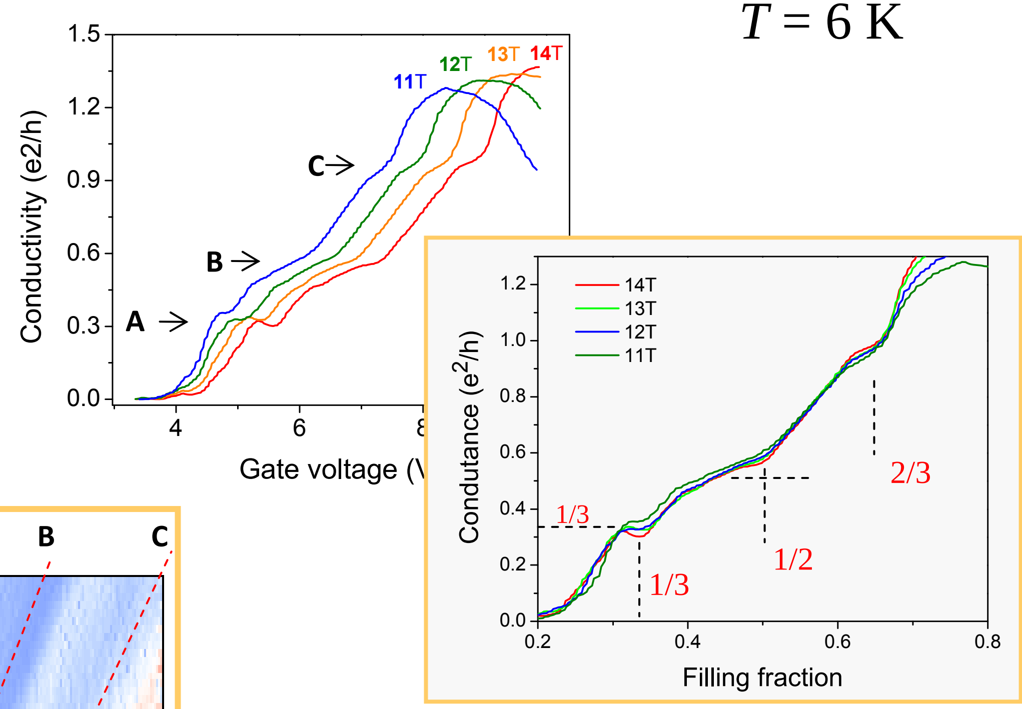
MR from delocalized states
Filling factor:

$$\nu = B/n\,\phi_0$$

Landau Fan Diagram : additional FQH states (?)



$T = 6$ K



Feature	Slope / Slope of 1	Cond. (e2/h)
A	0.32+.04	0.30
B	0.46+.04	0.52
C	0.68+.10	0.97

A → 1/3

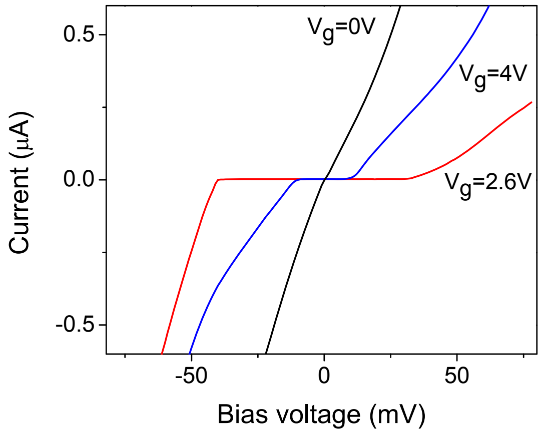
B → ~1/2 (?) ~2/5 (?)

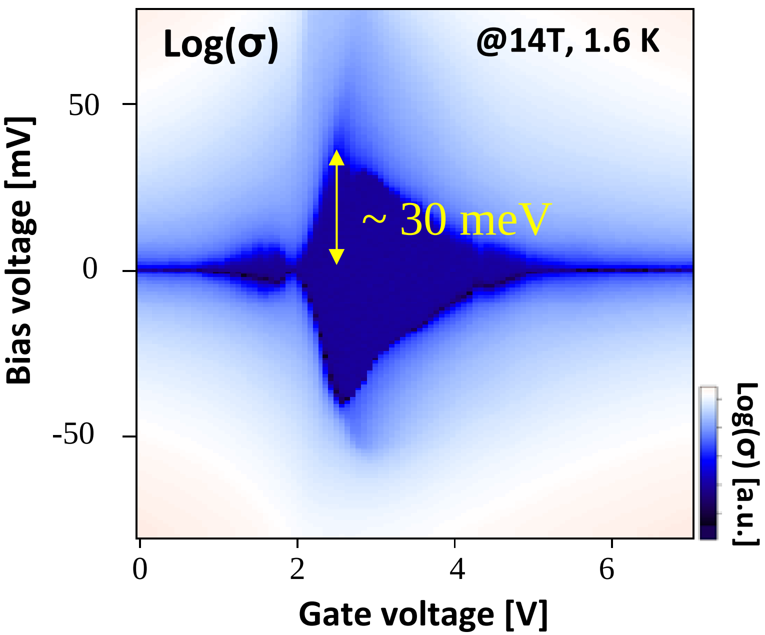
C → ~2/3 (?)

ν

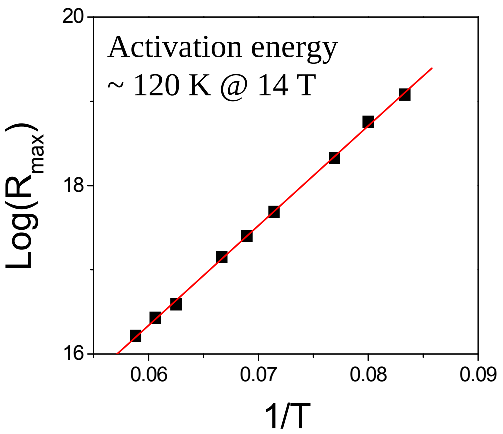
Insulating State at ν = 0: Size of Gap

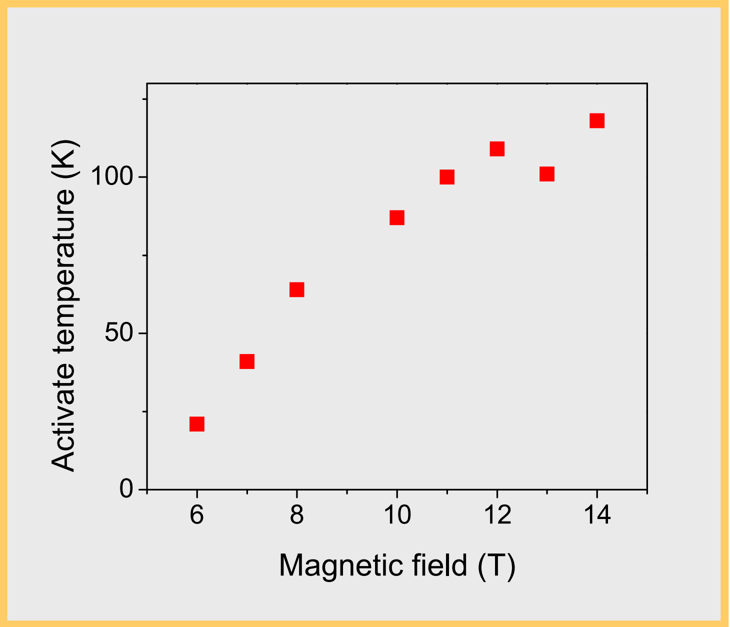
Non-linear transport





Activation Energy





Factor of ~ 10 larger than unsuspended sample, comparable to IR meas.

Summary

Symmetry breaking of zero energy LL in 'bulk' graphene

SU(4) symmetry breaking hierarchy

Pseudo Spin (ν = 0); Spin –manybody enhanced (ν = +/-1)

Insulating bulk state at high magnetic field

IR gap Measurement

Magnetic field dependent 'Bulk Gap' ν = 0 QH state

SU(8) Symmetry breaking in bilayer graphene sample

Spin degeneracy lifting at the charge neutrality point

Fractional Quantum Hall Effect in Suspended Graphene

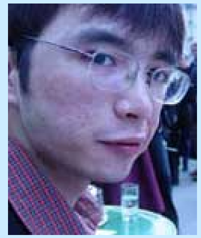
ν = 1/3 FQH state observed

Potential other FQH states 1/3< ν <1

Large gap in the insulating state at ν = 0

Acknowledgement

High magnetic field transport/ Suspended graphene



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