Hierarchy of Spin and Valley Symmetry Breaking in Quantum Hall Single Layer Graphene

arXiv: 0910.1388

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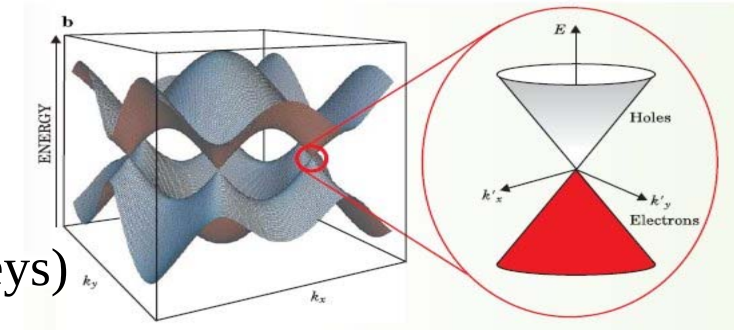
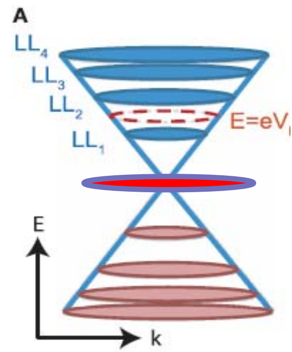
Graphene and Quantum Hall Effect in Graphene

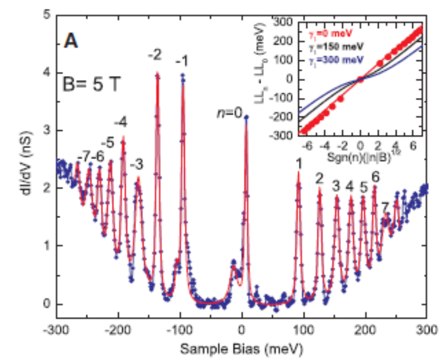
- Graphene --- a single layer of graphite
  - semiconductor on a honeycomb lattice
  - massless **Dirac**-fermion band structure
  - Two **inequivalent** points **K** and **K'=-K** (valleys)



- In a perpendicular magnetic field B,
  - the spectrum is quantized into **Landau Levels**:

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





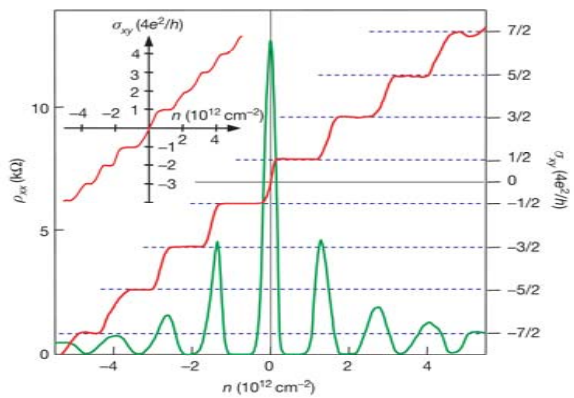
Stroscio group, Science **324,** 924 (2009)

  - a quantiezed **Hall conductance**

$$\sigma_{xy} = \nu\frac{e^2}{h}\ ,\ \nu = \pm 4\cdot(n+\frac{1}{2})$$

LL degeneracy: spin&valley

  - n=integer => ν=…-6,-2,2,6,10
- Central Landau Level n=0, E_n=0, ν=-2,+2



Y. Zhang,et.al, Nature 438, 201(2009)

K.S.Novoselov,et.al, Nature 438,197(2009)

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"Only problem" in graphene QHE

- The spin+valley symmetry of the central LL breaks down at higher magnetic field

- Conductance steps at

  -2, +2

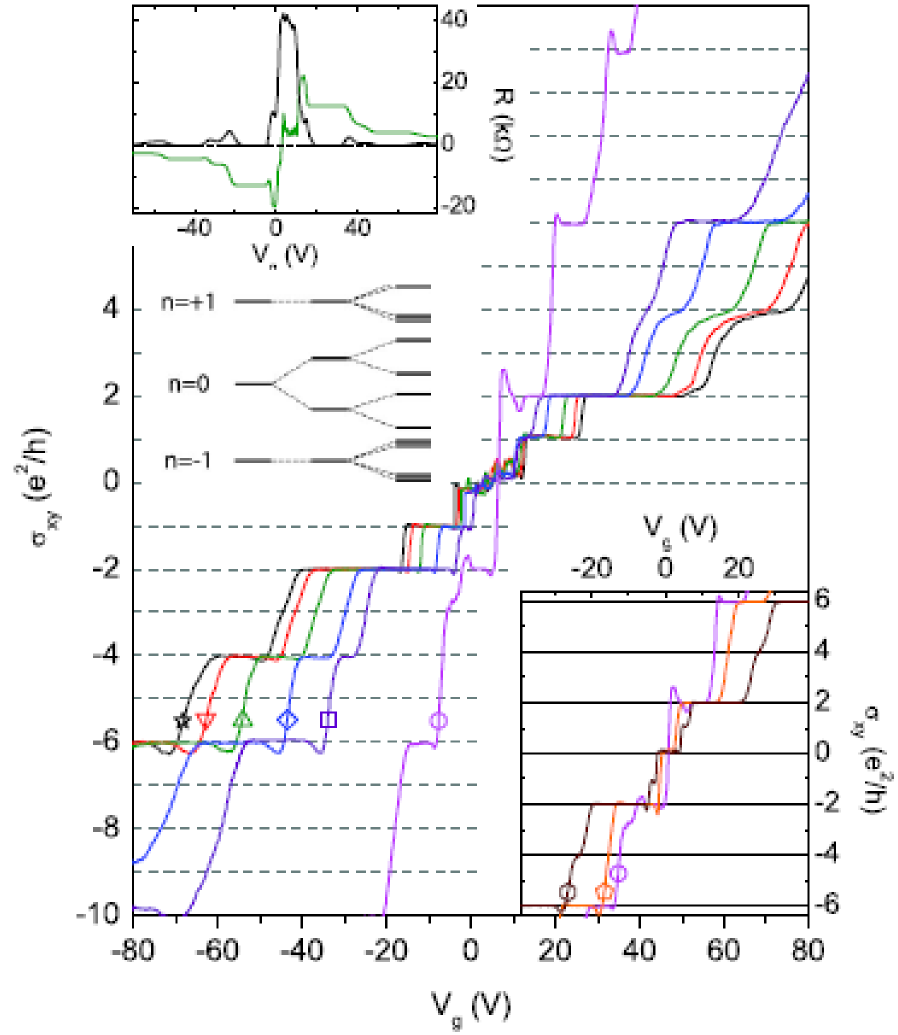
- Conductance steps at

  -2, 0, +2

- Conductance steps at

  -2, -1, 0, 1, 2

B



Y. Zhang, et, al., PRL **96,** 136806 (2006)

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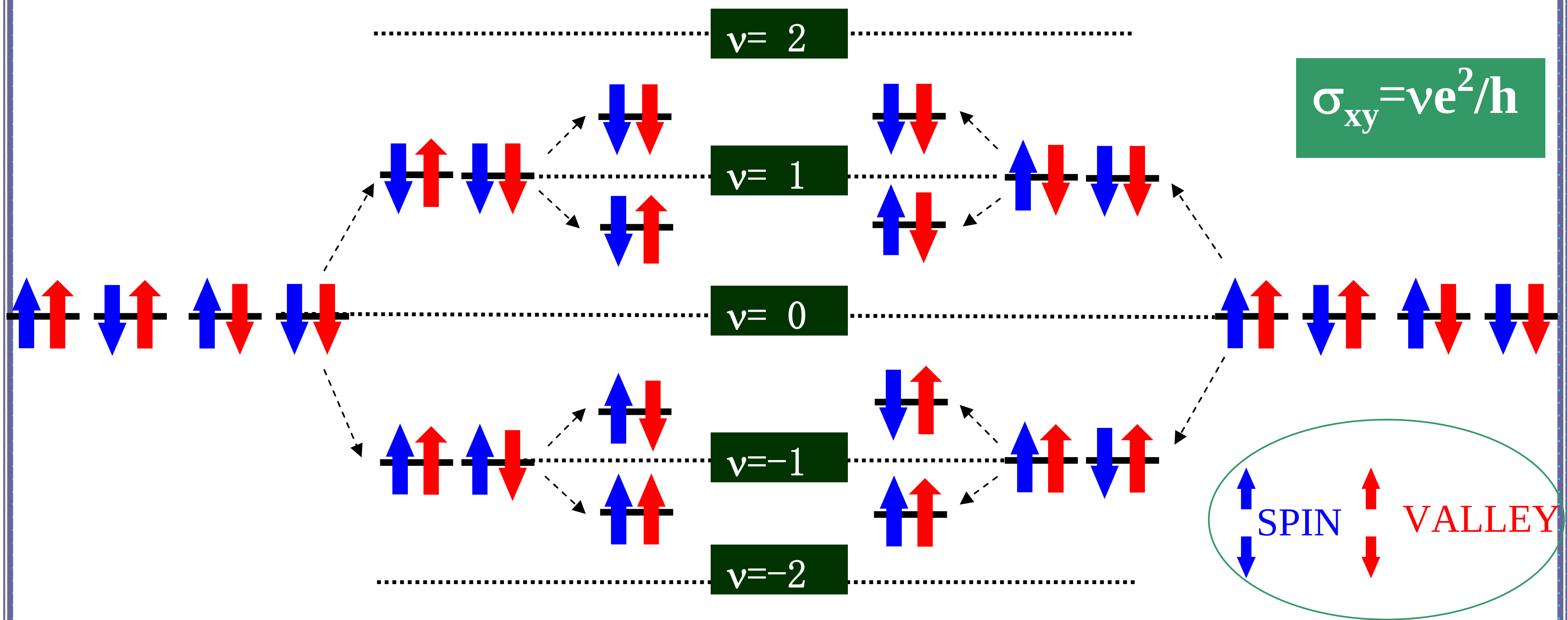
Which symmetry will be broken first, Spin or valley?

Spin+Valley symmetry ⇨ Valley symmetry ⇨ All symmetries broken ⇦ Spin symmetry ⇦ Spin+Valley symmetry



J.G.Checkelsky,L. Li,N.P.Ong, PRL 100,2008
PRB 79, 2009
J. Fuchs, P.Lederer, PRL 98, 2007

D.A. Abanin,P.A.Lee,L.S.Levitov,PRL 96,2006
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Z.Jiang,Y.Zhang,et.al, PRL 99, 2007

Mechanisms of symmetry breaking

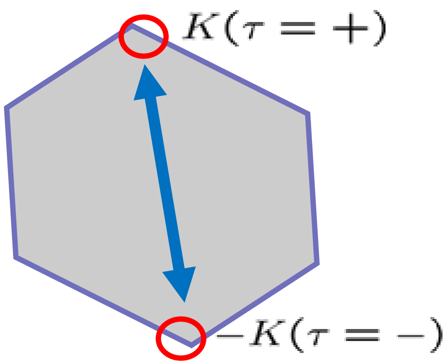
- LL n=0 ➔ Kinetic energy is quenched
- Hamiltonian governing LL physics consists of

σ=spin index
τ=valley index

- Coulomb exchange (dominant) H^{EX}
- Zeeman interaction $H^{B} \sim \sum_{\sigma\tau} \sigma B_{\sigma} \Psi^{\dagger}_{\sigma\tau}(r)\Psi_{\sigma\tau}(r)$
- Valley-scattering impurity $H^{imp} \sim \sum_{\sigma\tau} \tau V(r)\Psi^{\dagger}_{\sigma\tau}(r)\Psi_{\sigma\tau}(r)$
- Electron-phonon coupling $H^{el-ph} \sim \sum_{\sigma\tau} \lambda u_{2K}\Psi^{\dagger}_{\sigma\tau}(r)\Psi_{\sigma\bar{\tau}}(r)$

If phonon condenses (Kekule distortion), it will generate effective valley-polarizing field, much like spin-polarizing Zeeman field!

$$\sim \sum_{\sigma\tau} \lambda\langle u_{2K}\rangle \Psi^{+}_{\sigma\tau}\Psi_{\sigma\bar{\tau}} \sim U \sum_{\sigma\tau} \Psi^{+}_{\sigma\tau}\Psi_{\sigma\bar{\tau}}$$



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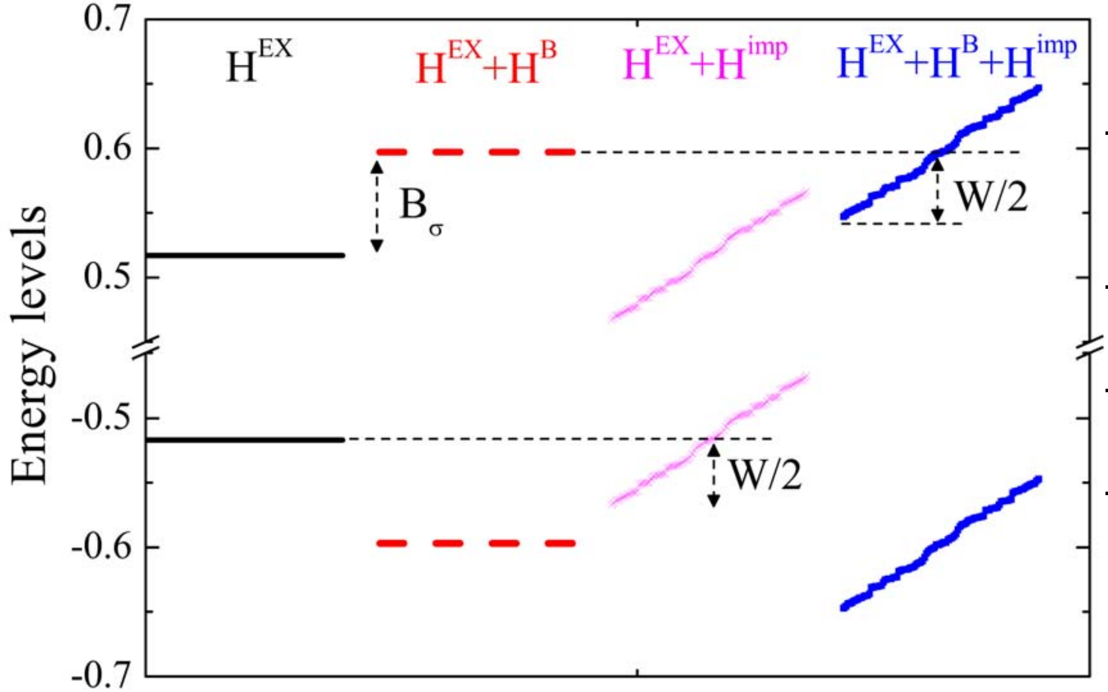
K. Nomura, S. Ryu, and D.-H. Lee, arXiv:0906.0159v1

Self-consistent Hartree-Fock theory(SCHFT)

- Energy levels at half-filling from self-consistent solutions



- The number of flux through the lattice is N_ϕ =50
- The impurity broadening is W=0.1
- The Zeeman field is B_σ=0.08
- H^{EX}->E^{EX}~0.52

- H^{EX} alone, the initial 4-fold degeneracy of the LL is split into two sublevels : $\pm E^{EX}$
- Inclusion of Zeeman field to Coulomb exchange => spin-SU(2) symmetry is broken
- Valley-scattering impurity does not result in additional splitting levels and gives rise to broadened energy levels of width W.

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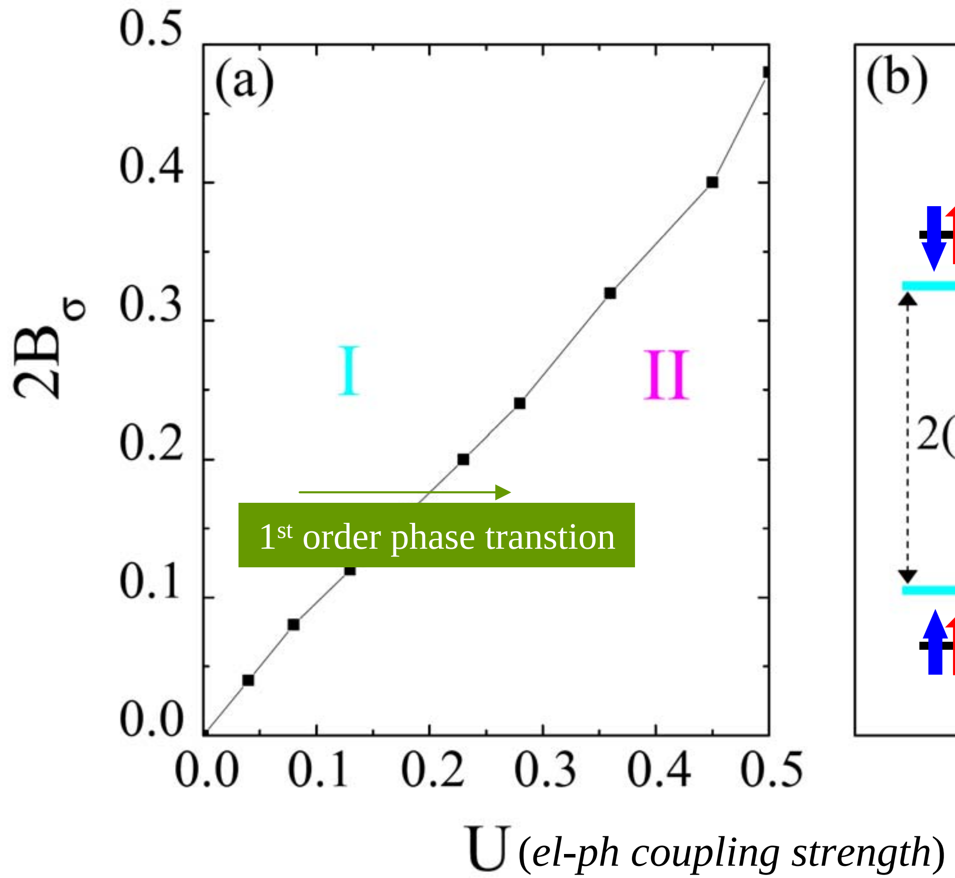
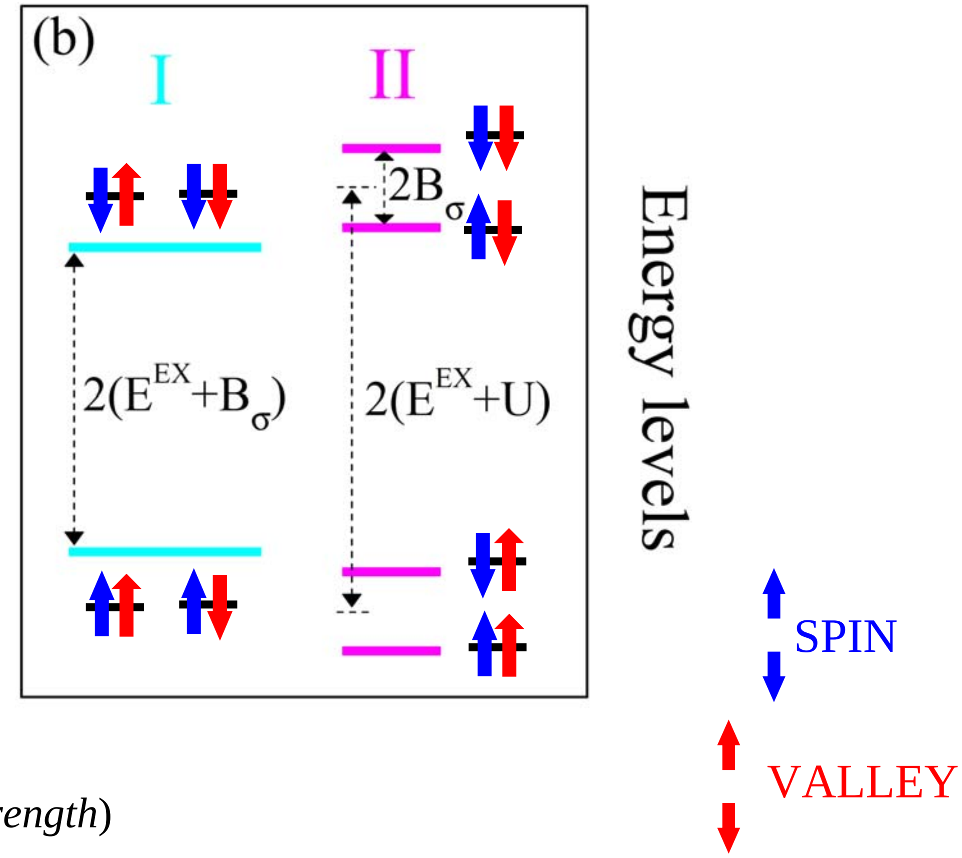
SCHFT: $H^{EX}+H^{el\text{-}ph}+H^{B}$ (half-filling case)

(a) Phase diagram of the CLL(n=0) (b) Schematic energy levels





- In I, Zeeman effect dominates, spin-polarized level splitting
- In II, el-ph interaction U dominates, main polarization direction is along valley axis

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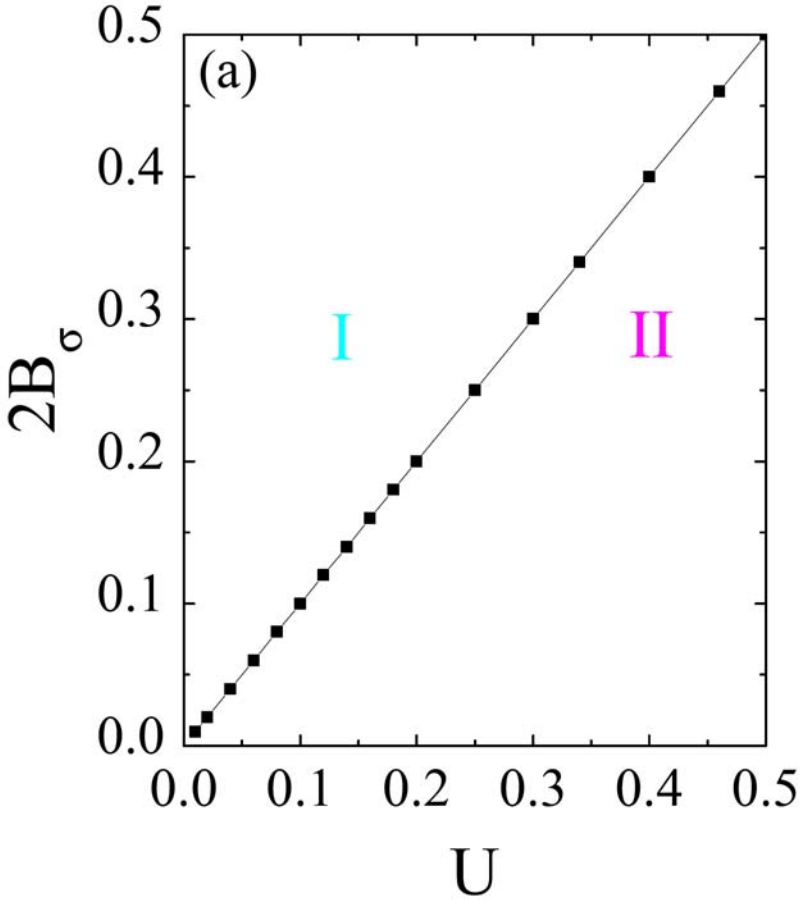
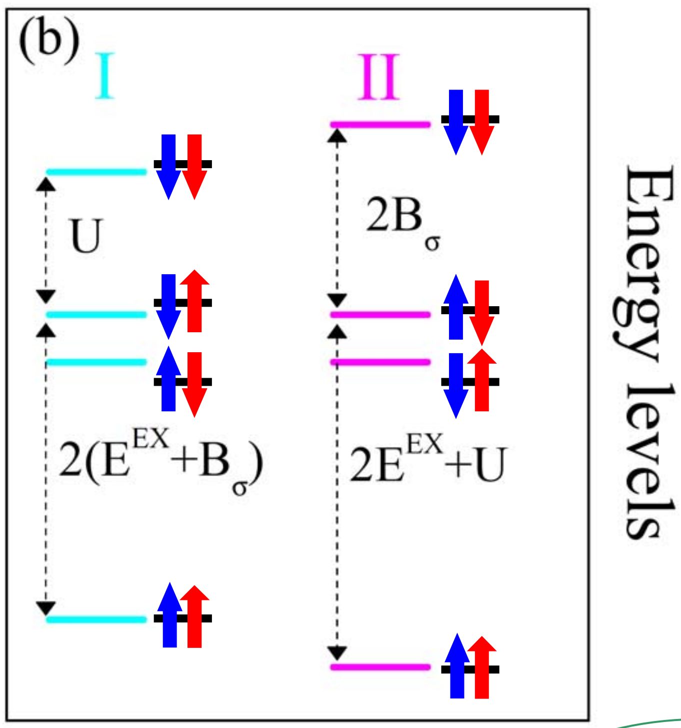
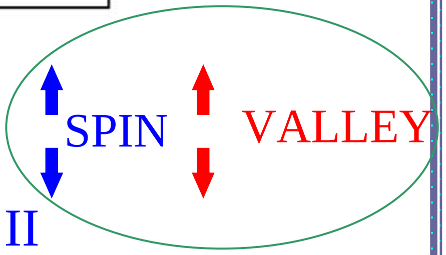
SCHFT: $H^{EX}+H^{el\text{-}ph}+H^{B}$ (quarter-filling case)







"valley-first" –split region I ⟷ "spin first" –split region II

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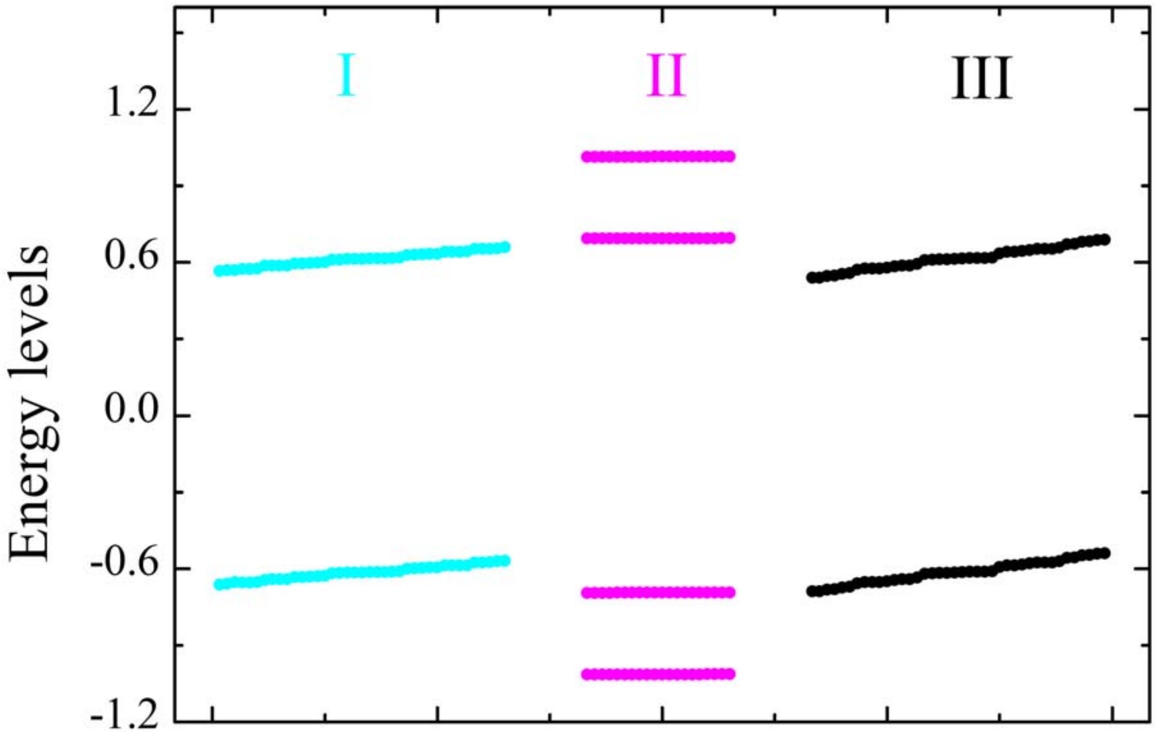
SCHFT: $H^{EX}+H^{el\text{-}ph}+H^{B}+H^{imp}$(half-filling case)

- Schematic energy levels



I: $(2B_\sigma,U)=(0.32,0.36)$, W=0.1

II: $(2B_\sigma,U)=(0.32,0.4)$, W=0.1

III: $(2B_\sigma,U)=(0.32,0.4)$, W=0.15

$(2B_\sigma,U)=(0.32,0.4)$, $W_c=0.12$

- In region I , the impurity does not alter the basic features of phase diagram ($2B_\sigma$, U),
- In region II, the impurity does not alter the features of phase diagram (2Bs, U) when $W<W_c$,
- When $W>W_c$ the original 4-fold splitting levels in region II disappear => Region III.

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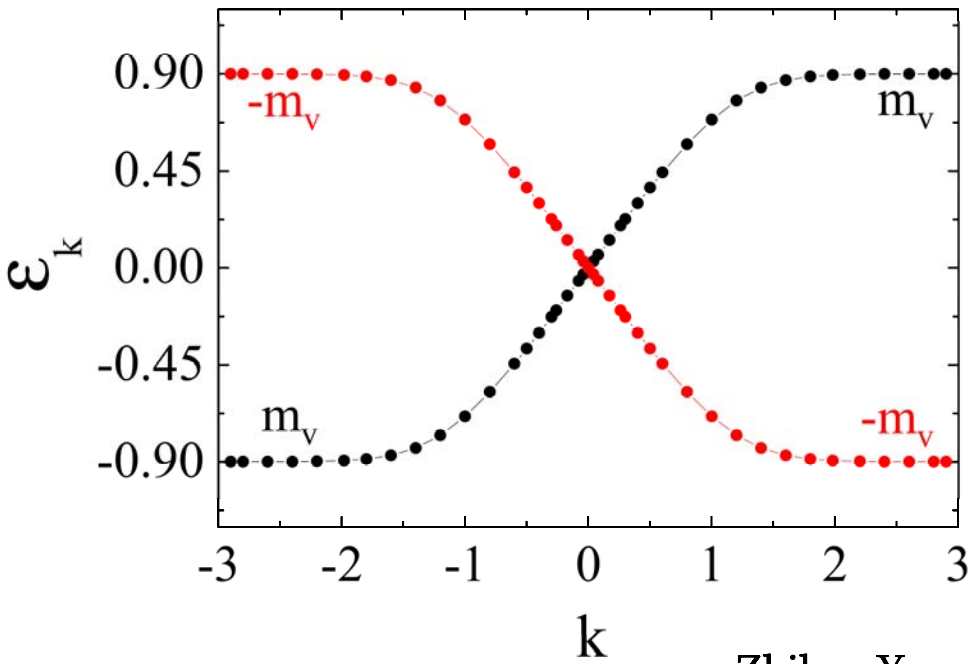
Midgap states beween LL of opposite valley polarties

- Valley domain walls may exist because E(σ,τ)=E(σ,-τ) due to Zeeman splitting
- Considering a spinless case first,

$$
\begin{aligned}
-i(y_k + \partial_y)v_+ + m(y)v_- &= \varepsilon_k u_+ \\
-i(y_k - \partial_y)v_- + m(y)v_+ &= \varepsilon_k u_- \\
i(y_k + \partial_y)u_- + m(y)u_+ &= \varepsilon_k v_+ \\
i(y_k - \partial_y)u_+ + m(y)u_- &= \varepsilon_k v_+
\end{aligned}
$$



Mass gap : $m(y) = m_v(y>0)$
$= -m_v(y<0)$

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Conlusion and Outlook

- Several microscopic mechanisms are explored=>breaking n=0 4-fold LL degeneracy in a single-layer graphene

  Coulomb exchange, Zeeman interaction, valley-scattering impurity, electron-phonon interaction

- The competitive nature of the valley-splitting(el-ph interaction) and spin-splitting(Zeeman interaction) leads to a phase diagram

  Either "spin first" or "valley first" level splitting

- Gapless states exist when LLs with opposite valley polarities form a domain wall

- Our calculation suggests full LL splitting implies CDW order

- Graphene QHE in single and bilayers shows interesting symmetry breaking pattern

  Bilayer case will be more complicated