Quantum Parity Hall Effect in ABA trilayer graphene

Yafis Barlas
University of Nevada, Reno

P. Stepanov, Y. Barlas, C. N. Lau et. al., Phys. Rev. Lett. (2016)
Y. Barlas, Phys. Rev. Lett. (2018)
P. Stepanov, Y. Barlas, A. H. M., C. N. Lau et. al., PNAS (2019)

U.S. DEPARTMENT OF ENERGY
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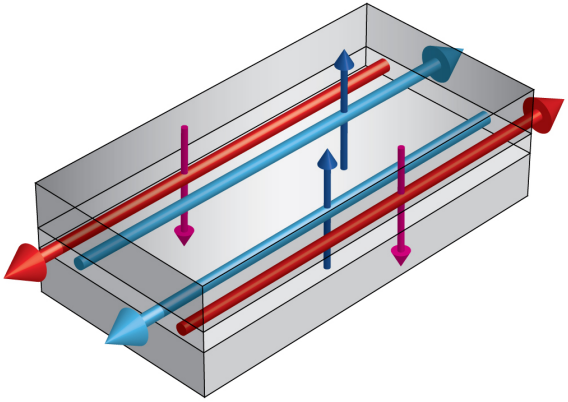
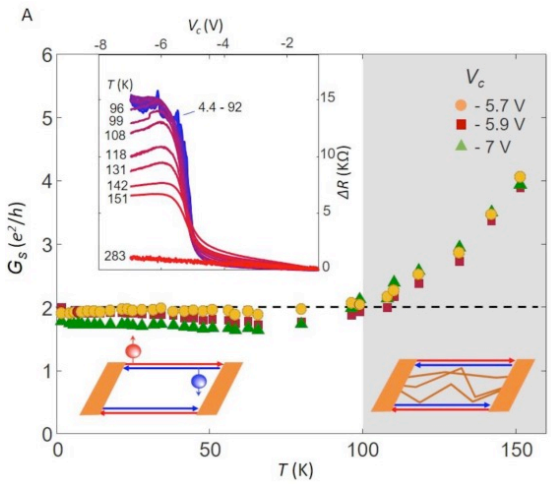
Symmetry protected topological phases (Graphene)

Time reversal symmetry (TMD spin Hall state)





Kane and Mele PRL (2005); Pablo Jarillo-Herrero group (2017)

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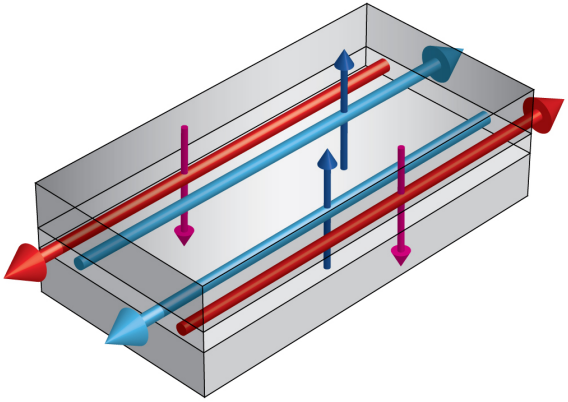
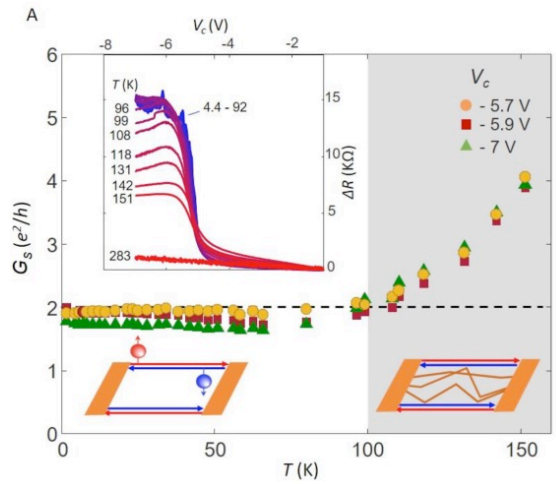
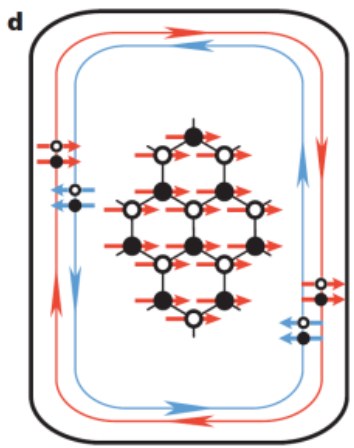
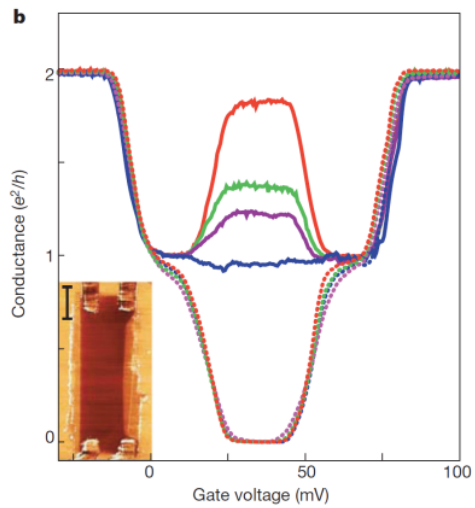
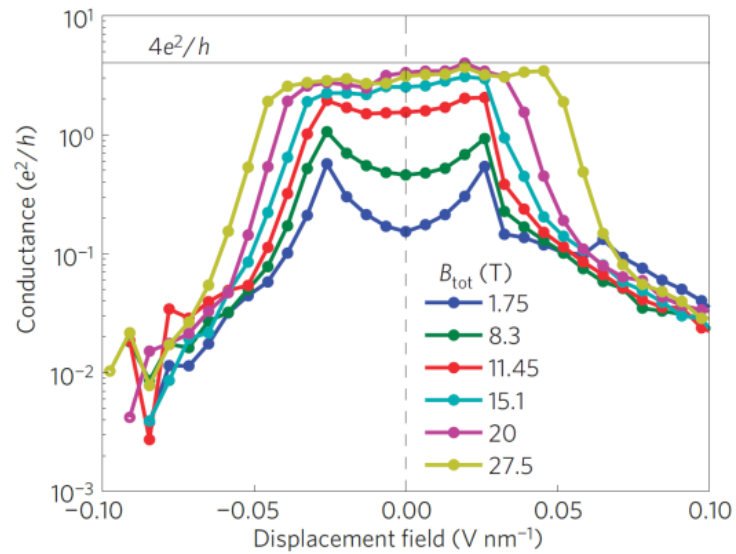




Spin rotational symmetry



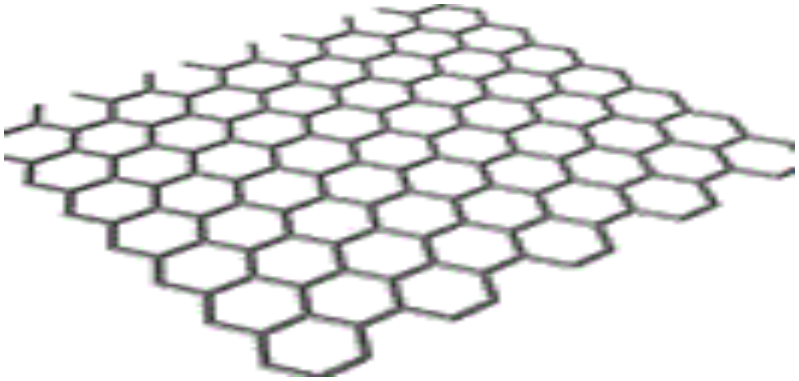


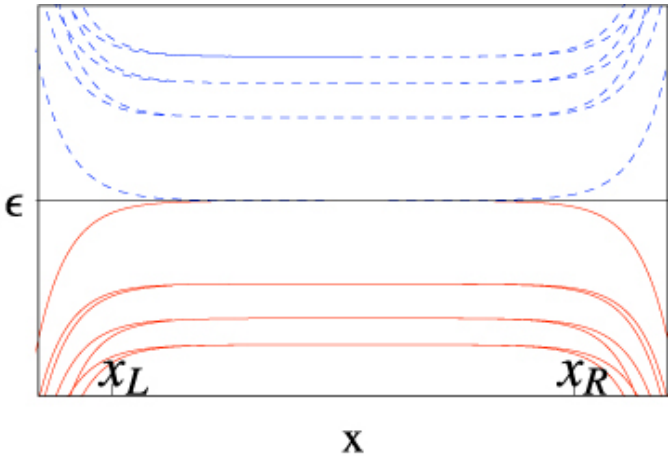


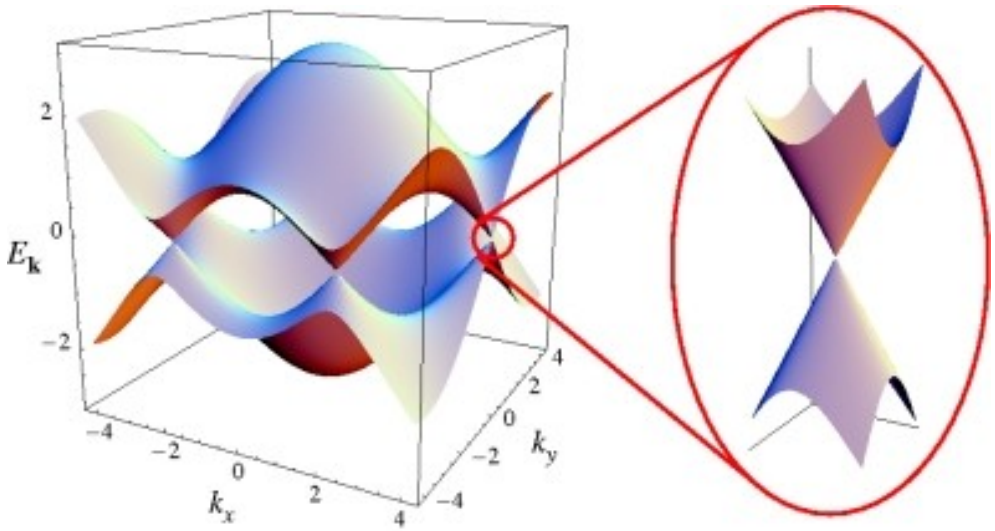
What about other symmetries? Crystal lattice symmetry

M. Khartinov PRL (2012); A. F. Young et. al. Nature (2014); P. Maher et. al. Nat. Phys (2013)

Dirac Fermions: Graphene Landau levels







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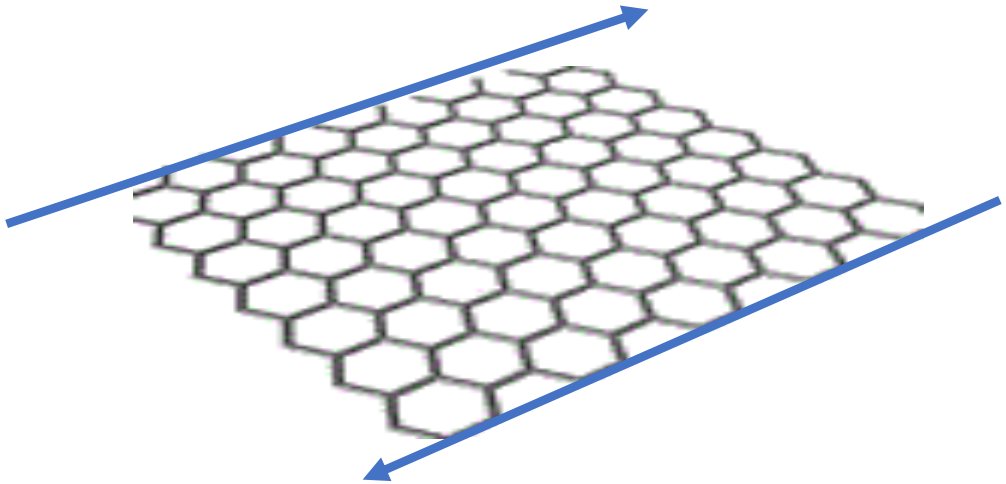

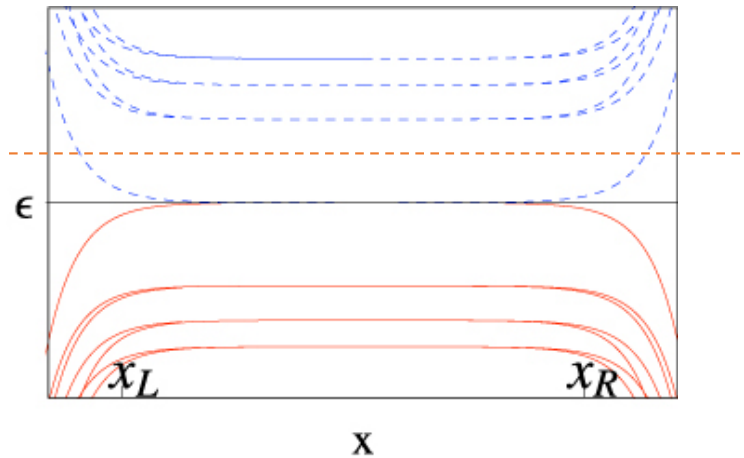

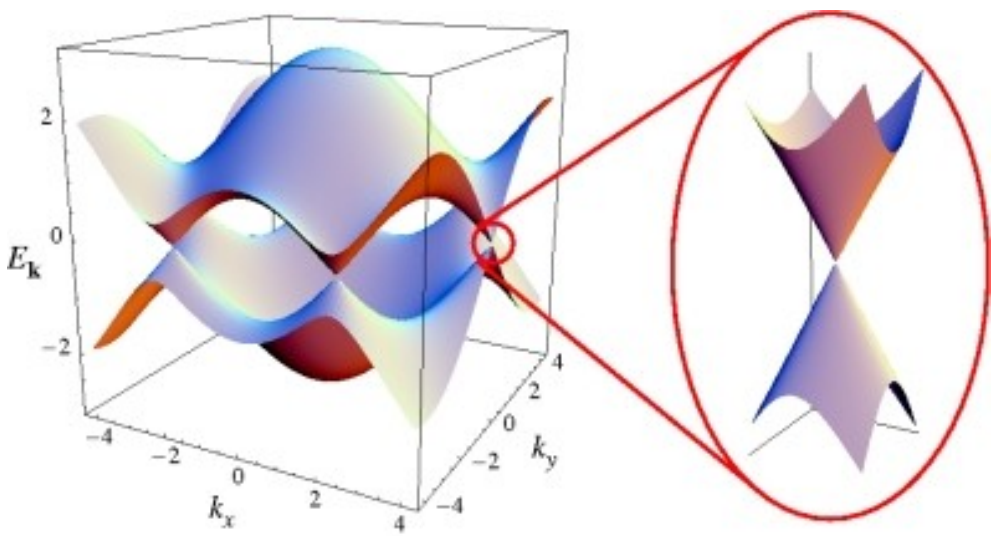

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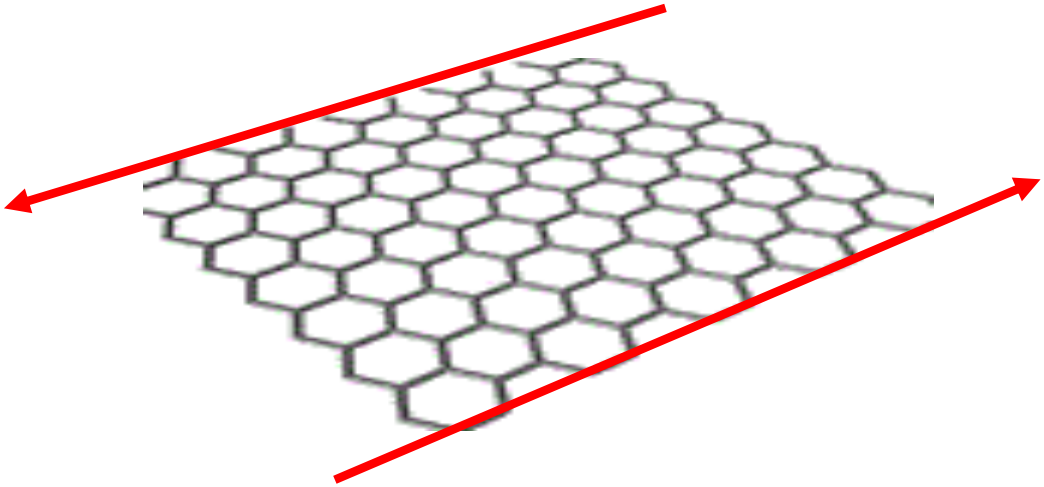
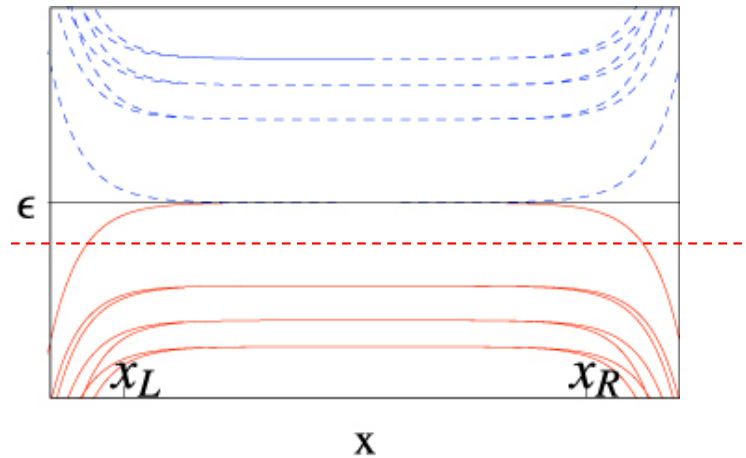
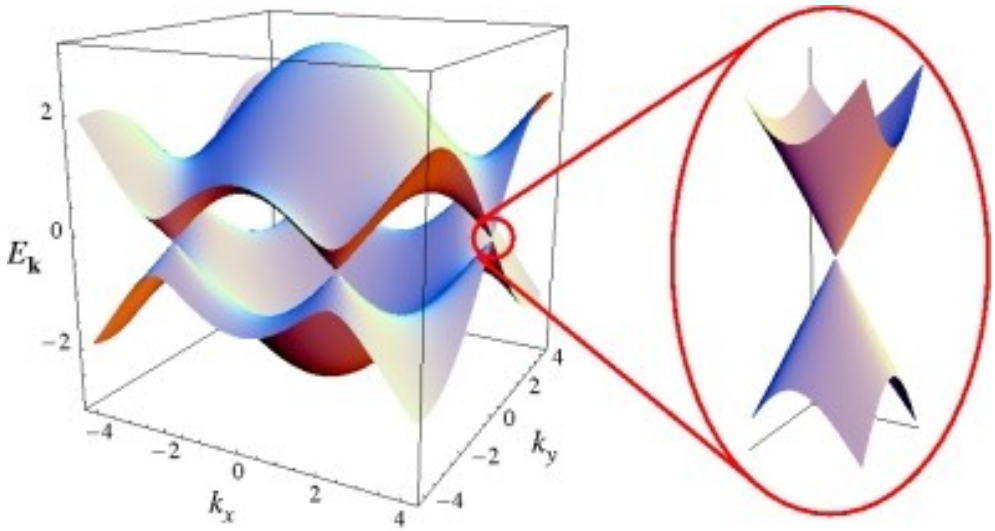
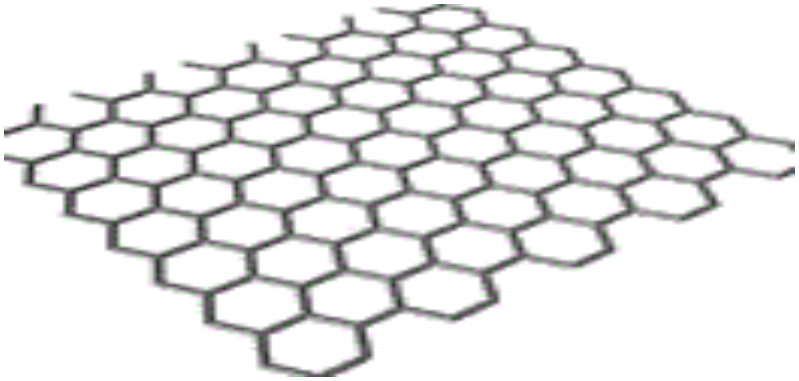
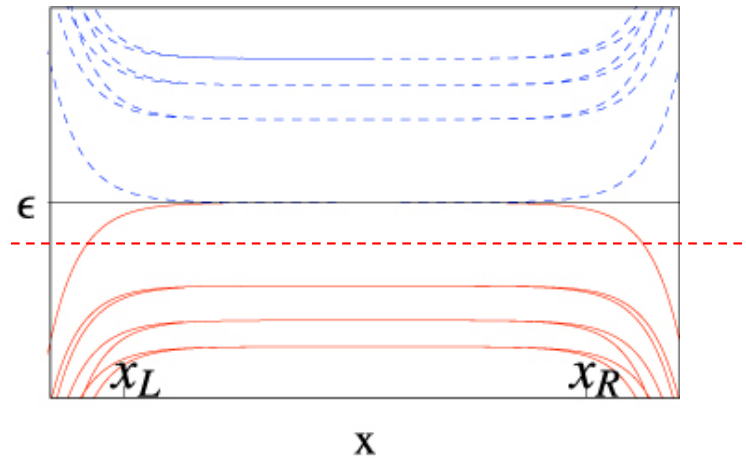


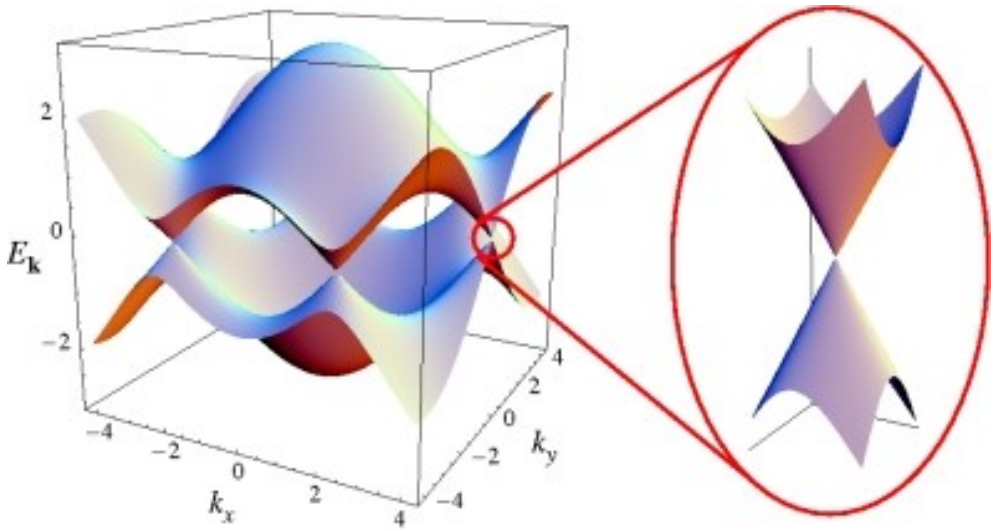


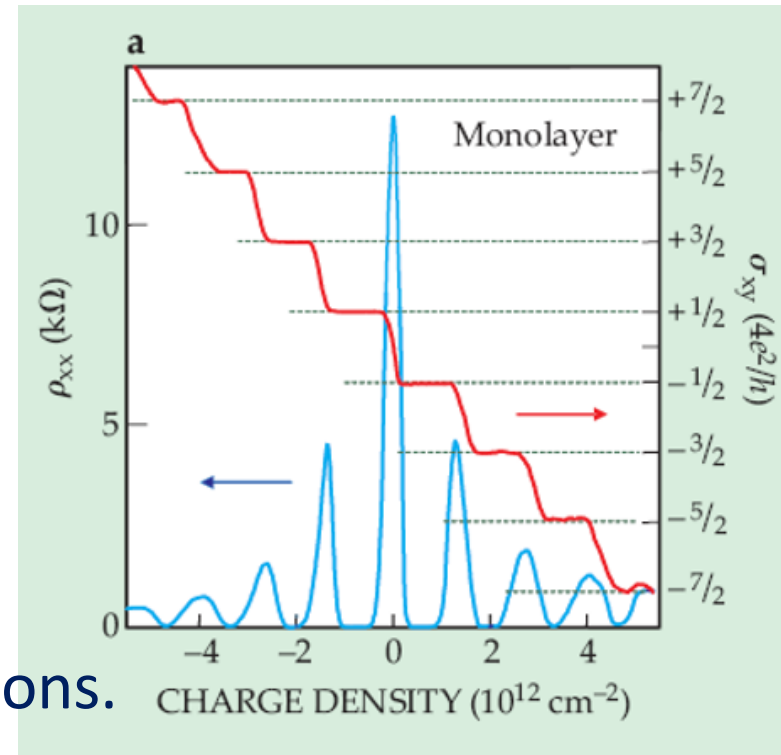


Dirac Fermions: Graphene Landau levels



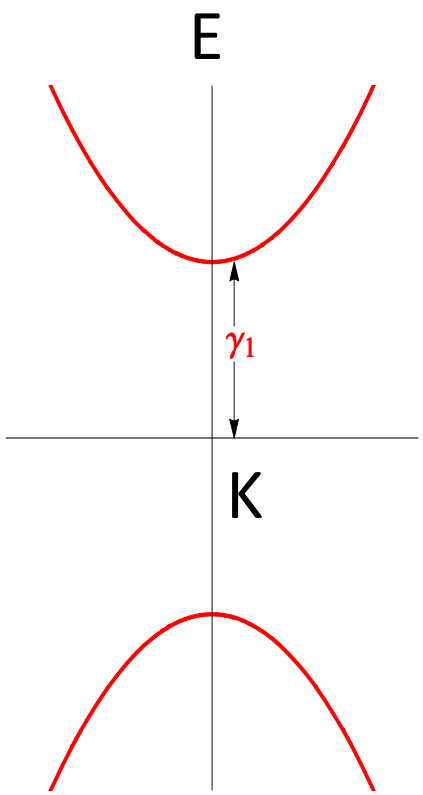


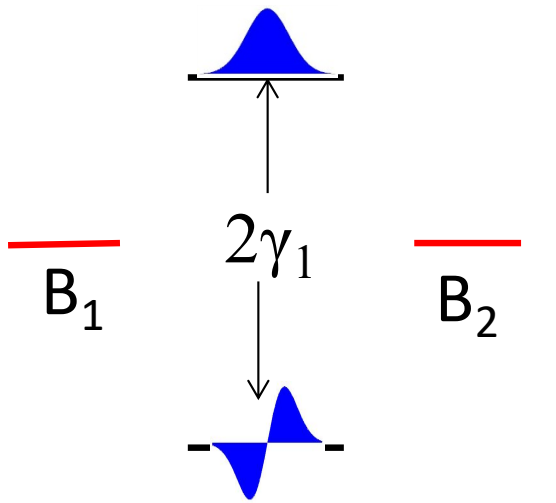


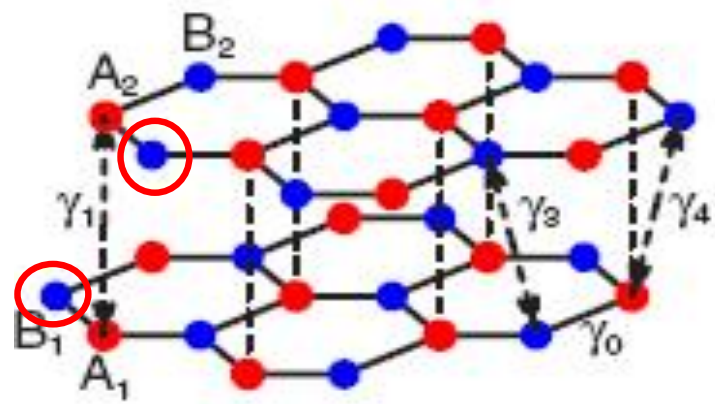


First conclusive evidence of Dirac fermions.

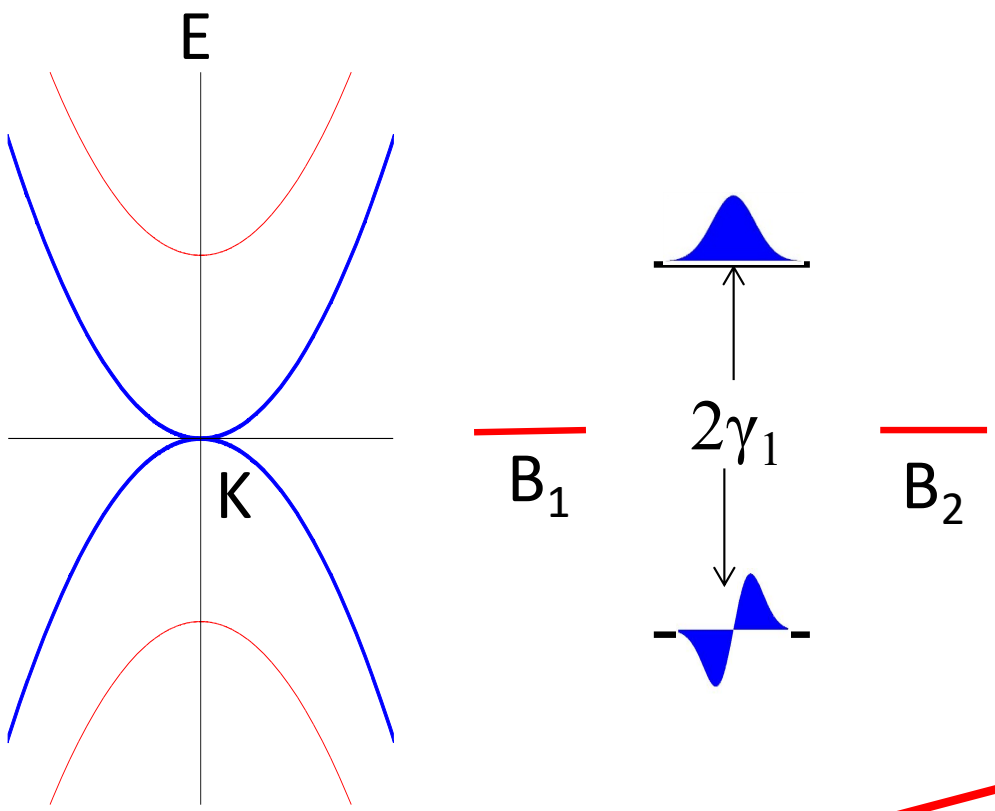
Bilayer graphene Landau levels

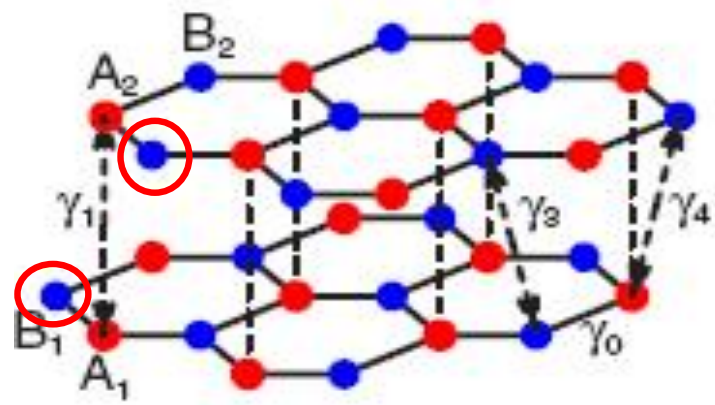


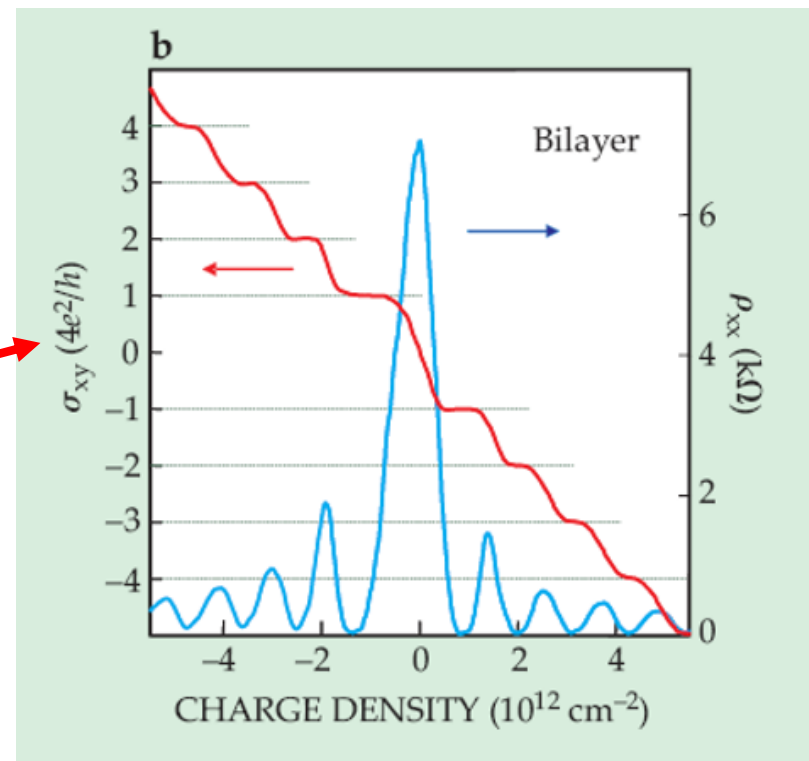




Bilayer graphene Landau levels

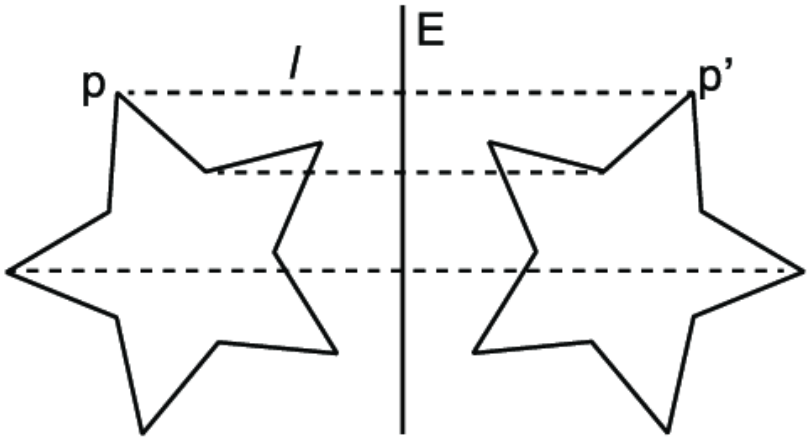


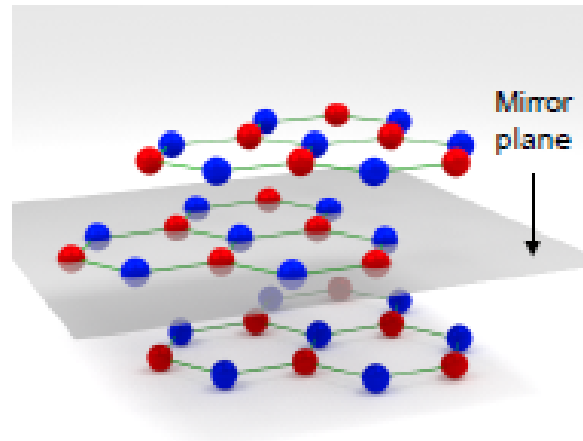




LL orbital degeneracy (n=0,1)

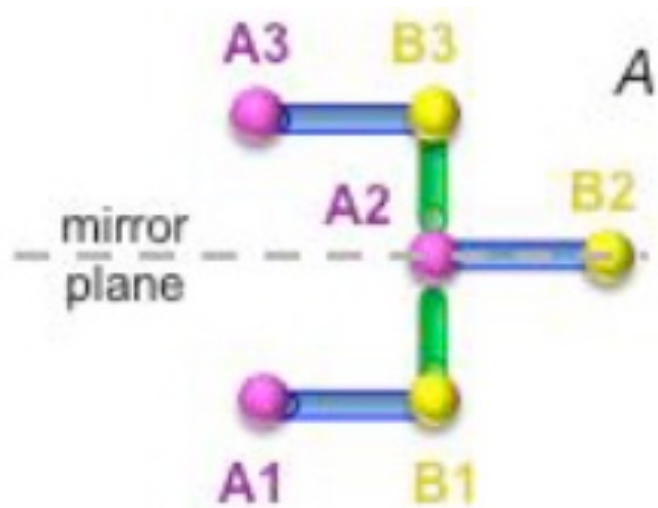
Mirror symmetry in ABA-trilayer graphene.





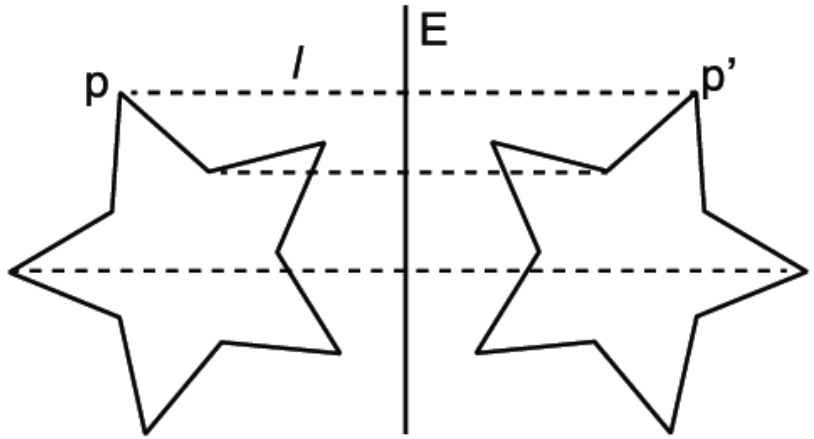
Under mirror symmetry:

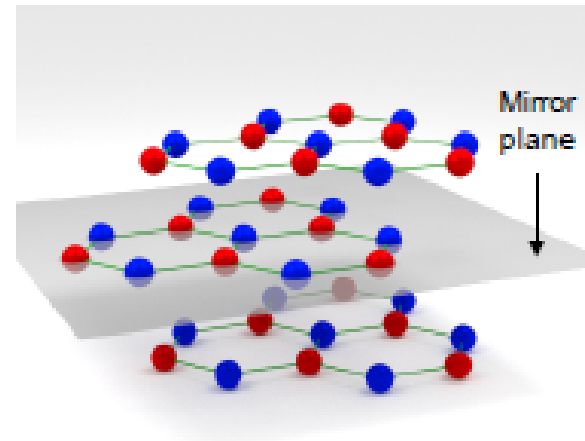
$$A_1 \leftrightarrow A_3; B_1 \leftrightarrow B_3; A_2 \leftrightarrow A_2; B_1 \leftrightarrow B_2$$



E. Henriksen et. al. PRX; M Serbyn and Abanin PRB; M Koshino and McCann PRB(2012);

Mirror symmetry in ABA-trilayer graphene.





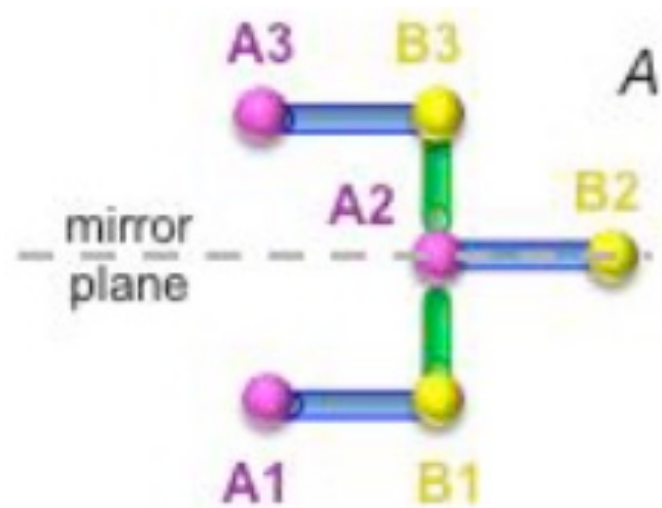
Under mirror symmetry:

$$A_1 \leftrightarrow A_3; B_1 \leftrightarrow B_3; A_2 \leftrightarrow A_2; B_1 \leftrightarrow B_2$$

Parity eigenstates (odd and even):

$$\left(\frac{A_1 - A_3}{\sqrt{2}}, \frac{B_1 - B_3}{\sqrt{2}}\right) \qquad \left(\frac{A_1 + A_3}{\sqrt{2}}, B_2\right)$$

Odd parity Even parity

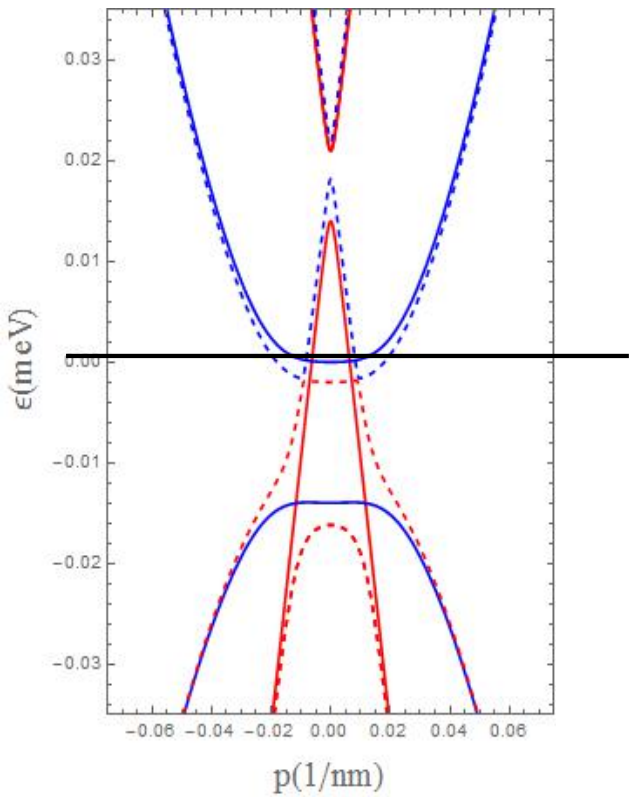


Electric field breaks mirror symmetry, gate tunable knob.

E. Henriksen et. al. PRX; M Serbyn and Abanin PRB; M Koshino and McCann PRB(2012);

Mirror symmetric Dirac semi-metals

Co-existence of electron and hole Fermi surfaces at the $n_{2D} = 0$



$$\left(\frac{A_1 - A_3}{\sqrt{2}}, \frac{B_1 - B_3}{\sqrt{2}}\right)$$

Odd parity, monolayer graphene like bands

$$\left(\frac{A_1 + A_3}{\sqrt{2}}, B_2\right)$$

Even parity, bilayer graphene like bands

Electric field breaks mirror symmetry, gate tunable.

M Serbyn and Abanin PRB; M Koshino and McCann PRB(2012); Y. Barlas, PRL. (2018)

LL spectrum of ABA-trilayer graphene.

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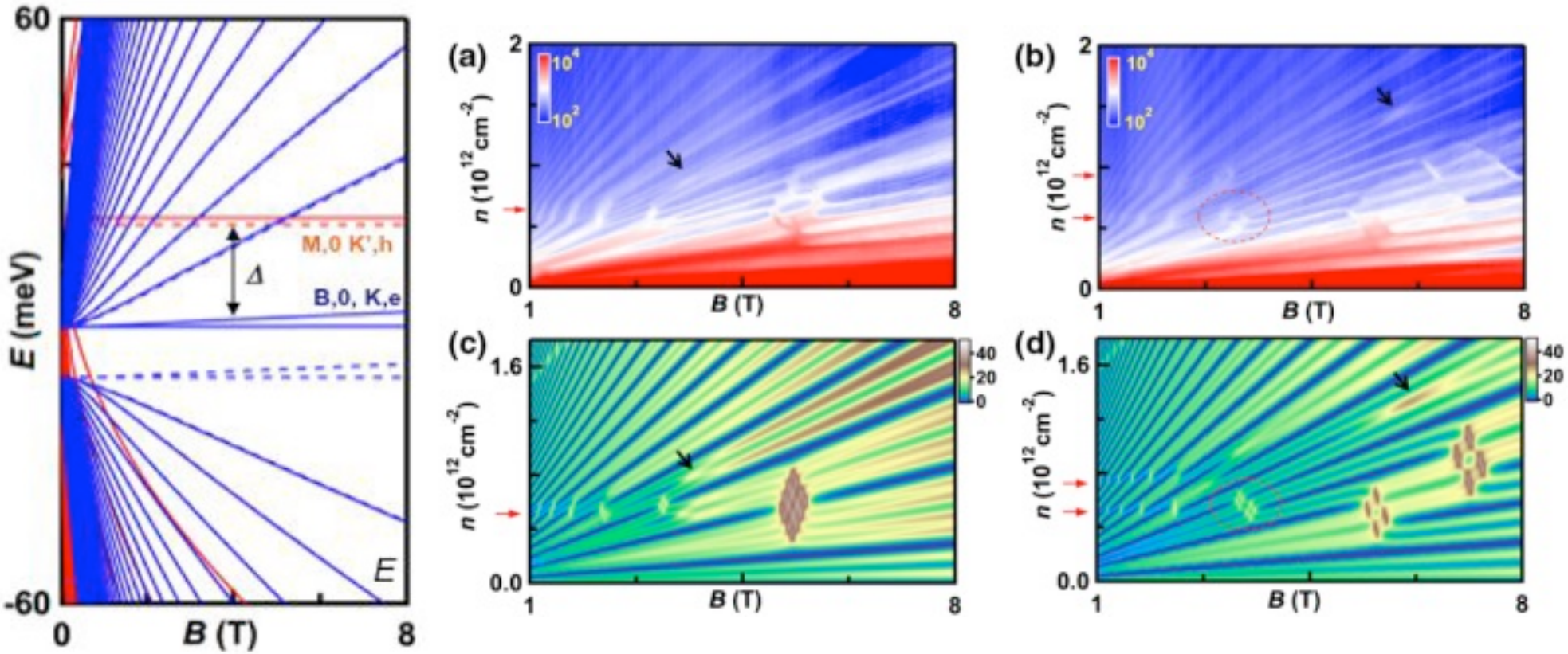

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P. Stepanov, Y. Barlas, Jeanie Lau et. al. , Phys. Rev. Lett. (2016)

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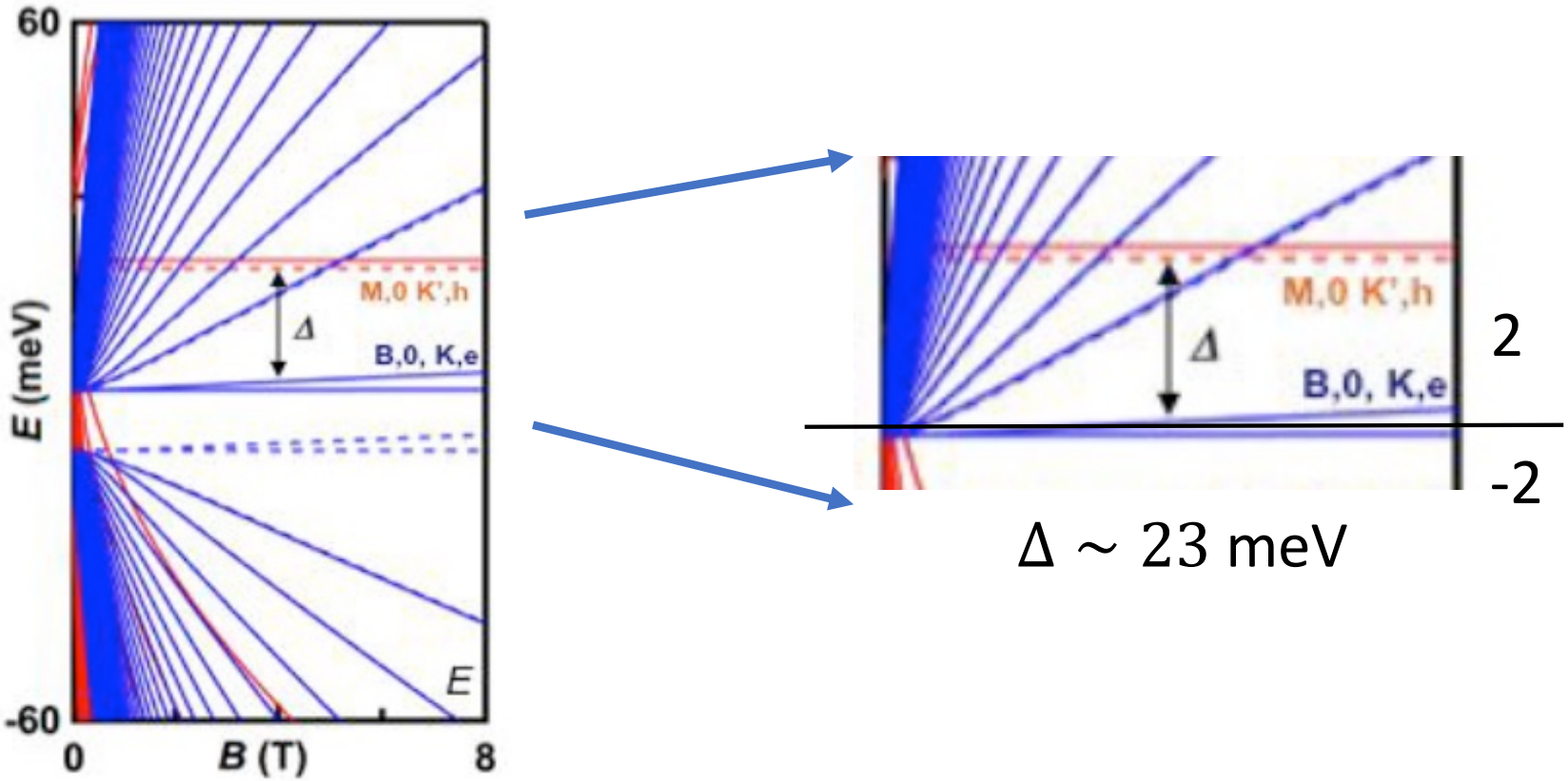


Electric field breaks mirror symmetry, gate tunable.

At neutral charge density $\nu = 0$, we have electron and hole LLs with different parities, with opposite topological invariants.

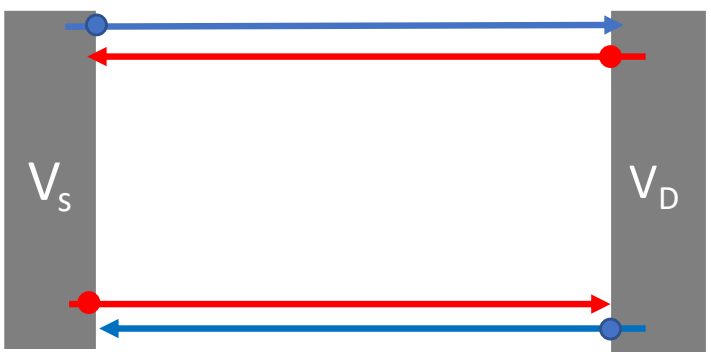
Y. Barlas, Phys. Rev. Lett. (2018)

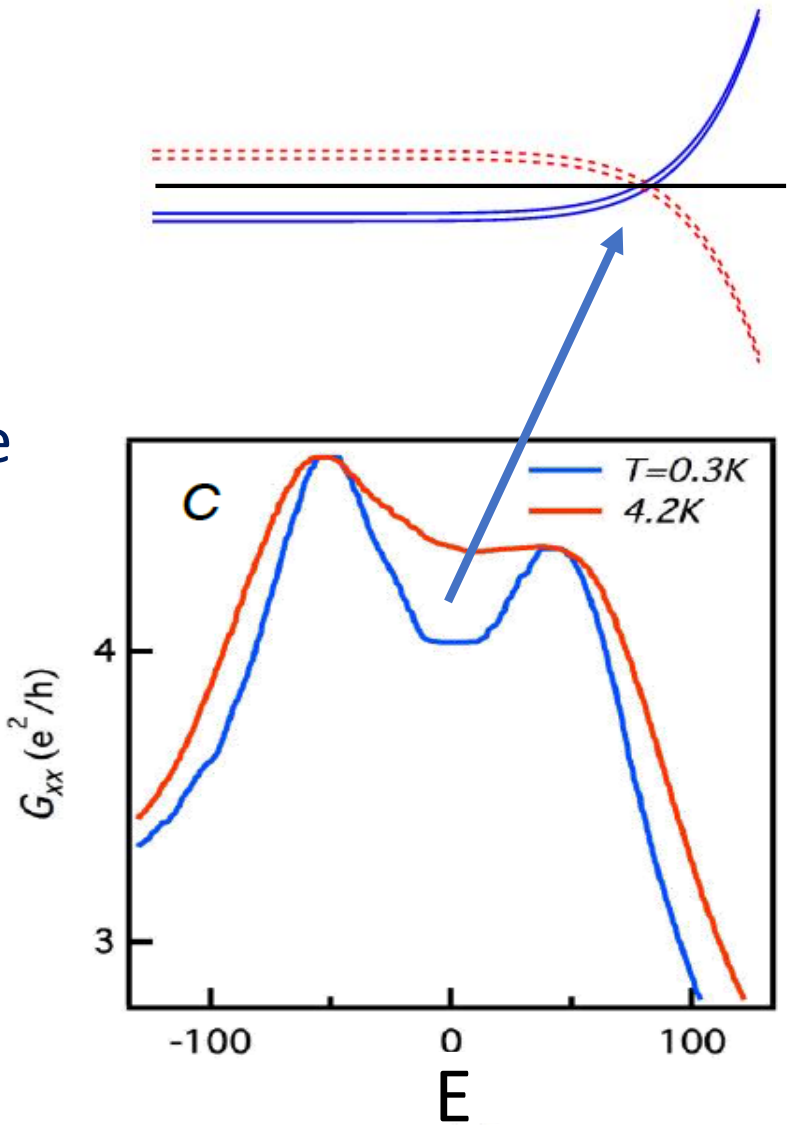
Quantum Parity Hall Effect

Counter-propagating edge states protected by mirror symmetry:

$$\sigma_{xy} = 0 \quad \sigma_{xx} = 4\frac{e^2}{h}$$

Quantized two-terminal conductance





P. Stepanov., Y. Barlas., A.H.M. C. N. Lau et. al., PNAS (2019)

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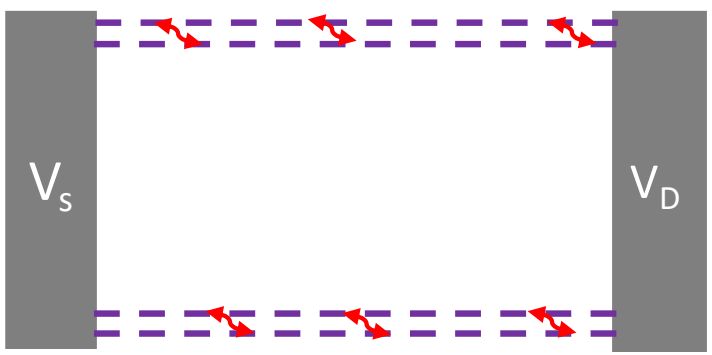
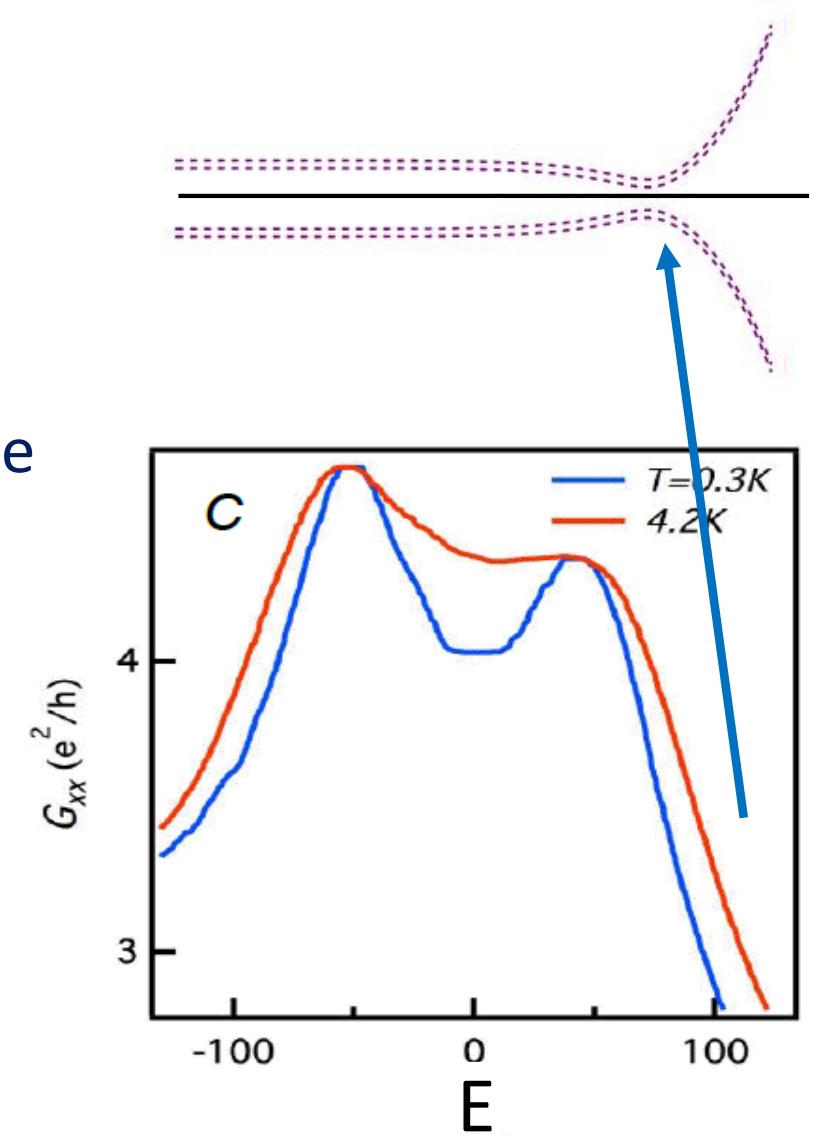


Backscattering → Localization



P.Stepanov., Y.Barlas., A.H.M. C. N. Lau et. al. PNAS (2019)

Experimental phase diagram

At least 4 distinct phases

Phase 1:

$$\sigma_{xx} = 4\frac{e^2}{h}$$

Phase 2:

$$\sigma_{xx} = 2\frac{e^2}{h}$$

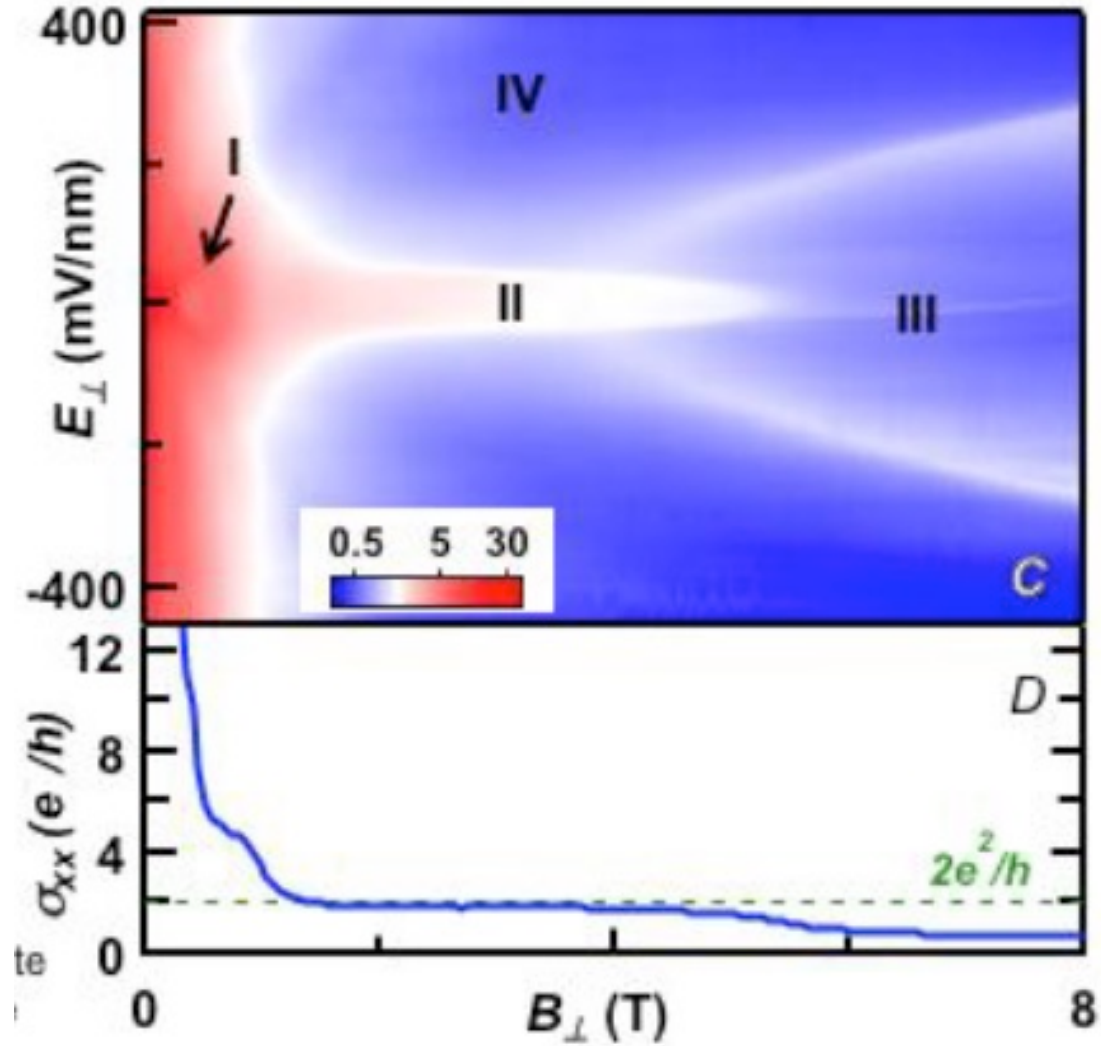
Phase 3:

$$\sigma_{xx} \to 0$$

Phase 4:

$$\sigma_{xx} \to 0$$

Layer polarized phase

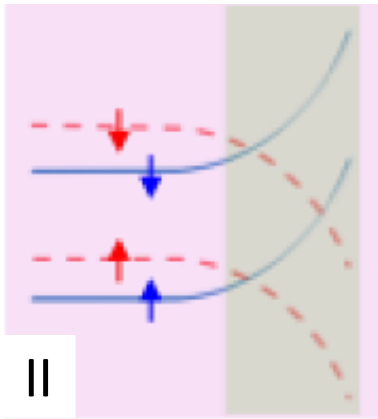


P. Stepanov., Y. Barlas., A.H.M. C. N. Lau et. al. PNAS (2019)

Interaction induced topological phases

Ferromagnetic exchange leads to spin splitting (enhanced Zeeman).

Self energy (Σ) lowers the energy of the odd parity hole LLs and raises the even parity electron LLs



Phase 2:

$$\Delta - E_Z < \Sigma < \Delta + E_z$$

P. Stepanov., Y. Barlas., A.H.M. C. N. Lau et. al. PNAS (2019)

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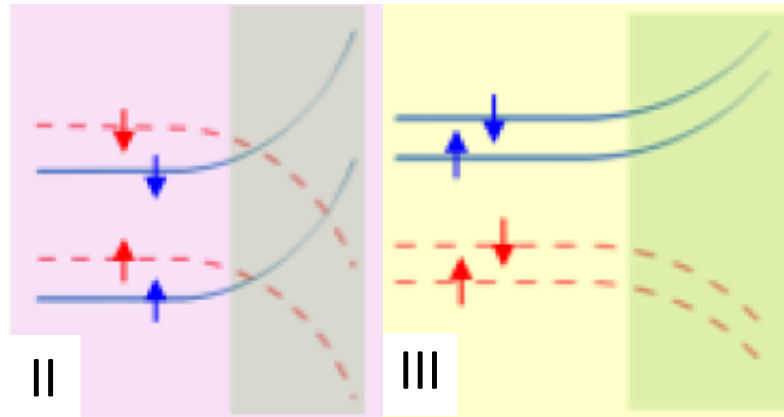
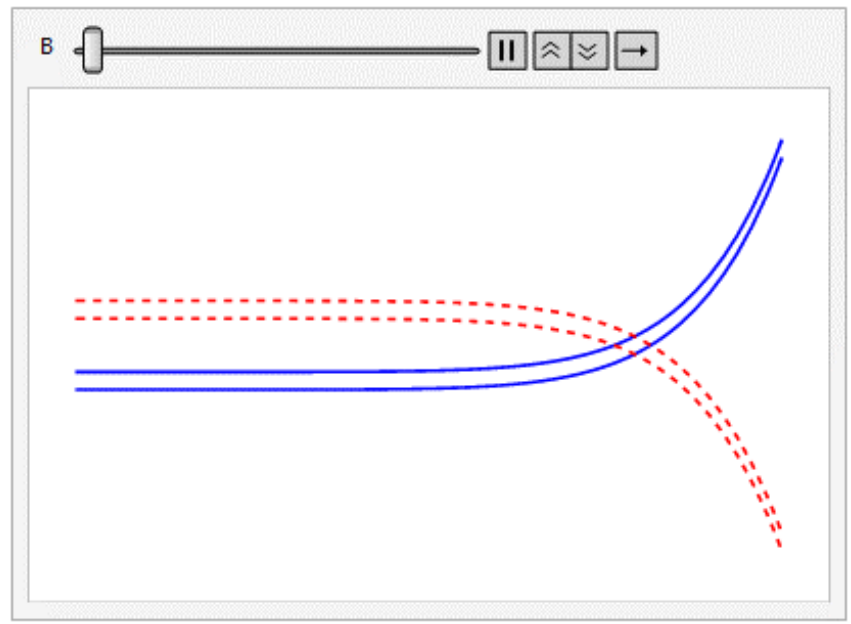


Phase 2:

$$\Delta - E_Z < \Sigma < \Delta + E_z$$

Phase 3:

$$\Sigma > \Delta + E_z$$

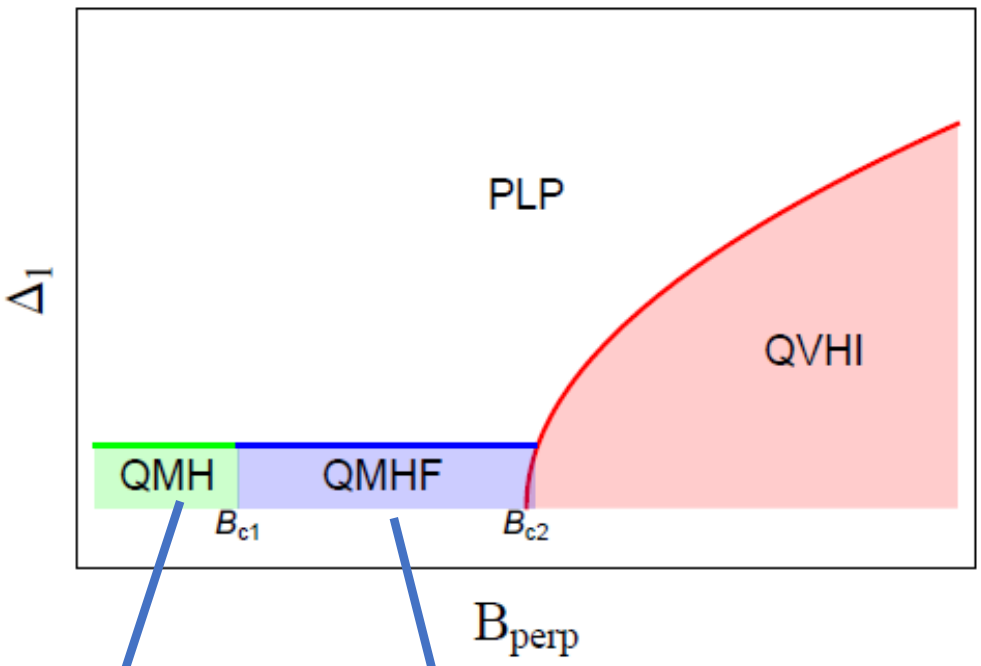


Transitions can be tuned by in-plane magnetic field.
Spin orbit coupling turns on when electric field is applied,

P. Stepanov., Y. Barlas., A.H.M. C. N. Lau et. al. PNAS (2019)

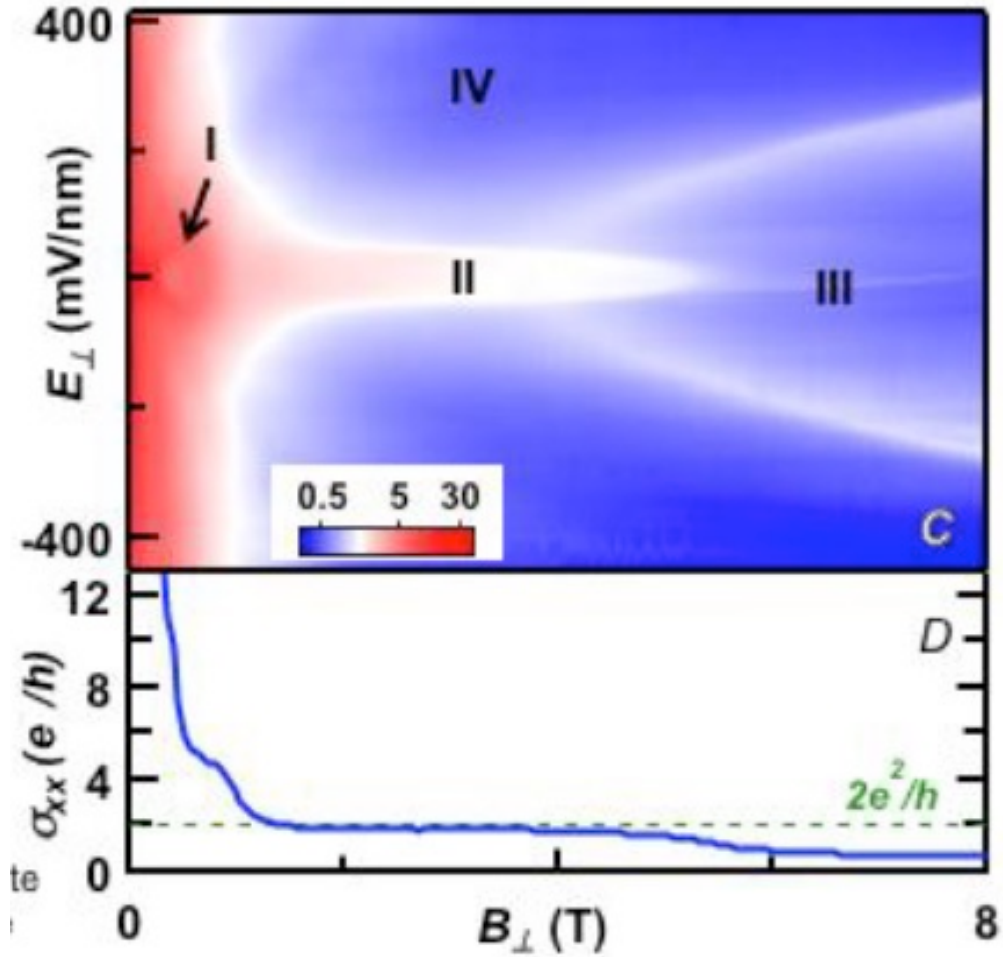
Role of interactions

Phase diagram calculated in mean field theory



$$\sigma_{xx} = 4\frac{e^2}{h}$$

$$\sigma_{xx} = 2\frac{e^2}{h}$$



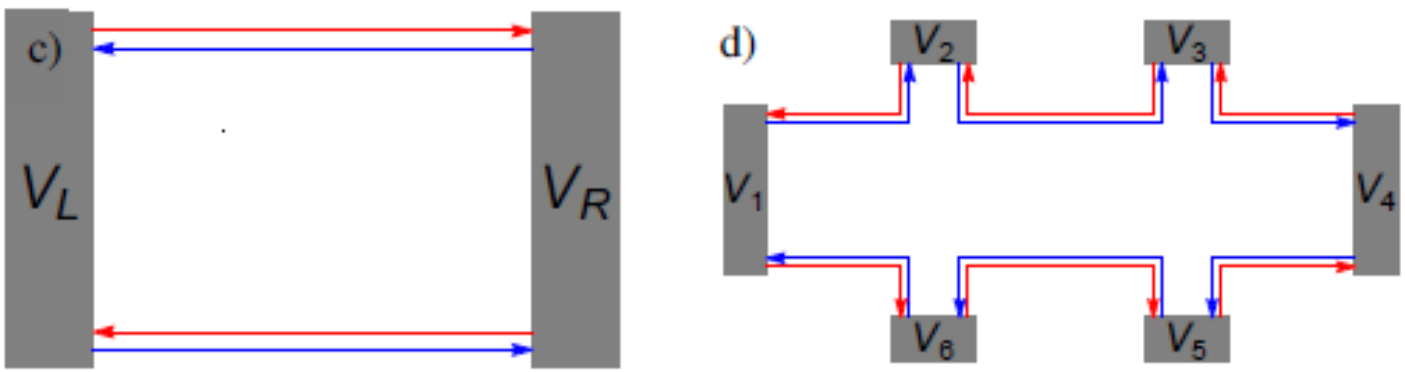
P.Stepanov., Y.Barlas., A.H.M. C. N. Lau et. al. PNAS (2019)

Correlated states at $\nu = \nu_e + \nu_o = 0$

Interactions can lead to correlated states at $\nu = \frac{1}{m} + (-\frac{1}{m}) = 0$

$$\Psi_0 = \prod_{i<j} (z_i - z_j)^m (w_i^\star - w_j^\star)^m \prod_k e^{-\frac{1}{4}(|z_k|^2 + |w_k|^2)}.$$

Zero energy ground states with neutral excitations.
No Hall conductance but a quantized two-terminal longitudinal conductance.



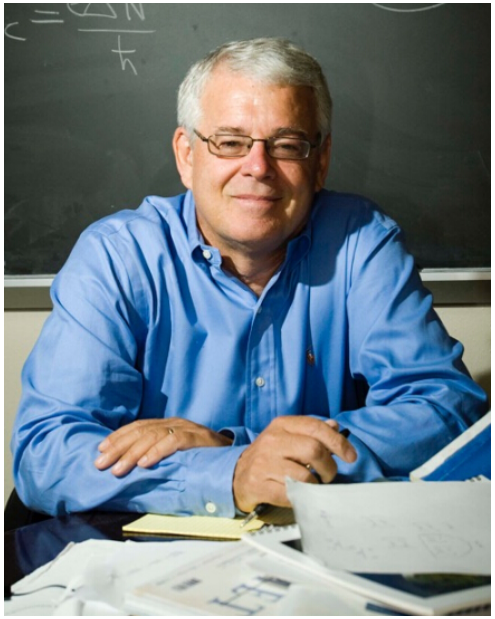
$$I = I_t - I_b = 2|\nu_\pm| \frac{e^2}{h}(V_L - V_R), \quad R_{14,26} = 0 \quad R_{14,14} = h/(2|\nu_\pm| e^2)$$

Y. Barlas, Phys. Rev. Lett. (2018)

Conclusion and Outlook

Symmetry protected topological states in 2D crystals.

- Parity Hall states in ABA-trilayers (dual-gated).
- Quantized two terminal conductance.
- Fractional Parity Hall states.
- New search of topological crystalline states (TMDs, HgTe??).

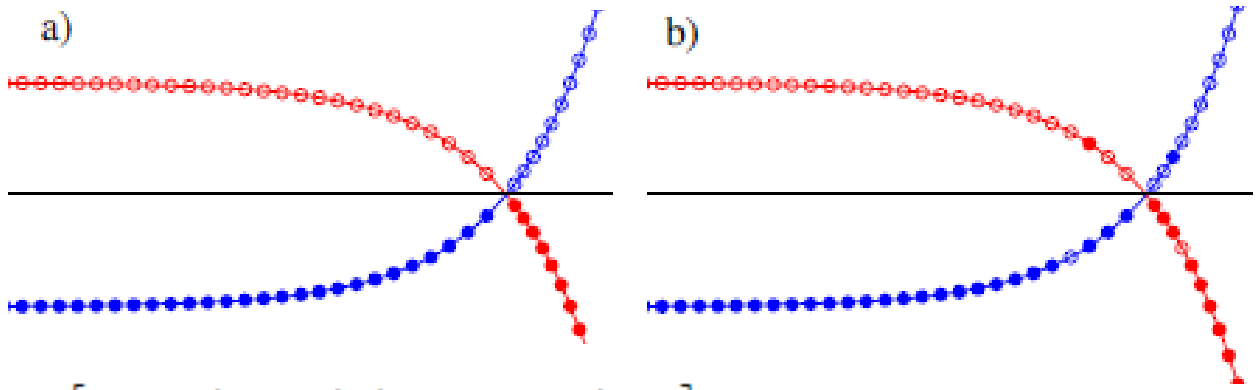


Thank you for your attention!

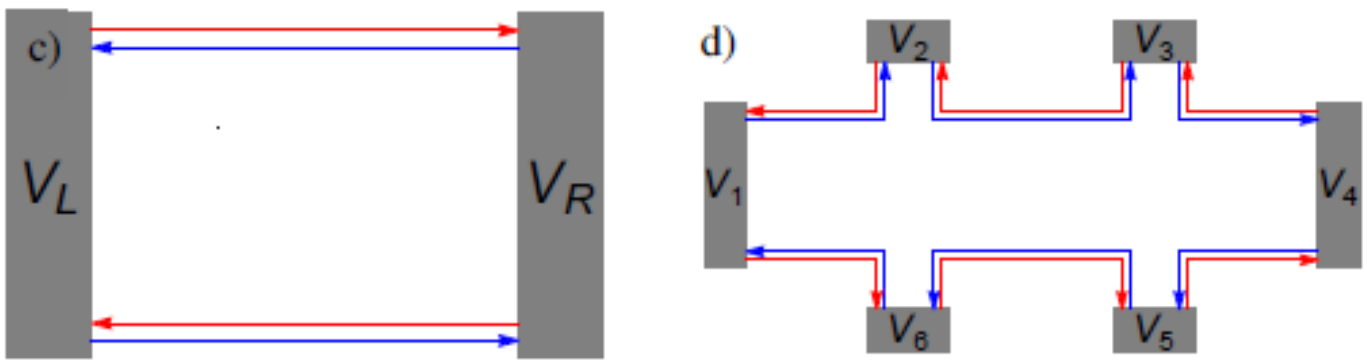
Effect of interactions on the edge states

$$S_0 = \frac{1}{4\pi|\nu_\pm|}\sum_{\eta=e,o}\int dxd\tau\partial_x\phi_\eta(i\eta\partial_\tau + v\partial_x)\phi_\eta, \qquad \frac{v_d}{2\pi|\nu_\pm|}\int dxd\tau\partial_x\phi_e\partial_x\phi_o,$$

Inter-edge interactions



$$S = \frac{1}{4\pi|\nu_\pm|}\sum_{\alpha=L(R)}\int dxd\tau\left[\partial_x\varphi_\alpha(isgn(\alpha)\partial_\tau + u\partial_x)\varphi_\alpha\right]$$



$$I = I_t - I_b = 2|\nu_\pm|\frac{e^2}{h}(V_L - V_R), \qquad R_{14,26} = 0 \qquad R_{14,14} = h/(2|\nu_\pm|e^2)$$

Y. Barlas, Phys. Rev. Lett. (2018)