Landau levels of disordered massless Dirac fermions when the Dirac cones are both shifted and tilted

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Particles governed by the massless Dirac equation are now realized not only in graphene [1] but also in various classes of systems encompassing an organic metal (with tilted Dirac cones) [2], molecular graphene [3] and cold atoms on optical lattices [4, 5]. While usually Dirac cones appear in pairs with the opposite Berry phases (which is dubbed the fermion doubling), theoretically a model has been proposed in which the doubling is lifted, where the half-integer contributions to the Hall conductivity result in different sequence of Chern numbers with extra plateaus [6]. While involving seemingly artificial complex transfer energies, this can be realized in cold atoms on optical lattices, where the Hall conductivity can be detectable [5]. On the other hand, usual wisdom is that the chiral symmetry causes the doubled Dirac cones, and that the symmetry protects sharp (δ-function like) zeroth Landau levels against disorder. So it becomes an intriguing question to ask what will happen to the zeroth Landau level in the singled-out Dirac cone.

With this background, we explore numerically the effect of disorder on the Landau levels for a lattice model where the energy offset between two Dirac cones can be controlled by an imaginary hopping between the next nearest-neighbor (NNN) sites. Previously, we have shown that for a disorder in the nearest-neighbor (NN) hopping, the $n = 0$ Landau levels become anomalously sharp as the Dirac cones are energetically shifted even when the disorder is short-ranged, quite unlike the case of the degenerated cones [7]. In the present paper, we extend the analysis to various other cases. Specifically, we are interested in the effect of tilted (as well as shifted) Dirac cones, which is realized by introducing a real part in the NNN hopping. While the tilting of the cones destroys the chiral symmetry, we can introduce a *generalized* chiral symmetry which protects the sharp $n = 0$ Landau levels [8]. Here we find that the $n = 0$ Landau levels indeed remain sharp even in the shifted cones when the disorder respects the generalized chiral symmetry [9]. By contrast, a disorder in the NN hopping, which destroys the symmetry, the sharpness is degraded when the cones are tilted (Fig. 1) .

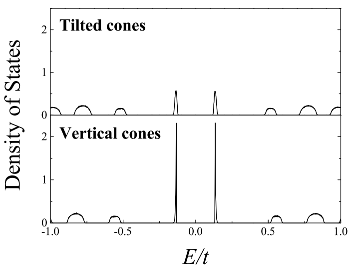

Fig. 1: Landau levels for Dirac cones with an energy shift $\delta E/t = 0.28$ (t: the NN hopping) for the bond disorder. The central two peaks are the $n = 0$ levels.

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