Universal properties of the Higgs resonance in (2+1)-dimensional U(1) critical systems
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Abstract
We present spectral functions for the magnitude squared of the order parameter in the scaling limit of the two-dimensional superfluid to Mott insulator quantum phase transition at constant density, which has emergent particle-hole symmetry and Lorentz invariance. The universal functions for the superfluid, Mott insulator, and normal liquid phases reveal a Higgs resonance which is relatively sharp and is followed by a damped oscillation (in the first two phases only) before saturating to the quantum critical plateau. In order to understand the counter-intuitive Higgs resonance in the insulating and normal phases, we invoke a picture of a scale-dependent Mexican hat. Our results are derived from analytically continued correlation functions obtained from path-integral Monte Carlo simulations of the Bose-Hubbard model.

Results
FIG. 1. Universal spectral functions for scalar response in the superfluid, Mott insulator, and normal liquid phases. For SF, the Higgs peak is at \( \omega = \Delta = 3.0(8) \) for Mi, \( \omega = \Delta = 3.2(8) \); and for NL, \( \omega = \Delta^* \approx 0.15(1) \). There is a secondary peak around \( \omega = \Delta^* + 15 \) in the SF and Mi phases, and all responses reach a quasi-plateau at the same height 0.6(1) at higher frequencies. The error bars on \( \Phi_{\omega} \) come from the spread of collapsed curves, while the ones on \( \Phi_{\omega} \) are based on the variance of the analytical continuation results [18].

Content
We perform Quantum Monte Carlo simulations for the homogeneous Bose-Hubbard model and aim to determine the universal scaling spectral functions when approaching the QCP from the SF, Mi and NL phases. We rely on the worm algorithm [16-18] in the path integral representation to perform the required large-scale simulations. By collapsing spectral functions evaluated along the trajectories specified by the dashed lines in Fig. 1, we extract universal features for all three phases. They are summarized in Fig. 2, which is our main result. Surprisingly, all of them include a universal resonance peak (relatively sharp in SF and Mi phases), followed by a broad secondary peak (in SF and Mi phases only) before merging with the incoherent critical quasi-plateau (the plateau value is the same in all cases, as expected). Our results are in agreement with scaling theory, and firmly establish that the damped Higgs mode survives in all three phases.

FIG. 2. Universal spectral functions for different values of \( \Delta_{1} \) along trajectory \( \omega = \Delta_{1} \). Inset: original data for \( S_{\omega}(\omega) \).

FIG. 3. (Color online) Collapse of spectral functions for different values of \( \Delta_{1} \) along trajectory \( \omega = \Delta_{2} \). Inset: original data for \( S_{\omega}(\omega) \).

FIG. 4. (Color online) Collapse of spectral functions for different \( \Delta_{1} \) along trajectory \( \omega = \Delta_{2} \) in the Mi phase, labeled by the detuning \( g_{\omega} = n \). Inset: original data for \( S_{\omega}(\omega) \).

FIG. 5. (Color online) Collapse of spectral functions for different \( \Delta_{1} \) along trajectory \( \omega = \Delta_{2} \) in the Mi phase, labeled by the detuning \( g_{\omega} = n \). Inset: original data for \( S_{\omega}(\omega) \).

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