Impact of Dissipation on Universal Fluctuation Dynamics in Open Quantum Systems

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Recent theoretical and experimental works have explored universal dynamics related to surface growth physics in *isolated* quantum systems. In this Letter, we theoretically elucidate that *dissipation* drastically alters universal particle-number-fluctuation dynamics associated with surface-roughness growth in one-dimensional free fermions and bosons. In a system under dephasing that causes loss of spatial coherence, we numerically find that a universality class of surface-roughness dynamics changes from the ballistic class to a class with the Edwards-Wilkinson scaling exponents and an unconventional scaling function. We provide the analytical derivation of the diffusion equation from the dephasing Lindblad equation via a renormalization-group technique and succeed in explaining the drastic change. Furthermore, we numerically find the same change of the universality class under a more nontrivial dissipation, i.e., symmetric incoherent hopping.

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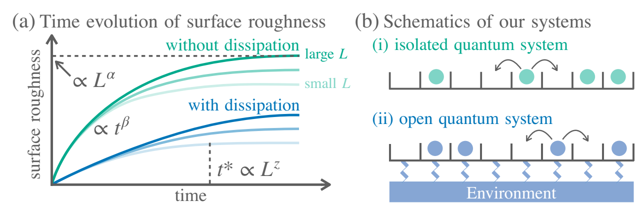
Introduction.—Universal dynamics has been explored for many years in classical statistical mechanics, and surface growth [1,2] has been one of the most fundamental subjects for deepening our understanding of universal aspects behind the nonequilibrium phenomena. Minimal theoretical models for the classical surface growth are the Kardar-Parisi-Zhang (KPZ) [3] and the Edwards-Wilkinson (EW) [4] equations, which exhibit universal dynamical scaling in the surface-height distribution [5,6]. Recent works found a signature of KPZ universality even in isolated quantum many-body systems by investigating two-point spatiotemporal correlation functions numerically [7–14] and experimentally [15,16]. Instead of computing the correlation function, a surface-height operator and quantum surface roughness were introduced in Refs. [17–19] by using the particle-number and spin fluctuations. Considering the particle-number fluctuations of isolated fermionic and bosonic lattice models, our previous Letters [17,19] found emergence of the Family-Vicsek (FV) scaling [20,21], the dynamical scaling of the surface roughness originally developed in classical surface growth [1]. As illustrated in Fig. 1(a), this scaling is characterized by three exponents α, β, and z, which determine universality classes of the dynamics [1].

In this Letter, we theoretically tackle a fundamental and intriguing question: "How does dissipation affect the universal fluctuation dynamics related to the surface-growth physics in quantum systems?" We consider open quantum systems with dissipation obeying the Lindblad equation [see Fig. 1(b)]. To investigate large-scale long-time dynamics, we use an exact numerical method with correlation matrices [22–24] and a renormalization-group-based analytical technique [25–27]. First, studying free fermions and bosons on a one-dimensional (1D) lattice under dephasing, we numerically find that the FV scaling emerges even in the open quantum system and that the dissipation changes the



(c) Table for the FV scaling exponents

Model	α	β	z
Edwards-Wilkinson model (EW class)	0.5	0.25	2
free fermions or bosons (Ballistic class)	0.5	0.5	1
free fermions + dephasing	0.490	0.245	2.00
free bosons + dephasing	0.498	0.264	1.91
free fermions + symmetric incoherent hopping	0.492	0.237	2.07
free bosons + symmetric incoherent hopping	0.508	0.263	1.94

this work

FIG. 1. (a) Schematic for the FV scaling with the scaling exponents α, β, and z. Shown is the surface roughness $w(L,t)$ as a function of system size L and time t. The curves with the same color and different opacities are the surface roughness for the same setup with different system sizes. The roughness grows with t^β for $t \ll t^*$, where the saturation time t^* scales as L^z. The saturated surface roughness is proportional to L^α. (b) Schematic for (i) an isolated system and (ii) an open system considered in this Letter. (c) Table for the scaling exponents of the FV scaling. The first two rows are the previously known exponents, while the remaining four rows are the main results in this Letter. We here show the exponents for a staggered initial state.

universality class from the ballistic class to a class with the EW scaling exponents [see Fig. 1(c)] and an unconventional scaling function. Second, we analytically explain the change of the exponents by deriving diffusion equations via the renormalization-group method. To the best of our knowledge, this is the first analytical derivation of the diffusion equations from the dephasing Lindblad equation. Third, we use symmetric incoherent hopping as a nontrivial dissipation, numerically finding the same change of the FV scaling exponents and the same unconventional scaling function. This strengthens the argument that the diffusive-type FV scaling is universal in open quantum systems under particle-number conservation. Figure 1(c) summarizes our results. Finally, we comment on the absence of the FV scaling in Lindblad equations without the particle-number conservation and discuss experimental possibilities for observing our theoretical predictions.

Setup.—We consider free fermions or bosons on a 1D lattice $\Lambda = \{1, 2, \ldots, L\}$ with an even number L of lattice points. Let $\hat{a}_j$ and $\hat{a}_j^\dagger$ be the annihilation and creation operators at a site $j \in \Lambda$. When the particles are fermions (bosons), the operators satisfy $[\hat{a}_j, \hat{a}_k^\dagger]_+ = \delta_{jk}$ ($[\hat{a}_j, \hat{a}_k^\dagger]_- = \delta_{jk}$), where we introduce the (anti)commutator $[\hat{A}, \hat{B}]_\pm = \hat{A}\hat{B} \pm \hat{B}\hat{A}$ for operators $\hat{A}$ and $\hat{B}$. We assume that a quantum state at time t, specified by a density matrix $\hat{\rho}(t)$, obeys the Lindblad equation [28]

$$\frac{d}{dt}\hat{\rho}(t) = -i[\hat{H}, \hat{\rho}(t)]_- + \mathcal{D}[\hat{\rho}(t)], \tag{1}$$

where $\hat{H}$ and $\mathcal{D}[\hat{\rho}(t)]$ are respectively a Hamiltonian and a dissipator. The Hamiltonian $\hat{H} = -\sum_{j=1}^{L-1}(\hat{a}_{j+1}^\dagger \hat{a}_j + \hat{a}_j^\dagger \hat{a}_{j+1})$ describes coherent dynamics for the noninteracting particles. In this Letter, we mainly consider two kinds of dissipators conserving the total particle number. One is the dephasing dissipator defined by

$$\mathcal{D}_{\mathrm{DEP}}[\hat{\rho}(t)] = \gamma \sum_{j=1}^{L} \left(\hat{n}_j \hat{\rho}(t) \hat{n}_j - \frac{1}{2}[\hat{n}_j^2, \hat{\rho}(t)]_+ \right) \tag{2}$$

with the particle-number operator $\hat{n}_j = \hat{a}_j^\dagger \hat{a}_j$ and a strength γ of the dephasing. The other is the dissipator for the symmetric incoherent hopping [23]:

$$\mathcal{D}_{\mathrm{SIH}}[\hat{\rho}(t)] = \gamma' \sum_{j=1}^{L} \left(\hat{R}_j \hat{\rho}(t) \hat{R}_j^\dagger - \frac{1}{2}[\hat{R}_j^\dagger \hat{R}_j, \hat{\rho}(t)]_+ \right) + \gamma' \sum_{j=1}^{L} \left(\hat{L}_j \hat{\rho}(t) \hat{L}_j^\dagger - \frac{1}{2}[\hat{L}_j^\dagger \hat{L}_j, \hat{\rho}(t)]_+ \right) \tag{3}$$

with the operators $\hat{R}_j = \hat{L}_j^\dagger = \hat{a}_{j+1}^\dagger \hat{a}_j$ and the strength parameter γ'. The first and second terms on the right hand side are responsible for the incoherent hopping from j to $j+1$ and vice versa, respectively. In this case, we use $\hat{H} = -\sum_{j=1}^{L}(\hat{a}_{j+1}^\dagger \hat{a}_j + \hat{a}_j^\dagger \hat{a}_{j+1})$ under a periodic boundary condition.

The physical quantity of interest is the surface roughness defined by a variance of a surface-height operator $\hat{h}_j = \sum_{k=1}^{j}(\hat{n}_k - \nu)$ with an initial filling factor ν [17–19]. This operator was introduced on the basis of a mathematical correspondence between a classical surface height $h(x,t)$ in the KPZ equation and a sound mode $\delta n(x,t)$ in the fluctuating hydrodynamics in 1D systems. Since correlation functions for $\partial_x h(x,t)$ and $\delta n(x,t)$ have the same scaling function in the stationary processes, one can define an effective surface height by $h_{\mathrm{eff}}(x,t) = \int_0^x \delta n(y,t)dy$ in the fluctuating hydrodynamics. The surface-height operator $\hat{h}_j$ is a quantum extension of $h_{\mathrm{eff}}(x,t)$. Using this surface-height operator, we define the surface roughness at a site $j \in \Lambda$ by $w_j(t) = \sqrt{\langle (\hat{h}_j - \langle \hat{h}_j \rangle_t)^2 \rangle_t}$ with the quantum statistical average $\langle \cdots \rangle_t = \mathrm{Tr}[\hat{\rho}(t) \cdots]$. In what follows, we focus on $j = L/2$ because the surface roughness grows for a longer time for this choice than the other j and introduce the notation $w(L,t) = w_{L/2}(t)$ for brevity (see Sec. I of the Supplemental Material [29]).

When the fluctuation of the surface height is scale invariant, the surface roughness shows the FV scaling [1,20,21] defined by

$$w(L,t) = s^{-\alpha} w(sL, s^z t) \propto \begin{cases} t^\beta & (t \ll t^*) \\ L^\alpha & (t^* \ll t). \end{cases} \tag{4}$$

Here, the scaling exponents α, β, and z satisfying the scaling relation $z = \alpha/\beta$ classify a universality class, and t^* is saturation time. Two well-known universality classes originally found in classical systems are the KPZ [3] and EW classes [4] characterized by $(\alpha, \beta, z) = (1/2, 1/3, 3/2)$ and $(1/2, 1/4, 2)$, which show superdiffusive $(1 < z < 2)$ and diffusive $(z = 2)$ transport, respectively. In quantum systems, free fermions have $(\alpha, \beta, z) \simeq (1/2, 1/2, 1)$ [17,19], which we call a ballistic class since the dynamical exponent z is unity.

Numerical method.—Instead of directly solving the Lindblad equation, we solve the equations of motion for two- and four-point correlation matrices [22–24] defined by $D_{mn} = \langle \hat{a}_m^\dagger \hat{a}_n \rangle_t$ and $F_{mnpq} = \langle \hat{a}_m^\dagger \hat{a}_n^\dagger \hat{a}_p \hat{a}_q \rangle_t$, respectively. As shown in Sec. II of the Supplemental Material [29], we exactly derive the closed equations of motion, which enable us to access the long-time universal dynamics in the open quantum systems. Note that a third quantization and a superoperator method are the well-known efficient techniques to solve the Lindblad equation [32–39], but they are inconvenient in the dephasing case since this dissipation generates quartic terms in the thermofield representation.

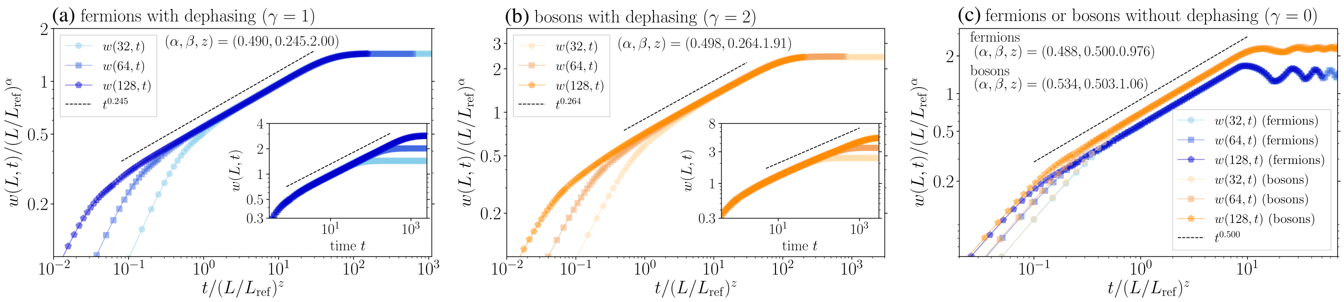


FIG. 2. Time evolution of the surface roughness for (a) fermions with $\gamma = 1$, (b) bosons with $\gamma = 2$, and (c) fermions and bosons with $\gamma = 0$. In the main panel, we show the surface roughness with the ordinate and abscissa normalized by $(L/L_{\mathrm{ref}})^{\alpha}$ and $(L/L_{\mathrm{ref}})^{z}$ with the reference system size $L_{\mathrm{ref}} = 32$ [40]. The estimated exponents (α, β, z) are (a) (0.490, 0.245, 2.00), (b) (0.498, 0.264, 1.91), and (c) (0.488, 0.500, 0.976) for the fermion and (0.534, 0.503, 1.06) for the boson. The insets for (a) and (b) show the time evolution of the surface roughness without normalizing the abscissa and the ordinate.

Solving the equations for the correlation matrices, we can calculate the surface roughness using the following formula:

$$w(L,t)^2 = \pm \sum_{m=1}^{L/2} \sum_{n=1}^{L/2} F_{mnmn}(t) + (1-\nu L) \sum_{m=1}^{L/2} D_{mm}(t) + \frac{\nu^2 L^2}{4} - \left(\sum_{m=1}^{L/2} D_{mm}(t) - \frac{\nu L}{2} \right)^2. \quad (5)$$

Here, the $-(+)$ sign is for fermions (bosons).

FV scaling under the dephasing.—We study how the dephasing [Eq. (2)] affects the surface-roughness dynamics. In this model, the dynamics occurs in a sector with a fixed total particle number, and hence, we expect that the surface roughness comprised of the local particle number exhibits dynamics whose timescale increases with the system size L. The initial states used here are a staggered state (SS) $|\mathrm{SS}\rangle = \prod_{j=1}^{L/2} \hat{a}_{2j}^{\dagger}|0\rangle$, a domain-wall state (DWS) $|\mathrm{DWS}\rangle = \prod_{j=1}^{L/2} \hat{a}_{j}^{\dagger}|0\rangle$, and a uniform state (US) $|\mathrm{US}\rangle = \prod_{j=1}^{L} \hat{a}_{j}^{\dagger}|0\rangle$ with the vacuum $|0\rangle$.

Figure 2 shows time evolution of the surface roughness for (a) fermions with $\gamma = 1$, (b) bosons with $\gamma = 2$, and (c) fermions and bosons with $\gamma = 0$. The initial state is SS. From Figs. 2(a) and 2(b), one can see that the FV scaling is well satisfied for both fermions and bosons with the dephasing, and the scaling exponents are almost the same as those for the EW class. Interestingly, we find that the scaling function has an unconventional form being different from that of the EW equation as discussed in Sec. III of the Supplemental Material [29] [see also Fig. 4(b)]. On the other hand, the isolated fermions and bosons show the FV scaling with the ballistic class [17,19] as shown in Fig. 2(c). Our numerical results clearly show that the dephasing alters the universality class from the ballistic class to the one with the EW-type exponents characterized by the diffusive dynamics with $z = 2$.

Next, we investigate dependence of the dynamics on γ. Figure 3(a) shows the time evolution of $w(L,t)$ for fermions with $\gamma = 1, 2^{-1}$, and 2^{-2}. We find that the surface roughness obeys $t^{0.25}$ in the late dynamics ($t \gtrsim 1/\gamma$), which corresponds to the EW exponent. This fact is clearly seen in the inset of Fig. 3(a). From this result, we argue that the change of the universality class occurs for infinitesimal dissipation strength γ, which indicates the strong impact of dissipation. To strengthen our argument, we also study whether the diffusive transport emerges in the dynamics starting from the DWS. As discussed in Ref. [16], the particle transfer from the left to right region is used to study the transport property. Here, we numerically compute $P_{\mathrm{tra}}(t) = [(N_{\mathrm{right}}(t) - N_{\mathrm{right}}(0)] - [N_{\mathrm{left}}(t) - N_{\mathrm{left}}(0)]$ with $N_{\mathrm{left}}(t) = \sum_{m=1}^{L/2} \langle \hat{a}_m^{\dagger}\hat{a}_m \rangle_t$ and $N_{\mathrm{right}}(t) = \sum_{m=L/2+1}^{L} \langle \hat{a}_m^{\dagger}\hat{a}_m \rangle_t$. If the transport is diffusive,

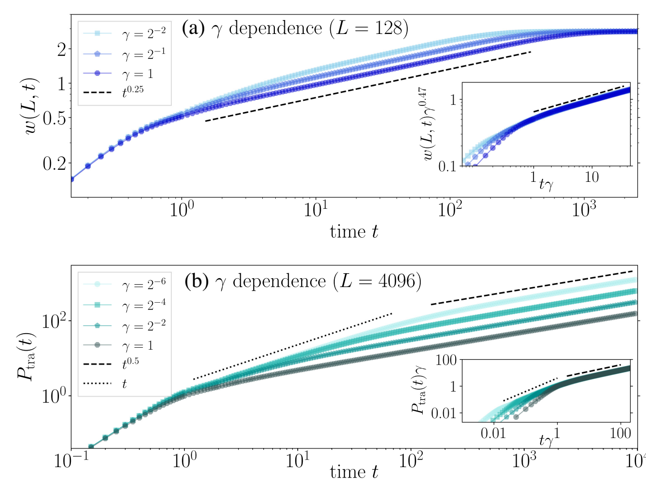


FIG. 3. Dependence of the fermionic dynamics on γ. (a) Time evolution of $w(128,t)$ for $\gamma = 1, 2^{-1}$, and 2^{-2}. The initial state is SS. In the inset, we normalize the time and the roughness by $1/\gamma$ and $1/\gamma^{0.47}$, respectively. This clearly exhibits that $\beta = 0.25$, the signature of the EW class (diffusive dynamics), emerges in $t \gtrsim 1/\gamma$. (b) Time evolution of $P_{\mathrm{tra}}(t)$ for $\gamma = 1, 2^{-2}, 2^{-4}$, and 2^{-6}. The initial state is DWS, and the system size is 4096. In the inset, we normalize the time and the roughness by $1/\gamma$. Similar to (a), the diffusive behavior $[P_{\mathrm{tra}}(t) \propto t^{0.5}]$ emerges for $t \gtrsim 1/\gamma$.

TABLE I. FV scaling exponents for the dephasing model of fermions ($\gamma = 1$) and bosons ($\gamma = 2$) [42]. The obtained FV scaling exponents are close to the exponents of the EW class. The fitting errors are the 3σ errors evaluated in the method of Ref. [43].

Initial state	α	β	z
	[Fermion]		
SS	0.490 ± 0.035	0.245 ± 0.005	2.00 ± 0.15
DWS	0.483 ± 0.061	0.249 ± 0.007	1.96 ± 0.26
	[Boson]		
SS	0.498 ± 0.067	0.264 ± 0.007	1.91 ± 0.29
DWS	0.503 ± 0.036	0.260 ± 0.005	1.95 ± 0.16
US	0.499 ± 0.052	0.262 ± 0.006	1.92 ± 0.23

we have $P_{\mathrm{tra}}(t) \propto t^{0.5}$. Figure 3(b) shows the time evolution of $P_{\mathrm{tra}}(t)$ for the fermions with $\gamma = 1, 2^{-2}, 2^{-4}$, and 2^{-6} in the large system size $L = 4096$ [41]. This result demonstrates that, for $\gamma \gtrsim 2^{-6}$, the ballistic behavior appears in the early dynamics ($1/\gamma \gtrsim t \gtrsim 1$) but the transport eventually becomes diffusive for a sufficiently long time ($t \gtrsim 1/\gamma$). This numerical finding strongly supports our argument.

We numerically investigate the dependence of the FV scaling exponents on the initial states. The detailed time evolution of the surface roughness is given in Sec. IV of the Supplemental Material [29]. The obtained exponents are summarized in Table I, which shows that the exponents are almost independent of the initial states if the initial surface roughness is small.

Renormalization-group analysis.—To understand the change of the universality class analytically, we use a perturbative renormalization-group method [25–27,44] and derive effective equations for D_{mm} and F_{mnmn}, which determine the surface roughness [Eq. (5)]. As derived in Sec. V of the Supplemental Material [29], when the dephasing strength γ is strong, the effective equations for the fermions and the bosons become

$$\frac{d}{dt} D_{mm} \simeq \frac{2}{\gamma} (D_{(m+1)(m+1)} + D_{(m-1)(m-1)} - 2D_{mm}), \quad (6)$$

$$\frac{d}{dt} F_{mnmn} \simeq \frac{2}{\gamma} (F_{(m+1)n(m+1)n} + F_{(m-1)n(m-1)n} + F_{m(n+1)m(n+1)} + F_{m(n-1)m(n-1)} - 4F_{mnmn}) \quad (7)$$

for $|m - n| > 2$. Taking the continuum limit for these equations, we obtain the one- and two-dimensional diffusion equations, which are responsible for the diffusive transport. As far as we know, this is the first analytical derivation of the diffusion equations from the dephasing Lindblad equation. As discussed in Sec. V of the Supplemental Material [29], the effective equations show similar dynamics to the exact numerical results. Our renormalization-group analysis can be applied to other Lindblad equations, offering an interesting method to study the Lindblad dynamics.

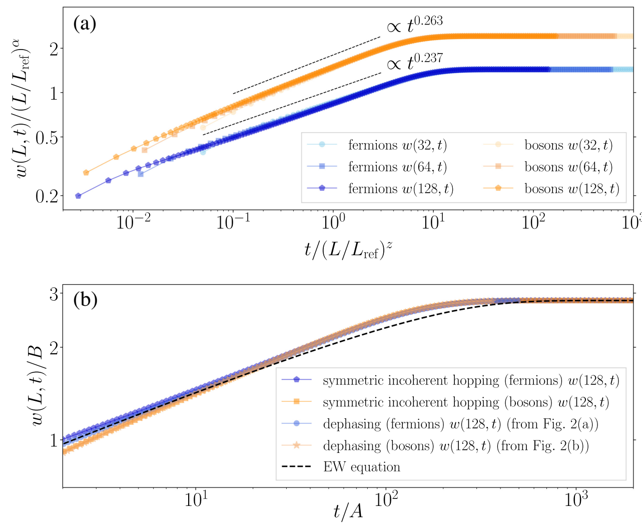


FIG. 4. Time evolution of the surface roughness under the symmetric incoherent hopping. (a) Surface roughness for fermions ($\gamma' = 2$) and bosons ($\gamma' = 4$) obtained by the Lindblad equation with the symmetric incoherent hopping. The ordinate and abscissa are normalized by $(L/L_{\mathrm{ref}})^{\alpha}$ and $(L/L_{\mathrm{ref}})^{z}$ with $L_{\mathrm{ref}} = 32$, and the estimated values of the FV scaling exponents are $(\alpha, \beta, z) = (0.492, 0.237, 2.07)$ for the fermions and (0.508, 0.263, 1.94) for the bosons. (b) Surface roughness for the four different Lindblad equations and the EW equation. The detail of the EW equation is given in Sec. III of the Supplemental Material [29]. The values of A and B for the Lindblad equations are determined such that all the curves in the late stages are collapsed to a single curve by eye. The result for the EW equation does not match the other curves for any values of A and B.

Our renormalization-group analysis explains the emergence of the EW exponents. The dynamical exponent z in the FV scaling is related to the correlation length $\xi(t) \propto t^{1/z}$ for the surface-height correlation [1]. Since the surface-height operator consists of the particle-number operator $\hat{n}_j$, and the effective equations support the diffusive particle transport, we expect $z = 2$. As discussed in Refs. [17,19], we have $\alpha = 0.5$ in typical systems. Then, the scaling relation leads to $\beta = \alpha/z = 0.25$.

While the above method is valid only for strong γ, in Sec. VI of the Supplemental Material [29], making several assumptions based on the exponential decay of the off-diagonal elements of the correlation matrices and focusing on the late stage of the dynamics ($t \gtrsim 1/\gamma$), we derive the same effective equations without assuming the strong dephasing. This supports the emergence of the EW scaling exponents for infinitesimally small dephasing.

FV scaling under the symmetric incoherent hopping.—We next show the emergence of the FV scaling in the Lindblad equation for the symmetric incoherent hopping [Eq. (3)]. The numerical method is similar to that for the dephasing case, and we use the SS state as an initial state.

Figure 4(a) displays $w(L,t)$ for the fermions and the bosons. The FV scaling clearly appears even under the symmetric incoherent hopping. The estimated scaling exponents are very close to those of the EW class. Surprisingly, as shown in Fig. 4(b), the scaling functions are almost the same as those of the dephasing Lindblad equations irrespective of the particle statistics, and the form of the functions is different from the EW scaling function. Our findings strengthen the argument that the open quantum systems with the particle-number conservation universally exhibit the FV scaling with the EW scaling exponents but with the non-EW scaling functions.

Discussion.—We have so far addressed the dissipation conserving the total particle number, but in general interactions with environments lead to gain and loss of the particles. As shown in Sec. VII of the Supplemental Material [29], we numerically solve the Lindblad equation with the inflow and outflow of the particles at all the sites, finding an absence of the FV scaling. We conjecture that the particle-number conservation can be essential for the emergence of the FV scaling because it ensures that the timescale of the surface-roughness growth becomes larger as the system size increases. Another interesting case is a boundary-driven system, where the particles are injected (removed) at the left (right) edge, and thus the particles in the bulk are locally conserved. We will leave exploration of the FV scaling for this interesting setup for a future issue.

We discuss experimental possibilities for observing our theoretical predictions. An experiment under photon scattering [45] is considered to be well described by the Lindblad equation for the dephasing [Eq. (2)]. Thus, the change of the universality class can be experimentally accessible when one observes dynamics beyond the dephasing timescale $1/\gamma$. As to the symmetric incoherent hopping, Refs. [46,47] theoretically proposed how to realize it experimentally, and in future the universal scaling may be explored on the basis of these proposals.

Conclusion.—We theoretically studied the surface-roughness dynamics described by the Lindblad equation with the two types of dissipation: one is the dephasing, and the other is the symmetric incoherent hopping. In both cases, we numerically found the emergence of a clear FV scaling. In the former case, we analytically elucidated that the universality class is altered due to the presence of the dephasing. From these numerical and analytical results, we argued that the change of the universality class occurs at infinitesimally small dissipation, suggesting the substantial impact of dissipation.

Our findings pave an intriguing avenue for exploring the universal fluctuation dynamics in open quantum systems. It is interesting to study whether open quantum many-body systems exhibit novel universal dynamics triggered by the interactions. It is also important to consider other dissipation such as asymmetric incoherent hopping [23,48–52], which has a close relation to classical stochastic processes, e.g., an asymmetric simple exclusion process [53,54].

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