

Kinetic magnetism and stripe order in the antiferromagnetic bosonic t - J modelTimothy J. Harris^{1,2,*}, Ulrich Schollwöck^{1,2}, Annabelle Bohrdt^{1,2,3} and Fabian Grusdt^{1,2,†}¹*Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC),**Ludwig-Maximilians-Universität München, Theresienstr. 37, D-80333 München, Germany*²*Munich Center for Quantum Science and Technology (MCQST), Schellingstr. 4, D-80799 München, Germany*³*University of Regensburg, Universitätsstr. 31, D-93053 Regensburg, Germany*

(Received 3 December 2024; revised 14 January 2026; accepted 1 June 2026; published 15 July 2026)

Unraveling the microscopic mechanisms governing the physics of doped quantum magnets is key to advancing our understanding of strongly correlated quantum matter. Quantum simulation platforms, e.g., ultracold atoms in optical lattices or tweezer arrays, provide a powerful tool to investigate the interplay between spin and charge motion in microscopic detail. Here, in a twist, we disentangle the role of particle statistics from the physics of strong correlations by exploring the strong coupling limit of doped bosonic quantum magnets, specifically the antiferromagnetic (AFM) bosonic t - J model. Using large-scale density matrix renormalization group calculations, we map out the phase diagram on the two-dimensional square lattice at finite doping. In the low-doping regime, bosonic holes form partially filled stripes, akin to those observed in high- T_c cuprates. As doping increases, a transition occurs to a partially polarized ferromagnetic (FM) phase, driven by the motion of mobile bosonic charge carriers forming Nagaoka polarons. At high doping or large t/J , the system evolves into a fully polarized FM. These findings shed light on the role of particle statistics in strongly correlated many-body systems, revealing connections to stripe formation and the physics of kinetic (Nagaoka-type) ferromagnetism. Our results may be realized in state-of-the-art quantum simulation platforms, including bosonic quantum gas microscopes, Rydberg atom tweezer arrays, and ultracold polar molecules, paving the way for future experimental studies of doped bosonic quantum magnets.

DOI: [10.1103/djyg-5jtg](https://doi.org/10.1103/djyg-5jtg)

Introduction. Developing a precise theoretical description of the complex interplay between spin and charge degrees of freedom in doped Mott insulators is a central challenge in strongly correlated many-body physics [1]. To date, the majority of the theoretical discussions have focused on two paradigmatic Hamiltonians—namely the two-dimensional (2D) Fermi-Hubbard and related t - J models—which are believed to capture the essential low-energy physics of high- T_c cuprate superconductors [2,3]. While these models have been pivotal in advancing our understanding of the rich variety of intertwined phases [4], e.g., through impressive recent progress in large-scale numerical simulations [5–7], it currently remains unclear to what extent the fermionic nature of the underlying charge carriers drives the emergence of these phases, as opposed to the competition between motional and magnetic degrees of freedom [8]. Addressing this distinction is crucial for uncovering the mechanisms underlying high- T_c superconductivity and related phases, as it disentangles the role of particle statistics from the intrinsic physics of strong correlations.

In this context, analog quantum simulation platforms, e.g., ultracold atoms trapped in optical lattices or tweezer arrays, provide a powerful approach to exploring the role of particle statistics in the formation of striped and superconducting phases [9–11]. These systems provide well-isolated and fully tunable realizations of minimal condensed matter models, allowing experiments to systematically probe the physics of strongly correlated ultracold quantum matter in microscopic detail [12–14]. Key advantages of these platforms include precise control over particle statistics, lattice geometry, doping and interactions, as well as high-fidelity state preparation and measurement protocols facilitated by spin and charge resolved detection and addressing techniques [15–20]. When combined with quantum gas microscopes [9,21,22], these simulators enable the measurement of multipoint correlation functions that go beyond the capabilities of traditional solid-state experiments [23–27].

Building on this approach, here we study the antiferromagnetic (AFM) bosonic t - J model, which describes the interplay of magnetic and motional degrees of freedom in a system of mobile bosonic holes with local AFM interactions. This model offers a unique opportunity to examine the impact of bosonic statistics in a setting similar to that of fermionic models. Moreover, the AFM bosonic t - J model can be realized in systems of ultracold atoms [28], polar molecules [29–31], and Rydberg tweezer arrays [31,32], making it an experimentally accessible platform for testing theoretical predictions.

Previous theoretical studies of the bosonic t - J model have been restricted to lower-dimensional systems, cases with only

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partial AFM couplings (e.g., $J_z > 0, J_\perp \leq 0$), or in the high-temperature regime [33–40]. However, the low-temperature (ground-state) phase diagram at strong coupling ($t/J \gg 1$) with fully AFM spin-exchange interactions remains largely unexplored, particularly in the numerically challenging finite doping regime.

In this work, we establish the $T = 0$ phase diagram of the AFM bosonic t - J model on the 2D square lattice at finite doping using large-scale density matrix renormalization group (DMRG) calculations [41–45] on finite-size cylinders [46]. At low doping, i.e., close to the Heisenberg AFM—where the ground state is independent of the underlying statistics of the charge carriers—our numerical simulations unveil signatures of stripe order associated with incommensurate AFM correlations, reminiscent of the physics of doped fermionic Hubbard and t - J models [47–49], establishing a connection between our results and the broader physics of doped Mott insulators. In this regime, the ground state remains a total spin singlet.

Beyond a critical doping value, $\delta > \delta_{pp}^*$, the interplay between Heisenberg-type AFM superexchange interactions and itinerant Nagaoka-type ferromagnetism (FM), mediated by the motion of mobile bosonic holes, drives a transition to a partially polarized (PP) FM phase, signified by a departure from a spin-singlet ground state. This transition is accompanied by the formation of so-called Nagaoka polarons—i.e., regions of enhanced FM correlations embedded in an otherwise AFM spin background—resulting in a strong suppression of local AFM correlations as we dope away from half-filling. These Nagaoka polarons are a hallmark of the competition between spin and charge degrees of freedom in strongly correlated systems and directly connect our results to the physics of kinetic (i.e., Nagaoka-type) ferromagnetism [50] recently explored in quantum simulations of the triangular lattice Hubbard model using ultracold fermions [51,52], arrays of quantum dots [53], and moiré heterostructures [54–56].

In the limit of large doping (i.e., for dilute systems) or for large t/J , spatially overlapping Nagaoka polarons begin to percolate throughout the system, leading to the formation of a fully polarized long-range SU(2) ferromagnetic ground state for $\delta > \delta_{FM}^*$ [52,57]. Our results are summarized in Fig. 1.

Model. We consider a model of two-component (i.e., spin-1/2) hard-core bosons on the 2D square lattice:

$$\hat{H}_{t-J} = -t \sum_{\langle i,j \rangle} \sum_{\sigma} \hat{P}_G (\hat{a}_{i\sigma}^\dagger \hat{a}_{j\sigma} + \text{H.c.}) \hat{P}_G + J \sum_{\langle i,j \rangle} \left(\hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j + \frac{3}{4} \hat{n}_i \hat{n}_j \right), \quad (1)$$

where $\hat{a}_{i\sigma}^\dagger$ ($\hat{a}_{i\sigma}$) are the creation (annihilation) operators for a boson on lattice site $\mathbf{i} = (i_x, i_y)$ in spin state $\sigma = \uparrow, \downarrow$; $\hat{n}_i = \sum_{\sigma} \hat{a}_{i\sigma}^\dagger \hat{a}_{i\sigma}$ and $\hat{\mathbf{S}}_i$ are the local density and spin operators, respectively. Here $\langle \mathbf{i}, \mathbf{j} \rangle$ denotes nearest-neighbor (NN) lattice sites, t is the NN tunneling matrix element, J is the isotropic Heisenberg superexchange coupling and $\hat{P}_G$ is the Gutzwiller projection operator, which projects out all states with double occupancies. The bosonic t - J model features both global SU(2) spin rotation symmetry and global U(1) particle number conservation symmetry, which we exploit in our numerical calculations [58].

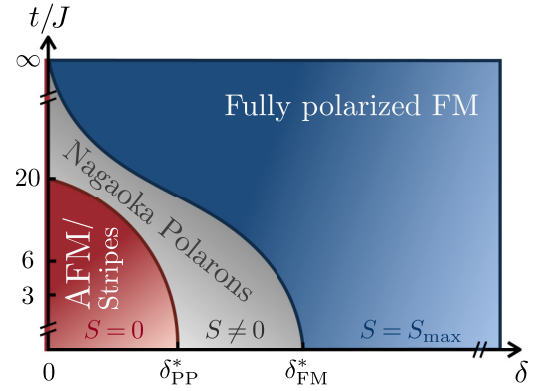


FIG. 1. Phase diagram of the AFM bosonic t - J model. Schematic phase diagram as a function of hole doping δ and interaction strength t/J . At half-filling ($\delta = 0$), the ground state is a long-range ordered Heisenberg AFM (red shaded region). At low doping, we also observe signatures of partially filled stripe order. As doping increases, a transition occurs at δ_{pp}^* to a partially polarized Nagaoka polaron regime (gray) and then to a fully polarized FM phase (blue) at δ_{FM}^* , characterized by total spin quantum numbers $S \neq 0$ and $S = S_{\max}$, respectively. Along the y axis, for $t/J \gtrsim 20$ ($t/J \rightarrow \infty$) previous numerical studies [59] have shown that a single dopant is sufficient to partially (or completely) polarize the system.

In the following, we fix the total particle number $N = N_\ell - N_h$, where $N_\ell = L_x \times L_y$ is the number of lattice sites and N_h the total number of holes doped into the system (i.e., $\delta = N_h/N_\ell$). Moreover, we work in the regime with fully AFM spin-exchange interactions, $J > 0$, where the model exhibits a sign problem [40] and set $J = 1$.

At half-filling ($\langle \hat{n}_i \rangle = 1$), the kinetic motion of holes is frozen out and the ground state of the model, Eq. (1), is a long-range ordered Heisenberg AFM [60]. In this regime, the ground state at strong coupling is identical for both fermionic and bosonic Hubbard systems with AFM interactions. Moreover, in the case of only a single dopant, it can be shown analytically that the ground state remains independent of the underlying particle statistics. However, in the finite doping regime, i.e., where multiple holes are present, the distinction between fermionic and bosonic charge carriers becomes crucial. In this case, the system's behavior is governed by the competition between the kinetic motion of holes and AFM superexchange interactions, leading to distinct correlated phases for fermionic and bosonic dopants.

Ground-state correlations at finite doping. We compute ground-state properties of the doped AFM bosonic t - J model, Eq. (1), via applying the DMRG algorithm [41–45] on finite cylinders [46] up to size $L_x \times L_y = 32 \times 6$ with open (periodic) boundaries along the x (y) direction(s). We explicitly perform calculations, which implement both global $U(1)_N \otimes SU(2)_S$ and $U(1)_N \otimes U(1)_{S_z}$ symmetries to systematically verify the reliability of our results, and keep up to $\chi \sim 10\,000$ SU(2) multiplets (i.e., equivalent to $\sim 30\,000$ U(1) states) [58].

Kinetic magnetism and Nagaoka polarons. To characterize the magnetic nature of the ground state at finite doping, we evaluate the total spin squared via summing over two-point

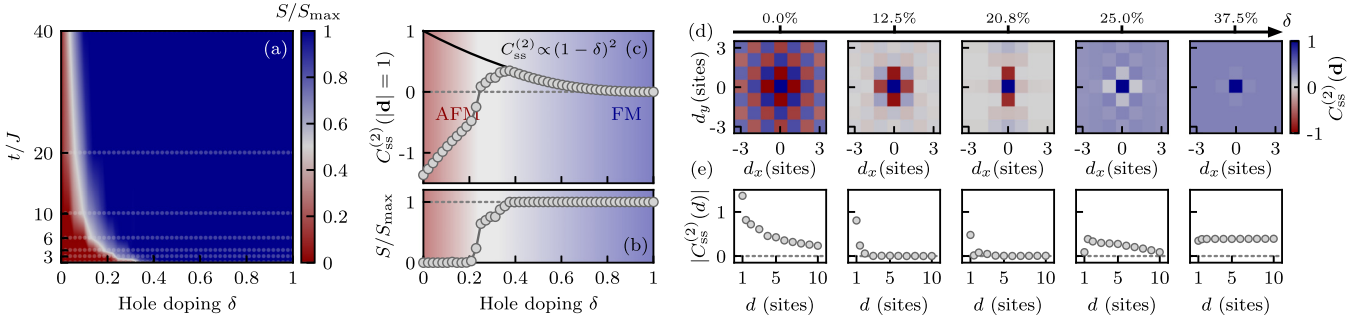


FIG. 2. Magnetic order in the AFM bosonic t - J model. (a) Total spin quantum number $S/S_{\max}$ as a function of hole doping δ and t/J obtained via DMRG simulations in the $S_z = 0$ symmetry sector (data points denoted by light gray circles). In (b) we show a horizontal cut through the heat map presented in (a) for $t/J = 3$, illustrating a clear transition between the AFM, partially polarized and fully polarized FM regimes. Positions of the critical doping values δ_{pp}^* and δ_{FM}^* are indicated by the background shading. (c) A qualitatively identical phase diagram is obtained by analyzing the NN spin-spin correlation function $C_{\text{ss}}^{(2)}(|\mathbf{d}| = 1)$, plotted here for $t/J = 3$ (see Supplemental Material [58]). In the fully polarized FM phase, the NN correlations decay as $C_{\text{ss}}^{(2)} \propto (1 - \delta)^2$ (black solid line) as expected for a doped SU(2) ferromagnet [58]. (d) Spin-spin correlations $C_{\text{ss}}^{(2)}(\mathbf{d})$ for $t/J = 3$ as a function of displacement $\mathbf{d}$ measured in a radius of interest (ROI) of $d = 3$ for increasing doping δ . The range and magnitude of AFM correlations decay quickly with increased doping and become uniformly FM beyond the critical doping $\delta_{\text{FM}}^* \approx 37.5\%$, indicating the formation of a long-range FM phase. (e) Azimuthal average of the sign-corrected spin correlations presented in (d). All DMRG calculations are performed on cylinders of size $L_x \times L_y = 16 \times 6$.

spin-spin correlation functions:

$$\langle \hat{S}^2 \rangle = \sum_{\mathbf{i}, \mathbf{j}=1}^{N_\ell} \langle \hat{S}_{\mathbf{i}} \cdot \hat{S}_{\mathbf{j}} \rangle. \quad (2)$$

Computing the correlation functions numerically allows us to access the total spin S of the ground state via the relation $\langle \hat{S}^2 \rangle = S(S + 1)$. A long-range SU(2) ferromagnet is characterized by maximum total spin quantum number $S_{\max} = (N_\ell - N_h)/2$. In Fig. 2(a), we plot the evolution of the total spin $S/S_{\max}$, normalized by its maximum value, as a function of doping for several values of t/J . We can clearly identify a regime close to half-filling ($\delta \approx 0$) where superexchange interactions dominate, resulting in a spin-singlet ground state with total spin $S = 0$.

As doping increases away from half-filling, the ground state transitions at $\delta = \delta_{\text{pp}}^*$ to a partially polarized (PP) phase, characterized by total spin $S \neq 0$. At even higher doping, specifically for $\delta = \delta_{\text{FM}}^* > \delta_{\text{pp}}^*$, the system transitions into a fully polarized FM phase where the total spin quantum number reaches its maximum value, $S = S_{\max}$ [see Fig. 2(b)]. The fully polarized FM phase remains stable even as $\delta \rightarrow 1$, which distinguishes our findings from previous numerical studies of itinerant magnetism in geometrically frustrated fermionic systems [61–63].

To connect with possible experiments, we compute the connected spin-spin correlation function

$$C_{\text{ss}}^{(2)}(\mathbf{d}) = \frac{4}{\mathcal{N}_{\mathbf{d}}} \sum_{\mathbf{i}-\mathbf{j}=\mathbf{d}} (\langle \hat{S}_{\mathbf{i}} \cdot \hat{S}_{\mathbf{j}} \rangle - \langle \hat{S}_{\mathbf{i}} \rangle \cdot \langle \hat{S}_{\mathbf{j}} \rangle), \quad (3)$$

where the normalization factor $\mathcal{N}_{\mathbf{d}}$ denotes the number of lattice sites $\mathbf{i}, \mathbf{j}$ at distance $\mathbf{d}$. In Fig. 2(c), we show the NN spin correlations $C_{\text{ss}}^{(2)}(|\mathbf{d}| = 1)$ as a function of doping δ for $t/J = 3$. At half-filling, superexchange interactions lead to a ground state characterized by strong NN AFM correlations (i.e., $C_{\text{ss}}^{(2)}(|\mathbf{d}| = 1) < 0$). However, as we increase the doping, this negative correlation is suppressed due to motion of

mobile bosonic holes in the system [see Figs. 2(c)–2(e)]. For $\delta < \delta_{\text{pp}}^*$, the ground state remains a total spin singlet, as holes and spins interact in a way consistent with the formation of magnetic polarons or striplike order [7]. Beyond the critical doping $\delta > \delta_{\text{pp}}^*$, as we enter the partially polarized FM phase, each hole binds to a finite bubble of nonzero magnetization, forming Nagaoka polarons. Indeed, the NN correlations eventually turn ferromagnetic [see Figs. 2(d) and 2(e)] and saturate beyond a critical doping value $\delta \gtrsim \delta_{\text{FM}}^*$, consistent with the picture of overlapping Nagaoka polarons driving a transition to a fully polarized FM phase [52].

For $\delta > \delta_{\text{FM}}^*$, the NN correlations decay as $\propto (1 - \delta)^2$, as expected for a doped long-range SU(2) FM. Notably, the shift of δ_{FM}^* to lower doping δ with increasing t/J is consistent with the Nagaoka picture of a fully polarized FM ground state emerging in the limit of infinitesimal positive doping as $t/J \rightarrow \infty$ [50].

Signatures of stripe order at low doping. In addition to signatures of kinetic magnetism and Nagaoka polarons observed in the magnetic correlations at intermediate to high doping, we also identify evidence for the emergence of partially filled stripes in the low-doping regime where the ground state is a total spin singlet (i.e., $0 < \delta < \delta_{\text{pp}}^*$). To investigate this, we compute the normalized hole-hole correlation function

$$C_{\text{hh}}^{(2)}(\mathbf{i}_0, \mathbf{j}) = \langle \hat{n}_{\mathbf{i}_0}^h \hat{n}_{\mathbf{j}}^h \rangle / \langle \hat{n}_{\mathbf{i}_0}^h \rangle, \quad (4)$$

where $\hat{n}_{\mathbf{i}}^h = 1 - \hat{n}_{\mathbf{i}}$ is the local hole density operator. The correlator $C_{\text{hh}}^{(2)}$ is suppressed if the presence of a hole at reference site $\mathbf{i}_0$ makes it less likely to find a second hole at site $\mathbf{j}$, while the correlator is enhanced if it is more likely [10]. In Fig. 3, we plot $C_{\text{hh}}^{(2)}$ together with the spin-spin correlations and integrated hole density along the long (open) x direction of the cylinder. In the ground state, we observe clear signatures of the formation of partially filled stripes, indicated by (i) a periodic modulation of the hole density along the cylinder, and (ii) the appearance of AFM domain walls at positions of maximum hole density.

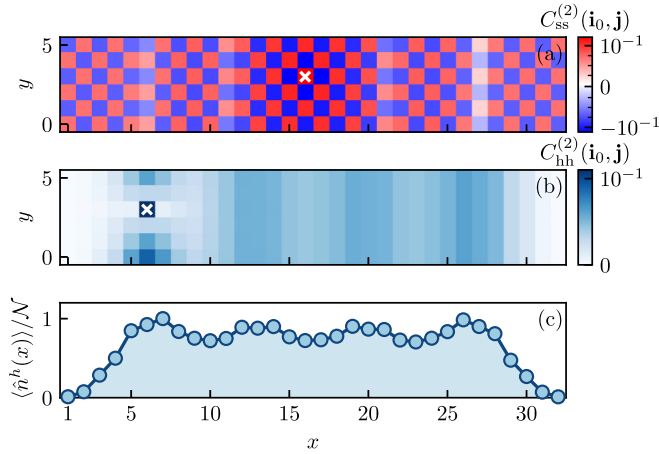


FIG. 3. Stripe order at low doping δ . (a) Spin-spin correlation function $C_{ss}^{(2)}(\mathbf{i}_0, \mathbf{j})$ relative to reference site $\mathbf{i}_0 = (16, 3)$ computed on a 32×6 cylinder for $t/J = 3$ and doping $\delta = 1/24$ in the $S = 0$ symmetry sector. Correlations are color coded utilizing a symmetric logarithmic scale, with linear interpolation between $[-10^{-4}, 10^{-1}]$. Domain walls in the AFM background are indicated by NN lattice sites with like-signed correlations along the x axis. (b) Normalized hole-hole correlation function $C_{hh}^{(2)}(\mathbf{i}_0, \mathbf{j})$ relative to reference site $\mathbf{i}_0 = (6, 3)$. Within a stripe, two holes form a bound object around the closed (periodic) direction of the cylinder. (c) Integrated hole density $\langle \hat{n}^h(x) \rangle = \sum_y \langle \hat{n}^h(x, y) \rangle / L_y$ —normalized to unity—as a function of position along the long (open) x direction of the cylinder. The density profile exhibits a periodic modulation, with hole rich regions corresponding to positions of AFM domain walls identified in (a). Reference sites are denoted by white crosses in (a) and (b).

The hole-hole correlations in Fig. 3(b) indicate that individual bosonic dopants form a bound object with well-defined internal structure. Specifically, given one hole at a reference site $\mathbf{i}_0$, the most probable location for a second hole is $\mathbf{i}_0 + (0, L_y/2)$, corresponding to binding along the short (periodic) y direction of the cylinder. Together with AFM domain walls and modulated hole density, we interpret this as evidence that the two holes bind to form a single, striplike object with filling $\nu = 1/3$. Within a given stripe, the dopants prefer to remain spatially separated along the y direction, consistent with a repulsive short-range interaction between holes, but an overall bound configuration at larger distances. This is consistent with analogous charge correlations detected for fermionic stripes on finite cylinders [64], but stands in contrast to the emergence of C_4 -symmetric, tightly bound hole pairs detected in previous numerical studies of paired phases in the 2D Fermi-Hubbard and t - J models [64,65].

Experimental realization. Our study is motivated by recent advances in experimental platforms, e.g., bosonic quantum gas microscopes [28], Rydberg atom tweezer arrays [31,32], and ultracold polar molecules [30]. Here, we outline a scheme to adiabatically prepare strongly correlated many-body ground states of doped bosonic quantum antiferromagnets in ultracold atom experiments. This approach utilizes the unique advantages of ultracold atom quantum simulators, including their high degree of (local) control and tunability, combined with near perfect isolation from the surrounding environment.

For concreteness, we consider a quantum gas microscope of ^{87}Rb atoms in a 2D square lattice geometry, where the effective spin-1/2 degrees of freedom are encoded in a pair of hyperfine states, e.g., $|\downarrow\rangle \equiv |F=1, m_F=-1\rangle$ and $|\uparrow\rangle \equiv |F=2, m_F=-2\rangle$. Ultracold bosons in optical lattices are already an established platform for studying spin physics, offering insights into both equilibrium and out-of-equilibrium dynamics [66–74]. Crucially, ^{87}Rb atoms allow for the generation of strong, locally programmable staggered fields, which can be employed to adiabatically prepare low-entropy states without crossing a phase transition, providing an additional advantage in realizing and exploring doped bosonic quantum magnets [28,58].

Natively, ultracold bosons in optical lattices realize the spin-1/2 Bose-Hubbard model with (repulsive) on-site interactions $U_{\sigma\sigma'}$ between atoms and tunneling amplitude t . Working in sufficiently deep optical lattices allows us to reach the strong coupling limit ($U_{\sigma\sigma'} \gg t$), where the low-energy physics (i.e., without double occupancy) is effectively described by the bosonic t - J model, Eq. (1), denoted here as $\hat{\mathcal{H}}(t, J)$, with ferromagnetic superexchange coupling $J = -4t^2/U < 0$ [75]. However, by leveraging the bounded nature of the spectrum in the low-energy sector, it is possible to flip the sign of the Hamiltonian in order to experimentally realize antiferromagnetic coupling between bosons [28,76–78]. This amounts to observing that the highest-energy eigenstate of the FM bosonic t - J model, $\hat{\mathcal{H}}(t, J)$, corresponds to the ground state of the AFM t - J Hamiltonian $-\hat{\mathcal{H}}(t, J) = \hat{\mathcal{H}}(t, -J)$, where we have exploited the fact that on a bipartite lattice the sign of the tunneling matrix element t can be exchanged via a local gauge transformation $\hat{a}_{j\sigma} \rightarrow (-1)^j \hat{a}_{j\sigma}$, leaving the overall physics invariant [28].

In practice, implementing this scheme requires preparation of the highest excited eigenstate of the FM Hamiltonian $\hat{\mathcal{H}}(t, J)$ with high fidelity. At half-filling, this can be achieved by locally projecting a strong staggered field of strength $h_z \gg |J|$ onto the lattice, for which a 2D Néel state corresponds to the highest excited eigenstate of the system. Starting from this initial configuration, adiabatically ramping down the staggered field, i.e., $h_z \rightarrow 0$, then prepares the highest excited state of $\hat{\mathcal{H}}(t, J)$. To prepare ground states of doped bosonic quantum AFMs imposes further constraints on the state preparation protocol, additionally requiring that all holes in the system can be locally controlled [28]. In this way, striped ground states could also be directly prepared.

Outlook. In this Letter, we have analyzed the delicate interplay between kinetic and magnetic exchange mechanisms in the phase diagram of the doped AFM bosonic t - J model. In particular, we identified a transition from AFM to FM ordered ground states as a function of doping and t/J , driven by the proliferation of Nagaoka polarons through the system. Additionally, we unveiled signatures of partially filled stripe order in the low-doping regime, providing further evidence of a connection between our model and the strongly correlated phases of the fermionic Hubbard and t - J models. Our results may be observed in state-of-the-art quantum simulation platforms, e.g., quantum gas microscopes of ultracold bosonic atoms in optical lattices [28], Rydberg atom tweezer arrays [31,32], and systems of ultracold polar molecules [30].

Future work may include extending our results to finite temperatures ($T > 0$), thereby quantifying the effects of thermal fluctuations on the observed phase diagram of the doped AFM bosonic t - J model, and exploring possible connections between low-temperature striped phases and the emergence of a pseudogap in doped bosonic systems [79–81]. From a practical perspective, it would also be interesting to investigate the influence of tunable hole-magnon couplings in the system [71,82] (e.g., how these may modify spin-charge correlations in the finite doping regime), as well as the feasibility of utilizing tools including engineered dissipation [83–87], entropy redistribution [88,89], and adiabatic cooling [28,73,90–94] to prepare strongly correlated many-body states of doped bosonic AFMs in ultracold atom experiments.

Note added. Recently, we became aware of a closely related work by Zhang *et al.* [95], in which they use DMRG to explore the phase diagram of the AFM bosonic t - J model. In contrast to our study, the authors focus on finite cylinders of width $L_y = 4, 8$ using a combination of canonical ensemble and grand-canonical ensemble simulations, respectively, for which they report a pair-density wave with commensurate AFM order instead of the striped phase with incommensurate AFM order that we report in cylinders of width $L_y = 6$. Addi-

tionally, we note a slight difference in model parameters, with local density-density interaction $+\frac{3}{4}\hat{n}_i\hat{n}_j$ used in this work, compared to $-\frac{1}{4}\hat{n}_i\hat{n}_j$ in Ref. [95].

Acknowledgments. We wish to thank Tizian Blatz, Immanuel Bloch, Antoine Browaeys, Lukas Homeier, Hannah Lange, Sebastian Paeckel, Lode Pollet, Henning Schlömer, David Wei, and Johannes Zeiher for valuable discussions. This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy EXC-2111 Grant No. 390814868 and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant Agreement No. 948141), ERC Starting Grant SimUcQuam. T.J.H. acknowledges funding by the Munich Quantum Valley (MQV) doctoral fellowship program, which is supported by the Bavarian state government with funds from the Hightech Agenda Bayern Plus. Numerical simulations were performed on the Arnold Sommerfeld Center for Theoretical Physics High-Performance Computing cluster and the KCS cluster at the Leibniz Supercomputing Center (LRZ).

Data availability. All data and code used to generate figures and numerical results presented in this work are available from the corresponding authors upon reasonable request.

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