Quantum algorithms for bosonic Hamiltonians and applications to lattice field theory

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Ground-state preparation for hadron structure and scattering

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Near-term applications → Compute **hadron structure observables** from QCD matrix elements

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$$\langle P|\mathcal{O}|P\rangle$$

Fragmentation Function (FF)

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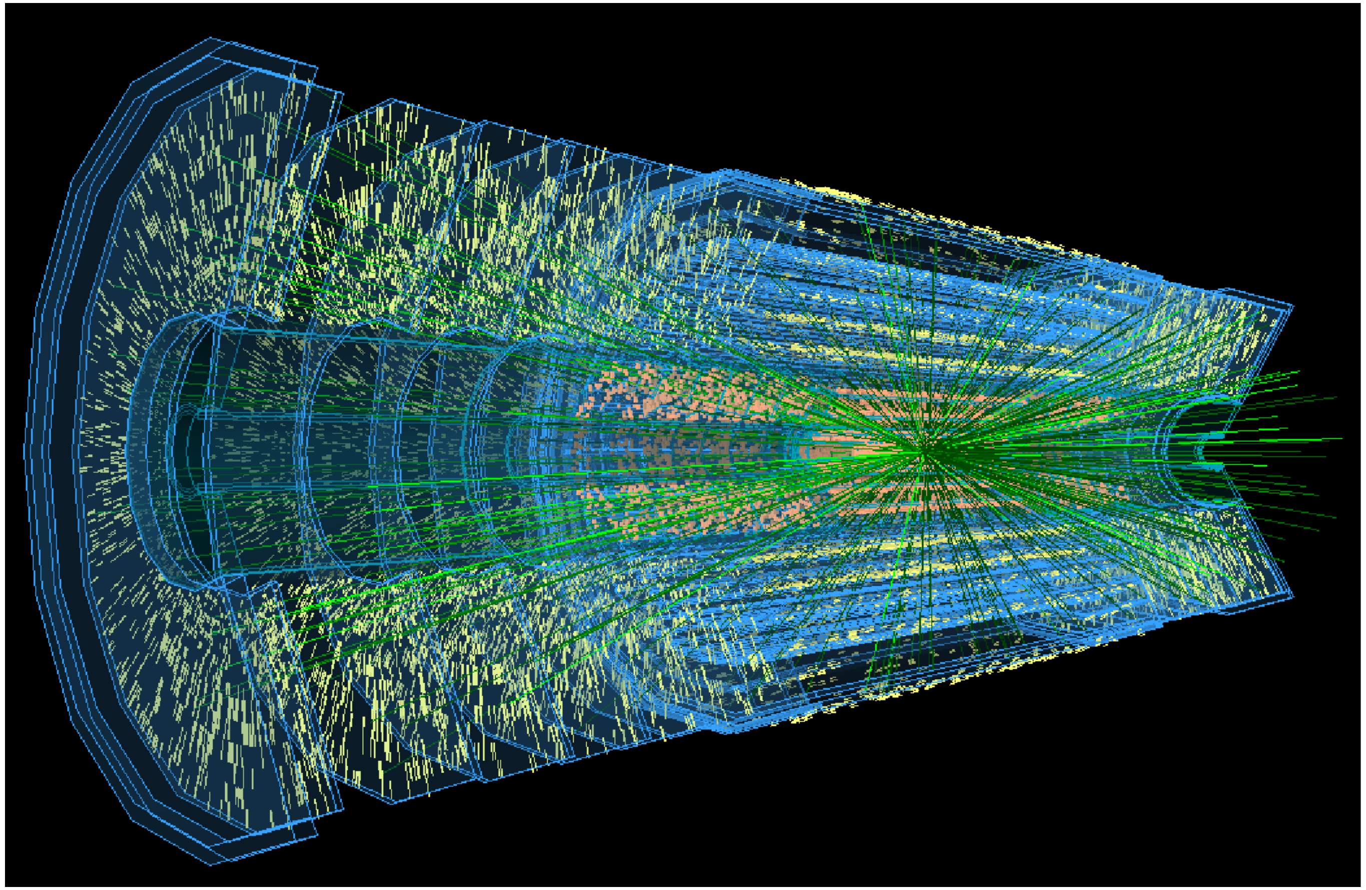
Parton Distribution Function (PDF)	Fragmentation Function (FF)
$\langle P\|\mathcal{O}\|P\rangle$	$\langle 0\|\mathcal{O}\|h, X\rangle$

Long-term applications → Predict complete scattering processes and experimental observables.

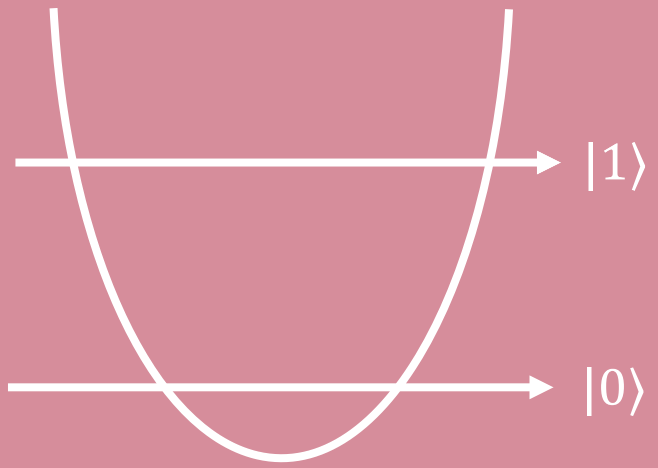
$$\sigma = \mathrm{PDF} \otimes \mathrm{Hard\ scattering} \otimes \mathrm{FF}$$

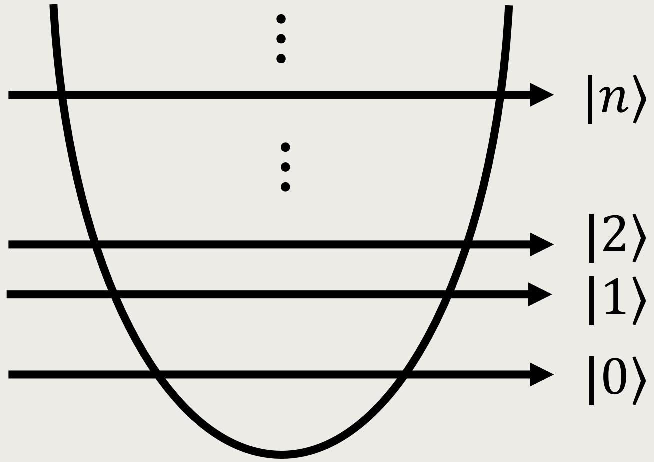


IFIC (CSIC-UV)

Qubits and Qumodes

	QUBIT	QUMODE
Nature of information	• **Discrete** → Two-level system	• **Continuous** → Harmonic oscillator with infinite many levels
State representation	• **Finite-**dimensional Hilbert state → <u>two-dimensional</u> per qubit	• **Infinite-**dimensional Hilbert state per qumode





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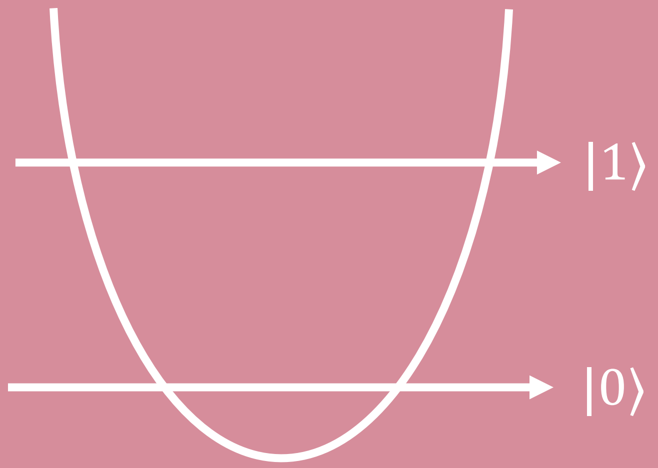
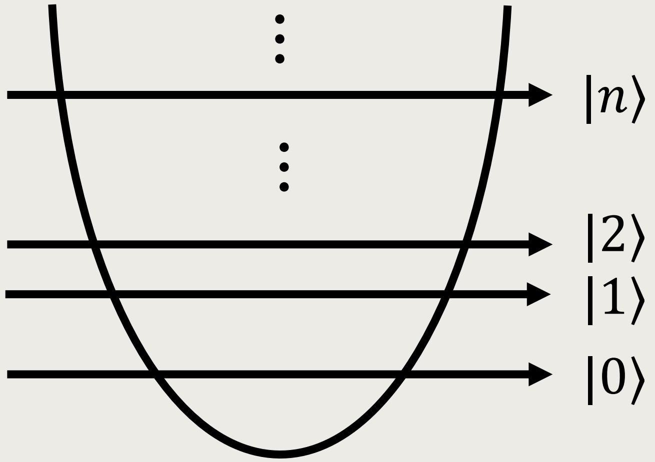


SPIN



BOSONS

From Collider Physics to Quantum Simulations

1 Use the **Hamiltonian** notation $\mathcal{L} = \bar{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi + g_s\,\bar{\psi}\,\gamma^\mu T^a\,\psi\,A^a_\mu - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} \rightarrow \mathcal{H} = \ldots$

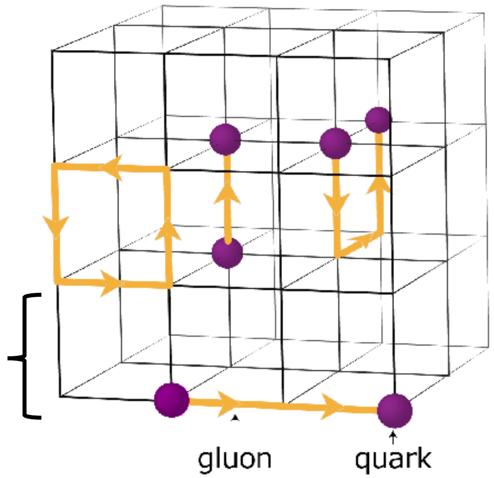
Girvin, Wiebe *et al.* 2025
Ale, Rainaldi, Rico, Ringer & Siopsis, 2026

From Collider Physics to Quantum Simulations

1. Use the **Hamiltonian** notation

2. **Discretize** spatial component

$$x = an \quad (n = 0, \ldots, L-1)$$



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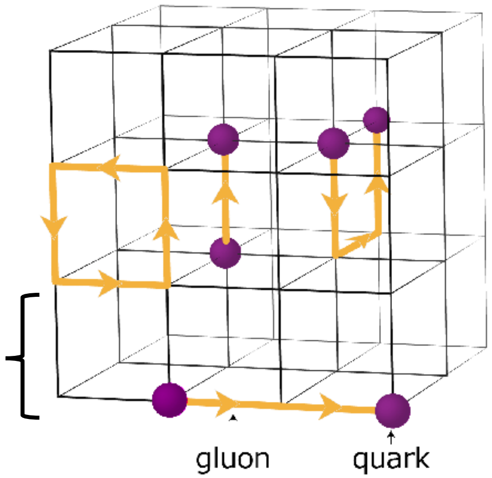

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Take **limits** $\mathrm{L} \to \infty,\ a \to 0$ +
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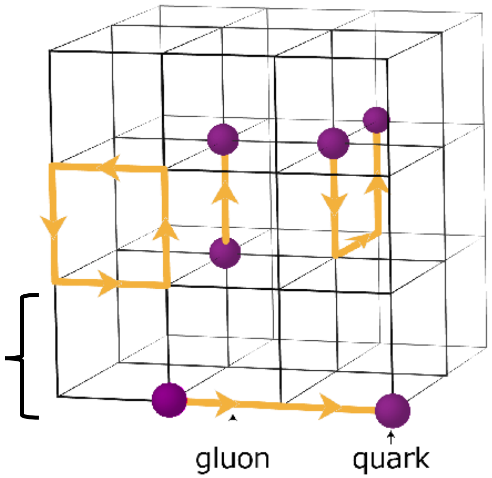

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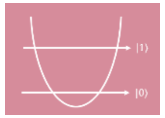
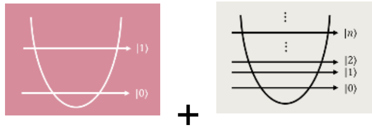
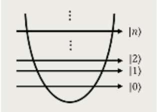


QUBIT



+

QUBIT-QUMODE COUPLING



QUMODE

3 Map to **qubits** and **qumodes**

$$\mathcal{L} = \bar{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi + g_s\,\bar{\psi}\,\overbrace{\gamma^\mu T^a}\,\psi\,A^a_\mu - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu}$$

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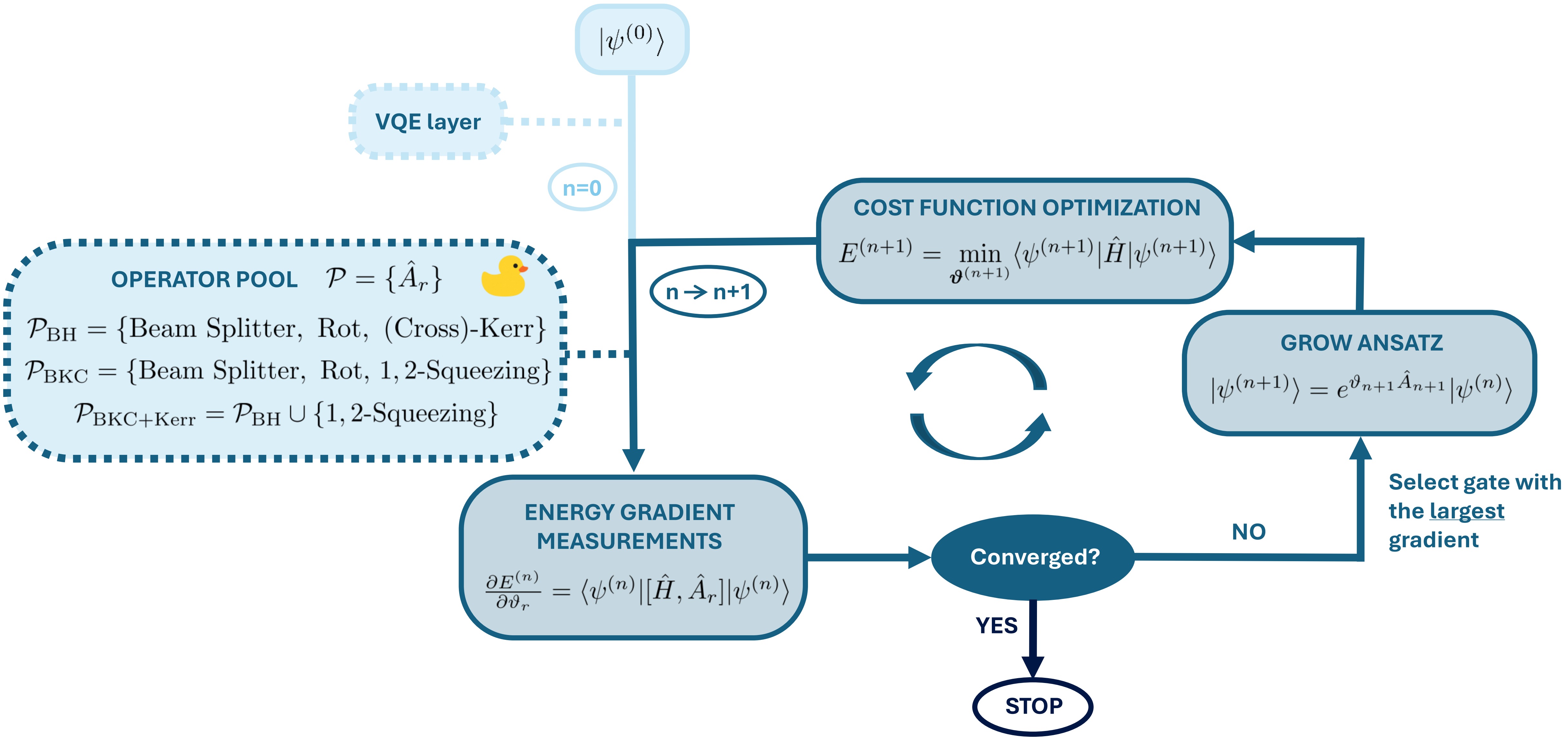
CV-ADAPT-VQE



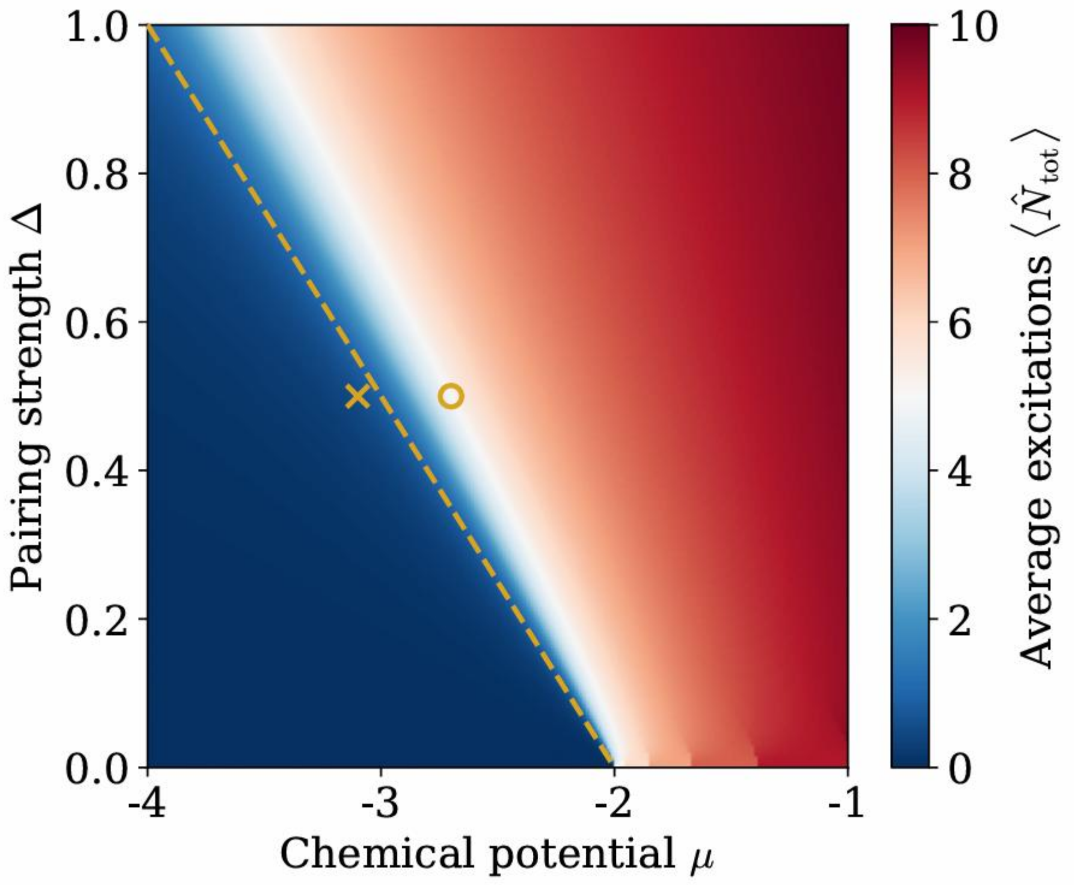
$|\psi^{(0)}\rangle$
VQE layer
n=0
COST FUNCTION OPTIMIZATION
$E^{(n+1)} = \min_{\boldsymbol{\vartheta}^{(n+1)}} \langle\psi^{(n+1)}|\hat{H}|\psi^{(n+1)}\rangle$
OPERATOR POOL $\mathcal{P} = \{\hat{A}_r\}$
$\mathcal{P}_{\mathrm{BH}} = \{\text{Beam Splitter},\ \text{Rot},\ \text{(Cross)-Kerr}\}$
$\mathcal{P}_{\mathrm{BKC}} = \{\text{Beam Splitter},\ \text{Rot},\ 1,2\text{-Squeezing}\}$
$\mathcal{P}_{\mathrm{BKC+Kerr}} = \mathcal{P}_{\mathrm{BH}} \cup \{1,2\text{-Squeezing}\}$
n → n+1
GROW ANSATZ
$|\psi^{(n+1)}\rangle = e^{\vartheta_{n+1}\hat{A}_{n+1}}|\psi^{(n)}\rangle$
Select gate with the largest gradient
ENERGY GRADIENT MEASUREMENTS
$\frac{\partial E^{(n)}}{\partial \vartheta_r} = \langle\psi^{(n)}|[\hat{H},\hat{A}_r]|\psi^{(n)}\rangle$
Converged?
NO
YES
STOP

CV-ADAPT-VQE: BKC model (non-number conserving)

$$\hat{H}_{\mathrm{BKC}} = \sum_r \left(-J\hat{a}_r^\dagger \hat{a}_{r+1} - \Delta \hat{a}_r \hat{a}_{r+1} + \mathrm{h.c.}\right) - \mu \sum_r \hat{n}_r$$

HARD-WALL

$N_S = 3$, local cutoff = 6



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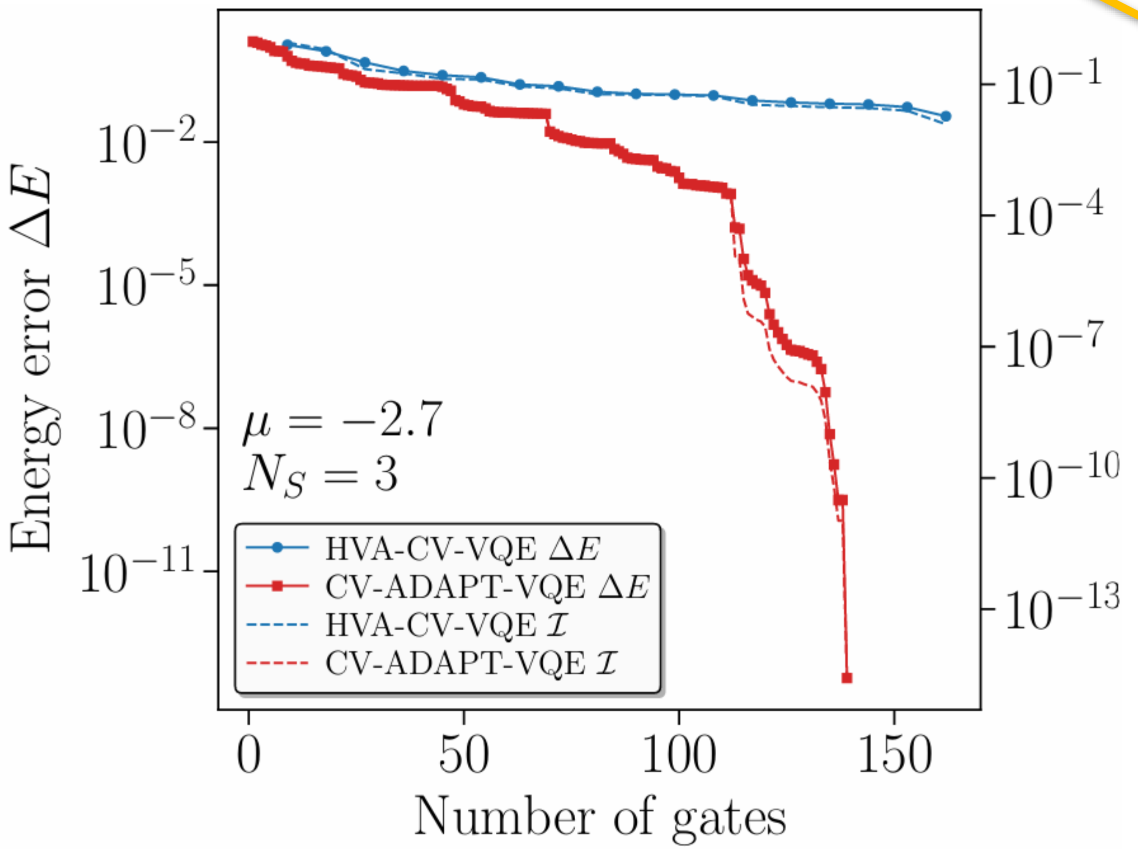
$N_S = 3 \quad \Delta = 0.5 \quad \mu = -2.7$



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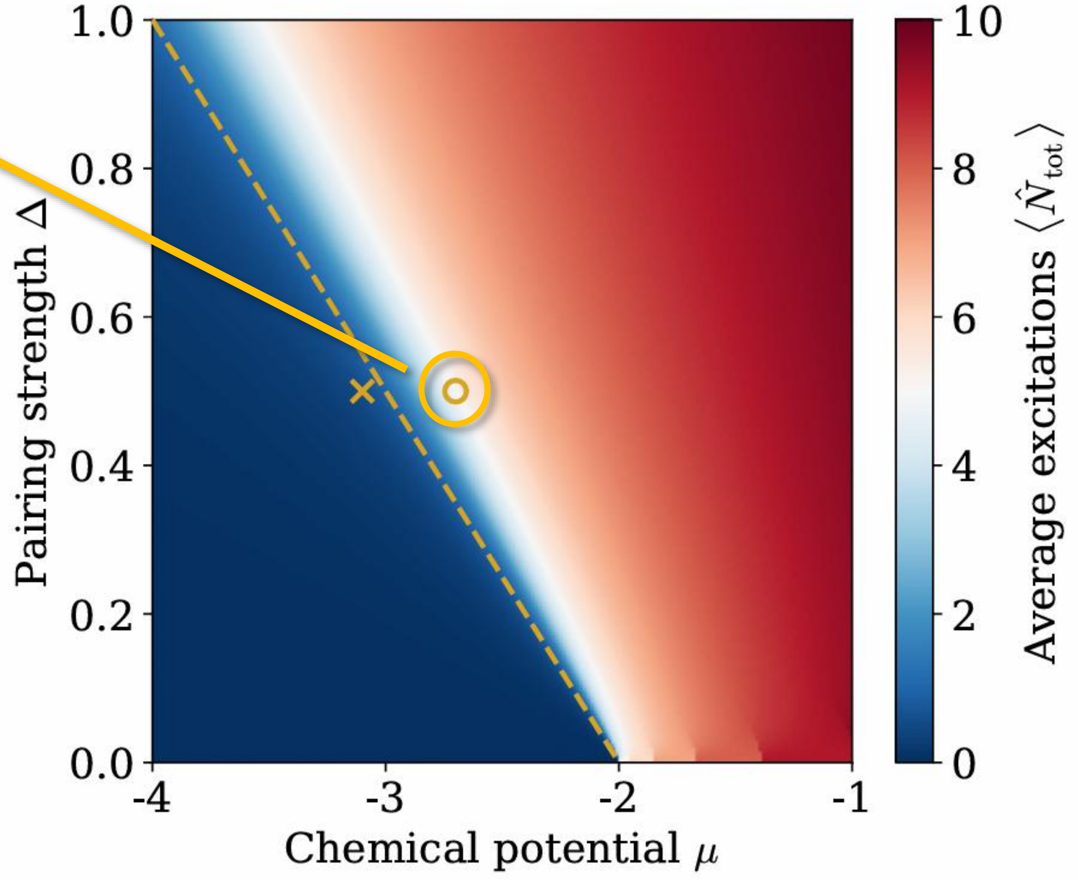

Outlook

CV-ADAPT-VQE

- Improve operator pools
- Scalable-circuits ADAPT-VQE
- Thermal state preparation
- Hybrid qubit-qumode architectures
- **Excitations** and **correlation** functions
- Real-time dynamics and scattering

Athanasakos, Tejedor-García, Araz, Ramôa, Sambasivam, Economou & Ringer, 2026, **arXiv:2606.05297**