Quantum simulations of hadron structure and strong field dynamics

Xingyu Guo (QUNU Collaboration)
South China Normal University

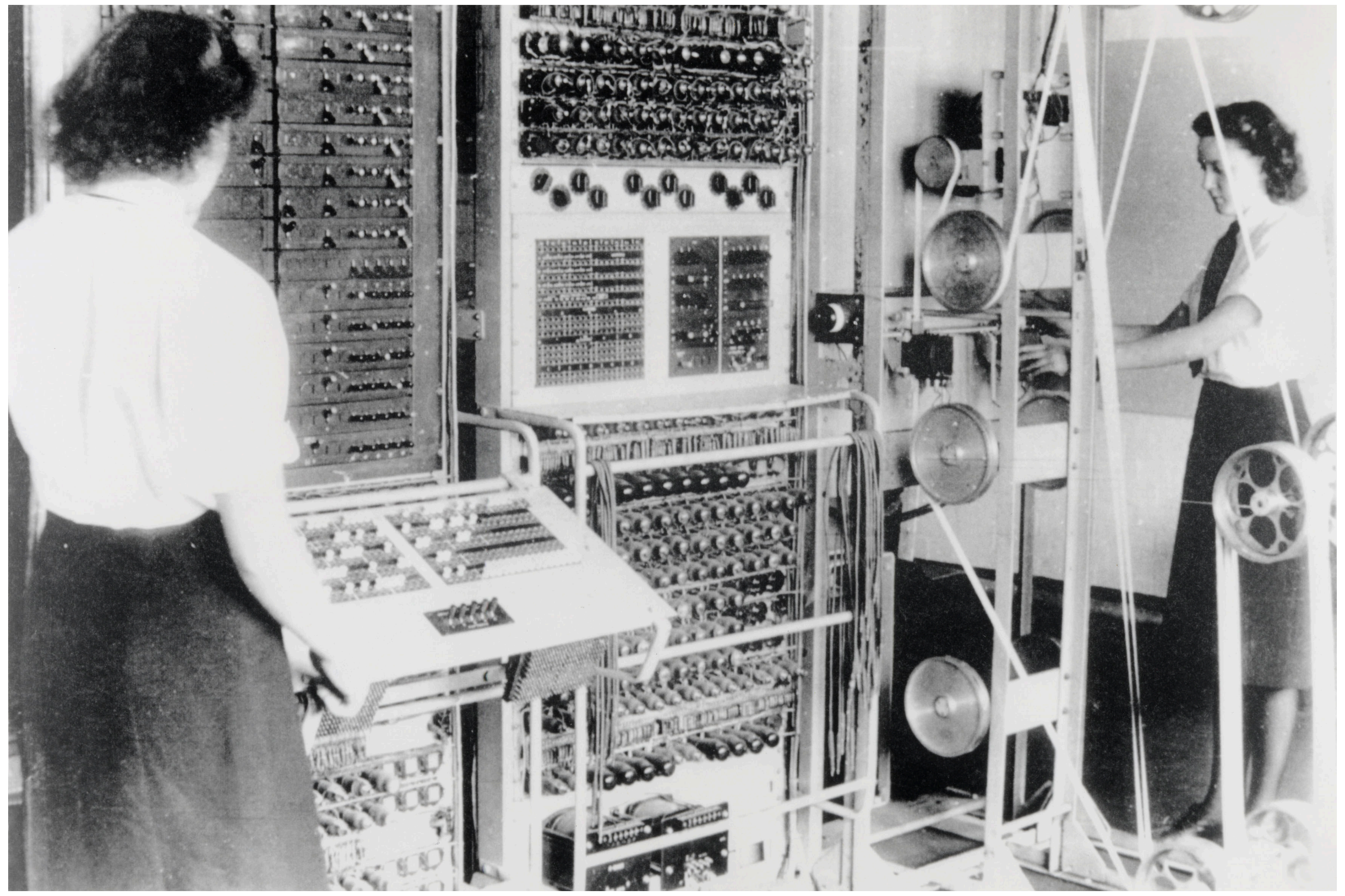
Quantum Computing and Machine Learning Workshop 2026

Outline

- Quantum simulation of Schwinger mechanism
- Quantum simulation of hadron structure
- Summary

Current State of Quantum Hardware

- Noisy intermediate-scale quantum (NISQ) devices
  - Error rate: 1%~0.1%
  - Number of qubits: 100 ~1000



Current State of Quantum Hardware

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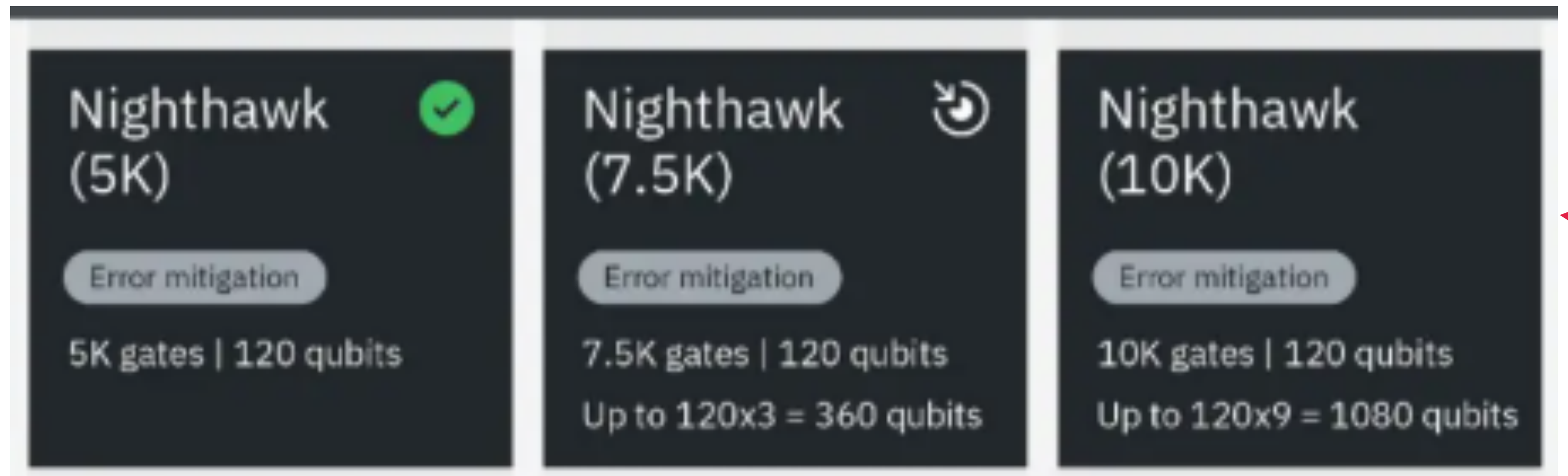
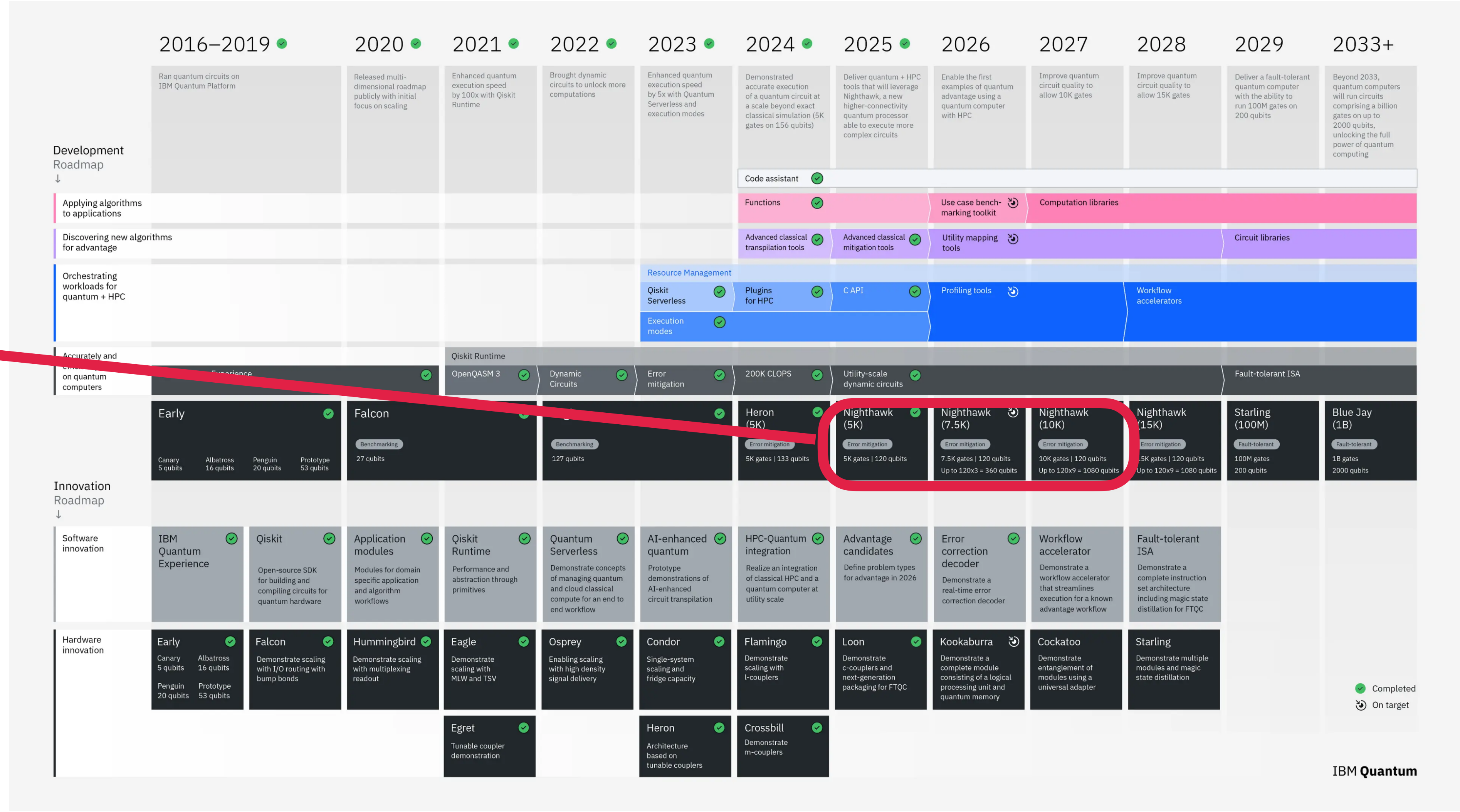
  - Simulation of 2+1D systems is becoming reasonable



https://www.ibm.com/quantum/hardware#roadmap



Current State of Quantum Hardware

- Noisy intermediate-scale quantum (NISQ) devices
  - Error rate: 1%~0.1%
  - Number of qubits: 100 ~1000
  - Simulation of 2+1D systems is becoming reasonable
- What meaningful study can we do now?
  - Search for effective, applicable algorithm
  - Meaningful topics with small, simple systems

Gauge Theory in 1+1D

- Schwinger Model:

$$H = -\bar{\psi}(i\gamma^{1}\mathrm{D}_{1} + m_{\alpha})\psi + \frac{1}{2}E^{2}$$

- Gauss's law:

$$\partial_x E = Q(x) \longrightarrow E(x) = E_0 + \int_0^x \mathrm{d}Q(y)$$

- The remaining gauge link can be eliminated by a gauge transformation.
- Pure fermionic Hamiltonian:

$$H = \frac{1}{2a}\sum_{n=1}^{N-1}\left(\phi_n^{\dagger}\phi_{n+1} + H.c.\right) + m\sum_{n=1}^{N}(-1)^n\phi_n^{\dagger}\phi_n + \frac{g^2a}{2}\sum_{n=1}^{N-1}\left[\varepsilon + \sum_{l=1}^{n}\left(\phi_l^{\dagger}\phi_l - \frac{1-(-1)^l}{2}\right)\right]^2$$

Schwinger Mechanism

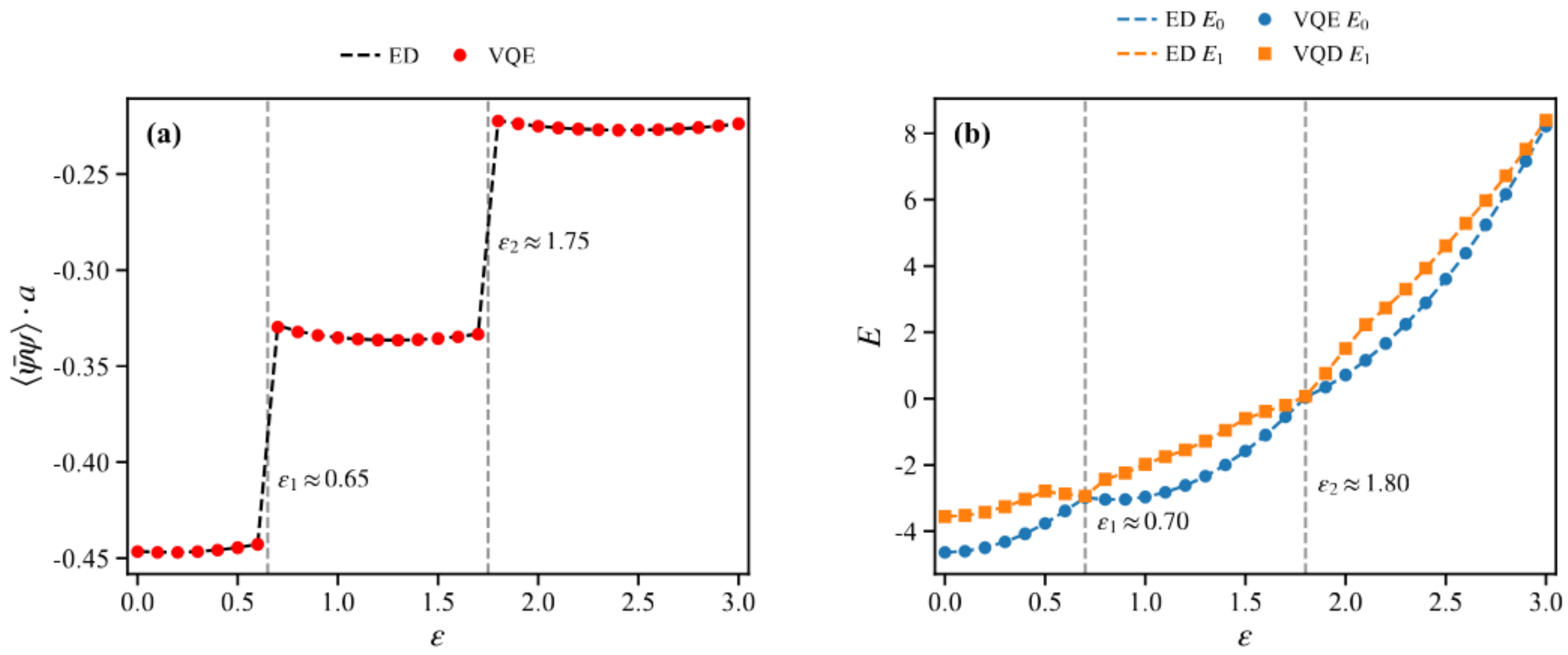
- Pair production under strong electric field.
- Strong field effect: no traditional perturbation method.
- Dynamical evolution: well-established in quantum simulation.
  - Trotterization
- State preparation: VQE + VQD

$$\langle \varphi(\theta) | H | \varphi(\theta) \rangle \qquad \langle \varphi(\theta) | H | \varphi(\theta) \rangle + \lambda \langle \varphi(\theta) | \varphi_0 \rangle$$

H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State with External Field

- "Jump" of the ground state.
  - First order phase transition at zero temperature.
- But there is no jump in the spectrum.



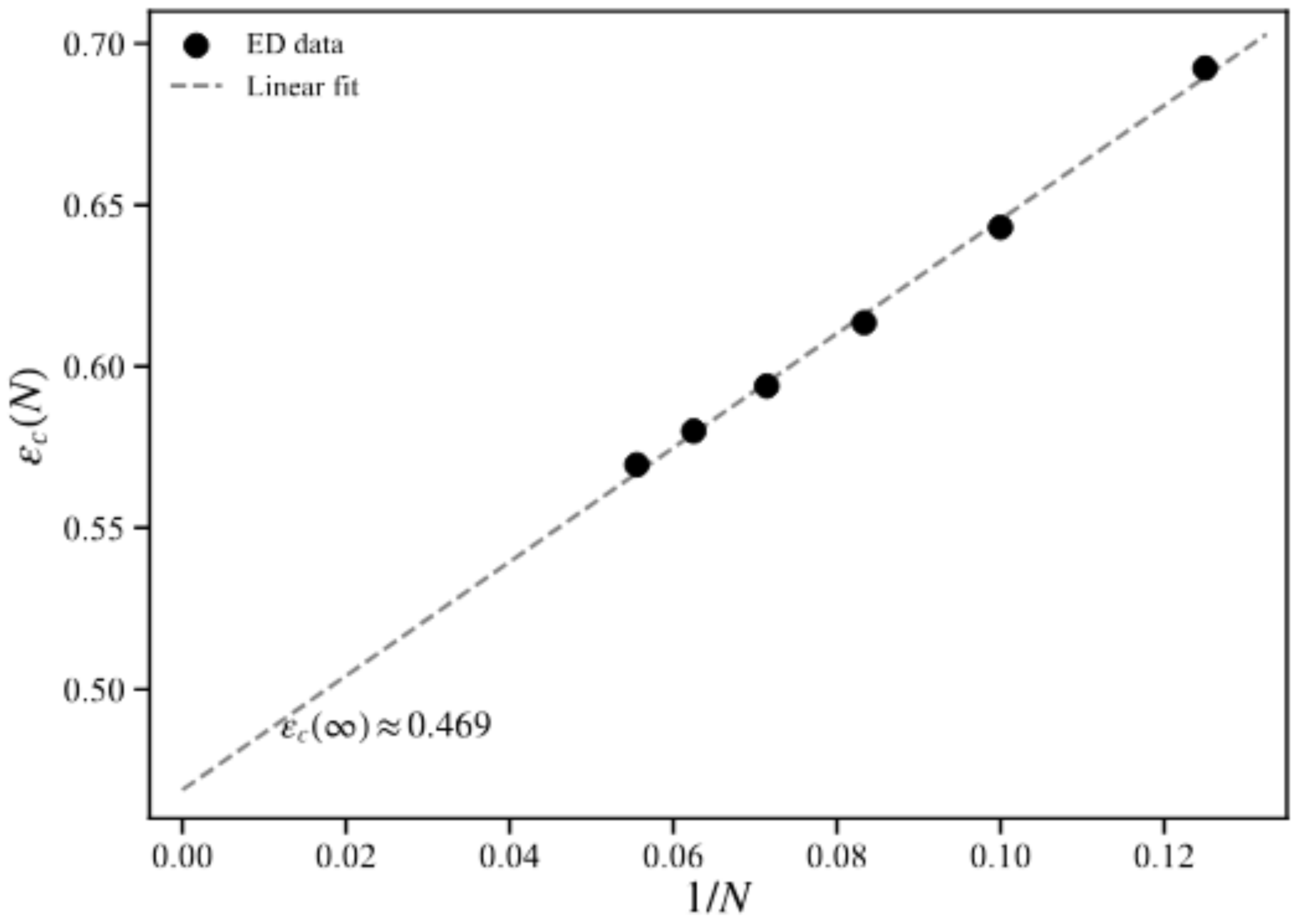
Chiral condensate of ground state

Energy of ground and first excited state

H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State with External Field

- The critical field strength $\epsilon_c \sim 1/N + \epsilon_c(\infty)$.
- $\epsilon_c(\infty)$ is smaller than the theoretical prediction: 0.5.
- Open boundary effect: $\langle H_k \rangle$ gives a negative contribution.

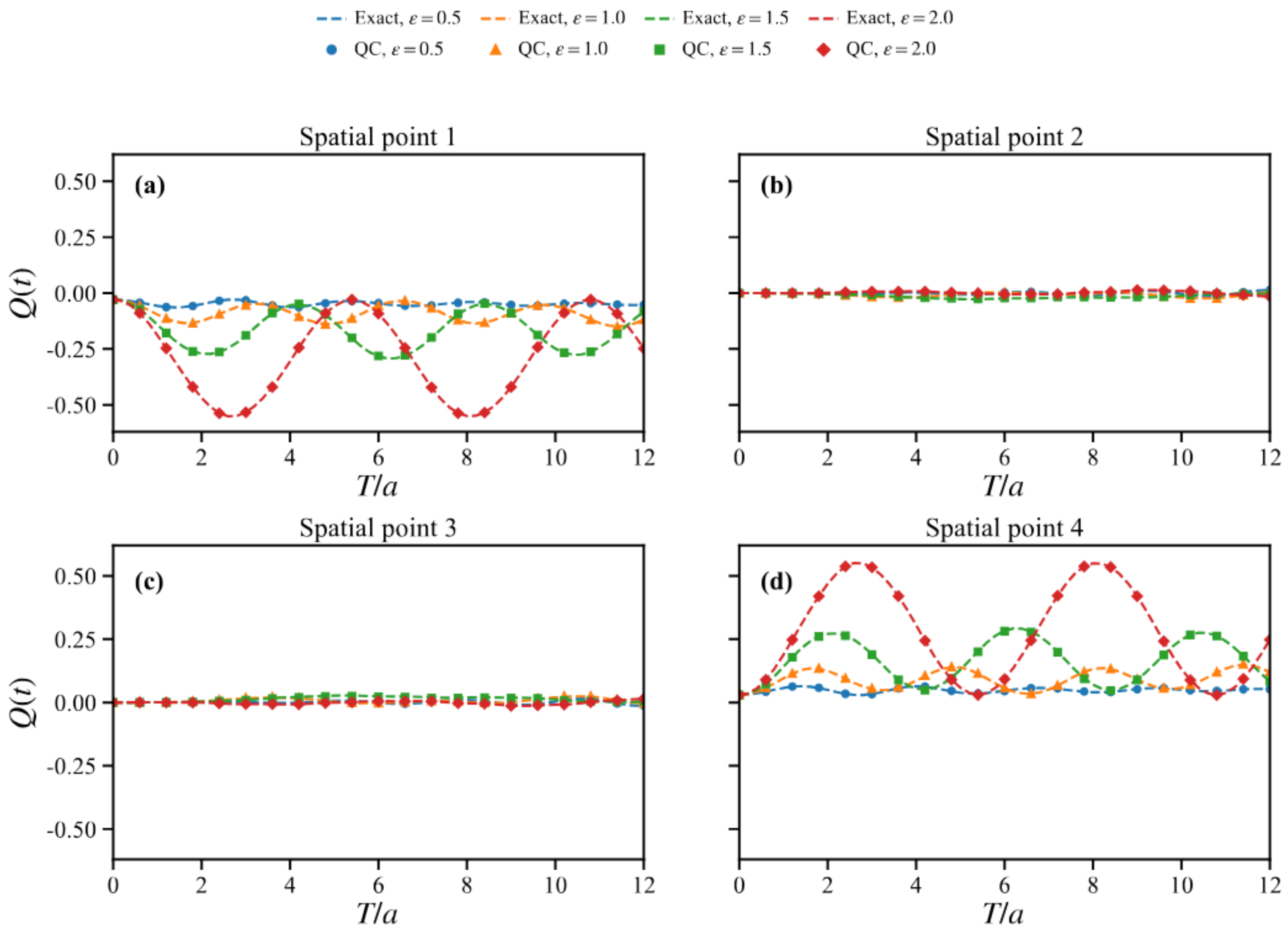


Fitting of the critical field strength

H. Chen, L. Cheng, XG, arXiv:2607.02894

Spatial Charge Distribution

- A pair of charge is periodically produced at the boundary.
- No critical field strength observed.
- Consistent with theoretic prediction.



Time evolution of spatial charge density

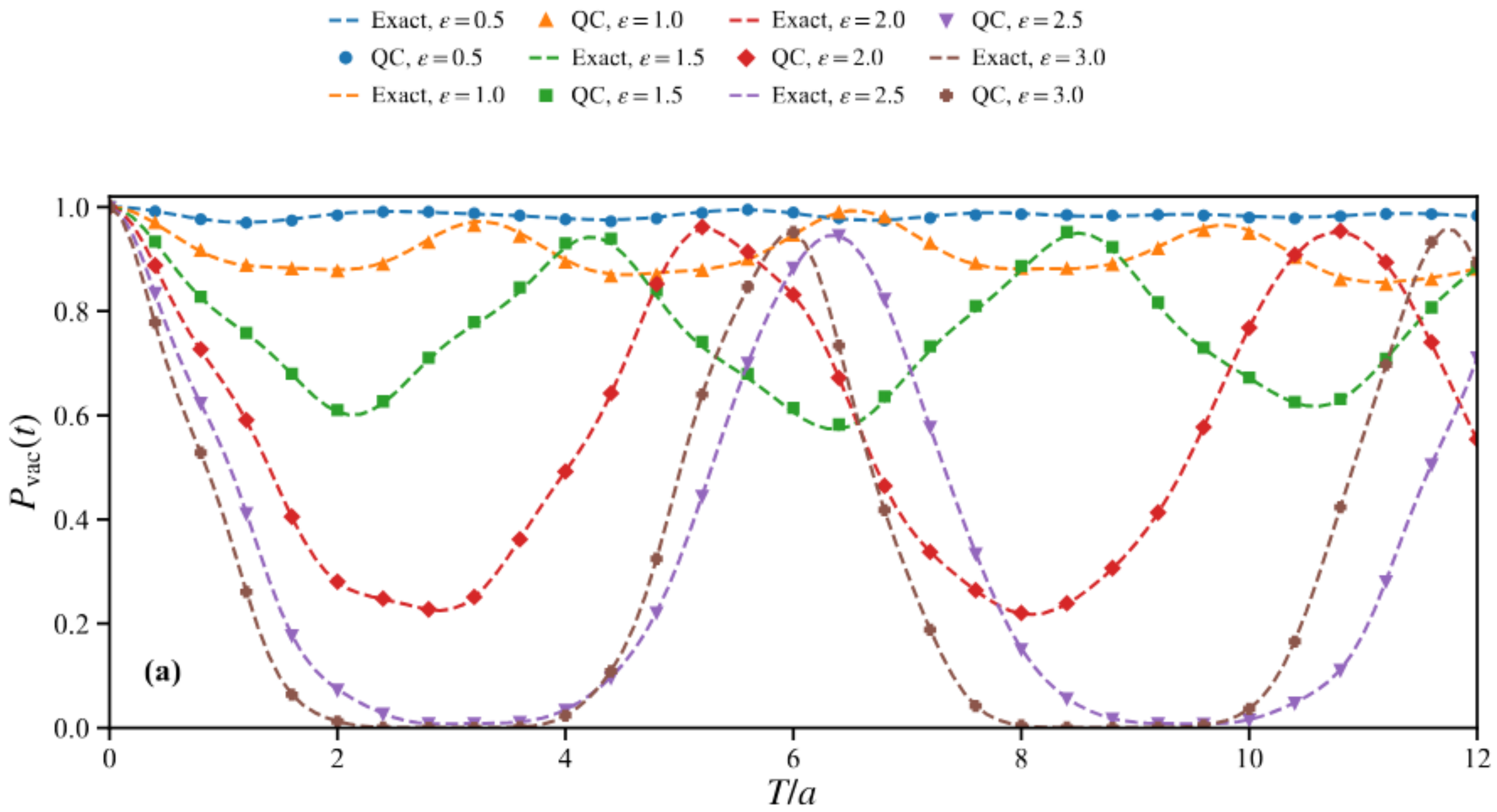
H. Chen, L. Cheng, XG, arXiv:2607.02894

Vacuum State Fidelity

- Vacuum state fidelity

$$P_{\text{vac}}(t) = |\langle\psi_0|\psi(t)\rangle|^2$$

- Describes how far the system deviates from the initial state.



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Vacuum State Fidelity

- Vacuum state fidelity

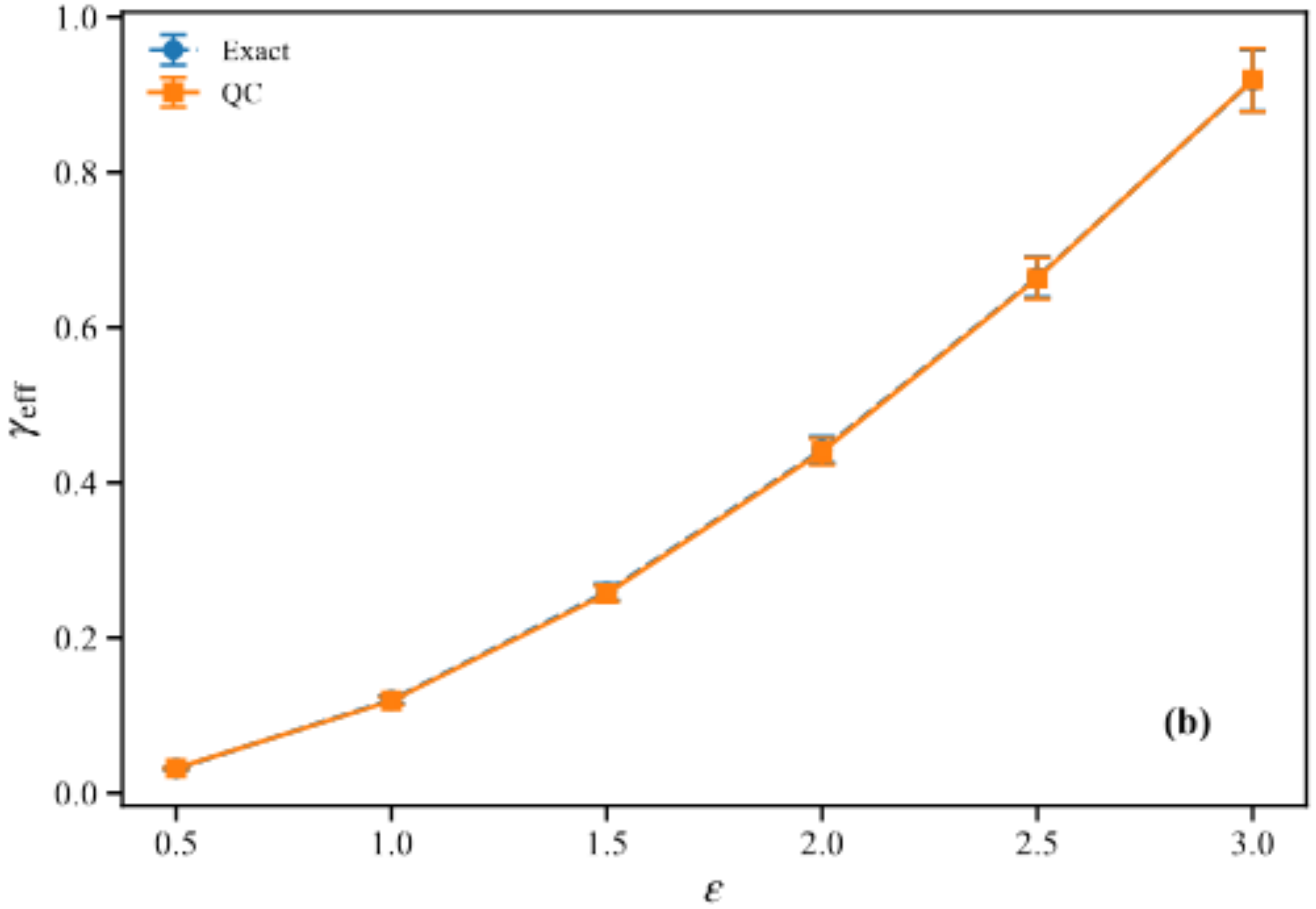
$$P_{\text{vac}}(t) = |\langle \psi_0 | \psi(t) \rangle|^2$$

- Describes how far the system deviates from the initial state.
- Fitting ($0 \le T/a \le 1.0$):

$$P_{\text{vac}}(t;\varepsilon) \simeq A(\varepsilon)\exp\left[-\gamma_{\text{eff}}(\varepsilon)t\right]$$

- In theory, pair production rate:

$$\Gamma \sim E^2 \exp(-a/E)$$



Fitted value of γ_{eff}

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Generalized Parton Distribution(GPD)

- GPD: parton distribution with longitudinal momentum transfer

$$H_{q/h}(x,\xi) = \int \frac{\mathrm{d}z}{4\pi} e^{-ixz\hat{n}\cdot P} e^{-iz\Delta\cdot\hat{n}} \langle h(p') \,|\, \bar{\psi}(z\hat{n})(\hat{n}\cdot\gamma) W(z\hat{n},0)\psi(0) \,|\, h(p)\rangle$$

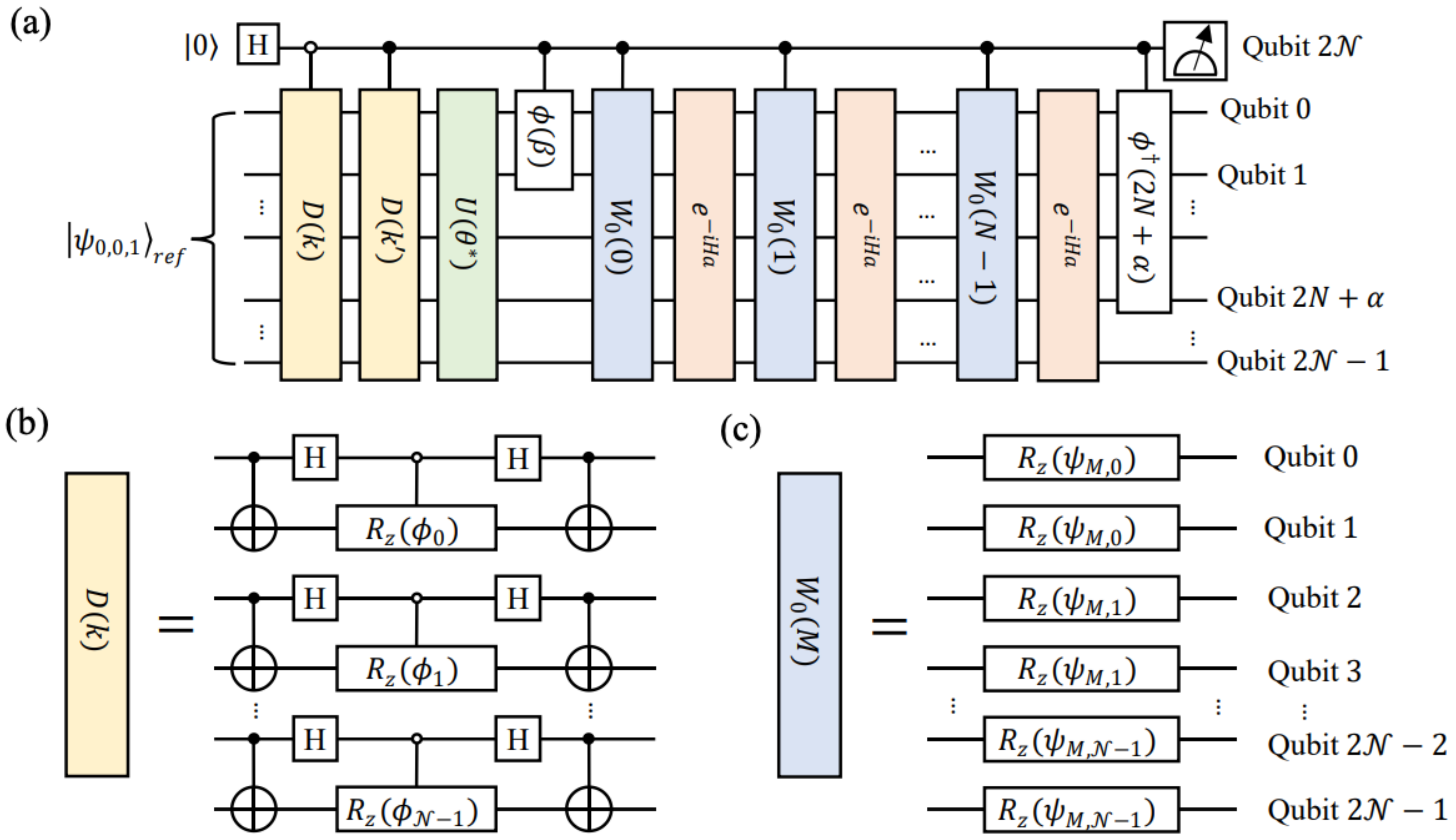
Where $P = (p' + p)/2, \Delta = p' - p, \xi = -\dfrac{\hat{n}\cdot\Delta}{2\hat{n}\cdot P}$

- Hadron states with different momentum
- Wilson line

$$W(z\hat{n},0) = \prod_{N'=0}^{N-1} e^{-iHa} e^{-iga\hat{A}_0(N')}$$

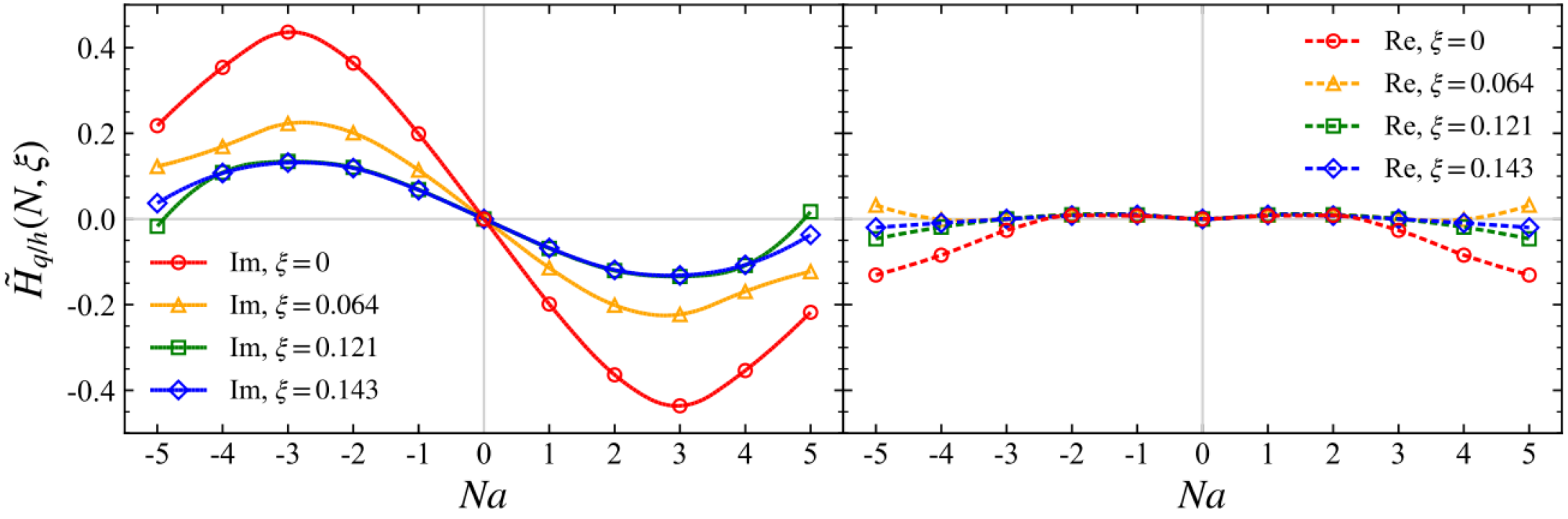
Generalized Parton Distribution(GPD)

- Quantum circuit:



T. Li, H. Xing, arXiv:2606.22602

Lightcone correlation function



- Real part comes from finite volume effect.

T. Li, H. Xing, arXiv:2606.22602

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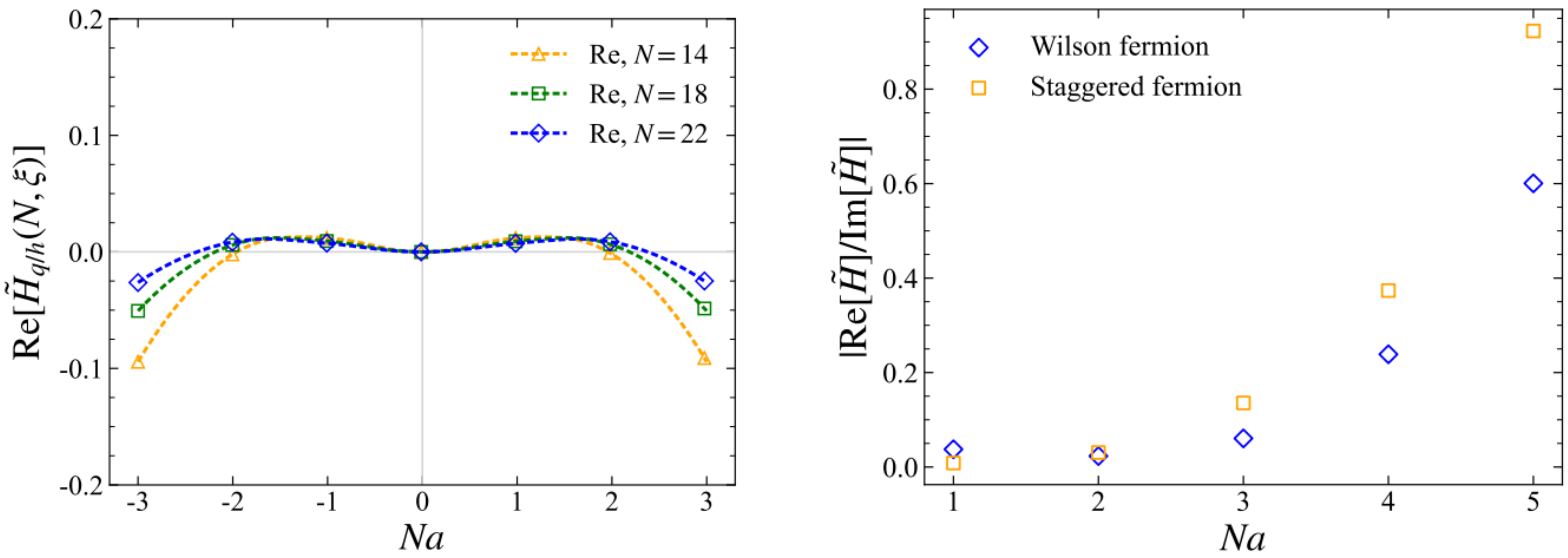
Lightcone correlation function

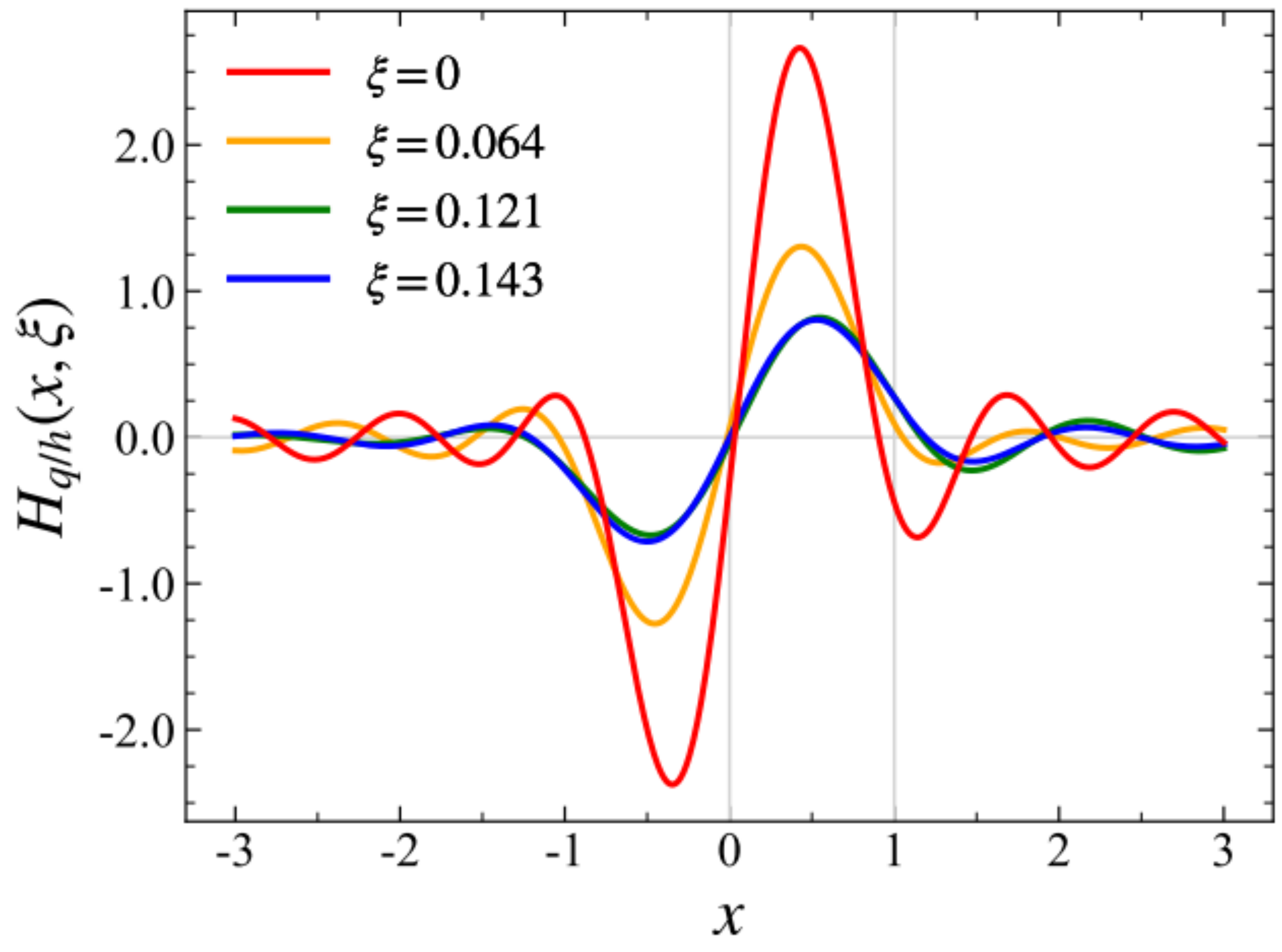


- Real part decreases with increasing lattice size.
- Wilson fermion gives better result than staggered fermion.

T. Li, H. Xing, arXiv:2606.22602

GPD

- GPD goes back to PDF at $\xi = 0$.
- Peak shifts to larger x when ξ increase.
- Behavior consistent with tensor network results.[arXiv:2511.17752]



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Hadronic Tensor

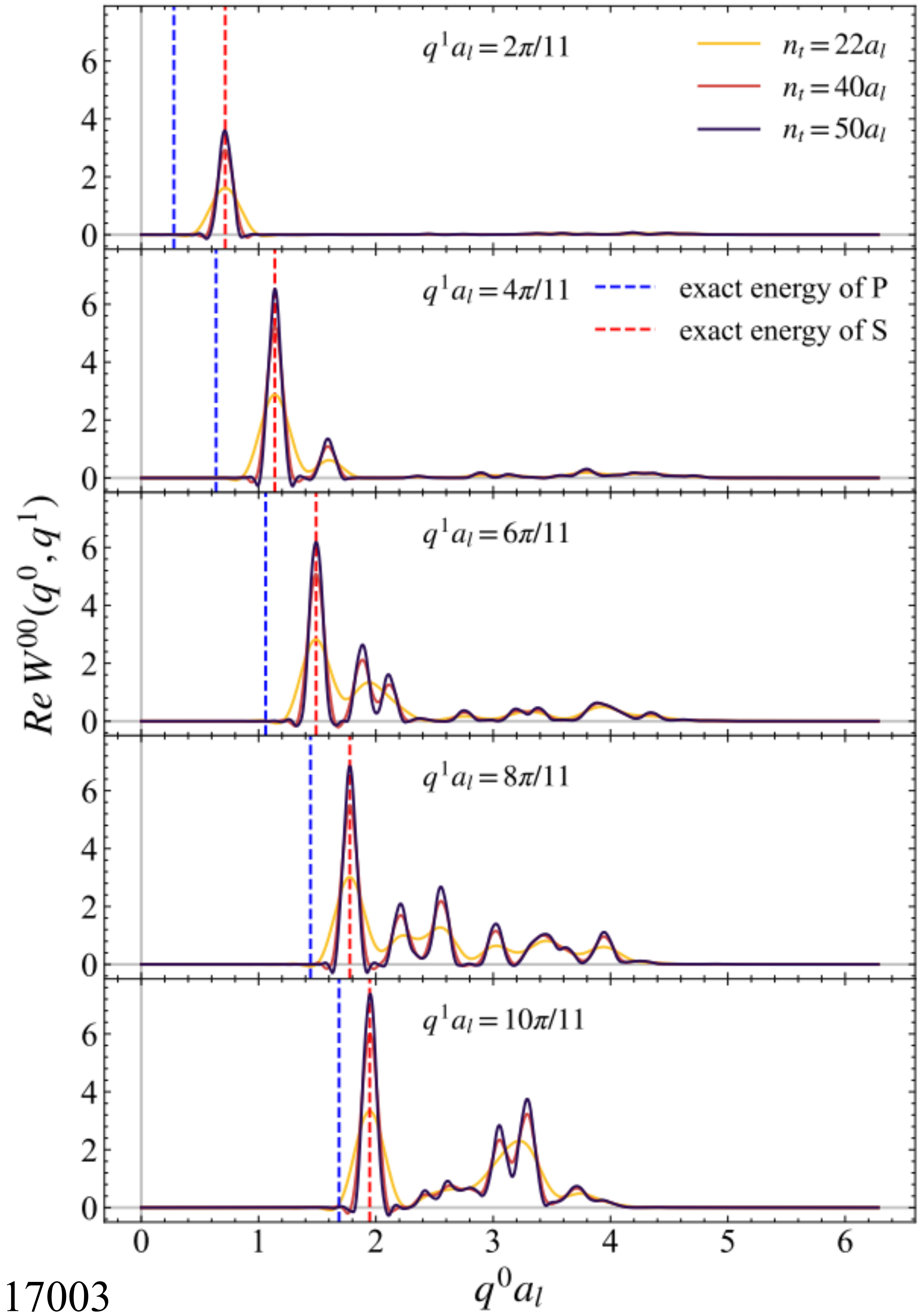
- Hadronic tensor: widely used scattering

$$W^{\mu\nu}(q) = \int \mathrm{d}^D z e^{iqz} \langle h | J^\mu(z) J^\nu(0) | h \rangle$$

- $W^{\mu\nu}(q) \sim \sum_X \int \mathrm{d}\Pi_X (2\pi)^D \delta^{(D)}(q + p_h - p_X) \langle h | J^\mu(0) | X \rangle \langle X | J^\nu(0) | h \rangle$
- $\int \mathrm{d}q^0 W^{00}(q) \sim |\langle h | J^0(0) | h \rangle|^2 \sim F^2(Q^2)$

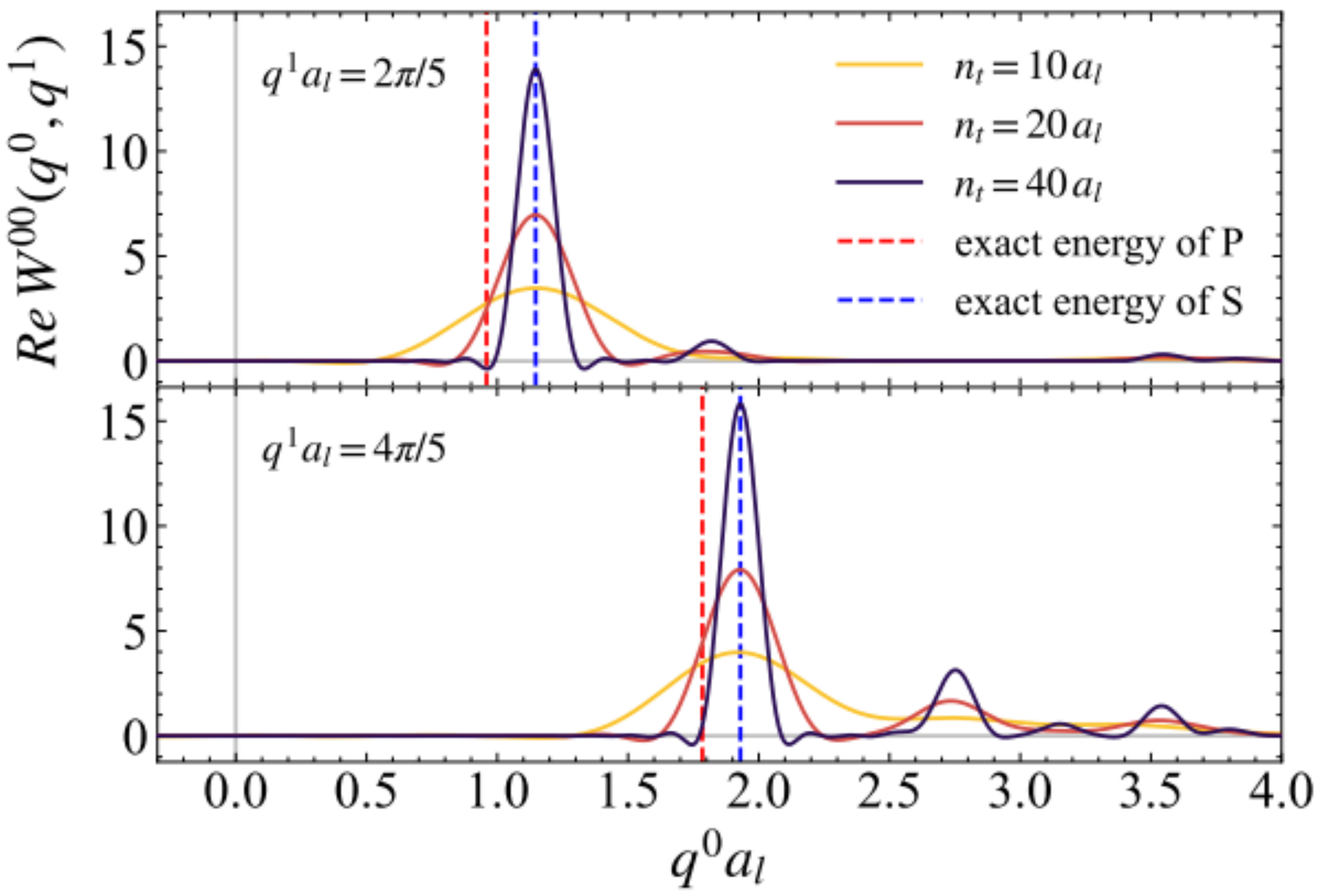
Hadronic Tensor in U(1) model

- Main peak correspond to S state.
- No contribution from P state due to C conservation.
- Also contributions from excited / multi particle states.

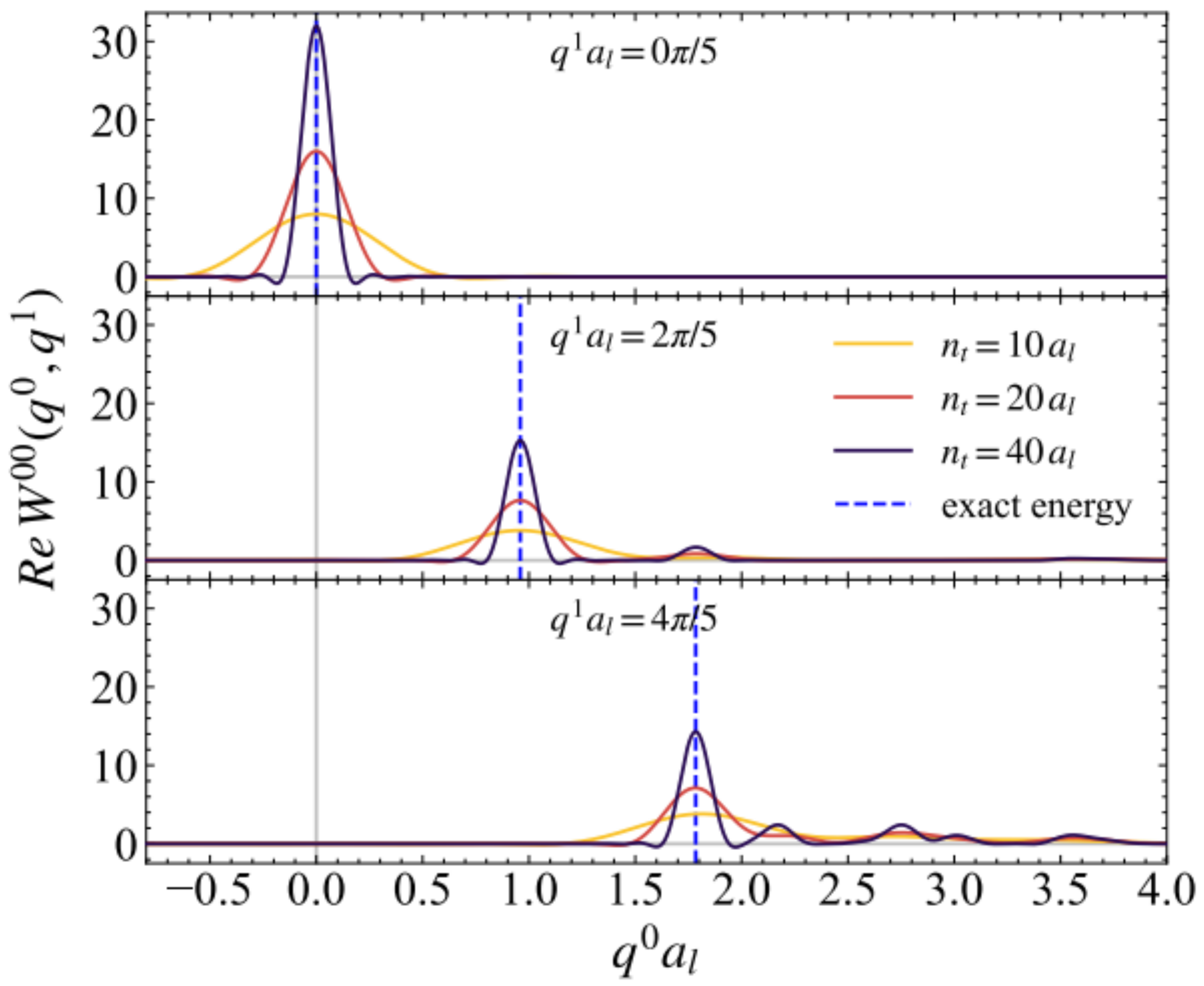


D. Zhou, T. Li, J. Liang, E. Wang, H. Xing, arXiv:2606.17003

Hadronic Tensor in SU(2) model



(a) $W^{00}(q)$ of meson state in SU(2) LGT.



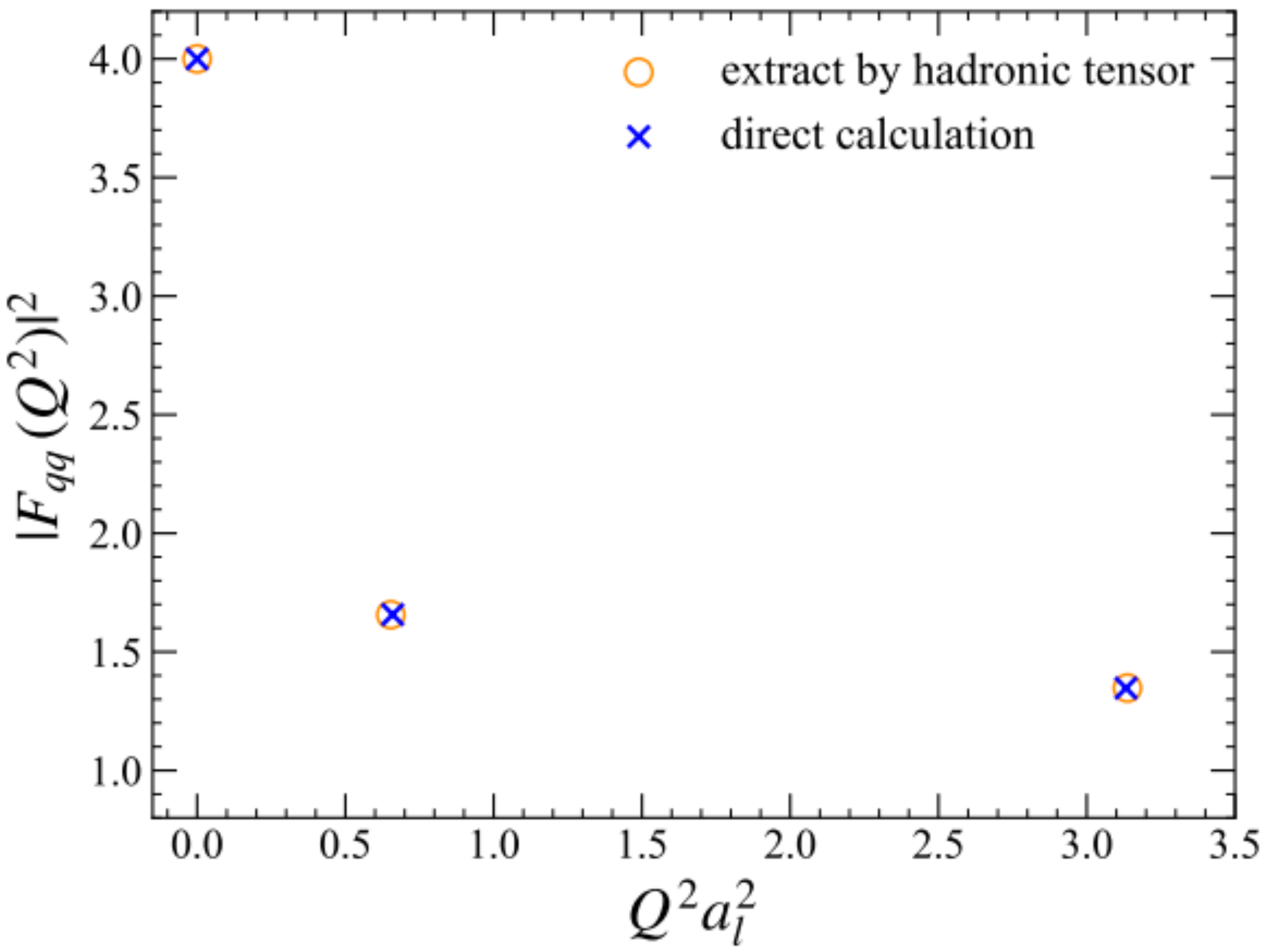
(b) $W^{00}(q)$ of baryon state in SU(2) LGT.

- In SU(2) model, mesons and baryons are very similar.
- Longer evolution time gives sharper peaks.

D. Zhou, T. Li, J. Liang, E. Wang, H. Xing, arXiv:2606.17003

Form factor in SU(2) model

- Results extracted from hadronic tensor agree very well from direct calculation.
- Shows the stability of quantum algorithm.



D. Zhou, T. Li, J. Liang, E. Wang, H. Xing, arXiv:2606.17003

Summary

- We studied Schwinger mechanism with Schwinger model.
- We also studied GPD and hadronic tensor with Schwinger and SU(2) model.
- Our results show that quantum algorithm can effectively simulate many quantities.

Thank you for your attention!