



QuantHEP 2026

Real-time dynamics of non-Abelian gauge theories: from Tensor Networks to Quantum Processors

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16 July 2026 · London

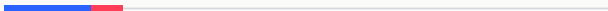
Why real-time string breaking?

- ⊙ Colliders turn color charges into **hadrons**
— “hadronization”
- ⊙ Mechanism: **string breaking** via **Schwinger pair production**
- ⊙ Models (Lund, ...): **fitted parameters**, not universal
- ⊙ First-principles QCD needs **real time** — Monte Carlo hits a **sign problem**

— **This talk** Tensor networks + quantum computing: sign-problem-free *statics and real-time dynamics*.

Testbed: **SU(2)** LGT in 1+1D, dynamical matter, **Loop-String-Hadron (LSH)** formulation.

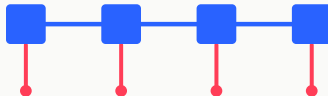
Classical: tensor networks for $SU(2)$ LGT



In collaboration with

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Z. Davoudi · I. Raychowdhury

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The loop-string-hadron (LSH) formulation

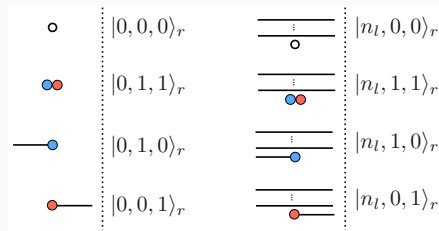
Recast the SU(2) Kogut–Susskind theory in **local, gauge-invariant** degrees of freedom.

- Site-local quantum numbers: loop
 $n_l \in \mathbb{Z} \geq 0$, string-in/out $n_i, n_o \in \{0, 1\}$
- Non-Abelian Gauss law is **built in**; only an **Abelian** constraint remains:

$$N_L(r) = N_R(r+1) \quad (\text{flux continuity})$$

$$N_L = n_l + n_o(1-n_i) \quad N_R = n_l + n_i(1-n_o).$$

Truncating flux at $j_{\max}$ gives local dimension
 $d = 8j_{\max} + 2$.



Local LSH basis states $|n_l, n_i, n_o\rangle_r$.

The LSH Hamiltonian

A **local** Hamiltonian $\hat{H} = \hat{H}_E + \hat{H}_M + \hat{H}_I$, with densities $\hat{H}_\bullet = \sum_r \hat{h}'_\bullet(r)$:

$$\hat{h}'_E = \frac{1}{2} \sum_{\alpha=L,R} \frac{\hat{N}_\alpha}{2} \left(\frac{\hat{N}_\alpha}{2} + 1 \right)$$



chromo-electric flux in/out

$$\hat{h}'_M = \mu(-1)^r (\hat{n}_i + \hat{n}_o)$$



matter content at a site

$$\mu = \frac{2m\sqrt{x}}{g}, \quad x = \frac{1}{a^2 g^2}$$

$$\hat{h}'_I = x \left\{ \sum_{\sigma=\pm} \bar{\mathcal{S}}_o^{+\sigma} \bar{\mathcal{S}}_i^{\sigma-} + \text{h.c.} \right\}$$

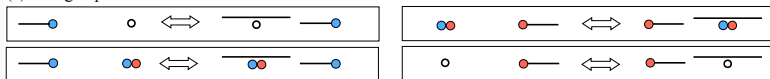


string-out / string-in pair

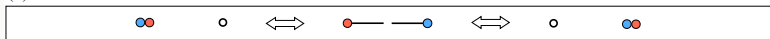
Hopping processes: the channels for string breaking

The hopping term $\hat{H}_I$ shifts string ends between neighbouring sites through a few elementary processes:

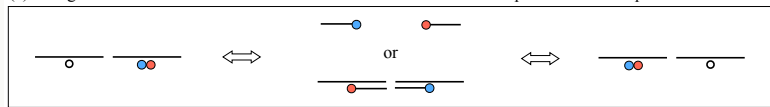
(a) String expansion/contraction



(b) Meson creation/annihilation



(c) String dissociation/recombination or meson creation/annihilation in presence of a loop



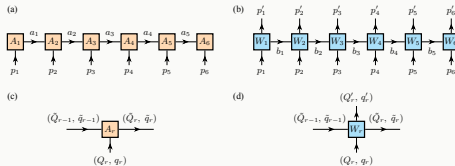
(d) Blocked states



Tensor-network ansatz: MPS & MPO

- LSH states → **matrix product states** (MPS); operators → MPO
- DMRG** for ground states & statics
- TDVP** (+ Krylov bond expansion) for real-time dynamics
- Bond dimension D controls the truncation; $d = 8j_{\max} + 2$ stays small even at large cutoff

Reaches **up to 200 sites** with controlled cutoff and volume/continuum extrapolations.

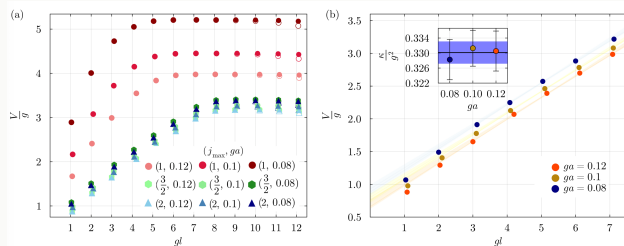


MPS (a) and MPO (b) tensor networks.

$$\hat{Q} = \sum_r (\hat{n}_i + \hat{n}_o), \quad \hat{q} = \sum_r (\hat{n}_o - \hat{n}_i)$$

Statics: confinement & the string tension

Static potential $V(gl) = E(gl) - E(0)$ between two static charges.



- Linear rise $\Rightarrow$ **confinement**
- Plateau at $gl \approx 7 \Rightarrow$ **string breaking**

Continuum string tension: $\kappa/g^2 = 0.330(3)$ at $m/g = 0.5$;

Dynamics: quenching a meson string

Apply a **Dirac meson-string operator** to the interacting vacuum $|\Omega\rangle$, then evolve:

$$|\phi(0)\rangle \propto \hat{S}_{r,\Delta r}^{\text{Dirac}} |\Omega\rangle, \quad |\phi(t)\rangle = e^{-i\hat{H}\tilde{t}} |\phi(0)\rangle, \quad \hat{S}_{r,\Delta r}^{\text{Dirac}} \propto \hat{S}_{r,\Delta r} - \hat{S}_{r+1,\Delta r}$$

$$\hat{S}_{r,\Delta r} \propto \sum_{\sigma_1, \dots, \sigma_{\Delta r} = \pm} \underbrace{\hat{S}_o^{+\sigma_1}(r)}_{\text{string-out}} \underbrace{\hat{\mathcal{L}}^{\sigma_1\sigma_2}(r+1) \cdots \hat{\mathcal{L}}^{\sigma_{\Delta r-1}\sigma_{\Delta r}}(r+\Delta r-1)}_{\text{chain of loop operators}} \underbrace{\hat{S}_i^{\sigma_{\Delta r}-}(r+\Delta r)}_{\text{string-in}}$$

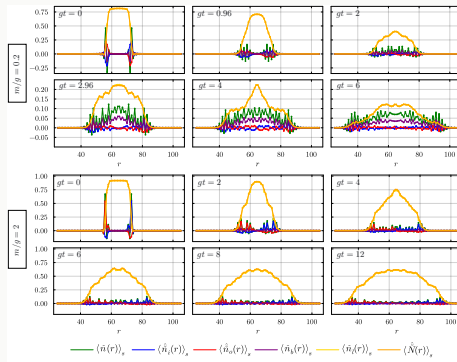
Built on the dressed vacuum, $|\phi(0)\rangle$ is a **superposition over string lengths** — the full flux tube plus shorter, partially-screened strings:

$$|\phi(0)\rangle \sim \text{red circle} \text{---} \text{orange bar} \text{---} \text{blue circle} + \text{red circle} \text{---} \text{blue circle} \text{---} \text{orange bar} \text{---} \text{blue circle} + \dots$$

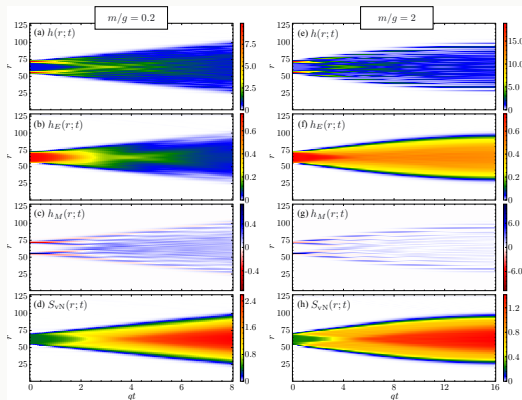
r $r+\Delta r$

Watching the string break: LSH excitation snapshots

Vacuum-subtracted LSH excitation profiles vs. site at successive times:



Two mass regimes



Energy, electric/mass-energy density & entanglement: light
(left) vs heavy (right).

Light ($m/g = 0.2$)

- ◉ full screening + particle showers
- ◉ ballistic transport ($V_h \approx 2.28$)

Heavy ($m/g = 2.0$)

- ◉ partial screening, tube persists
- ◉ suppressed production, non-ballistic

Takeaways – and toward quantum hardware

- ① **LSH tensor networks:** local, gauge-invariant, sign-problem-free – 128 sites, controlled cutoff
- ② **Statics:** continuum string tension $\kappa/g^2 = 0.330(3)$; clean confinement $\rightarrow$ string breaking
- ③ **Dynamics:** bare fermion mass **dictates the dynamics** – screening & particle showers vs a stretched flux tube

 **Next** Where classical TNs struggle, can a quantum device deliver? $\rightarrow$ a **120-qubit** simulation on IBM Heron.

Quantum: 120-qubit simulation on IBM Heron

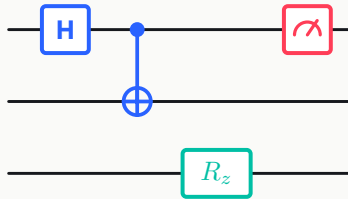


In collaboration with

F. Ilčić · R. Majumdar · Md. O. Ali · N. Earnest-Noble ·

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From lattice to qubits: hardware-efficient LSH encoding

- ◉ **Weak-coupling approximation**
freezes the loop DOF n_l — **removed from the dynamics**, leaving only the string ends
- ◉ Reduced state $|n_i, n_o\rangle_r$ is used **directly as the computational basis**:
2 qubits/site

SCV — staggered vacuum, odd sites filled



Meson — **string-out** — **string-in** on the central pair



A large frozen flux background ($n_l \gg 1$) threads every site.

Weak-coupling approximate Hamiltonian

An approximation is applied to the LSH Hamiltonian in the **weak-coupling** regime $x \gg 1$:

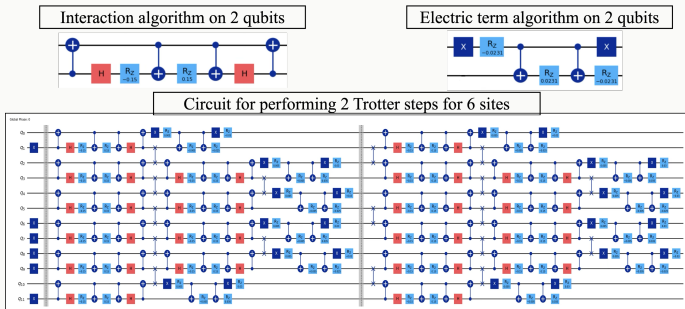
- ◉ **Interaction** $\rightarrow$ nearest-neighbour spin hopping

$$\hat{H}_I^{\text{approx}} = - \sum_r (\sigma_r^- \sigma_{r+1}^+ + \sigma_r^+ \sigma_{r+1}^-)$$

- ◉ **Electric** $\rightarrow$ average flux $\approx$ boundary flux: background becomes a **global phase** (dropped); residual on-site phase only for $|01\rangle$ (string-out)
- ◉ **Mass** $\rightarrow$ already diagonal, $\mu \hat{H}_M = \mu \sum_r (-1)^r (n_i + n_o)$

Building the circuit: gates & qubit layout

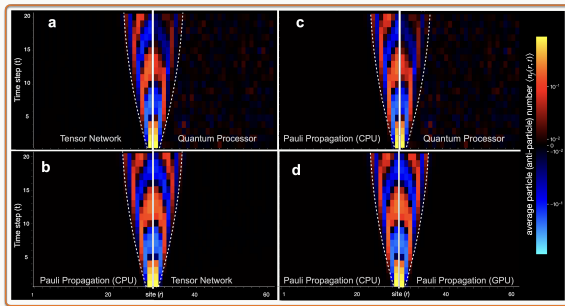
Trotter step $U(\delta_\tau) \approx e^{-i\tilde{m}\hat{H}_M} e^{-i\delta_\tau\hat{H}_E} e^{-ic\hat{H}_I}$: **mass** $\rightarrow$ 1-qubit R_z ; **electric & hopping** $\rightarrow$ 2-qubit. **Zigzag layout** $\Rightarrow$ NN interactions in 2 SWAP layers/step.



Scaling to 120 qubits

- Constant 2-qubit depth $13t - 1$ — independent of lattice size
- **60 sites** $\rightarrow$ 120 qubits; up to 25 Trotter steps
- Depth 324, 17,660 2-qubit + 90,955 total gates
- Only **readout error mitigation**; $P(1) = \frac{1 - \langle \sigma_z \rangle}{2}$ per qubit
- **Differential measurement** isolates the coherent meson signal from vacuum background — observables straight from noisy data

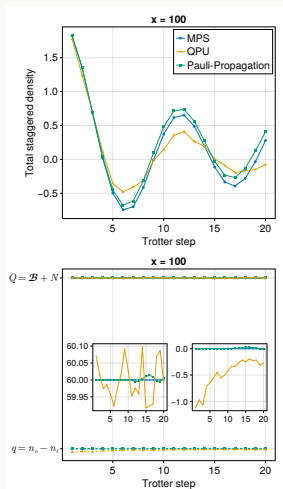
Real-time meson propagation: a light-cone structure



Space-time fermion number $\langle n_f(r, t) \rangle$ ($n_f = n_i + n_o$ on even sites, $2 - n_i - n_o$ on odd) from a central meson; each panel splits two methods (dashed lines guide the eye).

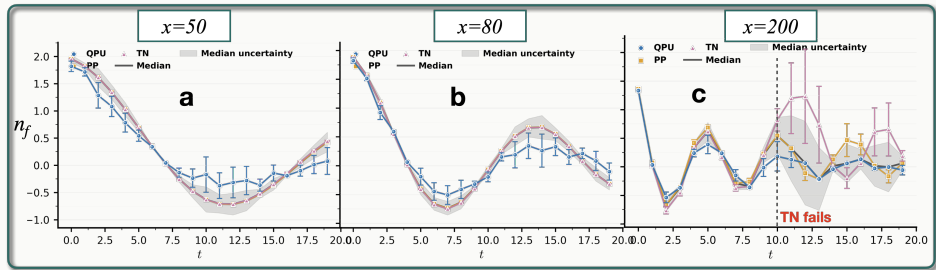
QPU vs TN vs Pauli Propagation: matching halves validate the approach · spread stays **light-cone confined**, edge curvature *suggestive of* confinement; internal stripes = breathing oscillation

Validation & symmetry protection



- ◉ **Gauge symmetry preserved:** charges $Q=60$ (within 0.33%), $q=0$ (within 2%) despite hardware noise
- ◉ Symmetry is a **free, built-in error check** — no mitigation beyond readout
- ◉ $n_f(t)$ oscillates & damps (thermalization); QPU/TN/PP statistically consistent

Robustness across coupling: where classical methods strain



Meson signal $n_f(t)$ at $x = 50, 80, 200$ — QPU (blue) tracks PP/TN; TN fails at $x=200$.

- QPU stays coherent at every x , fixed depth
- QPU $\approx$ const. 20 s/step
- TN fails at $x=200$; PP cost grows
- Classical cost climbs steeply

Summary & outlook: a hybrid path to the continuum

- ① **Classical tensor networks:** sign-problem-free statics & dynamics — string tension, string-breaking mechanisms up to 200 sites
- ② **Quantum hardware:** 60-site $SU(2)$ on 120 qubits — a confined light cone, robust with only readout mitigation
- ③ Where **classical methods stall** (weak coupling, entanglement wall), the **quantum device stays robust** $\Rightarrow$ a hybrid workflow

Outlook: next steps

Bridging the two halves — and pushing toward higher dimensions and QCD:

- ◉ **Wavepacket scattering:** localized hadron wavepackets from **uniform-MPS (uMPS)** ansätze for real-time scattering — $SU(2)$ now, $SU(3)$ next, in 1+1D
- ◉ **Higher dimensions:** Towards 2+1D gauge theories using Projected Entangled Pair States **PEPS** & tree tensor networks **TTN**.
- ◉ **Classical** → **quantum:** compile tensor-network (MPS) states into shallow circuits to prepare non-trivial initial states (interacting vacuum, meson strings, wavepackets) on hardware.

THANK YOU

Questions?

QuantHEP 2026

String-breaking statics and dynamics in a $(1+1)\text{D}$ $\text{SU}(2)$ lattice gauge theory

Gupta, Mathew *et al.* · [arXiv:2603.24698](https://arxiv.org/abs/2603.24698)

Observation of Robust and Coherent Non-Abelian Hadron Dynamics on Noisy Quantum Processors

Ilčić, Majumdar, Mathew *et al.* · [arXiv:2602.18080](https://arxiv.org/abs/2602.18080)

Backup slides

Backup: what the weak-coupling approximation drops

Exact LSH $\hat{h}'_I$ carries **loop-dependent** matrix elements $\propto \sqrt{\frac{n_l + \dots}{n_l + \dots}}$ from the SU(2) normalization.

Term	Exact LSH	Weak-coupling ($x \gg 1$)
Interaction	string operators $\times$ loop factors	pure spin hopping $\sigma^- \sigma^+$
Electric	$\frac{1}{2} \sum_{\alpha} \frac{N_{\alpha}}{2} (\frac{N_{\alpha}}{2} + 1)$	global phase + $ 01\rangle$ residual
Mass	$\mu(-1)^r (n_i + n_o)$	<i>unchanged</i> (already diagonal)

Loop factors $\rightarrow 1$ because $n_l \gg 1$ at large x ; validated against the **full** LSH Hamiltonian on tensor networks.

Backup: the flux cutoff $j_{\max}$ is controlled

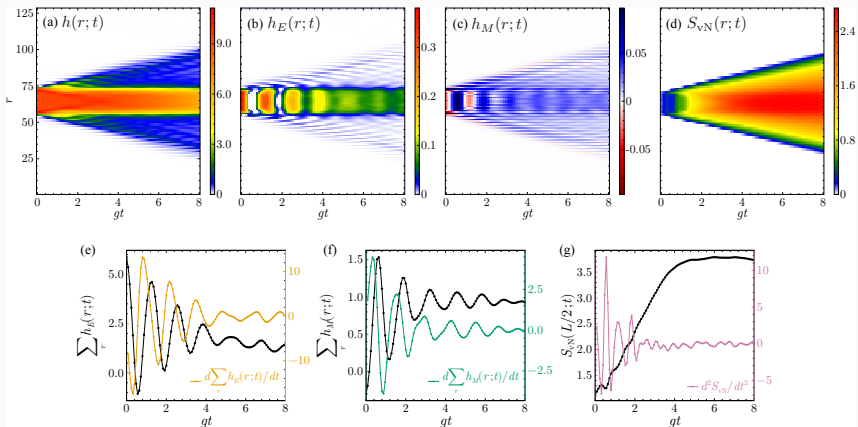
Truncating gauge flux at $j_{\max}$ caps the loop number; local dimension stays small:

$j_{\max}$	$d = 8j_{\max} + 2$
1/2	6
3/2	14
5/2	22

- ◉ Statics converge by $j_{\max} = \frac{5}{2}$; dynamics run at $\frac{5}{2}$
- ◉ Bond dimension D separately controls entanglement truncation

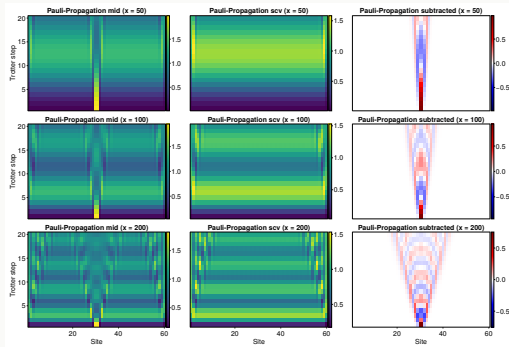
Systematic convergence in $j_{\max}$ is what lets us quote continuum-limit numbers with error bars.

Backup: low-cutoff ($j_{\max} = \frac{1}{2}$) dynamics



Backup: the Pauli-propagation classical baseline

- ⦿ Heisenberg-picture **Pauli propagation** (Rudolph *et al.* 2025)
- ⦿ Evolves observables as Pauli sums; **truncates** small-weight / small-coefficient terms
- ⦿ Efficient for **error-free** circuits — an *independent* classical cross-check alongside TN
- ⦿ **Onset of exponential cost** at long times / strong coupling, as truncation error grows



Pauli propagation vs. QPU/TN across parameters.