Modeling final state radiation on a quantum computer

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QuantISED HEP initiative

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~ Outline ~

Quantum machines ("quantum computers")

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Quantum machines ("quantum computers") Quantum modeling in HEP A toy model

> FIG. 1. The rightmost nodes of the above binary tree (leaves) uniquely correspond to trajectories in *{L, R}^N* where *^L* represents going left and *R* represents going right at a given node. As a generative model, trajectories are sampled according to the square of the square of the path through the path through the path through the path through the path through

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A simple, but real model $\|\cdot\|_{p\rangle\to\overline{\mathbb{R}^{\otimes N}+1}}$ Quantum machines ("quantum computers") Quantum modeling in HEP A toy model

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Quantum machines ("quantum computers") Quantum modeling in HEP A toy model A simple, but real model \blacksquare Mitigating of noise uniquely correspond to the trajectories in $|h\rangle \neq$ sting af raise and **R** represents going right at a given \mathbf{R} aling of noise and \mathbb{R} are sampled and \mathbb{R} the space of the space of the path through the path of the path through the path of the

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Quantum machines ("quantum computers") Quantum modeling in HEP A toy model A simple, but real model \blacksquare Mitigating of noise uniquely correspond to the trajectories in $|h\rangle \neq$ sting af raise and **R** represents going right at a given \mathbf{R} aling of noise and \mathbb{R} are sampled and \mathbb{R} the space of the space of the path through the path of the path through the path of the The future

What can be a proxy system?

…any quantum system, like a collection of spins.

9

The best quantum computer is the one that looks just like the system you are trying to model!

The best quantum computer is the one that looks just like the system you are trying to model!

> In this setup, the possibilities are endless; the key is efficiency.

Modern Universal Quantum Computers **13**

There is no consensus on architecture, but many efforts for universal quantum computing use superconductors.

> I'm not going to talk about hardware, though it is an exciting topic.

Modern Universal Quantum Computers **14**

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quantum computing now

A **qubit** is an abstract representation of a quantum system that can be in a superposition of two states (often thought of as a spin)

The best quantum computers have O(10) **qubits** with $O(1)$ connections per qubit and can stay coherent for O(1000) operations.

This is one of IBM's 20-qubit quantum computers. Lines represent connections.

ground state.

FIG. 2. Circuit for the *m*th step Apply unitary matrix *U1* to the third qubit

Apply unitary matrix *U₂* to the second qubit when the third is 0, else apply *U3*.

Apply unitary matrix *U₄* to both the first and second quits when the third is 0.

In practice: only* controlled operation that is allowed is CNOT (swap if 1 otherwise do nothing) … need to decompose. In our case the gate *U* consists of a *R^Y* (✓) rotation gradition. Only continuing operation that is anowed to Organize controlled which we have you

 $\overline{}$ CNOT "controlled not"

P = piler. *,* (H1) There is no compiler … need to do circuit decomposition by hand (!)

**Some computers are starting to have other basic operations, like the SWAP.*

In practice: only controlled operation that is allowed is CNOT (swap if 1 otherwise do nothing) … need to decompose.

> Circuit implementation is architecture-dependent *need to know what connections are available*

(can swap, but cannot copy ("clone") qubits!)

Challenges with current computers **25**

Most importantly: current quantum computers are super noisy. Need to minimize number of operations. \mathbf{A} and \mathbf{A} in \mathbf{A} and \mathbf{A} in \mathbf{A} in \mathbf{A} in \mathbf{A} explicitly state for \mathbf{A} lowing time evolution with *U^T* (*t, t*). In the unshaded region, ompators are **super noisy**. The data IBM allocation units and ⇠ 3*.*6 QPU*·*s)

Caveats aside, there is a good reason to be excited.

There have been impressive leaps in hardware, "firmware", & algorithms in the last years and interest has exploded. perhaps some misguided …

Will you have a QPU in your laptop 5 years from now?

No. But you may be able to run on a QPU in 5 years that allows you to make a calculation that was not possible before (!)

Caveats aside, there is a good reason to be excited.

There have been impressive leaps in hardware, "firmware", & algorithms in the last years and interest has exploded. **Now on to QFT!**

Will you have a QPU in your laptop 5 years from now?

No. But you may be able to run on a QPU in 5 years that allows you to make a calculation that was not possible before (!)

Why is this more challenging than e.g. quantum chemistry? (the "early" scientific adapter of QC)

 \rightarrow Continuous degrees of freedom (every spacetime point) + discrete and continuous quantum numbers.

Two traditional approaches:

Image credit: <http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg> Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

Quantum Field Theory

Pro: Full theory

Con: Dynamics are too hard

(already using super computers)

Pro: Can do highenergy dynamics Con: An approximation …and combinatorially many diagrams

Image credit: <http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg> Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

Perturbation theory

Quantum Field Theory **30**

Pro: Full theory

Con: Dynamics are too hard

(already using super computers)

Pro: Can do highenergy dynamics Con: An approximation

Perturbation theory

: L
de
^{frr} 1 Simulation at the Large Hadron Collider: length scales from 10-20 m to 1 m (!)

...only possible because 1 ϵ of the Markov Property: physics at different scales **factorizes**

1

 \blacktriangleright

1

Step 1: "Hard scatter"

very hard for lattice methods because high energy = fine grid

Step 1: "Hard scatter"

Step 2: "Matching"

Step 1: "Hard scatter"

Step 2: "Matching"

Step 3: "Parton Shower"

Step 1: "Hard scatter"

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Step 3: "Parton Shower"

Step 4: "Hadronization"

Step 1: "Hard scatter"

Step 2: "Matching"

Step 3: "Parton Shower"

Step 4: "Hadronization"

Step 5: Detector sim.

"Quantum effects" for the hard scatter **37** 60 10× tH (expected)

Total uncertainty

"Quantum effects" for the hard scatter **38** 60 10× tH (expected)

Total uncertainty

"Quantum effects" for matching $\mathcal{L}_{\mathcal{A}}$ to the two definition of the two definitions MAGISTIOL I d m 1 σ MG5_aMC+Pythia8 tt+tW (DR2) /∪ 1 1 σ

d m

[−]³ 10

Powheg+Pythia8 tt+tW (DS)

MG5_aMC+Pythia8 tt+tW (DR)

MG5_aMC+Pythia8 tt+tW (DR2)

39

 $\mathfrak n$ iain mass or a repi Invariant mass of a lepton and hadrons [GeV/c²]

"Quantum effects" for matching Data, stat. uncertainty $\mathcal{L}_{\mathcal{A}}$ to the two definition of the two definitions MAGISTIOL I d m 1 σ MG5_aMC+Pythia8 tt+tW (DR2) /∪ 1 1 σ

d m

[−]³ 10

Powheg+Pythia8 tt+tW (DS)

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MG5_aMC+Pythia8 tt+tW (DR2)

40

 $\mathfrak n$ iain mass or a repi Invariant mass of a lepton and hadrons [GeV/c²]

"Quantum effects" for the parton shower m fec on snower P=10. undeparte soft drops at the derived it deniangle interesting the parton of the parton [(m −⁴ (Powhere Pythia to the Pythia to the Pythia "Quantum effects" for the \sim ata¹¹ fax t **GET GREET CONSERVING CONSERVING** hota["] tar tl SUM TUTTER

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13 Tev, 32.9 fb, 32
13 Tev, 32.9 fb, 32

= 0.1

41

Go-to solution: Markov Chan Monte Carlo. This ignores most "quantum'0effects; full effects can be (painstakingly) included for some specific observables on a case-by-case basis. −4 −3 −2 −1

"Quantum effects" for the parton shower **42** m fec on snower P=10. undeparte soft drops at the derived it deniangle interesting the parton of the parton [(m −⁴ (Powhere Pythia to the Pythia to the Pythia "Quantum effects" for the \sim ata¹¹ fax t **GET GREET CONSERVING CONSERVING** hota["] tar tl SUM TUTTER

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"Quantum effects" for the parton shower P_1 to the Pythia text of the GUIS TUI III \mathbf{P} Powheg+Pythia8 tt+tW (DS)

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1970 - νι τον καταγωγή του στον καταγωγή του στον καταγωγή.

W boson \rightarrow two jets of hadrons

43

To drive the point home here is an observable where we can't distinguish between entanglement turned **"on"** and **"off"**.

How much the radiation from one jet "leans" toward the other. Final state radiation is a complex many-body quantum system.

Perhaps quantum tools can be used to incorporate quantum degrees of freedom!

Lines: quarks; curls: gluons; colors: quantum numbers

lution in quantum walks [12].

proximated as corrections to the MCMC [6], but cannot

Let's think of a parton the state of the state of \blacksquare shower like a tree. be directly implemented eciently in a classical MCMC This paper is organized as follows. Section II is organized as follows. Section II introduced as follows. Section I shower like a tree

Discretize "time". **Discretize "time".**

At each "time", a particle can radiate (go left) or not radiate (go right). measurement outcomes is more naturally *{L, R}^N* than $\sum_{i=1}^{n}$

 $\frac{1}{2}$, a particle uniquely correspond to the total to the trajectories in a *a*
(*AO right*) with a cultum tradem well: ends with conclusions and future outlook in Sec. VI. λ λ $leaf$ distribution. A solution to this problem is introduced in the \mathcal{A} $S_{\rm eff}$ is a quantum algorithm. An explicit implementation algorithm. An explicit impleand numerical results are presented in λ ends with conclusions with conclusions and future outlook in Sec. VI. We are the second to the second sec. VI. leaf

duces the quantum tree and illustrates how classical al-

gorithms cannot economic sample from its probability sample from its probability sample from its probability s
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distribution. A solution to this problem is introduced in the ~ 45 and \sim

Sec. III using a quantum algorithm. An explicit imple-

mentation of the quantum circuit is described in Sec. IV and the quantum circuit is described in Sec. IV and the sec. I

and numerical results are presented in \triangle

sents and *R* represents a given R representation of R $d = \log d - \log d$ is undervalue: N.B. not a quantum random walk: leaf = history is observable! leaf = history is observable!

 τ di ar<mark>i</mark> Markov chain of amplitudes: $A_{\text{leaf}} = \prod_{n=1}^{N} A_{\lambda_n}(n)$. \mathbf{A}^T $\lambda \in \{L, R\}^N$ cording to Pr(path) / *|A*leaf*|* Markov chain of amplitudes: A_1 , $\epsilon = \Pi^N$, A_2 vidence oficial of amplitude σ . The algorithm $\text{Im}(z)$ Solved by a classical MCMC $\qquad \lambda \in \{L, R\}^N$

nal result we extract violates unitarity, even though it can

Whet your appetite **46** Consider the following minimal change to the tree:

 $t \rightarrow t$ at the spin at the amplitudes \overline{t} is observable and the amplitudes \overline{t} Let's think of a parton shower like a tree.

Discretize "time".

At each "time", a particle **can flip spin (flip trees)** and radiate (go left) or not radiate (go right). \overline{f} and flin-enin-(flin-trace) **height possible and** *koo***liging (and** *higher left)* **are** \overline{A} and radiate (go left) or $\begin{array}{ccc} & & & \ & & \text{and} \end{array}$ amplitude to transition from spin *s*⁰ to *s^N* is given by

$$
A_{s_0,s_N} = \sum_{\substack{\vec{s}' \in \{\downarrow,\uparrow\}^N \\ s_0' = s_0, s_N' = s_N}} \prod_{n=1}^N A_{\lambda_n}^{s'_{n-1},s'_n}(n) \qquad \text{Int} \in
$$

there is a spin state associated with each depth. Only in the contract of \mathbf{C} as **Classical MCMC fails!**

only the final tree (spin) and leaf are observable. The eight

possible amplitudes for a given step are indicated with *A^s*1*,s*²

where s 1 is the initial spin and s ² is the spin and s ² is the final spin and s

a spin state as spin state and the trend in t be represented by two trees: one for spin down (left) and one for intermediate spins! ovon intermodiate opine. tiplications. To see this, consider the leaf corresponding \mathcal{L} Interference from summing over intermediate spins! ming over all possible spin trajectories. If the initial spin

Quantum solution to interfering trees (47 polynomial time. The algorithm implements the change im solution to interfering trees the 4 ✓ 1
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1 U INSTRUIT 0
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1940 ◆

 $W_{\rm eff}$ introduce a quantum algorithm which can be

Linear-time quantum circuit with one qubit / step + 1 qubit for the spin. $\sum_{n=1}^{\infty}$ and $\sum_{n=1}^{\infty}$ and $\sum_{n=1}^{\infty}$ and $\sum_{n=1}^{\infty}$ and $\sum_{n=1}^{\infty}$ ond gabit, didp , , gabit ion the dpin.

Results with a quantum simulator **48**

ber of steps used. The quantum algorithm will be able to

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 time. After describing the physics of the physics of the simplified the simplified the simplified the simplif

ber of steps used. The quantum algorithm will be able to step used. The quantum algorithm will be able to detec
The quantum algorithm will be able to detect the quantum algorithm will be able to detect the detect of the pr

ber of steps used. The quantum algorithm will be able to

(like the SM Higgs when $q_{12} \sim m/v$ and $q_1 = q_2 = 0$) T_{max} and T_{max} the file on **find** $\lim_{n \to \infty} a_n = m/2$ and $\lim_{n \to \infty} a_n = 0$ s when $g_{12} \thicksim$ m/v and g_{1} = g_{2} =0) $\overline{\mathcal{O}}$ lating high-multiplicity cross sections. This is performed s (like the SM Higger when α_{12} , m/s $\sum_{i=1}^n$ (like the SM Higgs when $g_{12} \sim m/v$ and $g_1 = g_2 = 0$) $T_{\rm tot}$ begin, consider a simple \sim IKE the SIVI Higgs when $g_{12} \sim m$ /V and g_{1} = g_{2} =U) (like the SM Higgs when *g12 ~ m/v* and *g1=g2=0*) $T_{\rm tot}$ and consider a simple \sim (like the SM Higgs when $g_{12} \sim m/v$ and g \bigcap $\mathcal{A}_2 = O(\alpha)$ $\overline{\mathcal{O}}$ e the SM Higgs when $g_{12} \sim m/v$ and $g_{1}=g_{2}=0$) \mathcal{L} Higher when α_{12} in polynomial α_{12} $m \cdot mggu$ witch g_{12} in produce $g_{1} - g_{2} - g_{1}$ \mathcal{L} begin, consider a simple \mathcal{L} $t_2 \thicksim m/v$ and $g_1 = g_2 = v$)

one scalar boson governed by the following Lagrangian scalar by the following Lagrangian: the following Lagra
The following Lagrangian: the following Lagrangian: the following Lagrangian: the following Lagrangian: the fo

factorizes as follows

ber of steps used. The quantum algorithm will be able to step used. The quantum algorithm will be able to the

model, we will introduce the quantum circuit and show

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The quantum algorithm will be able to the quantum algorithm will be able to the quantum algorithm will be able

✓⁰ ✓¹ *···* ✓*n*, the kinematic part of the amplitude

ˆ

(✓0*|*✓1)*A*

ˆ

ˆ

(✓2*|*✓1)*... A*

factorizes as follows

ber of steps used. The quantum algorithm will be able to

sample from the full probability distribution in polyno-

mial time. After describing the physics of the simplified

where *A*

model, we will introduce the quantum circuit and show

A ˆ

factorizes as follows

ⁿ(✓1*,...,* ✓*n*) = *A*

ⁿ(✓1*,...,* ✓*n*) = *A*

ˆ

ticle at angle ✓*ⁿ* given the angle of the previous emission.

 \mathcal{L}

✓⁰ ✓¹ *···* ✓*n*, the kinematic part of the amplitude

✓⁰ ✓¹ *···* ✓*n*, the kinematic part of the amplitude

The quantum circuit **1999 1999** Fig. 2. At each step, there are four operations, which are ne quantum d Fig. 2. At each step, there are four operations, which are <u>ne</u> duar

sub-circuit describing the one-step operations is shown in

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adjust particles *N U^p* F

adjust particles *N U^p* F

Table in the various \mathcal{L} is the various quantum circuit operator \mathcal{L} . The various \mathcal{L}

TABLE II. Complexity of the various quantum circuit oper-

BPN, D. Provasoli, W. de Jong, C. Bauer, 1904.03196 *|na*i Number of *f^a* log2(*N* + 1) composition of the resulting circuit into single qubit and

The quantum circuit - U_e ($e =$ emit) $\sqrt{51}$ $\frac{1}{10}$ $\frac{1}{10}$ The quanum cheun - ω_e (e $=$ Tha α ¹ in the state α ¹ is the state α t_{in} ine quantum circuit - U_{θ} (θ = θ no emission. The emission matrix is given by the emission. The emission matrix is given by the emission matrix
The emission matrix is given by the emission matrix is given by the emission matrix is given by the emission

tum circuit through the rotation *U*(*m*)

tum circuit through the rotation *U*(*m*)

sion matrix is given by

$$
U_e^{(m)} = \left(\sqrt{\frac{\Delta^{(m)}(\theta_m)}{1 - \Delta^{(m)}(\theta_m)}} - \sqrt{1 - \frac{\Delta^{(m)}(\theta_m)}{\Delta^{(m)}(\theta_m)}}\right)
$$

\n
$$
\Delta_i(\theta_m, \theta_{m+1}) = e^{-\Delta\theta P_i(\theta_m)}
$$

\n
$$
\Delta_i(\theta_m, \theta_{m+1}) = e^{-\Delta\theta P_i(\theta_m)}
$$

\n
$$
\Delta^{(m)}(\theta_m) = \Delta_{\phi}^{n_{\phi}}(\theta_m) \Delta_{f_1}^{n_{f_1}}(\theta_m) \Delta_{f_2}^{n_{f_2}}(\theta_m)
$$

\nThis is just one part of the circuit that calculates the no emission amplitudes
\n
$$
\begin{array}{r}\n\text{ln } + \\
\hline\n\text{ln } + \\
\hline\n\text
$$

^e on the qubit *|e*i.

^e on the qubit *|e*i.

BPN, D. Provasoli, W. de Jong, C. Bauer, 1904.03196

The circuit without scalar splitting **1999** the flavor of the flavor of the flavor of the flavor of the full evolution can be called \mathcal{L}_c

the probability of a boson being emitted only depends on $\mathcal{O}(n)$ and $\mathcal{O}(n)$

11. The *U* and *U†* gates are the same as in (B2), while

In words: rotate to the basis where there is no interference. "emi and their folder back to the physical basis at the end.
 interference, "emit" scalars (at the **amplitude** level), and then rotate back to the physical basis at the end.

> *p IS GAQUIII HIIGII This is exactly the interfering trees circuit !*

The circuit without scalar splitting **1989** the flavor of the flavor of the flavor of the flavor of the full evolution can be called \mathcal{L}_c electrodynamics. Realistic simulations of such collisions in collider- or cosmic-based high energy the radiation pattern is a complex, many-body quantum system. Classical Markov Chain Monte

the probability of a boson being emitted only depends on $\mathcal{O}(n)$ and $\mathcal{O}(n)$

will reduce proportionally to the proportionally to the interval as photon radiation from electrons in quantum

11. The *U* and *U†* gates are the same as in (B2), while

$\textsf{Note:}|\phi_i\rangle$ is not touched after timestep i and so one **U** *L* **U H**
 u i *l* **u d u l l i** *l l* **i l** *l l l l l l l*** ***l l l l l l***** can **reuse qubits** ... only need 2 total qubits (!) While quantum computers hold great promise for

Fine print: (1) re-measurement is not a feature of most current quantum computers and (2) this led p_{raise} and fair interference one p_p
 *p*₁ **p**₁ Fine print: (1) re-measurement is not a teature of most current quantum computers and (2) this led
us to a classical algorithm that can capture the full interference effects (but is not standard MCMC). databases \mathcal{C} and \mathcal{C} and \mathcal{C} and \mathcal{C} into primes \mathcal{C} and \mathcal{C} and \mathcal{C} into primes \mathcal{C} and \mathcal{C} into primes \mathcal{C} into primes \mathcal{C} into primes \mathcal{C} into \mathcal{C} into relies on r represents the perturbative expansion to expansion the perturbative expansion to expansion to ex-

Numerical results **54**

The predictions / simulations are realized on a real quantum computer!

Classical: exponential Naive quantum: 5th order Optimized quantum: 3rd

> angle of maximum emission

The fine print **55**

Results "out of the box" do not look this good. We optimized the nodes on the quantum computer and performed **readout error** and **gate error** corrections.

In the remaining slides, I'll give you a taste of ongoing work in improving these corrections.

Readout error corrections **56**

Qiskit Simulator IBM Q Johannesburg Readout Errors

 -75

 -60

 -45

 -30

Pr(Measured | True) [%]

On a quantum computer, the state may be 1 but readout as a 0, etc.

For n qubits, there is a 2n x 2n transition matrix.

HEP has proposed many solutions to this problem!

> …and we call them **unfolding**

BPN, M. Urbanek, W. de Jong, C. Bauer, npj Quantum Information 6 (2020)

Readout error corrections **1997** for a simple quantum field theory on a quantum field theory on a quantum computer. With future advances in \mathbb{F}^{\bullet} computing hardware, our algorithm will be able to improve precision calculations for many $\mathcal{L}(\mathcal{A})$

<u>que is necessary.</u>

! | evolution variable, meaning the matrices *U^F* , *UA,*# and I have proposed to use HEP $\frac{2}{3}$ | \cdot m evolution, we measure the physical state $\frac{1}{8}$ 10 techniques to correct the theorem coutput to donour f moutor roodout orrore 5 in pulci treauvut chors. \overline{S} 100000 \overline{S} unfolding techniques to correct will be a general position quantum field theory, where there are both continuous quantum computer readout errors. 50000

B. Circuit Evolution the number of quantum bits (or their continuous analog) → Circumvent known pathologies $\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{2}$ with more naïve methods $(!)$ $\left| \begin{array}{c} \frac{1}{2} \\ \frac{1}{2} \end{array} \right|$

BPN, M. Urbanek, W. de Jong, C. Bauer, npj Quantum Information 6 (2020) measure to be in the anciellary state. For a state in the state. For a state in the *a* sequence of *N* measurements on one qubit there are 2*^N* scribe inherently quantum physical systems without di-

have multiple terms as is the case with the displayed leaf Naïve inversion there are two ways to reach the leaf *|*0i*|*00i: always going \blacksquare if we go to a higher number of steps of steps of steps of steps or if we start the steps of steps $\mathsf{F}\mathsf{P}$ etandard p_{max} the number of the number of f these dynamics is known as the parton shower parton pand around the collinear and soft limit of emissions. includes infinitely many terms in the original ↵*^s* series ex-

[|] ²*,*2ⁱ ⁼¹

2

well-suited for describing the quantum properties of final state radiation. In particular, we develop the quantum properties of final state radiation. In particular, we develop the state radiation. In particular, we develo

a polynomial time p polynomial time p algorithm is explicitly demonstrated by explicitly demonstrated by $\mathcal{L}(\mathcal{L})$

 $A=\frac{1}{2}$ plus the second circuit block (B2 plus the condi-

cos²(✓#) cos²(✓*^F*) + sin²(✓*^F*)

l.

, (12)

*|*0i*|*0i*|*00i

 $t = \frac{1}{2}$

N |ij Í ≠ $\overline{}$ *N |ij* Í developing methods to lill activciy We are still actively reduce readout errors.

 $Pr(1 \to 0) > Pr(0 \to 1).$ **One can apply a simple** One can apply a simple $\overline{}$ *i*. *n* . *n* . *i* "rebalancing" in order to T_{max} improve precision. For example, note that

More on readout errors **58**

Gate error mitigation **69** solution to this challenge by promoting the *nⁱ* from Eq. 1 *insertion method* (RIIM).

One common technique is Zero Noise Extrapolation controlled unitary operation with two qubits. The *Uⁱ* represent

Idea: replace each CNOT by 2n+1 CNOTs. This doesn't change the answer without noise, but systematically increases the noise. Then, extrapolate to zero noise. RIIM technique is introduced in Sec. III. The potential of

Gate error mitigation **60** solution to this challenge by promoting the *nⁱ* from Eq. 1 to random variables to construct the *random identity insertion method* (RIIM).

Gate error mitigation **61** solution to this challenge by promoting the *nⁱ* from Eq. 1 *insertion method* (RIIM).

Gate error mitigation **62** solution to this challenge by promoting the *nⁱ* from Eq. 1 *insertion method* (RIIM).

One common technique is Zero Noise Extrapolation controlled unitary operation with two qubits. The *Uⁱ* represent

oplacing overy CNIOT determinicticall linear in the presence of the *New idea: promote ni to a random variable. Instead of replacing every CNOT deterministically, randomly replace.*

Gate error mitigation **63** perform. We leave the study of such noise to future invate error mitigations

fidelity (time constant) and requires some finite time to

those studied here can be used to remove noise other than be used to remove σ

A. He, **BPN**, W. de Jong, C. Bauer, PRA 102 (2020) 012426

Circuit with *N* noisy gates: traditional method needs *(n+1) x N* additional gates $\overline{\qquad \qquad }$ $\qquad \qquad$ $\qquad \qquad \qquad$ $\qquad \qquad$ $\qquad \qquad$ $e^{i\omega t}$ for the quantum simple harmonic orientation simple ω in ω and ω in ω people (n, 1) $T_{\rm 20}$ $\rm g$ additional gates

VII. NUMERICAL RESULTS

 W use \mathcal{A} to simulate the quantum circuits \mathcal{A} to simulate the quantum circuits \mathcal{A}

described below and demonstrate FIIM and RIIM. Sec-

Erminisue || 15⁰ Random method only needs *n+1* additional gates (!) $\begin{array}{c} \text{Area} \\ \text{or} \\ \text{c} \end{array}$ consider the $\begin{array}{c} \text{area} \\ \text{c} \end{array}$ this section, we use a slight modification of this simple

Future **65**

• QFT

- Extend shower model
	- Electroweak radiation in SM (full SU(2))
	- Phenomenology with scalar model (heavy DM?)
- Towards QCD
	- Other source of interference (kinematic, color)
	- Soft radiation
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	- Subexponential unfolding
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• Software-hardware interface

- Custom operations
	- Resetting qubits, repeated operations, qudits
- QFT-tailored hardware
	- Optimal lattice

The future

There is a long road ahead, but quantum algorithms are very promising for modeling high energy scattering processes.

At the same time, we can use our experience in experimental/ theoretical HEP to contribute to quantum computing **in general**.

The field of QIS is rapidly advancing and there are growing connections between experiment, theory, instrumentation, and computing.

Image credit: Flip Tanedo

Quantum Field Theory **71**

Pro: Full theory

Con: Dynamics are too hard

Con: An approximation (already using supercomputers)

Image credit: <http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg> Image Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

Perturbation theory

Number of quantum $H = \sum a^d \left[\frac{1}{-\pi(x)^2} + \right]$ bilities in weakly coupled, (d + 1)-dimensional φ⁴ theory with accuracy ±# scales as follows¹ e in d+1 dimensions gates to reach precision where T aq denotes a discretized derivative, that is, a finite-difference operator. The finite-difference operator.

rameter space near this phase transition, perturbative methods become unreliable; this region is

for calculating scattering amplitudes, although lattice field theory can be used to obtain static

$$
\sim \begin{cases} \left(\frac{1}{\epsilon}\right)^{1.5+o(1)}, & d=1, \\ \left(\frac{1}{\epsilon}\right)^{2.376+o(1)}, & d=2, \\ \left(\frac{1}{\epsilon}\right)^{3.564+o(1)}, & d=3. \end{cases}
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$$
H = \sum_{\mathbf{x}\in\Omega} a^d \left[\frac{1}{2}\pi(\mathbf{x})^2 + \frac{1}{2}(\nabla_a \phi)^2(\mathbf{x}) + \frac{1}{2}m_0^2 \phi(\mathbf{x})^2 + \frac{\lambda_0}{4!} \phi(\mathbf{x})^4 \right]
$$

conditions and lattice spacing a. The number of lattice spacing a. The number of lattice sites is E

freedom are promoted to Hermitian operators with the commutation relation

 m \mathfrak{p} , This (and subsequent) work is more $t = 2$, about formal scaling properties uous variable. To represent the field at a given site with finitely many α actual number of qubits is too large to make practical calculations yet.

For a great perspective piece, see Preskill's recent Lattice2018 talk:1811.10085
Lattice QFT with a Quantum Computer **1 73**

 $\frac{1}{2}$ pre- and post-processing will continue to be invalue to b This is the 1+1 Schwinger model; calculating the ρ of parity of modelling and Growth of the Schwinger modellinger modellinger modellinger modellinger modellinger pair from the vacuum. probability of finding an e+e-

 $r = "noise ratio";$ for $r > 1$, add $\sqrt{2}$ and UNU is mat correspond to the identity operation. extra CNOTs that correspond

FIG. 4. The probability of finding an *e*⁺*e* pair in the twospatial-site of the international model in the initial empty statement of the initial empty statement of the i lowing time evolution with *U^T* (*t, t*). In the unshaded region, autuar udiudidinis or ayriamics d Recent progress by simplifying the problem has led to sical and quantum computers to respectively tame the actual calculations of dynamics on a quantum computer!

Lattice QFT with a Quantum Computer **74** A attice \bigcap shown in the bottom plane of $\mathbf S$. In the bottom plot of $\mathbf S$

R. Hicks, C. Bauer, **BPN**, arXiv:2010.tomorrow