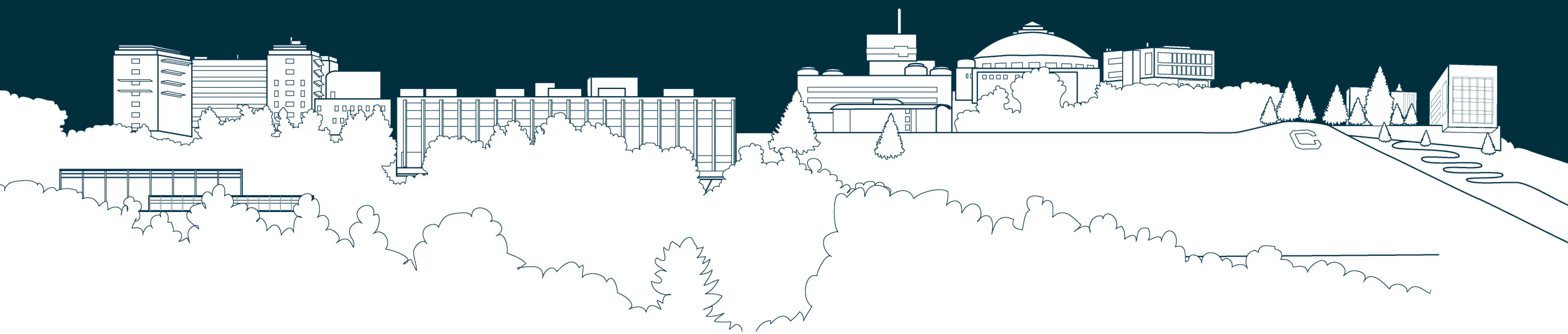
High Energy Scattering on a Quantum Computer

9/2/2021

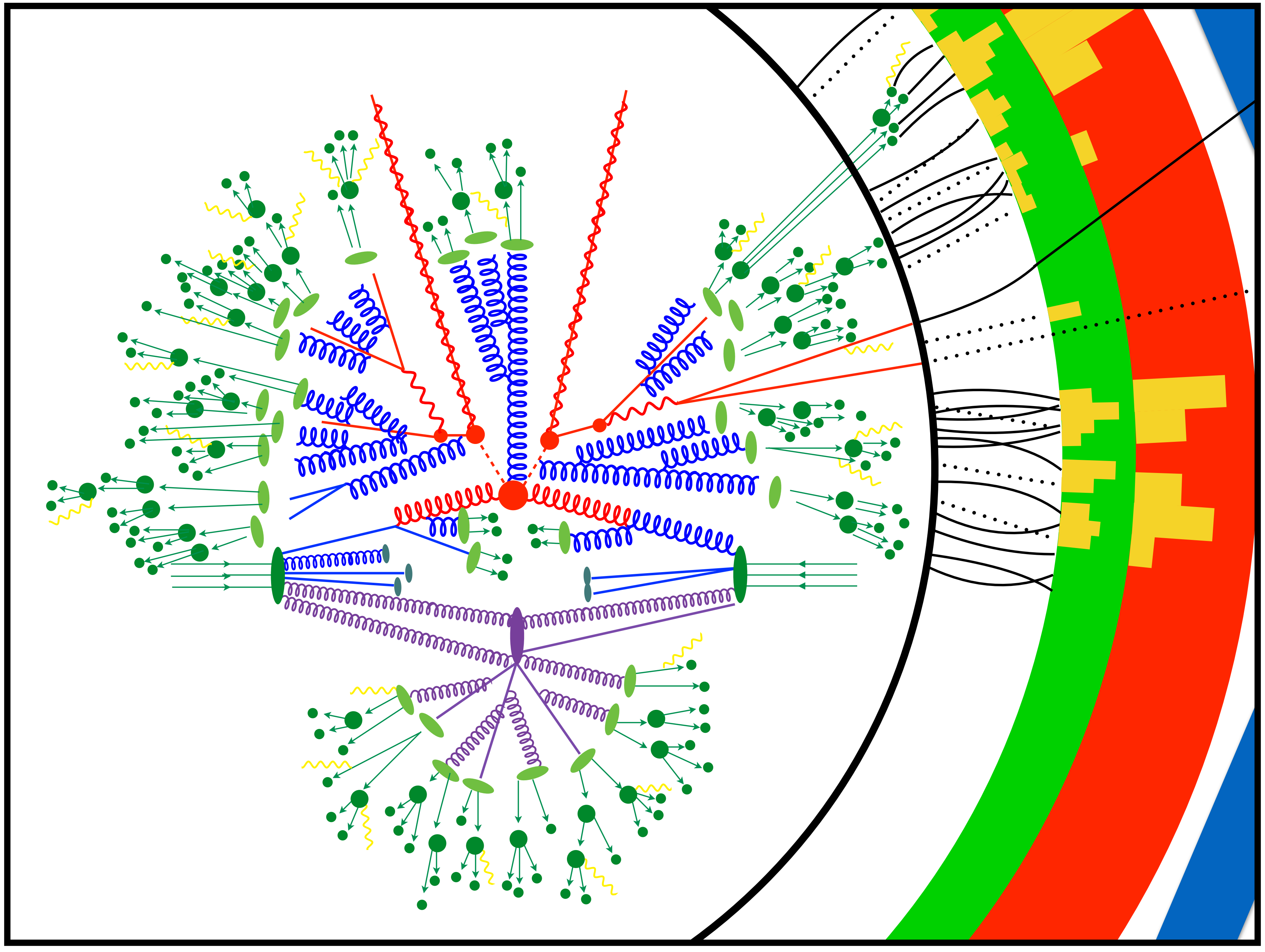


Ben Nachman
bpnachman@lbl.gov

LBNL Thursday Science Forum on Quantum Information Science

High Energy Physics

One of the holy grails of HEP is the full simulation of scattering processes at colliders



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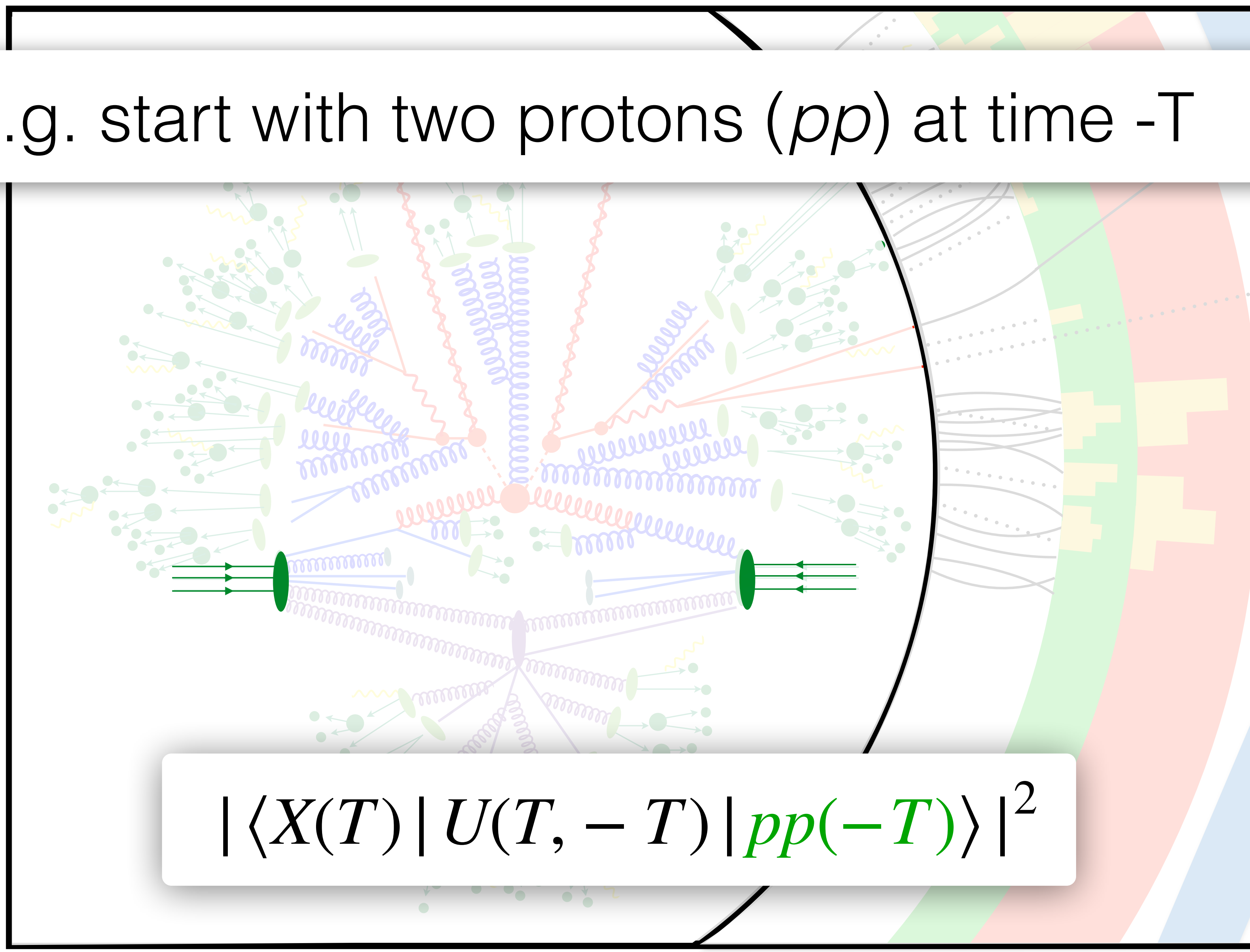

e.g. start with two protons (*pp*) at time -T

$$|\langle X(T)\,|\,U(T,-T)\,|\,pp(-T)\rangle\,|^2$$

High Energy Physics

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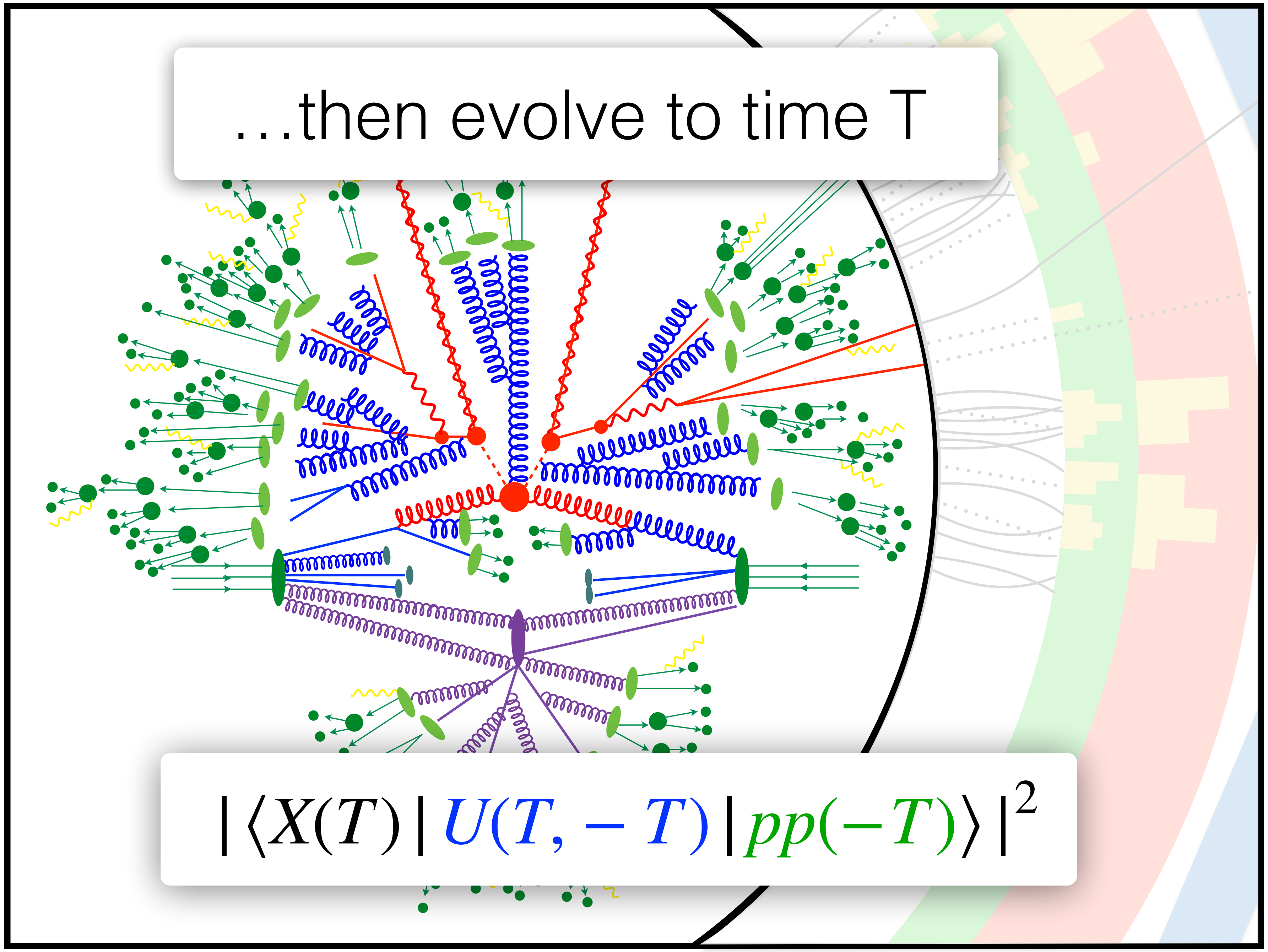

…then evolve to time T

$$|\langle X(T)|U(T,-T)|pp(-T)\rangle|^2$$

High Energy Physics

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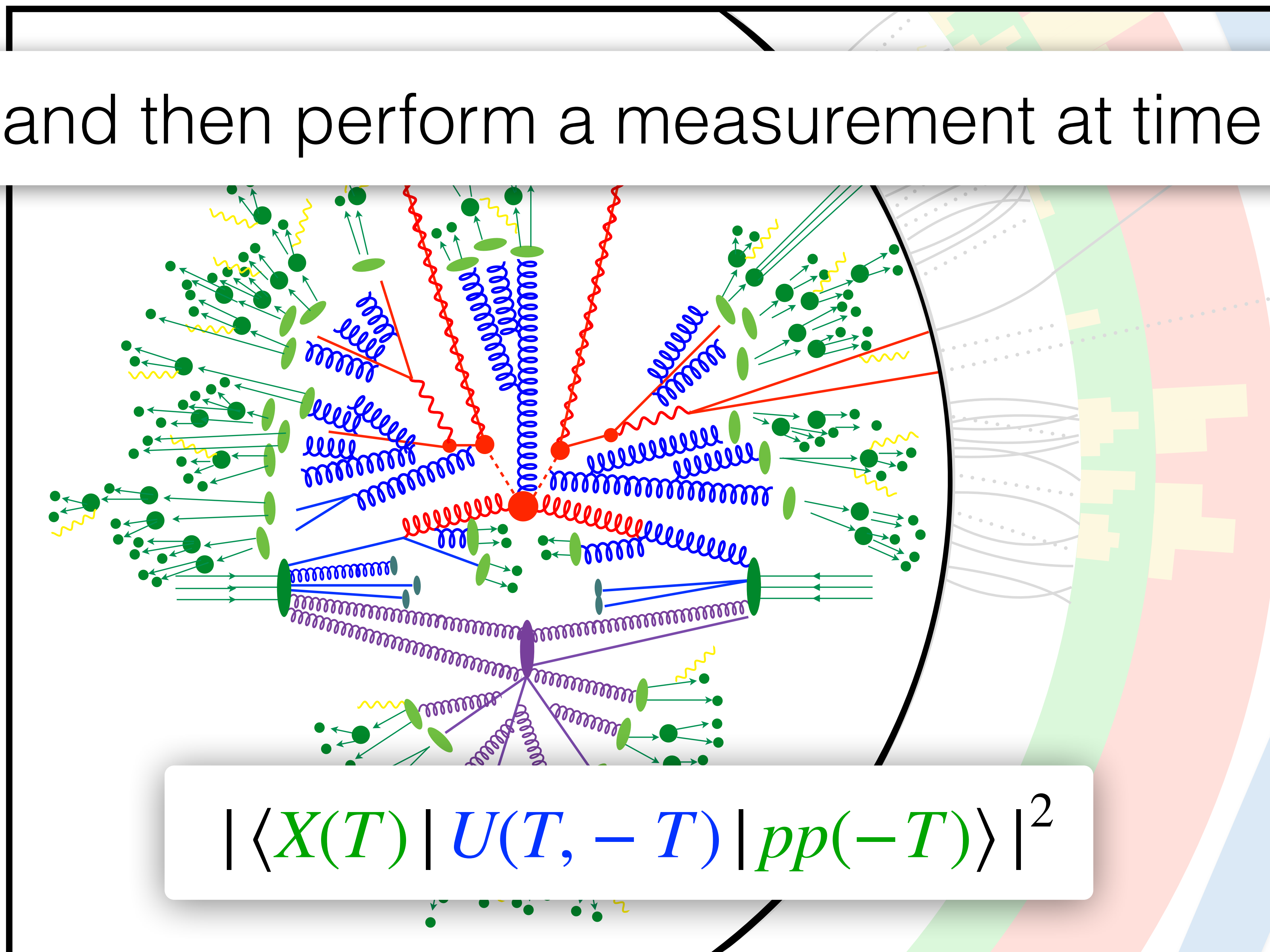

…and then perform a measurement at time T

$$|\langle X(T)|U(T,-T)|pp(-T)\rangle|^2$$

High Energy Physics

The theory governing all of this is **quantum field theory**

…and the quantum field theory of nature is well-approximated in many ways by the Standard Model of particle physics

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Two traditional approaches:

Lattice

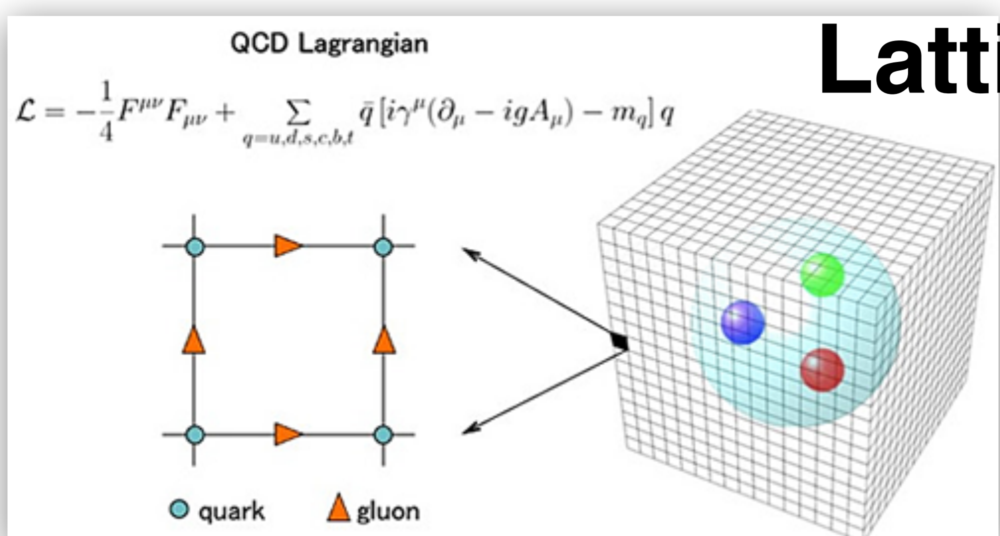


Image credit: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

Perturbation theory

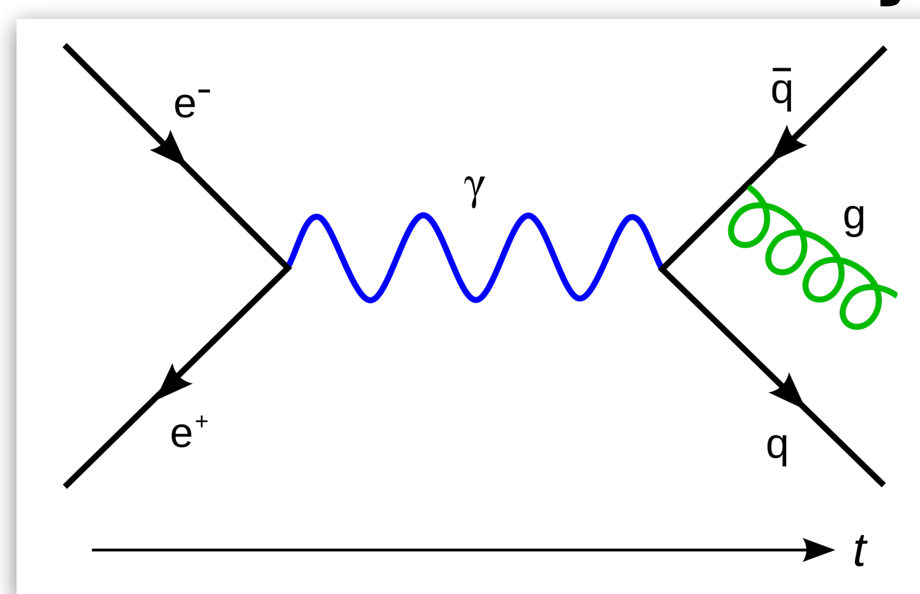


Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

High Energy Physics

The theory governing all of this is **quantum field theory**

...and the quantum field theory of nature is well-approximated in many ways by the Standard Model of particle physics

A key feature of QFTs is that **every** spacetime point has quantum degrees of freedom (thus a field)

Pro: Full theory

Con: Dynamics are too hard

(already using supercomputers)

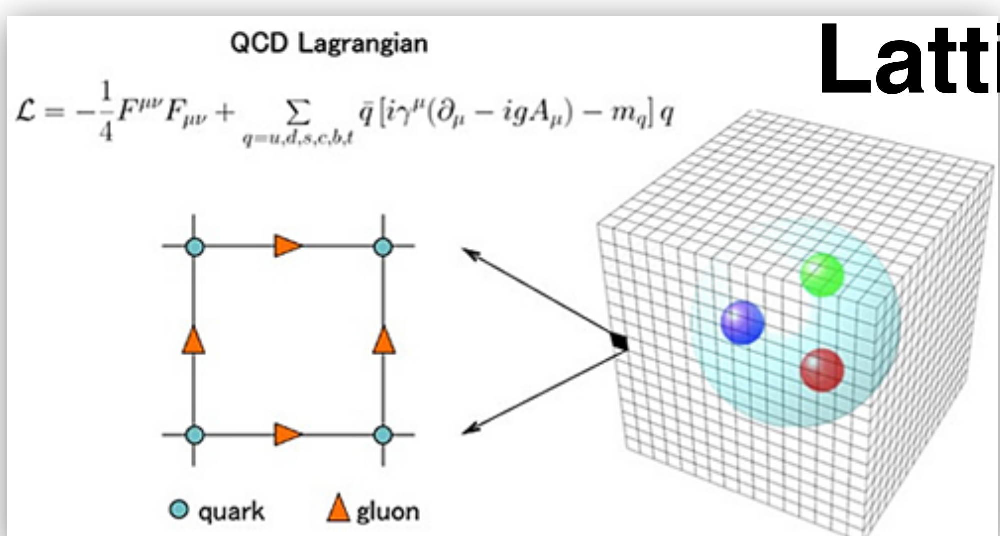
Pro: Can do high-energy dynamics

Con: An approximation

...and combinatorially many diagrams

Two traditional approaches:

Lattice



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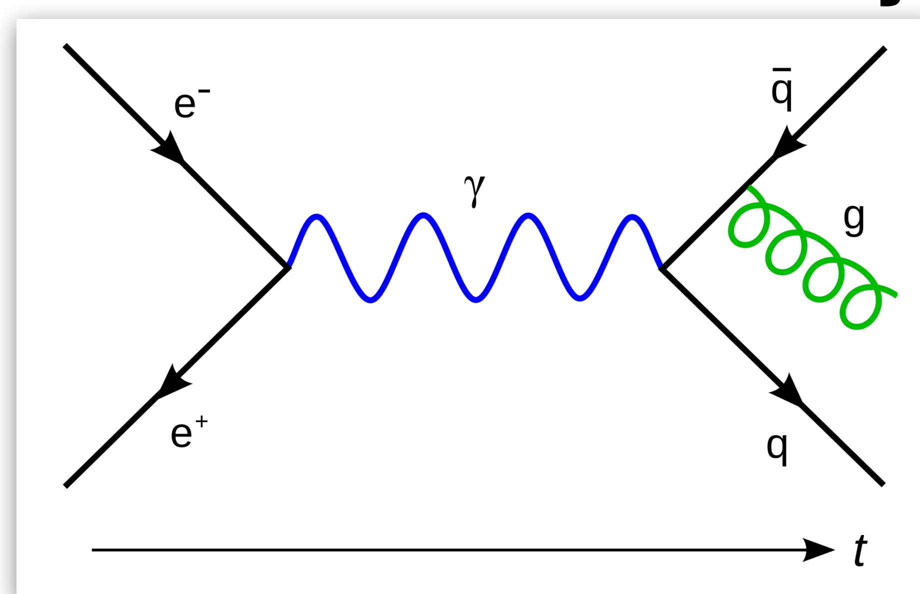


Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

QFT on a Quantum Computer

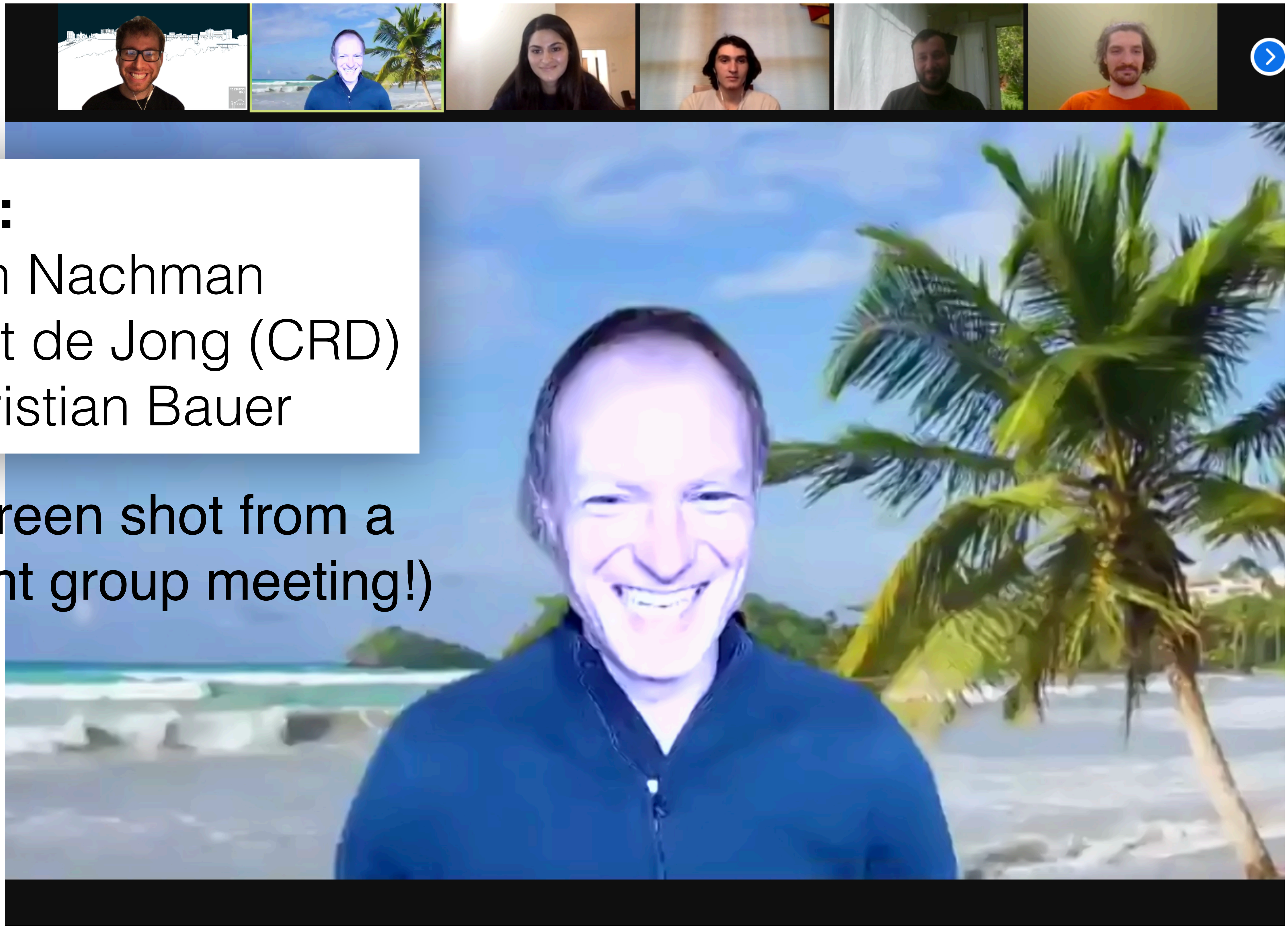
Pioneering work by S. Jordan, K. Lee and J. Preskill* showed that it is possible to simulate the time evolution of a QFT in polynomial time on a quantum computer.

*Our group studies **hybrid strategies** for approaching QFTs that make the best use of lattice methods and perturbation theory. Along the way, we have developed a suite of **error mitigation** protocols.*

*Science 336 (2012) 1130, 1111.3633

Quantum Computing for HEP @ LBL

PIs:
Ben Nachman
Bert de Jong (CRD)
Christian Bauer

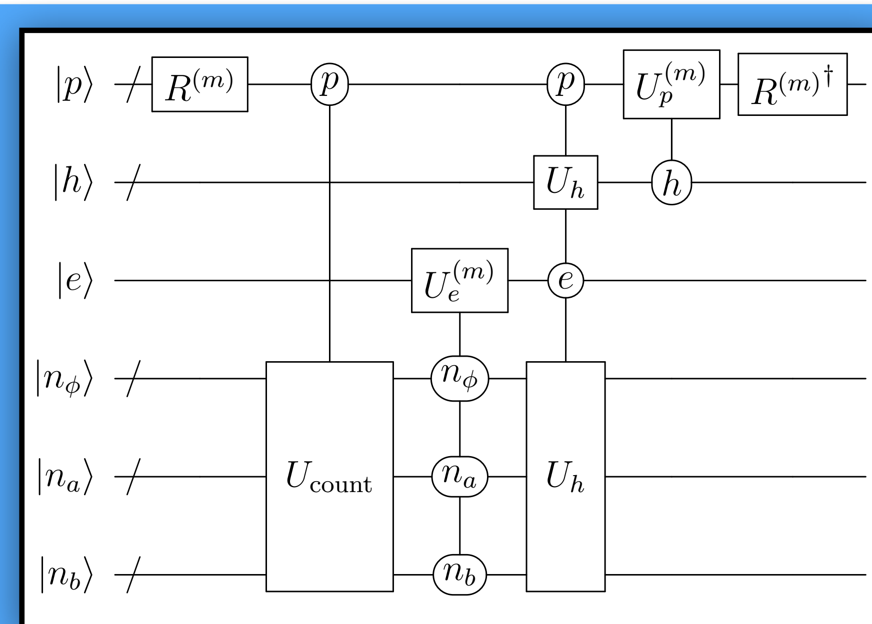


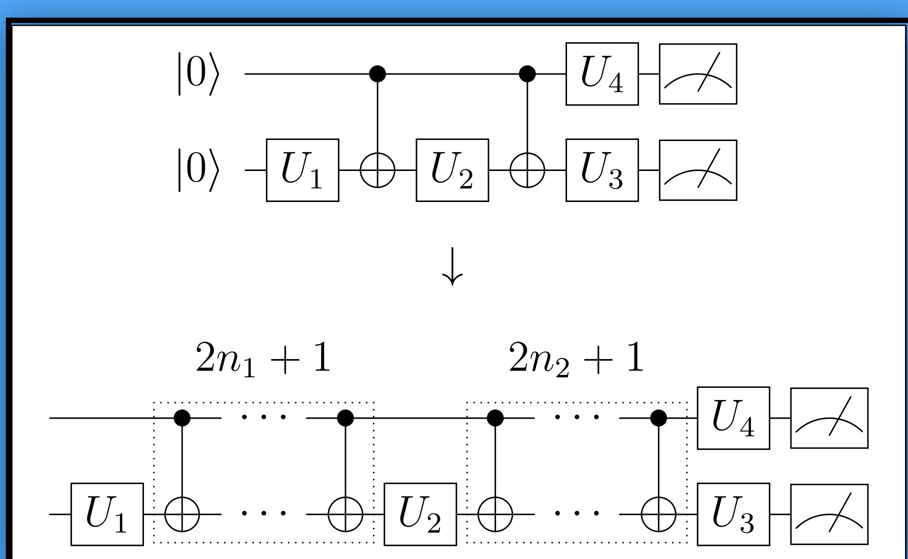
(screen shot from a recent group meeting!)

Quantum Computing for HEP

Our group explores two inter-related topics

Quantum algorithms for quantum field theory





Error mitigation for near term quantum computers

Quantum Computing for HEP

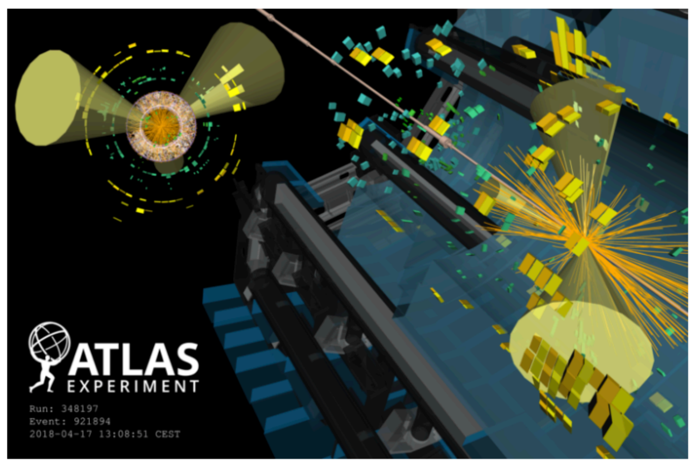
NEWS CENTER

Applying Quantum Computing to a Particle Process

Berkeley Lab team models parton showers using a quantum algorithm

News Release Glenn Roberts Jr. (510) 520-0843 • **February 12, 2021**

A team of researchers at Lawrence Berkeley National Laboratory (Berkeley Lab) used a quantum computer to successfully simulate an aspect of particle collisions that is typically neglected in high-energy physics experiments, such as those that occur at CERN's Large Hadron Collider.



An ATLAS particle collision event display from 2018 at CERN's Large Hadron Collider displays a spray of particles (orange lines) emanating from the collision of protons, and the detector readout (squares and rectangles). (Credit: ATLAS collaboration)

The quantum algorithm they developed accounts for the complexity of parton showers, which are complicated bursts of particles produced in the collisions that involve particle production and decay processes.

Classical algorithms typically used to model parton showers, such as the popular Markov Chain Monte Carlo algorithms, overlook several quantum-based effects, the researchers note in a study published online Feb. 10 in the journal Physical Review Letters that details their quantum algorithm.

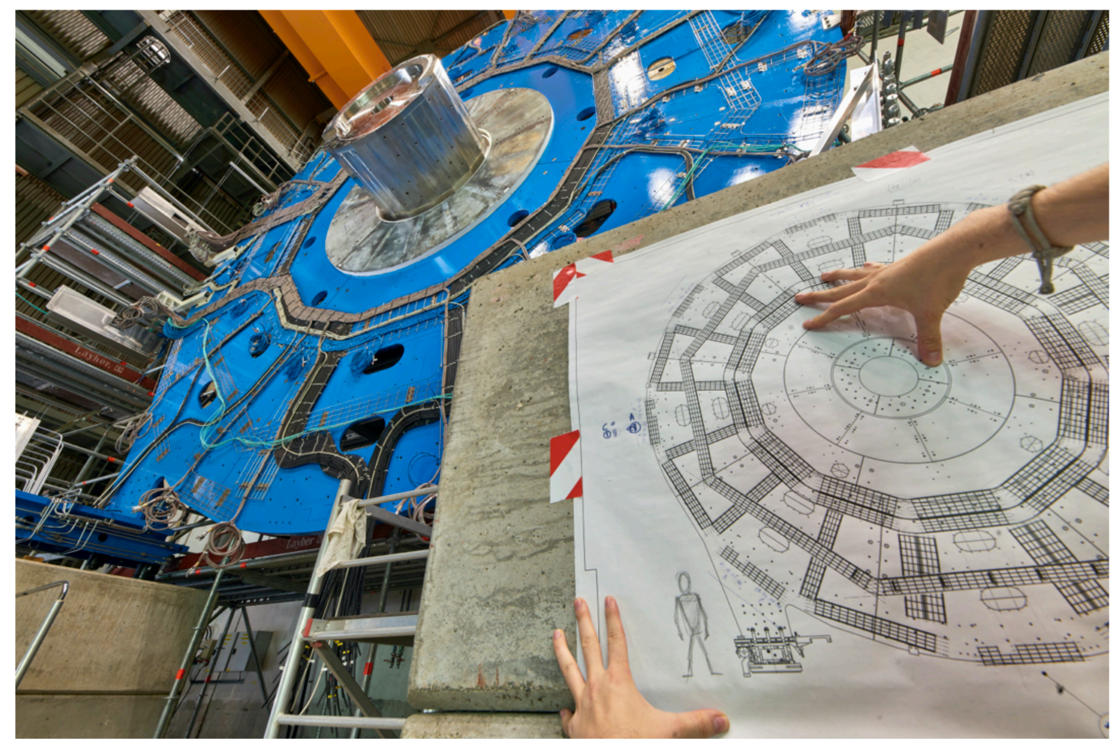
"We've essentially shown that you can put a parton shower on a quantum computer with efficient resources," said Christian Bauer, who is Theory Group leader and serves as principal investigator for quantum computing efforts in Berkeley Lab's Physics Division, "and we've shown there are certain quantum effects that are difficult to describe on a classical computer that you could describe on a quantum computer." Bauer led the recent study.

NEWS CENTER

Know When to Unfold 'Em: Study Applies Error-Reducing Methods from Particle Physics to Quantum Computing

'Unfolding' techniques used to improve the accuracy of particle detector data can also improve the readout of quantum states from a quantum computer

News Release Glenn Roberts Jr. (510) 520-0843 • **November 5, 2020**



A wheel-shaped muon detector is part of an ATLAS particle detector upgrade at CERN. A new study applies "unfolding," or error-correction techniques used for particle detectors, to problems with noise in quantum computing. (Credit: Julien Marius Ordan/CERN)

Borrowing a page from high-energy physics and astronomy textbooks, a team of physicists and computer scientists at the U.S. Department of Energy's Lawrence Berkeley National Laboratory (Berkeley Lab) has successfully adapted and applied a common error-reduction technique to the field of quantum computing.

Quantum Computing for HEP

NEWS CENTER

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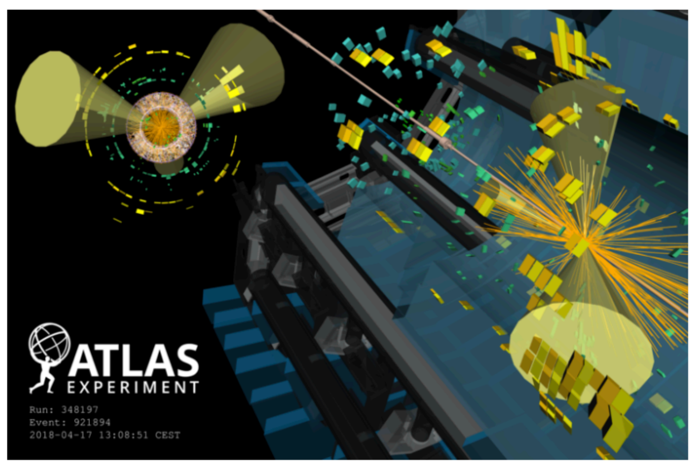

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NEWS CENTER

Know When to Unfold 'Em: Study Applies Error-

B. Nachman, D. Provasoli, W. de Jong, C. Bauer, Phys. Rev. Lett. 126 (2021) 062001

I. Georgescu, Nature Rev. Physics 3 (2021) 73

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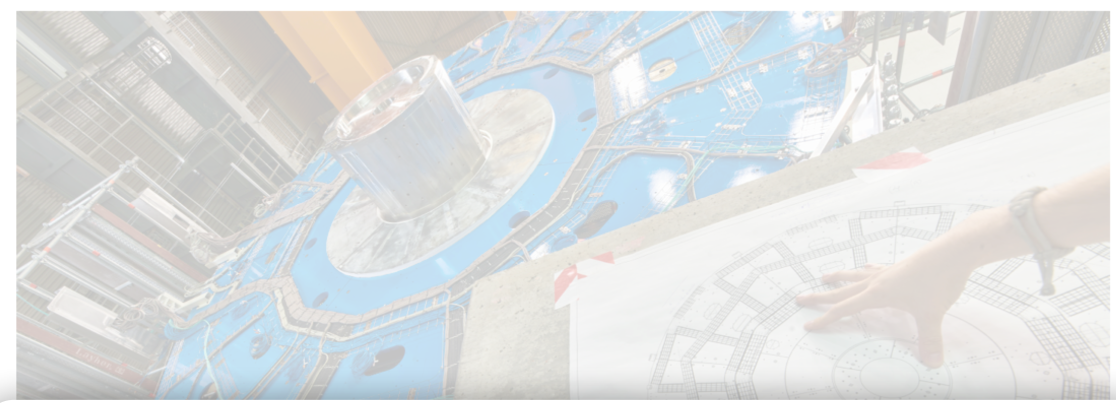


Today, we will talk about more recent work in this area, but this article was about our work on "parton showers" published in PRL this year and also featured in Nature Reviews Physics

QFT on a Quantum Computer

Proposals for *ab initio* calculations use lattice methods.

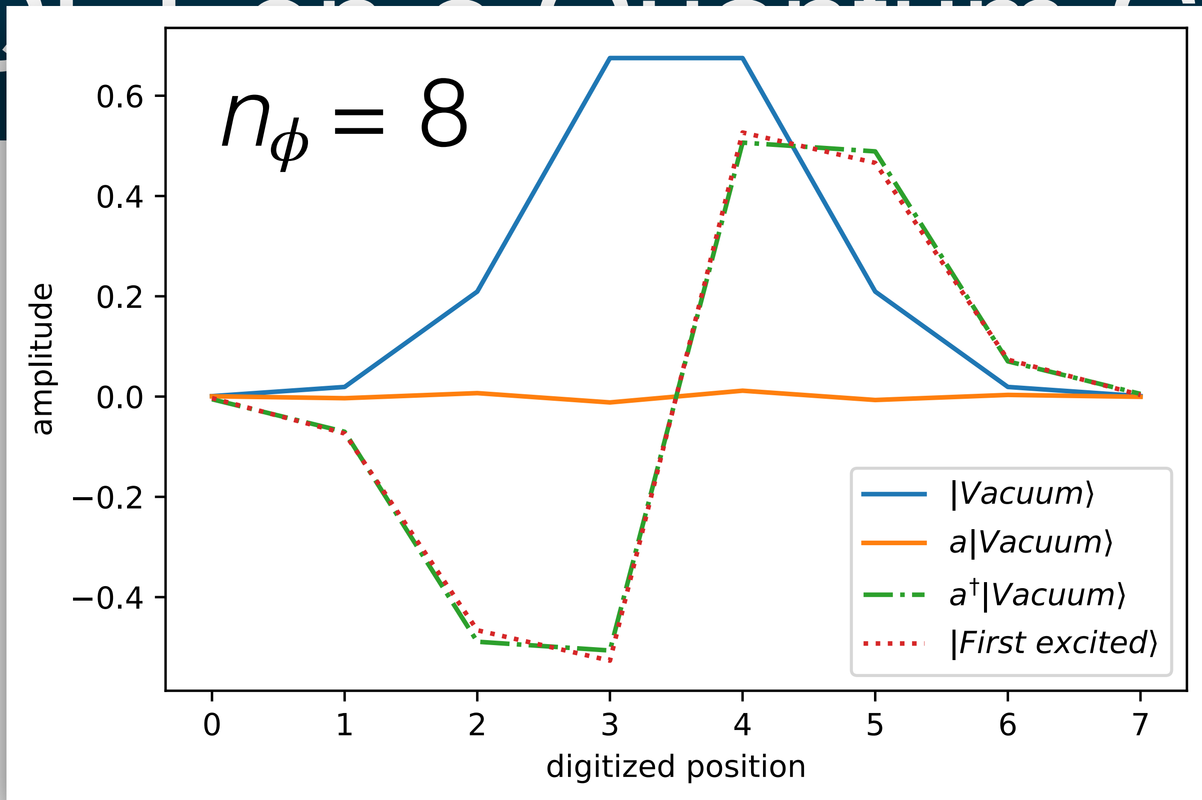
(and digitize the field values to make the infinite-dimensional Hilbert space finite)

Let's say we digitize our fields into n_ϕ values and have N lattice points in each of the d directions

Then, our Hilbert space is $n_\phi^{\,(N^d)}$ - dimensional

On a quantum computer, we will need $O(N^d \log(n_\phi))$ qubits.

QFT on a Quantum Computer



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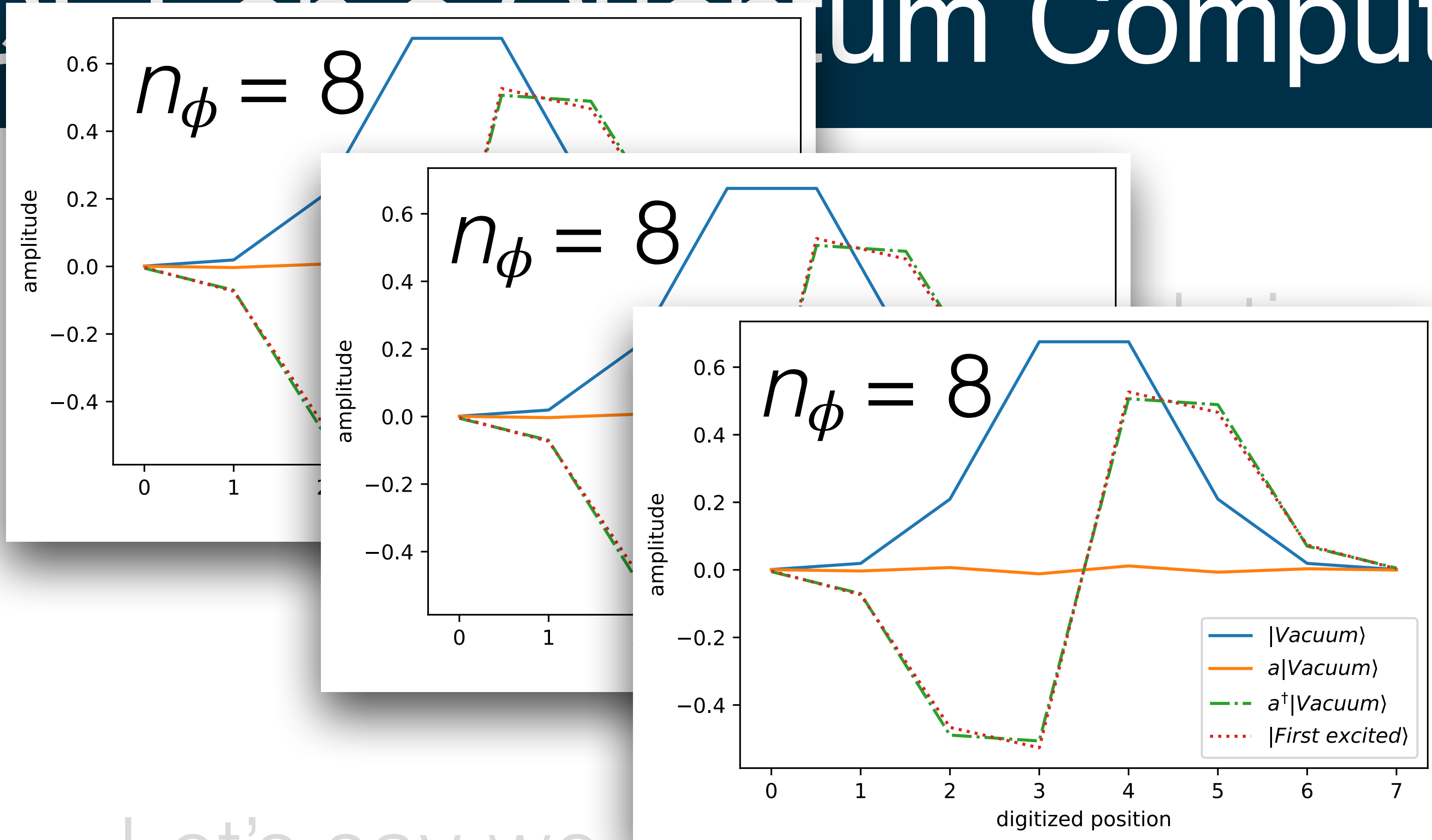

... use lattice methods.

...s to make the ...space finite)

N = 3, d = 1

Let's say we digitize our fields into n_ϕ values and have N lattice points in each of the d directions

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QFT on a Quantum Computer

On a quantum computer, we will need $O(N^d \log(n_\phi))$ qubits.

Let's put in some numbers.

Discretization and finite volume effects introduce UV/IR cutoffs. If the smallest lattice spacing is Δ, then the approximation of the continuum theory is good only when E is above ~ 1/NΔ and below ~1/Δ.

If we want to cover all of the relevant dynamics at the LHC; 10 MeV - 7 TeV, this means N ~ O(10^6)

(smallest resolvable transverse momentum between hadrons - beam energy)

QFT on a Quantum Computer

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~10^{18} qubits may be more than we will have in our lifetime…

If we want to cover all of the relevant dynamics at the LHC; 10 MeV - 7 TeV, this means N ~ $O(10^6)$

(smallest resolvable transverse momentum between hadrons - beam energy)

Solution: hybrid approach

Let's use **perturbation theory** to cover the highest energies, which would otherwise need the finest lattice spacings.

We can then try to identify objects in the theory that we could try to calculate using quantum computers.

$$\sigma = H \otimes J_1 \otimes \ldots \otimes J_n \otimes S$$

For hadronic jet physics at the LHC, the cross section factorizes* into a "**hard component**", "collinear components" and "soft components".

*The formal structure for this is Soft Collinear Effective Theory (SCET) which C. Bauer co-created many years ago

Solution: hybrid approach

Let's use **perturb**

which would ot

We can then tr

could try to calculate us quantum computers.

We don't need the full dynamic range of the LHC, so can use far fewer qubits …

~millions or billions of qubits may be possible in the not-to-distant future

$$\sigma = H \otimes J_1 \otimes \ldots \otimes J_n \otimes S$$

For hadronic jet physics at the LHC, the cross section factorizes* into a "**hard component**", "collinear components" and "soft components".

*The formal structure for this is Soft Collinear Effective Theory (SCET) which C. Bauer co-created many years ago

Soft Physics on a Quantum Computer

$$\sigma = H \otimes J_1 \otimes \ldots \otimes J_n \otimes S$$

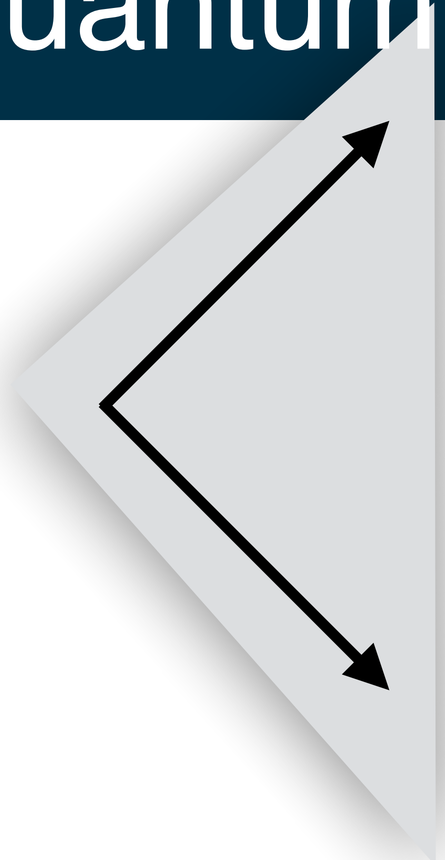
High-energy particles do not contribute to dynamics - they are instead modeled as static charges.

$$Y_n = \mathrm{P}\exp\left[ig\int_0^\infty \mathrm{d}s\; n\cdot A(x^\mu = n^\mu s)\right]$$

"Wilson Line"

where *n* is a light-like direction and *A* is the soft gauge field.

Soft Physics on a Quantum Computer



$$Y_n = \mathrm{P}\exp\left[ig\int_0^\infty \mathrm{d}s\ n\cdot A(x^\mu = n^\mu s)\right]$$

"Wilson Line"

where *n* is a light-like direction and *A* is the soft gauge field.

The matrix elements for the soft sector are $\langle X|\mathrm{T}[Y_n\, Y_{\bar{n}}^\dagger]|\Omega\rangle$

X = final state, *Ω* = ground state

Simplified Model

Our goal is the Standard Model, but given current resources, let's consider a simplified problem: 1+1 dimension and a massless scalar theory instead of a gauge theory.

Clearly, some of the complexity is lost, but many salient features remain.

$$H = \int \mathrm{d}x \, \frac{1}{2}\left(\dot{\phi}^2 - \phi\,\partial^2\phi\right),$$

$$Y_n = \mathrm{P}\exp\left[ig\int_0^\infty \mathrm{d}s\;\phi(x^\mu = n^\mu s)\right]$$

A key issue in 1+1 is that there are no transverse directions, so there are no collinear safe observables.

Simplified Model on a Lattice

$$H = \frac{\delta x}{2} \sum_{i=0}^{N-1} \left[\dot{\phi}_i^2 - \phi_i \left[\nabla^2 \phi \right]_i \right]$$

$$Y_n = \mathrm{P} \exp \left[i g \, \delta x \sum_{i=n_0}^{2n_0} \phi_{x_i}(t = x_i - n_0) \right]$$

$\phi_i \equiv \phi(x_i)$

n_0 is the lattice center

$$H = \int \mathrm{d}x \, \frac{1}{2} \left(\dot{\phi}^2 - \phi \, \partial^2 \phi \right) ,$$

$$Y_n = \mathrm{P} \exp \left[i g \int_0^\infty \mathrm{d}s \; \phi(x^\mu = n^\mu s) \right]$$

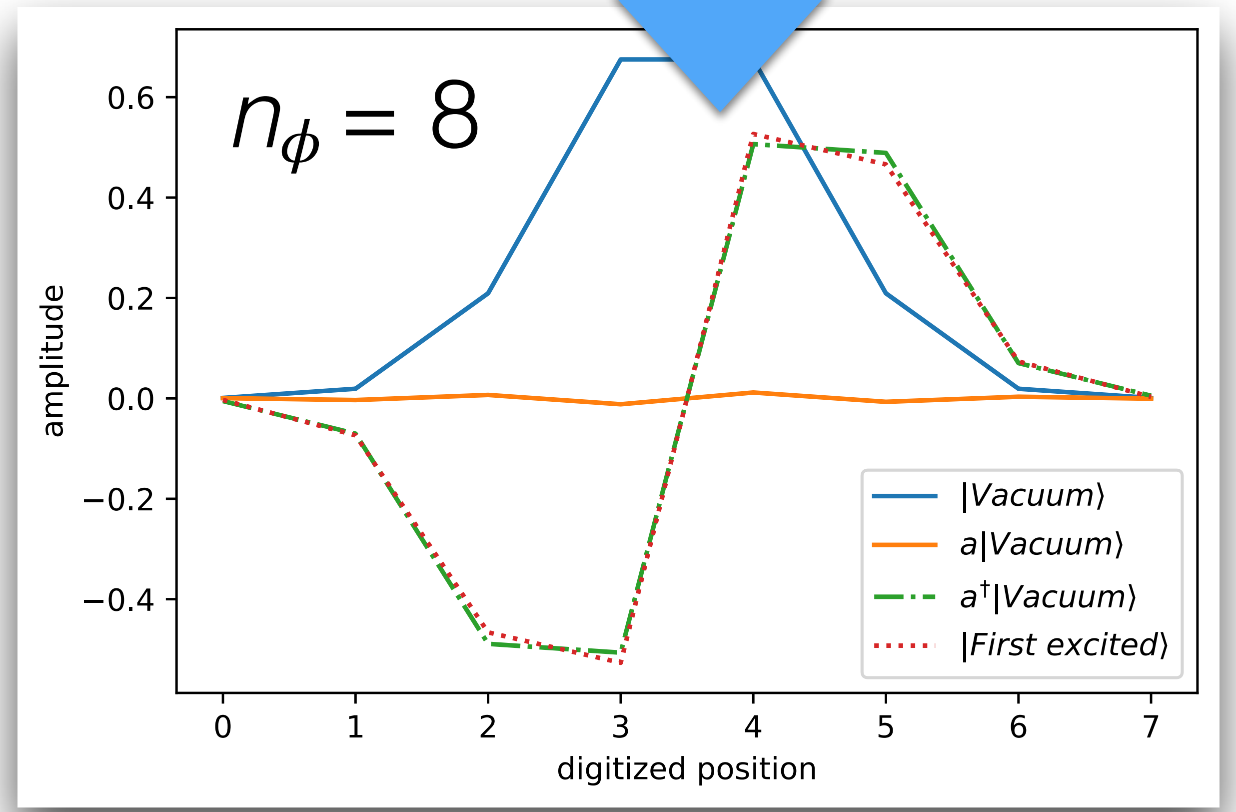
The spatial derivative term uses finite differences.

Simplified Model on a Lattice & Digitized

$$H = \frac{\delta x}{2} \sum_{i=0}^{N-1} \left[\dot{\phi}_i^2 - \phi_i \left[\nabla^2 \phi\right]_i \right]$$

$$Y_n = \mathrm{P} \exp\left[i g \, \delta x \sum_{i=n_0}^{2n_0} \phi_{x_i}(t = x_i - n_0) \right]$$

Uniformly spaced field values at each site



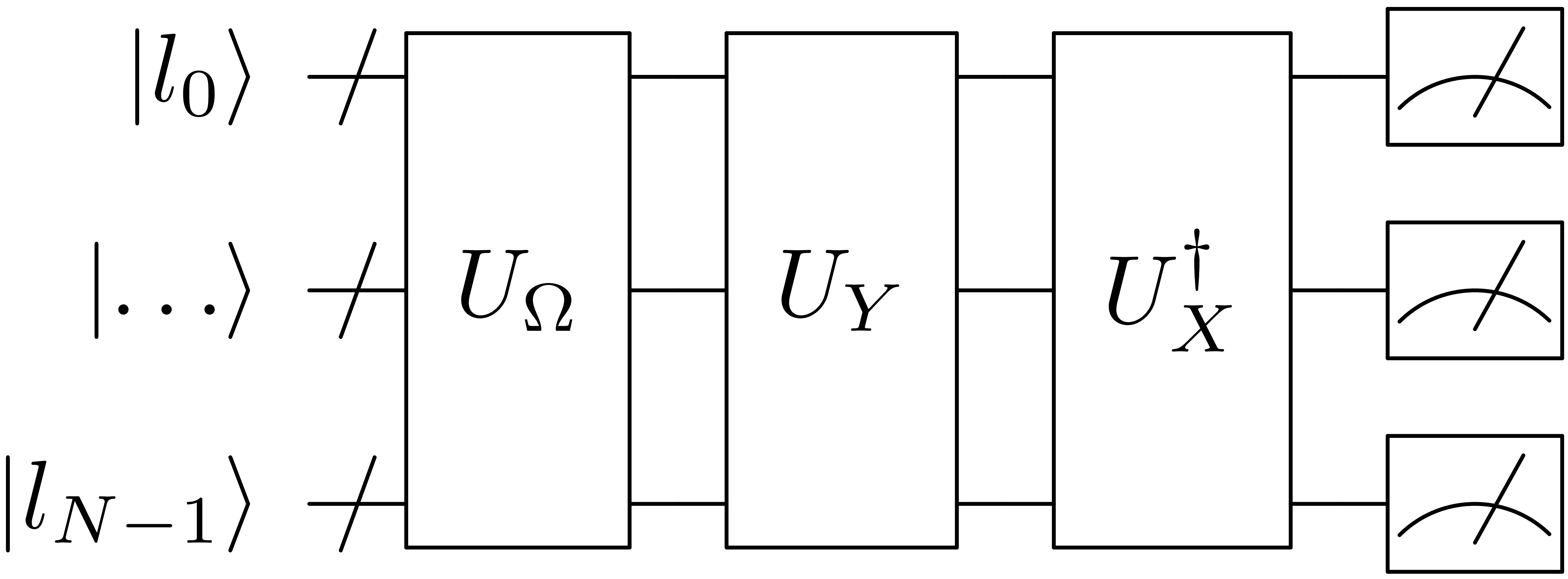
$$H = \pi^2 + \phi^2$$

so want a range that has equal precision for field and conjugate momentum*

*observation due to Marat Freytsis

Towards a Quantum Circuit

$$\langle X | \mathrm{T}[Y_n \, Y_{\bar{n}}^\dagger] | \Omega \rangle$$



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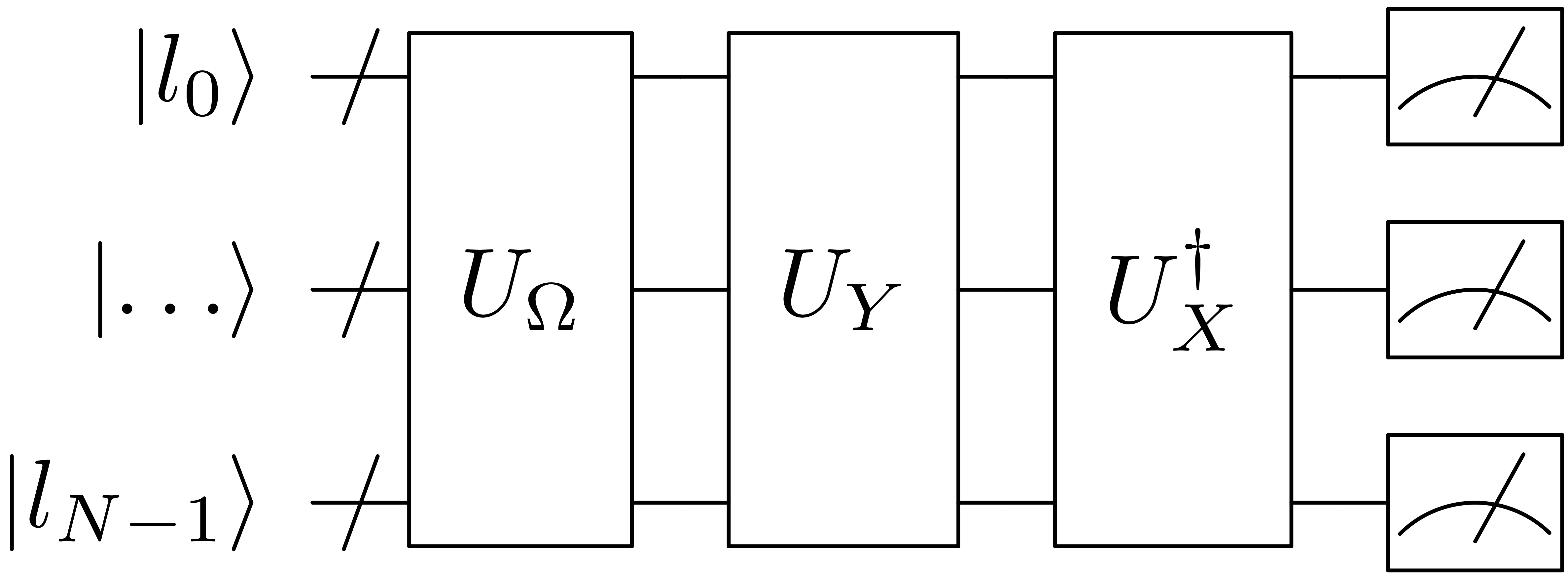

Register of n_ϕ
quits per site

Towards a Quantum Circuit

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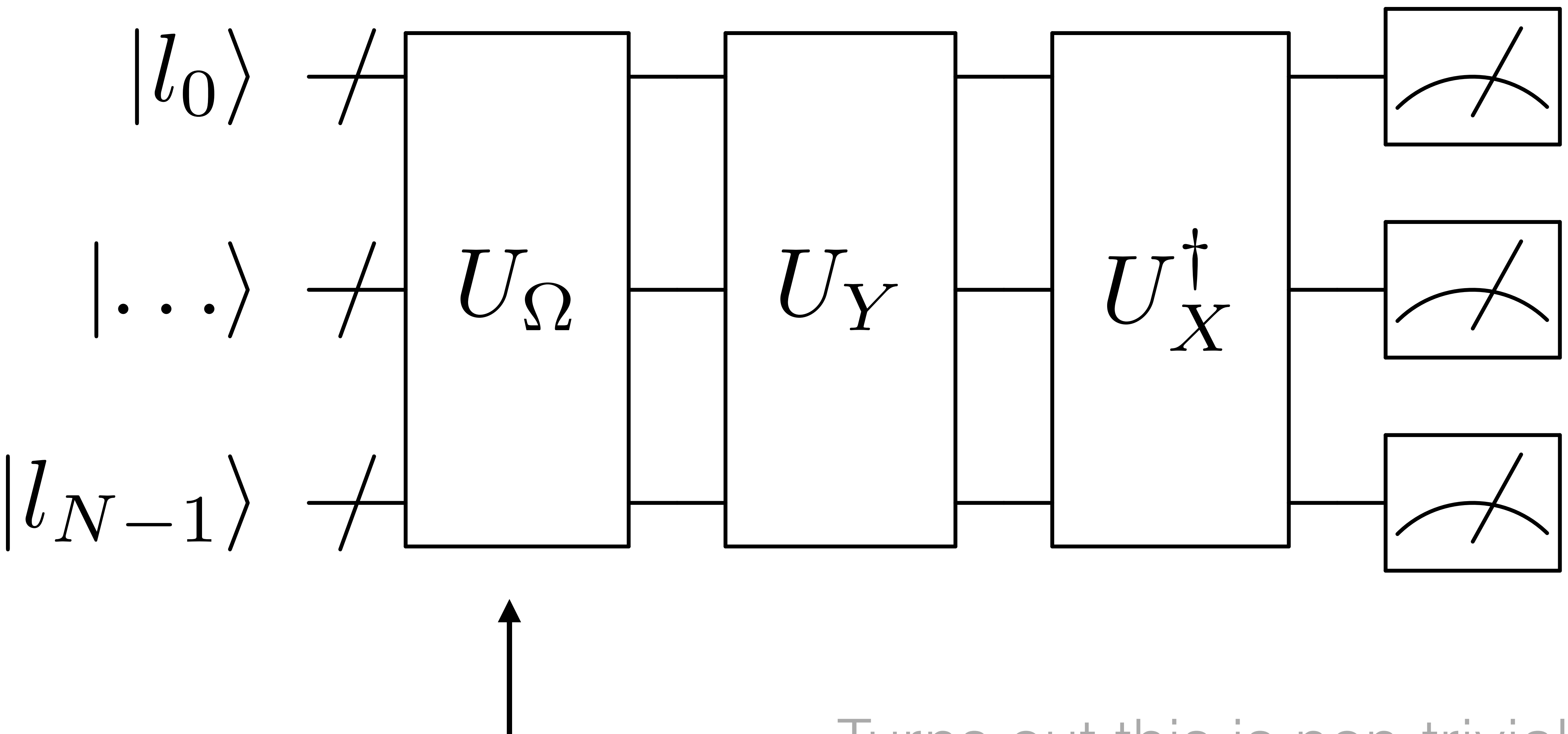
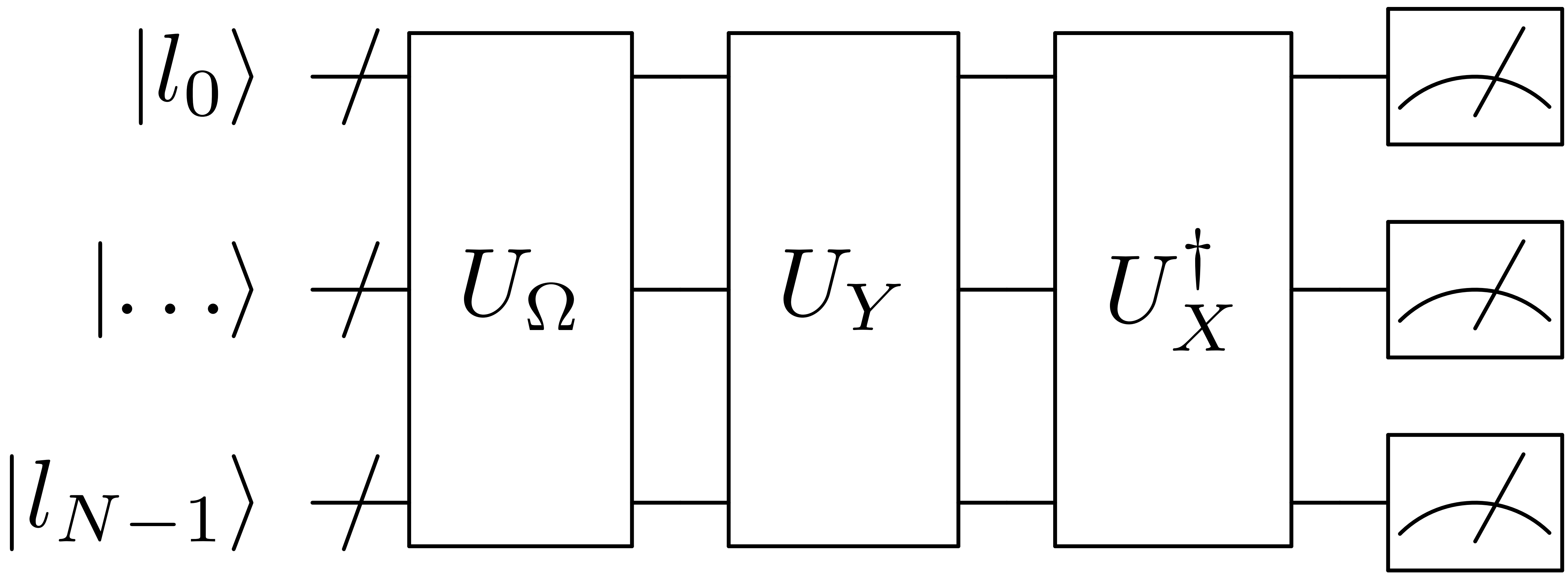


Prepare the ground state

Turns out this is non-trivial …
see *C. Bauer, P. Deliyannis, M. Freytsis, BN, 2109.soon*

Towards a Quantum Circuit

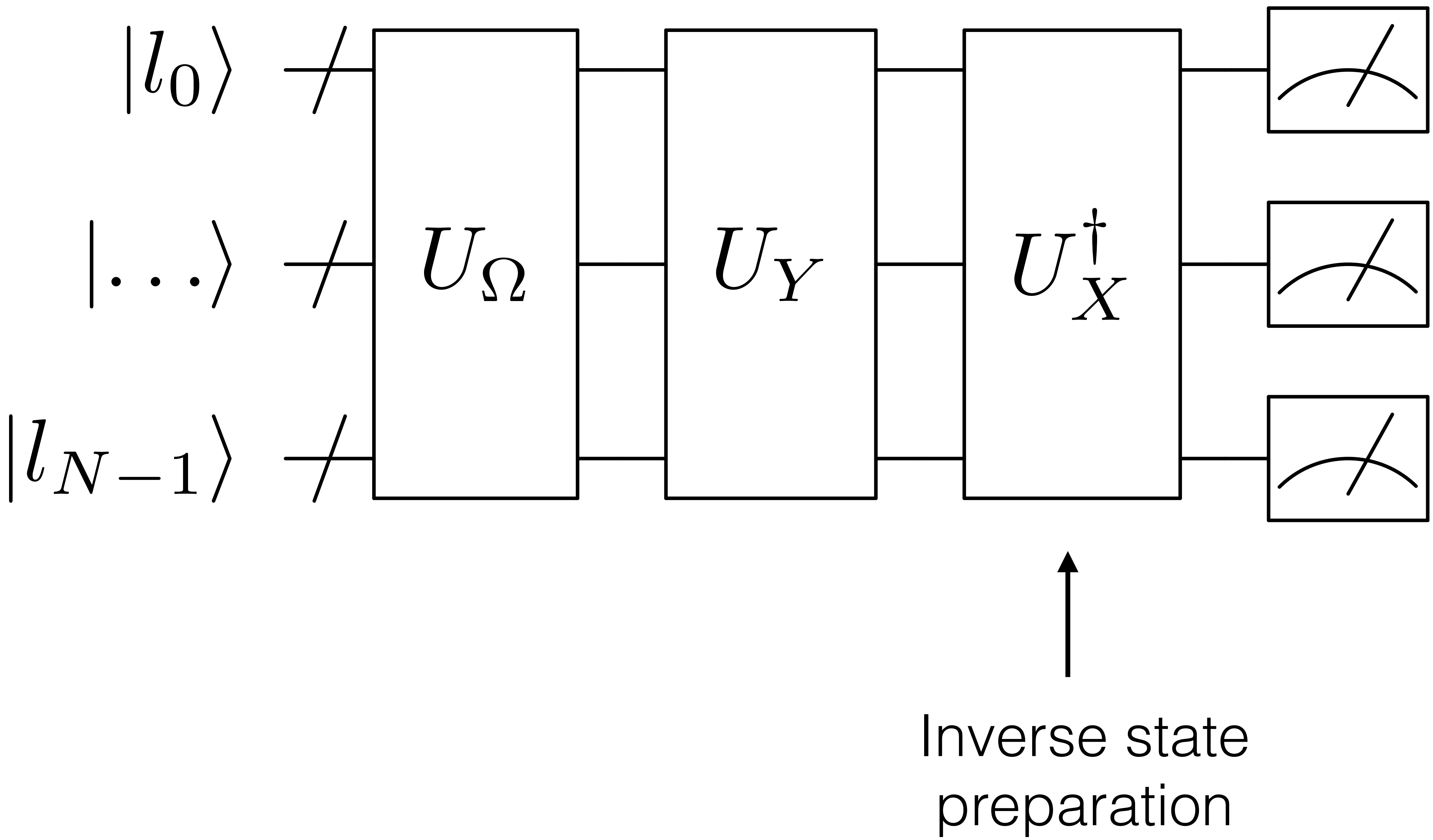
$$\langle X | \mathrm{T}[Y_n \, Y_{\bar{n}}^\dagger] | \Omega \rangle$$



Time-ordered product

Towards a Quantum Circuit

$$\langle X | \mathrm{T}[Y_n \, Y_{\bar{n}}^\dagger] | \Omega \rangle$$



Quantum Measurements

IBM Q Manhattan (65 superconducting qubits)

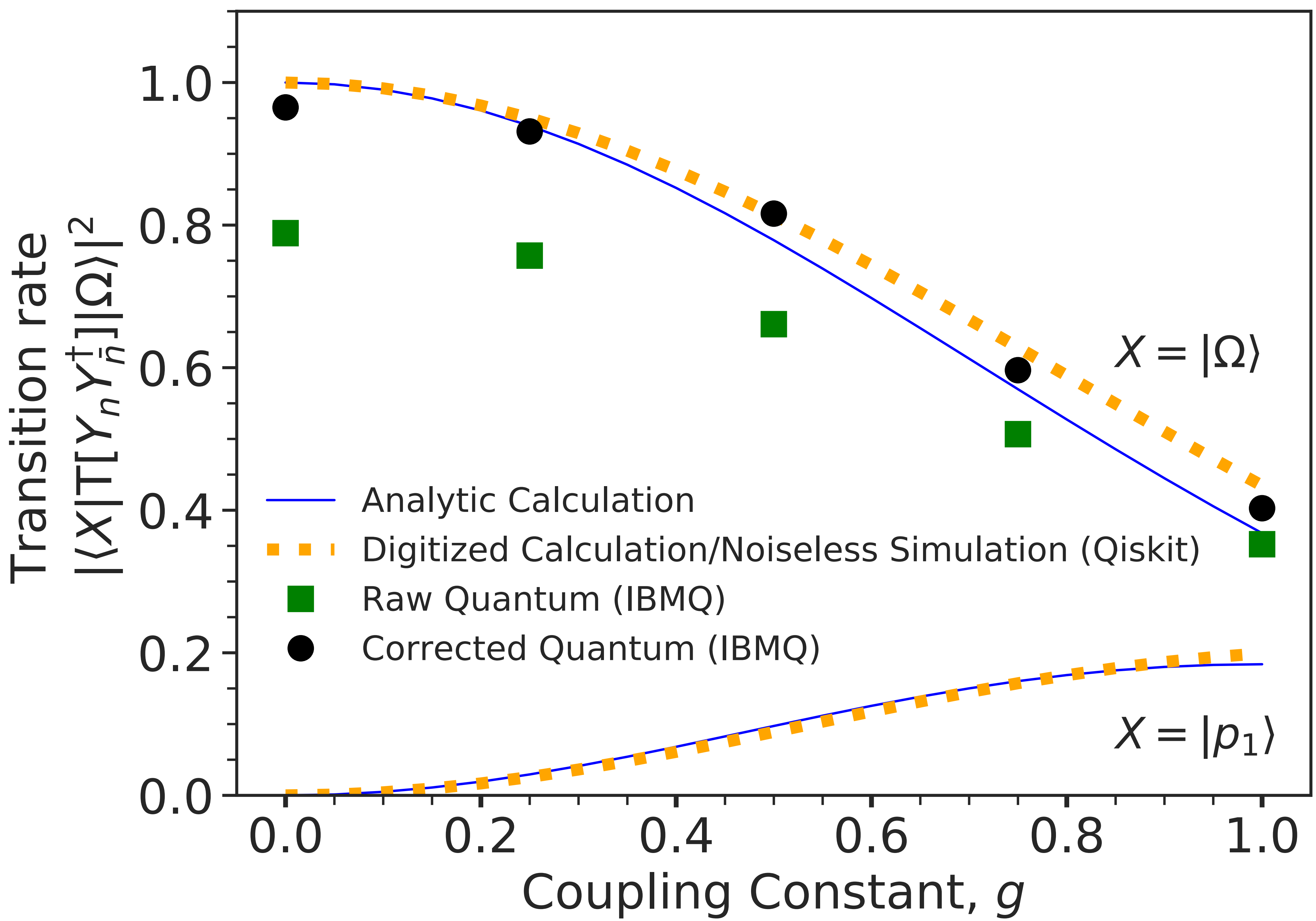
N = 3 sites, $n_\phi = 4$ (so 2 qubits per lattice site)

With only 3 lattice sites, the matrix element simplifies significantly - all time evolution cancels out:

$$\left|\langle X|\mathrm{T}[Y_n\, Y_{\bar{n}}^\dagger]|\Omega\rangle\right|^2 = \left|\langle X|e^{ig\delta x\left(\phi_{x_2}-\phi_{x_0}\right)}|\Omega\rangle\right|^2$$

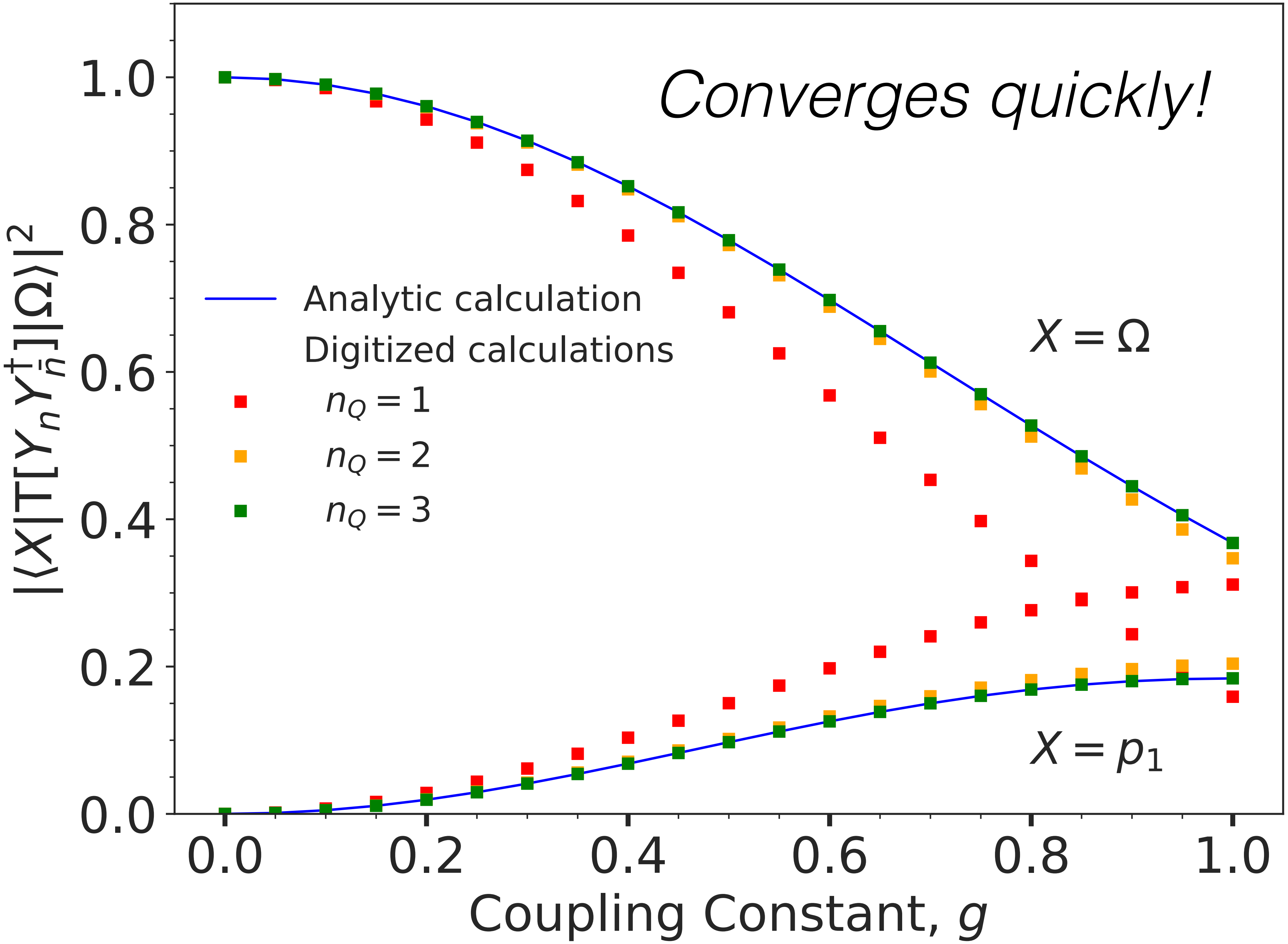
(this is because all time evolution operators act on initial or final eigenstate of Hamiltonian)

Quantum Measurements: results

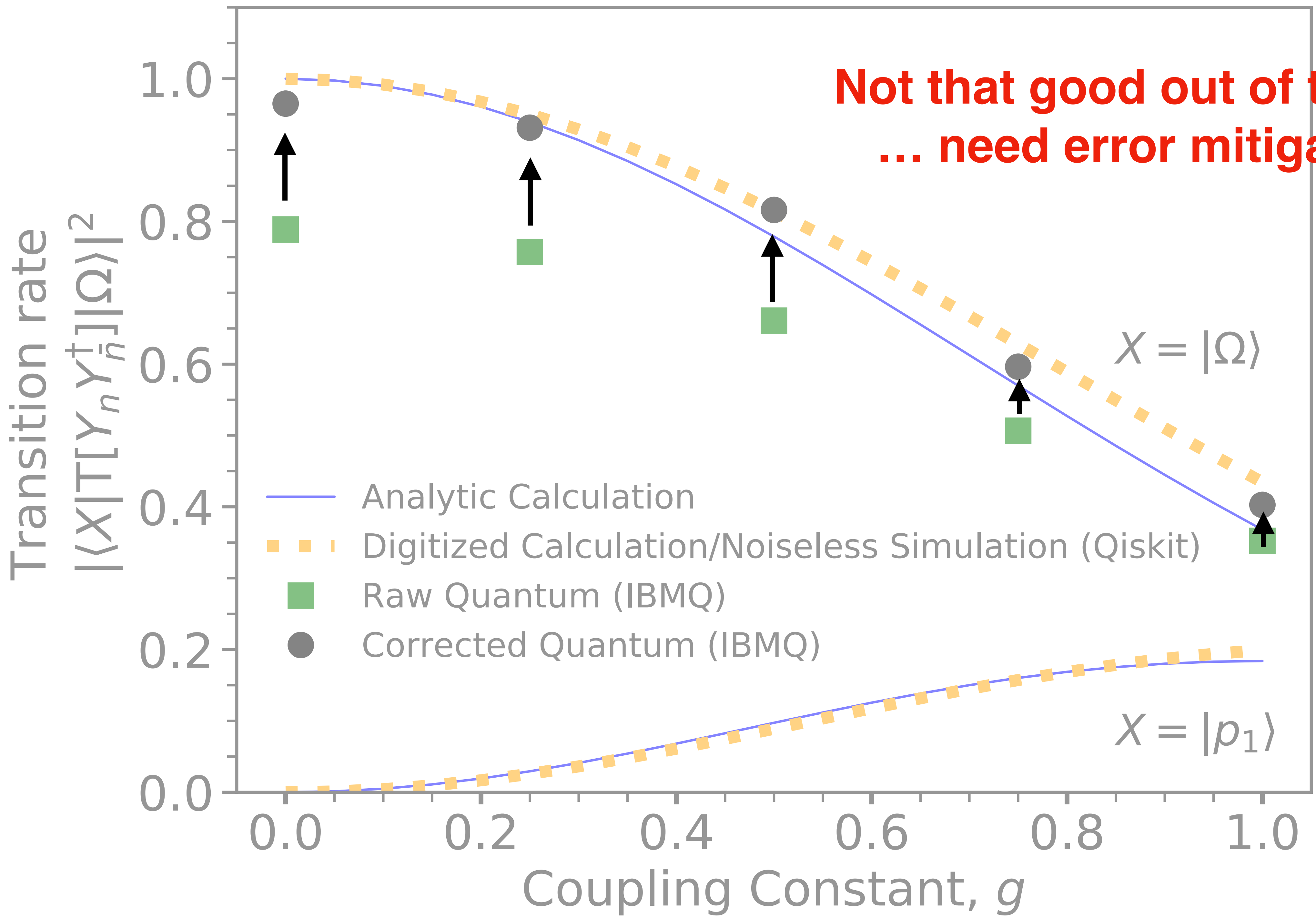


Quantum computer gives a good description of the analytical result!

Challenges: Digitization

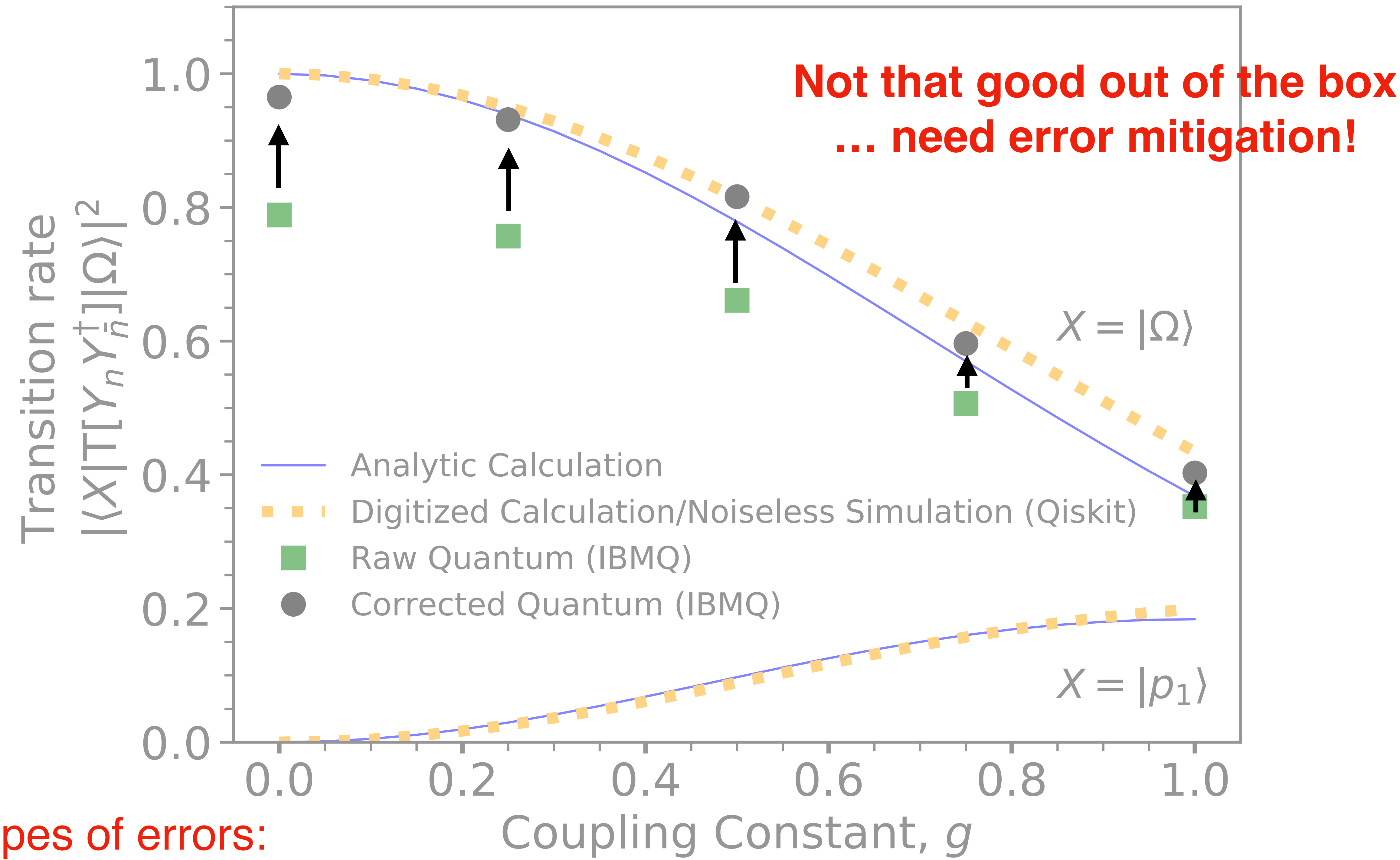


Challenges: Noise



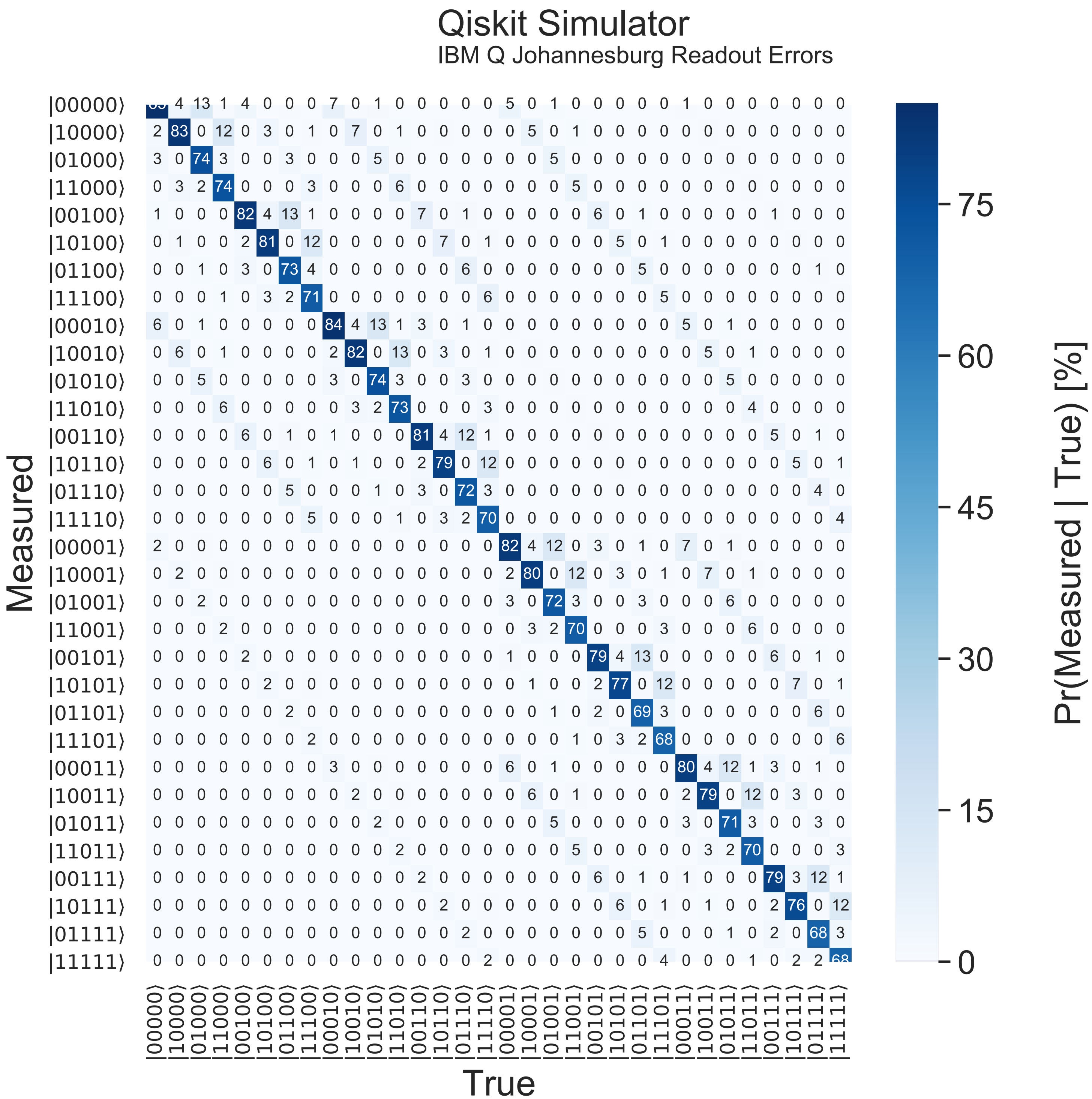
Not that good out of the box
… need error mitigation!

Challenges: Noise



Two types of errors:
Readout errors
and **Gate errors**

Readout error corrections



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

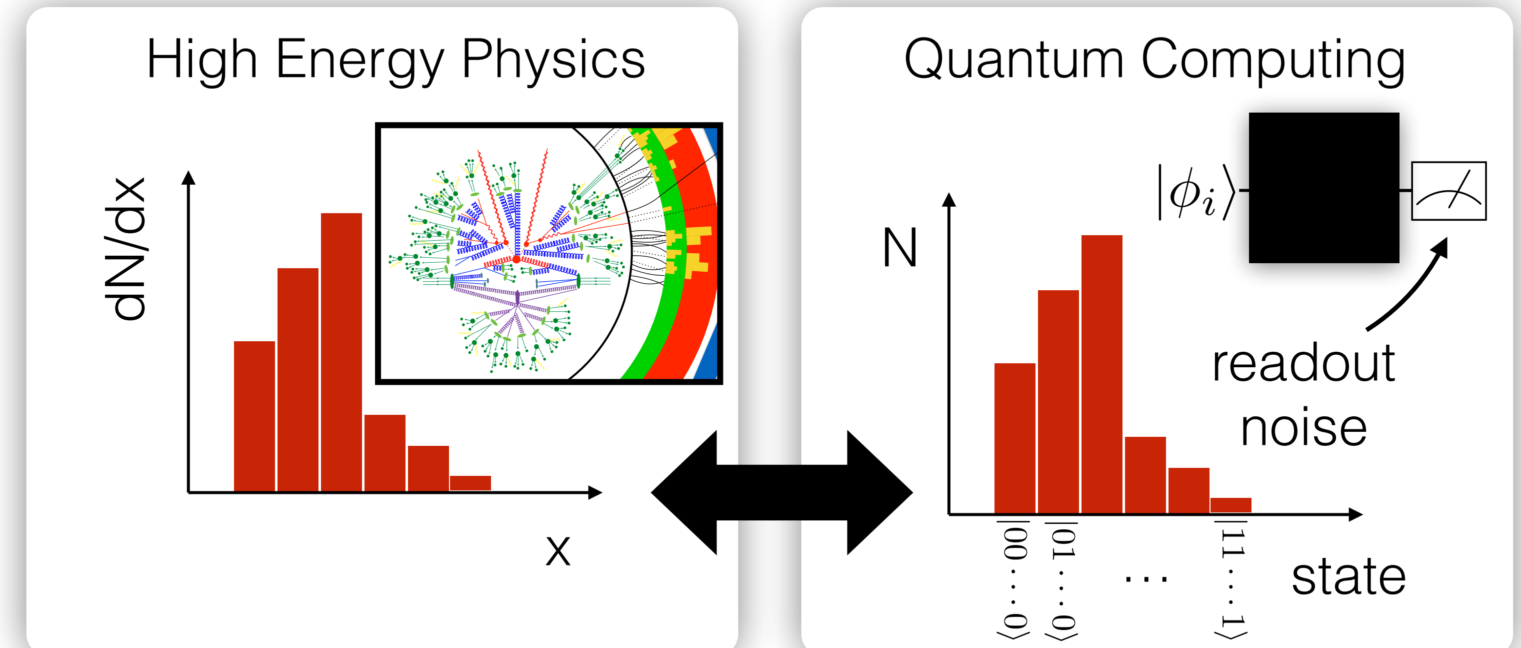
For n qubits, there is a $2^n \times 2^n$ transition matrix.

HEP has proposed many solutions to this problem!

…and we call them **unfolding**

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

Readout error corrections



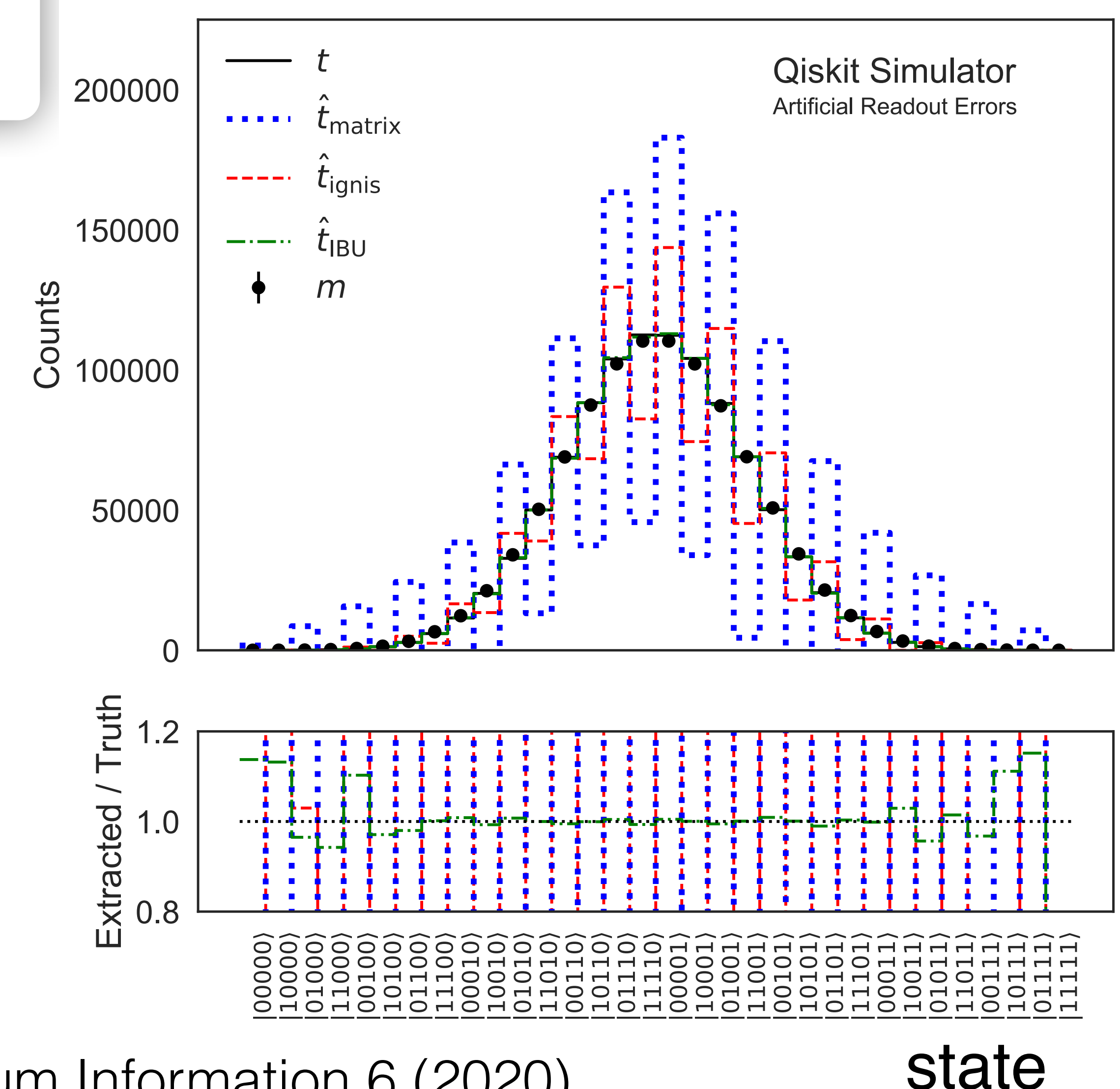
Naïve inversion

IBM standard

HEP standard

We have proposed to use HEP unfolding techniques to correct quantum computer readout errors.

→ Circumvent known pathologies with more naïve methods (!)

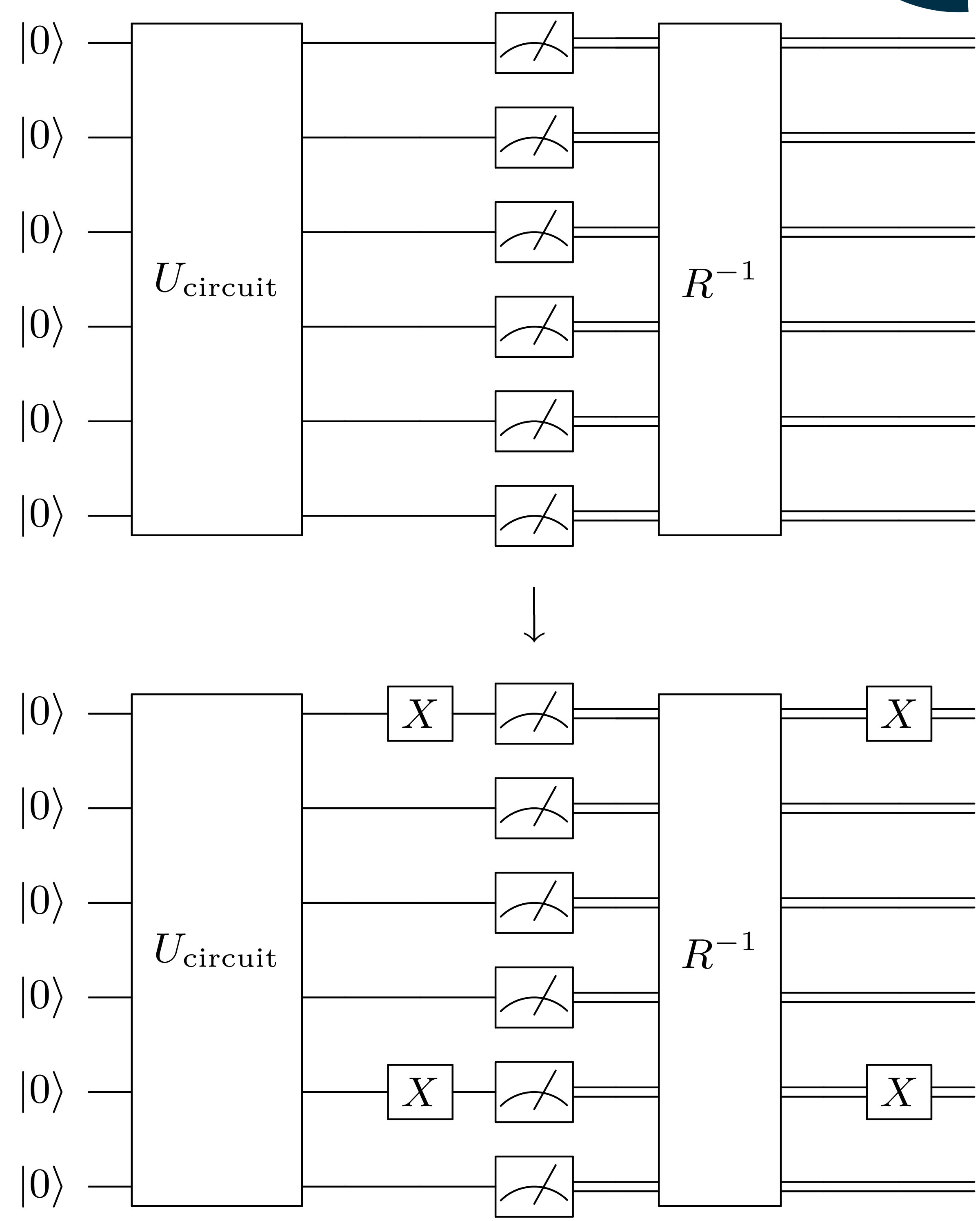


B. Nachman, M. Urbanek, W. de Jong, C. Bauer, npj Quantum Information 6 (2020)

More on readout errors

We are still actively developing methods to reduce readout errors.

For example, note that Pr(1 → 0) > Pr(0 → 1). One can apply a simple "**rebalancing**" in order to improve precision.



R. Hicks, C. Bauer, BPN, PRA 103 (2021) 022407

Even more on readout errors

In QFT simulations, we want to measure many observables simultaneously on a complex phase space.

…it is thus essential to apply measurement-by-measurement corrections. Matrix inversion is insufficient.

Even more on readout errors

In QFT simulations, we want to measure many observables simultaneously on a complex phase space.

…it is thus essential to apply measurement-by-measurement corrections. Matrix inversion is insufficient.

2108.12432 : **Hot off the press** - posted earlier this week!

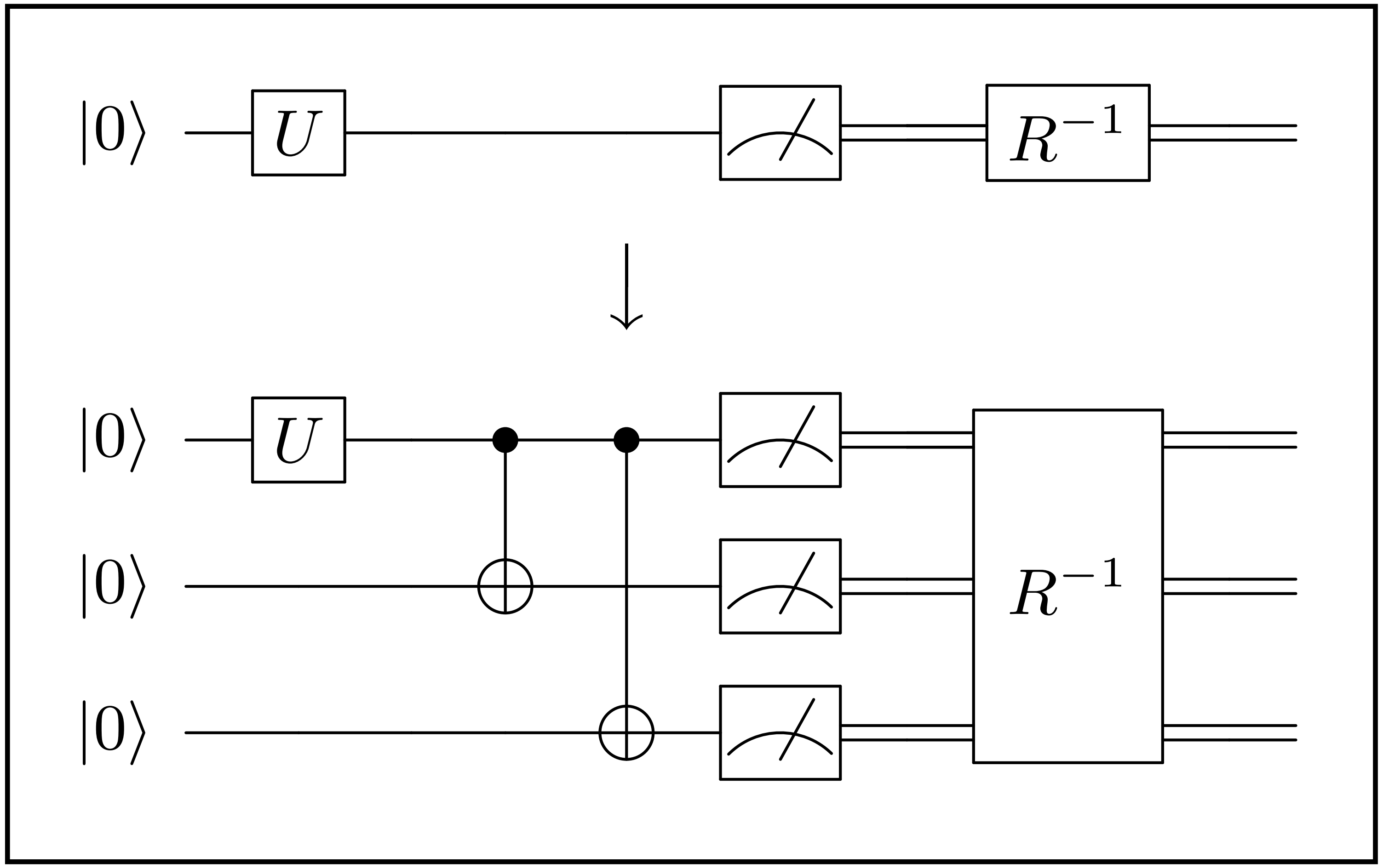
Active Readout Error Mitigation

Rebecca Hicks#,[1,*] Bryce Kobrin#,[1,†] Christian W. Bauer,[2,‡] and Benjamin Nachman[2,§]
[1] *Physics Department, University of California, Berkeley, Berkeley, CA 94720, USA*
[2] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
(Dated: September 1, 2021)

We have developed a new protocol for exactly this purpose!

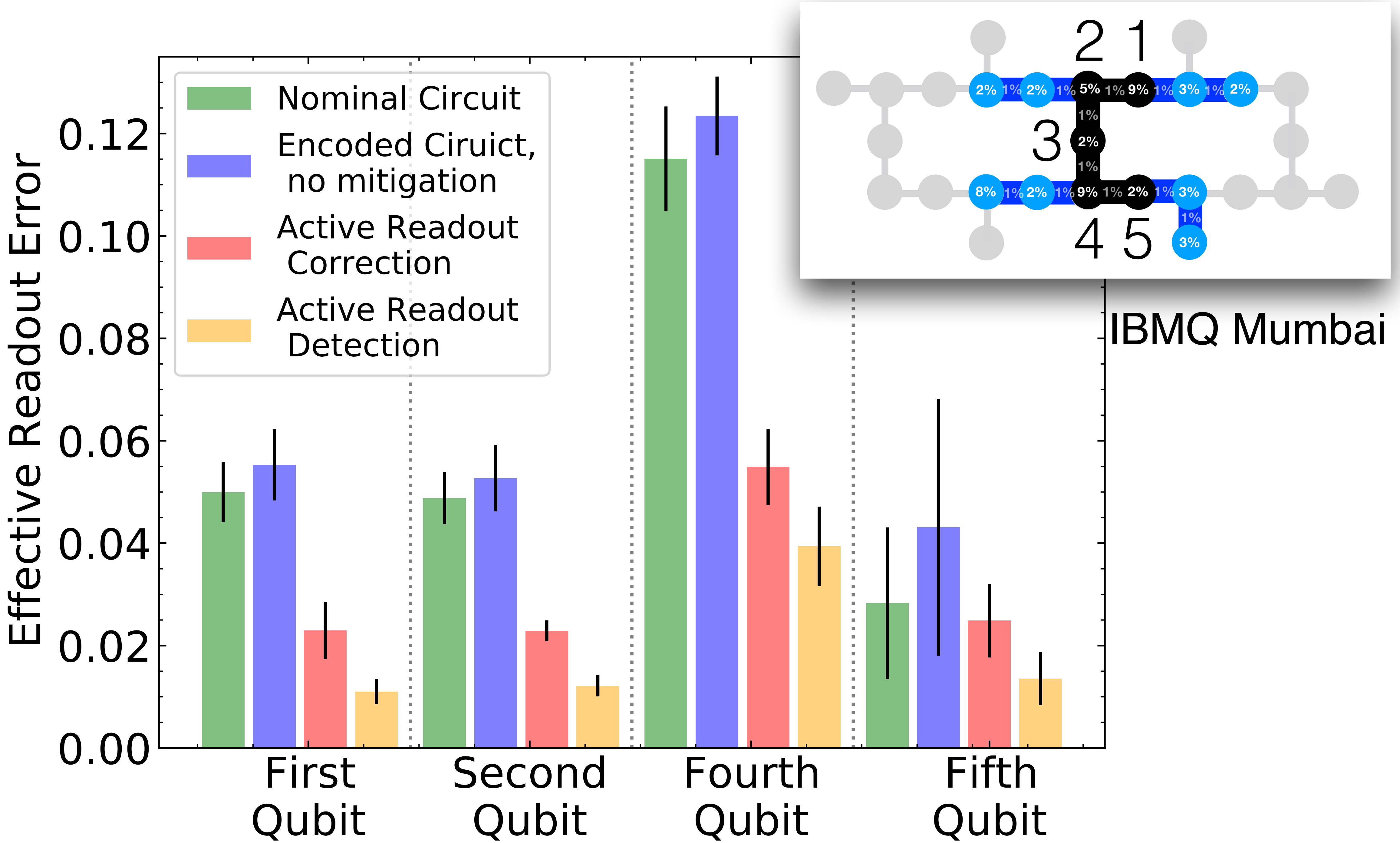
Active Readout Mitigation

When readout errors are larger than gate errors (as is often the case), we can trade one for the other



R. Hicks, B. Kobrin, C. Bauer, BPN, 2108.12432

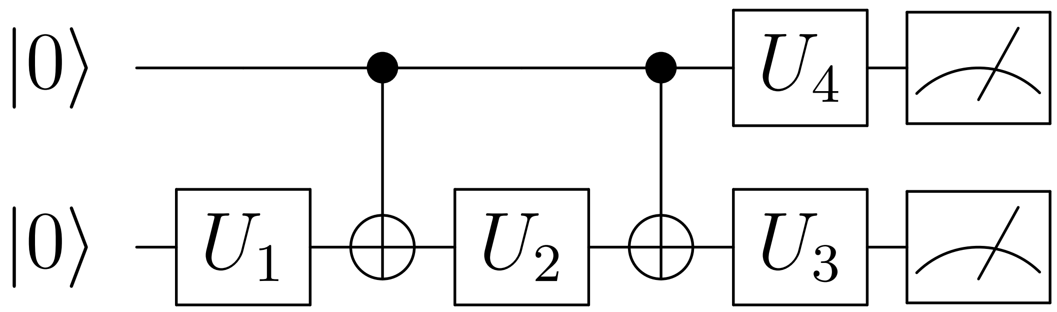
Active Readout Mitigation



IBMQ Mumbai

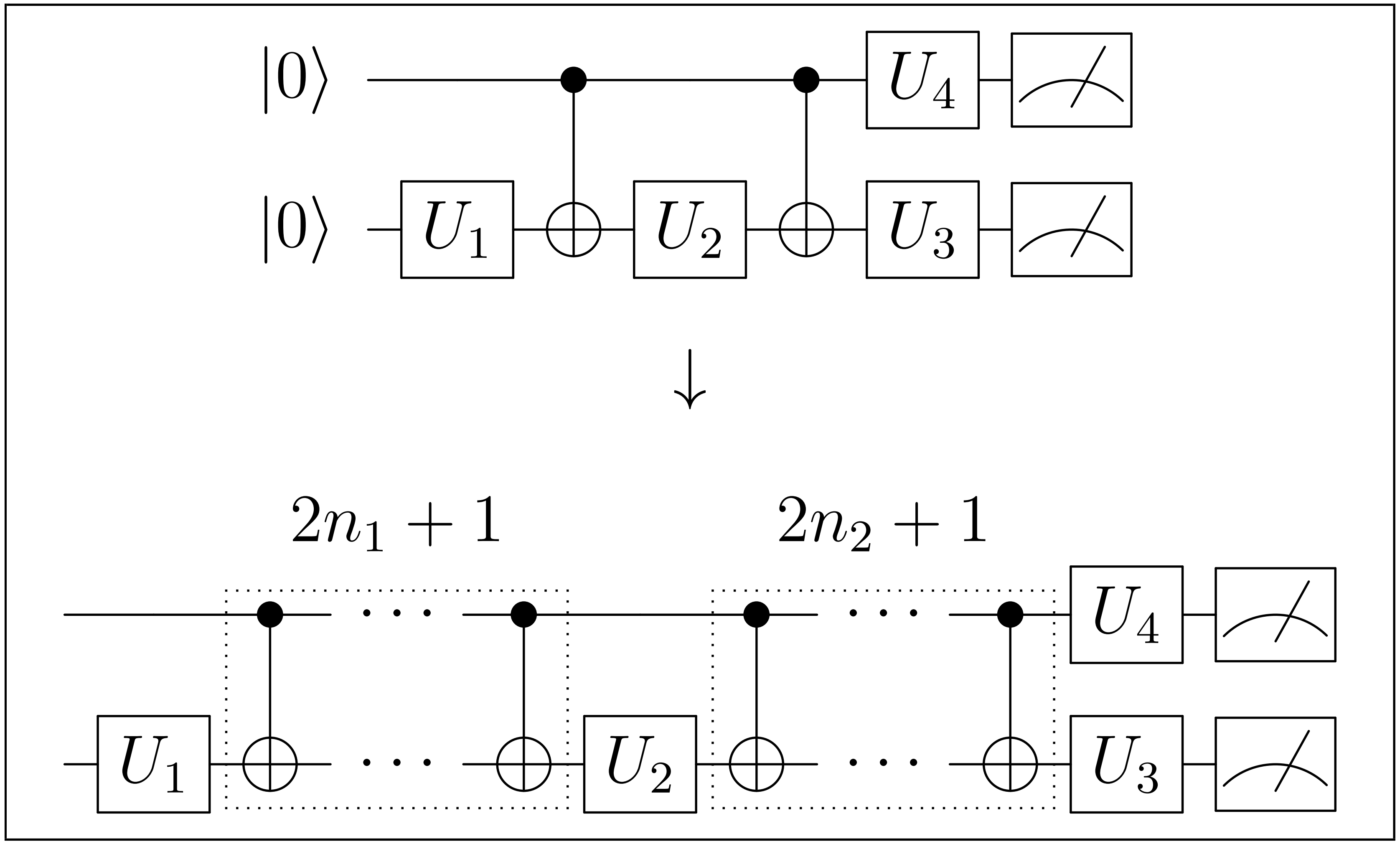
R. Hicks, B. Kobrin, C. Bauer, BPN, 2108.12432

Gate Errors



One common technique is **Zero Noise Extrapolation**

Gate Errors

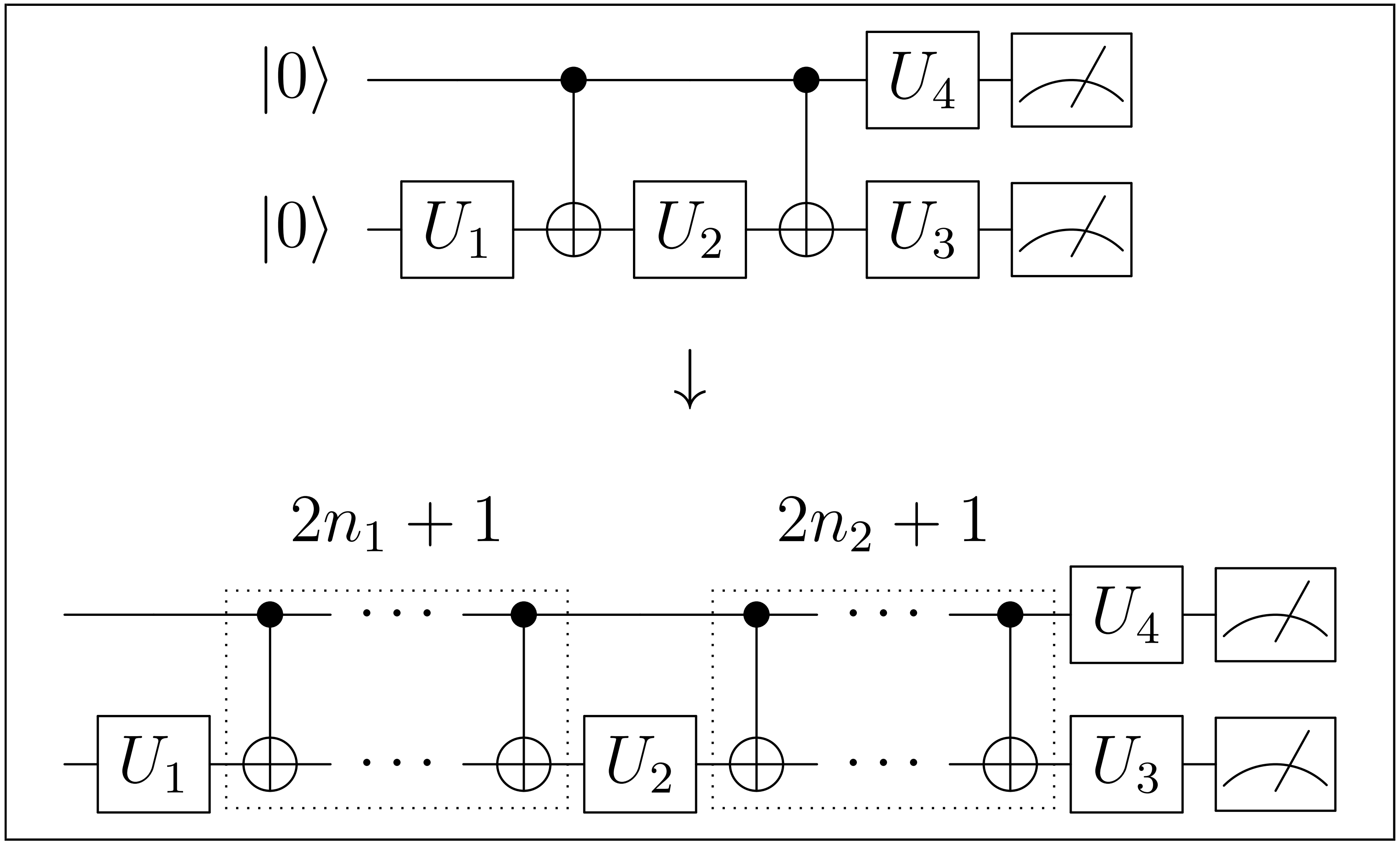


CNOT^2 = Identity

One common technique is **Zero Noise Extrapolation**

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.

Gate Errors



+ M. Urbanek, B. Nachman, V. Pascuzzi, A. He, C. W. Bauer, 2103.08591

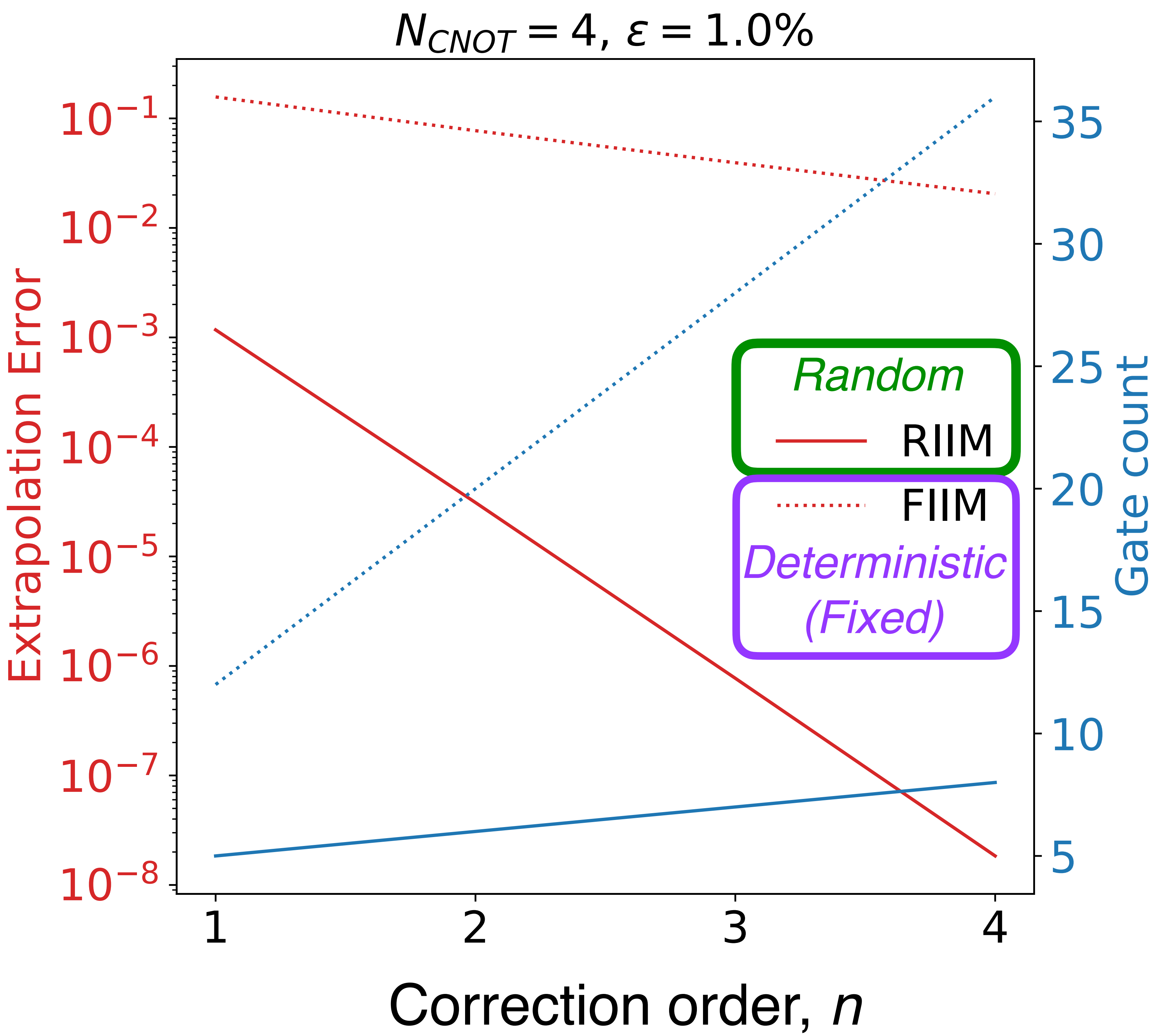
+ W. Jang, K. Terashi, M. Saito, C. W. Bauer, B. Nachman, Y. Iiyama, T. Kishimoto, R. Okubo, R. Sawada, J. Tanaka, 2102.10008

+ V. Pascuzzi, A. He, B. Nachman, C. W. Bauer, *in preparation*

We have explored a variety of methods that have different n_i per gate. When combined with other methods, this sets the state-of-the-art for moderately deep circuits.

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

Random Identity Insertion Method



One idea is to promote n_i to a random variable

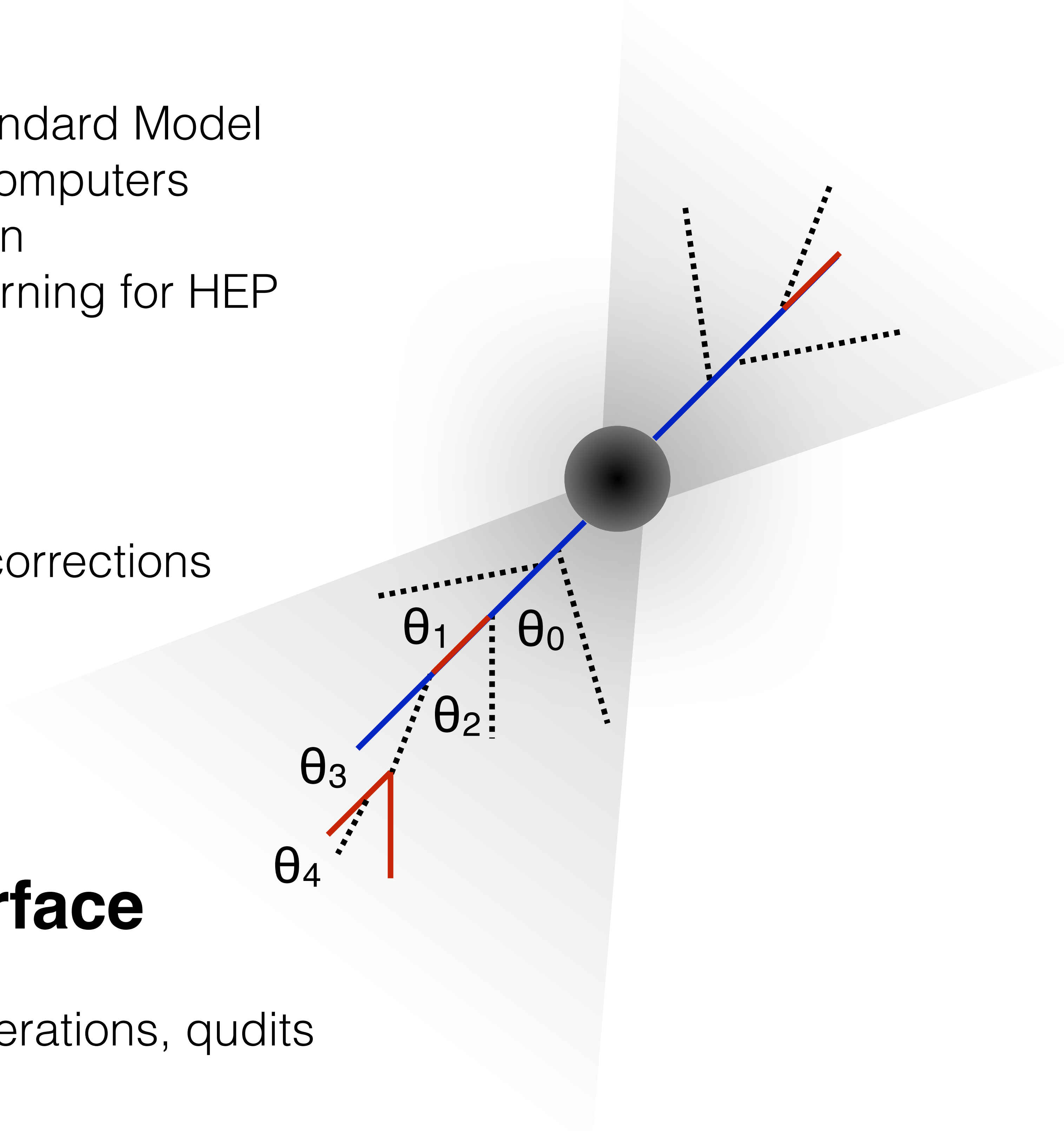
Circuit with N noisy gates: traditional method needs ***(n+1) x N*** additional gates

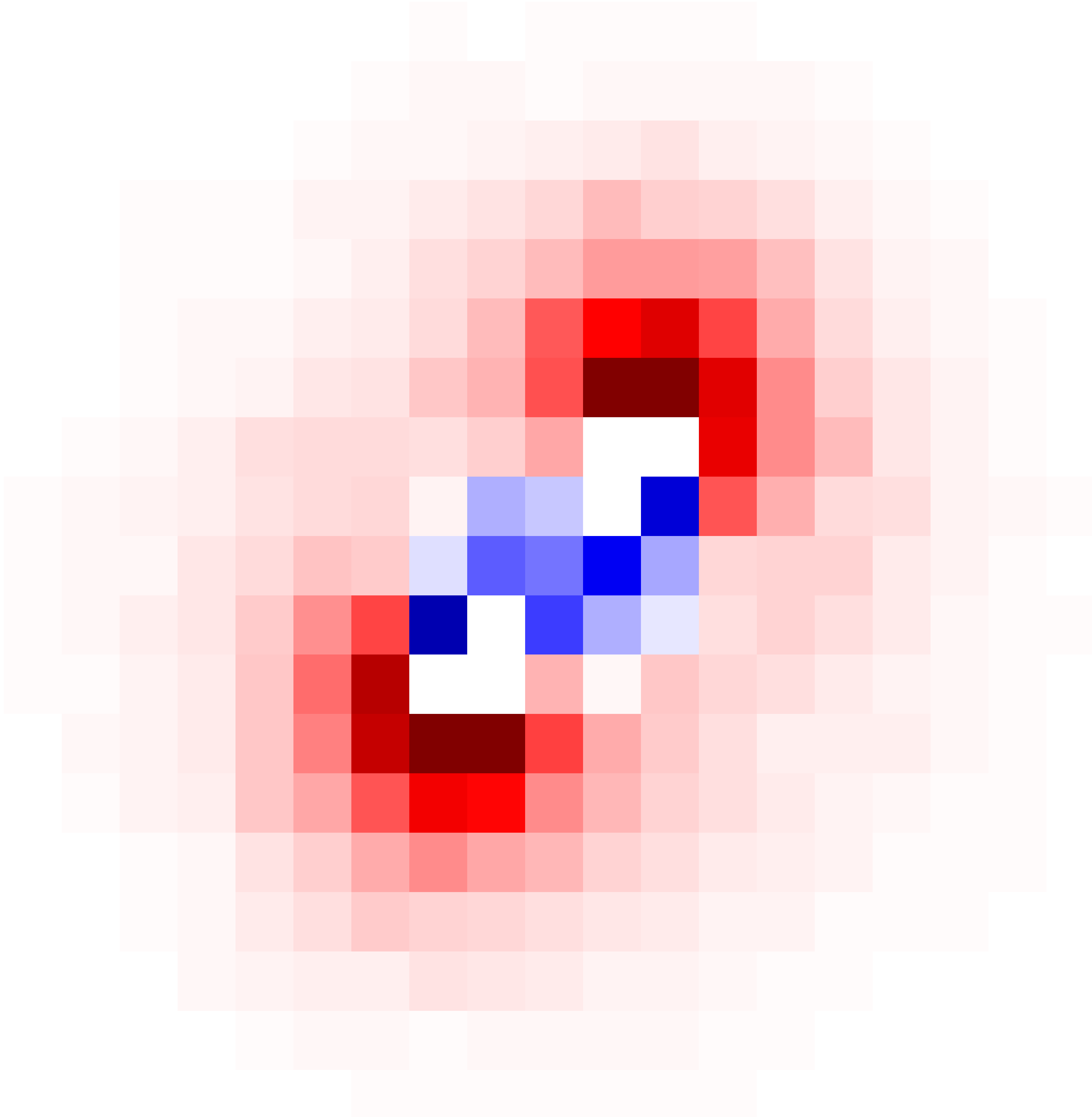
Random method only needs ***n+1*** additional gates (!)

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

Future

- **QFT**
  - Continue to push towards the Standard Model
    - Gauge theories on quantum computers
    - Multigaussian state preparation
  - Potential of quantum machine learning for HEP
- **Error Mitigation**
  - Readout errors
    - Combine active and passive corrections
  - Gate errors
    - Reduce circuit complexity
    - Robustness from symmetry?
- **Software-hardware interface**
  - Custom operations
    - Resetting qubits, repeated operations, qudits



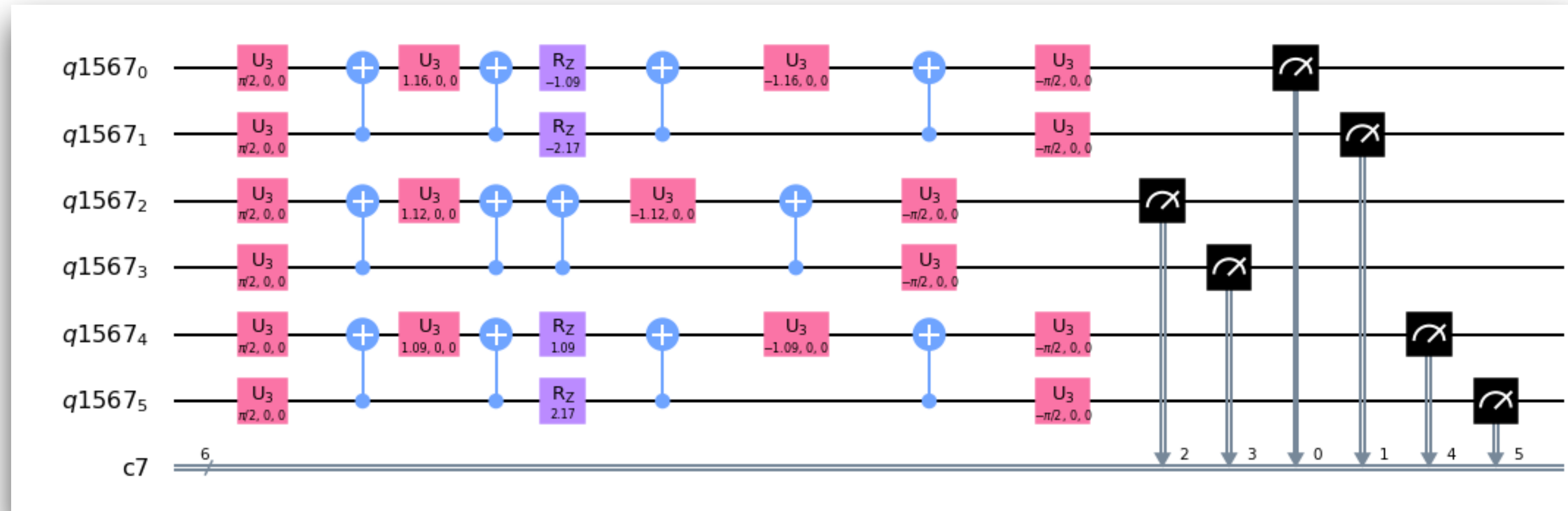


Fin.

C. Bauer, M. Freytsis, BPN, 2102.05044

Quantum Measurements: circuit

$U_3(\theta,0,0) = RY(\theta)$



(actually, it turns out we can eliminate all of the CNOTs on the middle two qubits)