Modeling final state radiation on a quantum computer

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AIDE|QC

UW EPE Seminar
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ATLAS EXPERIMENT

QuantISED HEP initiative

U.S. DEPARTMENT OF ENERGY

BERKELEY LAB

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Overview

> *I therefore believe it's true that with a suitable class of quantum machines you could imitate any quantum system, including the physical world.* - Feynman

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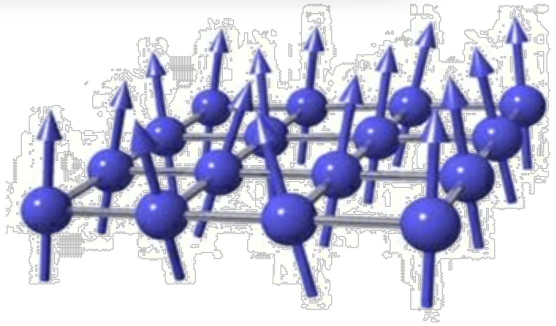

~ Outline ~

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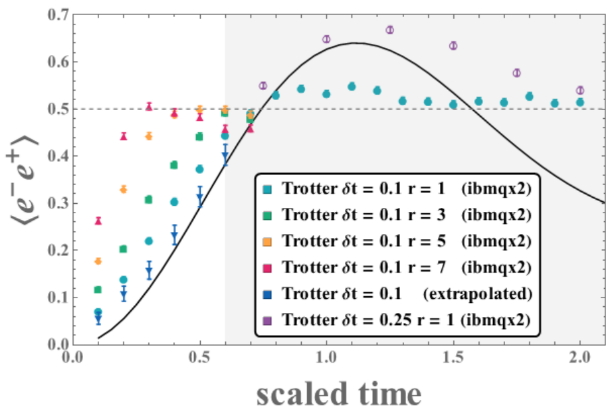

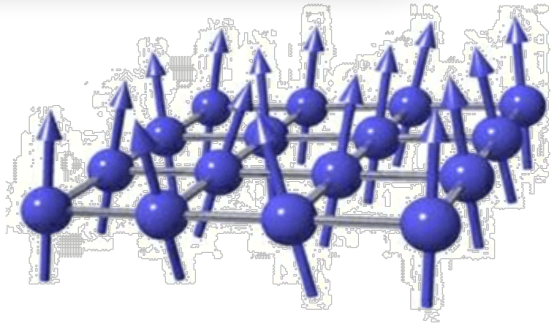

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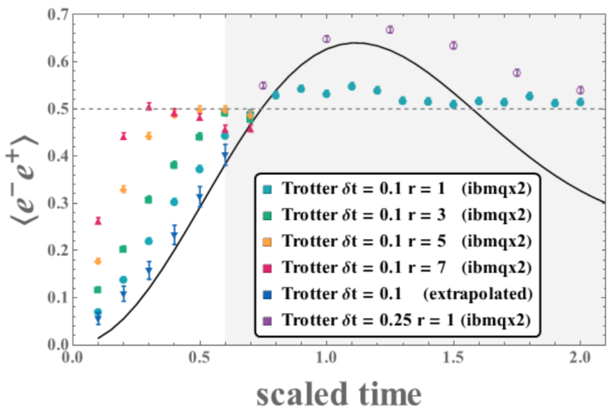

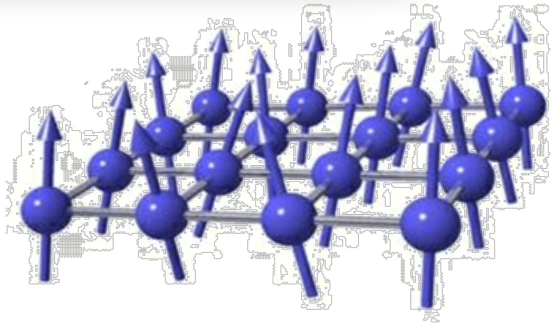

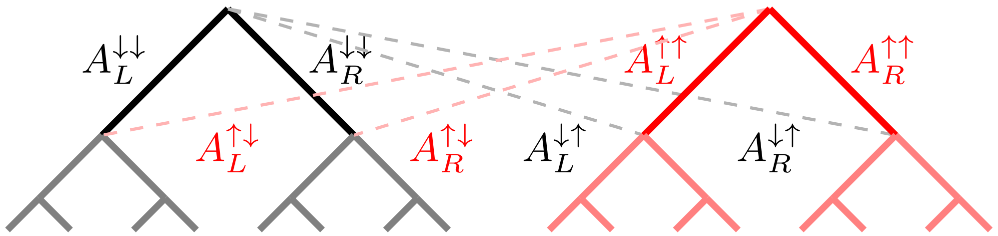

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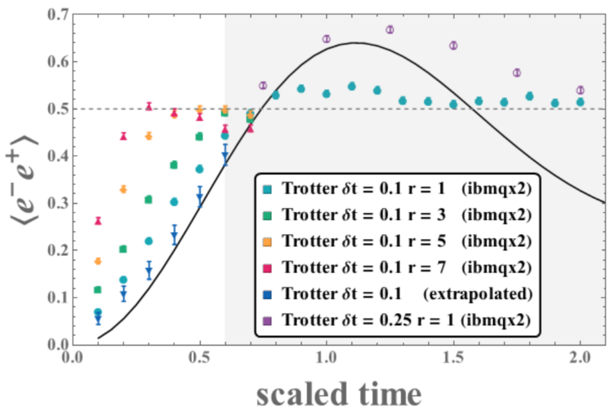

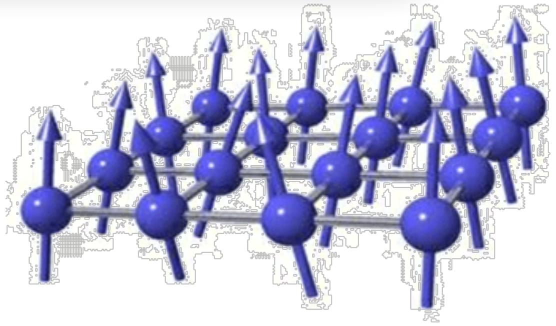

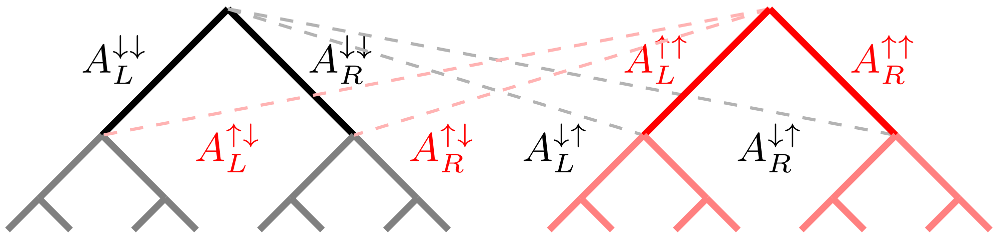

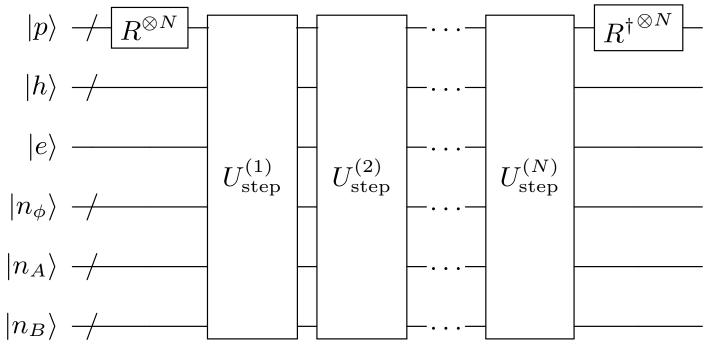

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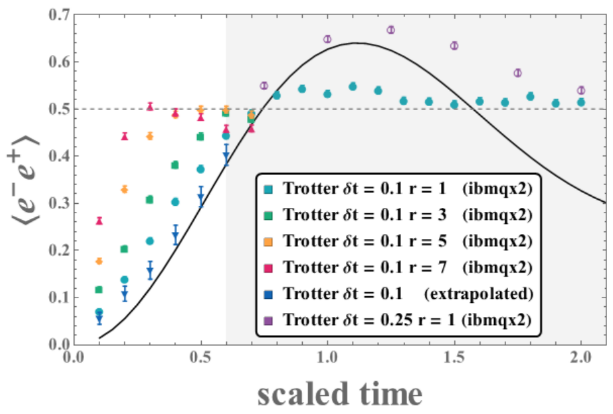

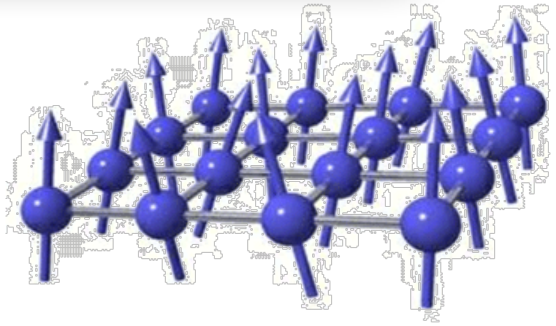

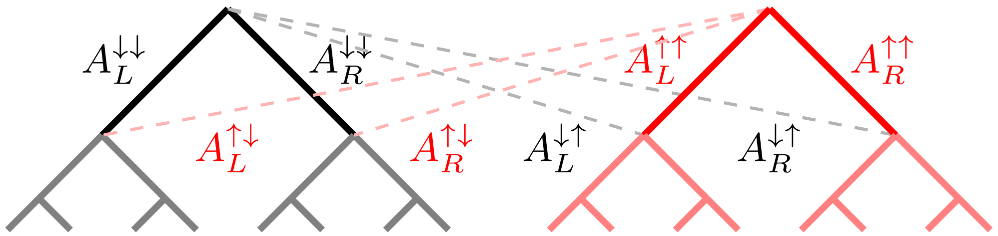

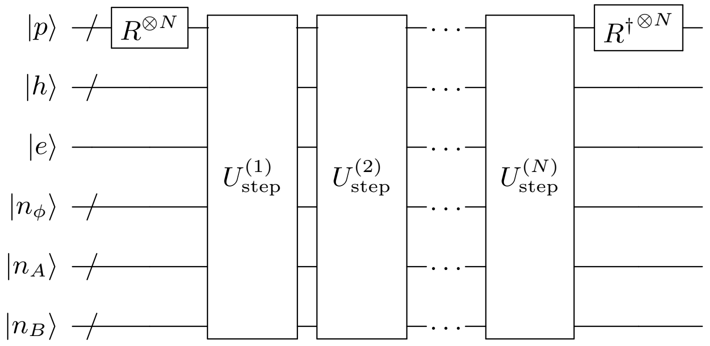

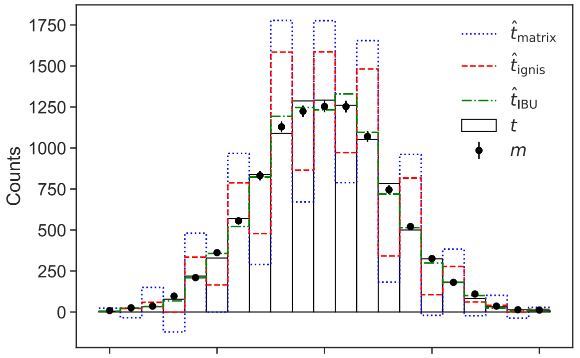

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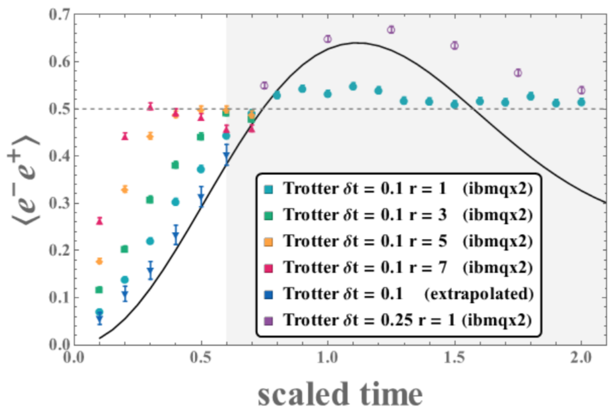
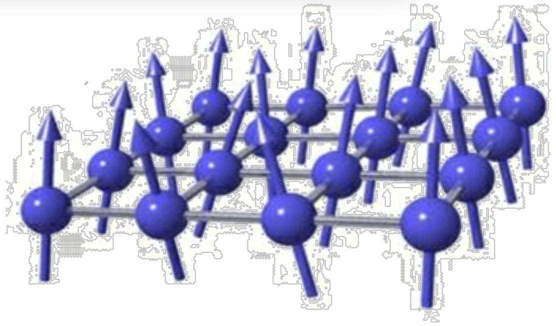
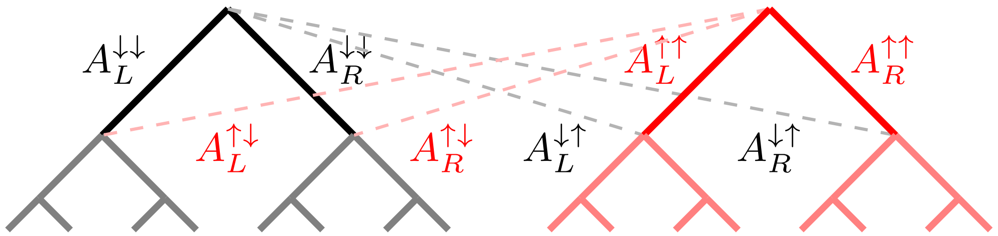
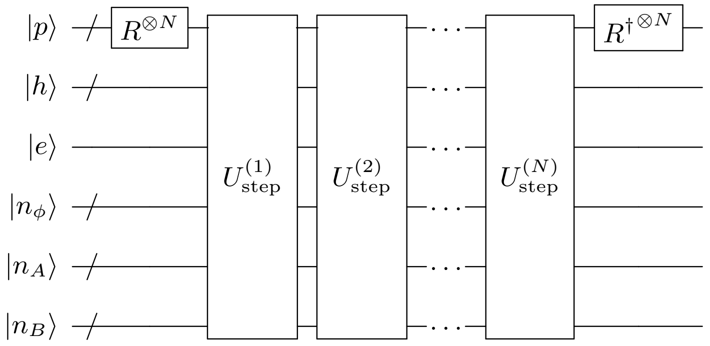
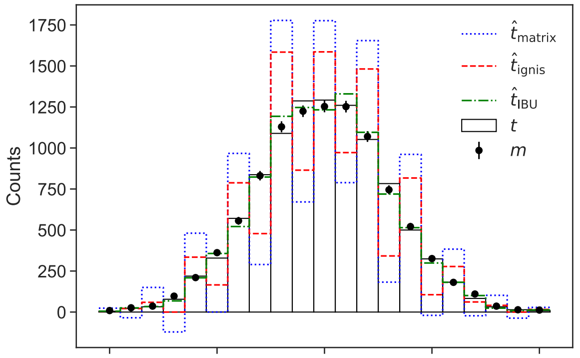
- Quantum machines (“quantum computers”)
- Quantum modeling in HEP
- A toy model
- A simple, but real model
- Mitigating of noise
- The future









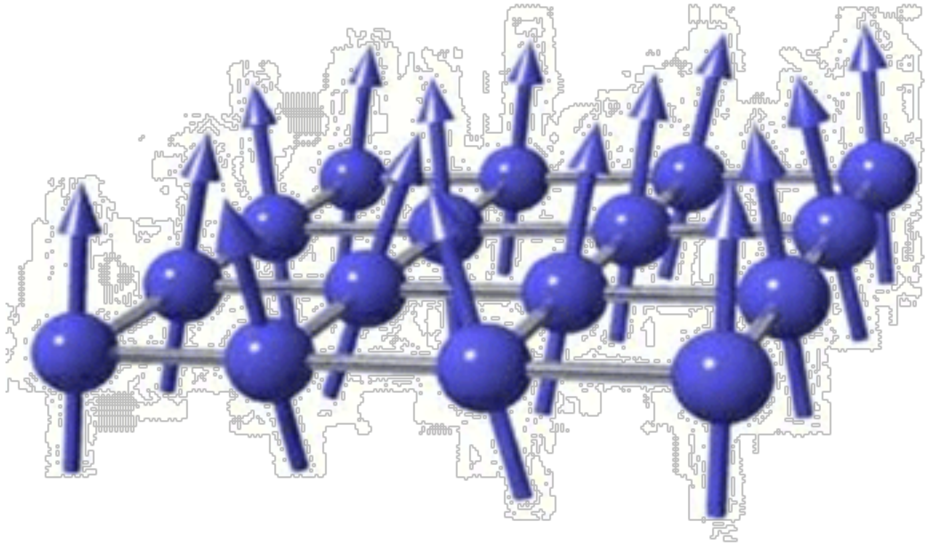


Quantum computers

Goal: implement our system's Hamiltonian (e.g. the SM) in a proxy system ("quantum computer") and let it evolve.

What can be a proxy system?

…any quantum system, like
a collection of spins.



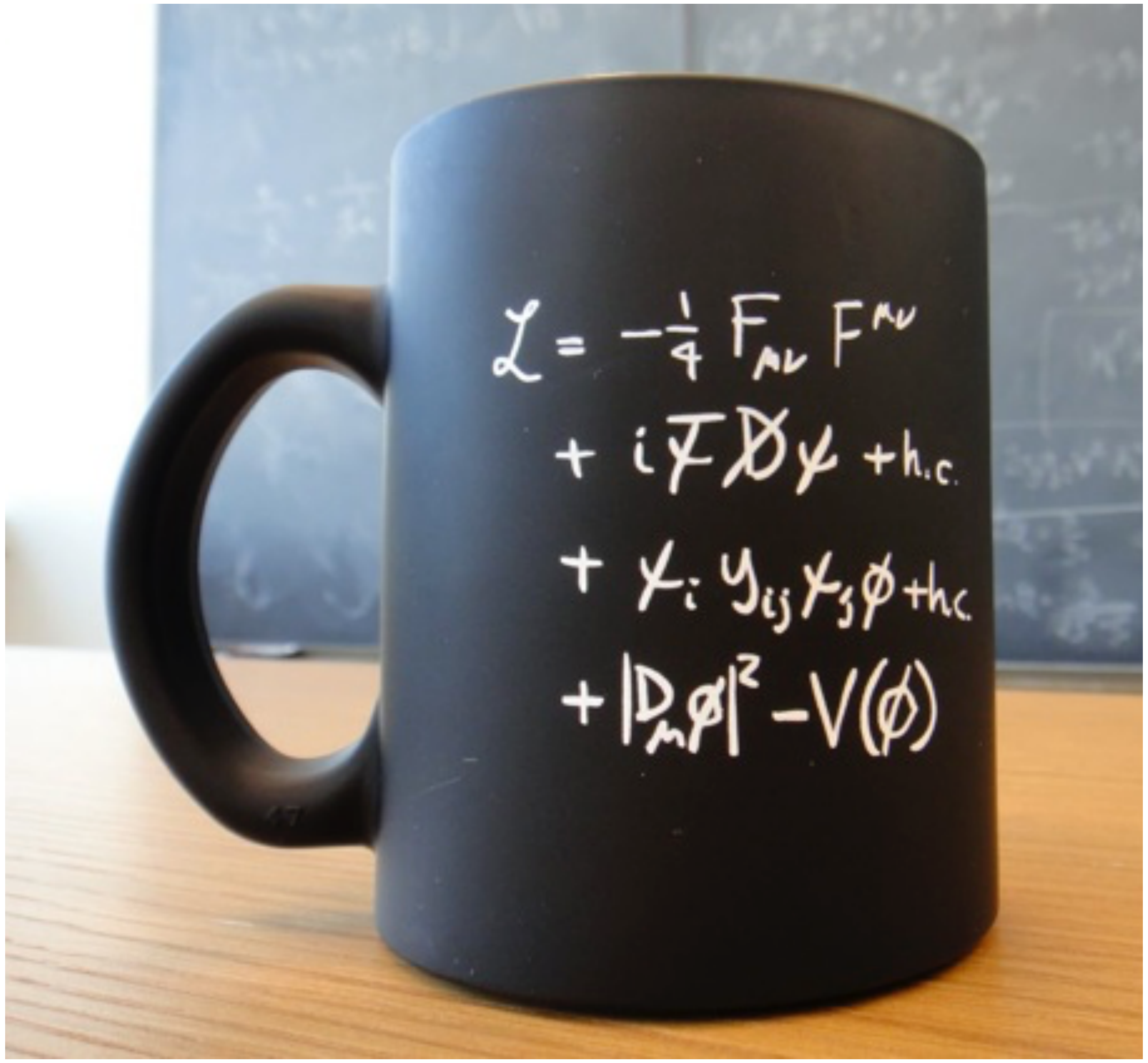


Image credit: Flip Tanedo

Analog versus Digital Quantum Circuits

Goal: implement our system’s Hamiltonian (e.g. the SM) in a proxy system (“quantum computer”) and let it evolve.

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

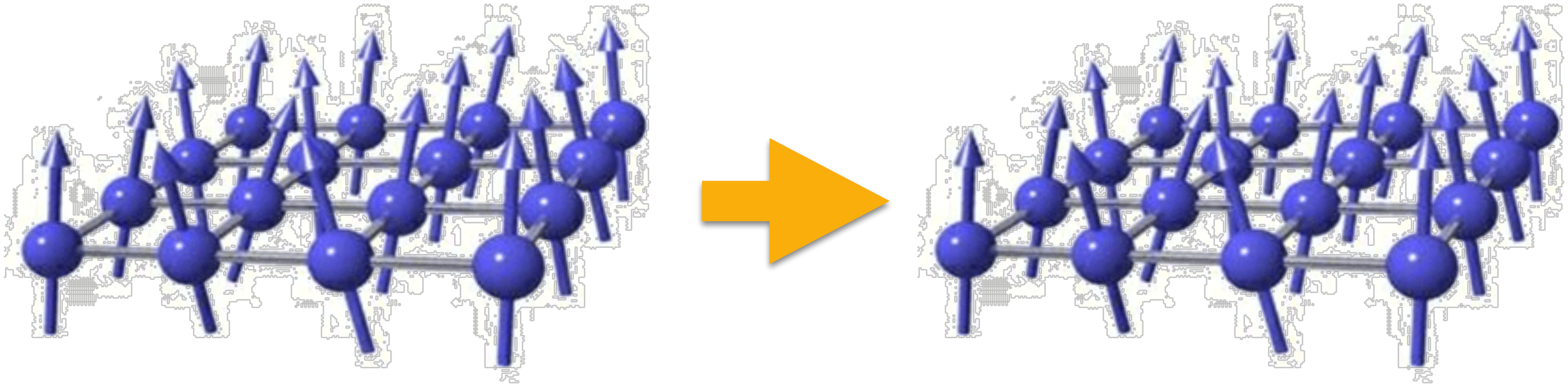


Image credit: https://www3.physik.uni-stuttgart.de/TR21/en/about/research.php

Analog versus Digital Quantum Circuits

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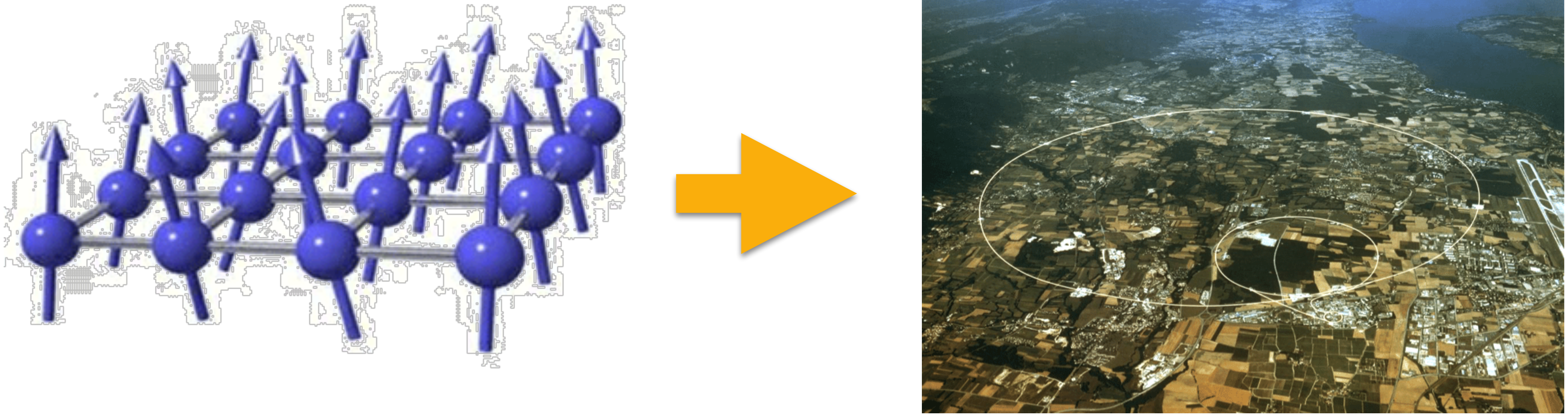
Not always possible!

Image credit: CERN

Analog versus **Digital** Quantum Circuits

Goal: implement our system's Hamiltonian (e.g. the SM) in a proxy system ("quantum computer") and let it evolve.

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



Modern Universal Quantum Computers

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

I’m not going to talk about hardware,
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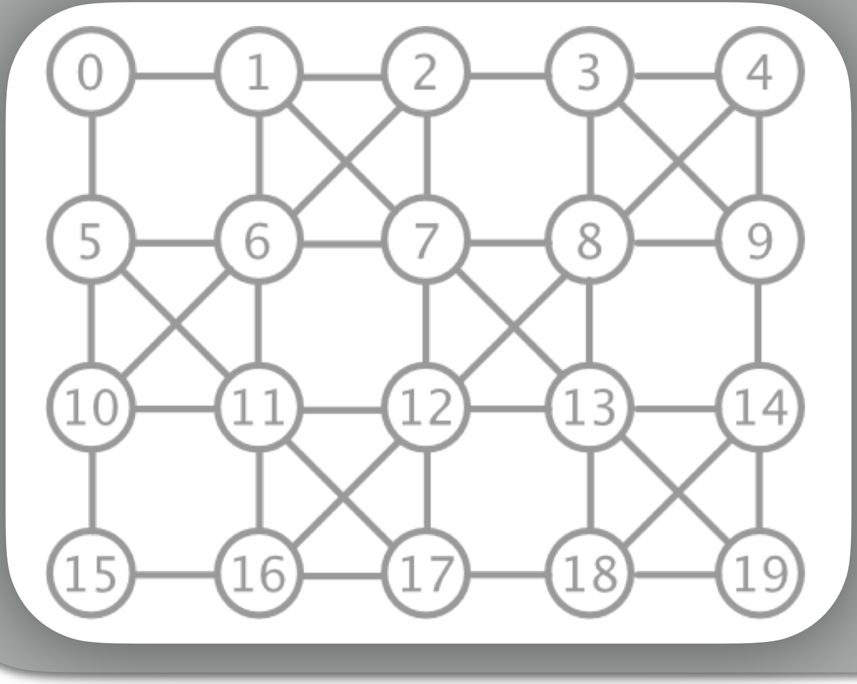
classical computing in the 1960's

quantum computing now

State-of-the-art quantum computers

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.

Programming

Just like a classical computer, one can write programs for a universal quantum computer.

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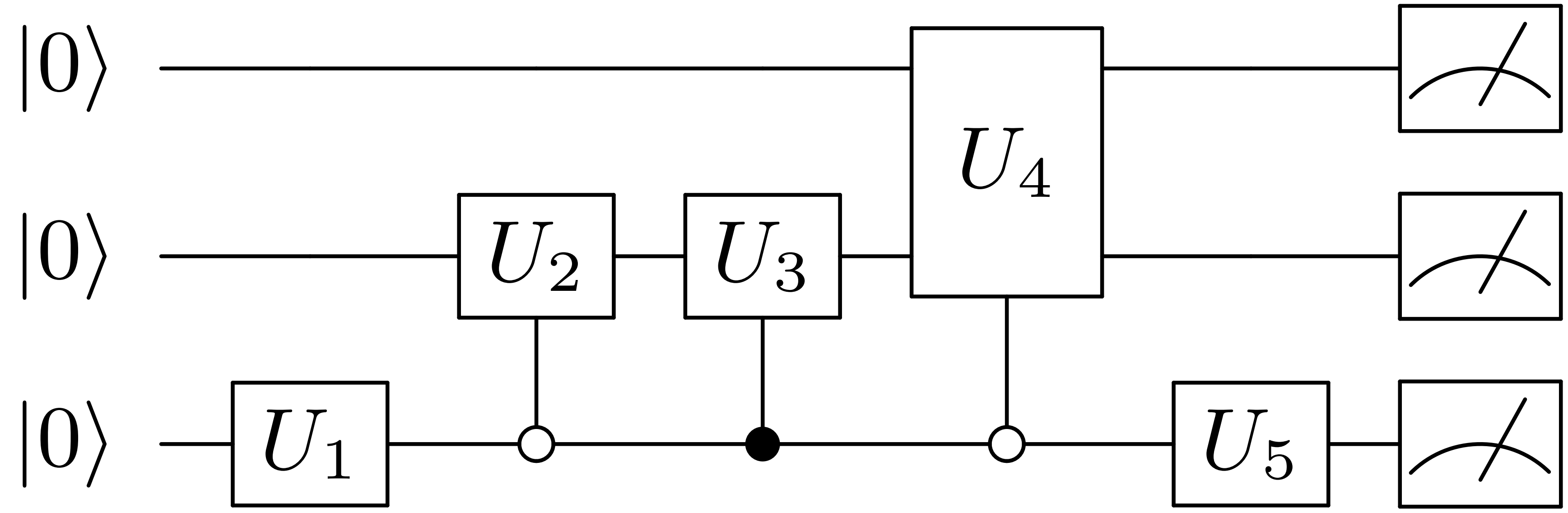

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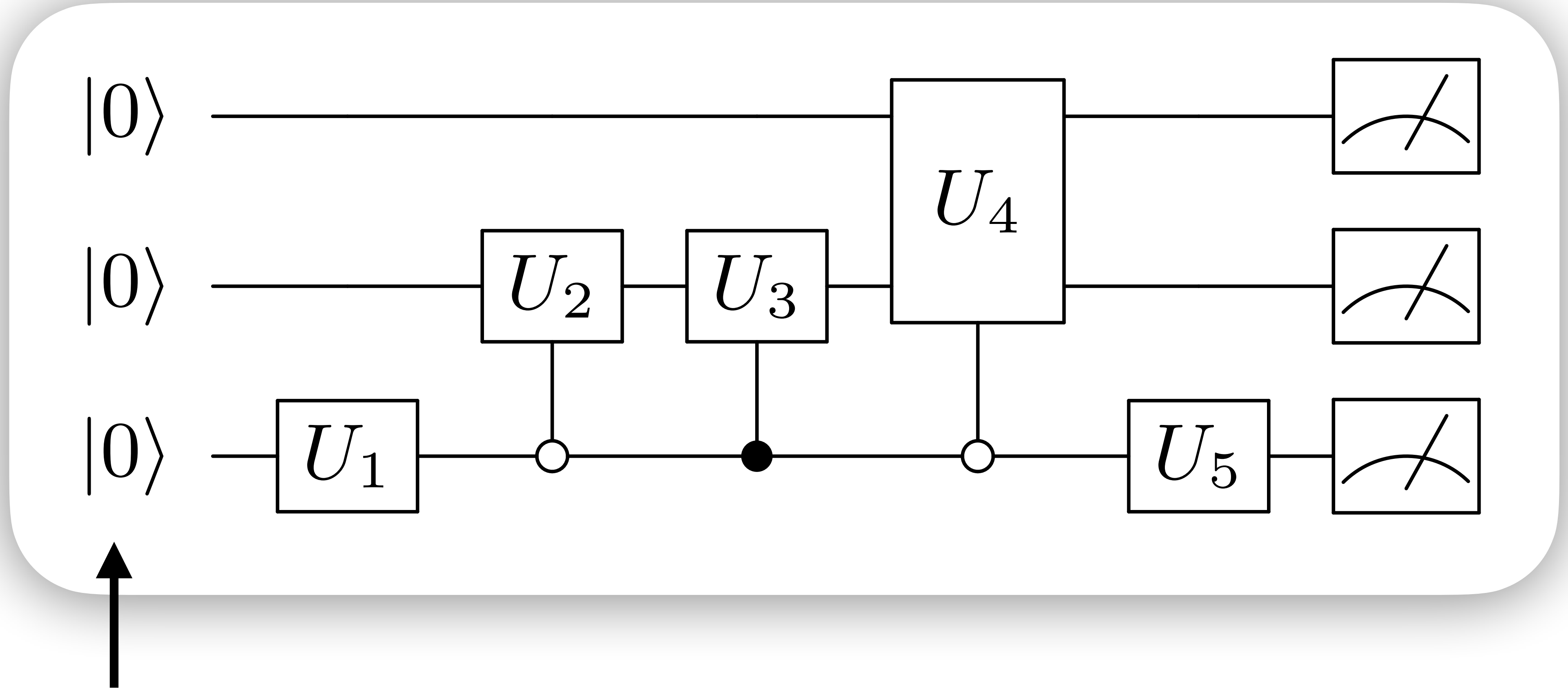

Initialize in the ground state.

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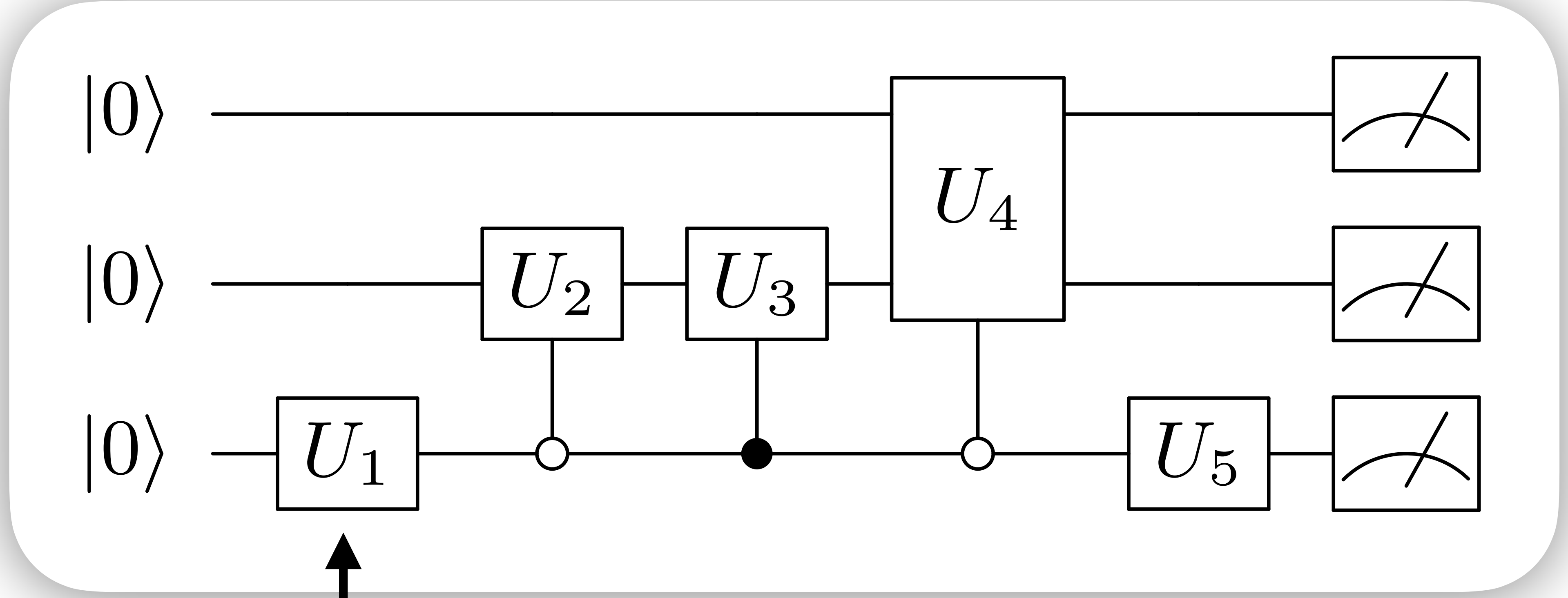
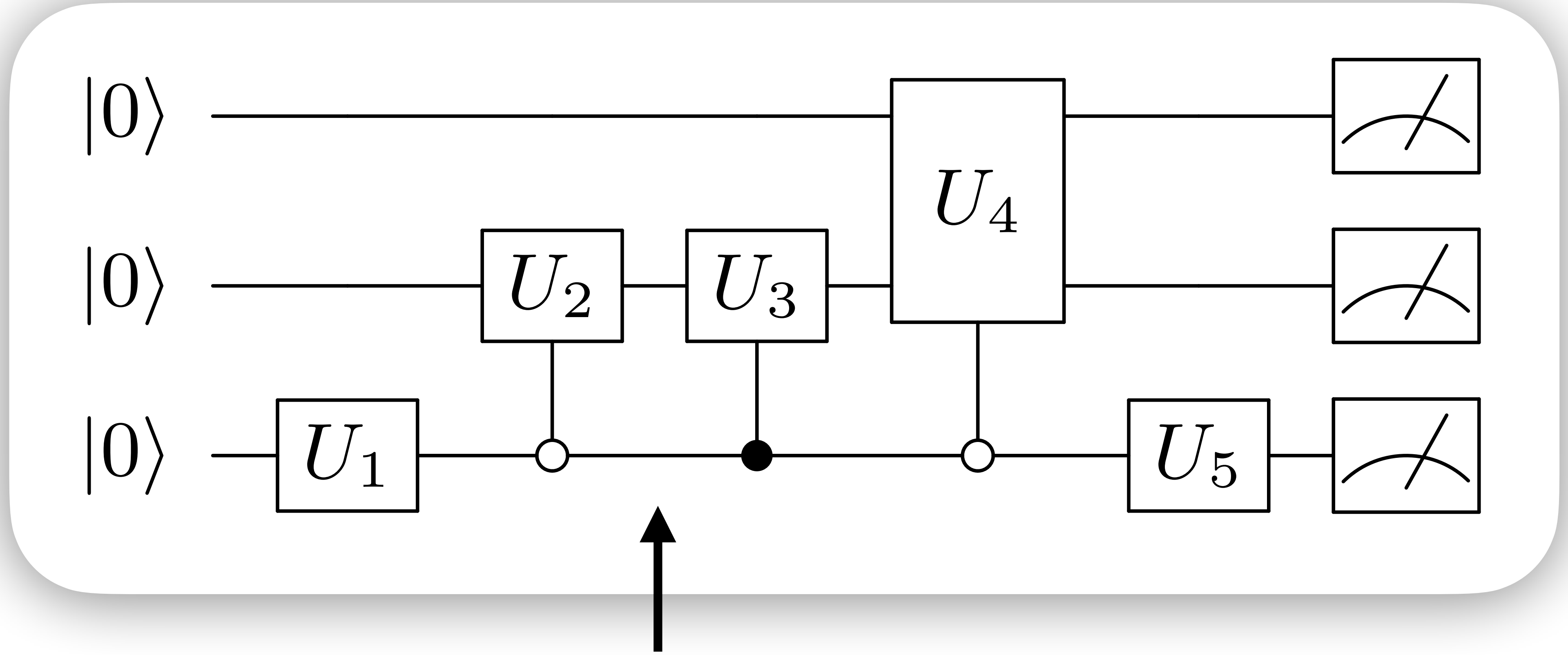
Just like a classical computer, one can write programs for a universal quantum computer.



Apply unitary matrix
U_1 to the third qubit

Programming

Just like a classical computer, one can write programs for a universal quantum computer.



Apply unitary matrix U_2 to the second qubit when the third is 0, else apply U_3.

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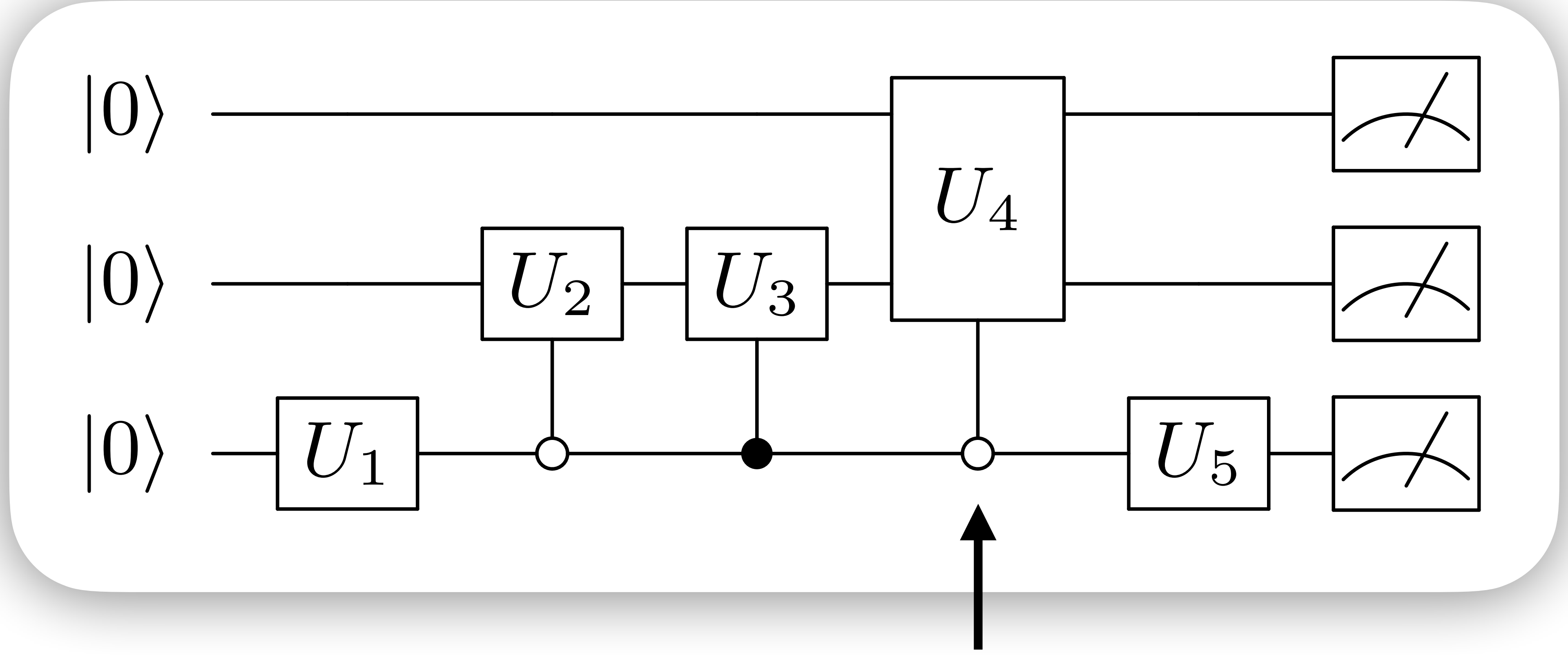

Apply unitary matrix U_4 to both the first and second quits when the third is 0.

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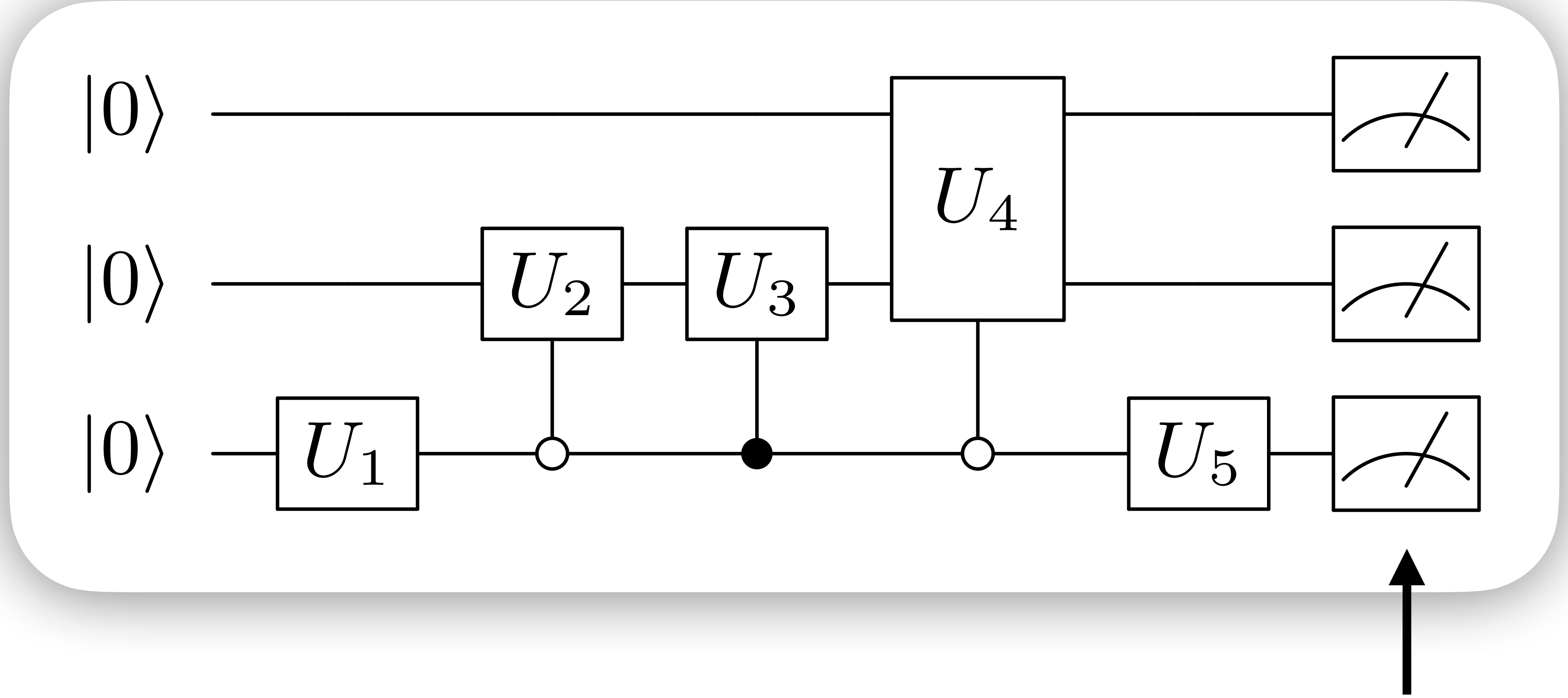
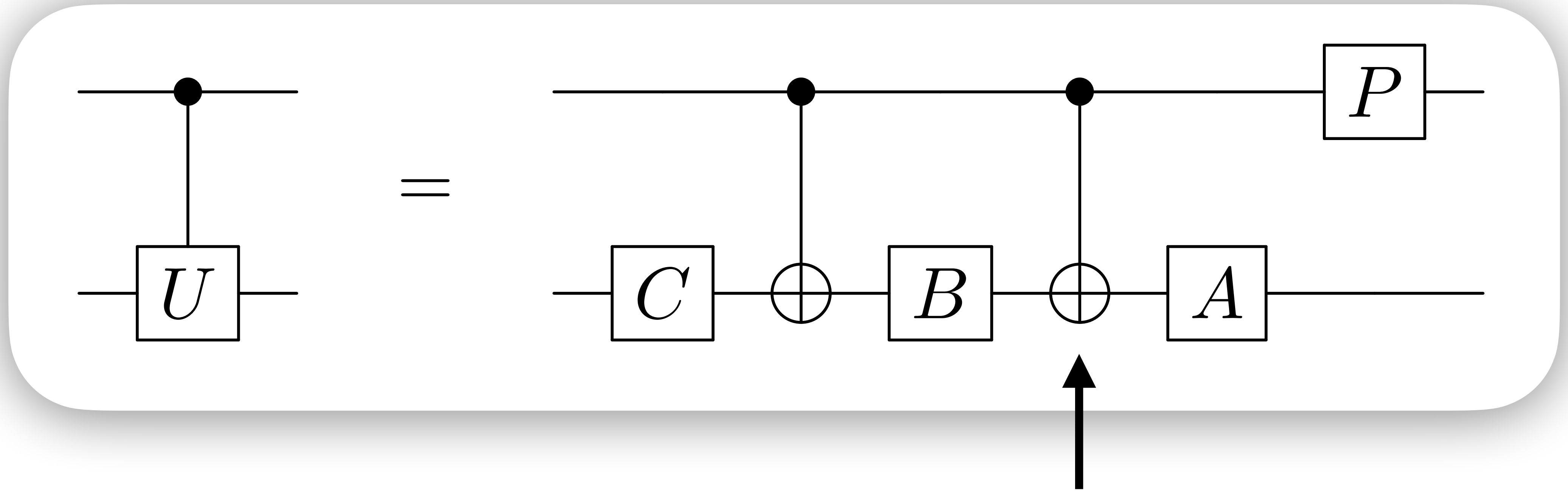


Measure all the qubits

Challenges with current computers

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



CNOT “controlled not”

There is no compiler … need to do circuit decomposition by hand (!)

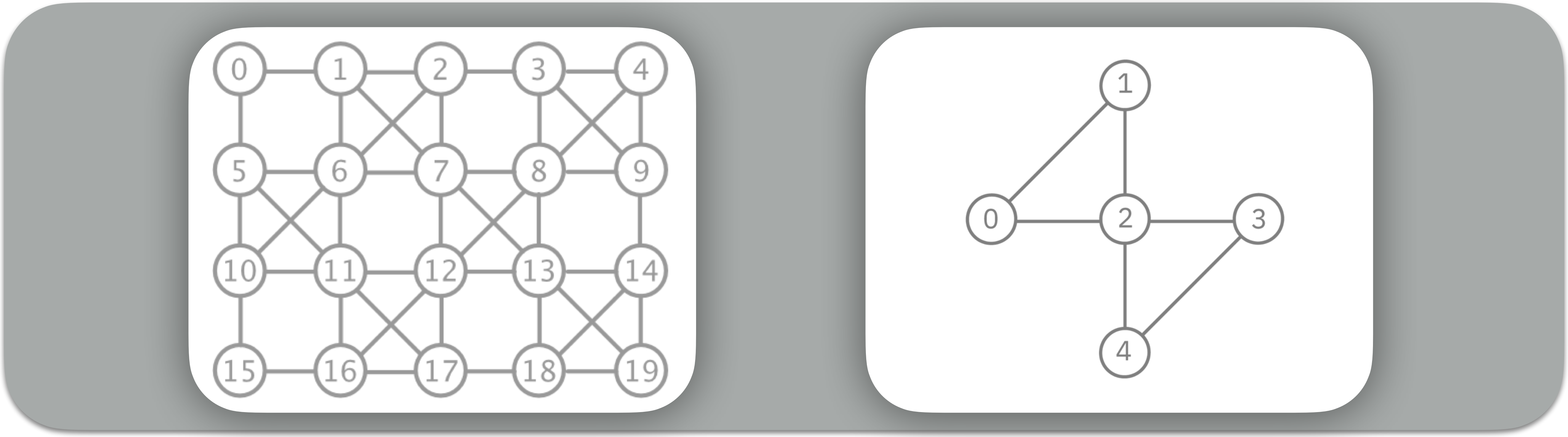
*Some computers are starting to have other basic operations, like the SWAP.

Challenges with current computers

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!)



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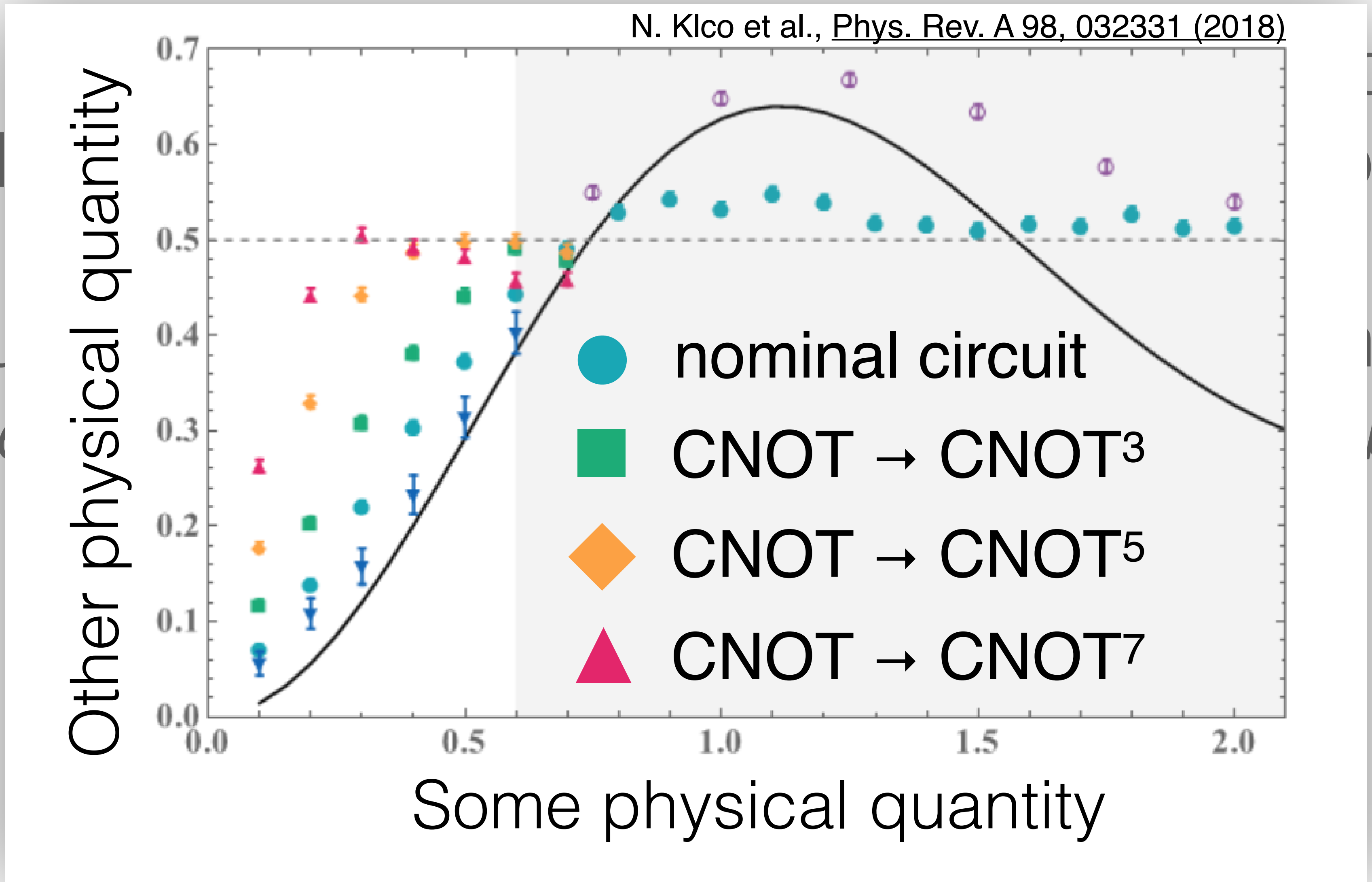
N. Klco et al., Phys. Rev. A 98, 032331 (2018)

N.B. CNOT^2
= identity

Most importantly: current quantum computers are **super noisy**. Need to minimize number of operations.

Potential of quantum computers

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 (!)

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Now on to QFT!

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Quantum Field Theory

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

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

Two traditional approaches:

Lattice

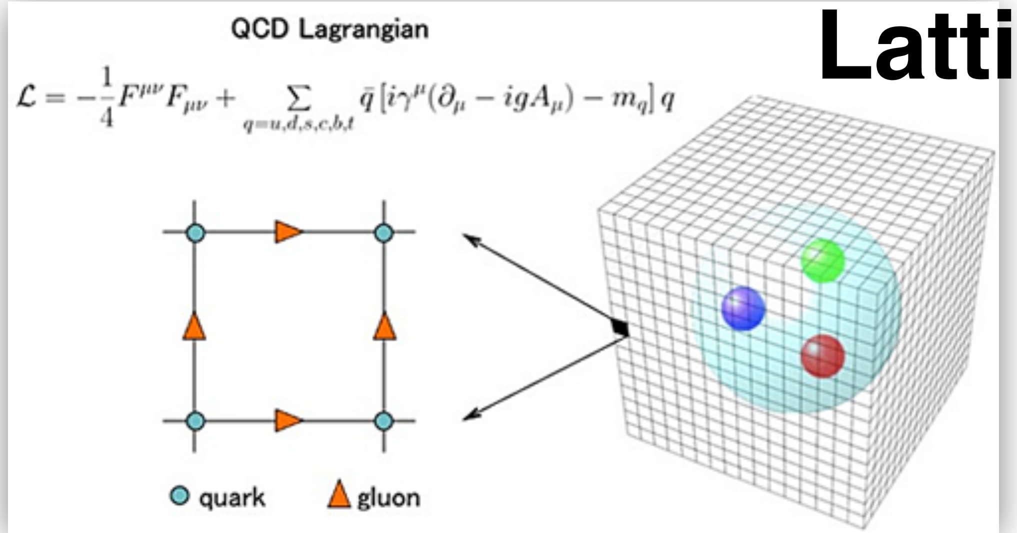


Image credit: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

Perturbation theory

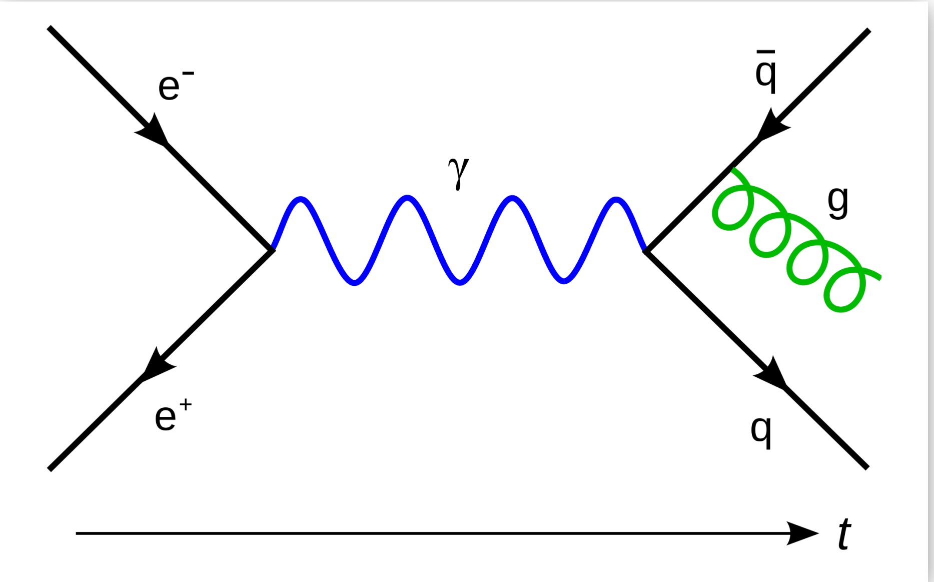


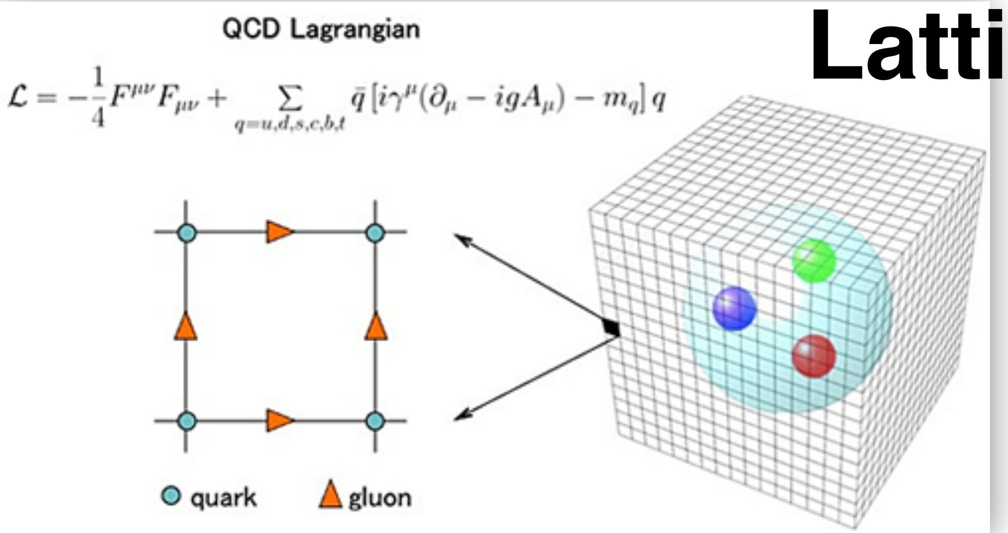
Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

Quantum Field Theory

Pro: Full theory

Con: Dynamics are too hard

(already using super computers)



Lattice

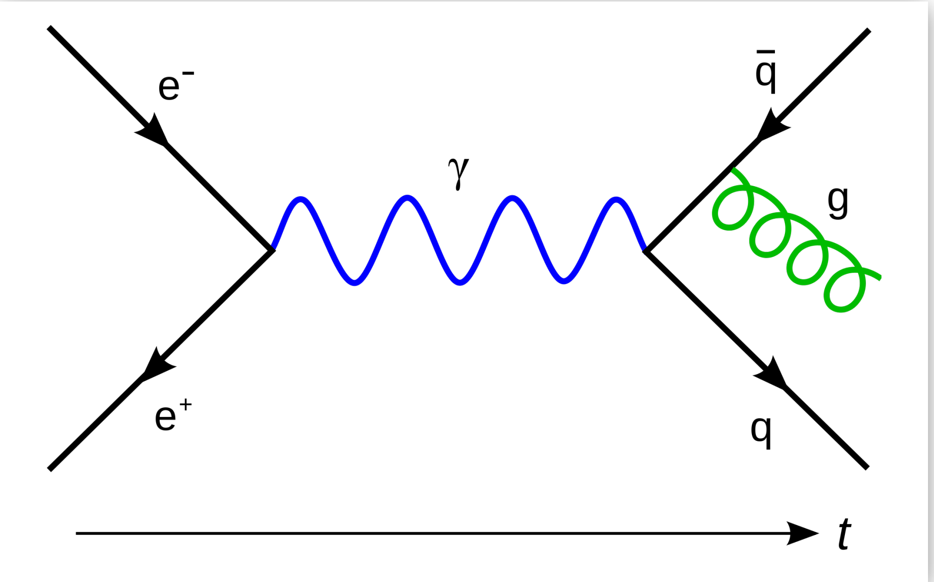
Image credit: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

Pro: Can do high-energy dynamics

Con: An approximation

…and combinatorially many diagrams

Perturbation theory



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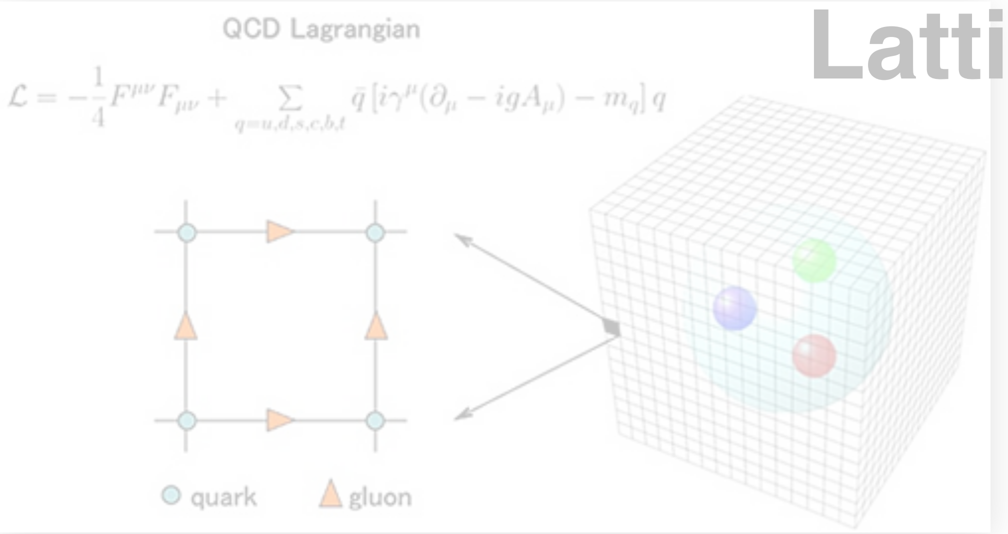

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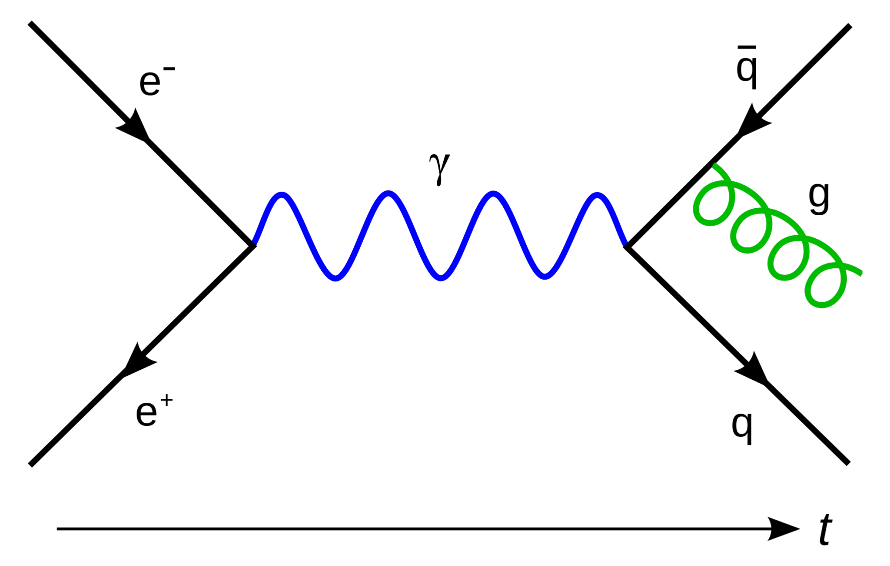

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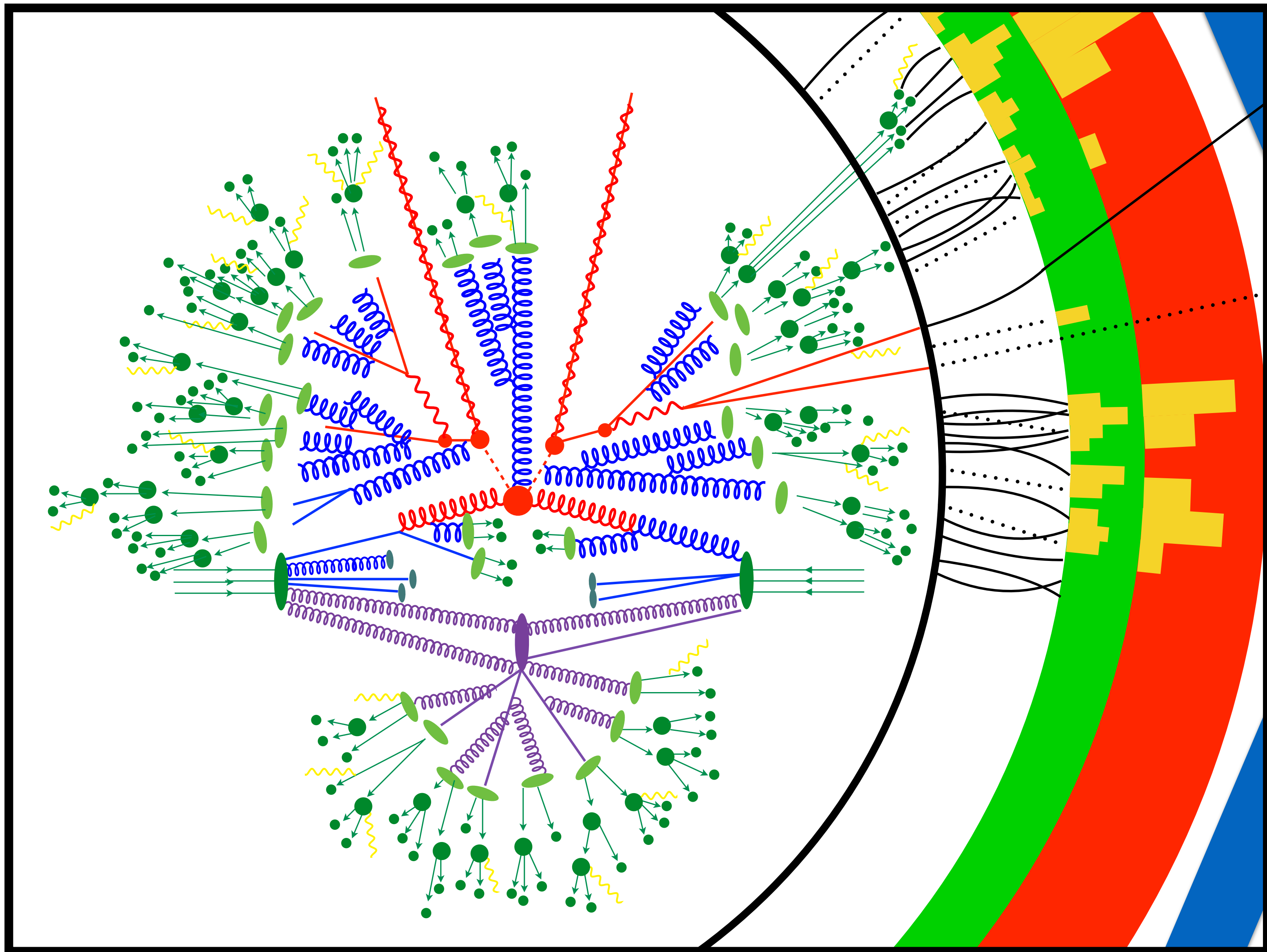
“Quantum effects” in high energy scattering

Let me take a step back and describe where we are in modeling inference & entanglement for high energy scattering experiments.

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

…only possible because of the Markov Property: physics at different scales **factorizes**

Image inspired by JHEP 02 (2009) 007



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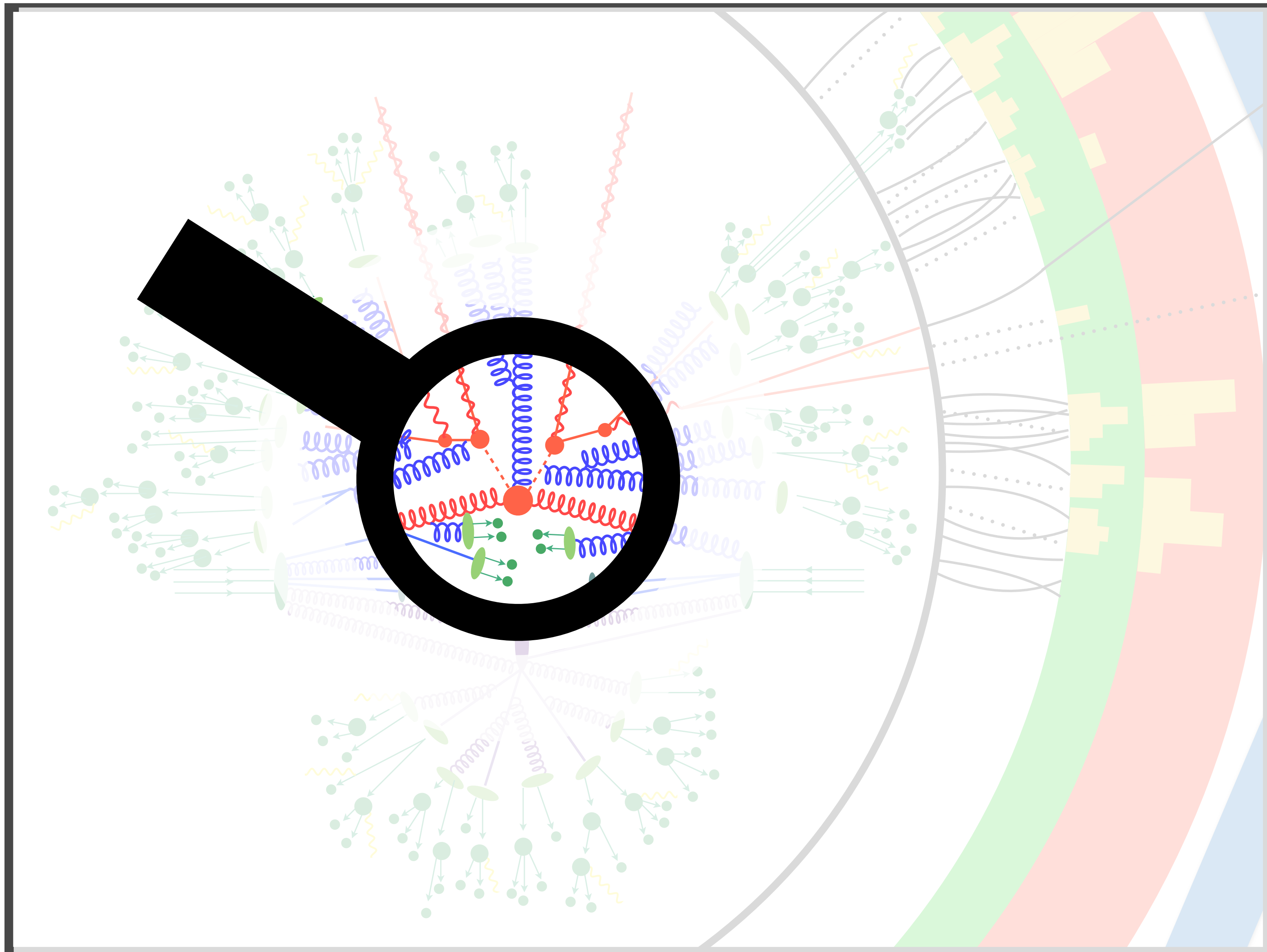
Step 1: “Hard scatter”

very hard for lattice methods because high energy = fine grid



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Step 1: “Hard scatter”

Step 2: “Matching”

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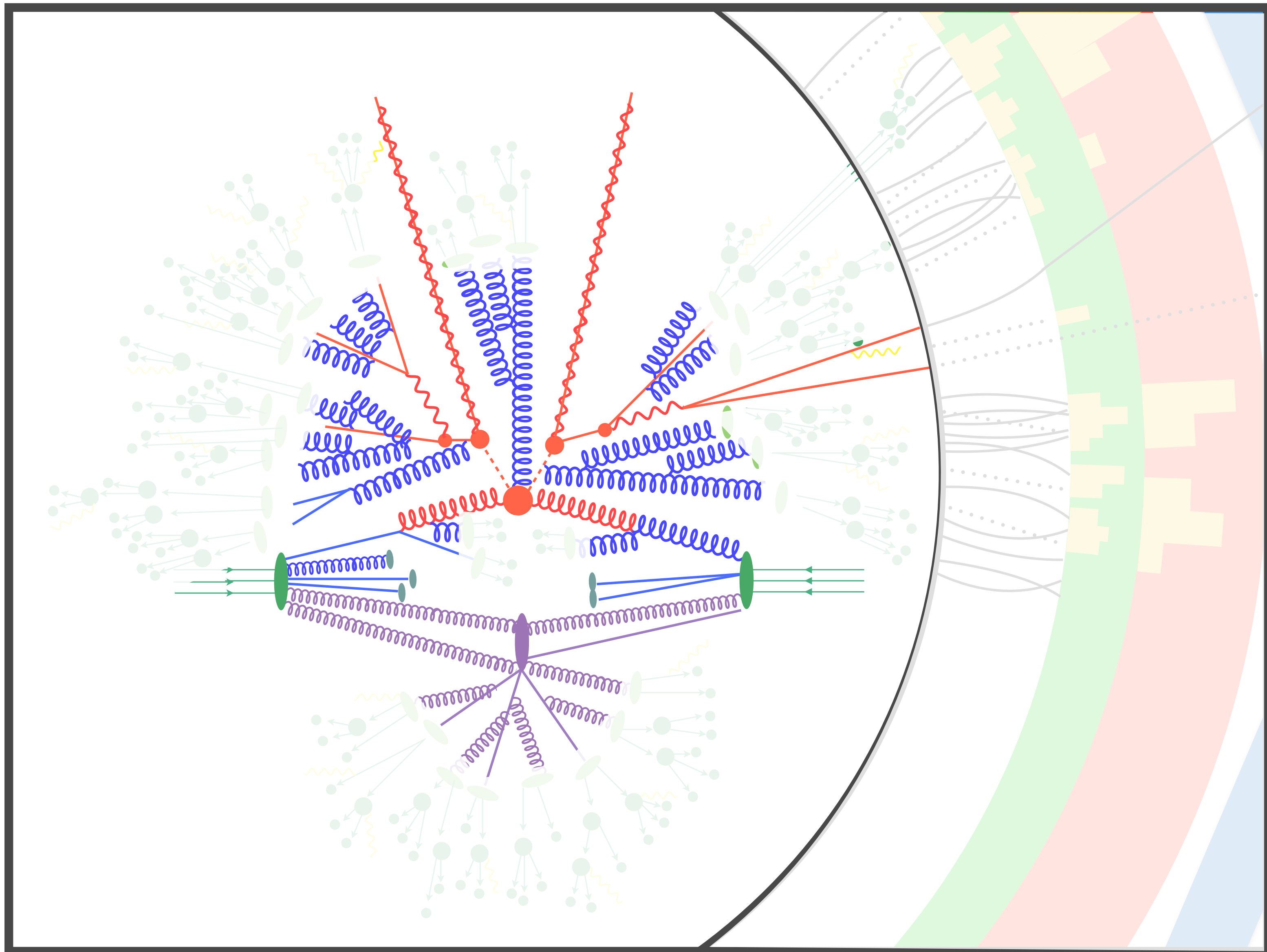

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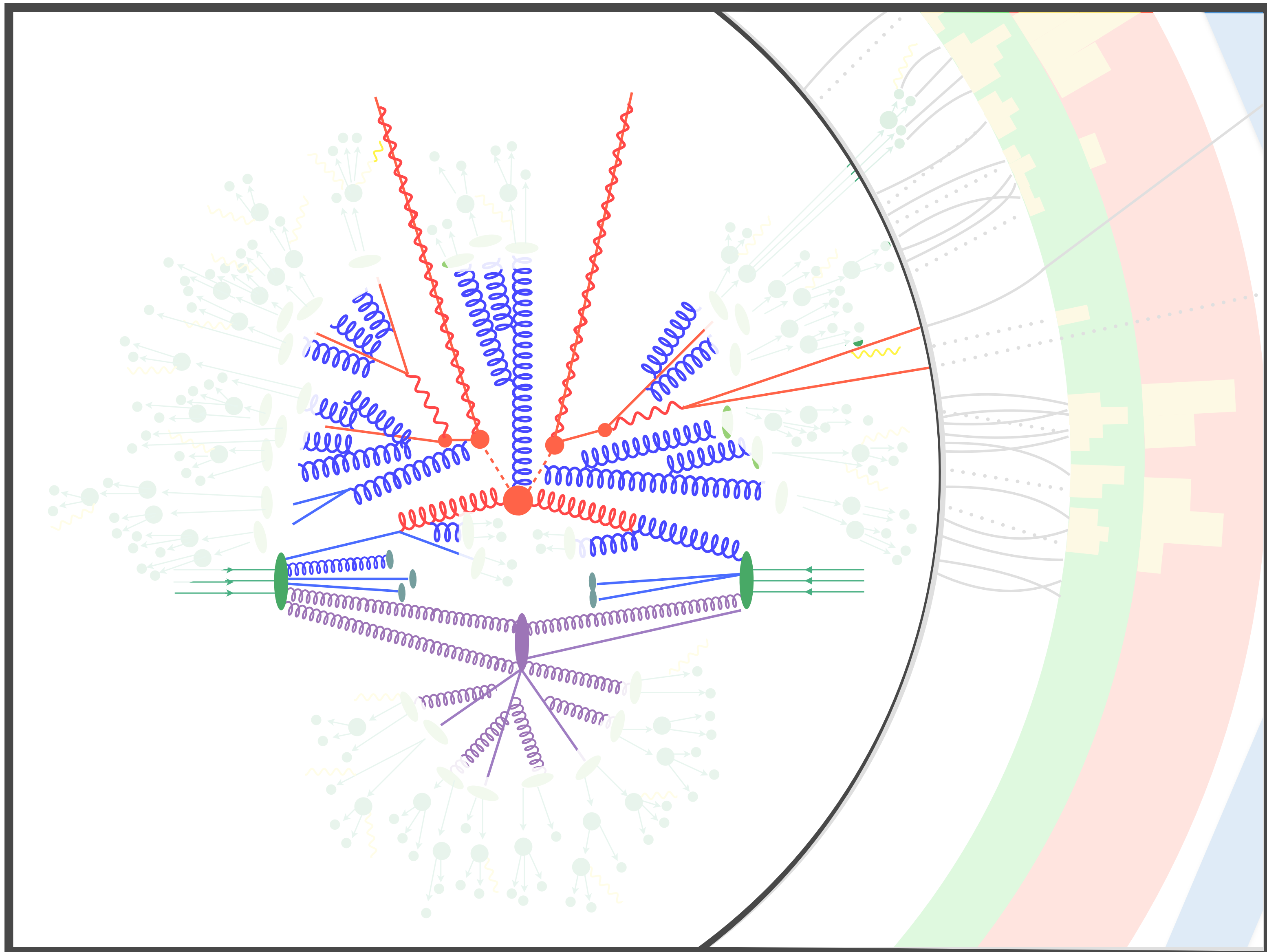
Step 1: “Hard scatter”

Step 2: “Matching”

Step 3: “Parton Shower”



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Step 4: “Hadronization”

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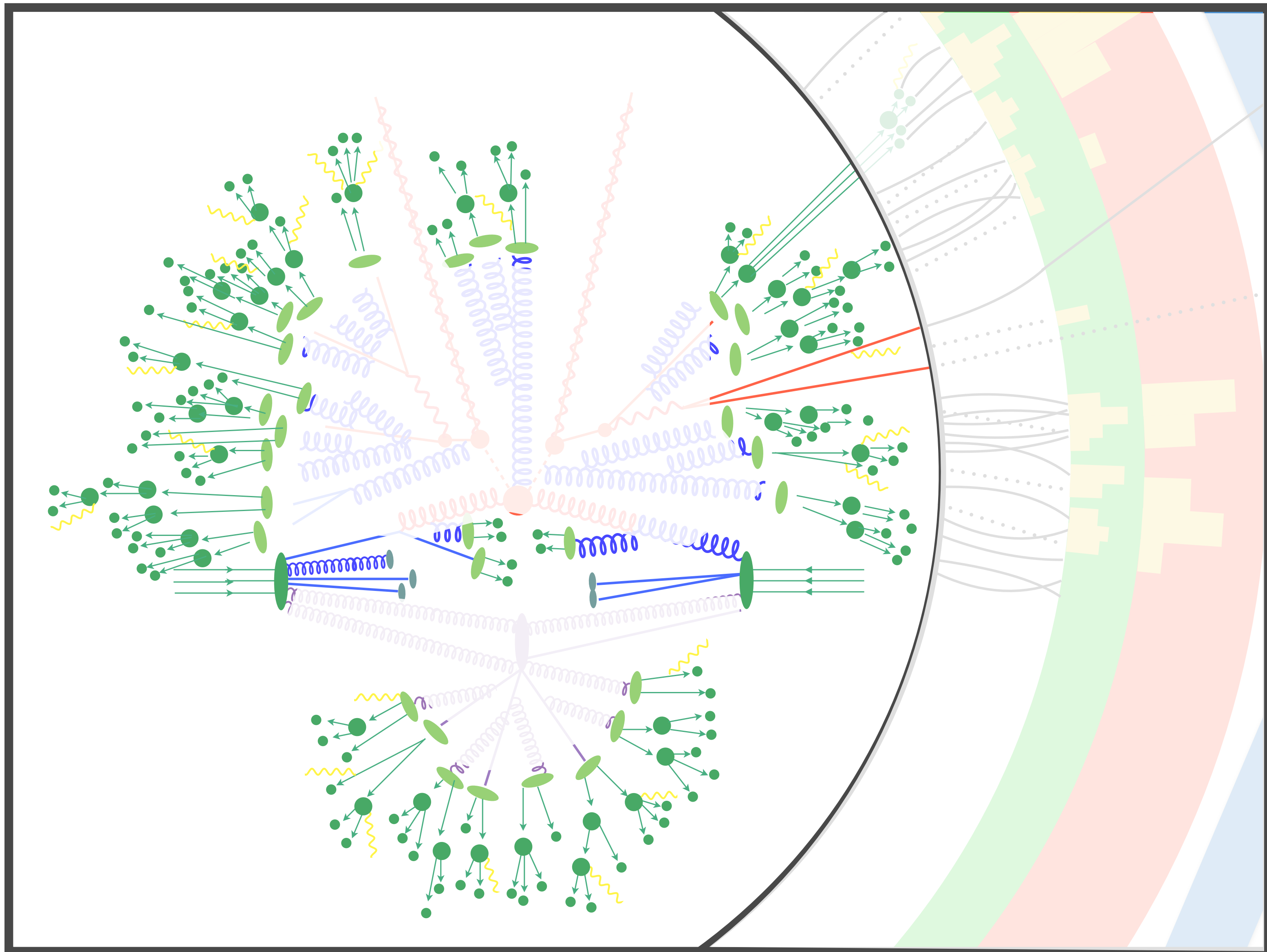

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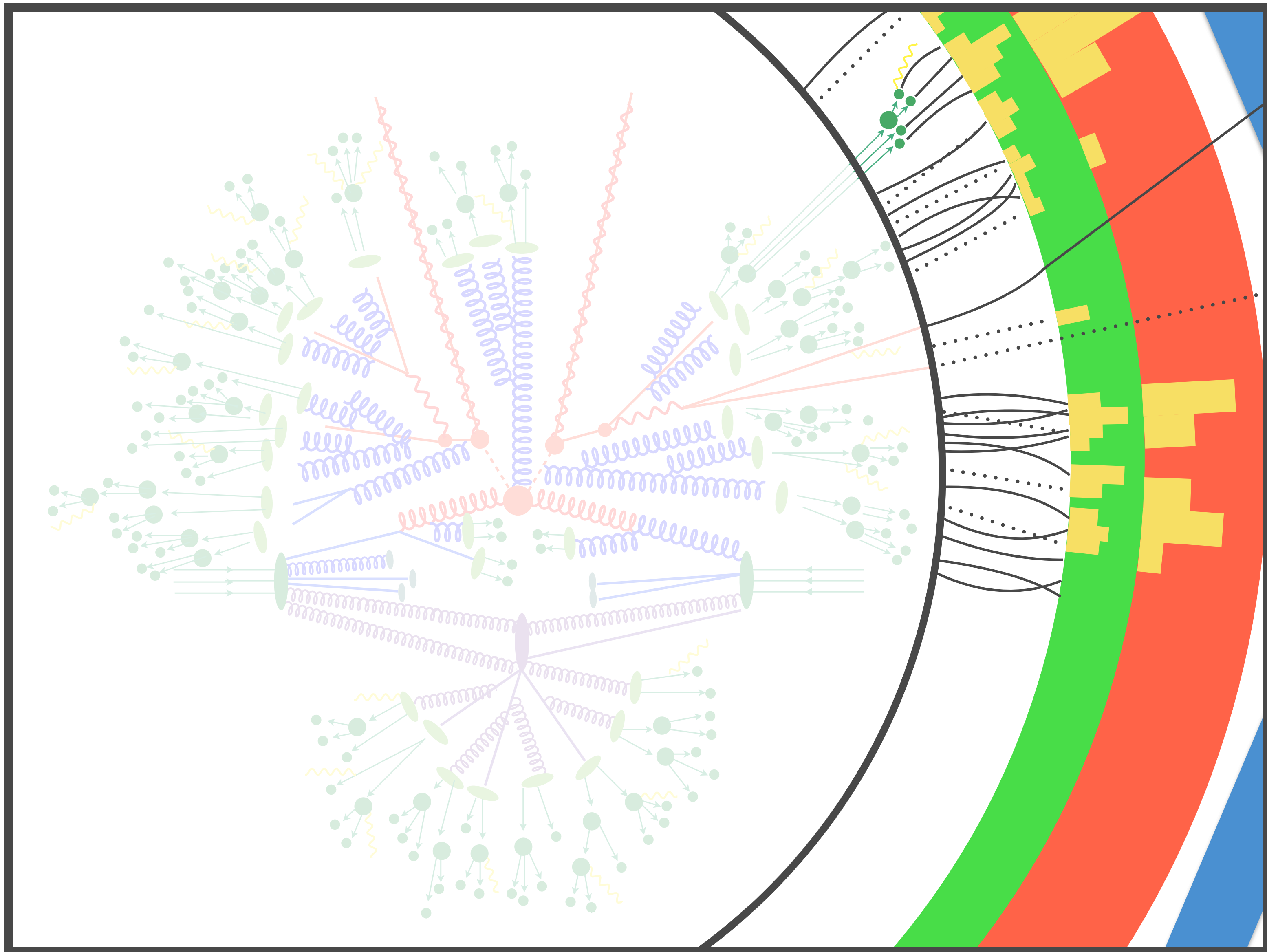
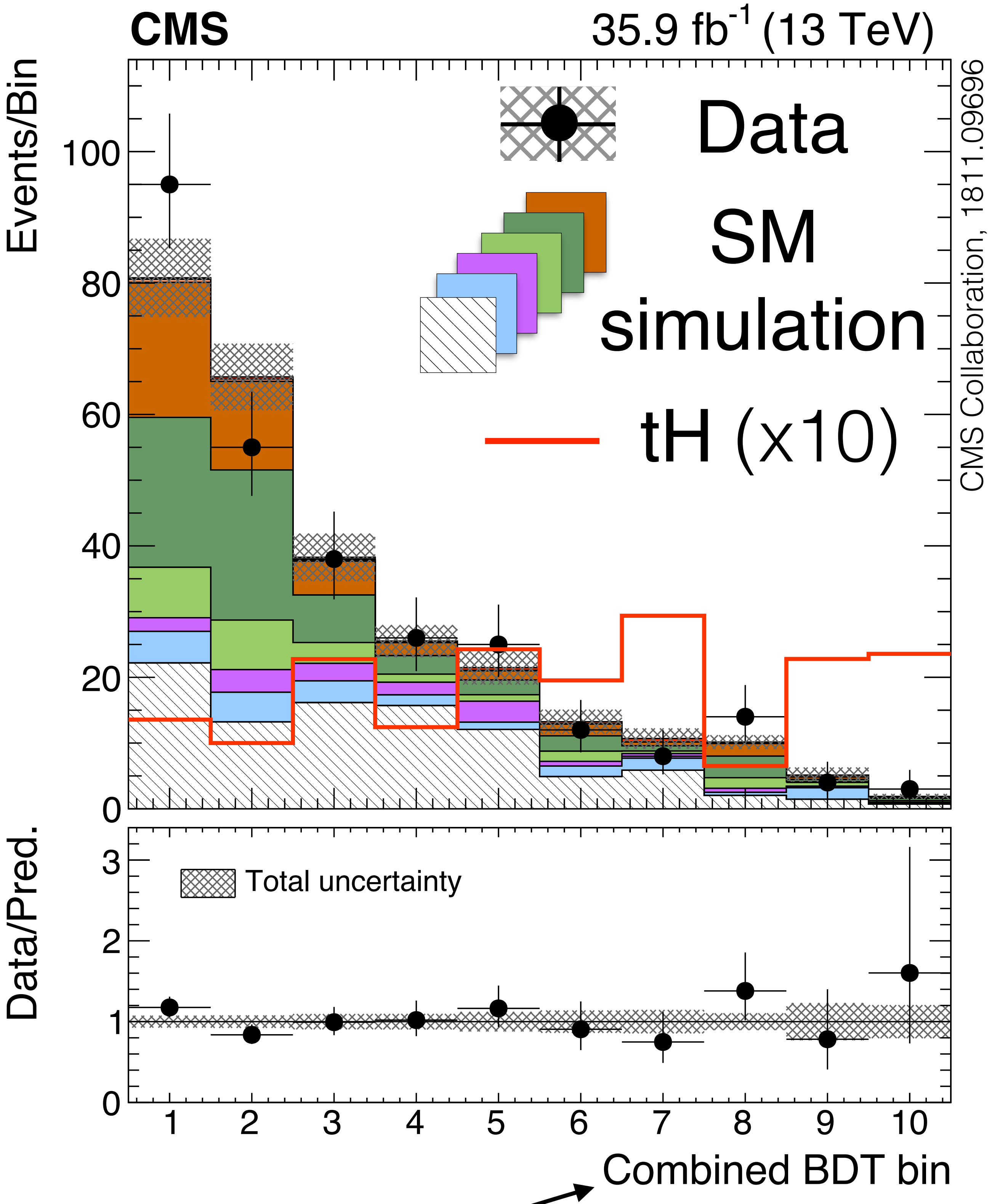
- Step 1: “Hard scatter”
- Step 2: “Matching”
- Step 3: “Parton Shower”
- Step 4: “Hadronization”
- Step 5: Detector sim.



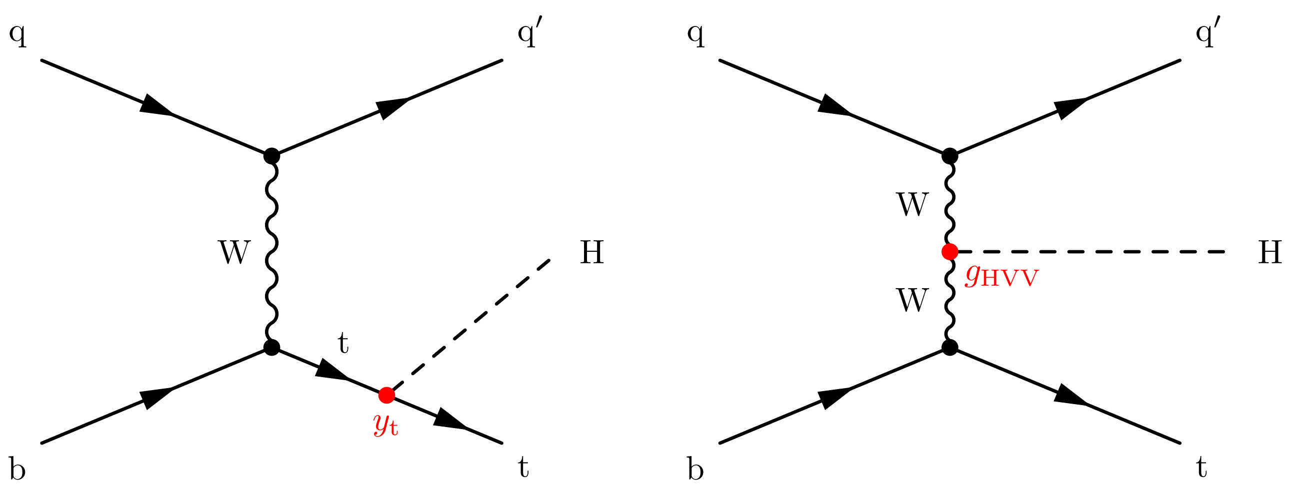
"Quantum effects" for the hard scatter



Boosted decision tree →

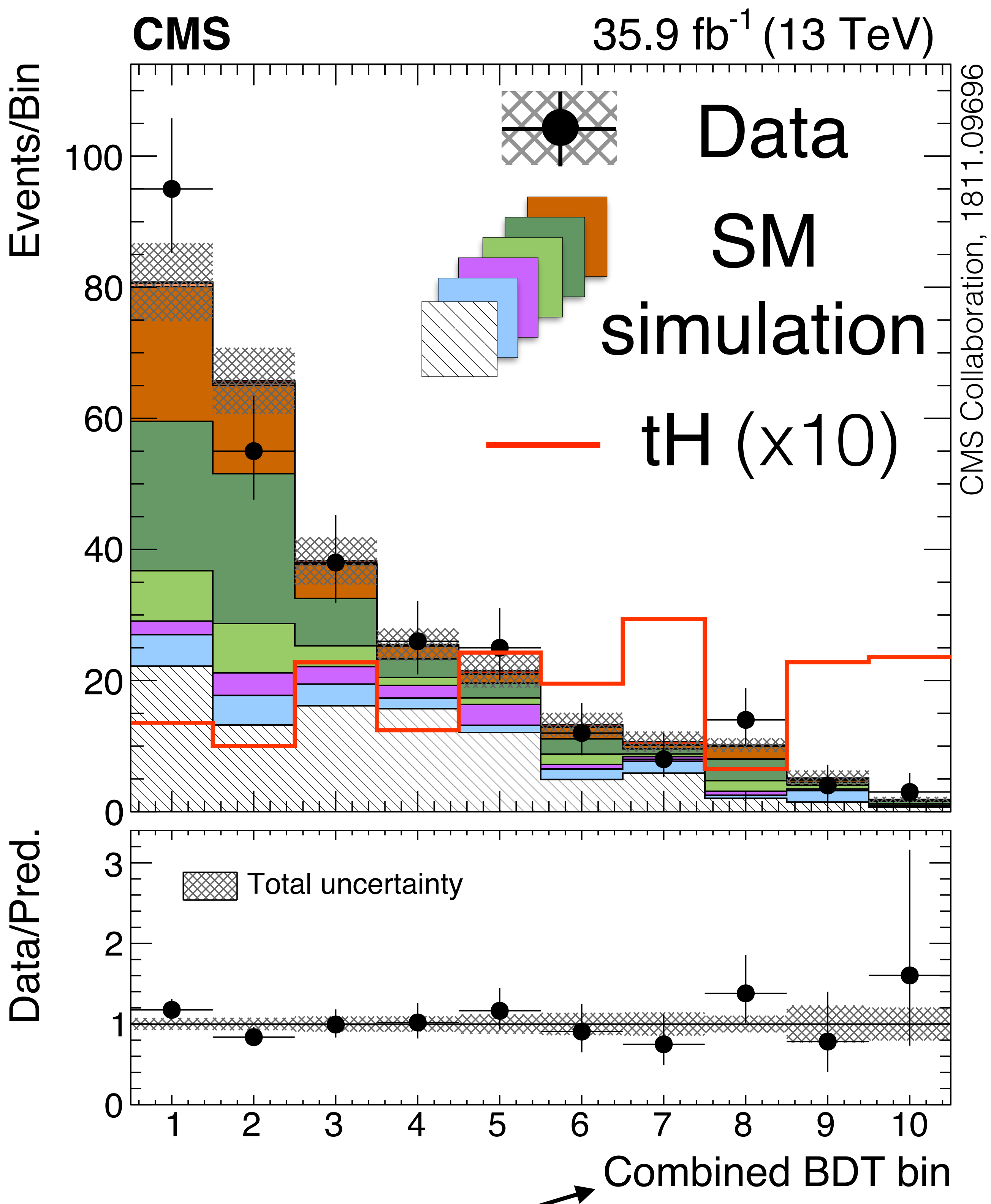
proton proton → Higgs boson + top quark

Two possible Feynman diagrams = interference



This is a huge effect, but we are confident enough in our hard scatter simulations to use them for machine learning!

“Quantum effects” for the hard scatter



Boosted decision tree

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~SOLVED WITH CLASSICAL COMPUTERS

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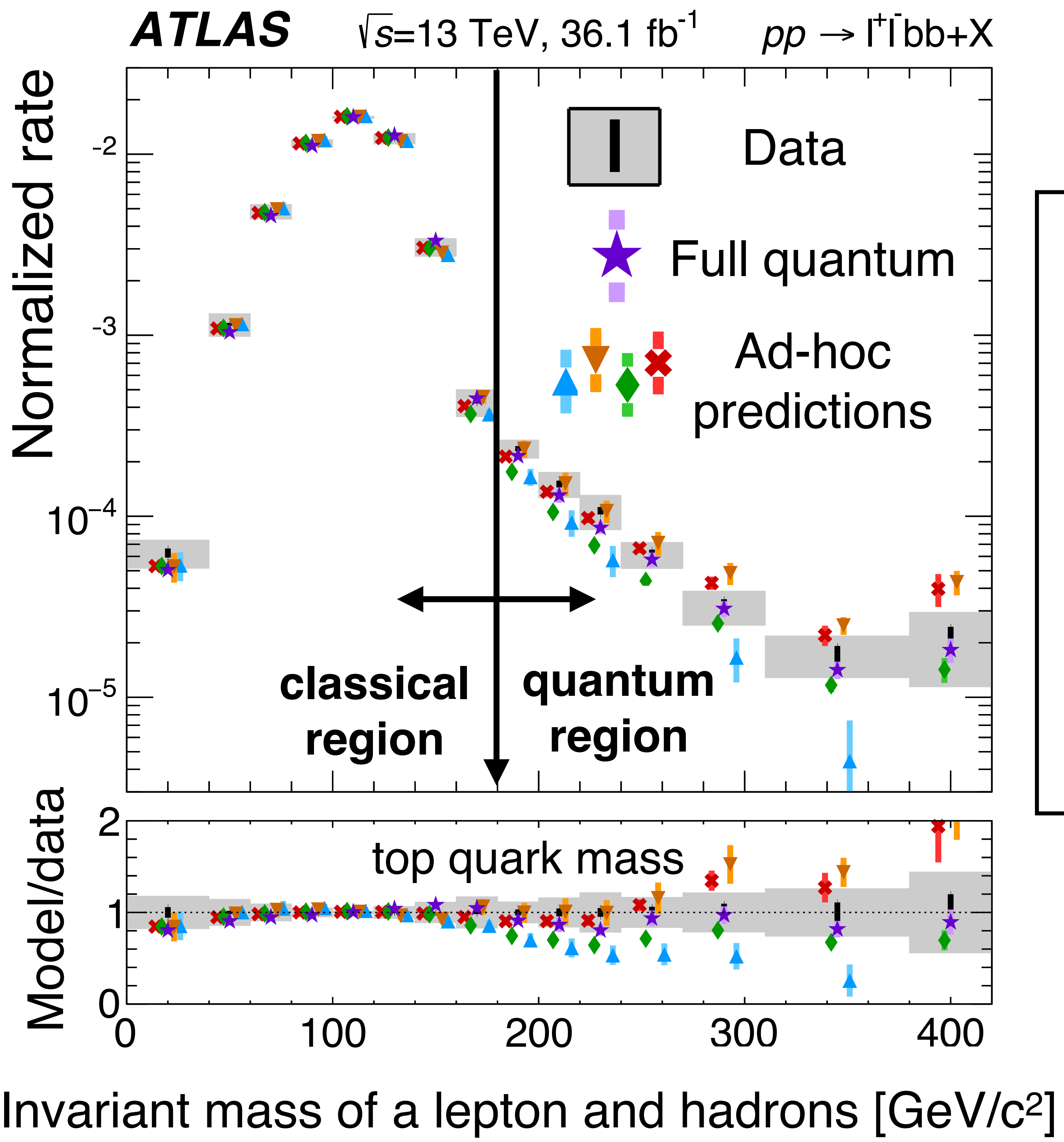
“Quantum effects” for matching

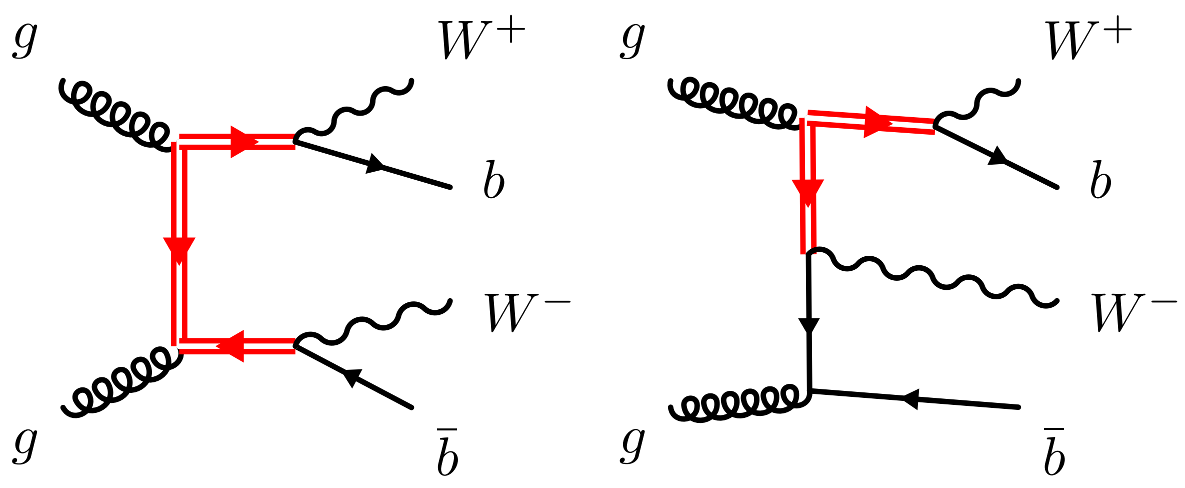
Phys. Rev. Lett. 121 (2018) 152002

Analysis Team: T. Eifert, C. Herwig, **BPN**



proton proton → two W bosons and two b-quarks

Multiple possible diagrams = interference

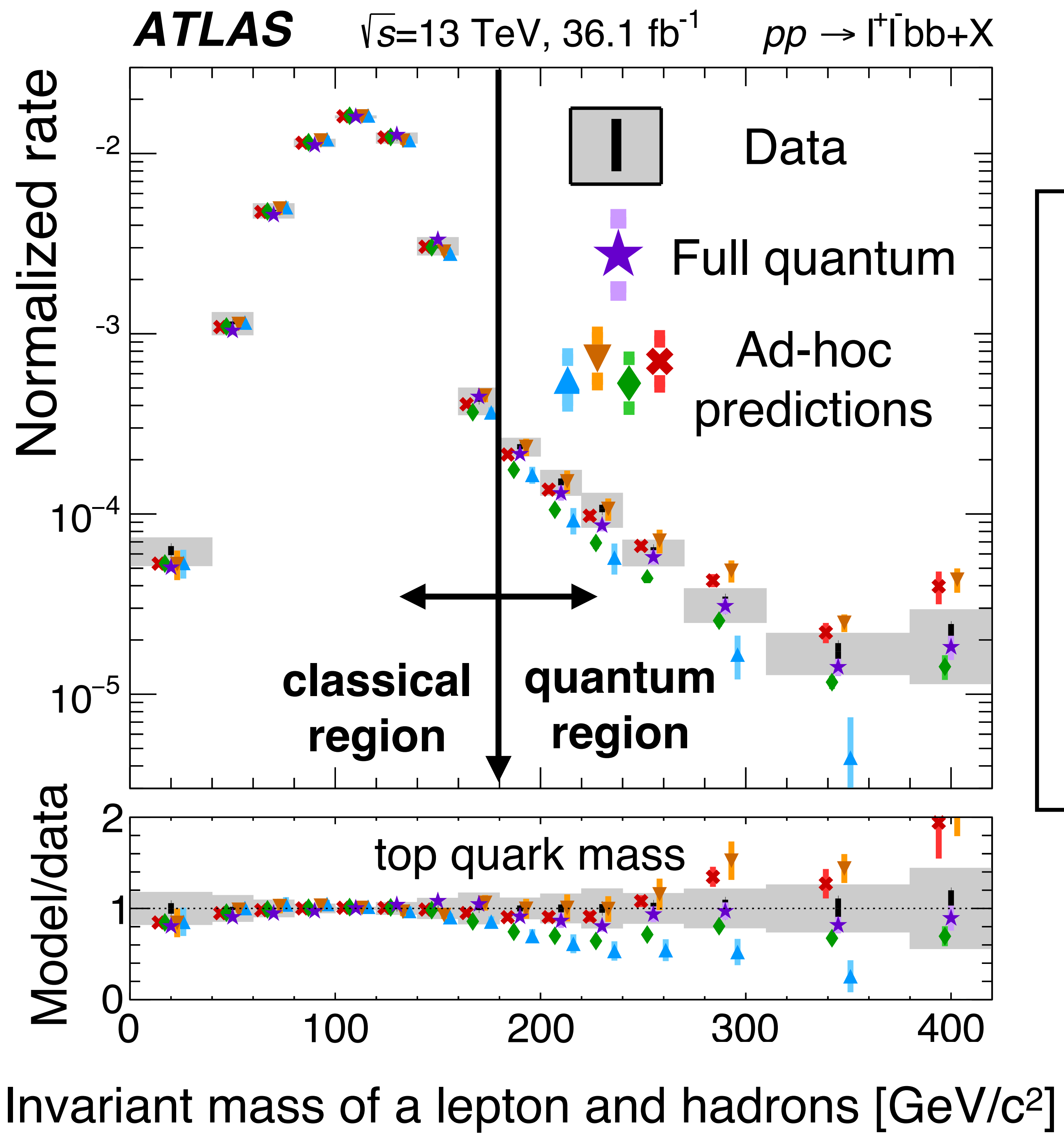


More complicated, but recent innovations are bringing to the same status as previous slide.

“Quantum effects” for matching

Phys. Rev. Lett. 121 (2018) 152002

Analysis Team: T. Eifert, C. Herwig, **BPN**



proton proton → two W bosons and two b-quarks

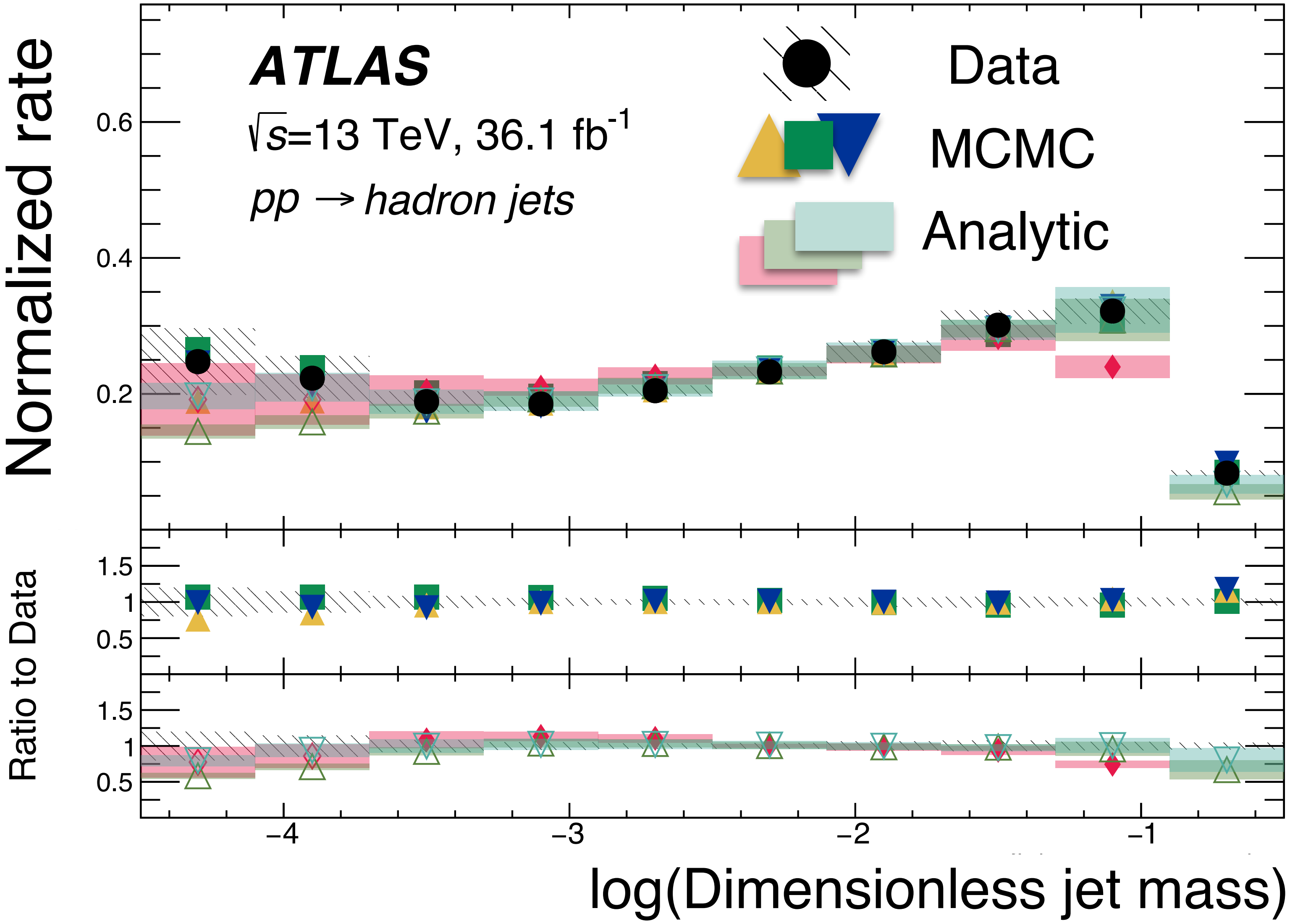
~SOLVED WITH CLASSICAL COMPUTERS

More complicated, but recent innovations are bringing to the same status as previous slide.

“Quantum effects” for the parton shower

Phys. Rev. Lett. 121 (2018) 152002

Analysis Team: **BPN**, J. Roloff, M. Swiatlowski



proton proton → two jets of hadrons

(easily hundreds of particles!)

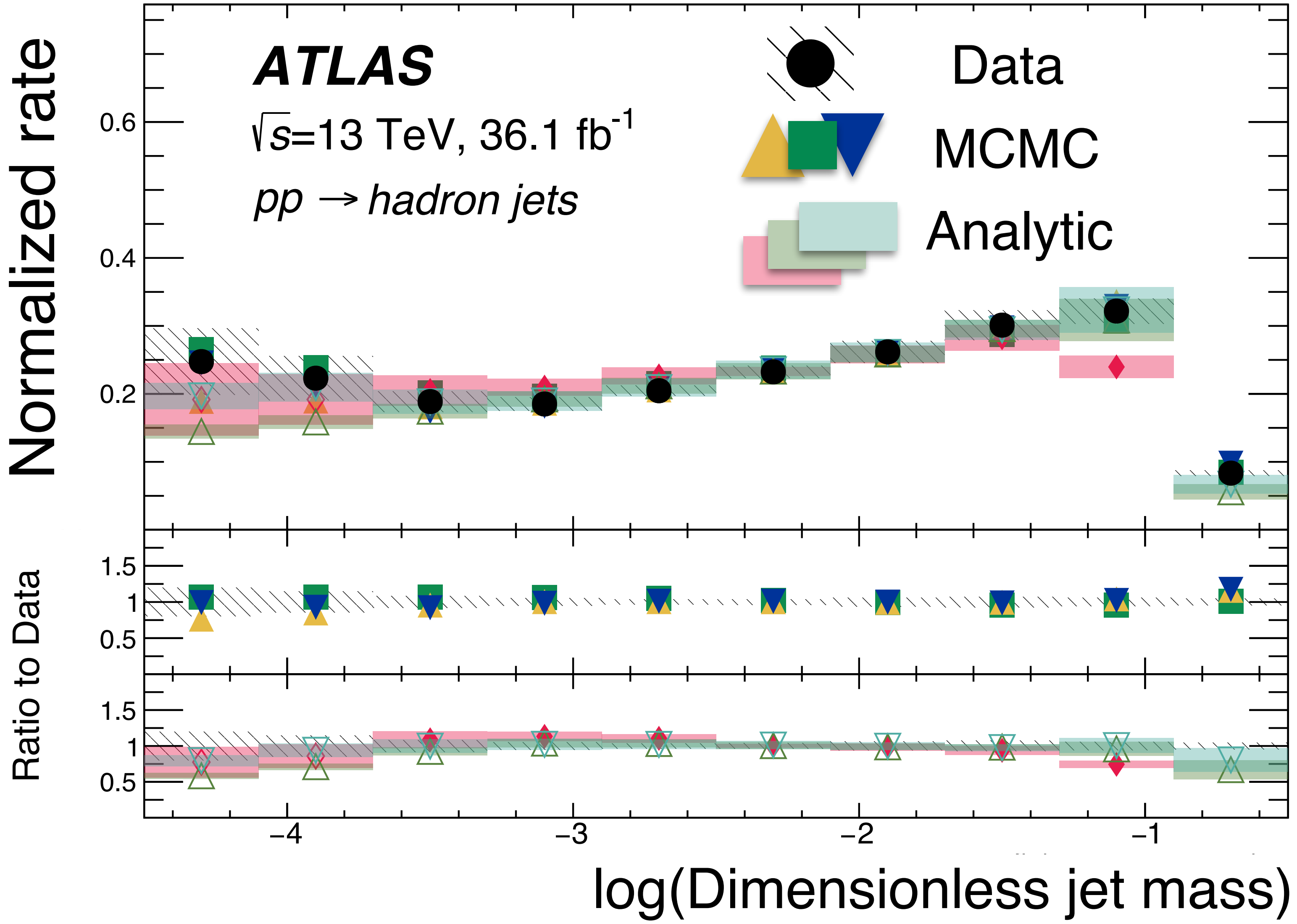
This is a complex many-body quantum system!

Go-to solution: Markov Chan Monte Carlo. This ignores most “quantum” effects; full effects can be (painstakingly) included for some specific observables on a case-by-case basis.

“Quantum effects” for the parton shower

[Phys. Rev. Lett. 121 (2018) 152002]

Analysis Team: **BPN**, J. Roloff, M. Swiatlowski



proton proton → two jets of hadrons

(easily hundreds of particles!)

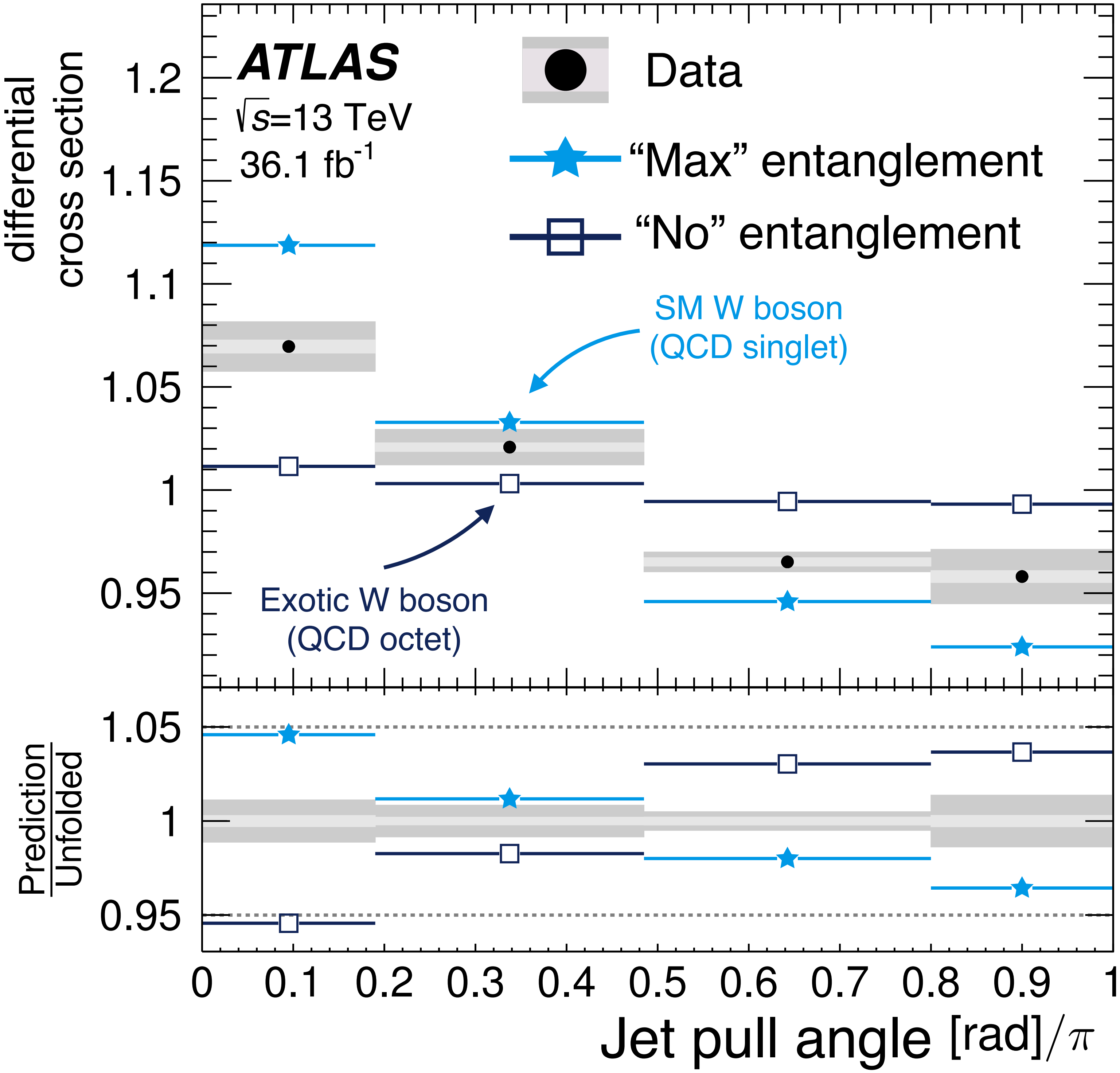
NOT SOLVED IN GENERAL!

Go-to solution: Markov Chan Monte Carlo. This ignores most “quantum” effects; full effects can be (painstakingly) included for some specific observables on a case-by-case basis.

“Quantum effects” for the parton shower

Eur. Phys. J. C 78 (2018) 847, Phys. Lett. B (2015) 475

Team: **BPN**, T. Neep, Y. Peters, M. Swiatlowski, F. Wilk



W boson → two jets of hadrons

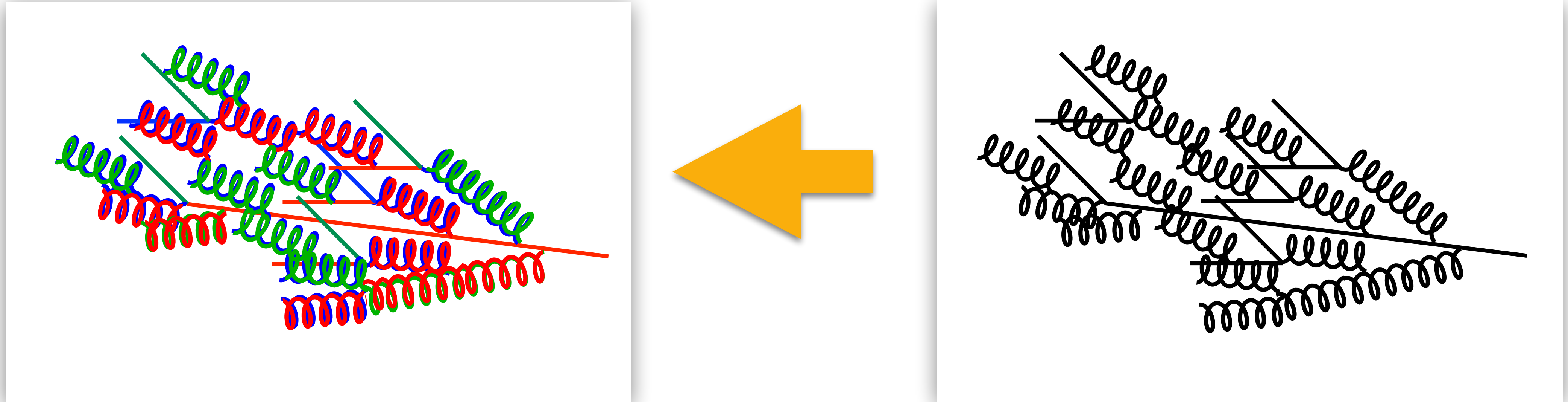
<u>To drive the point home</u> here is an observable where we can’t distinguish between entanglement turned **“on”** and **“off”**.

How much the radiation from one jet “leans” toward the other.

How might we solve this?

Final state radiation is a complex many-body quantum system.

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



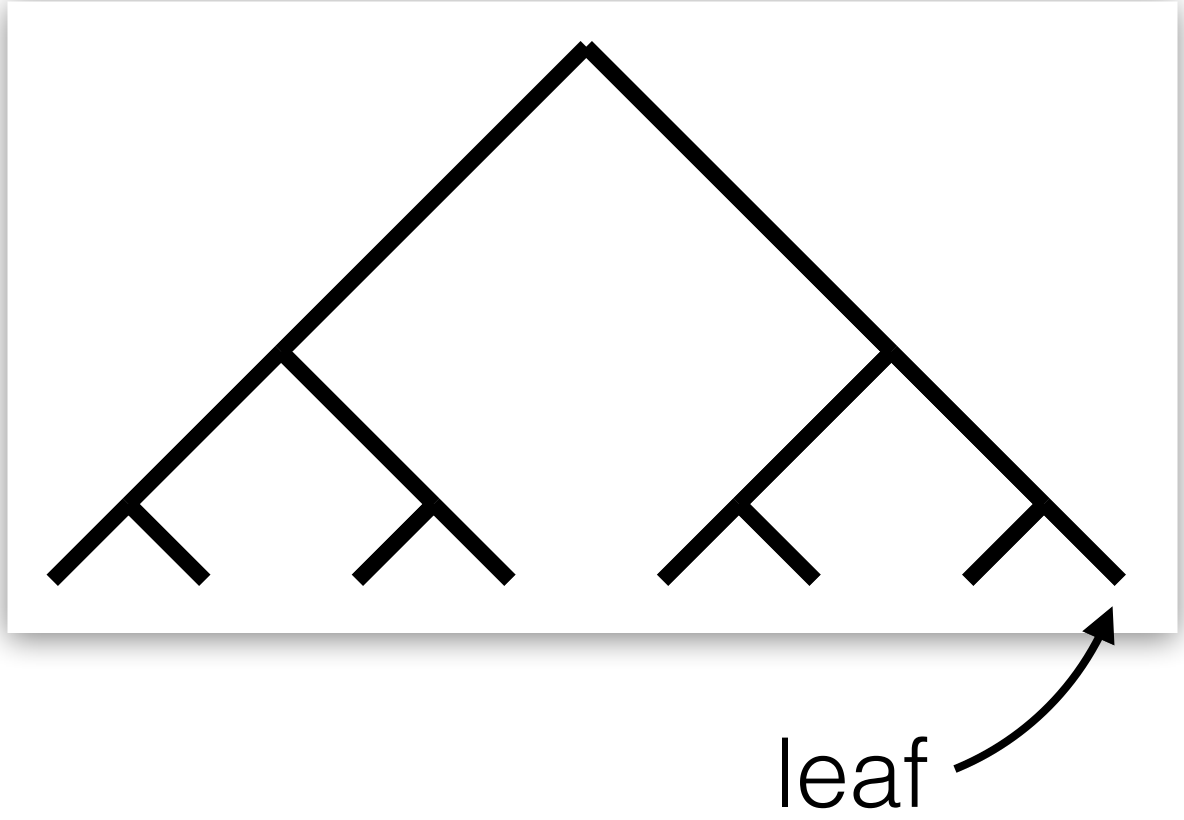
Lines: quarks; curls: gluons; colors: quantum numbers

Whet your appetite

Let’s think of a parton shower like a tree.

Discretize “time”.

At each “time”, a particle can radiate (go left) or not radiate (go right).



N.B. not a quantum random walk: leaf = history is observable!

Markov chain of amplitudes: $A_{\text{leaf}} = \prod_{n=1}^{N} A_{\lambda_n}(n)$

$\lambda \in \{L, R\}^N$

Solved by a classical MCMC

Whet your appetite

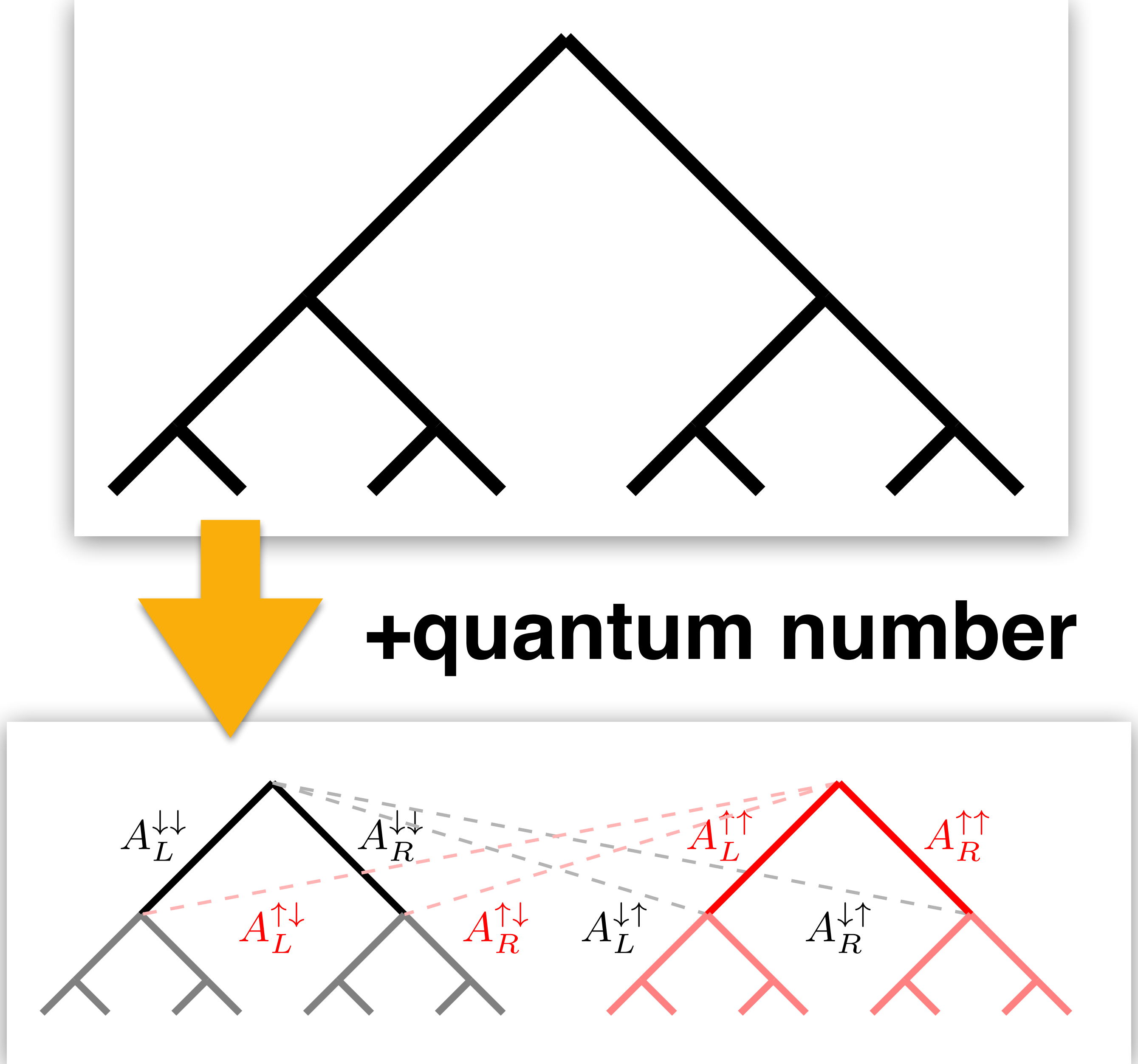
Let's think of a parton shower like a tree.

Discretize "time".

At each "time", a particle **can flip spin (flip trees)** and radiate (go left) or not radiate (go right).

$$A_{s_0,s_N} = \sum_{\substack{\vec{s}'\in\{\downarrow,\uparrow\}^N \\ s'_0=s_0,\, s'_N=s_N}} \prod_{n=1}^{N} A_{\lambda_n}^{s'_{n-1},s'_n}(n)$$

Classical MCMC fails!



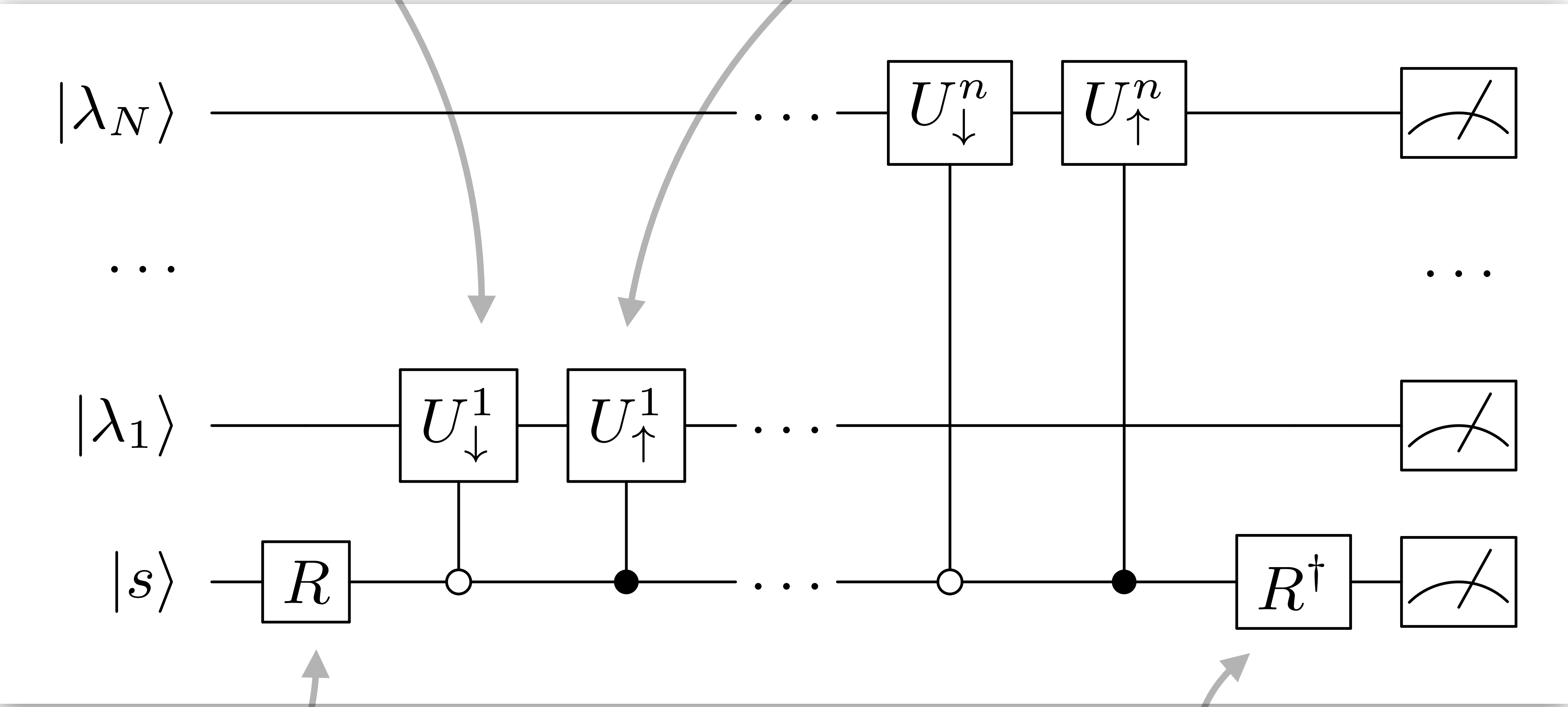
+quantum number

Interference from summing over intermediate spins!

Quantum solution to interfering trees

go left, given
spin down

go left, given
spin up



N.B. this only works if there exists such an R → subspace of full interfering tree problem.

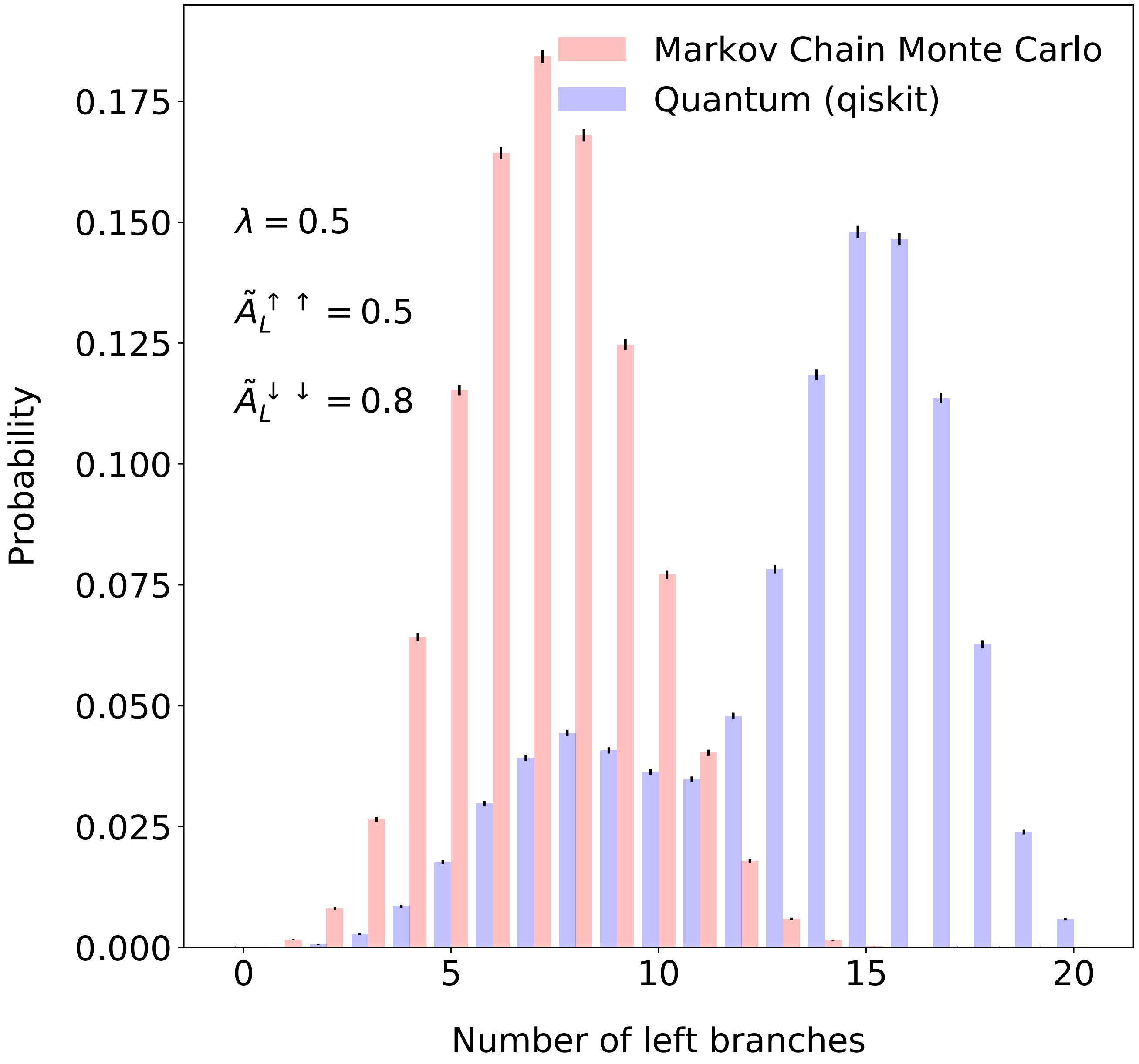
D. Provasoli, **BPN**, W. de Jong, C. Bauer, *Quantum Science and Tech. 5 (2020) 035004*

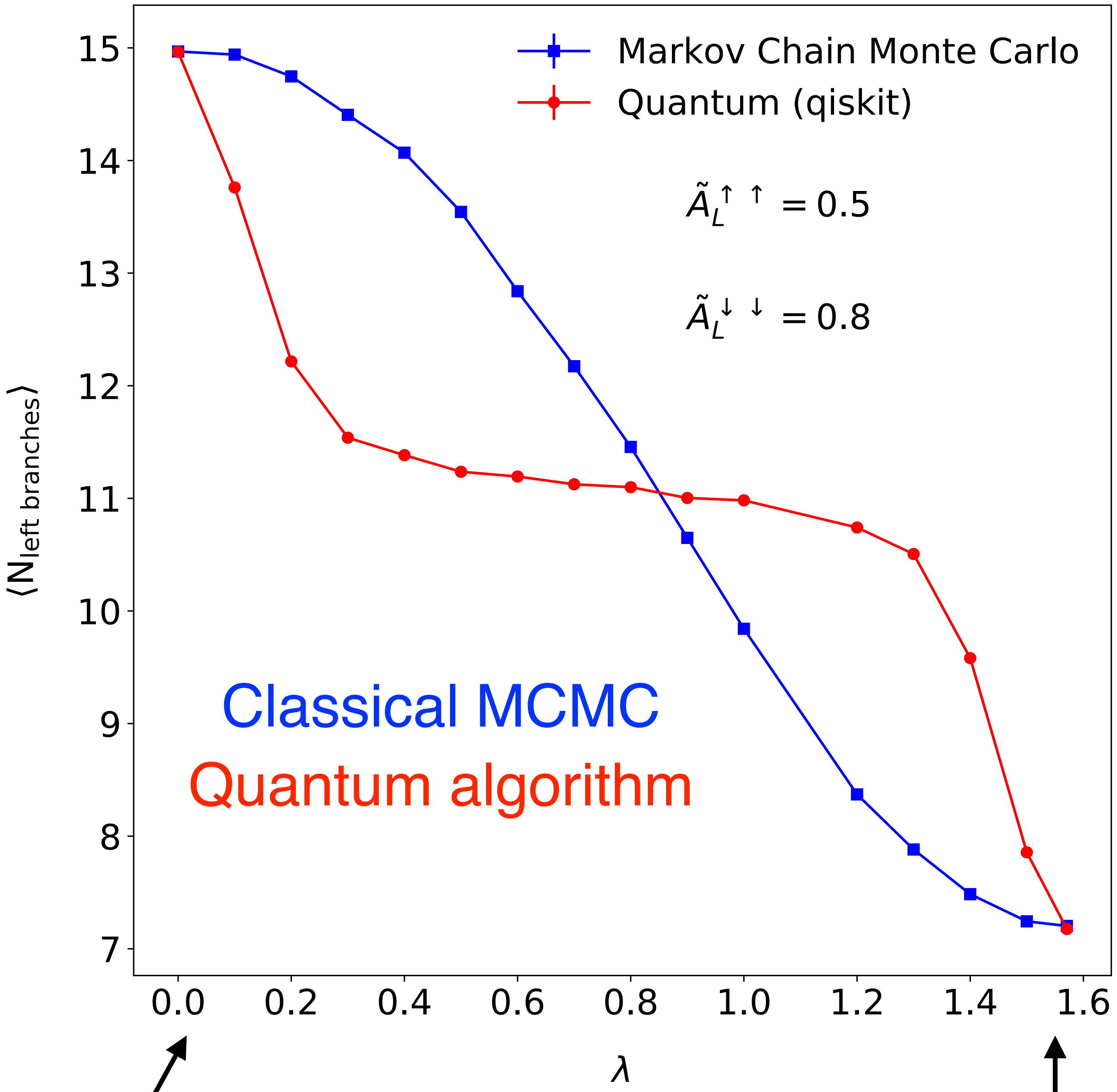
rotate into non-
interacting basis

rotate back into
physical basis

Linear-time quantum circuit with
one qubit / step + 1 qubit for the spin.

Results with a quantum simulator





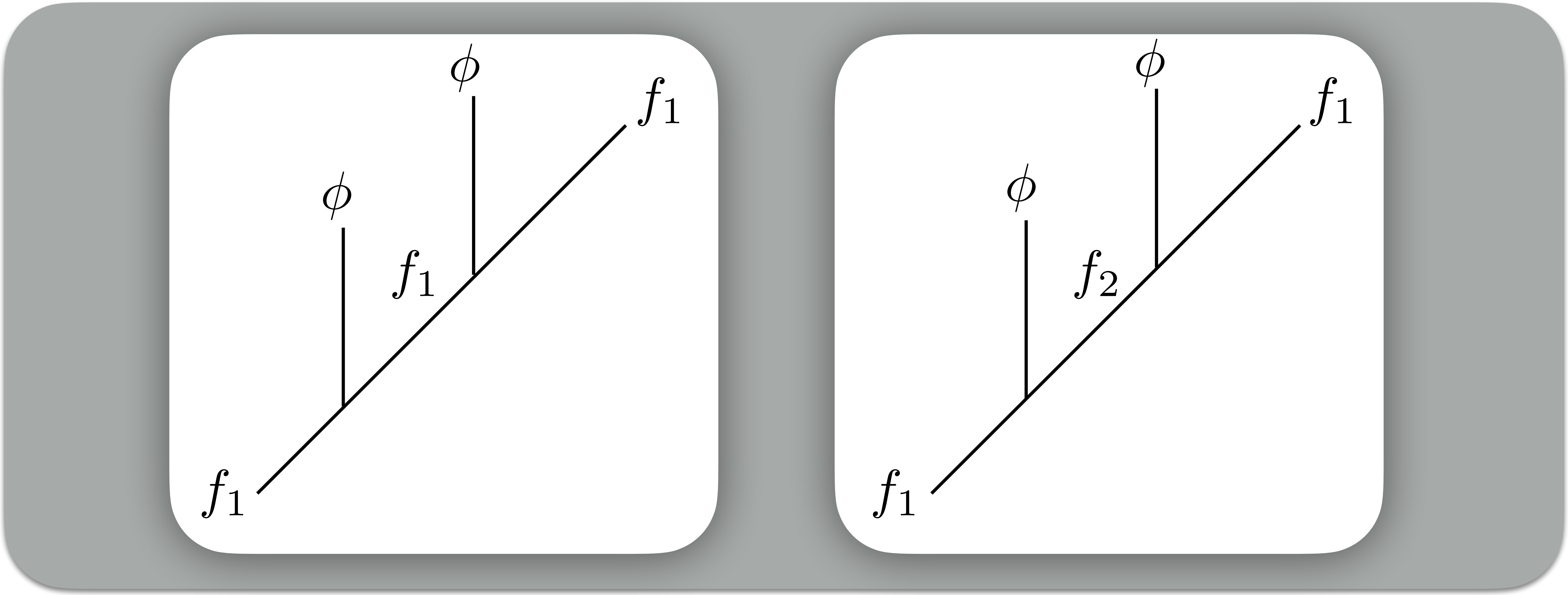
λ = rotation angle

no flipping ← no interference → flip every step

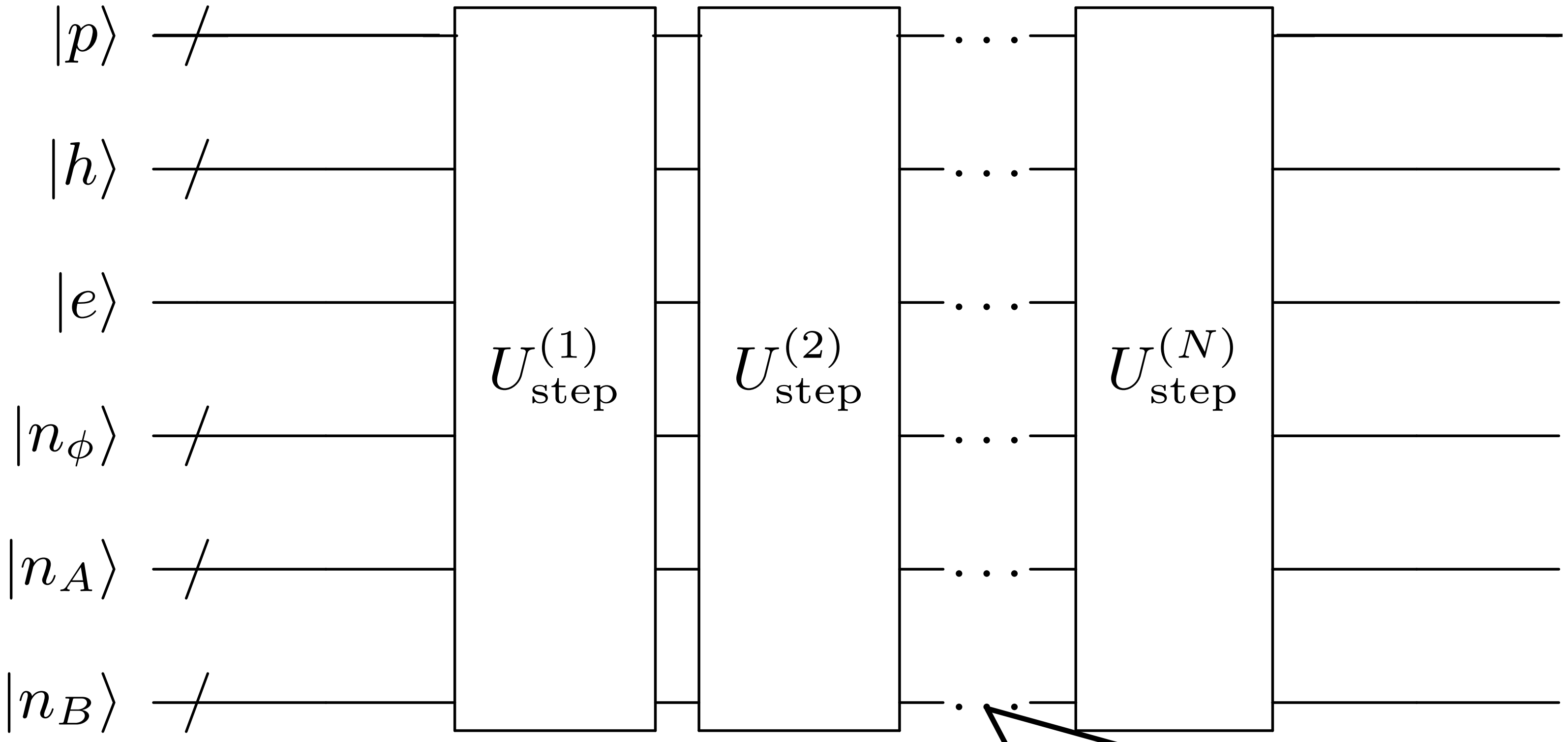
A more realistic model

$$\begin{aligned}\mathcal{L} = &\bar{f}_1 i(\not{\partial} + m_1) f_1 + \bar{f}_2(i\not{\partial} + m_2) f_2 + (\partial_\mu \phi)^2 \\ &+ g_1 \bar{f}_1 f_1 \phi + g_2 \bar{f}_2 f_2 \phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi\end{aligned}$$

(like the SM Higgs when $g_{12} \sim m/v$ and $g_1 = g_2 = 0$)



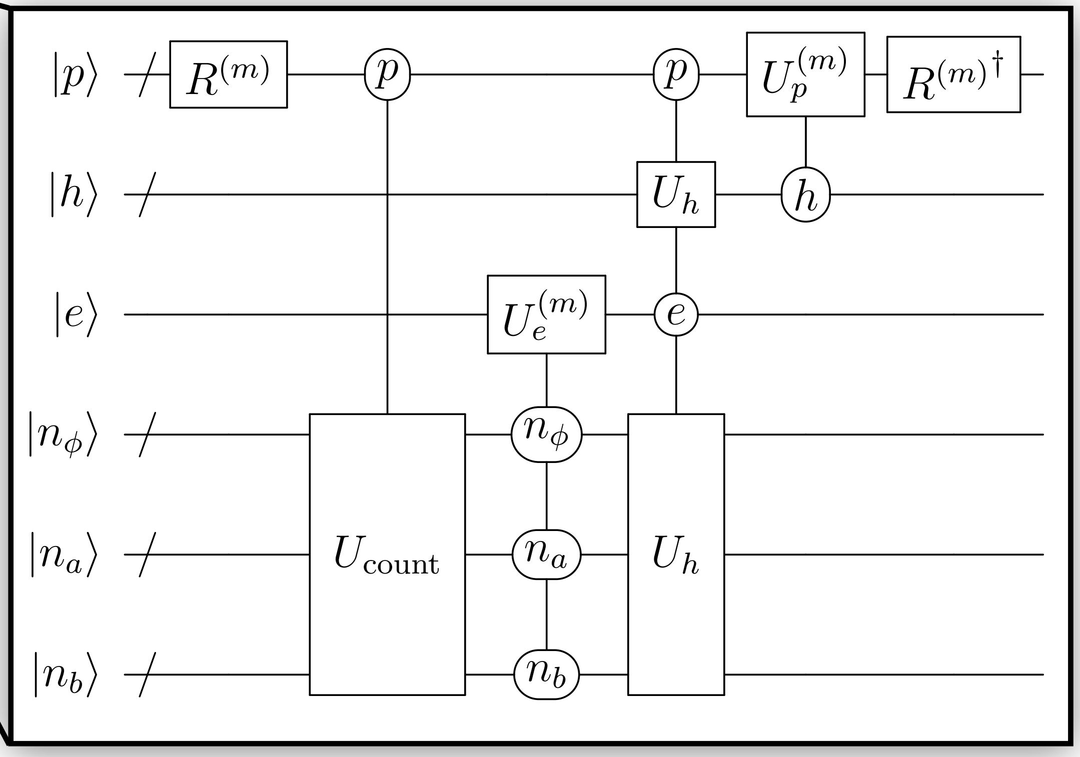
The quantum circuit



Circuit is complicated because the number of fermions is not constant:

$$\phi \to f\,\bar{f}$$

Register	Purpose	# of qubits
$\|p\rangle$	Particle state	$3(N+1)$
$\|h\rangle$	Emission history	$N\log_2(N+1)$
$\|e\rangle$	Did emission happen?	1
$\|n_\phi\rangle$	Number of bosons	$\log_2(N+1)$
$\|n_a\rangle$	Number of f_a	$\log_2(N+1)$
$\|n_b\rangle$	Number of f_b	$\log_2(N+1)$



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

The quantum circuit - U_e (e = emit)

$$U_e^{(m)} = \begin{pmatrix} \sqrt{\Delta^{(m)}(\theta_m)} & -\sqrt{1-\Delta^{(m)}(\theta_m)} \\ \sqrt{1-\Delta^{(m)}(\theta_m)} & \sqrt{\Delta^{(m)}(\theta_m)} \end{pmatrix}$$

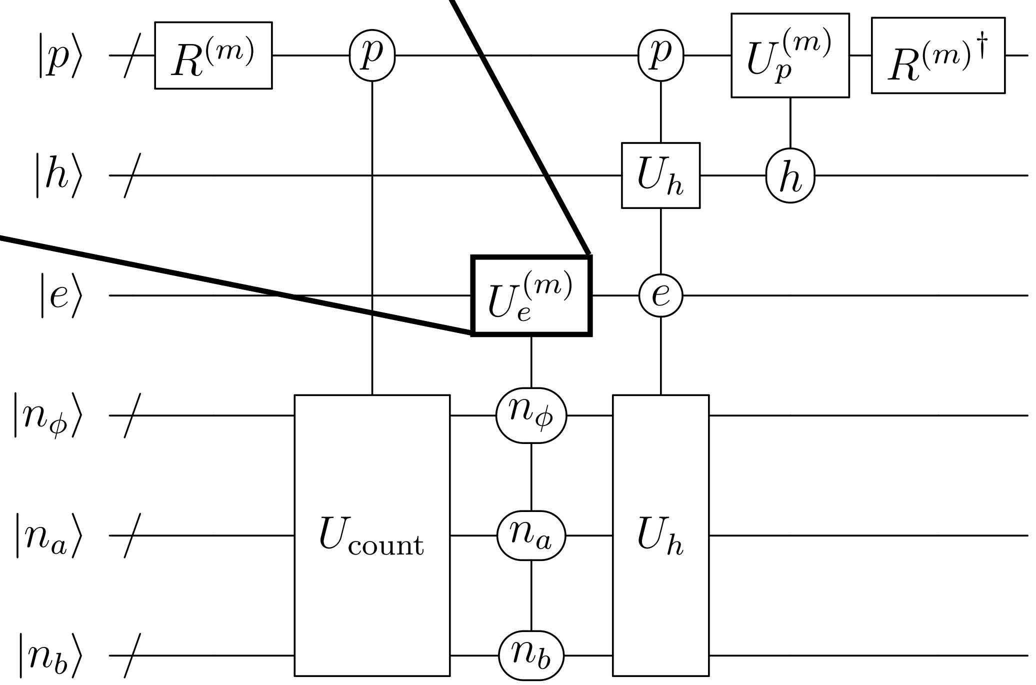
$$\Delta_i(\theta_m, \theta_{m+1}) = e^{-\Delta\theta P_i(\theta_m)}$$

(Sudakov factor)

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

Circuit is complicated because the number of fermions is not constant:

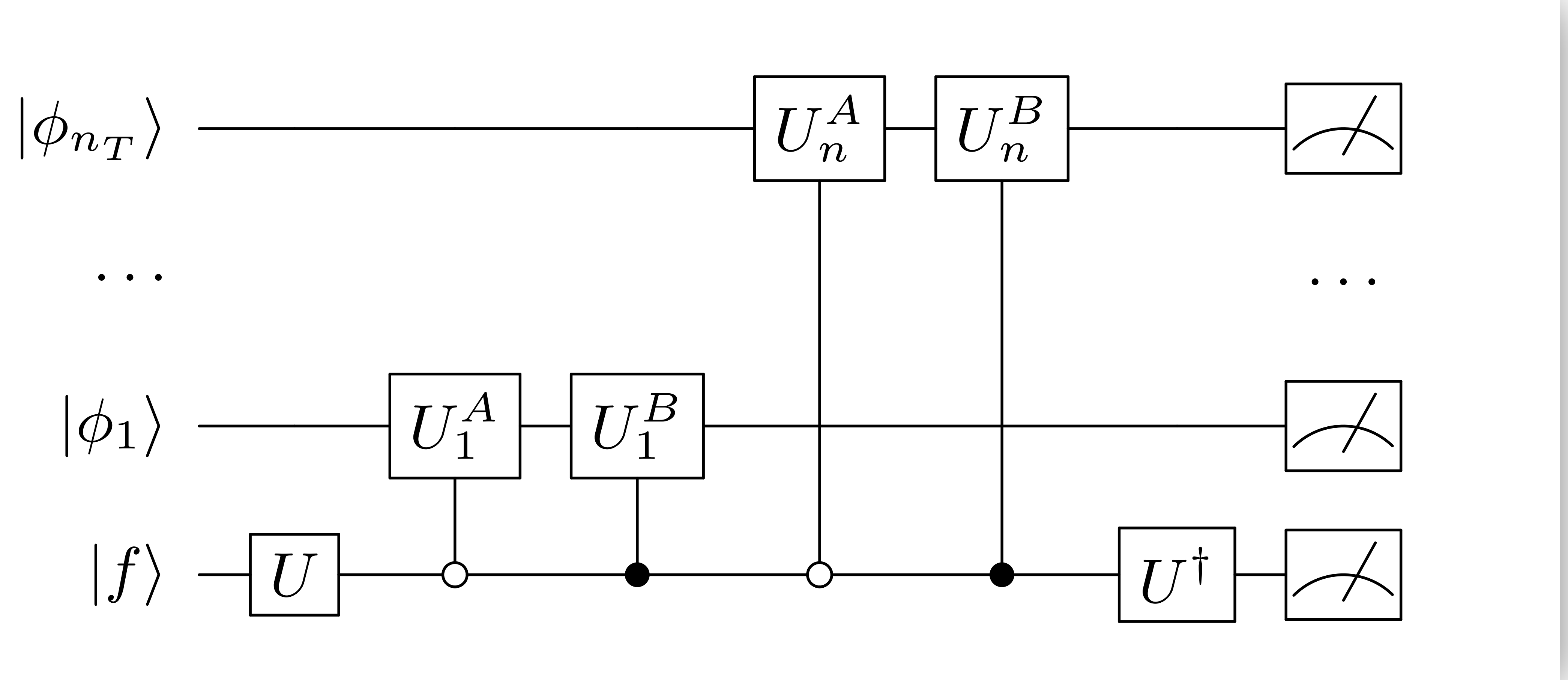
$$\phi \to f\bar{f}$$



This is just one part of the circuit that calculates the no emission amplitudes

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

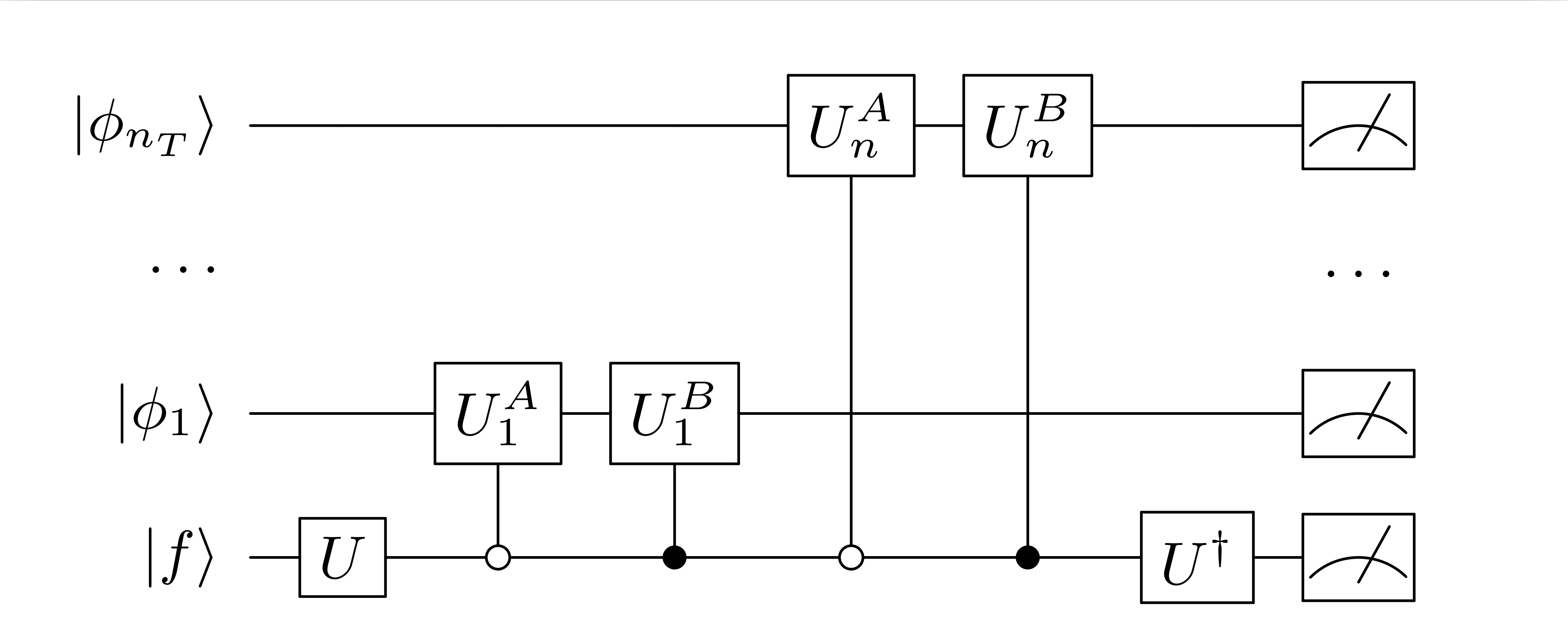
The circuit without scalar splitting



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

This is exactly the interfering trees circuit !

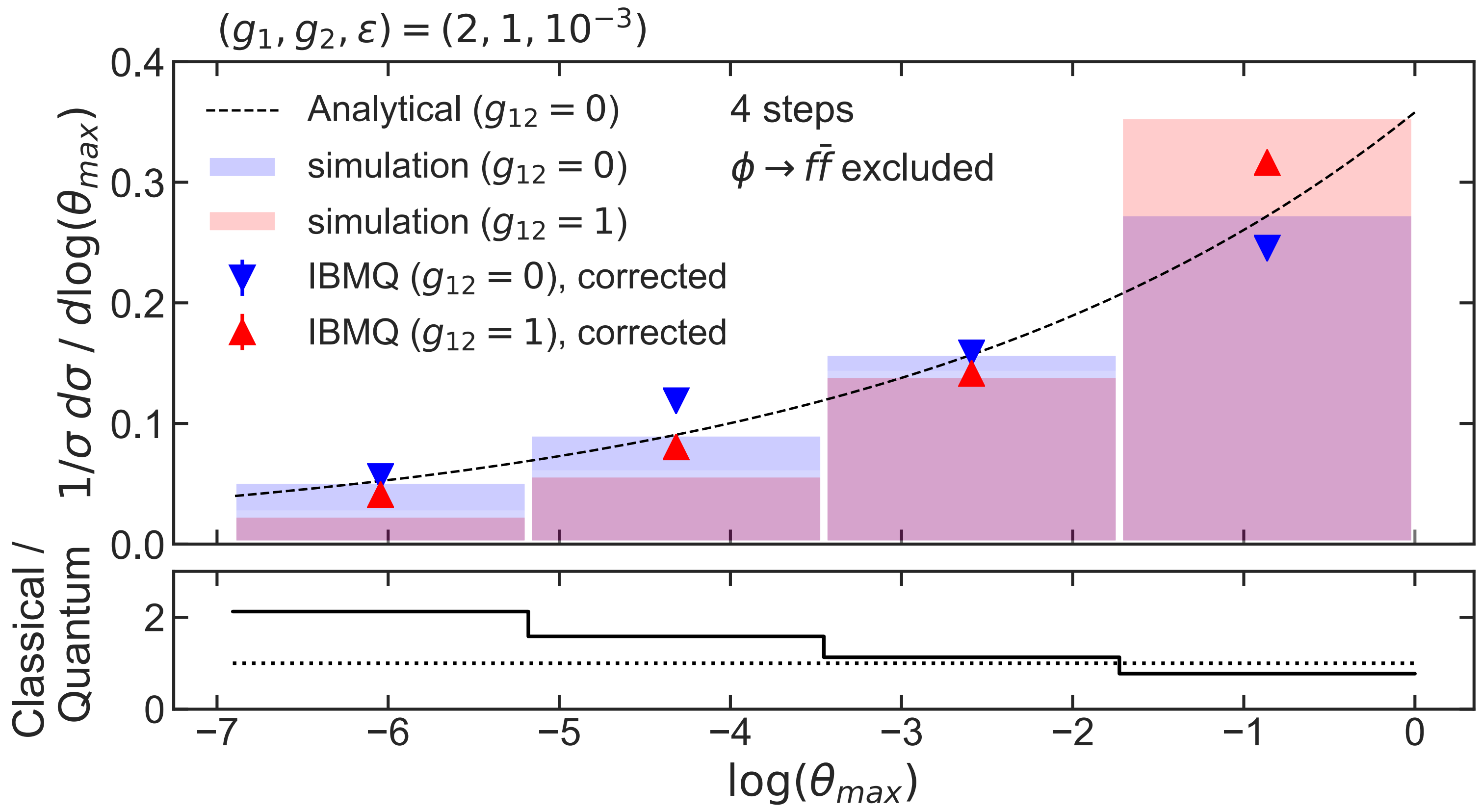
The circuit without scalar splitting



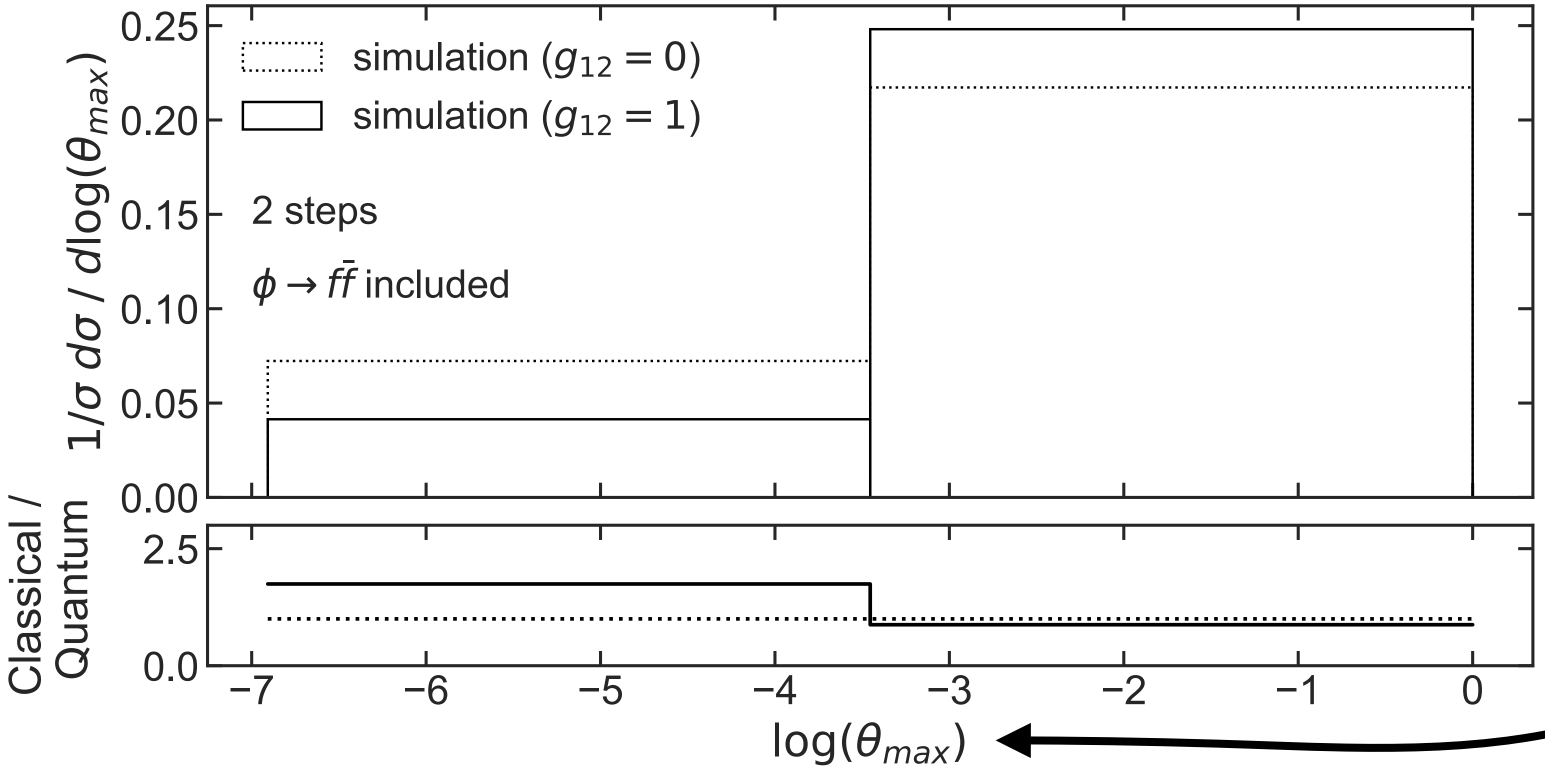
Note: $|\phi_i\rangle$ is not touched after timestep i and so one can **reuse qubits** … only need 2 total qubits (!)

Fine print: (1) re-measurement is not a feature 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).

Numerical results



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



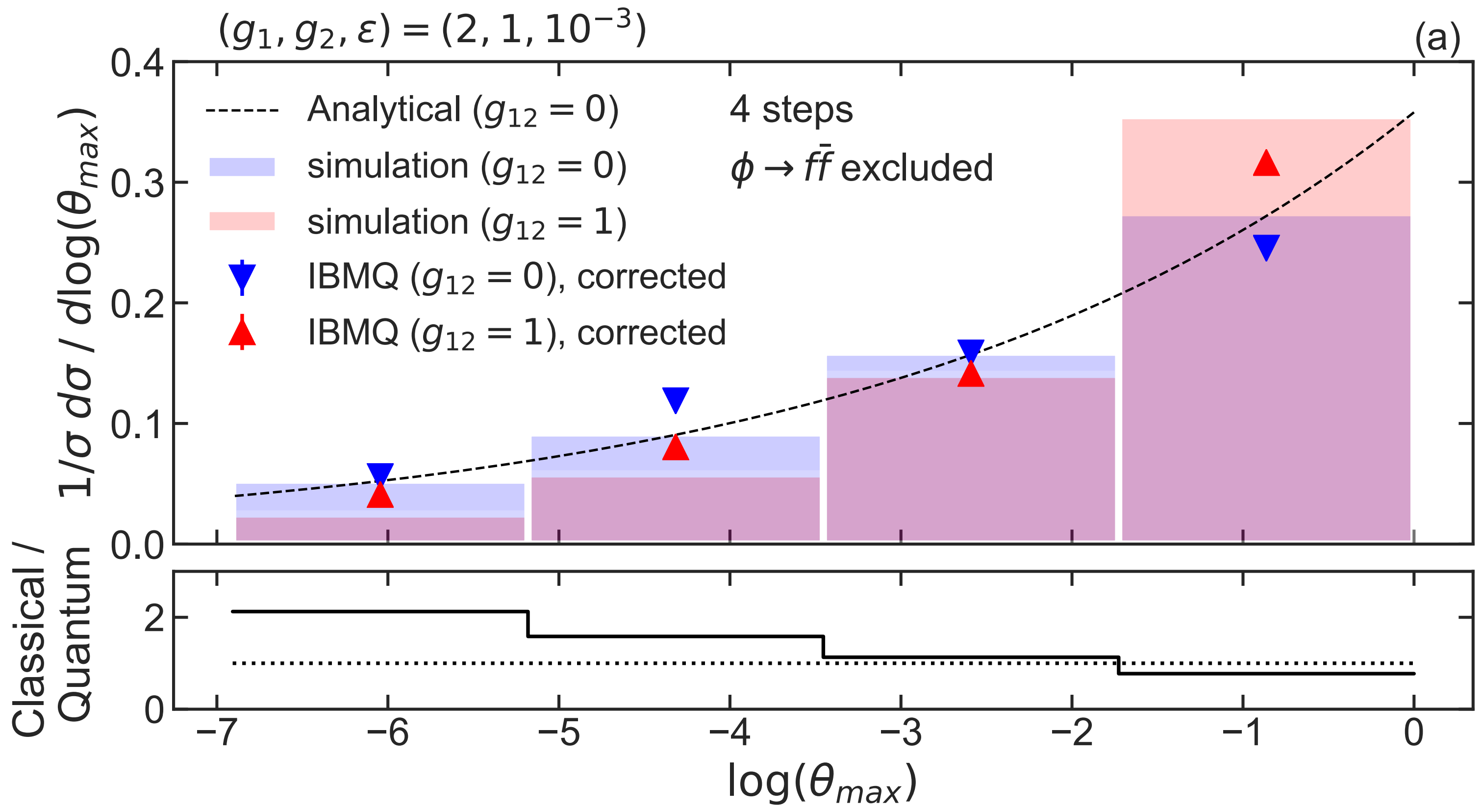
Classical: exponential

Naive quantum: 5th order

Optimized quantum: 3rd

angle of maximum emission

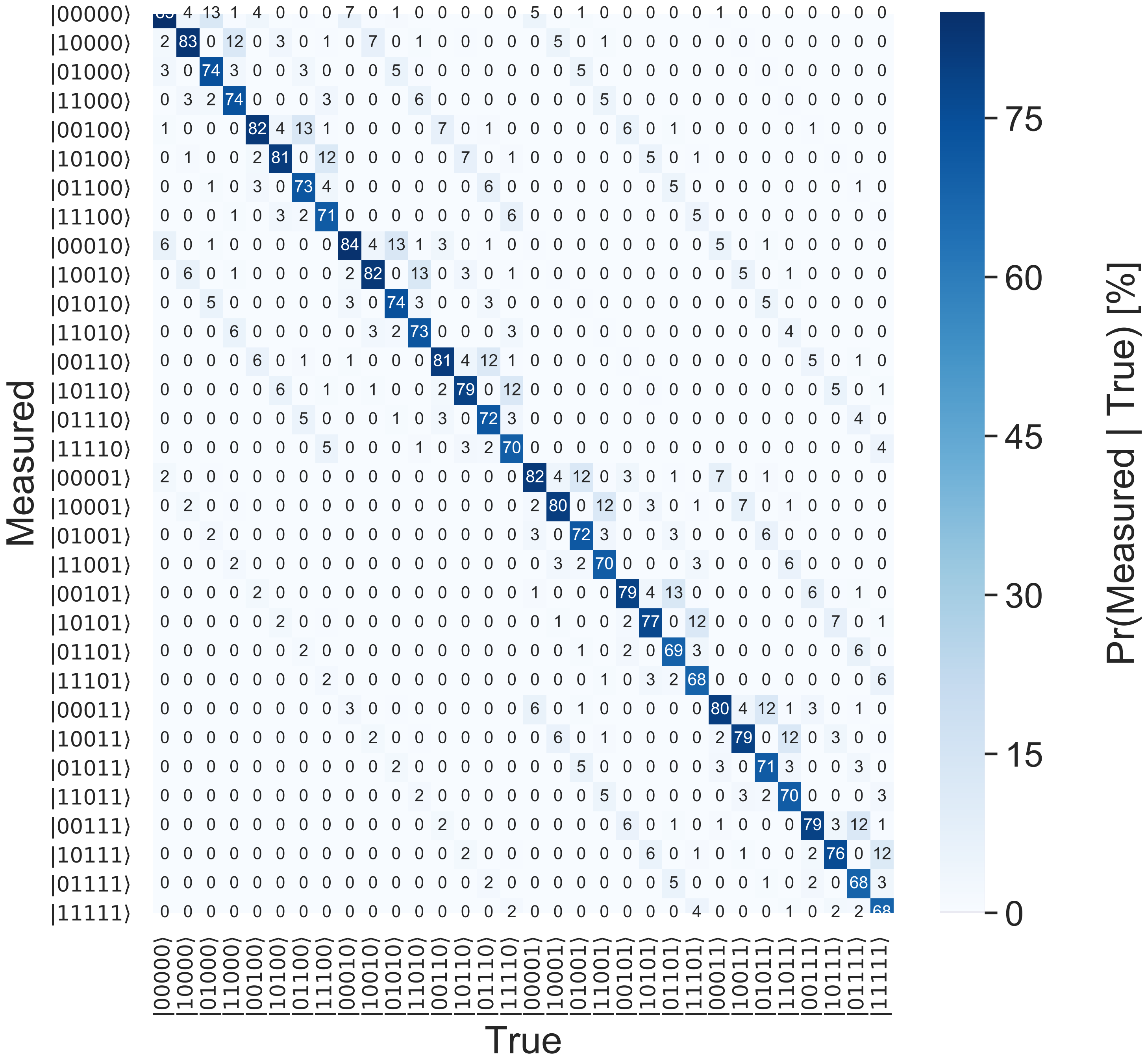
The fine print



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



Qiskit Simulator

IBM Q Johannesburg Readout Errors

	|00000⟩	|10000⟩	|01000⟩	|11000⟩	|00100⟩	|10100⟩	|01100⟩	|11100⟩	|00010⟩	|10010⟩	|01010⟩	|11010⟩	|00110⟩	|10110⟩	|01110⟩	|11110⟩	|00001⟩	|10001⟩	|01001⟩	|11001⟩	|00101⟩	|10101⟩	|01101⟩	|11101⟩	|00011⟩	|10011⟩	|01011⟩	|11011⟩	|00111⟩	|10111⟩	|01111⟩	|11111⟩
|00000⟩	[illegible]	4	13	1	4	0	0	0	7	0	1	0	0	0	0	0	5	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0
|10000⟩	2	83	0	12	0	3	0	1	0	7	0	1	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0	0	0	0	0	0
|01000⟩	3	0	74	3	0	0	3	0	0	0	5	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0
|11000⟩	0	3	2	74	0	0	0	3	0	0	0	6	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
|00100⟩	1	0	0	0	82	4	13	1	0	0	0	0	7	0	1	0	0	0	0	0	6	0	1	0	0	0	0	0	1	0	0	0
|10100⟩	0	1	0	0	2	81	0	12	0	0	0	0	0	7	0	1	0	0	0	0	0	5	0	1	0	0	0	0	0	0	0	0
|01100⟩	0	0	1	0	3	0	73	4	0	0	0	0	0	0	6	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	1	0
|11100⟩	0	0	0	1	0	3	2	71	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0
|00010⟩	6	0	1	0	0	0	0	0	84	4	13	1	3	0	1	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0	0
|10010⟩	0	6	0	1	0	0	0	0	2	82	0	13	0	3	0	1	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0
|01010⟩	0	0	5	0	0	0	0	0	3	0	74	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0
|11010⟩	0	0	0	6	0	0	0	0	0	3	2	73	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0
|00110⟩	0	0	0	0	6	0	1	0	1	0	0	0	81	4	12	1	0	0	0	0	0	0	0	0	0	0	0	0	5	0	1	0
|10110⟩	0	0	0	0	0	6	0	1	0	1	0	0	2	79	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	1
|01110⟩	0	0	0	0	0	0	5	0	0	0	1	0	3	0	72	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
|11110⟩	0	0	0	0	0	0	0	5	0	0	0	1	0	3	2	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
|00001⟩	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	82	4	12	0	3	0	1	0	7	0	1	0	0	0	0	0
|10001⟩	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	80	0	12	0	3	0	1	0	7	0	1	0	0	0	0
|01001⟩	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	72	3	0	0	3	0	0	0	6	0	0	0	0	0
|11001⟩	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	70	0	0	0	3	0	0	0	6	0	0	0	0
|00101⟩	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	79	4	13	0	0	0	0	0	6	0	1	0
|10101⟩	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	77	0	12	0	0	0	0	0	7	0	1
|01101⟩	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	69	3	0	0	0	0	0	0	6	0
|11101⟩	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	3	2	68	0	0	0	0	0	0	0	6
|00011⟩	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	6	0	1	0	0	0	0	0	80	4	12	1	3	0	1	0
|10011⟩	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	6	0	1	0	0	0	0	2	79	0	12	0	3	0	0
|01011⟩	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0	0	0	0	0	3	0	71	3	0	0	3	0
|11011⟩	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0	0	0	0	0	3	2	70	0	0	0	3
|00111⟩	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	6	0	1	0	1	0	0	0	79	3	12	1
|10111⟩	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	6	0	1	0	1	0	0	2	76	0	12
|01111⟩	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0	0	0	1	0	2	0	68	3
|11111⟩	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0	0	0	1	0	2	2	68

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

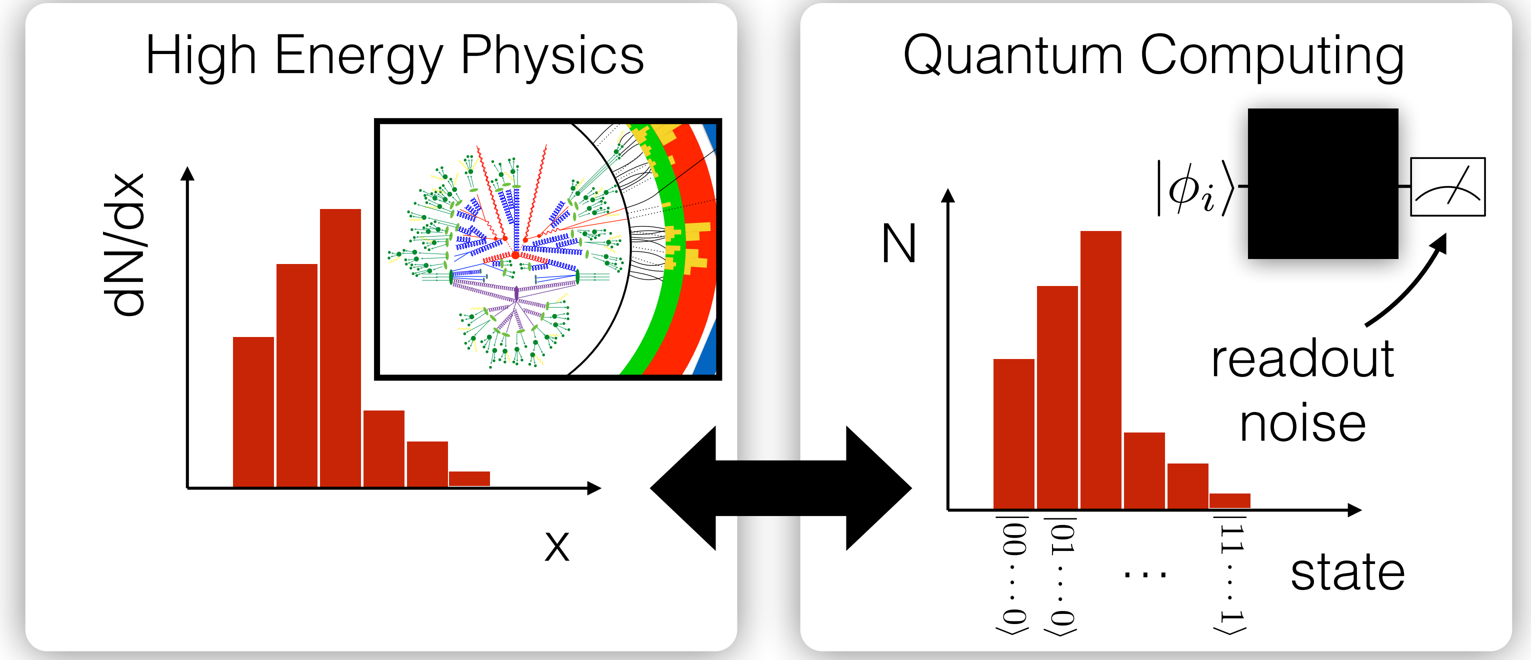
For n qubits, there is a 2^n x 2^n transition matrix.

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



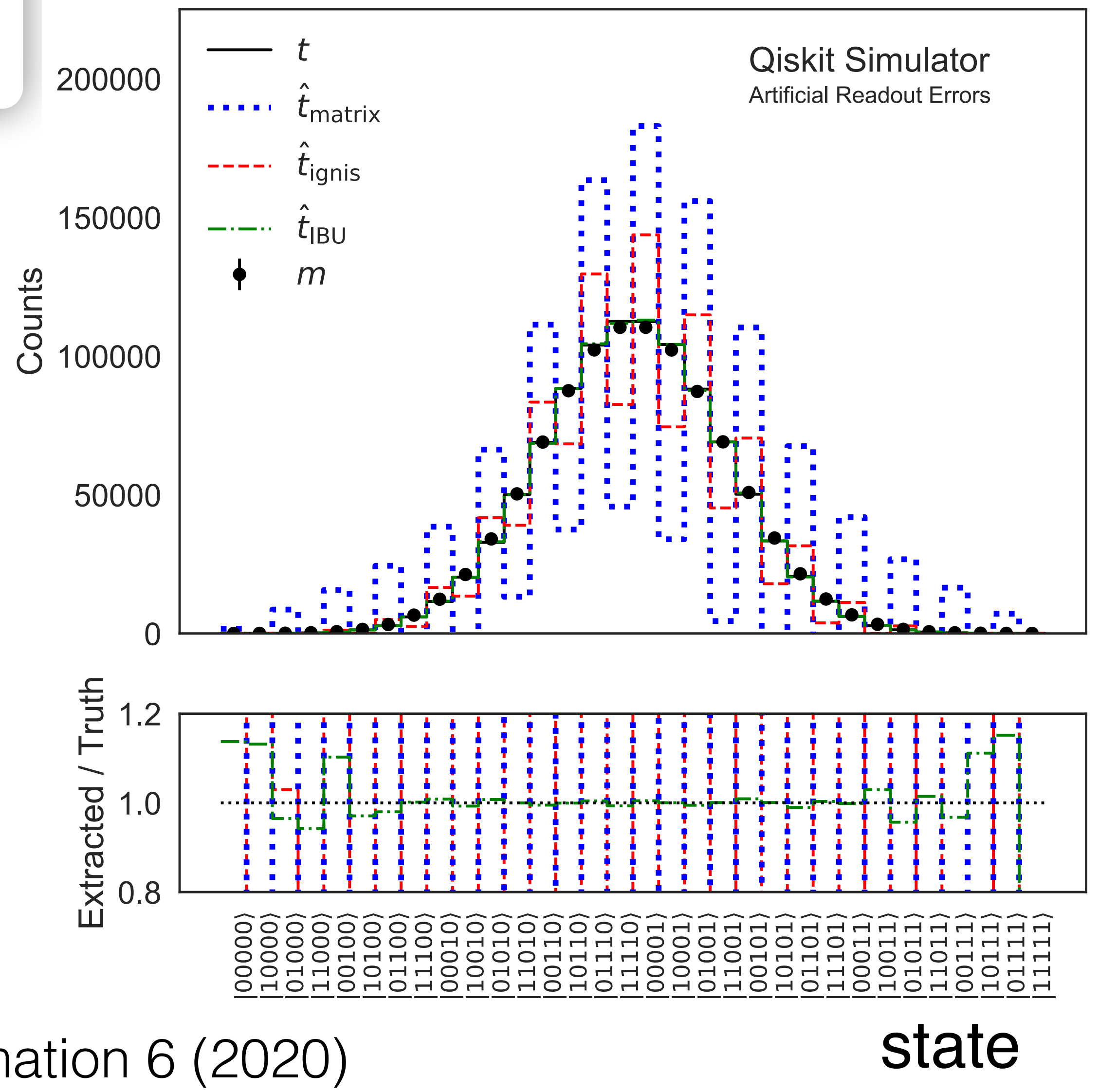
Naïve inversion

IBM standard

HEP standard

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

→ Circumvent known pathologies with more naïve methods (!)

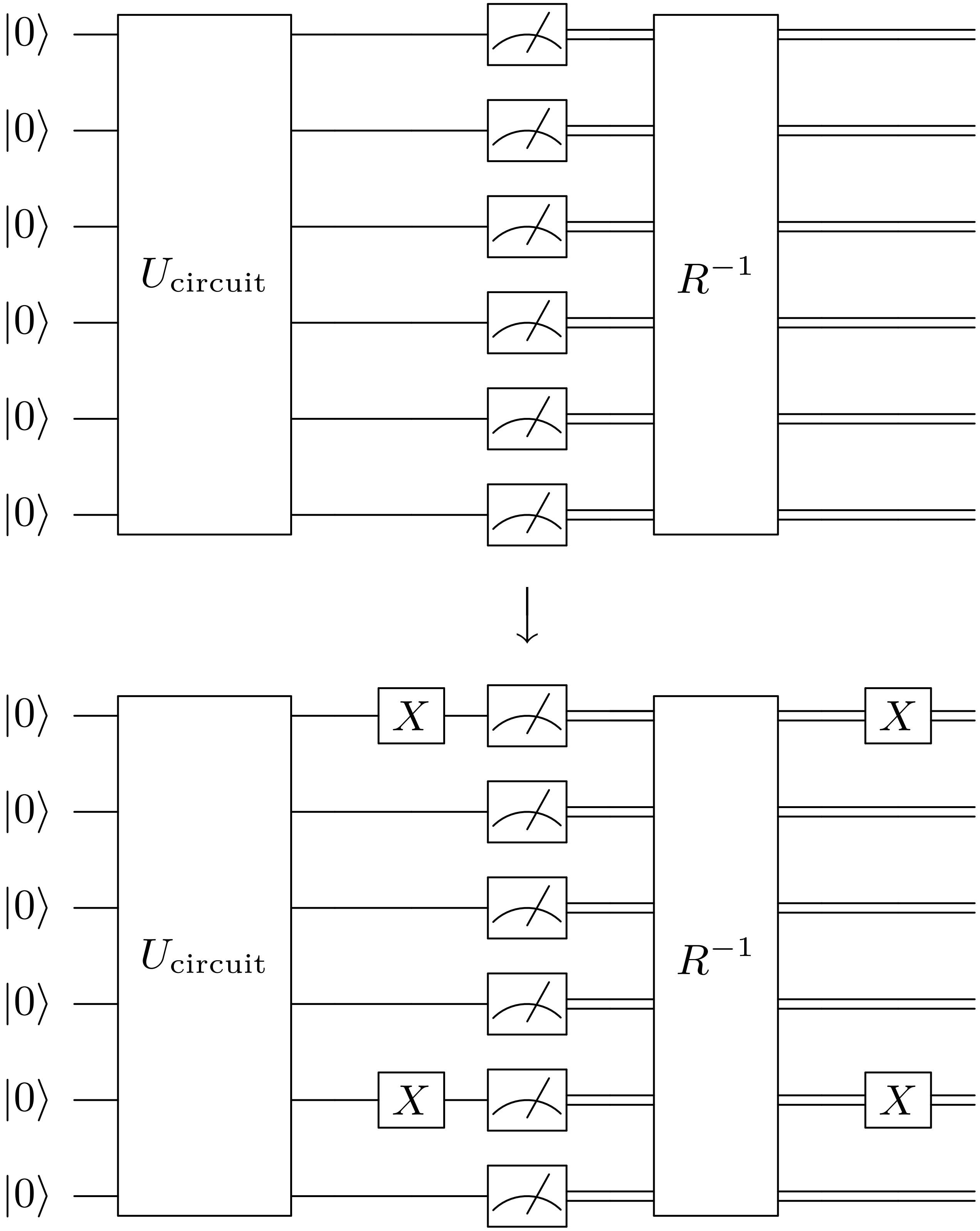


BPN, M. Urbanek, W. de Jong, C. Bauer, npj Quantum Information 6 (2020)

More on readout errors

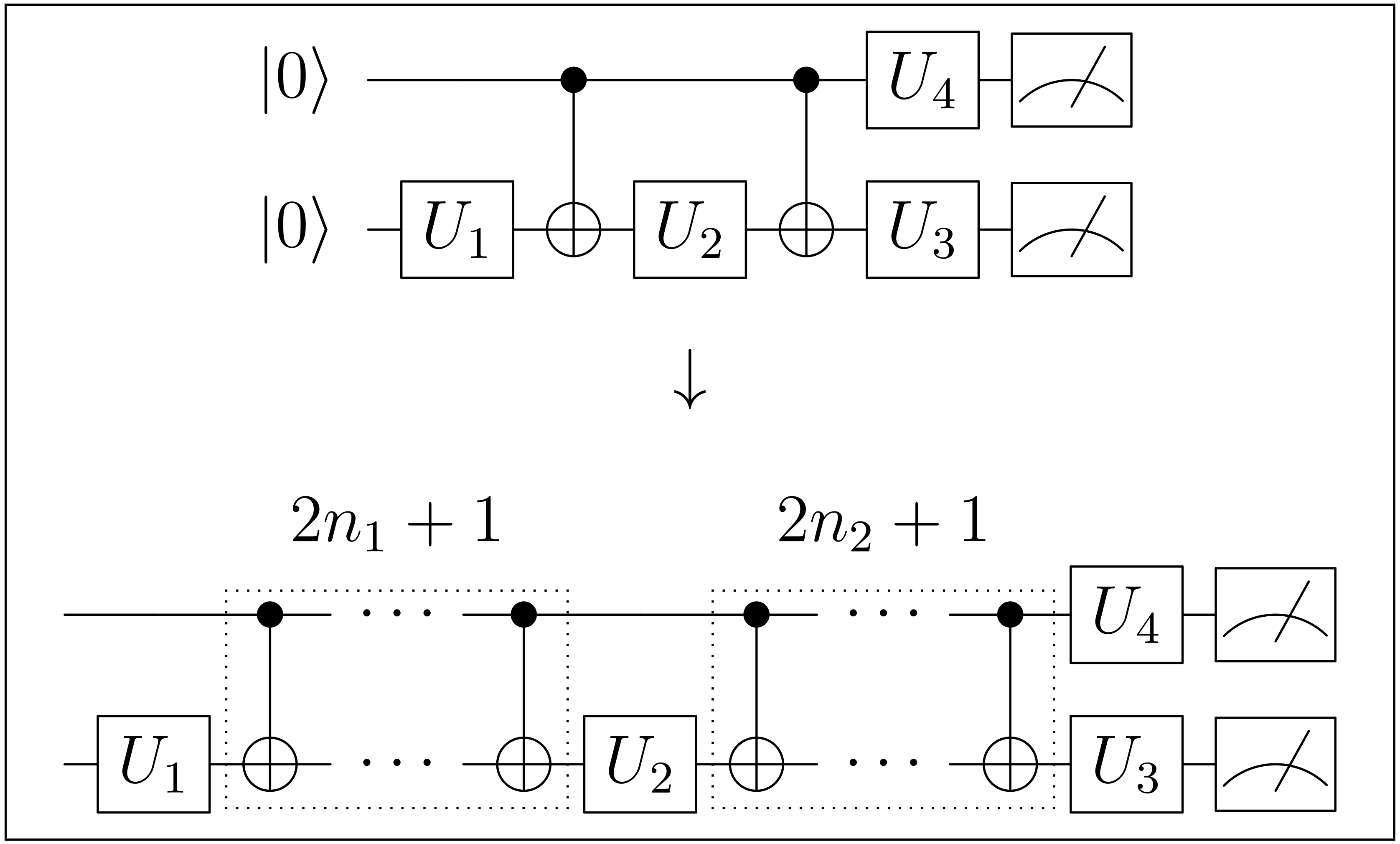
We are still actively developing methods to reduce readout errors.

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**, arXiv:2010.tomorrow

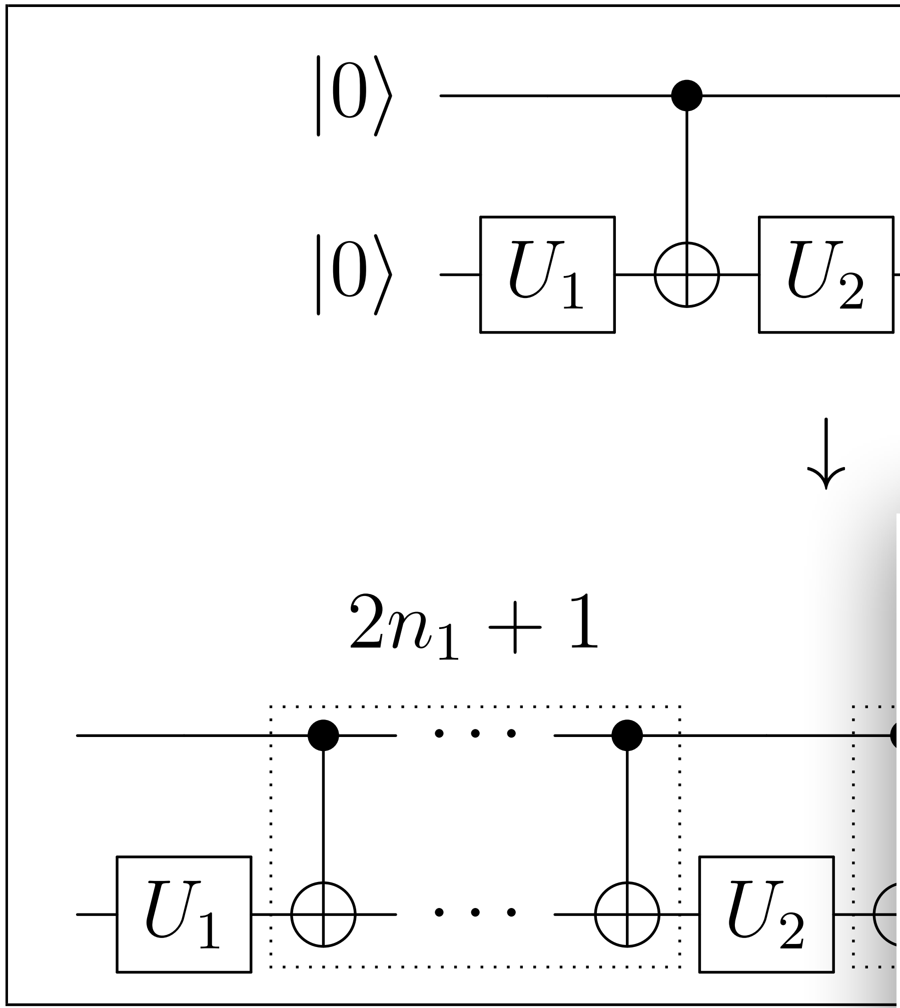
Gate error mitigation

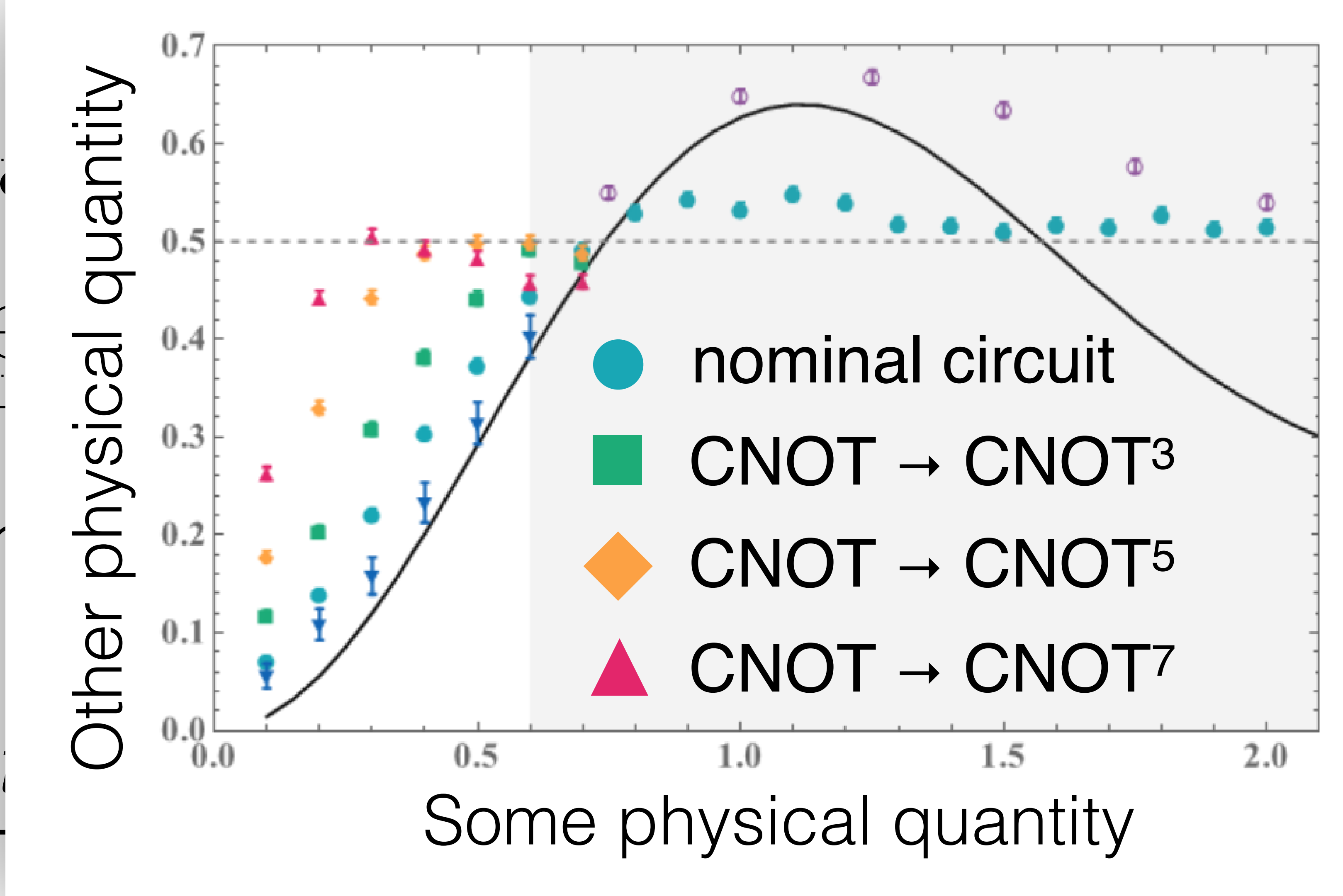


One common technique is **Zero Noise Extrapolation**

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 error mitigation





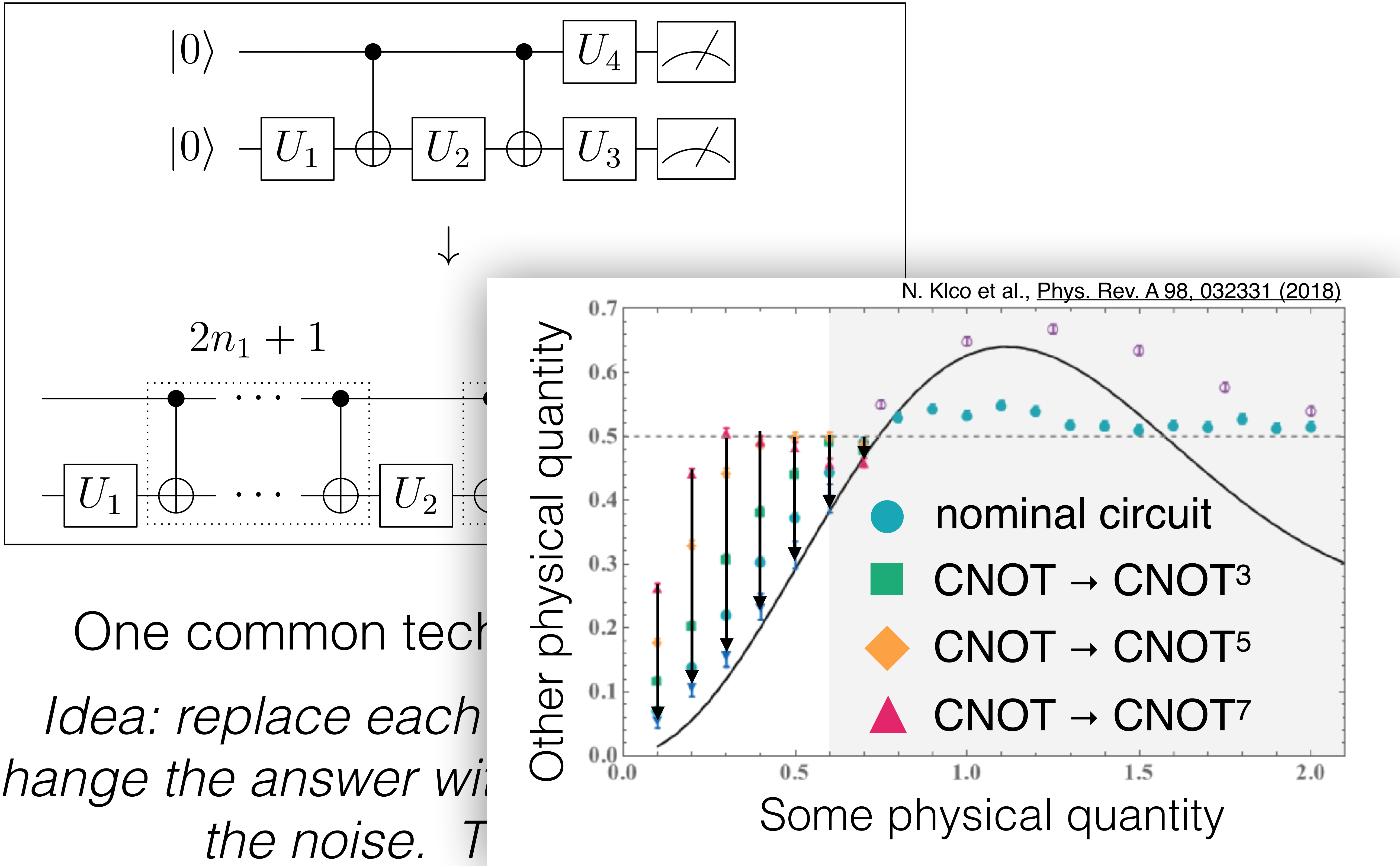
One common tech

Idea: replace each

change the answer wi *s*

the noise. T

Gate error mitigation



N. Klco et al., Phys. Rev. A 98, 032331 (2018)

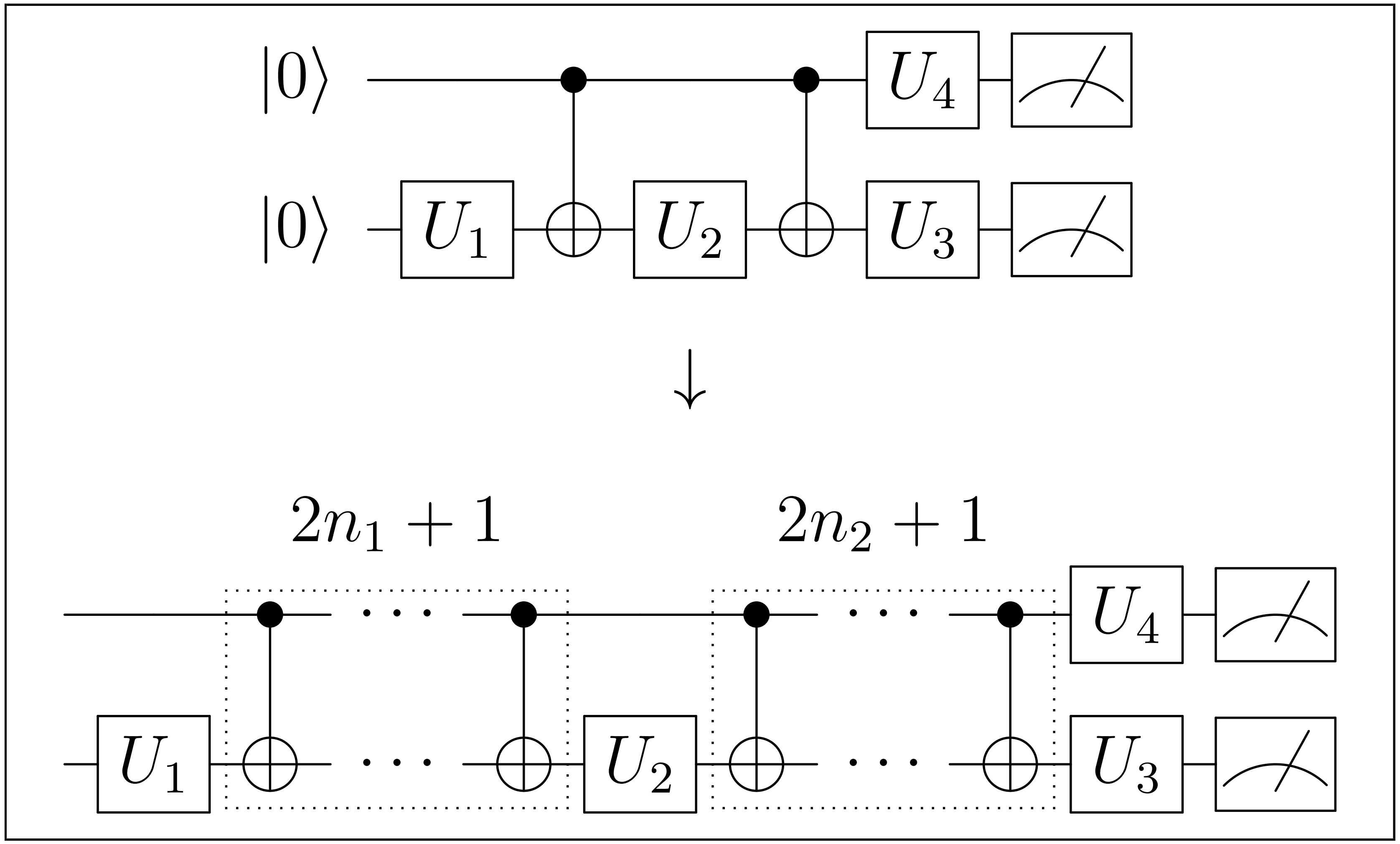
One common tech

Idea: replace each

change the answer wi *s*

the noise. T

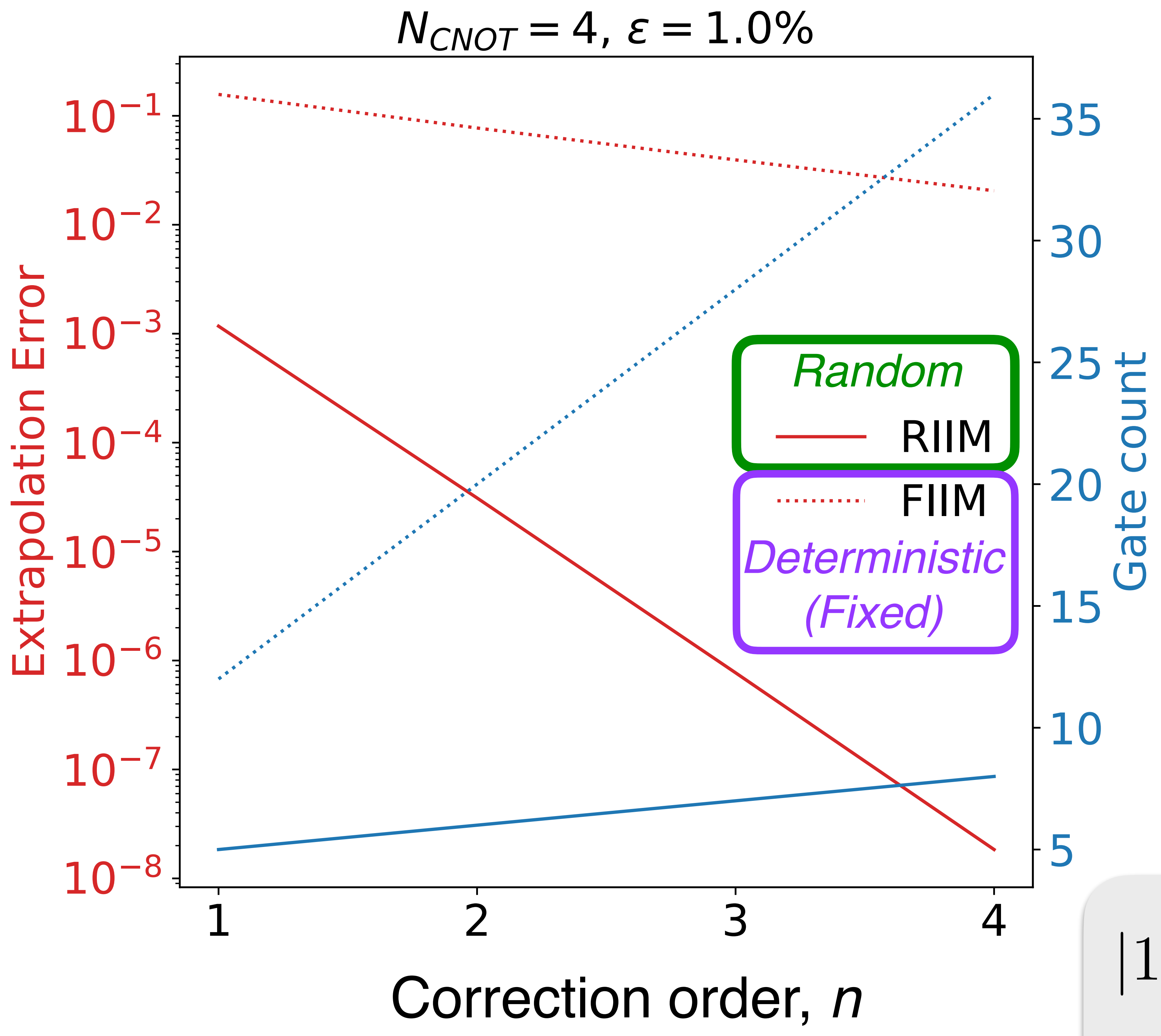
Gate error mitigation



One common technique is **Zero Noise Extrapolation**

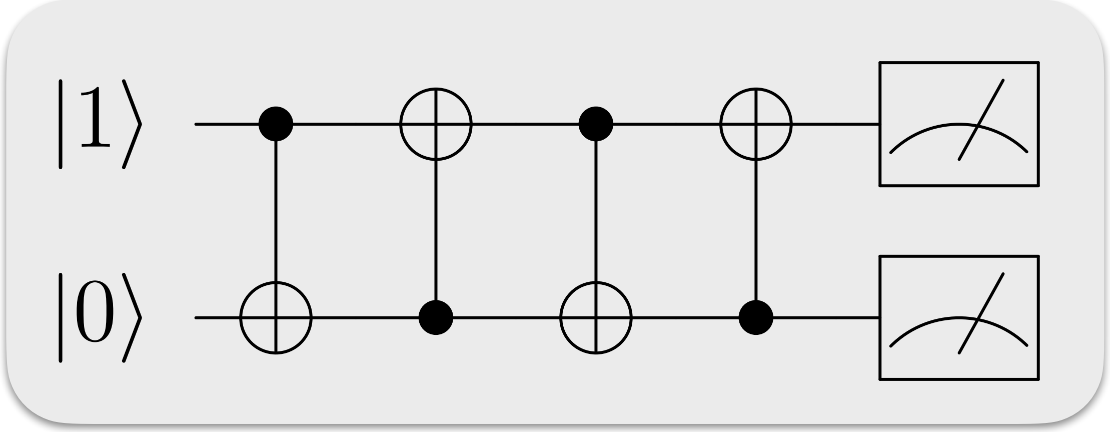
New idea: promote n_i to a ***random variable****. Instead of replacing every CNOT deterministically, randomly replace.*

Gate error mitigation



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

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

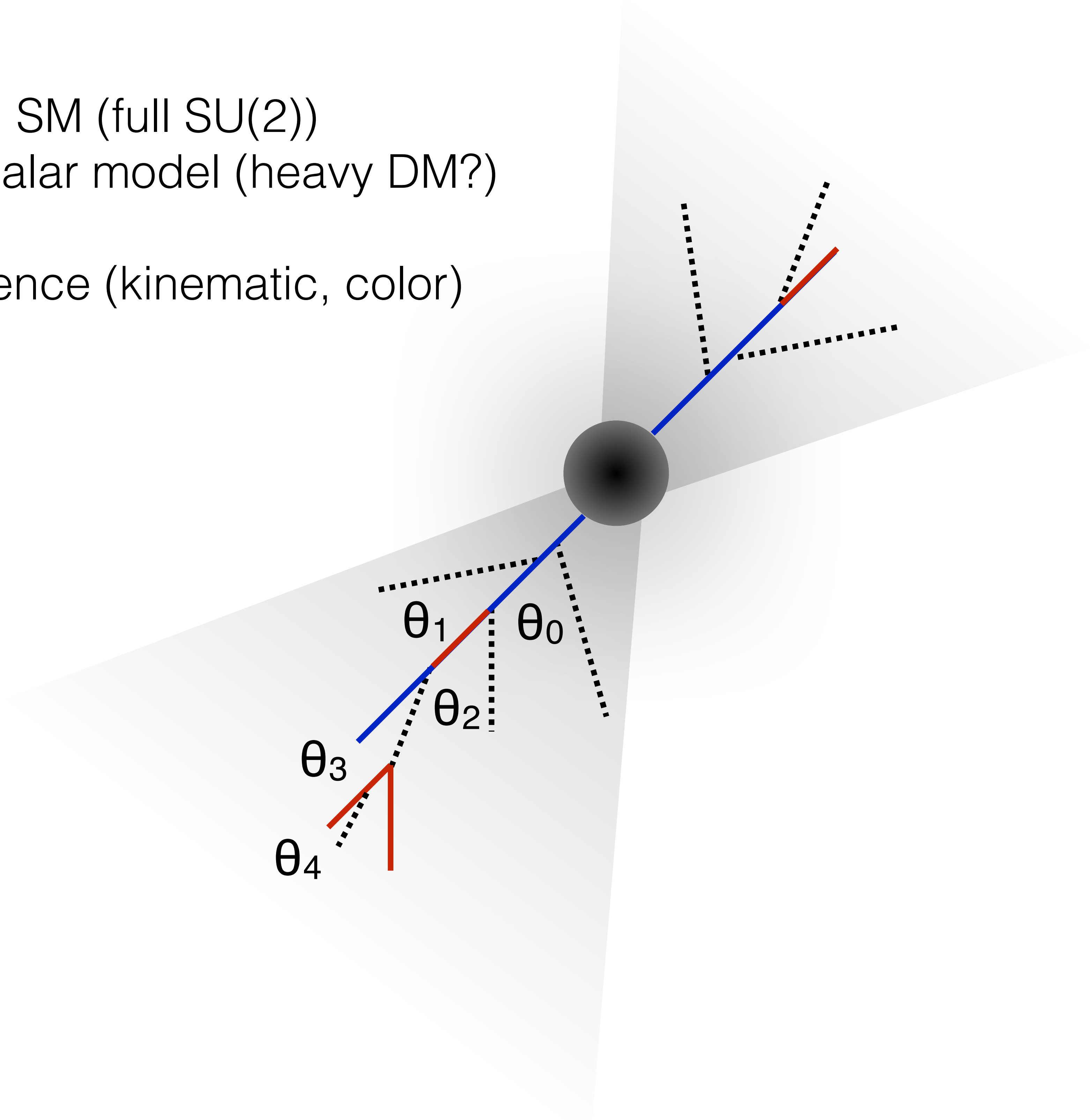


A. He, **BPN**, W. de Jong, C. Bauer, PRA 102 (2020) 012426

Future

Future

- **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
    - Hybrid lattice methods



Future

- **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)
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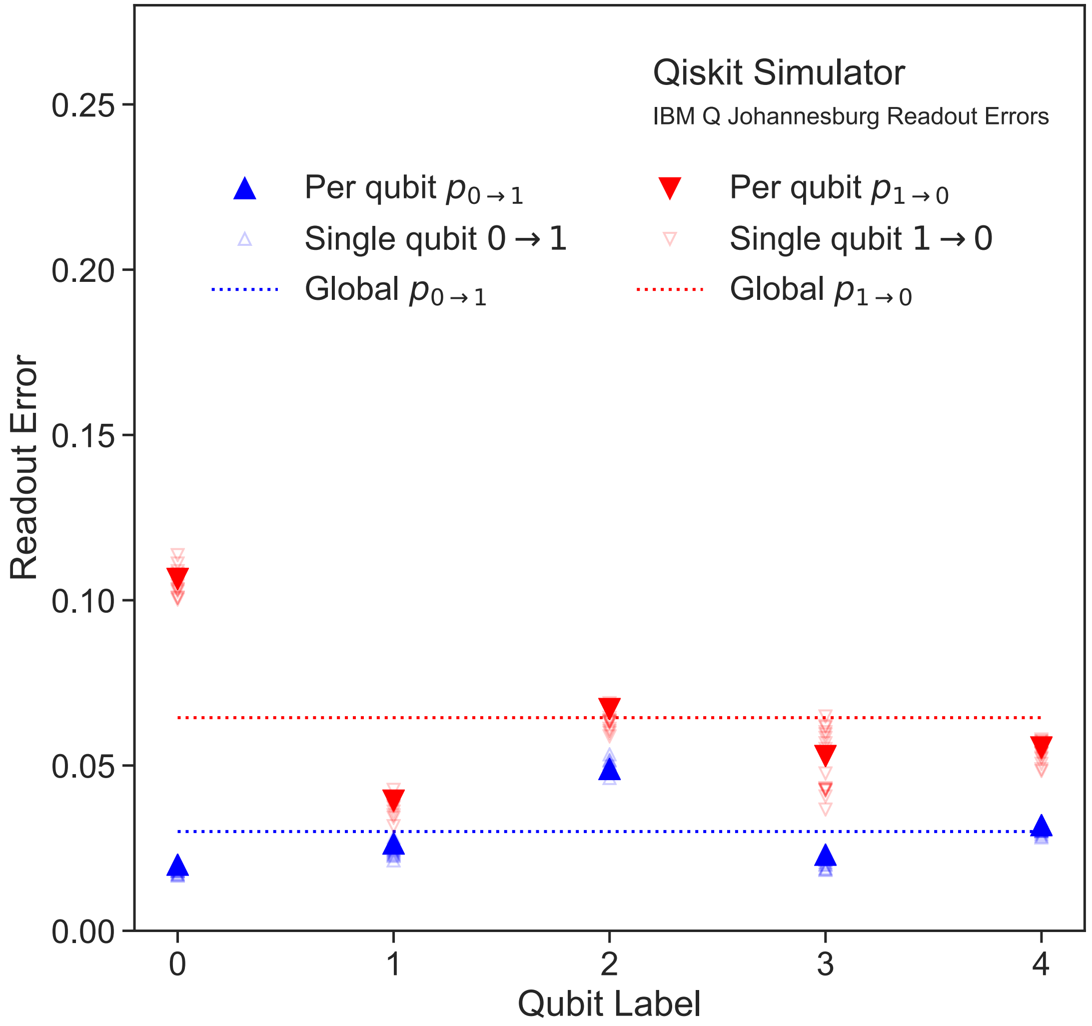
  - Readout errors
    - Subexponential unfolding
  - Gate errors
    - Parallel zero noise extrapolation
    - Interplay of active & passive mitigation



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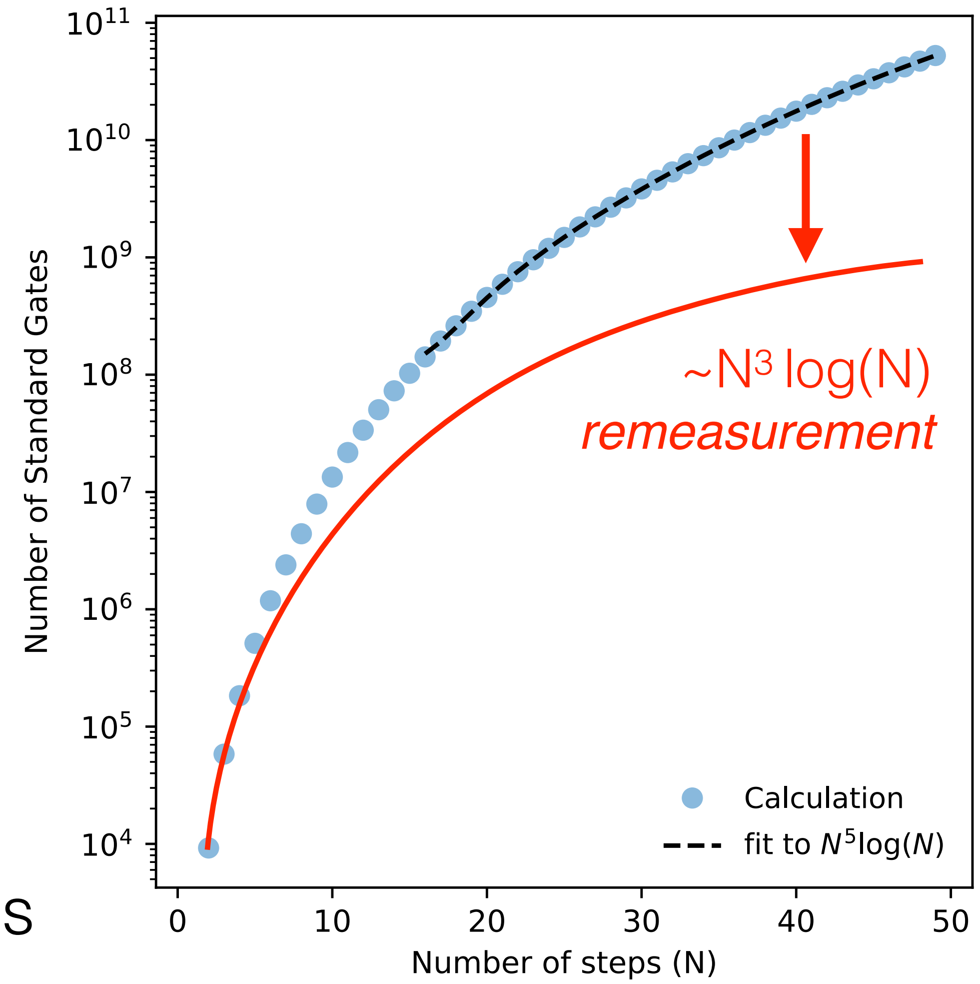
- **Software-hardware interface**
  - Custom operations
    - Resetting qubits, repeated operations, qudits
  - QFT-tailored hardware
    - Optimal lattice



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.

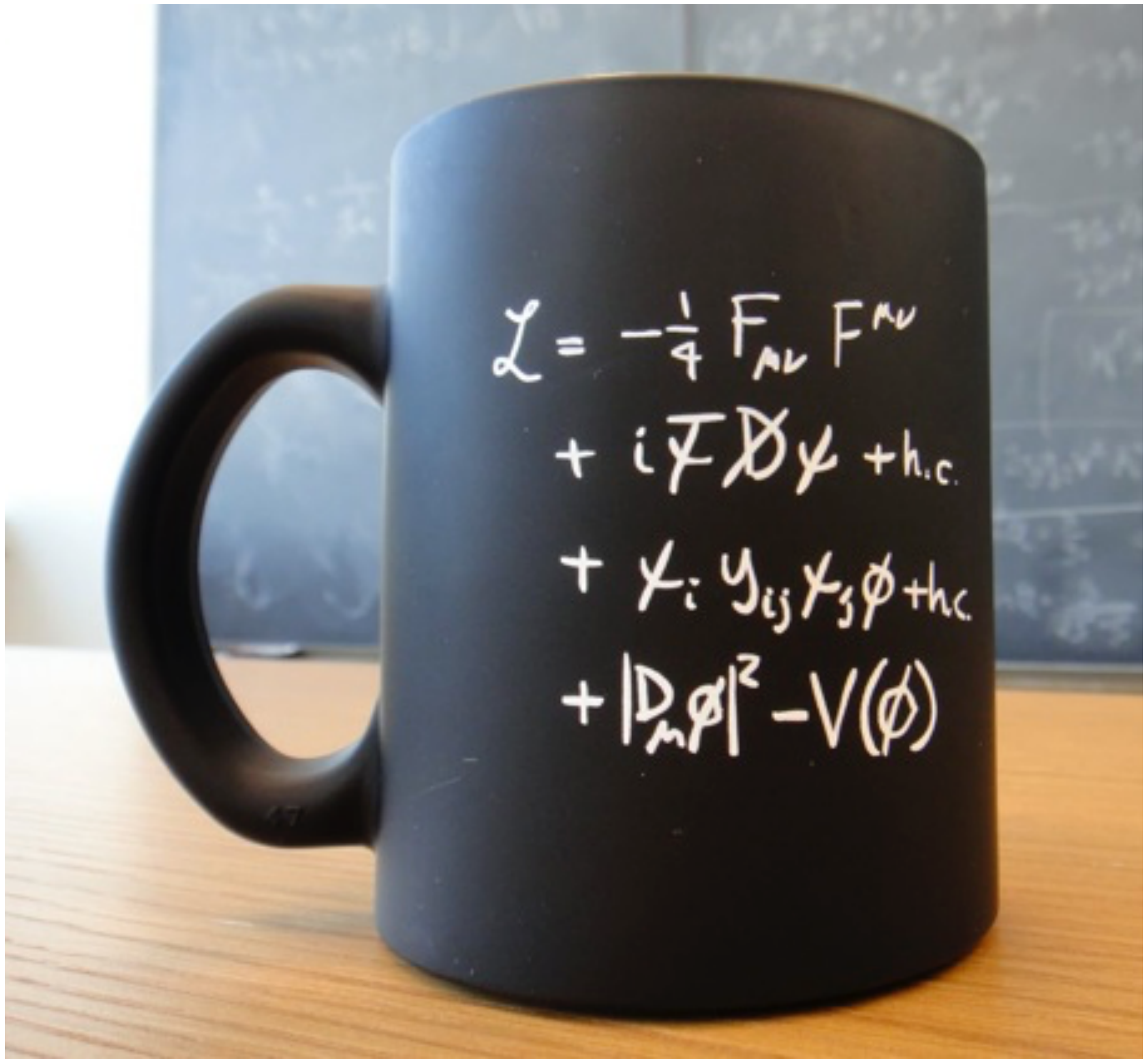
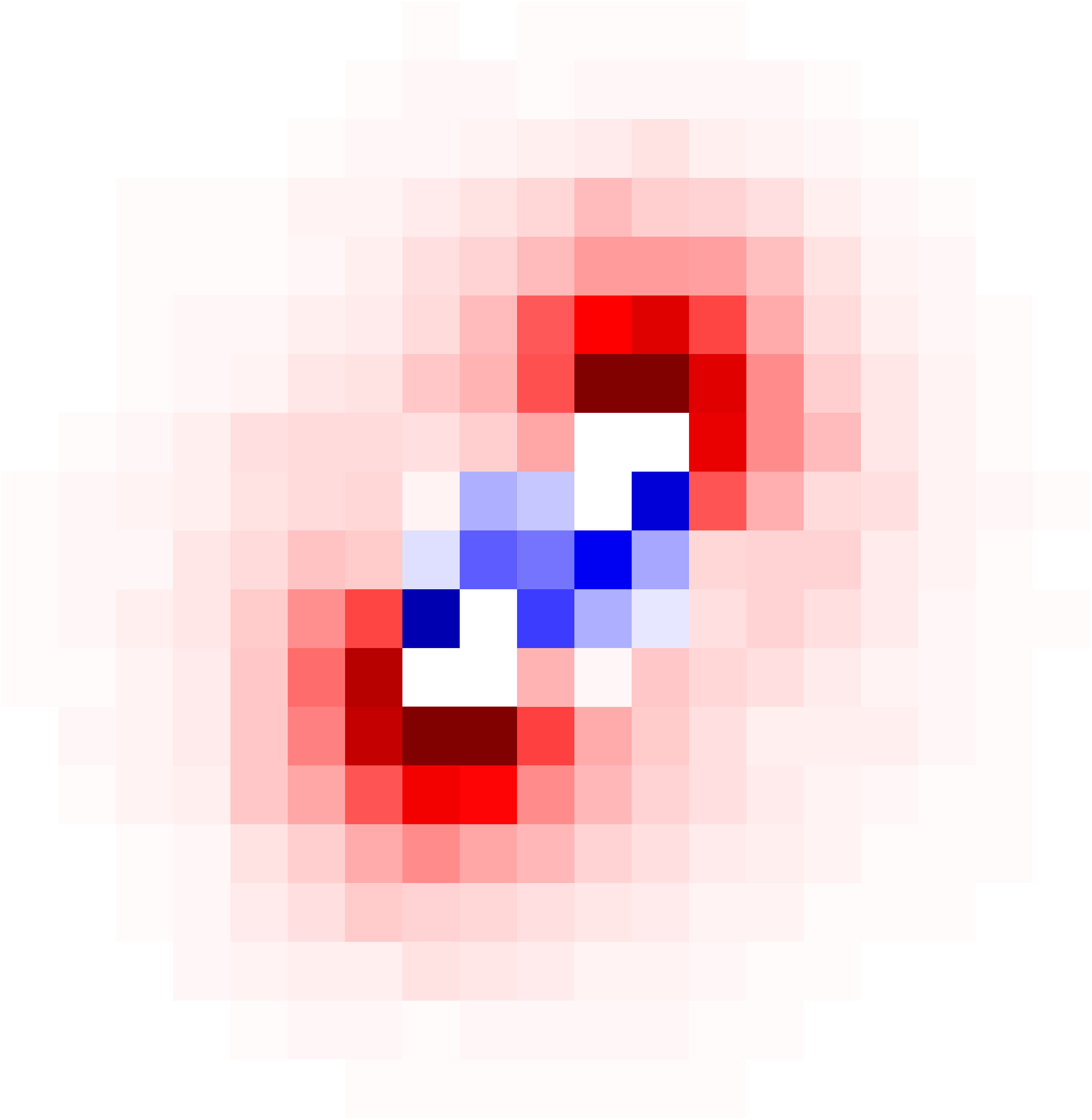


Image credit: Flip Tanedo



Fin.

Backup

Quantum Field Theory

Pro: Full theory

Con: Dynamics are too hard

(already using supercomputers)

Lattice

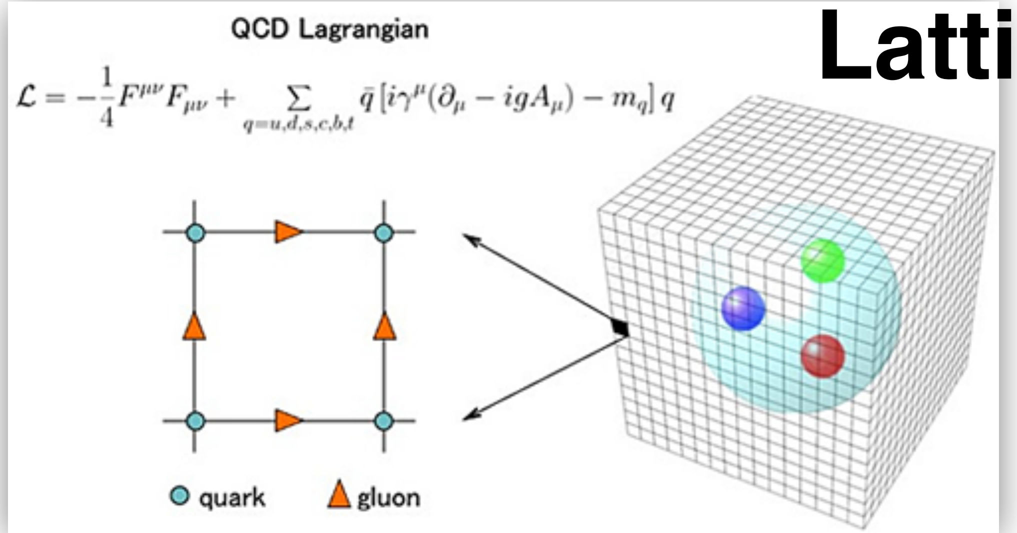


Image credit: http://lpc-clermont.in2p3.fr/IMG/theorie/LQCD2.jpg

Pro: Can do high-energy dynamics

Con: An approximation

Perturbation theory

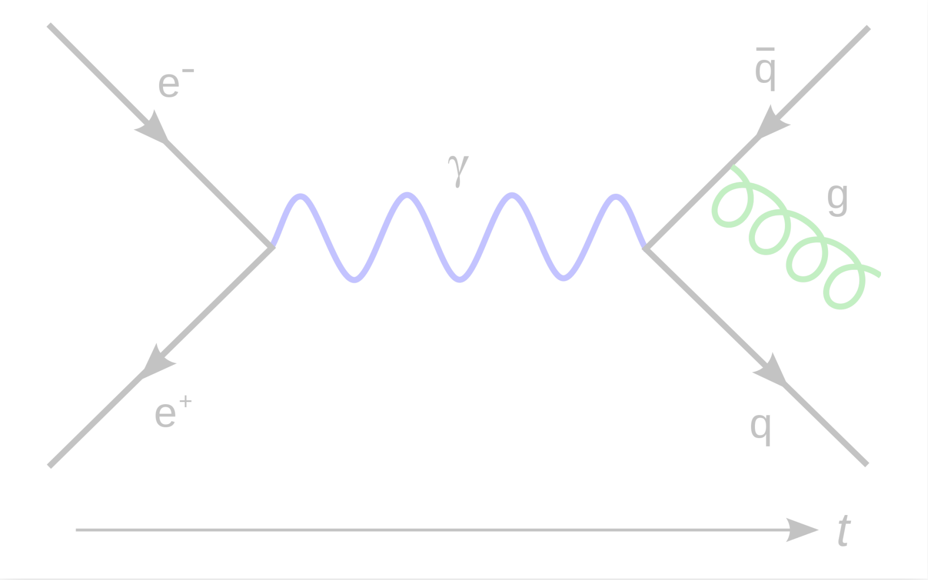


Image credit: https://en.wikipedia.org/wiki/Feynman_diagram

Lattice QFT with a Quantum Computer

Pioneering work by Preskill & collaborators
(Science 336 (2012) 1130).

Number of quantum gates to reach precision **e** in d+1 dimensions

$$\sim \begin{cases} \left(\frac{1}{\epsilon}\right)^{1.5+o(1)}, & d=1\,, \\ \left(\frac{1}{\epsilon}\right)^{2.376+o(1)}, & d=2\,, \\ \left(\frac{1}{\epsilon}\right)^{3.564+o(1)}, & d=3\,. \end{cases}$$

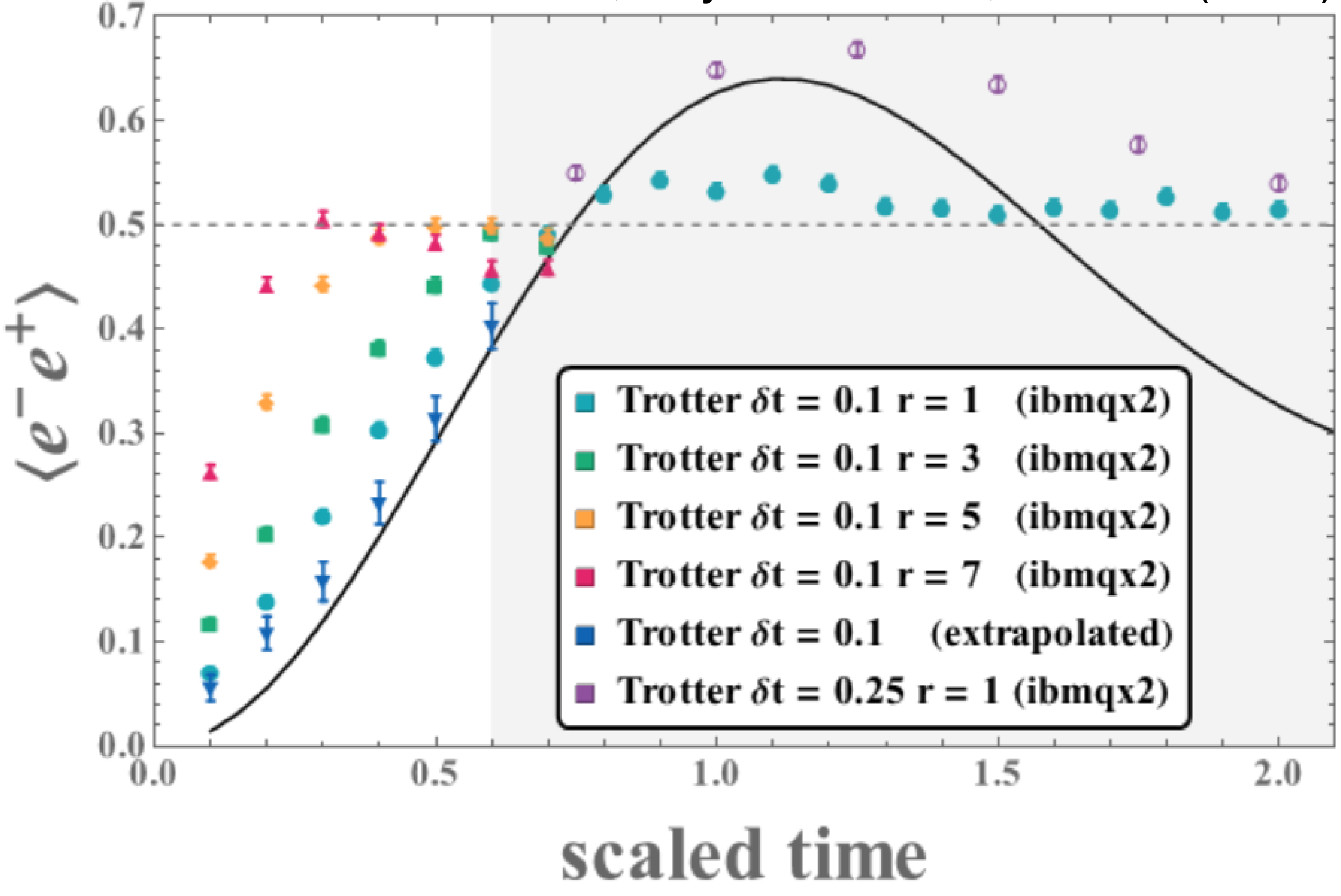
$$H=\sum_{\mathbf{x}\in\Omega} a^d\left[\frac{1}{2}\pi(\mathbf{x})^2+\frac{1}{2}(\nabla_a\phi)^2(\mathbf{x})+\frac{1}{2}m_0^2\phi(\mathbf{x})^2+\frac{\lambda_0}{4!}\phi(\mathbf{x})^4\right]$$

This (and subsequent) work is more about formal scaling properties - 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

Klco et al., Phys. Rev. A 98, 032331 (2018)

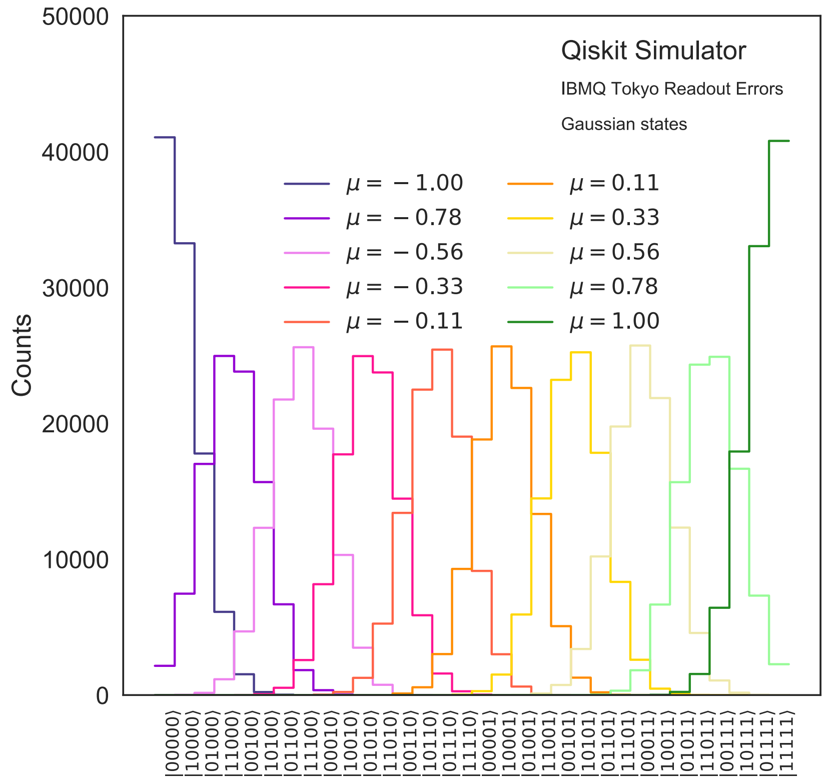


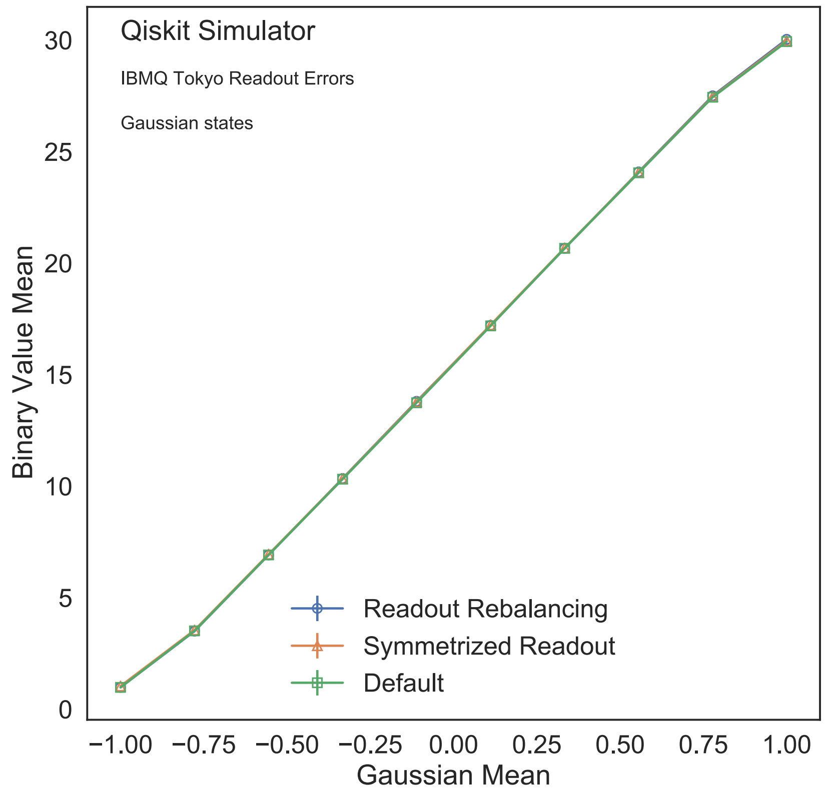
This is the 1+1 Schwinger model; calculating the probability of finding an e^+e^- pair from the vacuum.

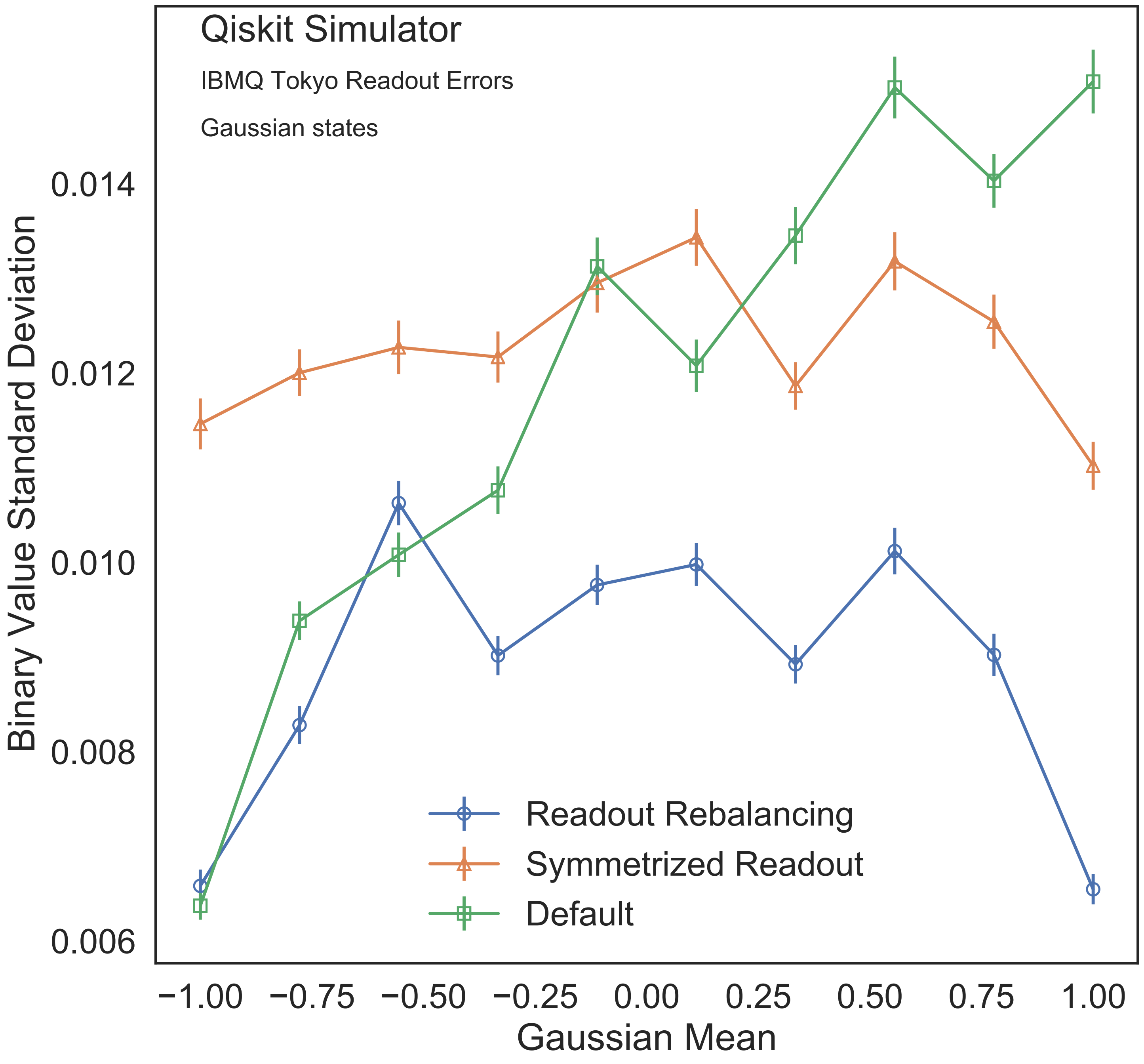
r = "noise ratio"; for r > 1, add extra CNOTs that correspond to the identity operation.

Recent progress by simplifying the problem has led to actual calculations of dynamics on a quantum computer!

Lattice QFT with a Quantum Computer







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