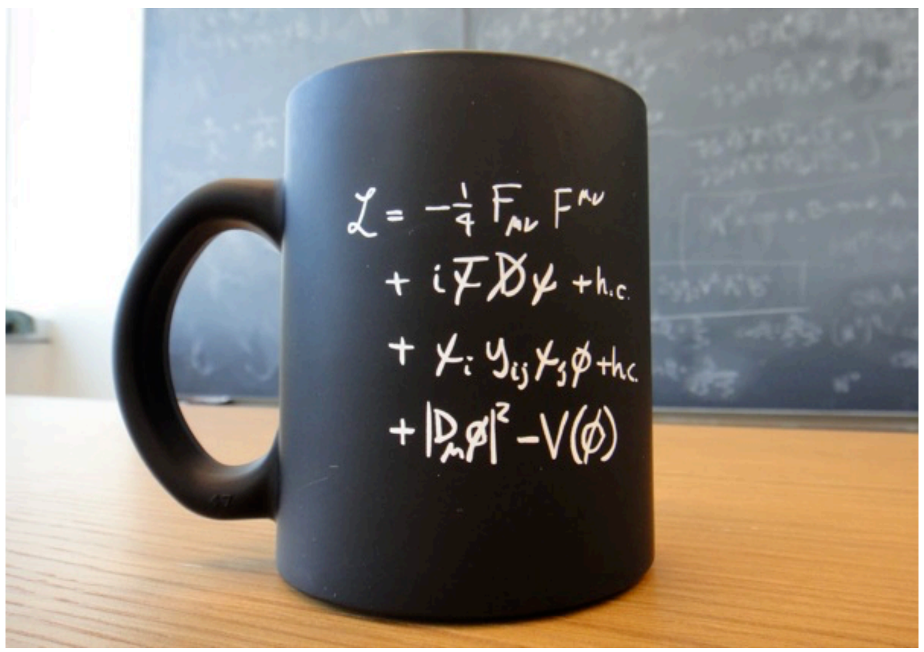
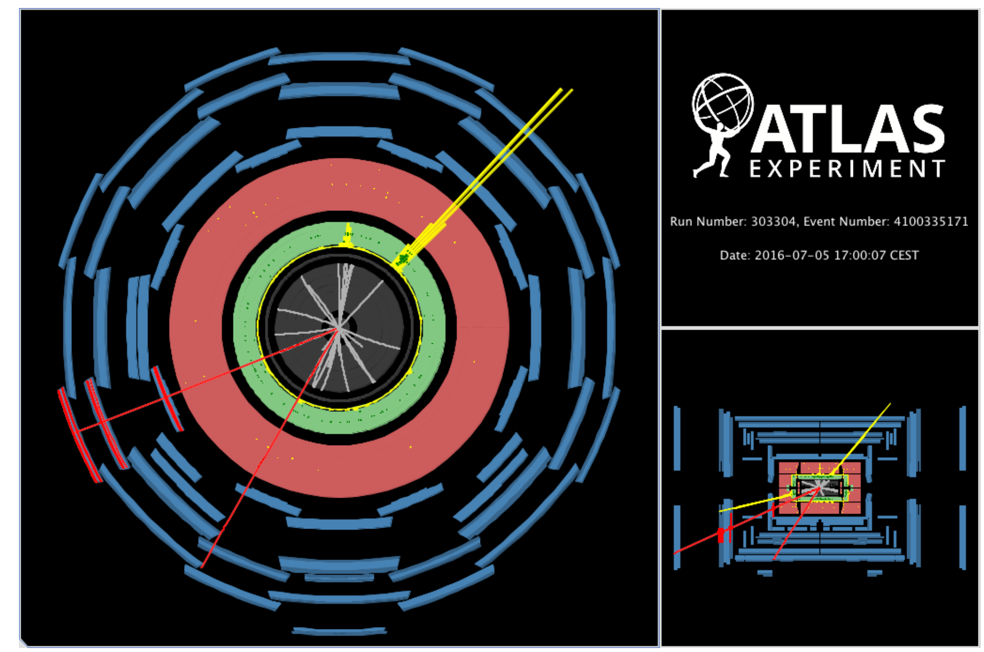
Quantum Computing Applications for HEP simulations

Christian Bauer

Major goal of HEP is to stress-test the SM and to find extensions that we know have to exist

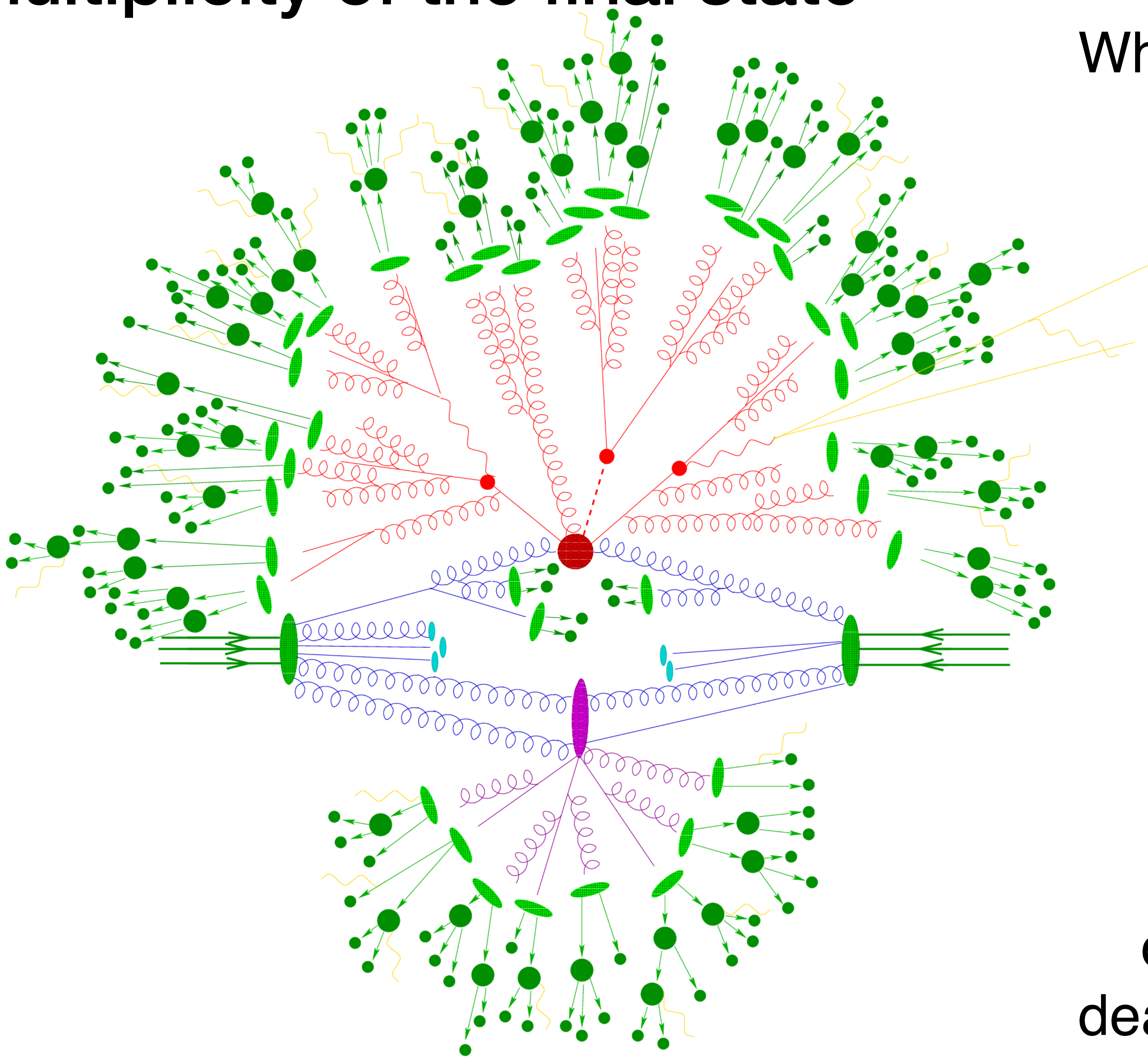
An important requirement in this regard is the ability to compare experimental measurements directly to theoretical predictions





For this, need to be able to go from Lagrangian to fully exclusive events

The issue with simulating full collider events is the high multiplicity of the final state



While the hard interaction only produces small number of particles, subsequent radiation produces lots more in final state.

Essentially impossible to compute full results in perturbation theory for such high multiplicity final states

Need ways to perform calculations that allows to deal with this high multiplicity

No known (classical) algorithm to do the required calculations in full generality

Effective Field Theory treatment to allow quantum simulation of non-perturbative physics

Formulation of Field Theories suited for simulation on quantum devices

HEP Quantum Computing at LBNL

Development of quantum parton showers

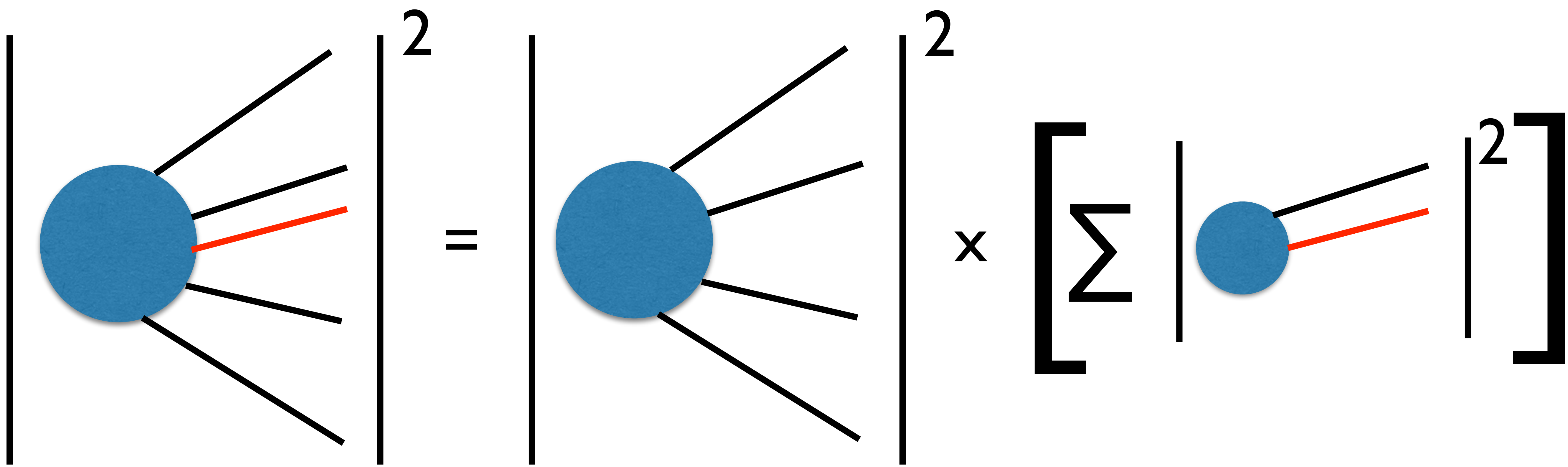
Improving techniques to use NISQ devices for near term simulations

Quantum Computing in Physics Division

Development of quantum parton showers

The usual derivation of parton showers is in terms of the collinear limit

In θ→0 limit, cross sections simplify



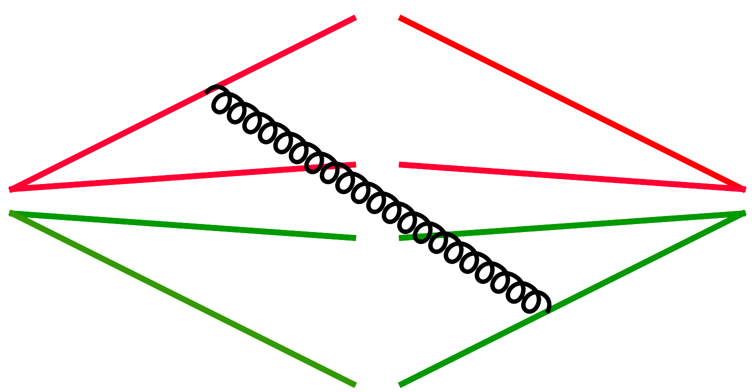
$$\sigma_N = \sigma_{N-1} \times \sum SP(t,z)$$

Conservation of probability:
P(no-emission) + P(≥1emission) = 1

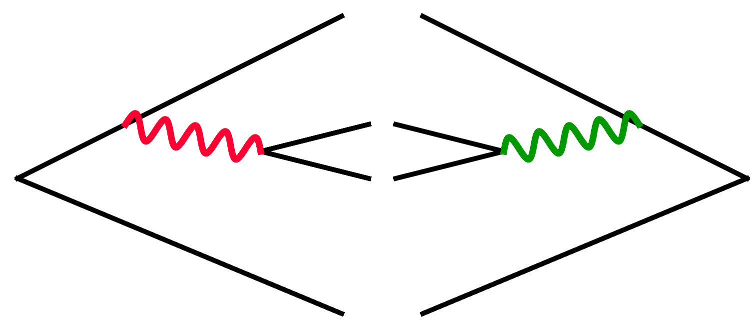
Probabilistic nature of algorithm means most quantum interference effects are lost

Several different interference effects can arise in the parton showers

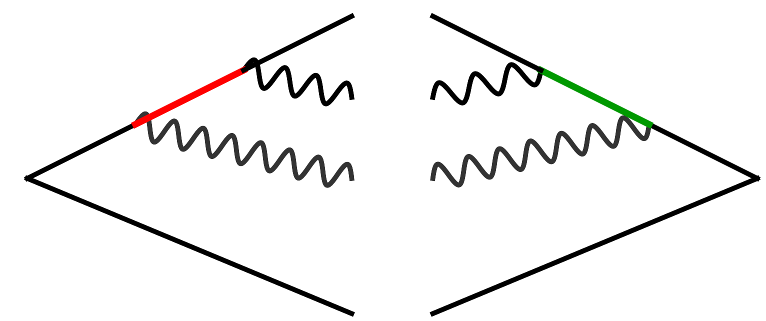
$1/N_C$ effects in dipole showers



γ/Z interference in EW showers



CKM interference in EW showers



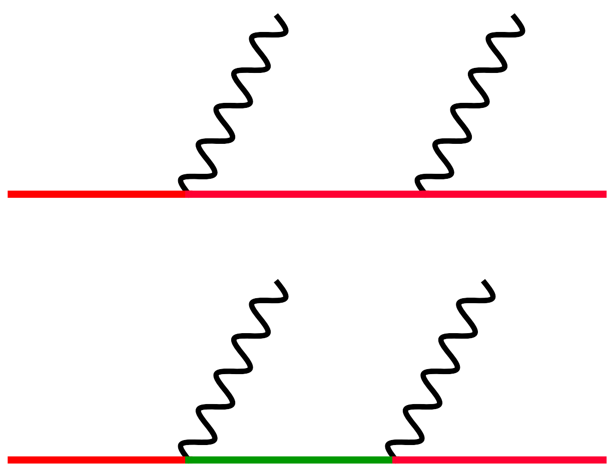
None of them described by traditional parton showers based on probabilistic MC approaches

Consider a simpler toy model that exhibits interference effects similar to the CKM case

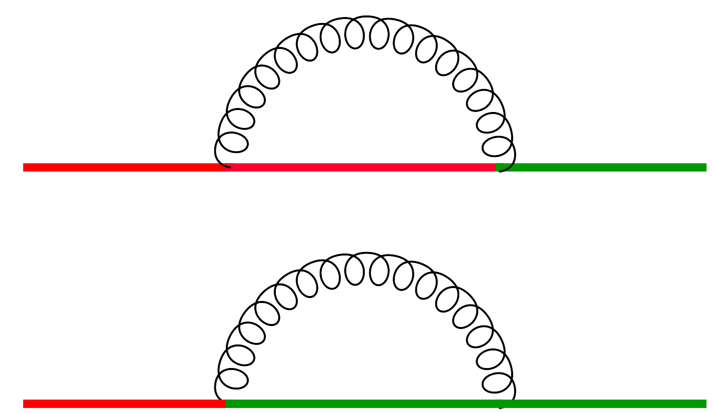
$$\mathcal{L} = \bar{f}_1(i\partial\!\!\!/ + m_1)f_1 + \bar{f}_2(i\partial\!\!\!/ + m_2)f_2 + (\partial_\mu\phi)^2$$
$$+ g_1\bar{f}_1 f_1\phi + g_2\bar{f}_2 f_2\phi + g_{12}\left[\bar{f}_1 f_2 + \bar{f}_2 f_1\right]\phi$$

The mixing g_{12} gives several interesting effects

Different real emission amplitudes give rise to interference



Virtual diagrams give rise to flavor change without radiation



Need to correct both real and virtual effects

Similar to including subleading color

Including the full interference effects of this toy model takes exponential resources classically using best algorithms

For each final state fermion, there are 2 possible amplitudes

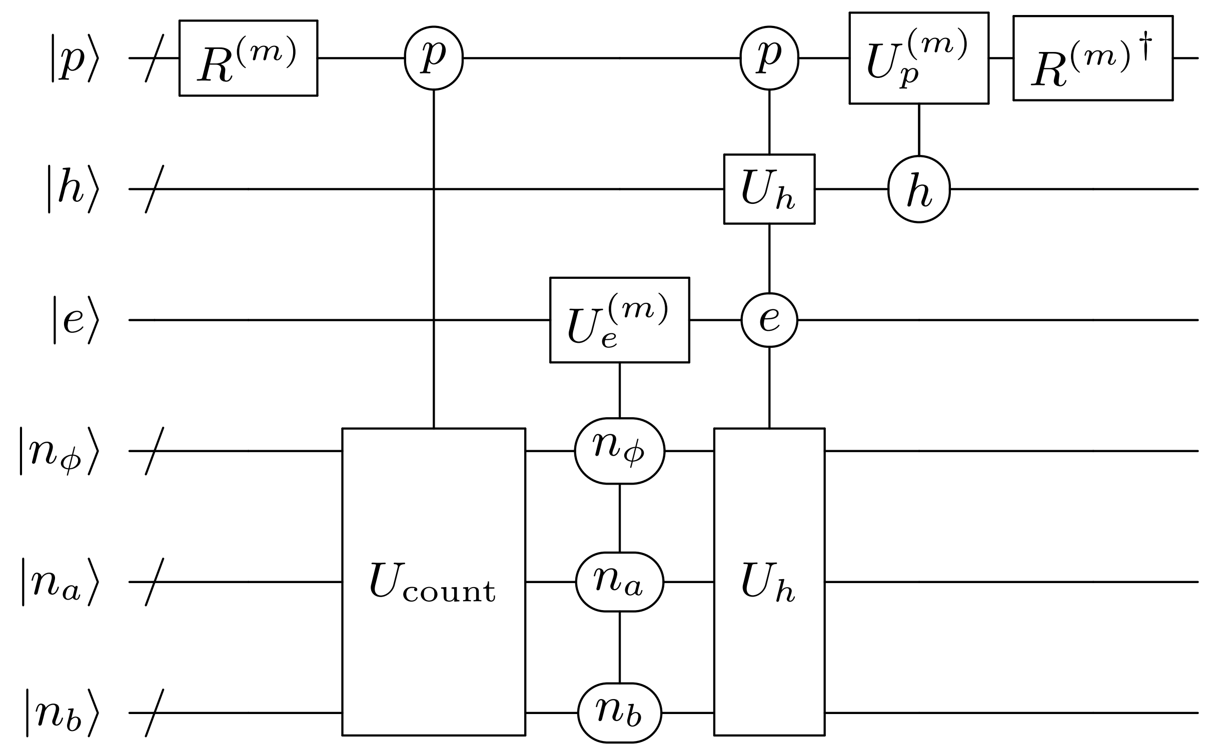
For N final state fermions, there are 2^N possible amplitudes that contribute

Best known classical algorithms scale with the number of amplitudes present

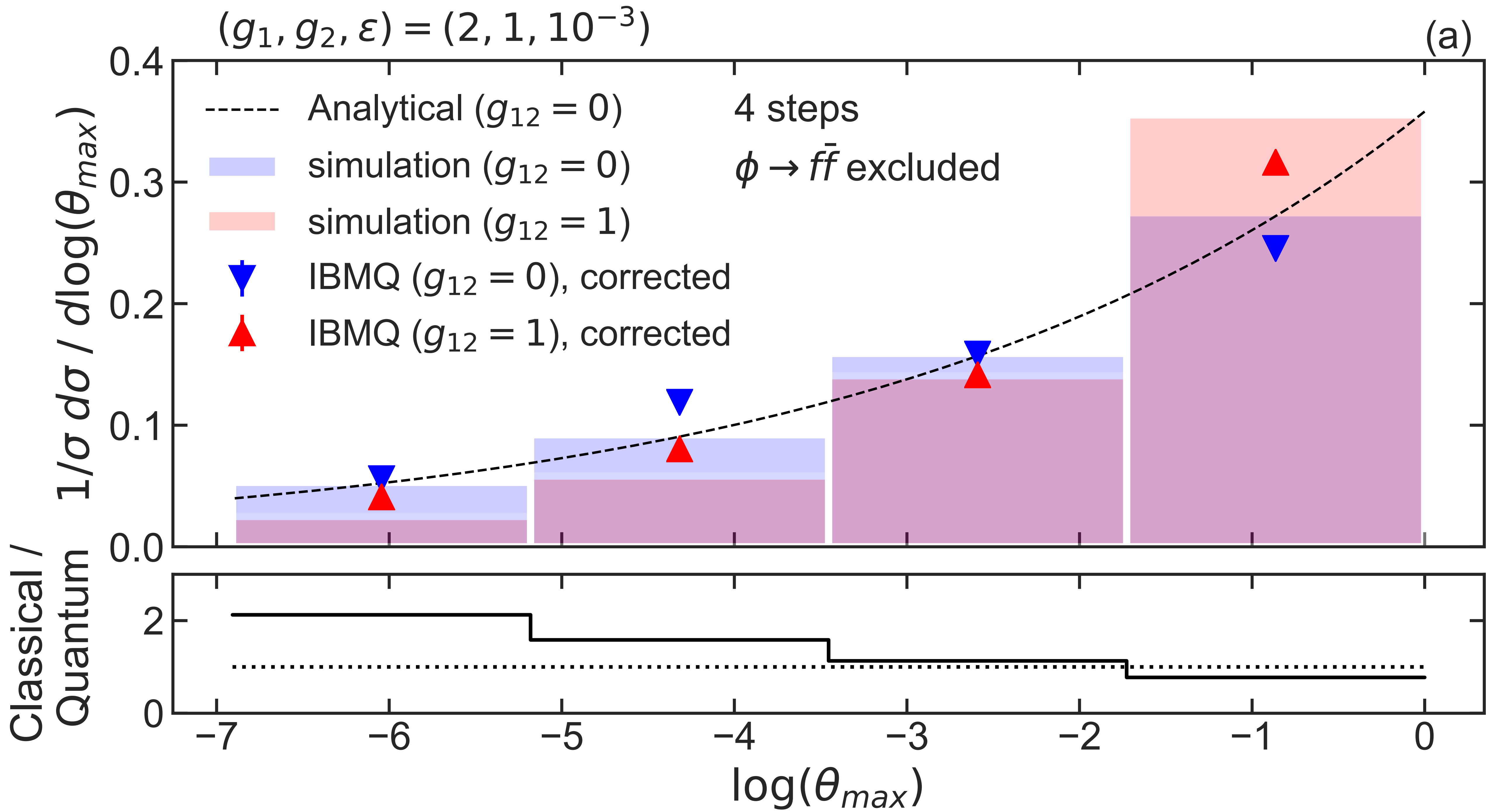
Makes impossible for classical shower to compute the relevant physics

A quantum computer can compute the 2^N amplitudes using polynomial number of operators

CWB, Freytsis, Nachmann, PRL 127, 212001



Operation	Scaling
count particles U_{count}	N lnN
decide emission U_e	N^4 lnN
create history U_h	N^5 lnN
adjust particles U_p	N^2 lnN



CWB, Freytsis, Nachmann, PRL 127, 212001

Currently working on improved algorithms, which take advantage of recently added remeasuring capabilities

Effective Field Theory treatment to allow quantum simulation of non-perturbative physics

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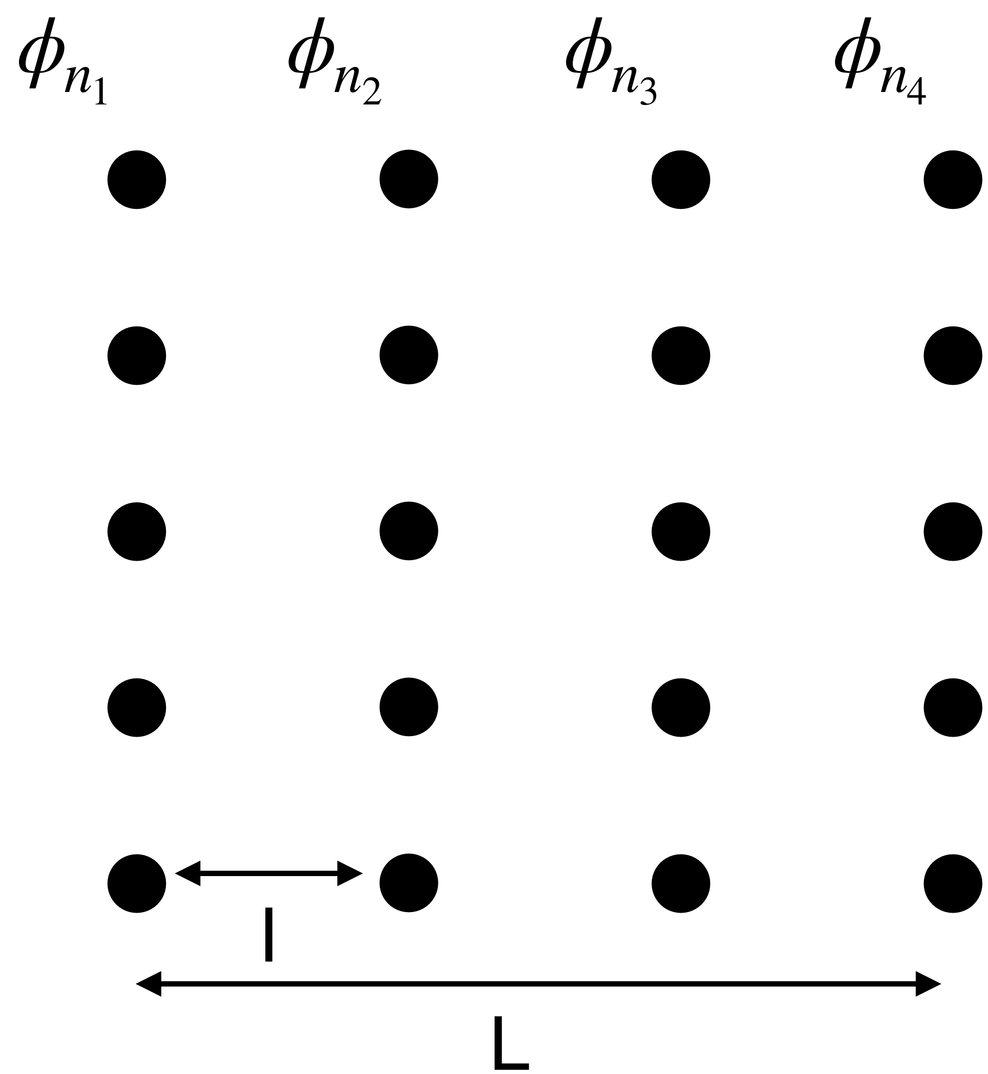
Can simulate full dynamics of QFT on quantum computer by reducing to finite dimensional Hilbert space

For scalar field theory, instead of having a continuous field ϕ at each position x, we put a digitized field ϕ_n at discrete points x_k arranged on a lattice



$$L = N\,l$$

Hilbert space has dimension

$$\left(n_\phi\right)^{N^d}$$

n_ϕ : # of digitized field values
N : # of lattice points per dim
d : # of dimensions

Problem reduced to matrix multiplication

Let's try to estimate the resources we need to simulate physics at the LHC

Energy rage that can be described by lattice is given by

$$\frac{1}{Nl} \lesssim E \lesssim \frac{1}{l}$$

To simulate full energy range of LHC need

$$100\,\mathrm{MeV} \lesssim E \lesssim 7\,\mathrm{TeV}$$

This needs $\mathcal{O}(70{,}000^3) \sim 10^{14}$ lattice sites

Assume I need at least 5 bit digitization $\Rightarrow n_\phi = 2^5 = 32$

Dimension of Hilbert space is

$$32^{10^{14}} \sim \infty$$

Number of qubits required

$$5 \times 10^{14}$$

Effective theories allow to separate short and long distance physics from one another

Goal is to separate ingredients that are calculable in perturbation theory from those that really benefit from non-perturbative techniques

Effective Field Theories (SCET)

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

Most interesting object in above equation is the soft function S, which lives at the lowest energies

For 1TeV jets with 100GeV mass, find

$$\Lambda_S = (100\,\mathrm{GeV})^2/(1000\,\mathrm{GeV}) = 10\,\mathrm{GeV}$$

Let's try to estimate the resources we need to simulate physics at the LHC

In the effective field theories required energy range is limited to

$$100\,\mathrm{MeV} \lesssim E \lesssim 10\,\mathrm{GeV}$$

This needs $\mathcal{O}(100^3) \sim 10^6$ lattice sites

Dimension of Hilbert space is
$$32^{10^6} \sim \infty$$

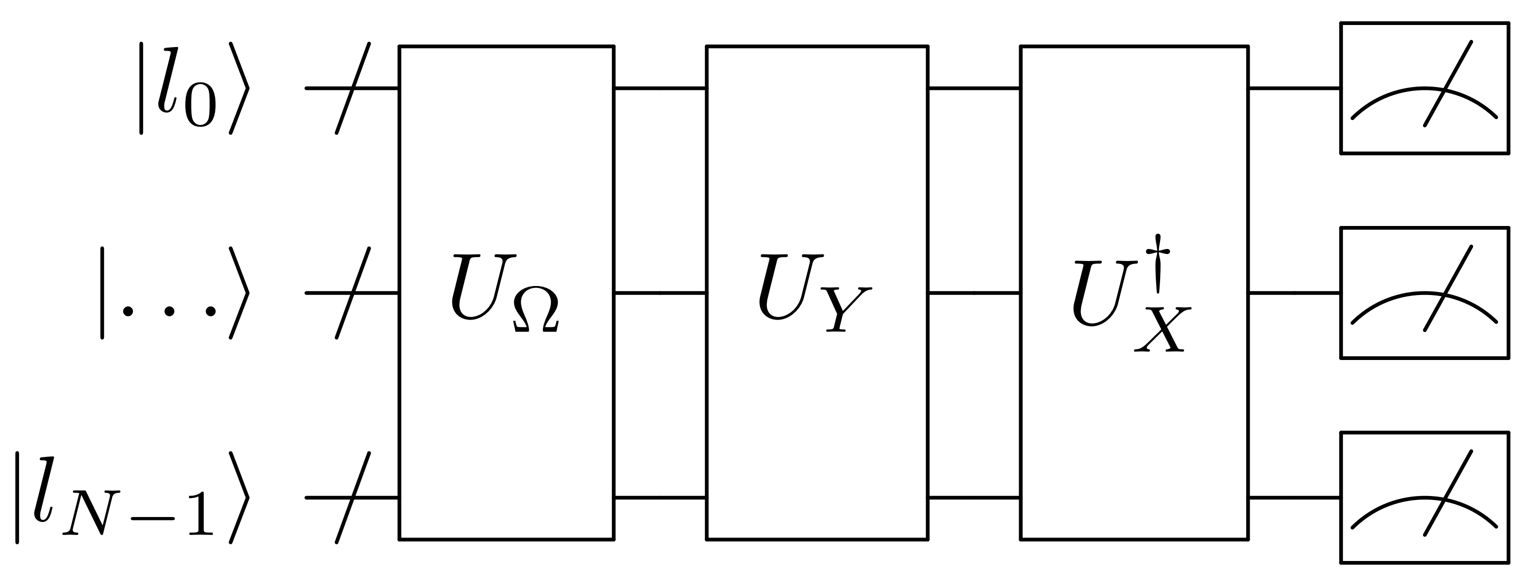
Number of qubits required
$$5 \times 10^6$$

Soft function is the expectation value of a “Wilson line” operator between initial and final state

$$S = \left| \langle X | T[Y_n Y_{\bar{n}}^\dagger] | \Omega \rangle \right|^2$$

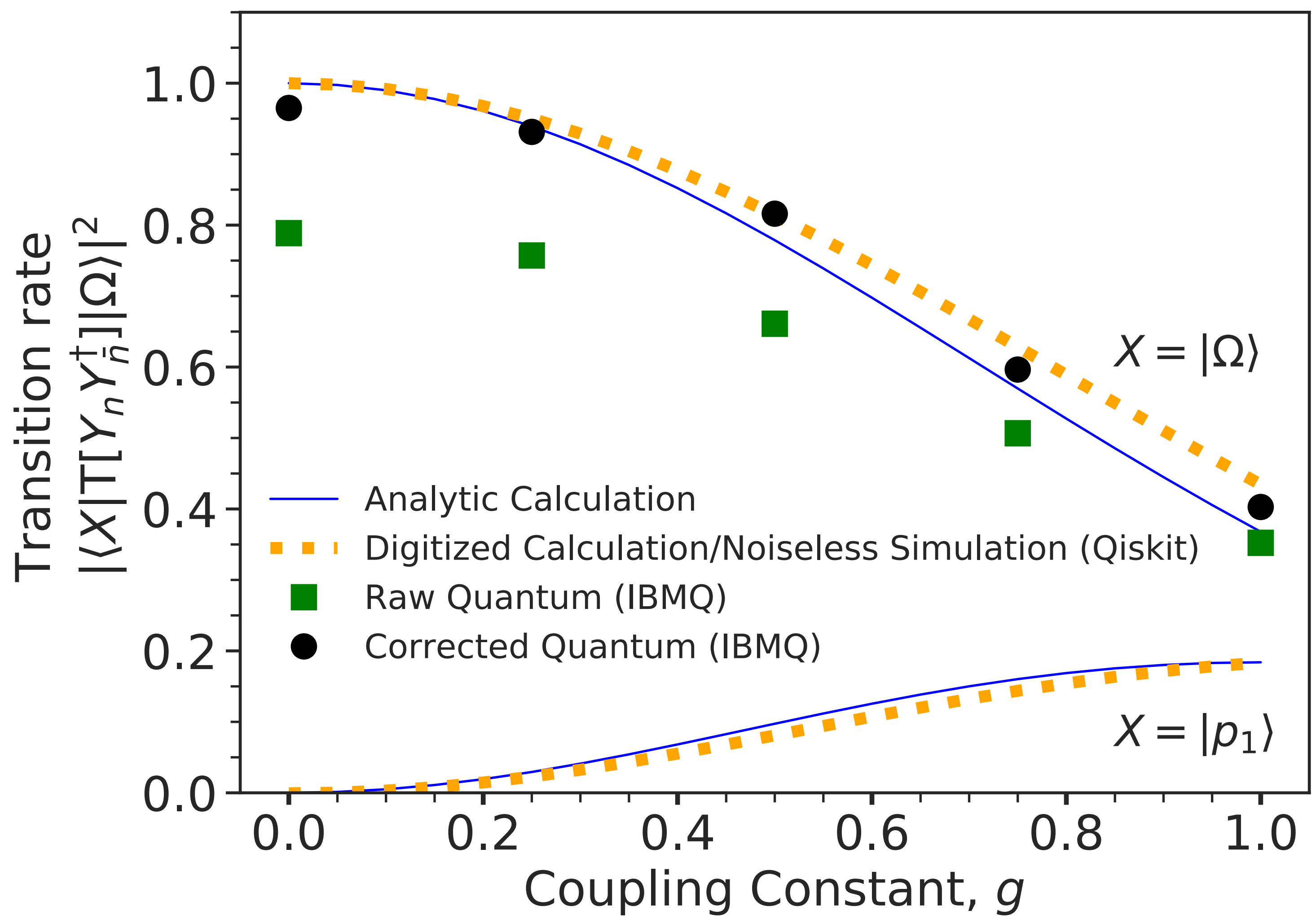
Have worked out quantum circuit to create vacuum state $|\Omega\rangle$, circuit for $T[Y_n Y_{\bar{n}}^\dagger]$ and circuit to measure final state $|X\rangle$

CWB, Freytsis, Nachman, PRL 127 (2021), 212001



Soft function is the expectation value of a “Wilson line” operator between initial and final state

CWB, Freytsis, Nachman, PRL 127 (2021), 212001



Quantum computer gives a good description of the analytical result

Currently working on implementing of these ideas for U(1) gauge theories

Formulation of Field Theories suited for simulation on quantum devices

Quantum Computing in Physics Division

The continuum Hamiltonian of QED is very simple, consisting of a magnetic and electric component

$$H = \int \mathrm{d}^d x \left[E^2(x) + B^2(x)\right]$$

E and B have simple relations to the gauge field
(working in $A_0 = 0$ gauge)

$$\overrightarrow{B}(x) = \overrightarrow{\nabla} \times \overrightarrow{A}(x)$$

$$\overrightarrow{E}(x) = -\partial \overrightarrow{A}(x)/\partial t$$

One can write Lattice version of Hamiltonian entirely in terms of rotors and magnetic fields

$$H = \sum_{p \in \text{plaq}} \left[g^2 H_E[R_i] + \frac{1}{g^2} H_M[B_i] \right]$$

There is considerable interest in “compact” U(1) gauge theory, where $-\pi < B_i < \pi$

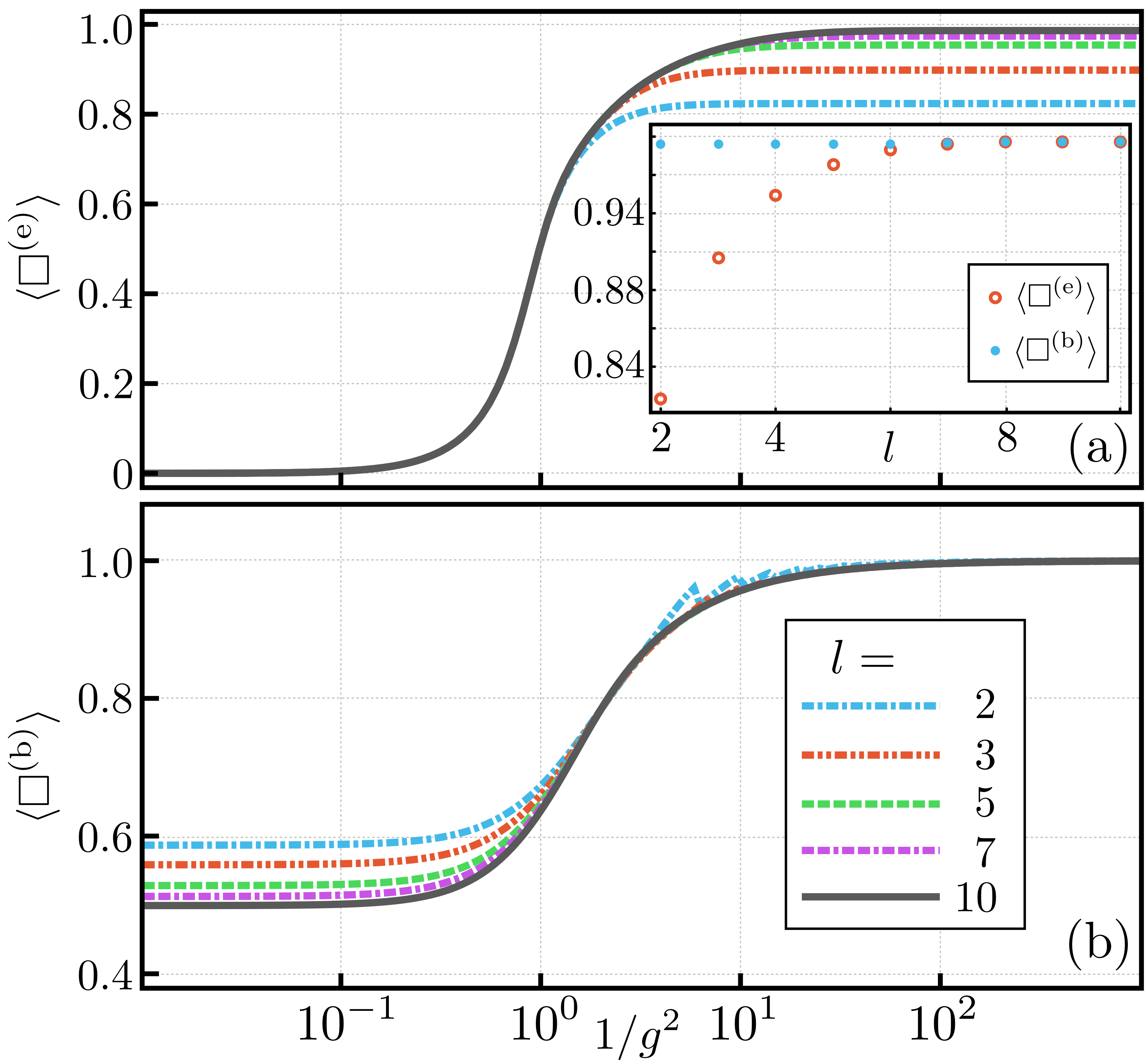
Since $[H_E, H_M] \neq 0$, H_E and H_B can not be diagonalized simultaneously

In limit $g \to \infty$ useful to work in electric basis, where H_E is diagonal

In limit $g \to 0$ useful to work in magnetic basis, where H_B is diagonal

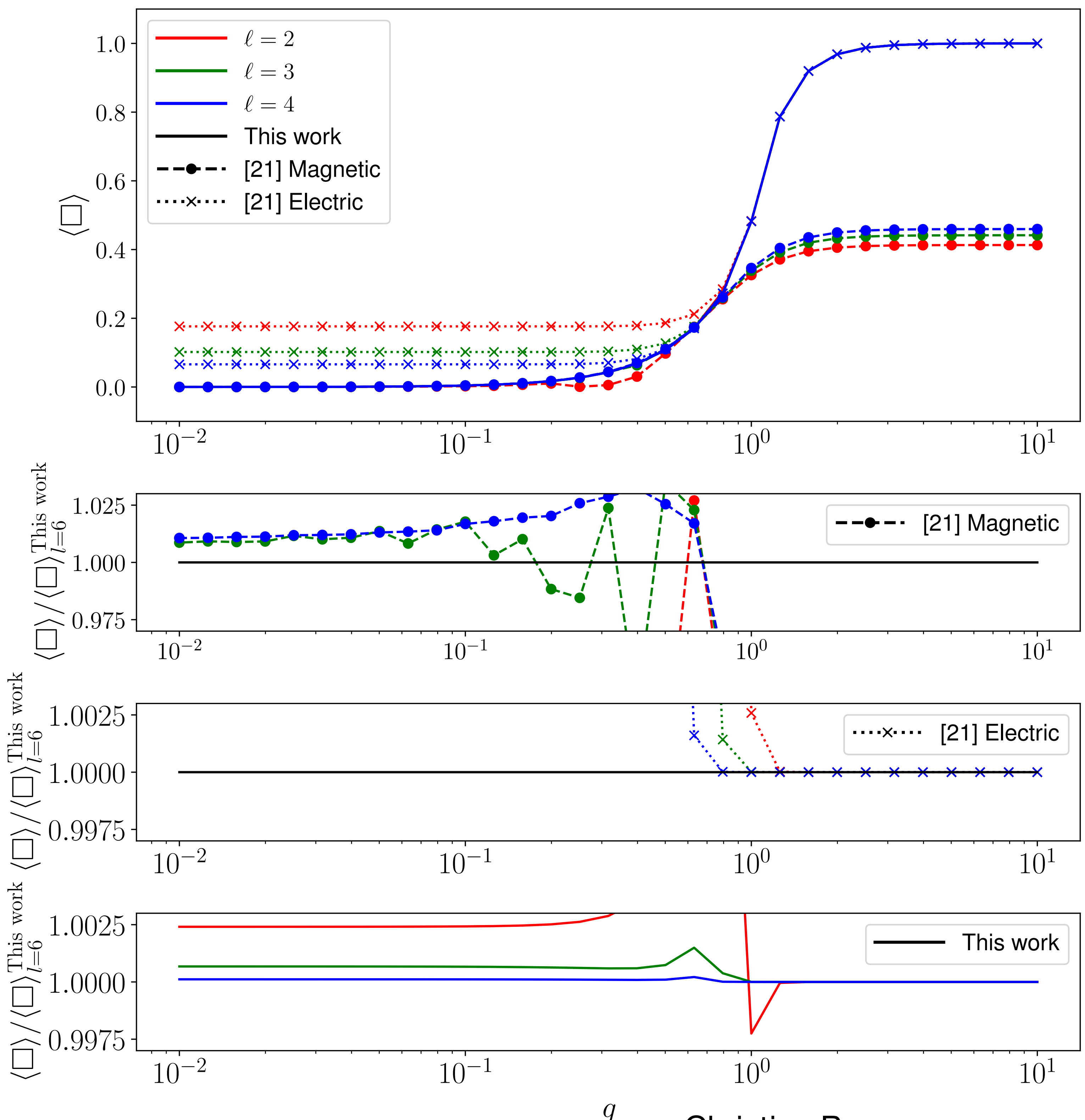
One can construct both magnetic and electric basis, and each work in the coupling limit they are designed for

Haase et al, 2006.14160



We developed a new representation of Hilbert space, that works in both limits of the coupling

CWB, Grabowska, 2111.08015



Does significantly better than the previous approach for all values of the coupling

Currently working on similar ideas for non-Abelian gauge theories

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- CWB, Freytsis, Nachman, PRL 127, 212001

Formulation of Field Theories suited for simulation on quantum devices

- CWB, Grabowska 2111.08015
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Development of quantum parton showers

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Improving techniques to use NISQ devices for near term simulations

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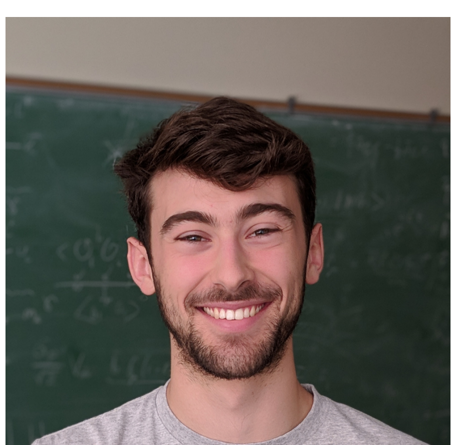

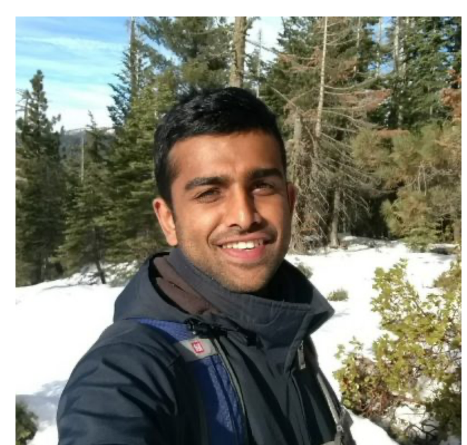


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QC Applications to HEP Applications