Quantum Simulation and Information Theory

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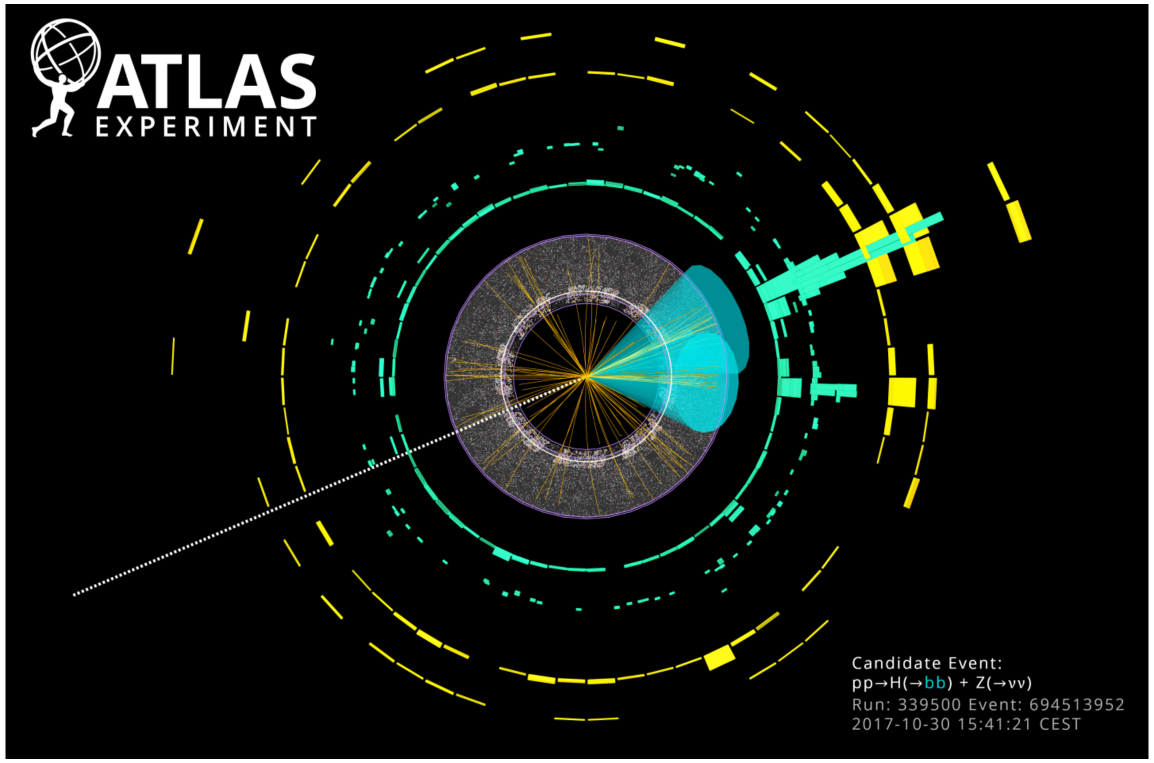
CERN TH

Particle Physics Theory

Modern day particle physics demands large scale computing

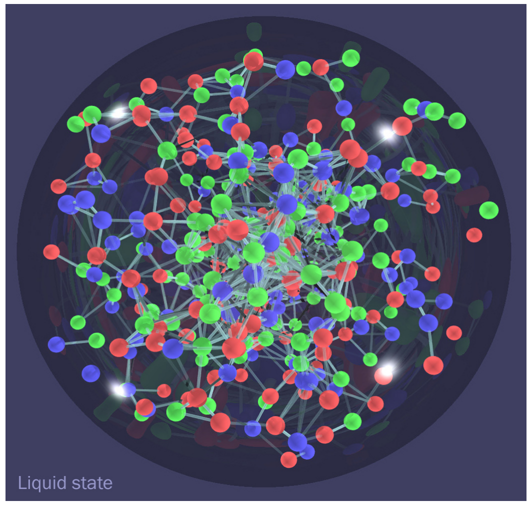
High Energy Collisions

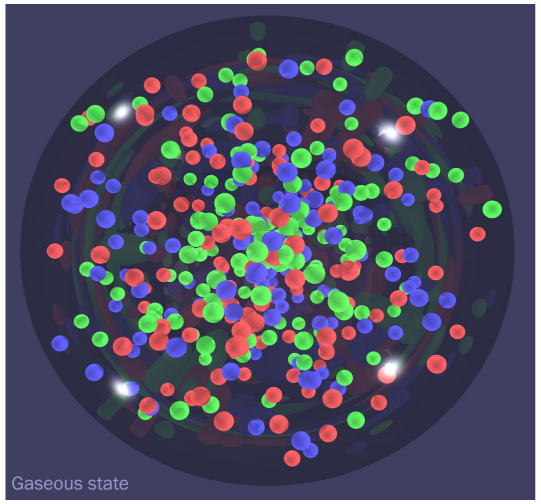
Monte Carlo simulation of hard, soft and hadronizing process



Heavy Ion Physics

Hydrodynamic evolution of quark gluon plasma





*RHIC

Particle Physics Theory

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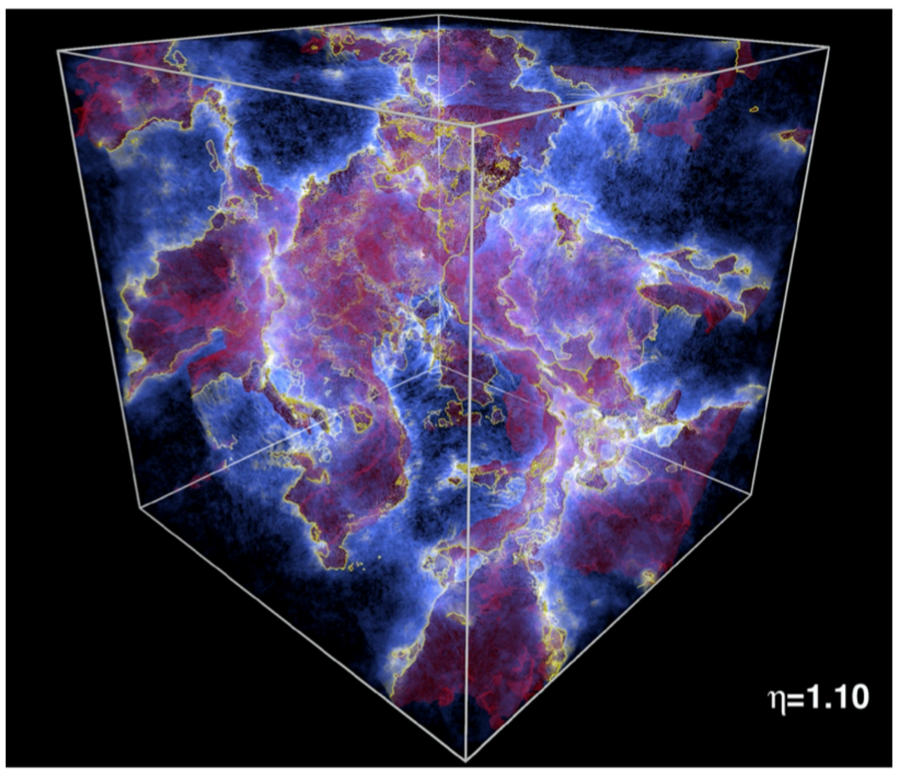
Cosmology/AstroParticle

Evolution of axion field in early universe

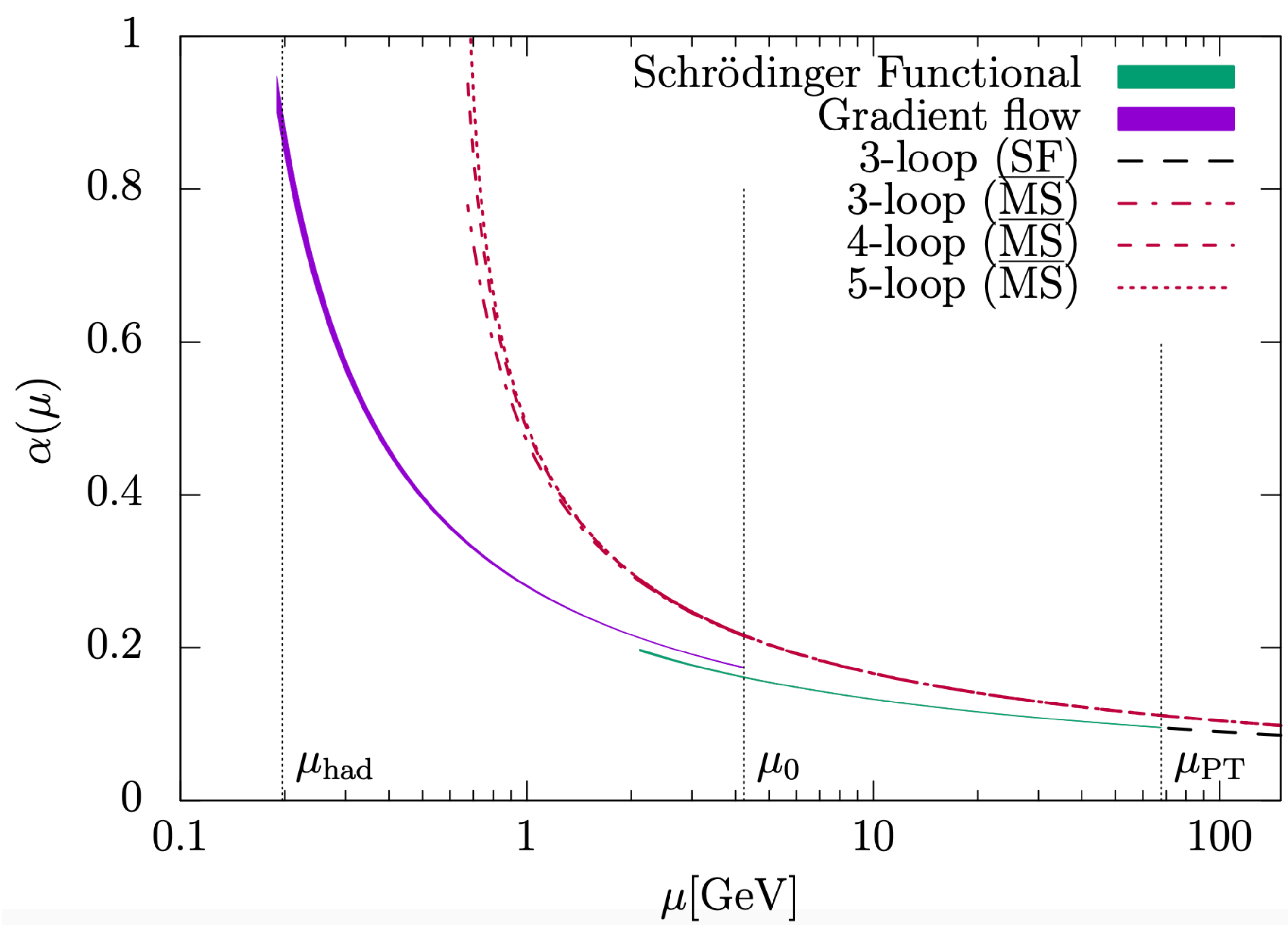


Animation: https://www.youtube.com/watch?v=1By1DMq1EpI&ab_channel=MalteBuschmann

arxiv: 1906.00967

Lattice QCD

Monte Carlo evaluation of euclidean correlation functions



ALPHA collaboration
arxiv:1706.03821

Why Quantum Computing?

Entanglement provides two important benefits

More efficient encoding

Small number of qubits corresponds to large number of states

Qubits	Unique Numbers
2	3
5	31
10	1023
30	1073741823
n	$2^n - 1$

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More efficient running

Built-in parallelism as computation is carried out on all $2^n - 1$ states simultaneously

Ex: Factorization Algorithms

Classical: one number at a time

Quantum: all at the same time

Why Quantum Computing?

Two places where we could benefit

Speed-up

"We can do this using classical algorithms, but it is just slower than we would like"

Ex: Low-lying hadronic spectrum

Feasibility

"We cannot do this at all using classical algorithm within any reasonable time"

Ex: QCD at finite density

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NOTE: Algorithmic developments can move a system of interest from "feasibility" to "speed-up" column

Generating Configurations in Lattice QCD

Physical pion mass, 100 configs, 192×96^3 lattice points with lattice spacing of 0.064 fm

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Cost in 2001: 640 billion core hours ✗

Cost in 2020 : 20 million core hours ✓

Speed-Up

Example: Properties of low lying hadron spectrum from lattice QCD

Calculational Needs

Small lattice spacing for appropriate UV regulator scale

Large box size to "fit" confined particles

Classical Hardware

20 million core hours

Quantum Hardware

Naive Number of Qubits
$\sim 20 \times 192 \times 96^3 \approx 3 \times 10^9$

So maybe not something for the Noisy Intermediate-Scale Quantum (NISQ) era…

Feasibility

Example: QCD at Finite Baryon Density

Working in Euclidean allows for Monte Carlo evaluation of correlation functions in some system…

Pure Glue

$$Z = \int dU\, e^{-S[U]} \longrightarrow \langle \mathcal{O} \rangle \approx \frac{1}{N} \sum_n \mathcal{O}_n$$

… but not all….

Finite Density QCD

$$Z = \int dU \underbrace{\det(D[U] + m + \mu\gamma_0)}_{\text{Highly oscillatory}^*} e^{-S[U]}$$

Idea: Quantum computation will not require Monte Carlo for these types of calculations

*arxiv: 0609076

Theory Branch

One of Our Overarching Goals

Calculate the phenomenological properties of the Standard Model and Beyond, ideally with quantifiable errors

More specific research interests

(not an exhaustive list!)

Neutrino Physics

String Theory

pQCD

Collider Physics

Hadron Spectrum

Chiral Gauge Theories

Properties of Quark Gluon Plasma

Inflation

Parton Showers

Dark Matter

Low energy inputs to experiment

Cosmology

Higgs Physics

Theory Branch

Possible avenues to explore

Classical Simulation

Software development for quantum simulators on classical hardware

Replacing Existing Codes

Investigating hybrid classical-quantum algorithms

Quantum Information

Error correction and mitigation

Speed-up

Theory Branch

Possible avenues to explore

QCD Applications

Simulations for collider physics

QCD phase diagram

Hadronic physics

Multi-loop amplitude calculations

Heavy Ion Simulation

High multiplicity collisions

Non-equilibrium phenomena

Quark-Gluon Plasma

BSM + Cosmo Applications

Early Universe simulations

Neutrino Oscillations

Feasibility

What's Already Out There

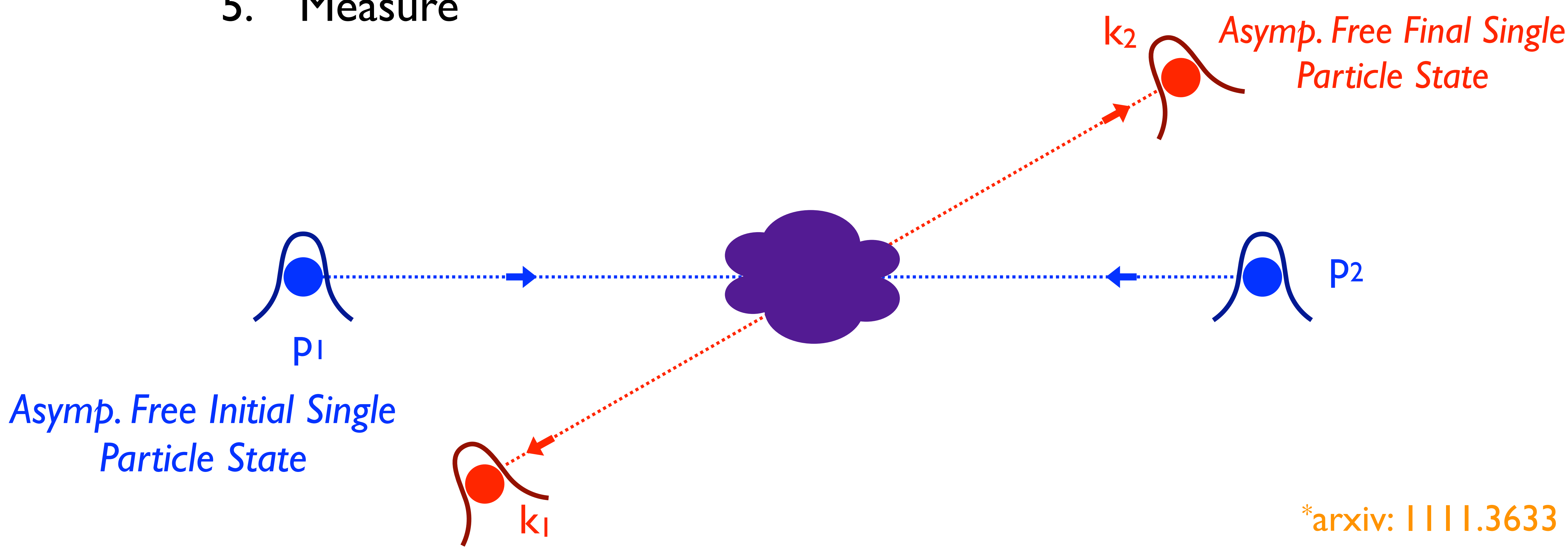
(Just a sampling)

Foundations of QFT Algorithms

Scattering Algorithm

Idea: One-to-one mapping of continuum procedure to discretized spacetime*

1. Prepare ground state of free theory
2. Excite wavepackets of free theory
3. Adiabatically turn on interactions
4. Evolve with fully interaction Hamiltonian
5. Measure



*arxiv: 1111.3633

Foundations of QFT Algorithms

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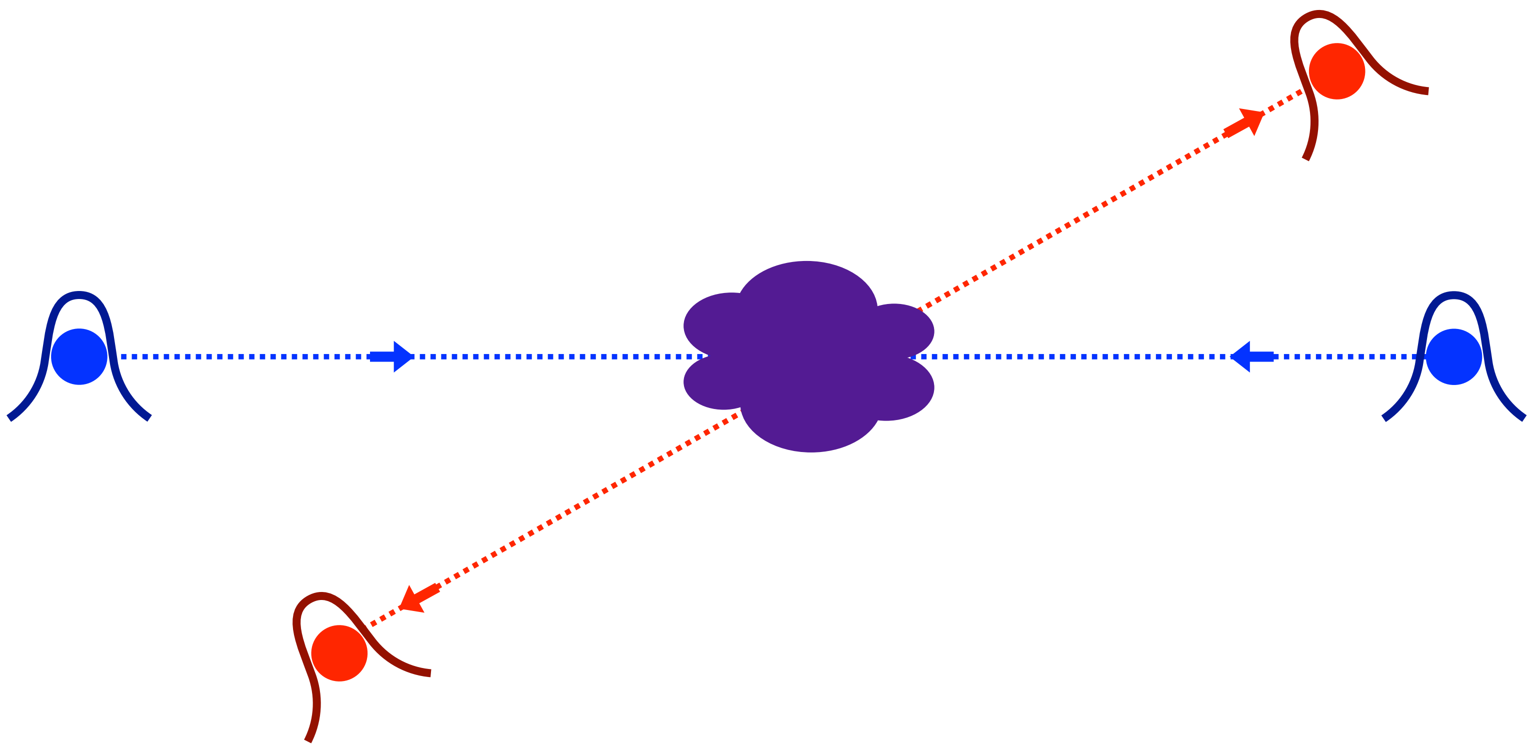


Digitization

Idea: Encode finite number of field values onto qubits

arxiv: 1808.10378

Finite Volume Effects

Idea: Ramifications of finite volume in Minkowski simulations unclear

arxiv: 2007.01155

Gauge Theory Formulations

Hamiltonian Formulation

Question: How do you encode gauge invariance into a Hamiltonian formulation, using a minimal amount of qubits

Complications

Satisfying Gauss's Law
Gauge Invariance

Truncation of Hilbert space
Define computational basis

Eliminate non-physical states
Reduce qubit cost

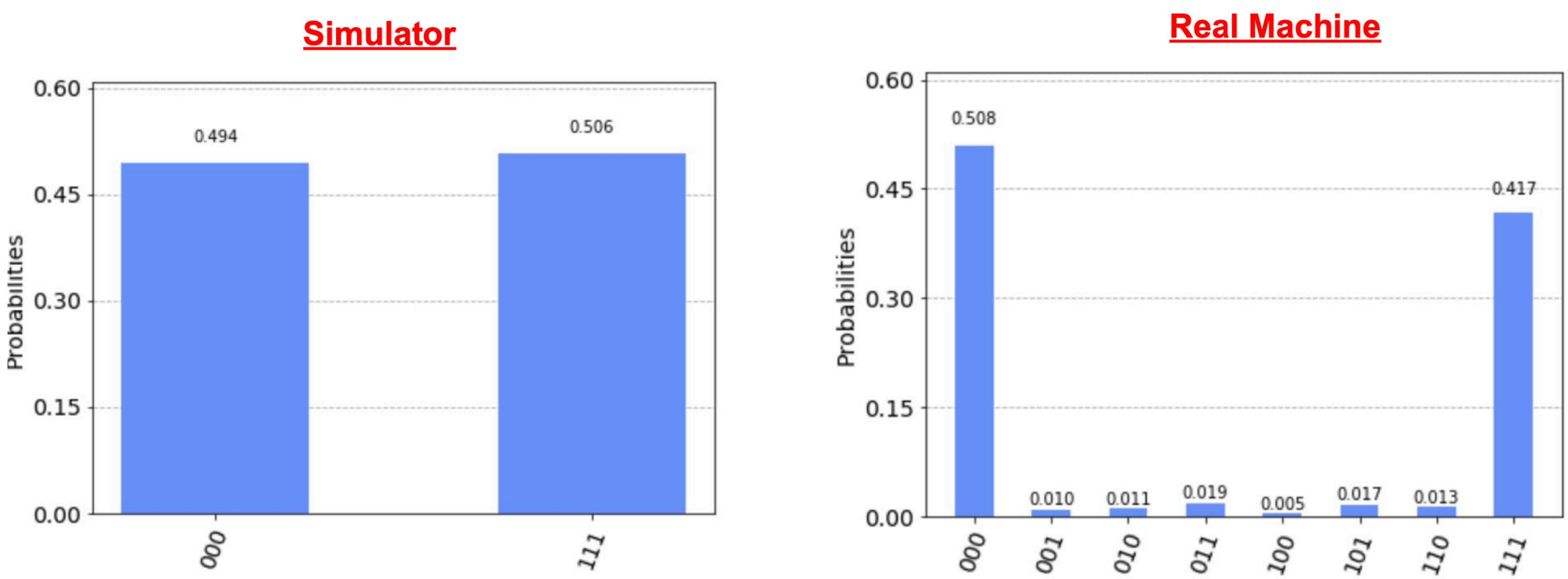
Lot of work already done on this question
(happy to provide resources for specific questions)

Software Packages

Multiple software packages that allow for quantum simulation on both classical and quantum hardware

[Qiskit](#) [Qibo](#)*

Testbeds for ideas and algorithms in the NISQ era



Measurement of GHZ State

*arXiv: 2009.01845

Summary

Modern day particle physics demands large scale computing

Quantum computing may allow us to probe interesting and highly relevant systems that are currently inaccessible classical computing

There is a lot of room for collaboration with other branches

Quantum technology is an exciting new frontier

We are just getting started!