High-Performance Computing for Lattice Quantum Chromodynamics

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Introduction of Quantum Chromodynamics

- In <u>theoretical physics</u>, **quantum chromodynamics** (**QCD**) is the study of the <u>strong interaction</u> between <u>quarks</u> mediated by <u>gluons</u>.
- What are hadrons, quarks, gluons and the strong force?
- Solving QCD is way more complex than Quantum Electrodynamics.



Lattice QCD

- Space-time Discretization
 - Quarks placed on lattice sites, gluons on lattice links.
- Why discretize and how can it help simulate QCD?
- Challenges:
 - Enormous computational grids (billions of variables).
 - Computational cost rises sharply as lattice spacing shrinks.



Why is Lattice QCD Computationally Intensive?

- Massive computational scale:
 - Complex linear algebra (Dirac matrix solves)
 - High-dimensional Monte Carlo integrals.
 - Millions to billions of lattice points.
- Scaling of computational complexity:
 - Requires extreme parallelism and specialized computing hardware.
 - Decreasing lattice spacing \rightarrow exponential computational increase.

Evolution of HPC Systems for Lattice QCD

- Historical Specialized Systems:
 - QCDSP (late 1990s): Digital signal processors.
 - QCDOC (mid-2000s): Custom chip with specialized torus network.
 - Inspired IBM Blue Gene architecture.
- Modern GPU-Accelerated Systems:
 - ExaScale Systems
 - QUDA software library optimized for GPUs.
- HPC and Lattice QCD has been a two way development street.

Major Achievements from Lattice QCD Simulations

- Proton Mass Calculation
- Muon g 2 anomaly
- Nuclear structure and Nuclear Physics
 - High precision studies enabled by leadership-class HPC.

Bottlenecks

- Communication overhead
- Memory bandwidth limitations for key kernels.



Future Work

- Quantum Computing: Solve currently intractable problems.
- Al and Machine Learning: Improve sampling efficiency and data analysis.





Any Questions?

Thank You!