Lattice Strong Dynamics: Using high-performance computing to explore the mystery of mass

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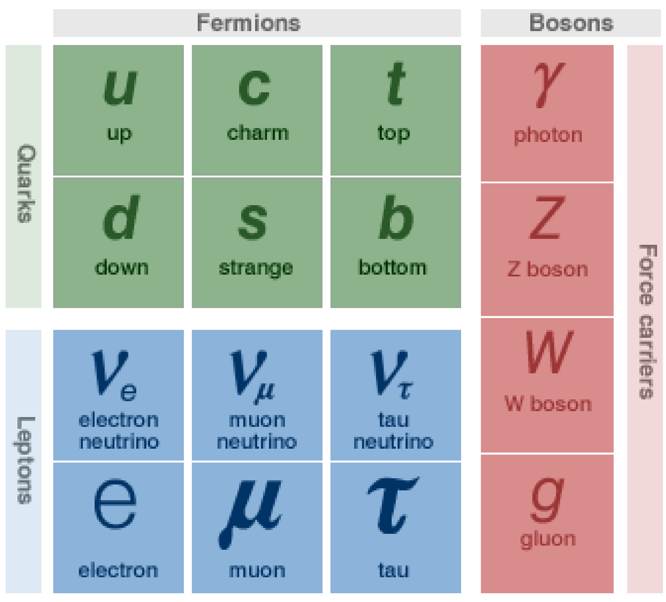
The Mystery of Mass

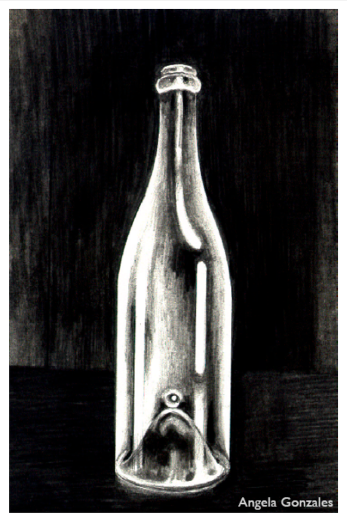
Elementary particles and forces



Our understanding of elementary particles and their interactions has been gradually constructed and precisely tested by vast arrays of experiments over the course of decades.

The symmetry principle

- Forces are known to obey certain symmetries.
- However, these symmetries appear to require all elementary particles to be exactly massless.
- The symmetries cannot be broken, but they can be **hidden**: present in the theory, but not manifest in physical states.
- Hiding a symmetry allows particles to acquire their observed masses.



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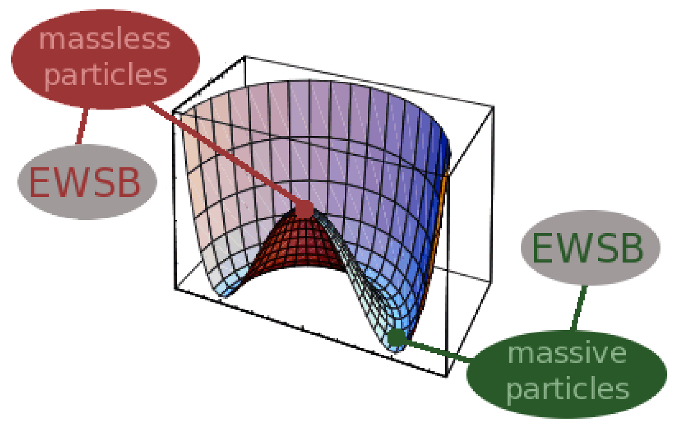


What hides the symmetry?

There are many possible ways to hide the relevant symmetry, and we don't yet know which is realized in nature.

The usual suspects

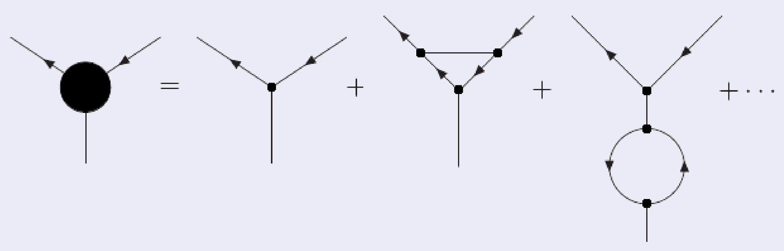
The **standard model** is the simplest mechanism for hiding the symmetry. It **predicts** the appearance of a *Higgs boson* at high energies. However, it is theoretically "unnatural".

Models with **new strong dynamics** avoid these theoretical problems. They **predict** a "zoo" of new bound states at high energies, like the strong nuclear force explored in the 1950s and 1960s. However, they are based on incalculable strong interactions.

The trouble with strong interactions

We rely on an approximation scheme to perform analytic calculations:

1. Solve the problem in the simplest case with the fewest interactions.
2. Add more interactions as an infinite series of small corrections.



Strong interactions are *not* small corrections, so this approach is invalid.

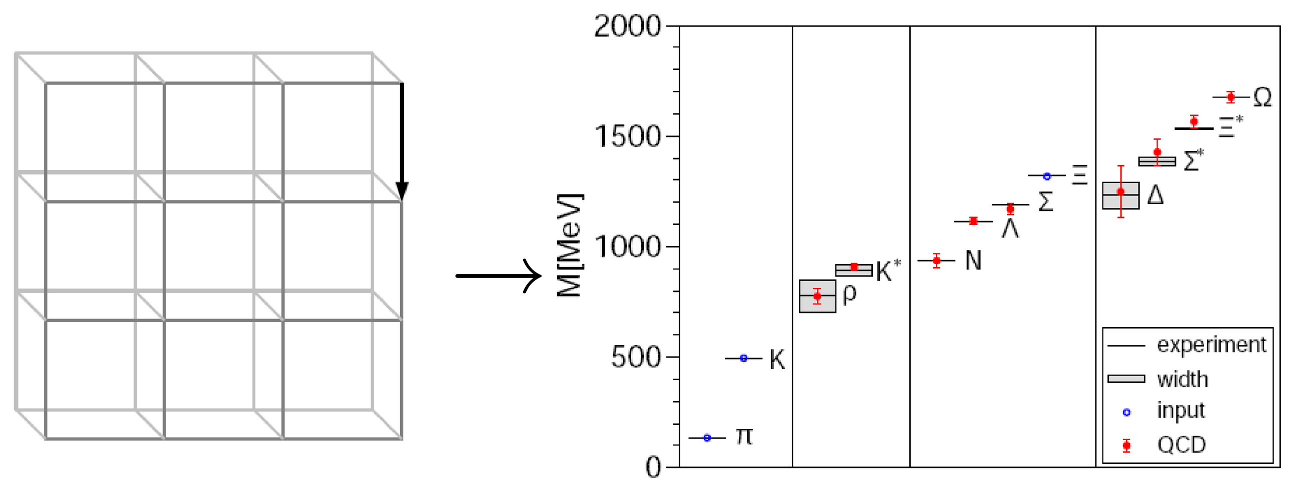
As a result, little is reliably known about theories of new strong dynamics, even though they have long been considered promising candidates.

Solving the Mystery

High-performance computing provides a new way to investigate theories that cannot be reliably studied using traditional methods.

Quantum field theory on a computer

- Represent space and time as a four-dimensional lattice of discrete sites.
- As the distance between the sites decreases, recover the original theory in continuous space and time.
- This method can directly investigate strong interactions, but pushes the limits of high-performance computing.



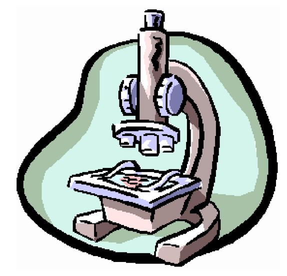
- Lattice calculations have focused on the strong nuclear force, which is now a mature field.
- We can now explore more speculative strongly-interacting theories.

Lattice Strong Dynamics Collaboration

- Formed in 2007 to perform computational studies of strongly interacting theories likely to produce observable signatures at the Large Hadron Collider.
- Now involves 18 researchers at eight institutions.

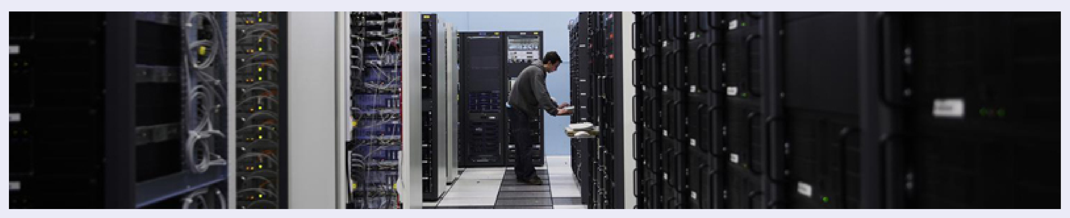
We also need microscopes

"Faith" is a fine invention
When Gentlemen can see –
But *Microscopes* are prudent
In an Emergency.
– Emily Dickinson, 1860



The Large Hadron Collider (LHC)

World's most powerful microscope, exploring the nanonanoscale, 10^{-18}m. Main goal: to solve the mystery of mass.



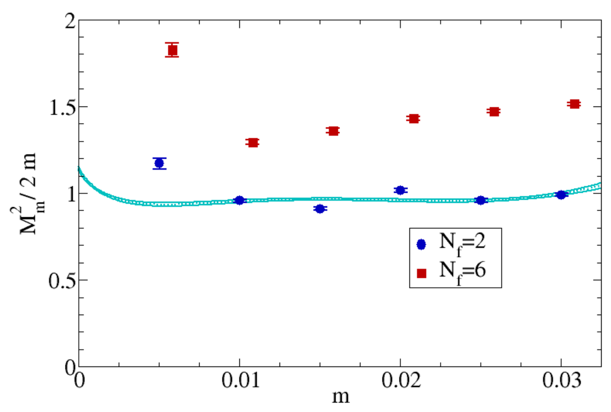
Recently began operation after decades of planning and construction.

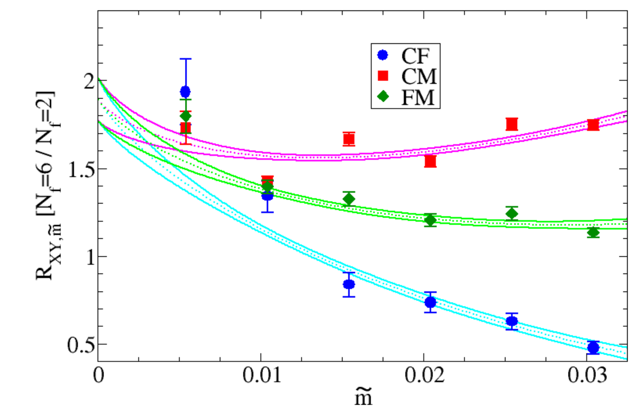
Recent Progress and Future Prospects

- Common tactic: use the strong nuclear force as a guide to theories of new strong dynamics.
- This approach predicts that strongly-interacting theories cannot successfully hide the symmetry and permit particle masses.
- Critical first question: are such predictions reliable?

Lattice Strong Dynamics – first results

- We find clear differences between the strong nuclear force and a similar theory with only one significant change.
- This shows that the strong nuclear force is not a reliable guide, and strongly-interacting theories are still viable.





Cost: $\sim$300 million core-hours on the BlueGene/L supercomputer at Lawrence Livermore Nat'l Lab.

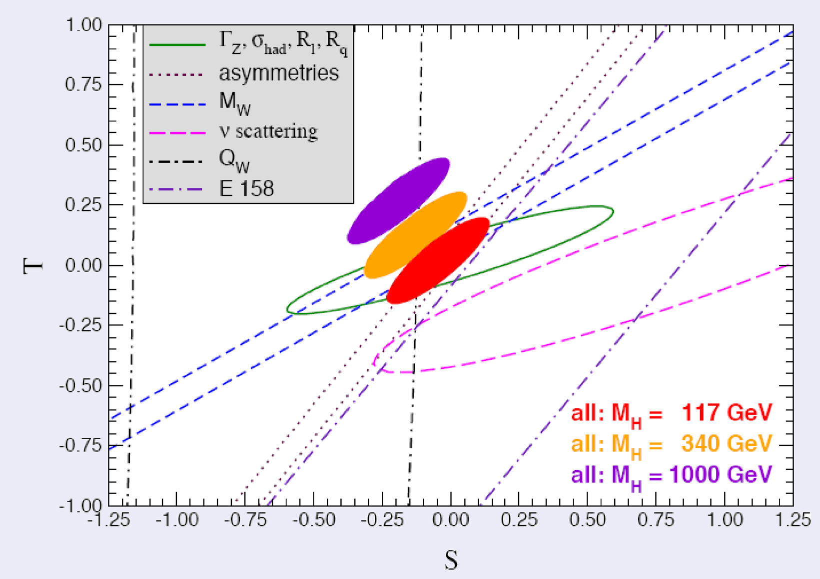
Lattice Strong Dynamics – next steps

- Continue to mine data already collected, to study more complicated features of the theory.
- Explore more of the vast number of possible strong theories.

Example: the S parameter

S measures the effects of the symmetry-hiding mechanism on the behavior of the Z boson and photon γ.

Experiment: $S = -0.04 \pm 0.09$, consistent with zero.



- Using the strong nuclear force as a guide, expect $S \sim 1$ for theories of new strong dynamics.
- We are now completing the first direct calculation of S for such theories.

We are on the verge of great progress

- High-performance computing now allows us to study otherwise-intractable strongly-interacting theories.
- These theories will soon be tested at the Large Hadron Collider.
- With the help of high-performance computing, we can prepare to understand whatever the LHC may see.

Acknowledgments

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