

# Lattice Strong Dynamics: Using high-performance computing to explore electroweak symmetry breaking David Schaich, Adam Avakian, Ron Babich, Richard Brower, Saul D. Cohen, Claudio Rebbi, and the Lattice Strong Dynamics (LSD) Collaboration

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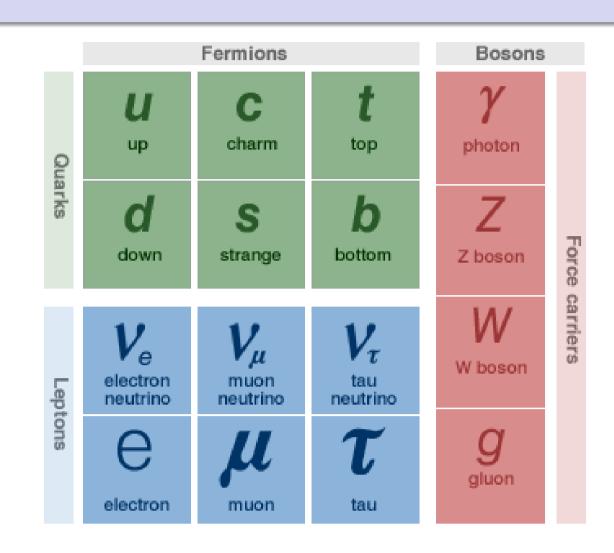


#### Abstract

Electroweak symmetry breaking is the process through which elementary particles acquire mass. Despite decades of intense experimental and theoretical effort, the specific mechanism responsible for this important process remains unknown: there are many possibilities, each with its own shortcomings. Solving this mystery is the main goal of the Large Hadron Collider that recently began operation outside of Geneva, Switzerland.

At the same time, recent advances in high-performance computing provide a new way to investigate theories of electroweak symmetry breaking that involve strong interactions. Because standard analytical methods cannot be applied to strong interactions, relatively little is reliably known about such theories, even though they have long been considered promising candidates. The large-scale computations required to perform quantitatively reliable analyses of these strongly-interacting theories are only now becoming feasible. We present some promising initial results from ongoing computational studies of new strong dynamics that may shed new light on electroweak symmetry breaking.

## Background



## Elementary particles and forces

- All known elementary particles
- are listed in the table to the left. • Matter is made of (spin-one-half) quarks and leptons,
- classified by the forces they feel. • Forces are carried by (spin-one) "gauge bosons": • Electromagnetism  $\longrightarrow$  photon  $\gamma$ 2 Weak force  $\longrightarrow Z$  and  $W^{\pm}$  bosons
- **3** Strong force  $\longrightarrow$  gluons gGravity not included

#### Example: electromagnetism The symmetry principle

Unified electroweak symmetry and electroweak symmetry breaking (EWSB)

That is, they are described by a common symmetry principle, known as electroweak symmetry.

• Very massive  $W^{\pm}$  and Z, with  $M_{W^{\pm}}$ ,  $M_{Z} \approx 90~M_{\rm proton} \approx 175,000~M_{\rm electron}$ 

It is often illustrated with the aid of a wine bottle like that pictured below.

B predicted by the theory.

A remarkable discovery of the twentieth century: electromagnetism and the weak interaction are "unified".

• Extremely short range,  $\lesssim 10^{-17}$  meter

• As mentioned above, we expect all gauge bosons, such as the  $W^{\pm}$  and Z, to have exactly zero mass.

To account for the clear differences between electromagnetism and the weak interaction,

• Further, the structure of the electroweak symmetry requires all quarks and leptons to be massless as well.

Forces correspond to "gauge symmetries" (invariance under mathematical transformations)

• While the photon  $\gamma$  and gluons are massless,

At first glance, such unification seems surprising:

Infinite range

Massless photon

Conserves parity

 Gauge boson masses break this invariance: the symmetry requires gauge bosons to be massless.

the  $W^{\pm}$  and Z are very massive.

The electric and magnetic fields **E** and **B** 

 $\mathbf{A} \to \mathbf{A} + \nabla \Lambda$ .  $\Phi \to \Phi - \frac{\partial H}{\partial x}$ 

However,  $m_{\gamma}^2 \left( \mathbf{A} \cdot \mathbf{A} - \Phi^2 \right)$  is not invariant.

can be written in terms of potentials  $\Phi$  and  $\mathbf{A}$ ,

 $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial \mathbf{A}} - \nabla \Phi \qquad \qquad \mathbf{B} = \nabla \times \mathbf{A}.$ E and B are invariant under the transformation

# Shortcomings of the standard model

- We have never seen an elementary spin-zero field like that hypothesized by the standard model.
- There may be deep reasons for this:

The Standard Model

- ▶ Spin-zero fields *require* new physics at very short distance scales (high energy scales). The standard model cannot be the end of the story.
- Further, spin-zero fields are extremely sensitive to physics at short distances. The theory must be unnaturally "fine-tuned" to describe nature.

Electroweak Symmetry Breaking (EWSB): The Mystery of Mass

• In order to explain observed particle masses, electroweak symmetry must be hidden (spontaneously broken).

using an elementary spin-zero field.

introduced over 40 years ago.

Electromagnetism becomes short-range, leading to the Meissner effect (expulsion of magnetic fields).

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

• Below we compare two major classes of possible mechanisms of electroweak symmetry breaking:

• These two classes have illustrative analogs in the simpler phenomenon of superconductivity.

• Superconductivity is a spontaneous symmetry breaking process that hides electromagnetism.

interacting to form spin-zero "Cooper pairs".

Superconductivity: spontaneous breaking of electromagnetism

• Just like the  $W^{\pm}$  and Z in EWSB, the photon  $\gamma$  "eats" something to become massive.

• First superconductivity was modeled (by Ginzburg and Landau)

• The standard model is the simplest EWSB mechanism,

• Three of these components are eaten by the  $W^{\pm}$  and Z,

Also provides masses for all quarks and leptons!

• Its EWSB is a single spin-zero field, with four components.

• However, all these masses remain arbitrary free parameters.

• Later it was explained (by Bardeen, Cooper and Schrieffer – BCS)

through the dynamics of spin-one-half electrons

the fourth is the **Higgs boson** predicted by the theory.

This isn't required, but is certainly convenient.

• The *standard model*, the simplest solution and the basis for many extensions

2 New strong dynamics, often called *technicolor* 

• As mentioned above, all quark and lepton masses are arbitrary free parameters;

the standard model cannot make any predictions about them.

None of this *rules out* the standard model, but it does motivate extensions and alternatives.

#### Completing the analogy with superconductivity

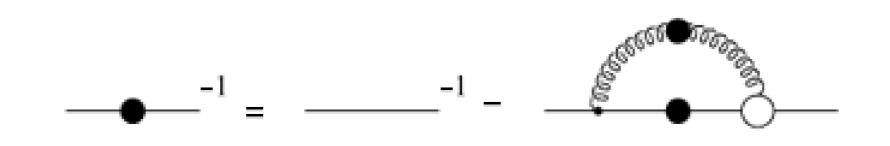
- The standard model is a relativistic generalization of the Ginzburg-Landau model of superconductivity applied to the electroweak symmetry instead of electromagnetism.
- Similarly to the BCS theory of superconductivity, electroweak symmetry can also be hidden by the dynamics of hypothetical spin-one-half particles. • Since we haven't seen such particles, their dynamics must involve **strong** interactions,
- unlike the BCS theory of electrons forming Cooper pairs.

# New Strong Dynamics (Technicolor)

- Theories of EWSB through new strong dynamics are known as "technicolor", since they were first modeled on quantum chromodynamics (QCD), the "color theory" of the strong nuclear force.
- QCD can in fact hide electroweak symmetry, but it would produce  $W^{\pm}$  and Z masses 2000 times too small.
- So instead technicolor proposes a *new* strong force that only affects *new* spin-one-half particles ("techniquarks"),
- binding them together into "technihadrons", analogs of the proton, neutron and other hadrons.
- The three lightest technihadrons are eaten by the  $W^{\pm}$  and Z, the rest remain as a "zoo" of particles that can be produced in high-energy collisions.
- Although quark and lepton masses are no longer provided automatically,
- new strong dynamics can be "extended" to produce (and possibly predict!) them.

#### The trouble with strong interactions

- Exact calculations in quantum field theories such as technicolor and the standard model are not possible. Instead we typically use an approximation scheme known as *perturbation theory*:
- We first solve the problem in the simplest possible case where all interactions vanish. 2 We then add in interactions as small corrections ("perturbations") to the non-interacting case.
- If the interactions are weak enough, the corrections are small, and perturbative results are reliable.
- For strong interactions, however, perturbation theory is not applicable, and we lose our main analytic tool. • As a result, relatively little is reliably known about theories of EWSB through new strong dynamics,
- even though they have long been considered promising candidates.

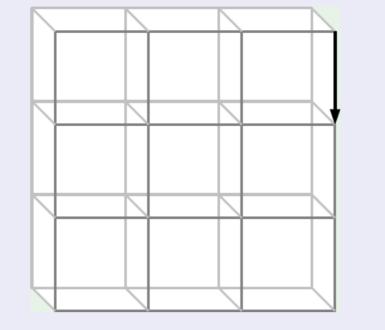


# Solving the Mystery: Theories and Experiments

#### High-performance computing

- Standard analytical methods cannot be applied to theories involving strong interactions,
- which include several promising explanations of electroweak symmetry breaking. • Quantitatively reliable calculations from first principles require large-scale high-performance computing.

#### Lattice gauge theory



- To perform quantum field theory calculations on a computer, we represent space and time as a four-dimensional lattice of discrete sites.
- Spin-one-half fields are defined only at the sites of the lattice, and are connected by spin-one fields, to maintain gauge invariance. • As the distance between the sites decreases,
- we return to the original theory defined in continuous space and time.
- Lattice gauge theories were first developed in the 1970s, as techniques used in analytic calculations.
- Later, lattice gauge theories were explicitly implemented on computers, using statistical methods to perform stochastic calculations.
- These calculations continue to push the limits of massively-parallel high-performance computing technology.

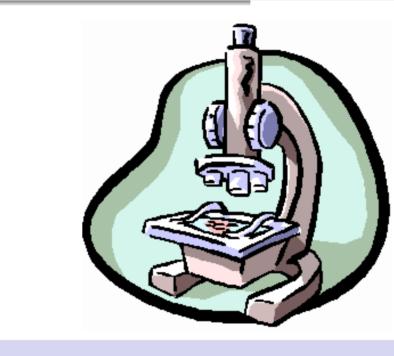
### Lattice QCD – and beyond

- Lattice calculations have focused on quantum chromodynamics (QCD), the gauge theory of the strong nuclear force.
- Lattice QCD is now a mature field: The plot to the right compares experimental data
- to lattice QCD results obtained by the BMW Collaboration. • It's time to turn to strongly-interacting theories beyond QCD,
- especially those that may play a role in electroweak symmetry breaking.
  - High-performance computing now provides a new way to investigate theories that have long been of considerable interest as possible mechanisms of EWSB, but which cannot be reliably studied using more traditional methods.

### We also need microscopes

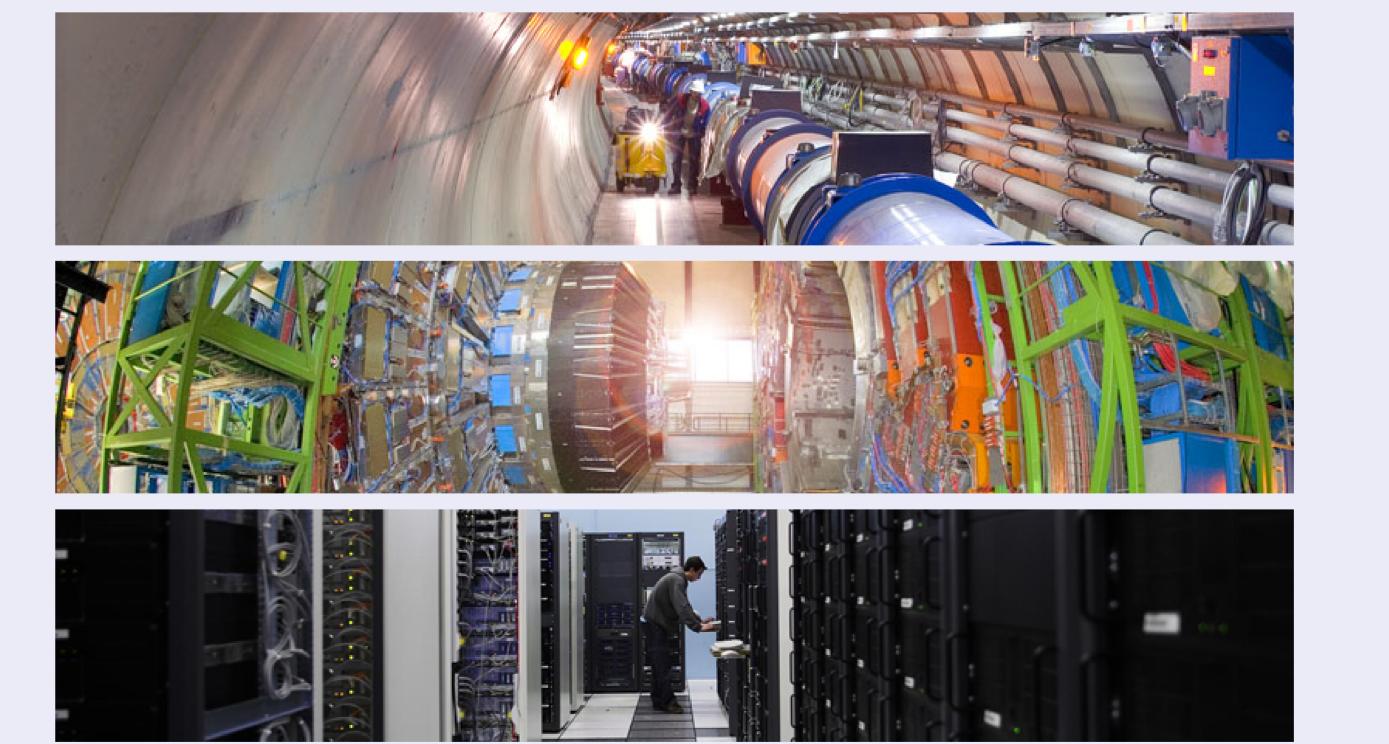
Even with advances made possible by high-performance computing, we still need data to determine which mechanism of electroweak symmetry breaking is realized in nature.

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



# The Large Hadron Collider (LHC)

The LHC is the world's most powerful microscope, capable of exploring the nanonanoscale,  $10^{-18}$  meter. Its main goal is to solve the mystery of electroweak symmetry breaking.



After decades of planning and construction, the LHC recently began operation at CERN, the European Organization for Nuclear Research, outside Geneva, Switzerland.

#### LHC vital stats

- The LHC is a complicated superconducting 26,659-meter-long ring of magnets, cooled to 1.9 K ( $-271.3^{\circ}$  C).
- It collides bunches of protons (and heavy ions) moving at 99.99999% the speed of light. • These bunches will collide every 25 nanoseconds, producing roughly 600 million collisions every second.
- 99.99% of the data produced must be *thrown away*; the remainder adds up to 15,000 terabytes per year.

Recent Progress and Future Prospects

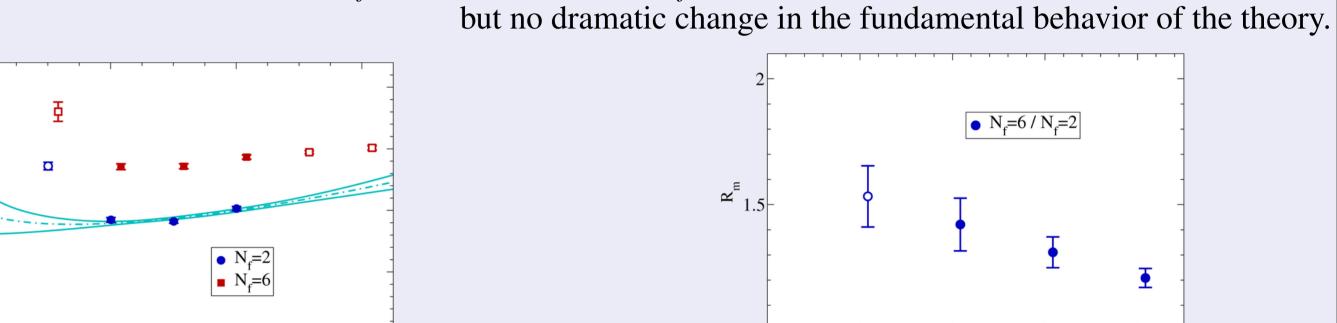
- Since direct analytic calculations of new strong dynamics have not previously been possible, these theories have often been modelled by analogy with quantum chromodynamics (QCD).
- QCD is the gauge theory of the strong nuclear force, for which we have a vast amount of experimental data.
- This approach assumes that new strong dynamics closely resemble QCD, which may be completely incorrect. • A critical first application of high-performance computing is to investigate this assumption,
  - and determine if predictions made with this method are meaningful.

#### The Lattice Strong Dynamics Collaboration

- The Lattice Strong Dynamics (LSD) Collaboration was formed in 2007, to perform computational studies of strongly interacting theories
- likely to produce observable signatures at the Large Hadron Collider. • Currently involves 18 researchers at eight institutions, including six members at BU.

### Lattice Strong Dynamics – first results

- Our first project studies a theory with only one significant difference from QCD:
- three pairs of light (u and d) (techni-)quarks instead of just the single pair in QCD. • Large numbers of techniquarks are used in several prominent technicolor models.
- We found clear differences between " $N_f = 2$ " QCD and this " $N_f = 6$ " theory,



• The plot on the left illustrates how the mass M of the lightest bound state of two (techni-)quarks

depends on the mass m of the (techni-)quarks themselves. • The plot on the right shows the ratio of a similar quantity between the two theories.

In the important limit  $m \to 0$ , there is a change of 40–80%.

The bulk of these calculations (approximately 150 million core-hours) were performed on the BlueGene/L supercomputer at Lawrence Livermore National Lab, pictured to the right (note the scale).



all: M<sub>H</sub> = 1000 GeV

•  $N_f = 6 / N_f = 2$ 

- As we complete further analyses of the  $N_f = 6$  theory, we are also beginning to study
- A theory with five pairs of light techniquarks ( $N_f = 10$ ), and
- ► A theory with a different gauge symmetry structure altogether.
- A very important analysis now nearing completion is the calculation of the "S parameter" in the  $N_f = 6$  theory.

# Precision electroweak observables

- So far, direct searches for new particles predicted by theories of EWSB (the Higgs boson, technihadrons, etc.) have only been able to place bounds on these theories. • A complimentary approach is to study the effects these theories may have
- on other quantities that can be measured with great precision. Such quantities include the mass of the  $W^{\pm}$  and Z bosons, and their decays into other kinds of particles.
- In practice, we relate these measurements to simple parameters that indicate the presence of certain effects. The most famous of these parameters are known as S and T.

# The S parameter

- Qualitatively, the S parameter measures the effects of the EWSB mechanism (e.g., new strong dynamics) on the behavior of the Z boson and photon  $\gamma$
- It is defined to be exactly zero if the standard model correctly describes nature.
  - Experiments measure  $S = -0.04 \pm 0.09$ , consistent with zero, as shown to the right.

► Simple arguments suggest that new strong dynamics

- would produce a large, positive  $S \sim 1$ . ▶ But until now, no quantitative calculation of S has been possible.
- Recently, groups in Japan and in the UK calculated  $S = 0.38 \pm 0.04$  and  $S = 0.42 \pm 0.07$  (respectively), if new strong dynamics behaved the same as QCD.
- The LSD Collaboration will soon complete the first calculation of S for new strong dynamics beyond QCD.

#### We will soon make great progress unraveling the mystery of EWSB

- High-performance computing has advanced to the point where we can study
- otherwise-intractable theories of electroweak symmetry breaking through new strong dynamics. • These theories will soon be tested at the Large Hadron Collider,
- which has been designed to discover the physics behind EWSB. • With the help of high-performance computing, we can prepare to understand whatever the LHC may see.
- Although it will take time to obtain data (and may take even longer to understand what the data mean)

we expect great progress in the near future.

#### and permit elementary particles to possess their experimentally-observed masses, we say that the electroweak symmetry is "broken".

Looking deeper, electroweak unification seems even more surprising:

Weak interaction

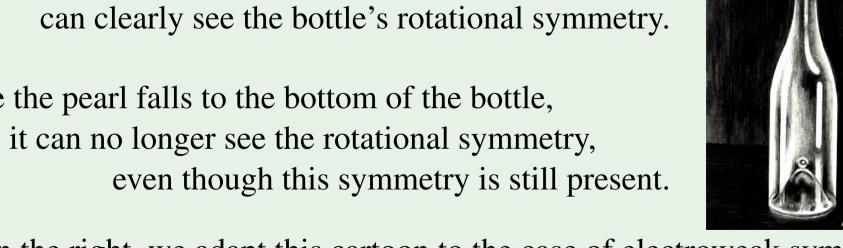
Violates parity

Question: How can electroweak symmetry be useful if we say it is "broken"? **Answer**: The symmetry actually remains in the theory, but is *hidden* in the ground state.

A pearl perched at the center of the wine bottle

Spontaneous symmetry breaking

Once the pearl falls to the bottom of the bottle, it can no longer see the rotational symmetry,



For historical reasons, this is called "spontaneous symmetry breaking".

- On the right, we adapt this cartoon to the case of electroweak symmetry breaking. • From our perspective, the theory describes massive  $W^{\pm}$  and Z bosons, along with the massless photon  $\gamma$ .
- From a perspective where the symmetry is manifest, the theory describes four massless gauge bosons (called  $b^1$ ,  $b^2$ ,  $b^3$  and a in the cartoon). These are two equivalent descriptions of the same physical system
- A final conundrum: massive gauge bosons have one more degree of freedom than massless gauge bosons.

while the rest of EWSB remains as the physically-observable E

- To remain consistent, the theory must include an "electroweak symmetry breaking sector", called **EWSB** in the cartoon above. • The  $W^{\pm}$  and the Z each "eat" a degree of freedom from EWSB to become massive,
  - The nature of this electroweak symmetry breaking sector EWSB remains unknown.