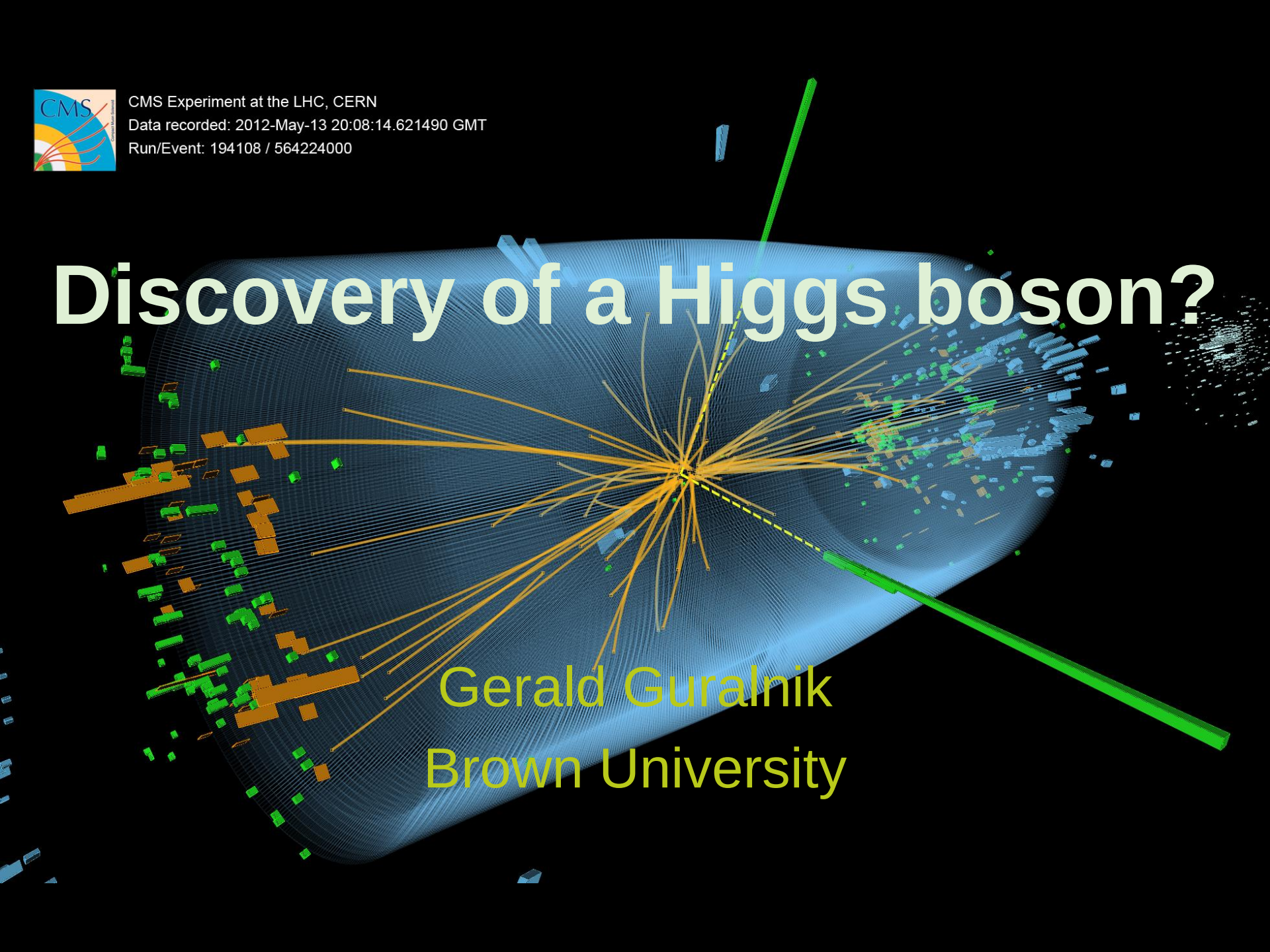


Discovery of a Higgs boson?

Gerald Guralnik
Brown University

Job Creation in Particle Physics:

or

How The Boson was Predicted

Special thanks to my colleagues

Ulrich Heintz, Meenakshi Narain (Brown)

and

C.R Hagen (Rochester)

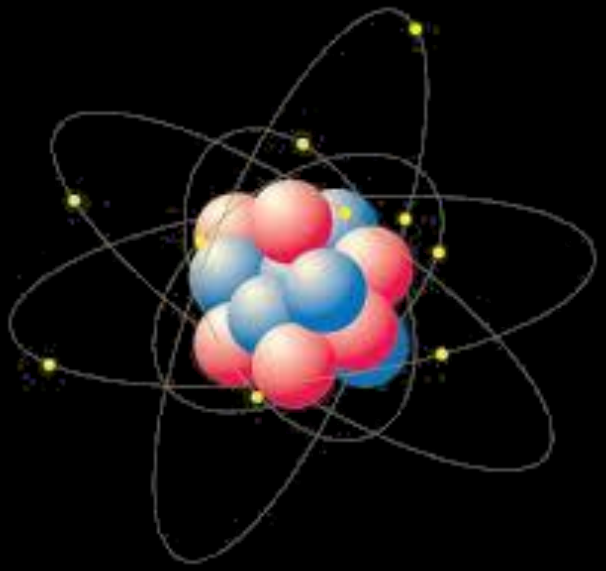
and

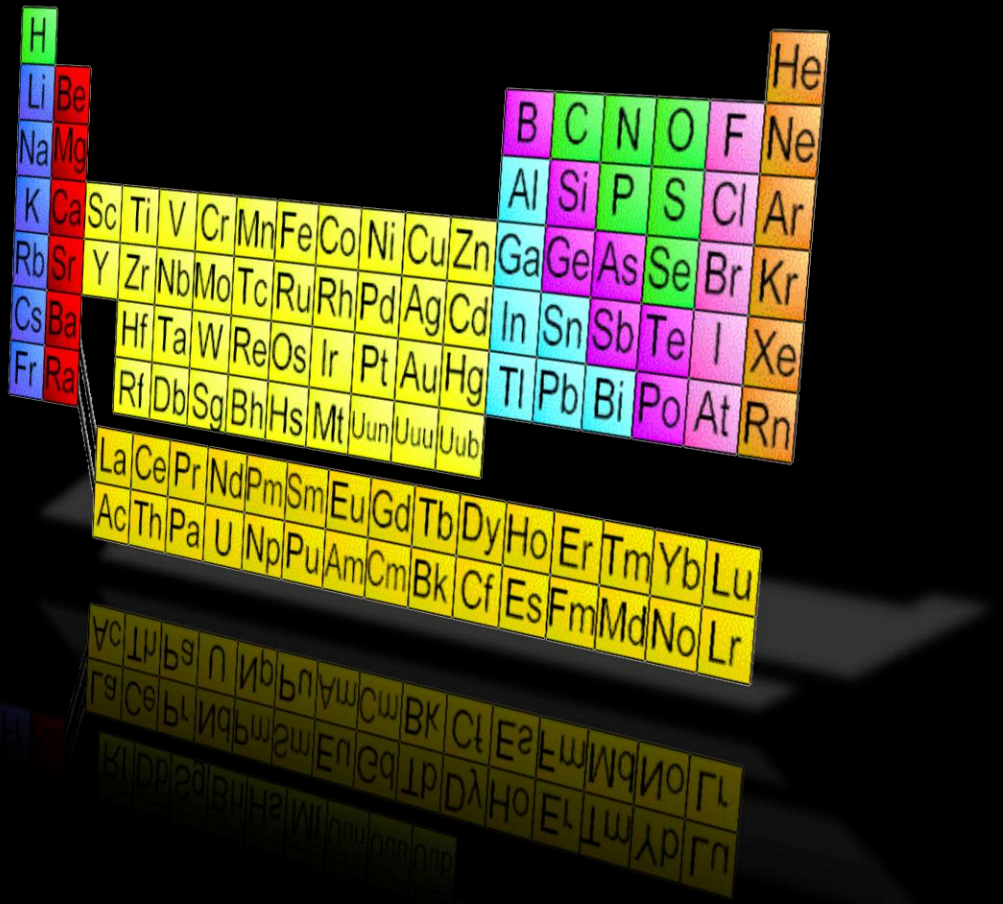
Tom Kibble (Imperial College)

for use of some of their slides and valuable discussions!

what is the Higgs boson?

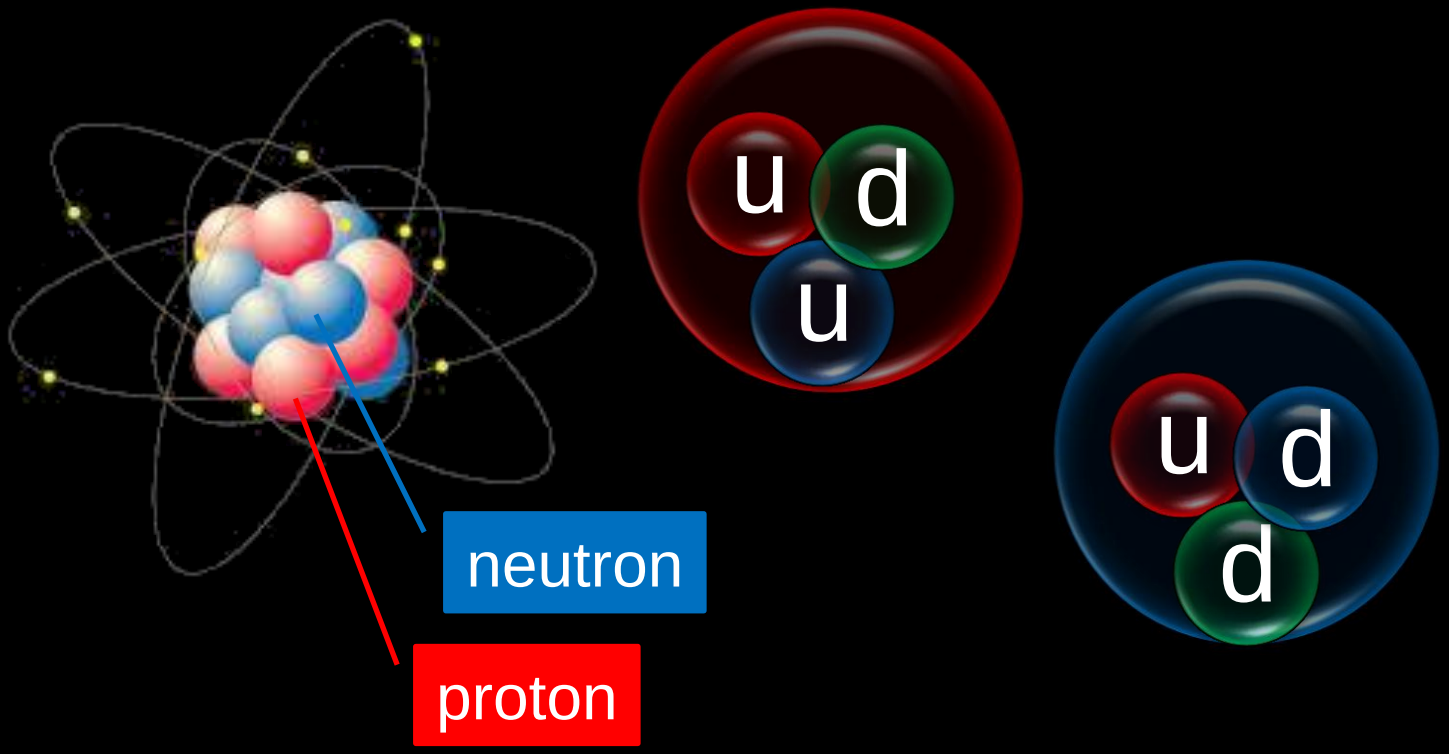
- the matter around us consists of atoms...
- there are many types of atoms and we know why
- the periodic table summarizes our understanding





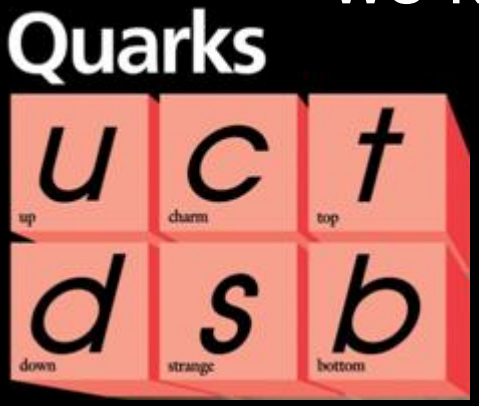
what is the Higgs boson?

- atomic nuclei are made of protons and neutrons
- we know why there are protons and neutrons (and many others...)
- they are made of different combinations of quarks

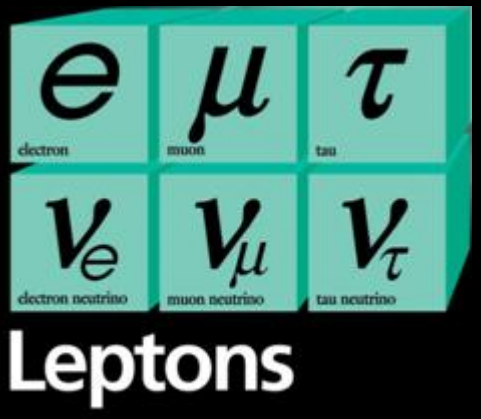


what is the Higgs boson?

we know there are six quarks



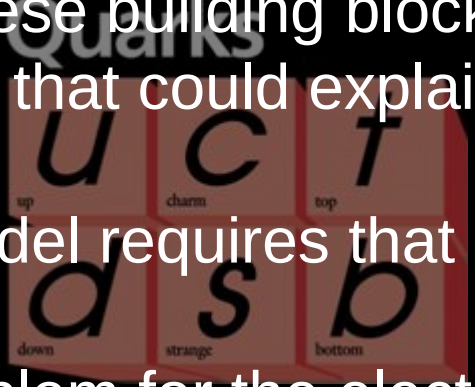
there are six leptons



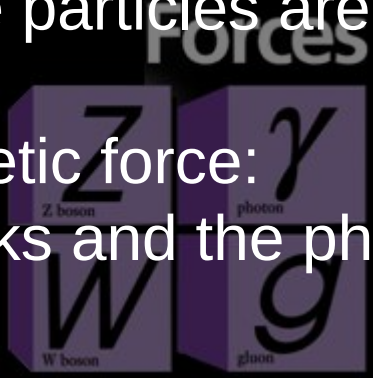
there are gauge bosons that are responsible for their interactions

what is the Higgs boson?

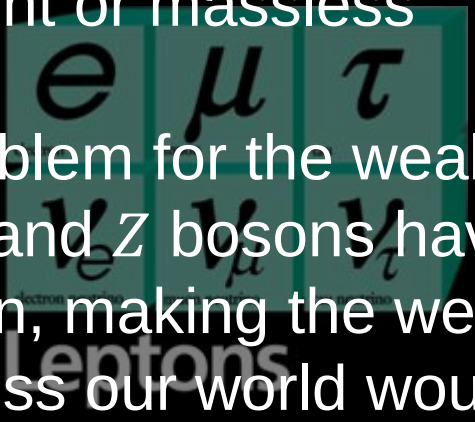
with these building blocks we can construct a model of matter, that could explain everything we observe



the model requires that all these particles are massless.



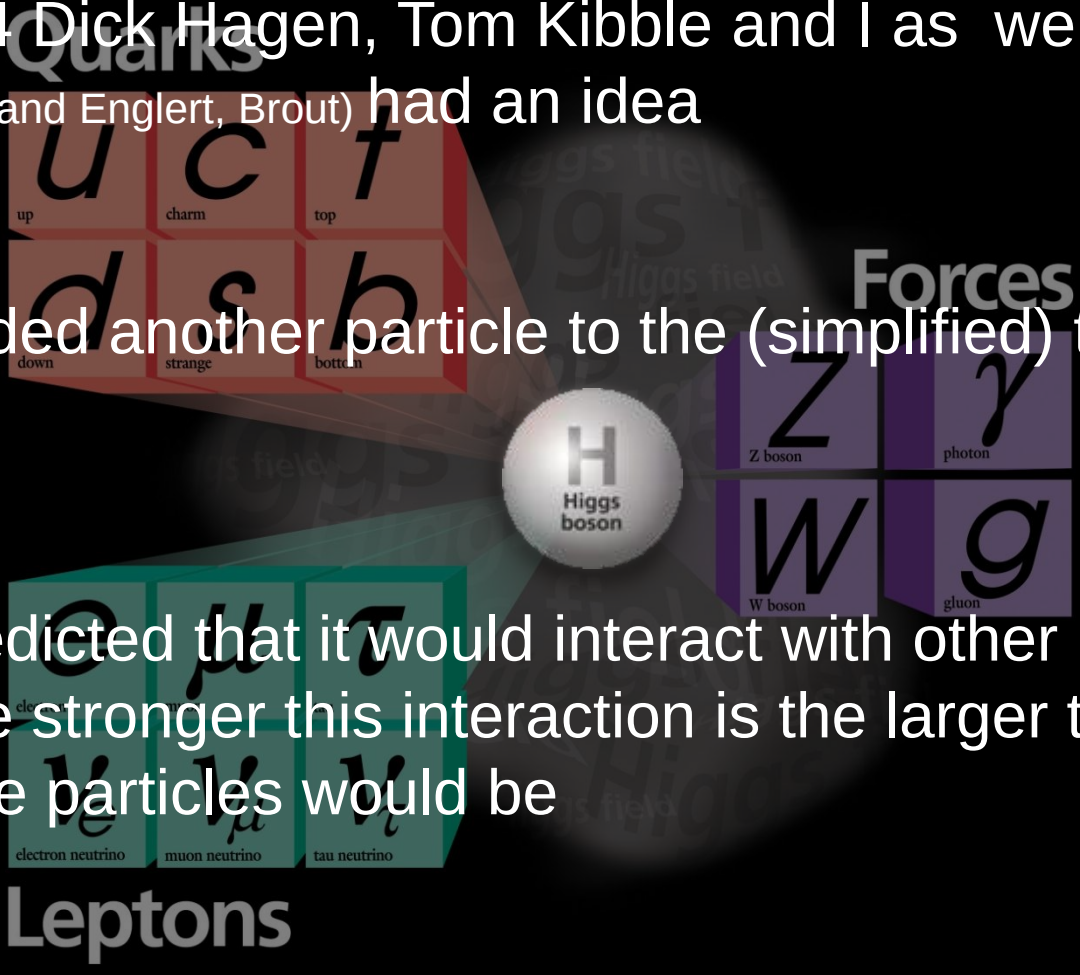
no problem for the electromagnetic force:
electron, neutrino, u and d quarks and the photon are very light or massless



big problem for the weak force:
the W and Z bosons have 150,000 times the mass of an electron, making the weak force short range. Were they massless our world would be completely different

what is the Higgs boson?

In 1964 Dick Hagen, Tom Kibble and I as well as Higgs (and Englert, Brout) had an idea

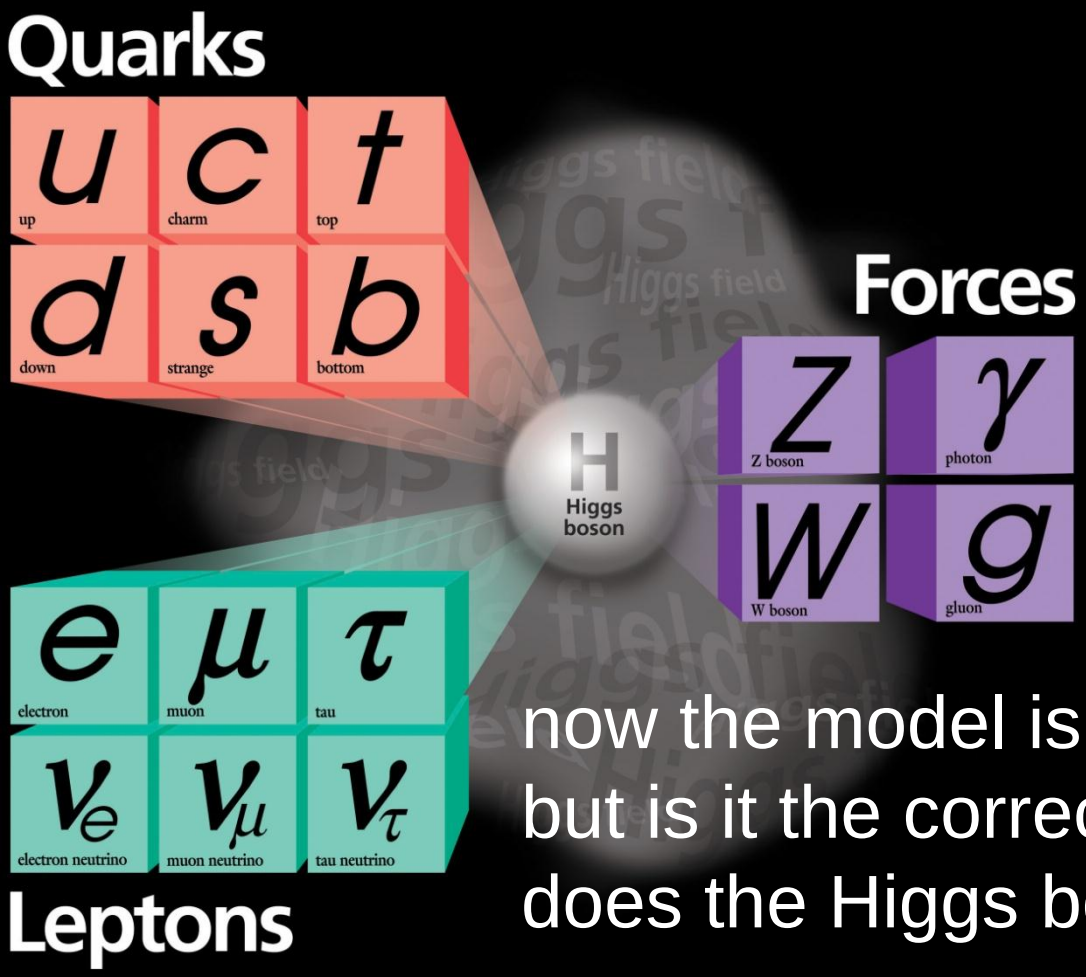


We added another particle to the (simplified) theory

We predicted that it would interact with other particles and the stronger this interaction is the larger the mass of these particles would be

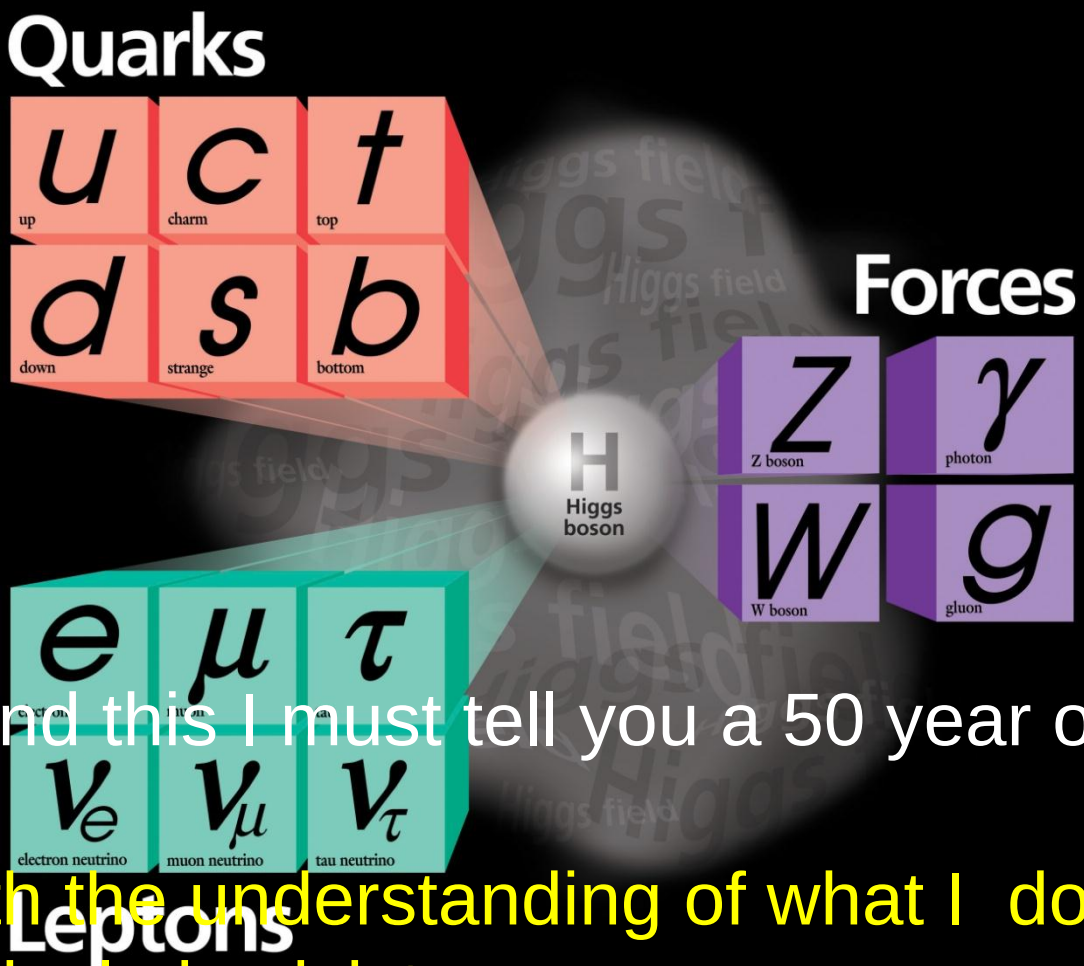
today this particle is called the Higgs boson

what is the Higgs boson?



now the model is complete
but is it the correct model?
does the Higgs boson exist?

How was the Boson Born?



To understand this I must tell you a 50 year old story!

It begins with the understanding of what I do in my job as a theoretical physicist.

As a theoretical physicist, I find the equations that predict or describe experimental results.

The most successful method to date is to create these equations by guessing in combination with a general concept called QFT

This is very hard and initially only worked to explain E&M but not weak or strong interactions. This eventually turned out to be caused by limited calculational techniques.

Before this was understood, most theorists gave up on QFT!

Revolution in the 60’s

- Fortunately - Field theory survived at a handful of universities – Harvard, Imperial College, and through Yoichiro Nambu at the University of Chicago.
- In 1960 Nambu and Jona-Lasinio published two sensational papers showing a new kind of solution of QFT
- Their solutions have less symmetry than the original theory.
- They are called **spontaneously broken symmetry** solutions.

Spontaneously Broken Symmetry and the Nambu-Goldstone Theorem

- This "**breaking**" of the **symmetry** in particle theories comes with a **price** - a very general theorem - the **Nambu-Goldstone Theorem**!
- **Solutions must always have a particle with zero mass!**
- Zero mass is a big problem – right now only one zero mass particle is experimentally observed – the photon - the particle associated with electromagnetism. Are these ideas **worthless** for "reality based" physics?

Spontaneously Broken Symmetry and the Nambu-Goldstone Theorem

- This is were I came in - 50 years ago (OMG), my thesis advisor at Harvard (Walter Gilbert –Nobel Prize Chemistry 1980) told me to study the Nambu papers and see what I could do with these ideas.
- **I obeyed**!!

Walter Gilbert

An Alternative Formulation of Electromagnetism

Can the photon be a Nambu-Goldstone massless particle?

I showed that the answer is yes – but starting with equations entirely different from the usual ones!

This was astonishing.

This was enough for a decent thesis – but was I happy?

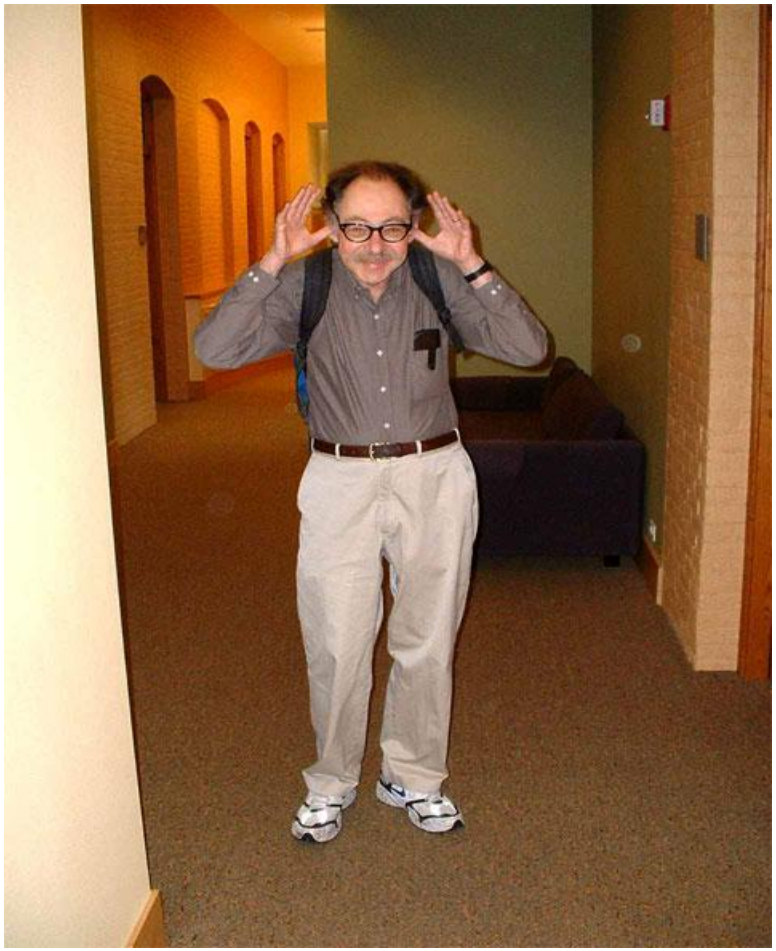
No – I wanted more!

An Embarrassing Attempt to Prove Normal Photons are Required to be Massless

- No one had (really) shown that the **usual theory** of Electromagnetism (**QED**) required a massless photon.
- In fact, Julian Schwinger – one of the greatest physicists of the 20th century said the zero mass only happened because the electromagnetic interaction was so weak.
- I thought he was just plain wrong.
- I used the Nambu-Goldstone theorem to “prove” his error.

An Embarrassing Attempt to Prove Normal Photons are Required to be Massless

- Gilbert approved of the chapter in my thesis that did this but –
- Sidney Coleman - an assistant professor and a good friend (at least until he sat on my exam) and already famous for his rapid mind and sharp tongue thought that this chapter was totally wrong.
- He prevailed and the chapter was removed from my thesis!
- **He was correct!**



Sidney Coleman

Picture taken much later than 1960’s

In the 1960’s he wore purple velvet suits!

Photo by Lubos Motl

Working at Harvard 1961

Lord May of Oxford, G. S. Guralnik and C.R. Hagen

Hagen prepares to start his posdoc at Rochester – 1963

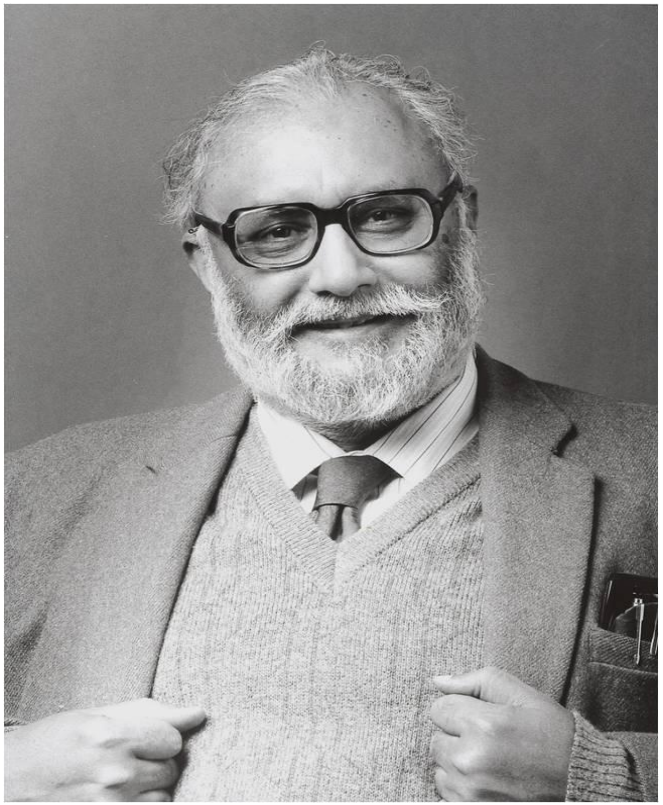
His love of expensive unreliable machinery made me think he was about to become an experimentalist!

Off to Imperial College - London

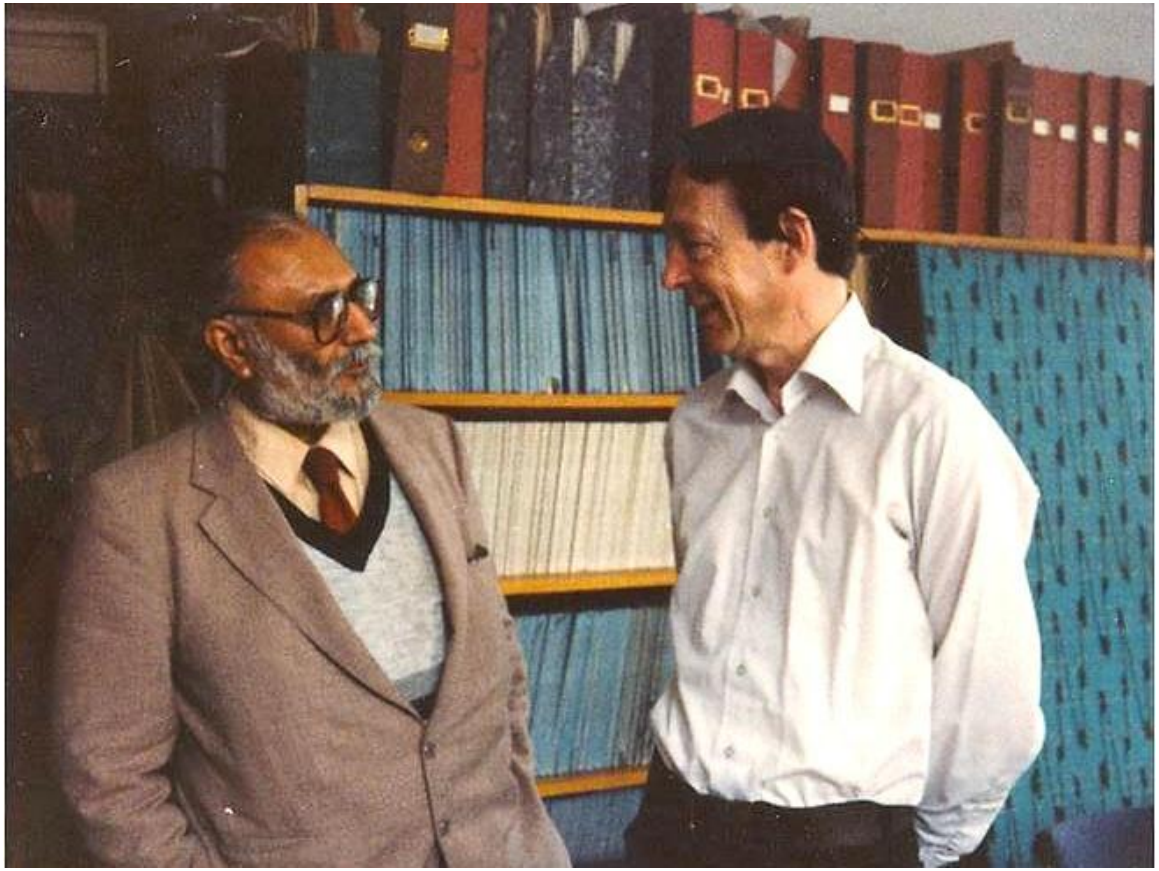
January 1964: New Ph.D. in hand, I began a postdoctoral fellowship at Imperial college London generously paid for by the U.S. N.S.F.

I.C. was very exciting with lots of excellent faculty and many visitors from all over the world.

The Imperial College theoretical physics group was founded in 1956 by Abdus Salam. My thesis advisor – Walter Gilbert – was Salam's thesis student and Salam referred to me as his "grandstudent".



Salam shared the 1979 Nobel prize in physics with Glashow and Weinberg for developing the unified electro-weak theory based on the discovery I am about to outline.



Abdus Salam and Tom Kibble

Kibble and I became good friends and talked about physics over (awful) lunches served in Imperial College dining rooms!

A very Subtle Error that Led to a Great Truth!

- I still believed that there was an absolute requirement in the usual theory of Electromagnetism that requires the photon is massless.
- I produced a **seemingly incontrovertible** proof (using the Nambu-Goldstone theorem) of this!
- I wrote a paper in April 1964 and sent it to the premier physics journal – Physical Review Letters (PRL) for consideration for publication.

A very Subtle Error that Led to a Great Truth!

- A few days after this paper was sent, I discovered a very **weird** mathematical totally unexpected **error** that destroyed my proof in one special case – the case that mattered for Electromagnetism.
- The paper should have been stopped but, because of a series of unlikely events including postal strikes it was published (Received: June 1, ‘64)

The Great Truth

- **Understanding that there was an error led to an astonishing conclusion!**

- The conditions needed to prove the **Nambu – Goldstone theorem** (accepted as automatic) for all field theories do not hold for the usual theory of Electromagnetism and similar but more complex theories.

- **THE THEOREM IS IRRELEVANT FOR THE THEORIES MOST RELEVANT TO OUR UNIVERSE!**

The Great Truth

- An amusing fact: Peter Higgs published a paper in Physics Letters (received July 27, 1964) that makes the same error but comes to a different conclusion. This paper, while famous, is wrong in a major way! Neither of us knew of the other's paper.
- After finding the error - I immediately realized that there is **another solution** to the equations of usual Electromagnetism characterized by spontaneous symmetry breaking **which does not have a zero mass photon!**

The Amazing Result

- Hagen, Kibble and I put these new ideas together in a paper making the following observations:
- **There is a new previously unsuspected solution for the quantum equations of Electromagnetism (interacting with a massless charged scalar field)**
- **This** spontaneously broken symmetry solution corresponds to a new phase (like water, ice and steam) and **is entirely different in behavior from the well known solution.**

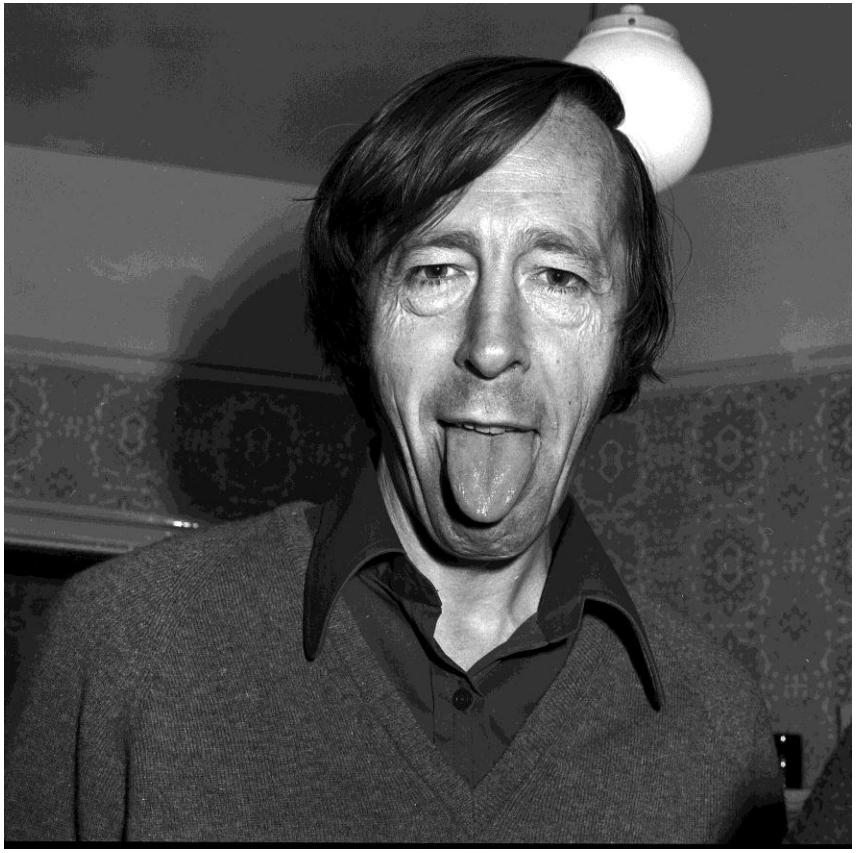
The Amazing Result

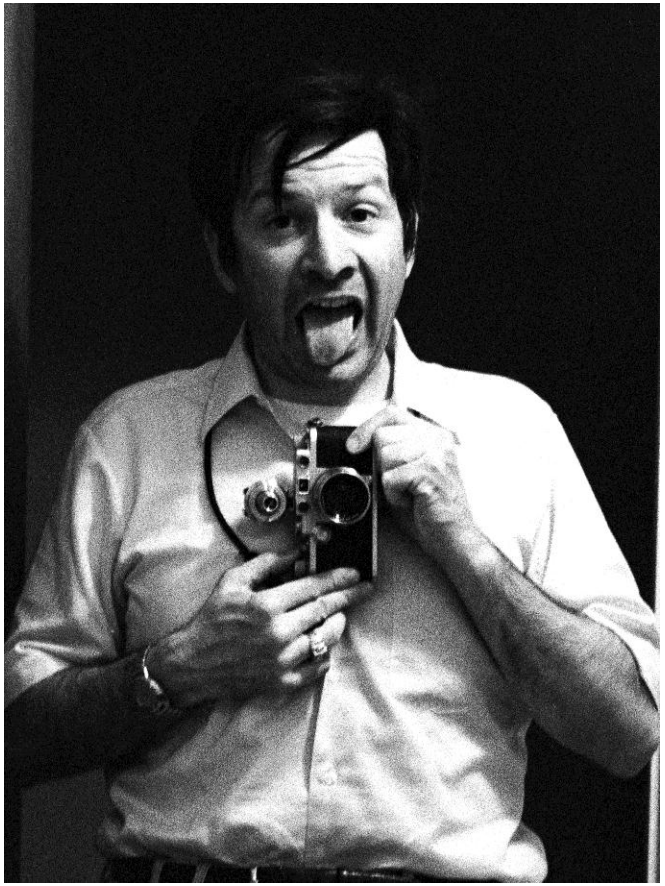
- The massless photon is gone!
- It is replaced by a spin-one particle with a non-zero mass!
- Part of the charged scalar field has helped make this particle
- **There is a lonely spin zero scalar particle left over!**

The Papers

- This “left over” particle corresponds to the “God Particle” or “Higgs boson”
- **We had generated mass through spontaneous breaking!**
- While this work was essentially completely done in late April 1964 we did not submit it until much later – received by PRL October 12, 1964.
- **Why the delay?**
- We were **afraid** we were **wrong**. I had learned the hard way that this is a treacherous problem.

Kibble and Guralnik search for guidance through emulation of Einstein (it did not work)
or
Should we Publish?





The Papers

- We applied every test we could think of and our work passed them!
- As our paper went to the mail, related work arrived by Englert and Brout and Higgs.
- We quickly read them, recognized that they addressed essentially the same problem and while they had some truth – they succumbed to traps – new or those we had avoided – we wrote them off.
- We still see serious errors in these papers !

The Rejection

- At the time, this work was radical and very surprising.
- We expected problems convincing the physics community
- We were **justified** in the **fear**!
- I gave many talks in Great Britain and Europe and often our claims were received with **skepticism** (at best).

The Rejection

- I gave a talk on this at a conference near Munich (July 1965) held in honor of **Werner Heisenberg** – a founder of Quantum mechanics and certainly one of the greatest physicists of the 20th century.
- He made it clear to me that he thought our theory was **Junk**!
- I was scared and thought it was the end of my short career.

The Rejection

- Julian Schwinger was there and gave me a ride in his brand new Iso Revolta. It cost a sizeable part of the money that he would receive from the Nobel Prize later in the year!
- He did not say a thing about my talk. I was upset!
- A small amusement – Edward Teller's wife came with us and teased him mercilessly about the car not having an automatic transmission.

1965 Iso Revolta

Not Schwinger's – random from web –
Conclusion: American theorists often like impractical vehicles!

Redemption

- On Hagen's recommendation Robert Marshak gave me a postdoctoral job at University of Rochester.
- He told me survival required I no longer work on symmetry breaking
- I worked on some ideas of Steven Weinberg's and explained something about mass yet again.
- This new work was instrumental in getting me an assistant professorship at Brown in academic year 1967.

Redemption

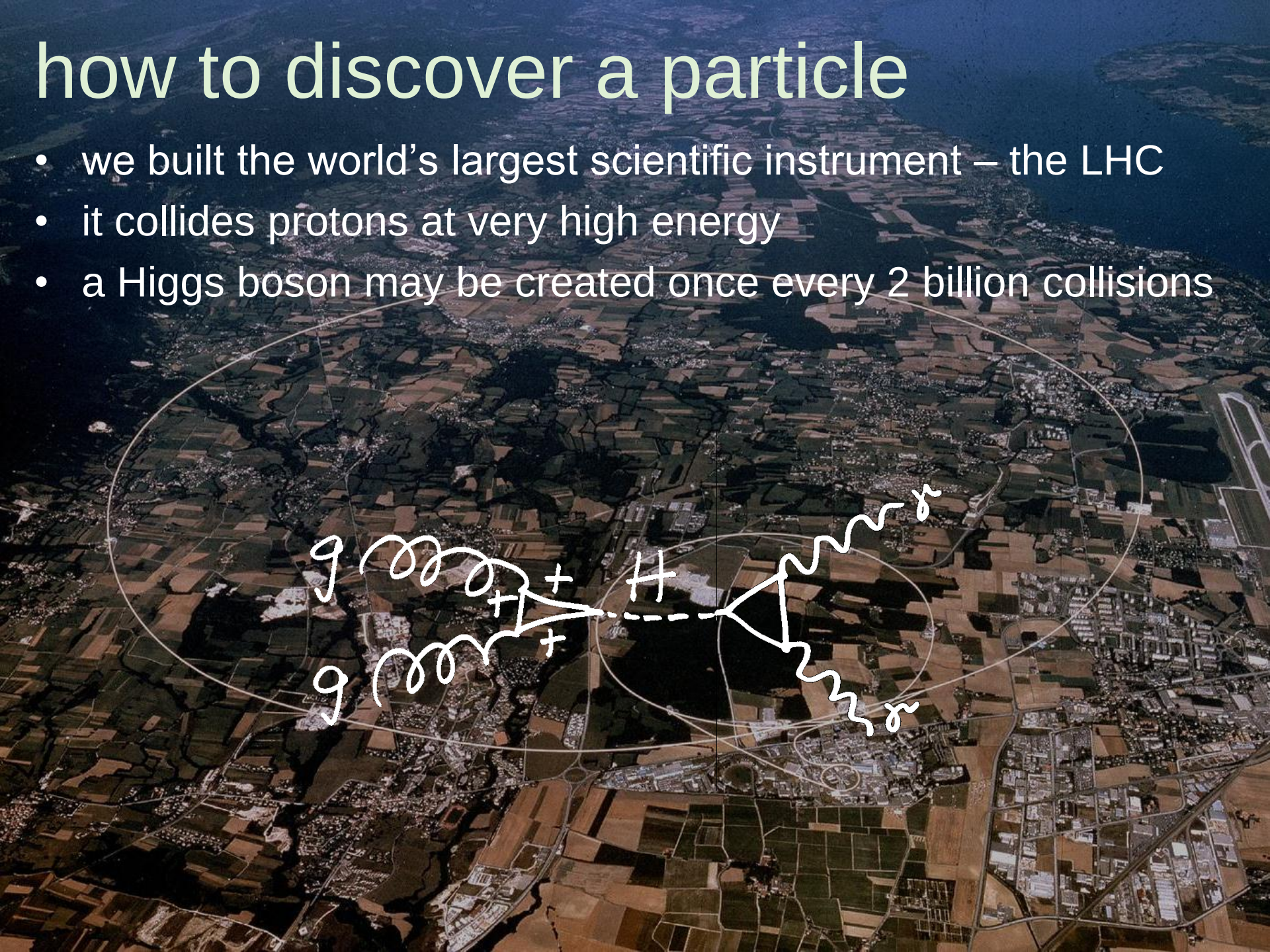
- Meanwhile Weinberg was working on the GHK (our) paper.
- He (and Salam) discovered the unified theory of electromagnetism and weak interactions and all of this now is the cornerstone of the “Standard Model of particle physics.
- This led to decades of search to verify the predictions of our model and even some recognition!

Sakurai Prize Ceremony February 2010

Peter Higgs could not make it - so no picture!

how to discover a particle

- we built the world's largest scientific instrument – the LHC
- it collides protons at very high energy
- a Higgs boson may be created once every 2 billion collisions



how to discover a particle

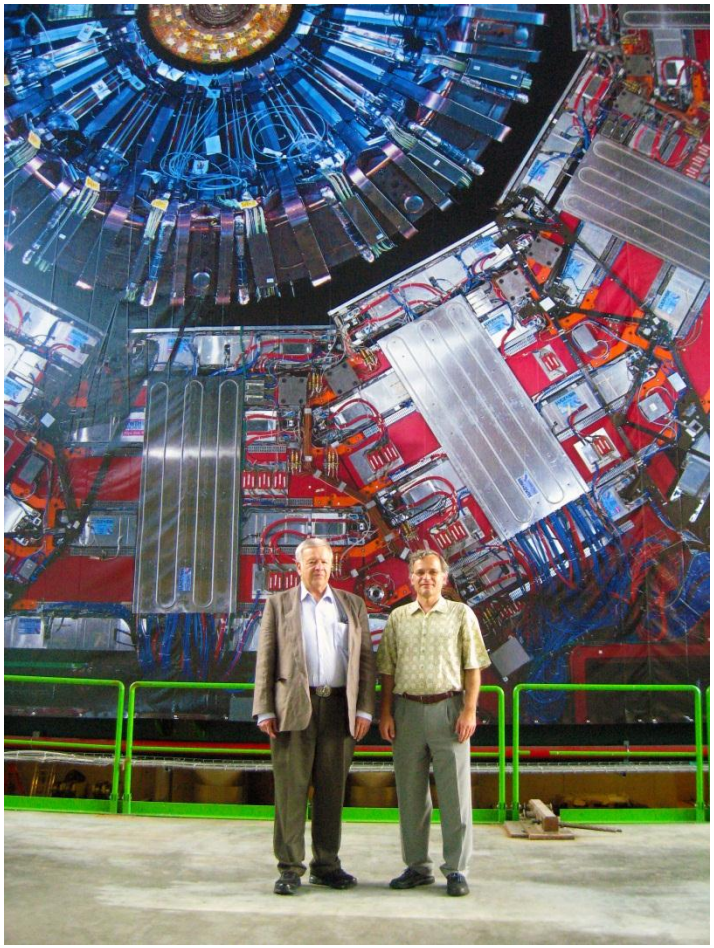
- we built detectors as big as cathedrals
- when a Higgs boson is created it immediately disintegrates
- about 1 every 500 Higgs bosons decays to two photons

- the detector measures their energies
- we compute the mass of the particle that they came from

$$E = mc^2$$

Hagen and Guralnik

On the way to CERN for July 4th 2012 announcement



G. Guralnik and Ulrich Heintz (Brown)

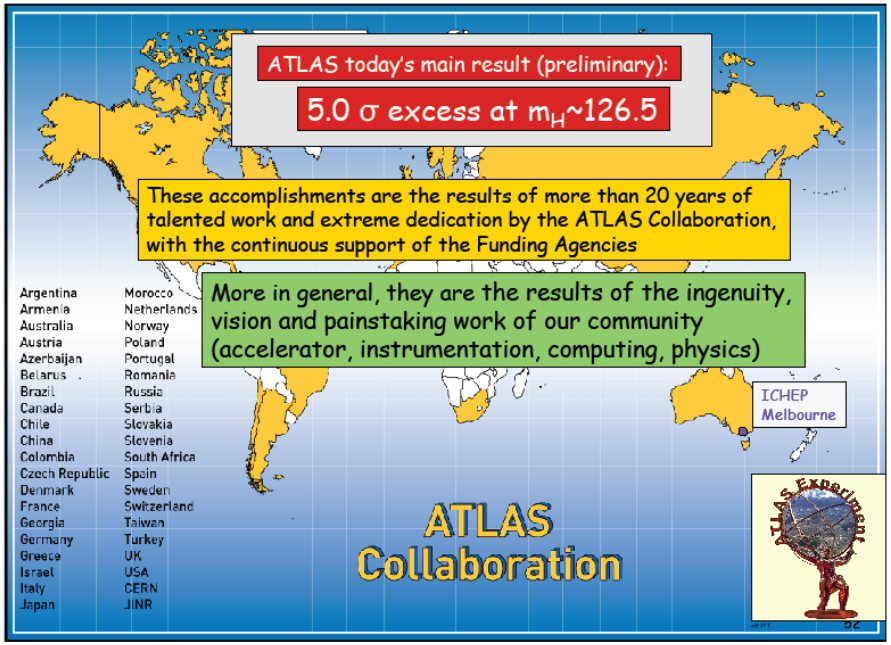
In the background is a life-size photograph of the CMS – Since I am a theorist they told me it was the real thing – but I caught on!

20% of the CMS Collaboration

Hope!

- July 4, 2012 – 5:30am

July 4, 2012



In summary

We have observed a new boson with a mass of

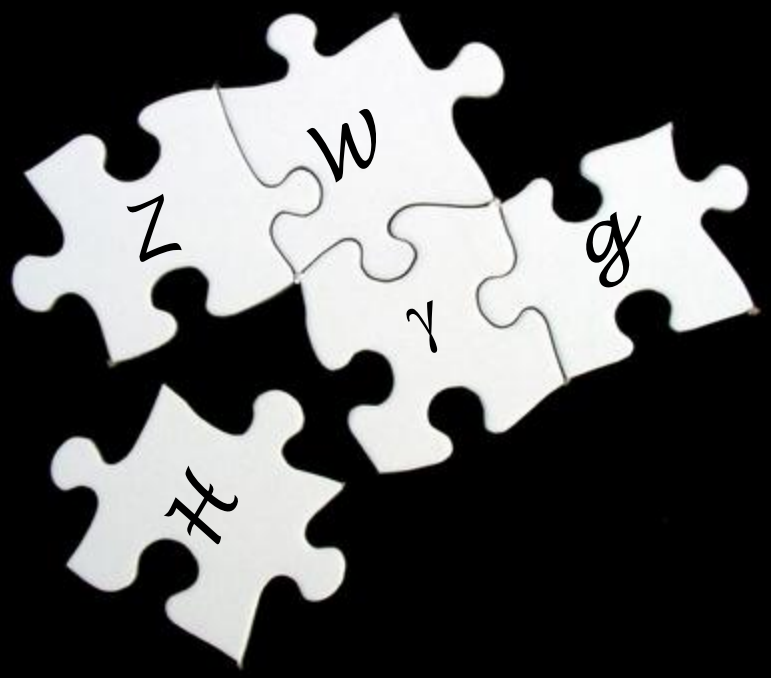
125.3 ± 0.6 GeV

at

4.9 σ significance !

there is definitely something!

is it THE elusive boson?



After the Presentations

Hagen is happy!

After the Presentations

I am Very Happy!

Dinner after the revelation!

The Physics and the food were outstanding on July 4th!

what does it all mean?

On a longer time scale, the advance of technology will reflect the coherent picture of nature we are now assembling. At the end of the 19th century physicists in England were exploring the properties of electric currents passing through a near vacuum. Although this was pure science, it led to our knowledge of the electron, without which a large part of today's technology would be impossible. If these physicists had limited themselves to work of obvious practical importance, they would have been studying the behavior of steam boilers.

Steven Weinberg in the New York Times, July 13, 2012

So, as for the question of what this Higgs boson thing ultimately "means": It means we should all try to have some intellectual humility [...] because the thing we're using to try to understand the world – the human brain – is [...] a pretty crude instrument.
Or, I should say: That's what I *think* the Higgs Boson means.

Robert Wright in the Atlantic, July 5, 2012

Triumph!

- These wonderful experiments have probably found the long **Elusive Boson** conjectured by half century old theoretical work!
- I feel so fortunate to have had the luck, the thrills and even the angst of working on, understanding and predicting this particle through work driven by pure curiosity and enabled by the luxury of government supported uninhibited mathematical wonderings.
- This is just the beginning of a new age in particle physics!