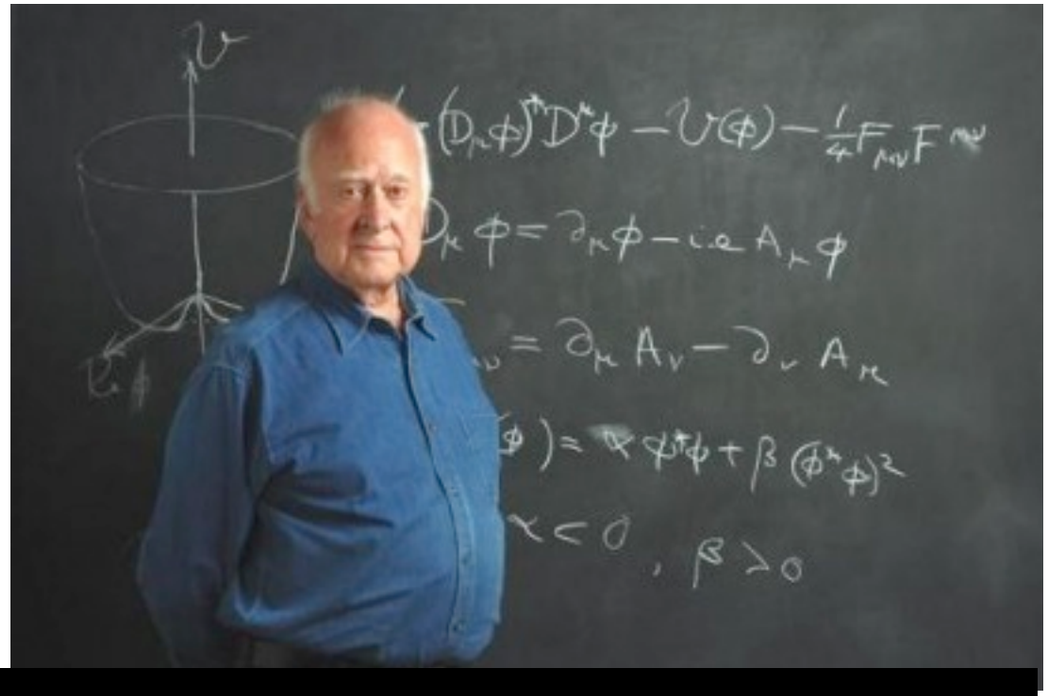
The Discovery of the Higgs Boson?

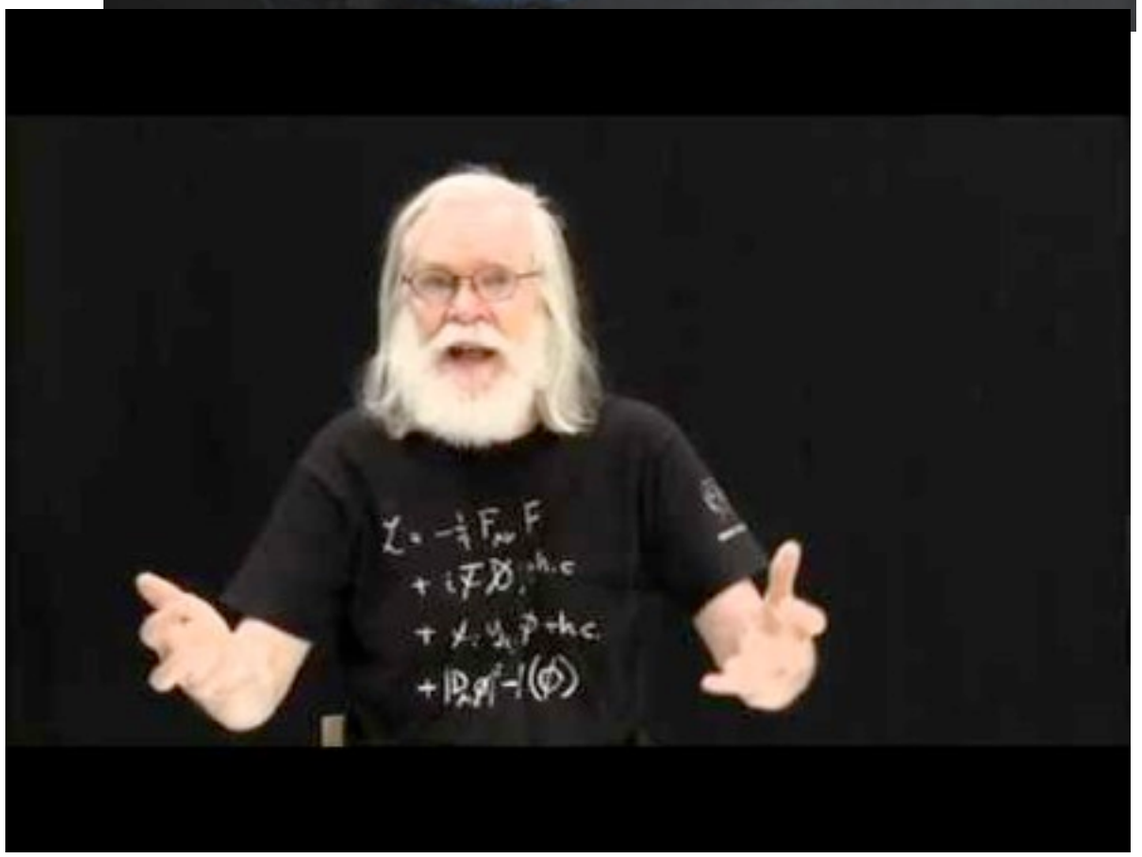
Frank Petriello

James Proudfoot

Special Director's Colloquium
July 11, 2012

If you've been watching the news the past week, you may have noticed the following...





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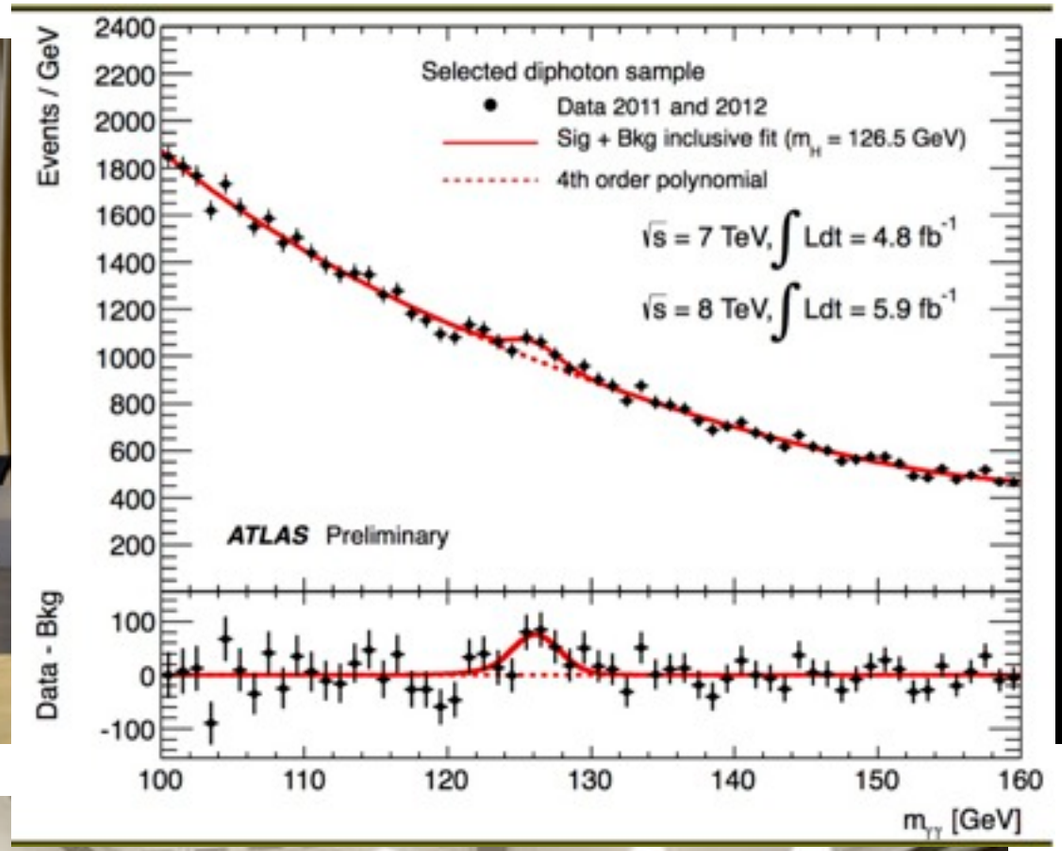
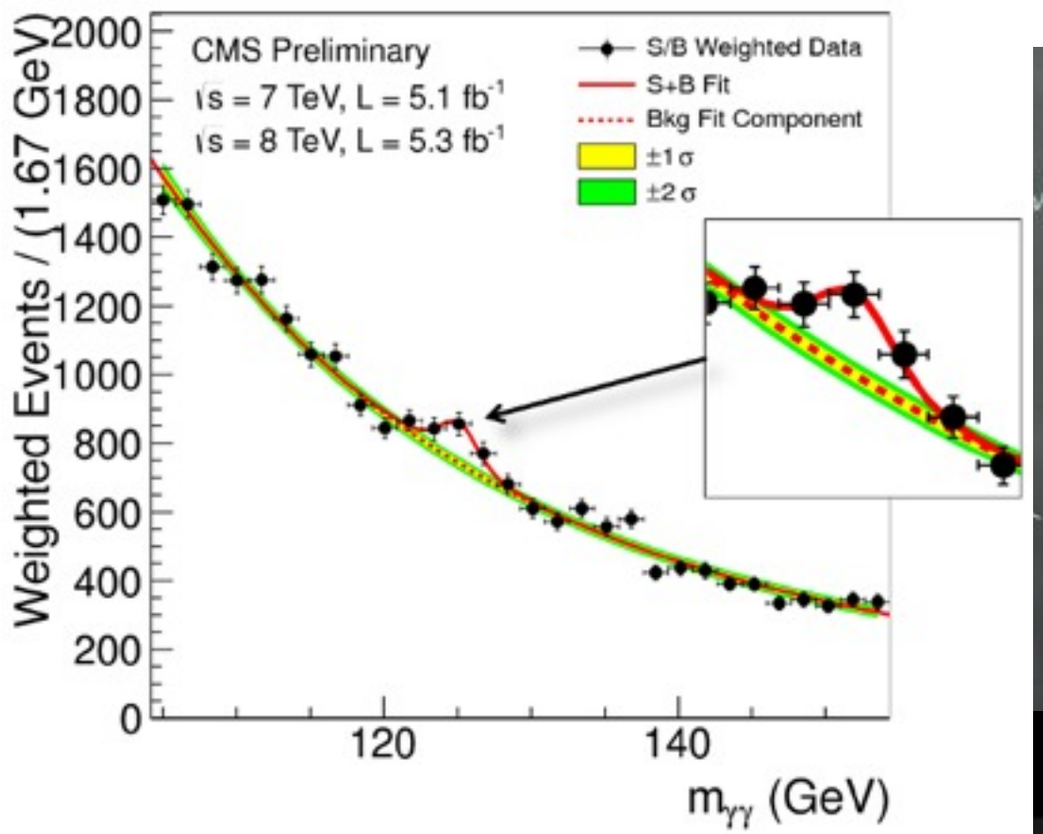
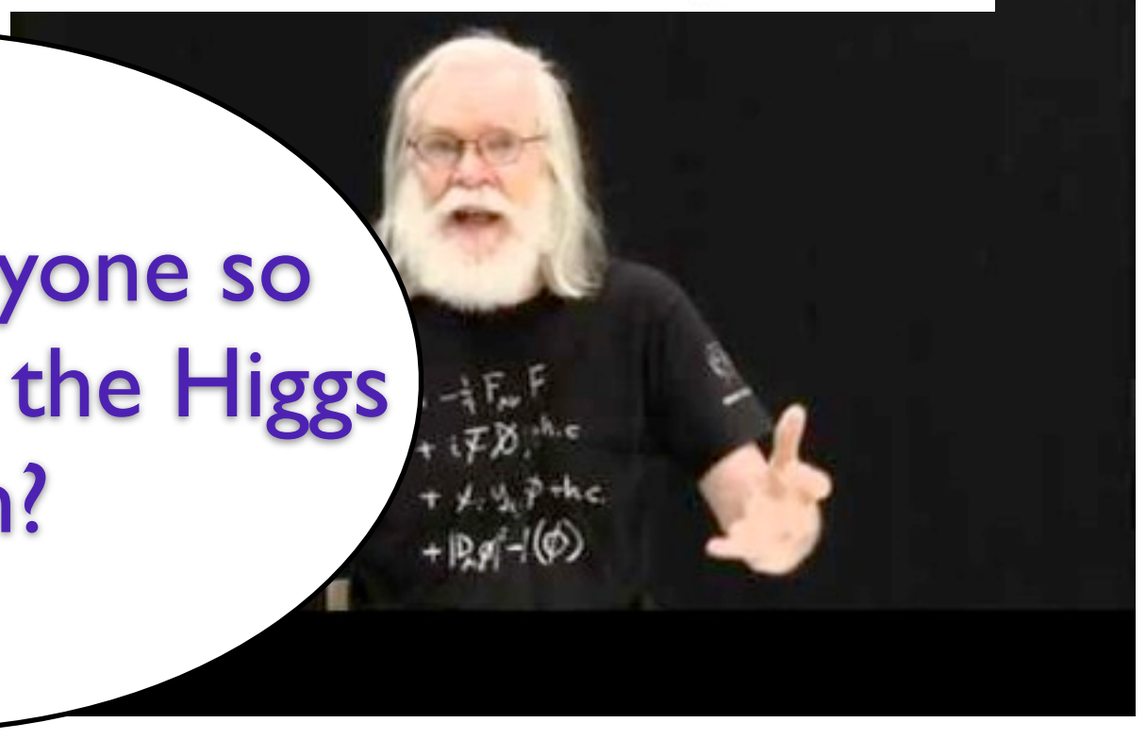




Why is everyone so excited about the Higgs boson?



Outline

- We'll try to convey to you why the Higgs boson is a big deal (part I), and how it was found after decades of searching (part II)

  - The role of symmetries in constructing physical theories
  - The Standard Model, a physicist's periodic table
  - Broken symmetry and the Higgs mechanism
  - Going beyond discovery

The beginning

- The guiding principle for much of physics throughout the 20th (and 21st so far) century was ***symmetry***
- Every symmetry in Nature leads to a conserved quantity - Emmy Noether
- Many familiar examples of this...

- Laws of physics unchanged under translation: linear momentum conserved

$$m_1v_1=m_2v_2$$

"For every reaction there is an equal and opposite reaction"

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Internal symmetries

- Subatomic particles possess similar, *internal*, symmetries
- Protons and neutrons related by an approximate *isospin* symmetry; each is a reflection of the other - Werner Heisenberg

- **This symmetry has predictive power!**

Predicted near equality of:

$$p+p \rightarrow \pi^{+}+d$$
$$p+n \rightarrow \pi^{0}+d$$

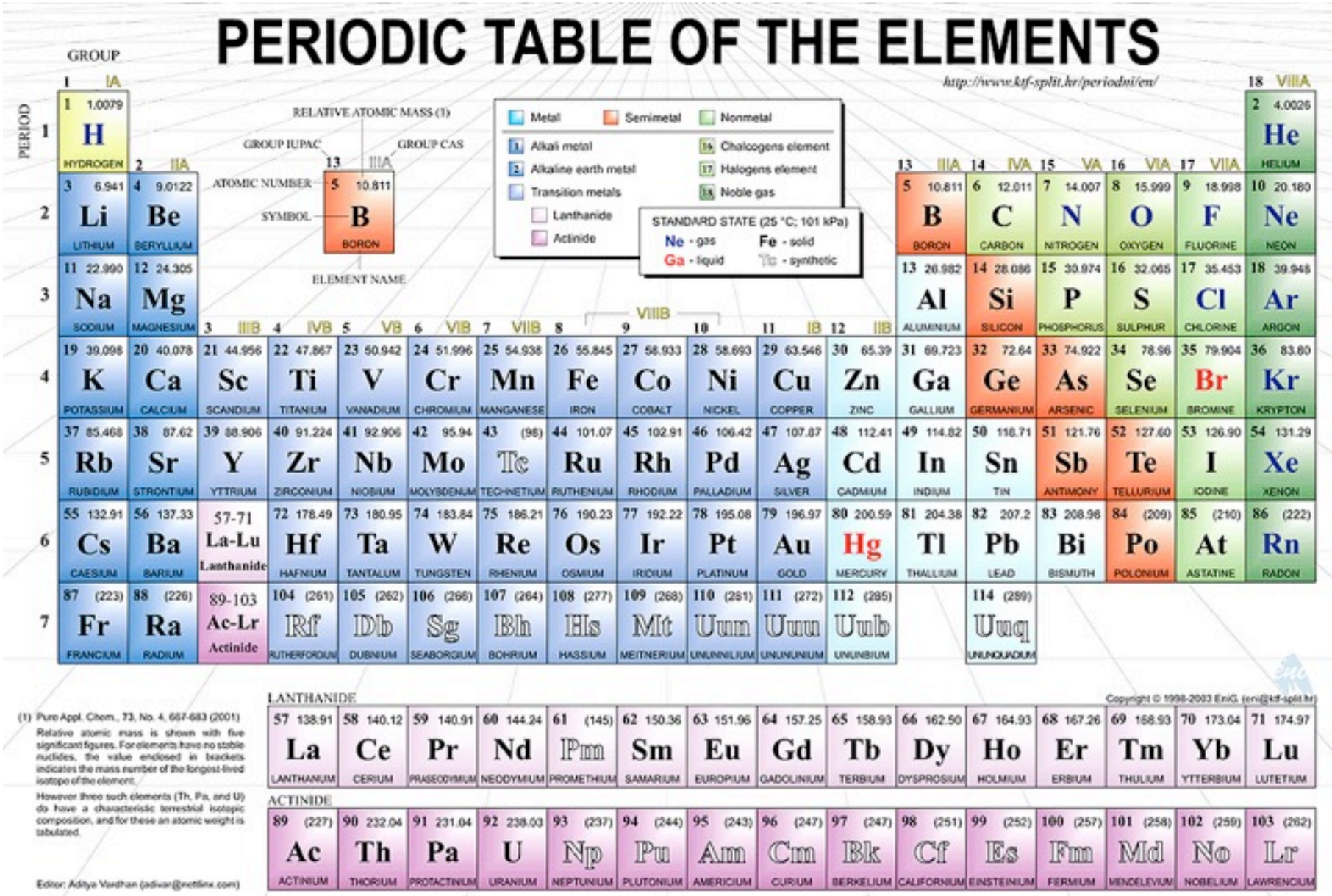
pions deuteron

The Standard Model and gauge symmetry

- Physicists have been successfully using similar internal symmetries, ***gauge symmetries***, to describe fundamental particles for several decades
- ***Gauge symmetries*** are mathematical constructs that predict force-carrying particles that mediate interactions in a ***calculable*** way
- The current gauge-theory formulation which describes all known phenomena in Nature is called the **Standard Model**

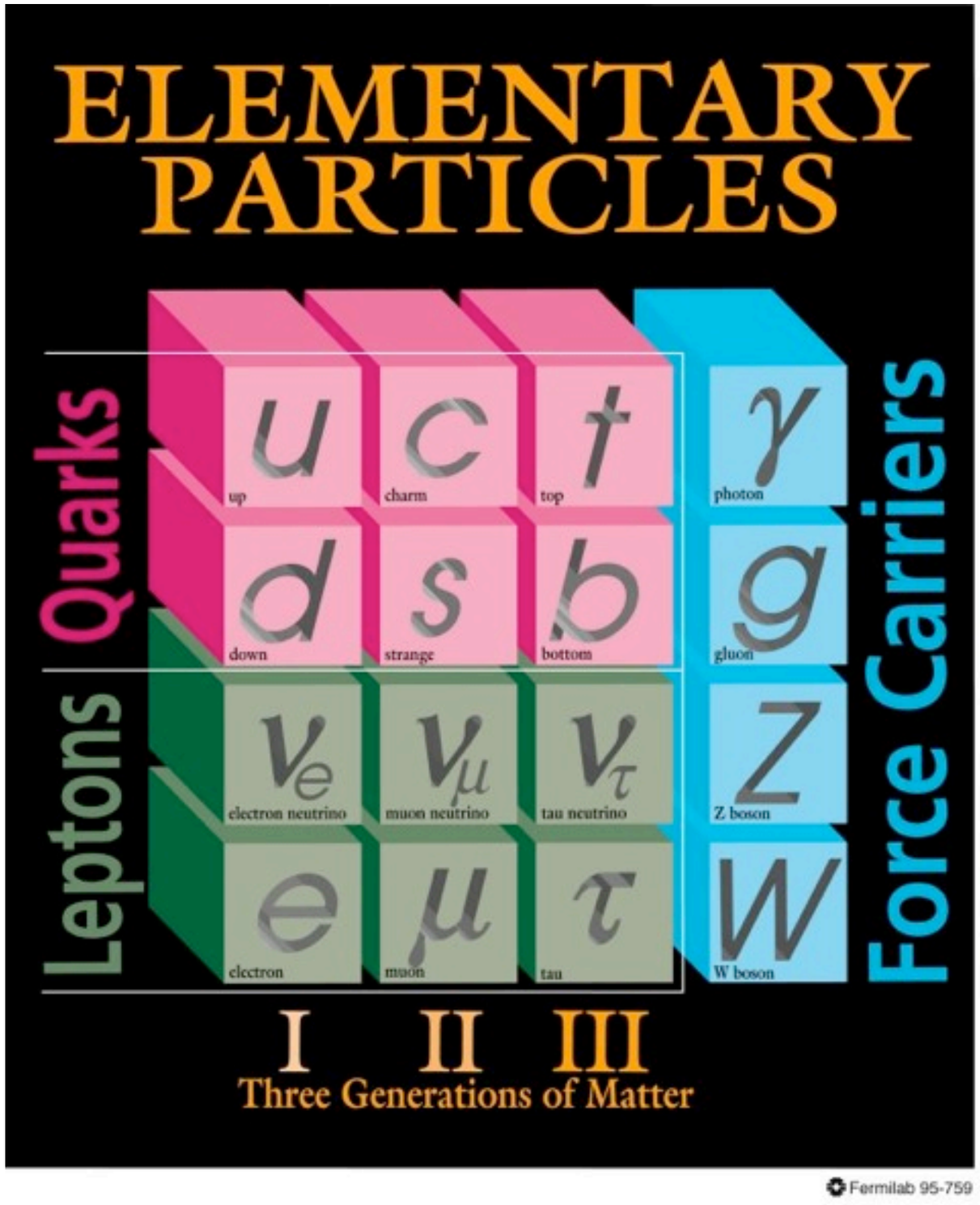
The chemist's periodic table

- Remember your high-school chemistry class?



- The Standard Model of particle physics is similar...

The particle physicist's periodic table



- Based on the gauge symmetry $SU(3)\times SU(2)\times U(1)$

describes the **strong force**, which binds quarks and gluons to form protons and neutrons

2004, Gross, Politzer, Wilczek: for discovering properties of the strong force

the Glashow-Salam-Weinberg model: describes the **weak force**, which mediates radioactive decay; and **electromagnetism**

1979, Glashow, Weinberg, Salam: for unifying the weak and EM forces

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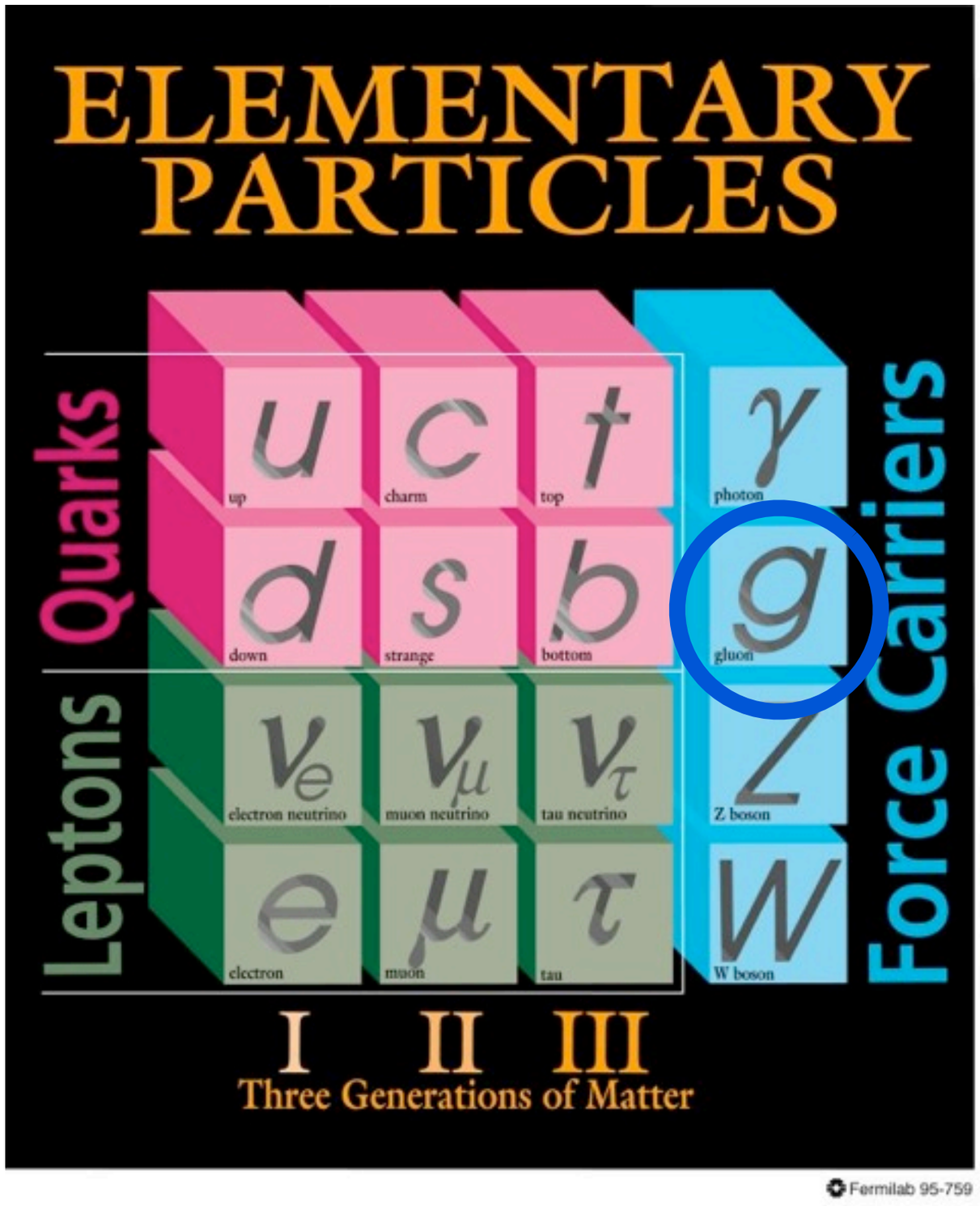

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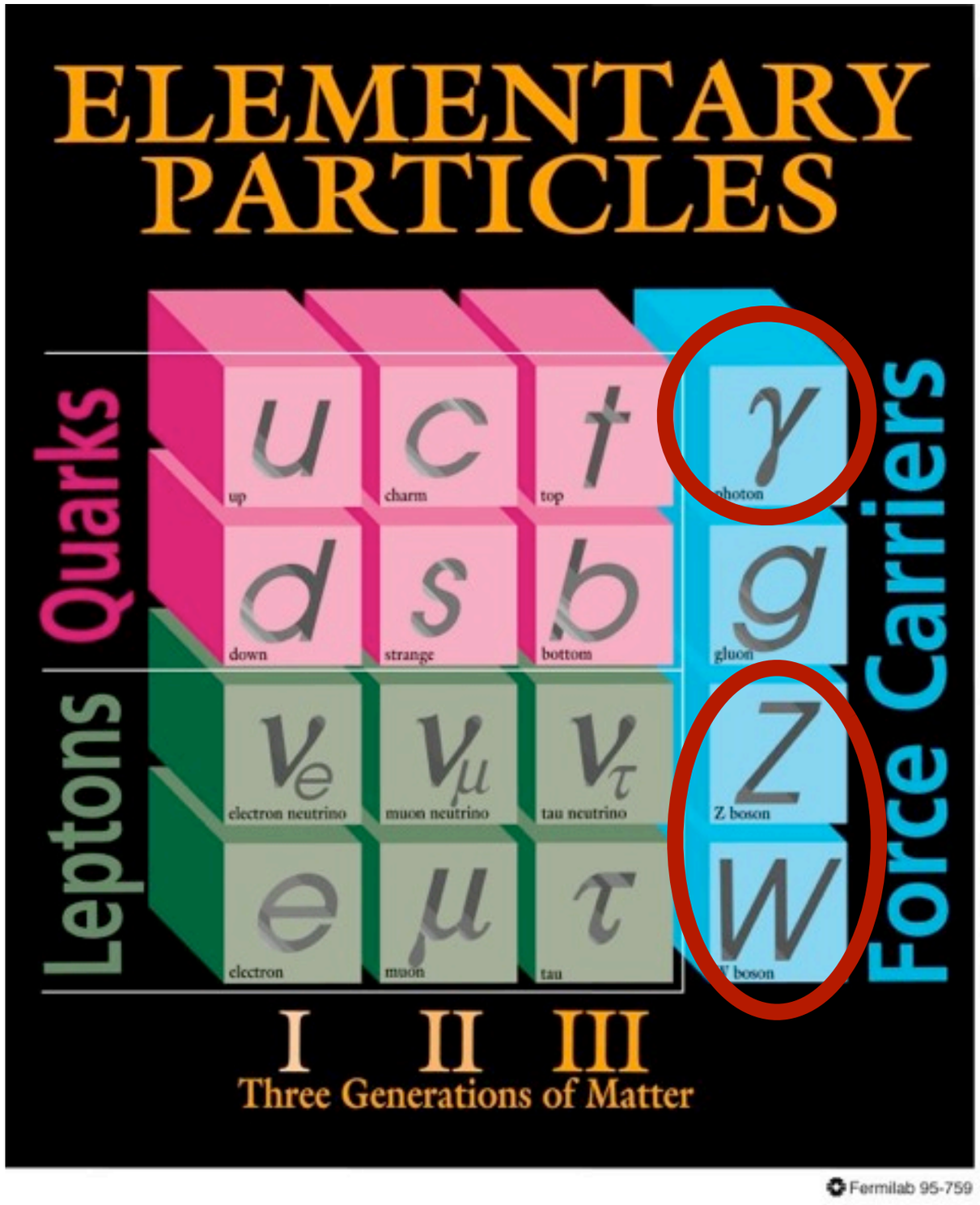

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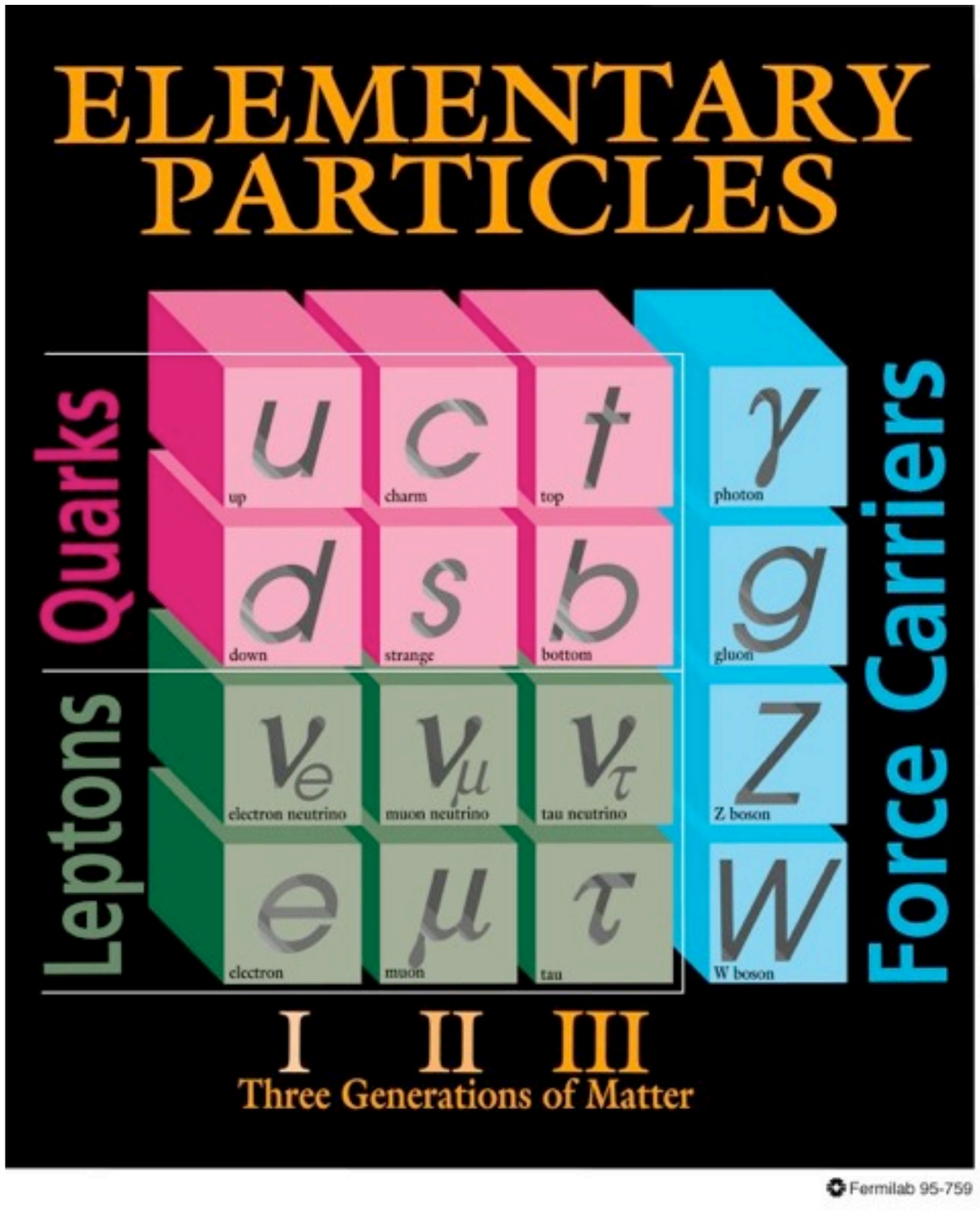

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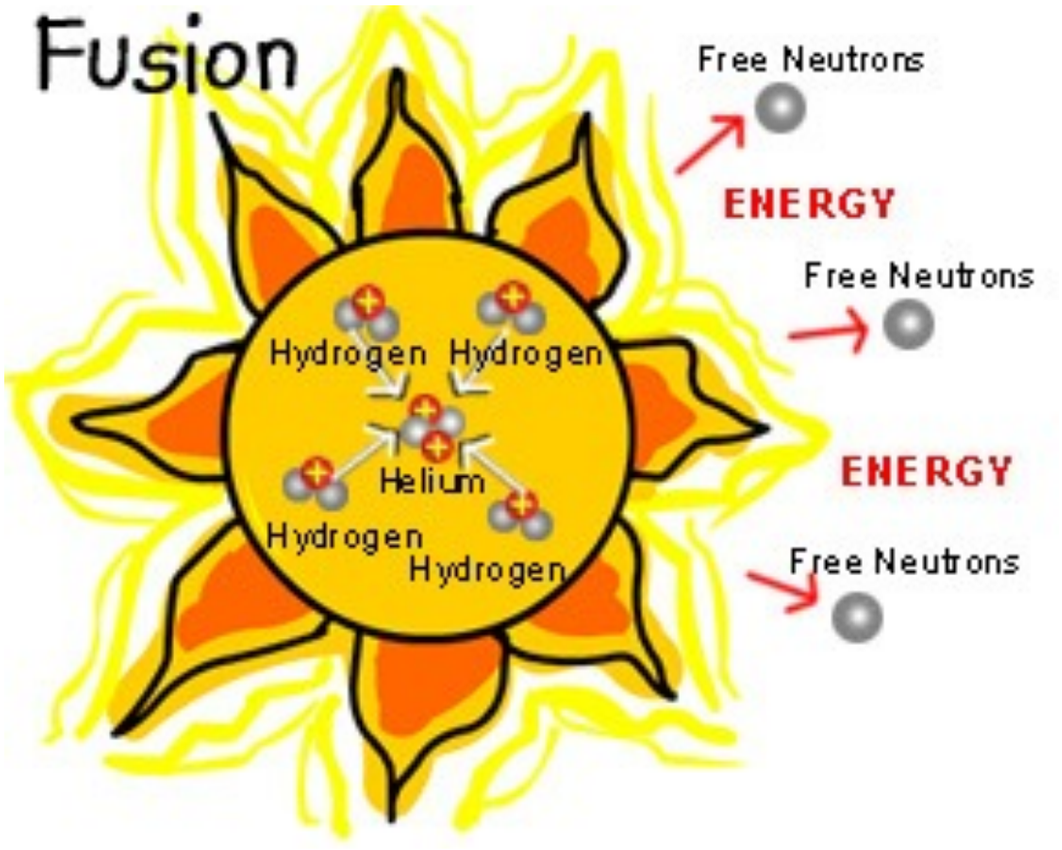
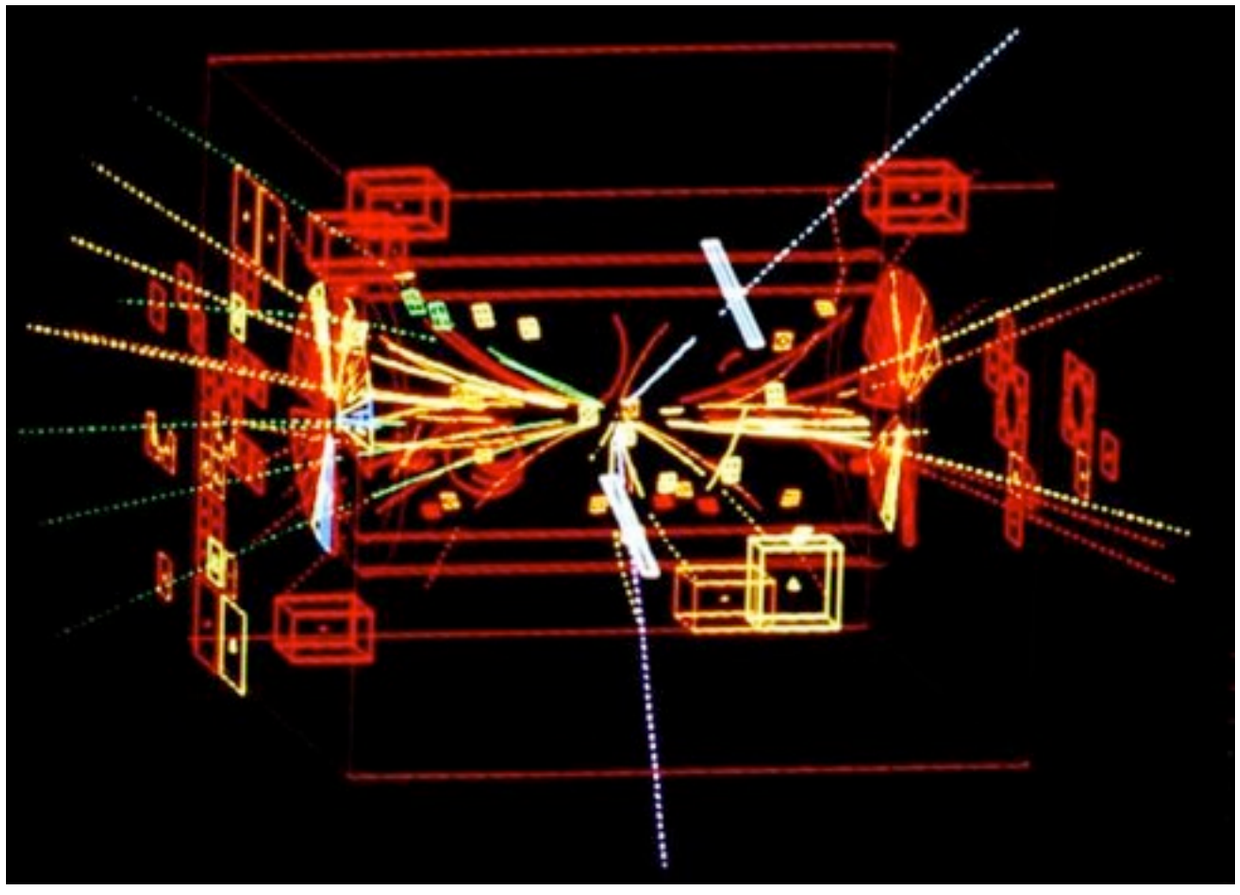
1999, 't Hooft, Veltman: for showing that the theory was internally consistent

Successes of the Standard Model

- The key aspect of the Standard Model is ***predictivity***; together with Einstein's theory of gravity, it describes all* known phenomena...



... from the largest scales (hydrogen fusion in stars)...



... to the smallest (first Z boson at the CERN experiment UA1)

1984, Rubbia, van der Meer

Massive problems

- But there's a problem... gauge symmetry predicts that the weak nuclear force is long-range, which contradicts what we observe
- Another way to say this: the weak force carriers, the W and Z bosons, must be massive; (~80-90 giga-electronvolts, or GeV) gauge symmetry requires them to be massless
- It also predicts that other particles such as the electron are massless

Spontaneous symmetry breaking

- The solution comes from ***spontaneous symmetry breaking***: the equations governing a theory's behavior are symmetric, but the lowest energy and most probable state (or "ground state") isn't

2008, Y. Nambu, for discovery of this mechanism in subatomic physics

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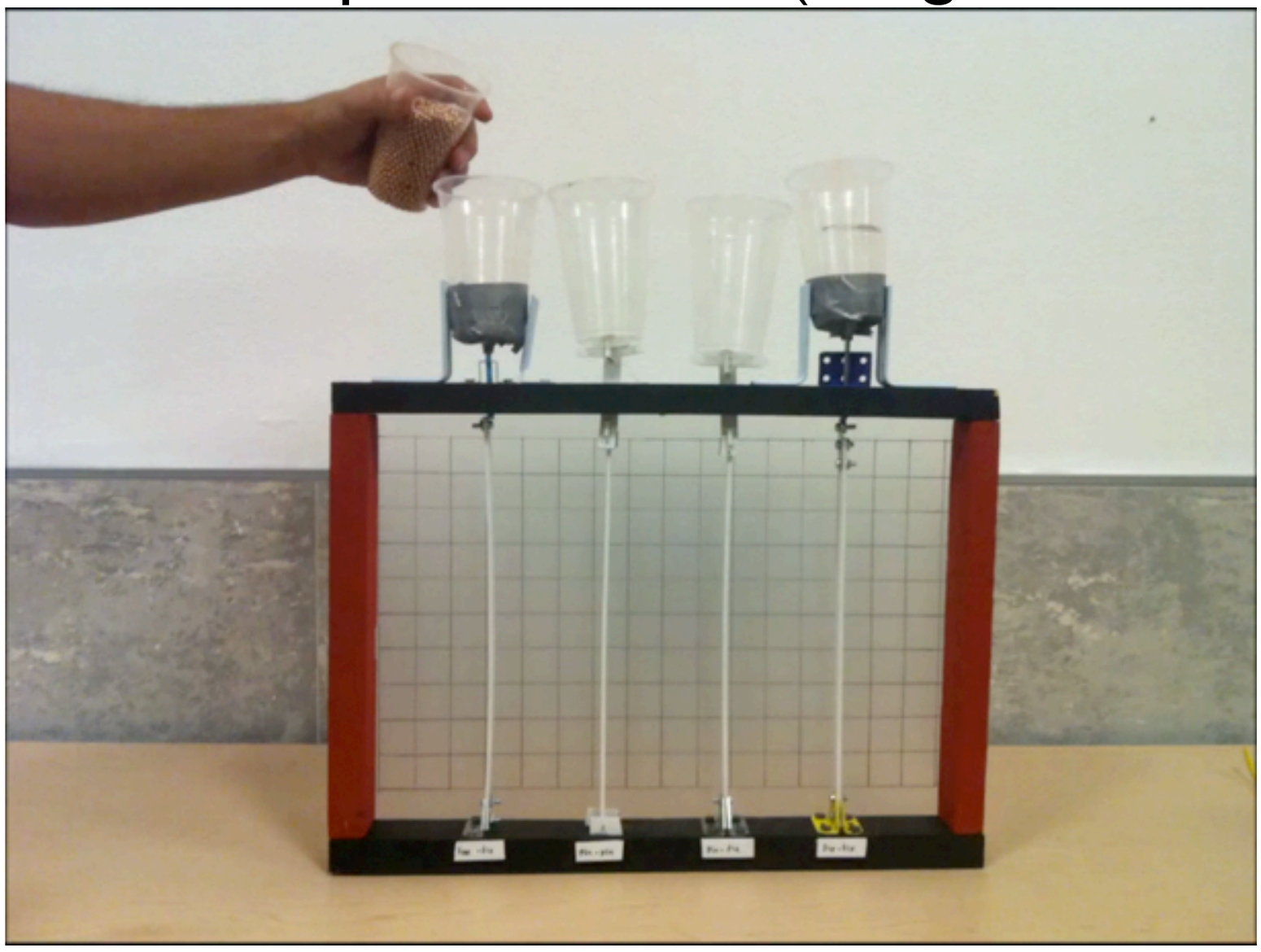

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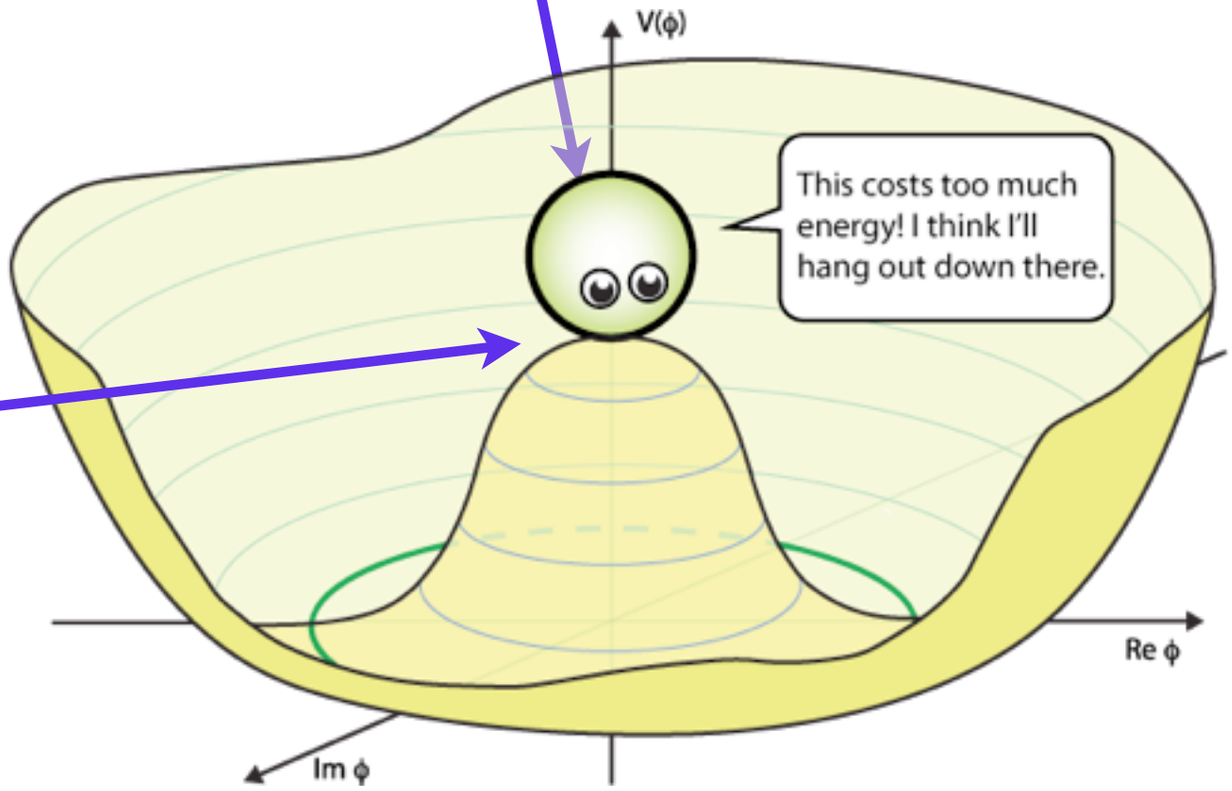
The Mexican hat potential and the Higgs mechanism

New field permeating space, the ***Higgs field*** → think of like an electric field

Symmetric (under rotations in this case) ground state

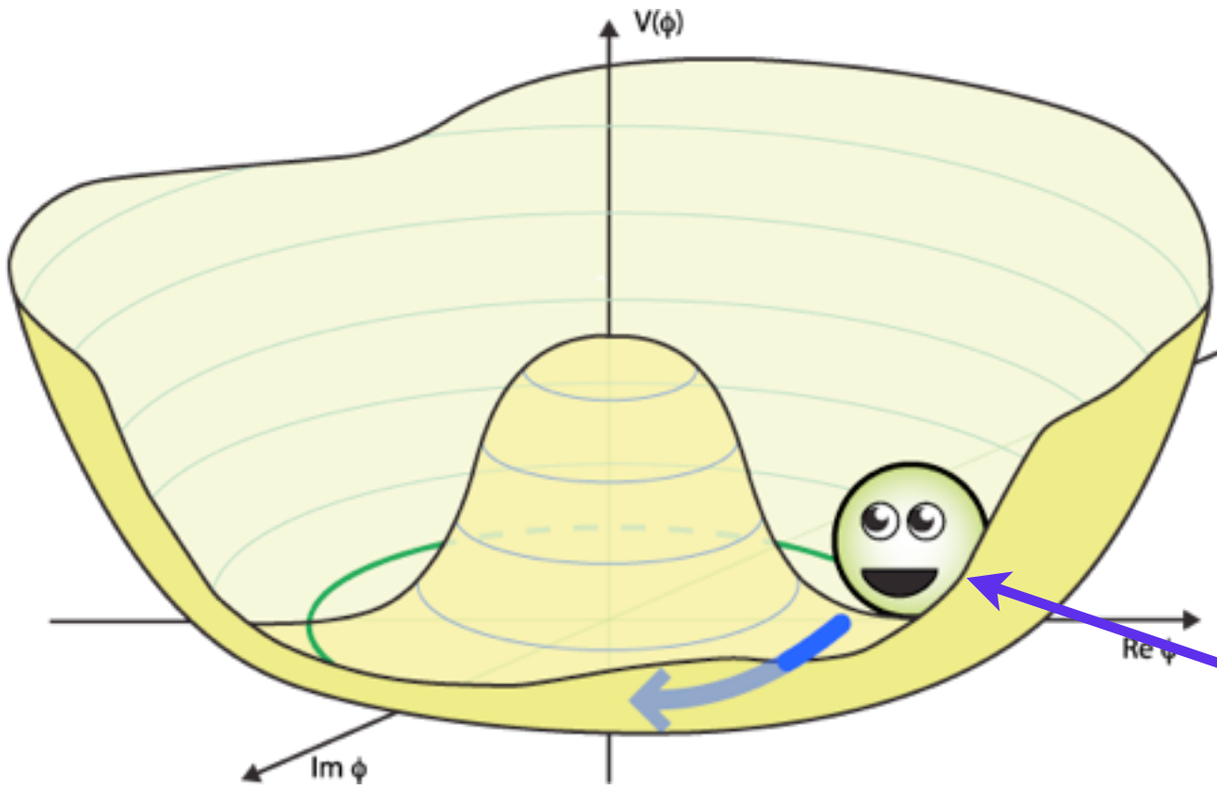


- Quantum Mechanics: fields ⇔ particles
- Fluctuations around bottom of potential: (pictured by the arrow in the diagram) *Goldstone bosons*. These give mass to the W and Z, and make the weak force short ranged

Brout, Englert; Higgs; Guralnik, Hagen, Kibble, ***1963-64!***

- Fluctuations up the sides: the ***Higgs boson***!

The Mexican hat potential and the Higgs mechanism



Energetically favorable asymmetric ground state

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How particles get mass

- Particles get mass through interactions with the Higgs field; stronger interaction ⇒ heavier mass

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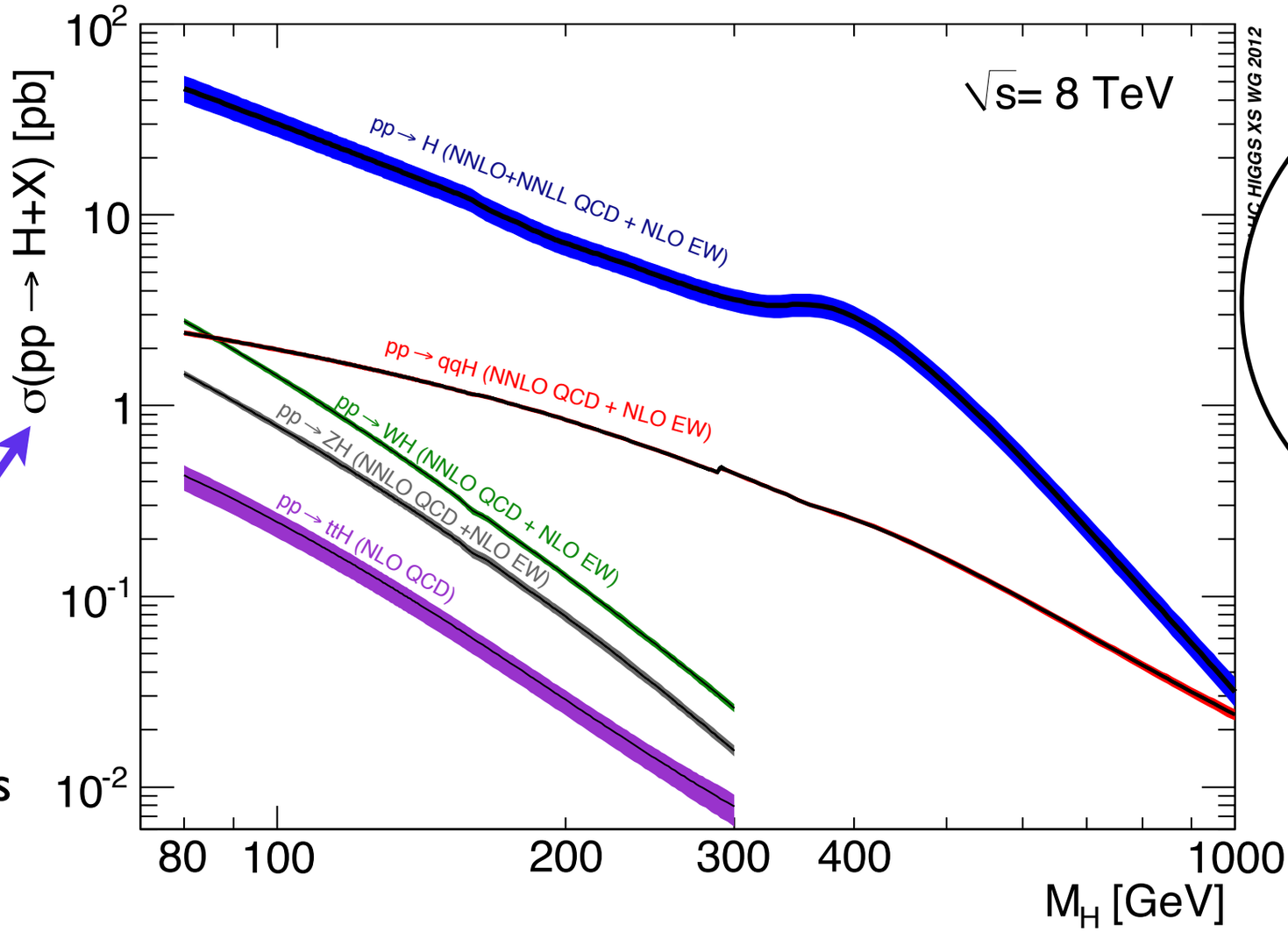
The Higgs boson

- In the simplest model, utilized in the Standard Model, the Higgs mechanism is accomplished by a single new scalar field; one additional Higgs boson is predicted
- ***Predictivity*** is again the key; all couplings of the Higgs boson to other Standard Model particles are determined

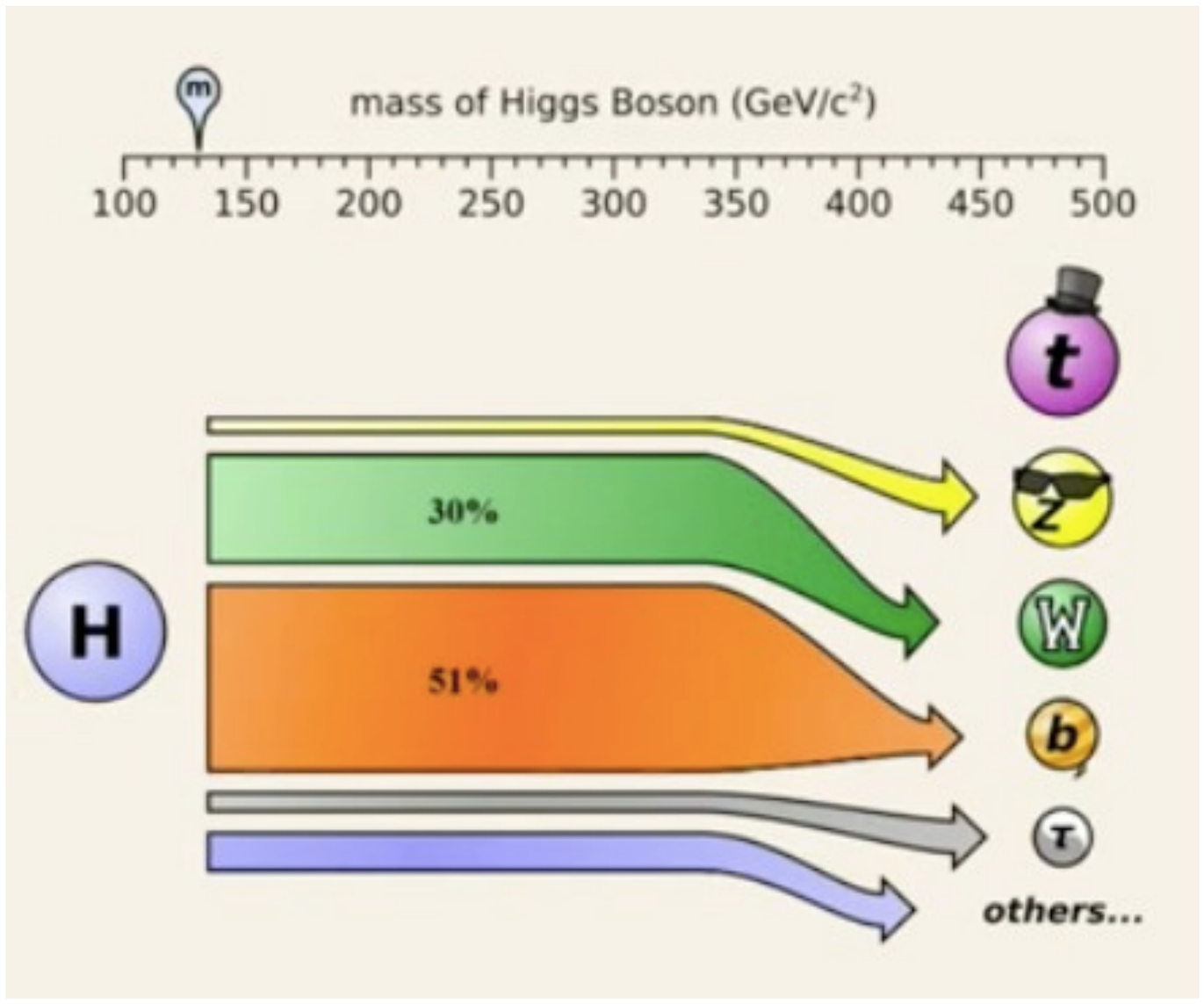


We know exactly its production rate...

ANL high energy theory group was instrumental in providing these predictions for experiment

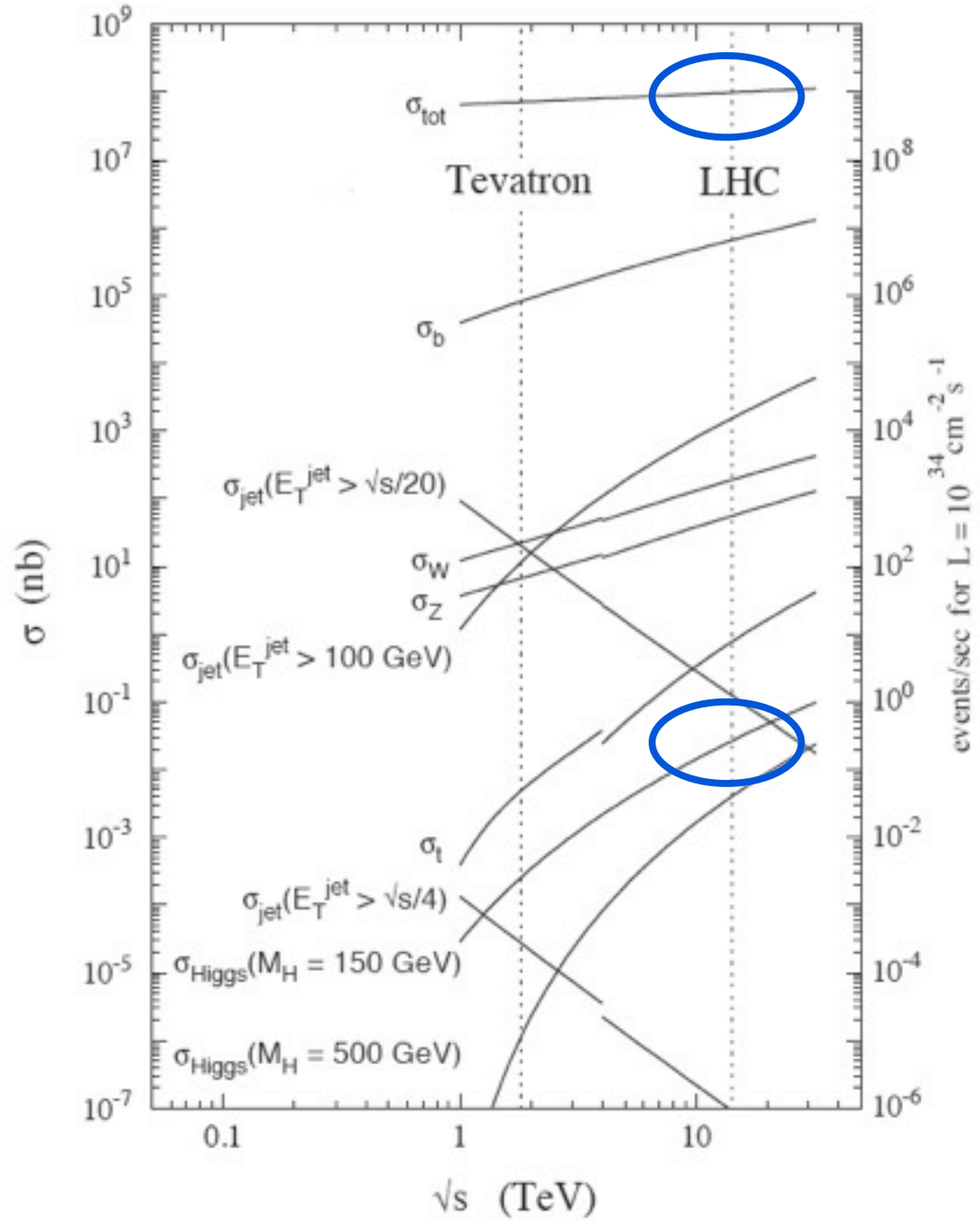
Decays of the Higgs boson

- The Higgs lives only 10^{-22} seconds... look for its decay products
- The fraction of Higgs decays to various final states can again be predicted



A needle in a haystack

- Only one problem... for every Higgs boson produced, 10 billion other events that look almost exactly alike!



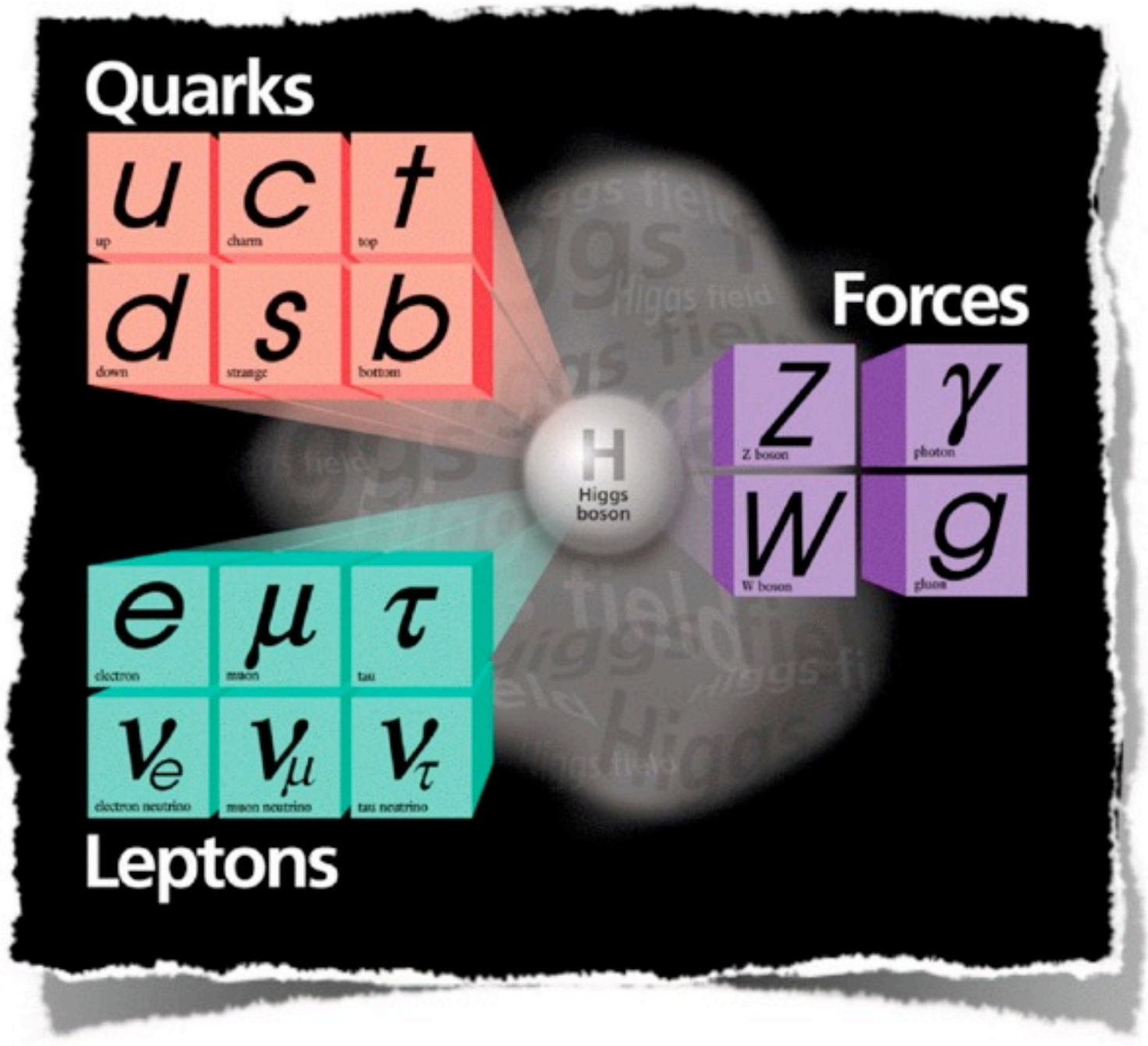
A needle in a haystack

- Only one problem... for every Higgs boson produced, 10 billion other events that look almost exactly alike!

- Need very clever experimentalists to find these rare events... thankfully we have them here at ANL (and elsewhere)
- Jimmy Proudfoot will pause in his search and tell you about the details next

The new Standard Model

- Now, thanks to their efforts, our periodic table of fundamental particles is extended... a Higgs-like boson found at ~125-127 GeV



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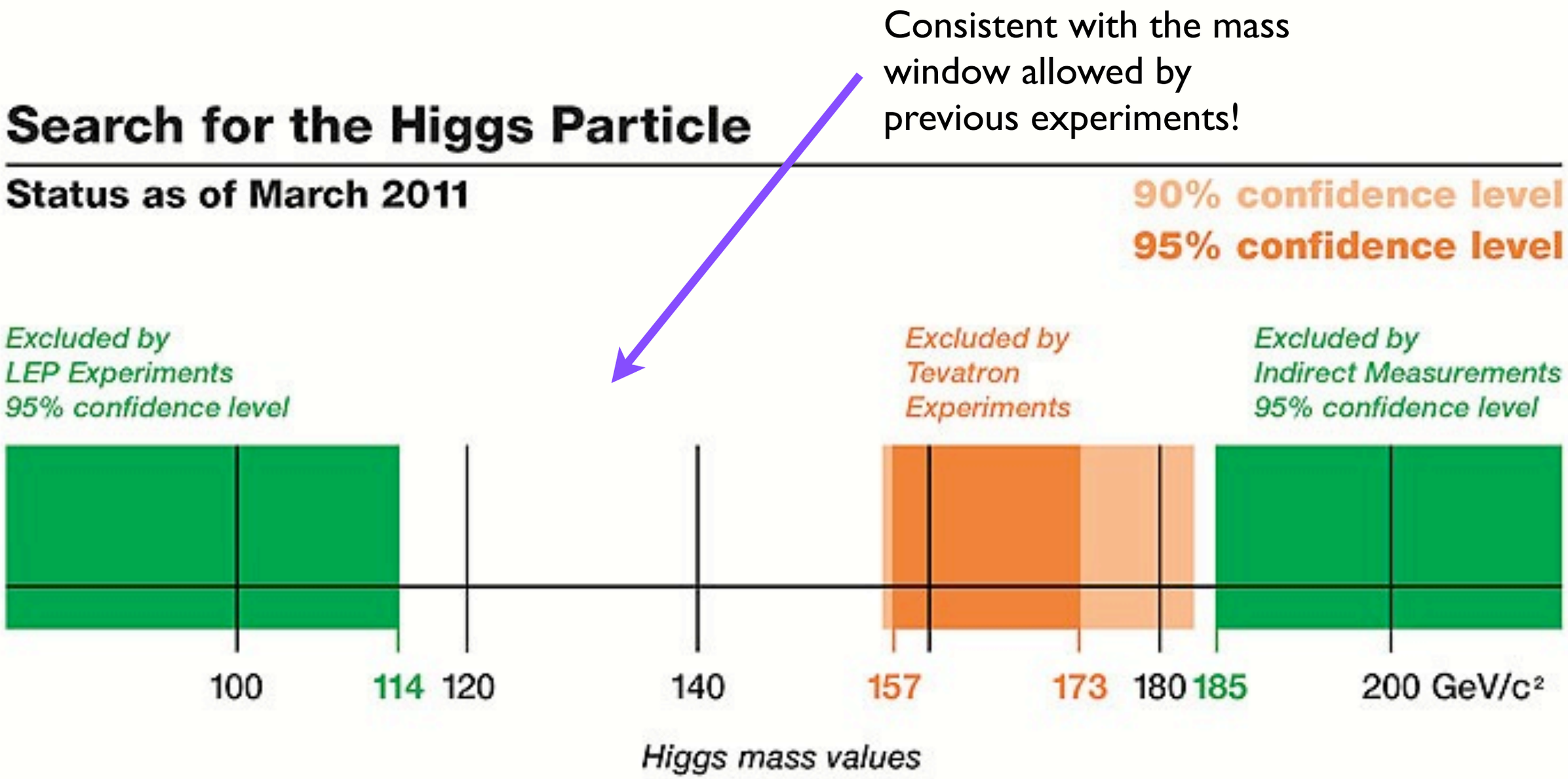
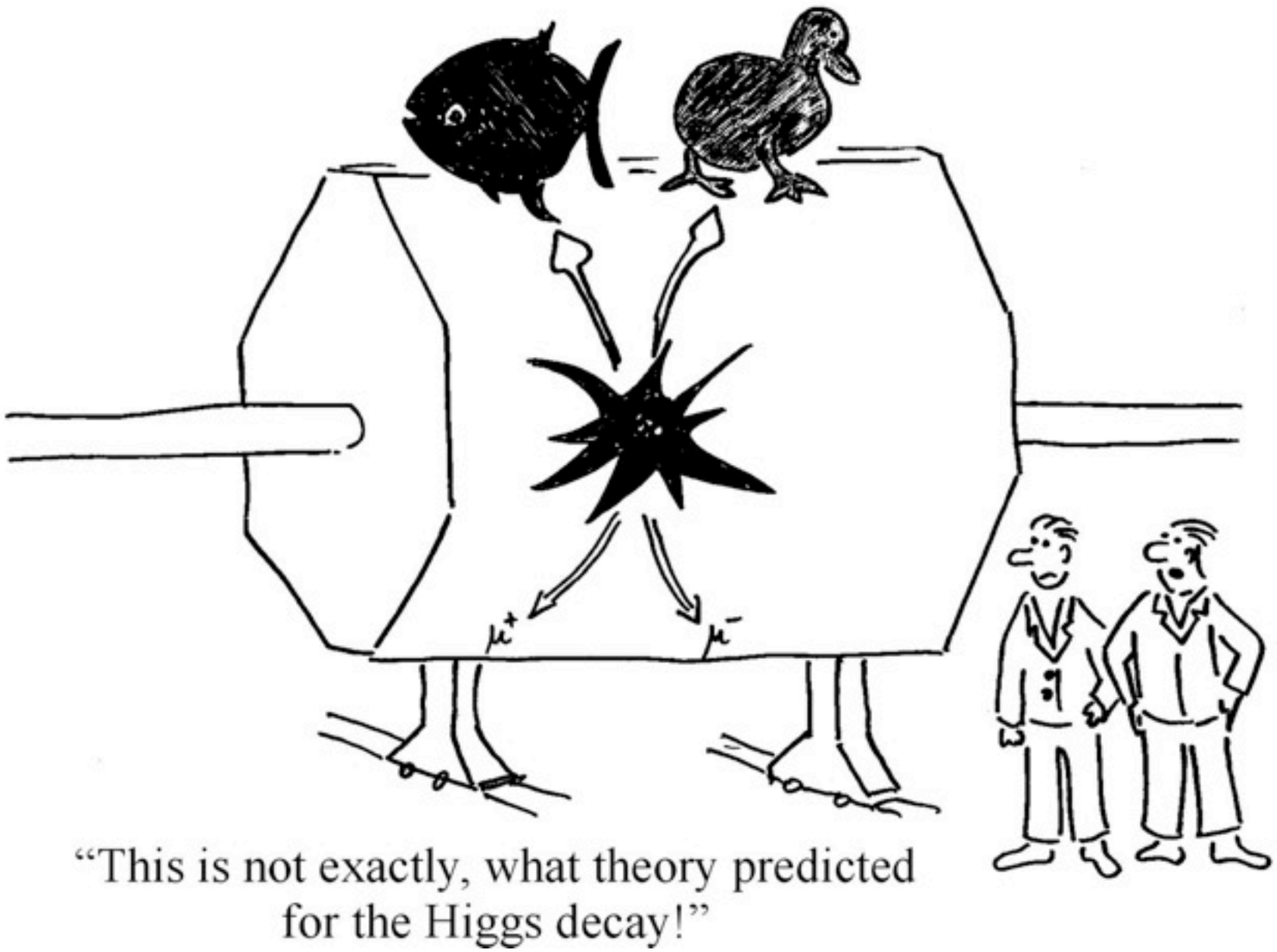


The Higgs as a portal beyond the Standard Model

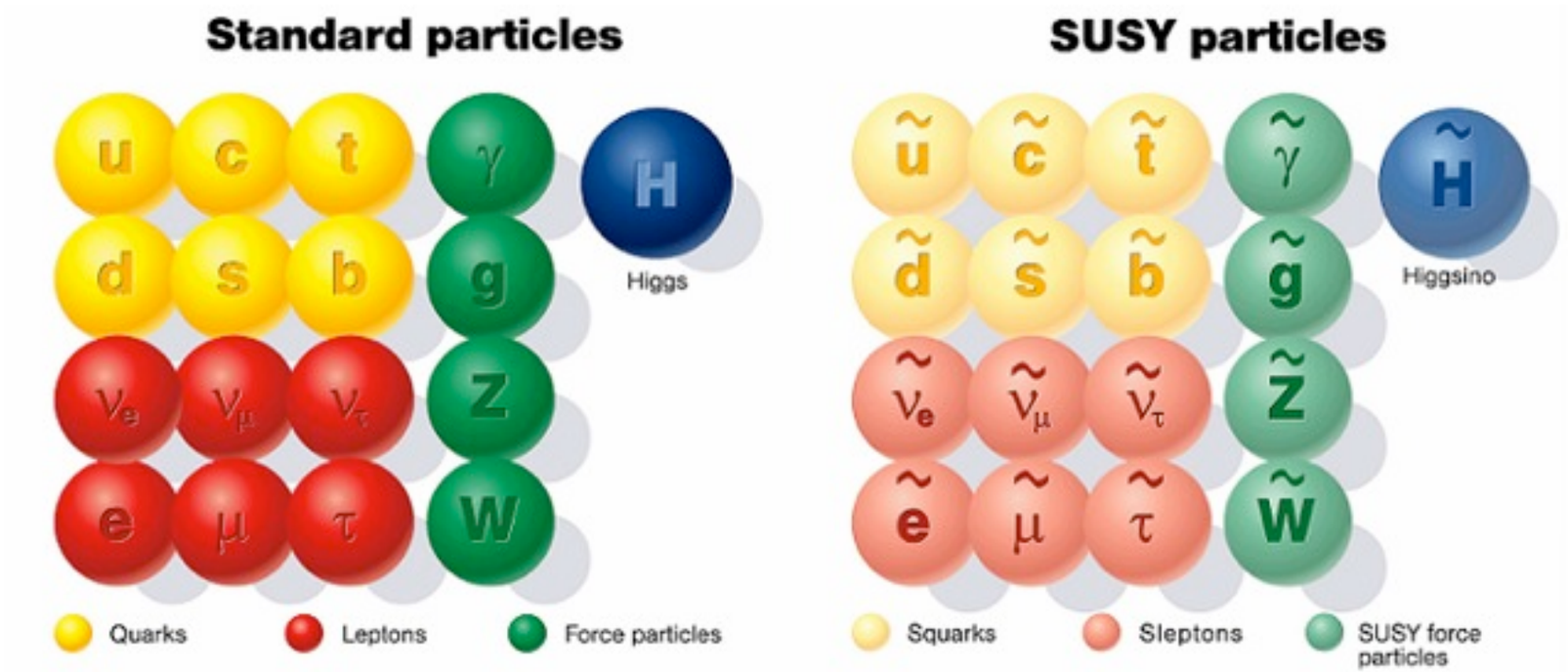


"This is not exactly, what theory predicted for the Higgs decay!"

- Discovery is just the beginning
- Is the Higgs mechanism described by a single scalar field like assumed in the Standard Model, or is it more intricate?
- Many reasons to expect the second...

Supersymmetry and extra dimensions

- *Supersymmetry* doubles the particle content of the Standard Model to explain confusing aspects of the Higgs potential



- Other models with extra dimensions modify gravity at short distances to better explain the large hierarchy between the Higgs mass and the energy at which gravity becomes as strong as the other forces

Passing the baton

- These questions and possibilities can only be addressed by data
- This year will mark the beginning of a program to systematically measure the properties of the newly discovered particle
- We're well equipped for the challenge