

The Discovery of the Higgs Boson?

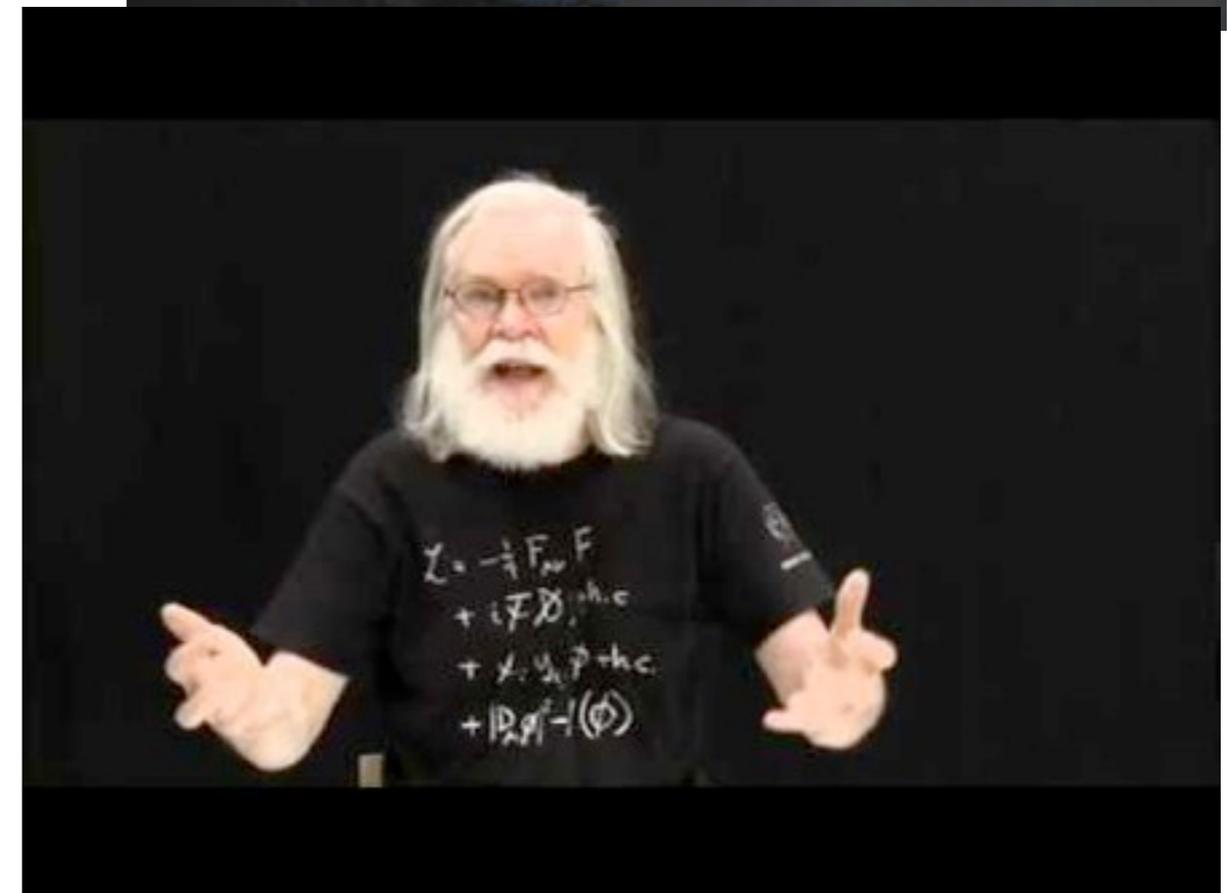
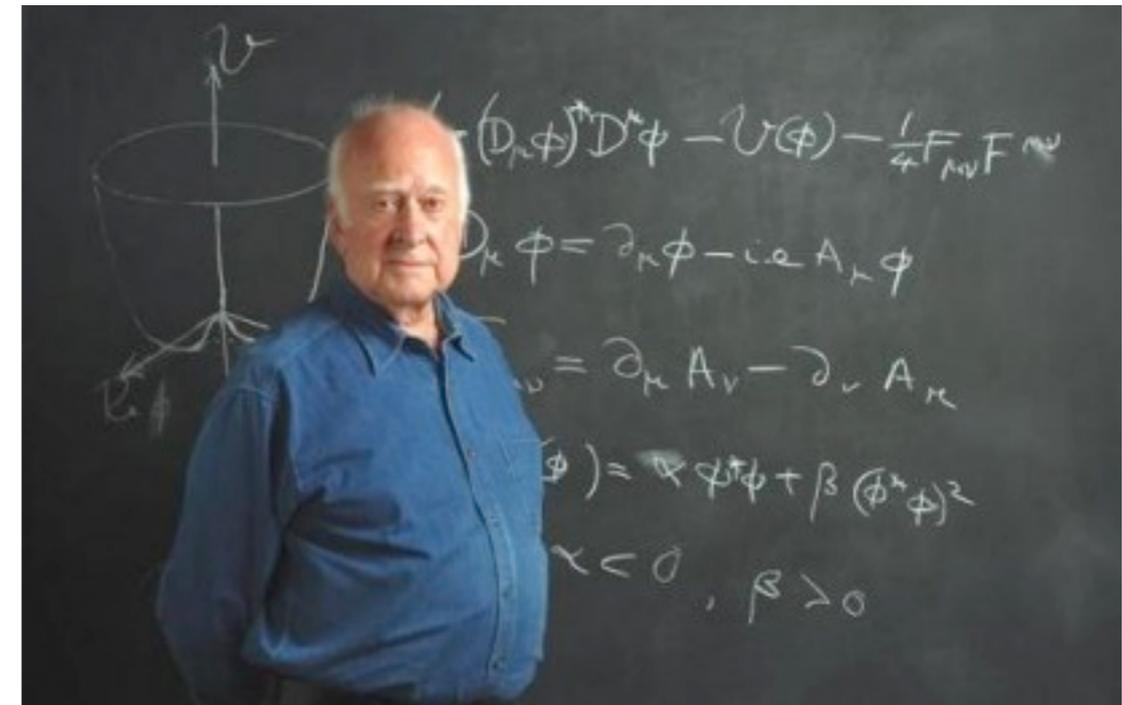
Frank Petriello

James Proudfoot

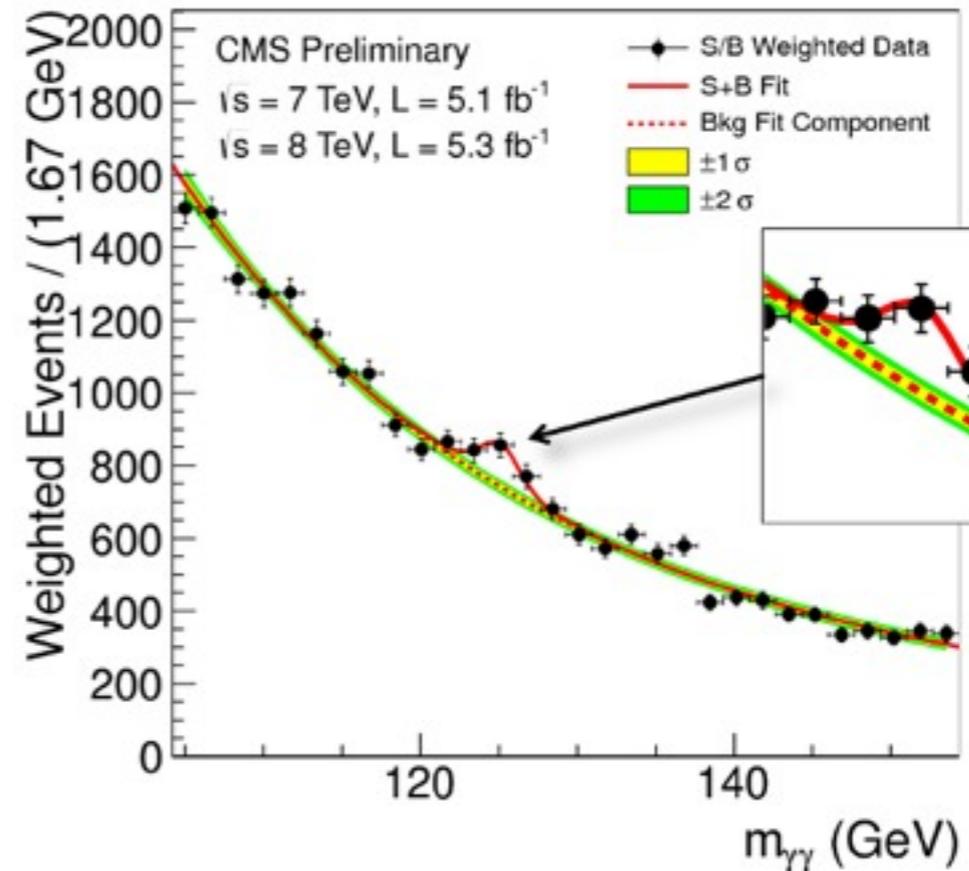
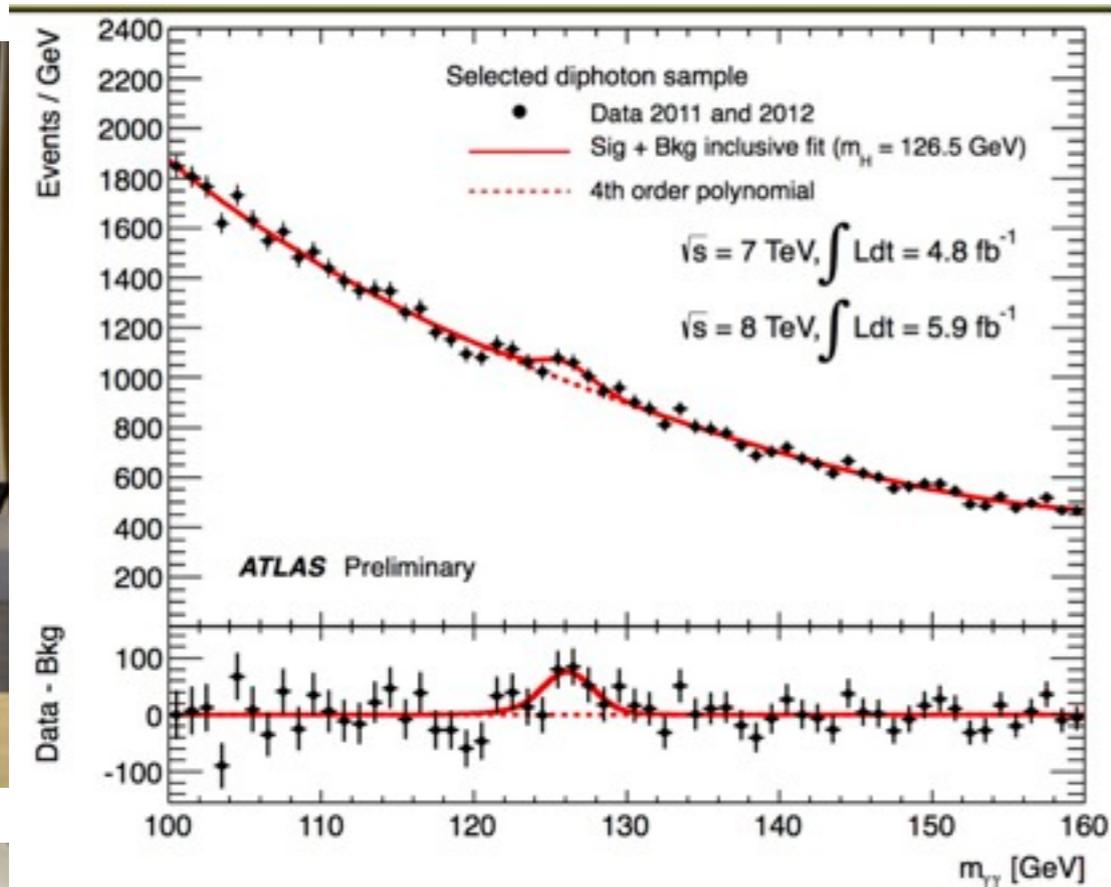
Special Director's Colloquium
July 11, 2012



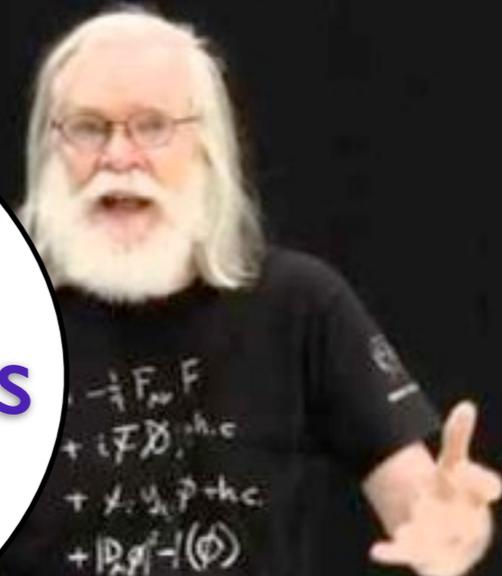
If you've been watching the news the past week, you may have noticed the following...



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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

$$m_1 v_1 = m_2 v_2$$

“For every reaction there is an equal and opposite reaction”

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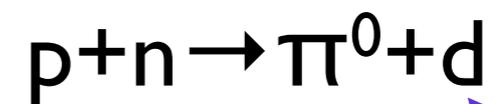
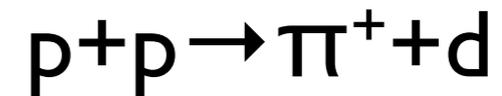
Internal symmetries

- 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!**

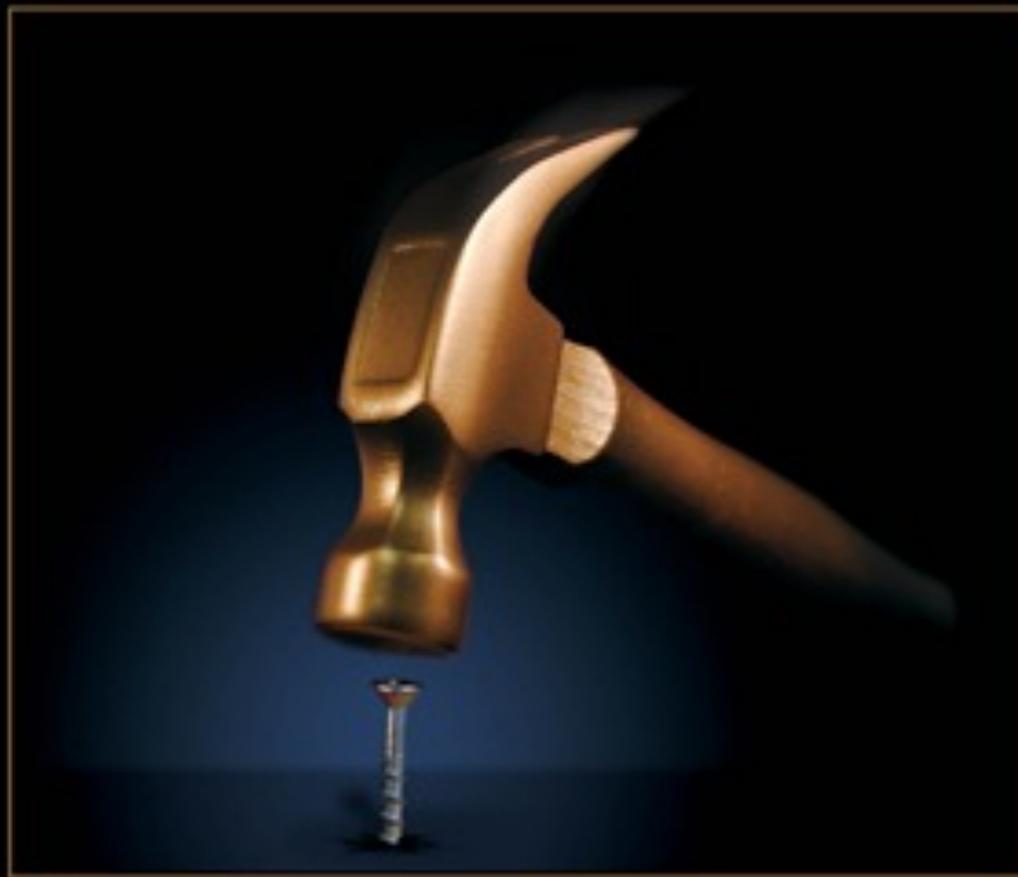
Predicted near equality of:



pions

deuteron

The Standard Model and gauge symmetry



GOLDEN HAMMER

When you have a golden hammer, everything looks like a nail.

- 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?

PERIODIC TABLE OF THE ELEMENTS

<http://www.ktf-split.hr/periodni/en/>

Legend:

- Metal (Blue)
- Semimetal (Orange)
- Nonmetal (Green)
- Alkali metal (1)
- Alkaline earth metal (2)
- Transition metals (3-10)
- Lanthanide (Lanthanide)
- Actinide (Actinide)
- Chalcogens element (16)
- Halogens element (17)
- Noble gas (18)

Standard State (25 °C; 101 kPa):

- Ne - gas
- Fe - solid
- Ga - liquid
- Tc - synthetic

PERIOD	GROUP I IA	GROUP II IIA	GROUP III IIA	GROUP IV IVA	GROUP V VA	GROUP VI VIA	GROUP VII VIIA	GROUP VIII VIIIA										
1	1 1.0079 H HYDROGEN							2 4.0026 He HELIUM										
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM	5 10.811 B BORON					6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON						
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM							13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON				
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIObIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRNIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

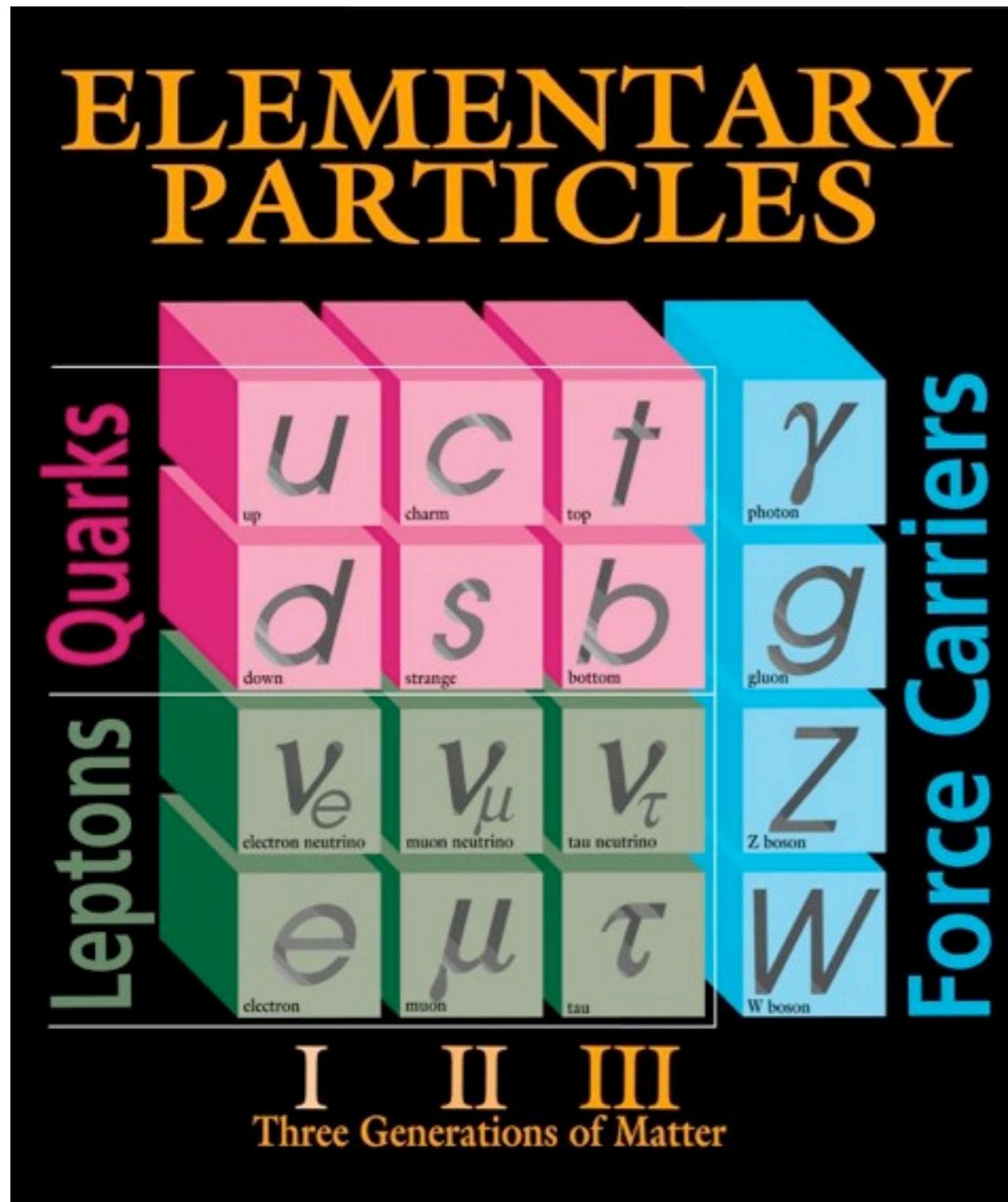
LANTHANIDE														
57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERIUM	71 174.97 Lu LUTETIUM

ACTINIDE														
89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 687-683 (2001)
Relative atomic mass is shown with five significant figures. For elements having no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.
Editor: Aditya Vardhan (adivar@rediffmail.com)

- 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



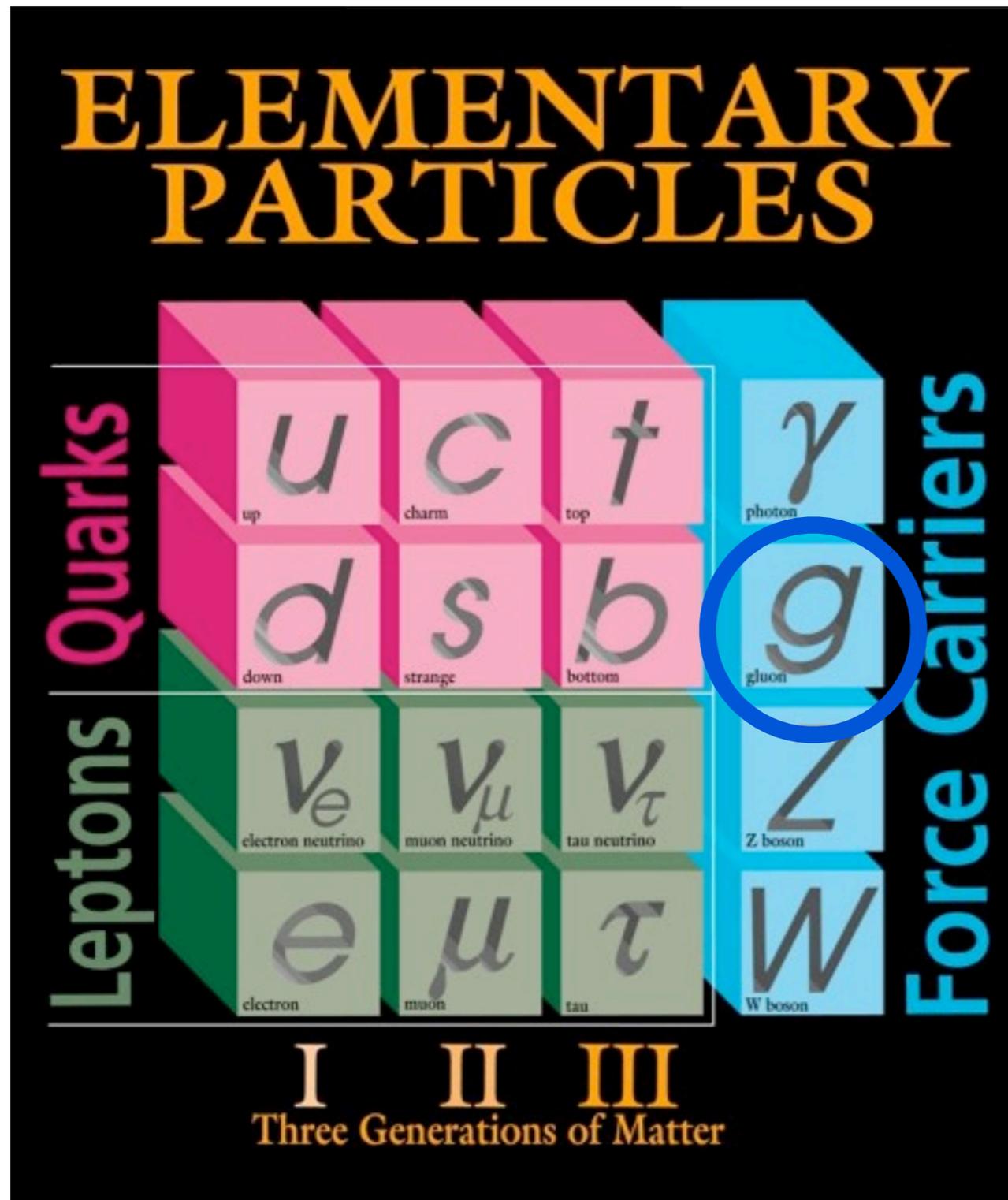
2004, Gross, Politzer, Wilczek: for discovering properties of the strong force

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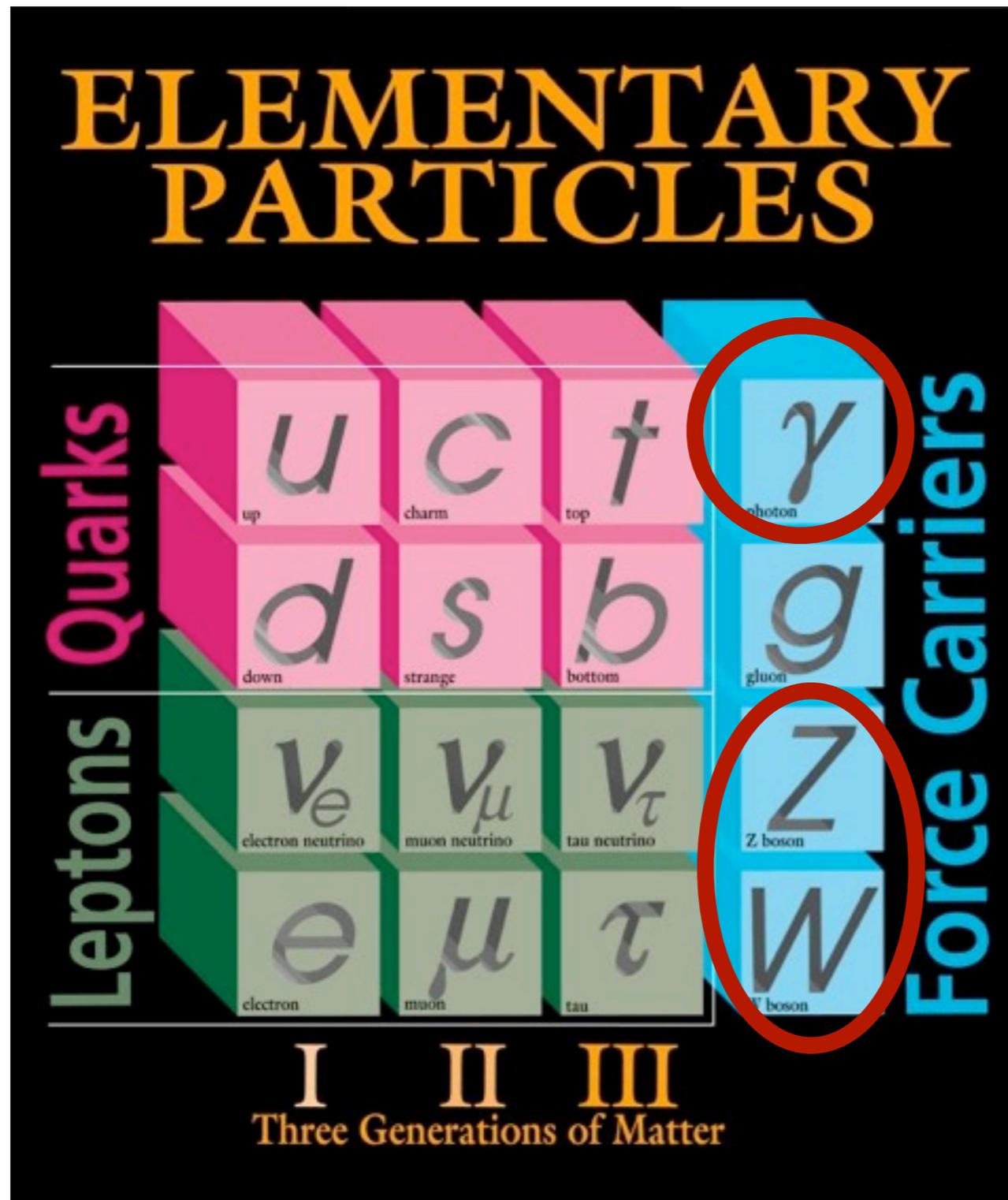
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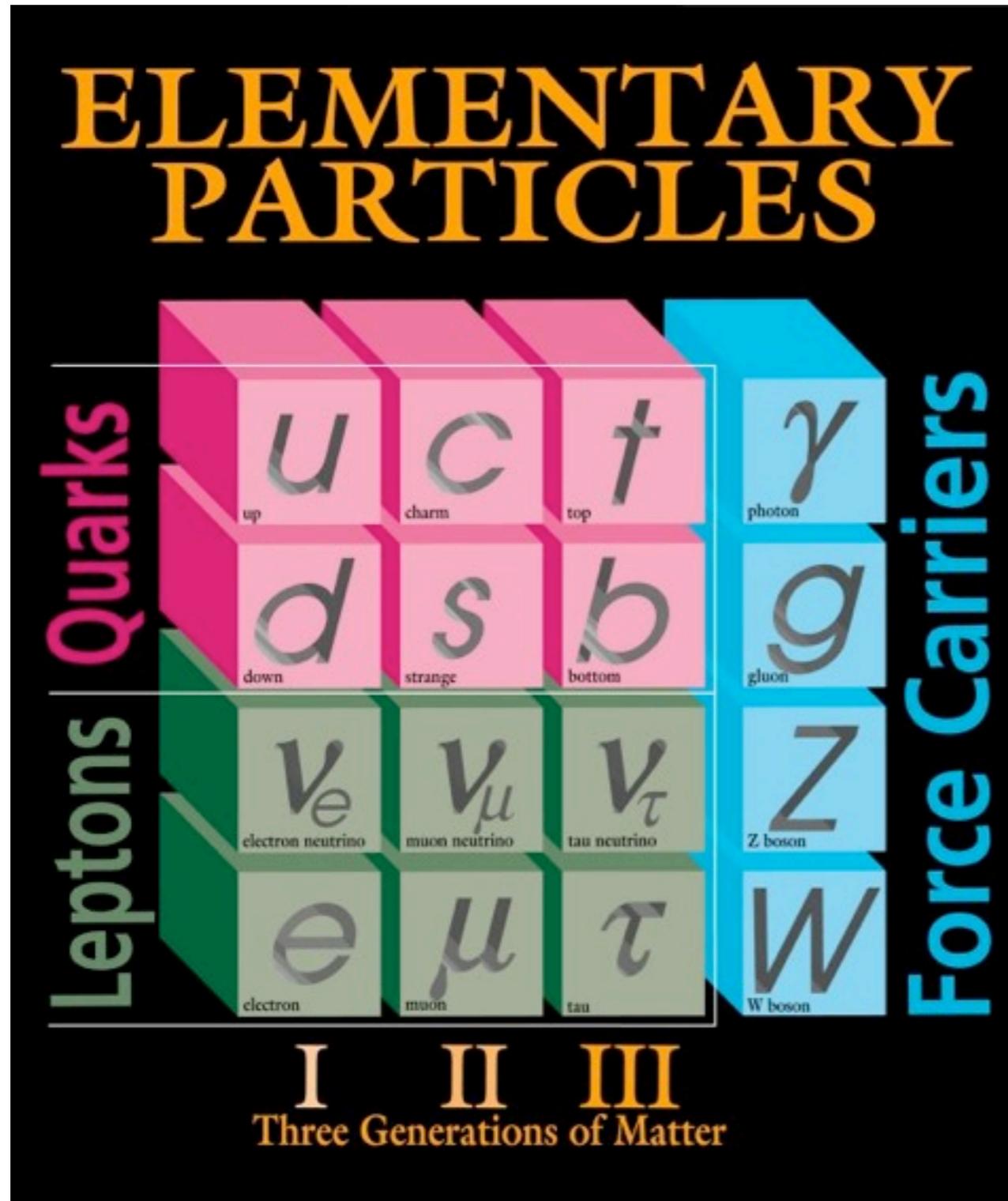
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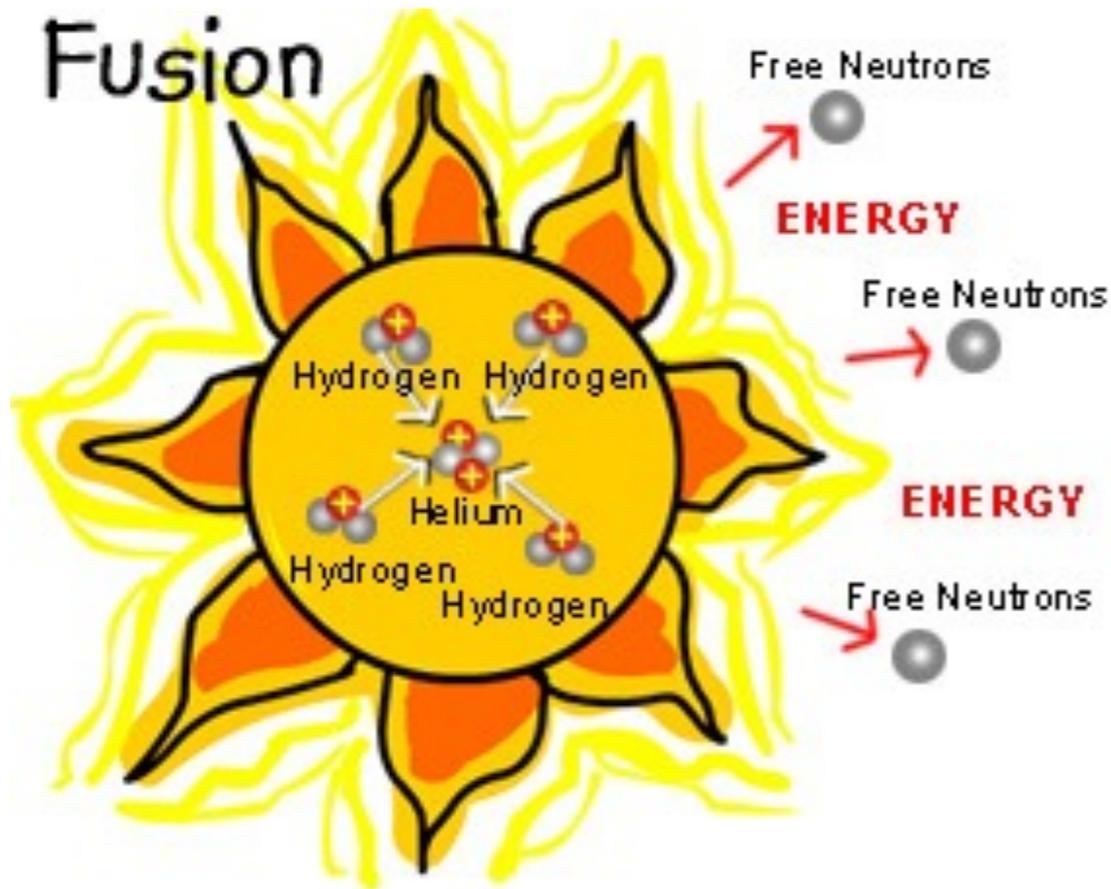
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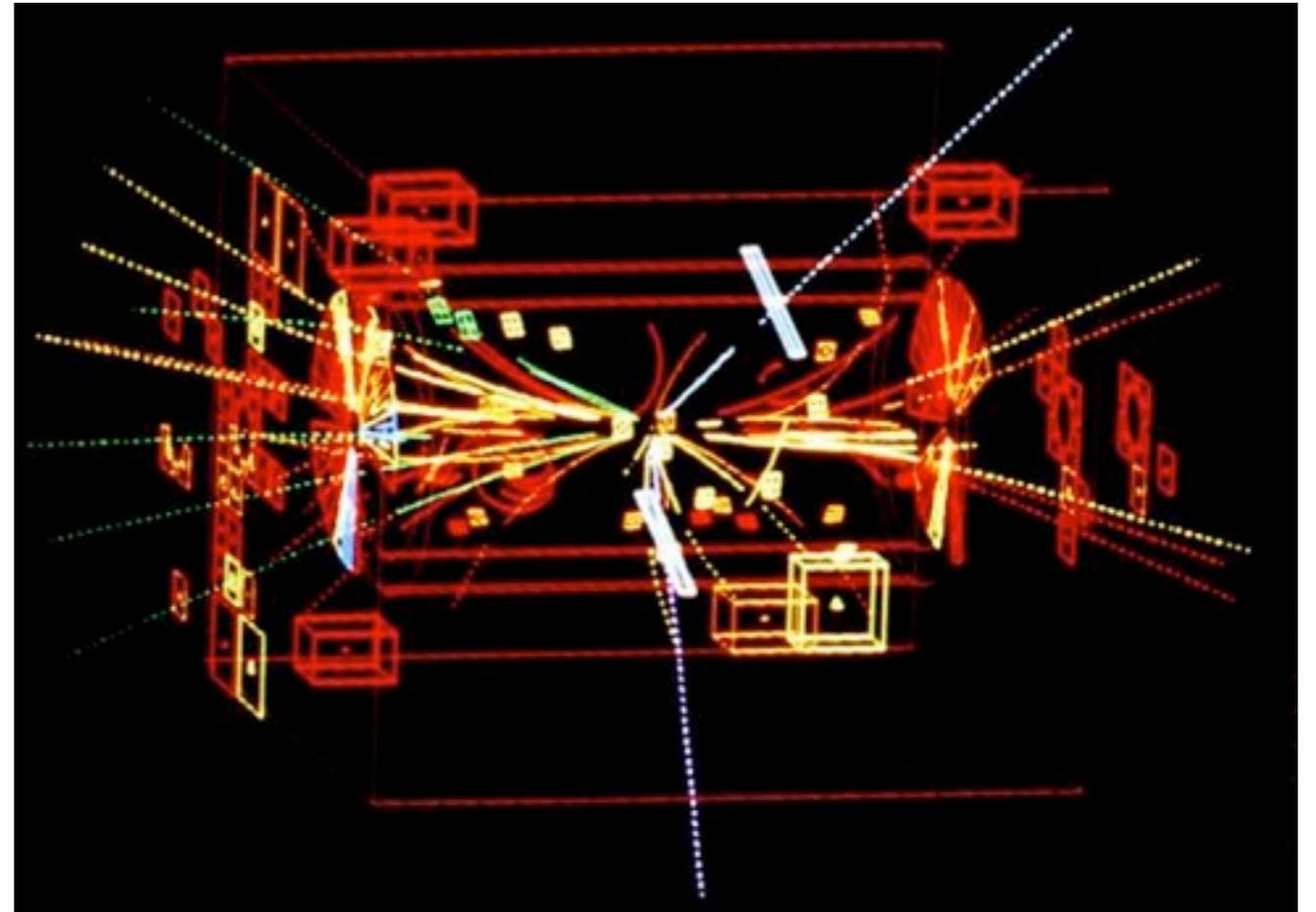
1999, 't Hooft, Veltman: for showing that the theory was internally consistent

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

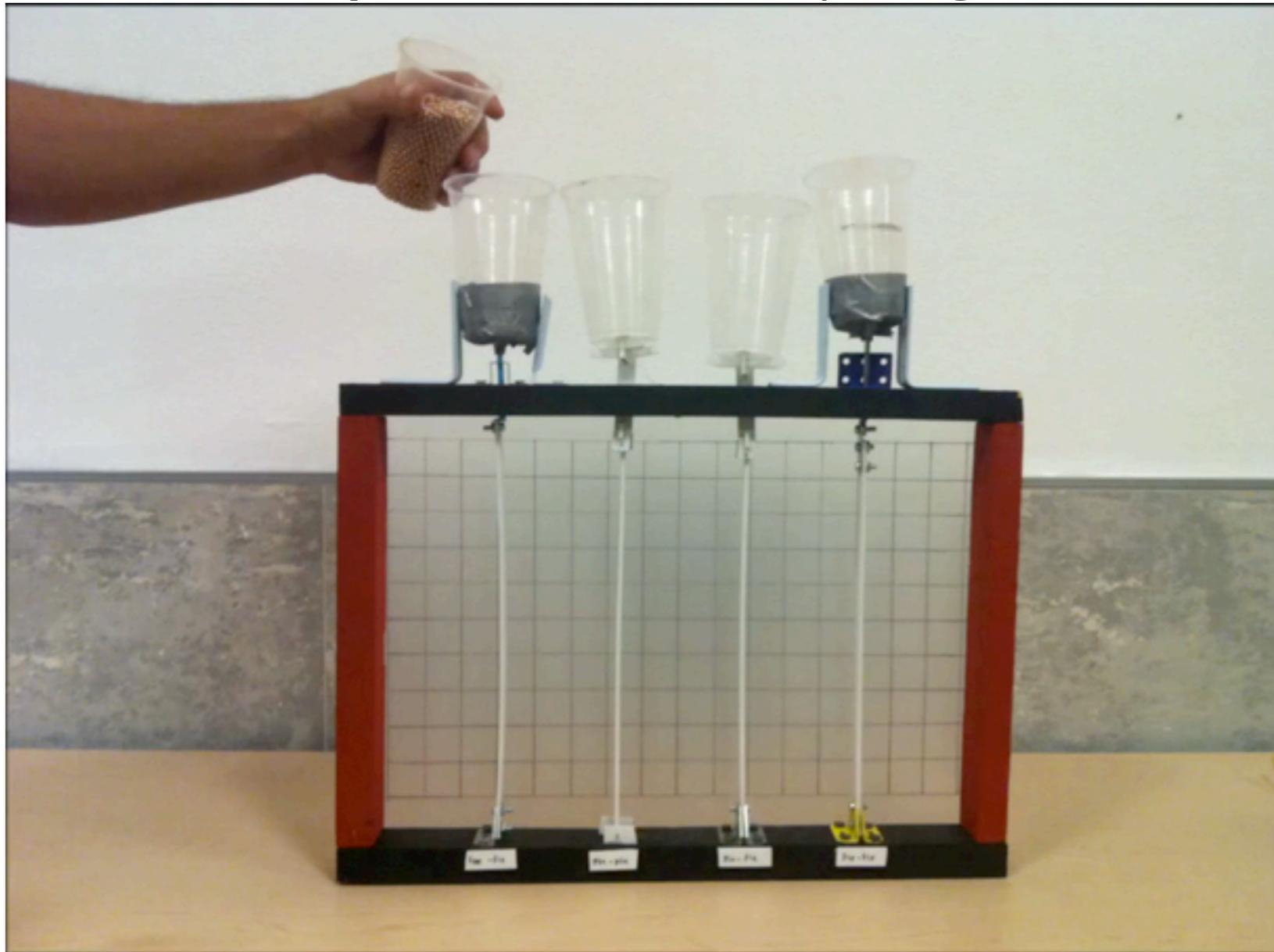
- The solution comes from ***spontaneous symmetry breaking***: the equations governing a theory's behavior are symmetric, but the lowest energy and most probable state (or “ground state”) isn't



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

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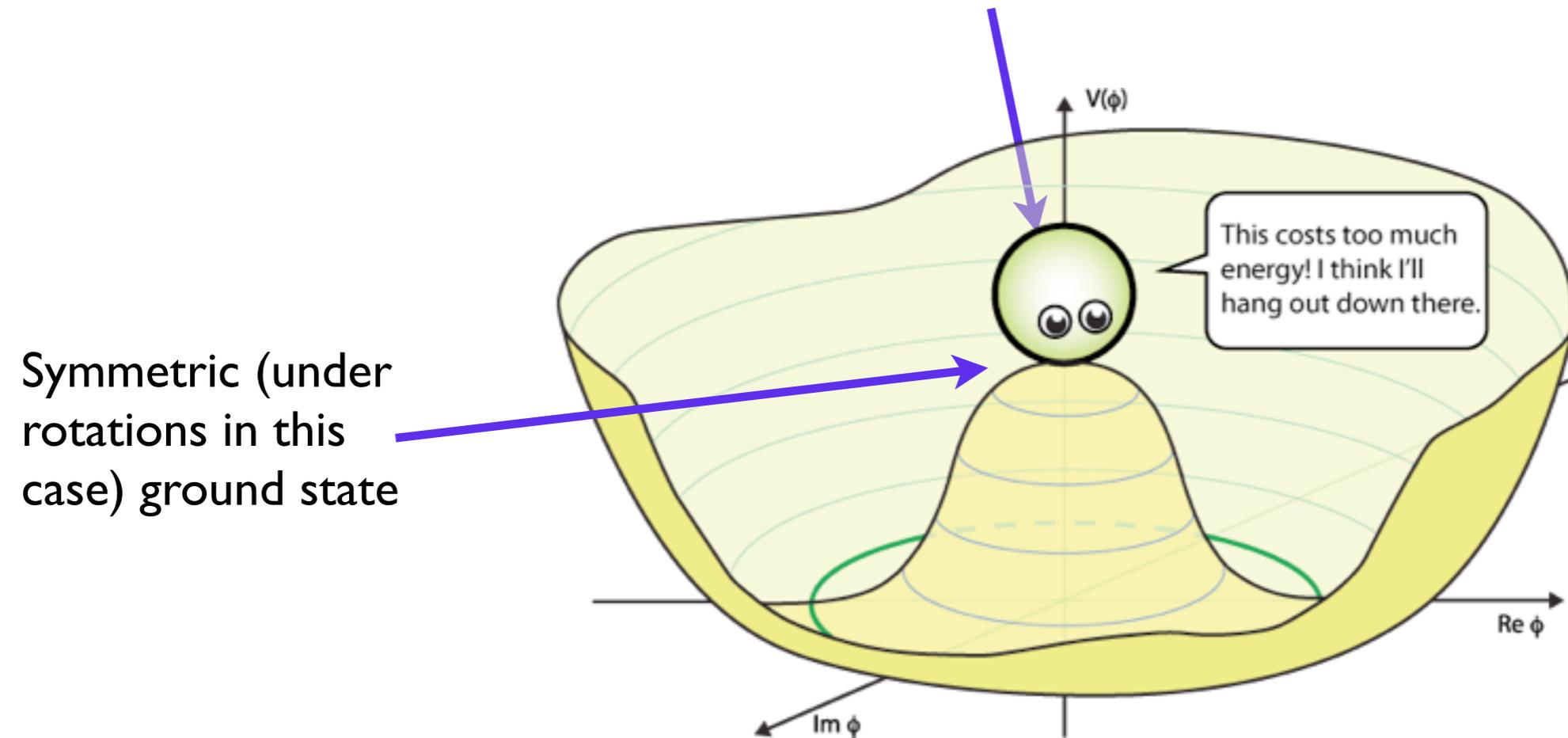
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The Mexican hat potential and the Higgs mechanism

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

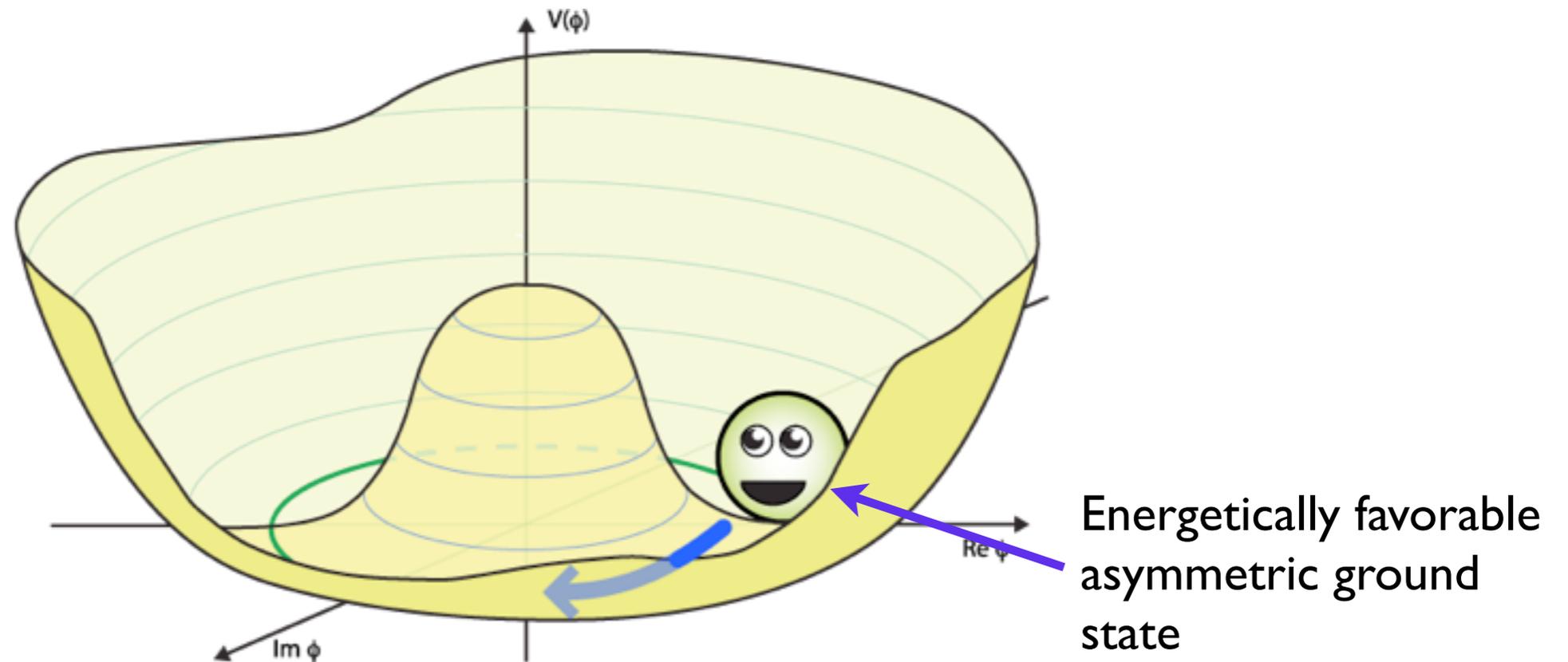


- Quantum Mechanics: fields \Leftrightarrow particles
- Fluctuations around bottom of potential: (pictured by the arrow in the diagram) *Goldstone bosons*. These give mass to the W and Z, and make the weak force short ranged

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

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

The Mexican hat potential and the Higgs mechanism



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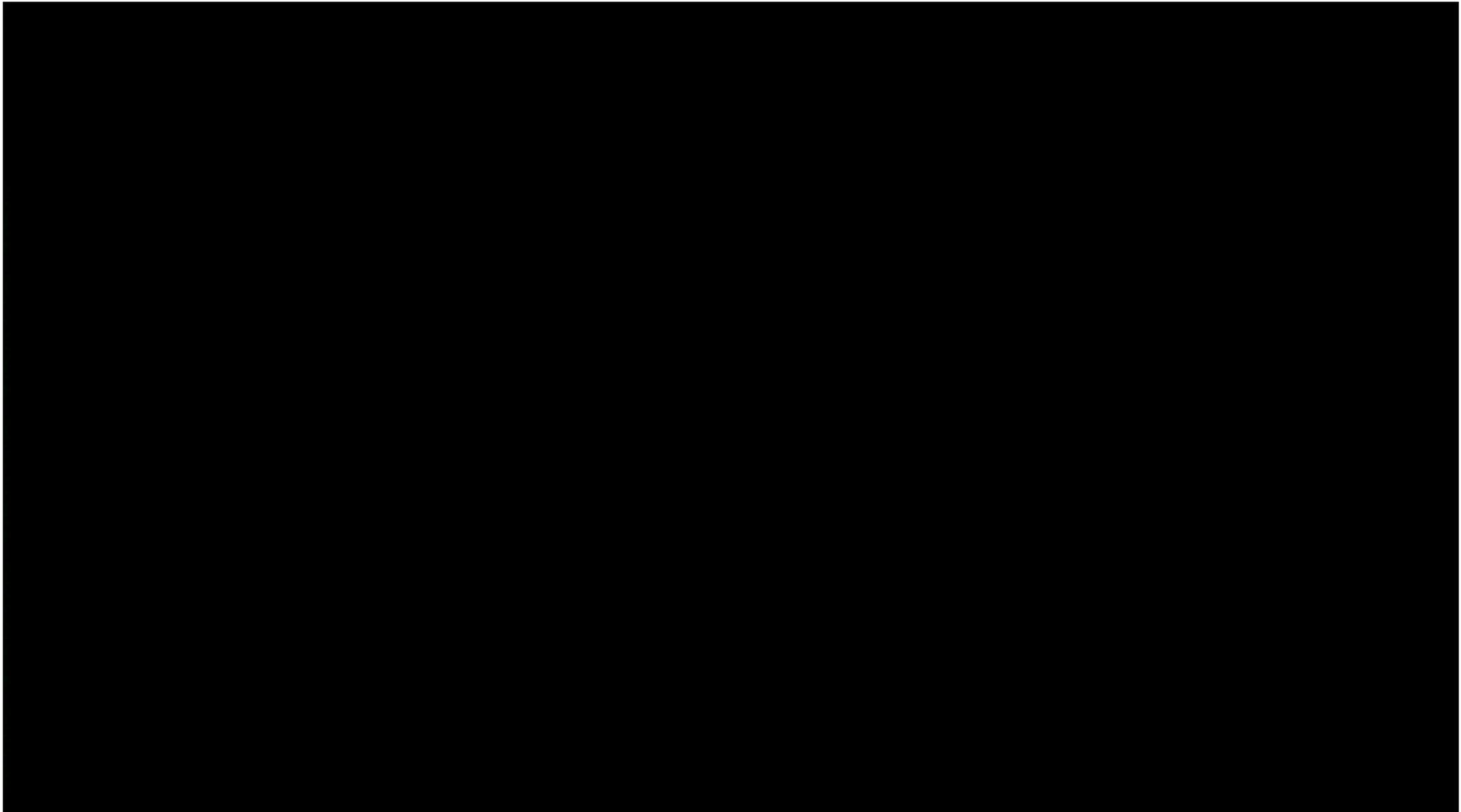
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How particles get mass

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

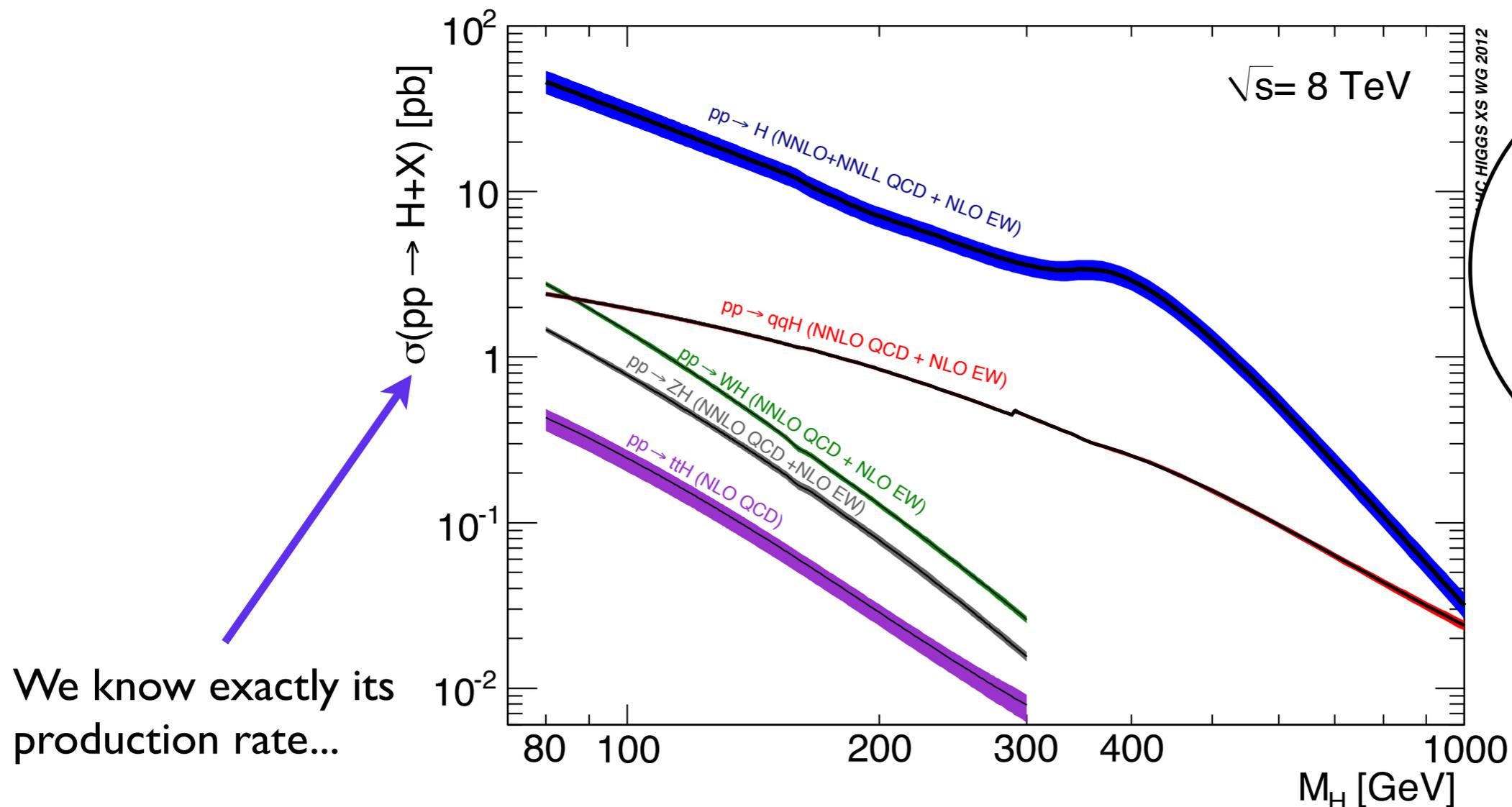
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The Higgs boson

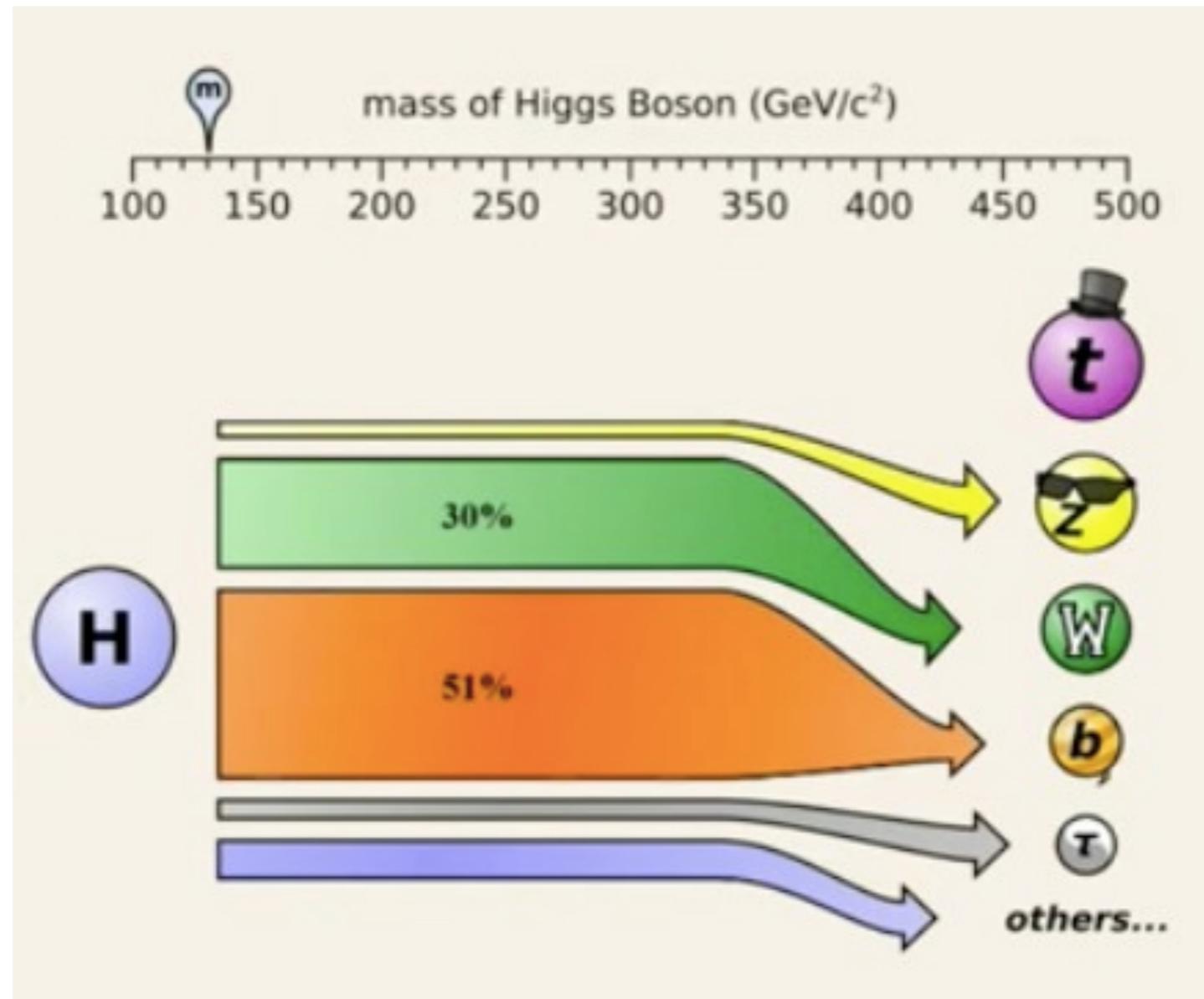
- In the simplest model, utilized in the Standard Model, the Higgs mechanism is accomplished by a single new scalar field; one additional Higgs boson is predicted
- **Predictivity** is again the key; all couplings of the Higgs boson to other Standard Model particles are determined



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

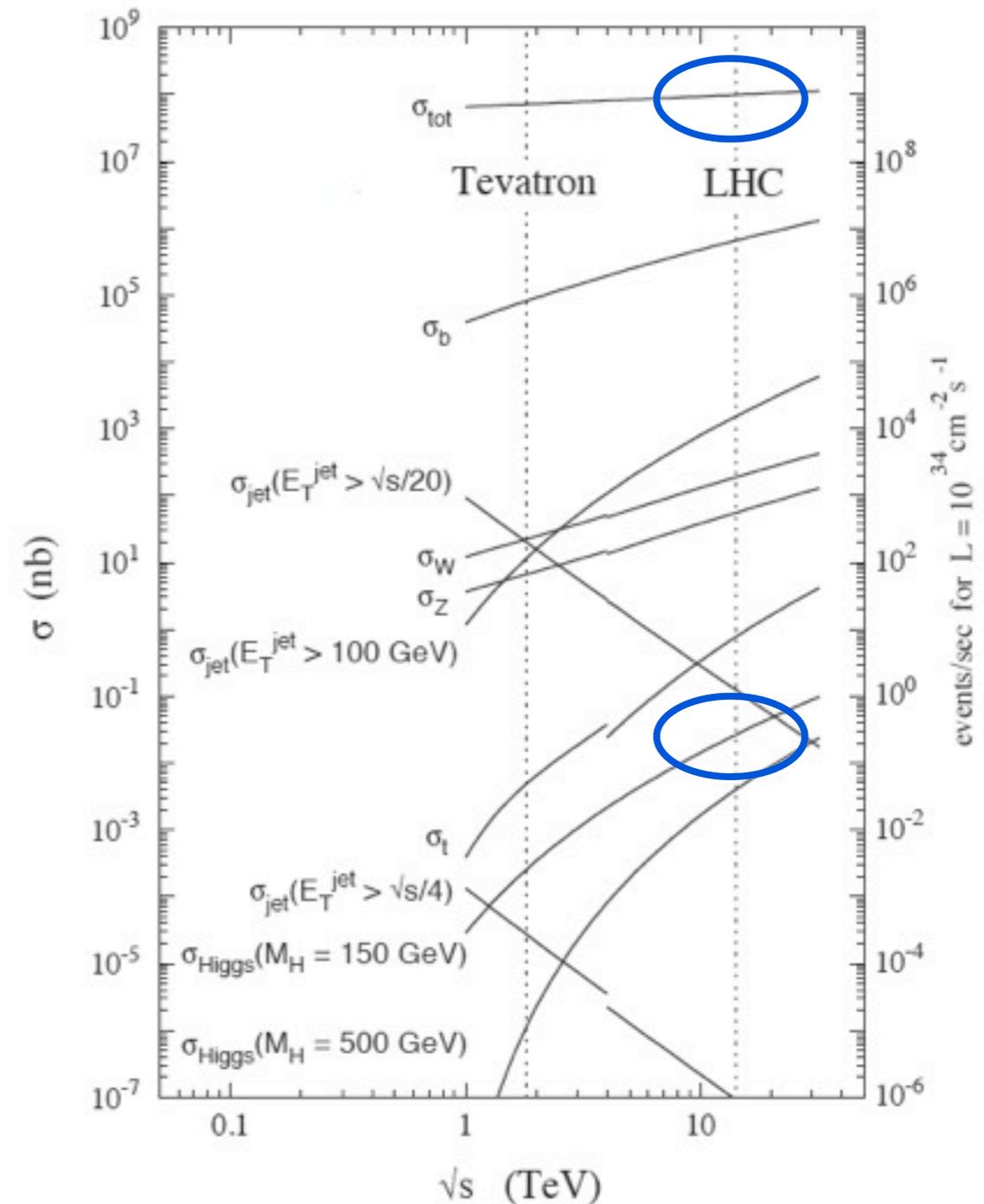
Decays of the Higgs boson

- 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

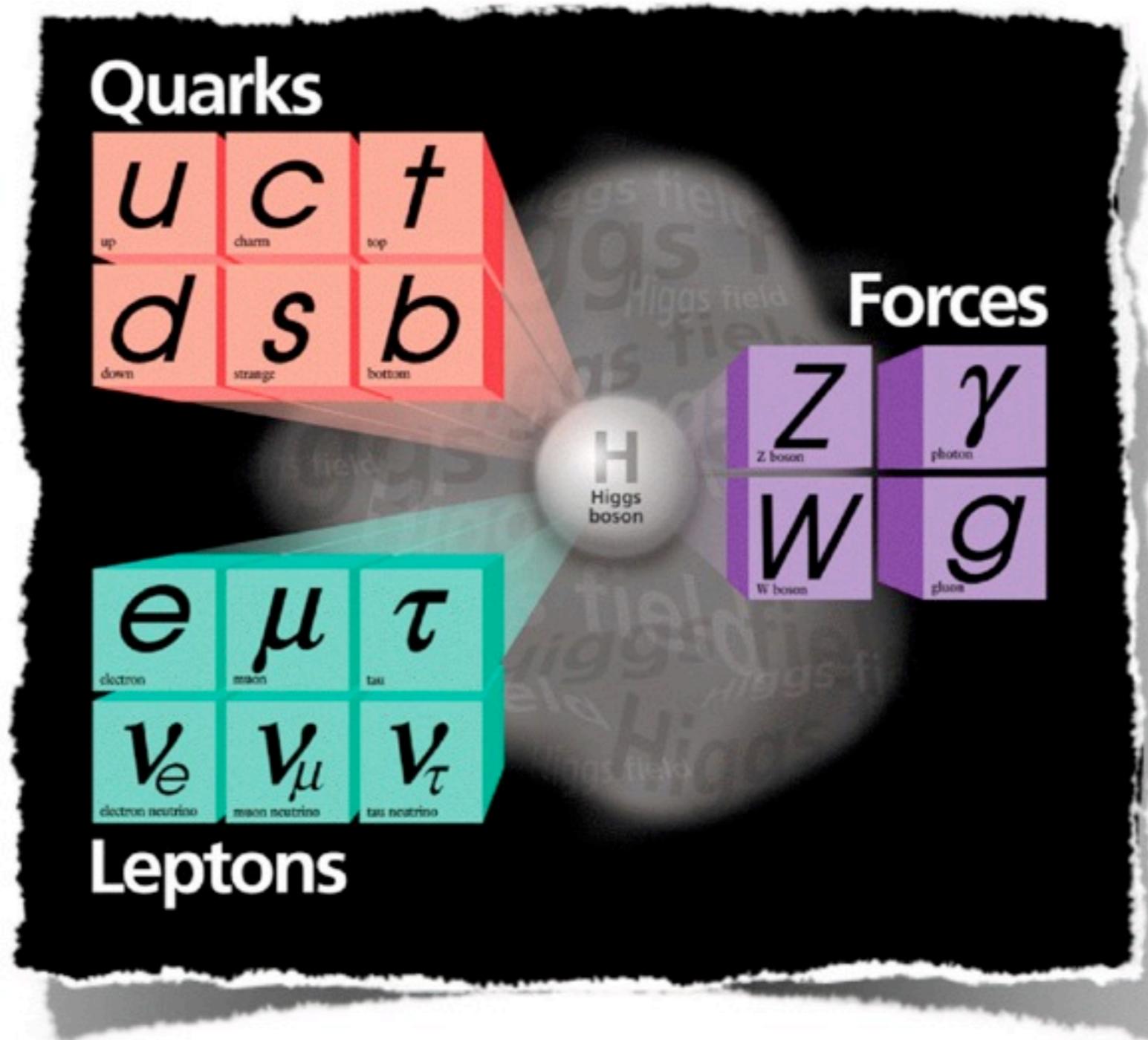
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- Need very clever experimentalists to find these rare events... thankfully we have them here at ANL (and elsewhere)
- Jimmy Proudfoot will pause in his search and tell you about the details next

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



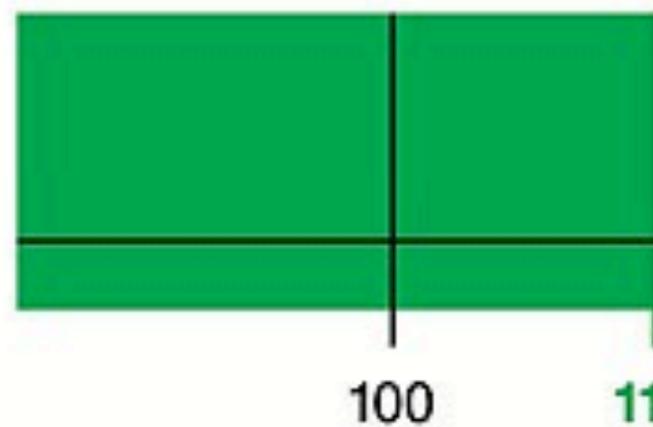
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Search for the Higgs Particle

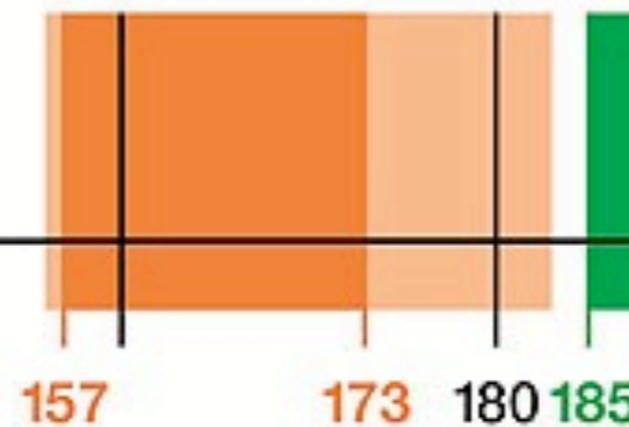
Status as of March 2011

Excluded by
LEP Experiments
95% confidence level



Consistent with the mass window allowed by previous experiments!

Excluded by
Tevatron
Experiments



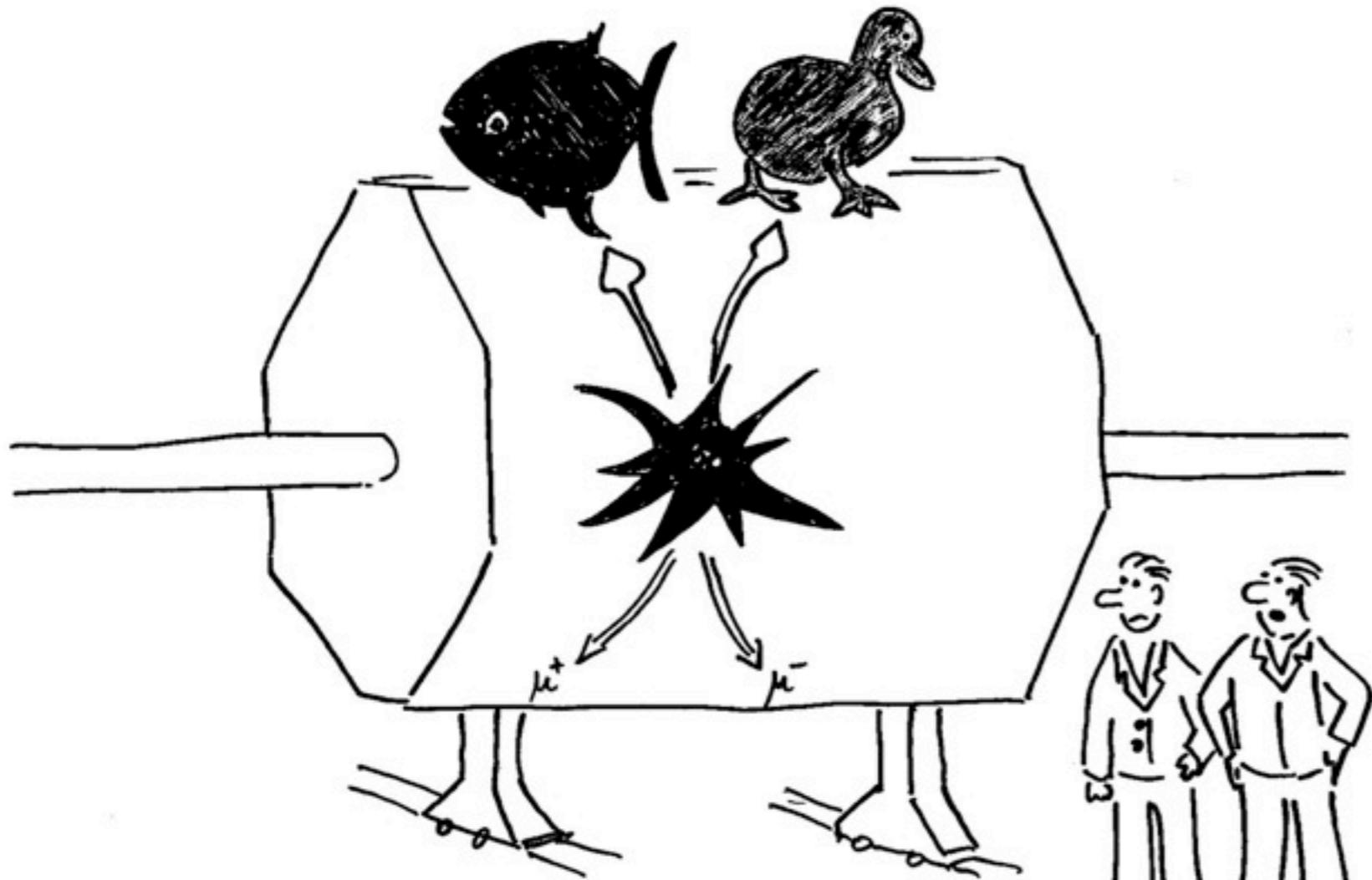
Excluded by
Indirect Measurements
95% confidence level



Higgs mass values

90% confidence level
95% confidence level

The Higgs as a portal beyond the Standard Model

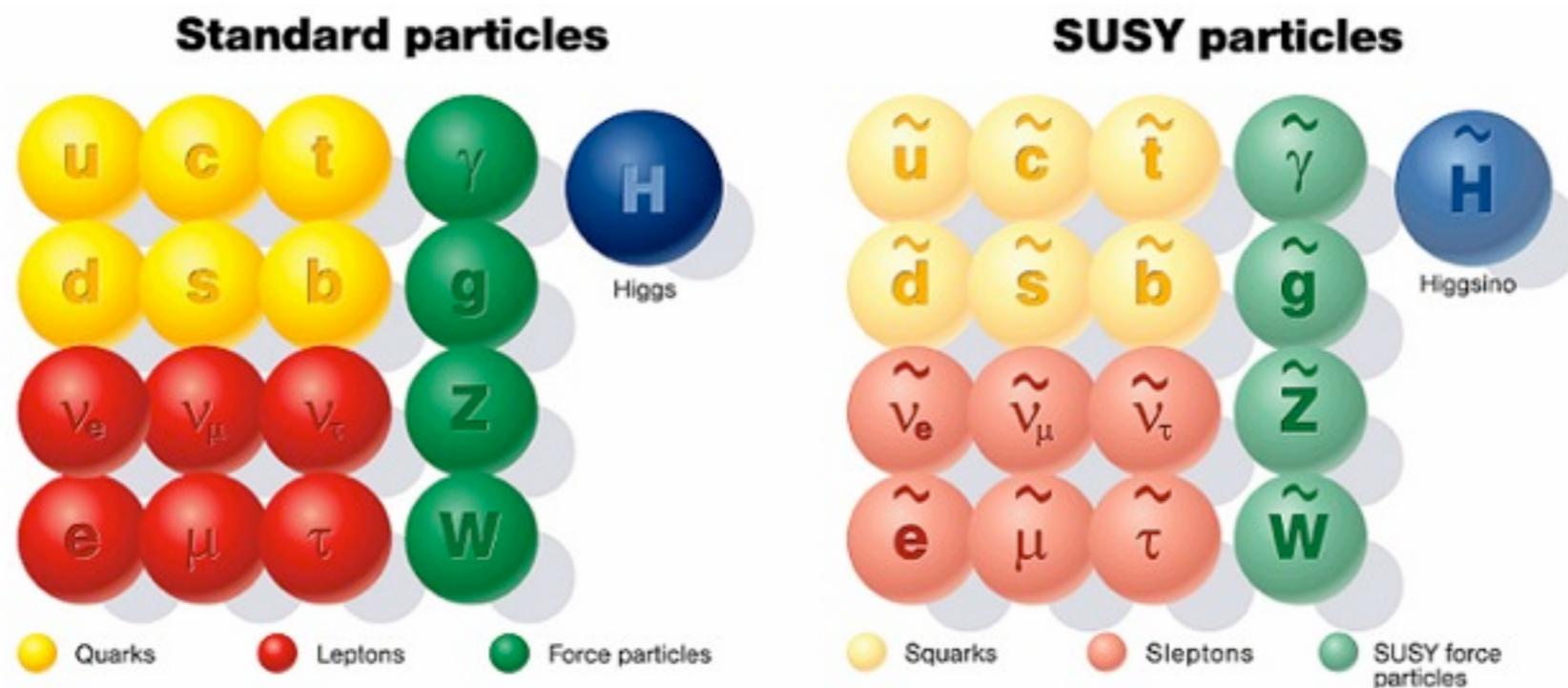


“This is not exactly, what theory predicted for the Higgs decay!”

- 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

