

# The building blocks of the SM



DF  
DEPARTAMENTO  
DE FÍSICA  
TÉCNICO LISBOA

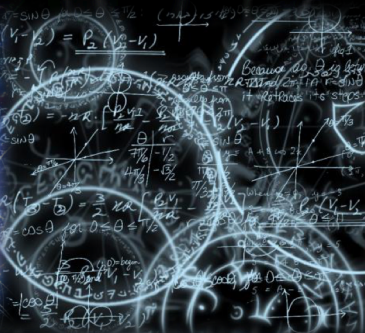
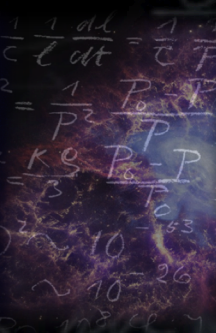
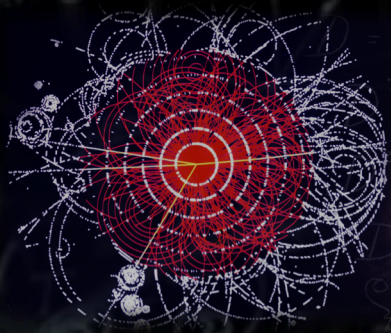


CFTP

Centro de Física Teórica de Partículas

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4th Lisbon Mini-School in Particle and Astroparticle Physics

Costa da Caparica, 11-13 February 2019

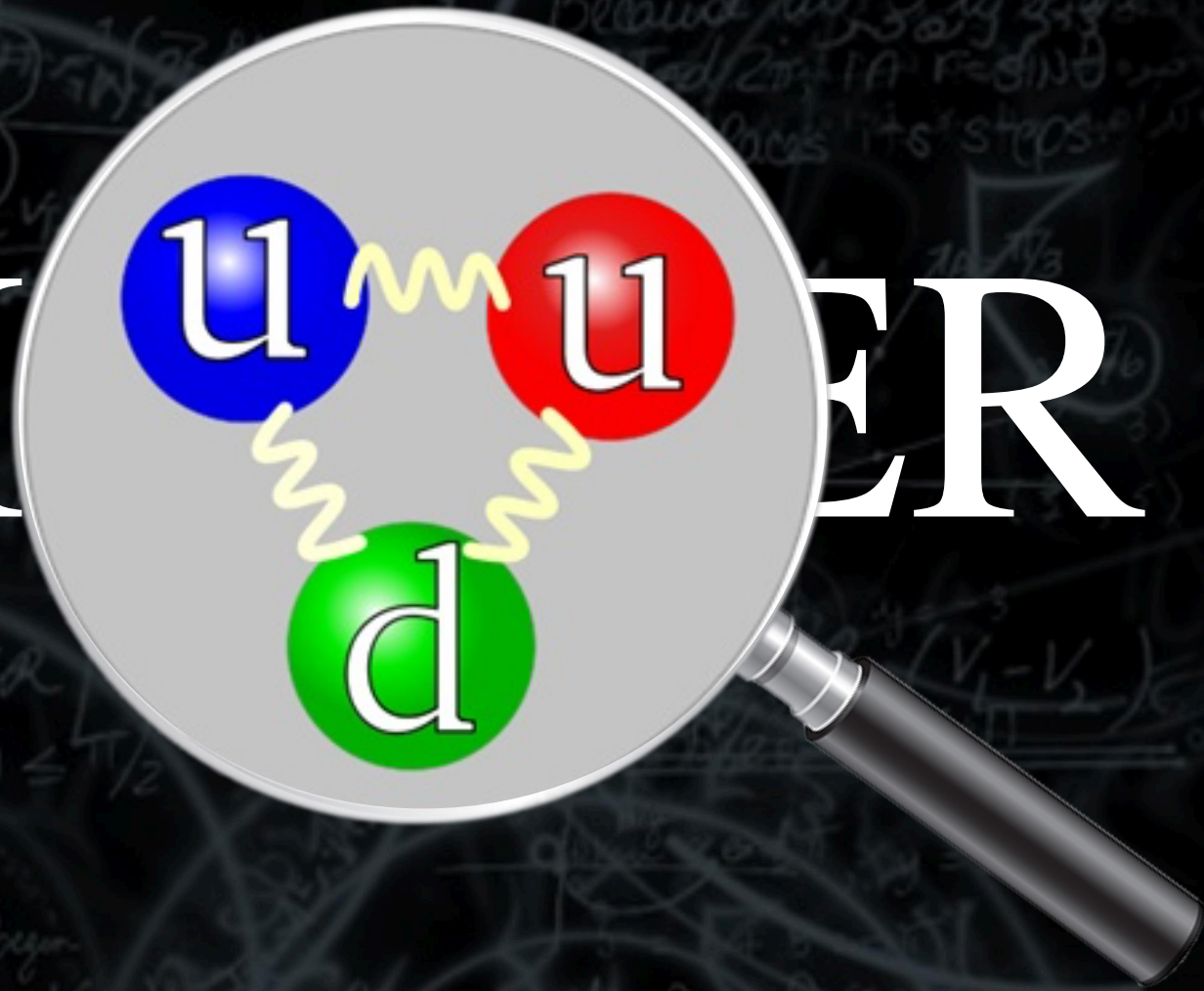




Particle physics (also called high energy physics) is the branch of physics that studies the nature of the particles that constitute matter (particles with mass) and radiation (massless particles). Although the word "particle" can refer to various types of very small objects (e.g. protons, gas particles, or even household dust), "particle physics" usually investigates the irreducibly smallest detectable particles and the irreducibly fundamental force fields necessary to explain them. By our current understanding, these elementary particles are excitations of the quantum fields that also govern their interactions. The currently dominant theory explaining these fundamental particles and fields, along with their dynamics, is called the Standard Model. Thus, modern particle physics generally investigates the Standard Model and its various possible extensions, e.g. to the newest "known" particle, the Higgs boson, or even to the oldest known force field, gravity.



# M U Q U A R





# NATURE IS COMPLEX, BUT AT THE MOST FUNDAMENTAL LEVEL IT SEEMS TO BE QUITE ORGANIZED

*Handwritten notes and calculations:*

$47,5$   
 $11,5$   
 $36,0$

$2n = 2 \cdot 11 = 22$   
 $2n = 2 \cdot 12 = 24$   
 $2n = 2 \cdot 13 = 26$   
 $2n = 2 \cdot 14 = 28$   
 $2n = 2 \cdot 15 = 30$   
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 $2n = 2 \cdot 27 = 54$   
 $2n = 2 \cdot 28 = 56$   
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 $2n = 2 \cdot 31 = 62$   
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 $2n = 2 \cdot 45 = 90$   
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 $2n = 2 \cdot 47 = 94$   
 $2n = 2 \cdot 48 = 96$   
 $2n = 2 \cdot 49 = 98$   
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 $2n = 2 \cdot 66 = 132$   
 $2n = 2 \cdot 67 = 134$   
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 $2n = 2 \cdot 97 = 194$   
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 $2n = 2 \cdot 99 = 198$   
 $2n = 2 \cdot 100 = 200$

$C = 12$   
 $O = 16$   
 $H = 1$   
 $N = 14$   
 $S = 32$   
 $Cl = 35,5$   
 $Br = 79,9$   
 $I = 126,9$   
 $F = 19$   
 $Ca = 40$   
 $Mg = 24$   
 $Al = 27$   
 $Si = 28$   
 $P = 31$   
 $Sb = 121,7$   
 $Te = 127,6$   
 $Bi = 208,98$   
 $Po = 209$   
 $At = 210$   
 $Rn = 222$   
 $Ac = 227$   
 $Th = 232$   
 $Pa = 231$   
 $U = 238$   
 $Np = 237$   
 $Pu = 244$   
 $Am = 243$   
 $Cm = 247$   
 $Bk = 247$   
 $Cf = 251$   
 $Es = 252$   
 $Fm = 257$   
 $Md = 258$   
 $No = 259$   
 $Lr = 260$

$Li = 7$   
 $Na = 23$   
 $K = 39$   
 $Rb = 85,4$   
 $Cs = 132,9$   
 $Fr = 223$   
 $Be = 9$   
 $Mg = 24$   
 $Ca = 40$   
 $Sr = 87,6$   
 $Ba = 137,3$   
 $Ra = 226$   
 $B = 10,8$   
 $C = 12$   
 $N = 14$   
 $O = 16$   
 $F = 19$   
 $Ne = 20,18$   
 $Al = 26,98$   
 $Si = 28,085$   
 $P = 30,9738$   
 $S = 32,06$   
 $Cl = 35,45$   
 $Ar = 39,948$   
 $Kr = 83,80$   
 $Xe = 131,29$   
 $Rn = 222$   
 $Sc = 44,9559$   
 $Ti = 47,88$   
 $V = 50,9415$   
 $Cr = 51,9961$   
 $Mn = 54,938044$   
 $Fe = 55,845$   
 $Co = 58,933195$   
 $Ni = 58,6934$   
 $Cu = 63,546$   
 $Zn = 65,39$   
 $Ga = 69,723$   
 $Ge = 72,630$   
 $As = 74,9216$   
 $Se = 78,96$   
 $Br = 79,904$   
 $Kr = 83,80$   
 $Rb = 85,4678$   
 $Sr = 87,62$   
 $Y = 88,90584$   
 $Zr = 91,224$   
 $Nb = 92,90638$   
 $Mo = 95,94$   
 $Tc = 98$   
 $Ru = 101,07$   
 $Rh = 102,9055$   
 $Pd = 106,42$   
 $Ag = 107,8682$   
 $Cd = 112,4118$   
 $In = 114,818$   
 $Sn = 118,710$   
 $Sb = 121,757$   
 $Te = 127,60$   
 $I = 126,90547$   
 $Xe = 131,29$   
 $Cs = 132,90545$   
 $Ba = 137,327$   
 $La = 138,90547$   
 $Ce = 140,12$   
 $Pr = 140,90766$   
 $Nd = 144,242$   
 $Pm = 145$   
 $Sm = 150,36$   
 $Eu = 151,964$   
 $Gd = 157,25$   
 $Tb = 158,92535$   
 $Dy = 162,5001$   
 $Ho = 164,93033$   
 $Er = 167,2593$   
 $Tm = 168,93223$   
 $Yb = 173,05469$   
 $Lu = 174,967$   
 $Ac = 227$   
 $Th = 232,0377$   
 $Pa = 231,036888$   
 $U = 238,02891$   
 $Np = 237,048173$   
 $Pu = 244,06422$   
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 $Cm = 247,071251$   
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 $Cf = 251,0824$   
 $Es = 252,083$   
 $Fm = 257,093$   
 $Md = 258,103$   
 $No = 259,113$   
 $Lr = 260,113$

### Tabela Periódica dos Elementos

■ metais alcalinos  
■ metais alcalinos-terrosos  
■ metais de transição  
■ outros metais  
■ não metais  
■ halogênios  
■ gases nobres  
■ novos materiais  
■ sólidos  
■ líquidos  
■ gases  
■ sintéticos

1 H Hidrogênio 1,008	2 He Hélio 4,0026																	18 Ar Argônio 39,948	19 K Potássio 39,0983	20 Ca Cálcio 40,078	21 Sc Escândio 44,9559	22 Ti Titânio 47,88	23 V Vanádio 50,9415	24 Cr Cromo 51,9961	25 Mn Manganês 54,938044	26 Fe Ferro 55,845	27 Co Cobalto 58,933195	28 Ni Níquel 58,6934	29 Cu Cobre 63,546	30 Zn Zinco 65,39	31 Ga Gálio 69,723	32 Ge Germânio 72,630	33 As Arsênio 74,9216	34 Se Selênio 78,96	35 Br Bromo 79,904	36 Kr Criptônio 83,80	37 Rb Rubídio 85,4678	38 Sr Estrôncio 87,62	39 Y Ítrio 88,90584	40 Zr Zircônio 91,224	41 Nb Níbio 92,90638	42 Mo Molibdênio 95,94	43 Tc Técnetio 98	44 Ru Ródio 101,07	45 Rh Ródio 102,9055	46 Pd Paládio 106,42	47 Ag Prata 107,8682	48 Cd Cádmio 112,4118	49 In Índio 114,818	50 Sn Estanho 118,710	51 Sb Antimônio 121,757	52 Te Telúrio 127,60	53 I Iodo 126,90547	54 Xe Xenônio 131,29	55 Cs Césio 132,90545	56 Ba Bário 137,327	57-71 La-Lu Lantanídeos	72 Hf Háfnio 178,49	73 Ta Tântalo 180,94788	74 W Wolfrâmio 183,84	75 Re Rênio 186,207	76 Os Osmínio 190,23	77 Ir Írídio 192,222	78 Pt Platina 195,084	79 Au Ouro 196,96657	80 Hg Mercúrio 200,59	81 Tl Telúrio 204,38	82 Pb Chumbo 207,2	83 Bi Bismuto 208,9804	84 Po Polônio 209	85 At Astato 210	86 Rn Radônio 222	87 Fr Frâncio 223	88 Ra Rádio 226	89-103 Ac-Lr Actinídeos	104 Rf Rutherfordio 261	105 Db Dubnio 262	106 Sg Seabórgio 263	107 Bh Bohrio 264	108 Hs Háscio 265	109 Mt Meitnério 266	110 Ds Darmstádio 271	111 Rg Roentgenio 272	112 Cn Copernício 285	113 Nh Nihônio 286	114 Fl Fleróvio 289	115 Mc Moscóvio 290	116 Lv Livermório 293	117 Ts Tenessio 294	118 Og Oganessio 294
57 La Lantanio 138,90547	58 Ce Célio 140,12	59 Pr Praseodímio 140,90766	60 Nd Neodímio 144,242	61 Pm Promécio 145	62 Sm Samarco 150,36	63 Eu Európio 151,964	64 Gd Gadolínio 157,25	65 Tb Terbio 158,92535	66 Dy Dísprio 162,5001	67 Ho Hólio 164,93033	68 Er Érbio 167,2593	69 Tm Térbio 168,93223	70 Yb Ítrio 173,05469	71 Lu Lutécio 174,967	89 Ac Actínio 227	90 Th Tório 232,0377	91 Pa Protactínio 231,036888	92 U Urânio 238,02891	93 Np Neptúlio 237,048173	94 Pu Plutônio 244,06422	95 Am Americônio 243,061381	96 Cm Curvônio 247,071251	97 Bk Berkelônio 247,071251	98 Cf Califórnio 251,0824	99 Es Einsteinônio 252,083	100 Fm Fermônio 257,093	101 Md Mendelevônio 258,103	102 No Nobelônio 259,113	103 Lr Lawrencônio 260,113																																																													

IS THERE A "PERIODIC TABLE" FOR THE  
**FUNDAMENTAL**  
 BUILDING BLOCKS OF MATTER?



# THE STANDARD MODEL OF FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

## FERMIONS

matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-2) \times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ middle neutrino*	$(0.009-2) \times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ heaviest neutrino	$(0.05-2) \times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

\*See the neutrino paragraph below.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

**The energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ) where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$  joule. The mass of the proton is 0.938 GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.

### Neutrinos

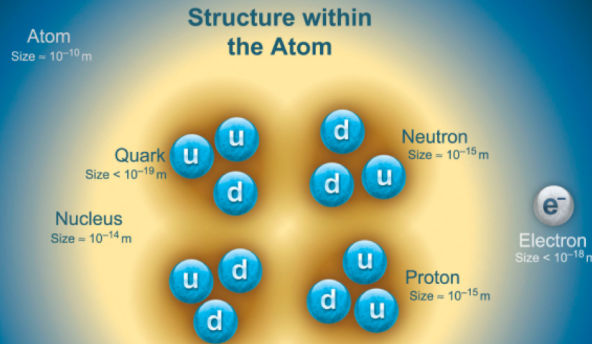
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states  $\nu_e$ ,  $\nu_\mu$ , or  $\nu_\tau$ , labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos  $\nu_1$ ,  $\nu_2$ , and  $\nu_3$  for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$  but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

## BOSONS

force carriers  
spin = 0, 1, 2, ...



Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
<b>W<sup>-</sup></b>	80.39	-1
<b>W<sup>+</sup></b>	80.39	+1
<b>Z<sup>0</sup></b>	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>H</b> Higgs	126	0

### Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons**  $q\bar{q}$  and **baryons**  $qqq$ . Among the many types of baryons observed are the proton ( $uud$ ), antiproton ( $\bar{u}\bar{u}\bar{d}$ ), and neutron ( $udd$ ). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion  $\pi^+$  ( $u\bar{d}$ ), kaon  $K^-$  ( $s\bar{u}$ ), and  $B^0$  ( $d\bar{b}$ ).

## Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

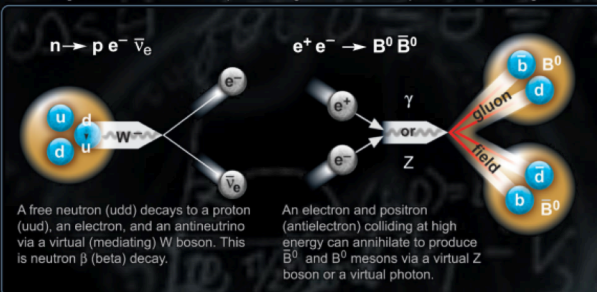
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	<b>W<sup>+</sup></b> <b>W<sup>-</sup></b> <b>Z<sup>0</sup></b>	$\gamma$	Gluons
Strength at $\left\{ \begin{array}{l} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{array} \right.$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

## Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

## Particle Processes

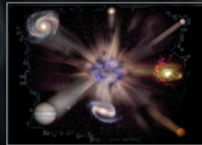
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.



A free neutron ( $udd$ ) decays to a proton ( $uud$ ), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron  $\beta$  (beta) decay.

An electron and positron (antielepton) colliding at high energy can annihilate to produce  $B^0$  and  $B^0$  mesons via a virtual Z boson or a virtual photon.

### Why is the Universe Accelerating?



The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

### Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

### What is Dark Matter?



Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

### Are there Extra Dimensions?



An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).



# ELEMENTARY PARTICLES

## FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-2) \times 10^{-9}$	0
<b>e</b> electron	0.000511	-1
$\nu_M$ middle neutrino*	$(0.009-2) \times 10^{-9}$	0
$\mu$ muon	0.106	-1
$\nu_H$ heaviest neutrino*	$(0.05-2) \times 10^{-9}$	0
$\tau$ tau	1.777	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
<b>u</b> up	0.002	2/3
<b>d</b> down	0.005	-1/3
<b>c</b> charm	1.3	2/3
<b>s</b> strange	0.1	-1/3
<b>t</b> top	173	2/3
<b>b</b> bottom	4.2	-1/3

**WHY THREE FAMILIES OF LEPTONS AND QUARKS?**  
(We have no idea...)



# INTERACTIONS AND THEIR MEDIATORS

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\begin{cases} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{cases}$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

## BOSONS

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.39	-1
$W^+$ W bosons	80.39	+1
$Z^0$ Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$g$ gluon	0	0

**CHALLENGE**

ARE THERE NEW INTERACTIONS/GAUGE  
BOSONS?  
(We have no idea...)

# THE NEWEST BOSON

Higgs Boson		spin = 0
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>H</b> Higgs	126	0

**THE ONLY KNOWN SPINLESS  
ELEMENTARY PARTICLE**



# (NON) ELEMENTARY PARTICLES

## H A D R O N S

### Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.  
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
$\mathbf{p}$	proton	$\mathbf{uud}$	1	0.938	1/2
$\bar{\mathbf{p}}$	anti-proton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	-1	0.938	1/2
$\mathbf{n}$	neutron	$\mathbf{udd}$	0	0.940	1/2
$\mathbf{\Lambda}$	lambda	$\mathbf{uds}$	0	1.116	1/2
$\mathbf{\Omega}^-$	omega	$\mathbf{sss}$	-1	1.672	3/2

### Mesons $q\bar{q}$

Mesons are bosonic hadrons.  
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
$\mathbf{\pi}^+$	pion	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.140	0
$\mathbf{K}^-$	kaon	$\mathbf{s}\bar{\mathbf{u}}$	-1	0.494	0
$\mathbf{\rho}^+$	rho	$\mathbf{u}\bar{\mathbf{d}}$	+1	0.770	1
$\mathbf{B}^0$	B-zero	$\mathbf{d}\bar{\mathbf{b}}$	0	5.279	0
$\mathbf{\eta}_c$	eta-c	$\mathbf{c}\bar{\mathbf{c}}$	0	2.980	0

Gernot will tell you more about hadrons and the physics of the strong interaction

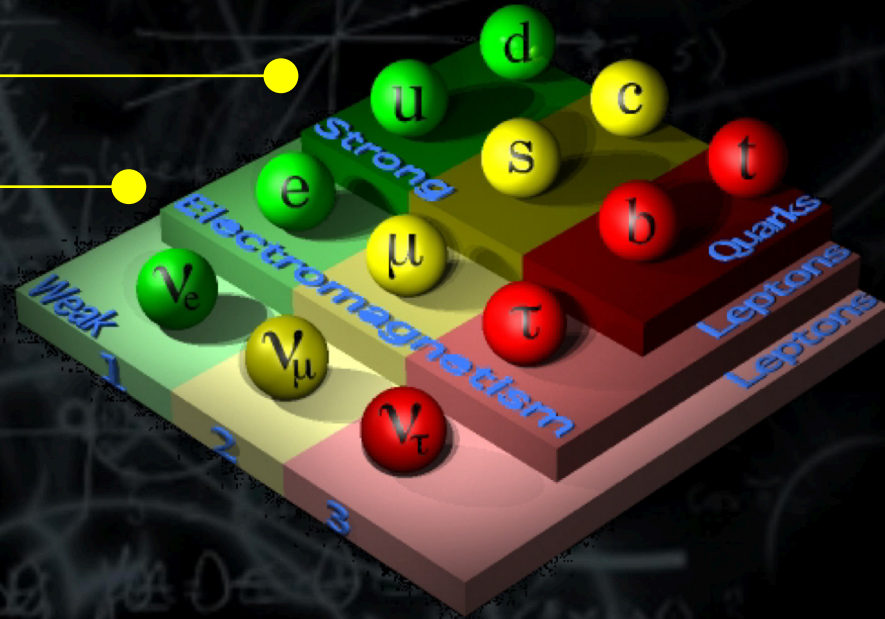
# PARTICLES AND INTERACTIONS (SUMMARY)

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons
Strength at $\begin{cases} 10^{-18} \text{ m} \\ 3 \times 10^{-17} \text{ m} \end{cases}$	$10^{-41}$ $10^{-41}$	0.8 $10^{-4}$	1 1	25 60

Strong (g)

Electromagnetic ( $\gamma$ )

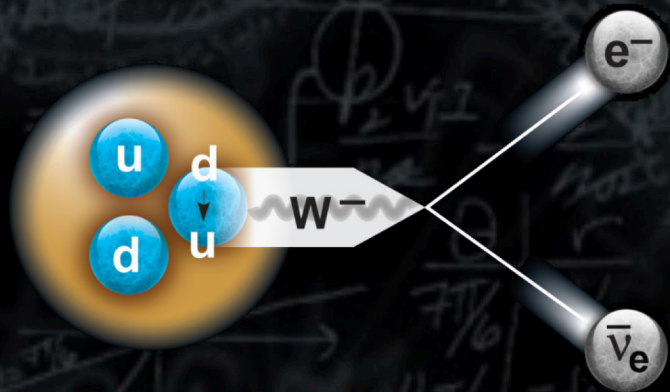
Weak ( $W^+$ ,  $W^-$ ,  $Z^0$ )





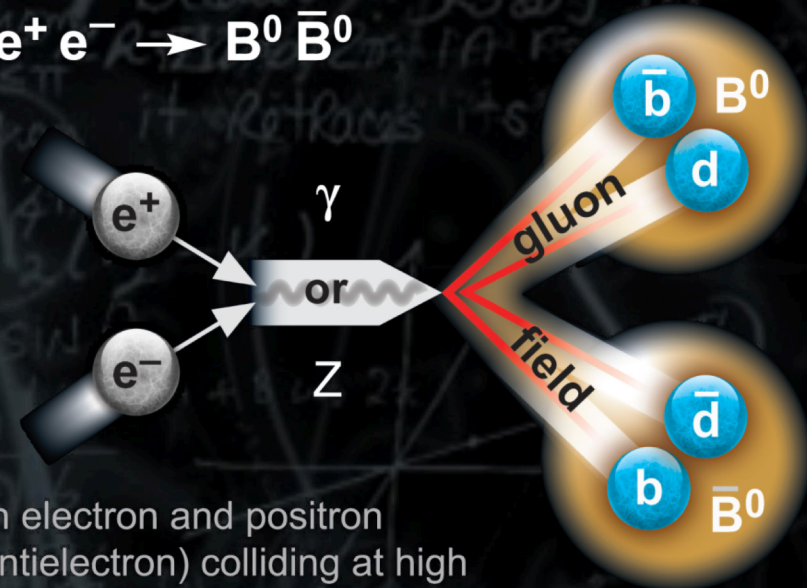
# PARTICLE PROCESSES

$$n \rightarrow p e^- \bar{\nu}_e$$



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

$$e^+ e^- \rightarrow B^0 \bar{B}^0$$

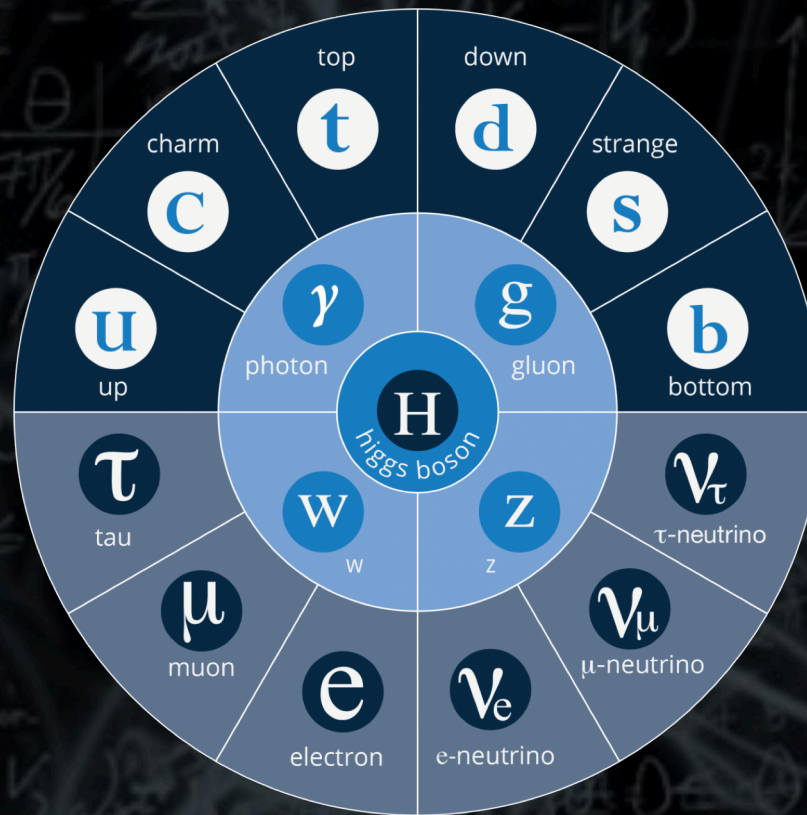


An electron and positron (antielectron) colliding at high energy can annihilate to produce B<sup>0</sup> and B̄<sup>0</sup> mesons via a virtual Z boson or a virtual photon.

## WHAT ARE THE RULES OF THE GAME?

WHAT ARE THE BASIC PRINCIPLES WHICH ALLOW US TO PREDICT  
HOW NATURE WORKS @ ITS MOST FUNDAMENTAL LEVEL?

# THE STANDARD MODEL (SM)

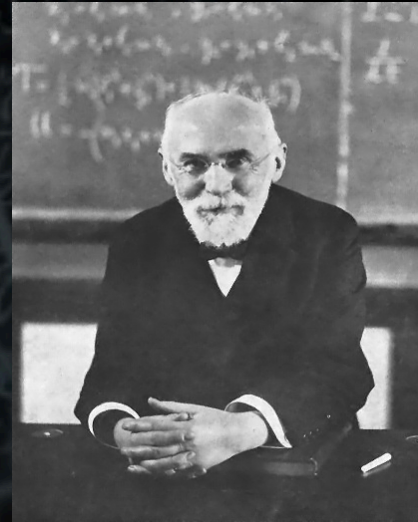




# SYMMETRY



Galileo



Lorentz



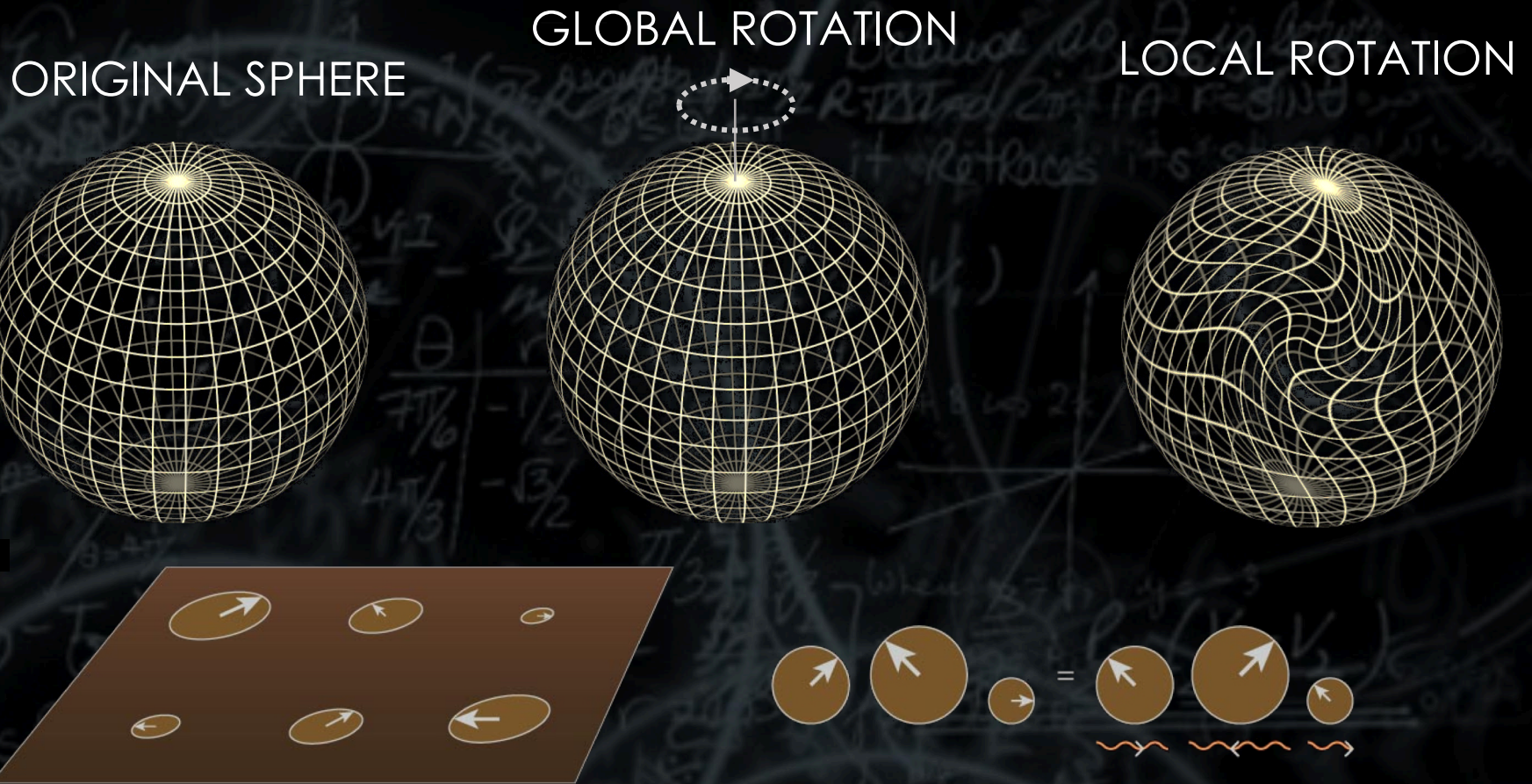
IN ORDER TO FULLY UNDERSTAND THE DEEP STRUCTURE OF THIS THEORY\* YOU NEED TO KNOW:

- RELATIVISTIC QUANTUM MECHANICS (CMQ-4/5<sup>TH</sup> YEAR MEFT)
- QUANTUM FIELD THEORY (CMQ, TC – 4/5<sup>TH</sup> YEAR MEFT)
  - GAUGE THEORIES (TU, 4/5<sup>TH</sup> YEAR MEFT)
  - PARTICLE PHYSICS (4/5<sup>TH</sup> YEAR MEFT)
    - QCD (4/5<sup>TH</sup> YEAR MEFT)

\* And to be able to construct your own theories.



# GAUGE SYMMETRIES – THE NEW PARADIGM



The gauge bosons (i.e. interactions) appear as a consequence of imposing invariance under local transformations

# GAUGE SYMMETRIES – THE NEW PARADIGM



$$\mathcal{L} = i\hbar\psi(\vec{r}, t)^* \frac{\partial\psi(\vec{r}, t)}{\partial t} - \frac{\hbar^2}{2m} \vec{\nabla}\psi(\vec{r}, t) \vec{\nabla}\psi(\vec{r}, t)^*$$

Global Transformation:  $\psi \rightarrow e^{i\alpha}\psi$  Invariant

Local Transformation:  $\psi \rightarrow e^{i\alpha(\vec{r}, t)}\psi$  Not invariant

**EXERCISE**



# STANDARD MODEL – THE RECIPE

THE SYMMETRY GROUP OF THE STANDARD MODEL IS:

$$SU(2)_L \times U(1)_Y$$



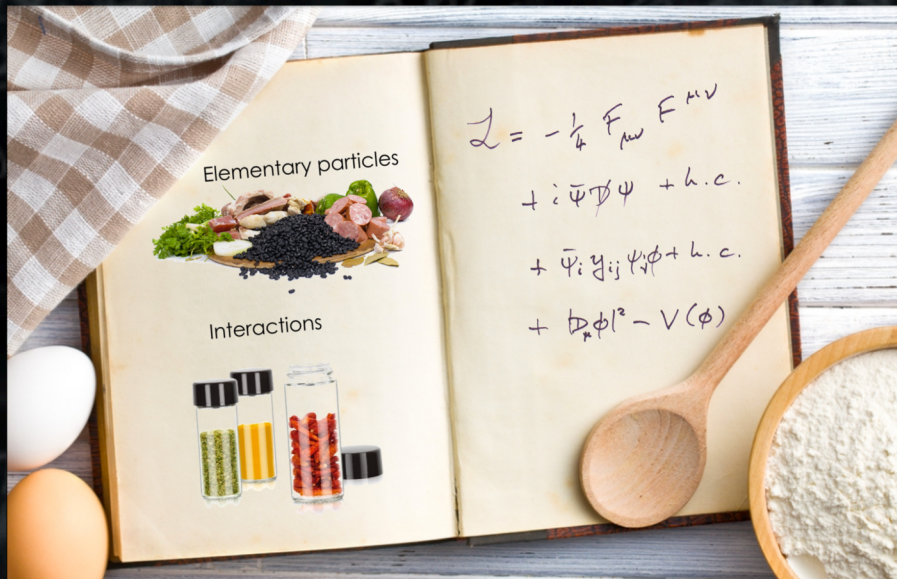
Glashow



Weinberg



Salam

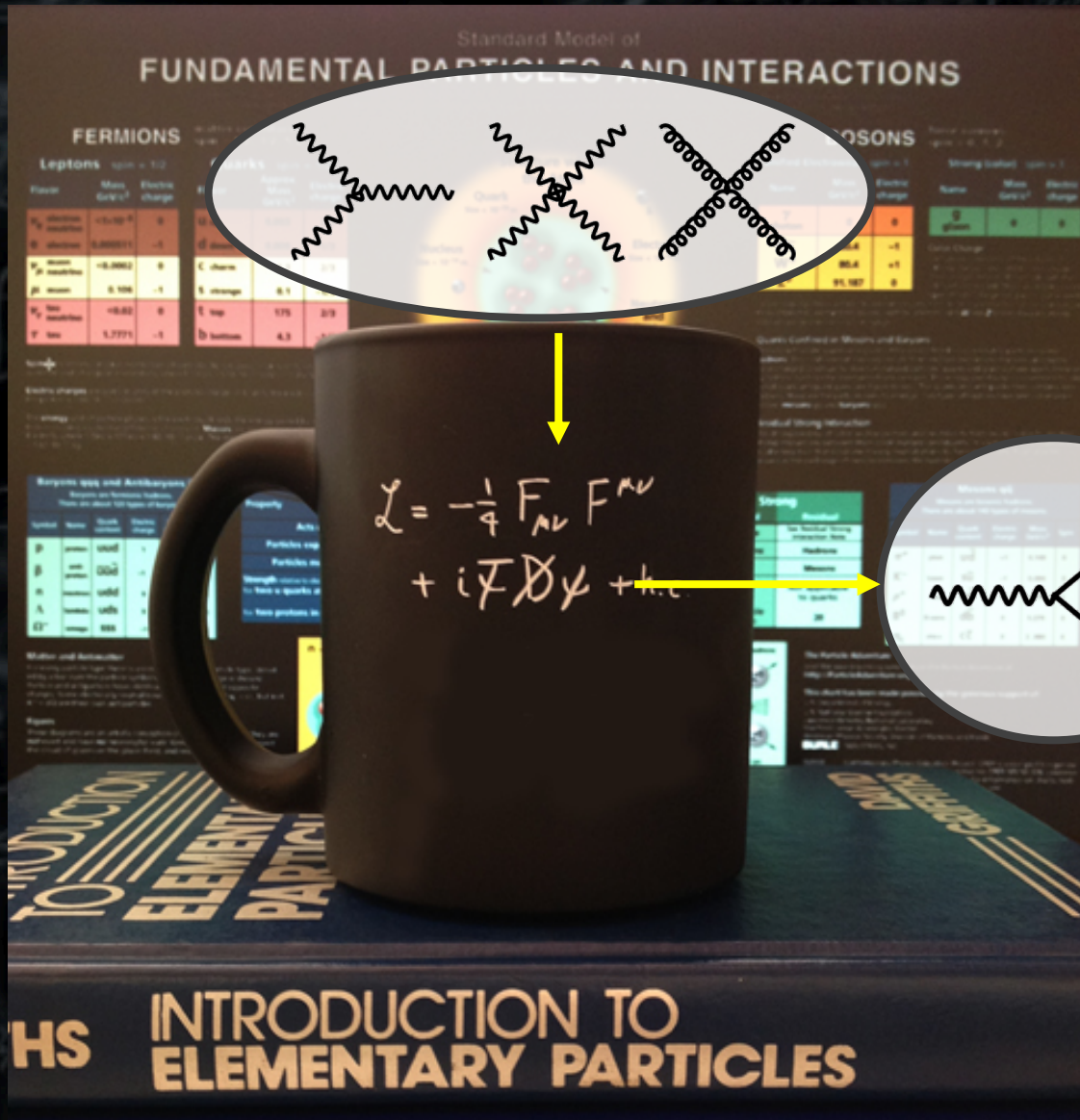


- 1) Place the elementary particles in the representations of the group
- 2) Write all possible terms in the Lagrangean which are invariant under gauge transformations

**RESULT:** THEORY WHICH DESCRIBES (ELECTROWEAK AND STRONG) INTERACTIONS OF QUARKS, LEPTONS AND GAUGE BOSONS

**BUT... ALL PARTICLES ARE MASSLESS!**

# THE SM IN A MUG – PART I





# LET THERE BE MASS!

## The ABEGHHK'tH mechanism

Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and 't Hooft



Kibble

Guralnik

Hagen

Englert

Brout

Higgs

How does the ABEGHHK'tH mechanism work?

THE HIGGS FIELD...

# THE SM IN A MUG – PART II

Standard Model of  
**FUNDAMENTAL PARTICLES AND INTERACTIONS**

**FERMIONS**

**Leptons** spin = 1/2

Flavor	Mass (GeV) <sup>c</sup>	Elect. charge
$\nu_e$ electron neutrino	< 10 <sup>-9</sup>	0
$e^-$ electron	0.000511	-1
$\nu_\mu$ muon neutrino	< 0.0002	0
$\mu^-$ muon	0.106	-1
$\nu_\tau$ tau neutrino	< 0.02	0
$\tau^-$ tau	1.7771	-1

**BOSONS**

Name	Mass (GeV) <sup>c</sup>	Electric charge
$\gamma$ photon	0	0
$W^\pm$	80.4	$\pm 1$
$Z^0$	91.187	0

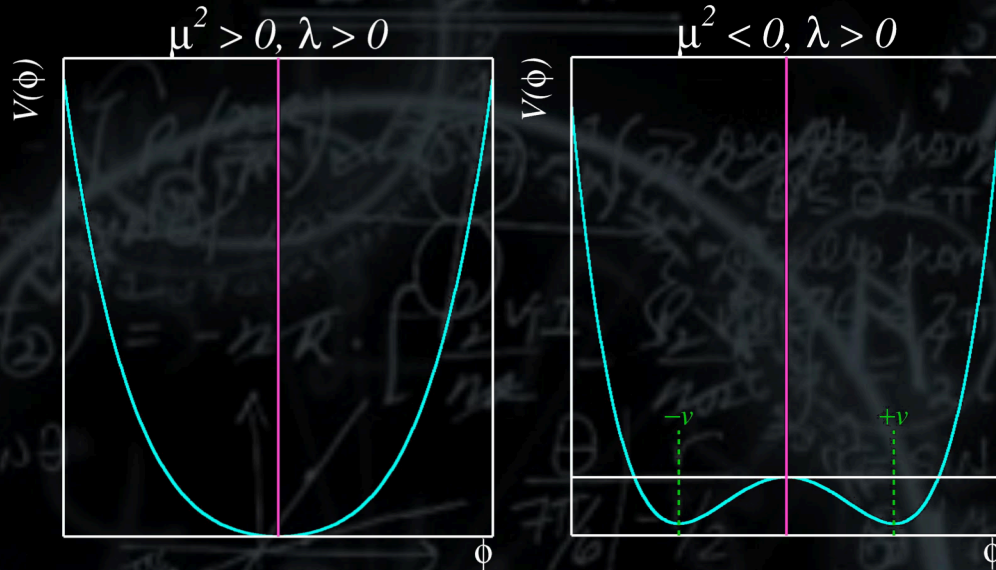
↓

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + \text{h.c.} + \chi_i y_{ij} \chi_j \phi + \text{h.c.} + |D_\mu \phi|^2 - V(\phi)$$

↙ ↘ ↗ ↖



# HIGGS MECHANISM



$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4$$

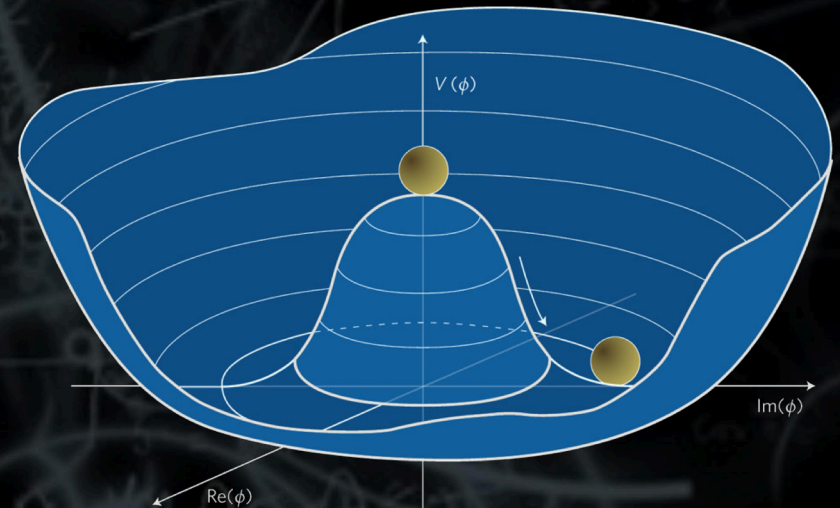
“IN VACUUM”:  $v = \sqrt{\frac{-\mu^2}{2\lambda}}$

Essential for the Higgs mechanism to work.

The symmetry is broken spontaneously!!

The weak gauge bosons (W e Z) and fermions acquire mass!

AND... THE PHOTON REMAINS MASSLESS!!!

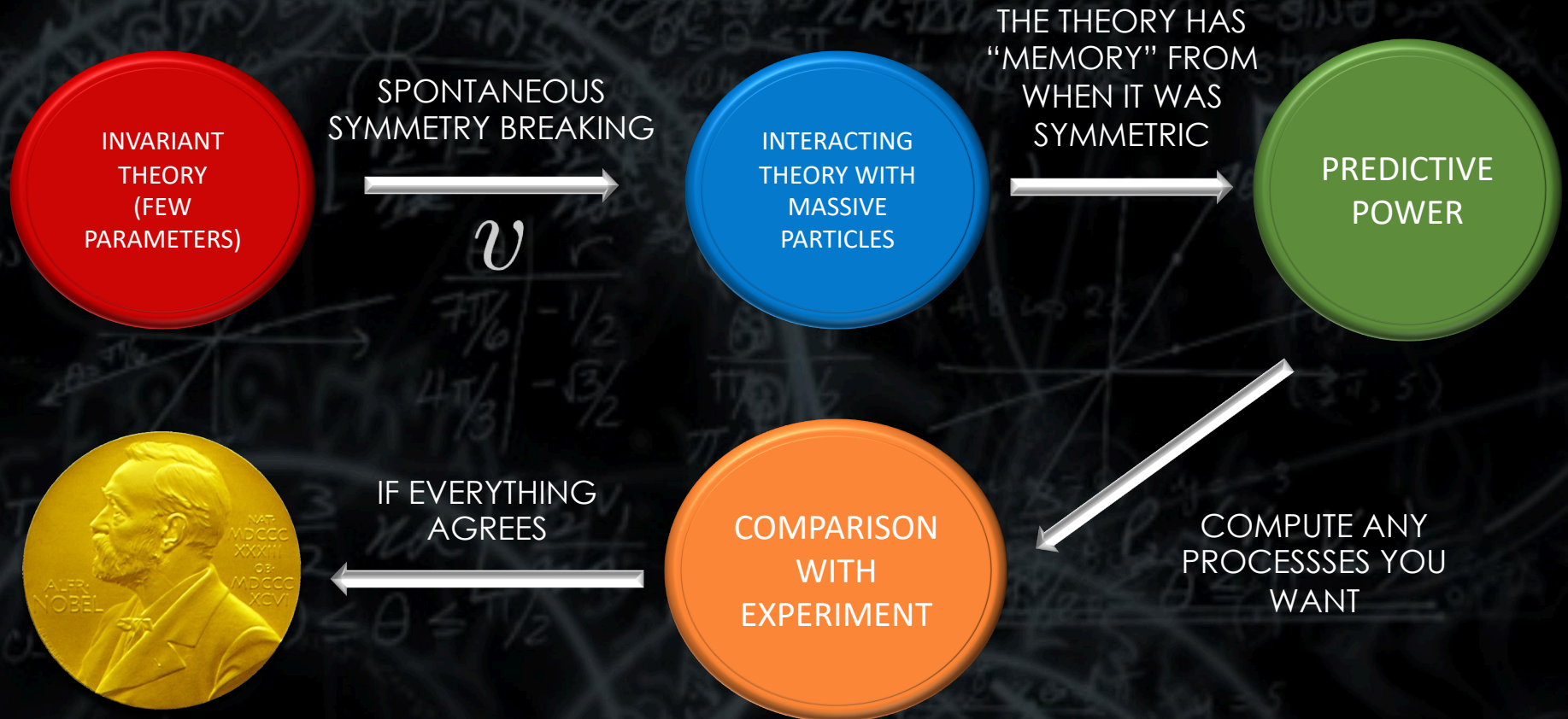


# HIGGS MECHANISM

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\mu^- W_\nu^+) - Z_\mu^0 (W_\mu^+ \partial_\nu W_\nu^- - W_\mu^- \partial_\nu W_\nu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\mu^- - W_\nu^- \partial_\mu W_\mu^+)) - \\
 & ig s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\mu^- W_\nu^+) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
 & Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
 & \beta_h \left( \frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
 & g \alpha_h M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
 & \frac{1}{3}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
 & \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
 & \frac{1}{2}g (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
 & M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig s_w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
 & \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
 & \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w c_w}{c_w^2} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^2 s_w^2 A_\mu A_\nu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_i^a (\bar{q}_i^c \gamma^\mu q_i^a) g_\mu^a - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma \partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + \\
 & m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
 & \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
 & \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep} \dagger_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep} \dagger_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep} \dagger_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep} \dagger_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep} \dagger_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa - \\
 & \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \bar{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
 & \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
 & \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- - \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}gM (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
 \end{aligned}$$



# MAKE IT INVARIANT TO BREAK IT AFTER ???!



# MAKE IT INVARIANT TO BREAK IT AFTER ???!



# USELESS EXERCISE!



# MAKE IT INVARIANT TO BREAK IT AFTER ??!

SOME PREDICTIONS:

$$M_Z \cos \theta_W = M_W, \quad \sin^2 \theta_W = 1 - M_W^2 / M_Z^2$$

$$M_W^2 \sin^2 \theta_W = \frac{e^2}{4\pi\sqrt{2} G_F}$$

THE W AND Z BOSONS WERE DISCOVERED  
AT CERN IN 1983.

$$M_W = 80.385 \pm 0.015 \text{ GeV}$$

$$M_Z = 91.1876 \pm 0.086 \text{ GeV}$$



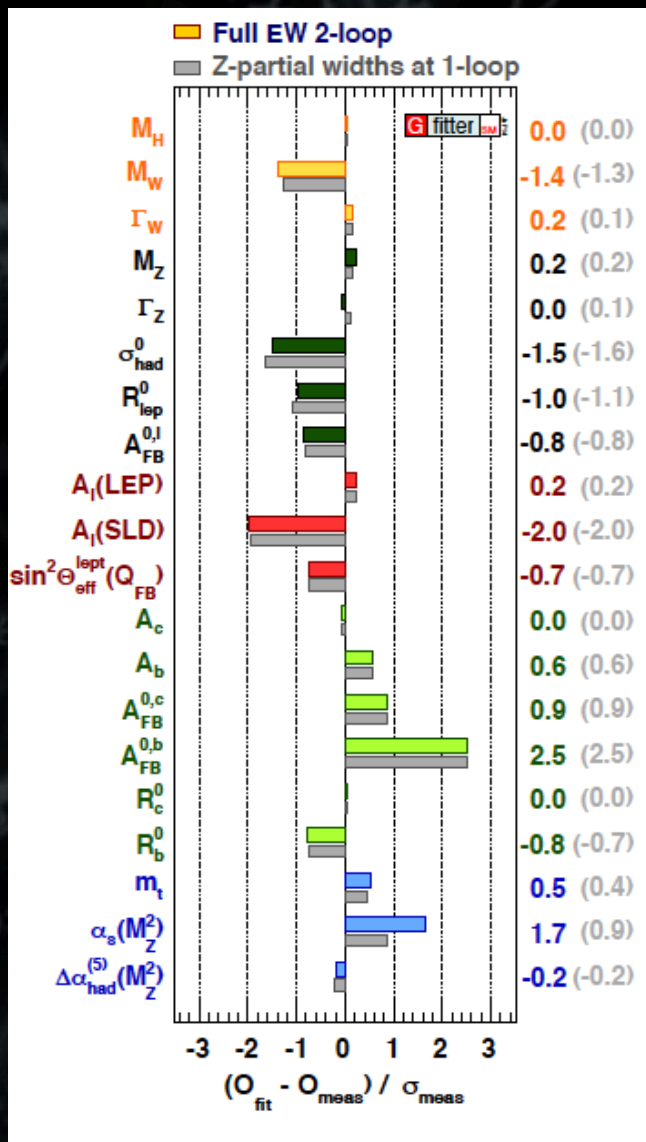
THE GARGAMELLE DETECTOR

The 1984 Physics Nobel Prize was awarded to  
Rubbia and Van De Meer

"for their decisive contributions to  
the large project, which led to  
the discovery of the field particles  
W and Z, communicators of weak  
interaction"



# PREDICTIVE POWER



The SM IS IN AGREEMENT WITH

ALMOST ALL EXPERIMENTAL

DATA AT THE

$\sim 2.5\sigma$

LEVEL



# NOBEL PRIZE THEORY



The Physics Nobel prize was awarded to Glashow, Weinberg & Salam in 1979;

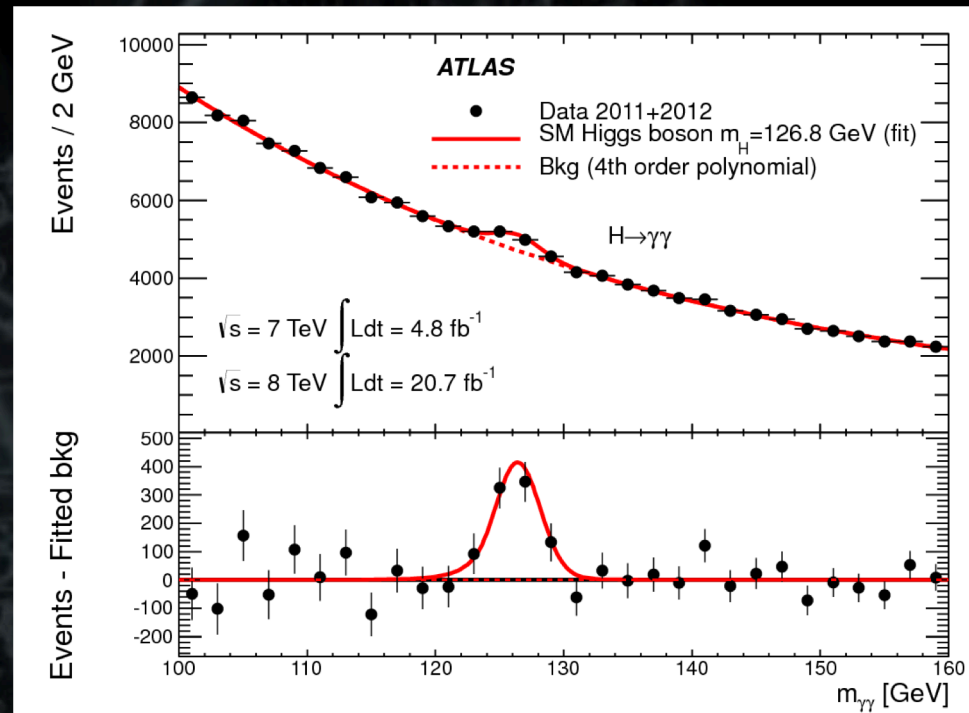
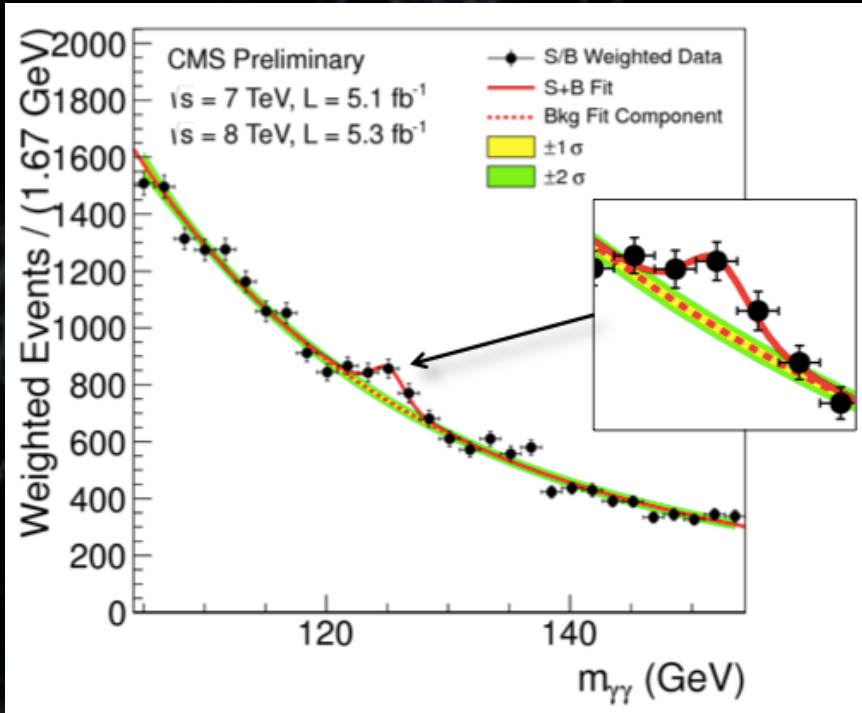


"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, the prediction of the weak neutral current".

**Until the 4<sup>th</sup> of July 2012, electroweak symmetry breaking was still to be confirmed.**

Until...

# BORN ON THE 4<sup>TH</sup> OF JULY



“The discovery of a particle consistent with the Higgs boson opens the way to more detailed studies, ... , and is likely to shed light on other mysteries of our Universe.”

Rolf Heuer, CERN D.G., Press Release July 4, 2012

“We are reaching into the fabric of the Universe at the level never done before... We are in the edge of a new exploration.”

Joe Incandela, CMS spokesperson, Press Conference, July 4, 2012



# THE MOST MEDIATIC SCIENTIFIC EVENT





# THE 2013 NOBEL PRIZE



KUNGL. VETENSKAPSK. AKADEMIEN  
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to François Englert and Peter W. Higgs for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.

## The Nobel Prize 2013 in Physics



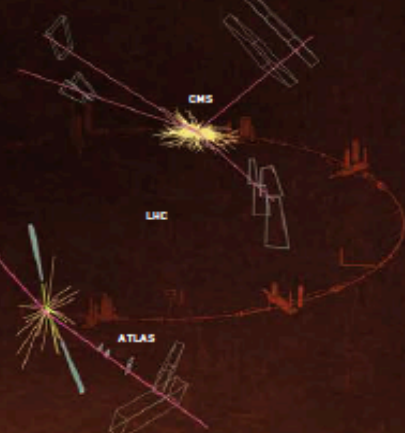
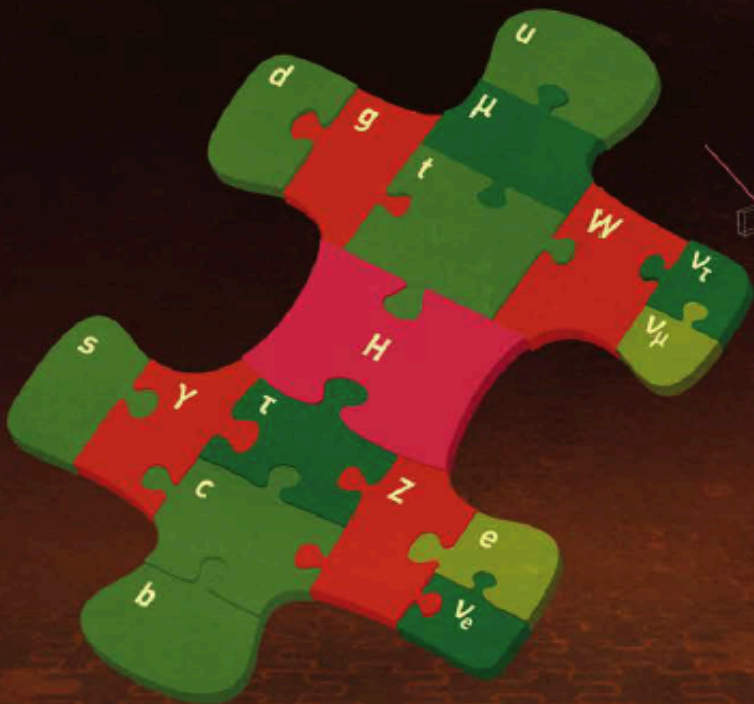
# Here, at last!

François Englert and Peter W. Higgs are jointly awarded the Nobel Prize in Physics 2013 for the theory of how particles acquire mass. In 1964, they proposed the theory independently of each other [Englert did so together with his now-deceased colleague Robert Brout]. In 2012, their ideas were confirmed by the discovery of a so-called Higgs particle, at the CERN laboratory outside Geneva in Switzerland.

The awarded mechanism is a central part of the Standard Model of particle physics that describes how the world is constructed. According to the Standard Model, everything from flowers and people to stars and planets – consists of just a few building blocks, matter particles, which are governed by forces mediated by force particles. And the entire Standard Model also rests on the existence of a special kind of particle, the Higgs particle.

The Higgs particle is a vibration of an invisible field that fills up all space. Even when our universe seems empty, this field is there. Had it not been there, nothing of what we know

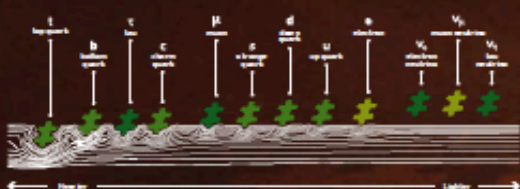
would exist because particles acquire mass only in contact with the Higgs field, and Higgs proposed the existence of the field on purely mathematical grounds, and the only way to discover it was to find the Higgs particle. The Nobel Laureates probably did not imagine that they would get to see the theory confirmed in their lifetimes. To do so required an enormous effort by physicists from all over the world. Almost half a century after the proposal was made, on July 4, 2012, the theoretical prediction could celebrate its biggest triumph, when the discovery of the Higgs particle was announced.



**ATLAS**  
In the collision, a short-lived Higgs particle is created, which decays into two muons (tracks in red) and two electrons (tracks in green).

**CMS**  
A short-lived Higgs particle is created in the collision and decays into four muons (tracks in red).

**The Particle Collider LHC**  
Protons – hydrogen nuclei – travel at almost the speed of light in opposite directions inside the circular tunnel, 27 kilometers long. The LHC [Large Hadron Collider] is the largest and most complex machine ever constructed by humans. In order to find a trace of the Higgs particle, two huge detectors, ATLAS and CMS, are capable of seeing the proton collision over and over again, 40 million times a second.



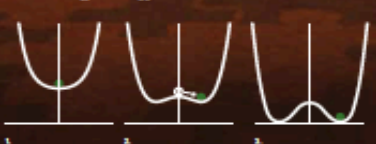
### ↑ The Field

Matter particles acquire mass in contact with the invisible field that fills the whole universe. Particles that are not affected by the Higgs field do not acquire mass, those that interact weakly become light, and those that interact strongly become heavy. For example, electrons acquire mass from the field, and if it suddenly disappeared, all matter would collapse as the suddenly massless electrons dispersed at the speed of light. The weak force carriers, W and Z particles, get their masses directly through the Higgs mechanism, while the origin of the neutrino masses still remains unclear.

### → Broken Symmetry

The Higgs mechanism relies on the concept of spontaneous symmetry breaking. Our universe was probably born symmetrical [1], with zero value for the Higgs field in the lowest energy state – the vacuum. But less than one billionth of a second after the Big Bang, the symmetry was broken spontaneously as the lowest energy state moved away [2] from the symmetrical zero-point. Since then, the value of the Higgs field in the vacuum state has been non-zero [3].

### Potential energy of the Higgs field



### The Puzzle

The Higgs particle [4] was the last missing piece in the Standard Model puzzle. But the Standard Model is not the final piece in the cosmic puzzle. One of the reasons for this is that the Standard Model only describes visible matter, accounting for one sixth of all matter in the universe. To find the rest – the mysterious so-called dark matter – is one of the reasons why scientists continue to chase unknown particles at CERN.



**François Englert**  
Brigden castle, born 1922 in Dierbeek, Belgium. Professor emeritus at Université Libre de Bruxelles, Brussels, Belgium.

**Peter W. Higgs**  
Dunelm castle, born 1929 in Newcastle upon Tyne, United Kingdom. Professor emeritus at University of Edinburgh, United Kingdom.

**FURTHER READING!** More information on the Nobel Prize in Physics 2013: <http://www.nobelprize.org>. See also the Nobel Prize press release: <http://www.nobelprize.org/press-releases/2013/09/04/2013-nobel-prize-physics>.  
 [1] <http://www.nobelprize.org/press-releases/2013/09/04/2013-nobel-prize-physics>.  
 [2] <http://www.nobelprize.org/press-releases/2013/09/04/2013-nobel-prize-physics>.  
 [3] <http://www.nobelprize.org/press-releases/2013/09/04/2013-nobel-prize-physics>.  
 [4] <http://www.nobelprize.org/press-releases/2013/09/04/2013-nobel-prize-physics>.



Lord Kelvin, 27 de Abril 1900

## Kelvin's dark clouds

Incapacity of detecting the Ether and the "Ultra-violet catastrophe"

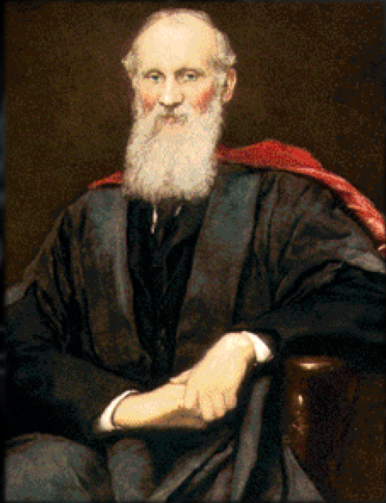
Physics would be limited to precision measurements of already-known quantities

**Kelvin couldn't be more wrong...**

Stephen Hawking (1998)

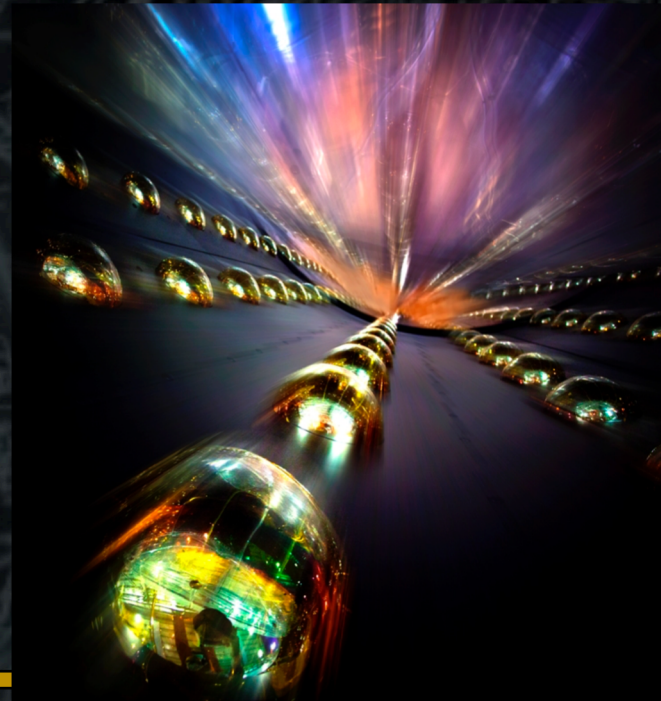
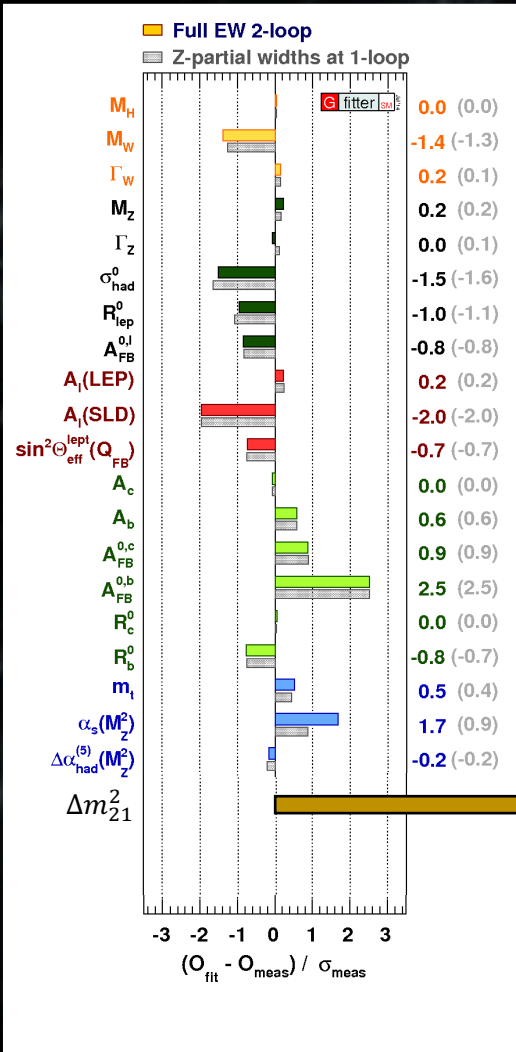
"WITH THE DISCOVERY OF THE HIGGS BOSON THERE'S NOTHING NEW TO BE DONE. JUST MEASURE THINGS WITH MORE PRECISION"

**IS HISTORY REPEATING ITSELF?**



# THE THEORY OF (ALMOST) EVERYTHING

HOW WELL DOES THIS THEORY BEHAVE WHEN YOU  
**NEUTRINO OSCILLATIONS**  
 COMPARE YOUR PREDICTIONS WITH EXPERIMENT?



2nd Lisbon Mini-School on Particle and Astroparticle Physics  
 6-8 February 2017  
 Hotel do Mar – Sesimbra

Hands on Neutrinos



# AND NOW WHAT?

# WHY PHYSICS BEYOND THE SM?

EXPERIMENTAL PROOFS THAT THERE MUST BE BSM PHYSICS



## BARYON ASYMMETRY OF THE UNIVERSE

TOO SMALL IN THE SM!!

**CHALLENGE**

### FERMIONS

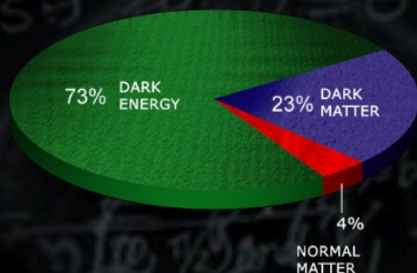
matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge	Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
$\nu_L$ lightest neutrino*	$(0-2) \times 10^{-9}$	0	<b>u</b> up	0.002	2/3
<b>e</b> electron	0.000511	-1	<b>d</b> down	0.005	-1/3
$\nu_M$ middle neutrino*	$(0.009-2) \times 10^{-9}$	0	<b>c</b> charm	1.3	2/3
$\mu$ muon	0.106	-1	<b>s</b> strange	0.1	-1/3
$\nu_H$ heaviest neutrino*	$(0.05-2) \times 10^{-9}$	0	<b>t</b> top	173	2/3
$\tau$ tau	1.777	-1	<b>b</b> bottom	4.2	-1/3

## NEUTRINO MASSES

NEUTRINOS ARE MASSLESS IN THE SM

**CHALLENGE**



## DARK MATTER PROBLEM

NO DARK MATTER CANDIDATE IN THE SM

**CHALLENGE**





# Chameleons of space



Takaaki Kajita in Japan and Arthur B. McDonald in Canada were key scientists in two large research groups that discovered that neutrinos change identities, which requires that neutrinos have mass. The discovery has changed our understanding of the innermost workings of matter and may prove crucial to our view of the universe.

The discovery of neutrino identity changes has resolved a neutrino puzzle that physicists had wrestled with for decades. Compared to theoretical calculations of the number of neutrinos, up to two-thirds of them were missing in measurements performed on Earth. The two research groups discovered that the neutrinos had changed identities, which led to the conclusion that neutrinos must have some mass, however small. This discovery was historic for particle physics, as its Standard Model requires neutrinos to be massless. Thus new physics is now needed. The Earth is constantly bombarded by neutrinos. Many are created in reactions

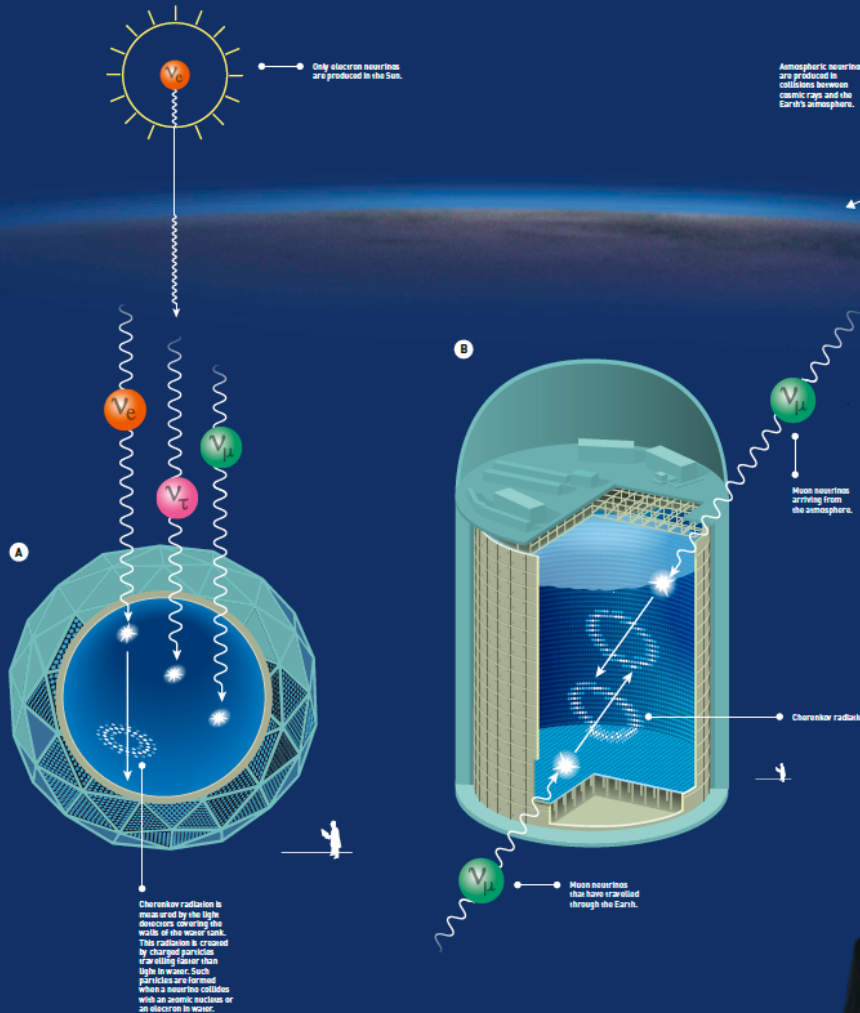
between cosmic radiation and the Earth's atmosphere. Others are produced in nuclear reactions inside the Sun. Thousands of billions of neutrinos stream through our bodies every second. The combined weight of neutrinos is estimated to be roughly equal to that of all visible stars in the universe. Hardly anything can stop the neutrinos; they are amongst nature's most elusive elementary particles. Experiments are continuing to uncover the all but hidden world of neutrinos. New discoveries about their deepest secrets are expected to change our current understanding of the history, structure and future of the universe.

There are three types of neutrinos: electron, muon and tau neutrinos. Each type is a mixture of three mass states.



**Neutrino oscillations**  
Neutrinos change identities as they travel through space. Quantum physics is required to explain this magic, where the neutrinos are represented by superposed waves that correspond to neutrino states with different masses. When the neutrinos travel, these waves go out of phase and are superposed in

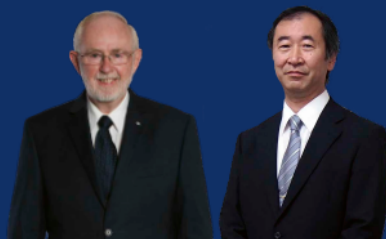
different ways. The superposition in any given location yields the probability of which type of neutrino is most likely to be found there. These probabilities vary from one location to another – oscillate – and the neutrinos appear in their various identities. This is only possible if neutrinos have mass.



- A Sudbury Neutrino Observatory**  
The detector measured neutrinos from the Sun. Its tank, filled with heavy water, was placed two kilometres under the surface of the Earth. Signals from all three types of neutrinos were registered in the tank. The sum of the neutrinos corresponded to what was expected, but there were not enough electron neutrinos – they must have changed identity.
- B Super-Kamiokande**  
The detector measured atmospheric neutrinos. Its tank, filled with water, was placed one kilometre under the surface of the Earth. The muon neutrinos that arrived straight at Super-Kamiokande from the atmosphere were more numerous than those that arrived at the detector after passing through the Earth. The muon neutrinos that travelled further thus had time to change identity and become another type of neutrino.

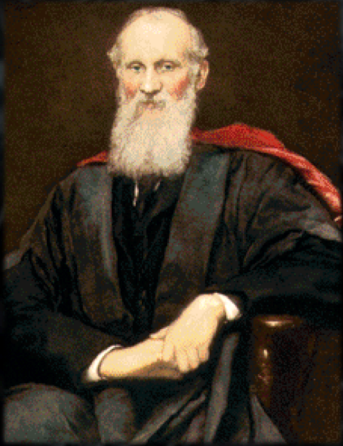
**Arthur B. McDonald**  
Canadian citizen. Born 1943 in Sydney, Canada. Professor Emeritus at Queen's University, Kingston, Canada.

**Takaaki Kajita**  
Japanese citizen. Born 1969 in Higashimatsuyama, Japan. Director of Institute for Cosmic Ray Research and Professor at University of Tokyo, Kashiwa, Japan.



# WHAT WOULD KELVIN SAY NOWADAYS?

“Twentieth first-Century Clouds over the electroweak theory”



“THE BEAUTY AND CLARITY OF THE ELECTROWEAK THEORY IS OBSCURED BY THREE CLOUDS”

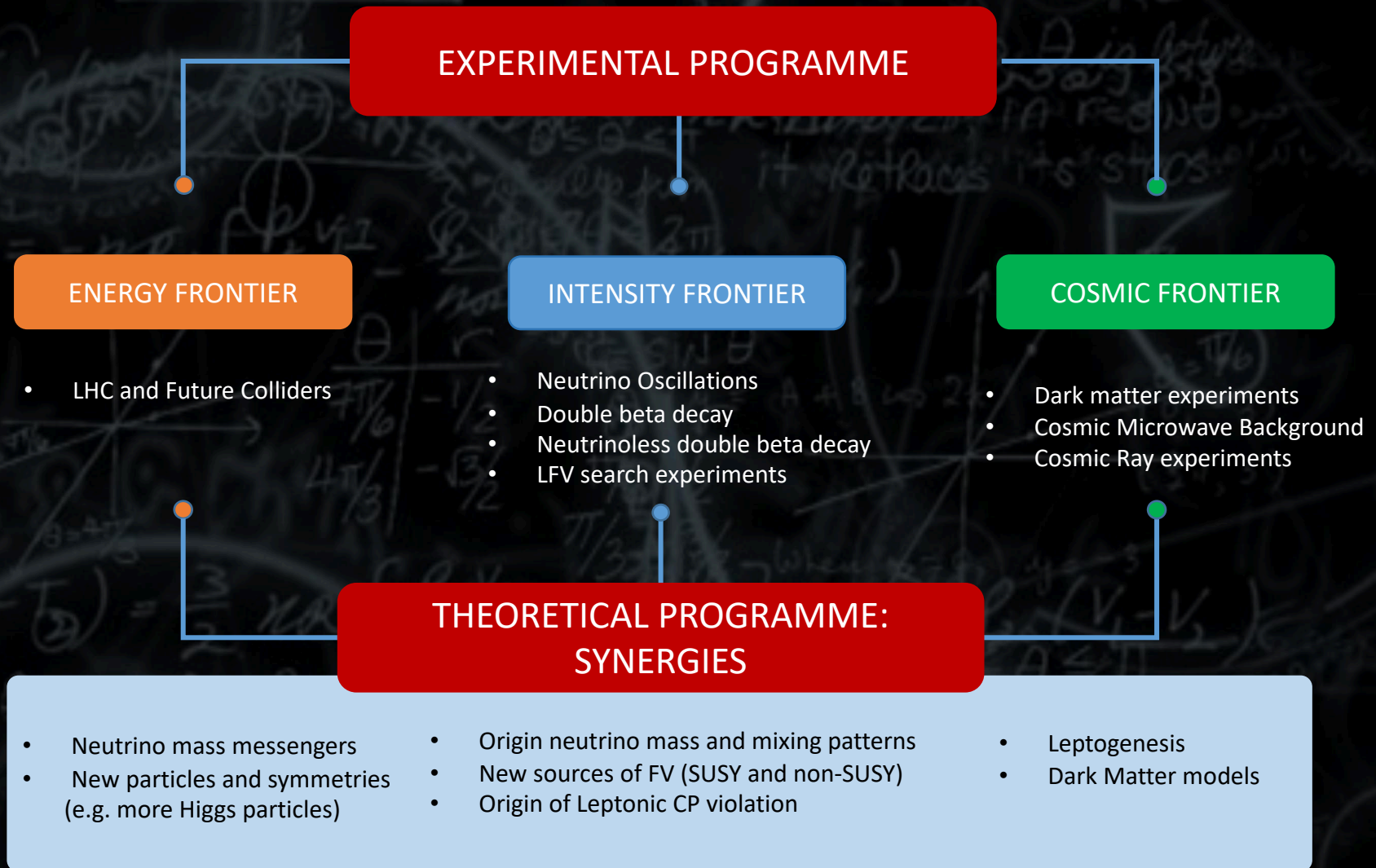
- NEUTRINO MASSES, DARK MATTER AND THE MATTER-ANTIMATTER ASYMMETRY

- WHY 3 FAMILIES?;
- HIERARCHY PROBLEM;
- FERMION MASS PROBLEM;
- WHY ARE NEUTRINOS MUCH LIGHTER THAN THE OTHER FERMIONS?
- ARE ELEMENTARY PARTICLES REALLY ELEMENTARY?
- SUPERSYMMETRY?
- NEW INTERACTIONS?

**CHALLENGE**



# FUTURE CHALLENGES



The background is a dark grey surface covered with faint, white mathematical sketches and equations. These include various trigonometric formulas like  $\sin \theta$ ,  $\cos \theta$ , and  $\frac{1}{2} \cos \theta$ , as well as vector diagrams, coordinate axes, and complex algebraic expressions. Some equations are underlined, such as  $\underline{\underline{P_2(V_2 - V_1)}}$  and  $\underline{\underline{P_2(V_1 - V_2)}}$ . There are also handwritten-style notes like "Because  $\theta$  is between  $0 \leq \theta \leq \pi$  it retraces its steps." and "begin" near a coordinate system.

# THANKS