The building blocks of the SM





FILIPE JOAQUIM

IST Dep. de Física e CFTP, Lisboa, Portugal

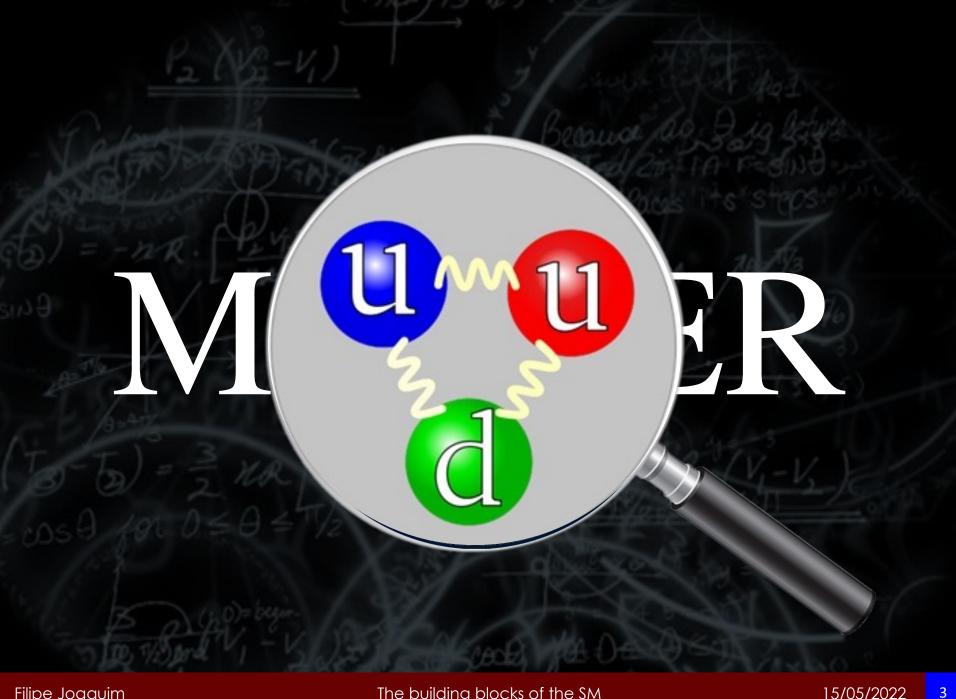


8th Lisbon Mini-School in Particle and Astroparticle Physics

15 May 2023



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.



THE STANDARD MODEL OF

FUNDAMENTAL PARTICLES AND INTERACTIONS

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

Quarks spin = 1/2 Leptons spin = 1/2 Mass Electric Electric Flavor Flavor Mass GeV/c² charge charge GeV/c2 $(0-2)\times10^{-9}$ **U** up 0.002 2/3 e electron 0.000511 -1 **d** down 0.005 -1/3 $(0.009-2)\times10^{-9}$ C charm 1.3 2/3 μ muon 0.106 -1 S strange 0.1 -1/3 $v_{\rm H}$ heaviest 0 t top 173 2/3

*See the neutrino paragraph below.

au tau

Neutrinos

Matter and Antimatter

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

b bottom

4.2

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ 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^2 (remember $E = mc^2$) where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c² = 1.67×10^{-27} kg.

-1/3

Atom

Structure within the Atom



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

	ЪС	3014		
Jnified Electroweak spin = 1				
Name	Name Mass GeV/c ²			
γ photon	0	0		
W-	80.39	-1		
W ⁺ W bosons	80.39	+1		
Z ⁰ Z boson	91.188			

	Strong (color) spin = 1				
ď	Name	Mass GeV/c ²	Electric charge		
	g gluon	0	0		
	Higgs Boson spin = 0				
	Name	Mass	Electric		

126

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

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.

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.

Н

Higgs

Two types of hadrons have been observed in nature mesons qq and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton (uud), 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 π^+ (ud), kaon K⁻ (sū), and B⁰ (db).



entire atom would be about 10 km across. Properties of the Interactions

The strengths of the interactions (force

If the proton and neutrons in this picture were

10 cm across, then the quarks and electrons

would be less than 0.1 mm in size and the

Property	Gravitational Interaction	Weak Interaction _{(Electro}	Electromagnetic _{oweak)} 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	γ	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

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 , γ , and η_c = $c\bar{c}$ but not K^0 = $d\bar{s}$) are their own antiparticles.

Neutrinos are produced in the sun, supernovae, reactors, accelerator

described as one of three neutrino flavor states $\nu_{\rm e}, \, \nu_{\rm tr}, \,$ or $\nu_{\rm tr},$ labelled by the type of charged lepton associated with its production. Each is a defined

exploration of the properties of neutrinos may yield powerful clues to puzzles

about matter and antimatter and the evolution of stars and galaxy structures.

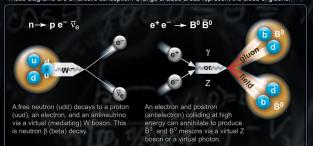
quantum mixture of the three definite-mass neutrinos $\nu_{\text{L}}, \nu_{\text{M}},$ and ν_{H} for

which currently allowed mass ranges are shown in the table. Further

collisions, and many other processes. Any produced neutrino can be

Particle Processes

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





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).

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ELEMENTARY PARTICLES

FERMIONS

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

Leptons spin =1/2					
Flavor	Mass GeV/c ²	Electric charge			
\$\mathcal{V}_L\$ lightest neutrino*e electron	(0-2)×10 ⁻⁹	0			
electron	0.000511	–1			
$\mathcal{V}_{\mathbf{M}}$ middle neutrino*	$(0.009-2)\times10^{-9}$	0			
μ muon	0.106	–1			
$\mathcal{V}_{\mathbf{H}}$ heaviest neutrino*	(0.05-2)×10 ⁻⁹	0			
au tau	1.777	-1			

A PARTICULAR STATE OF THE PARTY						
	Quar	KS spin	=1/2			
Flavor		Approx. Mass GeV/c ²	Electric charge			
u	up	0.002	2/3			
d	down	0.005	-1/3			
С	charm	1.3	2/3			
s	strange	0.1	-1/3			
t	top	173	2/3			
b	bottom	4.2	-1/3			





INTERACTIONS AND THEIR MEDIATORS

Property	Gravitational Interaction	Weak Interaction _{(Electro}	Electromagnetic oweak) 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	γ	Gluons
Strength at $\int_{0}^{10^{-18}}$ m	10-41	0.8	1	25
3×10 ⁻¹⁷ m	10 ⁻⁴¹	10-4	1	60

BOSONS

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

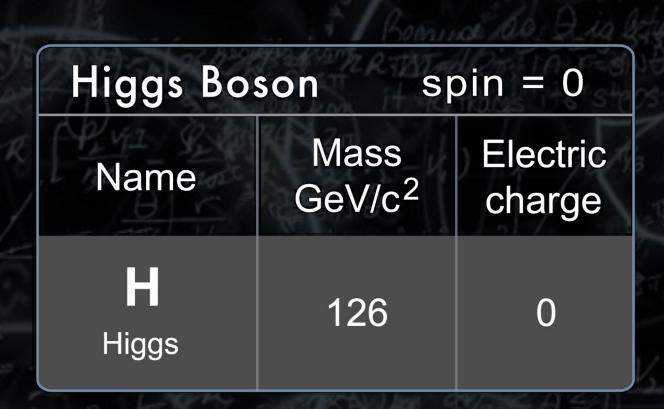
05				
Unified Electroweak spin = 1				
Mass GeV/c ²	Electric charge			
0	0			
80.39	-1			
80.39	+1			
91.188	0			
	Mass GeV/c ² 0 80.39 80.39			

Strong (c	olor) sp	oin = 1
Name	Mass GeV/c ²	Electric charge
g gluon	0	0



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

THE NEWEST BOSON



THE ONLY KNOWN SPINLESS ELEMENTARY PARTICLE

(NON) ELEMENTARY PARTICLES

HADROZY

Baryons qqq and Antibaryons qqq Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
р	proton	uud	1	0.938	1/2
p	anti- proton	ūūd	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	SSS	-1	1.672	3/2

Mesons qq

Mesons are bosonic hadrons.

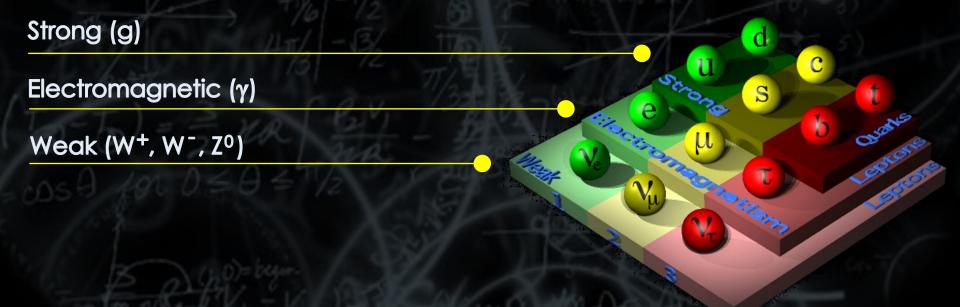
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
4 +	pion	ud	+1	0.140	0
K-	kaon	sū	-1	0.494	0
$ ho^+$	rho	ud	+1	0.770	1
B ⁰	B-zero	db	0	5.279	0
η_{c}	eta-c	cc	0	2 .980	0

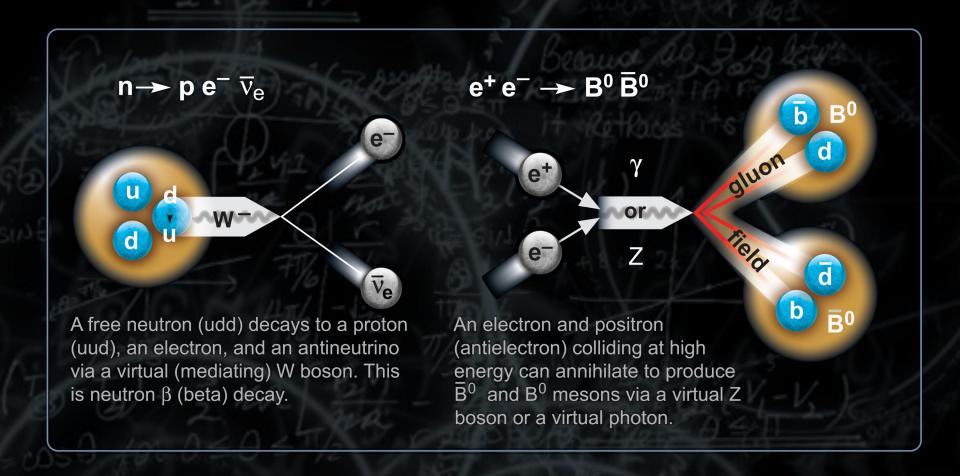
Gernot will tell you more about hadrons and the physics of the strong interaction

PARTICLES AND INTERACTIONS (SUMMARY)

Property	Gravitational Interaction	Weak Interaction _{(Electro}	Electromagnetic oweak) 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	γ	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



PARTICLE PROCESSES

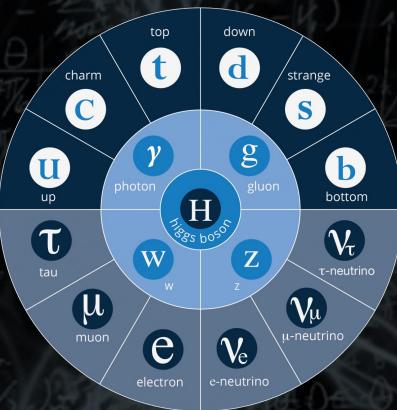


WHAT ARE THE RULES OF THE GAME?

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

THE STANDARD MODEL

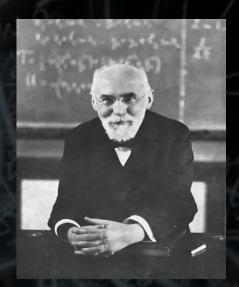
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SYMMETRY



Galileo



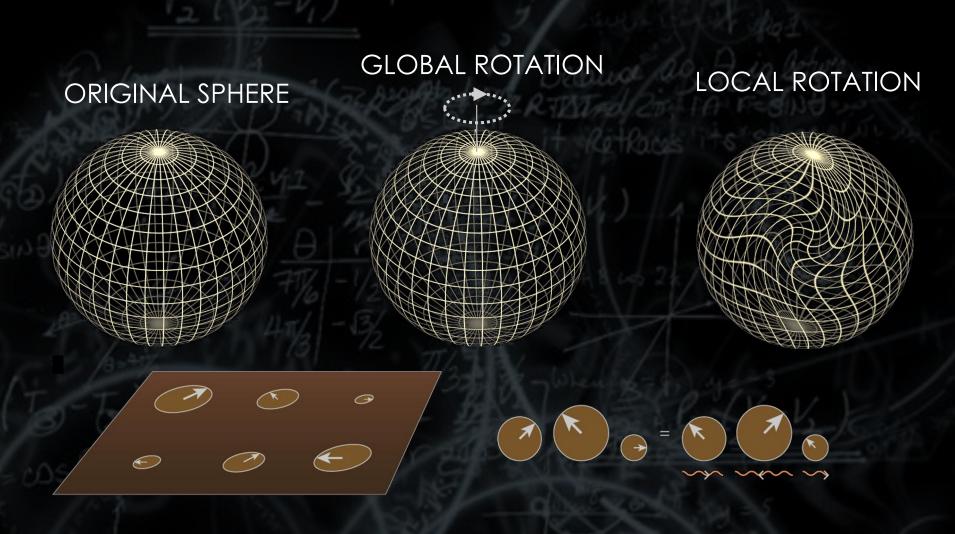
Lorentz

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

- QUANTUM FIELD THEORY (QFT, TC 4TH YEAR MEFT)
 - GAUGE THEORIES (MS, 4/5TH YEAR MEFT)
 - QCD (4/5TH YEAR MEFT)

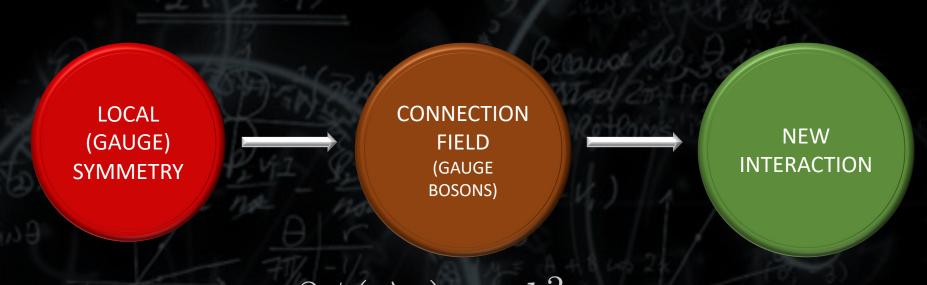
* And to be able to construct your own theories.

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: $\psi
ightarrow e^{i\alpha} \psi$ Invariant

Local Transformation: $\psi
ightarrow e^{ilpha(ec{r},t)}\psi$ Not invariant

EXERCISE

STANDARD MODEL - THE RECIPE

THE SYMMETRY GROUP OF THE STANDARD MODEL IS:

$SU(2)_{1} \times U(1)_{2}$









Glashow

Weinberg

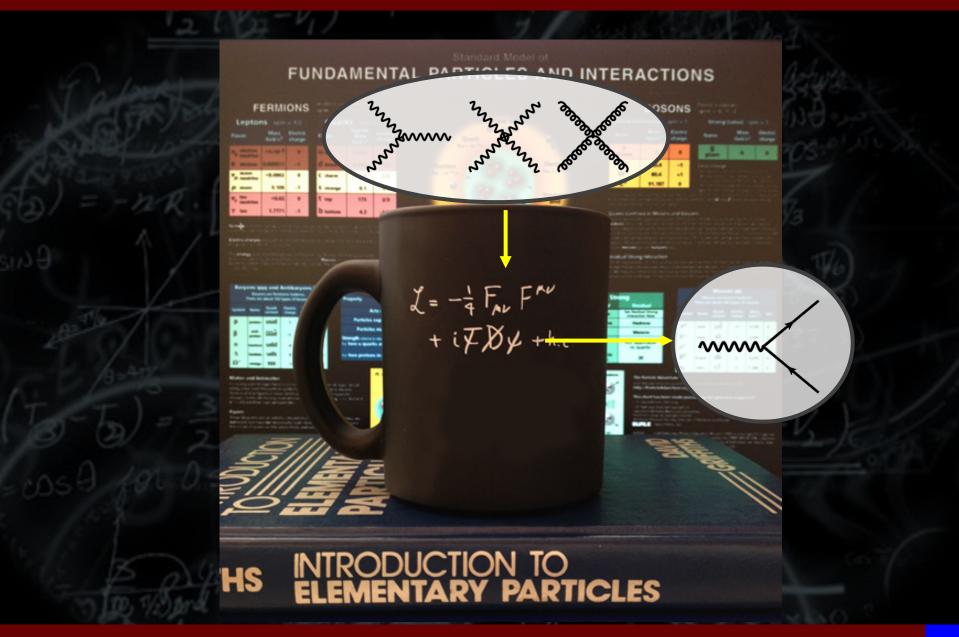
Salam

- 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

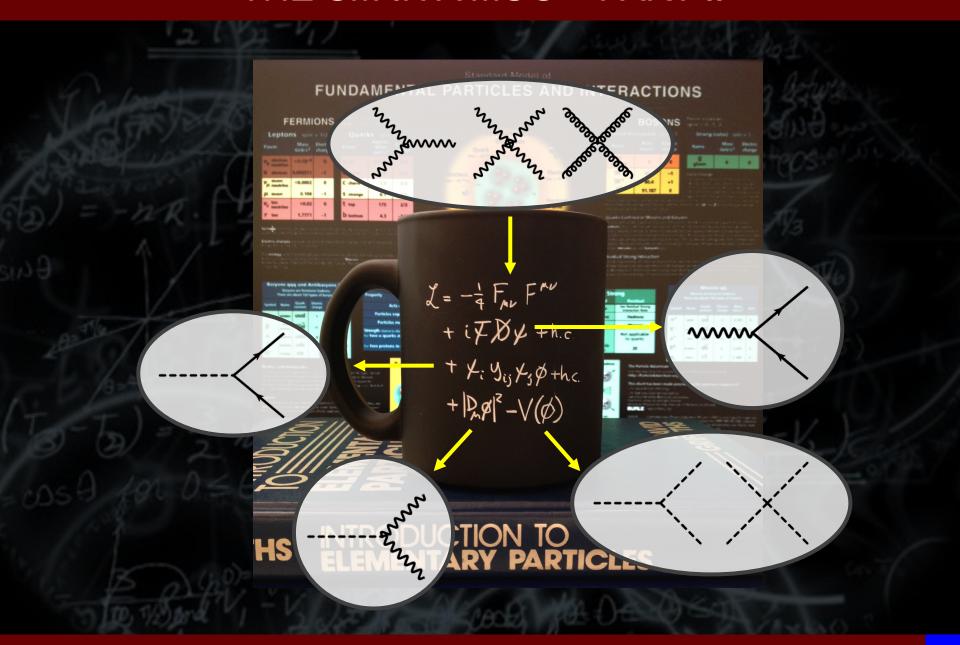
Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble and 't Hooft



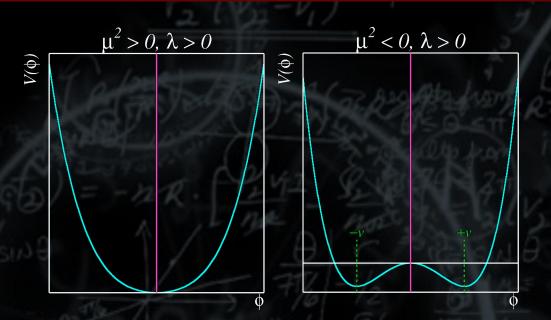
How does the ABEGHHK'tH mechanism work?

THE HIGGS FIELD...

THE SM IN A MUG - PART II



HIGGS MECHANISM



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

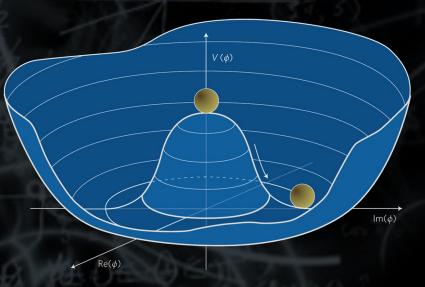
Essential for the Higgs mechanism to work.

The symmetry is broken spontaneously!!

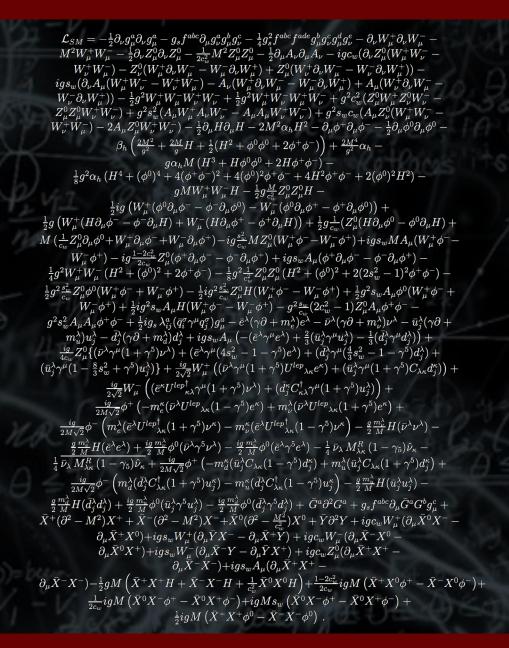
The weak gauge bosons (W e Z) and fermions acquire mass!

AND... THE PHOTON REMAINS

MASSLESS!!!



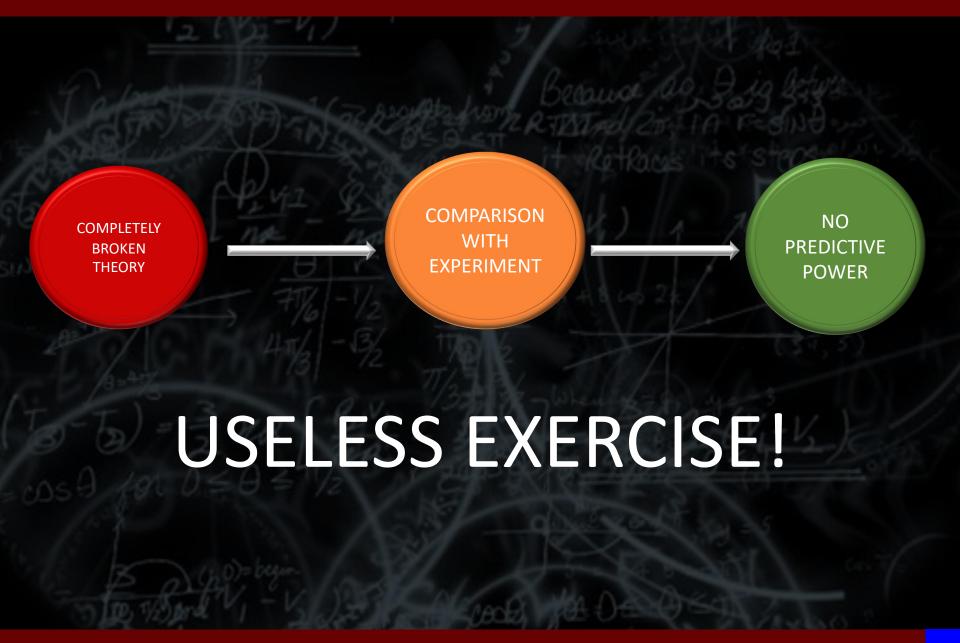
HIGGS MECHANISM



MAKE IT INVARIANT TO BREAK IT AFTER ??!!



MAKE IT INVARIANT TO BREAK IT AFTER ??!!



MAKE IT INVARIANT TO BREAK IT AFTER ??!!

SOME PREDICTIONS:

$$M_z \cos \theta_w = M_W \cdot \sin^2 \theta_W = 1 - M_W^2 / M_z^2$$

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

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

 $M_{W} = 80.385 \pm 0.015 \text{ GW}$ $M_{Z} = 91.1876 \pm 0.086 \text{ GW}$



THE GARGAMELLE DETECTOR



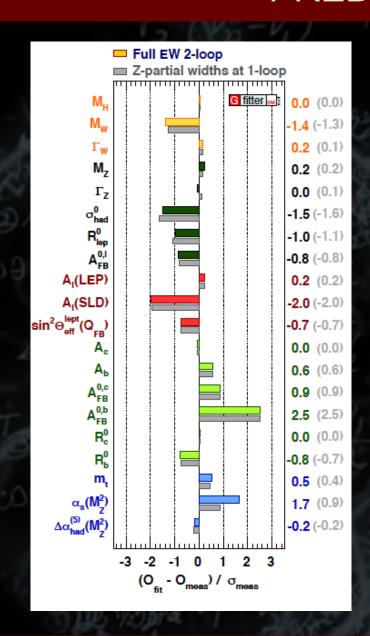


The 1984 Physics Nobel Prize was awarded to Rubbia and Van De Meer

"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;

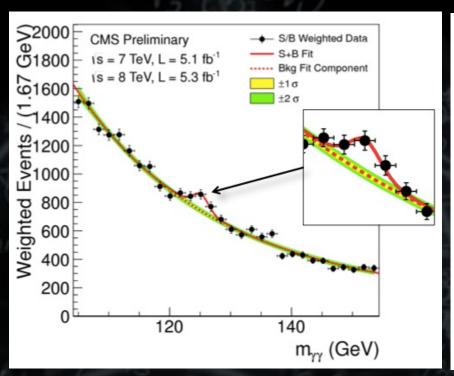


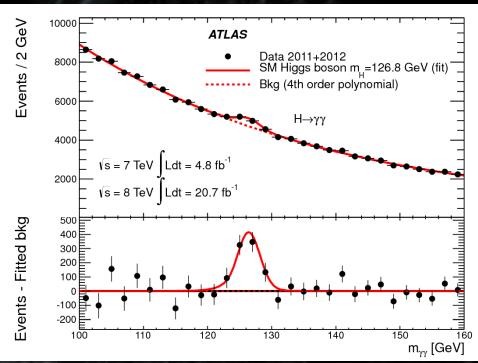
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, the prediction of the weak neutral current".

Until the 4th of July 2012, electroweak symmetry breaking was still to be confirmed.

Until...

BORN ON THE 4TH 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



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.

also rears on the existence of a special kind of carticle, the Pilgap particle. The Higgs puricle is a vibration of an revisible field that fills up all apace. Even when or universe seems empty, this field is there.

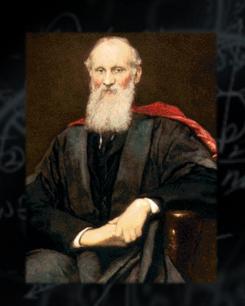
effort by physicists from all over the world. Almost half a century after the proposal was made, on July 6, 2012, the theoretical prediccould celebrate its biggest triumph, when the discovery of the Higgs particle was announce





Nineteenth-Century Clouds over the Dynamical Theory of Heat and Light"

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...

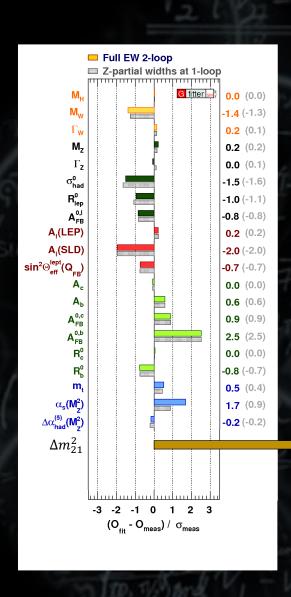


Stephen Hawking (1998)

"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

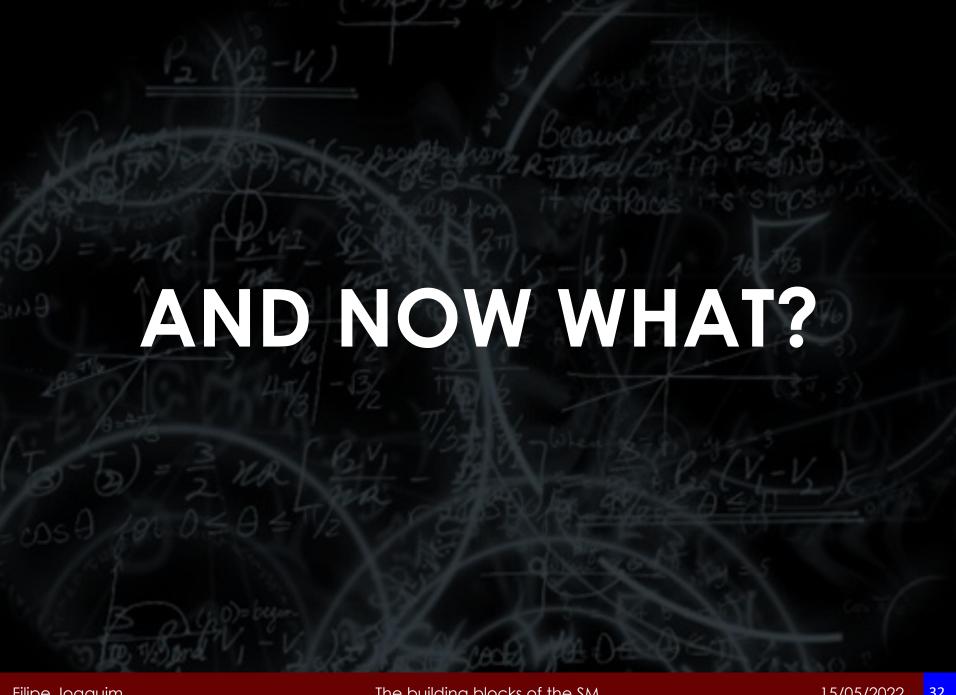


HOW WELL DOES THIS THEORY BEHAVE WHEN YOU COMPARE YOUR PREDICTIONS WITH EXPERIMENT?



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

Hands on Neutrinos



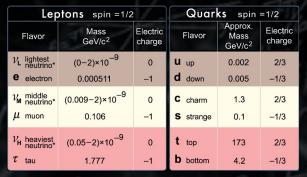
WHY PHYSICS BEYOND THE SM?

EXPERIMENTAL PROOFS THAT THERE MUST BE BSM PHYSICS

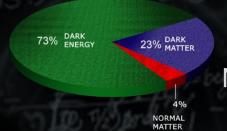


BARYON ASYMMETRY OF THE UNIVERSE
TOO SMALL IN THE SM!!

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



NEUTRINO MASSES
NEUTRINOS ARE MASSLESS IN THE SM



DARK MATTER PROBLEM

NO DARK MATTER CANDIDATE IN THE SM

Chameleons of space

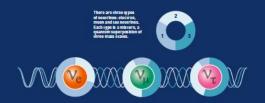
Takaaki Kajita in Japan and Arthur B. McDonald in Canada were key scientists in two large research groups that discovered that neutrinos change identities, which requires that neutrinos have mass. The discovery has changed our understanding of the innermost workings of matter and may prove crucial to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

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.

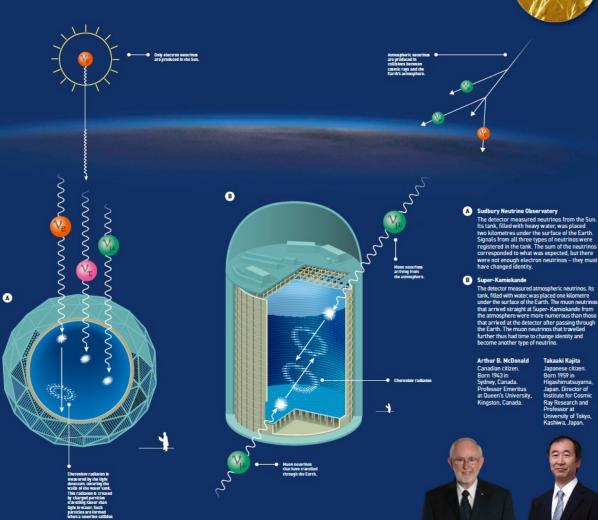
Hardly anything can stop the neutrinos; they are amongst nature's most elusive elementary particles. Experiments are continuing to uncover the all but hidden world of neutrinos. New discoveries about their deepest secrets are expected to change our current understanding of the history, structure and



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



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?



FUTURE CHALENGES

