The building blocks of the SM

DF DEPARTAMENTO DE FÍSICA TÉCNICO LISBOA

CFTP Centro de Física Teórica de Partículas

FILIPE JOAQUIM

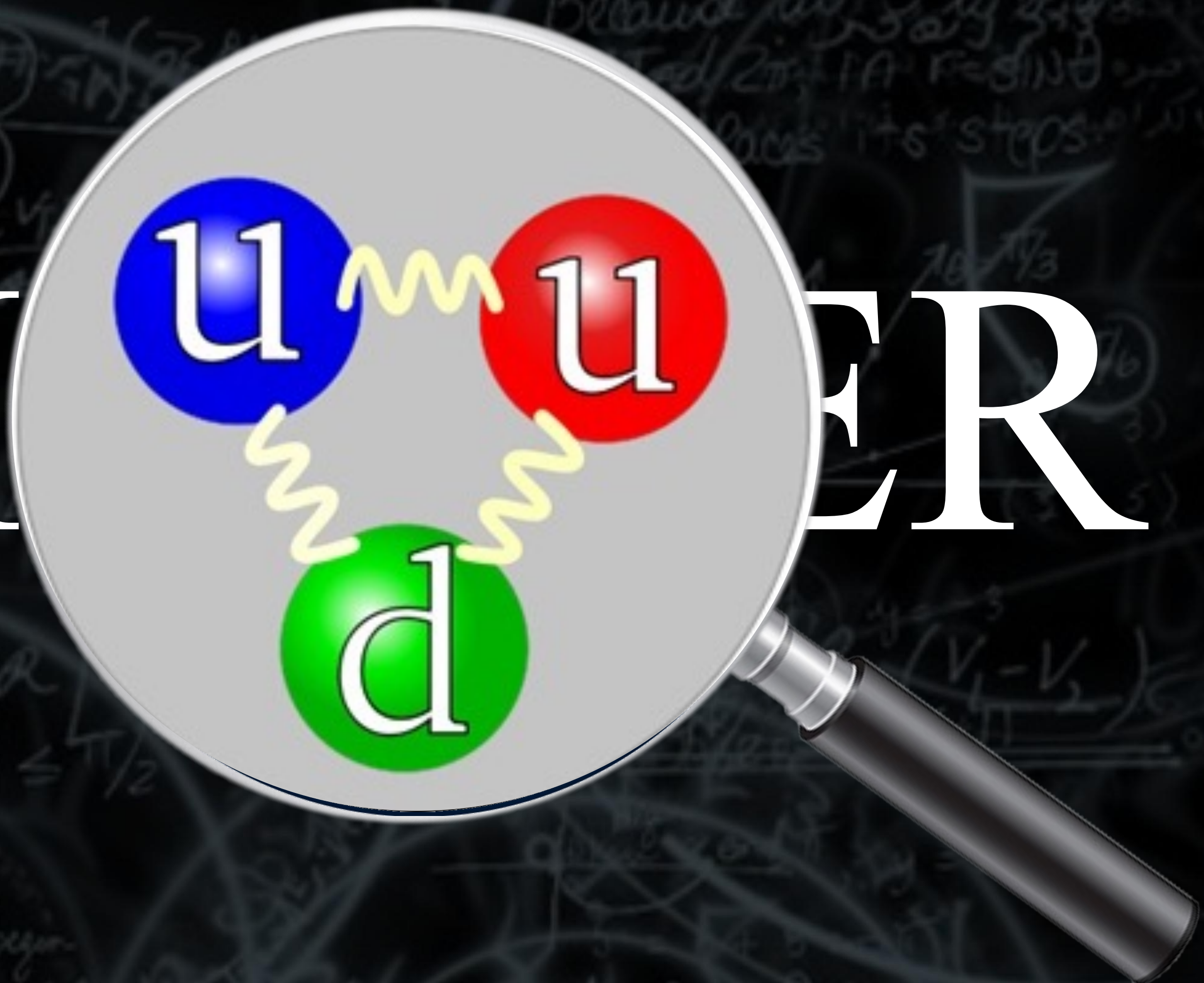
IST Dep. de Física e CFTP , Lisboa, Portugal

9th Lisbon Mini-School in Particle and Astroparticle Physics

5 February 2024

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 ER



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

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
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 ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

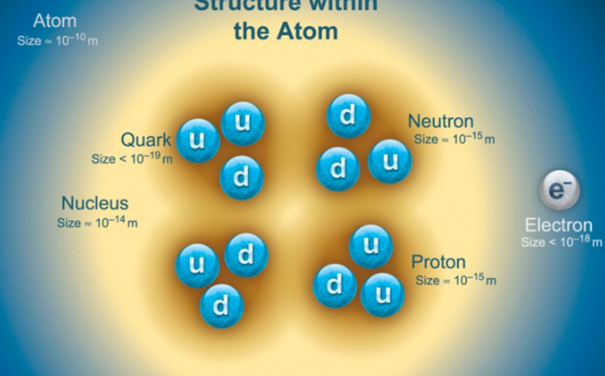
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

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 $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-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 ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos ν_L, ν_M, and ν_H 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, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom



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 entire atom would be about 10 km across.

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

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ 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^2	Electric charge
g gluon	0	0

Higgs Boson spin = 0

Name	Mass GeV/c^2	Electric charge
H 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 π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), and B^0 ($d\bar{b}$).

Learn more at ParticleAdventure.org

Properties of the Interactions

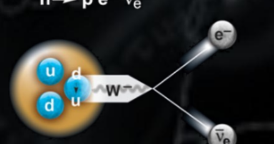
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

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)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Particle Processes

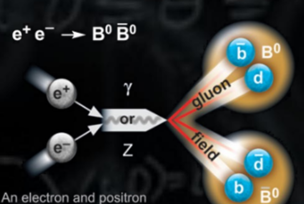
These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.

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



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 $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

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.

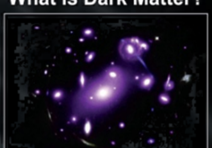
Why is the Universe Accelerating?

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).

U.S. Department of Energy, U.S. National Science Foundation, & Lawrence Berkeley National Laboratory.

ELEMENTARY PARTICLES

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

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

CHALLENGE

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

CHALLENGE

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	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ 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^2	Electric charge
g gluon	0	0

ARE THERE NEW INTERACTIONS/GAUGE BOSONS?

(We have no idea…)

THE NEWEST (fundamental) BOSON

Higgs Boson	spin = 0	
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

THE ONLY KNOWN SPINLESS ELEMENTARY PARTICLE

HADRONS

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 GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–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 $q\bar{q}$

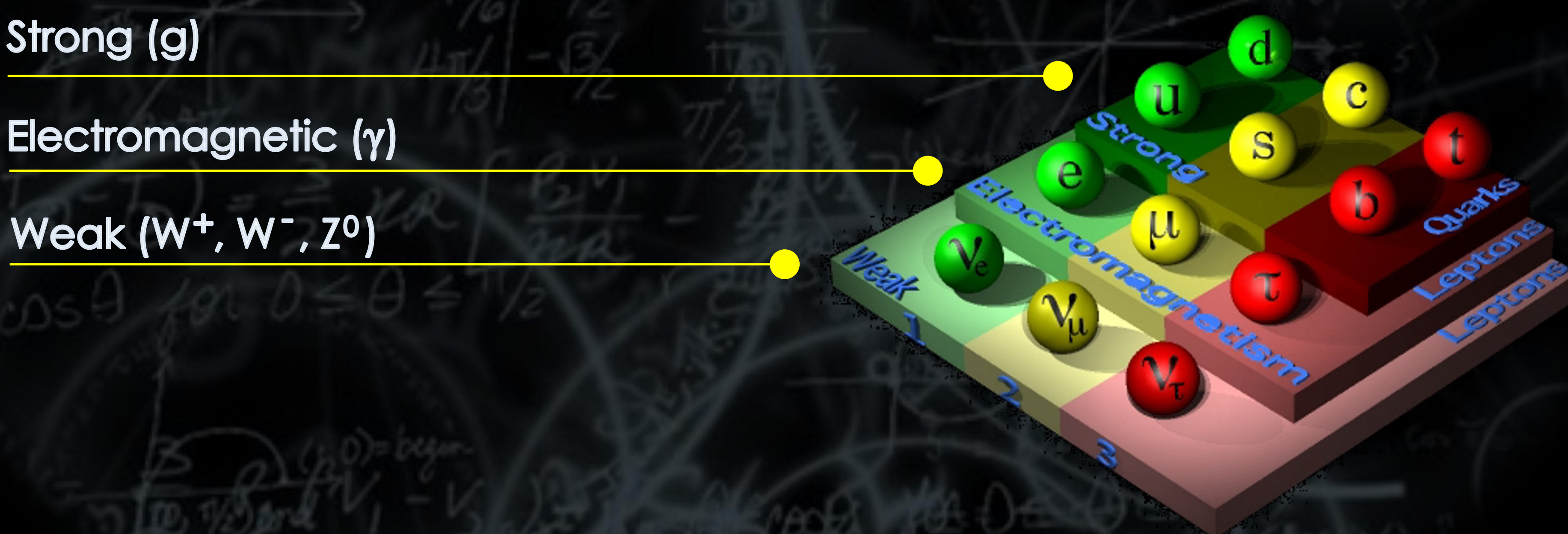
Mesons are bosonic hadrons.
There are about 140 types of mesons.

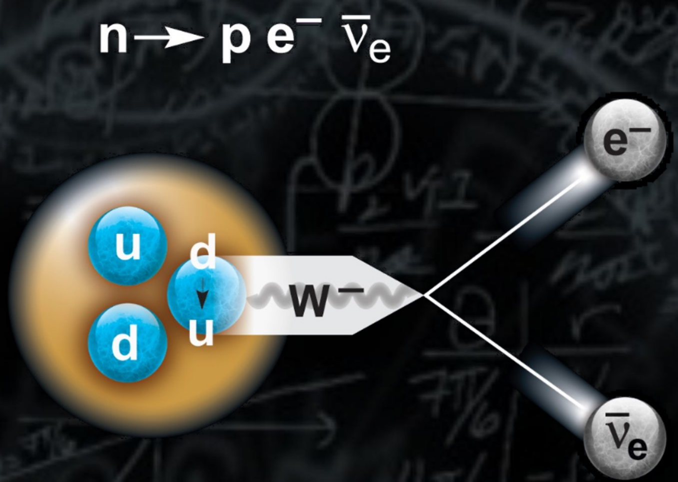
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

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

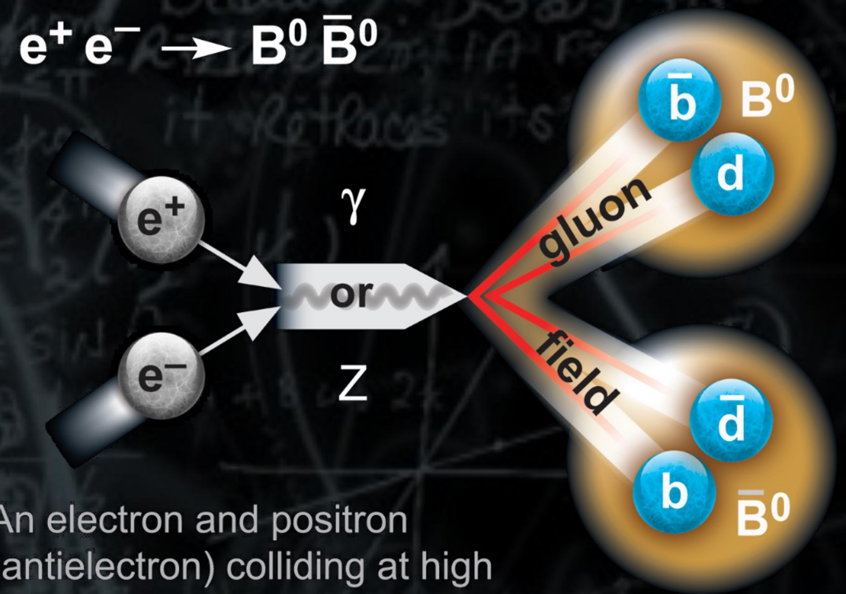
PARTICLES AND INTERACTIONS (SUMMARY)

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	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 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60





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.

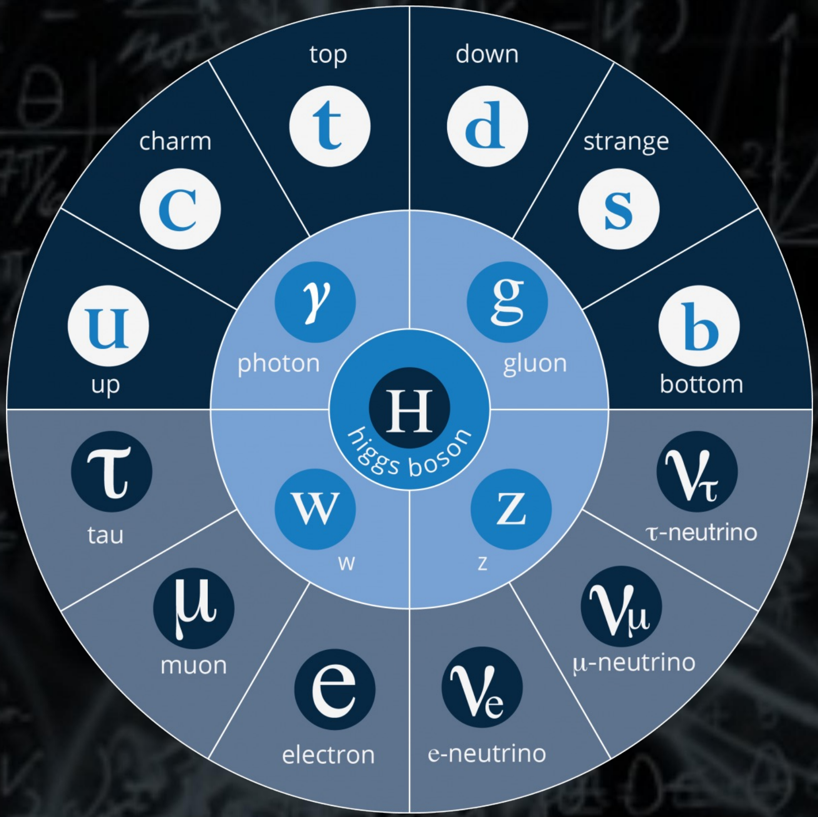


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

WHAT ARE THE RULES OF THE GAME?

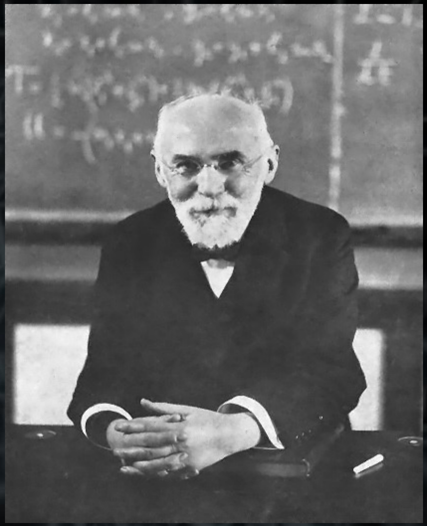
WHAT ARE THE BASIC PRINCIPLES WHICH ALLOW US TO PREDICT HOW NATURE WORKS @ ITS MOST FUNDAMENTAL LEVEL?

THE STANDARD MODEL (SM)



SYMMETRY

Galileo



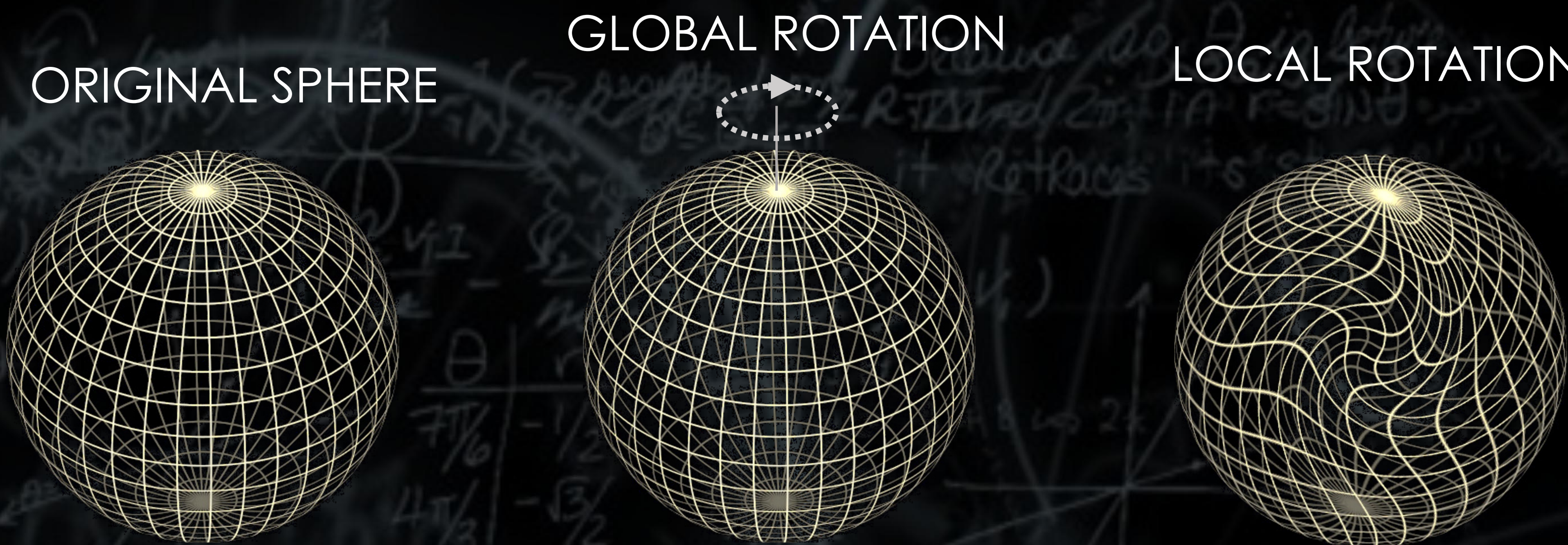
Lorentz

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

- QUANTUM FIELD THEORY (QFT - MEFT)
- GAUGE THEORIES (SM, MEFT)
- QCD (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

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

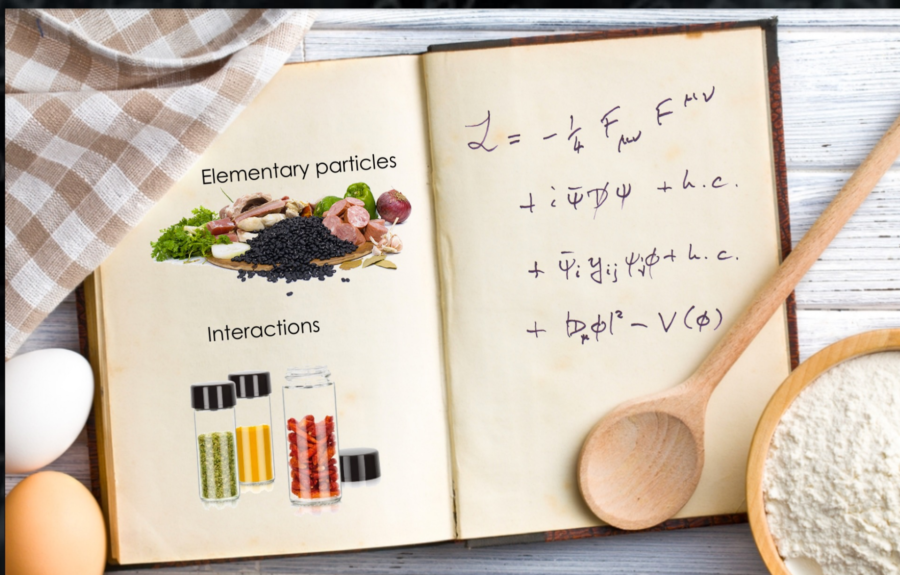
Global Transformation: $\psi \to e^{i\alpha}\psi$ Invariant

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

EXERCISE

THE SYMMETRY GROUP OF THE STANDARD MODEL IS:

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



Glashow

Weinberg

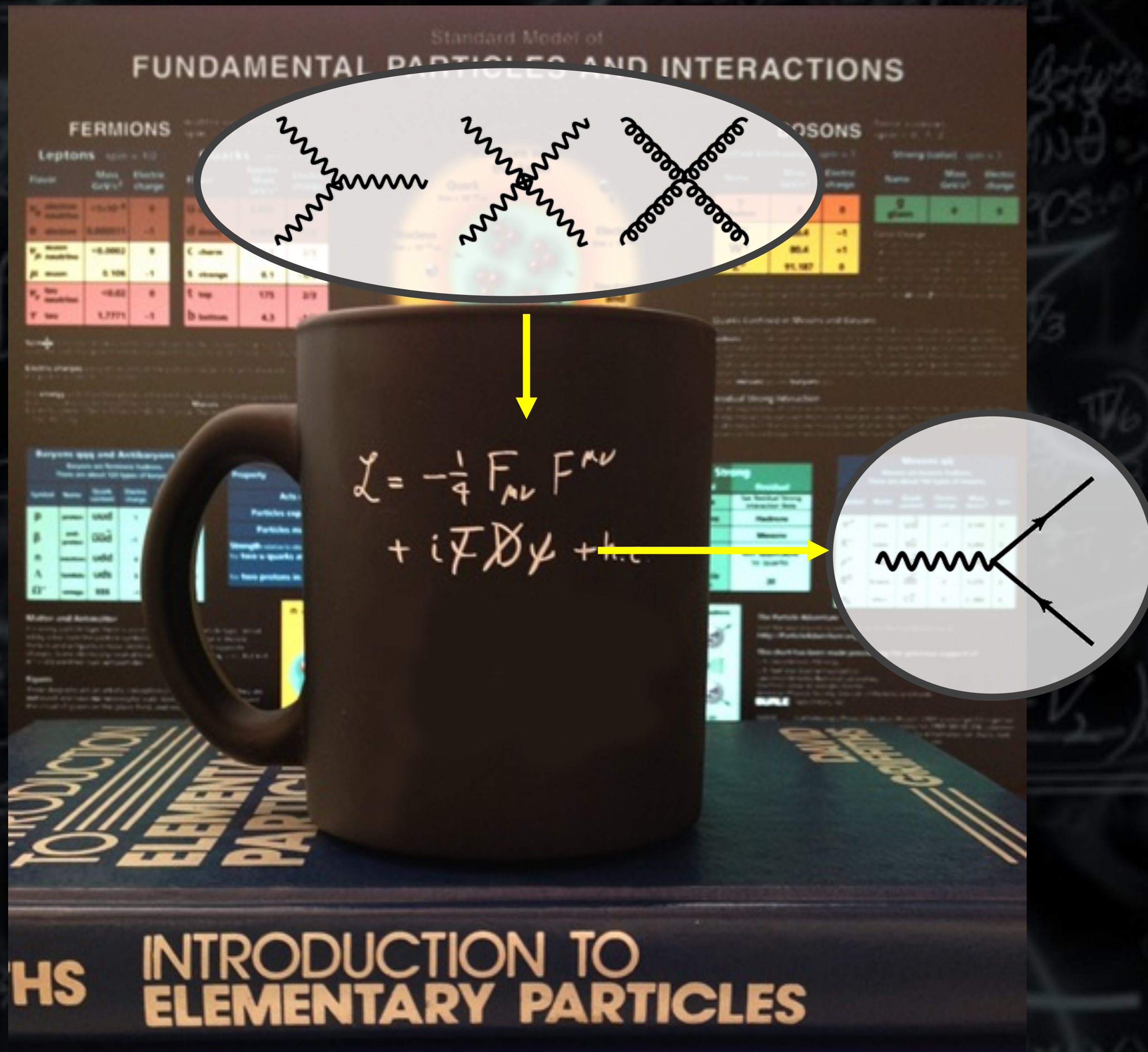
Salam

1) Place the elementary fermions in the representations of the group

2) Write all possible terms in the Lagrangean which are invariant under gauge transformations by introducing as many gauge fields as needed.

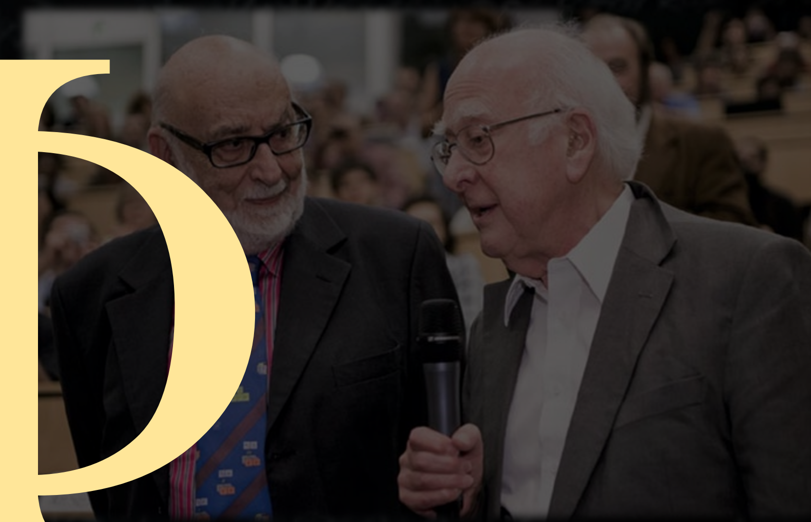
RESULT: THEORY WHICH DESCRIBES (ELECTROWEAK AND STRONG) INTERACTIONS OF QUARKS, LEPTONS AND GAUGE BOSONS

BUT… ALL PARTICLES ARE MASSLESS!


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
FERMIONS
Leptons
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
INTRODUCTION TO ELEMENTARY PARTICLES

The ABEGHHK'tH mechanism

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

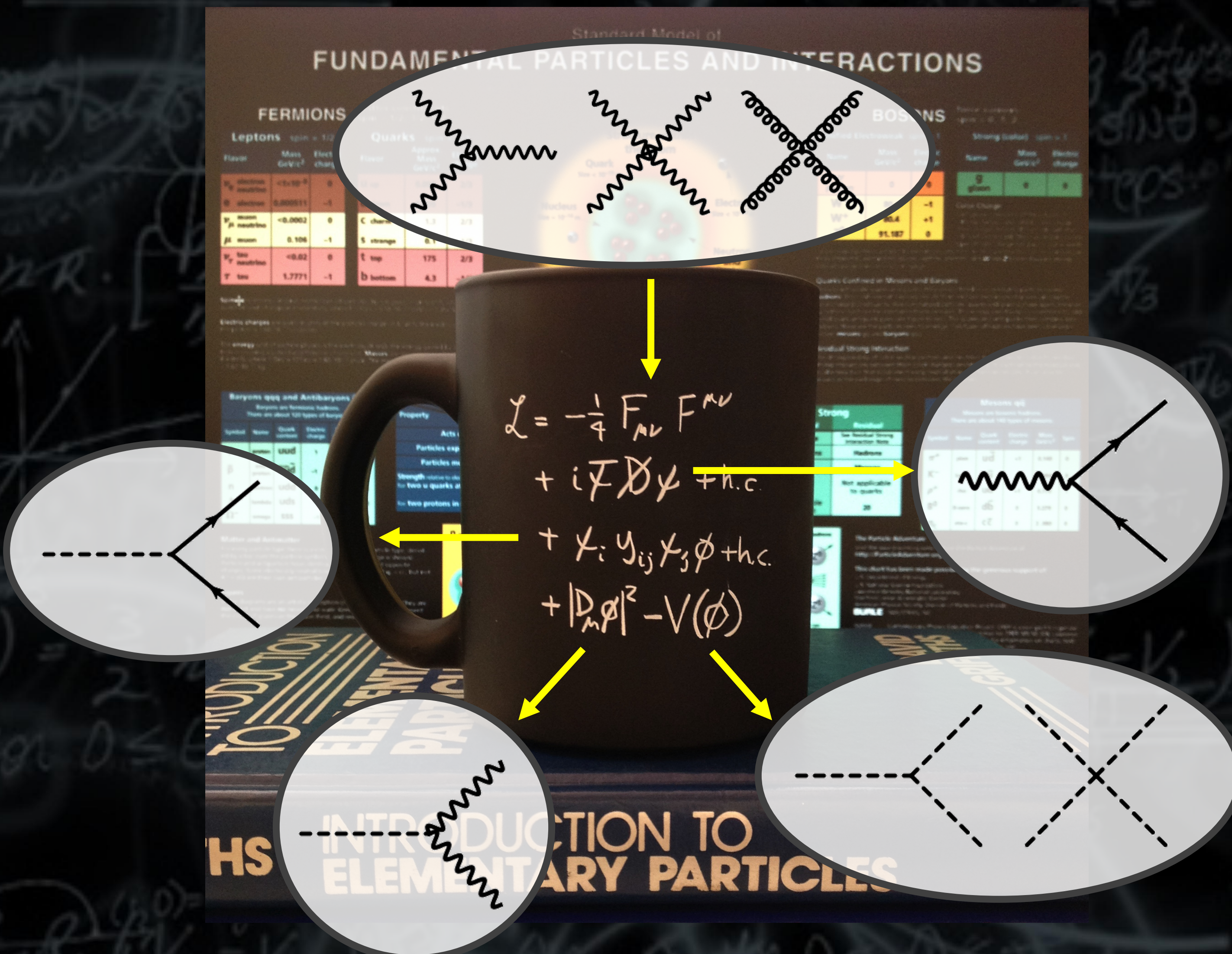


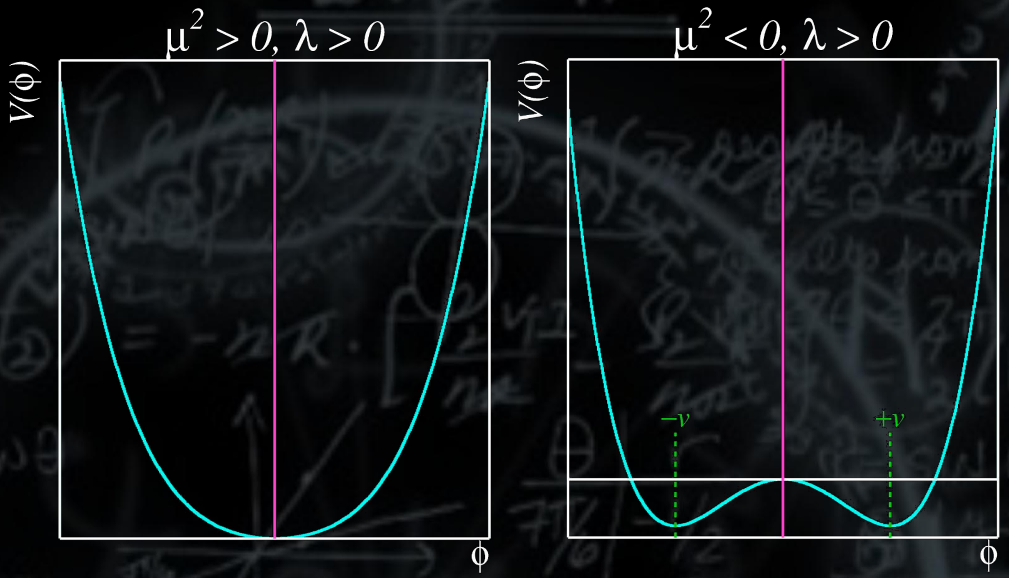
Kibble Guralnik Hagen Englert Brout Higgs

How does the ABEGHHK'tH mechanism work?

THE HIGGS FIELD...

THE SM IN A MUG – PART II





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

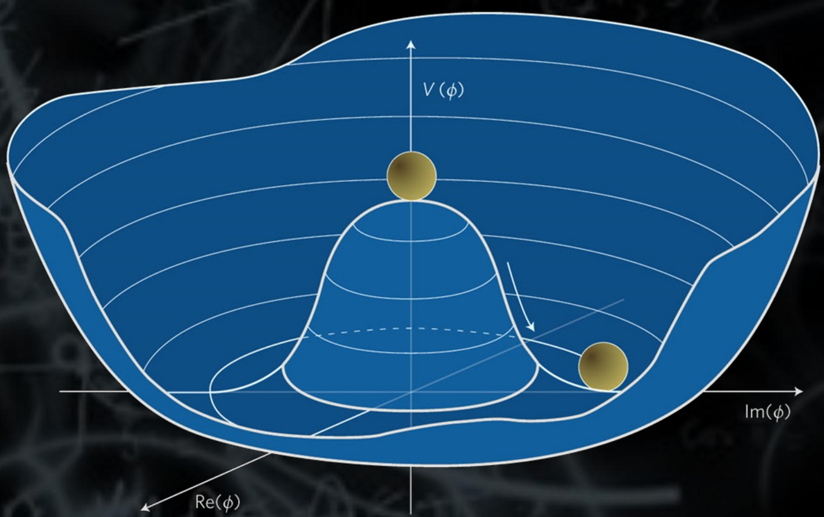
"IN VACUUM": $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

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} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
&igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
&\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
&\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{4}g^2W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
&\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2s_w^2A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
&m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
&\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
&\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
&\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \bar{G}^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar{G}^aG^bg^c_\mu + \\
&\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \\
&\partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \\
&\partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \\
&\partial_\mu\bar{X}^-X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \\
&\tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).
\end{aligned}
$$

MAKE IT INVARIANT TO BREAK IT AFTER ??!!

INVARIANT THEORY (FEW PARAMETERS)

SPONTANEOUS SYMMETRY BREAKING

v

INTERACTING THEORY WITH MASSIVE PARTICLES

THE THEORY HAS "MEMORY" FROM WHEN IT WAS SYMMETRIC

PREDICTIVE POWER

COMPUTE ANY PROCESSSES YOU WANT

COMPARISON WITH EXPERIMENT

IF EVERYTHING AGREES

MAKE IT INVARIANT TO BREAK IT AFTER ??!!

COMPLETELY BROKEN THEORY

COMPARISON WITH EXPERIMENT

NO PREDICTIVE POWER

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.

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

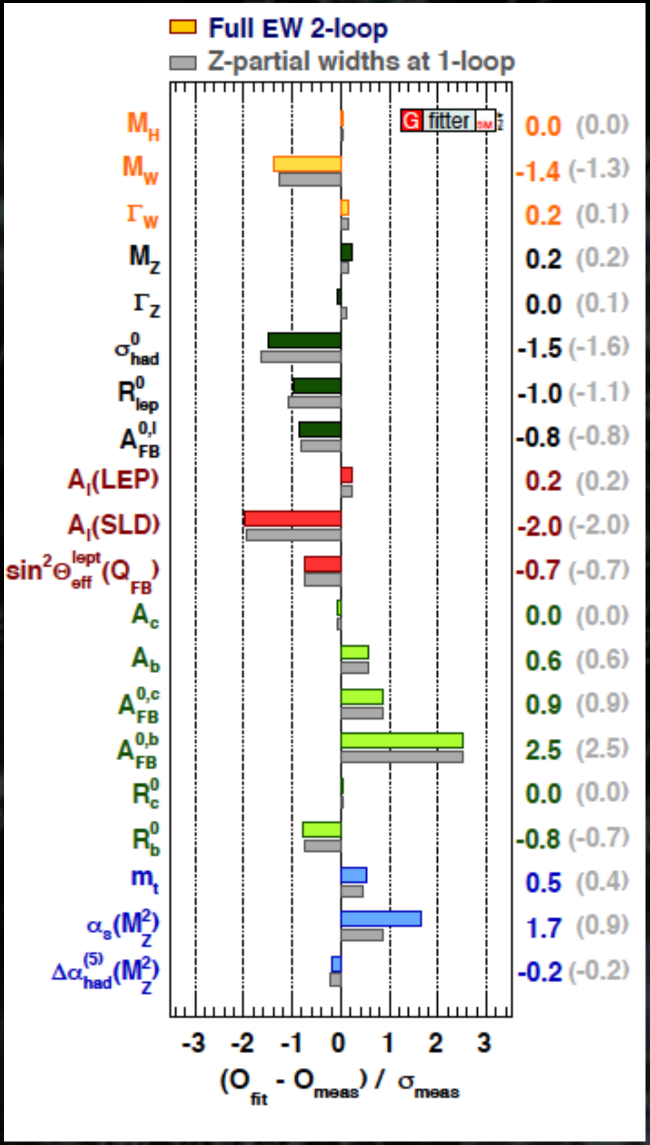
$$M_Z = 91.1876 \pm 0.086 \text{ GeV}$$

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

~ 2.5σ

LEVEL

NOBEL PRIZE THEORY

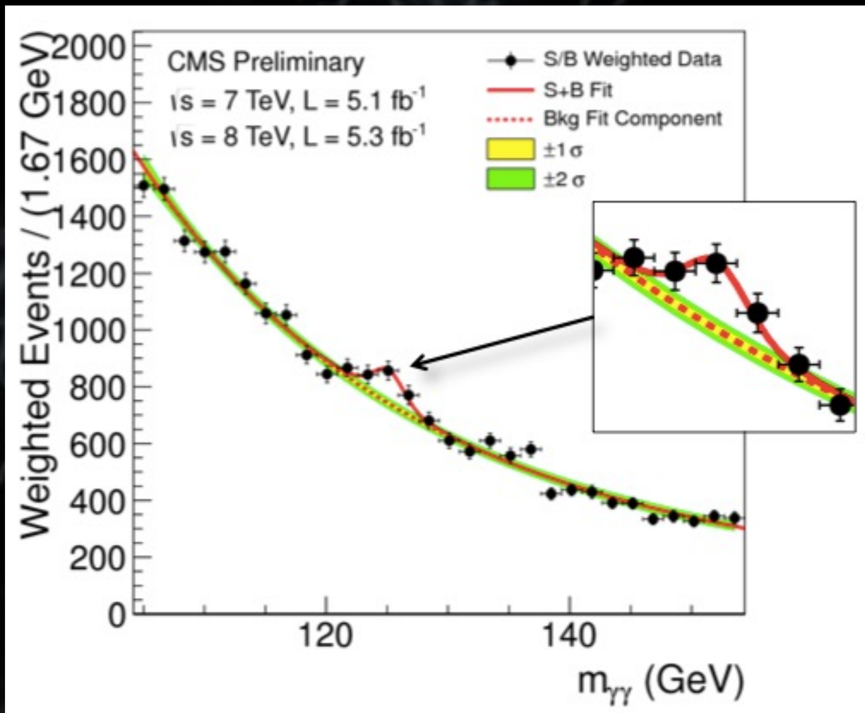
The Physics Nobel prize was awarded to Glashow, Weinberg & Salam in 1979;

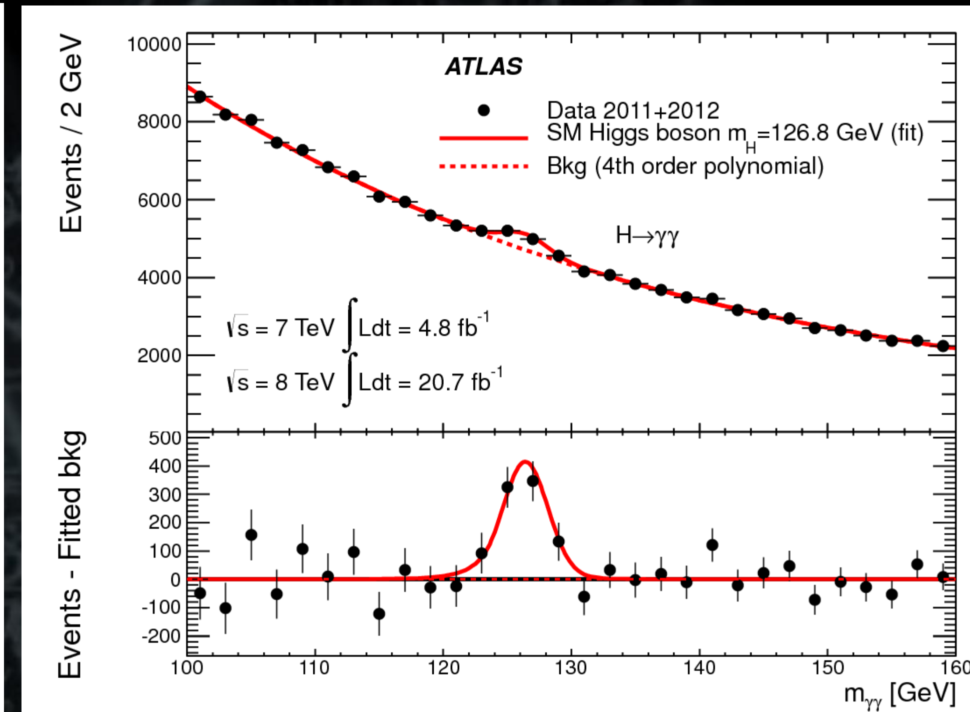
"for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, the prediction of the weak neutral current".

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

Until…

BORN ON THE 4^{TH} 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."

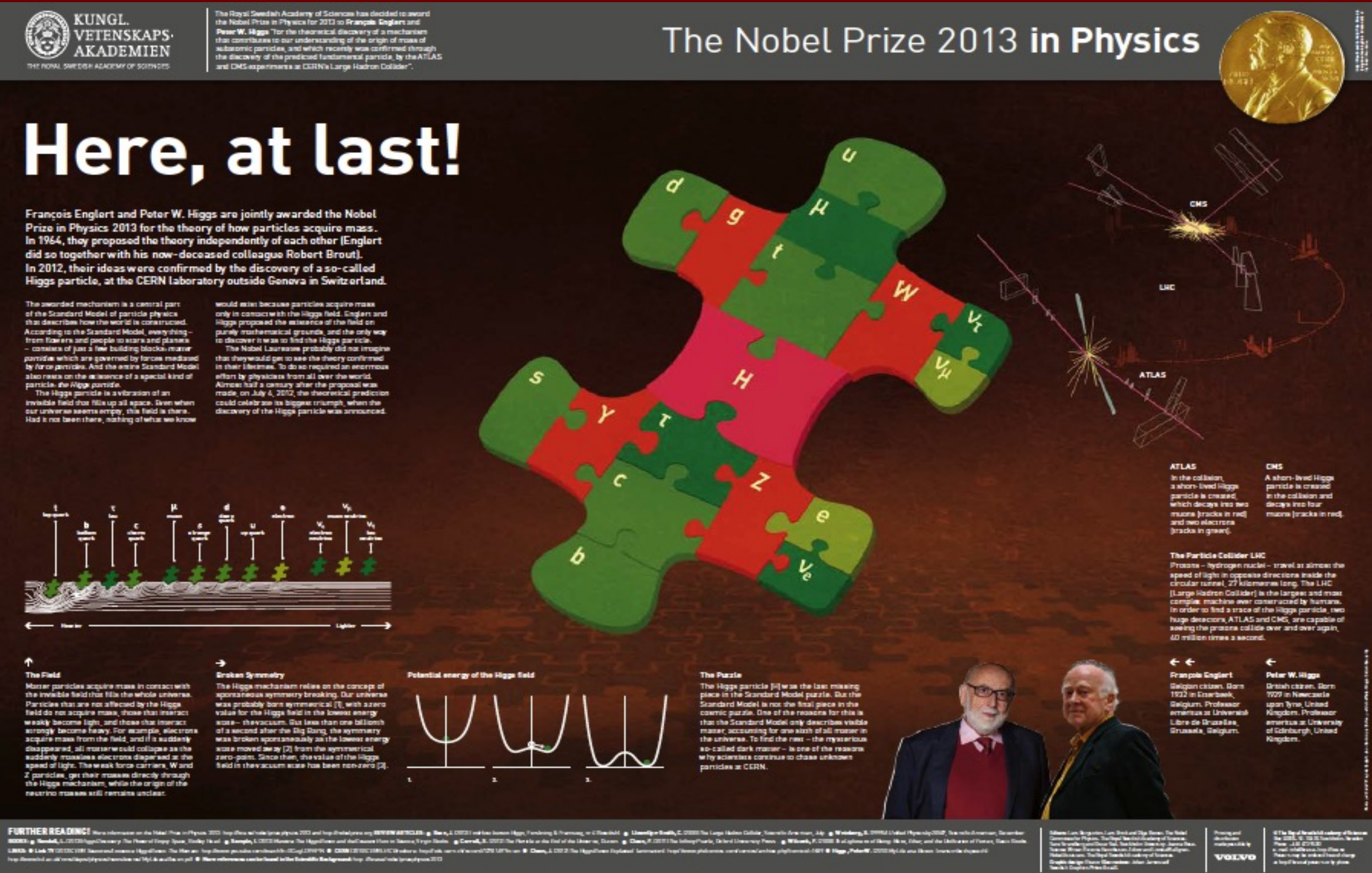
Rolf Heuer, CERN D.G., Press Release July 4, 2012

"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



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...

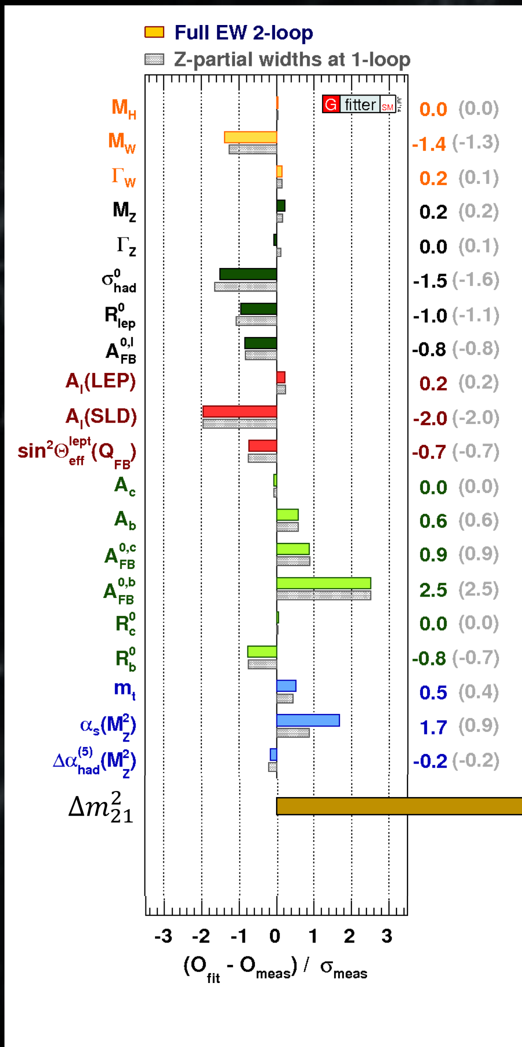
Stephen Hawking (1998)

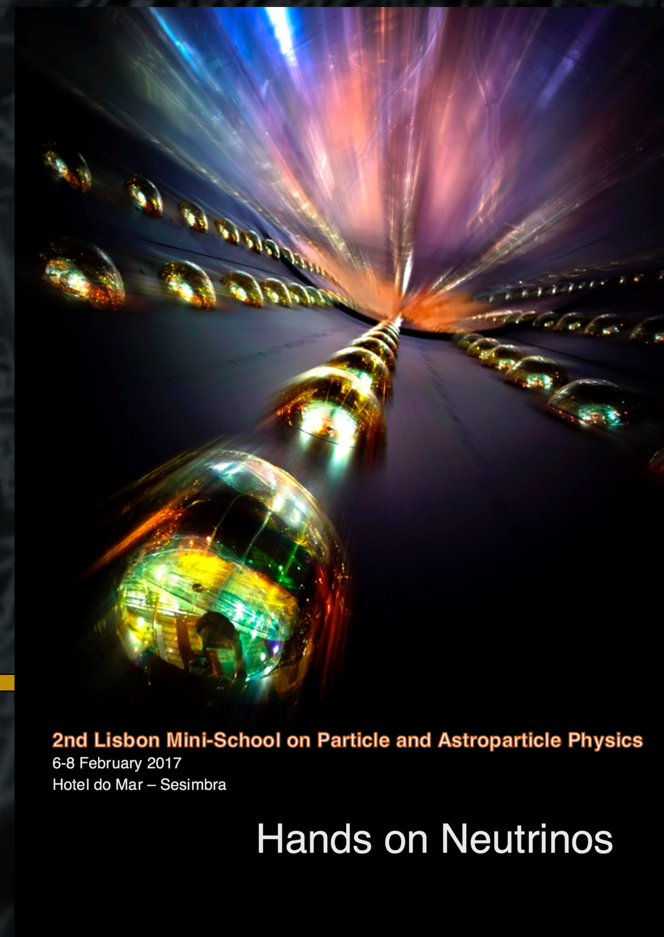
“WITH THE DISCOVERY OF THE HIGGS BOSON THERE’S NOTHING NEW TO BE DONE. JUST MEASURE THINGS WITH MORE PRECISION”

IS HISTORY REPEATING ITSELF?

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

NEUTRINO OSCILLATIONS





AND NOW WHAT?

WHY PHYSICS BEYOND THE SM?

EXPERIMENTAL PROOFS THAT THERE MUST BE BSM PHYSICS

BARYON ASYMMETRY OF THE UNIVERSE

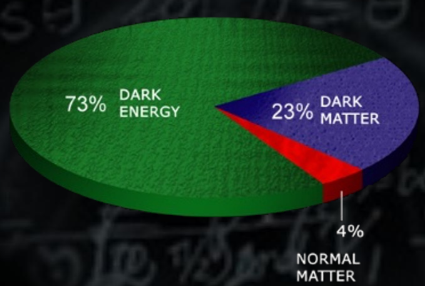
TOO SMALL IN THE SM!!

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

Leptons spin =1/2			Quarks spin =1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0	**u** up	0.002	2/3
e electron	0.000511	−1	**d** down	0.005	−1/3
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0	**c** charm	1.3	2/3
μ muon	0.106	−1	**s** strange	0.1	−1/3
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0	**t** top	173	2/3
τ tau	1.777	−1	**b** bottom	4.2	−1/3

NEUTRINO MASSES

NEUTRINOS ARE MASSLESS IN THE SM



DARK MATTER PROBLEM

NO DARK MATTER CANDIDATE IN THE SM

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2015 to **Takaaki Kajita** and **Arthur B. McDonald** "for the discovery of neutrino oscillations, which shows that neutrinos have mass".

The Nobel Prize 2015 **in Physics**

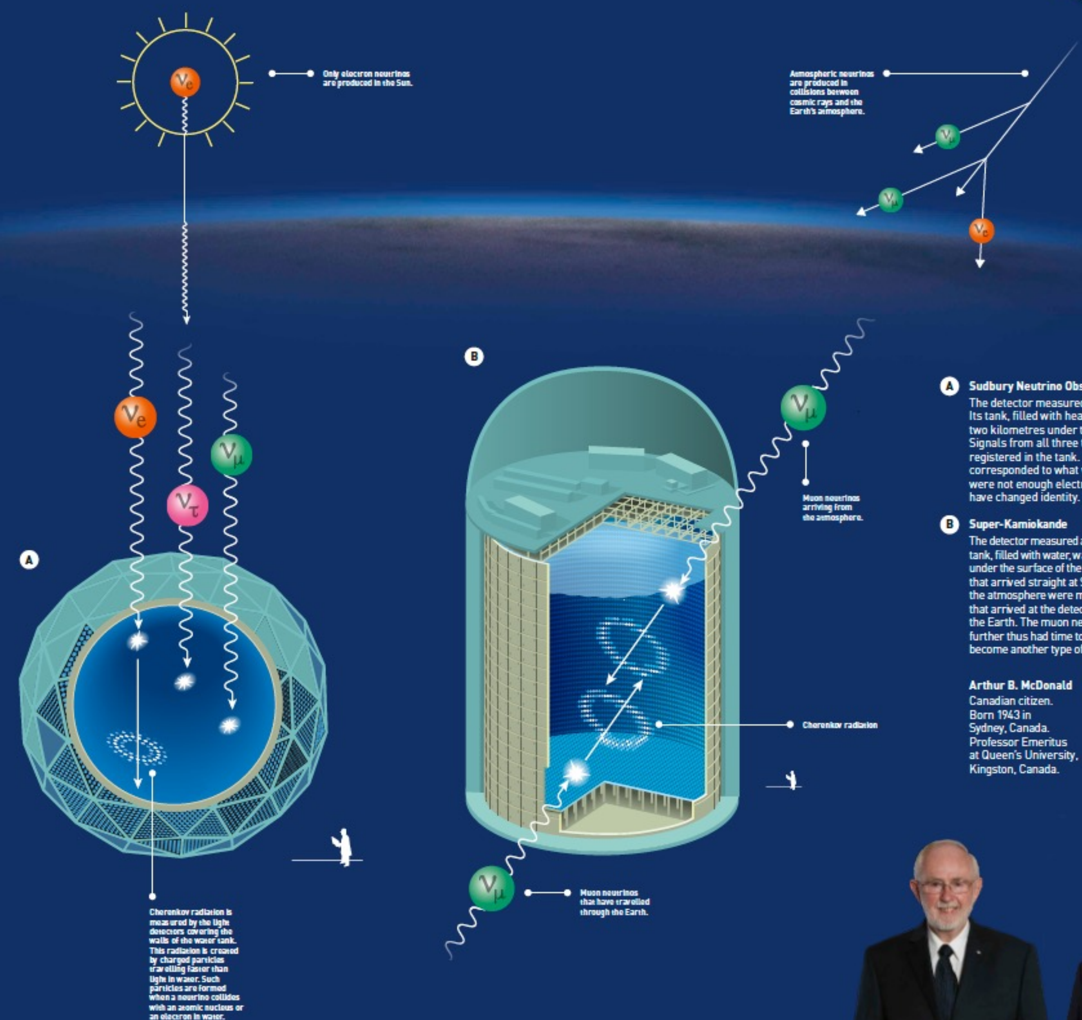
Chameleons of space

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, a quantum superposition 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.

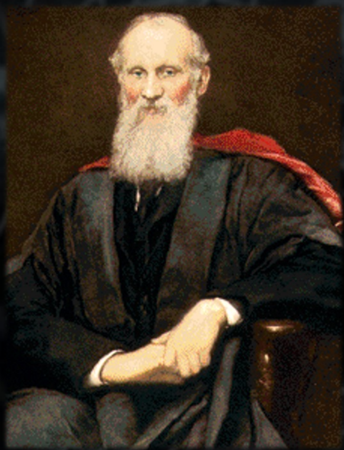
Takaaki Kajita
Japanese citizen. Born 1959 in Higashimatsuyama, Japan. Director of Institute for Cosmic Ray Research and Professor at University of Tokyo, Kashiwa, Japan.

FURTHER READING More information on the Nobel Prize in Physics 2015: http://kva.se/nobelphysics2015 and http://nobelprize.org **BOOKS:** ● **Jayawardhana, R.** (2013) *Neutrino Hunters: The Thrilling Chase for a Ghostly Particle to Unlock the Secrets of the Universe*, Scientific American/Farrar, Straus and Giroux ● **Close, F.** (2010) *Neutrino*, Oxford University Press **POPULAR SCIENCE ARTICLES:** ● **Hulth, P. O.** (2005) High Energy Neutrinos from the Cosmos, *http://nobelprize.org* ● **Bahcall, J. N.** (2004) Solving the Mystery of the Missing Neutrinos, *http://nobelprize.org* ● **McDonald, A. B., Klein, J. R.** and **Wark, D. L.** (2003) Solving the Solar Neutrino Problem, *Scientific American*, Vol. 288, no. 4, April ● **Kearns, E., Kajita, T.** and **Totsuka, Y.** (1999) Detecting Massive Neutrinos, *Scientific American*, Vol. 281, no. 2, August
LINKS: ● **Super-Kamiokande Homepage:** *www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html* ● **Sudbury Neutrino Observatory Homepage:** *www.sno.phy.queensu.ca* ● **More references can be found in the Scientific Background:** *http://kva.se/nobelphysics2015*

Editors: Lars Bergström, Olga Botner, Gunnar Ingelman and Anne L'Huillier, The Nobel Committee for Physics, The Royal Swedish Academy of Sciences; Joanna Rose, Science Writer; Sara Gustavsson, Editor, and Laura Alexis, Nobel Assistant, The Royal Swedish Academy of Sciences. **Graphic design:** Ricochet **Illustrations:** Johan Jarnestad/Infographics.se **Print:** ÅtetaS

Printing and distribution made possible by VOLVO

"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

CHALLENGE

- 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

EXPERIMENTAL PROGRAMME

ENERGY FRONTIER

- LHC and Future Colliders

INTENSITY FRONTIER

- Neutrino Oscillations
- Double beta decay
- Neutrinoless double beta decay
- LFV search experiments

COSMIC FRONTIER

- Dark matter experiments
- Cosmic Microwave Background
- Cosmic Ray experiments
- Gravitational waves

THEORETICAL PROGRAMME: SYNERGIES

- Neutrino mass messengers
- New particles and symmetries (e.g. more Higgs particles)

- Origin neutrino mass and mixing patterns
- New sources of FV (SUSY and non-SUSY)
- Origin of Leptonic CP violation

- Baryo/Leptogenesis
- Dark Matter models

THANKS