ISAPP
INTERNATIONAL SCHOOL ON ASTROPARTICLE PHYSICS

An Introduction to Particle Physics

8-19 June 2026
Institut Pascal
Paris-Saclay University, Orsay
France

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Outline

- A few historical highlights; What's matter?
- Quantum Field Theory, QED and QCD
- Weak Interaction
- Standard Model

1h30 presentation : necessarily extremely brief overview

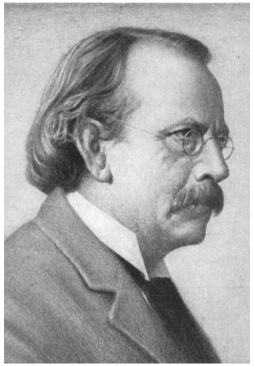
Further Details : Modern Particle Physics ; M. Thomson
NPAC Master Particle Physics Lectures ; E. Ben-Haim. B. Fuks & I

A few Historical Highlights
What's matter

The first elementary particle

To make a world you need
e, atomic >0 stuff

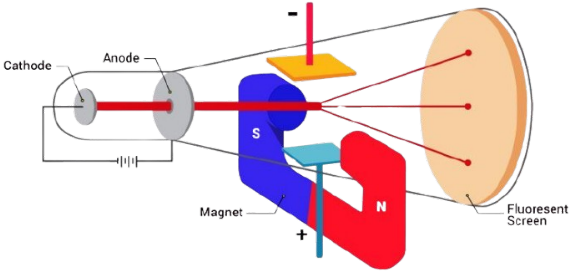
1897 : J. J. Thomson
Electron discovery



Cathode Rays are composed of
charged corpuscles

streams of electrons

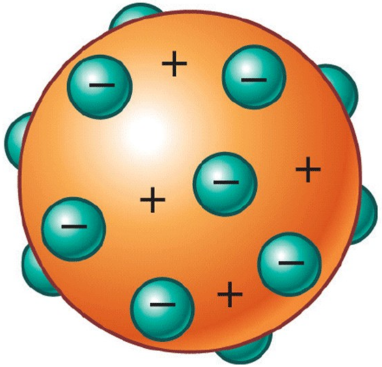
Cathode Rays in Crookes tubes



Cathode Rays electrons are extracted from cathode atoms ⇒ Atoms are not indivisible ⇒ Structure?

The Plum Pudding Model

No strong theoretical prejudice
just the simplest model conceivable
at the time



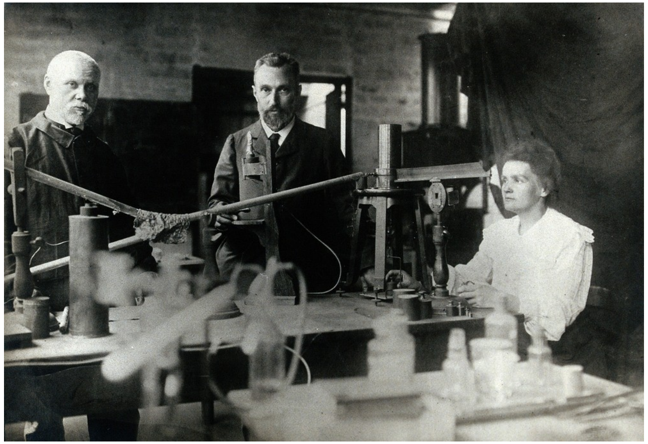
Electrons held by an uniform positive stuff

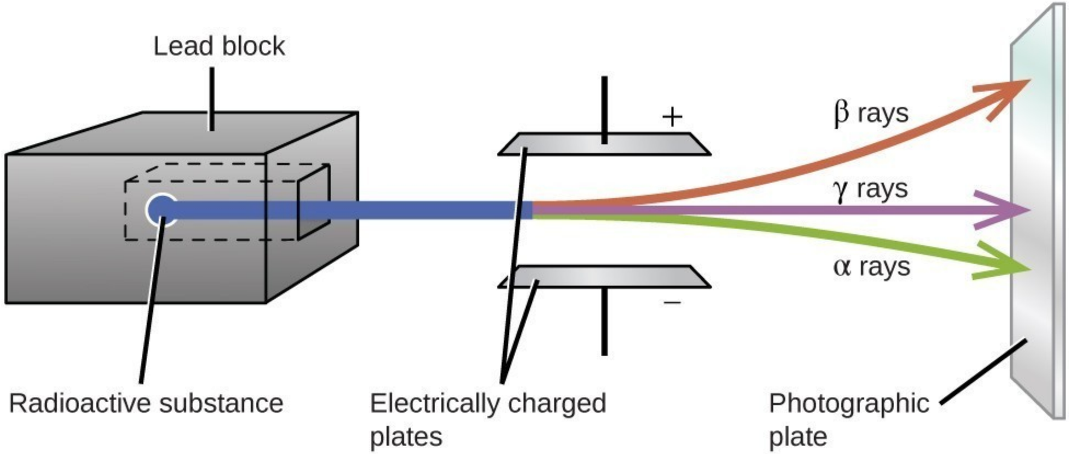
Force : Electromagnetism

How to probe this?

Rays Time

1896-1907: H. Becquerel, P. Curie et M. Sklodowska-Curie, E. Rutherford on radioactivity



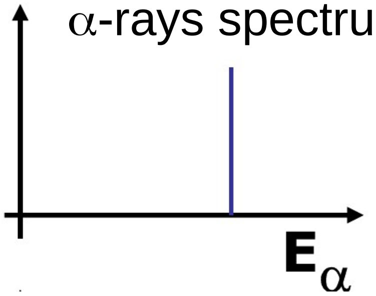


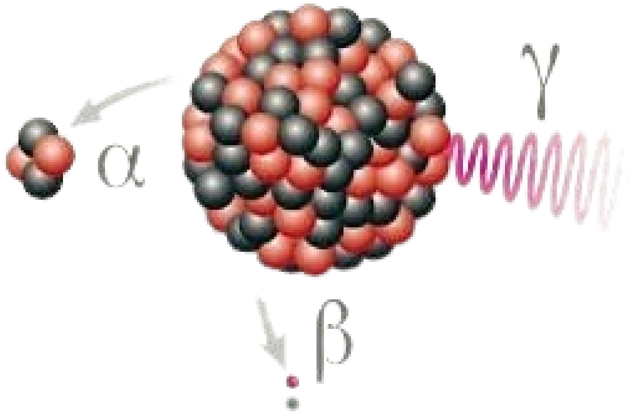
- γ-rays : very highly energetic electromagnetic rays, similar to X-rays but higher E
- β-rays : electrons ⇒ A mystery
- α-rays : nuclei of Helium atoms ⇒ A mean to probe atom

β Rays : a mystery

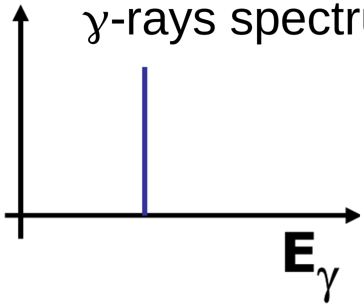
e, ν, atomic >0 stuff

Narrow
α-rays spectrum





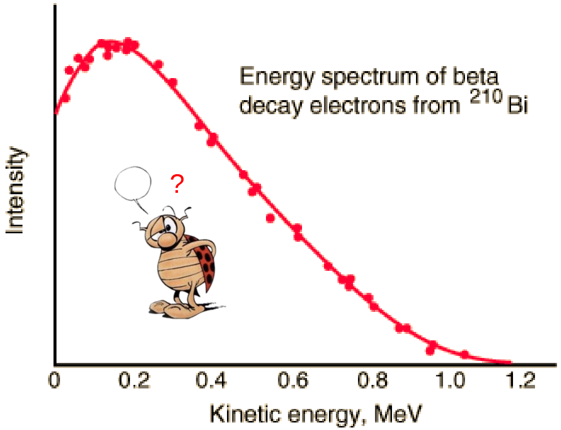
Narrow
γ-rays spectrum



Continuous
β-electron spectrum!

For a 2 body process?

$N \rightarrow N' + e^-$



1930 : W. Pauli Neutrino proposal

This is a three body decay

$N \rightarrow N' + e^- + \bar{\nu}_e$

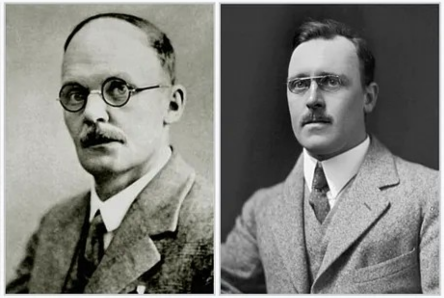
New neutral particle

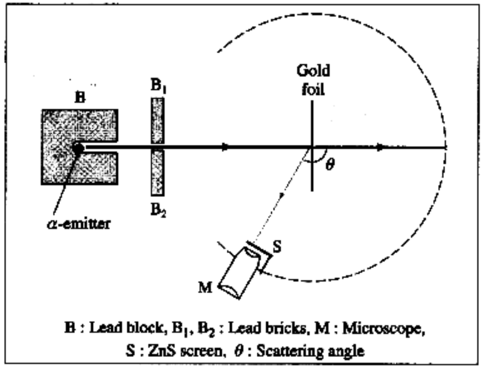
New Force : weak interaction

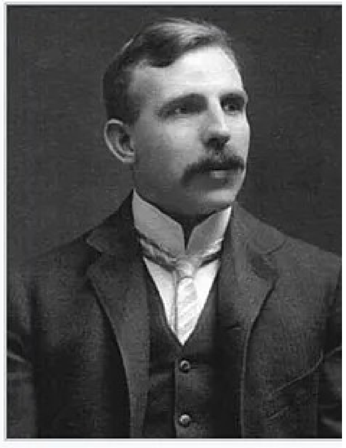
Probing the Atom

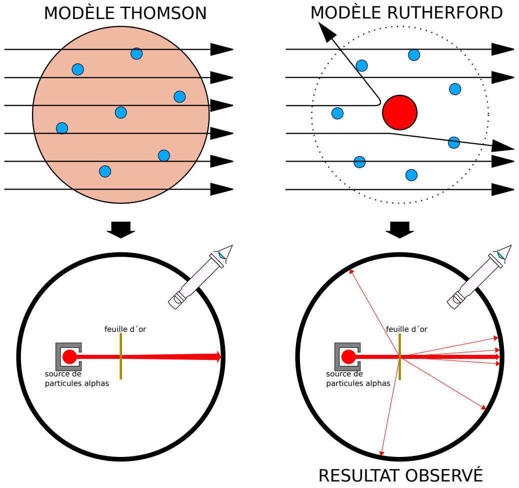
1909 : H. Geiger and E. Mardsen experiment

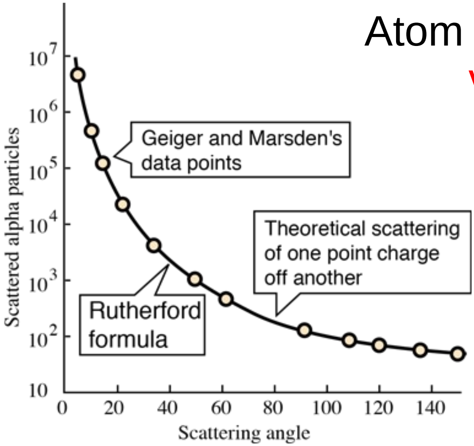
1911 : E. Rutherford interpretation





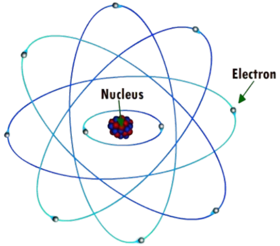






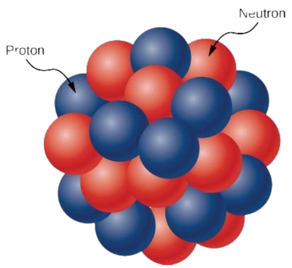
Atom mass is enclosed into a very small Nucleus

⇒ Planetary model of the atom



What the nucleus is made of

e, ν, p, n



1919 : Rutherford's proton, $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + p$

For a while : Nucleus = A protons + A-Z electrons

Good reason : a β-ray electron escapes from the atom; so surely it was sitting in the nucleus before

Major problem : Nuclear Spin of some atoms

1932 : Chadwick's neutron

So : Nucleus = A nucleons = Z protons + A-Z neutrons

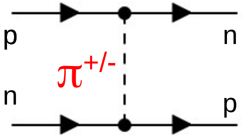
Now the β-decay is $n \rightarrow p + e^- + \bar{\nu}$

First a few more Particles

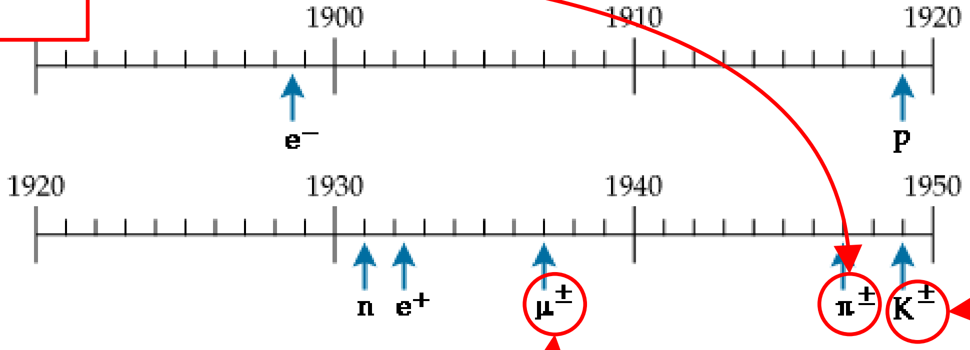
e, ν, p, n , … μ (?)

Predicted and found scalar pions to describe the nucleons interaction

1935 : H. Yukawa



New Force
Strong Interaction
between nucleons



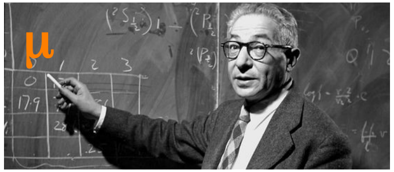
New strange mesons

Produced in pairs via Strong Interaction but decaying Weakly

Strangeness
new Quantum number

Looking for pions found … a heavy electron?

But who needs a heavy electron?

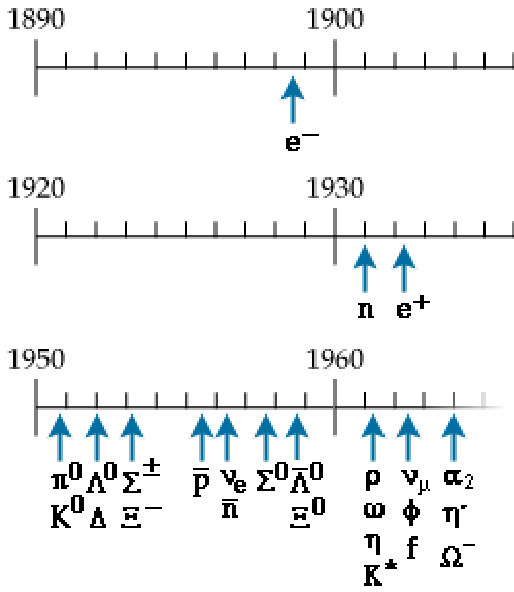


I. Rabi : Who ordered that?

Then the Deluge

e, ν, p, n … hundreds more?

In the 50’ and 60’, hundreds of new hadrons found first in cosmics rays then at accelerators



All elementary?

The particle zoo

+ hundreds more

“*Young man, if I could remember the names of these particles, I would have been a botanist.*”
E. Fermi to a student

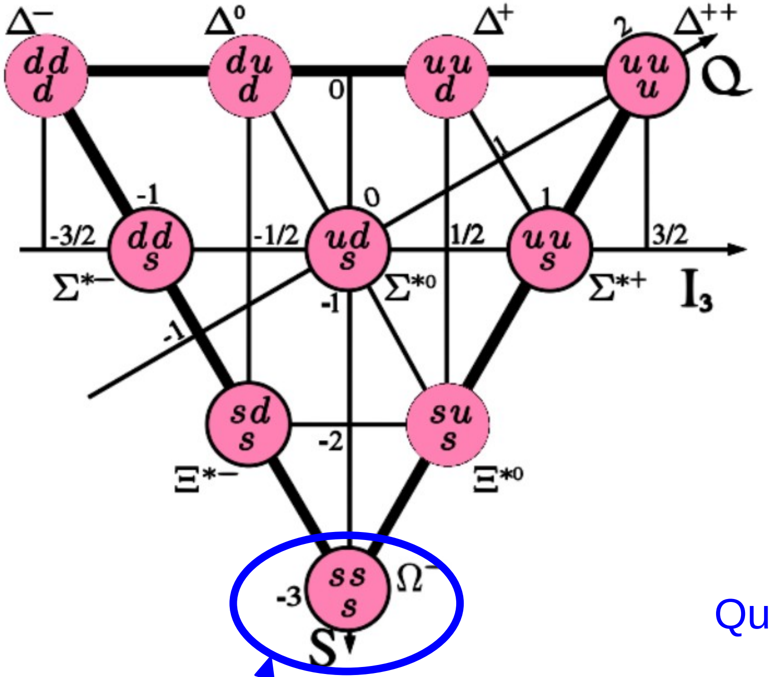
Few elementary bricks after all

e, ν_e, u, d
μ, ν_μ, s

1962 : M. Gell-Mann
Strangeness and Isospin

Highly successful classification of hadrons in $SU(3)_{flavor}$ multiplets

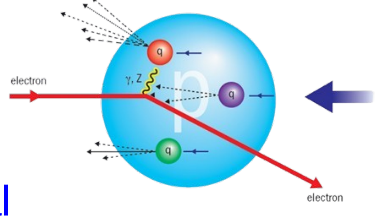
à la Mendeleïev
Classification + Predictions



Hadrons easily understood has made of quarks
u (+2/3) d (-1/3) s (-1/3)

Real particles or fictions?

1969 : Feynman Parton model
Deep Inelastic scattering



Quarks are real

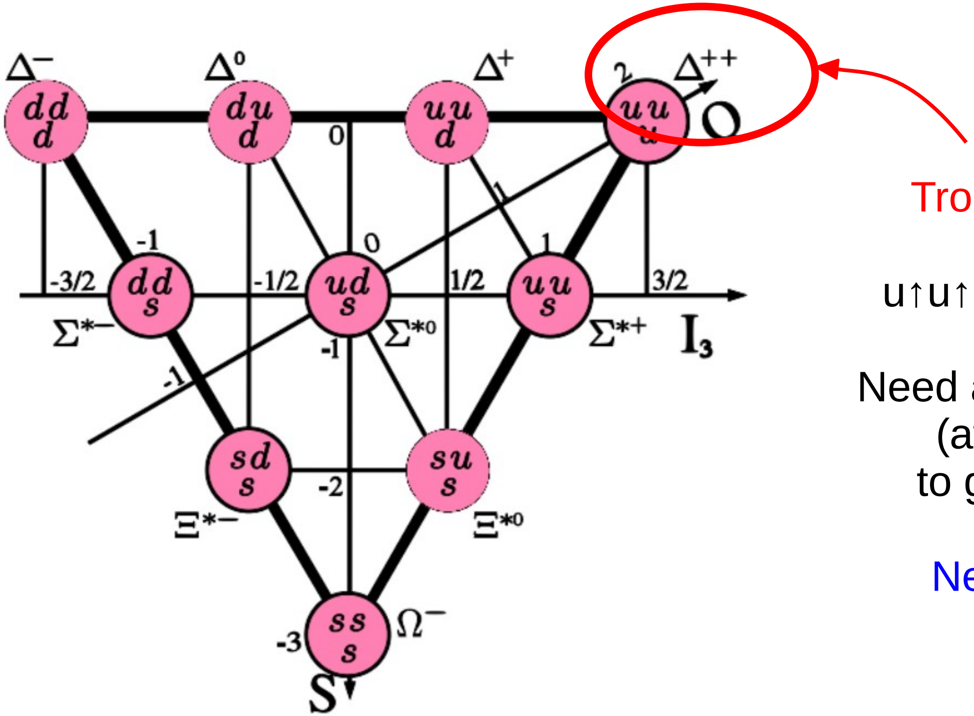
Renewed Strong interaction now between quarks

Few elementary bricks after all

e, ν_e, u, d
μ, ν_μ, s

1962 : M. Gell-Mann
Strangeness and Isospin

Highly successful
classification of hadrons
in $SU(3)_{flavor}$ multiplets



Troubles with the Δ^{++}

u↑u↑u↑ symmetric state

Need a degree of freedom
(at least 3 states)
to get statistics right

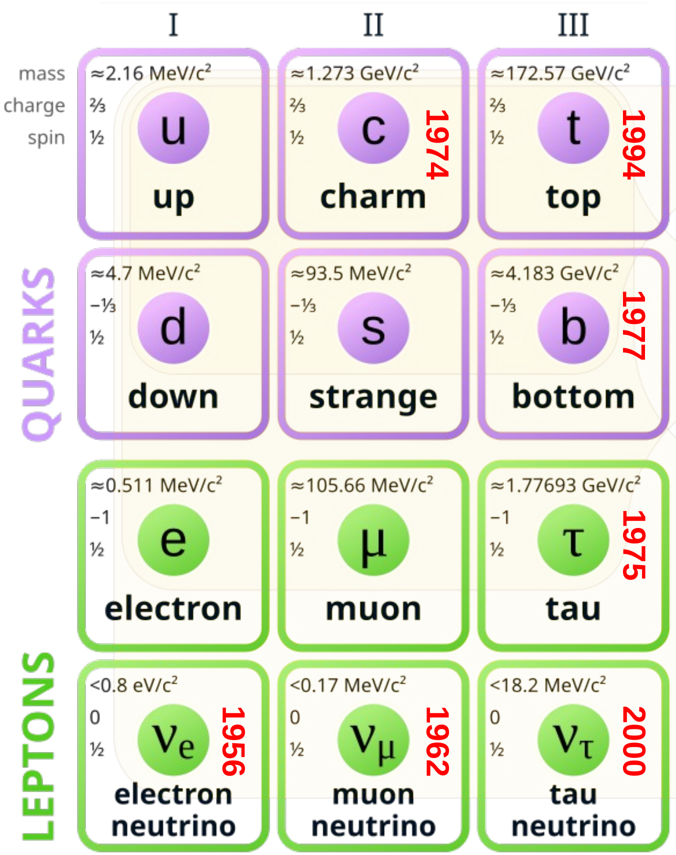
New quantum nber
Color

Matter - Fermions

Quarks and leptons

- Family pattern
  3 increasingly heavy families

- Extravagant Mass spectrum
  $m_t = 173$ GeV
  $m_e = 3 \times 10^{-6}\, m_t$
  $m_\nu < 6 \times 10^{-12}\, m_t$



Stable ordinary matter

Forces

- Gravity (too weak)
- Electromagnetism
- Strong Interaction
- Weak interaction

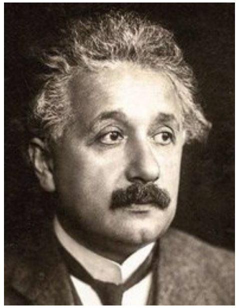
Decays : $M \rightarrow d_1 d_2 \ldots$

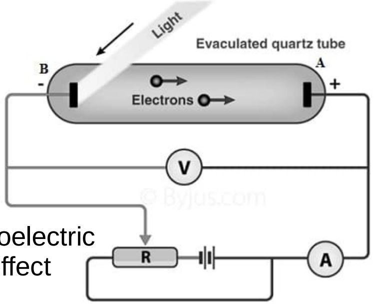
	Life time (s)
Strong	10^{-23}
EM	10^{-16}
Weak	10^{-13} - 900

Quantum Fields Theory

Electromagnetic Field and the Photon

1905 : A. Einstein
Light quantum hypothesis

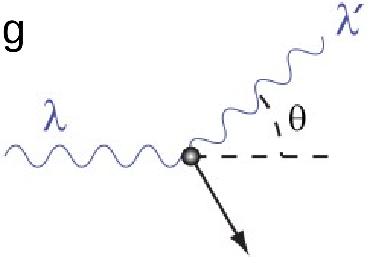




Photoelectric effect

$$E = \hbar\omega$$
$$\vec{p} = \hbar\,\vec{k}$$

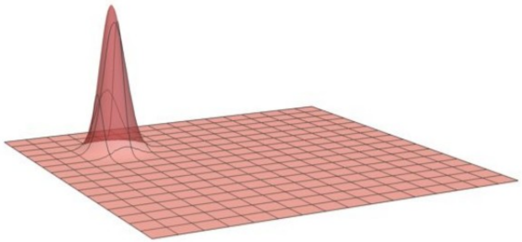
1923 : A. H. Compton
X-rays scattering



Light acts as a particle

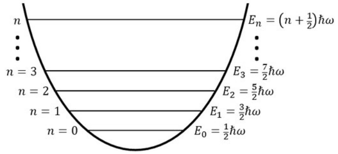
In some circumstances Radiation behaves as corpuscules ⇒ Wave/Particle duality

From 1927 : P. Dirac, W. Heisenberg, W. Pauli, E. Wigner, P. Jordan, E. Fermi



Quantum Electromagnetic field
Photons are the quanta of the Field

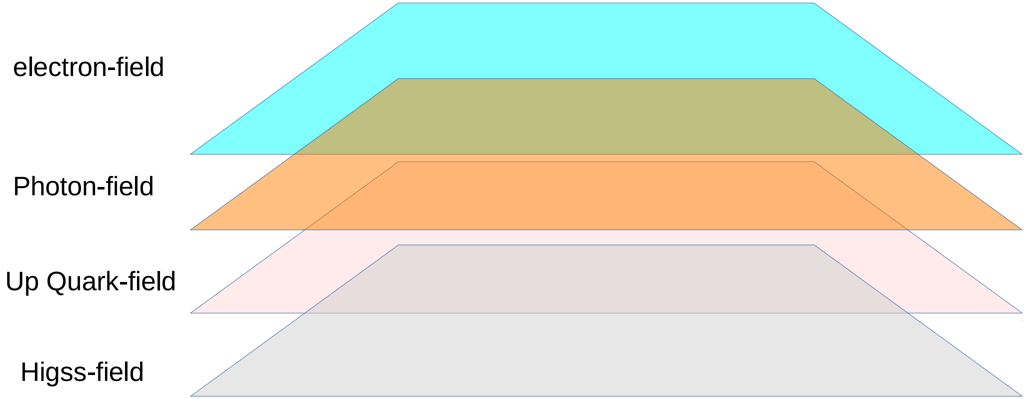
Modeled on the Quantum Harmonic Oscillator



Field is primary, particles are derived entities

Quantum Fields

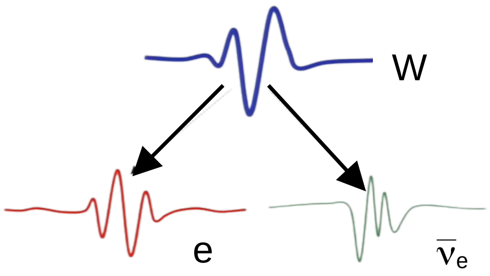
A few pervading fermionic and bosonic fields



- Force and matter are described in the same way
- Locality/Causality from the onset
- Particles inherit their properties (mass, spin) from their fields
- Particles can be created and destroyed; the fields remain

- Particles of a given type are all identical : excitations of the same stuff
- Interaction (decay, scattering): excitation passes from in-fields to out-fields
  ⇒ Final particles do not preexist hidden somehow in initial particles

The interesting thing : Fields in interaction



Building Interaction : Quantum Electrodynamics by "hand"

Dirac Lagrangian $\mathcal{L}_{Dirac} = \overline{\Psi}\,(i\gamma^\mu\partial_\mu - m)\,\Psi$

$$\begin{cases} \Psi & = \text{4-components vector, a spinor} \\ \gamma^\mu & = 4\times 4 \text{ matrices with interesting algebra} \end{cases}$$

Dirac Equation $(i\gamma^\mu\partial_\mu - m)\,\Psi = 0$

$\exists$ a conserved current $j^\mu = \overline{\Psi}\gamma^\mu\Psi$

How the electron field interacts with the Electromagnetic Field ?

Inspiration from the classical Lagrangian is $\mathcal{L}_{class} = J^\mu A_\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$

We can postulate

$$\mathcal{L}_{QED} = \overline{\Psi}\,(i\gamma^\mu\partial_\mu - m)\,\Psi + (e\overline{\Psi}\gamma^\mu\Psi)A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Quantum Electrodynamics by Gauge invariance

Dirac Lagrangian $\mathcal{L}_{Dirac} = \overline{\Psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\Psi$ $\left\{ \begin{array}{l} \text{is invariant under global } U(1) \text{ symmetry } \Psi \rightarrow \Psi e^{ie\alpha} \\ \text{Noether's theorem} \Rightarrow \exists \text{ a conserved current (known)} \end{array} \right.$

Now look at $\Psi \rightarrow \Psi e^{ie\alpha(x)}$ (local $U(1)$ symmetry) $\Rightarrow$ Do not work

Well ... can work (Fields redefinitions can undo the changes) if there is an interaction with a Vector Field

$$\Rightarrow \mathcal{L}_{QED} = \overline{\Psi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\Psi + e\overline{\Psi}\gamma^{\mu}\Psi A_{\mu} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \Leftarrow$$

By requiring a local U(1), we get

- a massless Vector Gauge Field, so the photon, is necessary
- the interaction electron/photon is prescribed

A recipe : to build an interaction, postulate a Local Gauge symmetry and look at what come out

When you get it right, it's obvious that it's right […] Because most of what happens is that more comes out than goes in

R. Feynman

Divergences and Renormalization

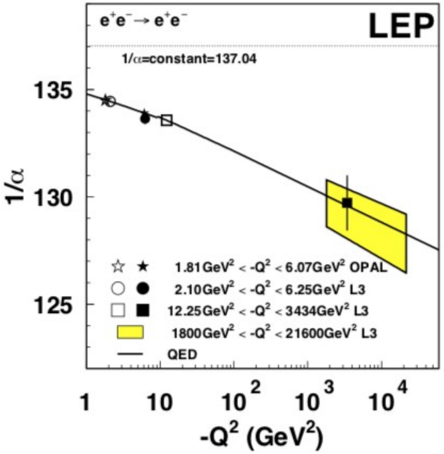
$$\alpha_{em} \equiv \frac{e^2}{4\pi} \sim \frac{1}{137} \ll 1 \text{ , allows perturbation expansion}$$

By the end of the 30's, higher order contributions are plagued by divergences! Nonsensical!

Inconsistent Quantum Field theory? First QFT crisis end of the 30's

End of 40's, Renormalization procedure saved QED
reformulate the theory using measurable quantities since bare quantities are inaccessible

J.S. Schwinger, R. Feynman, S. Tomonaga



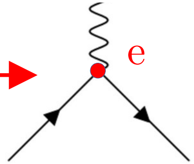
- Running (!) coupling constant : increases with E
- Anomalous magnetic moment
  - Electron
    Data/Theory OK up to 12 significant figures!
  - Muon
    Data/Theory Not OK… at the 10^{th} significant figure
    Recent progress from Lattice QCD computations

He saved us all

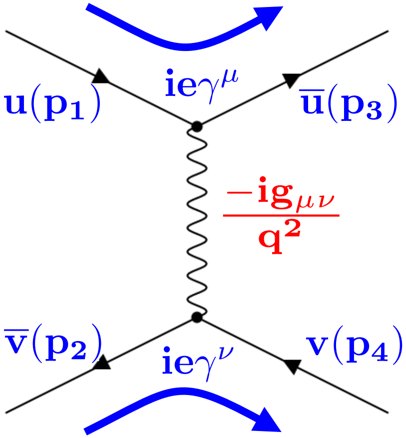
QFT computations are abstruse

Feynman's Diagrams and rules
an extraordinary graphic tool to handle them

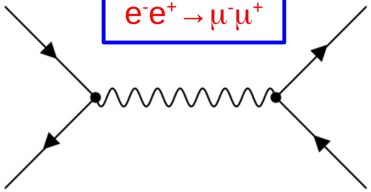
$e\,\overline{\Psi}\gamma^{\mu}\Psi A_{\mu}$ →



$e^-\mu^+ \rightarrow e^-\mu^+$

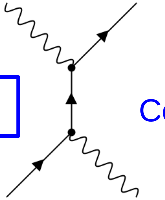


$e^-e^+ \rightarrow \mu^-\mu^+$



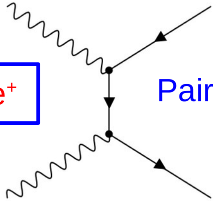
Pair annihilation

$\gamma e^- \rightarrow \gamma e^-$



Compton Scattering

$\gamma\gamma \rightarrow e^-e^+$

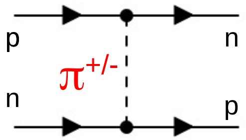


Pair creation

Like the silicon chips of more recent years, the Feynman diagram was bringing computation to the masses.
J. Schwinger

Strong Interaction - QCD

Yukawa theory vindicated
by the discovery of the pions



But coupling constant ~ 1, spoils QFT computations
Second QFT crisis In the 60's (particle zoo)!

But $SU(3)_{flavor}$ ⇒

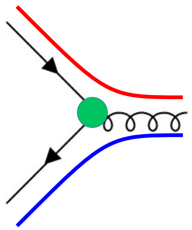
- right fermionic degrees of freedom, the quarks
- clue about the Gauge charge, the color ⇒ 3 color states ⇒ $SU(3)_c$ Gauge group

$SU(3)_c$: Yang-Mills Gauge Theory
(more tricky than U(1))

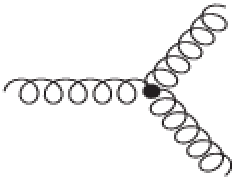
$$\begin{pmatrix} \Psi_r \\ \Psi_g \\ \Psi_b \end{pmatrix}$$

- 3^2-1 = 8 massless bosons, the gluons
- non-abelian : charged bosons

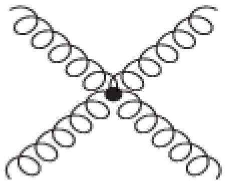
$$\begin{pmatrix} \text{mnemonic} \\ \text{SU(N)} \\ N^2 - 1 \ \ \text{bosons} \end{pmatrix}$$



$g = \sqrt{\alpha_S}$



3-gluon vertex ∝ g

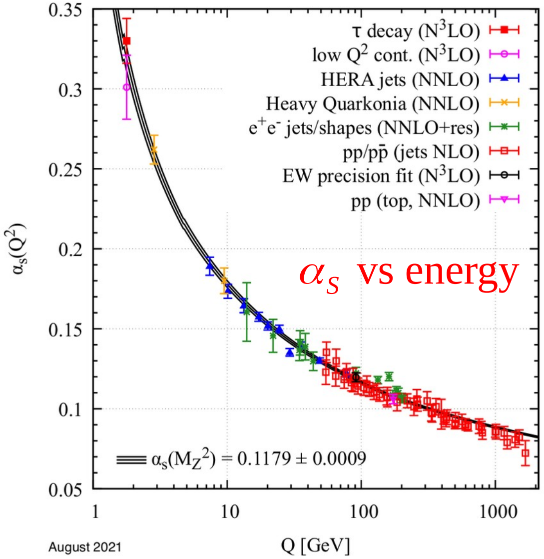


4-gluon vertex ∝ g^2

QCD

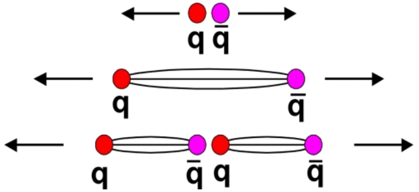
Running QCD constant
contrary to QED

coupling ↓ when E ↑ , distance↓

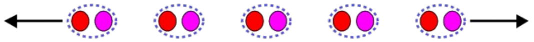


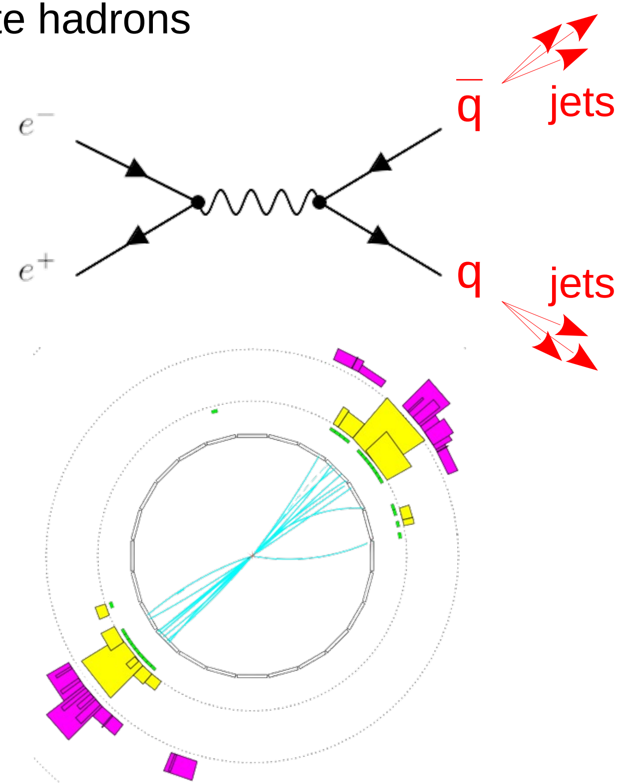
- Asymptotic freedom :
  factorization : hard interaction (free partons) then hadronization

- Confinement (not demonstrated)
  Quarks are confined within white hadrons



As energy decreases… hadrons freeze out





QCD predictions

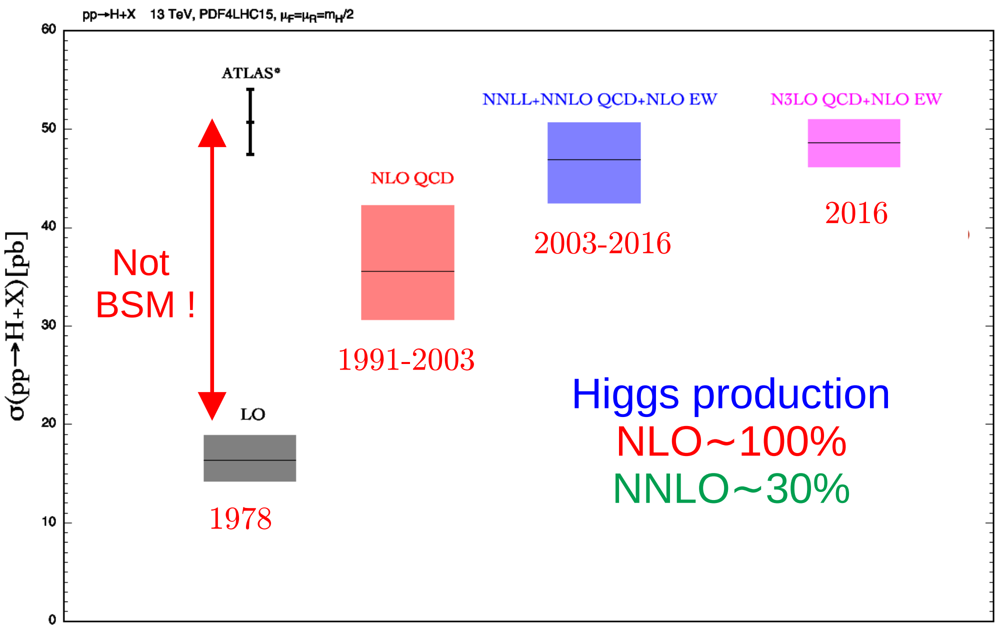
The QCD corrections are

Large and Hard to compute

LO gives only a taste, NLO can be huge

Crucial for precision SM and BSM physics at LHC

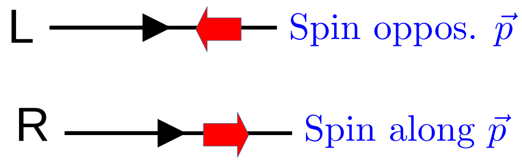
$\sigma\,(pp \to H + X)$ predictions vs Time



M. Grazzini at Higgs 10 Symposium, CERN, 07/22

Chirality

For a massless fermion



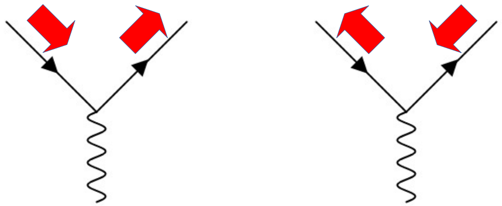
A field can be decomposed into chiral states

a Left state + a Right state

$$\Psi = \Psi_L + \Psi_R$$

- QED/QCD coupling

L and R parts
are treated the same and do not mix



- Fermion mass terms

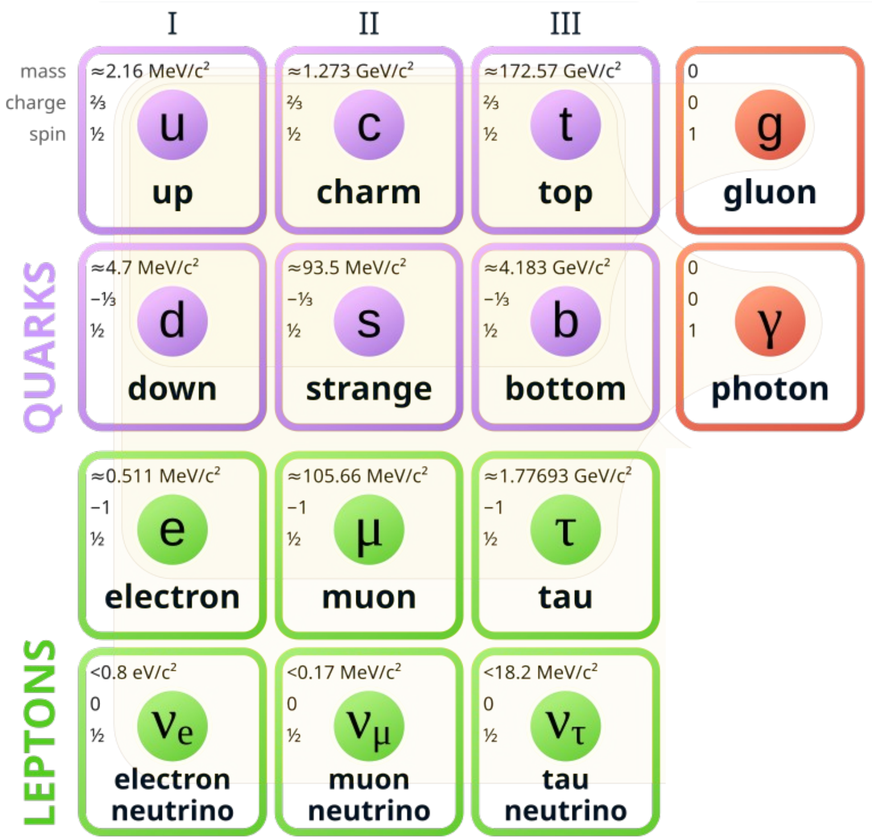
L and R parts
are treated the same but they do mix

$$m\overline{\Psi}\Psi = m\overline{\Psi}_R\Psi_L + m\overline{\Psi}_L\Psi_R$$

What do we have up to now

Quantum Fields
both for fermions and bosons

Particles as Field excitations



Local Gauge Invariance

Massless Gauge Bosons

U(1) QED, photon

$SU(3)_c$ QCD, 8 gluons

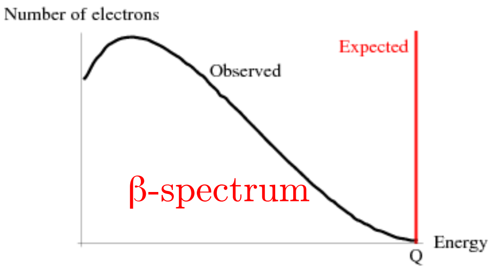
What about
the Weak Interaction ?

Weak Interaction

A New Particle and A New Interaction

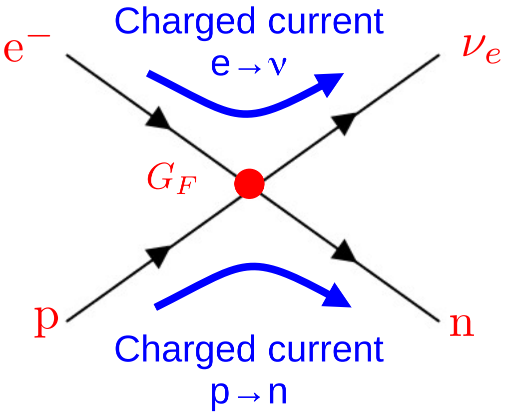
1930 Pauli neutrino hypothesis

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



1934 Fermi builds a theory of weak interaction using Pauli neutrino (2nd QFT)

Notable difference wrt QED : particles nature change through the Interaction



Contact Interaction

G_F has dimension

$[G_F] = E^{-2}$

Very successful theory

Doomed to fail $\sigma \propto G_F^2 E_{cm}^2$

Unitarity violation ~300 GeV

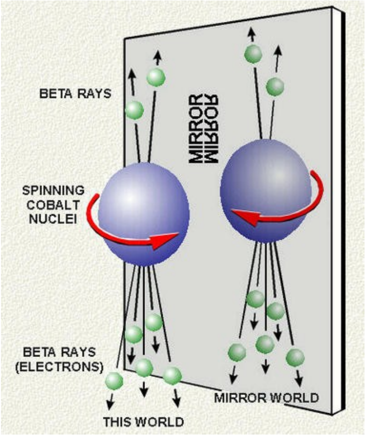
Parity violation

1956 : CS. Wu

Cobalt-60 weak decay

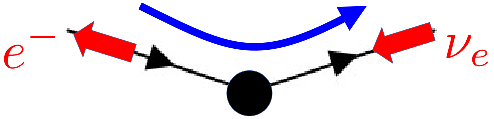
Electrons fly in the direction opposite to the Cobalt nucleus spin

⇒Weak interactions violate parity



1957 : Gell-Mann & Feynman

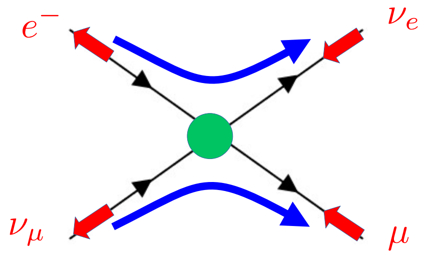
Only the Left part of particle interact
(and the Right part of antiparticles)

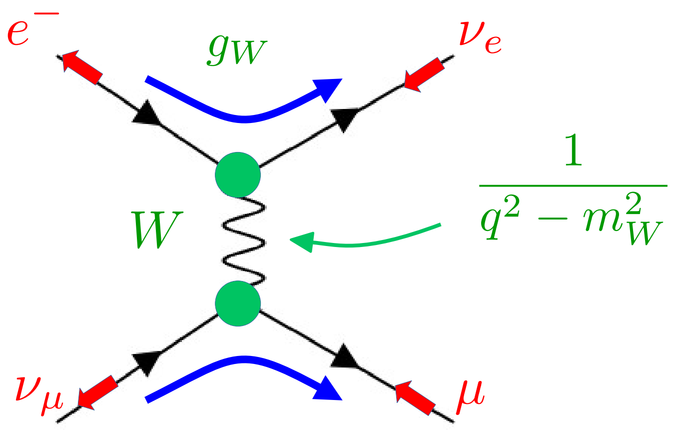


Maximal Parity violation

Intermediate Vector Bosons $W^{\pm}$

One parameter
G_F





Two parameters
g_W and m_W

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}$$

Weak because the
W boson is heavy
~100 GeV

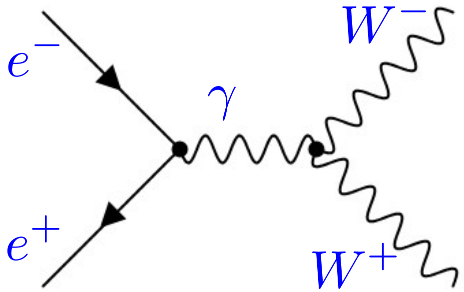
- At low energy , $q^2 \ll m_W^2$: we retrieve Fermi Theory $\quad \sigma \sim G_F^2 E_{cm}^2$
- At high energy , $q^2 \gg m_W^2$: Cross section damped $\quad \sigma \sim \frac{G_F^2 m_W^2}{\pi}$

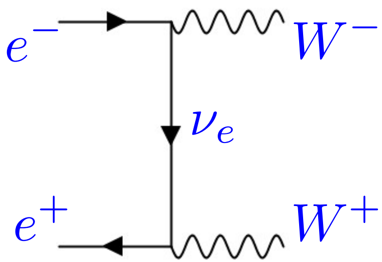
- The requirement of Unitarity at Tree level leads to the $W^{\pm}$ bosons
- $W^{\pm}$ are charged! $W^{\pm}$, and γ as the 3 Gauge bosons of some SU(2) ($3=2^2-1$)? Premature!

Necessity of a Neutral Vector Boson

We have to consider the production of the W bosons e.g. $e^- e^+ \to W^- W^+$

e.g. $e^- e^+ \to W^- W^+$





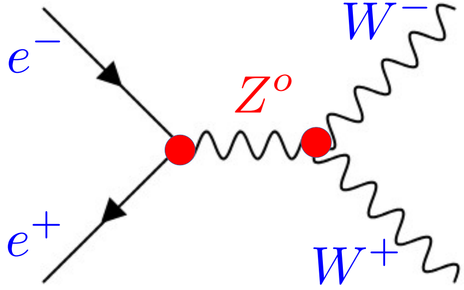
This process violates unitarity

To restore the Tree Level Unitarity (remove Leading divergence at least)

we have to introduce a new weak neutral boson, Z^o

with specific couplings ZWW and Zee

in particular this Z couple to both L and R but not equally

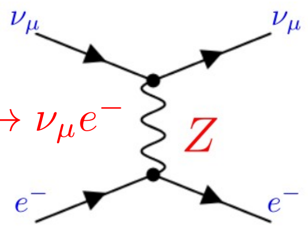


The Weak Bosons For real

1973 : Gargamelle
Discovery of
the Neutral Current

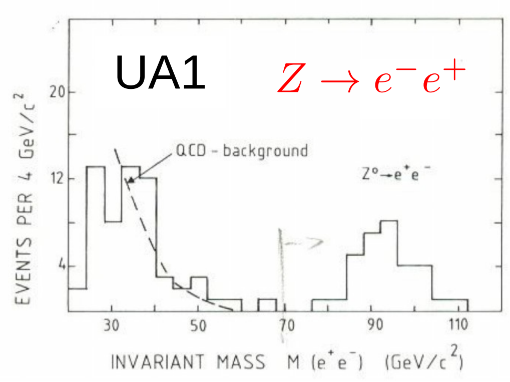
Neutrino beam
on a fixed Freon target

$\nu_\mu e^- \to \nu_\mu e^-$

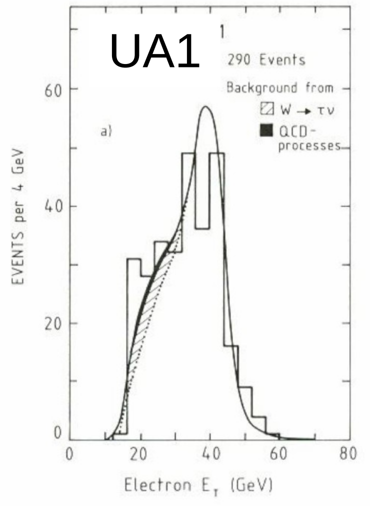


1983 : UA1, UA2
Discovery of W and Z

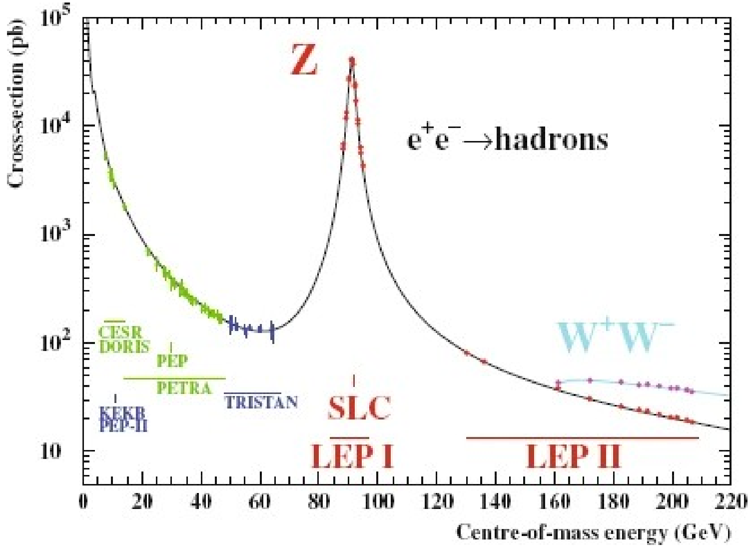
$p\bar{p}$ collider



$W^- \to \mu^- \overline{\nu}_\mu$



90's : LEP, SLC Detailed Z studies
e^-e^+ collider



Standard Model by Tree Level Unitarity

We have to consider processes involving the interactions of leptons, γ, W and Z^o bosons

$$
\begin{aligned}
\nu\bar{\nu} &\rightarrow W^-W^+ \\
e^-e^+ &\rightarrow W^-W^+ \\
\bar{\nu}e &\rightarrow W^-Z^o \\
e^-e^+ &\rightarrow Z^oZ^o \\
W^-W^+ &\rightarrow \gamma\gamma \\
W^-W^+ &\rightarrow W^-W^+ \\
W^-W^+ &\rightarrow Z^oZ^o \\
W^-W^+ &\rightarrow Z^o\gamma \\
W^-W^+ &\rightarrow hh \\
Z^oZ^o &\rightarrow hh \\
Z^oZ^o &\rightarrow Z^oZ^oh \\
Z^oZ^o &\rightarrow hhh
\end{aligned}
$$

All these processes violate unitarity at Tree level

but for specific couplings of all the gamers

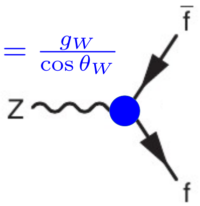
Even more a neutral scalar boson is also necessary!

Standard Model by Tree Unitarity

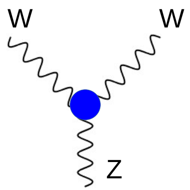
We have to consider processes involving the interactions of leptons, γ, W and Z° bosons

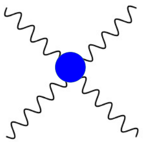
$$\sin\theta_W \equiv \frac{e}{g_W}$$

$g_Z = \frac{g_W}{\cos\theta_W}$



$g_{WWZ} = g_W \cos\theta_W$





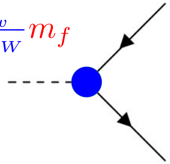
$g_{WWZZ} = g_W^2 \cos^2\theta_W$

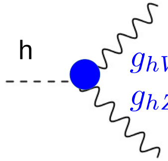
$g_{WW\gamma\gamma} = g_W^2 \sin^2\theta_W$

$g_{WWZ\gamma} = g_W^2 \sin\theta_W \cos\theta_W$

$g_{WWWW} = g_W^2$

$g_{hff} = \frac{g_w}{2m_W} m_f$





$g_{hWW} = g_W m_W$

$g_{hZZ} = g_Z m_Z$

$\frac{m_W}{m_Z} = \cos\theta_W$

All these processes violate unitarity at Tree level

but for specific couplings of all the gamers

Even more a neutral scalar boson is also necessary!

Unitarity at Tree level allows to derive
the full Electroweak Lagrangian as an effective Lagrangian

This constructivist approach was developed only as an afterthought
Still it gives a strong feeling of the inevitability of the SM

Standard Model
W, Z^o and γ
from Gauge invariance

Electroweak Unification : 1st try

For the γ we have $U(1)_{em}$

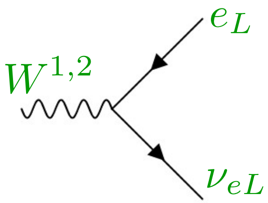
$W^{\pm}$ and Z^{o} as Gauge bosons? The 3 Gauge bosons of a $SU(2)$!

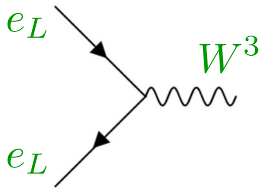
The $W^{\pm}$ know only the Left Part? A $SU(2)_L$!

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

3 bosons W^1, W^2,W^3

☺ $W^{1,2}$ couple to ≠ charges!





W^3 couples to same Charge! It is neutral! ☺

But W^3 couples only to L ☹

Our Z^o should couple to both L and R

The way out : Z^o and γ are mixtures of Gauge Bosons

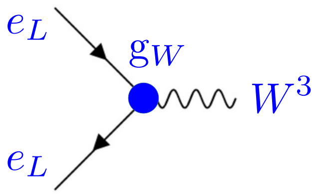
Next move : we keep $SU(2)_L$ but give up $U(1)_{em}$ group as fundamental symmetry

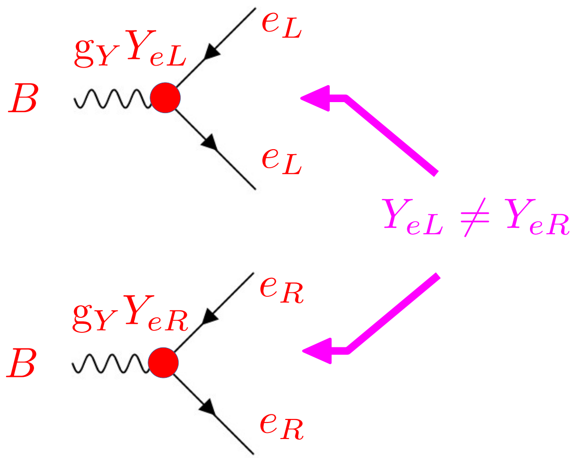
Electroweak Unification proper

$SU(2)_L$ x $U(1)_Y$

g_W g_Y

$U(1)_Y$ is chiral
L and R have
≠ hYpercharges





Electroweak Unification proper

$SU(2)_L$ x $U(1)_Y$

g_W g_Y

U(1)$_Y$ is chiral
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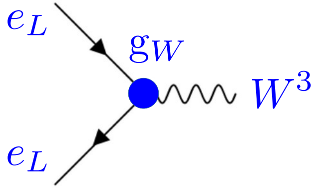
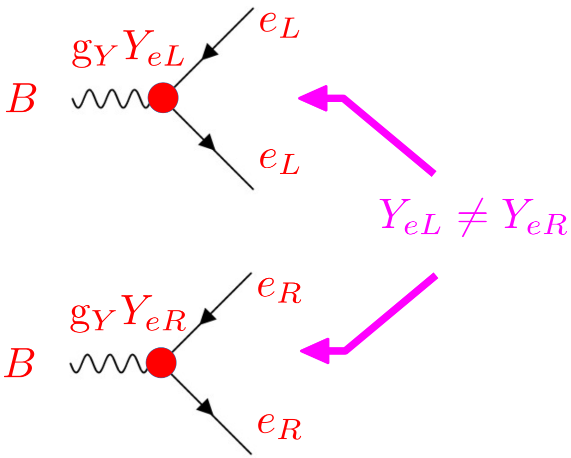


$$\begin{cases} A_\mu = W^3_\mu \sin\theta_W + B_\mu \cos\theta_W \\ Z_\mu = W^3_\mu \cos\theta_W - B_\mu \sin\theta_W \end{cases}$$

Make the A Field
equally coupling to the L and R

Possible with
$\tan\theta_W = g_Y/g_W$ and the appropriate Y



- The A is the EM Field ; we get back U(1)$_{em}$
- The Z-fermion couplings as expected
- Since γ and Z are partly W^3 which couples "naturally" to $W^{1,2}$, both γ and Z couple to $W^{\pm}$ as expected
  We get $WW\gamma$, WWZ, $WWZZ$, $WW\gamma\gamma$, $WWZ\gamma$ *vertices*

Hypercharges

Arguably the hypercharges pattern looks weird. However ...

Particles		Y
Left part	quarks	+1/6
	leptons	-1/2
Right part	up quark	+2/3
	down quark	-1/3
	electron	-1
	neutrino	0

Chiral theories suffer from Gauge anomalies destroying gauge invariance

Consistency conditions, to cancel them

$$\sum_{Left} Y^3 = \sum_{Right} Y^3$$

Magical!

$$3 \times 2 \times \left(\frac{1}{6}\right)^3 + 2 \times \left(-\frac{1}{2}\right)^3 = 3 \times \left(\frac{2}{3}\right)^3 + 3 \times \left(-\frac{1}{3}\right)^3 + (-1)^3$$

Nber of colors!

So it is necessary

- to have the Gauge groups $SU(3)_c \times SU(2)_L \times U(1)_Y$
- that fermions come in generation, (U, D, l, ν) (⇒ quark-lepton unification!) and they could barely have other charges than they have !

Standard Model
Higgs Mechanism

Higgs Mechanism

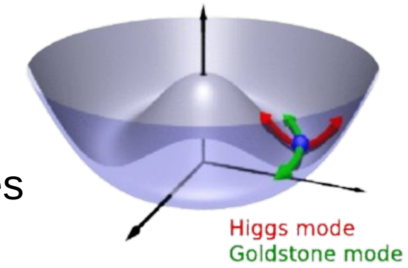
Major Issues : Chiral Gauge invariance ⇒ Massless Gauge bosons and massless fermions

$m\,\bar{\Psi}\Psi = m\,\bar{\Psi}_R\Psi_L + m\bar{\Psi}_L\Psi_R$

not invariant

A scalar Field can have a non zero value in vacuum

Around minimum
a massive Higgs (radial) and a massless Goldstone (angular) modes



SSB
Spontaneous
Symmetry
Breaking

If the scalar is subject to Gauge Symmetry the Goldstone is “eaten” by the Gauge Field that gets massive

Higgs Mechanism

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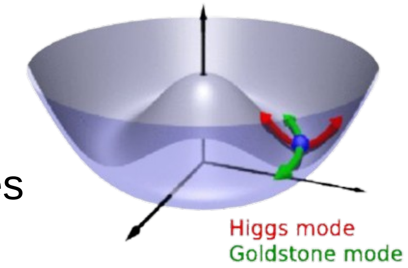


SSB
Spontaneous
Symmetry
Breaking

If the scalar is subject to Gauge Symmetry the Goldstone is “eaten” by the Gauge Field that gets massive

In the Standard Model, the Higgs field is a doublet of complex fields subject to $SU(2)_L \times U(1)_Y$

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \Phi_1 + i\Phi_2 \\ \Phi_3 + i\Phi_4 \end{pmatrix}$$

$$\mathcal{L}_\Phi = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi)$$

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \quad \rightarrow (\text{ SSB }) \rightarrow \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad v^2 = -\frac{\mu^2}{\lambda}$$

$$\mu^2 < 0 \text{ and } \lambda > 0$$

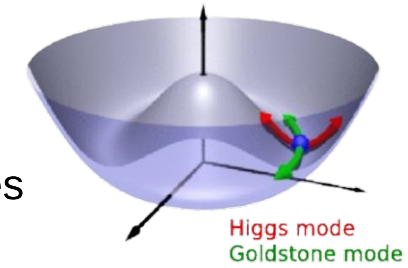
$$m_h^2 = 2v^2\lambda$$

Higgs Mechanism

Major Issues : Chiral Gauge invariance ⇒ Massless Gauge bosons and massless fermions

A scalar Field can have a non zero value in vacuum

Around minimum
a massive Higgs (radial) and a massless Goldstone (angular) modes



SSB
Spontaneous
Symmetry
Breaking

If the scalar is subject to Gauge Symmetry the Goldstone is “eaten” by the Gauge Field that gets massive

After SSB

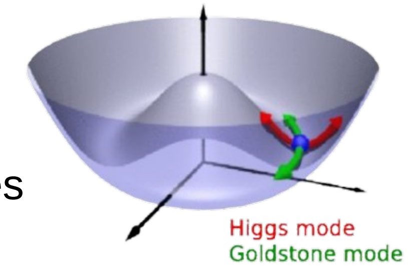
- 1 massive neutral scalar
- Mixing of the Neutral fields, i.e we get the Z and the γ, as mass eigenstates
- 3 massive bosons,W and Z, and the massless γ

Higgs Mechanism

Major Issues : Chiral Gauge invariance ⇒ Massless Gauge bosons and massless fermions

A scalar Field can have a non zero value in vacuum

Around minimum
a massive Higgs (radial) and a massless Goldstone (angular) modes



SSB
Spontaneous
Symmetry
Breaking

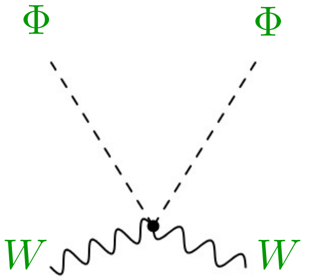
If the scalar is subject to Gauge Symmetry the Goldstone is "eaten" by the Gauge Field that gets massive

The degrees of freedom are redistributed

$$\left\{ \begin{array}{lc} 4 \text{ massless } SU(2)_L \times U(1)_Y \text{ bosons} & 4\times 2 \\ 1 \text{ Higgs complex fields doublet} & 2 \times 2 \\ & 12 \end{array} \right. \longrightarrow (\text{ SSB }) \longrightarrow \left\{ \begin{array}{lc} 3 \text{ massive } W^{\pm}, Z^o \text{ bosons} & 3\times 3 \\ 1 \text{ massless } \gamma & 2 \\ 1 \text{ scalar field} & 1 \\ & 12 \end{array} \right.$$

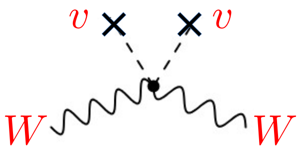
Masses Generation and Couplings to Higgs

Gauge Bosons

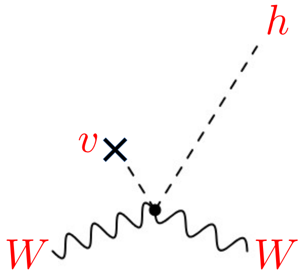


Gauge Interaction

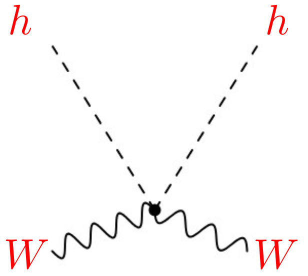
SSB
$\Phi = v + h$



Mass term

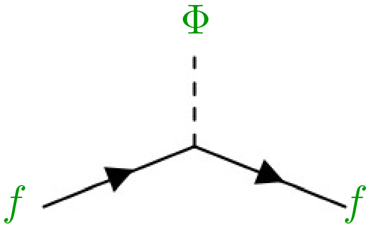


WWh 3-vertex



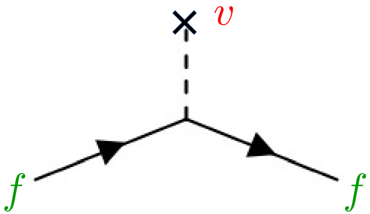
$WWhh$ 4-vertex

Fermions

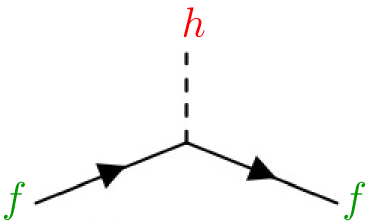


Yukawa Interaction

SSB
$\Phi = v + h$



Mass term



ffh 3-vertex

Mass generation
and
couplings to Higgs
are intimately related

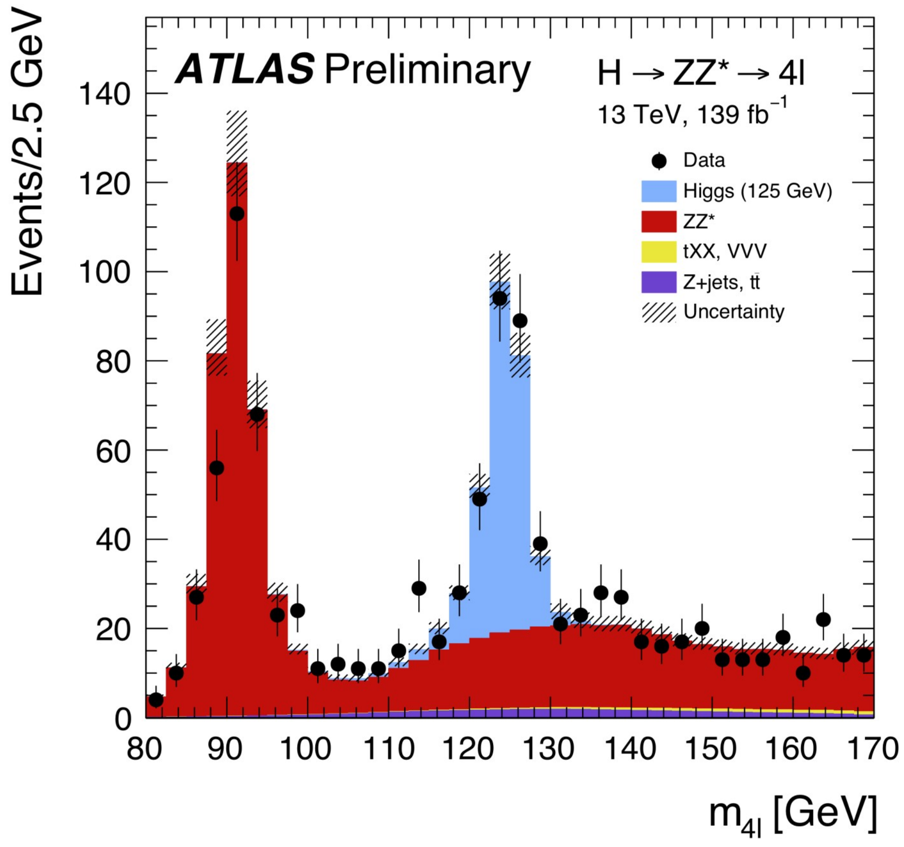
Couplings $\propto$ Mass

The Higgs for real

The Higgs boson was discovered at LHC in 2012

M_H =125.20 ± 0.11 GeV

Many of its couplings have been studied



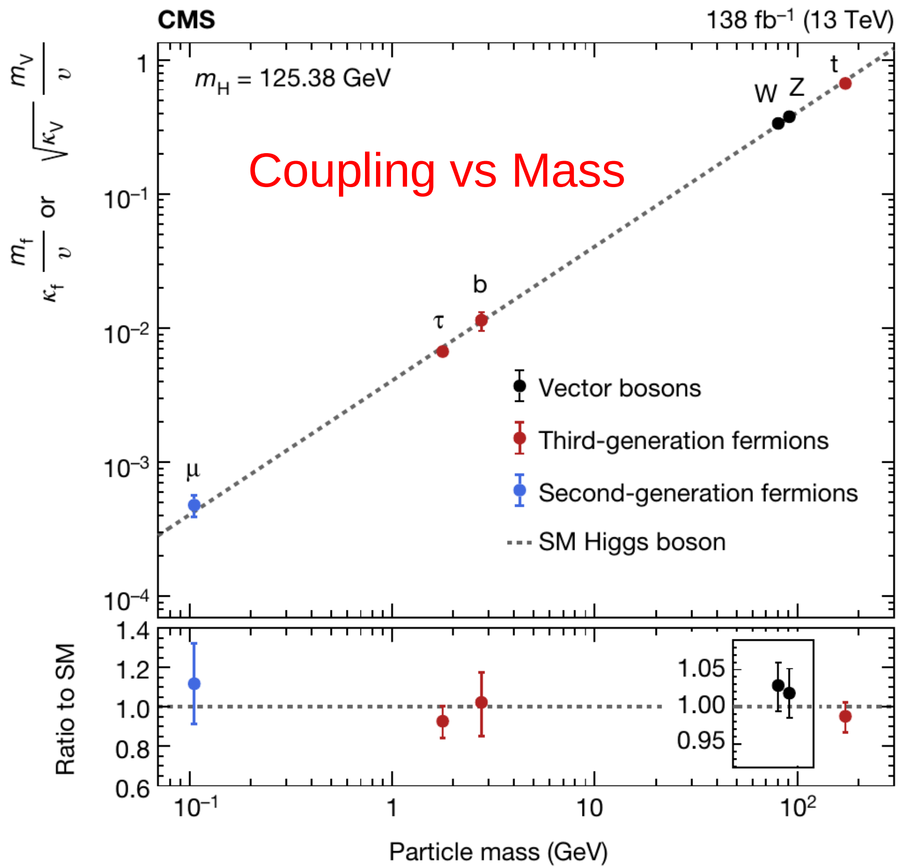
The Higgs for real

The Higgs boson was discovered at LHC in 2012

M_H =125.20 ± 0.11 GeV

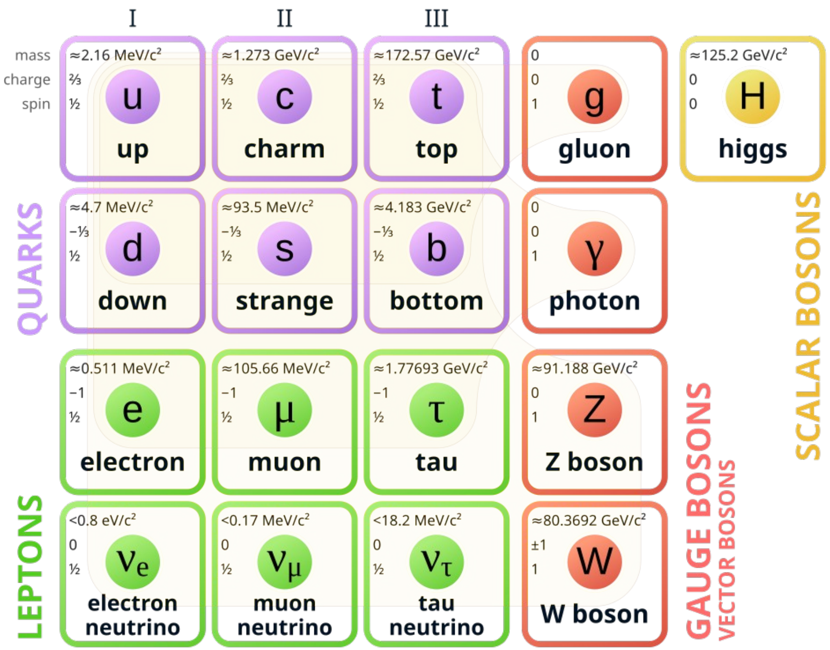
Many of its couplings have been studied

A most wonderful result
the couplings to fermions and bosons
scale with their masses exactly as predicted
over 3 orders of magnitude!



July 2022 Nature 607(7917):1-9, CMS

What do we have : the Standard Model



Fundamentally

- $SU(3)_c \times SU(2)_L \times U(1)_Y$
- a complex Scalar Field with nontrivial potential
  - massless fermions

Particles		$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Left	quarks	yes	yes	+1/6
	leptons	no	yes	-1/2
Right	up quark	yes	no	+2/3
	down quark	yes	no	-1/3
	electron	no	no	-1
	neutrino	no	no	0

Spontaneous Symmetry Breaking

- $U(1)_{em}$ QED, photon
- 3 massive bosons, $W^{\pm}$ and Z
- a massive scalar, H
- massive fermions

Least Understood Sectors

We don't know why there are 3 generations

More than 1 generation allows misalignment between mass and interacting states

CKM matrix for quarks, PMNS matrix for leptons

Those interact with W
Interaction states

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{ud} & V_{ub} \\ V_{cd} & V_{cd} & V_{cb} \\ V_{td} & V_{td} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Those interact with the Higgs
Mass states

These mixings are unconstrained : great opportunity for BSM physics

When complex (more than 2 generations), they allow CP violation (Sakharov conditions)

- Too small CP violation from quark sector due to small quarks mixing
- Possible large CP violation in lepton sector due to large neutrinos mixing

Conclusions

As Conclusions

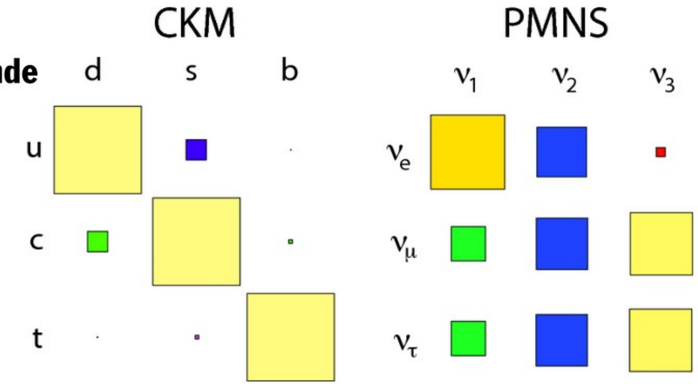
- Particle Physics is at least the Standard Model
  - There is a “necessity” chain from the Wu experiment which makes the Standard Model “inevitable”
  - Work remarkably well (few “tensions” e.g. B mesons)

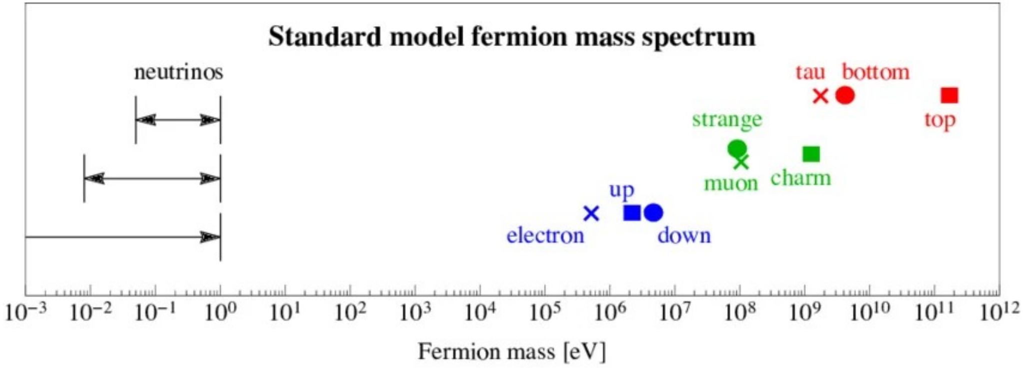
- It has many free parameters (19+?) and is often seen as an effective model

As Conclusions

- Particle Physics is at least the Standard Model
  There is a "necessity" chain from the Wu experiment which makes the Standard Model "inevitable"
  Work remarkably well (few "tensions" e.g. B mesons)

- It has many free parameters (19+?) and is often seen as an effective model
  - No Flavor theory
    - Why 3 generations?
    - Mass spectrum?
    - Why these mixing patterns (CKM, PMNS)?





As Conclusions

- Particle Physics is at least the Standard Model
  There is a "necessity" chain from the Wu experiment which makes the Standard Model "inevitable"
  Work remarkably well (few "tensions" e.g. B mesons)

- It has many free parameters (19+?) and is often seen as an effective model
  - No Flavor theory
    - Why 3 generations?
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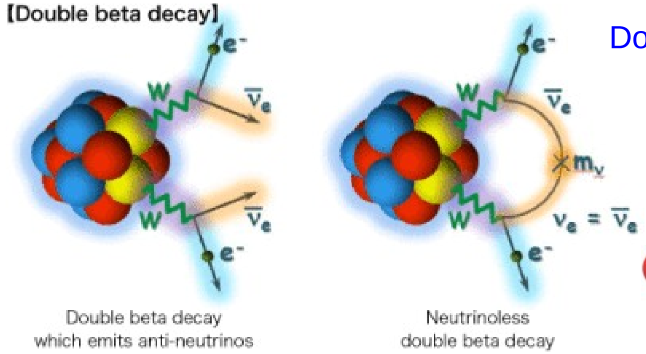
  - Neutrino nature : Dirac or Majorana?



Neutrinoless
Double beta decay

$\Delta L = 2$

BINGO

CUPID
CUORE UPgrade with Particle IDentification

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

CUORE

nEXO

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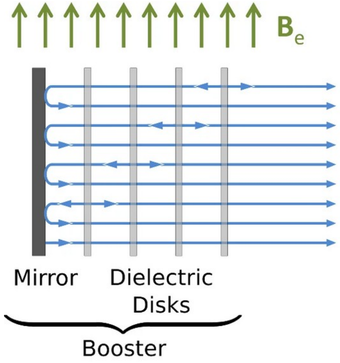

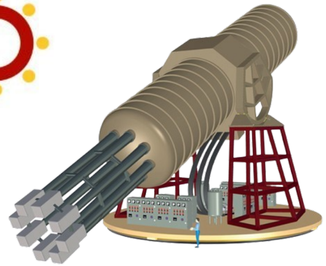

CAST

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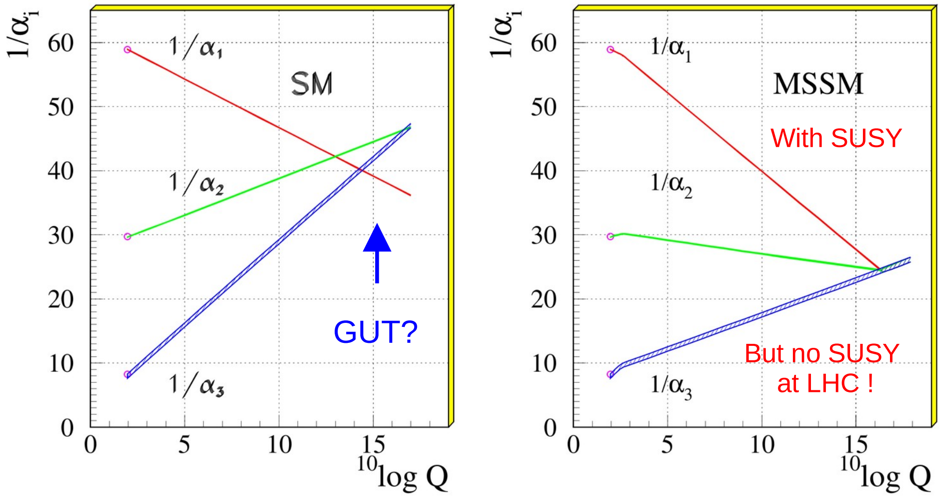

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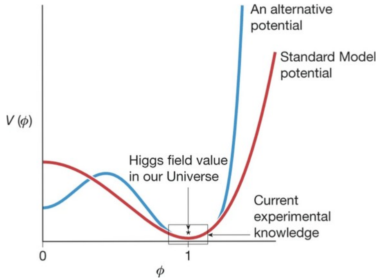
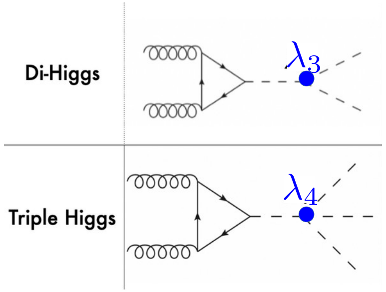
    No hint at LHC of new particles that could stabilize it



Mapping the Higgs potential at LHC and HL-LHC

$$V(h) = \frac{1}{2}m_h^2 h^2 + \lambda_3 v h^2 + \frac{1}{4}\lambda_4 h^4$$



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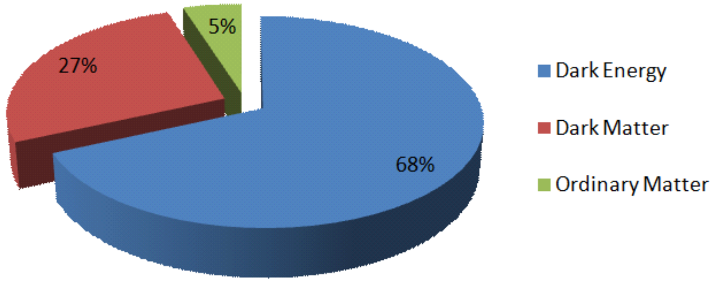
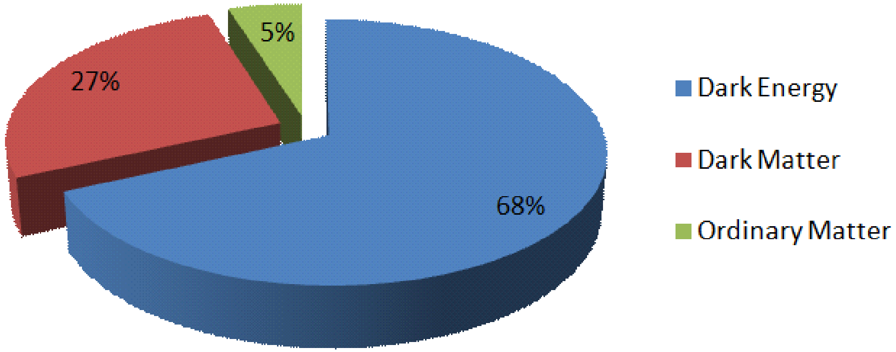
    No hint at LHC of new particles that could stabilize it
  - No Gravity, No Dark Energy, No Dark Matter
    And we are told that we deal with only 5% of the Universe stuff!



As Conclusions

There are more things in Heaven and Earth,
than are in the Standard Model



The Future is yours

Thank you for your attention

As Conclusions

Search for Beyond Standard Model Physics is well motivated
eg SUSY (strong case : Higgs stabilization, Dark matter, couplings unification)
But
LHC has put severe constrains on many BSM scenarios