Conclusion on Particle Physics

« Physics of both Infinities »
Ecole d'Eté France Excellence 2017

S. Muanza
CPPM Marseille, ATLAS Group
CNRS-IN2P3 & AMU

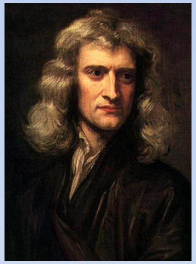
OUTLINE

1. Foundations of Modern Physics
2. Quantum Field Theory in a Nutshell
3. Standard Model
4. Beyond the Standard Model
5. Supersymmetry
6. Conclusions

1. Foundations of Modern Physics

1.A. Reminders on Classical Physics

- Main components:
  - Mechanics:
    - Study of bodies motion (kinematics) and their causes (forces)
    - Fundamental principle of dynamics I. Newton (1687)



$$\boxed{\vec{F} = \frac{d\vec{p}}{dt}}$$

  - Electromagnetism:
    - Common theory for all electric, magnetic and optical phenomena
    - Brilliant synthesis expressed in 4 equations J.C. Maxwell (1864)
    - Expt[al] proof: discovery of EM waves H. Hertz (1887)
  - Statistical Physics:
    - System with many particles
    - Deeper foundation for thermodynamics

$$\left\{\begin{aligned} rot\,\vec{E} &= -\frac{\partial \vec{B}}{\partial t} \\ div\,\vec{E} &= \frac{\rho}{\varepsilon_0} \\ rot\,\vec{B} &= \mu_0 \cdot \left(\vec{j} + \varepsilon_0 \cdot \frac{\partial \vec{E}}{\partial t}\right) \\ div\,\vec{B} &= 0 \end{aligned}\right.$$

- Global Framework:
  - Absolute 3-D Space
  - Absolute 1-D Time
  - Causality
  - Galilean Relativity

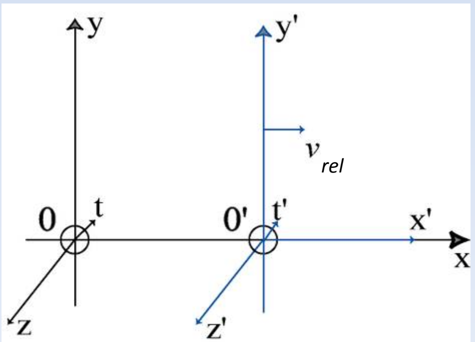
1. Foundations of Modern Physics

1.A. Reminders on Classical Physics

- Location in space: $\vec{r} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}$
- Location dans le temps: t
- Galileo Transform:

$$\begin{cases} x' = x - v_{rel} \cdot t \\ y' = y \\ z' = z \\ t' = t \end{cases}$$

G. Galileo (1593)



- Galilean Relativity:
  - Relativity Principle:
  « physics laws are identical in all inertial frames »

- Velocity (vector) addition formula

$$\vec{v} = \vec{v}' + \vec{v}_{rel}$$

1. Foundations of Modern Physics

1.A. Reminders on Classical Physics

Conservation Laws

- For an isolated system, conserved quantities:
  - Energy: E
  - Mass: m
  - Momentum: $\vec{p}$
  - Angular Momentum: $\vec{L} = \vec{r} \times \vec{p}$
  - Electric Charge: q

  - Conserved physical quantity:
    - constant along the time evolution of the system =>

$$\boxed{(Physical\ Quantity)_{initial} = (Physical\ Quantity)_{final}}$$

Conservation Laws & Symmetries

- For an isolated system:

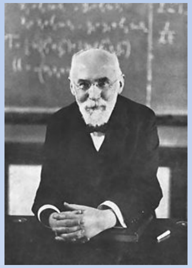
Conserved Quantity	Symmetry of the Physical System
Momentum: $\vec{p}$	Invariance wrt Translation in Space
Energy: E	Invariance wrt Translation in Time
Angular Momentum: $\vec{L}$	Invariance wrt Rotation in Space

Theorem by E. Noether (1918)

1. Foundations of Modern Physics

• Modern Physics relies on 2 pilars discovered in a « Double Revolution » in early 20th century

1.B. Special Relativity



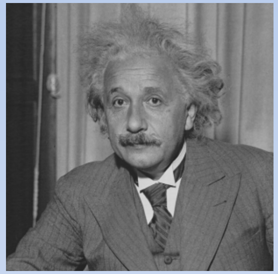
H. Lorentz (1904)
Nobel L. (1902)

$$\beta = \frac{v}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$c \approx 300\,000 \text{ km/s}$$

$$\boxed{E = \gamma \cdot m \cdot c^2}$$



A. Einstein (1905)
Nobel L. (1921)

$$\begin{cases} L = L_0/\gamma & \text{: length contraction} \\ T = \gamma \cdot T_0 & \text{: time dilatation} \end{cases}$$

• Lorentz Transform preserves the invariance of Maxwell's equations, contrarily to Galileo Transform

$$\boxed{\begin{cases} x' = \gamma \cdot (x - \beta \cdot c \cdot t) \\ y' = y \\ z' = z \\ t' = \gamma \cdot (-\frac{\beta}{c} \cdot x + t) \end{cases}}$$

• Generalisation of Relativity Principle:
  - speed of light is the same in all (inertial) frames
  - it's the maximal speed for any physical system

• Energy & matter are equivalent

• Time and space coordinates are no longer independent
  - Space-time H. Minkowski 1907

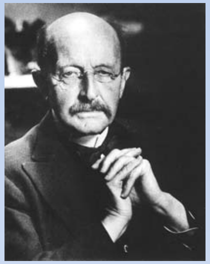
• Explains the Michelson-Morley's (1887) expt

1. Foundations of Modern Physics

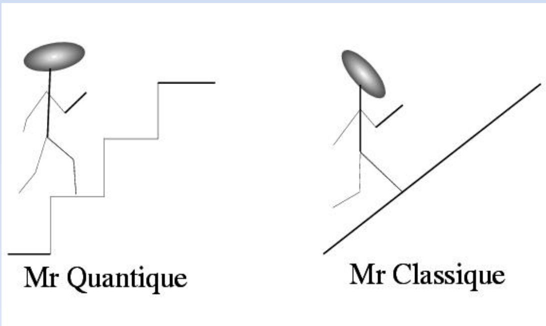
1.C. Quantum Mechanics

$$\boxed{E = n \cdot h \cdot \nu}$$

$h = 6.63 \times 10^{-34}\ J \cdot s$



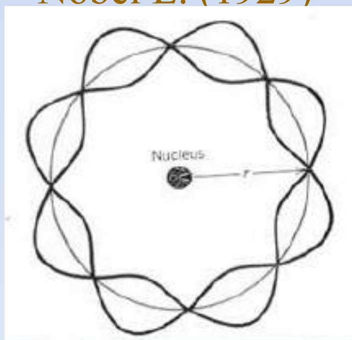
M. Planck (1900)
Nobel L. (1918)



• Explains black-body radiation

$$\boxed{\lambda = \frac{h}{p}}$$

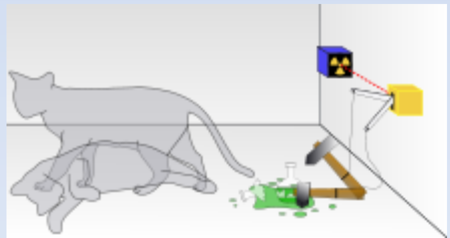
L. de Broglie (1924)
Nobel L. (1929)



• Explains atom stability

$$\boxed{-\frac{\hbar^2}{2m} \cdot \Delta\psi + V \cdot \psi = i\hbar \cdot \frac{\partial \psi}{\partial t}}$$

E. Schrödinger (1926)
Nobel L. (1933)



• NR QM Evolution equation

• Perturbation Method: complicated equations resolved by iterative approximations

$$E = E^{(0)} + \alpha \cdot E^{(1)} + \alpha^2 \cdot E^{(2)} + \ldots$$

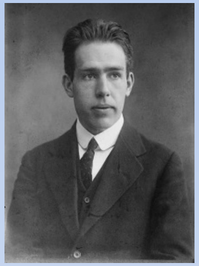
1. Foundations of Modern Physics

1.C. Quantum Mechanics

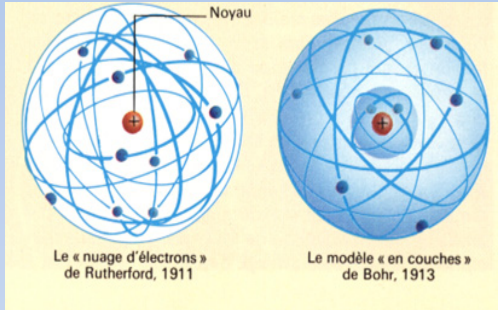
$$[R,P] = R \cdot P - P \cdot R = i\frac{h}{2\pi}$$

$$\Delta x \cdot \Delta p_x \geq \frac{h}{4\pi}$$

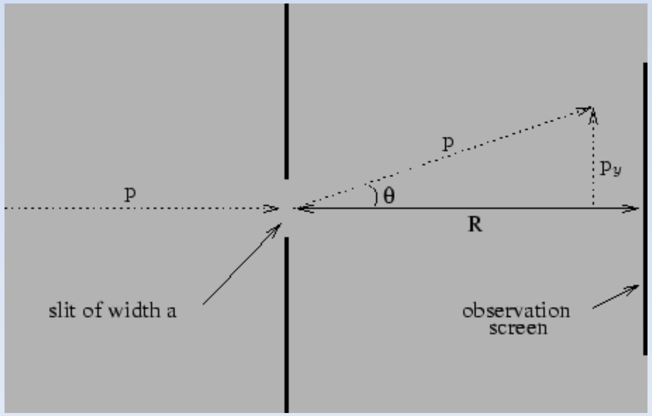
W. Heisenberg (1927)
Nobel L. (1932)

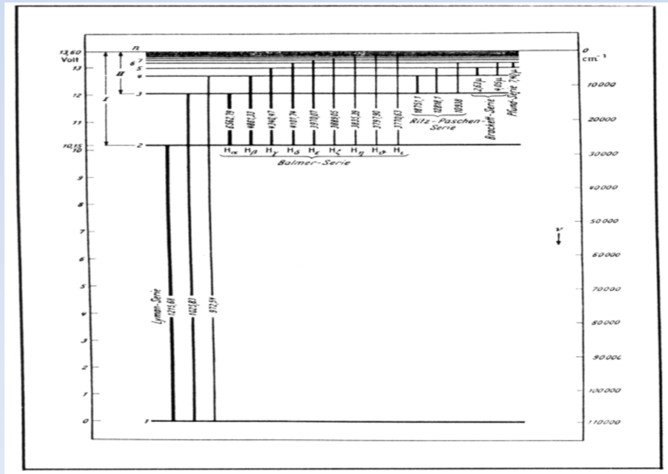


N. Bohr (1913)
Nobel L. (1922)



$$E_n = \frac{-1}{n^2} \cdot \frac{2\pi^2 \cdot m \cdot e^4}{h^2}$$

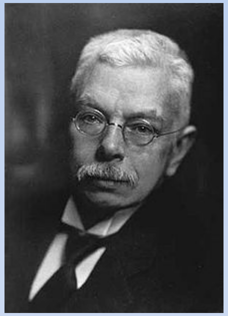




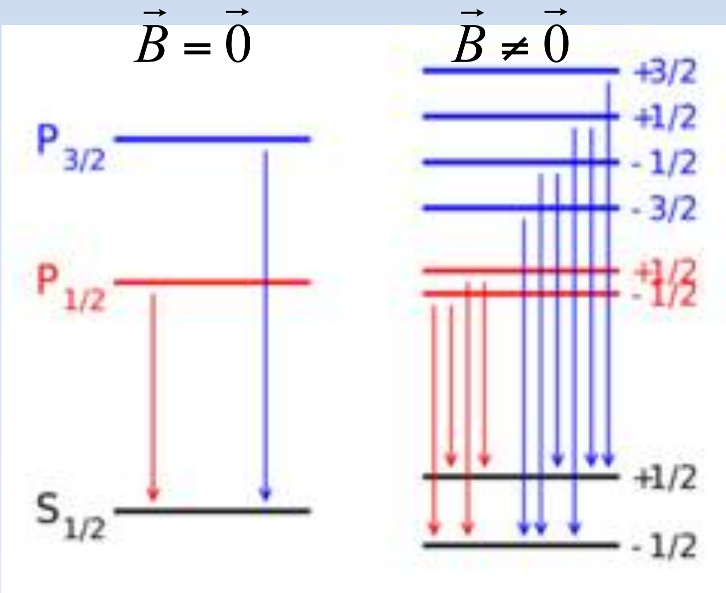
1. Foundations of Modern Physics

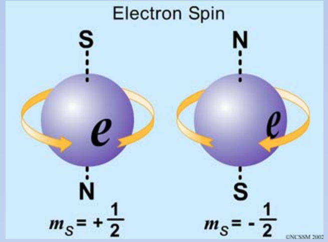
1.C. Quantum Mechanics

• Zeeman effect: magnetic field lifts degeneracy between quantum states



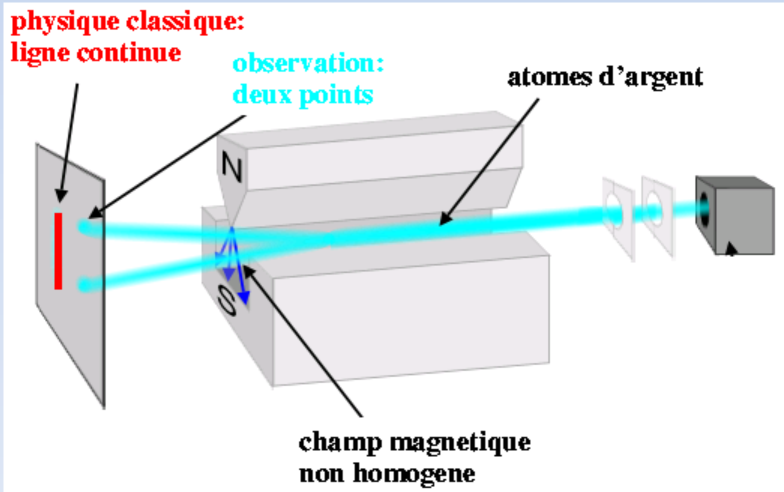
P. Zeeman (1886)
Nobel L. (1902)





S. Goudsmit & G. Uhlenbeck (1925)

• Spin: particle intrinsic magnetism,
« as if they were actually spinning »



Experiment by O. Stern et W. Gerlach (1922)
Nobel L.: O. Stern (1943)

• Application: MNR

1. Foundations of Modern Physics

1.C. Quantum Mechanics

• Pauli's Exclusion Principle:

« two electrons cannot simultaneously occupy the same quantum state »

W. Pauli (1925)
Nobel L. (1945)

• Spin-Statistics Theorem: M. Fierz (1939) W. Pauli (1940)

Name	Bosons	Fermions
Spin	Integer	½-Integer
Type of Elementary Particle	Interaction Carrier	Matter Building Block
Quantum Statistics	Bose-Einstein (1924)	Fermi-Dirac (1926)
Collective Behaviour	Gregarious « Sheep-like »	Individualistic « Pauli's Exclusion Principle »
Examples	Lasers, Superconductors, …	Electrons in atoms

1. Foundations of Modern Physics

1.D. Tensor Character of Physical Quantities

- **Scalar:**
  - Space: *« Requires no directions to be defined »*
  - *Scalar Field: 1 value per point in space*
  - *Any rotation leaves this field unchanged => S=0*
  - Ex: mass, time, temperature,…
- **Vector:**
  - Space: *« Requires 1 direction to be defined »*
  - *Vector Field: 3 indpt values per point in space*
  - *Any rotation => vector direction changes 1 turn => vector restored => S=1*
  - Ex: electric field, magnetic field, position, velocity, acceleration, force,…
- **Tensor:**
  - Space: *« Requires 2 directions to be defined »*
  - *Tensor Field: 5 indpdt values per point in space*
  - *Any rotation => 2 dirs change*
  - *Tensor r=2: ½-turn => tensor unchanged => S=2*
  - Ex: mechanical stress,…
- **Spinor:**
  - Space: *« Requires 2s+1 dirs to be defined »*
  - *Spinor Field: 2s+1 indpdt projections on space directions*
  - *Any rotation => components changed 2 turns => spinor restored => S=1/2*
  - Ex: electron in relativistic quantum mechanics (Dirac equation),…

2. QFT in a Nutshell

2.A. Motivation

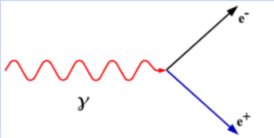
- To construct a sensible theory of subatomic systems, requires to comply simultaneously with both: Special Relativity & Quantum Mechanics
- This is achieved in Relativistic Quantum Field Theory (QFT)

$$E_{kin} = (\gamma - 1) \cdot m \cdot c^2$$

- Energy-Matter equivalence: $\boxed{E = \gamma \cdot m \cdot c^2}$

$$E_{mass} = m \cdot c^2$$

- Particle creation/annihilation:



- QFT copes with physical system that have variable (even infinite) number of particles
  - It uses creation and annihilation operators at given points in space-time
  - It also introduces particle propagation between 2 points in space-time, but at max. speed = c. No instataneous propagation of forces like in classical physics.

2. QFT in a Nutshell

2.B. Elementary Fermions

- Dirac equation: for a single free particle with S=1/2 (say an electron) denoted ψ(x,t), the dynamical equation that replaces Schrödinger equation in relativistic QFT is the Dirac equation
- It starts of from the following expression of matter-energy equivalence:

$$\boxed{\mathrm{E}^2 = p^2 \cdot \mathrm{c}^2 + m^2 \cdot c^4}$$

And it linearizes this equation by using α and β matrices:

$$\boxed{\left[\beta mc^2 + \left(\sum_{j=1}^{3} \alpha_j \cdot p_j\right)\right]\psi(x,t) = i\hbar \frac{\partial \psi(x,t)}{\partial t}}$$

2. QFT in a Nutshell

2.B. Elementary Fermions

- Elementary fermions are the « building blocks » of matter
- For an unknown reason there is 2 replica of the first family:

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*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	–1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	–1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	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

2. QFT in a Nutshell

2.C. Elementary Bosons

- Klein-Gordon equation: for a single free particle with S=0 (a Higgs boson) denoted $\phi(x,t)$, the dynamical equation that replaces Schrödinger equation in relativistic QFT is the Klein-Gordon equation
- It starts of from the following expression of matter-energy equivalence:

$$\boxed{\mathrm{E}^2 = p^2 \cdot \mathrm{c}^2 + m^2 \cdot c^4}$$

And through the correspondence principle, one gets:

$$\boxed{\Delta\phi(x,t) - \frac{1}{c^2} \cdot \frac{\partial^2 \phi(x,t)}{\partial t^2} = \frac{m^2 c^2}{\hbar^2} \cdot \frac{\partial \phi(x,t)}{\partial t}}$$

2. QFT in a Nutshell

2.C. Elementary Bosons

- Elementary bosons are the fundamental interactions « carriers »
- There are 4 fundamental interactions:
  - Gravitation:
    - Classically described by a $1/r^2$ attractive force by I. Newton 1687
    - Extended to a non-quantum gauge theory in General Relativity by A. Einstein 1915
    - Responsible for the cohesion of matter at large scales (solar system, galaxies,…)
  - Electromagnetism (EM):
    - Classically described by Maxwell equations
    - Responsible for the cohesion of matter in atoms and molecules
  - Strong Interaction:
    - Discovered in subatomic phenomena
    - Responsible for the cohesion of the nucleon (n,p) and the nucleus
  - Weak Interaction:
    - Discovered in subatomic phenomena
    - Responsible for decays of some nuclei, neutron,…
  - They are explained in QFT by exchange of gauge bosons

2. QFT in a Nutshell

2.C. Elementary Bosons

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

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

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

	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

2. QFT in a Nutshell

2.C. Elementary Bosons

- Gravitation:
  - Not treated by most particle physics theories because the strength is negligibly small
  - No satisfactory quantum theory of gravity yet!
  - Expect the carrier, the graviton, to have S=2
  - Range: infinite; Relative intensity (@ low energy): 10^{-39}
- Electromagnetism (EM):
  - QFT: Quantum Electro Dynamics (QED)
  - Abelian Symmetry group: $U(1)_{EM}$, 1 generator, the photon (γ), S=1
  - Photon couples to elecrtic charge
  - Range: infinite; Relative Intensity: 10^{-3}
- Strong Interaction:
  - QFT: Quantum Chromo Dynamics (QCD)
  - Non-Abelian Symmetry group: $SU(3)_C$, 8 generators, the gluons (g), S=1
  - Gluons couple to colour charge and have self-couplings
  - Range: 10^{-15} m; Relative Intensity: 1
- Weak Interaction:
  - QFT: Electroweak Theory
  - Non-Abelian Symmetry group: $SU(2)_L$, 3 generators, W^+, W^-, Z^0, S=1
  - Weak gauge bosons couple to weak hypercharge
  - W & Z bosons couple differently to L-handed or R-handed fermions (P violation)
  - W does not couple to R-handed fermions
  - Range: 10^{-18} m; Relative intensity: 10^{-14}

2. QFT in a Nutshell

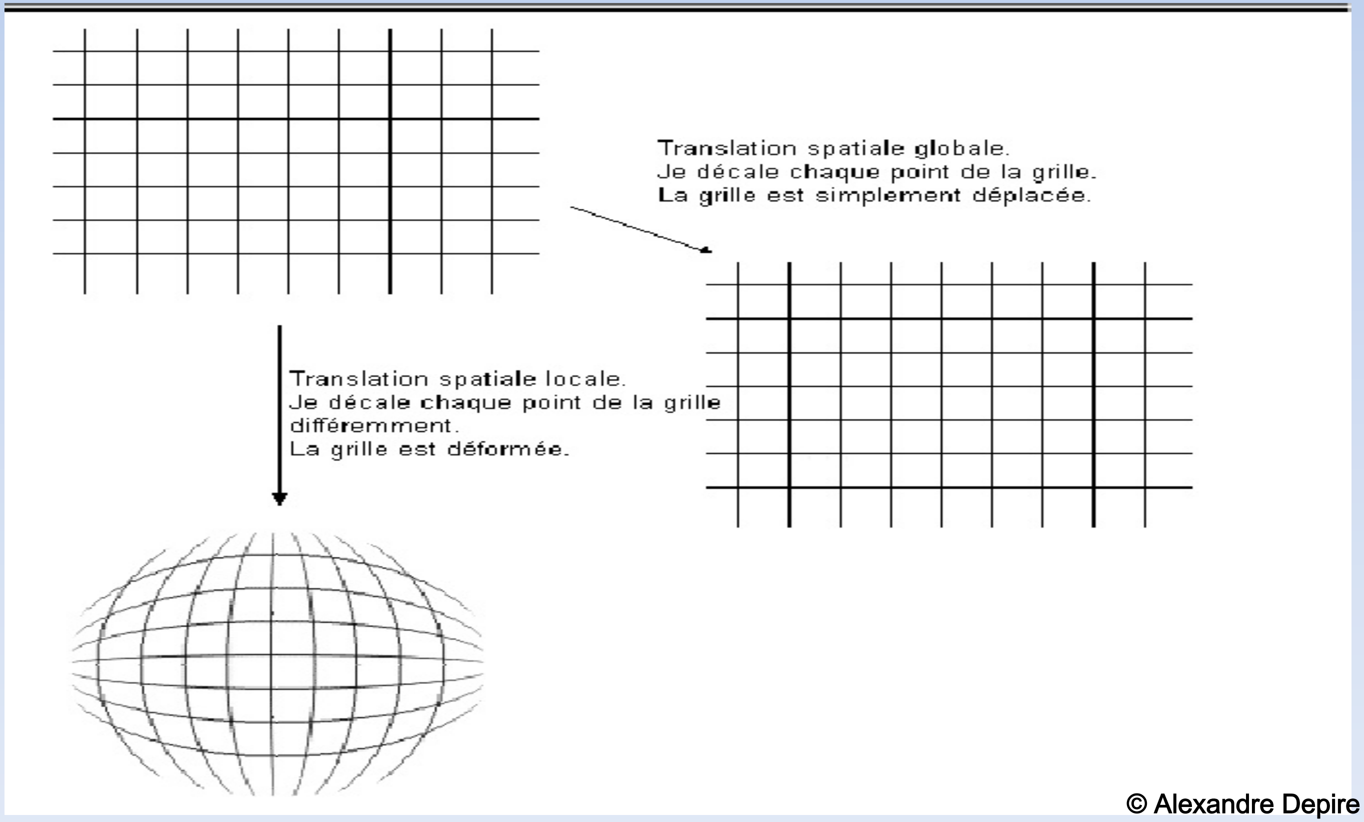
2.C. Elementary Bosons

• Global Symmetry:

Symmetry operations are applied the same way for each point of the physical system

• Local Symmetry:

Symmetry operations are applied differently for each point of the physical system

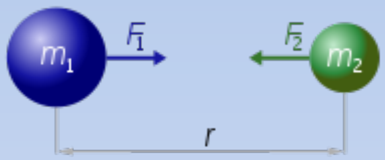


• What is required to keep the system invariant when applying local symmetry is exactly the gauge interactions!

2. QFT in a Nutshell

2.C. Special Case of Gravitation

• Till the beginning of the 20th century, Newton's theory prevailed:



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

• force is exerted on instantaneously (irrespective of the distance r)

• this conflicts with Special Relativity!

• In 1915 Einstein extended Relativity to frames with arbitrary respective motions (accelerated frames). This is General Relativity theory:

• local matter-energy density deforms space-time locally

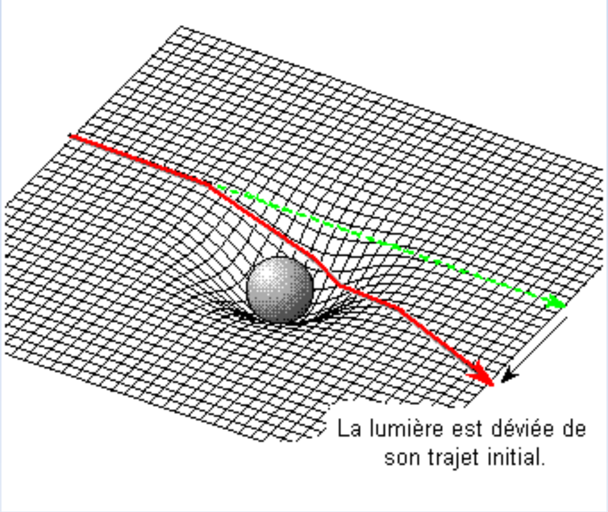
• body trajectories are geodesic in this space-time

• this theory is based upon invariance wrt to a local change of coordinates

• the theory is not quantized

• it's a geometrical gauge theory

• Application: your GPS!

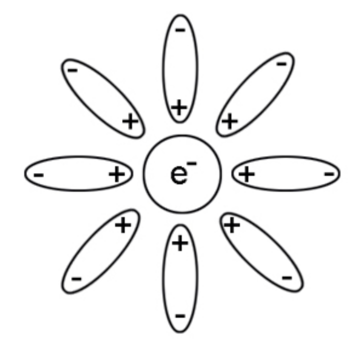


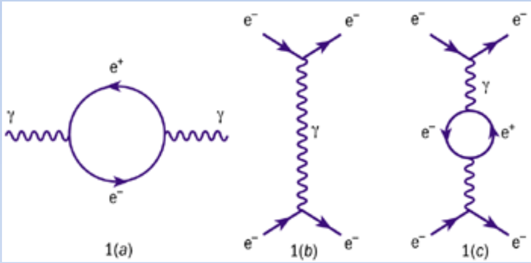
2. QFT in a Nutshell

2.C. Elementary Bosons

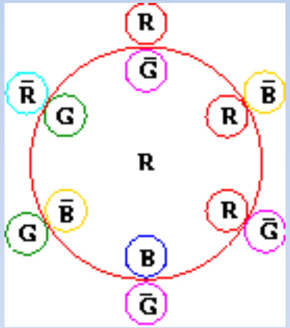
- The evolution of the interactions coupling constants with energy depend on the way these interactions polarize the quantum vacuum

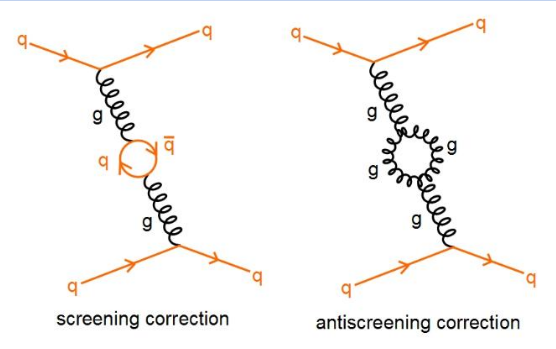
- Electromagnetism (EM): screening effect

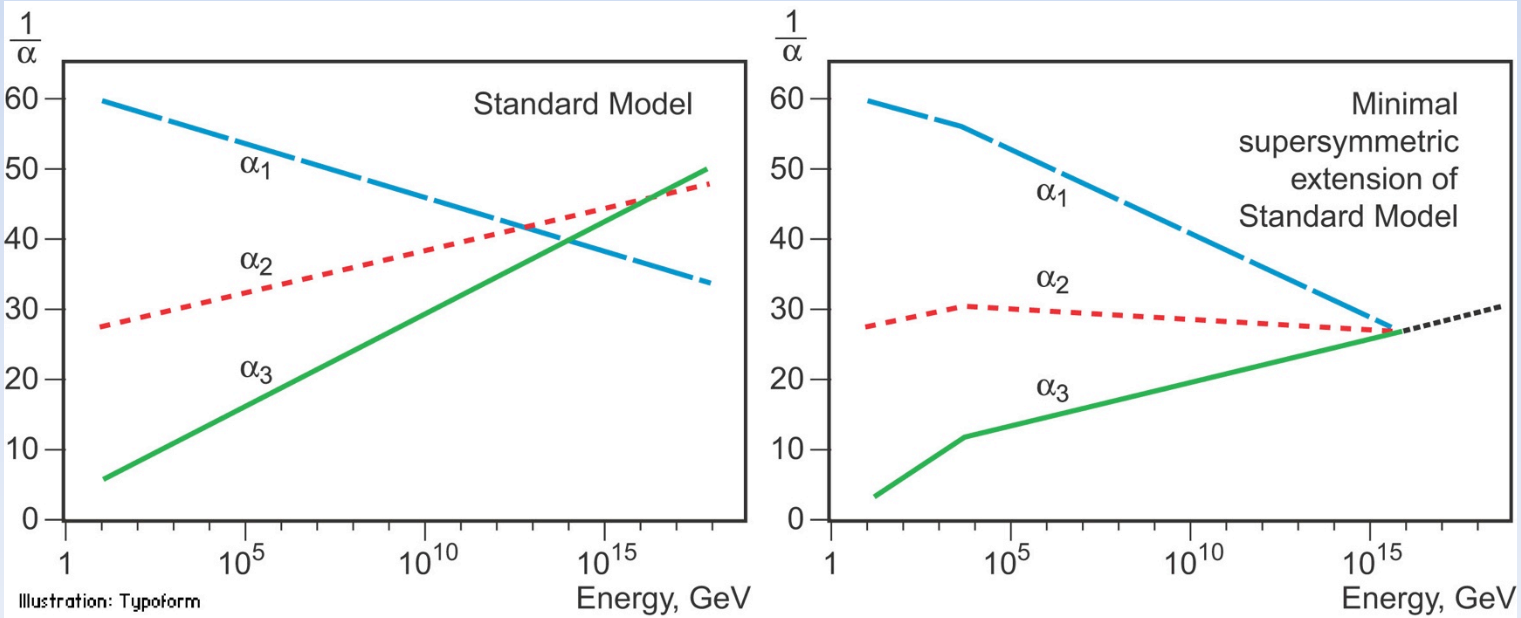




- Strong Interaction: both screening and anti-screening effects







2. QFT in a Nutshell

2.D. Consequences of QM

- Observing a Particle Physics phenomenon requires to have three separate magnifying lenses
- Theses lenses are direct consequences of SR & QM:

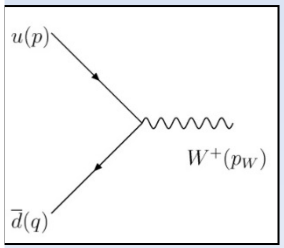
1. Since QM is intrinsically probablistic one needs a STATISTICAL LENS: repeat measurements MANY TIMES so as to measure the mean value (and other stat. moments) with sufficient precision
2. The basis of wave mechanics is that all particle have both corpuscle and wave properties. All particle have an associated wave which has a de Broglie's wavelength:

$$\boxed{\lambda = \frac{\mathbf{h}}{\mathbf{p}}}$$

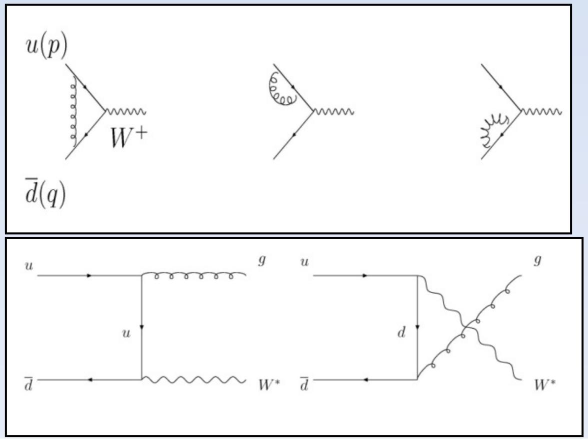
Therefore to probe matter at small scales, one needs High Energy. This defines a HIGH ENERGY LENS.

3. The 3rd lens required for accurate theory prediction is the QUANTUM LENS. It is due to the fact that in QM almost no physics cases can be exactly solved! Instead one uses approximate methods, most often a perturbative development:

$$\boxed{\mathcal{M} = \mathcal{M}^{(0)} + \boldsymbol{\alpha} \cdot \mathcal{M}^{(1)} + \boldsymbol{\alpha}^2 \cdot \mathcal{M}^{(2)} + \ldots}$$



Leading Order



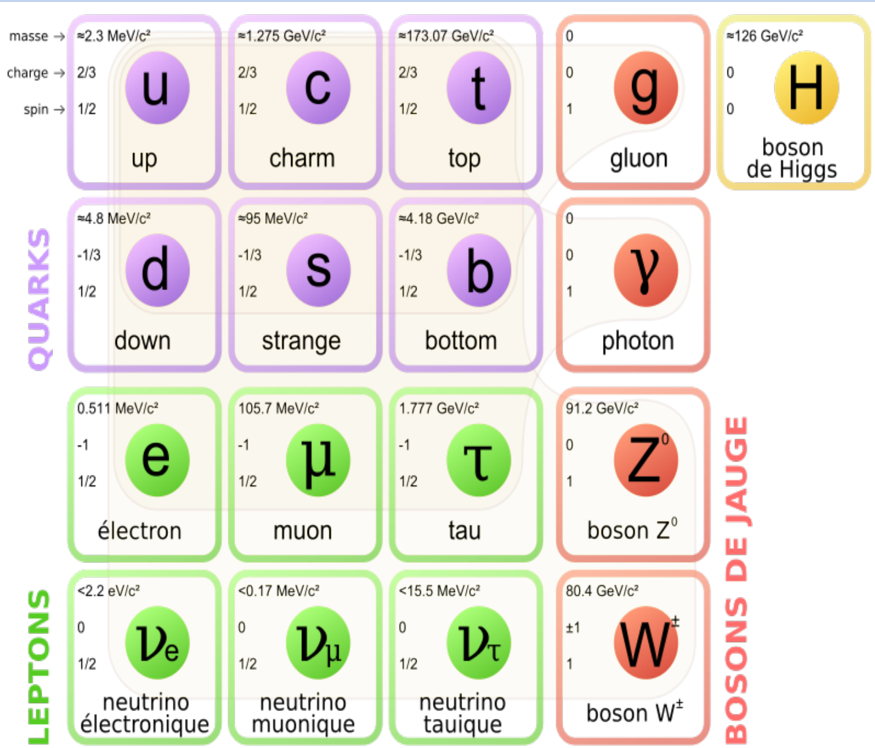
Next-to-Leading Order
(aka 1-Loop Corrections)

3. Standard Model

3.A. Description

- As all QFT, the SM is defined by its PARTICLE CONTENT and its SYMMETRIES

- PARTICLE CONTENT:



- SYMMETRIES:
  - Poincaré group:
    - Lorentz group (rot., boost)
    - Translation
  - Discrete: invariance under

$$\boxed{C \cdot P \cdot T}$$

    - C: charge conjugation
    - P: space reversal
    - T: time reversal
  - Gauge: invariance under

$$\boxed{G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}$$

3. Standard Model

3.B. Exact Gauge Symmetries

- In the SM, the masses of most particles are protected (from large quantum corrections) by some symmetries
- $SU(3)_C$: gauge invariance forbids introducing a mass term for the gluons => gluons are massless
- $U(1)_{EM}$: gauge invariance forbids introducing a mass term for the photon => photon is massless
- $SU(2)_L$: chirality forbids introducing mass terms for the charged fermions => charged fermions are massless
- All particles are massless: this CANNOT be!
- Mixing SR and QM enables to estimate the range of the interactions:
    - Start from Heisenberg inequality: $\boxed{\Delta E \cdot \Delta t \geq \frac{\hbar}{2}}$
    - Plug in matter-energy equivalence: $\boxed{\mathbf{E_{mass} = m \cdot c^2}}$

  …

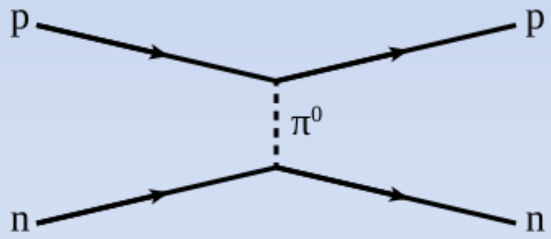
    - Compton wavelength: $\boxed{\lambda_C = \frac{h}{m \cdot c}}$

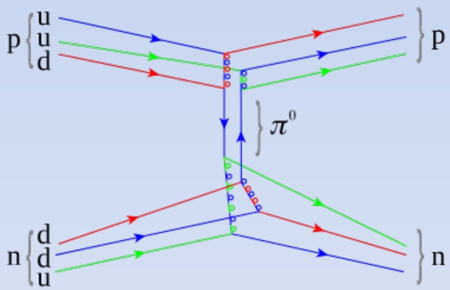
3. Standard Model

$$\lambda_C = \frac{h}{m \cdot c}$$

3.B. Exact Gauge Symmetries

- $U(1)_{EM}$: is fine. Massless photon is compatible with gauge invariance and with infinite range interaction.
- $SU(3)_C$: strong interactions are observed to be short-ranged. But this can be explained by the large value of α_S. Historically that's how H. Yukawa (1934) made the first model of strong interaction via the exchange of pion, a particle he predicted to be 200 heavier than the electron. This prediction was confirmed with the discovery of $\boxed{\pi^{\pm}}$ in cosmic rays by G. Occhialini et al. (1947). The mass of the pion is compatible with the range of strong interactions.





- $SU(2)_L$: however, for weak interactions, there is no such thing as strong coupling and confinement! So here, we cannot solved the contradiction between observed short range and gauge invariance which implies infinite range!
The reason is that the exact gauge symmetry mentioned before are too high compared to Nature! For weak interaction, one needs a spontaneous symmetry breaking!

3. Standard Model

3.C. Broken Gauge Symmetry

• So far we discussed essentially symmetries and found it's a very useful concept. Yet we know that Nature is not fully symmetric. What to do then?

- either a physical system does not respect a given symmetry
  => we forget about this symmetry, we simply cannot apply it
- or the system fully respect this symmetry
  => we apply it as shown before
- or the system is close to being symmetric but isn't quite…
  => here is a situation where possibly the level of symmetry needs to be reduced

• Symmetry breaking:
- Situation where:
  - the equations have a symmetry,
  - but the solution has lost this symmetry

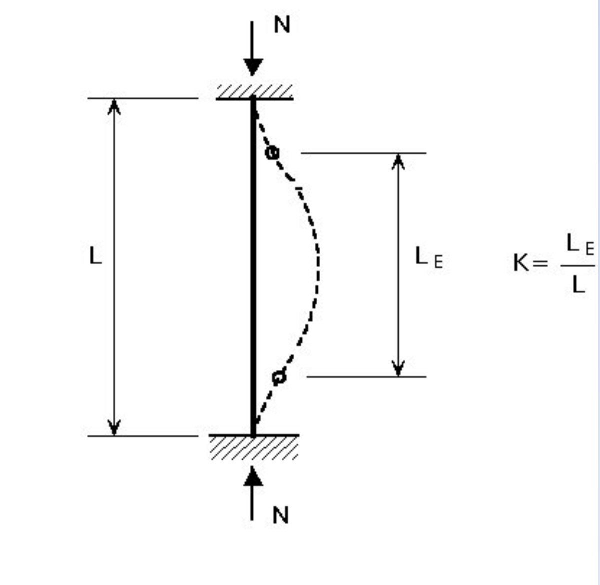
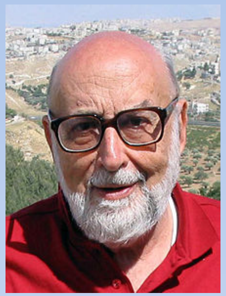


Figure 2 Equivalent column length

3. Standard Model

3.C. Broken Gauge Symmetry

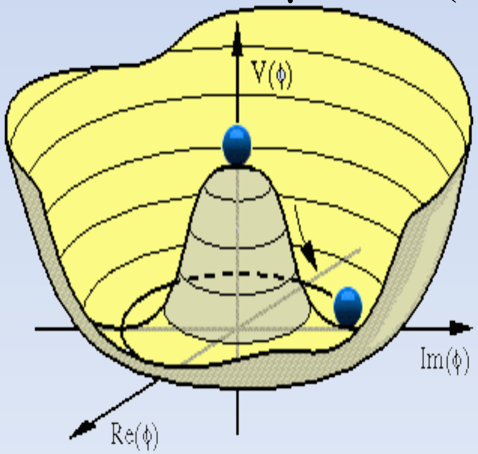


P. Higgs & F. Englert (1964)
Nobel L. (2013)

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \Rightarrow \text{1 neutral scalar particle } H^0$$

$$V(\Phi) = \mu^2 \,|\Phi^\dagger \Phi| + \lambda \,|\Phi\ \Phi^\dagger|^2$$

$\lambda > 0$ et $\mu^2 < 0$ (arbitrary choice)



Breaking of Electroweak Symmetry

$$\boxed{SU(2)_L \times U(1)_Y \to U(1)_{EM}}$$

Mass Generation

- Gauge Bosons:
  - $m_W = \dfrac{g \cdot v}{2}$
  - $m_Z = \dfrac{g \cdot v}{2\cos\theta_W}$
  - $m_\gamma = 0$

$v = \sqrt{\frac{-\mu^2}{\lambda}} \approx 246\,\text{GeV}$

- Charged Fermions:
  - $m_f = \dfrac{\lambda_f v}{\sqrt{2}}$
- Higgs Boson:
  - $m_H = \sqrt{2\lambda}\, v$

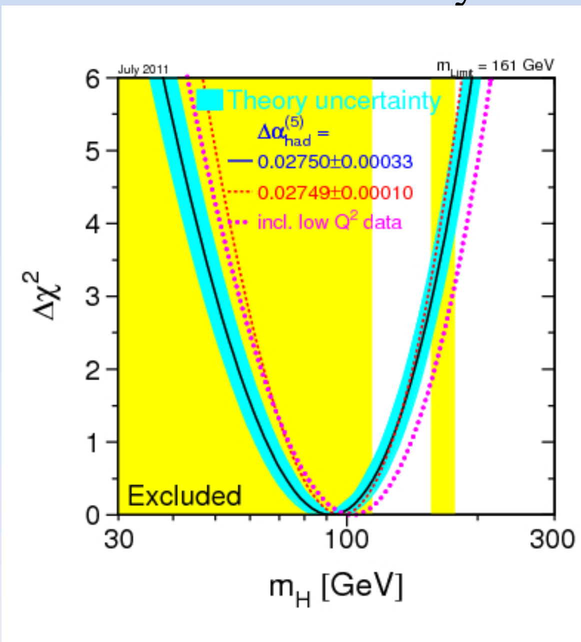
3. Standard Model

3.C. Broken Gauge Symmetry

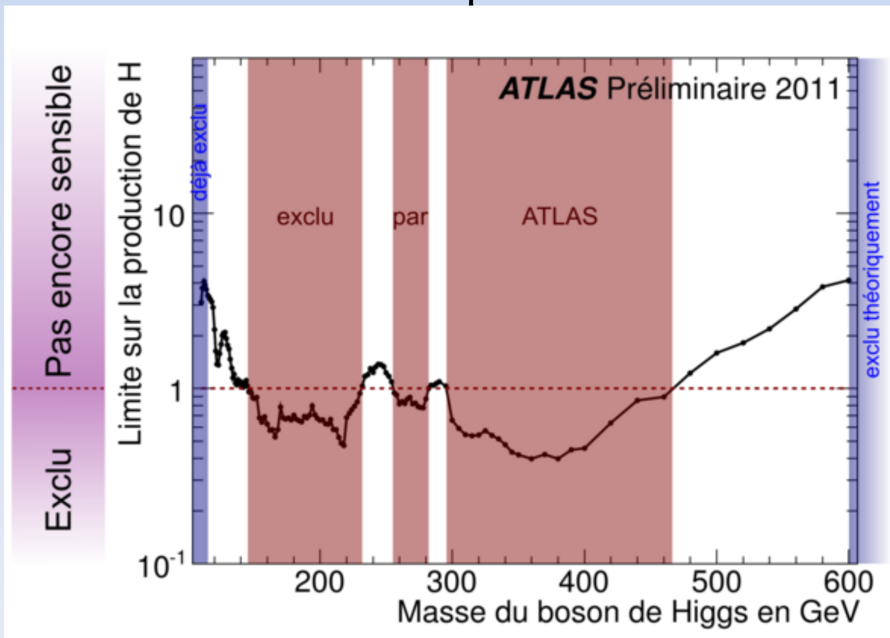
« Analogy: fame »

- The SM does not predict the Higgs boson mass
- But there were constraints (before the LHC era):

indirect from theory:



direct from experiments:



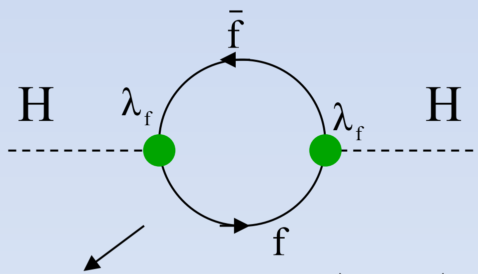
3. Standard Model

3.C. Broken Gauge Symmetry

- In QFT, to ensure a mass is stable, its quantum corrections need to be relatively small

- In the SM, the masses of:
  - gauge bosons, are protected by gauge invariance
  - charged fermions, are protected by chirality
  - Higgs boson has no symmetry to protect it!

  $\Rightarrow$ In the context of Grand Unification (10^{16} GeV) its quantum corrections could be extremely large



$$m_H^2(1\text{–}\mathrm{Loop}) = m_H^2(\mathrm{Bare}) + N_f \frac{\Lambda_f^2}{8\pi^2}\left| -\Lambda^2 + 6m_f \mathrm{Log}\left(\frac{\Lambda}{m_f}\right) - 2m_f^2 \right|$$

- Besides, unitary constraints requires the Higgs boson mass to be at most ~800 GeV

3. Standard Model

3.D. Long List of Discoveries

- …
- Bottom quark (1977):
  - E288 experiment at FNAL, Chicago USA
  - TEVATRON: $\boxed{\mathbf{p + N}}$ collisions at $\boxed{\sqrt{s} = 400\ \mathrm{GeV}}$ (fixed target)
- W and Z bosons (1983):
  - UA1 & UA2 experiments at CERN, Geneva CH
  - SppS: $\boxed{\mathbf{p + \bar{p}}}$ collisions at $\boxed{\sqrt{s} = 630\ \mathrm{GeV}}$
- Top quark (1995):
  - CDF & D0 experiments at FNAL, Chicago USA
  - TEVATRON: $\boxed{\mathbf{p + \bar{p}}}$ collisions at $\boxed{\sqrt{s} = 1.8\ \mathrm{TeV}}$
- Higgs Boson (2012):
  - ATLAS & CMS experiments at CERN, Geneva CH
  - LHC: $\boxed{\mathbf{p + p}}$ collisions at $\boxed{\sqrt{s} = 7-8\ \mathrm{TeV}}$

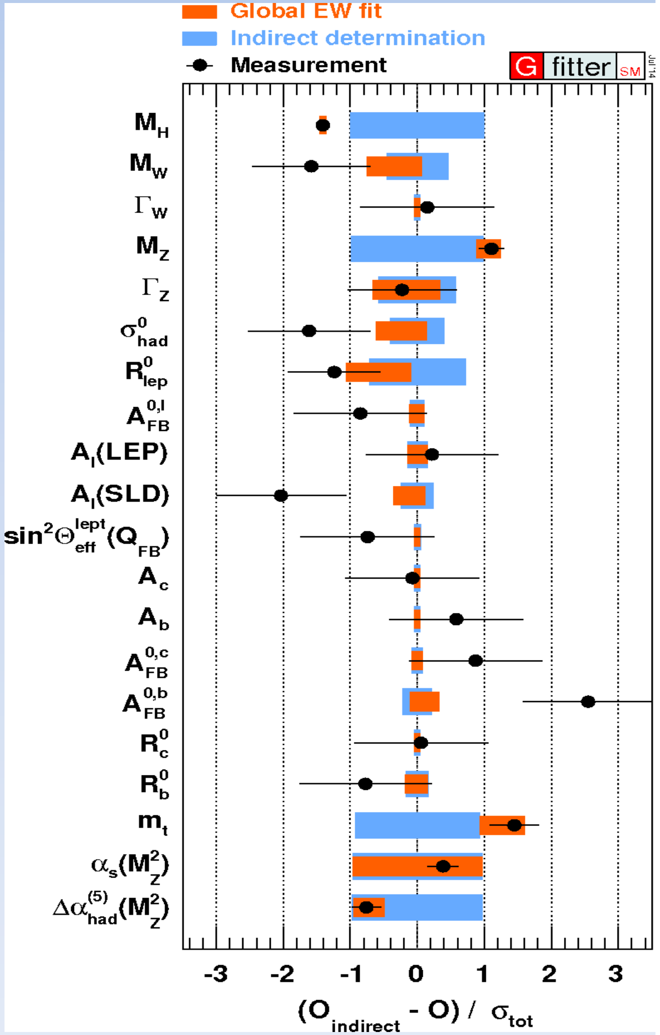
3. Standard Model

3.E. Global Fit

- Remarquable agreement with experimental data:

- Theory:
  - NNLO EW and NNLO EW-QCD
- Experiment:
  - EW Precision measurements

- χ^2 Global Fit of Data to SM:
  - χ^2_{min} / Nd.o.f. = 17.8 / 14
  - $P(\chi^2) = 22\%$



3. Standard Model

3.F. Open Questions

- The SM has 19 UNPREDICTED parameters:

  - Gauge couplings:
    - g_1, g_2, g_3 (or α, α', α_S)
  - Charged Fermions masses (or Yukawa couplings):
    - $e/\mu/\tau$ and $u/d/s/c/t/b$
  - Higgs potential parameters:
    - μ^2, λ
  - 3 CKM matrix elements + 1 phase (CPV)
  - 1 CPV parameter in QCD sector

3. Standard Model

3.F. Open Questions

- Neutrinos:
  - Expt: flavour oscillations => non-zero masses
  - Not explained by the SM
  - SM could accomodate this provided:
    - Breaking of lepton number conservation, or
    - New Right-handed neutrinos

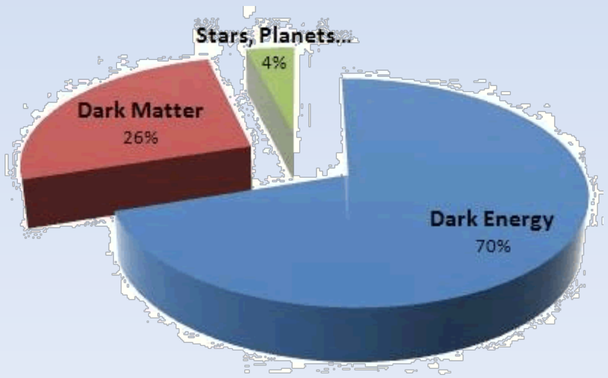
- Except for ν masses, the SM explain all the phenomena observed in HEP experiments

- Yet, even at the HE frontier it is incomplete / unsatisfactory:
  - Non natural Higgs boson sector
  - No quantum theory of gravity

3. Standard Model

3.F. Open Questions

- Large scale gravitational puzzles:
  - SM explains about 4% of the energy density in the Universe
  - Cold Dark Matter (about 26%):
    - Rotation curves of spiral galaxies
    - Large scale formations,…
    - No SM particles can explain that!
  - Dark Energy (about 70%):
    - The Universe expansion is accelerating!
    - No SM particles / fields / interactions can explain that!



3. Standard Model

3.G. Extension of the SM

- How to extend the SM so as to resolve its open questions?

Extended Gauge Group:
$SU(2)_L \times SU(2)_R$, $SU(5)$, $SO(10)$, E_6, E_8,…

Supersymmetry

Extra-Dimensions

Strong Electroweak Symmetry Breaking

4^{th} generation

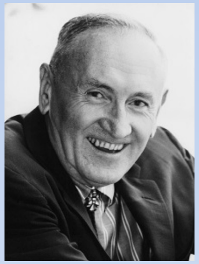
Compositrness

Or a combination of hese hypotheses

4. Beyond the Standard Model

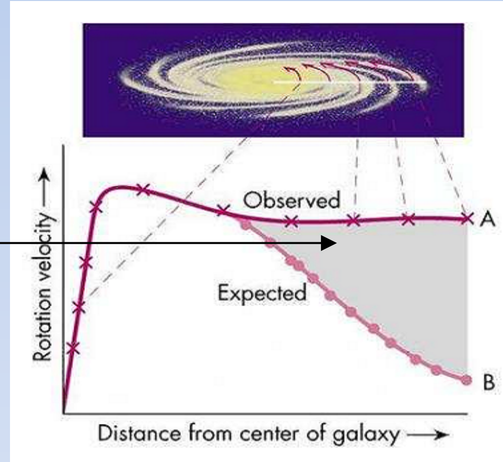
4.A. Dark Matter

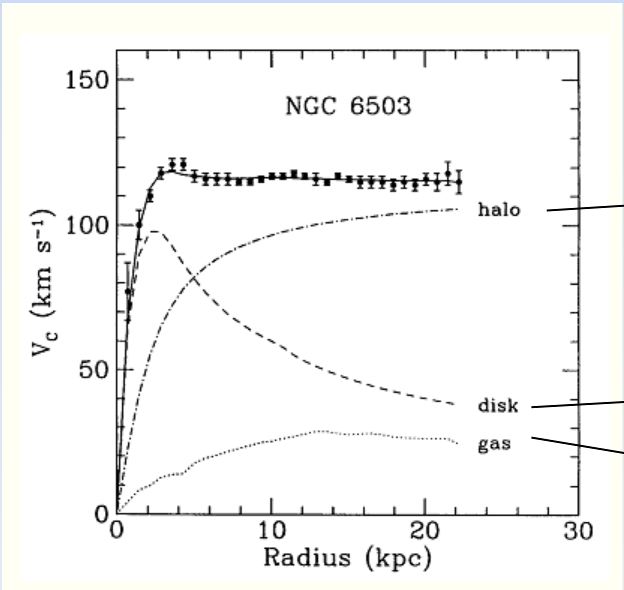
• The rotation curves of spiral galaxies are incompatible with the presence of only visible matter (stars)



F. Zwicky (1933)

$$v = \sqrt{\frac{GM(r)}{r}}$$





Dark Matter halo

stars

Gas disks

4. Beyond the Standard Model

4.A. Dark Matter

- Identikit of the suspect:
    - Massive Particle,
    - No Electric Charge,
    - No Colour Charge,

    => Sensitive to weak interaction only

- Question: Is there a SM particle which is a candidate for Cold Dark Matter?
- Answer: No

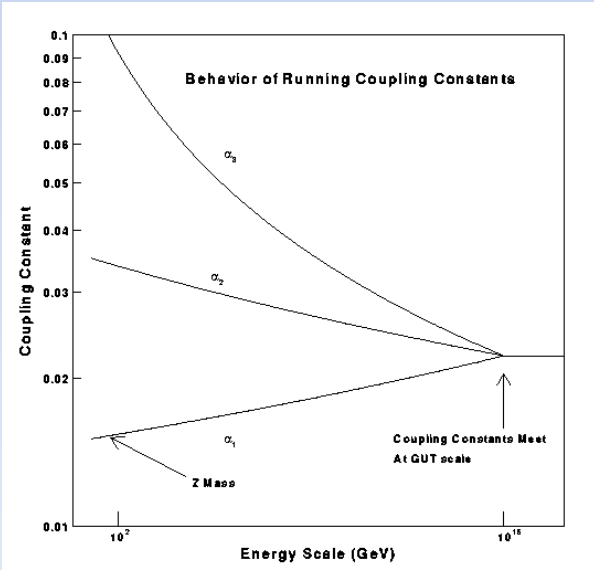
4. Beyond the Standard Model

4.B. Grand Unification

- Definition: Unified Theory of Strong and Electroweak Interactions

H. Georgi (1974)

S. Glashow (1974)
Nobel L. (1979)



$$\psi_L = \begin{pmatrix} 0 & \bar{u}_3 & \bar{u}_2 & u_1 & d_1 \\ \bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ \bar{u}_2 & \bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \longleftarrow SU(5)$$

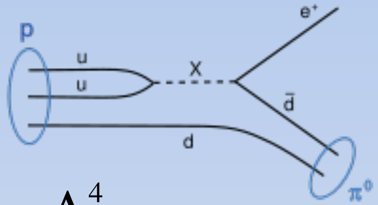
4. Beyond the Standard Model

4.B. Grand Unification

- Theoretical Predictions:

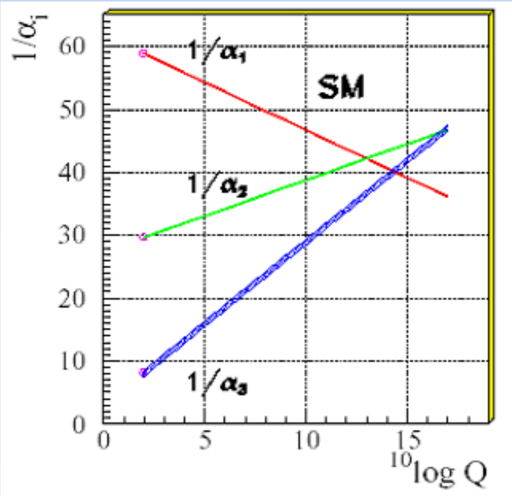
Unified Equal Coupling Constant for Strong and EWK Intractions

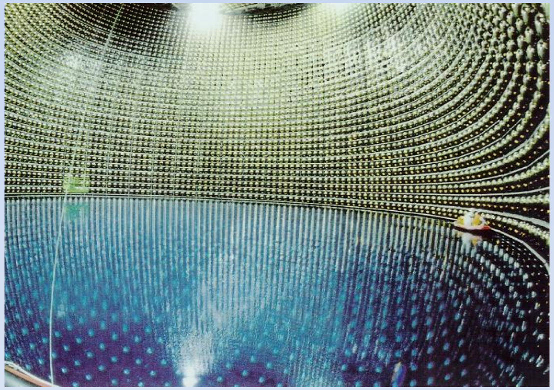
Proton Decay



$$\tau_p^{Th} \approx \frac{\Lambda_{GUT}^4}{m_p^5} \approx 10^{28-30}\ years$$

- Experimental Tests:





$$\tau_p^{Ex} > 8.2 \times 10^{33}\ years$$

Experiment Super-Kamiokande (2005)

- Conclusion:
  - Model is « dead », but not burried!
  - Considered very elegant and as a « near shot »…

5. Supersymmetry

5.A. Introduction

- Definition: Symmetry between fermions (½-integer spin) and bosons (integer spin)

$$\boxed{Q|S\rangle = |S \pm 1/2\rangle}$$

$$\boxed{\{Q,\overline{Q}\} = Q\cdot\overline{Q} + \overline{Q}\cdot Q \propto P_\mu} \longrightarrow$$

2 consecutive SUSY transformations are equivalent to a space-time translation!

- If Q is a local SUSY transform then the system is invariant under change of local coordinates: this is a definition for General Relativity!!!

$\Rightarrow$ Local Supersymmetry includes a (non quantum) theory of gravitation! (aka Supergravity)

- Extended Supersymmetry:
  - Maximum number of supersymmetries is:
    - $\mathcal{N} = 4$, for global SUSY
    - $\mathcal{N} = 8$, for local SUSY

5. Supersymmetry

5.B. Particle Content

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	$+1$	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	-1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	-1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	-1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	-1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	-1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	-1	$\widetilde{G}$	(same)

5. Supersymmetry

• Question 1: Is SUSY present in the Standard Model?

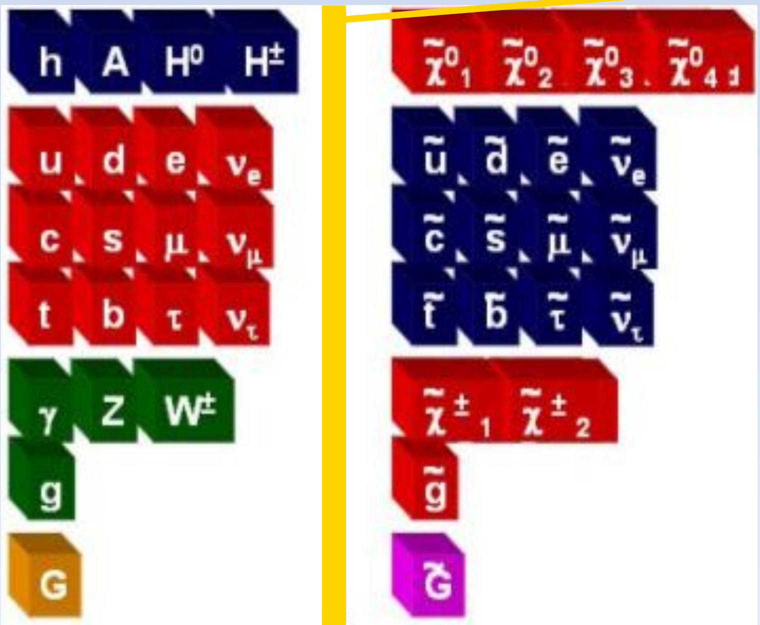
• Answer 1: No, because there are many more fermionic degrees of freedom than bosonic ones

• Conclusion 1: One needs to associate a SUSY partner (Beyond the Standard Model) to each Standard Model particle

• Question 2: Is SUSY an exact symmetry of Nature (at accessible energy scales)?

• Answer 2: No, otherwise we would have discovered the Selectron (S=0). Compared to the electron it would have the same mass, same electric charge, but would obey Bose-Einstein Statistics!

• Conclusion 2: SUSY must be a broken symmetry!



5. Supersymmetry

The MSSM

• The MSSM is the « Minimal Supersymmetric Standard Model » :

- $\mathcal{N} = 1$
- Minimal particle content
- Same gauge group as the SM:

$$G_{MS} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

- Without additional hypotheses, it has 105 unpredicted parameters (+19 from SM)!

• In order to preserve some predictivity to this model, one adds a number of phenomenological hyoptheses

• R-Parity:

$$\boxed{R_P = (-1)^{2S+3(B-L)}}$$

+1 for SM particles

-1 for SUSY particles

- if conserved

=> No rapid proton decay

=> pair production of SUSY particles

=> a LSP (Lightest SUSY Particle) appears at the end of each SUSY decay chain

=> the LSP is stable

5. Supersymmetry

mSUGRA

- mSUGRA is the « Minimal Model of SUperGRAvity » :
  - Many phenomenological hypotheses on top of the MSSM,
  - Grand Unification is assumed: $M_{GUT} = 2 \times 10^{16}$ GeV

  - SUSY breaking occurs in a « hidden sector » which communicates with the « visible sector » only through gravitational interactions:
    - which depends:
      - neither on the electric charge,
      - nor on the colour charge,
      - nor on the flavour
    - depends only on spin

TeV Scale

Visible Sector
m(part.) < m(spart.)

Very High Energy

Hidden Sector
~~SUSY~~

Interactions Indpdt of Flavour, Charges

$\langle 0 | F | 0 \rangle \neq 0$

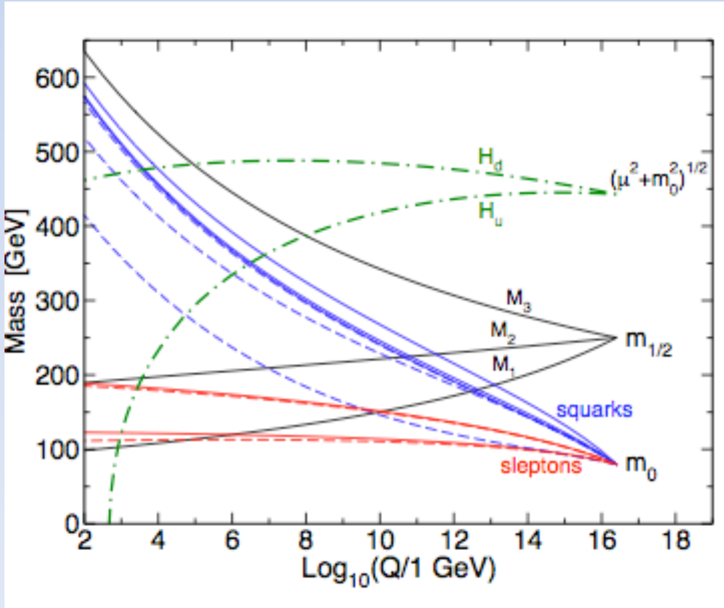
5. Supersymmetry

mSUGRA (2)

- Free Parameters:
  - m_0: universal scalar mass
  - $m_{1/2}$: universal gaugino mass
  - A_0: universal trilinear coupling
  - $\tan\beta$: ratio of vacuum expectation values of the 2 Higgs doublets
  - SIGN(μ): where μ is the higgsino mass term

- Higgs Sector:

$$\boxed{m_{h^0} < 136 \text{ GeV}}$$

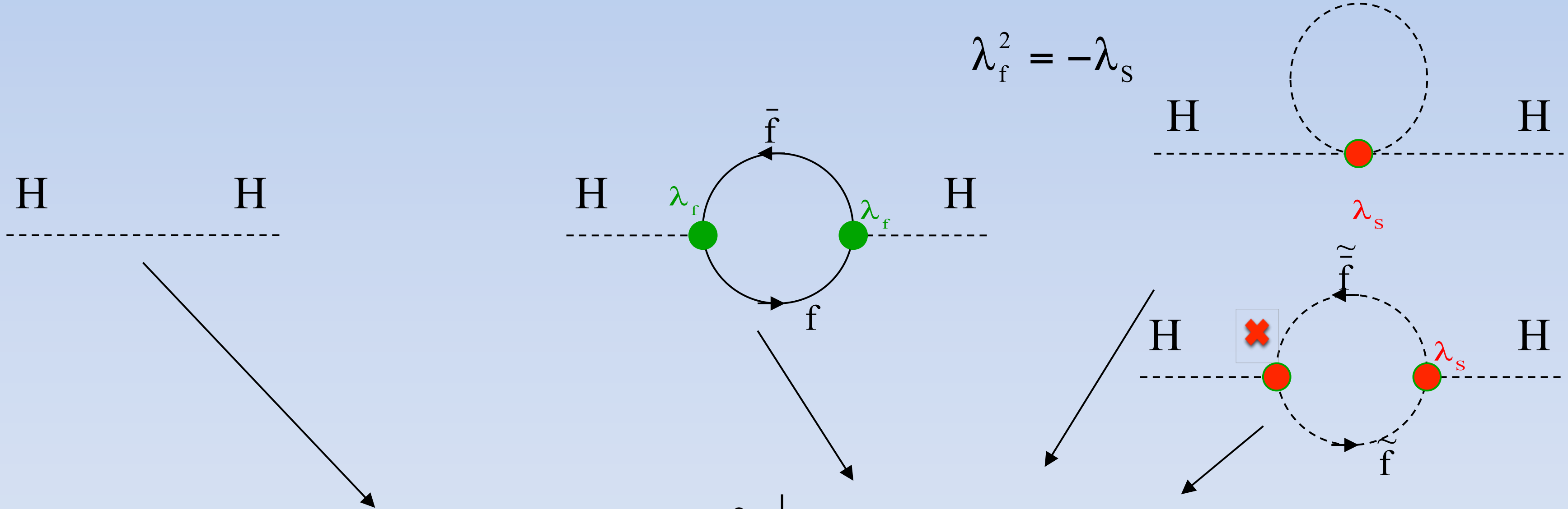


5. Supersymmetry

Response to Open Questions
Stabilisation of the Higgs Boson Mass

1 fermion $\longleftrightarrow$ 2 scalars

$$\lambda_f^2 = -\lambda_S$$



$$m_H^2(1\text{-Loop}) = m_H^2(1^{st}\ \text{order}) + N_f \frac{\lambda_f^2}{4\pi^2} \left| (m_f^2 - m_S^2)\cdot \mathrm{Log}\left(\frac{\Lambda}{m_S}\right) + 3m_f^2 \cdot \mathrm{Log}\left(\frac{m_S}{m_f}\right) \right|$$

- Possible to maintain $m_H < 800$ GeV if: $\boxed{\left|(m_f^2 - m_S^2)\right| < O(1\ \text{TeV}^2)}$

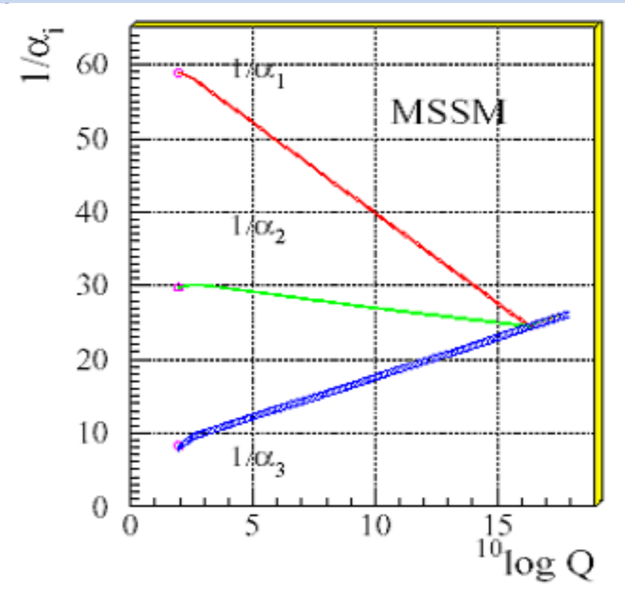
Meaning some SUSY partners have mass of O(1 TeV), therefore accessible at the LHC!

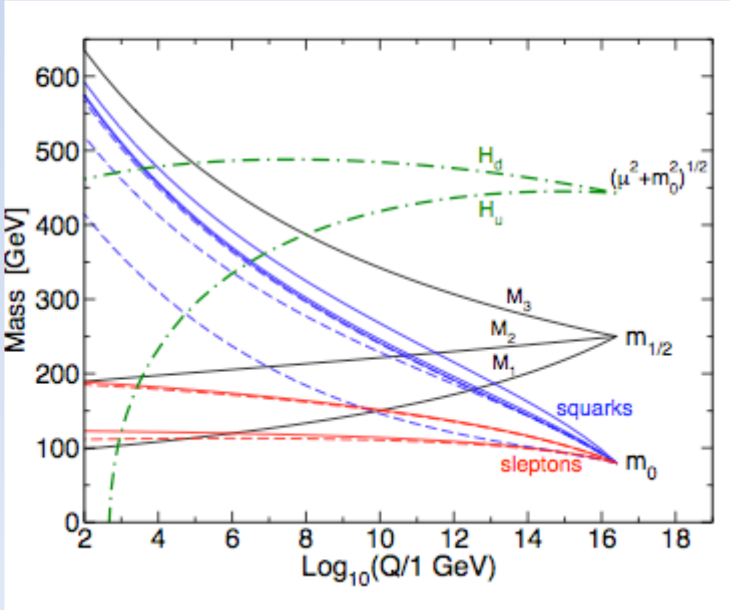
5. Supersymmetry

Response to Open Questions

- Non-trivial extension of the Poincaré group
- Candidate for Cold Dark Matter particle
- Grand Unification
- Prospect for a quantum theory of gravity and for a unified theory of all fundamental interactions
- Radiative Breaking of the EWK Symmetry

$$\left\{Q,\overline{Q}\right\}\propto P_\mu$$

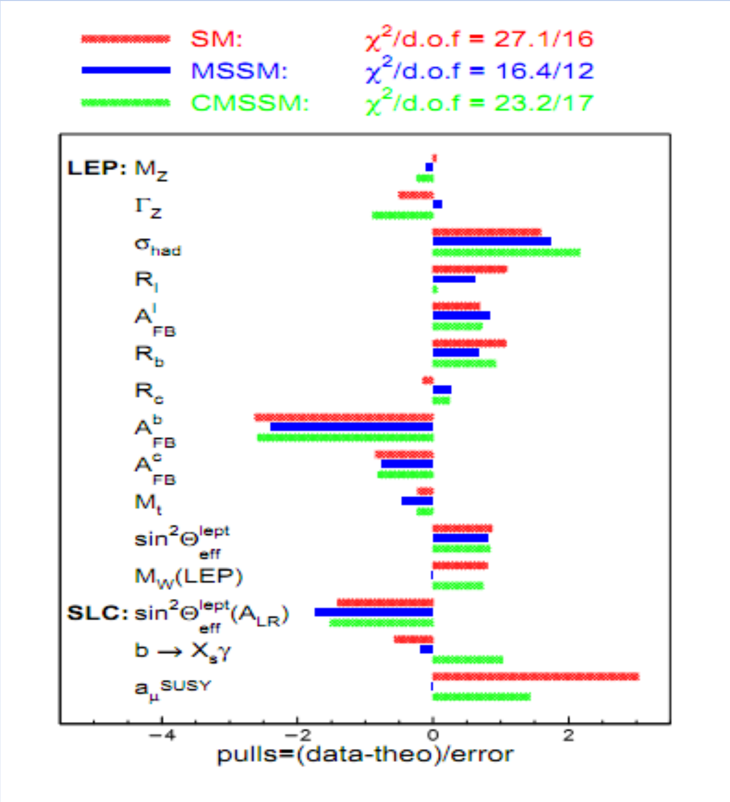


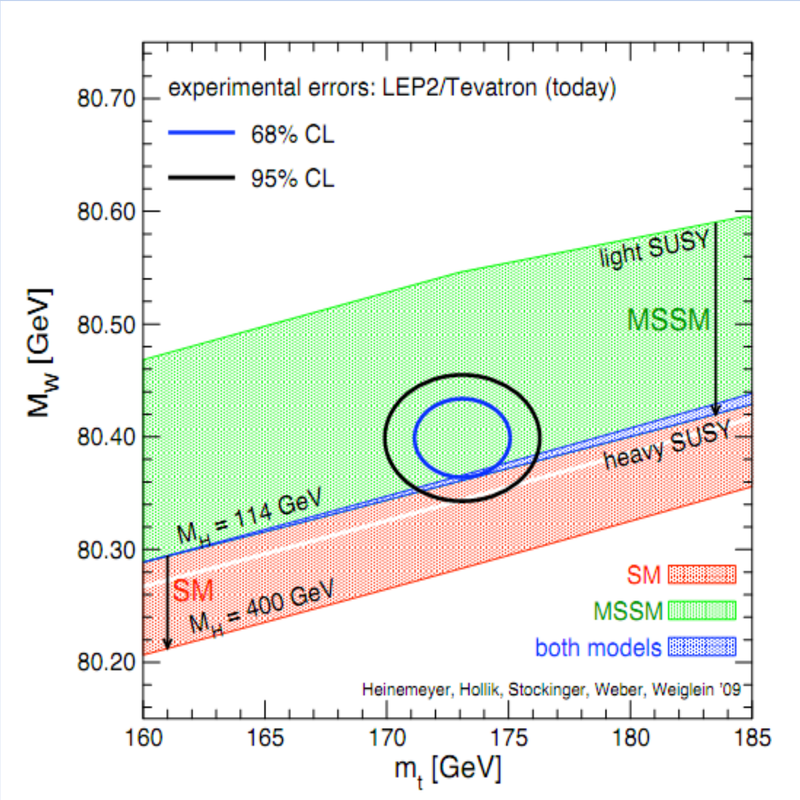


5. Supersymmetry

Electroweak Prescision Measurements

• The MSSM is compatible with all the known data and has a better χ^2 in global fits than the SM

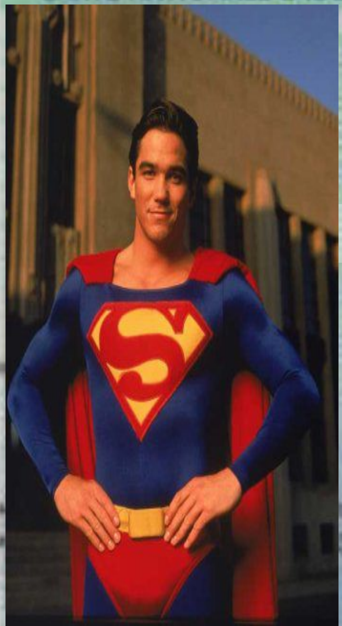




5. Supersymmetry

RÉPUBLIQUE PDG 20??

CARTE NATIONALE D'IDENTITÉ N° : 2 — Nationalité ???



Gauge Group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

SuperSymmetry

Nber of Space Dimensions: D=3

Symmetry Breakings: Higgs Mechanism, SUSY X

Sexe : Very Sexy — Né(e) le : 1971

à : ???

Flavours : 3 generations of Quarks & Leptons

Signature du titulaire : Gol'fand, Likthman, Volkov, Akulov, Wess, Zumino, Georgi, Dimopoulos,…

Nber of add'l free parameters: 105

TOP SECRET # <<<<<<<<<<<<<<<<<<<<<<<

$$Q|S\rangle = |S \pm \tfrac{1}{2}\rangle$$ << <

Doubled Mass Spectrum

Embeded in SU(5), SO(10), E_6,…

(Space-Time) x (Internal Symmetries)

Extra-Dim. in Superstring Theory

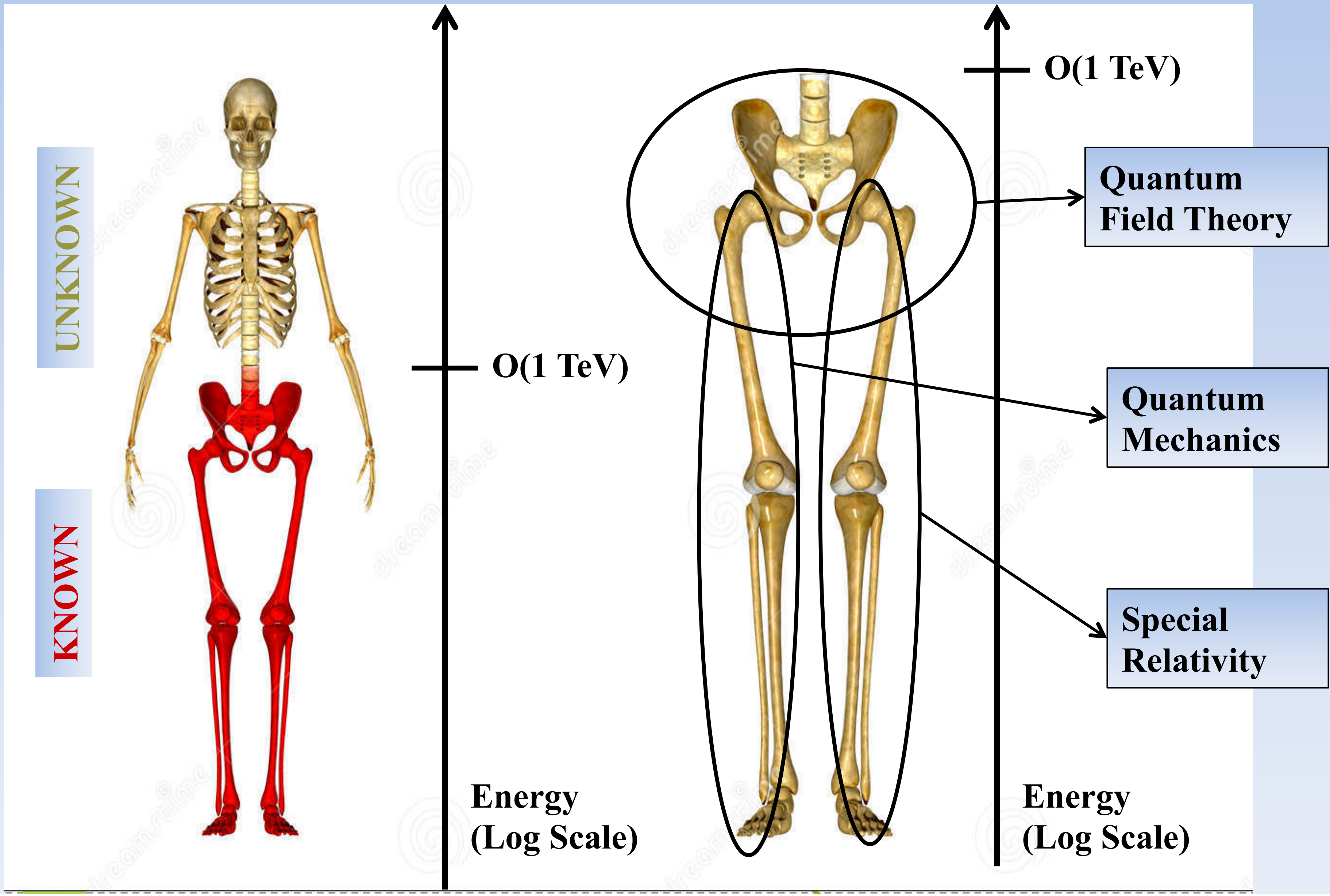
- 2HDM: SM Particle Masses
- Radiative Breaking

- In a Hidden Sector
- Transmitted to Visible Sector through
  - gravity, gauge, or anomaly interaction
- Masses of SUSY particles

Reducible to :
- 4+1/2: mSUGRA,
- 5: mGMSB,
- 5: mAMSB,
- 19: pMSSM,…

To be discovered:
- Stake: Nobel Laureate

6. Conclusions



6. Conclusion

6.A. What's Known

- We presented what is known and well tested in Particle Physics
- It explains very successfully most of the observed High Energy experimental data
    - At the exception of neutrino mass

- We detailed as much as possible (without much math) the foundations of Particle Physics
- It is a Relativistic Quantum Field Theory, and as such it relies on:
    - Special Relativity, and
    - Quantum Mechanics

6.B. What's Unknown

- Much bigger than what is known…
- Mechanism responible for the neutrino mass
- Grand Unification?
- Quantum Theory of Gravity?
- Flavour puzzles (origin of 3 generations, of CKM matrix, sources of CPV,…)

- Biggest chunk of the unknown:
    - Cold Dark Matter
    - Dark Energy

BACK-UP