Physics beyond the Standard Model (PBSM). COMHEP 2024

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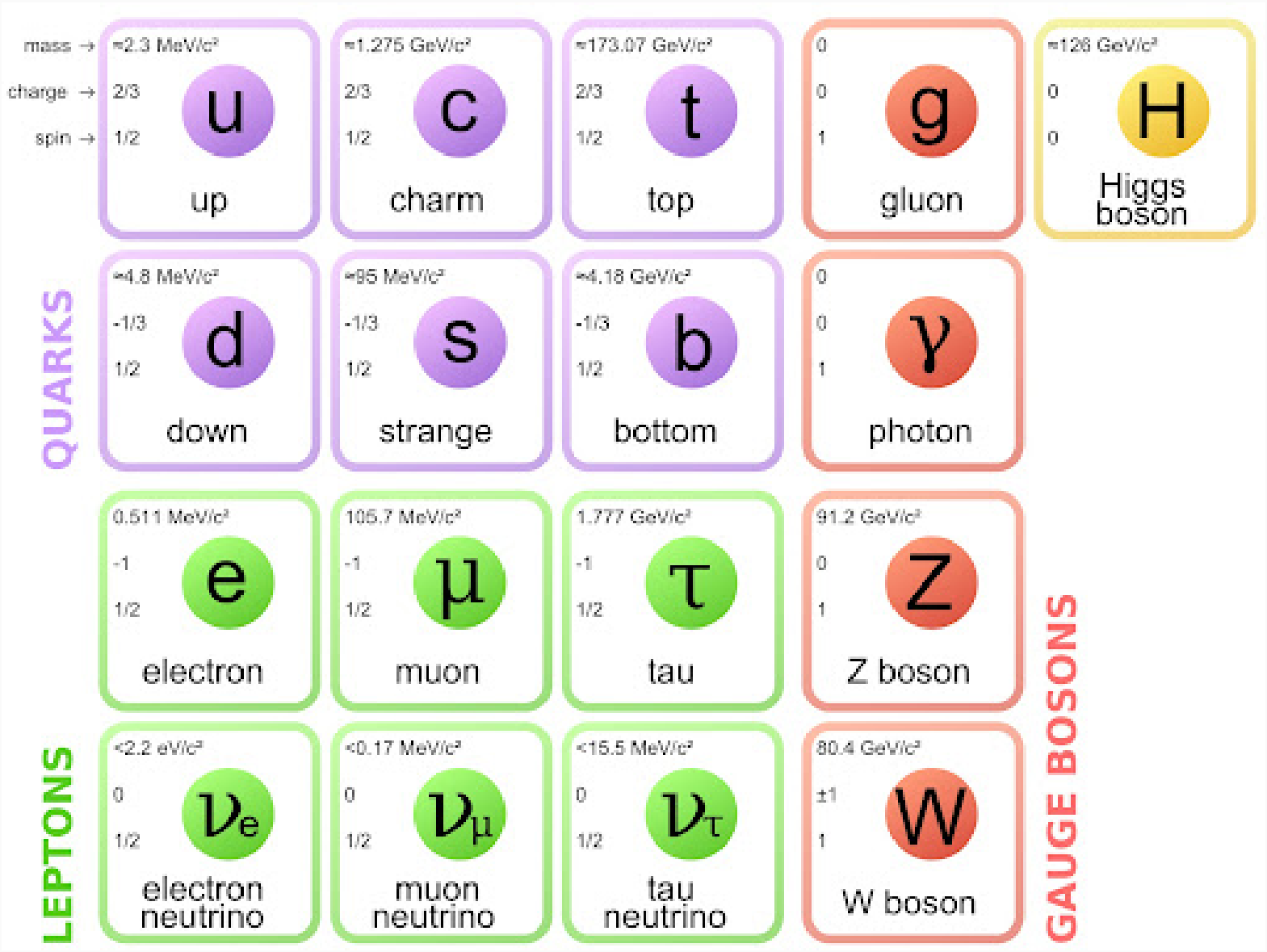
Standard Model

- I: A local gauge group: $SU(c)_c \otimes SU(2)_L \otimes U(1)_Y$
  $SU(3)_c$ Unbroken. Confining.
  $Q = T_{3L} + Y/2$
- II: The particle content
  Three families of quarks and leptons. $i = 1, 2, 3$
  Left handed doublets
  $(U_i, D_i)_L \sim (3, 2, 1/3)$; $(\nu_{E_i}, E_i^-)_L \sim (1, 2, -1)$
  Right handed singlets
  $U_{iL}^c \sim (3^*, 1, -4/3)$; $D_{iL}^c \sim (3^*, 1, 2/3)$; $E_{iL}^+ \sim (1, 1, 2)$
  No right handed neutrinos
- III: Spontaneous symmetry breaking.
  $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \longrightarrow SU(3)_c \otimes U(1)_Q$
  Via Higgs Mechanism. $H = (H^+, H^0) \sim (1, 2, 1)$. Survives h^0

Remark: Marshak. 1978 Too complicated to be the right model

Particle content



SM and the Scientific method

The SM is able to explain:

- I: The (V-A) theory
- II: IVB model
- III: P Violation
- IV: $\Delta I = 1/2$ rule

It predicts:

- Existence of Weak Neutral current (Via Z^0)
- Charm quark (GIM mechanism)
- CP Violation (with three families) V_{CKM}
- Phenomenological values for $M_{W^\pm}$, M_{Z^0}
- Existence of the Higgs scalar.

Shortcomings of the SM

Things not explained by the SM:

- Dark energy & Dark matter
- Neutrino masses and oscillations
- Baryon-antibaryon asymmetry.
- Charge quantization.
- Gravity not included.

Besides: Too many unexplained parameters (19), in a Yukawa sector poorly understood (Fermion mass hierarchy problem).

- 9 Fermion masses (6 quarks & 3 charged leptons)
- 3 mixing angles $\theta_i, \quad i = 1, 2, 3$ in V_{CKM}.
- Fine structure constants ($\alpha_j, \quad j = 1, 2, 3$)
- δ_{CP}, θ_S
- Higgs mass m_h. ($\mu, \quad \lambda$ in the scalar potential).

Number of families in nature. Origen of CP violation.

In the SM neutrinos are massless (Pure left handed Weyl fermion fields).

Beyond SM (General)

- Enlarge the fermion content.
- Enlarge the scalar sector.
- Enlarge the gauge group.
- Include discrete symmetries.
- Include texture Zeros.
- New ways of electroweak symmetry breaking (Technicolor. Quark condensates. Cooper pairs,...)
- Include anomalous symmetries (Peccei-Quinn).
- Preons, pre-preons, Rizhons.
- Enlarge the number of dimensions.
- Extend the Lie Algebras to Graded Lie Algebras.
- SUSY as a local gauge theory.
- Modify the Quantum field theory (Strings, Branes, ...).
- What else???

Beyond SM (Enlarge the Fermion Content)

1. Three right handed neutrinos ν_{iR}, $i = 1, 2, 3$.
   - Dirac masses for neutrinos.
   - Seesaw mechanism.
   - Neutrino oscillations.
2. Four (or more) sequential families.
3. Supersymmetry (MSSM, NMSSM, etc.)
   - Naturalness (Higgs mass unstable to quantum corrections. Scalar self energy cuadratical divergent which means Hierarchy problem.)
   - Gauge coupling unification.
   - Dark Matter.
4. Exotic Vector-Like non sequential electrons and quarks (Up & Down).
   (Universal seesaw mechanisms).

Fourth family.
J.A.Herrera, R.H.Benavides, W.A.Ponce. Phys.Rev D78, 073008 (2008).

$\beta(\alpha) = \frac{\alpha^2}{\pi}\left(-\frac{11N}{6} + \frac{n_f}{3}\right)$. $N = 3$ for $SU(3)_c$.

$\beta_3 < 0$ for assymptotic freedom $\Longrightarrow n_f \leq 16 \Longrightarrow 8$ families.

$M_{Z^0} = 91.1876 \pm 0.0021 \quad GeV/c^2$.

$\Gamma_{Z^0} = 2.4952 \pm 0.0023 \quad GeV = 1/\tau$.

$\Gamma_{vis} \approx 1.9 \;\; GeV$

$\Gamma_{invis} \approx 0.5...0.6 \;\; GeV \;\; GeV$

One neutrino type $M_\nu < M_{Z^0}/2 \approx 0.17 GeV \quad \Longrightarrow \quad n_\nu = 3$

Besides

$$M_{mix} = \begin{pmatrix} M_{CKM} & x \\ x' & \approx 1 \end{pmatrix}, \quad M_{CKM} \text{ almost unitary}$$

Little room for mixing of the fourth family.

Rich CP violation structure (three Dirac δ phases.)

SUSY

Supersymmetry is not a theory. It is a PRINCIPLE

In which the force equations and the matter equations are identical.

$$\text{PARTICLE} \leftrightarrow \text{SPARTICLE}$$

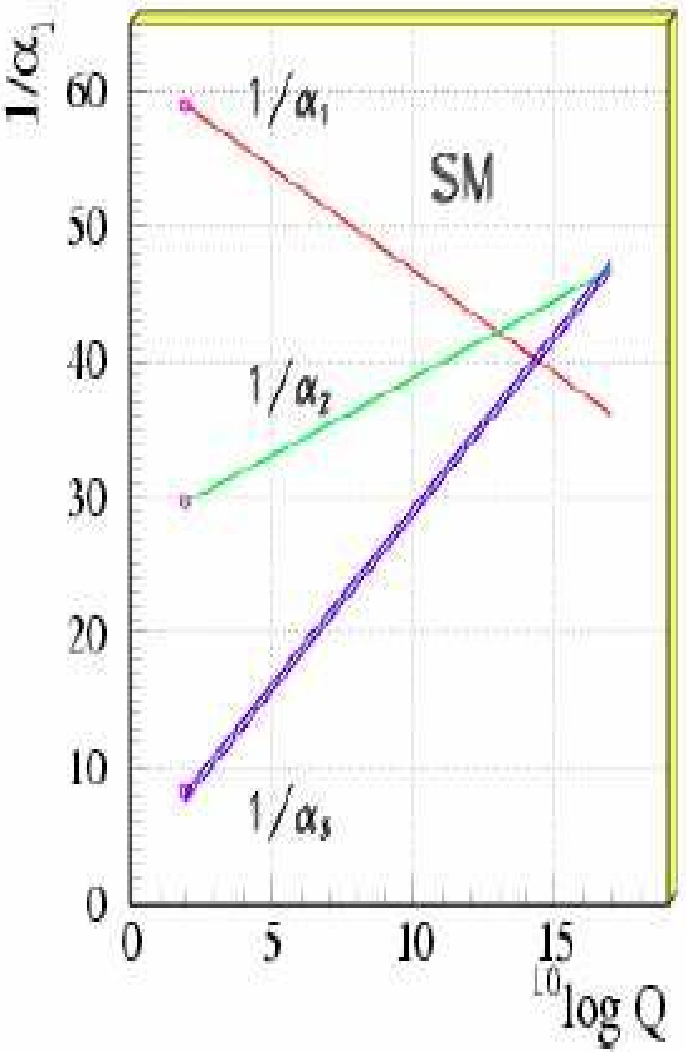
MODELS

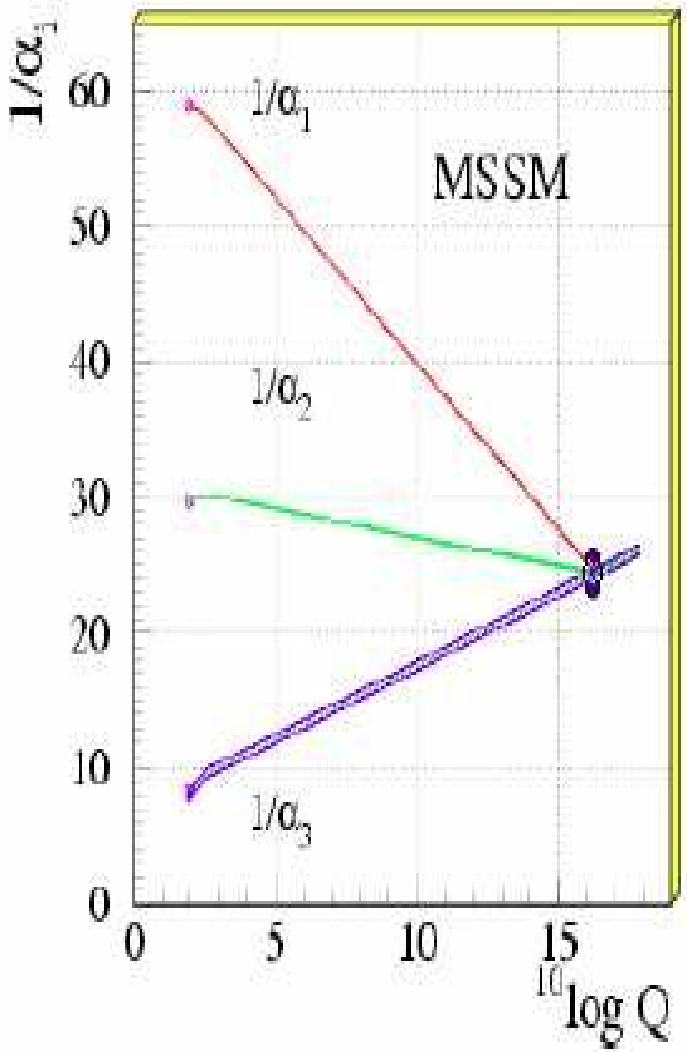
- The Wess-Zumino model (Toy model)
- MSSM (1981 Georgi & Dimopoulos. J. Ellis)
- NMSSS (Solve the μ problem with chiral superfield)
- SUSY GUT's
- Supergravity
- Superstrings

$m_p \neq m_{sp}$. So, it must be broken (dynamically o expontaneously).

W.A.P., D. Restrepo *et al*. "Supersymmetric one family model without higgsinos". (3-3-1. No μ problem). Phys Rev D67, 075002 (2003).

SUSY Unification





But not SUSY signals at the LHC.

Beyond SM (Enlarge the Scalar sector)

1. Complex scalar singlet.
   Zero electric charge. Couple to matter at loop level. Dark Matter.
2. Two Higgs doublets (THDM).
   - Couple to different families
   - Both couple to the three families
3. Scalar triplet.
   Majorana masses for left handed weyl neutrinos
   (Witten Mechanism.)
4. Three or more scalar doublets.
   Yithsbey (poster). M.Mondragon (3,4 HDM with Z_4)

Beyond SM (Enlarge the gauge group.)

1. Left-Right symmetric model: $SU(2)_R \otimes SU(2)_L \otimes U(1)_{(B-L)}$.
2. Universal and non universal $U(1)$: $SU(2)_L \otimes U(1)_Z \otimes U(1)_{Z'}$.
   W.A.P. Phys Rev D36, 962 (1987). Universal Anomally free.
   E.Rojas, Y.Giraldo, R.H.V, W.A.P, (2015-24)....Non Universal
3. 3-3-1 model $SU(3)_c \otimes SU(3)_L \otimes U(1)_X$.
   - Universal (anomaly cancellation in each family).
   - Family models (anomaly cancelation between families).
   - Economical 3-3-1 model
     W.A.P., Y.Giraldo, L.A.S., Phys. Rev. D67 , 075001 (2003).
4. Chiral color $SU(3)_{cR} \otimes SU(3)_{cL}$.
5. Technicolor. Walking technicolor.
6. Local gauge family symmetry $G_H \otimes SU(2)_L \otimes U(1)_Y$.
   $G_H = U(1)_H, SU(2)_H, SU(3)_H$.
   L.A.Wills, A.Z., W.A.P., Z.Physik C73, 711 (1997).
7. Grand Unified Theories (GUT).

3-3-1 models
W.P., Y.G., L.A.S. Phys Rev. D67, 075001 (2003)

The Latin American Model (IFT S.Paulo, La Plata, UdeA, UNAL, Pasto)
The Pasto Model (Y.G., J.H., J.C., E.R., R.H.)
$SU(3)_c \otimes SU(3)_L \otimes U(1)_X$
$Q = a\lambda_3 + \frac{b}{\sqrt{3}}\lambda_8 + XI_3. \quad a = 1/2 \quad SU(3)_L \longrightarrow SU(2)_L$
Extra gauge bosons $K_\mu^{\pm(\frac{1}{2}\pm b)}$

- $b = 1/2$ The minimal model (Pleitez-Frampton model)
  Phys.Rev. D46,410 (1992).
  $(e^-, \nu_e, e^+)_L, \quad (u, d, J_i)_L, \quad (-b, t, J_3)_L \quad Q[J] = -4/3, 5/3$
- $b = 3/2$ Without exotic electric charges. Many models
  $(e^-, \nu_e, N^0)_L, \quad (-\nu_e, e^-, E^-)_L$
  $(u, d, D)_L, \quad (d, u, U)_L, \quad$ etc.
- The economical model

MANY MODELS FOR ONLY 3 FAMILIES

O.Zapata, W.A.P., Phys. Rev. D74, 093007 (2006). Without hierarchy

Texture Zeros
R.H.B., J.D.G., W.A.P. Phys.Rev. D87, 053016 (2013)

$J^{-}_{\mu L} = \bar{U}_{0L}\gamma_\mu D_{0L} = \bar{U}_L\gamma_\mu V_{CKM} D_L; \quad V_{CKM} = V_{CKM}(\theta_{12}, \theta_{13}, \theta_{23}, \delta^{cp})$

$-\mathcal{L}_M = \bar{U}_{0L} M_U U_{0R} + \bar{D}_{0L} M_D D_{0L} + H.C.$

$M_U; \quad M_D$: arbitrary 3x3 matrices: $18 \times 2 = 36$ parameters

POLAR THEOREM $M_U; \quad M_D$: Hermitian $9 \times 2 = 18$ parameters
12 real and 6 phases (5 phases absorbed) $\longrightarrow$12 real, 1 phase

Weak basis transformation: $(M_U)_{11} = (M_D)_{11} = (M_U)_{13} = (M_U)_{31} = 0$.
Three natural texture zeros $\longrightarrow$ 9 real, 1 phase

Enough to accomodate 6 masses, 3 mixing angles and 1 CP phase.

So: one more texture zero implies:

$\theta_{ij} = \theta_{ij}(m_{u1}, m_{u2}, m_{u3}, m_{d1}, m_{d2}, m_{d3})$

Reduce the number of free parameters.

GUT´s

- Pati-Salam $SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$.
  $[SU(4)]^3$ for two families
  $[SU(6)]^{\times} Z_3 3$ for three families. Proton stable
  J.B.Florez, W.A.Ponce.,A.Zepeda. PR D49,4954(1994).
- Georgi-Glashow $SU(5)$
  Rule out $\tau_P \approx 1.67 \times 10^{34}$ Yrs.
- $SO(10)$
- E_6.
- Trinification $SU(3)^3 \times Z_3$
- Flipped $SU(5) \otimes U(1)$, $SO(10) \otimes U(1)$, $E_6 \otimes U(1)$, $SU(3)^3 \otimes U(1)$
  Make proton more stable.
- Family models $SO(14)$, $SO(18)$, E_8

Proton decay

Proton is stable in the context of the SM.

Sakharov in 1967

Patti: India (1985) deep underground carbon mines (to avoid background noise).

Kamiokande, SuperKamiokande.

$\tau_p \approx 1.67 \times 10^{34}$ years. Go to the moon

$SU(4)_c \longrightarrow SU(3)_c \otimes U(1)$

$4 \longrightarrow 3(1/3) + 1(-1)$

$\overline{d} + e^-$

Something similar happens in $SU(5)$

Kaluza-Klein

5 dimensions

$B, C = 0, 1, 2, 3, 5.$ Tilde means five dimensions

$$\tilde{g}_{BC} = \begin{pmatrix} g_{\mu\nu} + \phi^2 A_\mu A_\nu & \phi^2 A_\mu \\ \phi^2 A_\nu & \phi^2 \end{pmatrix}$$

$g_{\mu\nu}$: 4 dimensional Einstein Metric tensor

A_μ : Four Vector EM potential. ϕ : Auxiliar escalar field

$\mu, \nu = 0, 1, 2, 3.$ $i, j = 1, 2, 3$

Get 5 dimensional Christoffel symbols, Ricci tensor and Ricci scalar

$$\tilde{\Gamma}^C_{AB} = \tfrac{1}{2}\tilde{g}^{CD}(\partial_A \tilde{g}_{DB} + \partial_B \tilde{g}_{DA} - \partial_D \tilde{g}_{AB})$$

$$\tilde{R}_{AB} = \partial_C \tilde{\Gamma}^C_{AB} - \partial_B \tilde{\Gamma}^C_{AC} + \tilde{\Gamma}^C_{AB}\tilde{\Gamma}^D_{CD} - \tilde{\Gamma}^C_{AD}\tilde{\Gamma}^D_{BC}$$

$$\tilde{R} = \tilde{g}^{AB}\tilde{R}_{AB}$$

And the action: $S \sim \int \tilde{R}\sqrt{-\tilde{g}}\, d^5x$

Compactify the 5 dimensions.

Strings. Elementary particles are strings. Open and/or closed

- Bosonic string. Anomaly free in 26 dimensions
- Include Fermions via SUSY. Anomaly free in 10 dimensions.
- Spin can be understood in a classical simple way.
- Fourier expansion includes spin.
  0,1/2,1,3/2 (gravitino),2 (graviton).
- Gravity can be included in a natural way.
- Perturbation theory from Mathematical two brane theory.
- M theory (11 dimesions). Edward Witten.