Standard Model and Beyond

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SM Overview

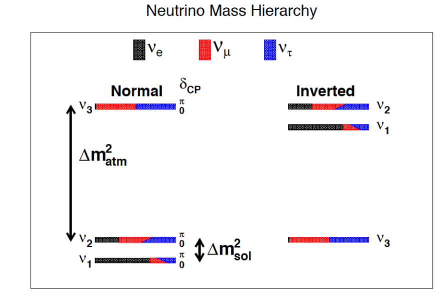
- **Standard Model is defined by**
  - **4-dimension QFT (Invariant under Poincare group).**
  - **Symmetry: Local** $SU(3)_C \times SU(2)_L \times U(1)_Y$.
  - **Particle content (Point particles):**
  - **3 fermion (quark and Lepton) Generations.**
  - **No Right-handed neutrinos ? Massless Neutrinos.**
- **Symmetry breaking: one Higgs doublet.**
- **No candidate for Dark Matter.**
- **SM does not include gravity.**

Evidence for Physics Beyond the SM

1- Neutrino Mass:

- **In the SM, quarks and electrons acquire masses through Yukawa couplings :** $\mathcal{L}_{Yuk} \sim \bar{Q}_L \phi u_R$.
- **Neutrinos remain massless because there are no RH ν in the SM.**
- **However, it has proven experimentally (from neurino oscillations) that $m_\nu \neq 0$.**

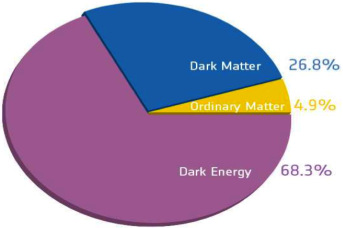
parameter	best fit value $\pm$ 1σ	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	(0.270, 0.344)
θ_{12} (degrees)	$33.48^{+0.77}_{-0.74}$	(31.30, 35.90)
$\sin^2\theta_{23}$	$[0.451^{+0.001}_{-0.001}]$ or $0.577^{+0.027}_{-0.035}$	(0.385, 0.644)
θ_{23} (degrees)	$[42.2^{+0.1}_{-0.1}]$ or $49.4^{+1.6}_{-2.0}$	(38.4, 53.3)
$\sin^2\theta_{13}$	$0.0219^{+0.0010}_{-0.0011}$	(0.0188, 0.0251)
θ_{13} (degrees)	$8.52^{+0.20}_{-0.21}$	(7.87, 9.11)
δ_{CP} (degrees)	251^{+67}_{-59}	(0, 360)
Δm^2_{21} $\times 10^{-5}$ eV^2	$7.50^{+0.19}_{-0.17}$	(7.03, 8.09)
(normal) Δm^2_{31} $\times 10^{-3}$ eV^2	$+2.458^{+0.046}_{-0.047}$	(+2.325, +2.599)
(inverted) Δm^2_{32} $\times 10^{-3}$ eV^2	$-2.448^{+0.047}_{-0.047}$	(-2.590, -2.307)



- **Needs a mechanism to give ν masses...**

Evidence for Physics Beyond the SM

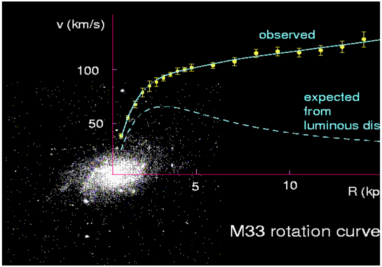
2- Dark Matter:



- Most astronomers, cosmologists and particle physicists are convinced that 90% of the mass of the Universe is due to some non-luminous matter, called 'Dark Matter/Energy'.
- The velocity of rotating objects

$$v(r) = \sqrt{\frac{G\ M(r)}{r}}$$

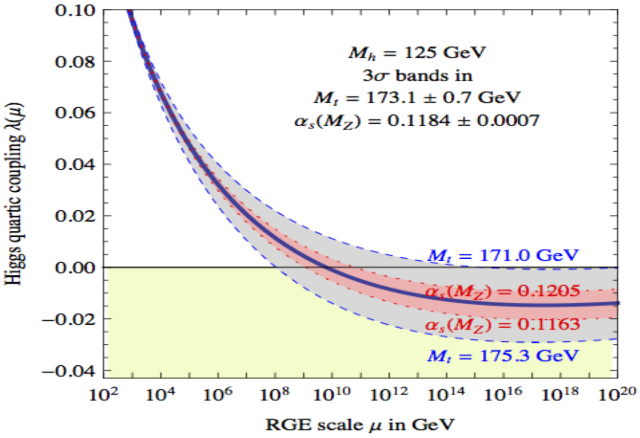
- The observation of 1000 spiral galaxies showed that away from the centre of galaxies the rotation velocities do not drop off with distance.
- The explanation for these is to assume that disk galaxies are immersed in extended DM halos.
- Dark Matter must be non-baryonic. No such candidate in the Standard Model



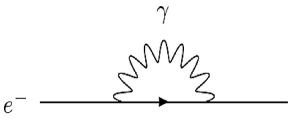
Evidence for Physics Beyond the SM

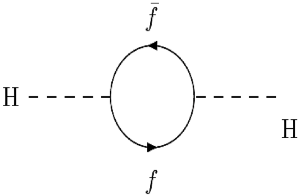
3- Higgs Vacuum Stability:

- **Qadratic coupling evolves to zero or negative values. Recall that in SM** $M_H = \sqrt{\lambda} v$



4- Higgs Mass Hierarchy:





$$\delta m_e = 2\frac{\alpha_{em}}{\pi} m_e \log\frac{\Lambda}{m_e} + \ \ldots$$

$$\delta m_H^2(f) = -2N_f\frac{|\lambda_f|^2}{16\pi^2}[\Lambda^2 - 2m_f^2 \ln\frac{\Lambda}{m_f} \ + \ldots]$$

$m_e \to 0$, Chiral Symmetry

m_H^2 no symmetry, Quadratic div.!!

$$\Lambda = 10^{19} \text{ GeV}$$

$$\delta m_e \ = \ 0.24 \, m_e$$

$$\delta m_H^2 \ \simeq \ 10^{30} \text{ GeV}$$

Evidence for Physics Beyond the SM

In addition, there are a number of questions we hope will be answered:

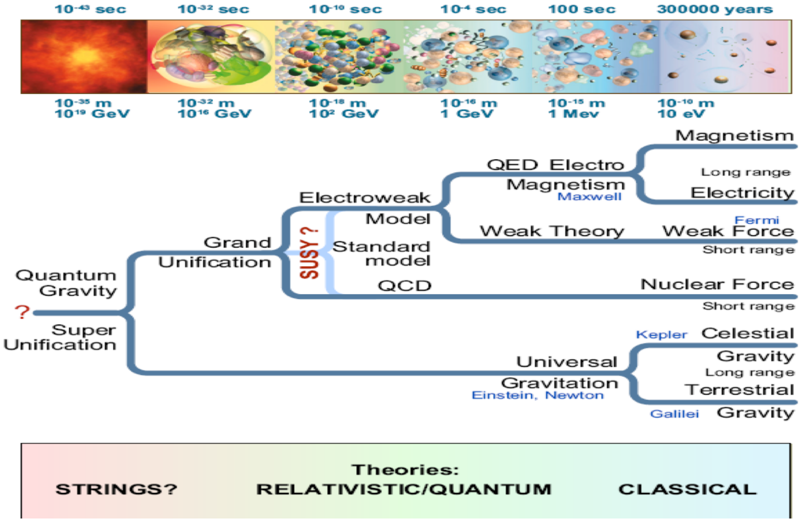
- **Electroweak symmetry breaking, which is not explained within the SM.**
- **Why is the symmetry group is** $SU(3) \times SU(2) \times U(1)$?
- **Can forces be unified?**
- **Why are there three families of quarks and leptons?**
- **Why do the quarks and leptons have the masses they do?**
- **Can we have a quantum theory of gravity?**
- **Why is the cosmological constant much smaller than simple estimates would suggest?**

Discovery Timeline

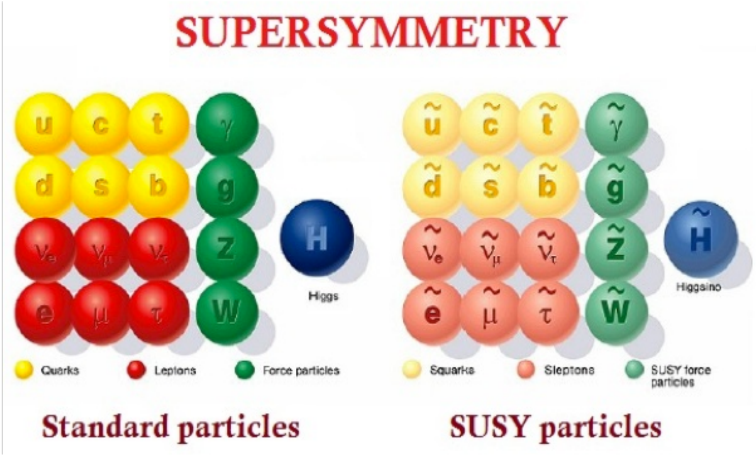
- **1897 electron**
- **1937 muon**
- **1959 neutrino (proposed in 1933)**
- **1968 up, down, strange (proposed in 1964)**
- **1974 charm (proposed in 1970)**
- **1975 tau (proposed in 1971)**
- **1977 bottom (proposed in 1964)**
- **1996 top (proposed in 1964)**
- **2012 Higgs (proposed in 1962)**

Directions of BSM

- **Extension of gauge symmetry.**
- **Extension of Higgs Sector.**
- **Extension of Matter Content.**
- **Extension with Flavor Symmetry.**
- **Extension of Space-time dimenstions (Extra-dimensions).**
- **Extension of Lorentz Symmetry (Supersymmetry).**
- **Incorporate Gravity (Supergravity).**
- **One dimension object (Superstring).**



10-43 sec
10-32 sec
10-10 sec
10-4 sec
100 sec
300000 years
10-35 m 10^19 GeV
10-32 m 10^16 GeV
10-18 m 10^2 GeV
10-16 m 1 GeV
10-15 m 1 Mev
10-10 m 10 eV
Magnetism
QED Electro Magnetism
Maxwell
Long range
Electricity
Electroweak Model
SUSY ?
Fermi
Weak Theory
Weak Force
Short range
Grand Unification
Standard model
QCD
Nuclear Force
Short range
Quantum Gravity
?
Super Unification
Kepler
Celestial Gravity
Long range
Universal Gravitation
Einstein, Newton
Terrestrial Gravity
Galilei
Theories:
STRINGS?
RELATIVISTIC/QUANTUM
CLASSICAL


SUPERSYMMETRY
u
c
t
γ
d
s
b
g
ν_e
ν_μ
ν_τ
Z
H
Higgs
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W
Quarks
Leptons
Force particles
Standard particles
$\tilde{u}$
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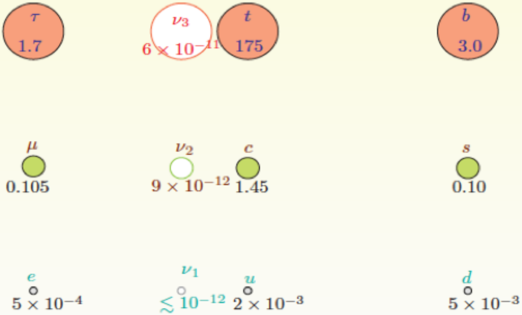
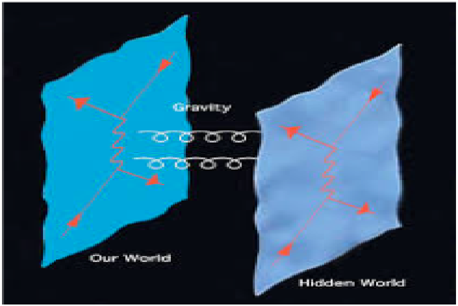
$\tilde{\nu}_e$
$\tilde{\nu}_\mu$
$\tilde{\nu}_\tau$
$\tilde{Z}$
$\tilde{H}$
Higgsino
$\tilde{e}$
$\tilde{\mu}$
$\tilde{\tau}$
$\tilde{W}$
Squarks
Sleptons
SUSY force particles
SUSY particles

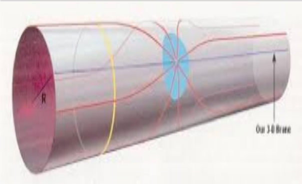
Flavour physics: who ordered that??

- 3 families with identical gauge quantum numbers.
- Strong hierarchy between generations.
- Small quark, large lepton mixing angles.



Extra Dimension and Brane World





SMALL EXTRA DIMENSION wrapped in a circle (circumference of tube) modifies how gravity (red lines) spreads in space. At distances smaller than the circle radius (blue patch), the lines of force spread apart rapidly through all the dimensions. At much larger distances (yellow circle), the lines have filled the extra dimension, which has no further effect on the lines of force.

SM Extension with Right-handed Neutrino (ν_R)

- **Introducing the right-handed neutrinos ν_R implies**

$$\mathcal{L} = Y_\ell \bar{L} \phi e_R + Y_\nu \bar{L} \tilde{\phi} \nu_R + M \overline{\nu_R^c} \nu_R$$

Nothing prevents adding then a mass term for right-handed neutrino.

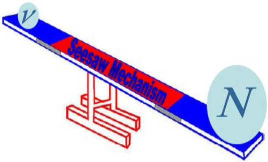
- **Type I Seesaw Mechanism**

$$\mathcal{L} = \frac{1}{2} (\nu_L, \nu_R) \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

- **For $m_D \ll M$, one finds**

$$m_{\nu_\ell} \simeq -m_D^2/M, \qquad M_R \simeq M$$

with mixing angle: $\tan 2\theta = 2 m_D / M \ll 1$.



- $m_D = Y_\ell v$**, so to get** $m_{\nu_\ell} \sim O(1) eV$**, either:**

$$Y_\ell \sim O(1) \quad \& \quad m_D \sim O(100) GeV \quad \Rightarrow \quad M \simeq 10^{13} GeV$$

OR

$$Y_\ell \sim O(10^{-6}) \ \& \ m_D \sim O(10^{-4}) GeV \quad \Rightarrow \quad M \simeq 1 TeV.$$

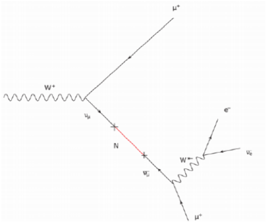
Search for right-handed neutrinos

- **The right-handed neutrino, N_R or ν_R, mixes with the three active neutrinos.**

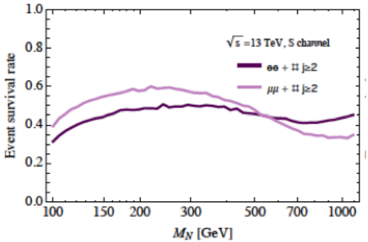
- **In terms of mass eigenstates, the gauge interaction Lagrangian is given by:**

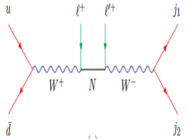
$$\mathcal{L} = -\frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{l=e}^{\tau} \sum_{m=1}^{3} U_{lm}^* \bar{\nu}_m \gamma^\mu P_L l \right) - \frac{g}{\sqrt{2}} W_\mu^+ \left(\sum_{l=e}^{\tau} V_{l4}^* N_R^c \gamma^\mu P_L l \right) - \frac{g}{2\cos\theta_W} Z_\mu \left(\sum_{l=e}^{\tau} V_{l4}^* N_R^c \gamma^\mu P_L \nu_l \right) + \text{H.c},$$

- **A signature of ν_R signal consists of two same-sign muons, one electron and missing transverse energy .**



- **Or the following signal:** $p\ p \to \ell^\pm\ \ell'^\pm + j\ j$





- **Cross section observable only if $\nu_\ell - \nu_R$ mixing is $> 10^{-2}$. However even for $M_{\nu_R} \sim 100$ GeV, $\theta \sim 10^{-6}$ (Not observable at LHC).**

TeV Seesaw with $B-L$ forces (Z')

- **The $B-L$ extension of the SM is based on the gauge group**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

In this model:

1. **Three right-handed neutrinos, N_R^i, $i = 1, 2, 3$; with $B-L$ charge $= -1$.**
2. **An extra gauge boson corresponding to $B-L$ gauge symmetry, Z'.**
3. **An extra SM singlet scalar, χ with $B-L$ charge $= +2$, are introduced.**

S.K(2007)

Particle	ℓ_L	e_R	N_R	ϕ	χ
Y_{B-L}	-1	-1	-1	**0**	$+2$

Neutral Gauge Bosnon Z'

- **The $U(1)_Y$ and $U(1)_{B-L}$ gauge kinetic mixing can be absorbed in the covariant derivative redefinition. In this basis, one finds**

$$M_Z^2 = \frac{1}{4}(g_1^2 + g_2^2)v^2, \qquad M_{Z'}^2 = g_{BL}^2 v'^2 + \frac{1}{4}\tilde{g}^2 v^2$$

- **The mixing angle between Z and Z':**

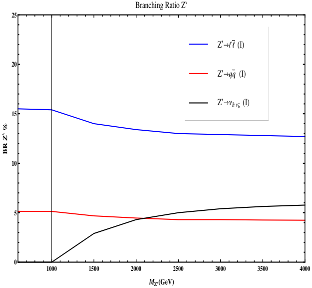
$$\tan 2\theta' = \frac{2\tilde{g}\sqrt{g_1^2 + g_2^2}}{\tilde{g}^2 + 16(\frac{v'}{v})^2 g_{BL}^2 - g_2^2 - g_1^2}$$

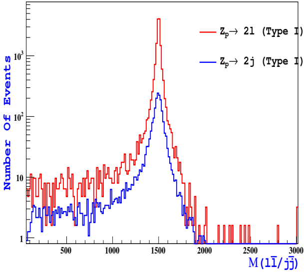
- **The decay widths of $Z' \to f\bar{f}$ are given by**

$$\Gamma(Z' \to l^+ l^-) \approx \frac{(g'' Y^l_{B-L})^2}{24\pi} m_{Z'}$$

$$\Gamma(Z' \to q\bar{q}) \approx \frac{(g'' Y^q_{B-L})^2}{8\pi} m_{Z'} \left(1 + \frac{\alpha_s}{\pi}\right),$$

$$\Gamma(Z' \to t\bar{t}) \approx \frac{(g'' Y^q_{B-L})^2}{8\pi} m_{Z'} \left(1 - \frac{m_t^2}{m_{Z'}^2}\right) \times \left(1 - \frac{4m_t^2}{m_{Z'}^2}\right)^{1/2} \left(1 + \frac{\alpha_s}{\pi}\right)$$



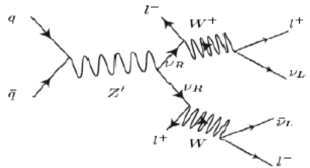


Signature of ν_R at the LHC

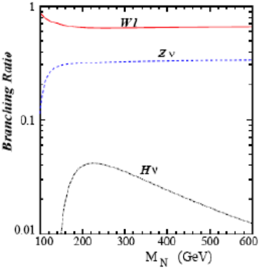
- **In BLSM, seesaw effect observable at LHC even with tiny $\nu_\ell - \nu_R$ mixings.**

S.K., K. Huitu, et al (2008)

$$\mathcal{L}_{int.} \sim -g" C_\mu [(\overline{\nu_R})_i \gamma^\mu (\nu_R)_i + b_{ij} \overline{(\nu_L)^c}_i \gamma^\mu (\nu_R)_j + h.c.] + \frac{g_2}{\sqrt{2}} [W^-_\mu l^+_i \gamma^\mu U_{ij} (\nu_L)_j + b_{ij} W^-_\mu l^+_i \gamma^\mu (\nu_R)^c_j + h.c.],$$



The decay modes, which go through the Higgs H or H' and Z boson, can be neglected compared to the main mode $\nu_R \rightarrow W l$.



These decays are very clean with four hard leptons in the final states and large missing energy due to the associated neutrinos.

SM Extension with Singlet Scalar

- **The extension of the SM Higgs sector with singlet scalar χ is natural in several models beyond the SM, *e.g.*, SM $\times U(1)'$.**

- **In this class of model, the Higgs potential is given by**

$$V(\phi,\chi) = m_1\phi^+\phi + m_2\chi^+\chi + \lambda_1(\phi^+\phi)^2 + \lambda_2(\chi^+\chi)^2 + \lambda_3(\phi^+\phi)(\chi^+\chi)$$

- **For $V(\phi,\chi)$ bounded from below, it is required:**

$$\lambda_3 > -2\sqrt{\lambda_1\lambda_2}, \quad \lambda_1, \lambda_2 > 0$$

For non-zero local minimum, we require

$$\lambda_3^2 < 4\lambda_1\lambda_2$$

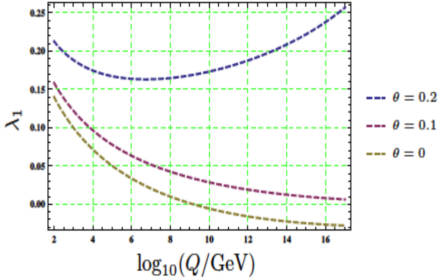
Higgs Vacuum Stability in $U(1)'$ Extension of the SM

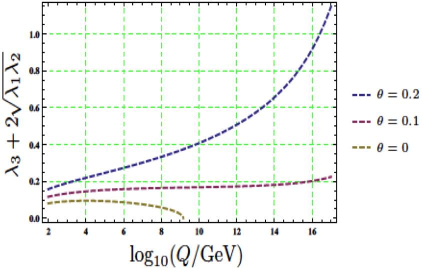
- **In SM $\times U(1)'$, like BLSM, the physical Higgs mass eigenstates are given by**
$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \phi^0 \\ \chi \end{pmatrix},$$
where the mixing angel θ is given by
$$\tan 2\theta = \frac{\lambda_3 v v'}{\lambda_1 v^2 - \lambda_2 v'^2}.$$

- **The masses of light and heavy Higgs particles are given by**
$$m^2_{h,H} = \lambda_1 v^2 + \lambda_2 v'^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + (\lambda_3 v v')^2},$$

The RGEs of the scalar couplings: λ_1, λ_2 and λ_3 in the context of $B-L$ extension of the SM, are given by

$$\frac{d\lambda_1}{dt} = \frac{1}{16\pi^2}\Big(24\lambda_1^2 + \lambda_3^2 + 12\lambda_1 Y_t^2 - 6Y_t^4) + \frac{9}{8}g_2^4 + \frac{3}{8}g_1^4 + \frac{3}{4}g_2^2 g_1^2 + \frac{3}{4}g_2^2\tilde{g}^2$$
$$+ \quad \frac{3}{4}g_1^2\tilde{g}^2 + \frac{3}{8}\tilde{g}^4 - 9\lambda_1 g_2^2 - 3\lambda_1 g_1^2 - 3\lambda_1\tilde{g}^2\Big),$$
$$\frac{d\lambda_2}{dt} = \frac{1}{8\pi^2}\left(10\lambda_2^2 + \lambda_3^2 - \frac{1}{2}Tr\left[(Y_N)^4\right] + 48{g_1'}^4 + 4\lambda_2 Tr\left[(Y_N)^2\right] - 24\lambda_2{g_1'}^2\right),$$
$$\frac{d\lambda_3}{dt} = \frac{\lambda_3}{8\pi^2}\left(6\lambda_1 + 4\lambda_2 + 2\lambda_3 + 3Y_t^2 - \frac{9}{4}g_2^2 - \frac{3}{4}g_1^2 - \frac{3}{4}\tilde{g}^2 + 2Tr\left[(Y_N)^2\right] - 12{g_1'}^2 + 6\frac{\tilde{g}^2{g_1'}^2}{\lambda_3}\right),$$





- **The RG running of the quartic coupling λ_1 in the BLSM with type-I seesaw, for three values of the scalar mixing angle θ for SM-like Higgs mass $m_h = 125$ GeV.**

- **The evolution of the second stability condition, $\lambda_3 + 2\sqrt{\lambda_1\lambda_2}$, up to the GUT scale.**

- **At $\theta = 0$, the running of λ_1 coincides with that of the SM. Hence one again finds that the Higgs potential becomes unstable at an energy scale $\gtrsim 10^{9\text{-}10}$ GeV.**

- **With $\theta \neq 0$, initial values of λ_1 at EW scale is larger than its value in the SM and also its scale dependence becomes rather different. One finds that with not very large mixing, λ_1 and also $\lambda_3 + 2\sqrt{\lambda_1\lambda_2}$ can remain positive up to the GUT scale. Hence the Higgs vacuum stability is accomplished.**