On the Origin of Neutrino Masses

Pavel Fileviez Perez

University of Wisconsin-Madison, USA

NuFact09, IIT, Chicago

Collaborators

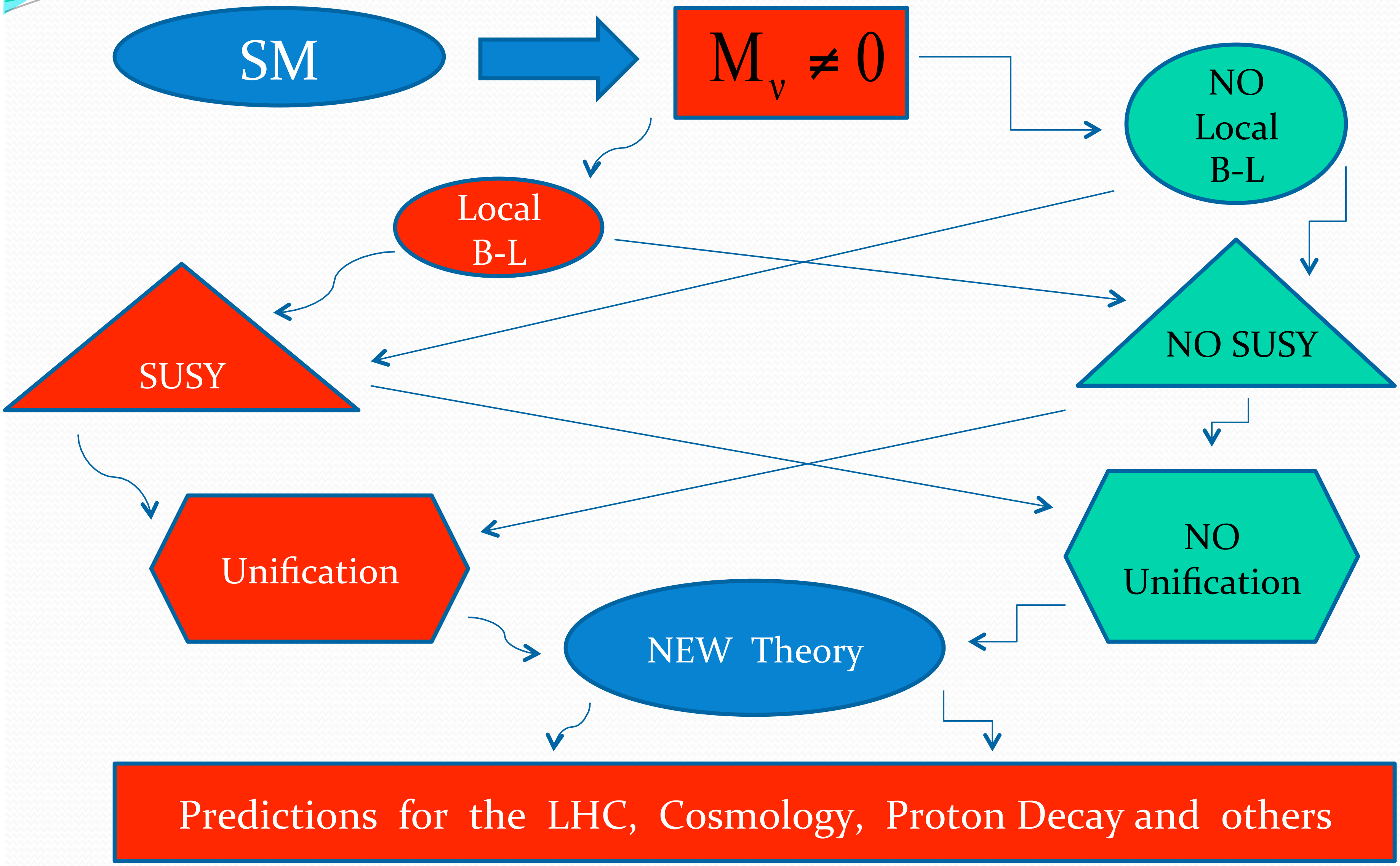
In the US:
V. Barger (Madison)
S. Blanchet (Maryland)
L. Everett (Madison)
T. Han (Madison)
G. Y. Huan (UC-Davis)
S. Spinner (Madison)
M. B. Wise (Caltech)

In Europe:
I. Dorsner (Italy)
R. Gonzalez-Felipe (Portugal)
G. Rodrigo (Spain)
G. Senjanovic (Italy)

In Asia:
K. Wang (IPMU, Japan)
T. Li (Pekin Univ., China)
H. Iminniyaz (Pekin Univ., China)

In Latinamerica:
M. A. Diaz (Chile)

Aim


SM
$M_\nu \neq 0$
NO
Local
B-L
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SUSY
NO SUSY
Unification
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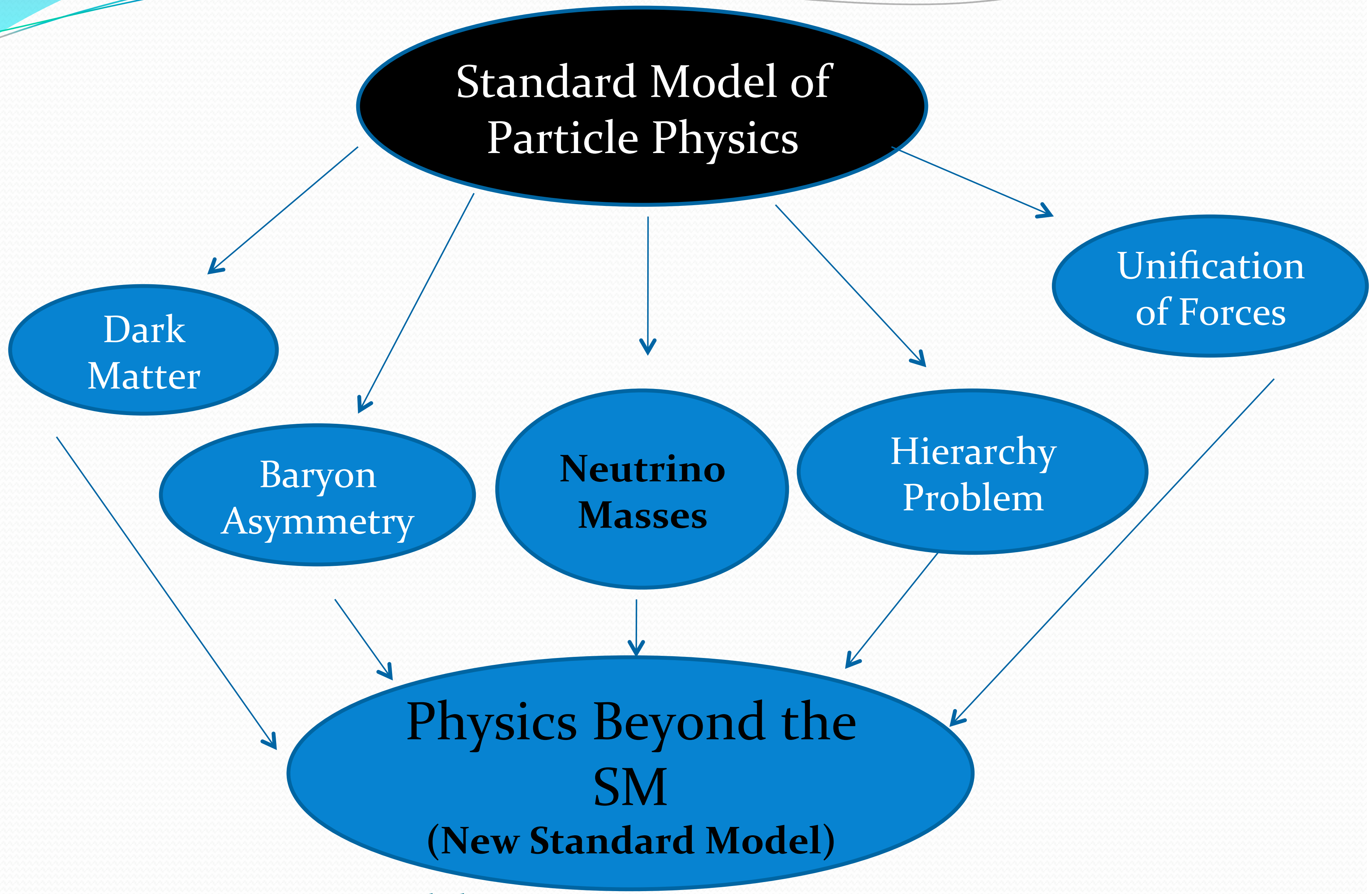
NEW Theory
Predictions for the LHC, Cosmology, Proton Decay and others

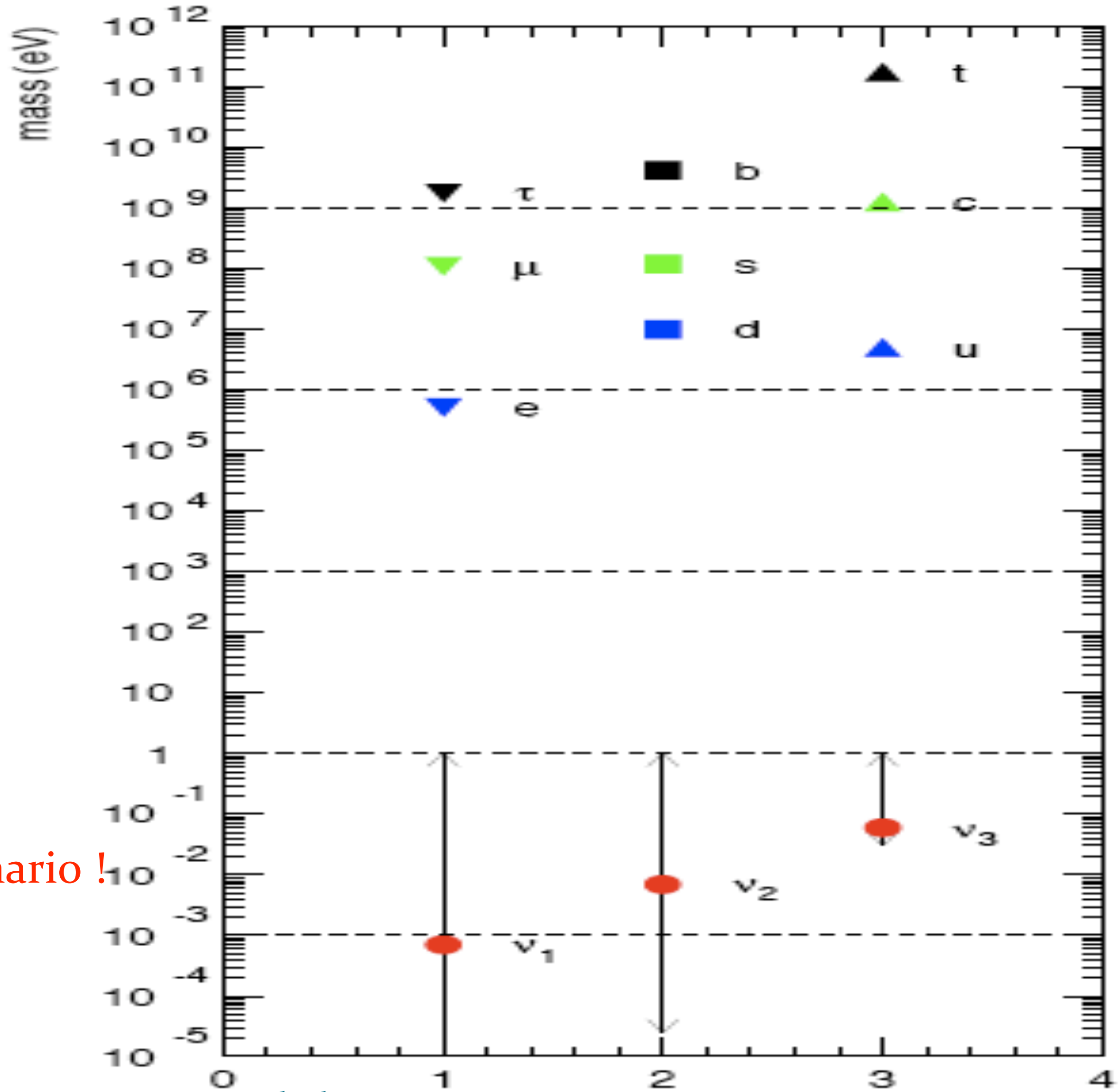
Outline

- Introduction
- Mechanisms for neutrino masses
- Grand unification and massive neutrinos
- Summary

INTRODUCTION


Standard Model of Particle Physics
Dark Matter
Baryon Asymmetry
Neutrino Masses
Hierarchy Problem
Unification of Forces
Physics Beyond the SM
(New Standard Model)

FERMIONIC SPECTRUM IN THE SM



A possible scenario !

Neutrino Properties

The leptonic mixing matrix is given by:

$$\begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{12}s_{13}s_{23}e^{i\delta} - c_{23}s_{12} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -c_{23}s_{12}s_{13}e^{i\delta} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

$$K_M = diag(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2})$$

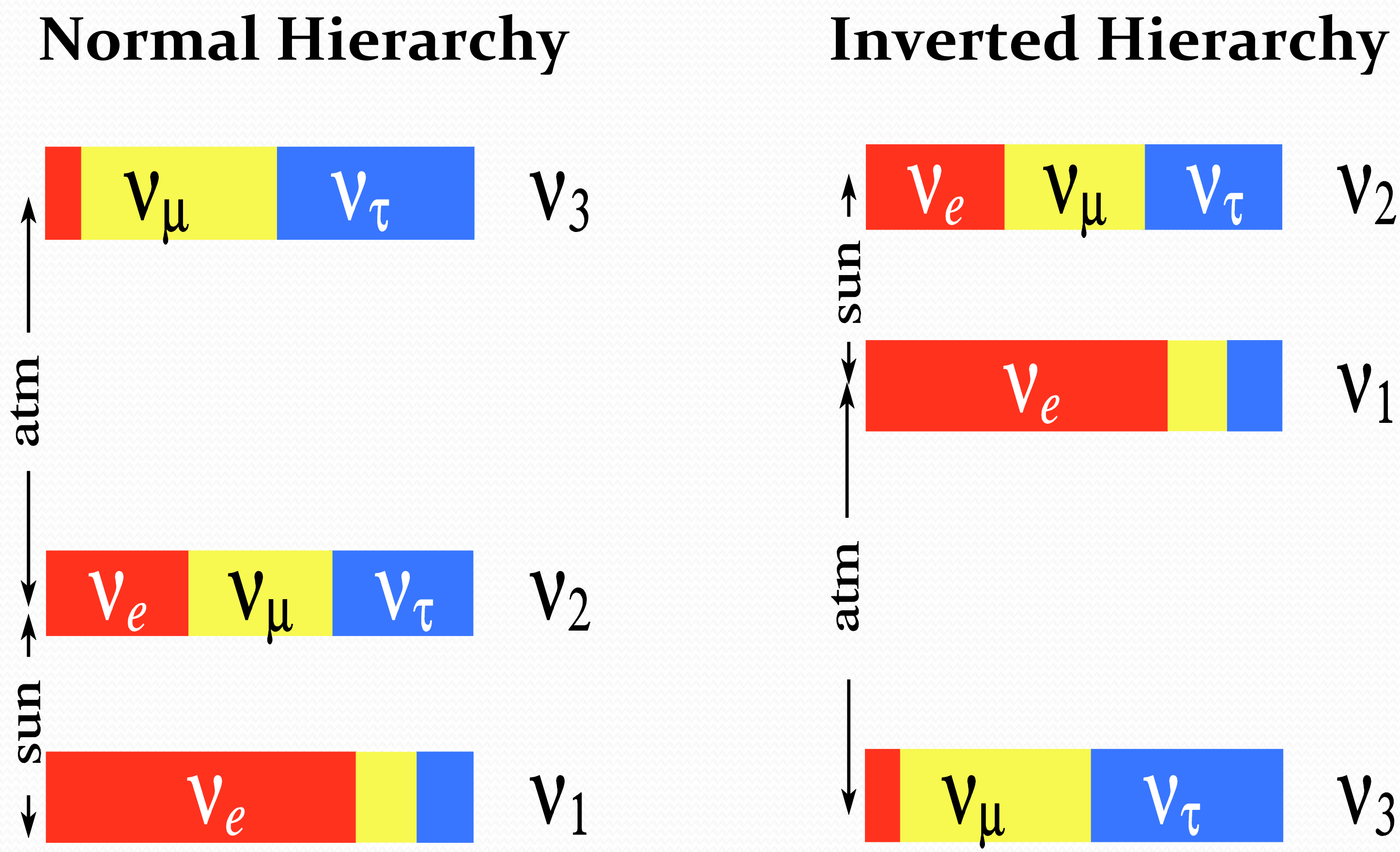
The experimental constraints are:

$$\Delta m^2_{21} = (7.2 - 8.9) \times 10^{-5}\mathrm{eV}^2$$

$$|\Delta m^2_{23}| = (2.1 - 3.1) \times 10^{-3}\mathrm{eV}^2$$

$$30^0 < \theta_{12} < 38^0, \quad 36^0 < \theta_{23} < 54^0, \quad \theta_{13} < 10^0$$

Neutrino Spectrum



Neutrinos

In the SM the lepton number (or B-L) is an accidental symmetry and the neutrinos are massless !

Today we know that the neutrinos are massive and they can be:

Dirac Fermion: $\nu^C \sim (1,1,0)$ (L is conserved by hand!)

$$-\mathcal{L}_\nu^D = Y_\nu \, l \, H \, \nu^C + \text{h.c.} \Longrightarrow M_\nu^D = Y_\nu \, v/\sqrt{2}$$

If $Y_\nu \sim 10^{-11}$ one gets $M_\nu \sim 1$ eV.

Majorana Fermion: $(L$ is broken$)$ Weinberg'79

$$-\mathcal{L}_\nu^M = c_\nu \ (l\ H)^2 / \Lambda_\nu \ + \ \text{h.c.}$$

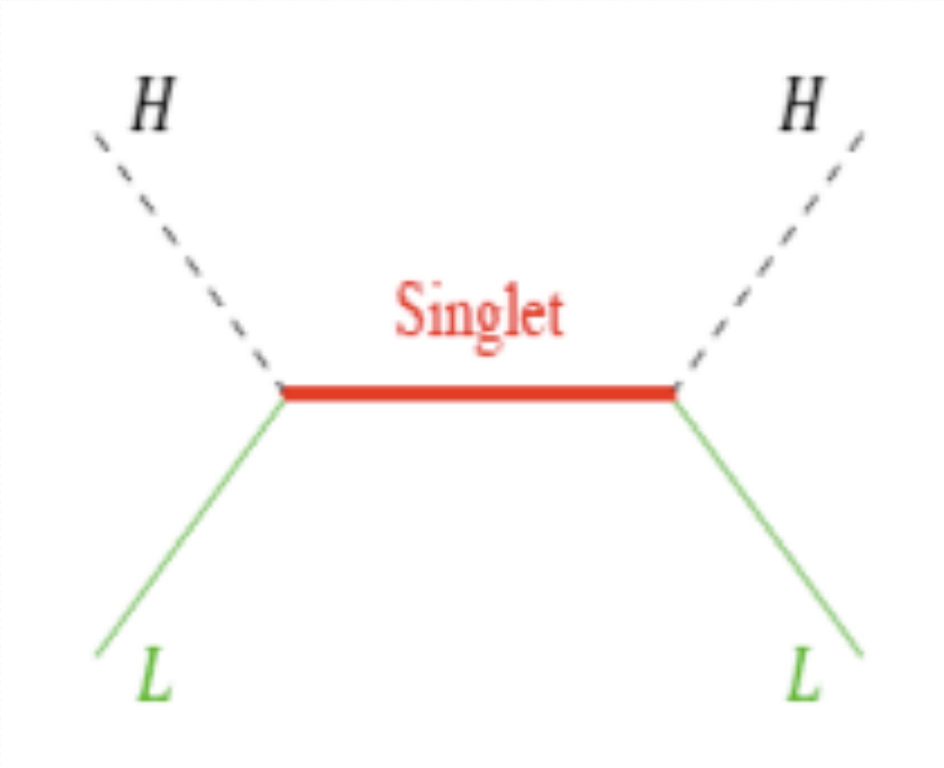
$$\Longrightarrow \ M_\nu^M \ = \ c_\nu \ v^2 / 2\Lambda_\nu$$

What is the origin of this operator?

If $c_\nu \sim 1$ and $\Lambda_\nu \sim 10^{14-15}$ GeV one gets $M_\nu \sim 1$ eV.

Mechanisms for Neutrino Masses

TYPE I SEESAW MECHANISM



Minkowski'77;
Yanagida'79; Gell-Mann, Ramond, Slansky'79;
Glashow'80; Mohapatra, Senjanovic'80

TYPE I SEESAW

Extra Fermions: $\nu^C \sim (1,1,0)$

$$-\mathcal{L}^I = Y_\nu \, l \, H \, \nu^C + \frac{1}{2} M \nu^C \nu^C + \text{h.c.}$$

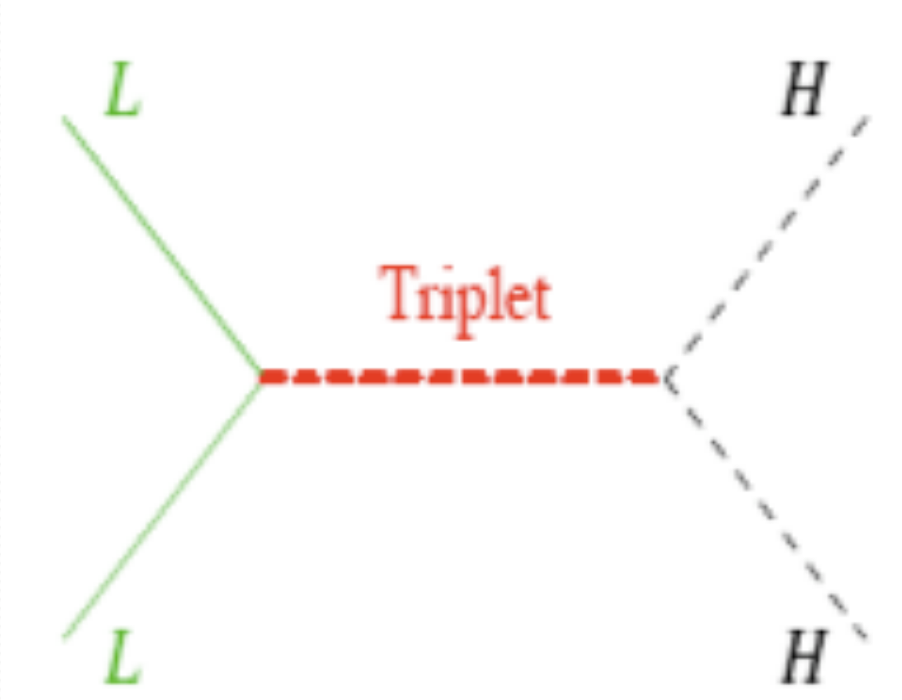
$$\Rightarrow \quad \mathcal{M}_\nu^I = \frac{v^2}{2} Y_\nu \, M^{-1} \, Y_\nu^T$$

$Y_\nu ? \quad M ?$

if $\mathrm{Y}_\nu \sim 1$ and $\mathrm{M} \sim 10^{14-15}$ GeV one has $\mathcal{M}_\nu^{\mathrm{I}} \sim 1$ eV

M is defined by the $\mathrm{U(1)_{B-L}}$ breaking scale

TYPE II SEESAW MECHANISM



Type II Seesaw

Konetschny, Kummer'77
Chen, Li'80; Lazarides, Shafi, Wetterich'81; Schechter, Valle'80; Mohapatra, Senjanovic'81

Extra Scalar: $\Delta \sim (1,3,1)$

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_\nu^{II} = -Y_\nu \, l \, \Delta \, l \; + \; \mu \, H \Delta^\dagger H \; + \; \text{h.c.} \; + \; ...$$

$$\Rightarrow \quad \mathcal{M}_\nu^{II} = Y_\nu \; \mu \; v^2 / M_\Delta^2$$

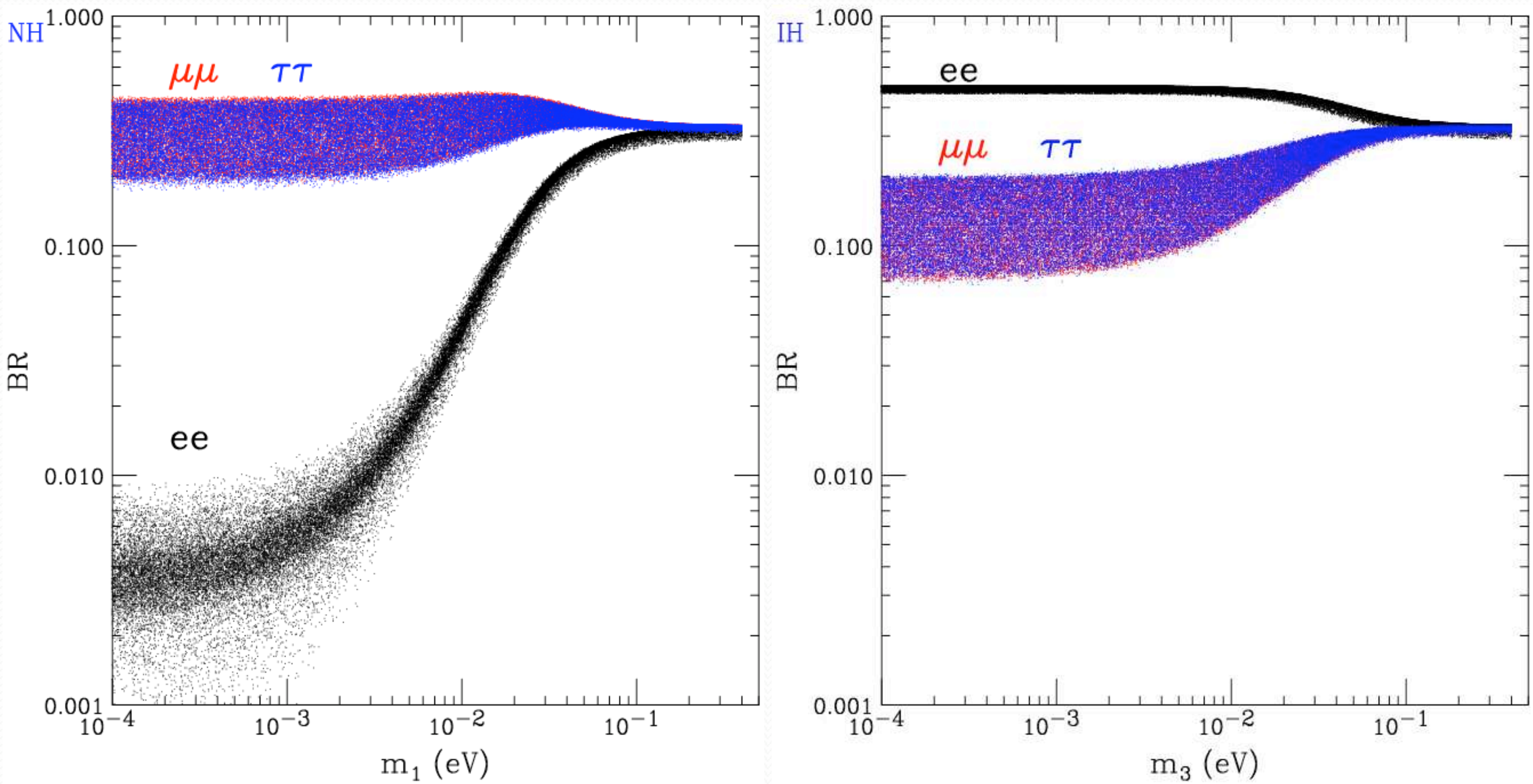
$Y_\nu ? \quad M_\Delta ? \quad \mu ?$

if $\text{Y}_\nu \sim 1$ and $\text{v}_\Delta \sim 1$ eV one gets the natural neutrino scale

P.F.P., T. Han, G.Y. Huang, T. Li, K. Wang'08

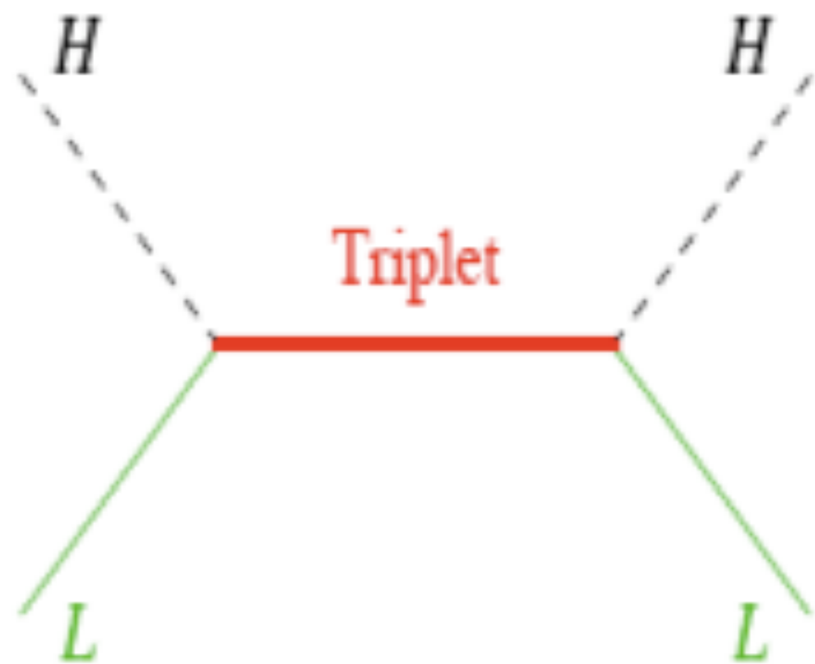
HIGGS DECAYS AND NEUTRINO MASSES

$$H^{++} \rightarrow e_i^+ e_j^+$$



See Talk by F. de Aguila. See also Garayoa, Schwetz; F. de Aguila et al, and others

TYPE III SEESAW MECHANISM



Type III Seesaw

Foot, Lew,He,Joshi'89; Ma'98; Bajc, Senjanovic'07; P. Fileviez Perez'07

Extra Fermions: $\rho \sim (1,3,0)$

$$\rho = \begin{pmatrix} \rho^0/\sqrt{2} & \rho^+ \\ \rho^- & -\rho^0/\sqrt{2} \end{pmatrix}$$

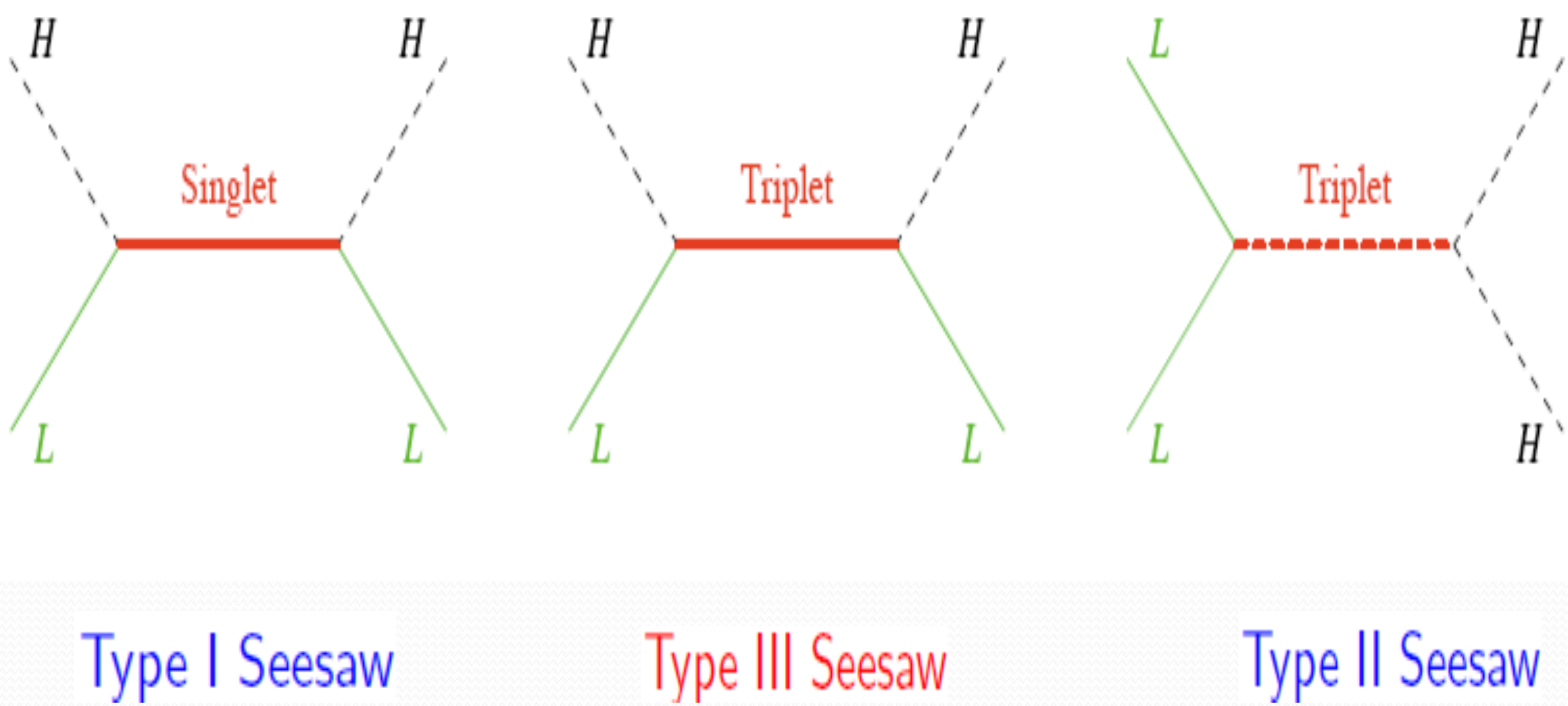
$$-\mathcal{L}^{III} = Y_\nu \, l \, \rho \, H \; + \; M_\rho \, \mathrm{Tr}\rho^2 \; + \; \mathrm{h.c.}$$

$$\mathcal{M}_\nu^{III} = v^2 \, Y_\nu \, M_\rho^{-1} \, Y_\nu^T / 2$$

$Y_\nu ? \quad M_\rho ?$

If $Y_\nu \sim 1$ and $M_\rho \sim 10^{14-15}$ GeV one has $M_\nu^{III} \sim 1$ eV.

Seesaw Mechanisms at Tree Level

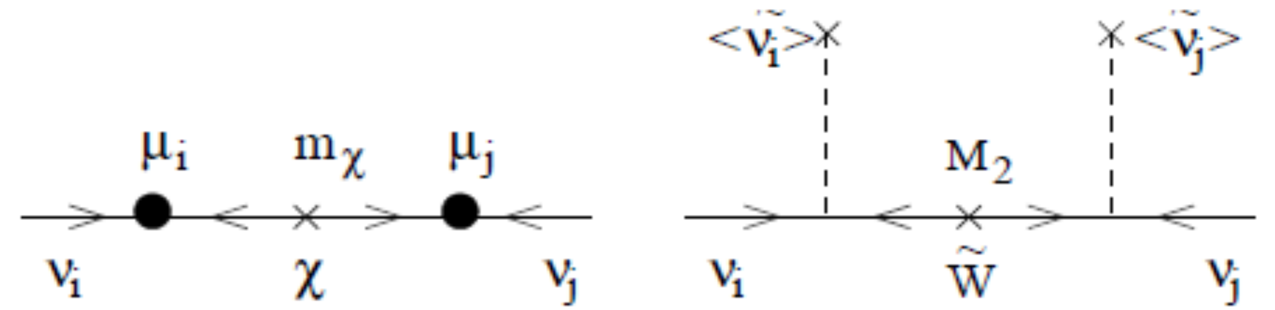


R-Parity Violation in SUSY

In the MSSM:

$$R = (-1)^{3(B-L)+2S}$$

$$W_{RpV} = \epsilon_i \hat{L}_i \hat{H}_u + \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_j^C + \lambda'_{ijk} \hat{Q}_i \hat{L}_j \hat{D}_k^C + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C$$



We need a mechanism for spontaneous R-parity violation !!!!

V. Barger, P.F.P., S. Spinner, *Phys. Rev. Lett.102:181802,2009*

Local B-L and Spontaneous R-Parity Violation

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

Matter: $\hat{Q}$ $\hat{L}$ $\hat{U}^C$ $\hat{D}^C$ $\hat{E}^C$

$\hat{N}^C \sim (1,1,0,1)$ (for anomaly cancellation)

-Some R-Parity Violating couplings

$$\frac{1}{2} g_{BL}\ v_R\ \nu^C\ \tilde{B}' \qquad \frac{1}{2} g_2\ v_L\ \nu\ \tilde{W}^0 \qquad \frac{1}{2} g_1\ v_L\ \nu\ \tilde{B}$$

Neutrino-Neutralino Mass Matrix

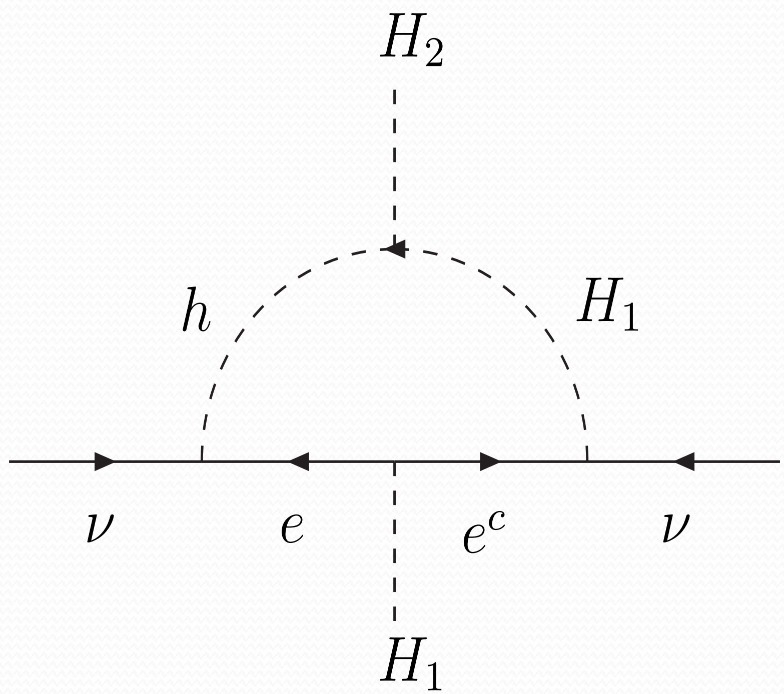
$$\left(\nu,\ \nu^c,\ \tilde{\chi}^0\right) \Rightarrow \mathcal{M}_N = \begin{pmatrix} 0 & M_\nu^D & \Gamma \\ \left(M_\nu^D\right)^T & 0 & G \\ \Gamma^T & G^T & M_{\tilde{\chi}^0} \end{pmatrix}$$

Type I Seesaw and RpV: $M_\nu = (\tilde{M}_\nu^D) M_{\nu^C}^{-1} (\tilde{M}_\nu^D)^T \ + \ \Gamma M_{\tilde{\chi}^0}^{-1} \Gamma^T$

MECHANISMS AT ONE-LOOP LEVEL

Zee Model

A. Zee'80



The Zee-Wolfenstein model is ruled out !

The general model still alive. See He'03

Zee Model

A. Zee'80

Extra Higgses: $h \sim (1,1,1)$ $H_2 \sim (1,2,1/2)$

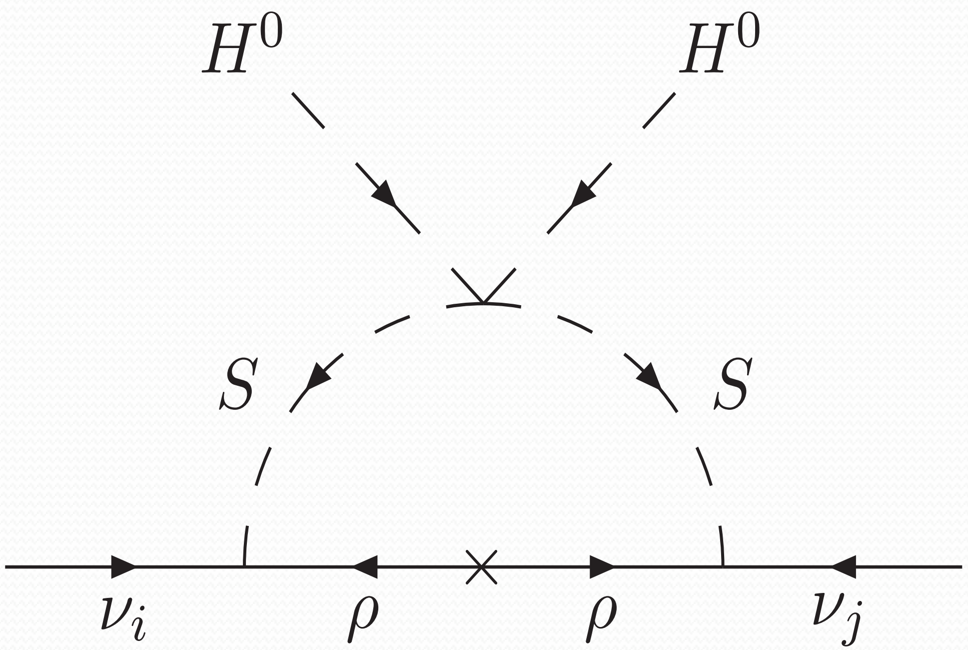
$$-\mathcal{L}_{Zee} = Y\, l\, l\, h + \mu\, H_1\, H_2\, h^\dagger + Y_1\, e^C\, H_1^\dagger\, l + Y_2\, e^C\, H_2^\dagger\, l + \text{h.c.}$$

$$\boxed{Y = -Y^T}$$

$$\mathcal{O}_5^\nu = c_{11}\, l\, l\, H_1^2 + c_{12}\, l\, l\, H_1\, H_2 + c_{22}\, l\, l\, H_2^2$$

P.F.P., M. B. Wise, arXiv:0906.2950

COLORED MECHANISM



P.F.P., M. B. Wise, arXiv:0906.2950

COLORED MECHANISM

$$-\mathcal{L} = Y_2 \, l \, S_1 \, \rho_1 \; + \; M_{\rho_1} \mathrm{Tr} \, \rho_1^2 \; + \; \lambda_2 \mathrm{Tr} \left(\mathrm{S}_1^\dagger \mathrm{H} \right)^2 \; + \; \mathrm{h.c.}$$

1) $\rho_1 \sim (8, 1, 0), \quad S_1 \sim (8, 2, 1/2)$

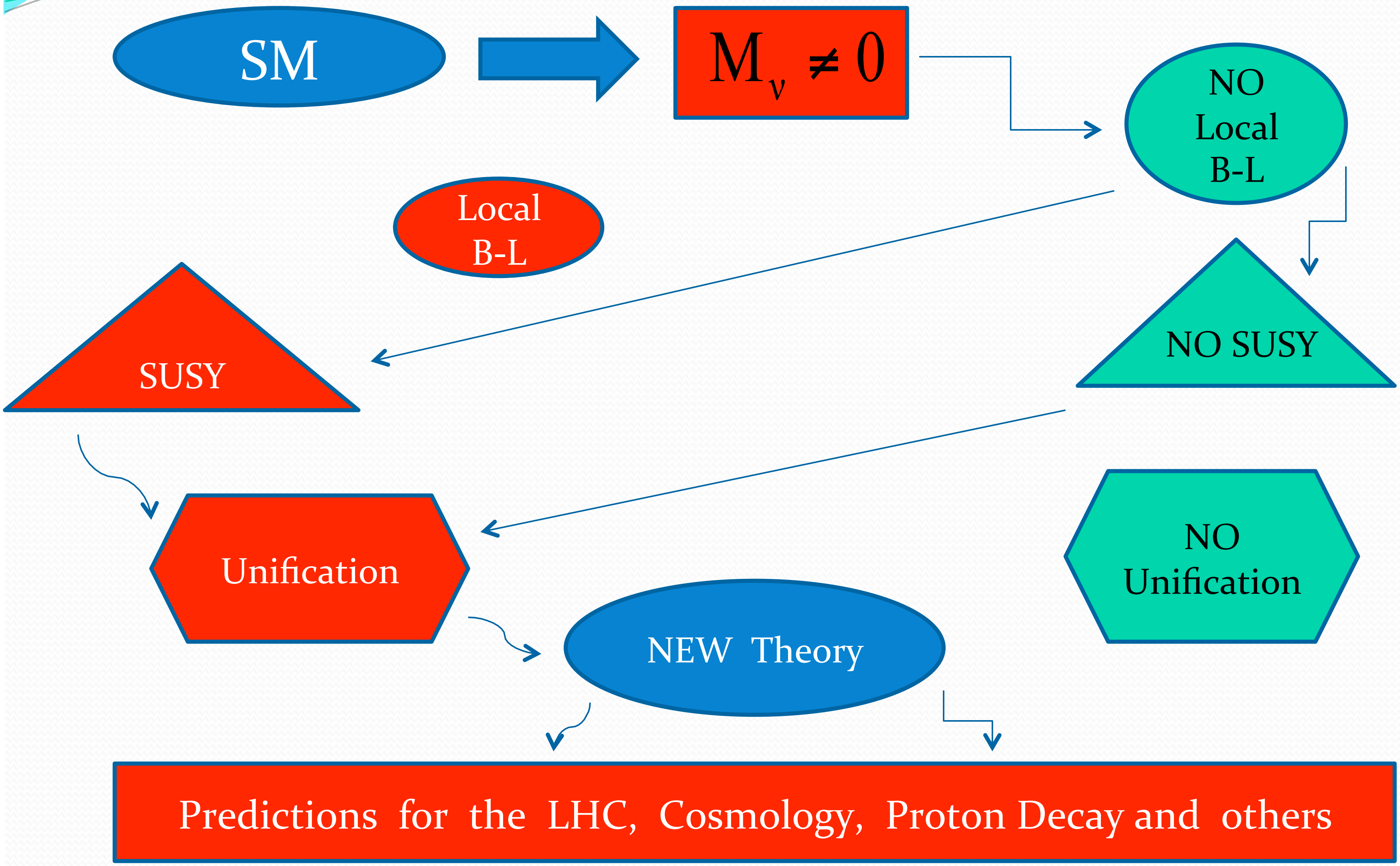
$$\mathcal{M}_\nu^{ij} = Y_2^{i\alpha} \, Y_2^{j\alpha} \, \frac{\lambda_2}{4\pi^2} \, v^2 \, \frac{M_{\rho_1^\alpha}}{M_{S_1}^2}.$$

$M_{\rho_1} = 200$ GeV, $v = 246$ GeV and $M_{S_1} = 2$ TeV $\Rightarrow$ $Y_2^2 \lambda_2 \sim 10^{-8}$

Grand Unification

and

Massive Neutrinos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Neutrino Masses and Renormalizable SU(5)

Georgi-Glashow Model

Georgi, Glashow'74

Symmetry: $SU(5)$

Gauge Bosons: $A_\mu = (G_\mu, W_\mu, B_\mu, V_\mu, \bar{V}_\mu)$

Fermions:

$$\mathbf{10} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & u_3^C & -u_2^C & u_1 & d_1 \\ -u_3^C & 0 & u_1^C & u_2 & d_2 \\ u_2^C & -u_1^C & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^C \\ -d_1 & -d_2 & -d_3 & -e^C & 0 \end{pmatrix}, \ \overline{\mathbf{5}} = \begin{pmatrix} d_1^C \\ d_2^C \\ d_3^C \\ e \\ -\nu \end{pmatrix}$$

Higgs Sector:

$$5_H = \begin{pmatrix} T_1 \\ T_2 \\ T_3 \\ H^+ \\ H^0 \end{pmatrix}, \; 24_H = \begin{pmatrix} \Sigma_8 & \Sigma_{(3,2)} \\ \Sigma_{(\bar{3},2)} & \Sigma_3 \end{pmatrix} + \frac{1}{2\sqrt{15}} \begin{pmatrix} 2 & 0 \\ 0 & -3 \end{pmatrix} \Sigma_{24}$$

Ruled out by unification and/or fermion masses !

Why the Georgi-Glashow model is ruled out ?

- Unification of gauge couplings in disagreement with the values of α_s, $\sin\theta_W$ and α_{em} at the electroweak scale

- $M_E = M_D^T$ at the GUT scale

- $M_\nu = 0$

$$M_D = M_E^T$$

$\Rightarrow$

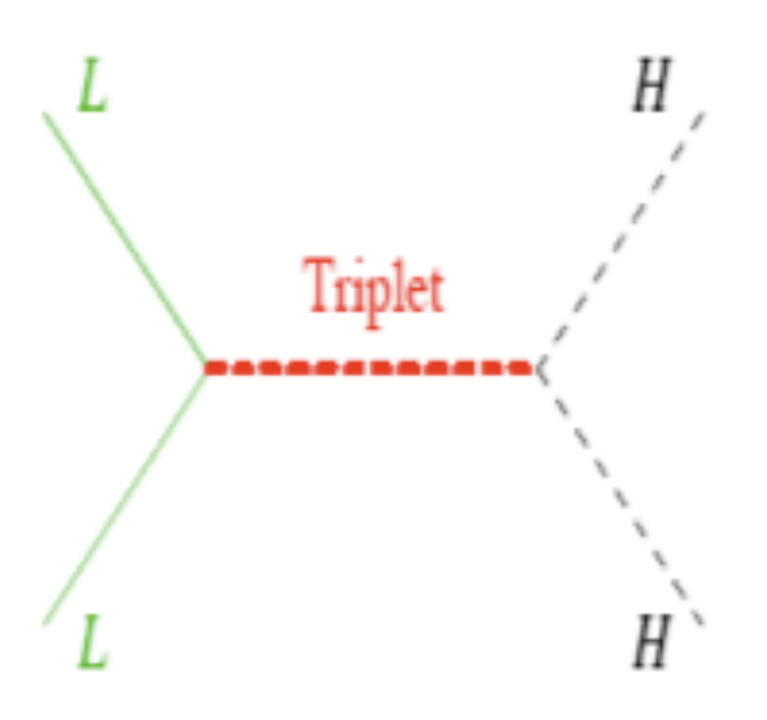
$$- \ 45_H$$

$$- \ \text{h.d.ops}$$

Neutrino Masses: $M_\nu \neq 0$

- Type I seesaw: 1_i, i=1,2,..
- Type II seesaw: $\Delta \subset 15_H$ $\left(15_H \bigoplus \overline{15}_H\right)$
- Type III seesaw: $\rho \subset 24$

Type II Seesaw



$$\Delta \subset 15_H$$

I. Dorsner, P. Fileviez Pérez Nucl.Phys.B723:53-76,2005

Type II – SU(5)

Higgs Sector: 5_H, 24_H, 15_H

$$15_H = \underbrace{(1,3,1)}_{\Phi_a} \oplus \underbrace{(3,2,1/6)}_{\Phi_b} \oplus \underbrace{(6,1,-2/3)}_{\Phi_c}$$

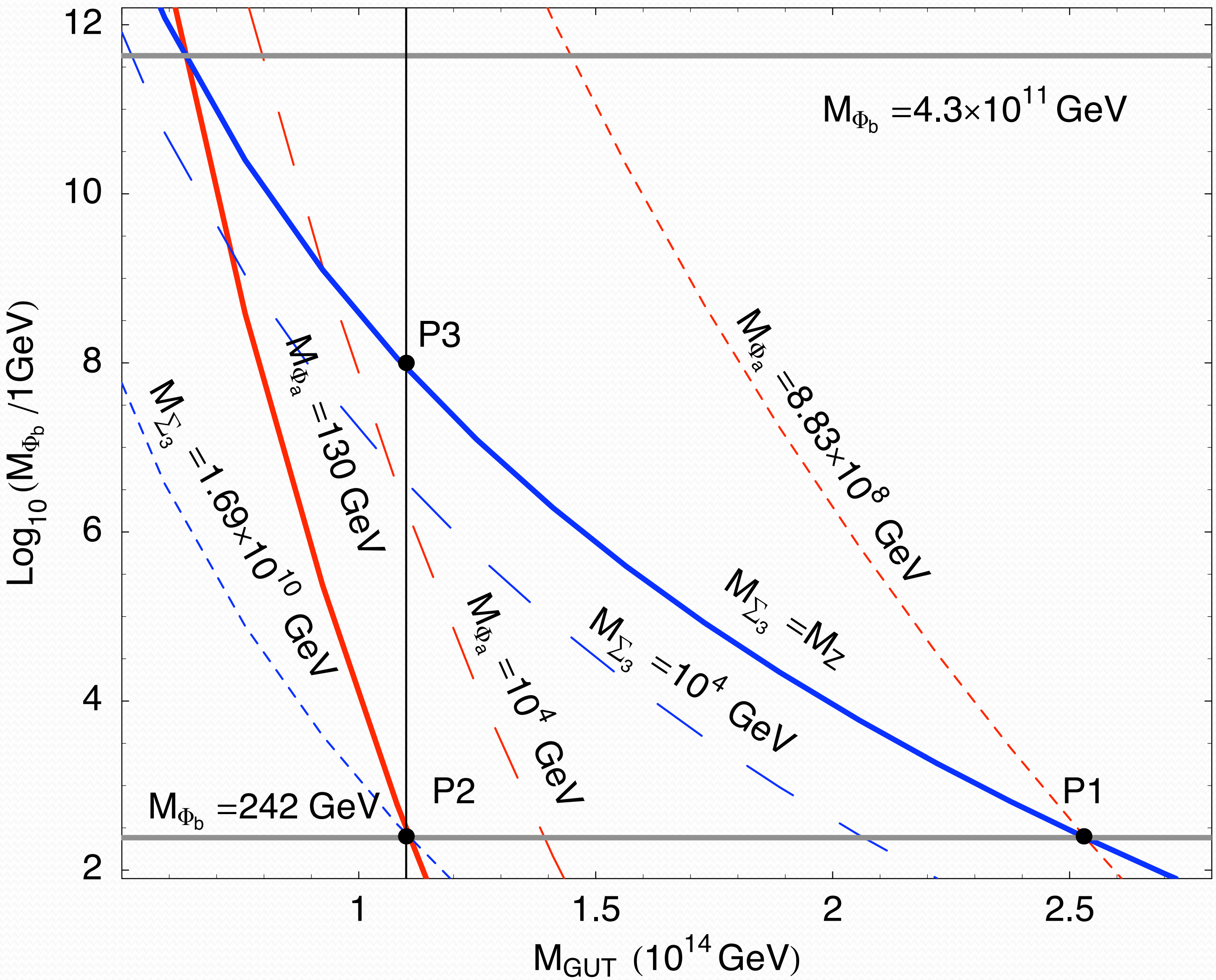
$$\Phi_a = i\sigma_2 \Delta$$

Neutrino Masses: Type II seesaw mechanism

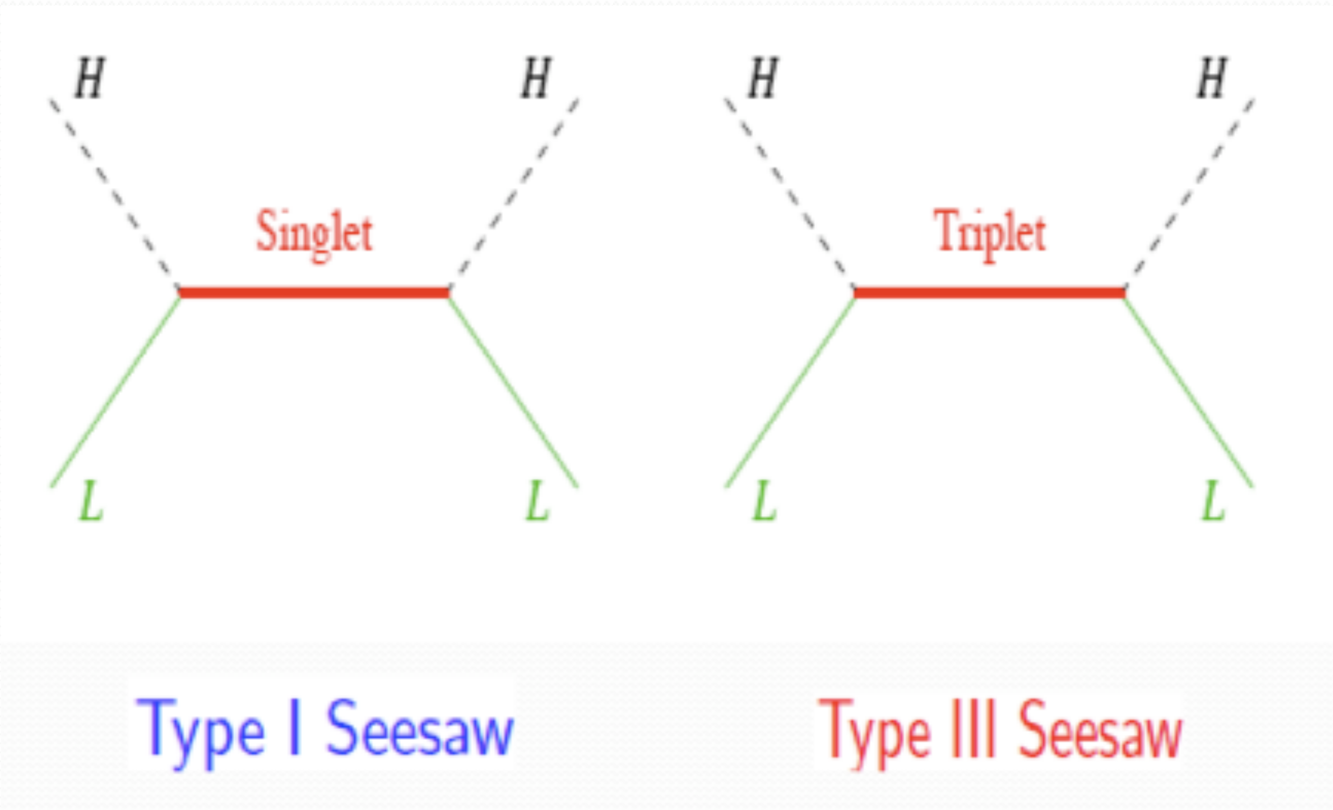
$$V_\nu = Y_\nu \, \bar{5} \, \bar{5} \, 15_H + \mu \, 5_H^* \, 5_H^* \, 15_H + \text{h.c.}$$

$$M_\nu = Y_\nu \, \mu \, v^2 / M_\Delta^2$$

I. Dorsner, P. Fileviez Pérez, G. Rodrigo, PRD: 125007,2007



Type I plus Type III Seesaw



Adjoint SU(5)

P. Fileviez Pérez, PLB 654 (2007) 189.

Matter: $\bar{5} = (d^C, e, \nu)$, $10 = (u^C, Q, e^C)$, 24

Higgs Sector: 5_H, 24_H, 45_H

$$24 = \underbrace{(8,1)}_{\rho_8} \oplus \underbrace{(1,3)}_{\rho_3} \oplus \underbrace{(3,2)}_{\rho_{(3,2)}} \oplus \underbrace{(\bar{3},2)}_{\rho_{(\bar{3},2)}} \oplus \underbrace{(1,1)}_{\rho_0}$$

Neutrino Mass: Type I and Type III seesaw

$$V_\nu = \alpha_i \, \bar{5}_i \, 24 \, 5_H \; + \; p_i \, \bar{5}_i \, 24 \, 45_H$$

See also: P. Fileviez Pérez, PRD 76 (2007) 071701.

P. Fileviez Pérez, PLB 654 (2007) 189.

Neutrino Masses in Adjoint SU(5)

$$V = c_\alpha \, \bar{5}_\alpha \, 24 \, 5_H + p_\alpha \, \bar{5}_\alpha \, 24 \, 45_H + M \, \mathrm{Tr} \, 24^2 + \lambda \, \mathrm{Tr} \left(24^2 24_H \right) + \mathrm{h.c.}$$

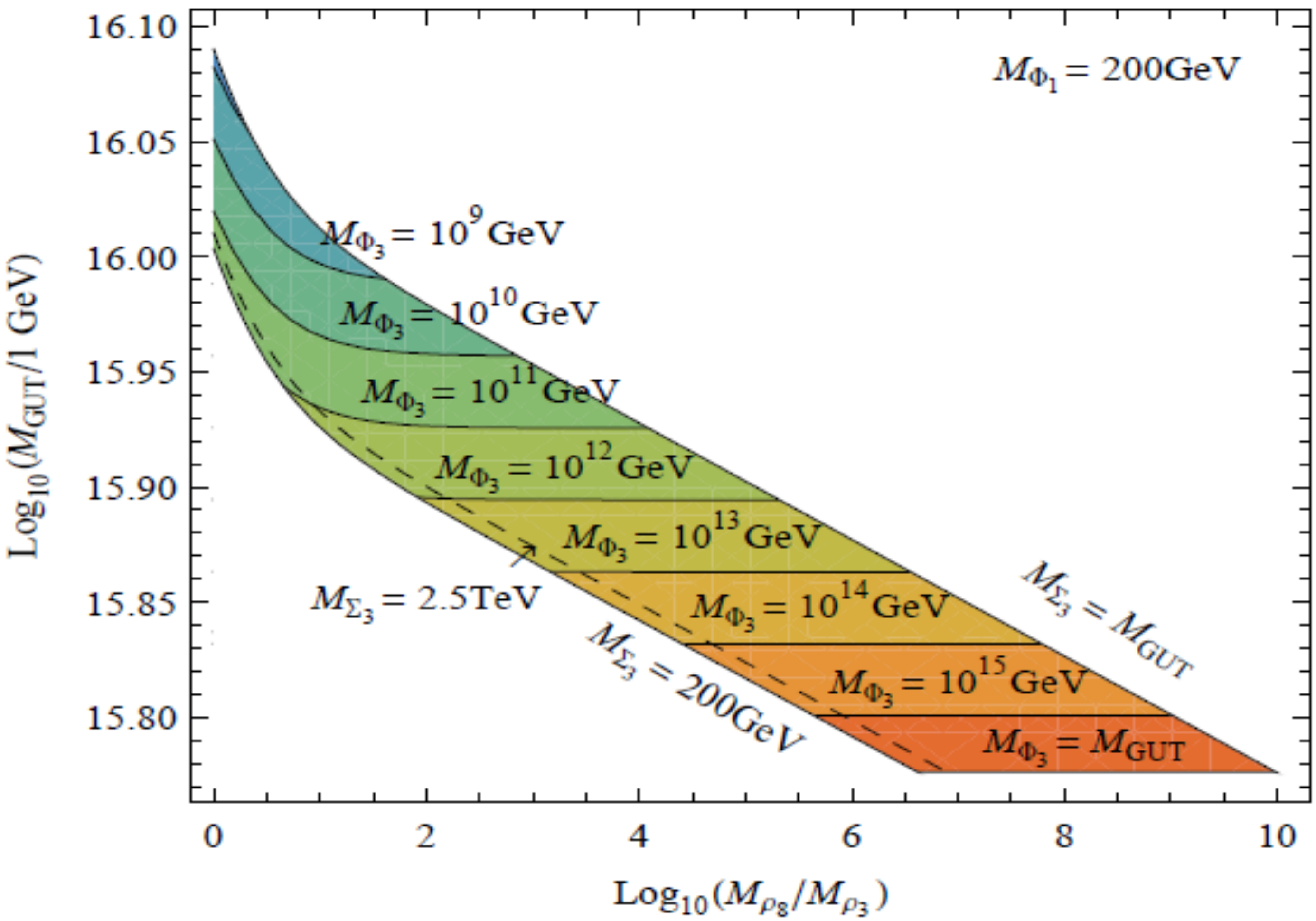
$$\rho_3 = \frac{1}{2} \begin{pmatrix} T^0 & \sqrt{2} T^+ \\ \sqrt{2} T^- & -T^0 \end{pmatrix} .$$

$$M^\nu_{\alpha\beta} = \left(\frac{h_{\alpha 1} \, h_{\beta 1}}{M_{\rho_3}} + \frac{h_{\alpha 2} \, h_{\beta 2}}{M_{\rho_0}} \right) v_0^2 .$$

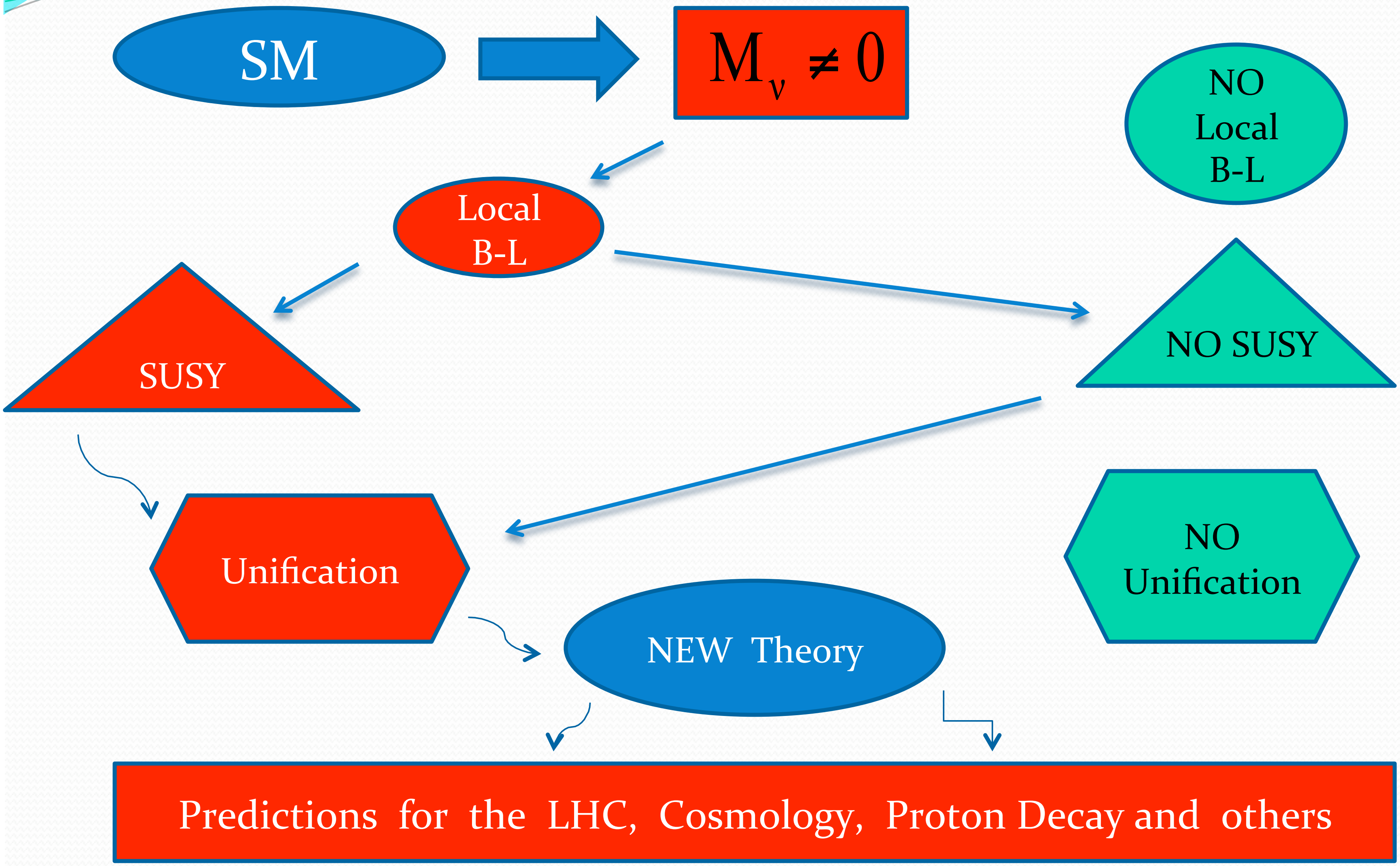
One Massless Neutrino !

See also Bajc, Senjanovic'07

P. Fileviez Pérez, H. Iminniyaz, G. Rodrigo, PRD 78 (2008) 015013.



Unification at the one-loop level.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Neutrino Masses and Renormalizable SO(10)

Georgi'75, Fritzsch, Minkowski'75

SO(10) Unification

Gauge Symmetry: $SO(10)$

Matter: $16 = (Q,\ L,\ u^C,\ d^C,\ e^C,\ \nu^C)$

Higgs Sector: $10_H = 5_H \bigoplus \bar{5}_H = (H, T) \bigoplus (\bar{H}, \bar{T})$

$45_H, \ldots.$

Naïve SO(10)

$$-\mathcal{L}_Y = Y_{10}\ 16\ 16\ 10_H\ +\ \text{h.c.}$$

$$M_U = M_\nu^D = v_{10}^u\ Y_{10}\quad (\textit{wrong!})$$

$$M_D = M_E = v_{10}^d\ Y_{10}\quad (\textit{wrong!})$$

$$Y_{10} = Y_{10}^T$$

Realistic Renormalizable SO(10)

$$-\mathcal{L}_Y = Y_{10}\ 16\ 16\ 10_H \ + \ Y_{126}\ 16\ 16\ \overline{126}_H \ + \ \text{h.c.}$$

$$M_U = v_{10}^u \ Y_{10} \ + \ v_{126}^u \ Y_{126}$$

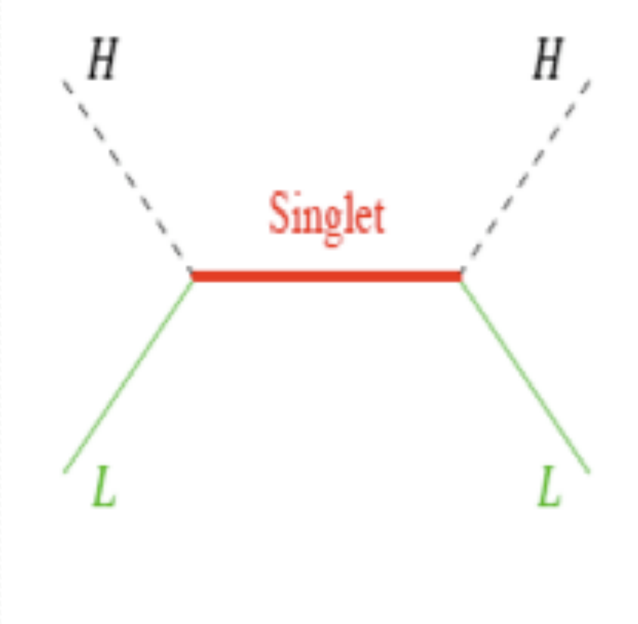
$$M_\nu^D = v_{10}^u \ Y_{10} \ - \ 3\ v_{126}^u \ Y_{126}$$

$$M_D = v_{10}^d \ Y_{10} \ + \ v_{126}^d \ Y_{126}$$

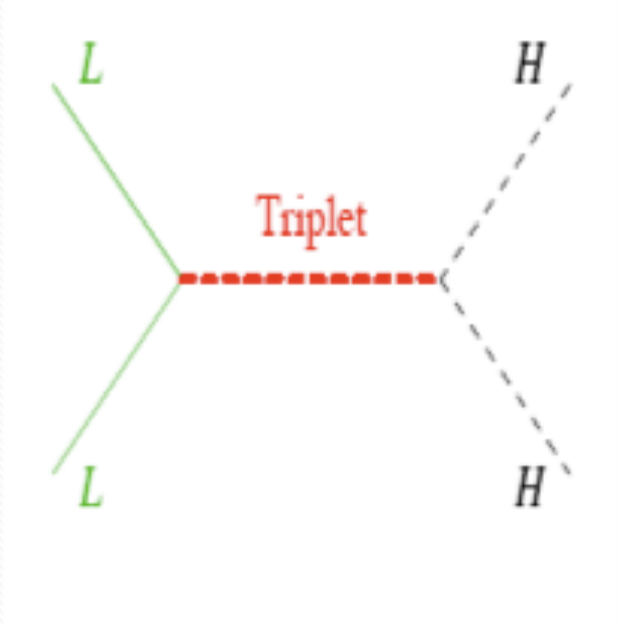
$$M_{\nu_R} = Y_{126}\ v_R$$

$$M_\nu = -M_\nu^D \ M_{\nu_R}^{-1} \ M_\nu^D \ + \ Y_{126}\ v_L$$

Type I plus Type II Seesaw



Type I Seesaw



Type II Seesaw

For the study of neutrino masses in this context see:

Babu, Mohapatra'93

Bajc, Senjanovic, Vissani'02, '04

Goh, Mohapatra, Ng'03

Fukuyama, Okada'03

Bertolini, Frigerio, Malinsky'04

Aulakh, Bajc, Melfo, Senjanovic, Vissani'04,'05'06

Bertolini, Schwetz, Malinsky'06

Bajc, Dorsner, Nemedev'08

	type-II		mixed'		mixed		type-I	
$\|\xi\|$	0		10^{-4}		0.3587		3.59×10^6	
$\arg(\xi)$	–		0.866π		1.018π		1.318π	
$\|r\|$	0.3278		1.9977		0.47896		0.3551	
$\arg(r)$	0.408π		1.849π		0.0013π		0.0057π	
f_u	16.62		11.51		18.77		19.23	
f_ν	1.671×10^{-10}		4.519×10^{-10}		8.732×10^{-10}		3.613×10^{-17}	
observable	pred.	pull	pred.	pull	pred.	pull	pred.	pull
m_d [MeV]	0.7662	**−1.16**	0.4956	**−1.82**	1.122	−0.29	0.4719	**−1.87**
m_s [MeV]	31.33	**1.85**	22.46	0.15	22.85	0.22	19.99	−0.33
m_b [MeV]	1147	0.61	1096	0.25	1078	0.13	1029	−0.35
m_u [MeV]	0.5543	0.02	0.5576	0.03	0.5512	0.00	0.5538	0.02
m_c [MeV]	213.1	0.17	213.5	0.18	210.6	0.03	213.1	0.16
m_t [MeV]	78030	−0.29	77411	−0.34	81659	−0.05	78117	−0.29
$\sin\phi_{23}^{\rm CKM}$	0.0345	−0.43	0.0352	0.08	0.0351	0.03	0.0349	−0.13
$\sin\phi_{13}^{\rm CKM}$	0.00331	0.23	0.00319	−0.02	0.00319	−0.01	0.00323	0.06
$\sin\phi_{12}^{\rm CKM}$	0.2245	0.11	0.2243	0.02	0.2243	0.01	0.2243	0.01
$\delta_{\rm CKM}$ [°]	79.35	**1.38**	59.47	−0.04	61.41	0.10	61.11	0.08
$\sin^2\theta_{23}^{\rm PMNS}$	0.3586	**−2.17**	0.5126	0.19	0.5027	0.04	0.4944	−0.09
$\sin^2\theta_{13}^{\rm PMNS}$	0.0145	0.93	0.0106	0.68	0.0066	0.43	0.0095	0.61
$\sin^2\theta_{12}^{\rm PMNS}$	0.2829	**−1.08**	0.3078	−0.09	0.3094	−0.02	0.3078	−0.09
$\Delta m_{21}^2[10^{-5}{\rm eV}^2]$	7.863	−0.12	7.894	−0.02	7.898	−0.01	7.896	−0.01
$\Delta m_{31}^2[10^{-3}{\rm eV}^2]$	2.385	0.50	2.232	0.09	2.210	0.03	2.223	0.06
$m_1/\sqrt{\Delta m_{21}^2}$	0.279		0.478		0.382		0.361	
$\delta_{\rm PMNS}$ [°]	−0.70		−59		−0.70		4.9	
α_1 [°]	1.1		30		1.8		−2.1	
α_2 [°]	91		126		−84		90	
χ^2		14.5		4.1		0.35		4.3

TABLE II: Parameter values and predictions in four example solutions corresponding to different terms dominating the neutrino mass matrix: type-I, type-II, or both contributions of comparable size (mixed and mixed'). In the column "pred." the predicted values P_i for the observables are given, the column "pull" shows the number of standard deviations from the observations, $(P_i - O_i)/\sigma_i$, using the data and errors from Tab. I. Deviations of more than 1σ are highlighted in boldface. The final χ^2 is the sum of the squares of the numbers in the "pull" column. See the text for comments on the values of the leptonic CP phases.

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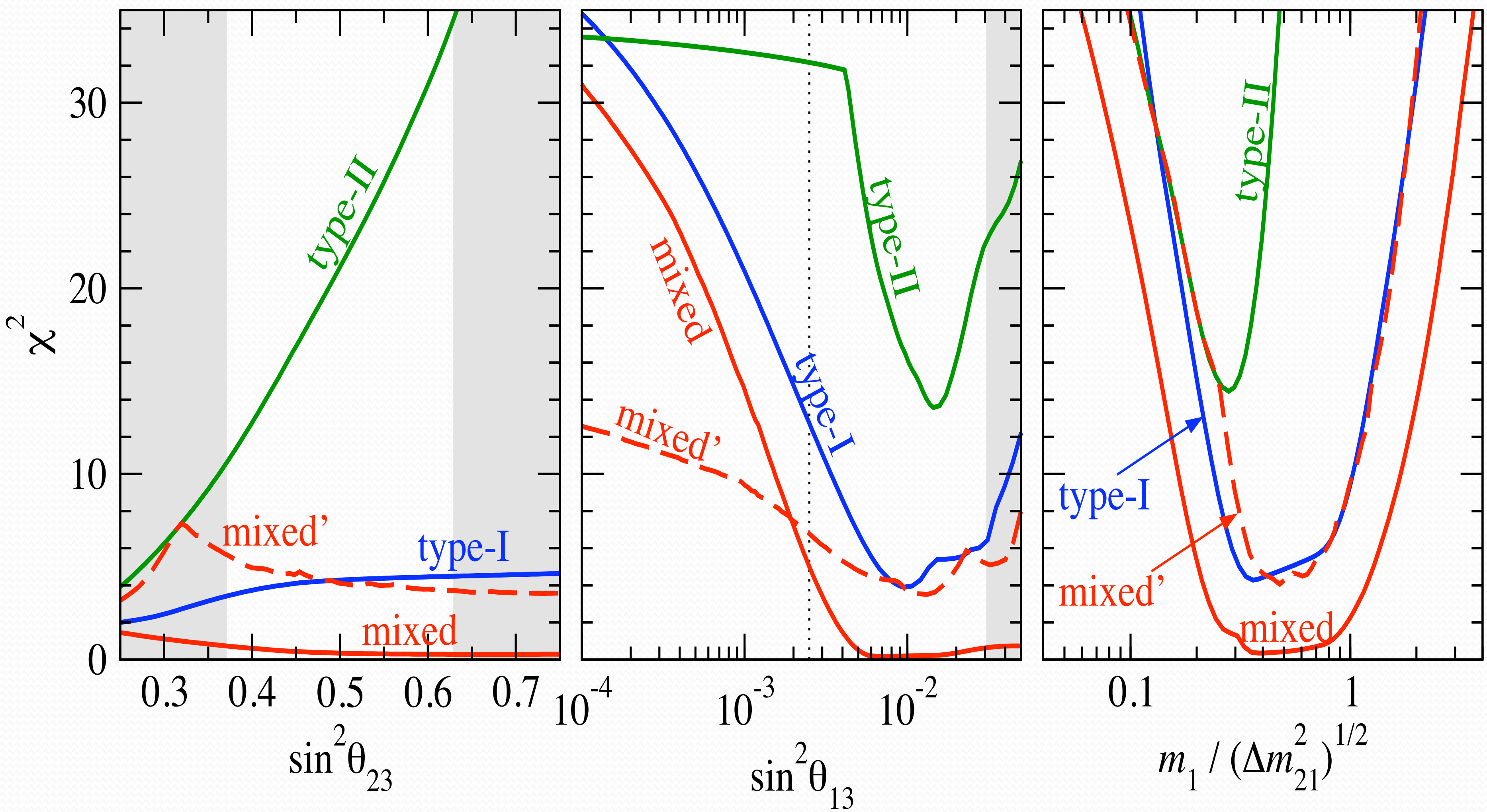
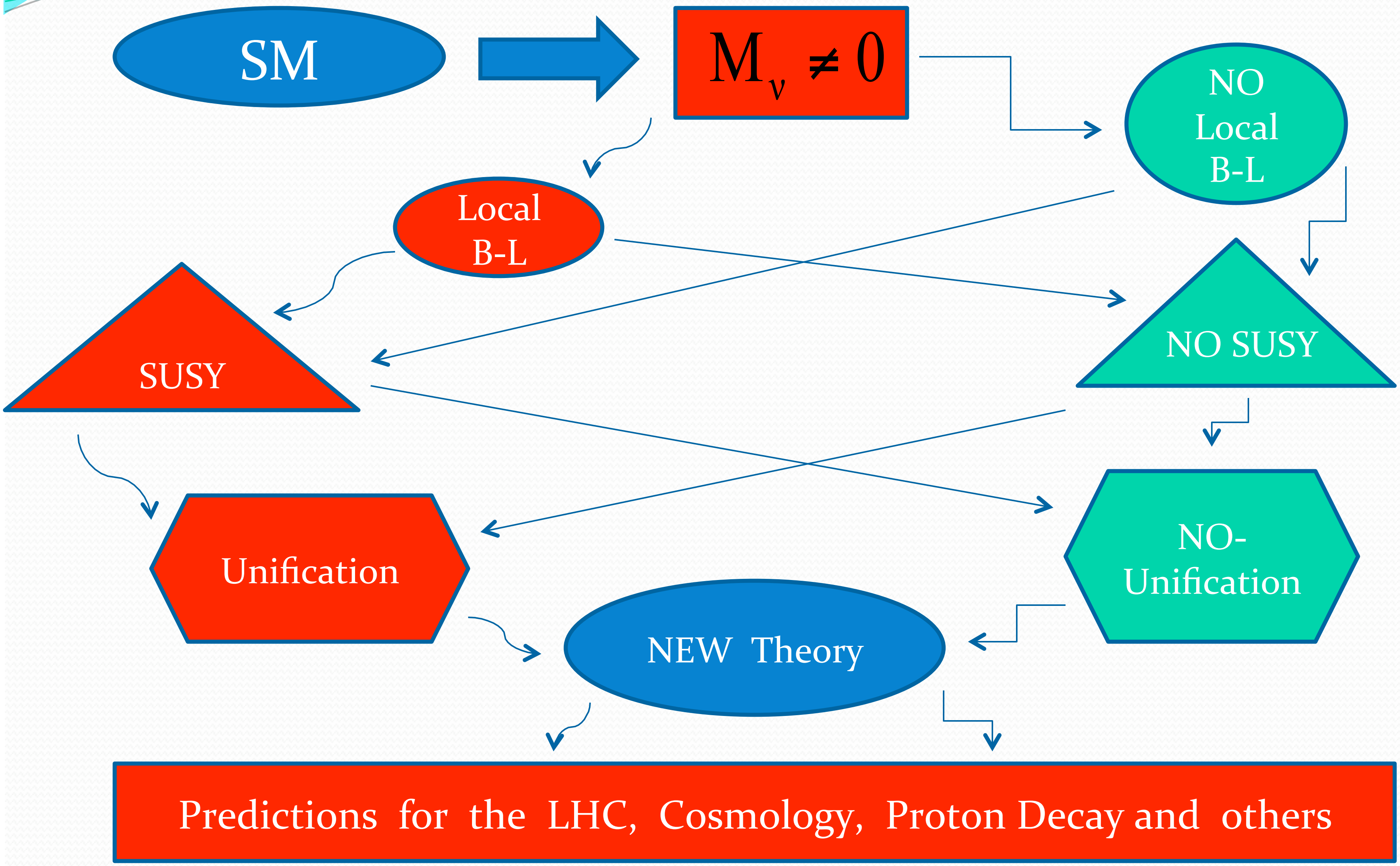


Summary

- We have presented a new mechanism for neutrino masses at one-loop level called “ Colored Mechanism ”.
- It has been shown that if the seesaw scale is low one could learn about the neutrino spectrum at the LHC in the case of Type II seesaw.
- We have discussed how to realize the different seesaw mechanisms in the simplest grand unified theories pointing out the possible predictions.
- In the context of SO(10) theories we have seen the possibility to make some predictions without assuming extra symmetries.
- All the experimental efforts will be of great importance to undertstand how to prove the mechanism for neutrino masses.

THANKS !!!!


SM
$M_\nu \neq 0$
NO Local B-L
Local B-L
SUSY
NO SUSY
Unification
NO-Unification
NEW Theory
Predictions for the LHC, Cosmology, Proton Decay and others