Flavor symmetries and DM stability

Eduardo Peinado

Departamento de Física Teórica
Instituto de Física UNAM

Segundo Taller "Más allá del Modelo Estándar y Astropartículas"
September 29th – October 1st 2025 @ IFUNAM

MODELO ESTÁNDAR DE LAS PARTÍCULAS E INTERACCIONES ELEMENTALES

FERMIONES
Constituyentes de la materia
espín = 1/2, 3/2, 5/2, ...

Leptones espín =1/2

Sabor	Masa GeV/c^2	Carga eléctrica
ν_L neutrino* ligero	$(0-2)\times10^{-9}$	0
e electrón	0.000511	−1
ν_M neutrino* mediano	$(0.009-2)\times10^{-9}$	0
μ muón	0.106	−1
ν_H neutrino* pesado	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	−1

Quarks espín =1/2

Sabor	Masa aprox. GeV/c^2	Carga eléctrica
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

BOSONES
Mediadores de fuerzas
espín = 0, 1, 2, ...

Electrodébil Unificada espín = 1

Nombre	Masa GeV/c^2	Carga eléctrica
γ fotón	0	0
W^-	80.39	−1
W^+ bosones W	80.39	+1
Z^0 bosón Z	91.188	0

Fuerte (color) espín = 1

Nombre	Masa GeV/c^2	Carga eléctrica
g gluón	0	0

Bosón de Higgs espín = 0

Nombre	Masa GeV/c^2	Carga eléctrica
H Higgs	125	0

SM poster, PDG

MODELO ESTÁNDAR DE LAS

PARTÍCULAS E INTERACCIONES ELEMENTALES

FERMIONES

Constituyentes de la materia
espín = 1/2, 3/2, 5/2, ...

Leptones espín =1/2			Quarks espín =1/2		
Sabor	Masa GeV/c^2	Carga eléctrica	Sabor	Masa aprox. GeV/c^2	Carga eléctrica
ν_L neutrino* ligero	$(0-2)\times10^{-9}$	0	u up	0.002	2/3
e electrón	0.000511	–1	d down	0.005	–1/3
ν_M neutrino* mediano	$(0.009-2)\times10^{-9}$	0	c charm	1.3	2/3
μ muón	0.106	–1	s strange	0.1	–1/3
ν_H neutrino* pesado	$(0.05-2)\times10^{-9}$	0	t top	173	2/3
τ tau	1.777	–1	b bottom	4.2	–1/3

BOSONES

Mediadores de fuerzas
espín = 0, 1, 2, ...

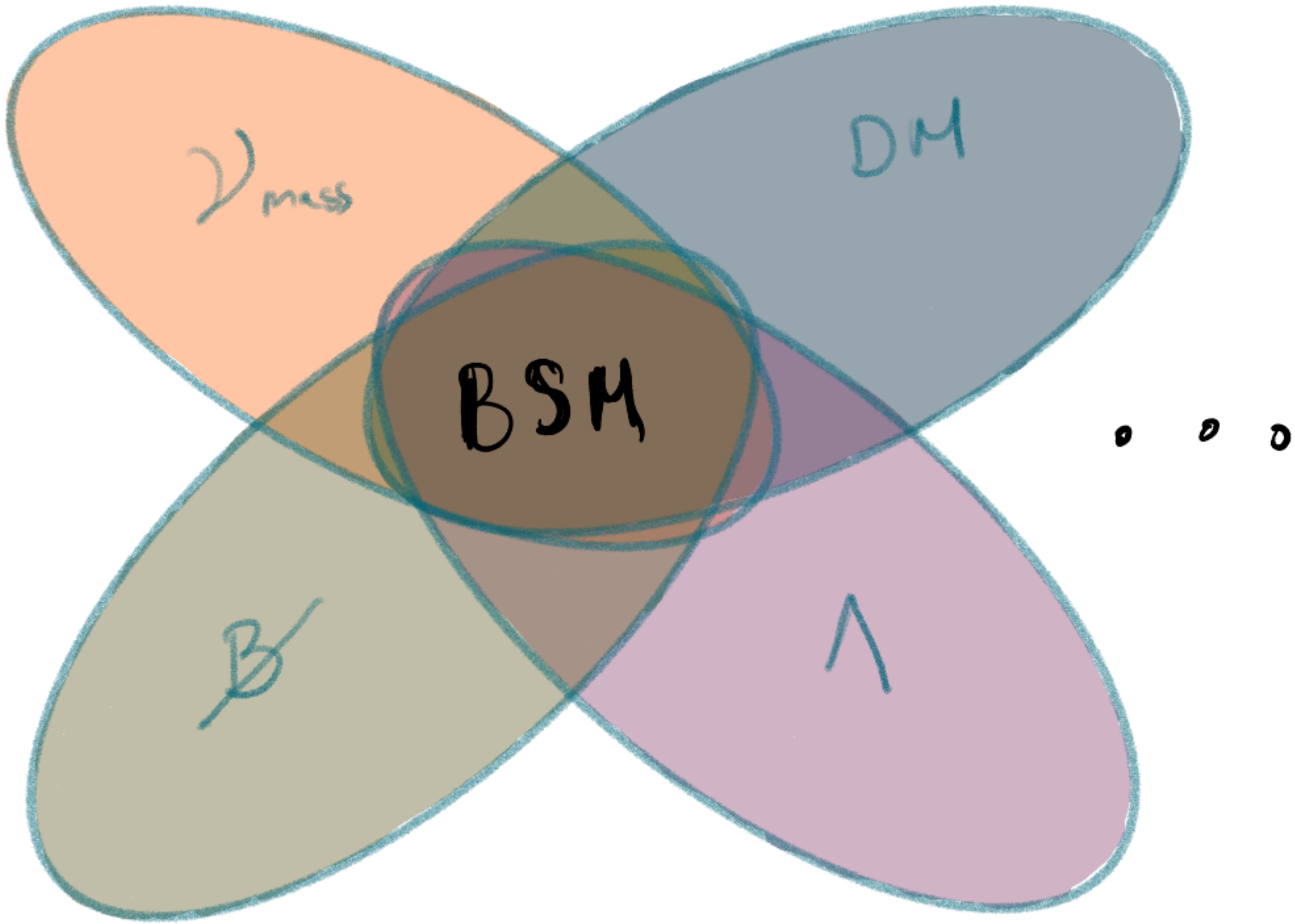
Electrodébil Unificada espín = 1		
Nombre	Masa GeV/c^2	Carga eléctrica
γ fotón	0	0
W^-	80.39	–1
W^+ bosones W	80.39	+1
Z^0 bosón Z	91.188	0

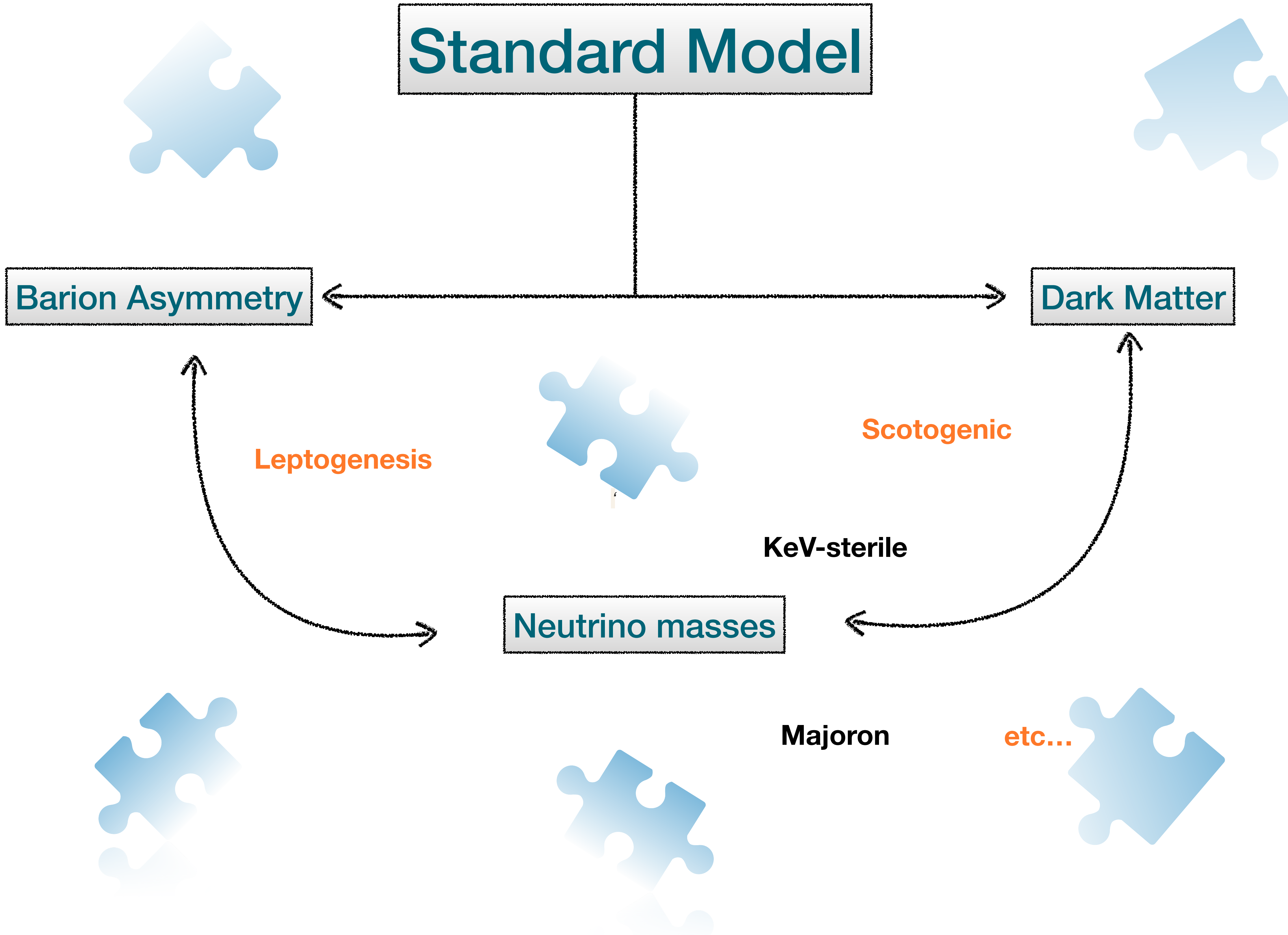
Fuerte (color) espín = 1		
Nombre	Masa GeV/c^2	Carga eléctrica
g gluón	0	0

Bosón de Higgs espín = 0		
Nombre	Masa GeV/c^2	Carga eléctrica
H Higgs	125	0

SM poster, PDG

$$\mathbf{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y} \xrightarrow{\text{EWSB}} \mathbf{SU(3)_C \otimes U(1)_Q}$$


ν_{mass}
DM
BSM
$\not{B}$
Λ
. . .


Standard Model
Barion Asymmetry
Dark Matter
Leptogenesis
Scotogenic
KeV-sterile
Neutrino masses
Majoron
etc...

Dirac Fermion mass

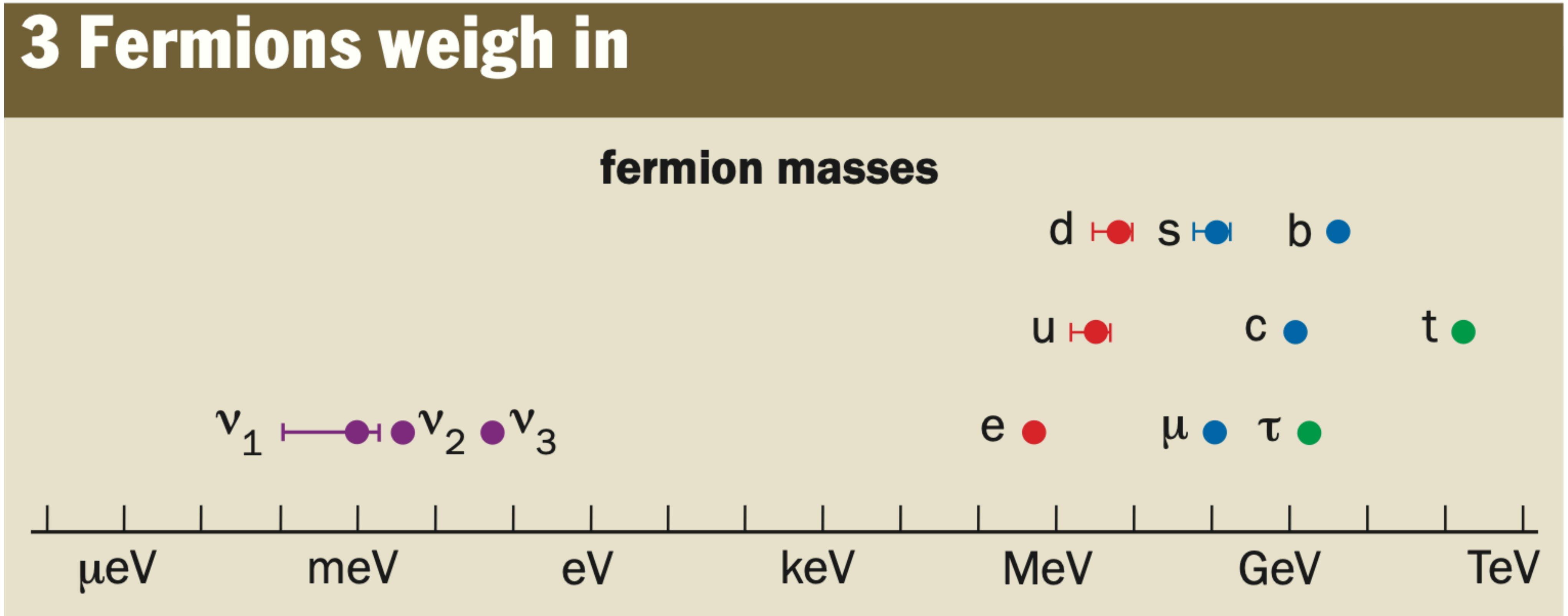
$$m\bar{\Psi}\Psi = m(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L)$$

SM is chiral $u_L \neq u_R$

$$y\bar{\Psi}_L H\Psi_R \xrightarrow{EWSB} m\bar{\Psi}_L\Psi_R \quad \checkmark$$

Majorana Fermion mass

$$\overline{\Psi_L^c}\Psi_L \quad \text{and} \quad \overline{\Psi_R^c}\Psi_R$$



H. Murayama, Physics World 2002

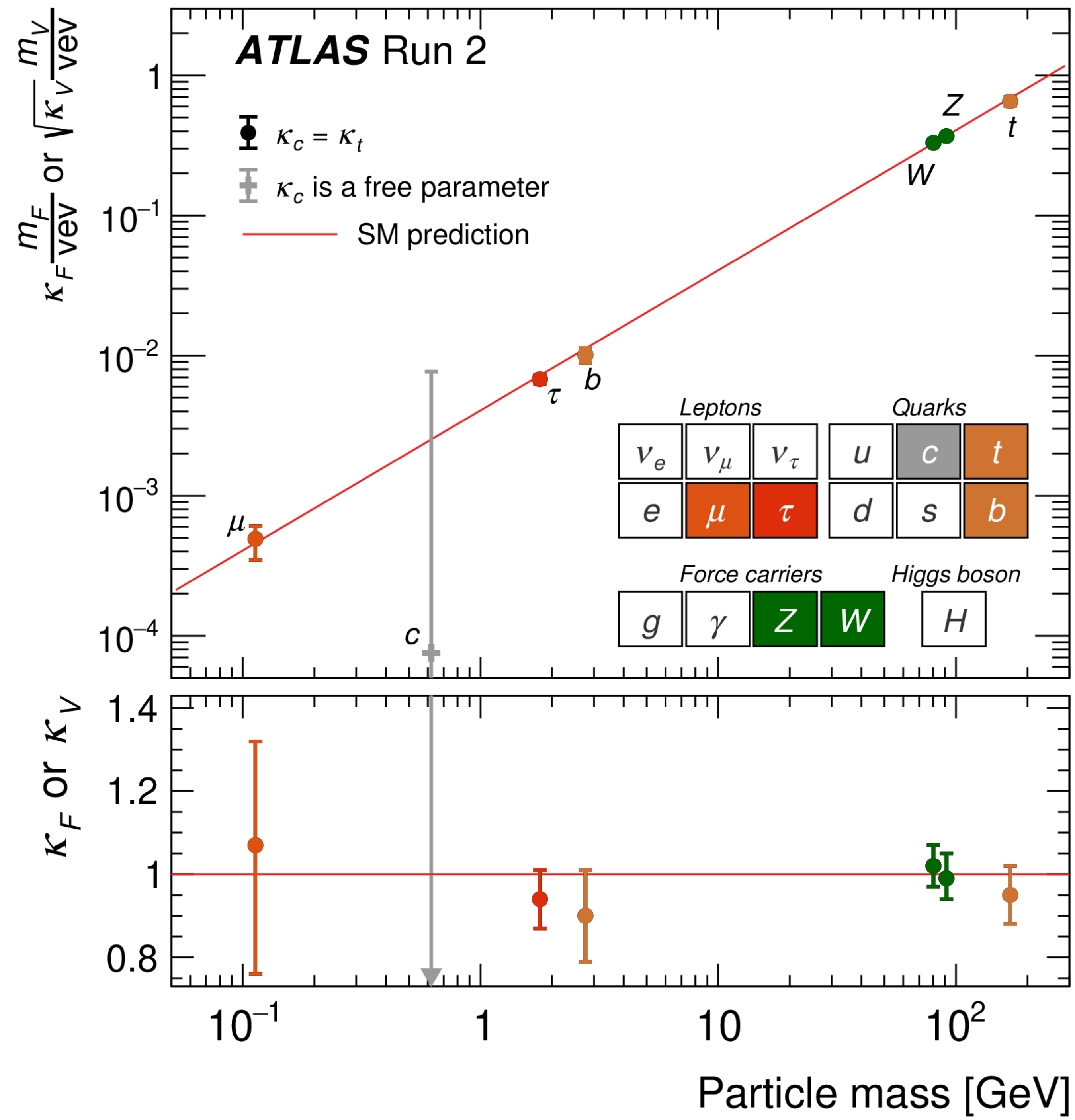
$$m_u \sim 10^{-3} m_c \sim 10^{-5} m_t$$
$$m_d \sim 10^{-1} m_s \sim 10^{-3} m_b$$
$$m_e \sim 10^{-3} m_\mu \sim 10^{-4} m_t$$

$$\Delta m_{31}^2 / \Delta m_{21}^2 \sim 30$$

$$\mathcal{L} = i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R}$$
$$+ i\overline{q'^{D}_{\alpha R}}\not{D}q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}}\not{D}q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$
$$+ \left(D_\rho\Phi\right)^\dagger\left(D^\rho\Phi\right) + \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$
$$- \left(Y'^{l}_{\alpha\beta}\,\overline{L'_{\alpha L}}\,\Phi\,l'_{\beta R} + Y'^{l*}_{\alpha\beta}\,\overline{l'_{\beta R}}\,\Phi^\dagger\,L'_{\alpha L}\right)$$
$$- \left(Y'^{D}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,\Phi\,q'^{D}_{\beta R} + Y'^{D*}_{\alpha\beta}\,\overline{q'^{D}_{\beta R}}\,\Phi^\dagger\,Q'_{\alpha L}\right)$$
$$- \left(Y'^{U}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,(i\sigma_2\Phi^*)\,q'^{U}_{\beta R} + Y'^{U*}_{\alpha\beta}\,\overline{q'^{U}_{\beta R}}\,(-i\Phi^T\sigma_2)\,Q'_{\alpha L}\right)$$

Fermion masses:

m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
m_b	$4.18\ GeV$
m_t	$174\ GeV$



(Image: ATLAS Collaboration/CERN) 2025

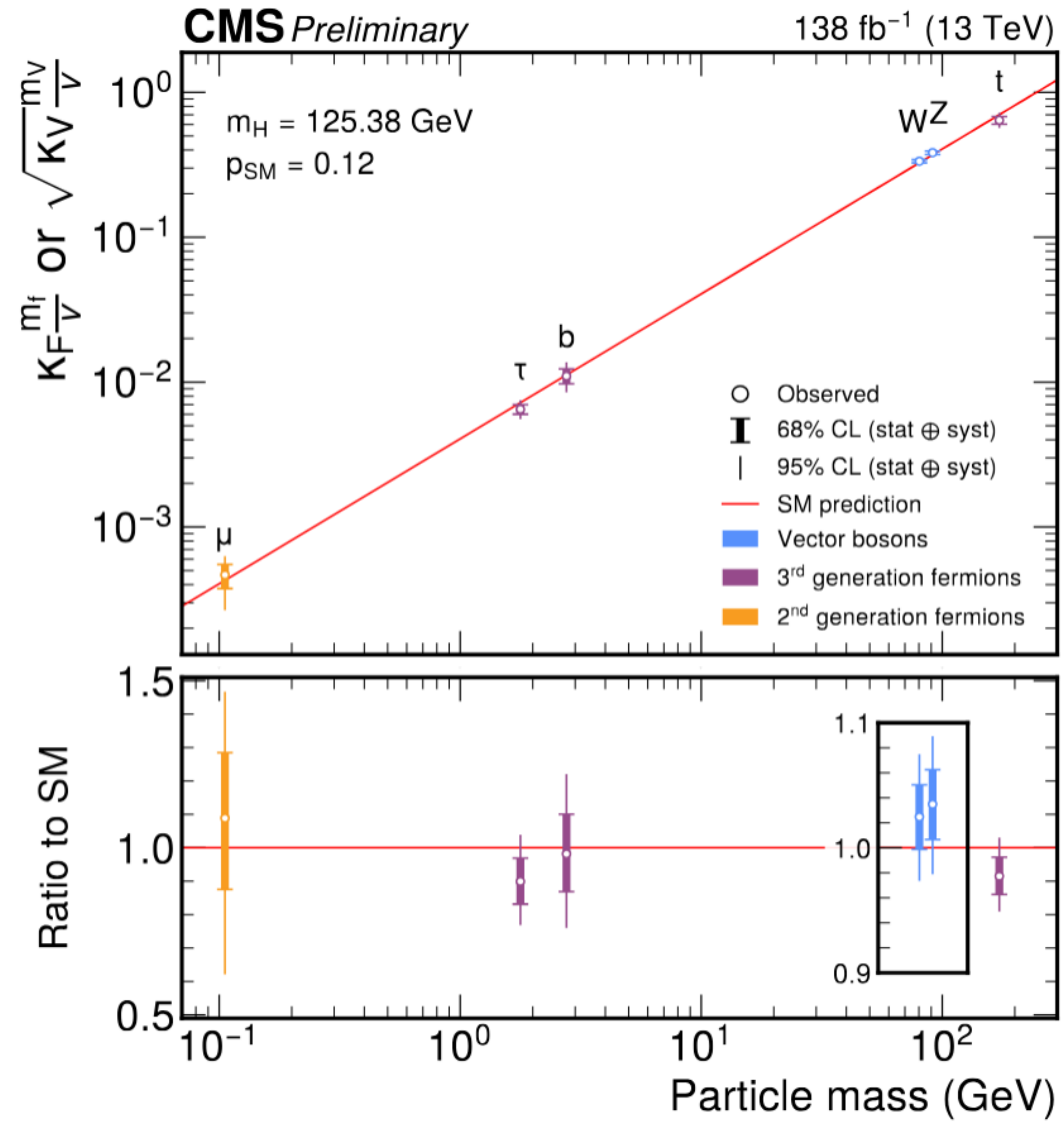
$y_e \sim 10^{-6}$, $y_t \sim 1$

$y_\nu \sim 10^{-13}$

$$
\begin{aligned}
\mathcal{L} = & \, i\overline{L'_{\alpha L}}\not{D}L'_{\alpha L} + i\,\overline{Q'_{\alpha L}}\not{D}Q'_{\alpha L} + i\overline{l'_{\alpha R}}\not{D}l'_{\alpha R} \\
& + i\overline{q'^{D}_{\alpha R}}\not{D}q'^{D}_{\alpha R} + i\overline{q'^{U}_{\alpha R}}\not{D}q'^{U}_{\alpha R} - \frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + \left(D_\rho\Phi\right)^\dagger\left(D^\rho\Phi\right) + \mu^2\Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2 \\
& - \left(Y'^{l}_{\alpha\beta}\,\overline{L'_{\alpha L}}\,\Phi\,l'_{\beta R} + Y'^{l*}_{\alpha\beta}\,\overline{l'_{\beta R}}\,\Phi^\dagger\,L'_{\alpha L}\right) \\
& - \left(Y'^{D}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,\Phi\,q'^{D}_{\beta R} + Y'^{D*}_{\alpha\beta}\,\overline{q'^{D}_{\beta R}}\,\Phi^\dagger\,Q'_{\alpha L}\right) \\
& - \left(Y'^{U}_{\alpha\beta}\,\overline{Q'_{\alpha L}}\,(i\sigma_2\Phi^*)\,q'^{U}_{\beta R} + Y'^{U*}_{\alpha\beta}\,\overline{q'^{U}_{\beta R}}\,(-i\Phi^T\sigma_2)\,Q'_{\alpha L}\right)
\end{aligned}
$$

Fermion masses:

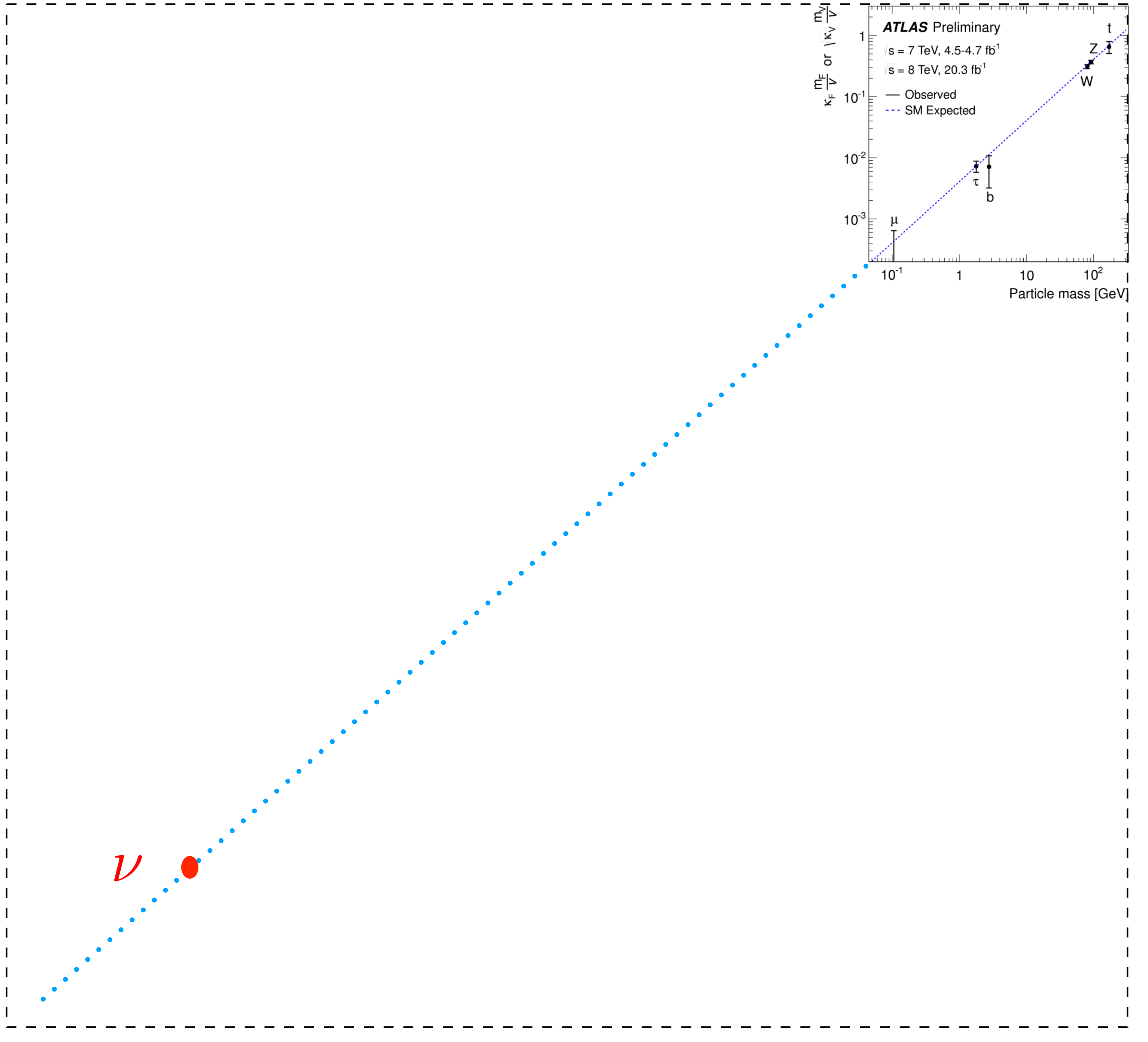
m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
m_b	$4.18\ GeV$
m_t	$174\ GeV$



(Image: ATLAS Collaboration/CERN) 2025

$y_e \sim 10^{-6}$, $y_t \sim 1$

$y_\nu \sim 10^{-13}$


ATLAS Preliminary
s = 7 TeV, 4.5-4.7 fb^{-1}
s = 8 TeV, 20.3 fb^{-1}
Observed
SM Expected
t
Z
W
τ
b
μ
Particle mass [GeV]
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
ν

Tree-level neutrino masses (Majorana)

$$2 \otimes 2 = 1 + 3$$

Type-I seesaw

$$\bar{L}\ \tilde{H}\ N \qquad 2 \otimes 2 \otimes 1$$

Type-II seesaw

$$\bar{L}^c\ \Delta\ L \qquad 2 \otimes 3 \otimes 2$$

Type-III seesaw

$$\bar{L}\ \tilde{H}\ \Sigma \qquad 2 \otimes 3 \otimes 2$$

Type I see-saw

$N_i : \{1, 1, 0\}$

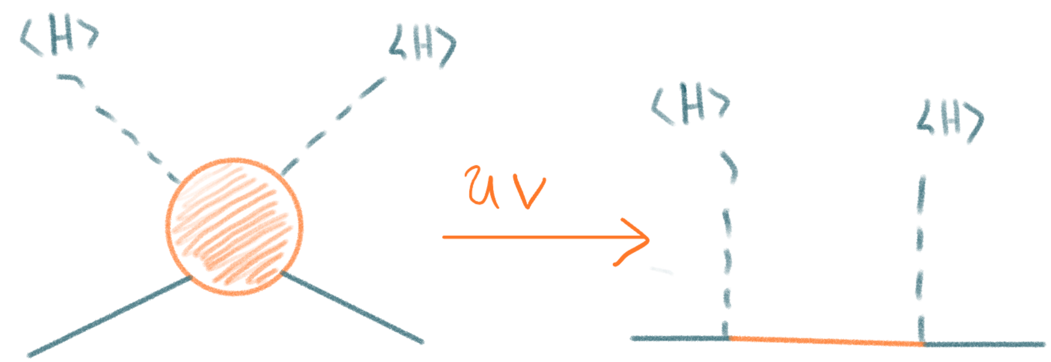
$B-L$ anomaly-free $n=3$

In basis $\nu = (L, N^c)$

$\mathcal{L} \sim \frac{1}{2} \bar{\nu}^c M_n \nu$

$$M_n = \begin{pmatrix} 0 & yv \\ yv & M \end{pmatrix}$$

$$\mathcal{L}_f = \bar{L} \not\partial L + \bar{\ell} \not\partial \ell + \bar{N} \not\partial N - y^{\ell}_{ij} \bar{L}_i H \ell_j - y^{\nu}_{ij} \bar{L}_i \tilde{H} N_j - M \bar{N}_i^c N_j + h.c.$$



Type I see-saw

$N_i : \{1, 1, 0\}$

$\mathcal{L}_f = \bar{L}\not\partial L + \bar{\ell}\not\partial \ell + \bar{N}\not\partial N - y^{\ell}_{ij}\bar{L}_i H \ell_j - y^{\nu}_{ij}\bar{L}_i \tilde{H} N_j - M\bar{N}^c_i N_j + h.c.$

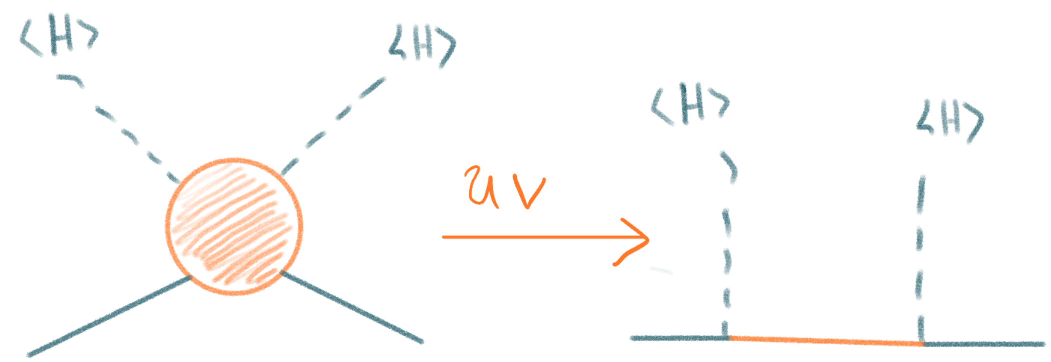
$B-L$ anomaly-free $n=3$

In basis

$\nu = (L, N^c)$

$\mathcal{L} \sim \frac{1}{2}\bar{\nu}^c M_n \nu$

$$M_n = \begin{pmatrix} 0 & yv \\ yv & M \end{pmatrix}$$



If $M \gg \langle H \rangle$

$m_1 \sim \frac{(yv)^2}{M}$

$m_2 \sim M$

for $y \sim 1$

$M \sim 10^{14}$ GeV

$m_\nu \sim 0.1$ eV

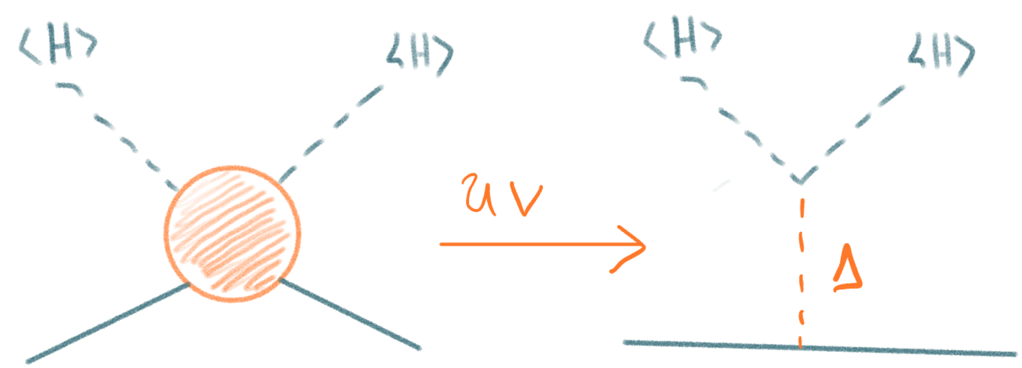
Type II see-saw

$\overline{\nu^c}\,\nu$ has $I=+1$ $\quad L=\begin{pmatrix}\nu\\ \ell\end{pmatrix}:\{1,2,-\tfrac{1}{2}\}$

$Y=-1$

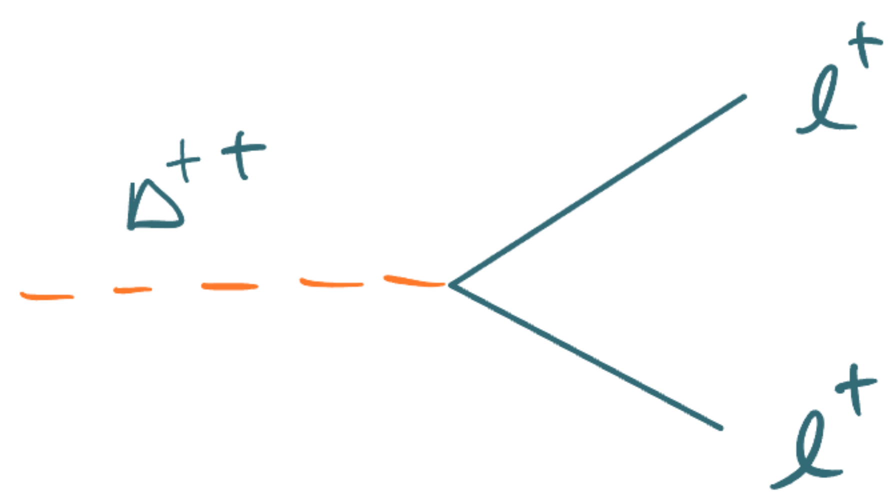
$\Delta:\{1,3,1\}$

$$\Delta=\begin{pmatrix}\Delta^{++}\\ \Delta^{+}\\ \Delta^{0}\end{pmatrix}$$



$$\mathcal{L}_{mass}=\overline{L^c}\,\Delta\,L$$

$$V\supset\kappa\,H^{\dagger}\Delta H$$



$$v_\Delta\simeq\frac{\kappa v^2}{M_\Delta^2}$$

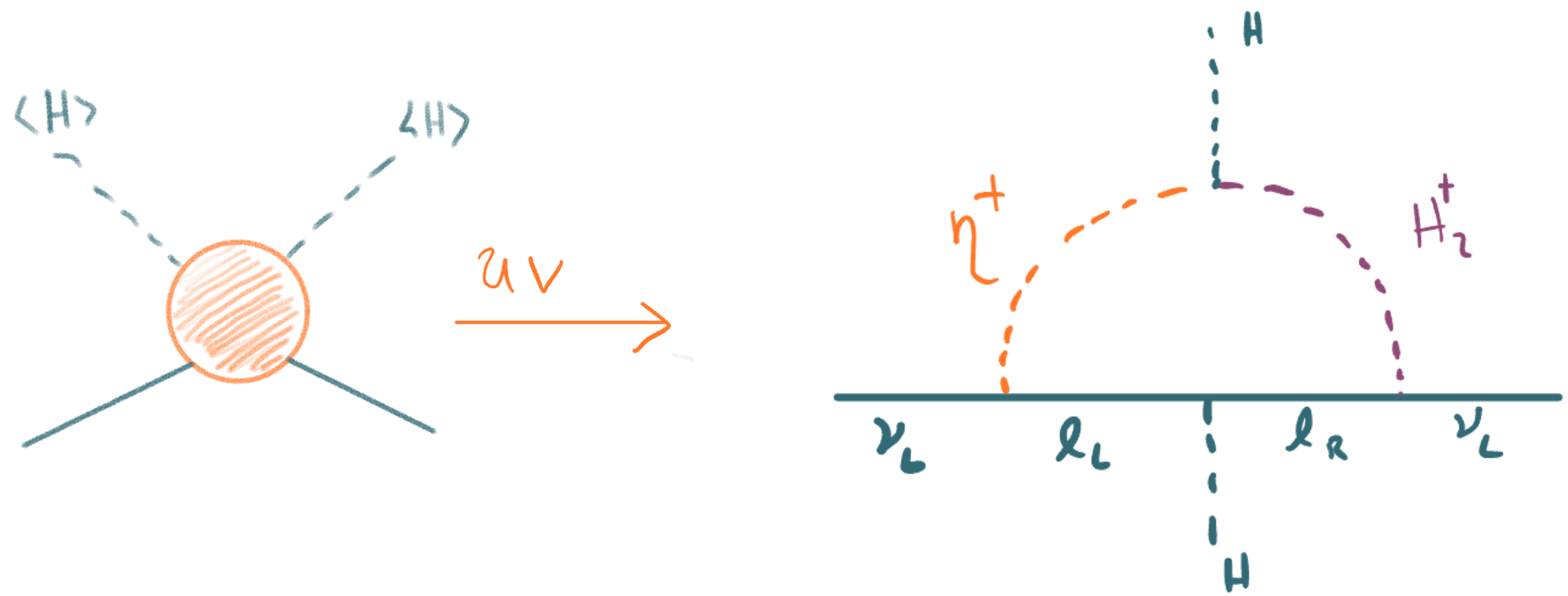
One-loop neutrino masses

Interaction

$\overline{\nu_L^c}\, e_L \Rightarrow I = 0 \quad Y = -1 \Rightarrow \eta^+ : \{1, 1, +1\}$

$H \eta^+ H_2 \quad H_2 : \{1, 2, \tfrac{1}{2}\}$

$$\mathcal{L} = -Y \bar{L} H \ell - f \bar{L}^c L \eta^+ - \tilde{Y} \bar{L} \tilde{H}_2 \ell + \mu H \eta^+ H_2$$



Two-loop neutrino masses

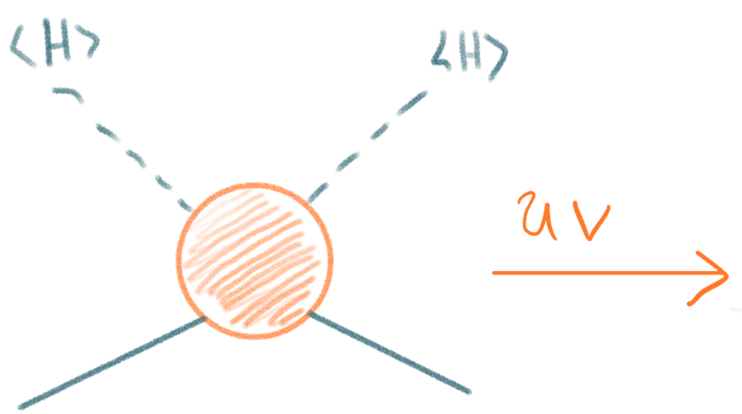
Interaction

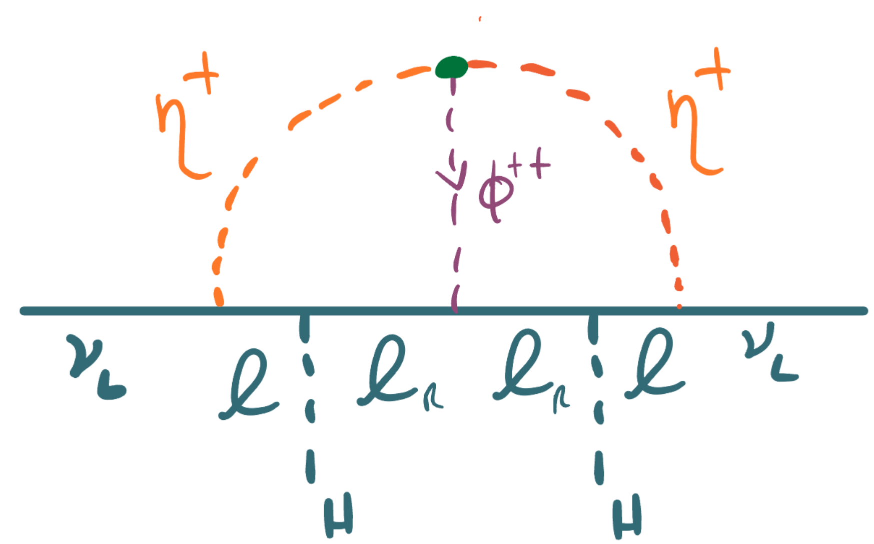
$\bar{\nu}_L^c e_L \Rightarrow I = 0 \quad Y = -1 \Rightarrow \eta^+ \eta^+ \bar{\Phi}^{++}$

$\eta^+ : \{1, 1, +1\}$

$\Phi^{++} : \{1, 1, -2\}$

$$\mathcal{L} = -Y \bar{L} H \ell - f \bar{L}^c L \eta^+ - \bar{\ell}^c_R \ell_R \Phi^{++} - \eta^+ \eta^+ \phi^{--}$$

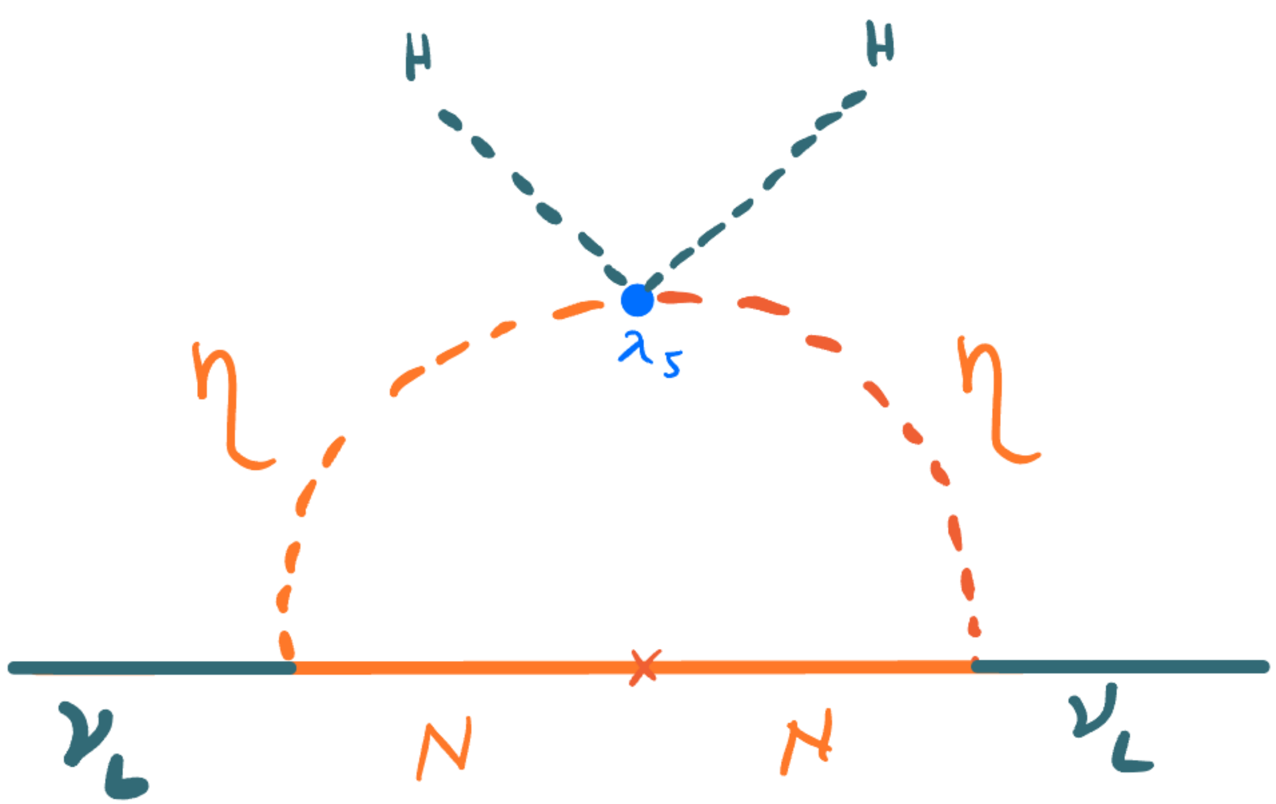




Scotogenic neutrino masses

		Z_2
N :	$\{1, 1, 0\}$	-1
η :	$\{1, 2, \frac{1}{2}\}$	-1

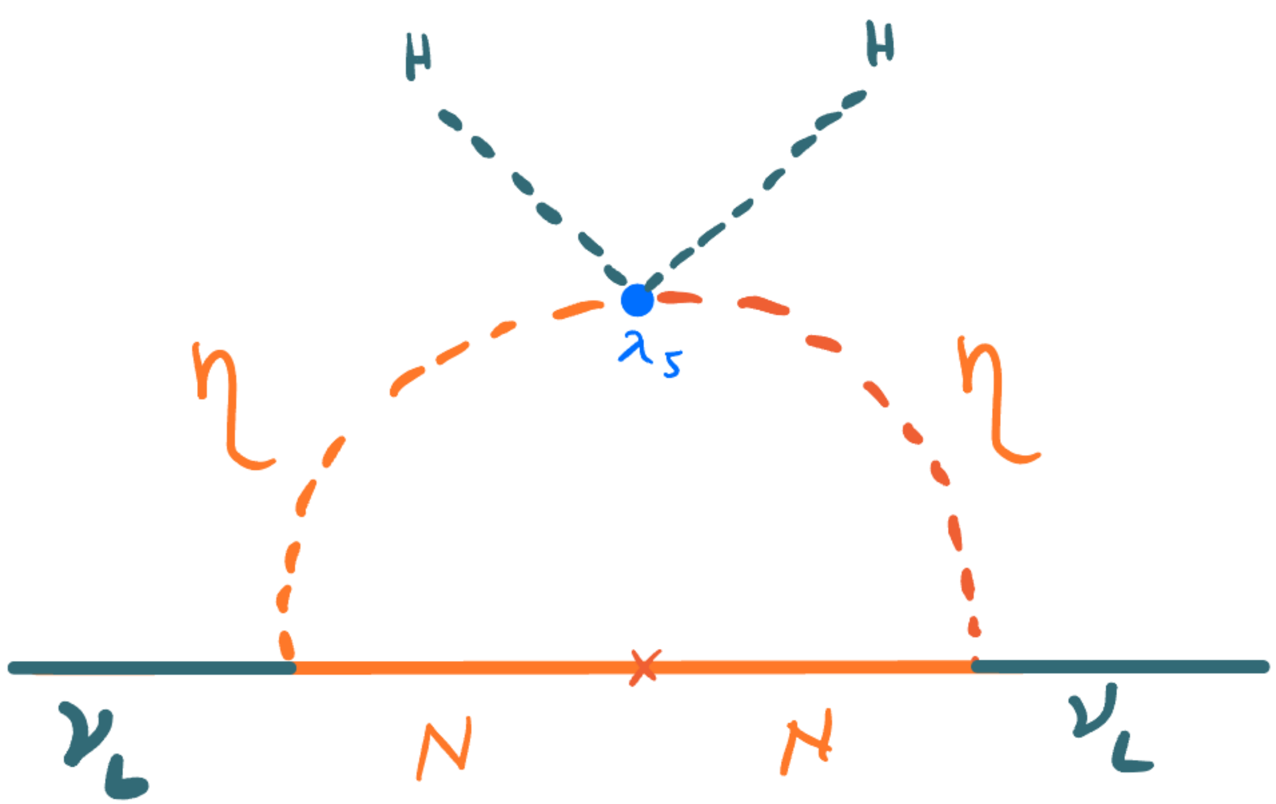
$$\mathcal{L} = -Y \bar{L} H \ell - \tilde{Y} \bar{L} \tilde{\eta} N - M_N \overline{N^c} N - \lambda_5 (H \eta^\dagger)^2 + h.c.$$
$$+ \lambda_4 H^\dagger H \eta^\dagger \eta$$

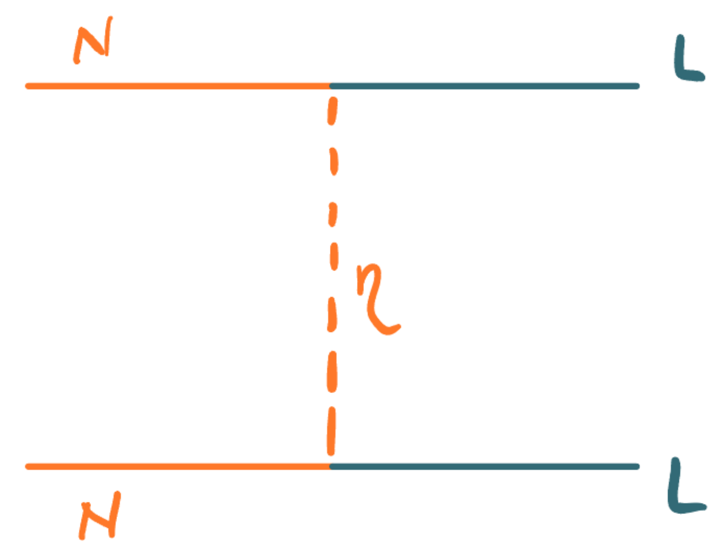


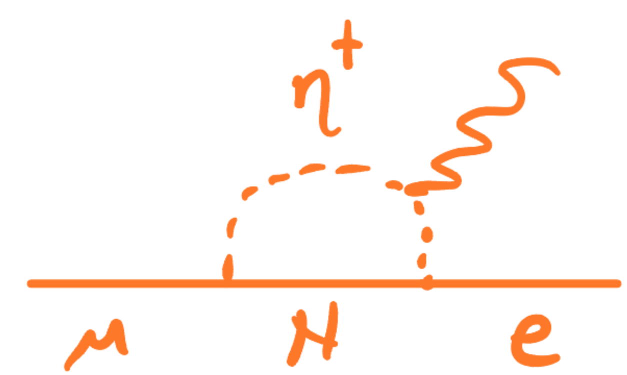
Scotogenic neutrino masses

		Z_2
$N:$	$\{1, 1, 0\}$	-1
$\eta:$	$\{1, 2, \frac{1}{2}\}$	-1

$$\mathcal{L} = -Y \bar{L} H \ell - \tilde{Y} \bar{L} \tilde{\eta} N - M_N \overline{N^c} N - \lambda_5 (H \eta^\dagger)^2 + h.c. + \lambda_4 H^\dagger H \eta^\dagger \eta$$







Flavor Symmetries

To explain quark masses and mixings

Wilczek and Zee (1977)
Weinberg (1977)

$$\lambda_C = \sqrt{\frac{m_d}{m_s}}$$

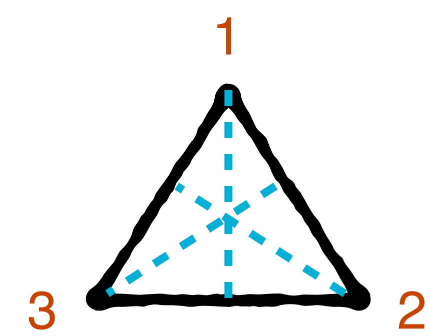
Cabibbo (1963)
Gatto Satori, Tonin (1968)

Flavor Symmetries

To explain quark masses and mixings

Wilczek and Zee (1977)
Weinberg (1977)

Pakvasa and Sugawara(1978)
Sartori(1979)
Wyler(1979)



$$\lambda_C = \sqrt{\frac{m_d}{m_s}}$$

Cabibbo (1963)
Gatto Satori, Tonin (1968)

Small mixing angle

$$V_{CKM} \sim \begin{pmatrix} 1 & \lambda_C & \lambda_C^3 \\ -\lambda_C & 1 & \lambda_C^2 \\ \lambda_C^3 & -\lambda_C^2 & 1 \end{pmatrix}$$

Flavor Symmetries

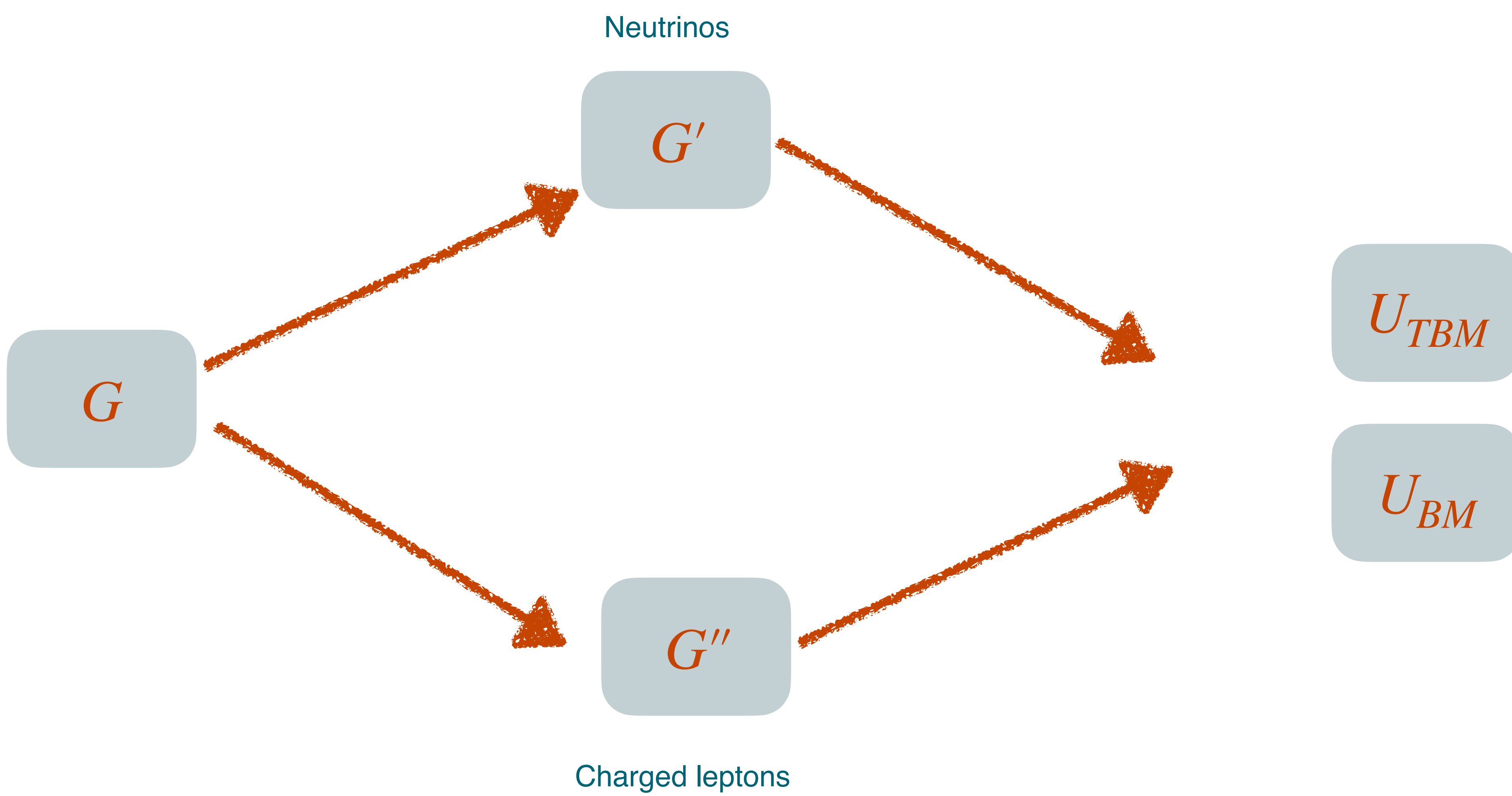
Massive neutrinos

Grimus and L. Lavour (2001)
Hirsch et. al. (2003)
Kubo, Mondragon et. al (2003)
Caravaglios, Morisi (2005)

E. Ma and G. Rajasekaran (2001)
E. Ma (2001)
Babu, Ma, Valle (2002)

Chen, Frigerio, Ma (2004)
Altarelli Feruglio (2005)
.....

Breaking FS



Large **solar** and **atmospheric**

Small reactor $\theta_{13} \sim 0$

Correlations $m_{\nu_i} - \theta_{ij}$

tri-maximal

bi-maximal

Harriso, Perkin, Scott

$$U_{\mathrm{HPS}} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

A_4

S and T $\qquad S^2 = T^3 = (ST)^3 = \mathcal{I}.$

$\mathbf{1},\ \mathbf{1}',\ \mathbf{1}''$ and $\mathbf{3}$

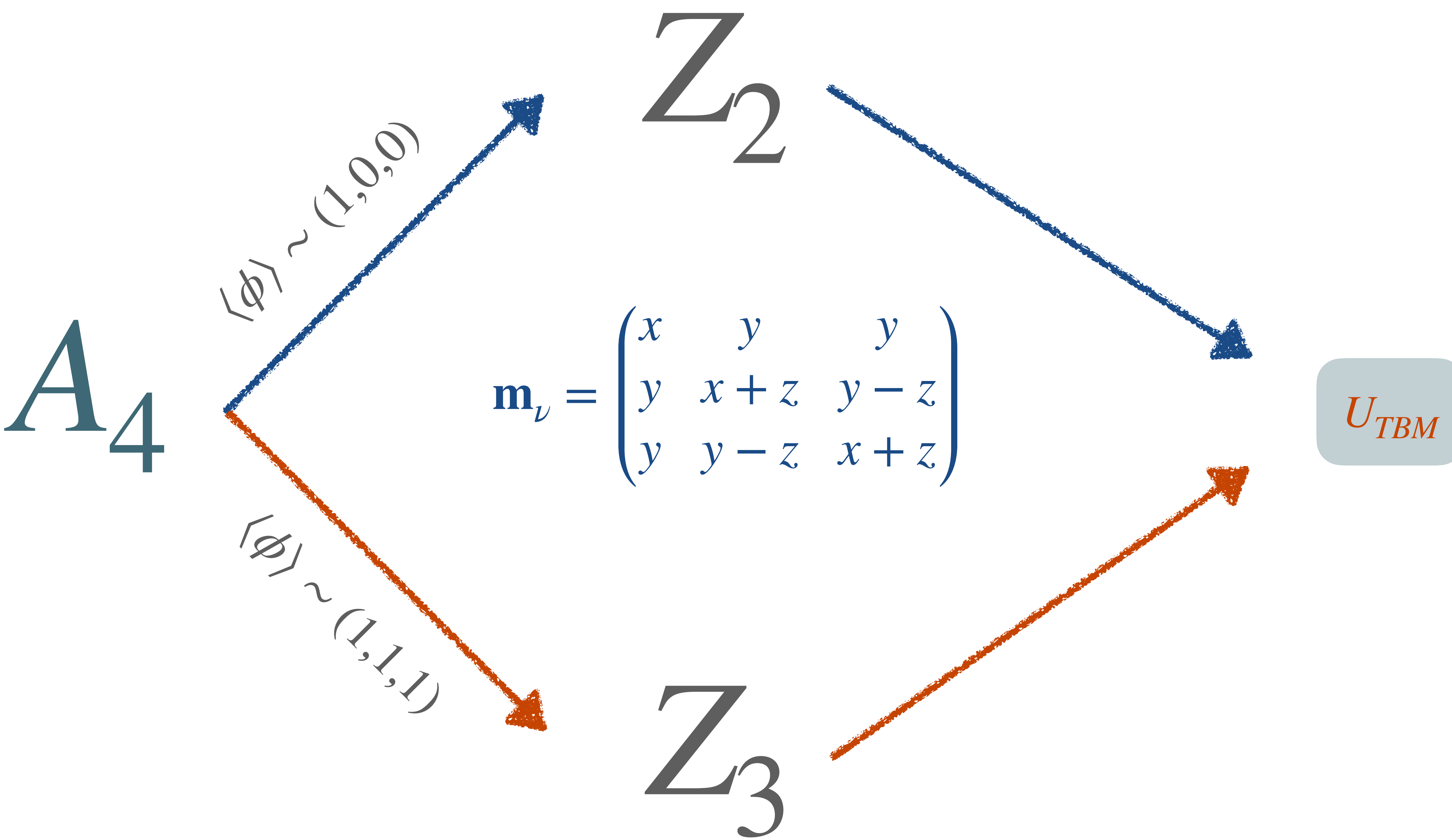
1	$S=1$	$T=1$
$1'$	$S=1$	$T=e^{i4\pi/3}\equiv\omega^2$
$1''$	$S=1$	$T=e^{i2\pi/3}\equiv\omega$

$$\phi = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad \phi' = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix} \quad T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

$$S\phi = \phi \qquad T\phi' = \phi'$$

Altarelli-Feruglio



$$\mathbf{m}_\nu = \begin{pmatrix} x & y & y \\ y & x+z & y-z \\ y & y-z & x+z \end{pmatrix}$$

DM stability

Instead of breaking A4 in two different directions

$$\langle\phi\rangle = (1,0,0)$$

Preserves "S" (Z_2)

$$\langle\phi\rangle = (1,1,1)$$

Preserves "T" (Z_3)

DM stability

Instead of breaking A4 in two different directions

$$\langle \phi \rangle = (1,0,0)$$

Preserves "S" (Z_2)

~~$$\langle \phi \rangle = (1,1,1)$$~~

~~Preserves "T" (Z_3)~~

No TBM, but Z2 unbroken → DM Stability

DDM

For a model for quarks and leptons see:
Boucenna, Morisi, EP, Shimizu, Valle (2012)

Hirsch, Morisi, EP and Valle (2010)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3

DDM

For a model for quarks and leptons see:
Boucenna, Morisi, EP, Shimizu, Valle (2012)

Hirsch, Morisi, EP and Valle (2010)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3

$$\langle \eta \rangle \sim (1,0,0)$$

DDM

For a model for quarks and leptons see:
Boucenna, Morisi, EP, Shimizu, Valle (2012)

Hirsch, Morisi, EP and Valle (2010)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3

Z_2

$$\langle \eta \rangle \sim (1,0,0)$$

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \longrightarrow \begin{pmatrix} T_1 \\ -T_2 \\ -T_3 \end{pmatrix}$$

DDM

For a model for quarks and leptons see:
Boucenna, Morisi, EP, Shimizu, Valle (2012)

Hirsch, Morisi, EP and Valle (2010)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	H	η
$SU(2)$	2	2	2	1	1	1	1	1	2	2
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	1	3

$$Z_2$$

$$\langle \eta \rangle \sim (1,0,0)$$

$$\begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} \longrightarrow \begin{pmatrix} T_1 \\ -T_2 \\ -T_3 \end{pmatrix}$$

Only 2 active RH neutrinos

$$m_{light} = 0$$

DDM

Inverted mass order

$$\theta_{13} = 0$$

$$m_\nu = \begin{pmatrix} y & ab & ac \\ ab & b^2 & bc \\ ac & bc & c^2 \end{pmatrix}$$

$$m_3 = 0$$

$$\begin{pmatrix} 0 \\ -c/b \\ 1 \end{pmatrix}$$

$$m_{\beta\beta} \sim 0.03 - 0.05 \text{ eV}$$

$A_4 \to Z_2$

$$\langle \eta \rangle \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix} \longrightarrow \begin{pmatrix} N_1 \\ -N_2 \\ -N_3 \end{pmatrix} \qquad \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \longrightarrow \begin{pmatrix} \eta_1 \\ -\eta_2 \\ -\eta_3 \end{pmatrix}$$

$A_4 \to Z_2$

$$\langle \eta \rangle \sim \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

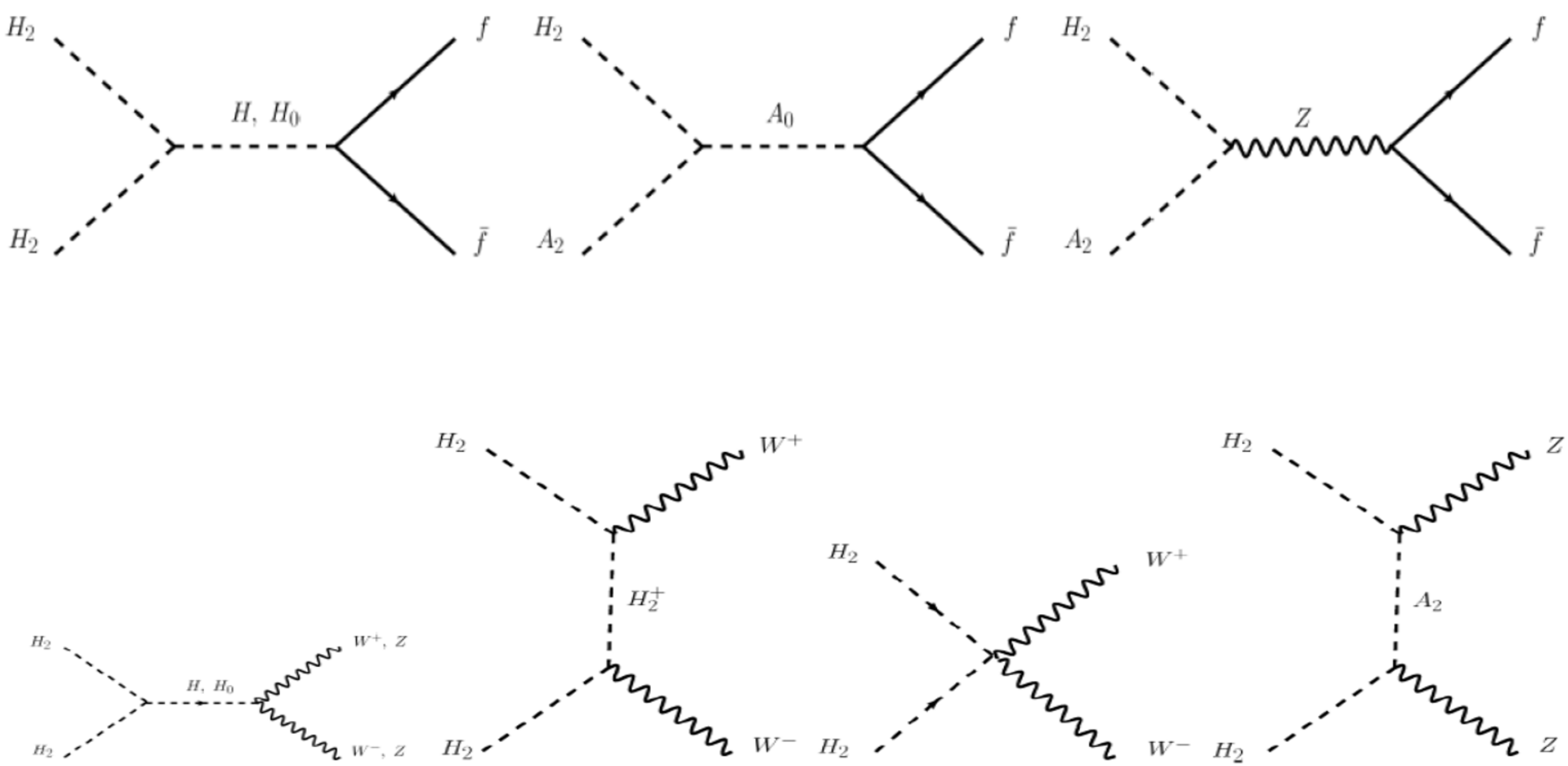
$$H = \begin{pmatrix} \tilde{H}_0^+ \\ (v_h + \tilde{H}_0 + i\tilde{A}_0)/\sqrt{2} \end{pmatrix}, \quad \eta_1 = \begin{pmatrix} \tilde{H}_1^+ \\ (v_\eta + \tilde{H}_1 + i\tilde{A}_1)/\sqrt{2} \end{pmatrix}$$

→ even

$$\eta_2 = \begin{pmatrix} \tilde{H}_2^+ \\ (\tilde{H}_2 + i\tilde{A}_2)/\sqrt{2} \end{pmatrix}, \qquad \eta_3 = \begin{pmatrix} \tilde{H}_3^+ \\ (\tilde{H}_3 + i\tilde{A}_3)/\sqrt{2} \end{pmatrix}$$

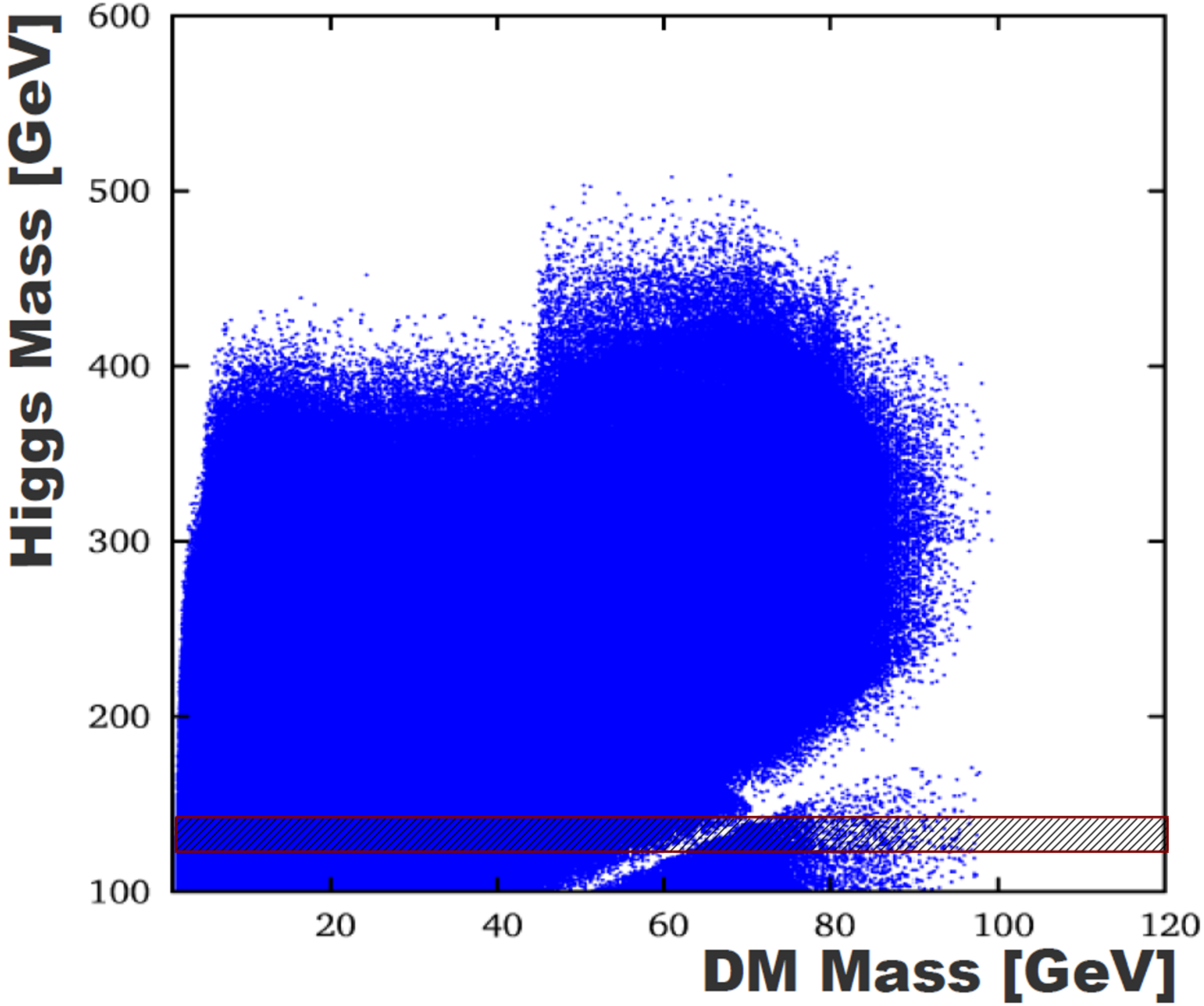
→ odd

DM annihilation channels



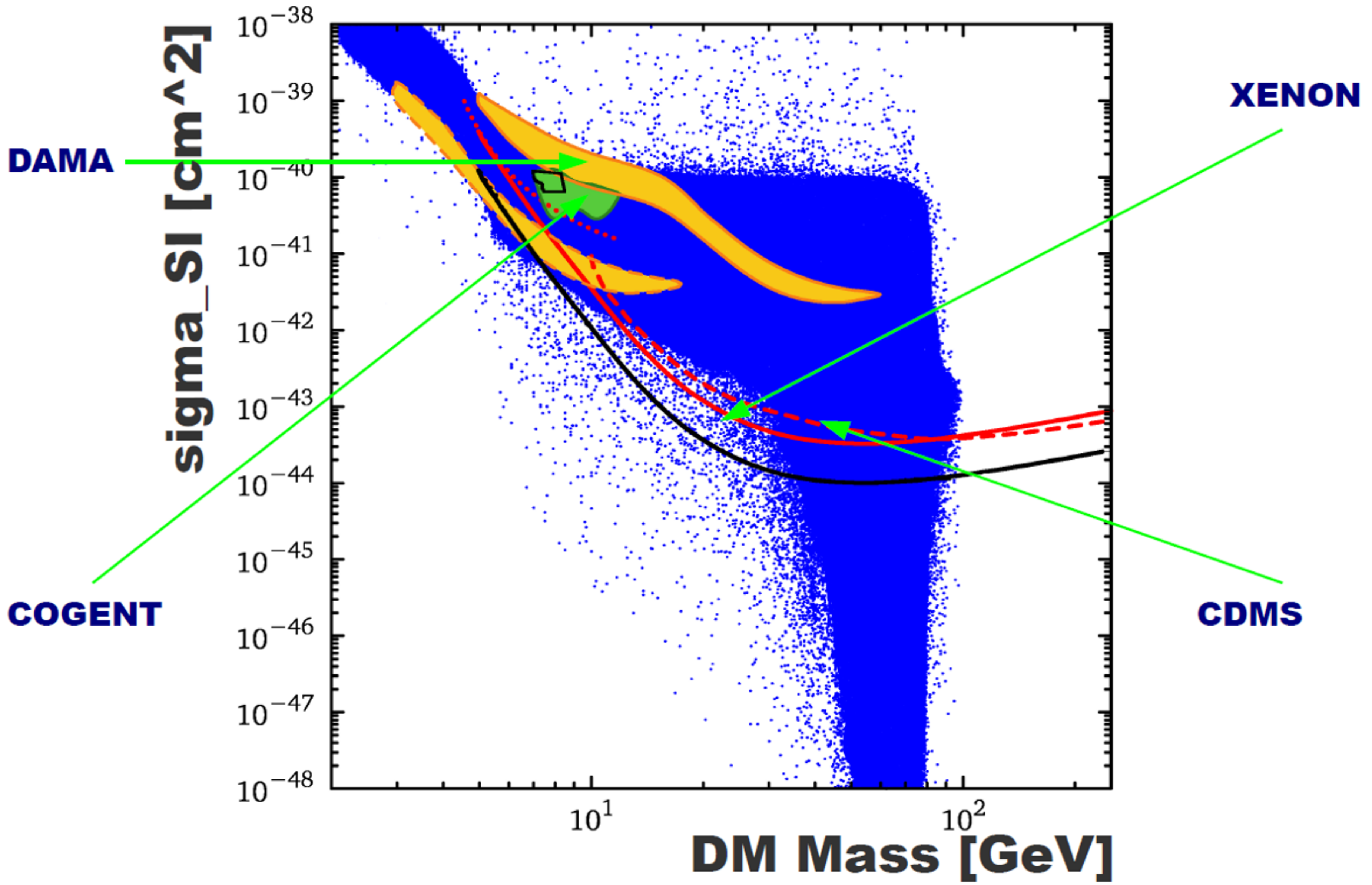
Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

DDM predictions



Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

DDM predictions



... Direct Detection

Boucenna, Hirsch, Morisi, EP, Taoso, Valle (2011)

Fixing θ_{13}

Not only with A4 but D4 the prediction is small or zero reactor mixing angle

Meloni, Morisi, EP (2011)
Meloni, Morisi, EP (2011)

Solution: breaking A_4 at the seesaw scale

Lamprea, EP (2015)
Ferro, de la Vega, EP (2019)

Predictions: Different zero textures

A_4 beaking at the seesaw scale

Lamprea, EP (2016)

Ferro, de la Vega, EP (2019)

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

$$\bar{N}_T^c N_T \phi \qquad \bar{N}_T^c N_1 \phi \qquad \bar{N}_T^c N_5 \phi$$

L_e	L_μ	L_τ	N_4	N_5	Neutrino matrix	Type
$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{1}$	$\mathbf{1}'$	$\begin{pmatrix} X & 0 & X \\ 0 & 0 & X \\ X & X & X \end{pmatrix}$	B_3
$\mathbf{1}$	$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{1}$	$\mathbf{1}''$	$\begin{pmatrix} X & X & 0 \\ X & X & X \\ 0 & X & 0 \end{pmatrix}$	B_4
$\mathbf{1}''$	$\mathbf{1}$	$\mathbf{1}'$	$\mathbf{1}$	$\mathbf{1}'$	$\begin{pmatrix} 0 & 0 & X \\ 0 & X & X \\ X & X & X \end{pmatrix}$	A_1
$\mathbf{1}''$	$\mathbf{1}'$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}'$	$\begin{pmatrix} 0 & X & 0 \\ X & X & X \\ 0 & X & X \end{pmatrix}$	A_2

Lamprea, EP (2016)

	L_e	L_μ	L_τ	l_e^c	l_μ^c	l_τ^c	N_T	N_4	N_5	H	η	ϕ
SU(2)	2	2	2	1	1	1	1	1	1	2	2	1
A_4	1	$1'$	$1''$	1	$1''$	$1'$	3	1	$1''$	1	3	3

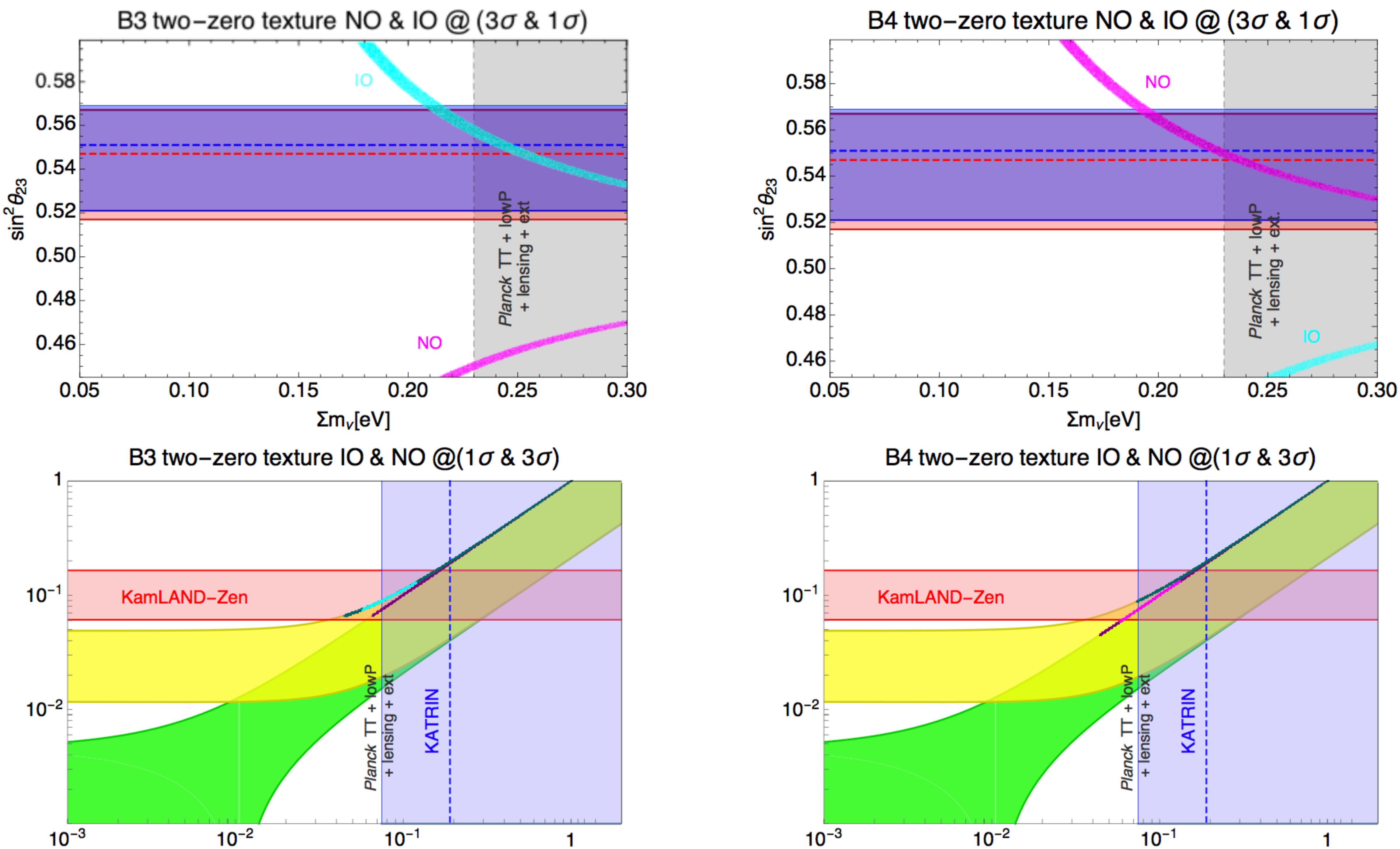
$$\langle\phi\rangle = (1,0,0) \qquad A_4 \longrightarrow Z_2$$

Two zero-texture B3

$$m_\nu^{(A)} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

Frampton, Glashow ,Marfatia
Merle, Rodejohan
Xing, Fritsch
Ludl, Morisi, Peinado
Meroni, Meloni, Peinado
…

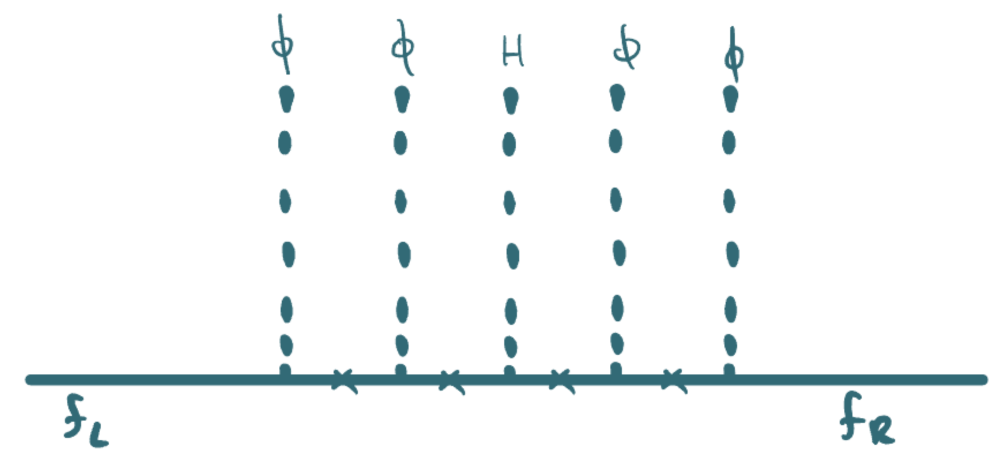
Lamprea, EP (2016)



ν mass hierarchy

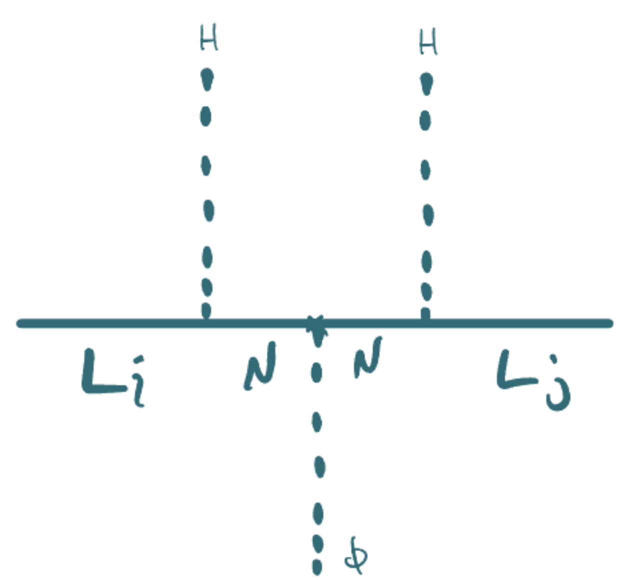
Charged fermions hierarchy

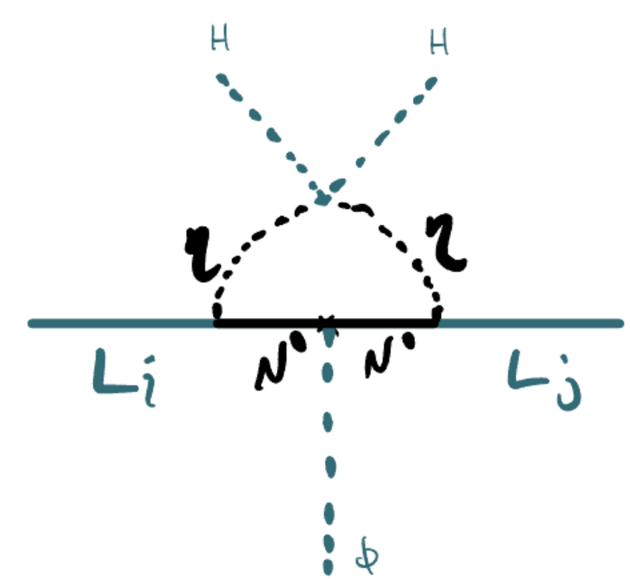
Froggatt, Nielsen (1979)



One mechanism for each scale

Ivanov (2018)
Rojas, Srivastava, Valle (2019)
Aranda, Bonilla, EP (2019)





Rank-1 matrices

Minimal A4

	L_e	L_μ	L_τ	l_e	l_μ	l_τ	N_T	H	η
$SU(2)$	2	2	2	1	1	1	1	2	2
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	$\frac{1}{2}$	$\frac{1}{2}$
A_4	$1''$	1	$1'$	$1''$	1	$1'$	3	1	3

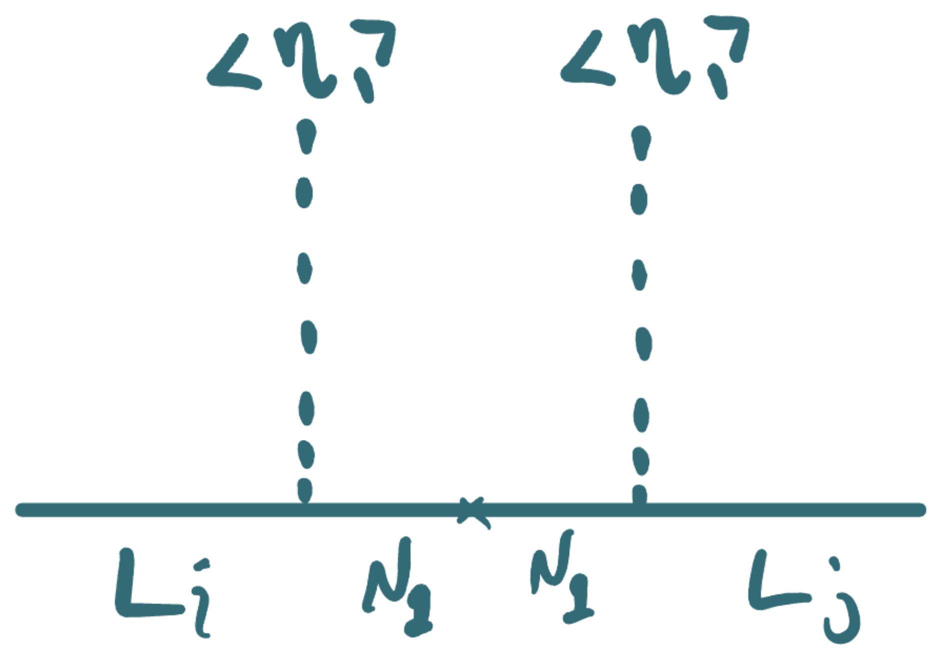
Bonilla, Herms, Medina, EP (2023)

$$A_4 \longrightarrow Z_2$$

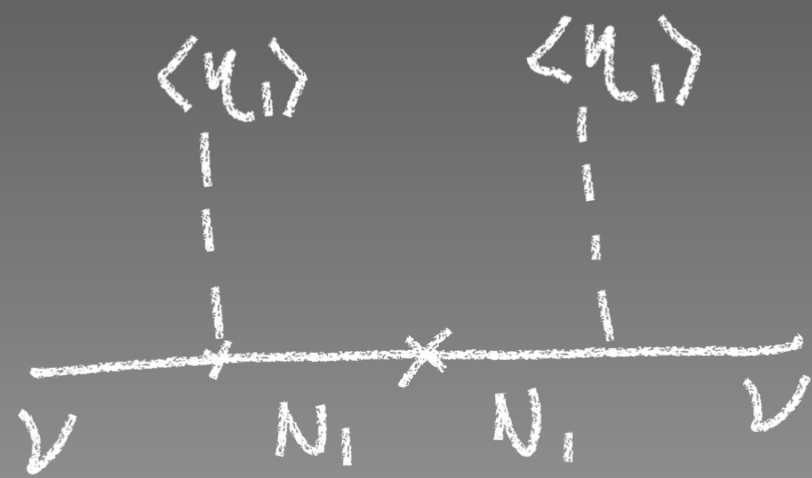
$$\langle \eta^0 \rangle = \begin{pmatrix} v_{\eta_1} \\ 0 \\ 0 \end{pmatrix}$$

Only N_1 is active

Rank-1 matrix



Bonilla, Herms, Medina, EP (2023)

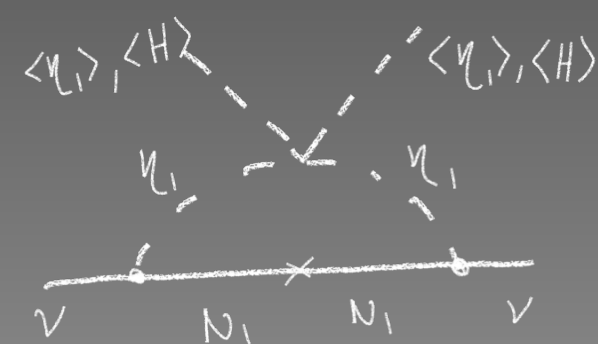


$$M_\ell = \bar{M}_\ell$$

$$m_\nu = m_\nu^{tree} + m_\nu^{1\text{-}loop}$$

$$m_\nu^{atm} = m_\nu^{tree}$$

$$m_\nu^{sol} = m_\nu^{1\text{-}loop}$$



The same Yukawa couplings

Neutrino Masses (NO)

$\Delta m^2_{31} \sim$ Seesaw (tree-level)

$$H, \quad N_1, \quad \eta_1$$

$\Delta m^2_{21} \sim$ Scotogenic (one-loop)

$$N_2, \quad N_3, \quad \eta_2, \quad \eta_3$$

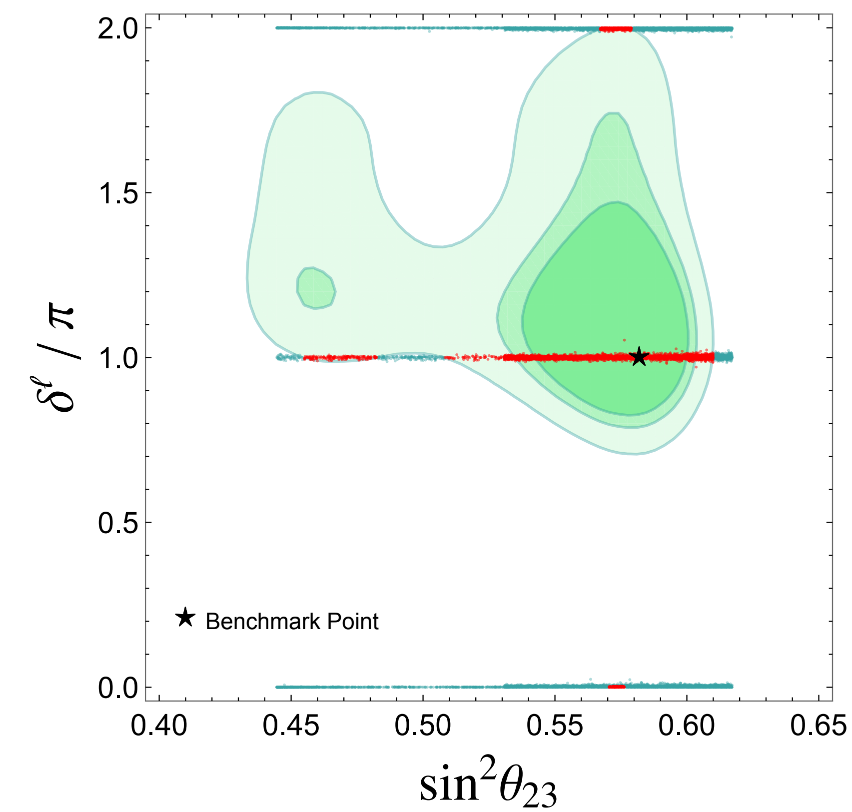
CP-violation in the scalar sector is necessary to fit lepton mixing

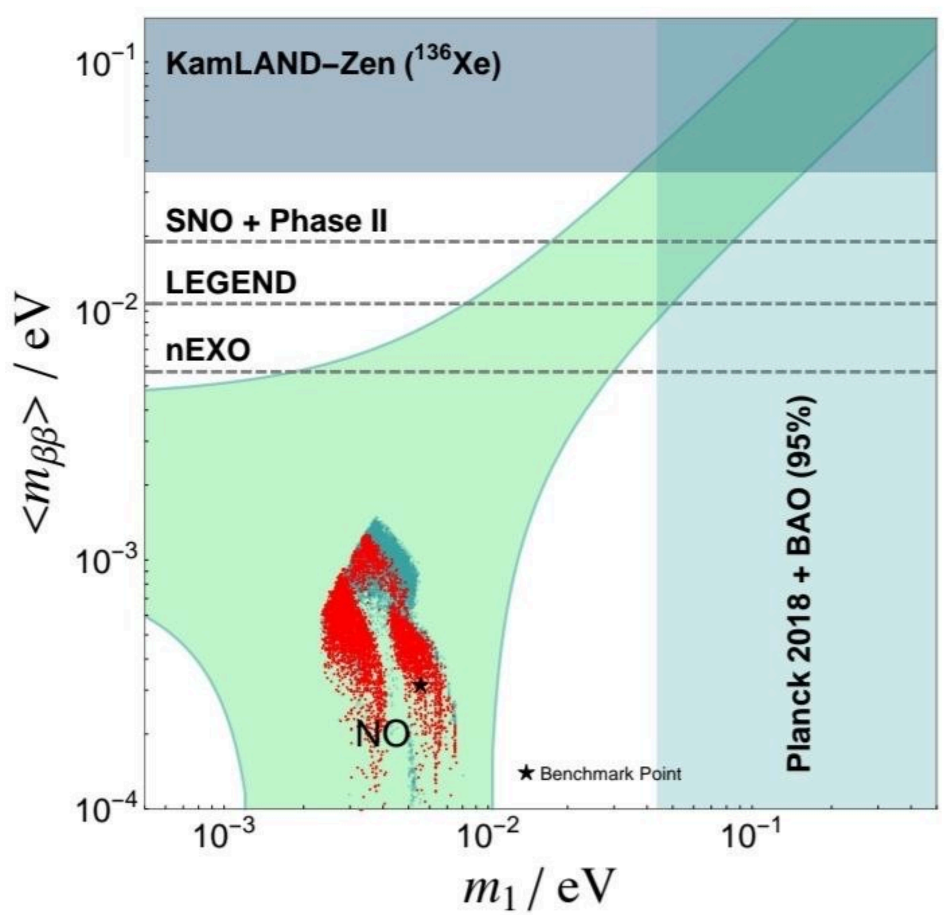
$$M^2_{\text{neutral}} = \begin{pmatrix} M^2_{H'_0 H'_1} & 0 & 0 & 0 \\ 0 & M^2_{A'_0 A'_1} & 0 & 0 \\ 0 & 0 & M^2_{H'_2 H'_3} & \boxed{M^2_{\text{CPV}}} \\ 0 & 0 & \boxed{M^2_{\text{CPV}}} & M^2_{A'_2 A'_3} \end{pmatrix}$$

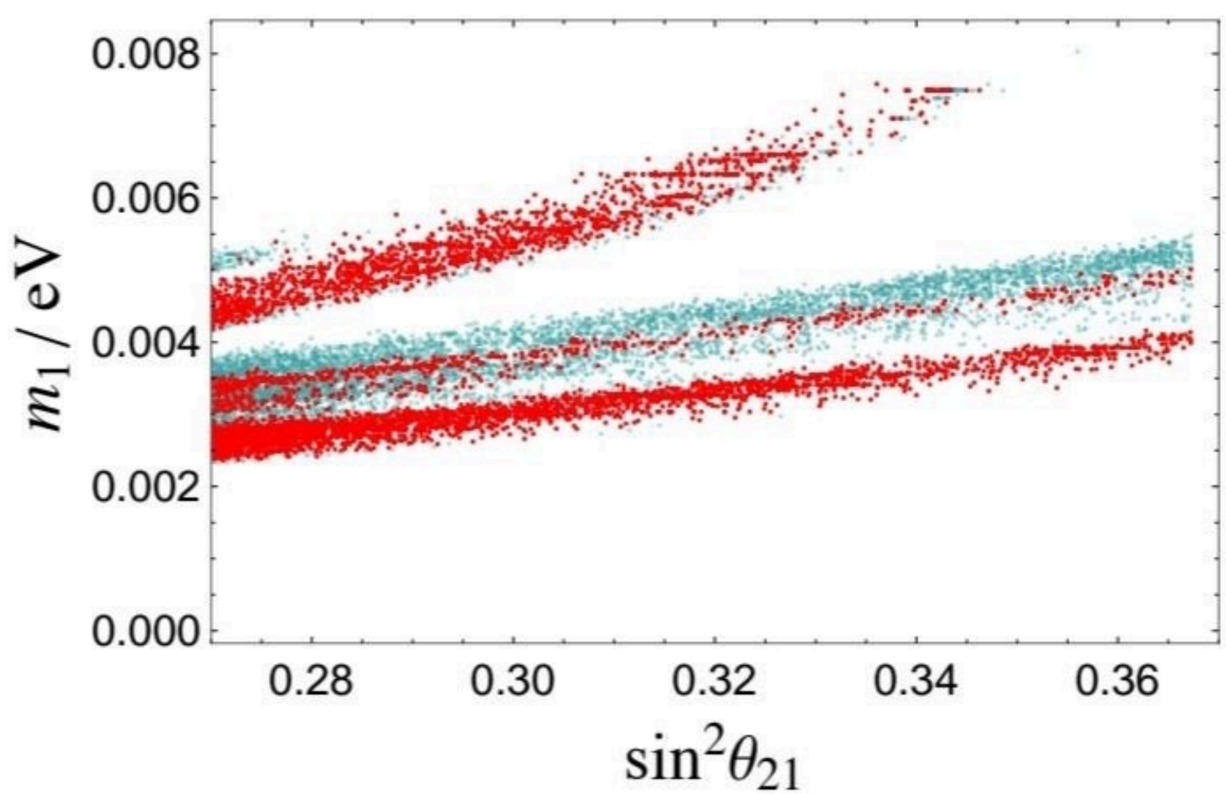
$$\sin^2\theta^l_{12} \qquad \sin^2\theta^l_{23} \qquad \delta^{CP}$$

$$\Delta m^2_{21} \qquad \Delta m^2_{31}$$

	L_e	L_μ	L_τ	l_e	l_μ	l_τ	N_T	H	η
$SU(2)$	2	2	2	1	1	1	1	2	2
$U(1)_Y$	$-\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{2}$	-1	-1	-1	0	$\frac{1}{2}$	$\frac{1}{2}$
A_4	$1''$	1	$1'$	$1''$	1	$1'$	3	1	3







Conclusions

- The minimal DDM model naturally explains DM stability and explain the hierarchy in the neutrino sector
- The Higgs potential needs to violate CP
- The model is severely constrain and can be ruled out soon