Neutrino mass models and dark matter

Eduardo Peinado

Instituto de Física
Universidad Nacional Autónoma de México

3rd Colombian Meeting on High Energy Physics
Universidad Santiago de Cali, Cali Colombia 2018

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Eduardo Peinado
DesPeinado

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N. Bernal's talk

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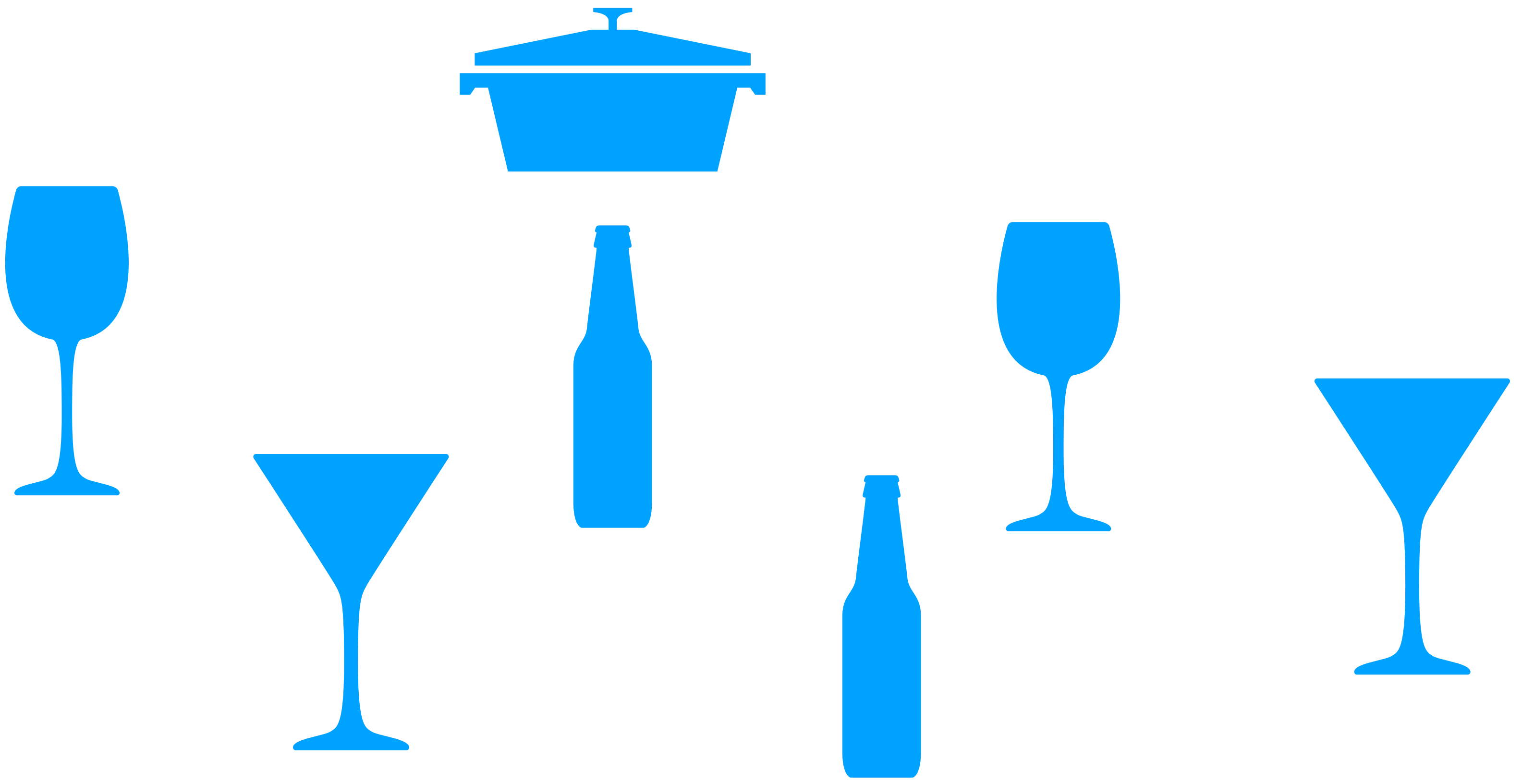
Universidad Nacional Autónoma de México

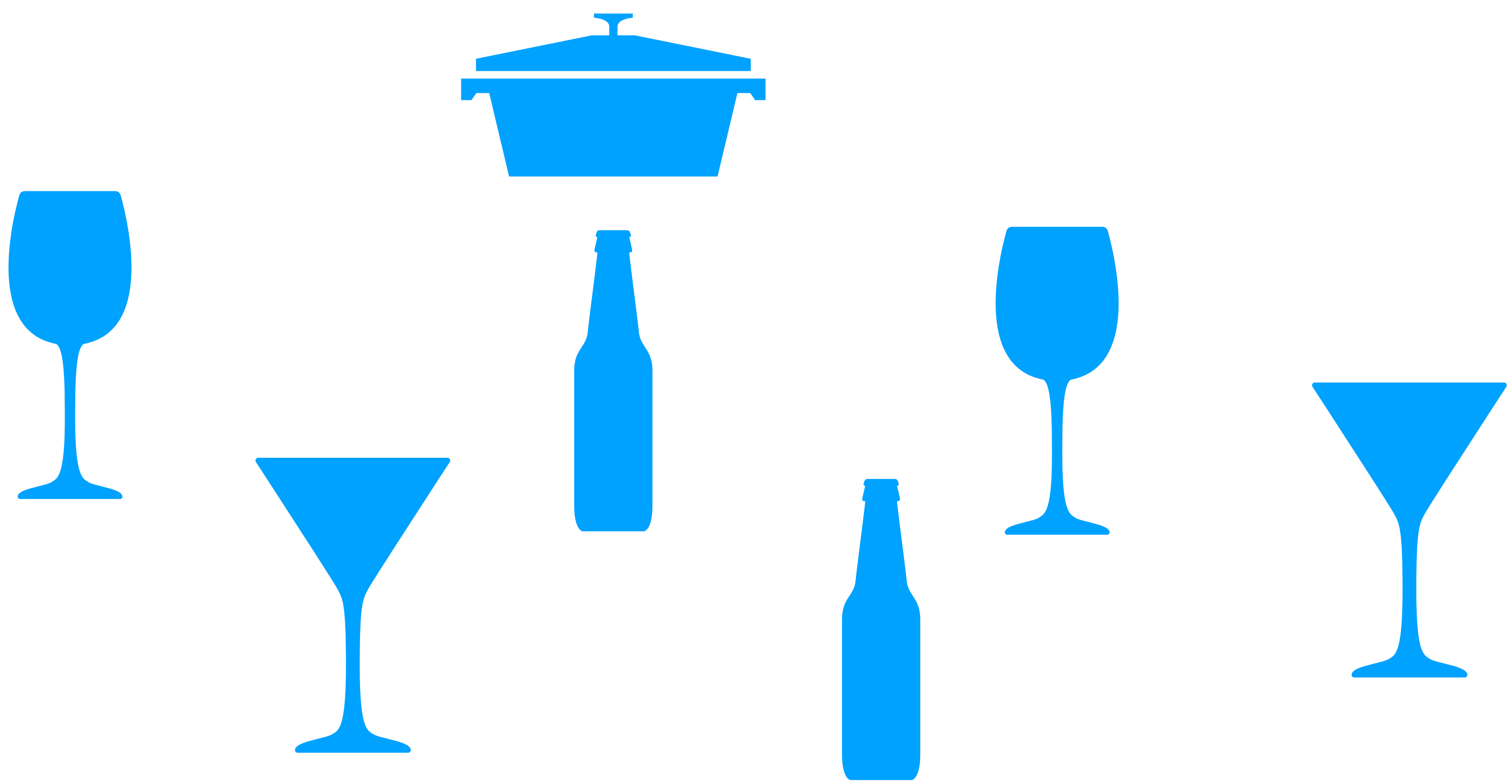
3rd Colombian Meeting on High Energy Physics
Universidad Santiago de Cali, Cali Colombia 2018

Thanks to the organizers



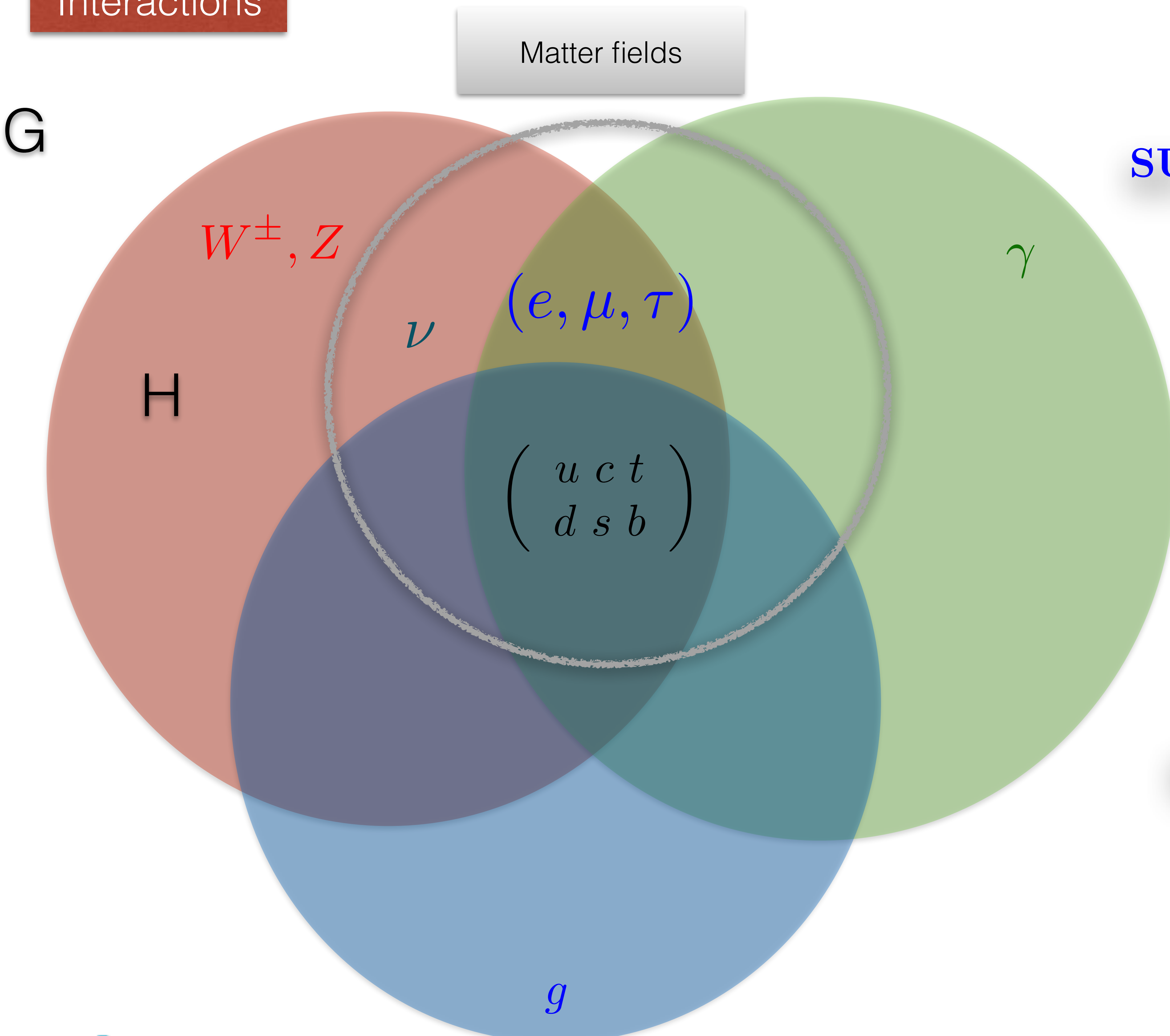
After Social Colombian diner

Thanks to the organizers



After Social Colombian ~~diner~~
Drinking
Dancing

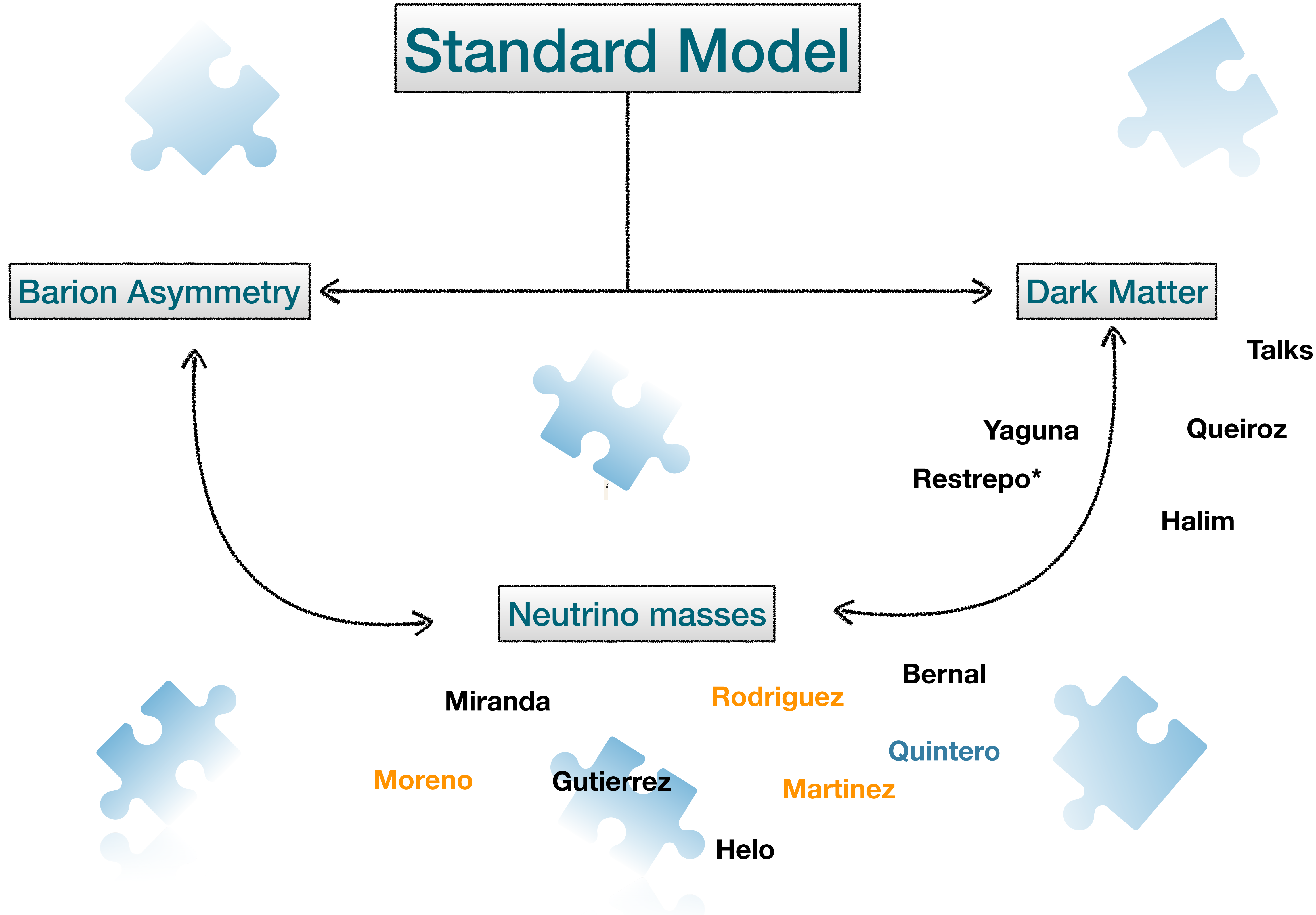
Interactions



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

Higgs Mechanism

$\mathbf{SU(3)_C \otimes U(1)_Q}$


Standard Model
Barion Asymmetry
Dark Matter
Neutrino masses
Talks
Yaguna
Queiroz
Restrepo*
Halim
Bernal
Miranda
Rodriguez
Quintero
Moreno
Gutierrez
Martinez
Helo

Neutrino oscillations

Omar’s talk

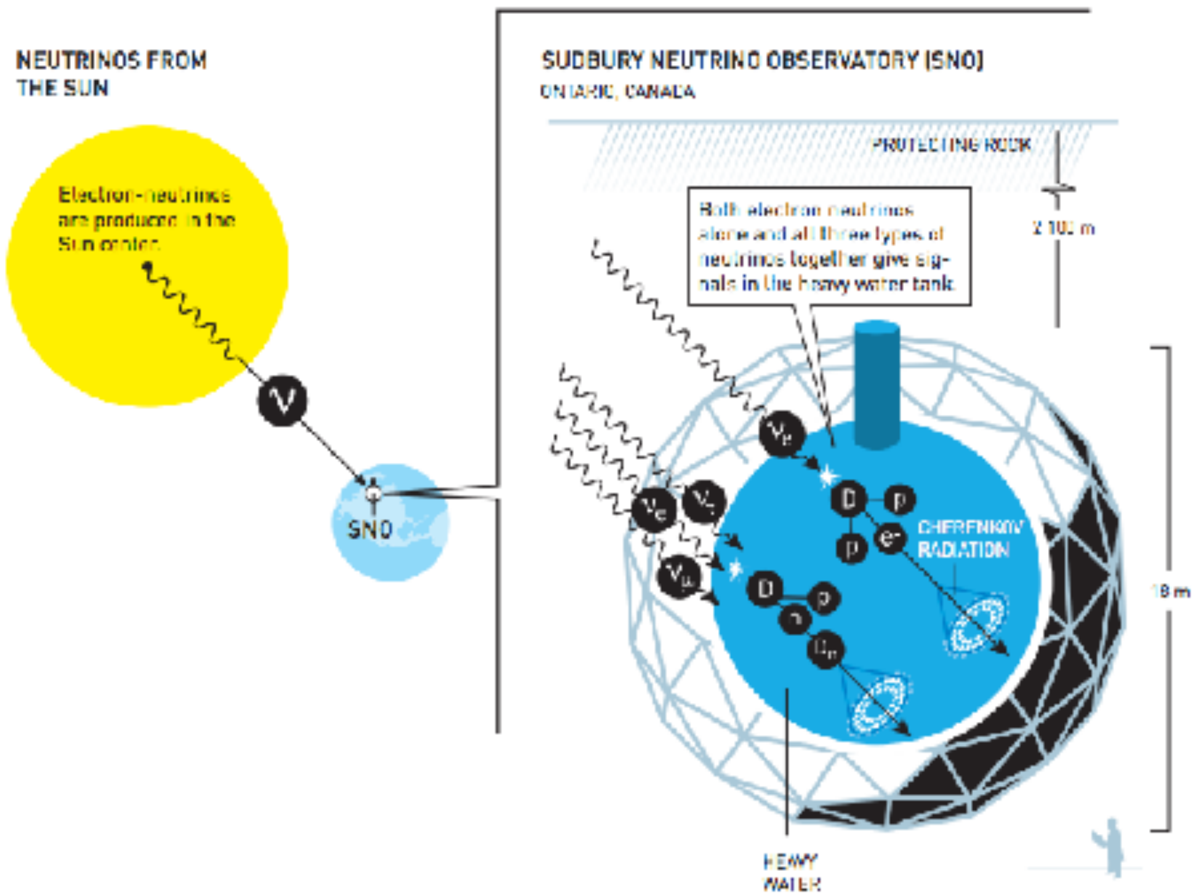


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Weak eigenstates

Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

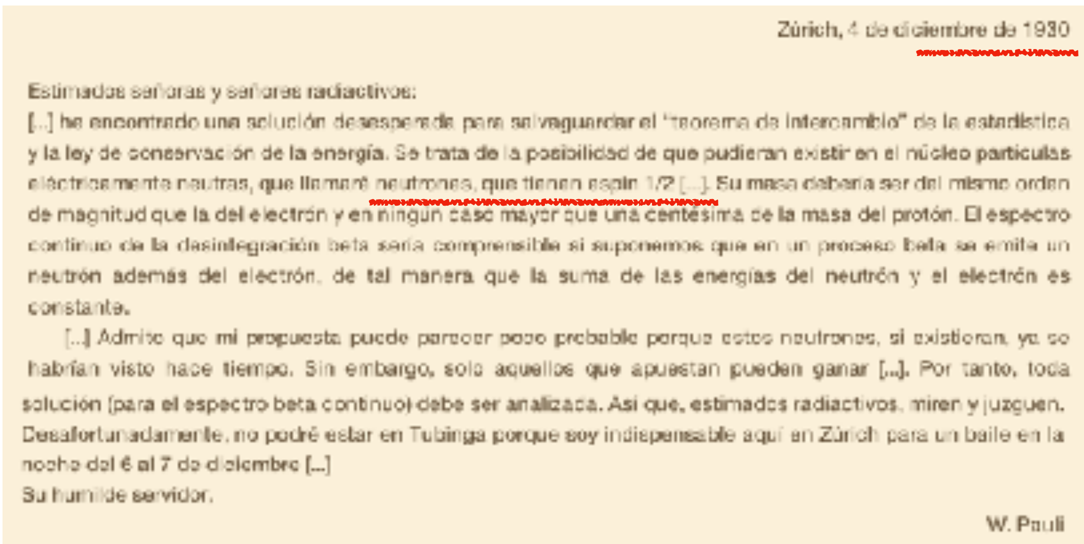
Massive particles

$$P\left(\nu_\mu \to \nu_e\right) = \left|\langle \nu_e | \nu_\mu(t)\rangle\right|^2 = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E_\nu}\right)$$

Neutrinos

What we do (not) know

Pauli 1930

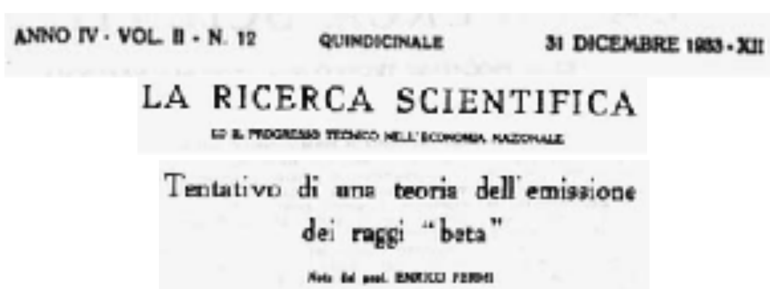

Zürich, 4 de diciembre de 1930

Estimados señoras y señores radiactivos:
[...] he encontrado una solución desesperada para salvaguardar el "teorema de intercambio" de la estadística y la ley de conservación de la energía. Se trata de la posibilidad de que pudieran existir en el núcleo partículas eléctricamente neutras, que llamaré neutrones, que tienen espín 1/2 [...]. Su masa debería ser del mismo orden de magnitud que la del electrón y en ningún caso mayor que una centésima de la masa del protón. El espectro continuo de la desintegración beta sería comprensible si suponemos que en un proceso beta se emite un neutrón además del electrón, de tal manera que la suma de las energías del neutrón y el electrón es constante.

[...] Admito que mi propuesta puede parecer poco probable porque estos neutrones, si existieran, ya se habrían visto hace tiempo. Sin embargo, solo aquellos que apuestan pueden ganar [...]. Por tanto, toda solución (para el espectro beta continuo) debe ser analizada. Así que, estimados radiactivos, miren y juzguen. Desafortunadamente, no podré estar en Tubinga porque soy indispensable aquí en Zürich para un baile en la noche del 6 al 7 de diciembre [...]
Su humilde servidor.

W. Pauli

Fermi 1933


ANNO IV - VOL. II - N. 12 QUINDICINALE 31 DICEMBRE 1933 - XII

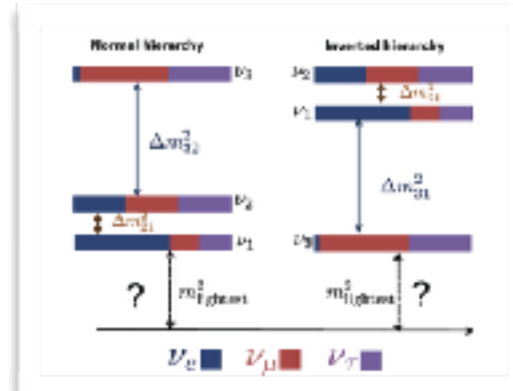
LA RICERCA SCIENTIFICA

Tentativo di una teoria dell'emissione dei raggi "beta"

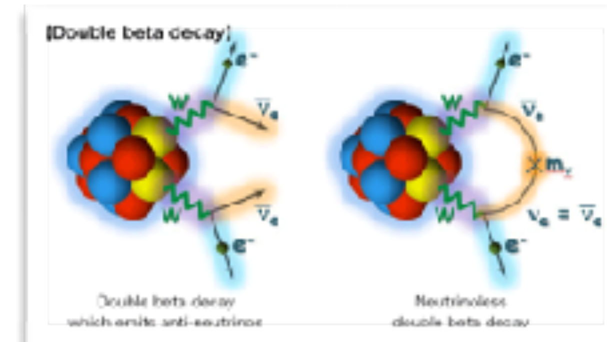
Nota del prof. ENRICO FERMI

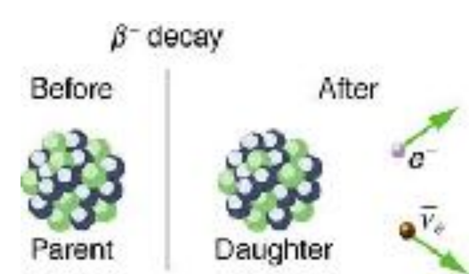
(33) 30 years later

O. Miranda's talk



Data favors Direct Hierarchy
And CP violation





$$m_{\nu e}^{eff} \leq 0.6\ eV$$

$$\sum m_\nu \leq 0.2\ eV$$

Oscillation parameters

de Salas, Forero, Ternes, Tortola, Valle (2018)

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50±0.03	2.44–2.57	2.41–2.60
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/°$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/°$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/°$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/°$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.21^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/°$	218^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/°$	281^{+23}_{-27}	229–328	202–349

- 2 nearly maximal mixings
- One small $\mathcal{O}(\lambda_C)$
- CP violation
- 2 squared mass differences

Oscillation parameters

PDG (2018)

$$V_{\rm CKM} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

de Salas, Forero, Ternes, Tortola, Valle (2018)

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NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

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tri-maximal

bi-maximal

Harriso, Perkin, Scott

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

Three ways to test

Beta decay

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

***Majorana neutrinos**

Neutrinoless double beta Decay

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

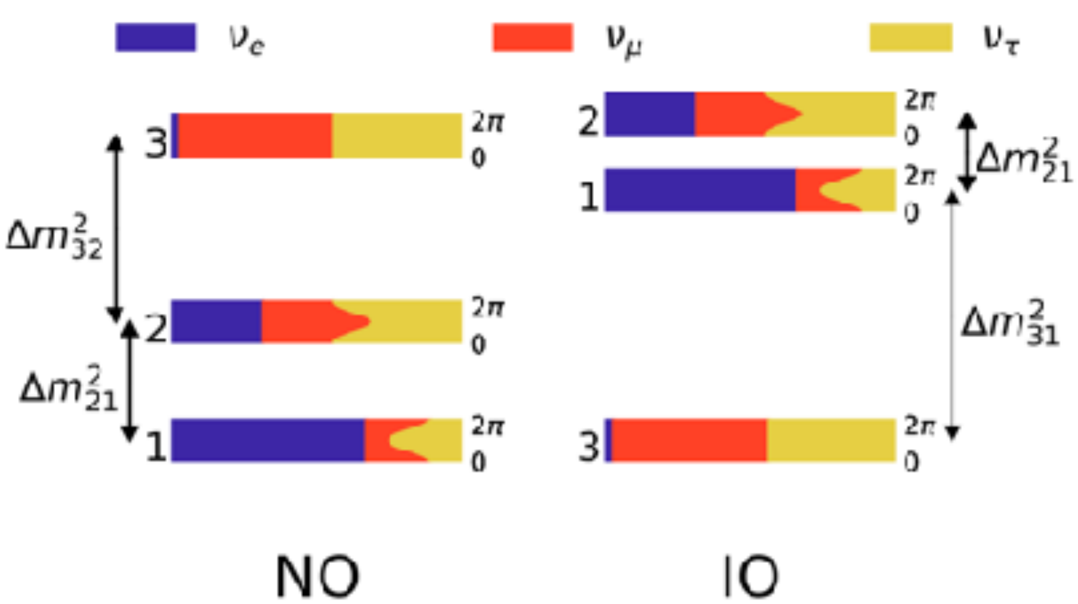
Cosmology

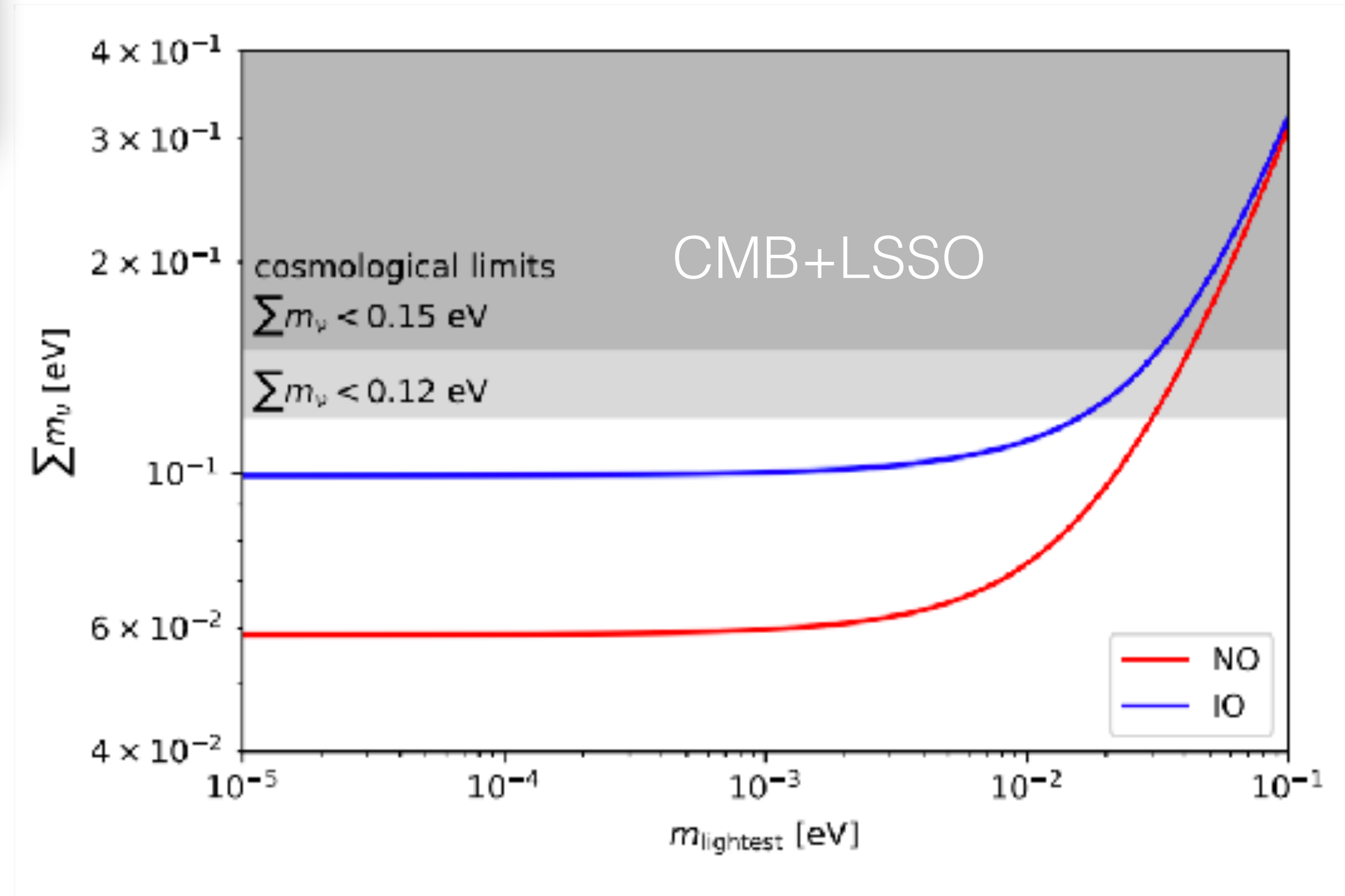
$$\Sigma = m_1 + m_2 + m_3$$

Trident

de Salas, Gariazzo, Mena, Ternes, Tortola (2018)

$$\sum m_\nu^{\rm NO} = m_1 + \sqrt{m_1^2 + \Delta m_{21}^2} + \sqrt{m_1^2 + \Delta m_{31}^2}\,,$$
$$\sum m_\nu^{\rm IO} = m_3 + \sqrt{m_3^2 + |\Delta m_{31}^2|} + \sqrt{m_3^2 + |\Delta m_{31}^2| + \Delta m_{21}^2}$$

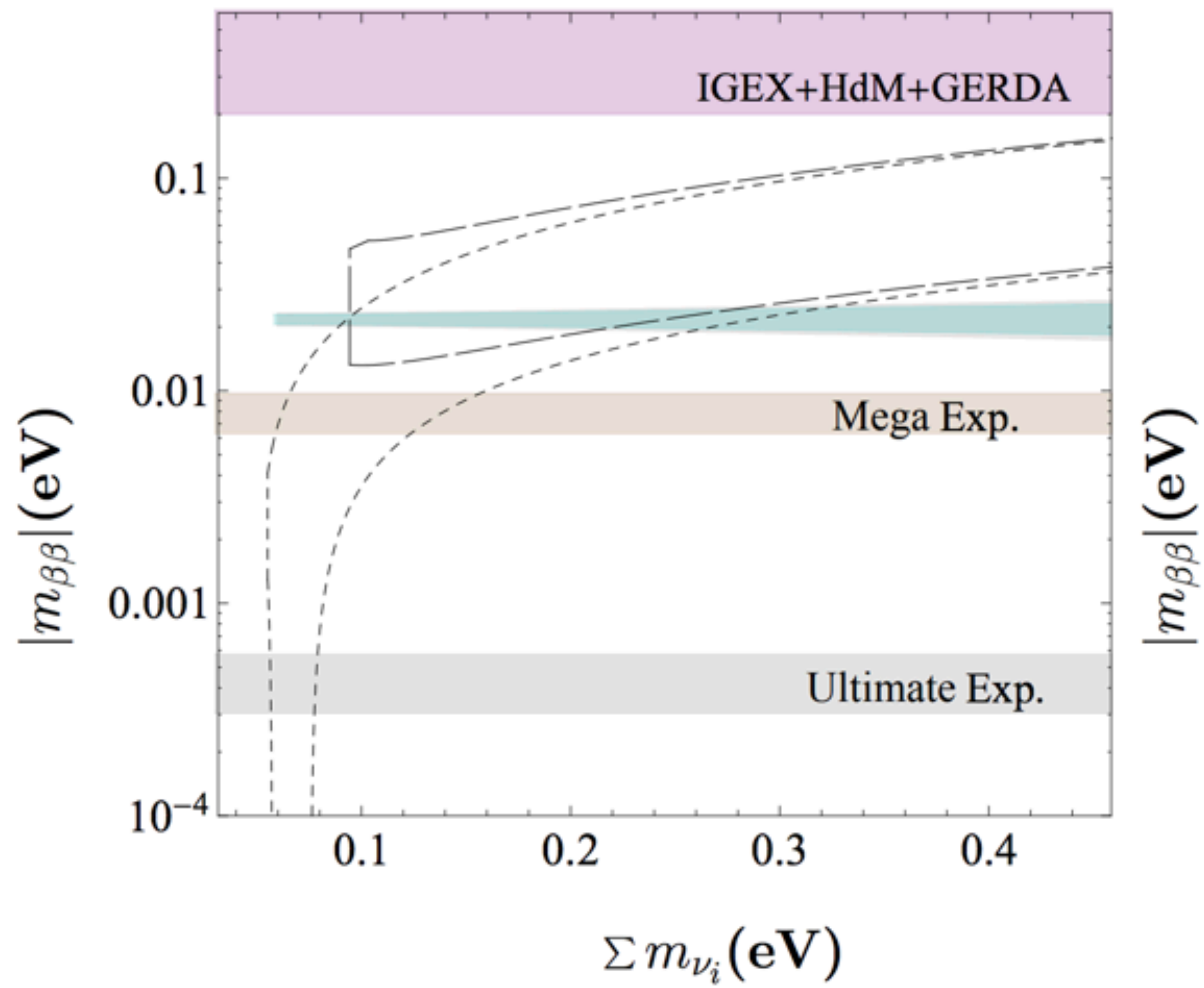




Trident

Meroni, EP (2014)

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



$$\Sigma = m_1 + m_2 + m_3$$

Trident

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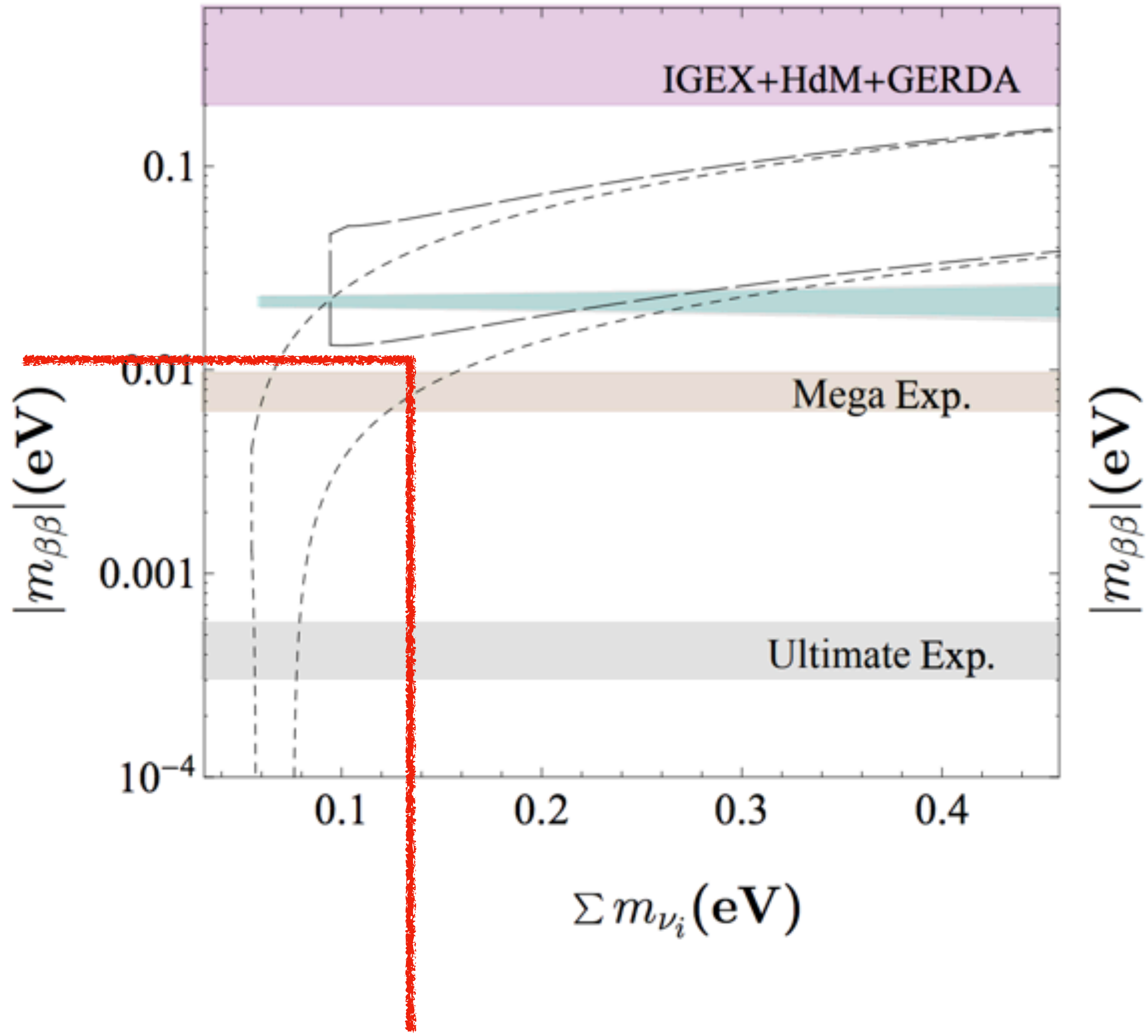

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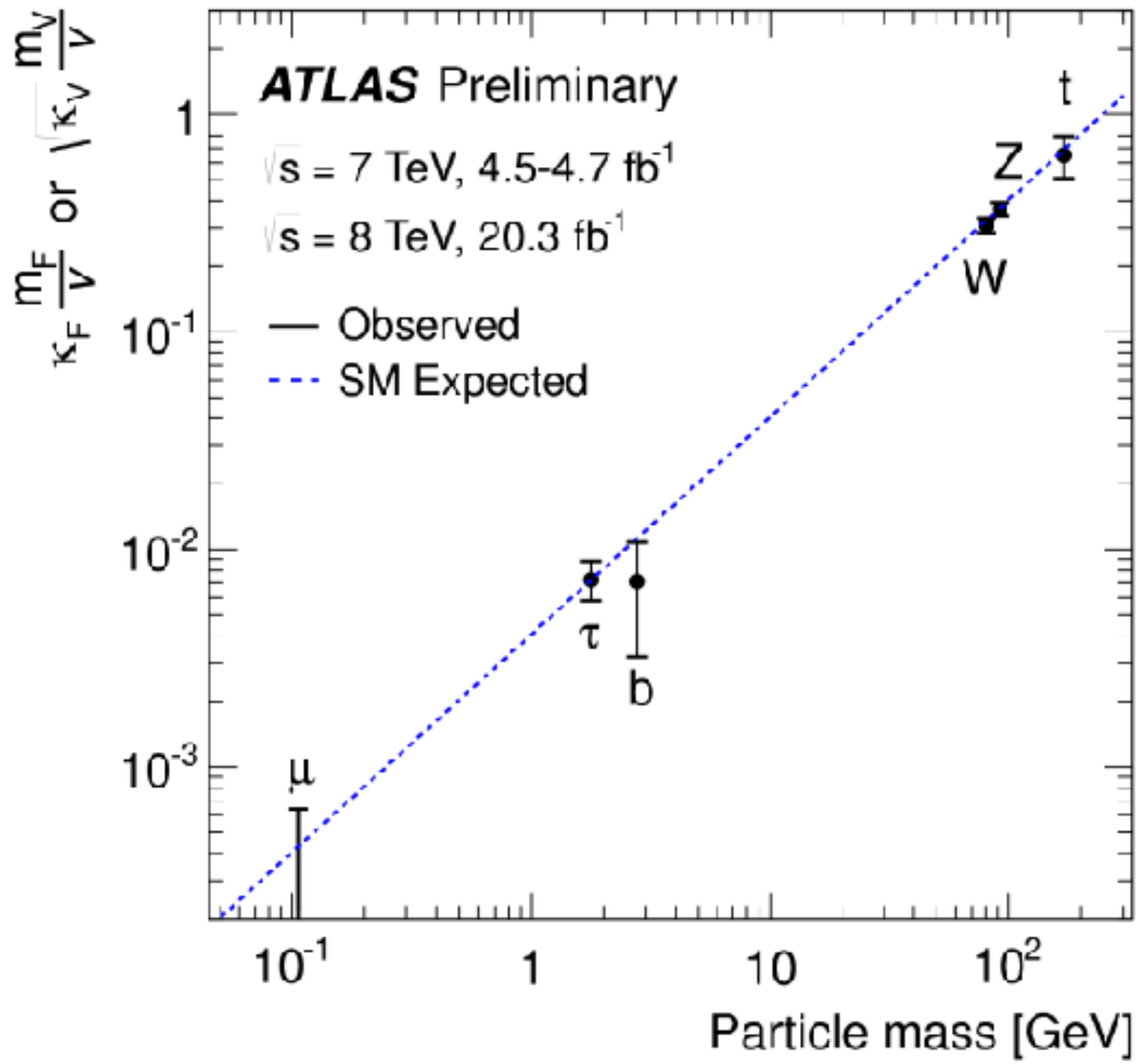
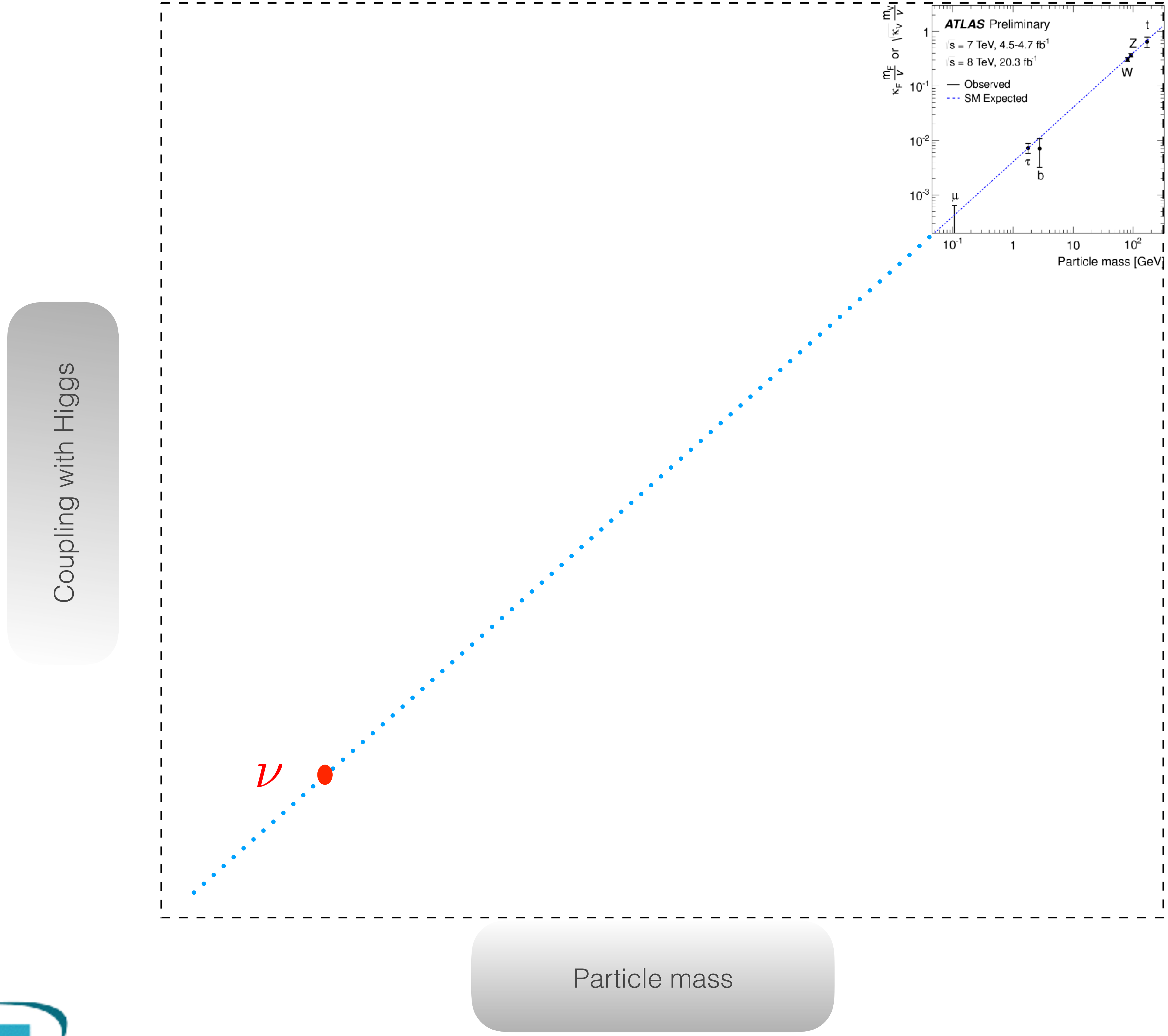
$$\Sigma = m_1 + m_2 + m_3$$

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



Fermion masses:

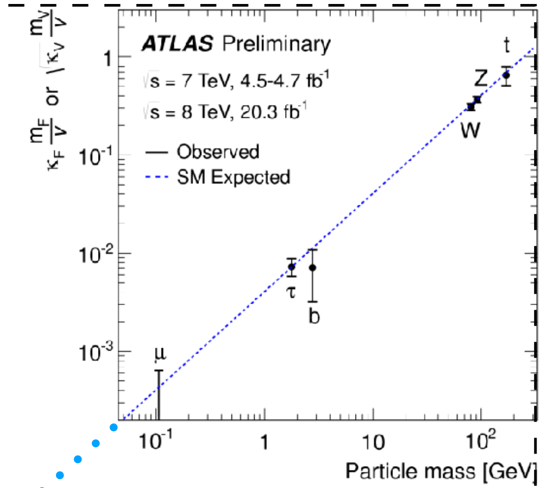
m_e	$.5\ MeV$
m_d	$4.8\ MeV$
m_u	$2.3\ MeV$
m_μ	$105\ MeV$
m_s	$95\ MeV$
m_c	$1.275\ GeV$
m_τ	$1.776\ GeV$
m_b	$4.18\ GeV$
m_t	$174\ GeV$

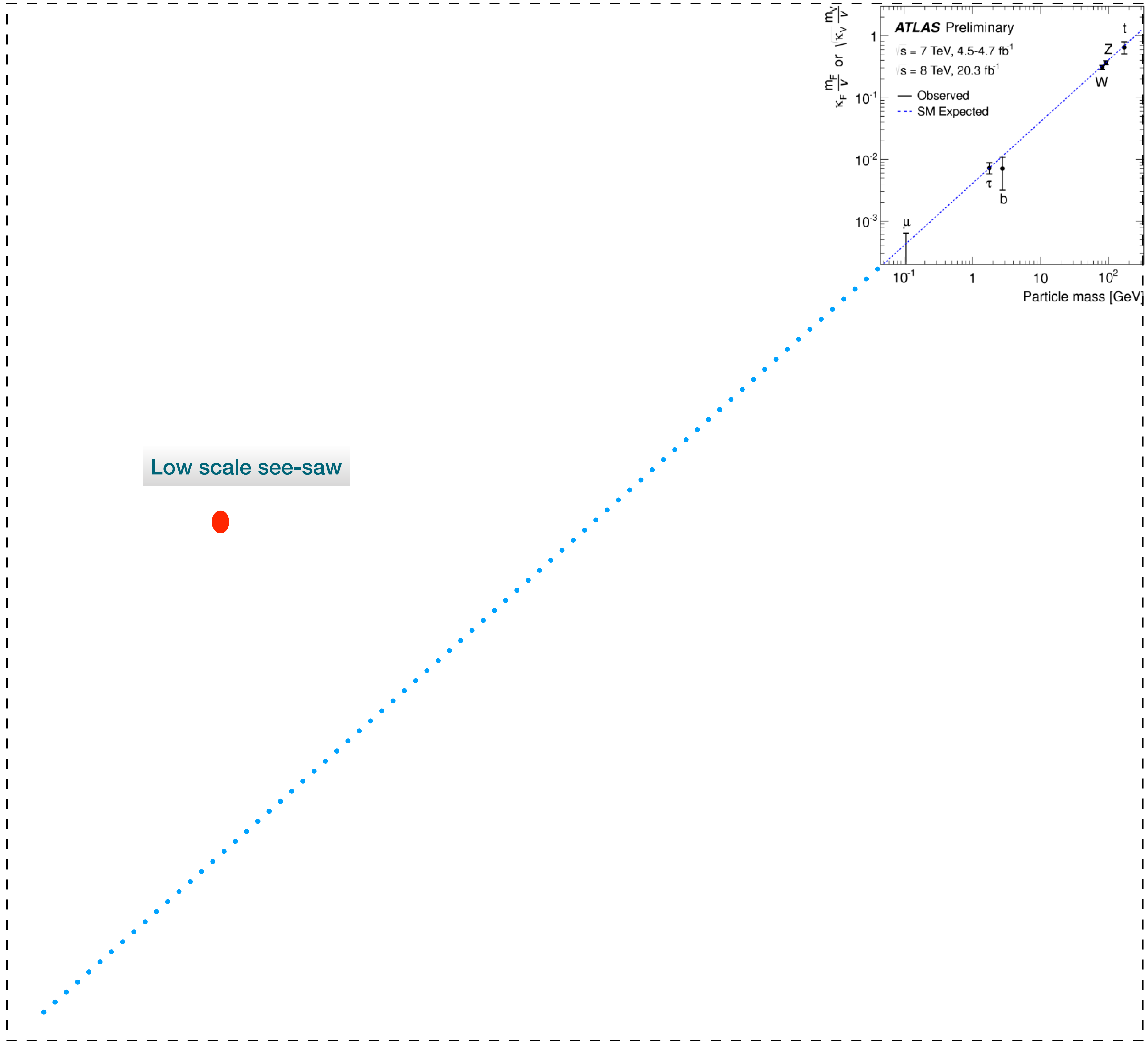


ATLAS Preliminary
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Observed
SM Expected
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
1
10^{-1}
10^{-2}
10^{-3}
μ
τ
b
W
Z
t
10^{-1}
1
10
10^2
Particle mass [GeV]
ν
Coupling with Higgs
Particle mass

ν • $y \sim O(1)$

$$\frac{v}{M_N}$$





ATLAS Preliminary
s = 7 TeV, 4.5-4.7 fb-1
s = 8 TeV, 20.3 fb-1
Observed
SM Expected
Particle mass [GeV]
t
Z
W
τ
b
μ
Low scale see-saw

small (¿effective?) coupling

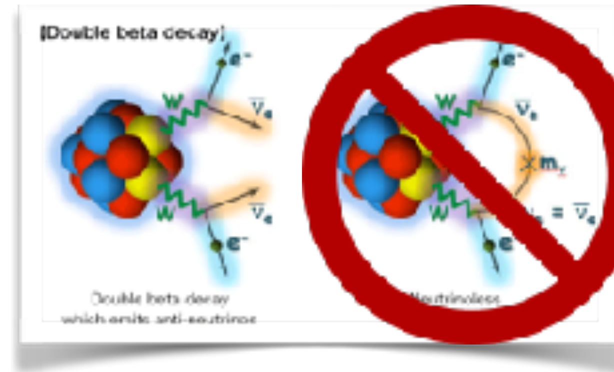
Restrepo's

¿Dirac o Majorana?

Big coupling

Rodriguez's

small (¿effective?) coupling

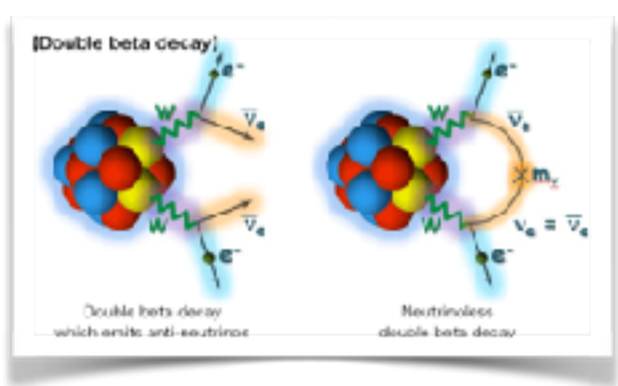


Restrepo's

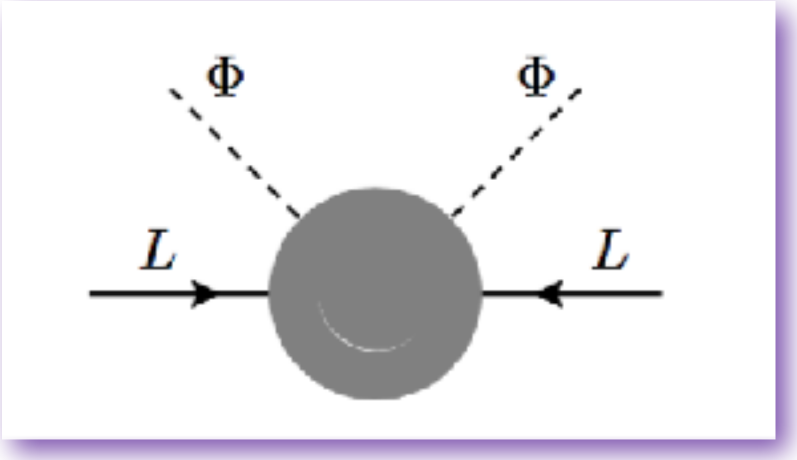
¿Dirac o Majorana?

Big coupling

Rodriguez's



The simplest effective source of Majorana neutrino masses dim 5 Weinberg operator



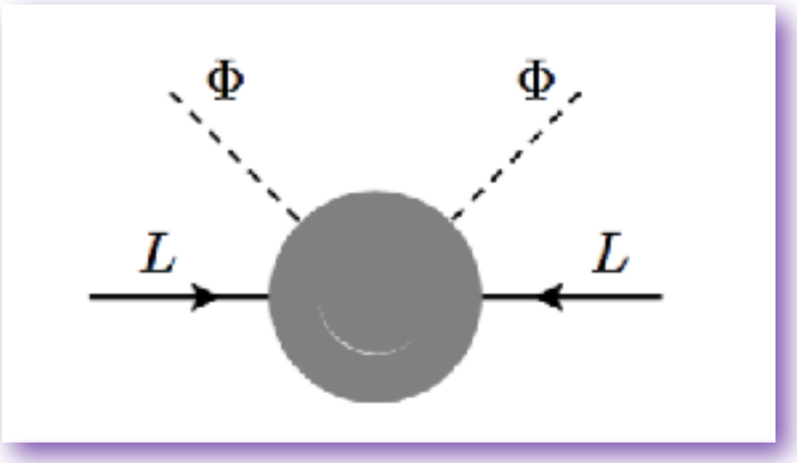
Weinberg, S. (1980)

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5$$

$$\mathcal{L}_5 = LL\Phi\Phi \qquad \Delta L = 2$$

Schechter, Valle (1982)

- **The simplest effective source of Majorana neutrino masses dim 5 Weinberg operator**



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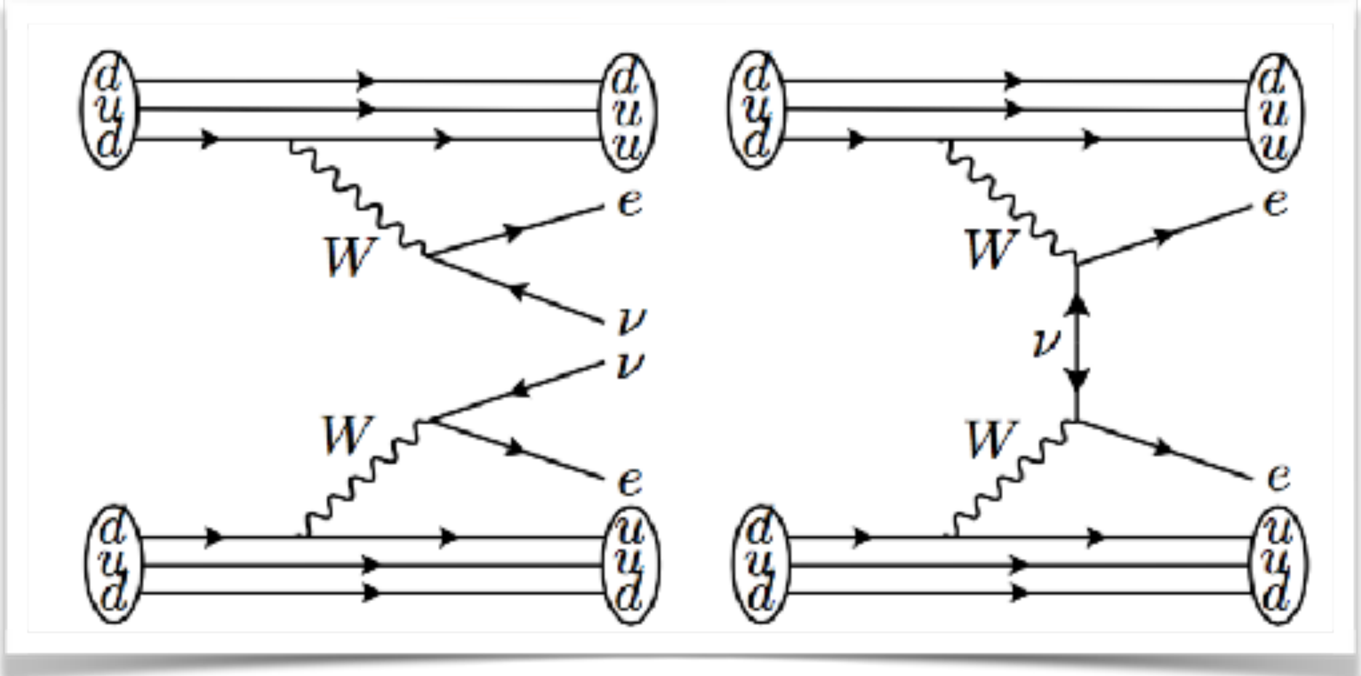
$$\mathcal{L}_5 = LL\Phi\Phi$$

$$\Delta L = 2$$

- **Implications?**

Schechter, Valle (1982)

$$0\nu\beta\beta$$



Seesaw Majorana

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

type I seesaw

LHN $\qquad 2 \otimes 2 \otimes 1$

type II seesaw

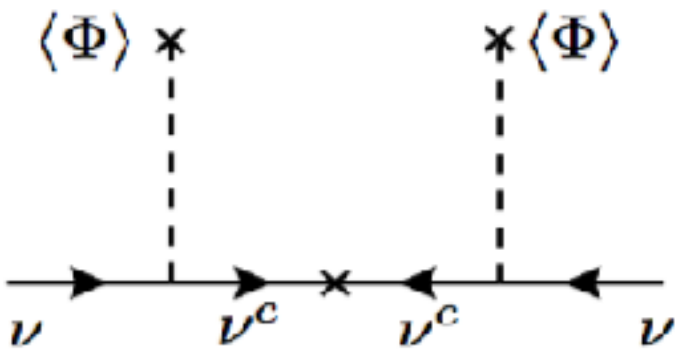
$L\Delta L$ $\qquad 2 \otimes 3 \otimes 2$

type III seesaw

$LH\Sigma$ $\qquad 2 \otimes 3 \otimes 2$

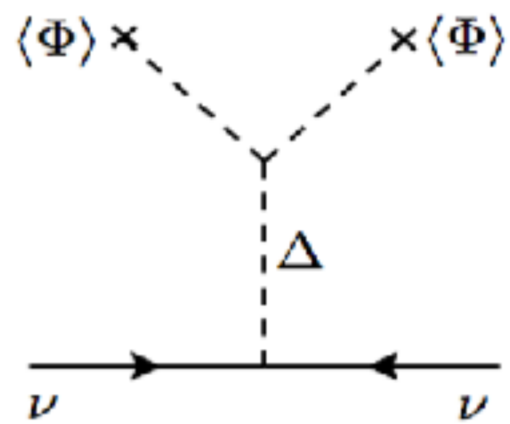
Seesaw Majorana

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



type I seesaw

LHN $\quad 2 \otimes 2 \otimes 1$



type II seesaw

$L\Delta L$ $\quad 2 \otimes 3 \otimes 2$

type III seesaw

$LH\Sigma$ $\quad 2 \otimes 3 \otimes 2$

Type III

Seesaw Majorana

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

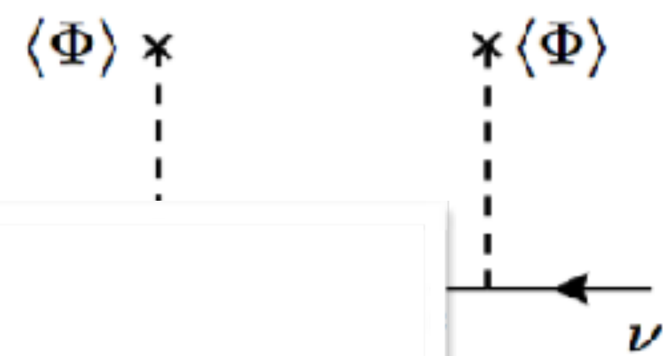
type I

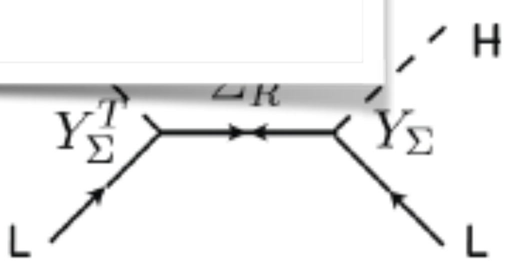
type I

type II

$$\mathcal{M}_\nu = \begin{bmatrix} M_1 & M_D \\ M_D^T & M_2 \end{bmatrix}$$

$$LH\Sigma \qquad 2 \otimes 3 \otimes 2$$





Inverse see-saw

- **New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets) SU(2) singlets: (ν_i^c,S_i) transforming as**

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

Seesaw Majorana

Inverse see-saw

- New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets) SU(2) singlets: (ν_i^c, S_i) transforming as

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_\nu^T \langle\Phi\rangle & 0 \\ Y_\nu \langle\Phi\rangle & 0 & M^T \\ 0 & M & \mu \end{bmatrix}$$

Seesaw Majorana

Inverse see-saw

- **New features emerge when the seesaw is realized with non-minimal lepton content (Isosinglets)   SU(2) singlets: (ν_i^c, S_i) transforming as**

$field$	L
ν_i	$+1$
N	-1
S_i	$+1$

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_\nu^T \langle \Phi \rangle & 0 \\ Y_\nu \langle \Phi \rangle & 0 & M^T \\ 0 & M & \mu \end{bmatrix}$$

violates L in 2 units

$\mu_{ij} S_i S_j$ mass terms

smallness of neutrino mass is related to the smallness of the parameter mu "natural" in the sense of 't Hooft

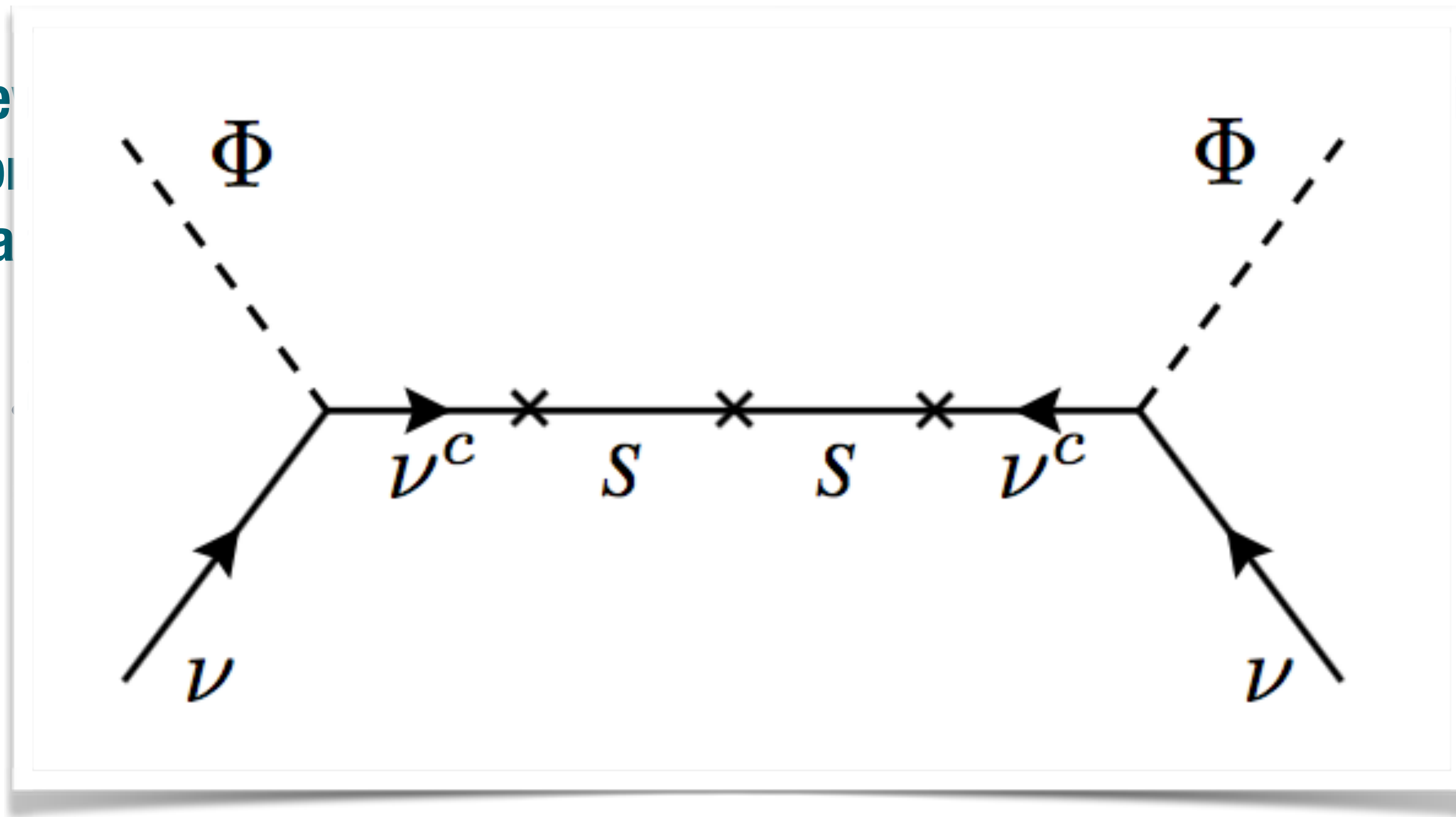
$$m_\nu \to 0 \quad \text{as} \quad \mu \to 0$$

t'Hooft, G. (1982)

Seesaw Majorana

Inverse see-saw

Ne… …mal lepton
co…
tra…



0
M^T
μ

violates L in 2 units

… is related to the
… mu "natural" in
…Hooft

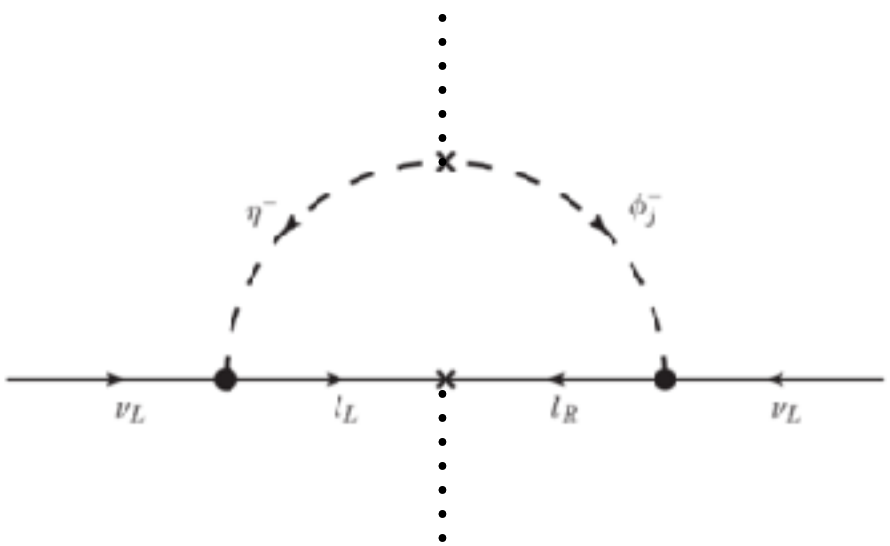
$$m_\nu{}^{\text{inverse}} = M_D M^{T^{-1}} \mu M^{-1} M_D^T.$$

m_ν

t'Hooft, G. (1982)

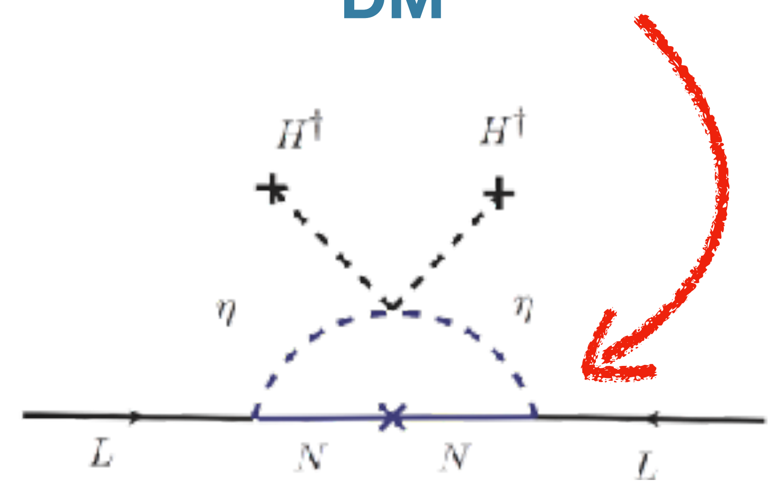
in the limit as $\mu \to 0$ the lepton number symmetry is restored.

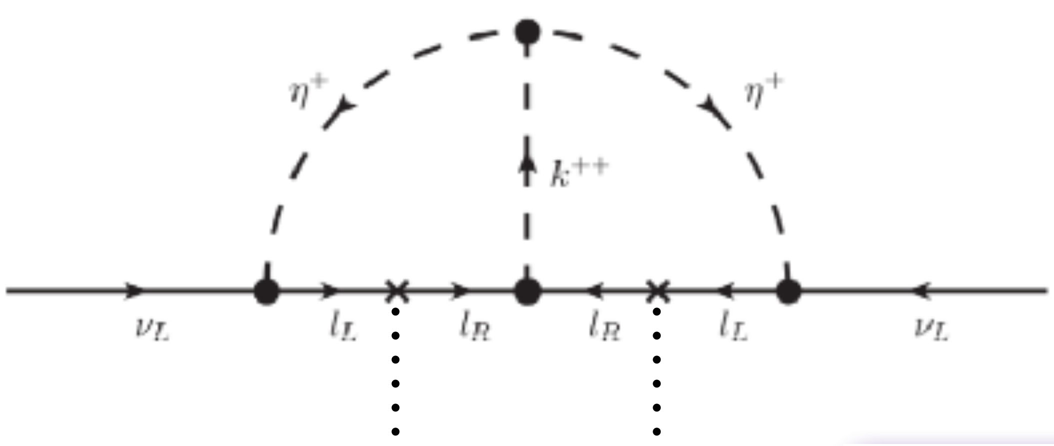
Radiative mass generation



Zee model

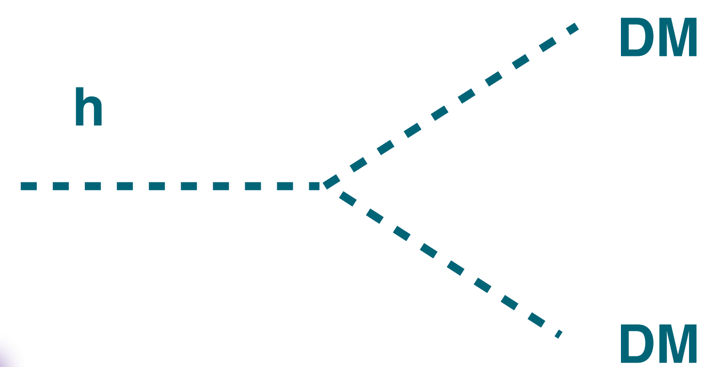
DM

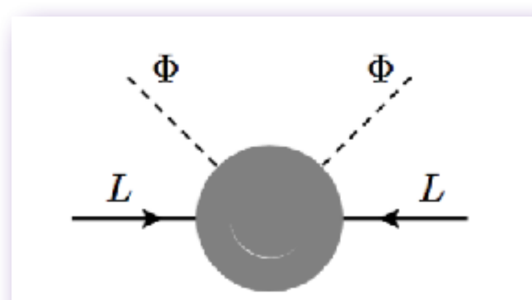




Zee Babu

Higgs portal (scalar DM)





DM stability

Deshpande and Ma (1978)

$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ $\{1, 2, \frac{1}{2}\}_\phi$

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

SM ⊗ Z2

	ϕ	η
Z_2	$+1$	-1

$$\begin{aligned} V &= \mu^2\phi^\dagger\phi + \mu_\eta^2\eta^\dagger\eta + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\eta^\dagger\eta)^2 \\ &+ \lambda_3\phi^\dagger\phi\eta^\dagger\eta + \lambda_4\phi^\dagger\eta\eta^\dagger\phi + \lambda_5(\phi^\dagger\eta\phi^\dagger\eta + h.c) \end{aligned}$$

EWSB

$\phi \to \langle 0|\phi|0\rangle \equiv v = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu \end{pmatrix}$ $\langle\eta\rangle = 0$

DM stability

as for all stable particles in the Standard Model!

Symmetry

DM stability

as for all stable particles in the Standard Model!

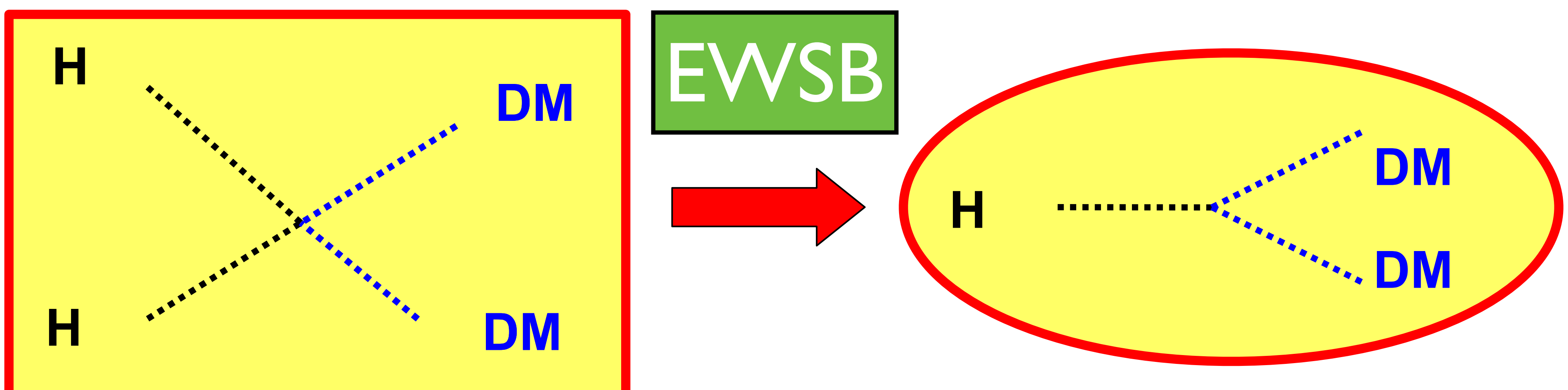
Symmetry

Deshpande and Ma (1978)

SM + scalar

Z_2 + -

$$\lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + h.c.\right]$$



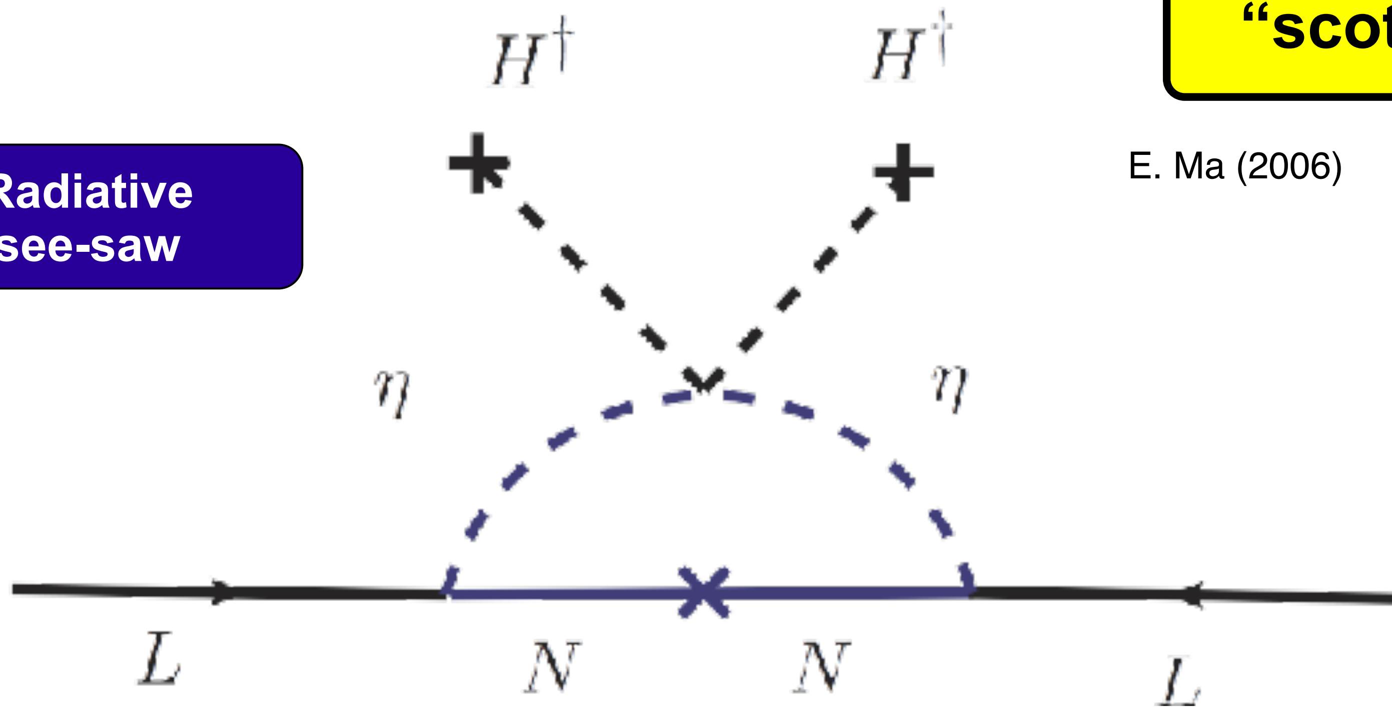
Higgs portal

A. Zee (1980)

“scotogenic”

Radiative see-saw

E. Ma (2006)



If $M_k^2 >> m_0^2$, then

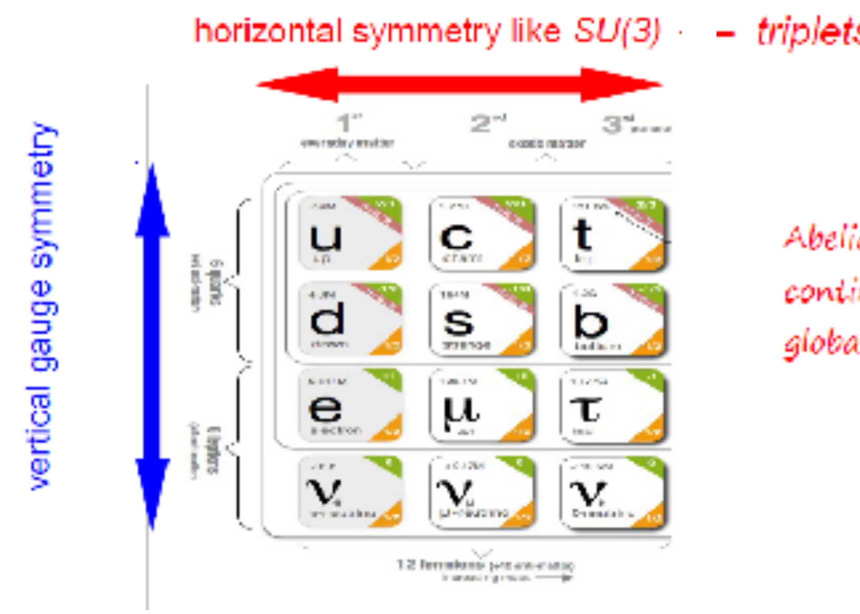
$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda_5 v^2}{8\pi^2} \sum_k \frac{h_{ik} h_{jk}}{M_k} \left[\ln \frac{M_k^2}{m_0^2} \quad 1 \right]$$

Flavor symmetries

S. Ramo's talk

$Z_n \qquad S_3 \qquad S_n$

A_4



Abelian, non abelian continuous, discrete, global, local

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

$1,\ 1',\ 1''$ and 3

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

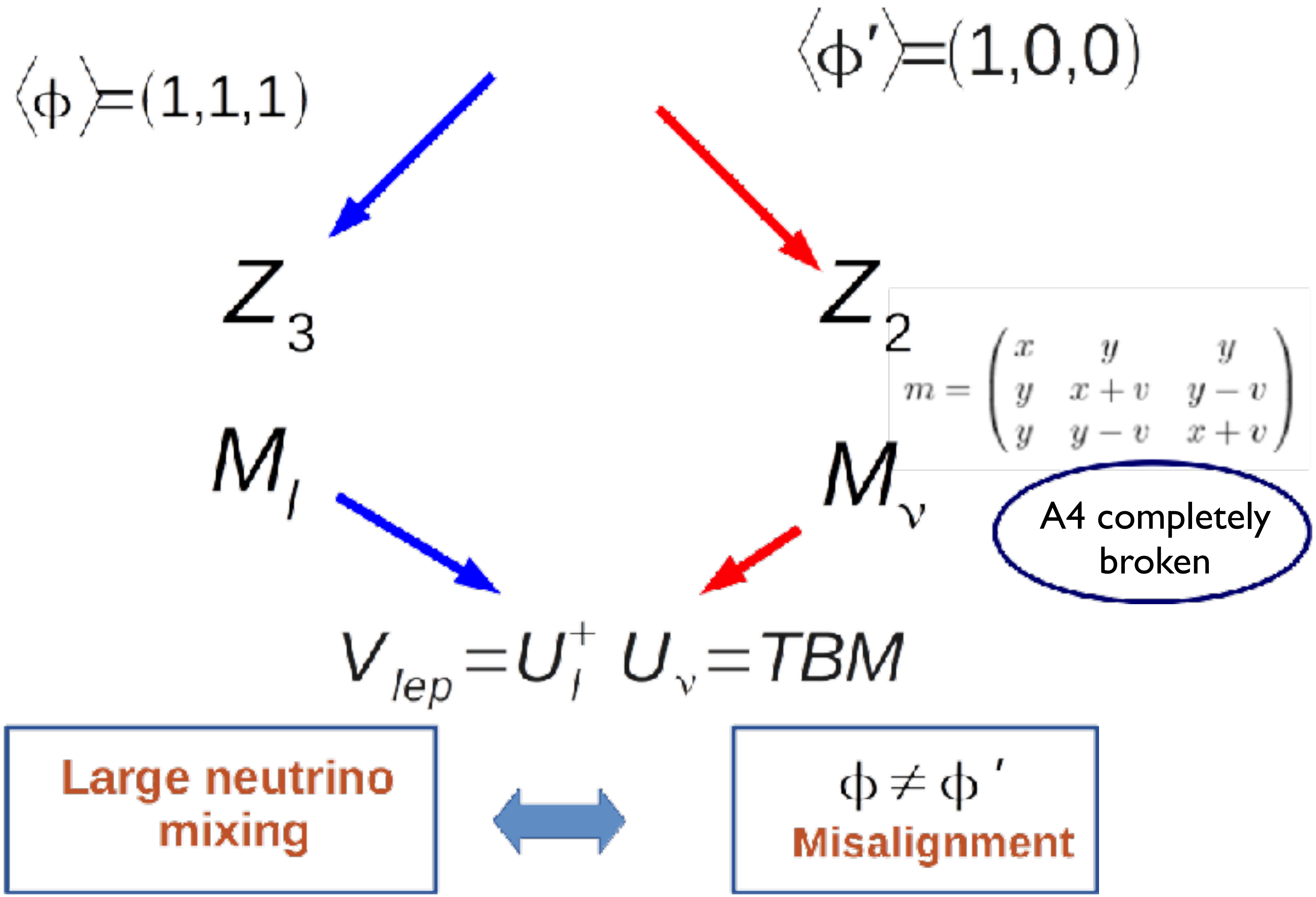
$$\phi = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \qquad \phi' = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

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

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

TBM from A4

Altarelli Feruglio (2005)



TBM from A4

Altarelli Feruglio (2005)

$\langle \phi \rangle = (1,1,1)$ → Z_3 → M_l

$\langle \phi' \rangle = (1,0,0)$ → Z_2 → M_ν

$$m = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix}$$

A4 completely broken

tri-maximal

bi-maximal

Harriso, Perkin, Scott

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

$$V_{lep} = U_l^+ U_\nu = TBM$$

Large neutrino mixing ⟷ $\phi \neq \phi'$ **Misalignment**

Stability from flavor symmetry

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix} \xrightarrow{\text{SSB}} \langle \phi \rangle = \begin{pmatrix} v \\ 0 \\ 0 \end{pmatrix}$$

$$S\phi = \phi$$

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

$$A_4 \longrightarrow Z_2$$

$$\begin{pmatrix} t_1 \\ t_2 \\ t_3 \end{pmatrix} \longrightarrow \begin{pmatrix} t_1 \\ -t_2 \\ -t_3 \end{pmatrix}$$

EW scale breaking

Hirsch et al (2011)

Seesaw scale breaking

M. Lamprea and EP (2016)

Seesaw estabilidad de DM y simetría

M. Lamprea and 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

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

Seesaw estabilidad de DM y simetría

M. Lamprea and 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

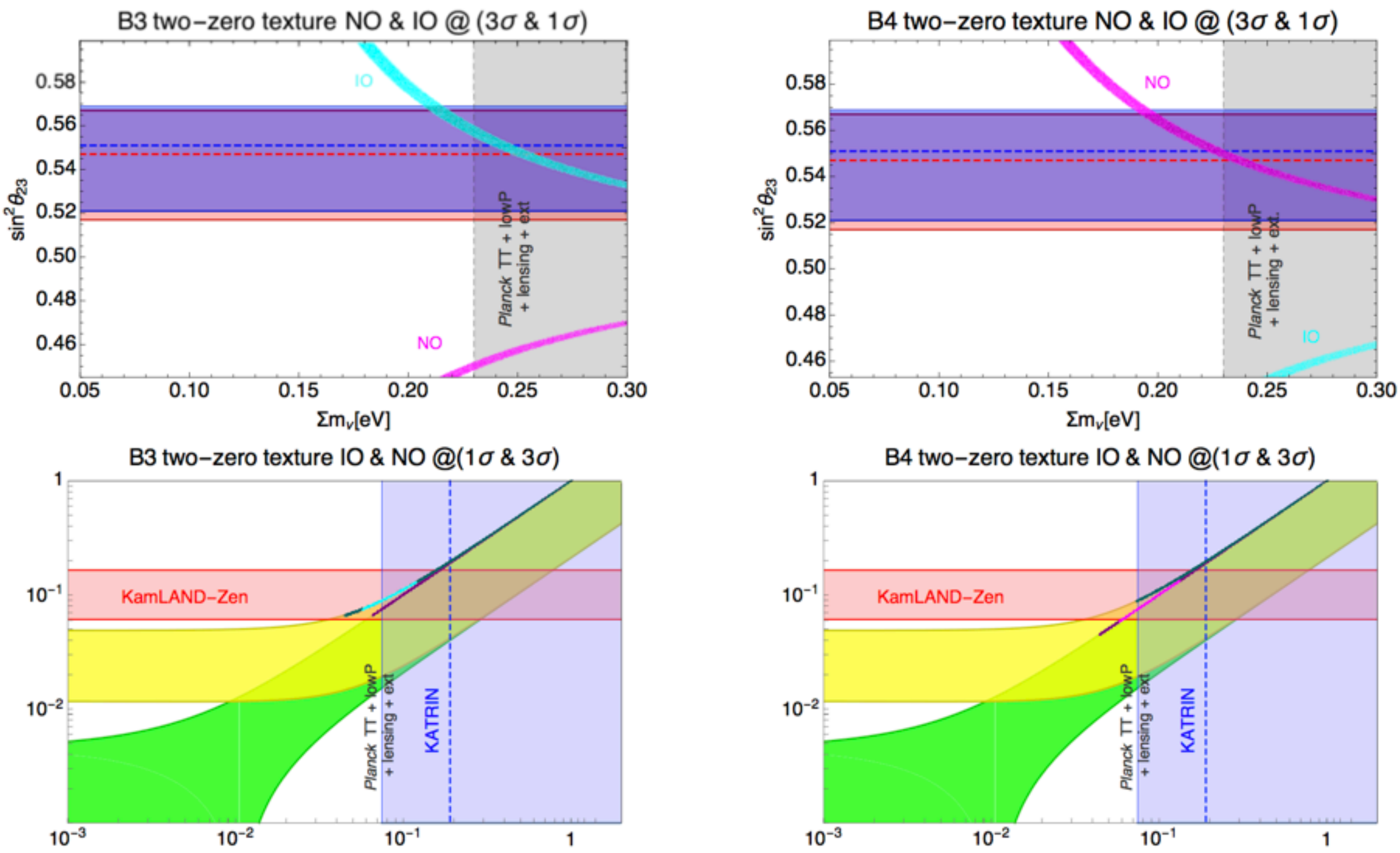
$$m_\nu^{(A)} \equiv \begin{pmatrix} a & 0 & b \\ 0 & 0 & c \\ b & c & d \end{pmatrix}$$

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

Tridente

M. Lamprea and EP (2016)

de Salas, Forero, Ternes, Tortola, Valle (2018)



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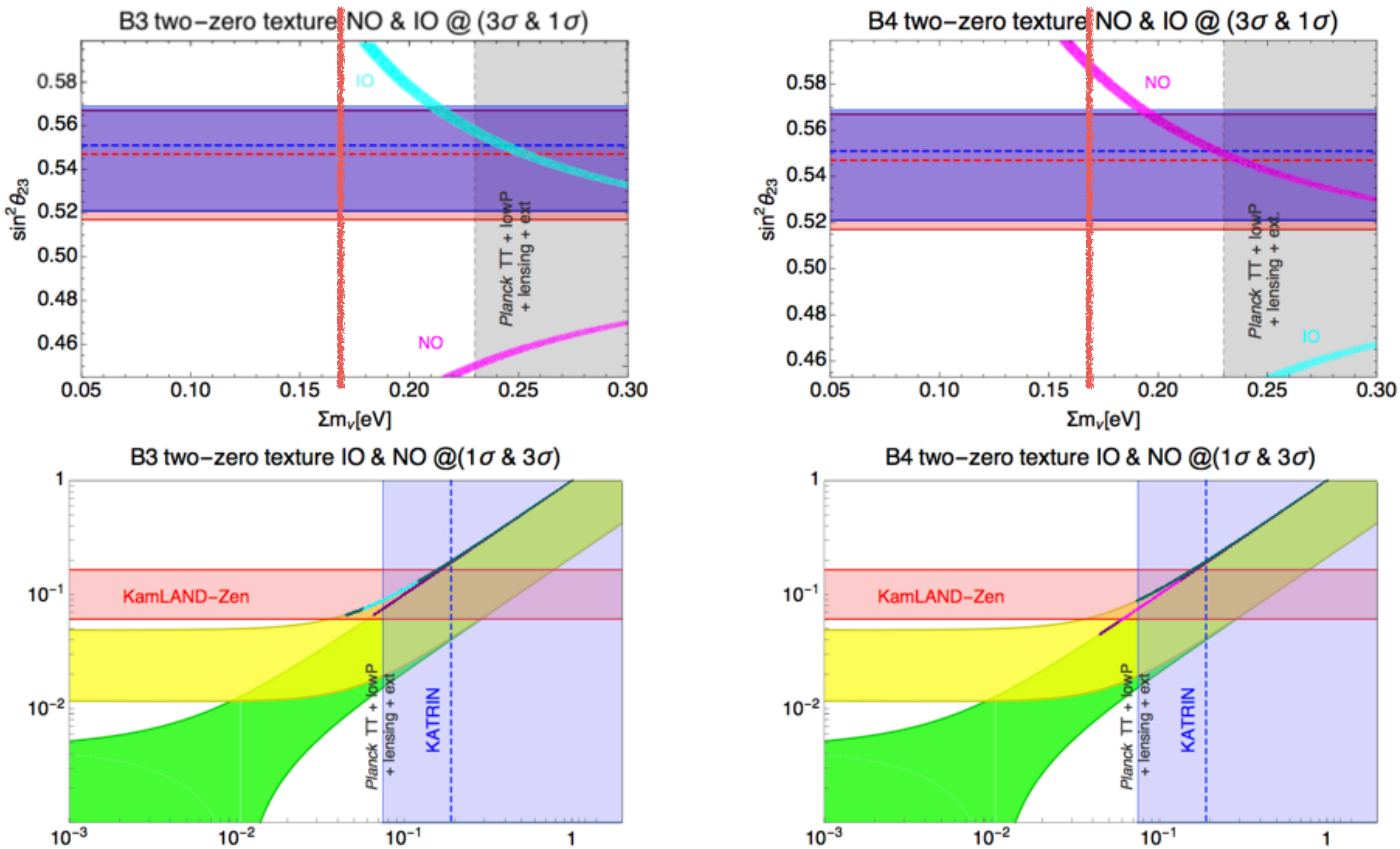
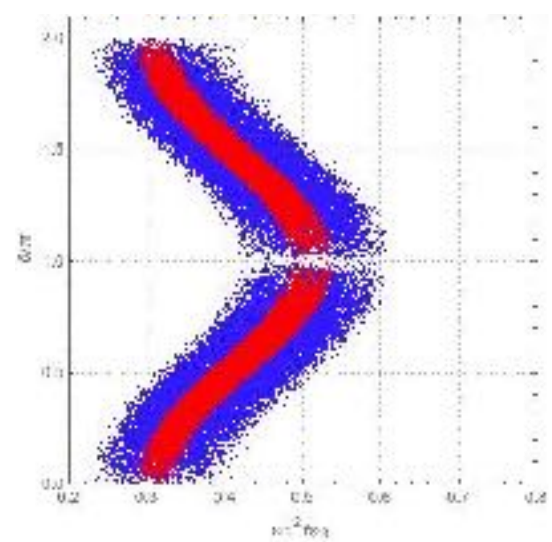


More on A4 stability

Ferro-Hernandez, García de la Vega,EP (2018)

$$A_4 \to Z_2$$

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



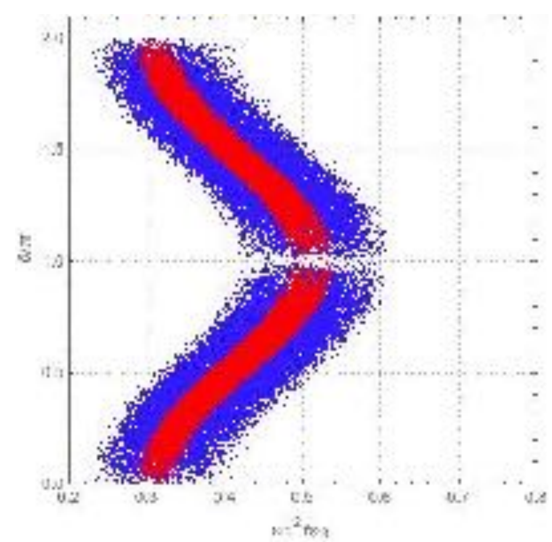
$zero \; 0\nu\beta\beta$

More on A4 stability

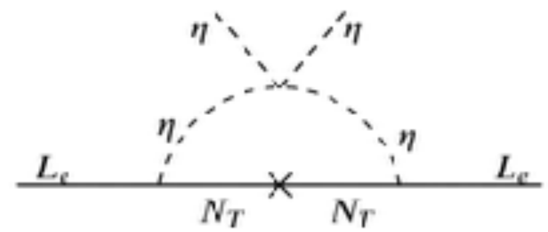
Ferro-Hernandez, García de la Vega,EP (2018)

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

$zero\ 0\nu\beta\beta$

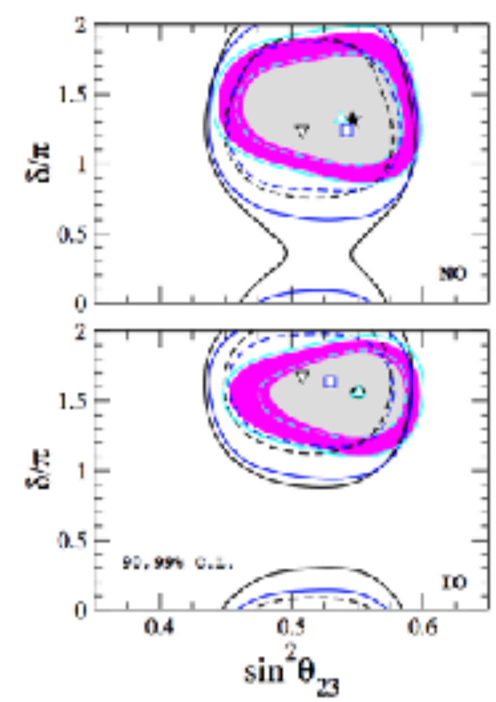


$$A_4 \to Z_2$$



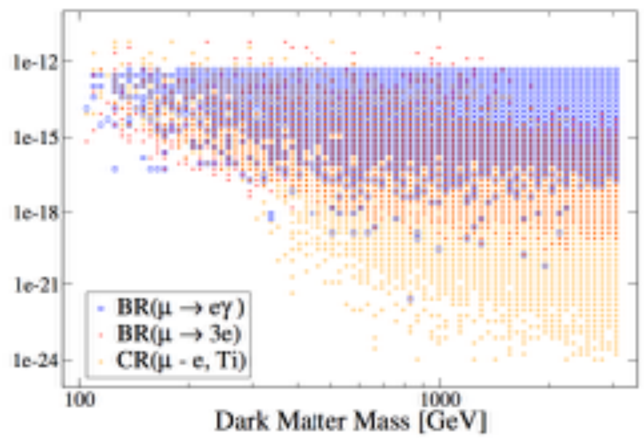
$0\nu\beta\beta$

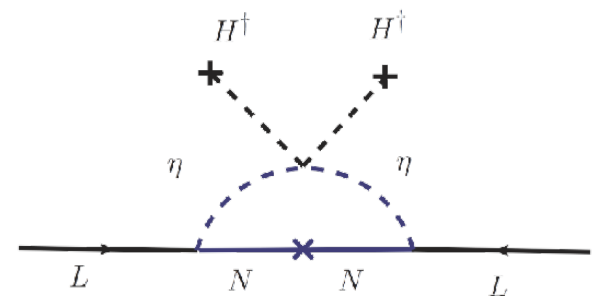
Valencia fit 2018

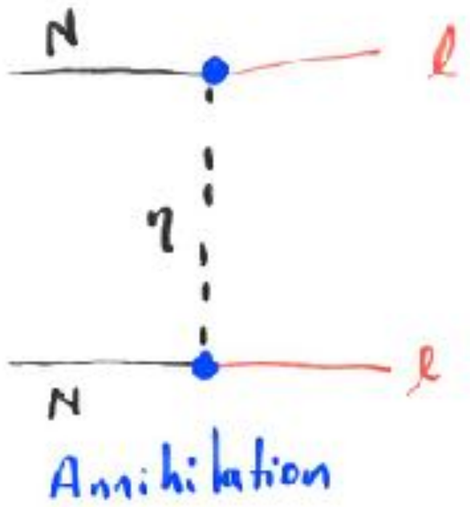


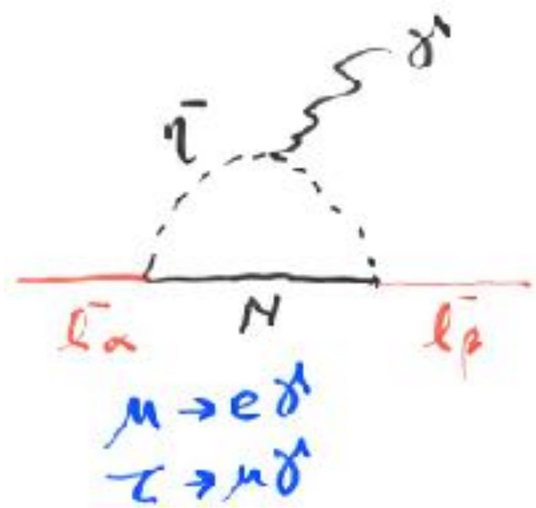
Fermionic DM in the Scotogenic

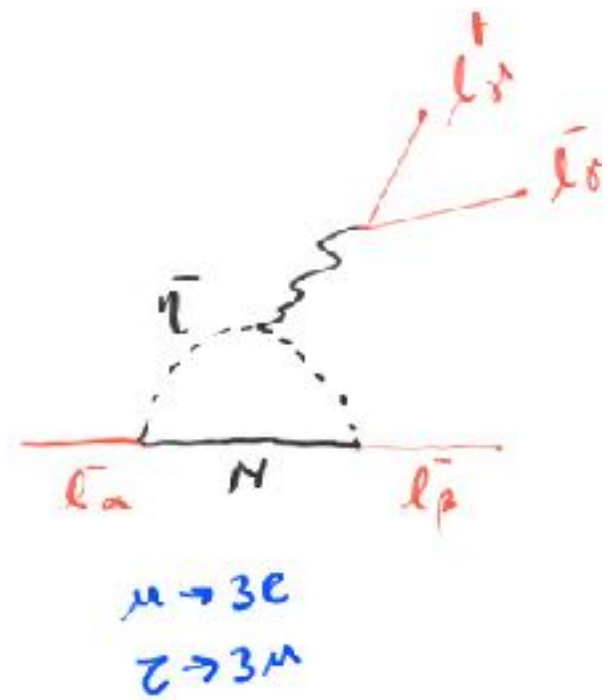
Vicente and Yaguna (2014)



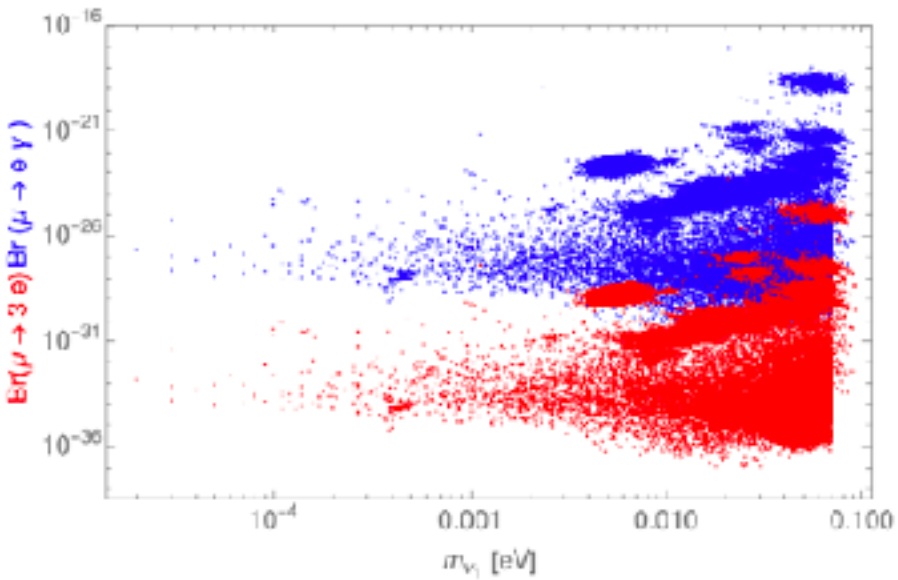




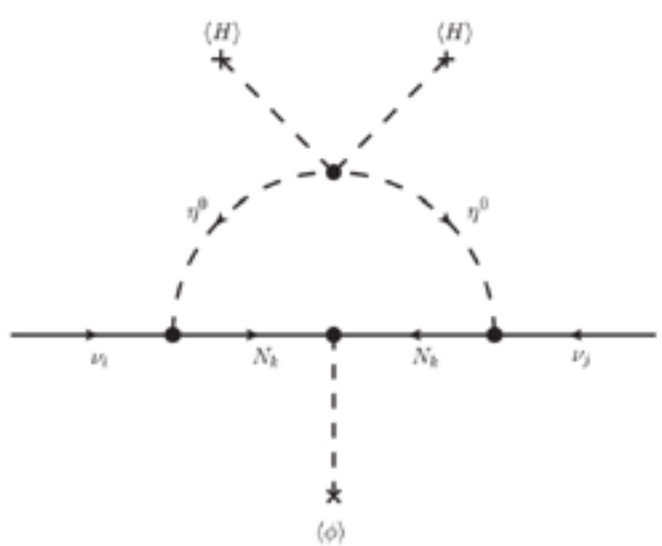


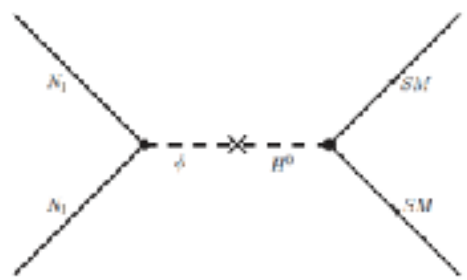


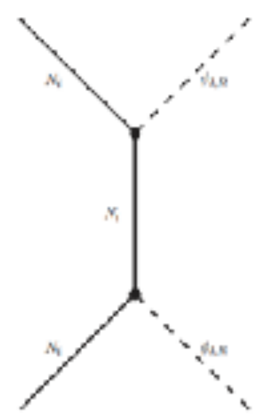
Fermionic DM in the Scotogenic

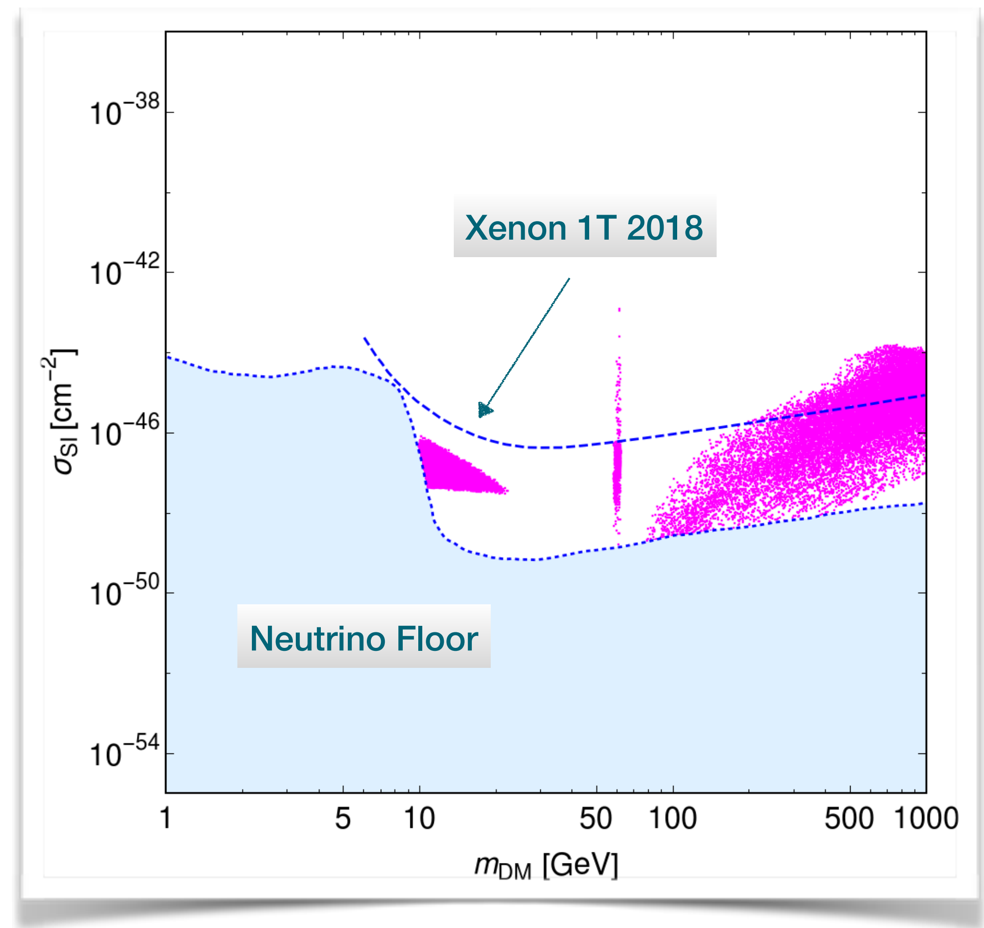


Bonilla, Lamprea, Lineros, de la Vega, Peinado (2018-2019?)





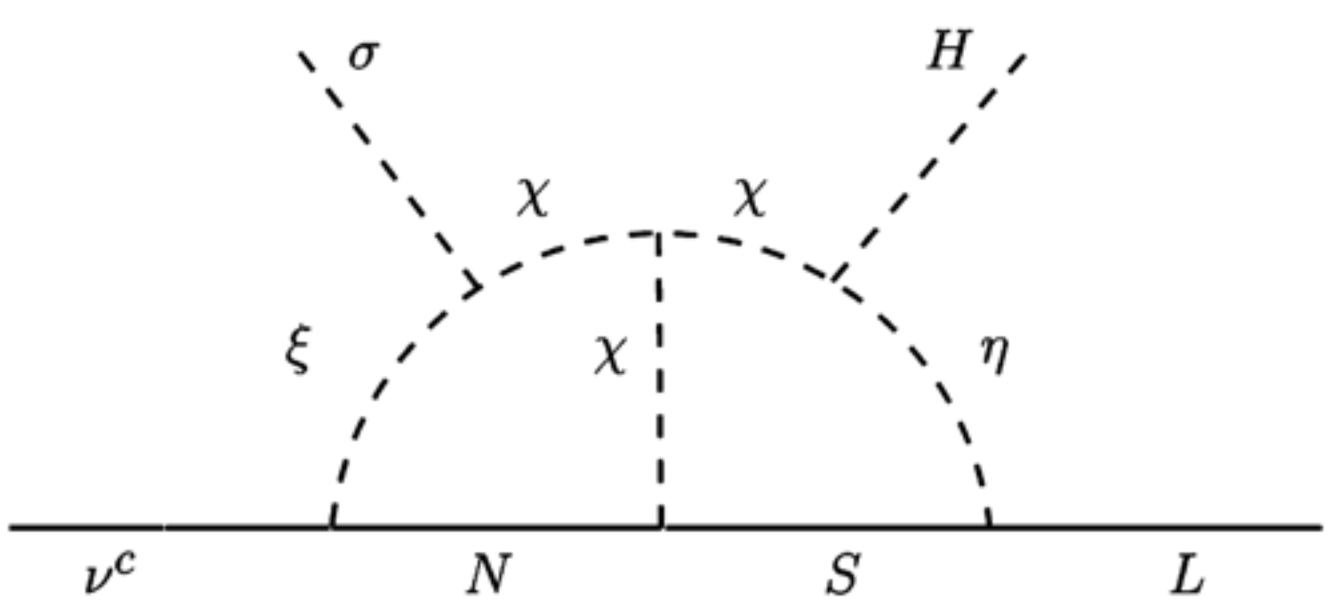




Dirac neutrinos and DM stability

Bonilla, Ma, EP, Valle (2016)

	$\bar{L}$	ν^c	H	η	N	S	σ	ξ	χ
$SU(2)_L$	2	1	2	2	1	1	1	1	1
$U(1)_D$	-1	3	0	0	-1	1	2	-2	0
Z_3^{DM}	1	1	1	α	α	α	1	α^2	α
Z_3	ω	ω^2	1	1	ω	ω^2	1	1	1



3 Simetries:
NO tree-level
DM-Two Loops
Forbidden Majorana

Dirac neutrinos and DM stability

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava (2018)

Dirac or Majorana

$$U(1)_{B-L} \to \mathcal{Z}_m \left\{ \begin{array}{l} \mathcal{Z}_m \equiv \mathcal{Z}_{2n+1} \text{ with } n \in \mathbb{Z}^+ \\ \text{Neutrinos are Dirac particles} \\ \mathcal{Z}_m \equiv \mathcal{Z}_{2n} \text{ with } n \in \mathbb{Z}^+ \\ \text{Neutrinos can be Dirac or Majorana} \\ \Downarrow \\ L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix} \begin{array}{l} \nsim \omega^n \text{ under } \mathcal{Z}_{2n} \Rightarrow \text{Dirac Neutrinos} \\ \sim \omega^n \text{ under } \mathcal{Z}_{2n} \Rightarrow \text{Majorana Neutrinos} \end{array} \end{array} \right.$$

Restrepo's talk

Anomaly free

$$\nu_{R_i} \sim \left\{ \begin{array}{lll} (-1,-1,-1) & \bar{L}\tilde{H}\nu_R & \checkmark \\ (-4,-4,5) & \bar{L}\tilde{H}\nu_R & \times \quad \bar{L}H^c\chi_1 \ldots \chi_i \nu_{R_i} \end{array} \right.$$

Dirac neutrinos and DM stability

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava (2018)

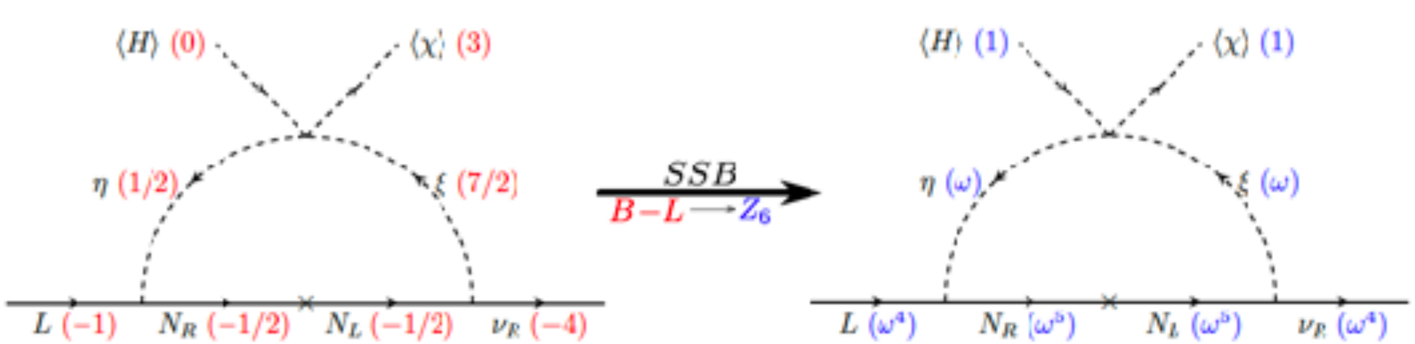
DM stability

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$	$\mathcal{Z}_6$
Fermions	L_i	$(\mathbf{2}, -1/2)$	-1	ω^4
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	$(\omega^4, \omega^4, \omega^4)$
	N_{L_i}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
	N_{R_i}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
Scalars	H	$(\mathbf{2}, 1/2)$	0	1
	χ	$(\mathbf{1}, 0)$	3	1
	η	$(\mathbf{2}, 1/2)$	$1/2$	ω
	ξ	$(\mathbf{1}, 0)$	$7/2$	ω

$$U(1)_{B-L} \to \mathcal{Z}_m$$

$$m = 2n$$
$$n > 2$$

$$Z_4, \; Z_6, \ldots$$



(a) General $U(1)_{B-L}$ charge assignment.

(b) General remnant $\mathcal{Z}_n$ charge assignment.

More details in arXiv:1812.01599

Dirac neutrinos and DM stability

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava (2018)

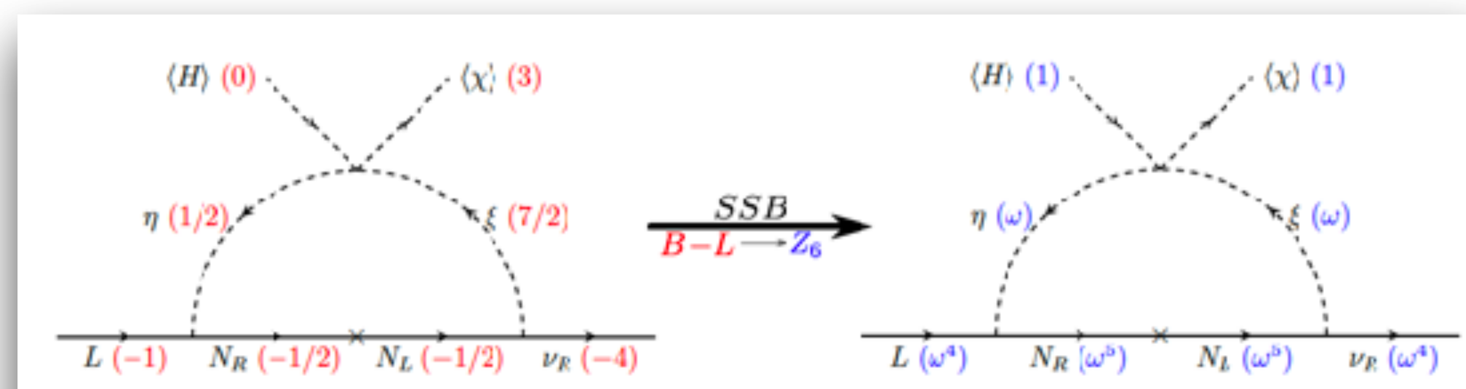
DM stability

	Fields	$SU(2)_L \otimes U(1)_Y$	$U(1)_{B-L}$	$\mathcal{Z}_6$
Fermions	L_i	$(\mathbf{2}, -1/2)$	-1	ω^4
	ν_{R_i}	$(\mathbf{1}, 0)$	$(-4, -4, 5)$	$(\omega^4, \omega^4, \omega^4)$
	N_{L_i}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
	N_{R_i}	$(\mathbf{1}, 0)$	$-1/2$	ω^5
Scalars	H	$(\mathbf{2}, 1/2)$	0	1
	χ	$(\mathbf{1}, 0)$	3	1
	η	$(\mathbf{2}, 1/2)$	$1/2$	ω
	ξ	$(\mathbf{1}, 0)$	$7/2$	ω

$$U(1)_{B-L} \to \mathcal{Z}_m$$

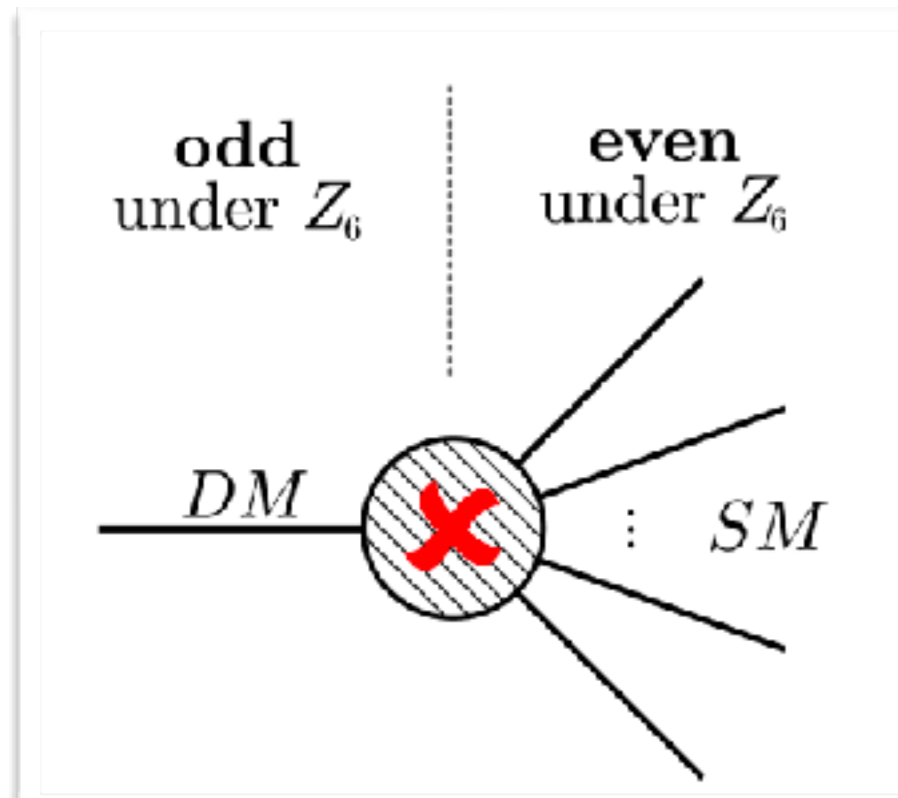
$$m = 2n$$
$$n > 2$$

$$Z_4, \; Z_6, \ldots$$



(a) General $U(1)_{B-L}$ charge assignment.

(b) General remnant Z_n charge assignment.



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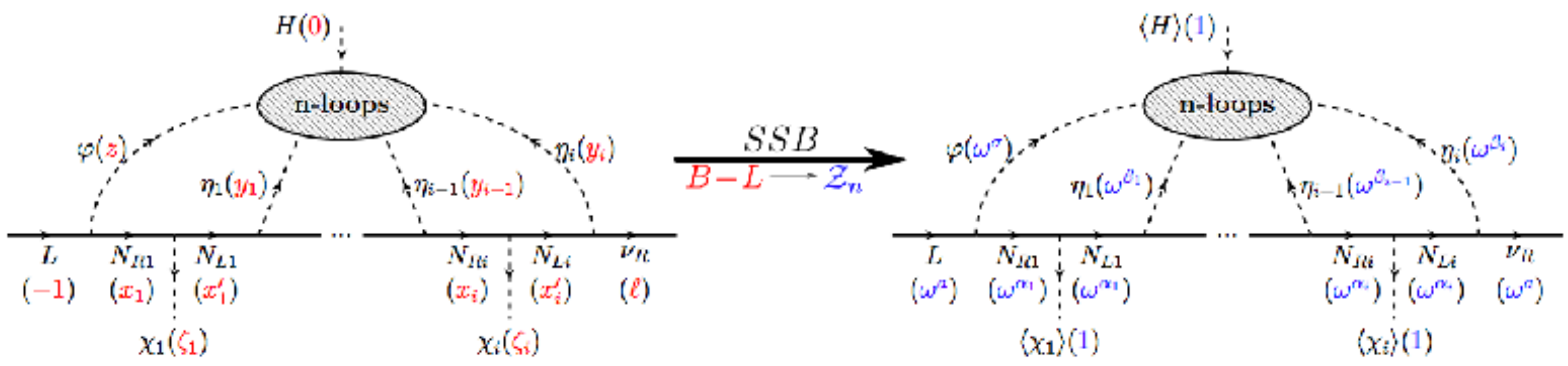
Dirac neutrinos and DM stability

Bonilla, Centelles-Chulia, Cepedello EP, Srivastava (2018)



(a) General $U(1)_{B-L}$ charge assignment.

(b) General residual Z_n charge assignment.

If SM leptons even power

DM (F or S) transforming as odd
Automatically stable

If SM leptons odd power

Scalar DM transforming as odd
Automatically stable

Fermionic DM transforming as even
Automatically stable

Conclusions

- It is possible to link DM with neutrino physics
- Neutrino mass generation and DM
- Oscillation pheno with the stability
- Neutrino nature with DM stability (and the smallness of neutrino masses)

Gracias