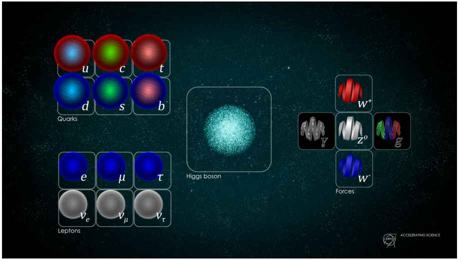
Ugo de Noyers

Unraveling Dark Matter and neutrino mysteries with a scotogenic approach

in collaboration with Maud Sarazin
and Björn Herrmann

June 4, 2024

Standard Model and its limitations



$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

Advantages

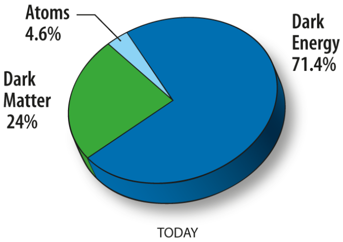
- Higgs boson prediction
- Observables well tested experimentally

Major problems

- Gravity not included
- Description of the visible matter only
- Neutrinos remain massless

Unexplained phenomena

Dark Matter nature unknown despite its abundance

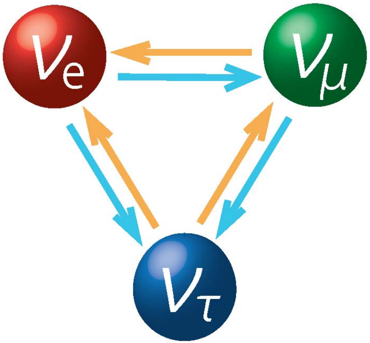


Planck measurements[a] :

$$\Omega h^2 = 0.1200 \pm 0.0012$$

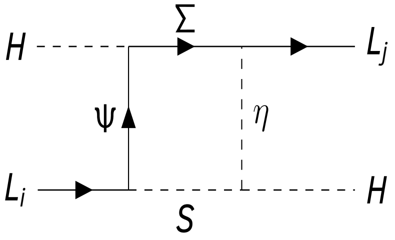
[a] arXiv:1807.06209v4

Neutrino oscillations linked to them having a mass



$$P(\nu_i \longleftrightarrow \nu_j) \propto \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

T12G topology



	Ψ_1	Ψ_2	Σ_1	Σ_2	S	η
$SU(3)_C$	1	1	1	1	1	1
$SU(2)_L$	2	2	3	3	1	2
$U(1)_Y$	1	-1	0	0	0	1
$[M]$	$3/2$	$3/2$	$3/2$	$3/2$	1	1

Same gauge symmetry as SM

Addition of an extra symmetry $\mathbb{Z}_2$:

SM particles are even under this symmetry

BSM particles are odd

Why this topology?

- T12A topology already been studied by Björn Herrmann and Maud Sarazin
- T12A model only allows for 2 neutrino masses to be generated
- Variant of T12A with extra fermion singlet can generate 3 neutrino masses
- Phenomenology of a fermion singlet F has been studied so now we wanted to study the one of a fermion triplet

Lagrangian of our model

$$-\mathcal{L}_{\text{scalar}} \supset M_H^2|H|^2 + \lambda_H|H|^4 + \frac{1}{2}M_S^2 S^2 + \frac{1}{2}\lambda_{4S}S^4 + M_\eta^2|\eta|^2 + \lambda_{4\eta}|\eta|^4$$
$$+ \frac{1}{2}\lambda_S S^2|H|^2 + \lambda_\eta|\eta|^2|H|^2 + \frac{1}{2}\lambda_{S\eta}S^2|\eta|^2 + \lambda_\eta'|\eta^\dagger H|^2$$
$$+ \frac{1}{2}\lambda_\eta''\left(\left(\eta^\dagger H\right)^2 + \text{h.c.}\right) + \kappa\left(S\eta^\dagger H + \text{h.c.}\right)$$
$$-\mathcal{L}_{\text{fermion}} \supset \frac{1}{2}M_{\Sigma_1}\overline{\Sigma}_1\Sigma_1 + \frac{1}{2}M_{\Sigma_2}\overline{\Sigma}_2\Sigma_2$$
$$+ M_\Psi\Psi_1\Psi_2 + y_{1j}\Psi_1\Sigma_j H + y_{2j}\overline{\Psi}_2\Sigma_j H$$
$$+ g_\Psi^k\Psi_2 L_k S + g_{\Sigma_j}^k\eta\Sigma_j L_k + g_R^k\tilde{\eta}\Psi_1 e_k^c + \text{h.c.}$$

MCMC algorithm

36 parameters to scan in the MCMC algorithm $\Longrightarrow$ consequent computational time to scan a 36-D hypercube

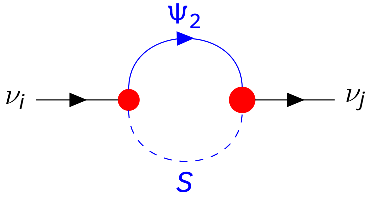
Use of Casas-Ibarra parametrization to take in account experimental constraints in neutrino sector

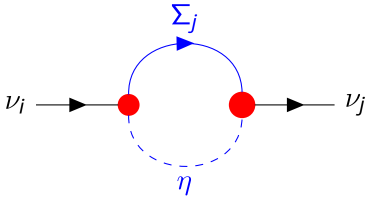
Likelihood computed as $\mathcal{L}_n = \prod_i \mathcal{L}_i^n$ with $\ln\left(\mathcal{L}_i^n\right) = -\frac{\left(\mathcal{O}_i^n - \mathcal{O}_i^{\text{exp}}\right)^2}{2\sigma_i^2}$

33 experimental constraints were taken in account

Observables computed thanks to **SPheno** and **micrOMEGAs**

Advantages: mass generation of 3 neutrinos





Couplings determined thanks

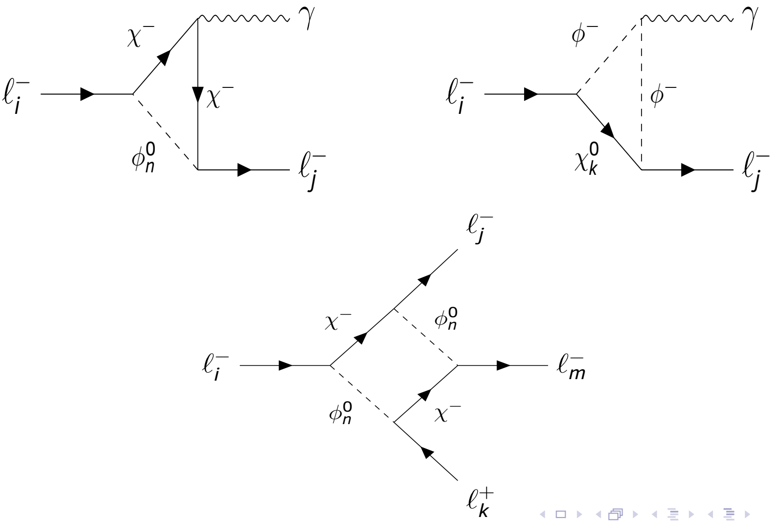
to Casas-Ibarra parametrization

$$M_\nu = \mathcal{G}^t M_L \mathcal{G}$$

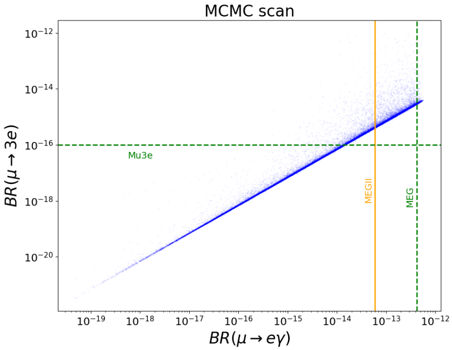
$$\mathcal{G} = \begin{pmatrix} g^e_\Psi & g^\mu_\Psi & g^\tau_\Psi \\ g^e_{\Sigma_1} & g^\mu_{\Sigma_1} & g^\tau_{\Sigma_1} \\ g^e_{\Sigma_2} & g^\mu_{\Sigma_2} & g^\tau_{\Sigma_2} \end{pmatrix}$$

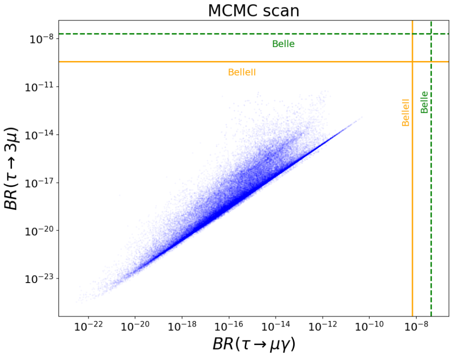
Constraints: Lepton Flavor Violation

$$-\mathcal{L}_{\text{fermion}} \supset g_R^k e_k^c \tilde{\eta} \Psi_1 + (g_\Psi^k \Psi_2 L_k S + g_{\Sigma_j}^k \eta \Sigma_j L_k)$$



Constraints: Lepton Flavor Violation



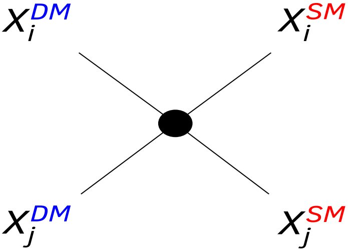


Advantages: stability of Dark Matter particle

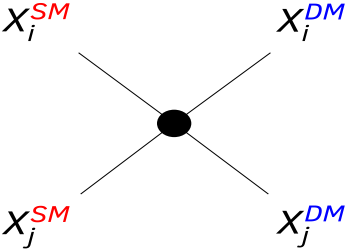
Boltzmann equation in FLRW model

$$\frac{dn}{dt} + 3Hn = -\langle \sigma v \rangle \left(n^2 - (n^{\mathrm{eq}})^2 \right)$$

with $\Omega h^2 = \frac{n m_{\mathrm{DM}}}{\rho_c}$

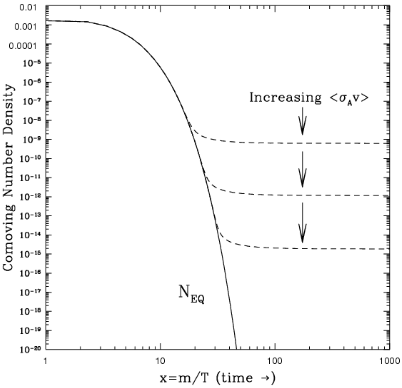


Freeze-out process

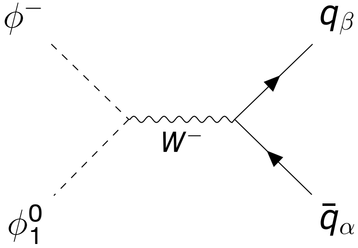


Freeze-in process

Satisfying DM relic density



Coannihilations



$$\left(\phi_1^0, \phi_2^0, A^0\right) = U_\phi \left(S, \eta^0, A^0\right)$$

$$\frac{dn}{dt} = -3Hn - \sum_{i,j=1}^{N} \langle \sigma_{ij} v_{ij} \rangle \left(n_i n_j - n_i^{eq} n_j^{eq}\right)$$

Diagonalization of mass matrices

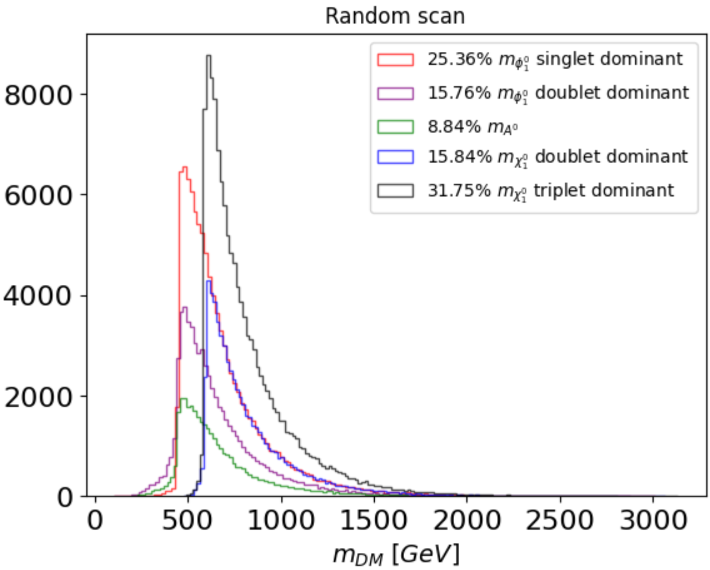
$$\mathcal{M}_{\chi^0} = \begin{pmatrix} M_{\Sigma_1} & 0 & \frac{v}{\sqrt{2}}y_{11} & \frac{v}{\sqrt{2}}y_{21} \\ 0 & M_{\Sigma_2} & \frac{v}{\sqrt{2}}y_{12} & \frac{v}{\sqrt{2}}y_{22} \\ \frac{v}{\sqrt{2}}y_{11} & \frac{v}{\sqrt{2}}y_{12} & 0 & M_\Psi \\ \frac{v}{\sqrt{2}}y_{21} & \frac{v}{\sqrt{2}}y_{22} & M_\Psi & 0 \end{pmatrix}$$

$$\Longrightarrow \boxed{\left(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0\right) = U_\chi \left(\Sigma_1^0, \Sigma_2^0, \Psi_1^0, \Psi_2^0\right)}$$

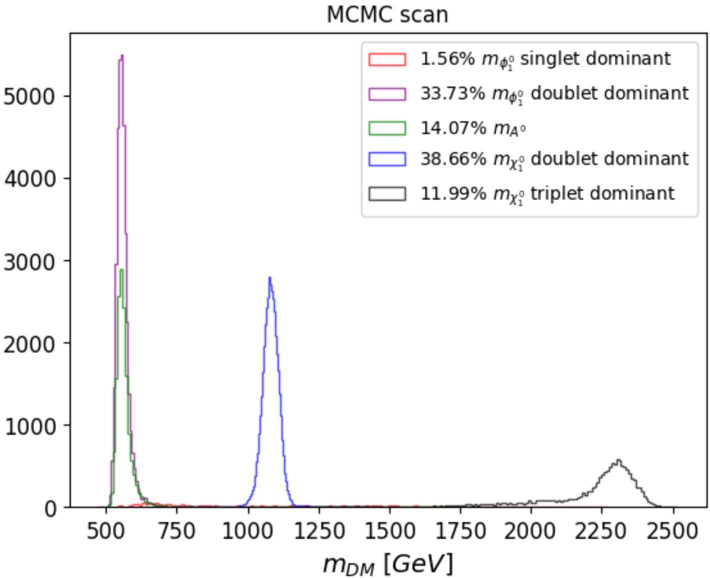
$$\mathcal{M}^2_{\phi^0} = \begin{pmatrix} M_S^2 + \frac{1}{2}v^2\lambda_S & v\kappa & 0 \\ v\kappa & M_\eta^2 + \frac{1}{2}v^2\lambda_L & 0 \\ 0 & 0 & M_\eta^2 + \frac{1}{2}v^2\lambda_A \end{pmatrix}$$

$$\Longrightarrow \boxed{\left(\phi_1^0, \phi_2^0, A^0\right) = U_\phi \left(S, \eta^0, A^0\right)}$$

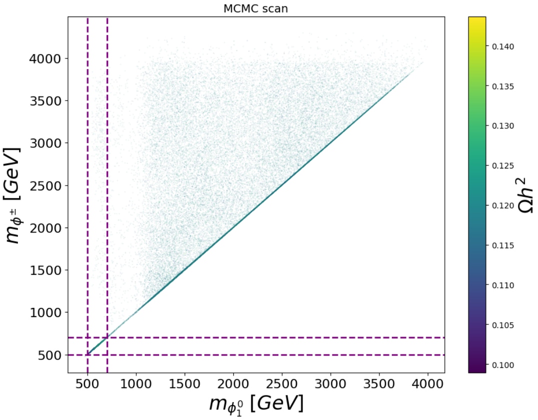
Dark matter candidate



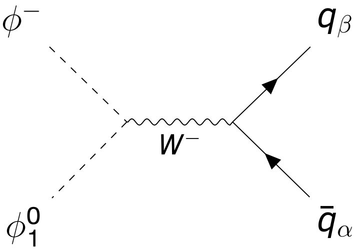
Dark matter candidate



Satisfying DM relic density: scalar sector



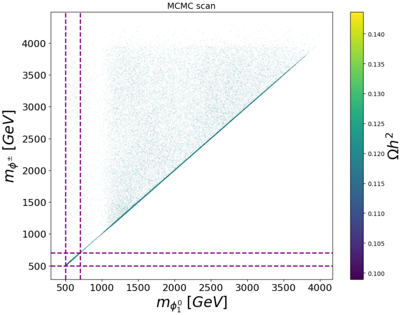
Coannihilations

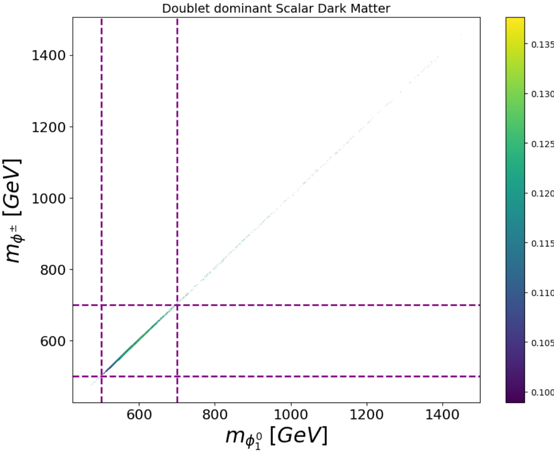


$$\left(\phi_1^0, \phi_2^0, A^0\right) = U_\phi \left(S, \eta^0, A^0\right)$$

$$\eta = \begin{pmatrix} \eta^+ \\ \frac{1}{\sqrt{2}}\left(\eta^0 + iA^0\right) \end{pmatrix}$$

Satisfying DM relic density: scalar sector





Satisfying DM relic density: fermion sector

More sources of Coannihilations processes
Direct impact on triplet mass

Coannihilations

$$\boxed{\left(\chi_1^0, \chi_2^0, \chi_3^0, \chi_4^0\right) = U_{\chi^0}\left(\Sigma_1^0, \Sigma_2^0, \Psi_1^0, \Psi_2^0\right)}$$

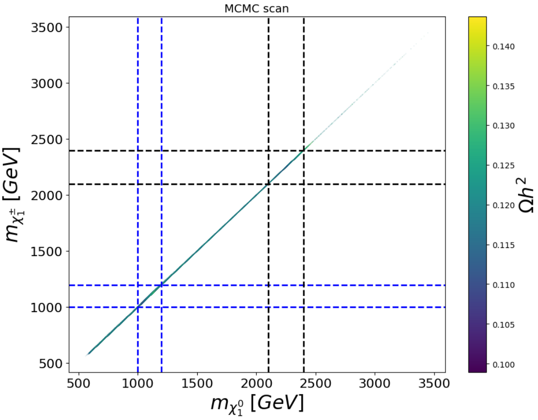
$$\boxed{\left(\chi_1^+, \chi_2^+, \chi_3^+\right) = U_{\chi^+}\left(\Sigma_1^+, \Sigma_2^+, \Psi_2^+\right)}$$

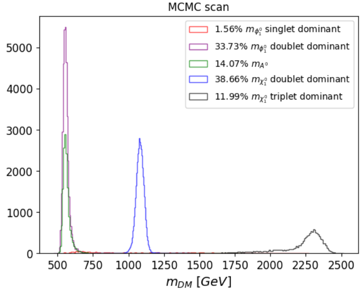
$$\boxed{\left(\chi_1^-, \chi_2^-, \chi_3^-\right) = U_{\chi^-}\left(\Sigma_1^-, \Sigma_2^-, \Psi_1^-\right)}$$

$$\Sigma_j = \begin{pmatrix} \frac{\Sigma_j^0}{\sqrt{2}} & \Sigma_j^+ \\ \Sigma_j^- & -\frac{\Sigma_j^0}{\sqrt{2}} \end{pmatrix}$$

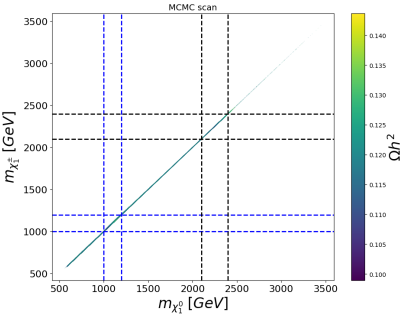
$$\Psi_1 = \begin{pmatrix} \Psi_1^0 \\ \Psi_1^- \end{pmatrix}, \Psi_2 = \begin{pmatrix} -\Psi_2^+ \\ \Psi_2^0 \end{pmatrix}$$

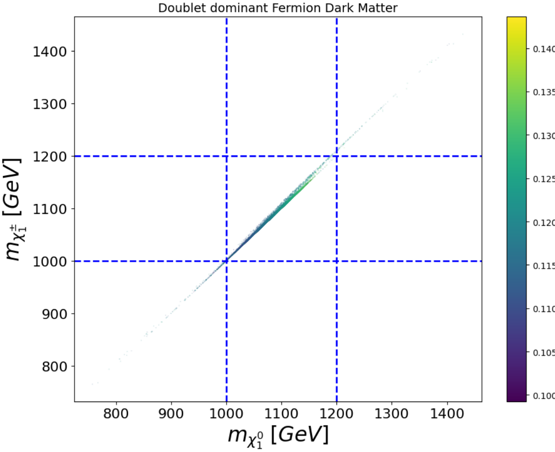
Satisfying DM relic density: fermion sector



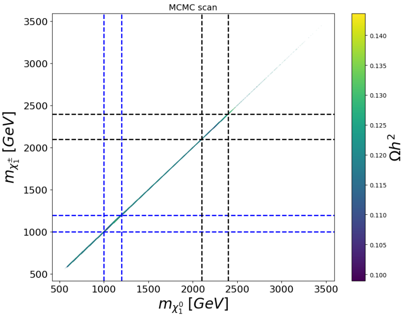


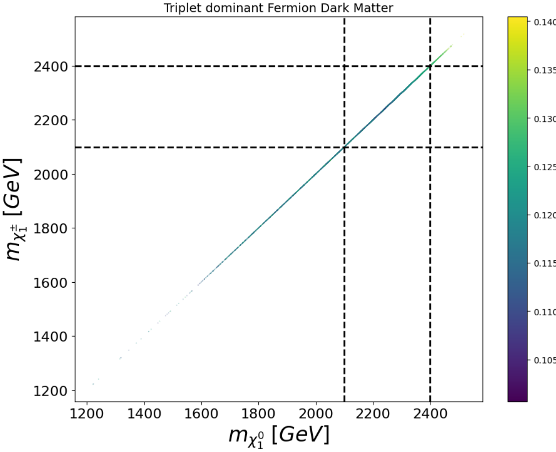
Satisfying DM relic density: fermion sector





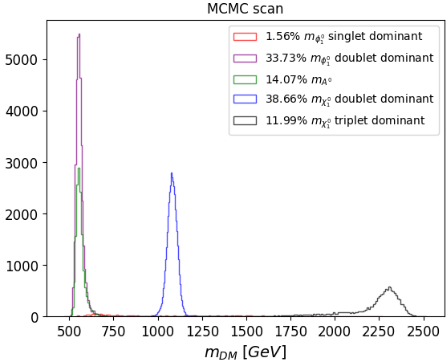
Satisfying DM relic density: fermion sector





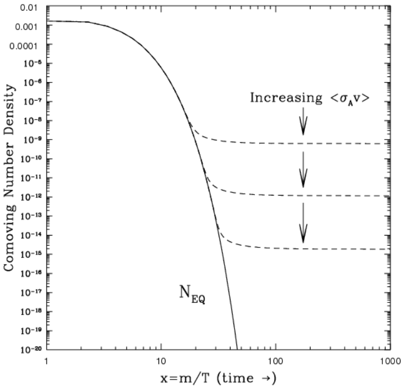
Summary

- Extension of SM that deals with DM and neutrino masses
- Regions in parameter space satisfying major constraints (DM relic density, direct detection, Higgs mass, neutrino mass differences, LFV)
- Mass of BSM particles are reachable at the LHC



Thanks for your attention

Details on Freeze-out



Features

- DM in thermal equilibrium with thermal bath deep within the radiation-dominated epoch
- as $\Gamma \lesssim H$ DM decouples first chemically and then kinematically from the thermal bath
- Correct relic density can be reached by different ways

Casas-Ibarra parametrization

- Diagonalization of the neutrino mass matrix by the PMNS matrix $M_\nu = V^\dagger_{\text{PMNS}} D_\nu V^*_{\text{PMNS}}$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix expresses the mismatch between the rotations of the LH charged leptons and the neutrinos

$$V_{\text{PMNS}} = V^\dagger_{eL} V_{\nu L}$$

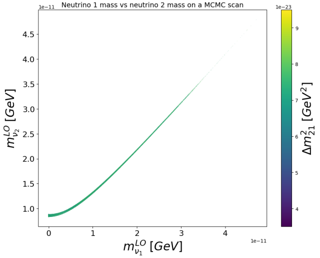
- Decomposition of neutrino mass matrix in different terms $M_\nu = \mathcal{G}^t M_L \mathcal{G}$

Combining those two statements leads to

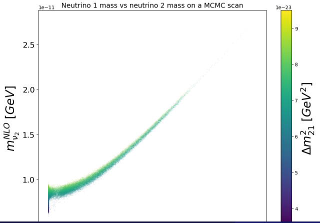
$$\boxed{\mathcal{G} = U_L D_L^{-1/2} R D_\nu^{1/2} V^*_{\text{PMNS}}}$$

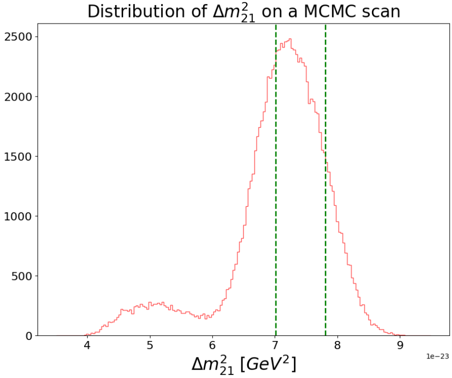
with $R^t R = R R^t = \mathbb{I}_3$

At LO level



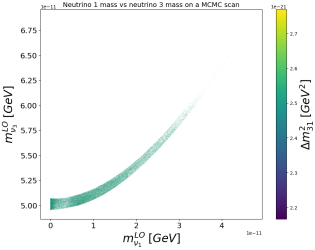
At NLO level



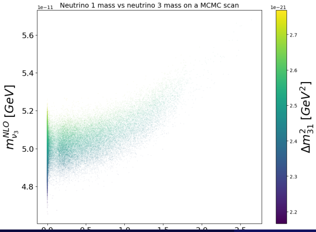


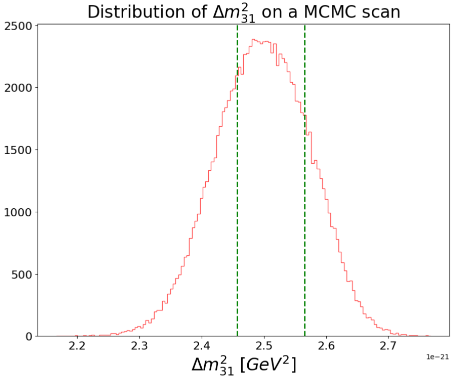
Second bump might be linked to loop corrections

At LO level



At NLO level





Clean peak