FLASY 2022 Workshop

Lisboa, Portugal, 27 June – 1 July, 2022

Flavour and dark matter in a hybrid seesaw/scotogenic model

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Motivation

The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
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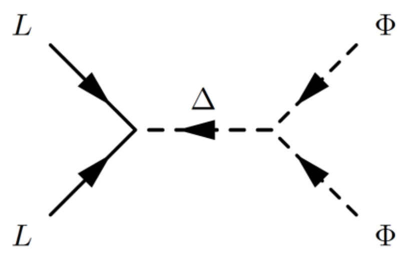
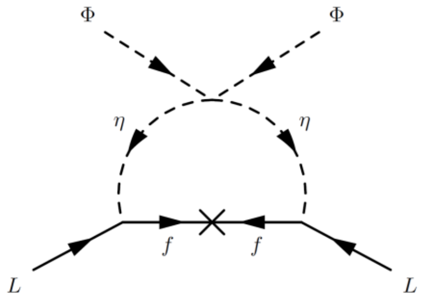
Konetschny *et al.* (1977), Cheng *et al.* (1980), Lazarides *et al.* (1981), Valle *et al.* (1980), Magg *et al.* (1980), Mohapatra *et al.* (1981)



Scotogenic Model

Ma (2006)



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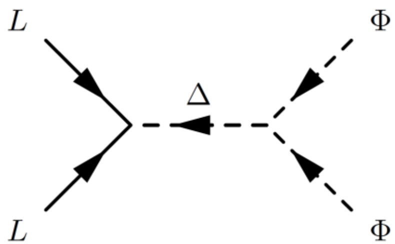

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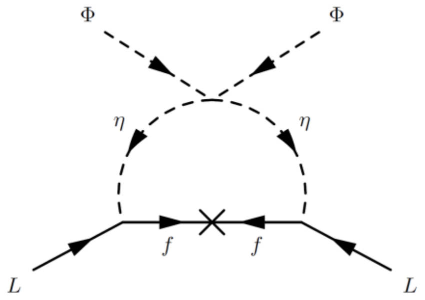

Our approach:

Model where **both mechanisms** contribute to neutrino masses with a **single discrete symmetry** to accommodate: **spontaneous CP violation**, **neutrino oscillation data** and **dark matter stability**

Scoto/type-II seesaw model

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Particle content and flavour symmetry:

	Fields	$\mathrm{SU}(2)_\mathrm{L} \otimes \mathrm{U}(1)_\mathrm{Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
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Vacuum configuration

$$\langle \phi^0 \rangle = \frac{v}{\sqrt{2}} \, , \; \langle \eta^0_{1,2} \rangle = 0 \, , \; \langle \Delta^0 \rangle = \frac{w}{\sqrt{2}} \, , \; \langle \sigma \rangle = \frac{u \, e^{i\theta}}{\sqrt{2}}$$

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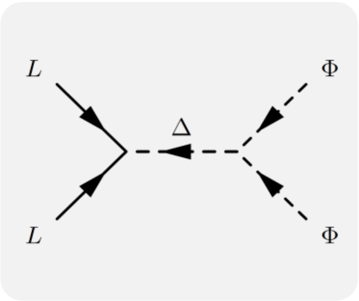
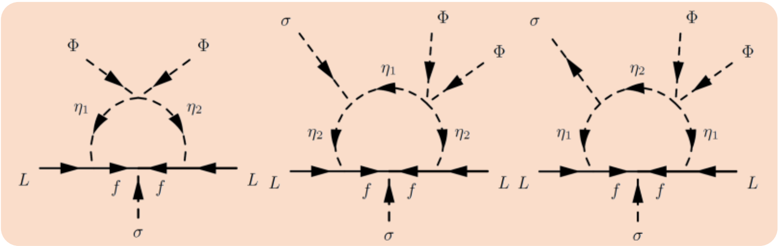


Type-II seesaw



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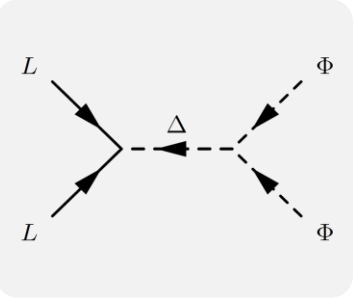

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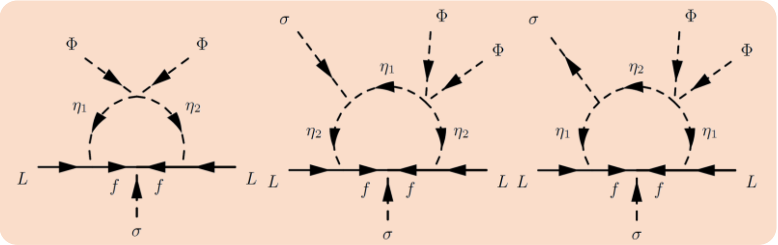

Scotogenic

Effective neutrino mass matrix

$$\mathrm{M}_\nu = \begin{pmatrix} \mathcal{F}_{11} M_f\, y_e^2 + \sqrt{2} w\, y_1\, e^{-i\theta} & \mathcal{F}_{12} M_f\, y_e y_\mu & 0 \\ \cdot & \mathcal{F}_{22} M_f\, y_\mu^2 & \sqrt{2} w\, y_2 e^{-i\theta} \\ \cdot & \cdot & 0 \end{pmatrix}$$

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- Lagrangian is required to be CP invariant: CP is **spontaneously broken** by the **complex VEV** of σ and is **successfully** transmitted to the leptonic sector
- New Z_8 symmetry leads to **low-energy predictions** for neutrino mass and mixing parameters
- Presence of **dark particles** (odd under remnant Z_2 after SSB): **fermion f** and **scalars $\eta_{1,2}$**

Spontaneous CP violation and neutrino data

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Scalar potential contains:

$$V_\sigma = m_\sigma^2 \, |\sigma|^2 + \frac{\lambda_\sigma}{2} \, |\sigma|^4 + m_\sigma'^2 \left(\sigma^2 + \sigma^{*2}\right) + \frac{\lambda'_\sigma}{2} \left(\sigma^4 + \sigma^{*4}\right)$$

CPV solution to the minimisation conditions

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High-energy parameters

The presence of **two texture zeros in the neutrino mass matrix** leads to **testable low-energy constraints**

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix},$$

$$\mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix},$$

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Alcaide, Salvado, Santamaria (2018)

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$\Longleftrightarrow$ **Matching**

$$\widehat{\mathbf{M}}_\nu = \mathbf{U}^* \,\mathrm{diag}(m_1, m_2, m_3)\, \mathbf{U}^\dagger$$

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Lepton mixing: Rodejohann, Valle (2011)

$$\mathbf{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix}$$

Normal Ordering (NO):

$$m_1 = m_{\text{lightest}},\ m_2 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2},\ m_3 = \sqrt{m_{\text{lightest}}^2 + \Delta m_{31}^2}$$

$$m_{\beta\beta} = \left| c_{12}^2 c_{13}^2\, m_1 + s_{12}^2 c_{13}^2\, m_2\, e^{-i\alpha_{21}} + s_{13}^2\, m_3\, e^{-i\alpha_{31}} \right|$$

Global fit of neutrino oscillation data

Salas *et al.* (2020), Esteban *et al.* (2020), Capozzi *et al.* (2021)

Neutrino sector predictions

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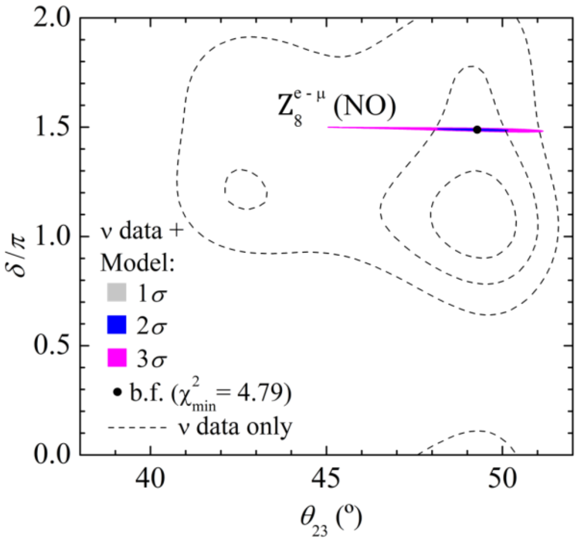
δ and θ_{23}



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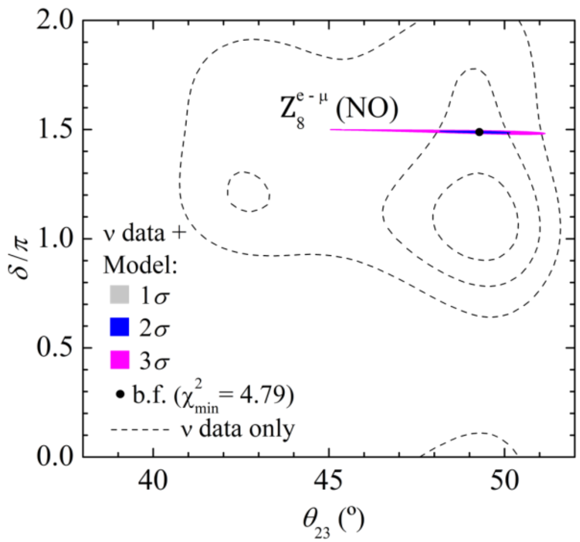

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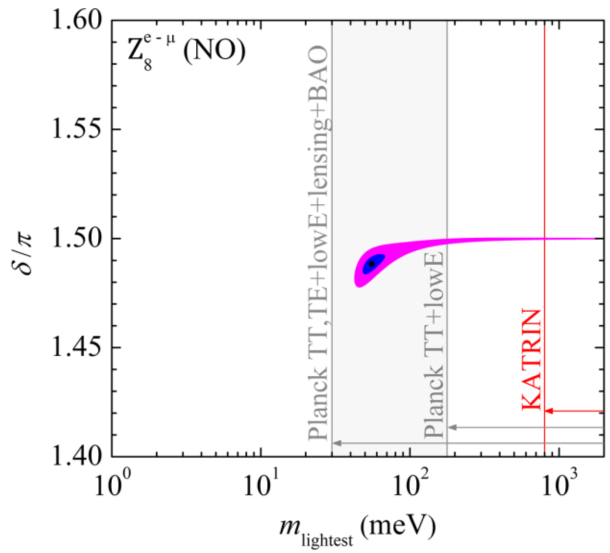
Lightest neutrino mass



- Lower limit ~ 40 meV (3 σ) **now being probed by cosmology**
- Upper limit ~ 60 meV (2 σ)

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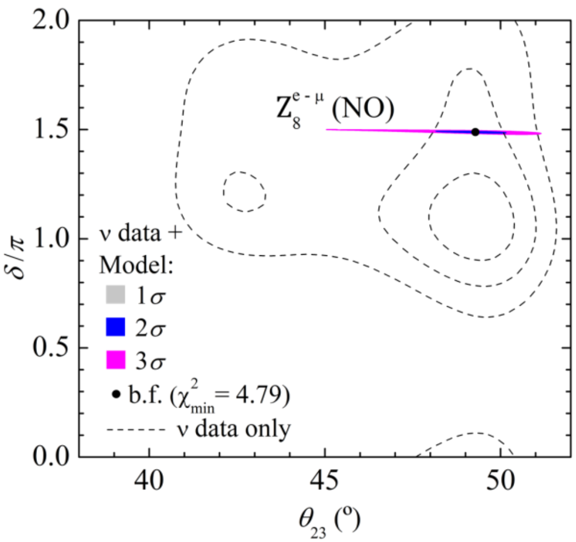

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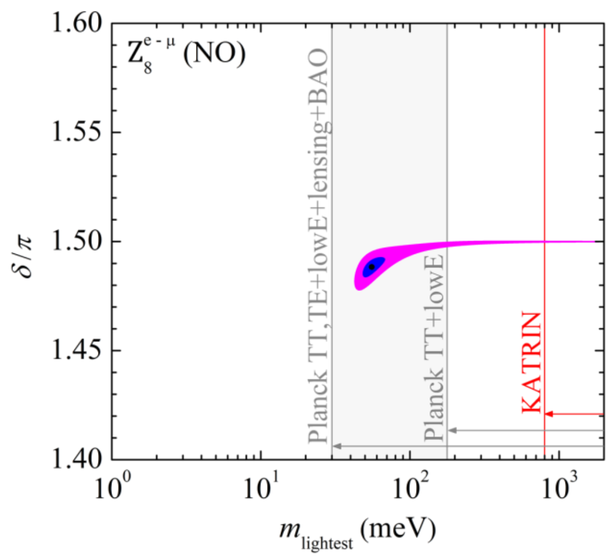

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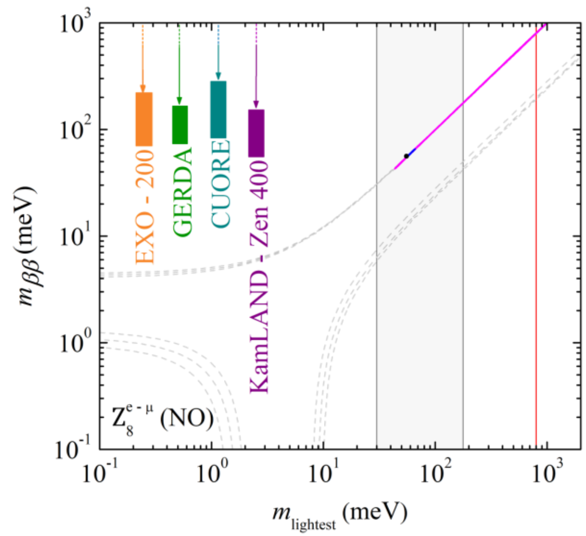

- Current KamLAND-Zen 400 almost excludes this case, will be **tested by near-future $0\nu\beta\beta$ experiments**

Charged-lepton flavour violation

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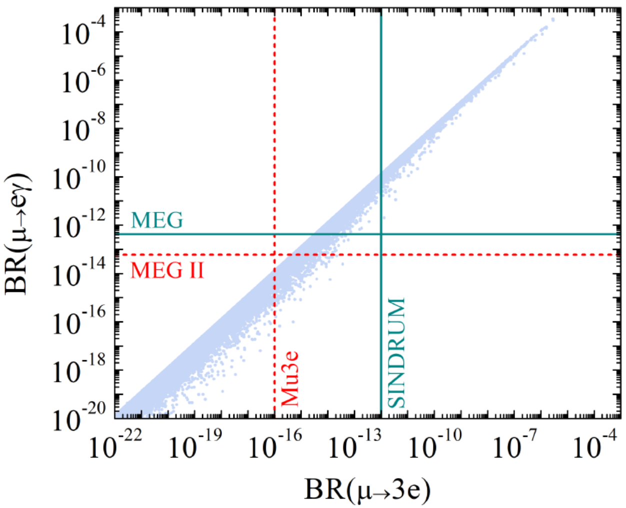

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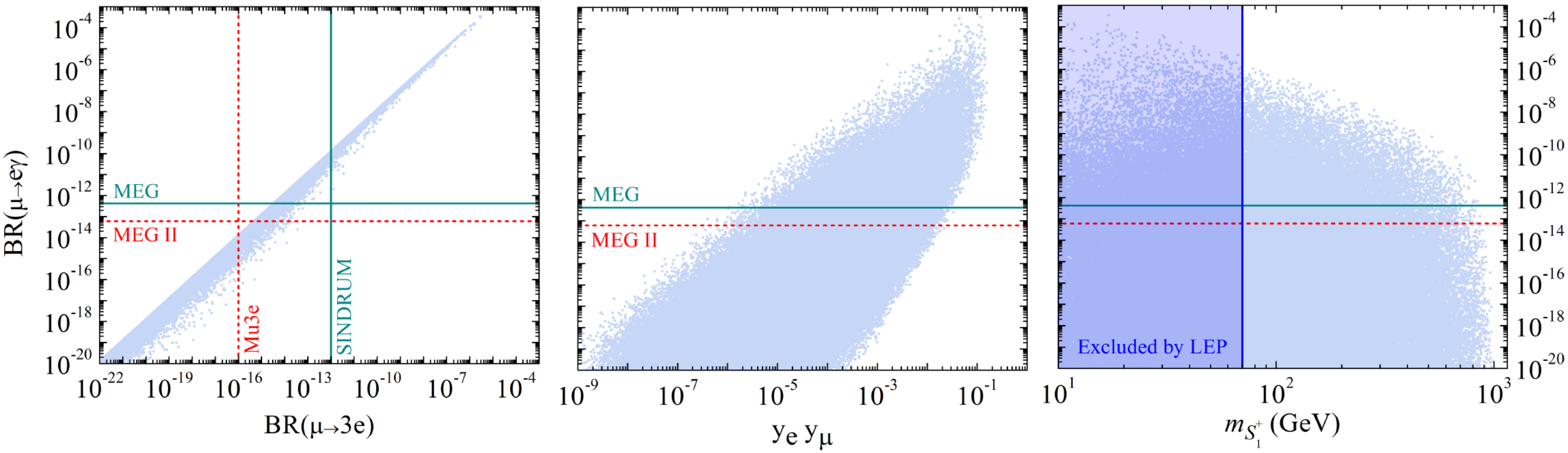


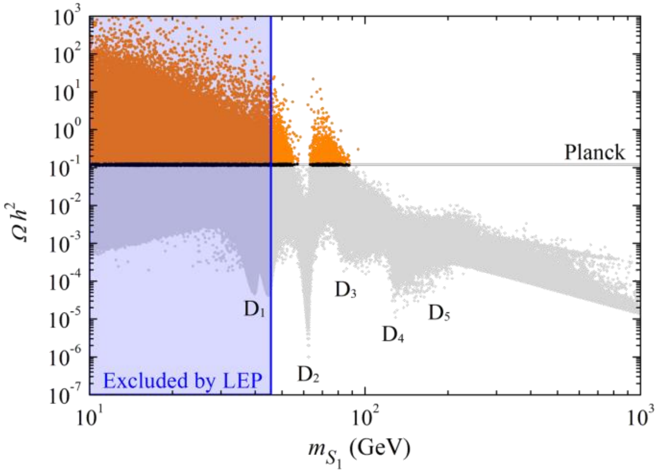
- Large fraction of **parameter space is excluded by current cLFV constraints**
- Scotogenic cLFV processes are **mediated at loop level by dark charged scalars**

$$\frac{\mathrm{BR}(\mu \to e\gamma)}{4.2 \times 10^{-13}} \approx 1.98 \times 10^{10} \left(\frac{70\ \mathrm{GeV}}{m_{S_1^+}}\right)^4 \sin^2(2\varphi) y_e^2 y_\mu^2 \left| g\left(\frac{M_f^2}{m^2_{S_1^+}}\right) - \frac{m^2_{S_1^+}}{m^2_{S_2^+}} g\left(\frac{M_f^2}{m^2_{S_2^+}}\right) \right|^2$$

Scalar Dark Matter

Scalar Dark Matter

Relic density

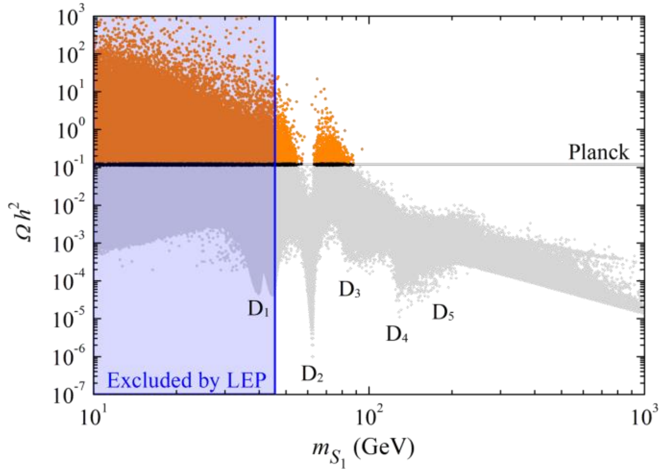


The case of **scalar DM:**

lightest neutral scalar S_1

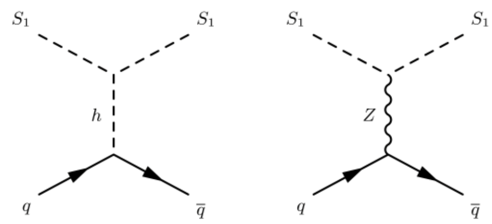
Scalar Dark Matter

Relic density

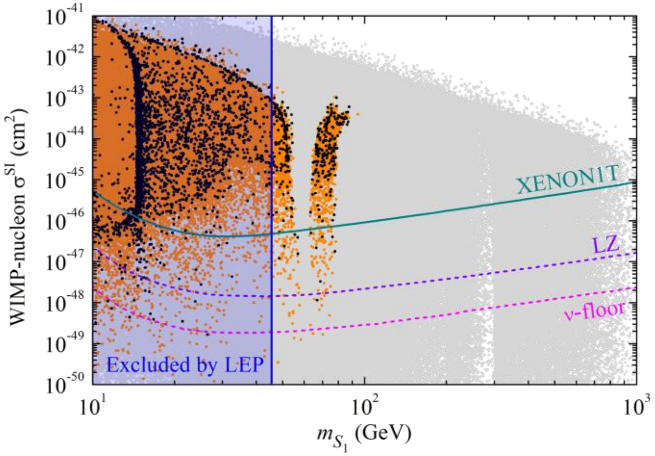


The case of **scalar DM:**

lightest neutral scalar S_1



WIMP-nucleon SI elastic cross-section



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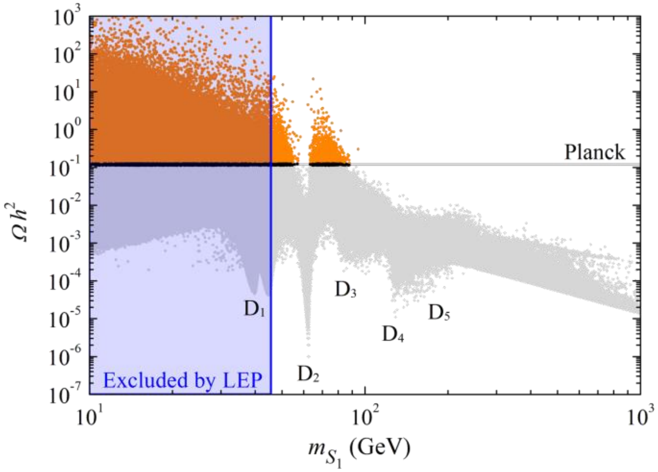

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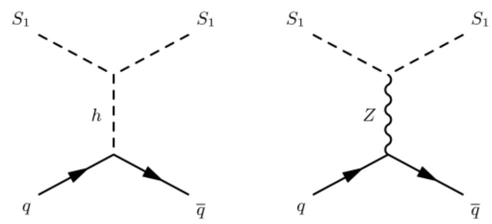

Direct Detection + LHC Higgs data

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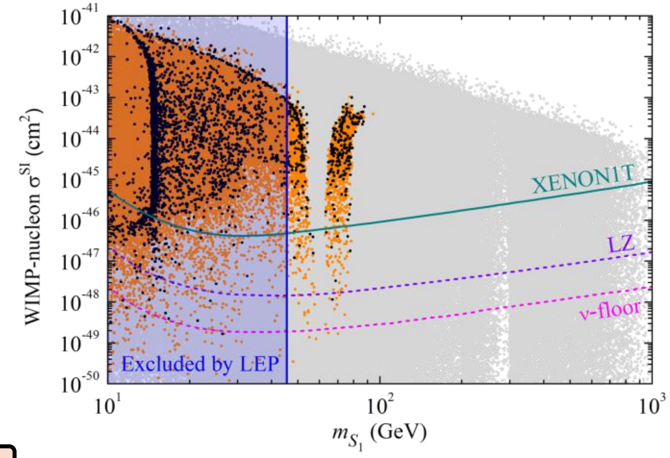

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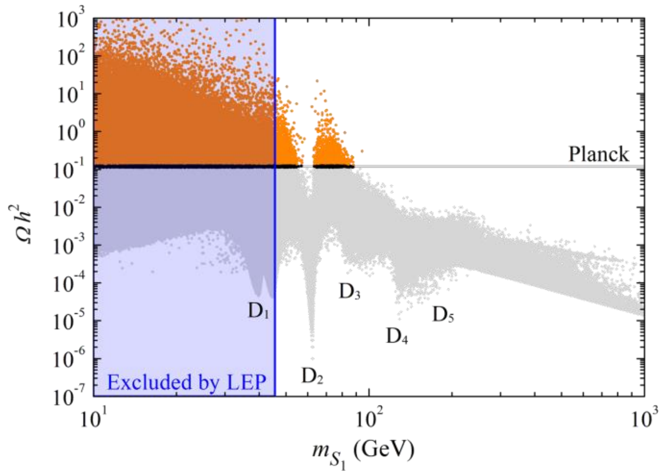

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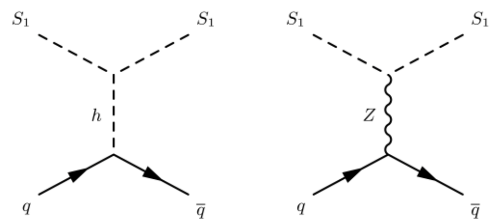

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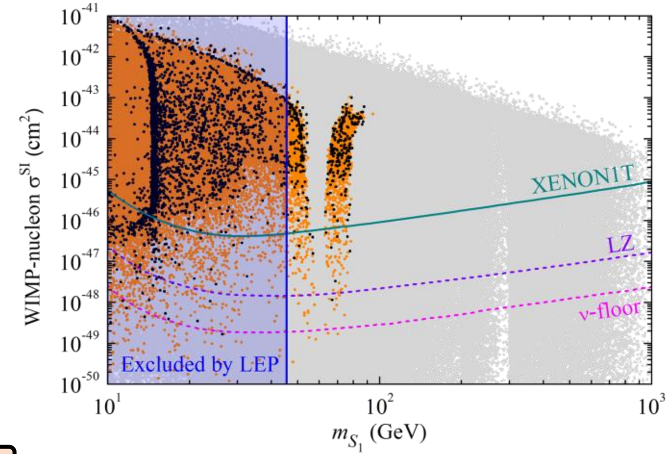
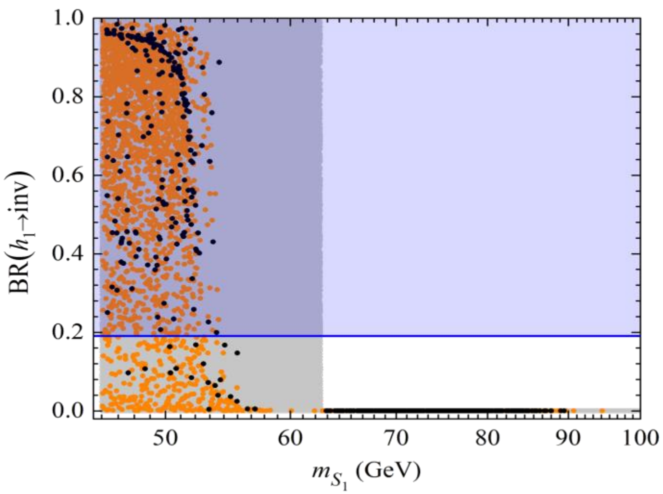


Direct Detection + LHC Higgs data

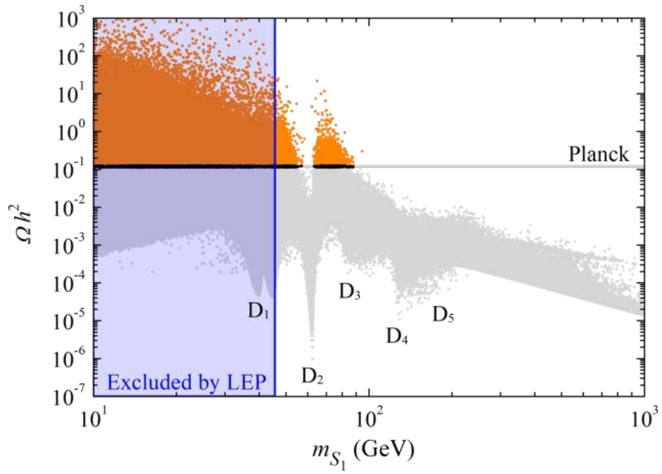
Higgs invisible decay



$$\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$$

Scalar Dark Matter

Relic density



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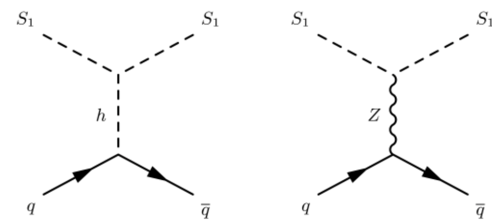

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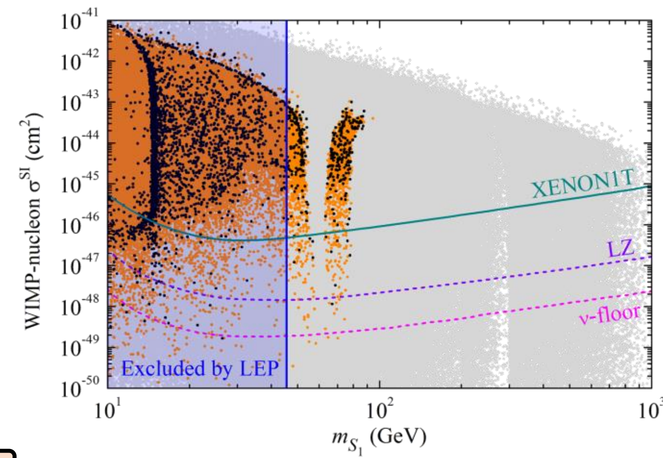

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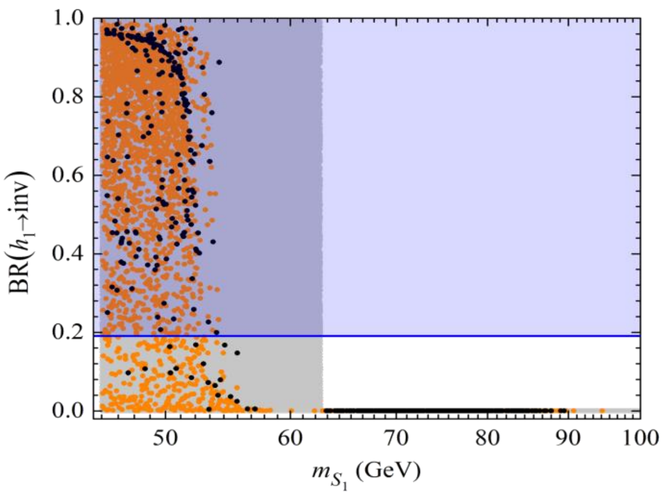

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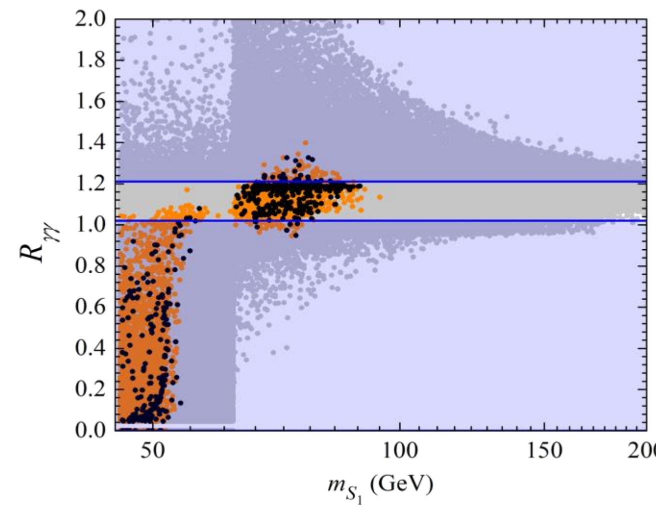
$$R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$$

Higgs to photon-photon



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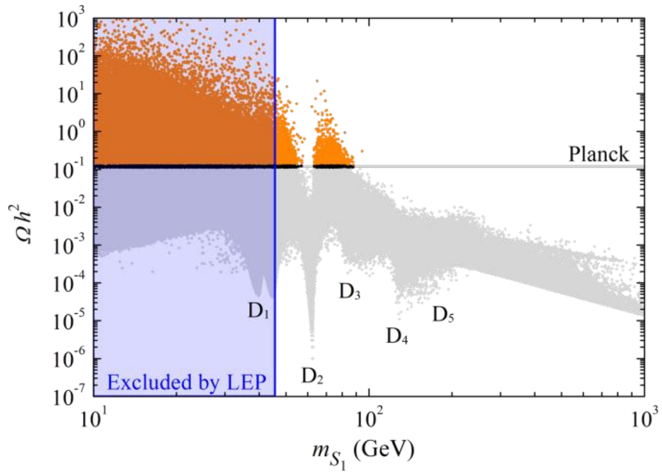

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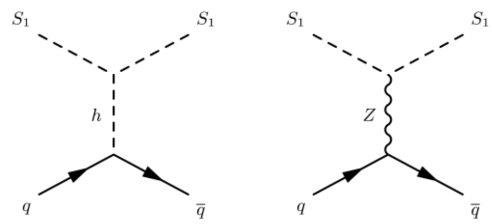

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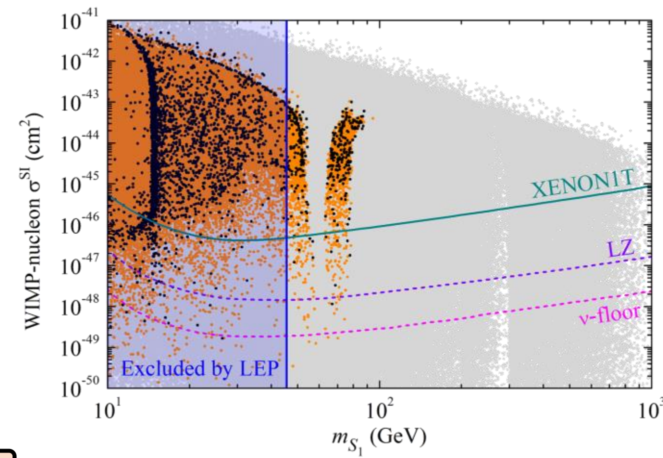

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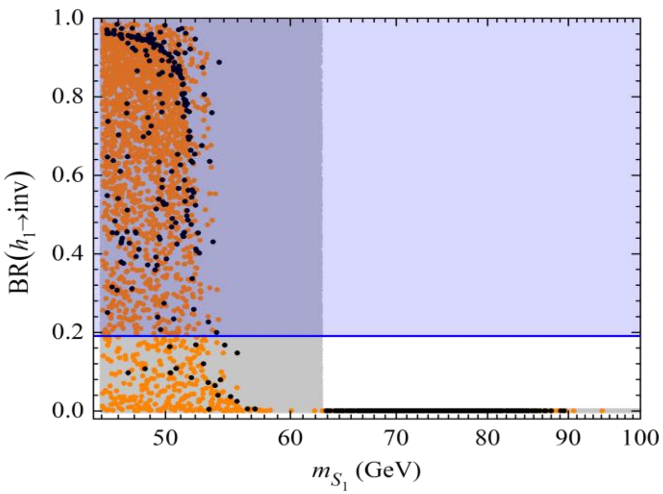

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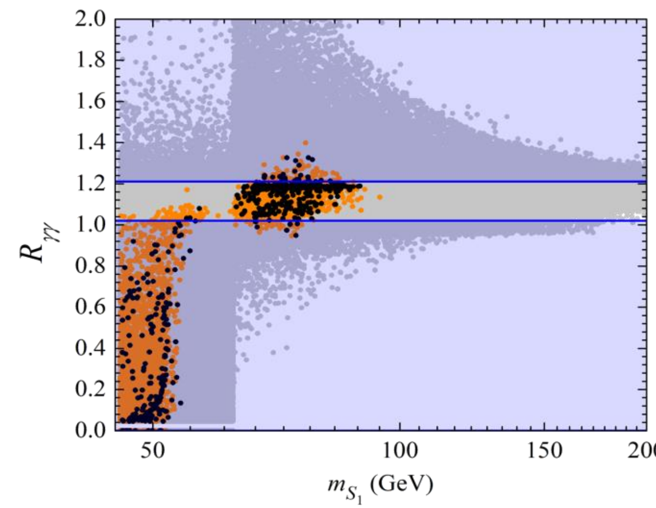

Fermion Dark Matter

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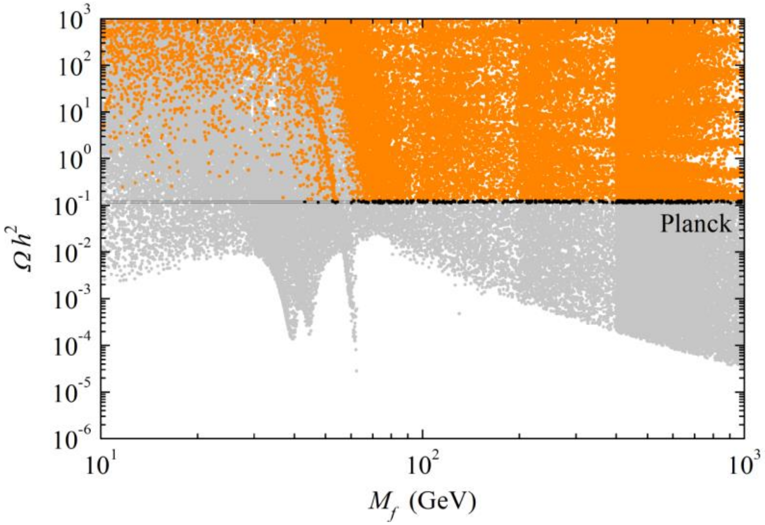

The case of **fermionic DM:**

fermion f

Allowed mass region:

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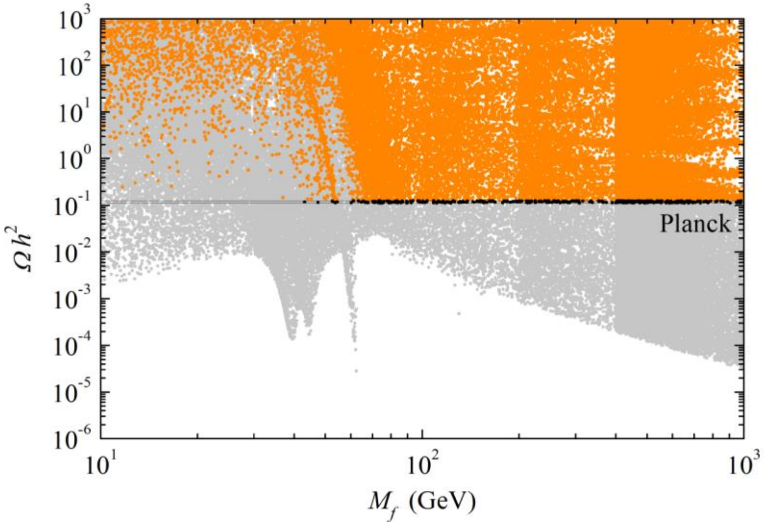
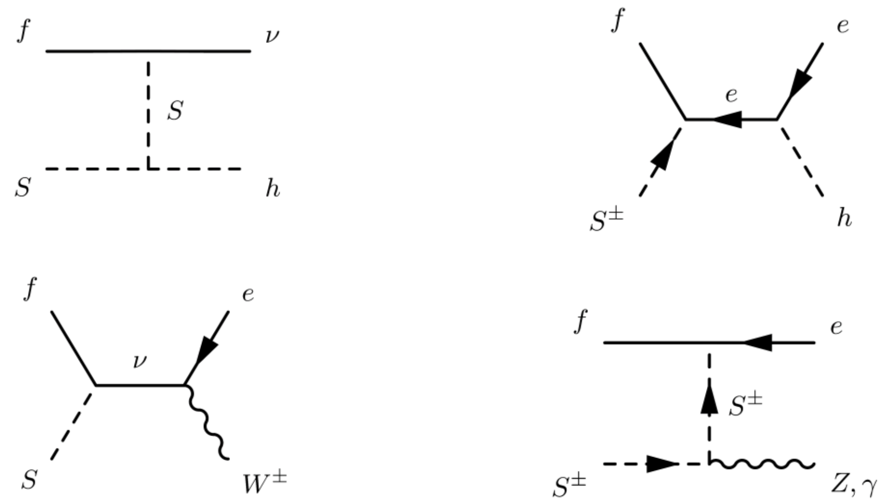
Fermion Dark Matter

Relic density



Co-annihilation channels, e.g. :



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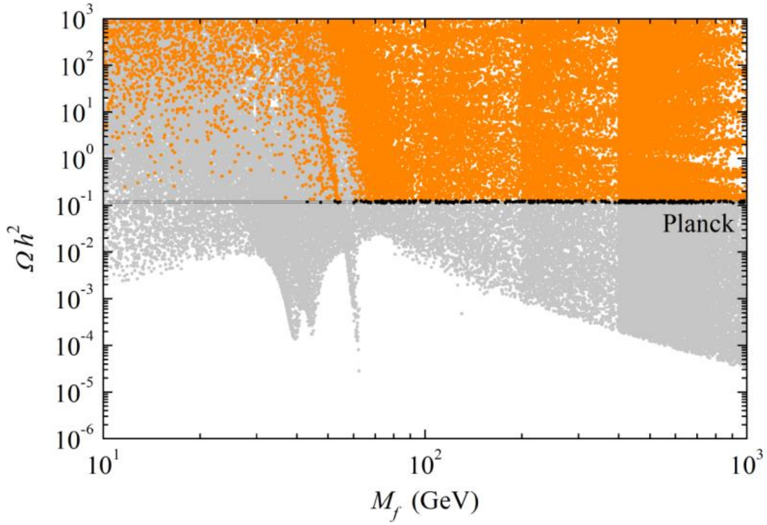

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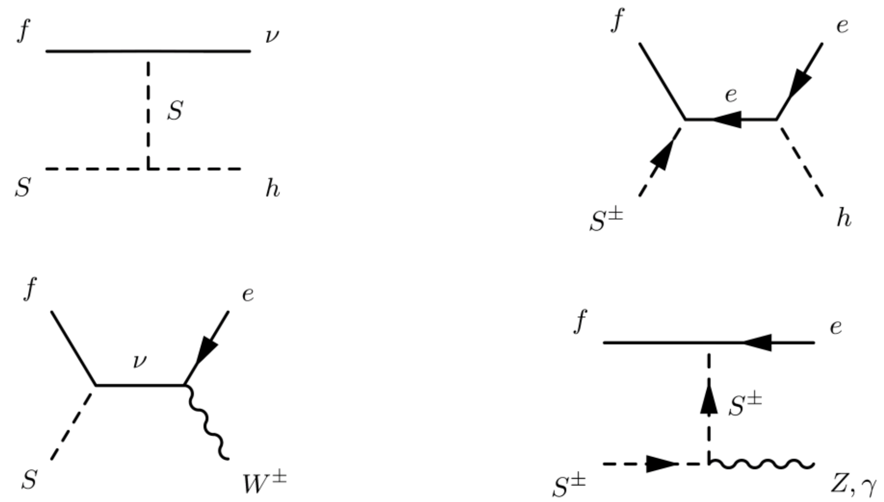

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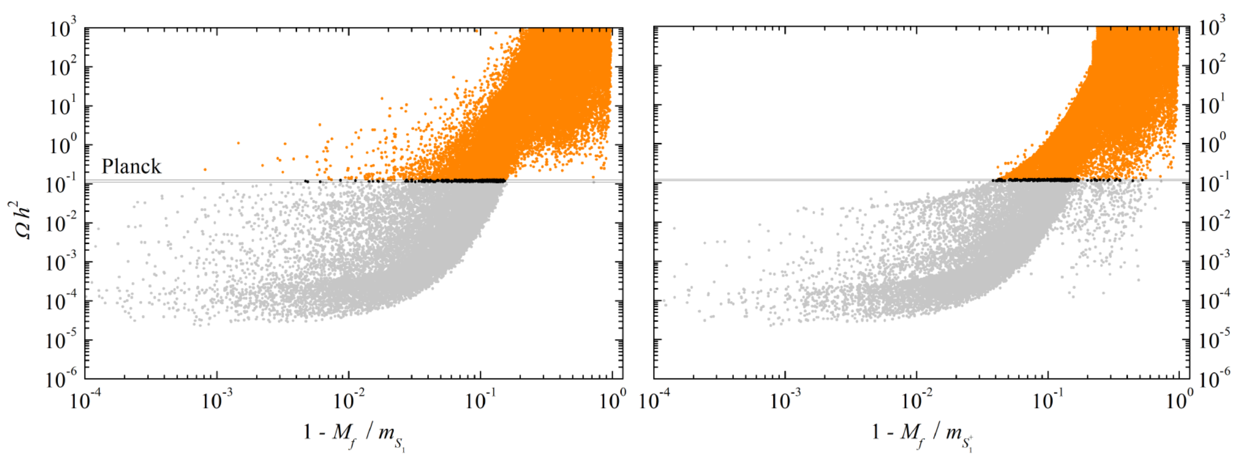

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