TÉCNICO LISBOA

Beyond the Standard Model BrainStorming Meeting

Gr@v Seminar

Aveiro, Portugal, 10-14 October, 2022

CFTP Centro de Física Teórica de Partículas

Flavour and dark matter in a scoto/seesaw model

Henrique Brito Câmara

henrique.b.camara@tecnico.ulisboa.pt

CFTP/IST, U. Lisbon

In collaboration with: D. M. Barreiros and F. R. Joaquim

arXiv: **2204.13605** [hep-ph]

JHEP 08 (2022) 030

FCT Fundação para a Ciência e a Tecnologia · PORTUGAL 2020 · REPÚBLICA PORTUGUESA · COMPETE 2020 · PROGRAMA OPERACIONAL CAPITAL HUMANO POCH

Motivation

Beyond the Standard Model

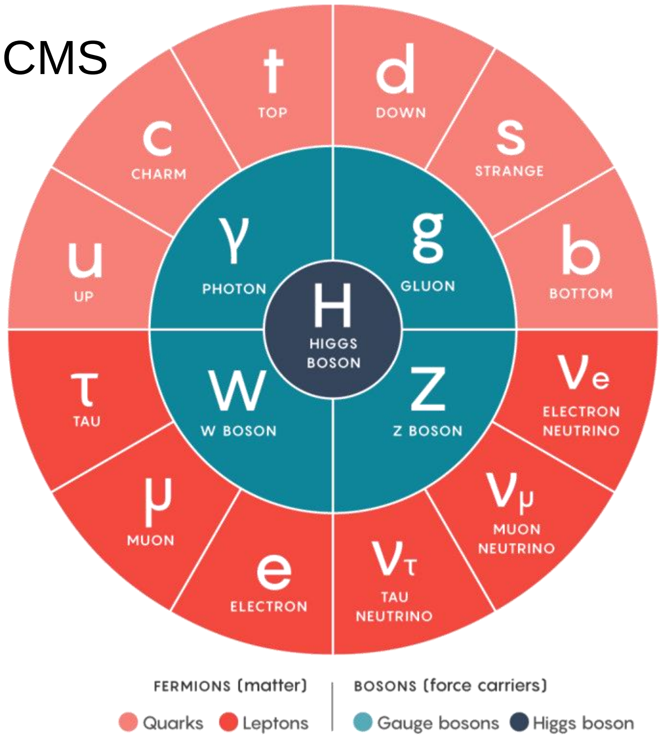
The Standard Model of Particle Physics

- Describes the strong, weak and electromagnetic interactions between fundamental particles,
- Provides predictions for numerous experimental observables which are in remarkable agreement with collected data,
- Discovery of Higgs boson in 2012 by ATLAS and CMS

collaborations at LHC completed the SM puzzle

The Standard Model of Particle Physics

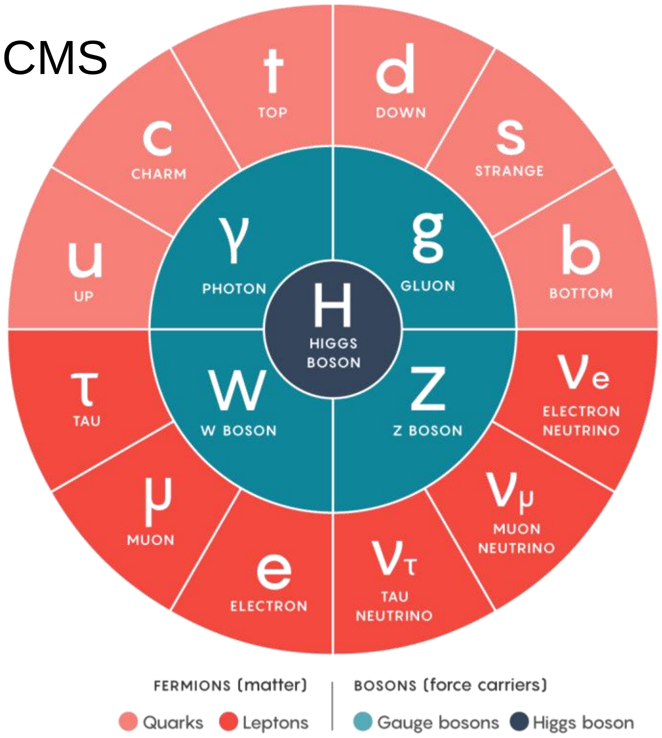
- Describes the strong, weak and electromagnetic interactions between fundamental particles,
- Provides predictions for numerous experimental observables which are in remarkable agreement with collected data,
- Discovery of Higgs boson in 2012 by ATLAS and CMS collaborations at LHC completed the SM puzzle



Beyond the Standard Model

The Standard Model of Particle Physics

- Describes the strong, weak and electromagnetic interactions between fundamental particles,
- Provides predictions for numerous experimental observables which are in remarkable agreement with collected data,
- Discovery of Higgs boson in 2012 by ATLAS and CMS collaborations at LHC completed the SM puzzle



Evidences for Physics beyond the SM

- Baryon asymmetry of the Universe,
- **Neutrino oscillations that imply massive neutrinos and lepton mixing,**
- **Dark matter.**

Neutrino oscillation data

Neutrino oscillation data

- Transition probability for flavour evolution in space-time:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{j,k} \mathbf{U}'^{*}_{\alpha j} \mathbf{U}'_{\beta j} \mathbf{U}'_{\alpha k} \mathbf{U}'^{*}_{\beta k} \exp\left(-i \frac{\Delta m^2_{jk} L}{2E}\right) \ , \ \Delta m^2_{jk} = m^2_j - m^2_k .$$

Neutrino oscillation data

- Transition probability for flavour evolution in space-time:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{j,k} \mathbf{U}'^{*}_{\alpha j}\mathbf{U}'_{\beta j}\mathbf{U}'_{\alpha k}\mathbf{U}'^{*}_{\beta k} \exp\left(-i\frac{\Delta m^2_{jk} L}{2E}\right) \;,\; \Delta m^2_{jk} = m^2_j - m^2_k .$$

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

Neutrino oscillation data

- Transition probability for flavour evolution in space-time:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{j,k} \mathbf{U}'^{*}_{\alpha j} \mathbf{U}'_{\beta j} \mathbf{U}'_{\alpha k} \mathbf{U}'^{*}_{\beta k} \exp\left(-i \frac{\Delta m^2_{jk} L}{2E}\right) \;,\; \Delta m^2_{jk} = m^2_j - m^2_k .$$

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

Global fit of neutrino oscillation data

Parameter	Best Fit $\pm 1\sigma$	3σ range
$\theta_{12}(^\circ)$	34.3 ± 1.0	$31.4 \to 37.4$
$\theta_{23}(^\circ)$[NO]	49.26 ± 0.79	$41.20 \to 51.33$
$\theta_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$	$41.16 \to 51.25$
$\theta_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\theta_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta(^\circ)$[NO]	194^{+24}_{-22}	$128 \to 359$
$\delta(^\circ)$[IO]	284^{+26}_{-28}	$200 \to 353$
$\Delta m^2_{21}\left(\times 10^{-5}\,\text{eV}^2\right)$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\text{eV}^2\right)$ [NO]	$2.55^{+0.02}_{-0.03}$	$2.47 \to 2.63$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\text{eV}^2\right)$ [IO]	$2.45^{+0.02}_{-0.03}$	$2.37 \to 2.53$

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

Neutrino oscillation data

- Transition probability for flavour evolution in space-time:

$$P\left(\nu_\alpha \to \nu_\beta\right) = \sum_{j,k} \mathbf{U}'^*_{\alpha j}\mathbf{U}'_{\beta j}\mathbf{U}'_{\alpha k}\mathbf{U}'^*_{\beta k} \exp\left(-i\frac{\Delta m^2_{jk}L}{2E}\right) \;,\; \Delta m^2_{jk} = m^2_j - m^2_k.$$

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

Global fit of neutrino oscillation data

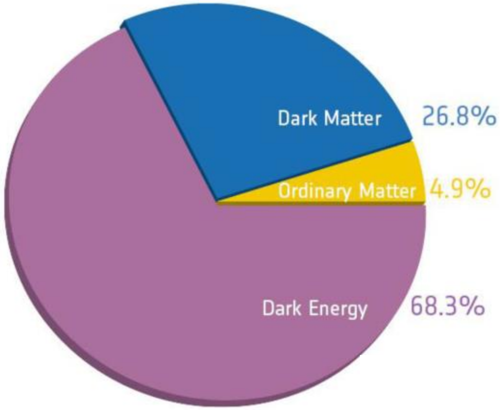
Parameter	Best Fit $\pm 1\sigma$	3σ range
$\theta_{12}(^\circ)$	34.3 ± 1.0	$31.4 \to 37.4$
$\theta_{23}(^\circ)$[NO]	49.26 ± 0.79	$41.20 \to 51.33$
$\theta_{23}(^\circ)$[IO]	$49.46^{+0.60}_{-0.97}$	$41.16 \to 51.25$
$\theta_{13}(^\circ)$[NO]	$8.53^{+0.13}_{-0.12}$	$8.13 \to 8.92$
$\theta_{13}(^\circ)$[IO]	$8.58^{+0.12}_{-0.14}$	$8.17 \to 8.96$
$\delta(^\circ)$[NO]	194^{+24}_{-22}	$128 \to 359$
$\delta(^\circ)$[IO]	284^{+26}_{-28}	$200 \to 353$
$\Delta m^2_{21}\left(\times 10^{-5}\,\text{eV}^2\right)$	$7.50^{+0.22}_{-0.20}$	$6.94 \to 8.14$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\text{eV}^2\right)$ [NO]	$2.55^{+0.02}_{-0.03}$	$2.47 \to 2.63$
$\lvert\Delta m^2_{31}\rvert\left(\times 10^{-3}\,\text{eV}^2\right)$ [IO]	$2.45^{+0.02}_{-0.03}$	$2.37 \to 2.53$

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

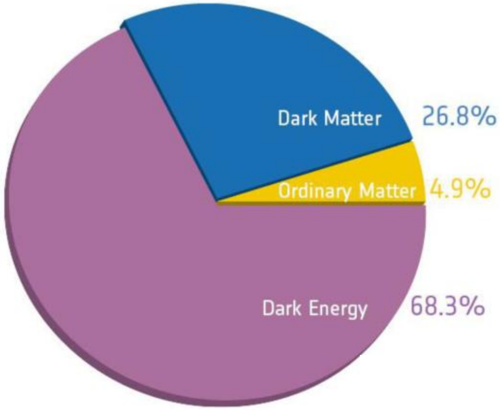
- **Open questions in neutrino physics:**

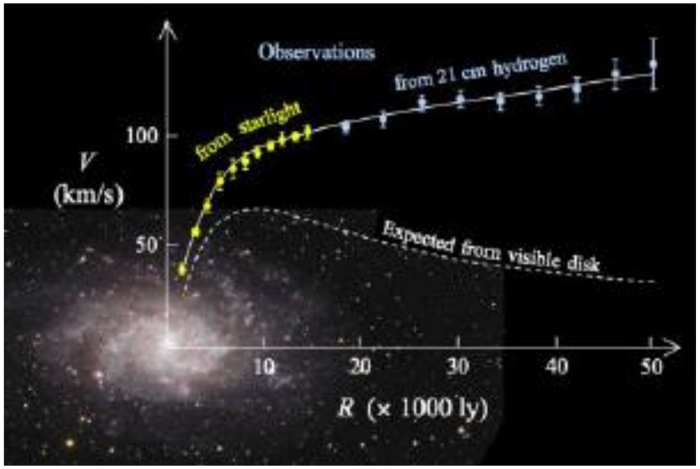
  - **What is the absolute neutrino mass scale ?**
  - **The mass ordering ?**
  - **Is there leptonic CP violation ?**
  - **Are neutrinos Majorana or Dirac fermions ?**
  - **How can we explain the tiny neutrino masses ?**
  - **And the lepton mixing pattern ?**

Evidence of dark matter



Evidence of dark matter





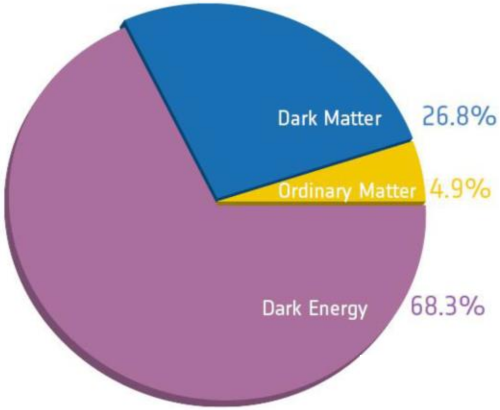
Astrophysical evidence

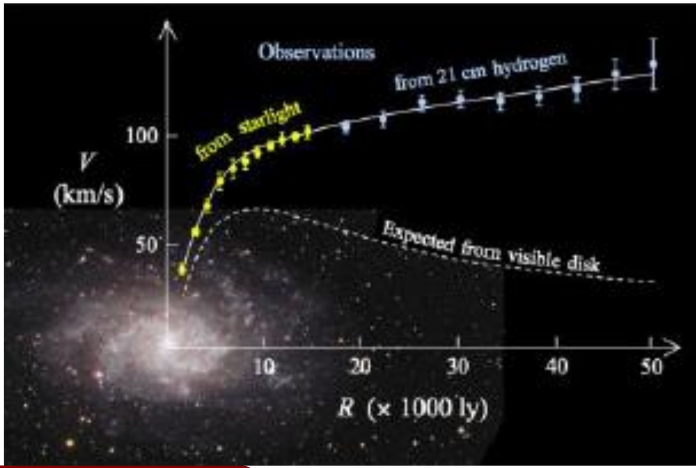
Galactic rotation curves

Cosmic microwave background

Big Bang nucleosynthesis …

Evidence of dark matter





Astrophysical evidence

Galactic rotation curves

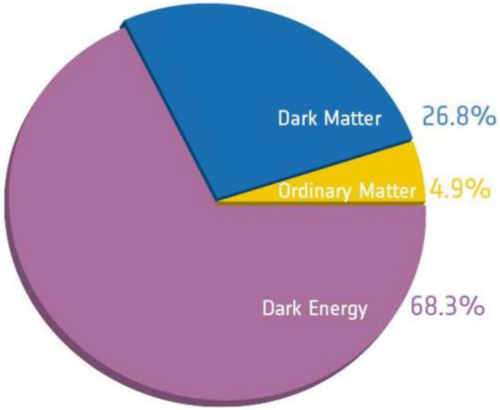
Cosmic microwave background

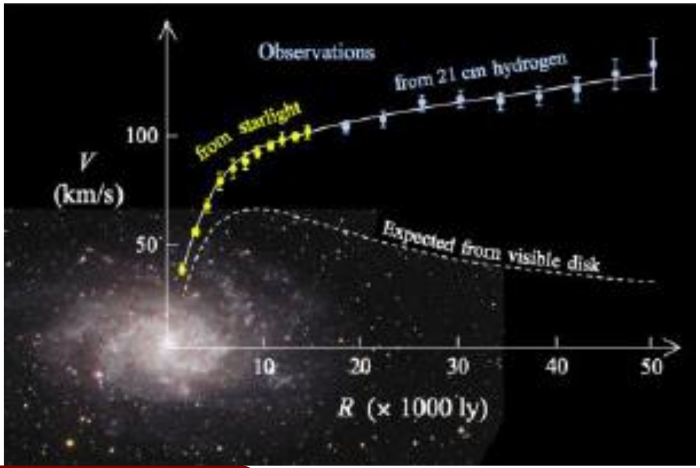
Big Bang nucleosynthesis …

Relic density Planck 2018

$$0.1126 \leq \Omega_{\rm CDM} h^2 \leq 0.1246$$

Evidence of dark matter





Astrophysical evidence

Galactic rotation curves

Cosmic microwave background

Big Bang nucleosynthesis …

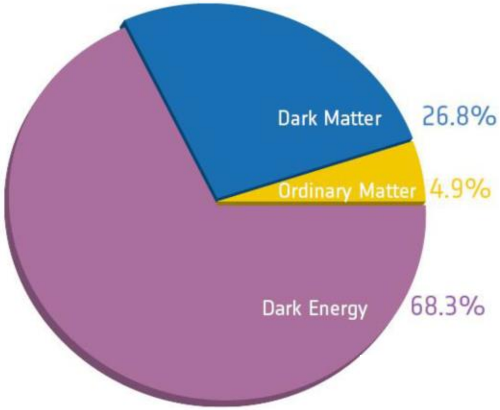
Relic density Planck 2018

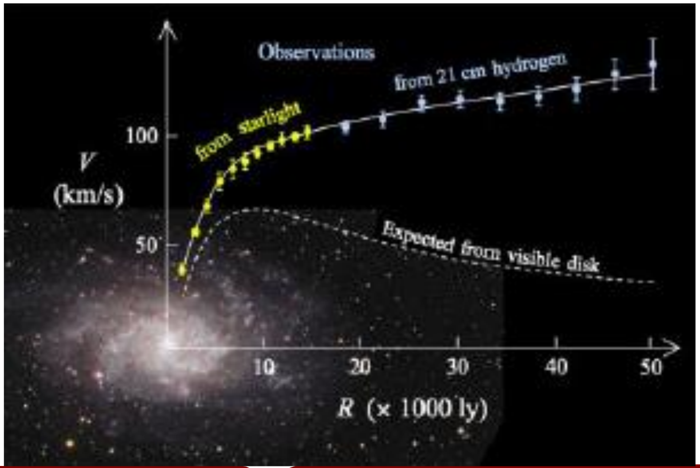
$$0.1126 \leq \Omega_{\rm CDM} h^2 \leq 0.1246$$

DM particle candidate is:

- **Cold,**
- **Electrically-neutral,**
- **Non-baryonic,**
- **Stable.**

Evidence of dark matter





Astrophysical evidence

Galactic rotation curves

Cosmic microwave background

Big Bang nucleosynthesis …

Relic density Planck 2018

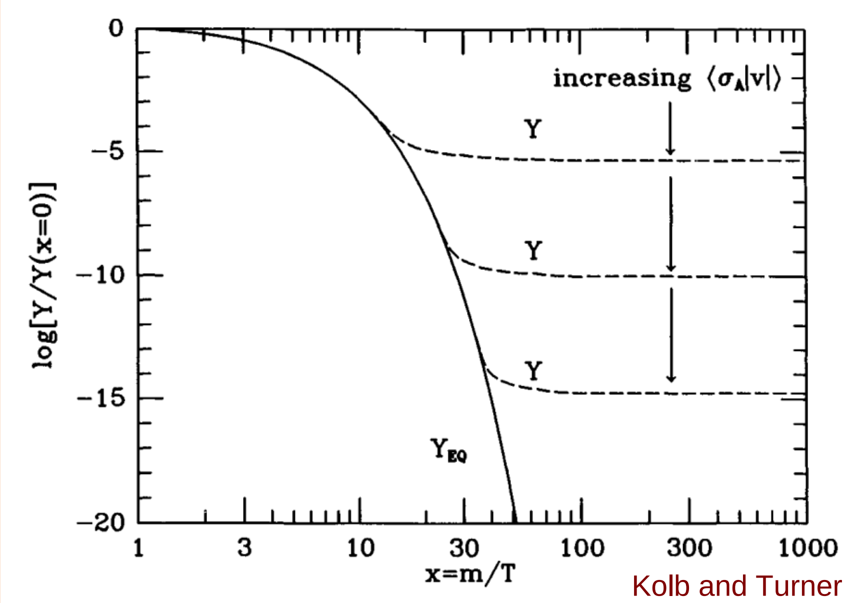
$$0.1126 \leq \Omega_{\rm CDM}h^2 \leq 0.1246$$

DM particle candidate is:

- **Cold,**
- **Electrically-neutral,**
- **Non-baryonic,**
- **Stable.**

WIMP Freeze-out

$$\frac{dn_\psi}{dt} + 3Hn_\psi = -\langle\sigma_A|v|\rangle[n_\psi^2 - (n_\psi^{\rm EQ})^2]$$



Kolb and Turner

Our idea

The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Our idea

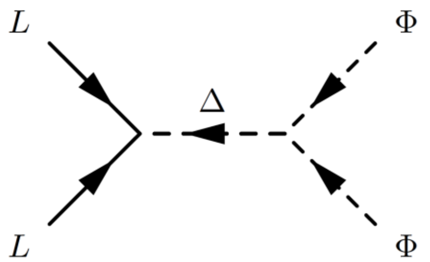
The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

Type-II seesaw model

Konetschny *et al.* (1977), Cheng *et al.* (1980), Lazarides *et al.* (1981), Valle *et al.* (1980), Magg *et al.* (1980), Mohapatra *et al.* (1981)



Our idea

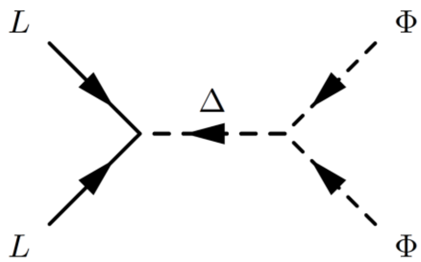
The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

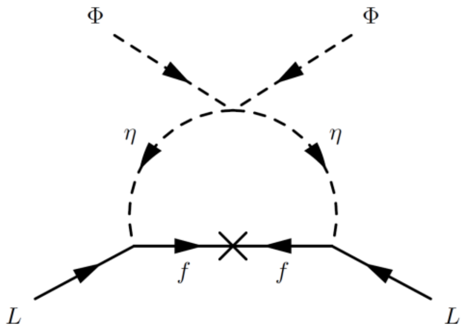
Type-II seesaw model

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)



Our idea

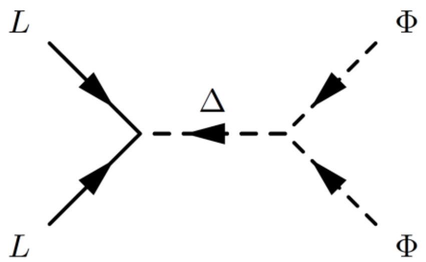
The Standard Model cannot explain:

- **Neutrino flavour oscillations** which imply massive neutrinos and lepton mixing
- Observed **dark matter** abundance

Straightforward and **elegant** solutions:

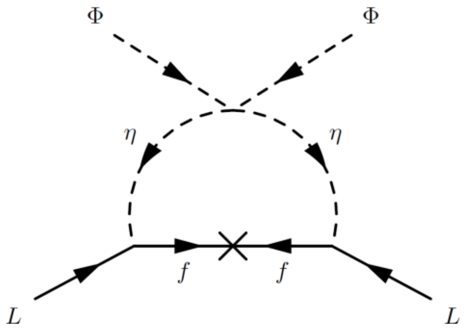
Type-II seesaw model

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)



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

Particle content and flavour symmetry

	Fields	$\mathrm{SU(2)_L \otimes U(1)_Y}$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Particle content and flavour symmetry

	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- 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 $\eta_{1,2}$**

Particle content and flavour symmetry

	Fields	$SU(2)_L \otimes U(1)_Y$	$\mathcal{Z}_8^{e-\mu *} \to \mathcal{Z}_2$
Fermions	ℓ_{eL}, e_R	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- 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 $\eta_{1,2}$**

CP symmetry

- Lagrangian is required to be CP invariant which makes all couplings real
- CP is **spontaneously broken** by the **complex VEV** of σ and is **successfully** transmitted to the leptonic sector

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	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$1 \to +$
	$\ell_{\mu L}, \mu_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^6 \to +$
	$\ell_{\tau L}, \tau_R$	$(\mathbf{2}, -1/2), (\mathbf{1}, -1)$	$\omega^2 \to +$
	f	$(\mathbf{1}, 0)$	$\omega^3 \to -$
Scalars	Φ	$(\mathbf{2}, 1/2)$	$1 \to +$
	Δ	$(\mathbf{3}, 1)$	$1 \to +$
	σ	$(\mathbf{1}, 0)$	$\omega^2 \to +$
	η_1	$(\mathbf{2}, 1/2)$	$\omega^3 \to -$
	η_2	$(\mathbf{2}, 1/2)$	$\omega^5 \to -$

* $\mathcal{Z}_8^{e-\tau}$ and $\mathcal{Z}_8^{\mu-\tau}$ are other possible charge assignments

Z_8 discrete symmetry

- New Z_8 symmetry reduces number of parameters in the Lagrangian
- 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 $\eta_{1,2}$**

CP symmetry

- Lagrangian is required to be CP invariant which makes all couplings real
- CP is **spontaneously broken** by the **complex VEV** of σ and is **successfully** transmitted to the leptonic sector

Vacuum configuration

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

Scalar sector and spontaneous CP violation

Scalar potential contains:

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

Scalar sector and spontaneous CP violation

Scalar potential contains:

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

CPV solution to the minimisation conditions

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

$$\cos(2\theta) = -\frac{m_\sigma'^{\,2}}{2u^2\lambda'_\sigma}$$

Scalar sector and spontaneous CP violation

Scalar potential contains:

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

CPV solution to the minimisation conditions

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

⬇

$$\cos(2\theta) = -\frac{m_\sigma'^{\,2}}{2u^2\lambda'_\sigma}$$

Higgs triplet, doublet and singlet

$$V \supset \ \mu_\Delta \left(\Phi^\dagger \Delta i\tau_2 \Phi^* + \mathrm{H.c.}\right)$$

$$w \simeq -\frac{\sqrt{2}\mu_\Delta v^2}{v^2\lambda_{\Delta 3} + u^2\lambda_{\Delta\sigma} + 2m_\Delta^2}$$

Naturally small triplet VEV

$$\begin{pmatrix} \phi^0_{\mathrm{R}} \\ \sigma_{\mathrm{R}} \\ \sigma_{\mathrm{I}} \end{pmatrix} = \mathbf{K} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

We consider triplet decoupled from remaining states

Scalar sector and spontaneous CP violation

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

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

$$\cos(2\theta) = -\frac{m_\sigma'^2}{2u^2\lambda'_\sigma}$$

Higgs triplet, doublet and singlet

$$V \supset \; \mu_\Delta \left(\Phi^\dagger \Delta i\tau_2 \Phi^* + \mathrm{H.c.}\right)$$

$$w \simeq -\frac{\sqrt{2}\mu_\Delta v^2}{v^2\lambda_{\Delta 3} + u^2\lambda_{\Delta\sigma} + 2m_\Delta^2}$$

Naturally small triplet VEV

$$\begin{pmatrix} \phi^0_{\mathrm{R}} \\ \sigma_{\mathrm{R}} \\ \sigma_{\mathrm{I}} \end{pmatrix} = \mathbf{K} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

We consider triplet decoupled from remaining states

Dark sector: two inert doublets

$$\begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = \mathbf{R} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}$$

Charged lepton flavour violation

$$\begin{pmatrix} \eta^0_{\mathrm{R}1} \\ \eta^0_{\mathrm{R}2} \\ \eta^0_{\mathrm{I}1} \\ \eta^0_{\mathrm{I}2} \end{pmatrix} = \mathbf{V} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \end{pmatrix}$$

Neutrino mass generation and dark matter

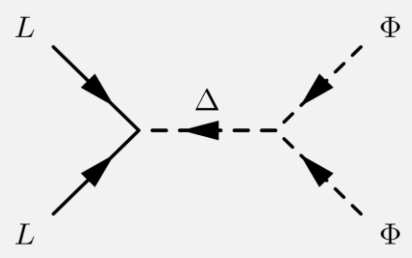
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell^c_L}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}^1_f\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}^2_f\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw

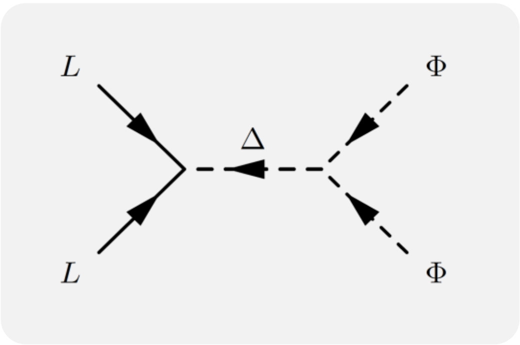


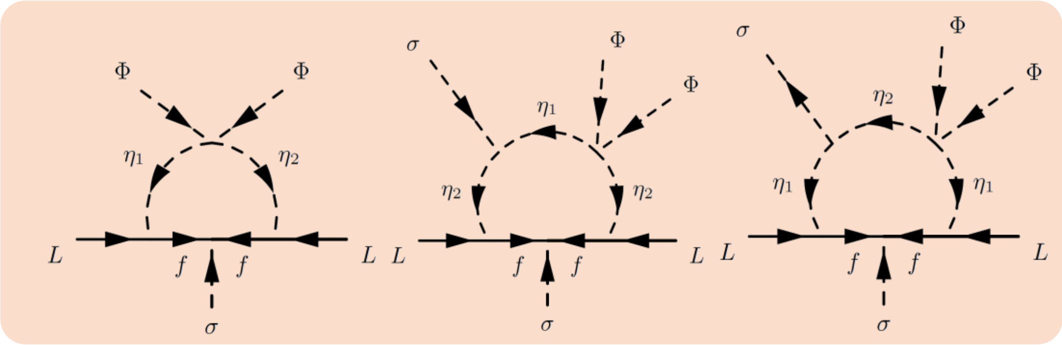
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw

Scotogenic

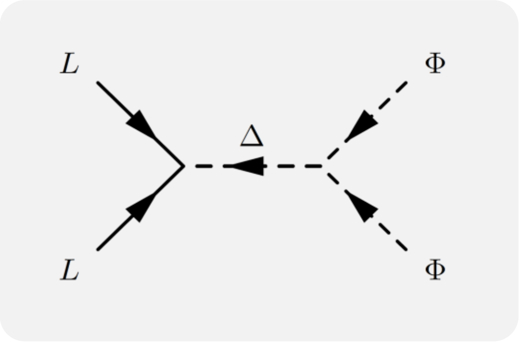




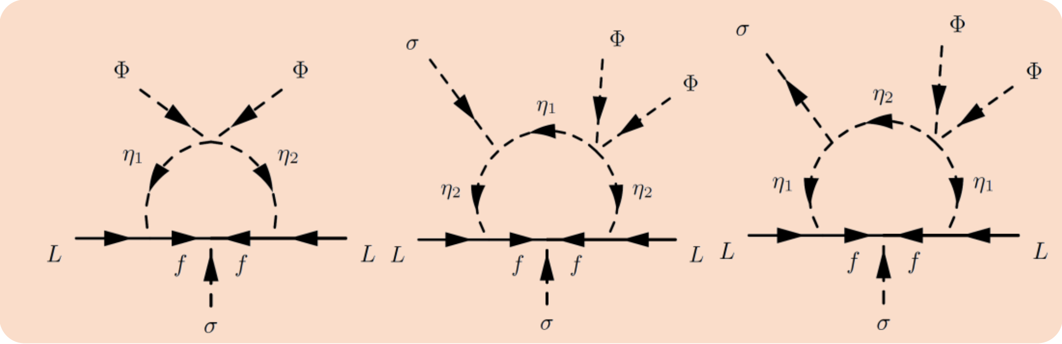
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic

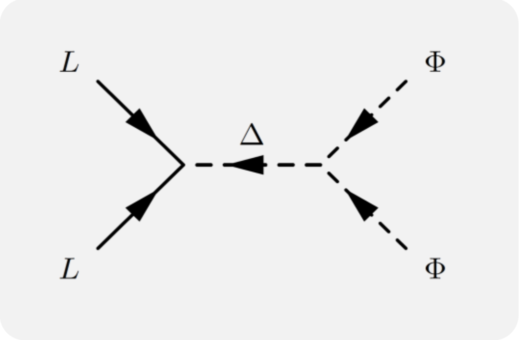


$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

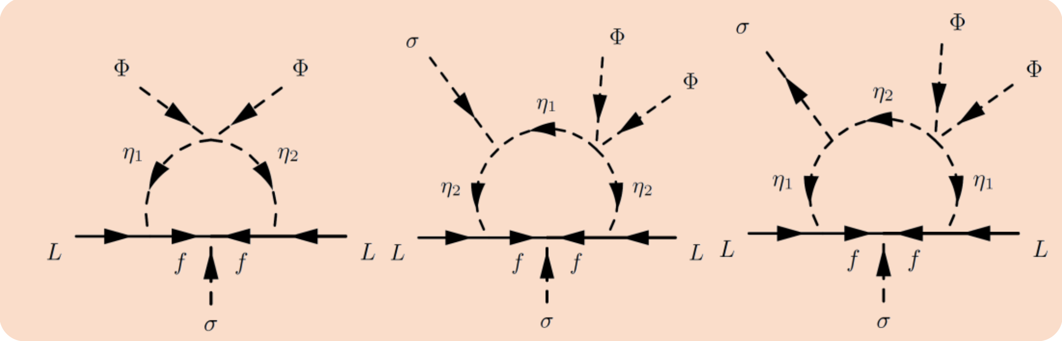
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic



$\mathcal{Z}_8^{e-\mu}$

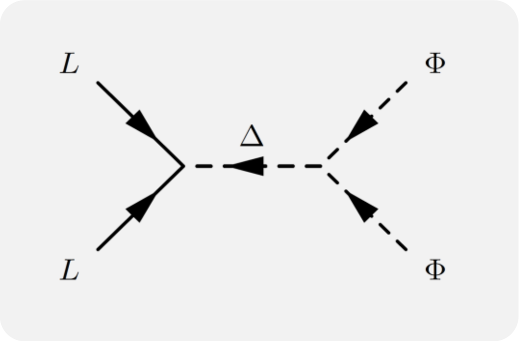
$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \quad \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

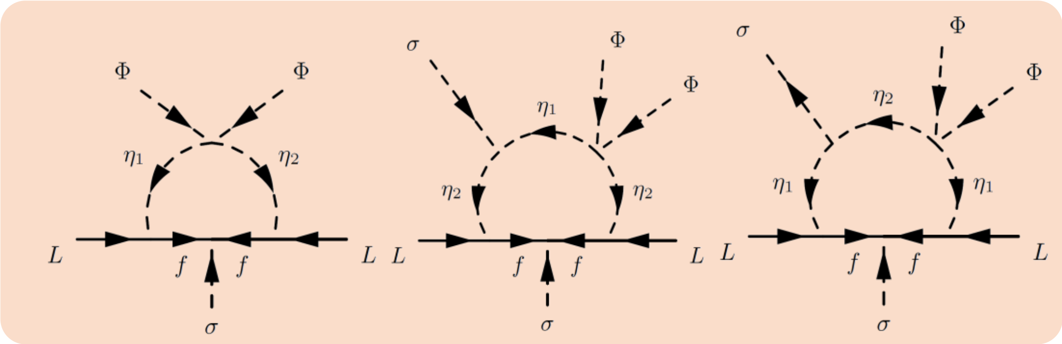
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\,e_R + \overline{\ell_L^c}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}_f^1\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}_f^2\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw



Scotogenic



$\mathcal{Z}_8^{e-\mu}$

$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \quad \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} e^{-i\theta}$$

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

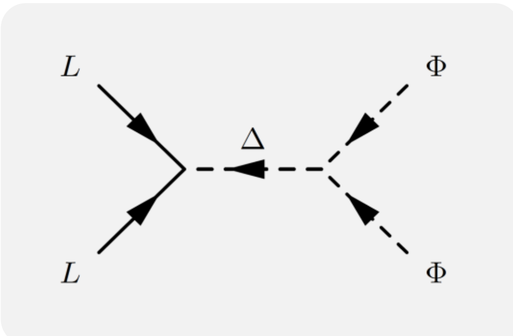
Effective neutrino mass matrix

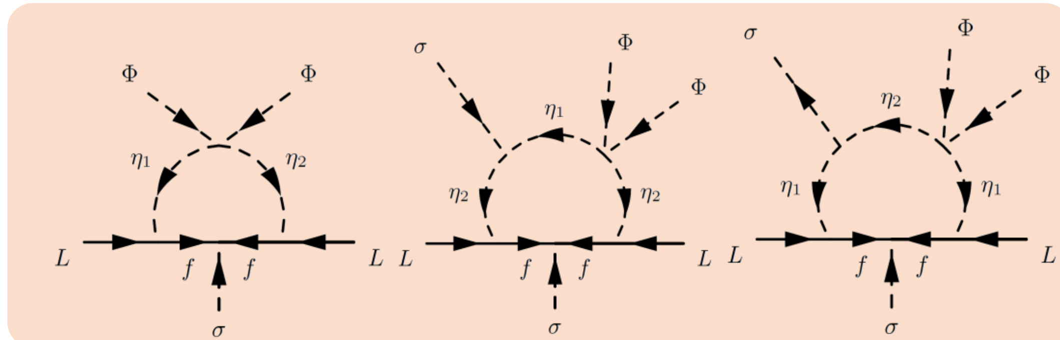
Neutrino mass generation

$$-\mathcal{L}_{\text{Yuk.}} = \overline{\ell_L}\mathbf{Y}_\ell\,\Phi\, e_R + \overline{\ell^c_L}\mathbf{Y}_\Delta i\tau_2\Delta\ell_L + \overline{\ell_L}\mathbf{Y}^1_f\tilde{\eta}_1 f + \overline{\ell_L}\mathbf{Y}^2_f\tilde{\eta}_2 f + \frac{1}{2}y_f\,\sigma\overline{f^c}f + \text{H.c.}$$

Type-II seesaw

Scotogenic





$$\mathcal{Z}_8^{e-\mu}$$

$$\mathbf{Y}_\ell = \begin{pmatrix} \times & 0 & 0 \\ 0 & \times & 0 \\ 0 & 0 & \times \end{pmatrix}$$

$$\mathbf{Y}^1_f = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \quad \mathbf{Y}^2_f = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \quad \mathbf{Y}_\Delta = \begin{pmatrix} y_1 & 0 & 0 \\ 0 & 0 & y_2 \\ 0 & y_2 & 0 \end{pmatrix} \; e^{-i\theta}$$

Spontaneous origin for leptonic CP violation

$$\langle\sigma\rangle = \frac{u\,e^{i\theta}}{\sqrt{2}}$$

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

Effective neutrino mass matrix

Neutrino sector

Compatibility with neutrino data

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

High-energy parameters

Compatibility with neutrino data

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

High-energy parameters

Matching ⟷

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

Low-energy parameters

Compatibility with neutrino data

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

Matching

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

High-energy parameters **Low-energy parameters**

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

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}, \quad \mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix}, \quad \mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$

Alcaide, Salvado, Santamaria (2018)

Compatibility with neutrino data

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

Matching

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

High-energy parameters **Low-energy parameters**

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

$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ \cdot & \times & \times \\ \cdot & \cdot & 0 \end{pmatrix}, \quad \mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ \cdot & 0 & \times \\ \cdot & \cdot & \times \end{pmatrix}, \quad \mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix}$$

Alcaide, Salvado, Santamaria (2018)

Predictions for **lightest neutrino mass** and **effective Majorana mass**

$$\text{NO:} \quad m_2 = \sqrt{m_1^2 + \Delta m_{21}^2}, \quad m_3 = \sqrt{m_1^2 + \Delta m_{31}^2}$$

$$\text{IO:} \quad m_1 = \sqrt{m_3^2 + |\Delta m_{31}^2|}, \quad m_2 = \sqrt{m_3^2 + \Delta m_{21}^2 + |\Delta m_{31}^2|}$$

$$\text{NO} : \; m_{\beta\beta} = \left| c_{12}^2 c_{13}^2\, m_{\text{lightest}} + s_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2}\, e^{-i\alpha_{21}} + s_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{31}^2}\, e^{-i\alpha_{31}} \right|$$

$$\text{IO} : \; m_{\beta\beta} = \left| c_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + |\Delta m_{31}^2|} + s_{12}^2 c_{13}^2 \sqrt{m_{\text{lightest}}^2 + \Delta m_{21}^2 + |\Delta m_{31}^2|}\, e^{-i\alpha_{21}} + s_{13}^2\, m_{\text{lightest}}\, e^{-i\alpha_{31}} \right|$$

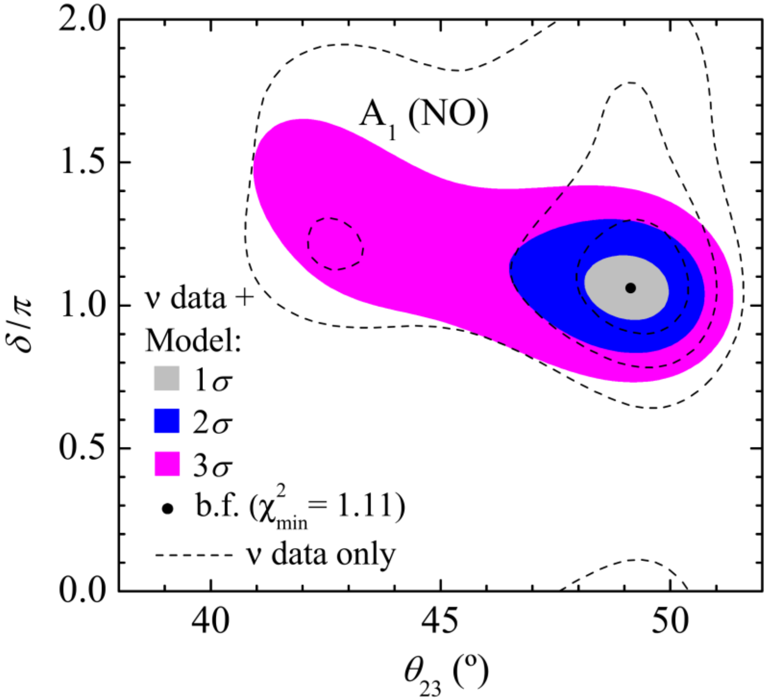
Neutrino sector predictions: A1 case

$$\mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ . & \times & \times \\ . & . & \times \end{pmatrix} \qquad (\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{11} = 0$$

Neutrino sector predictions: A1 case

$$\mathcal{Z}_8^{\mu-\tau} \rightarrow \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix} \qquad (\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{11} = 0$$

δ and θ_{23}

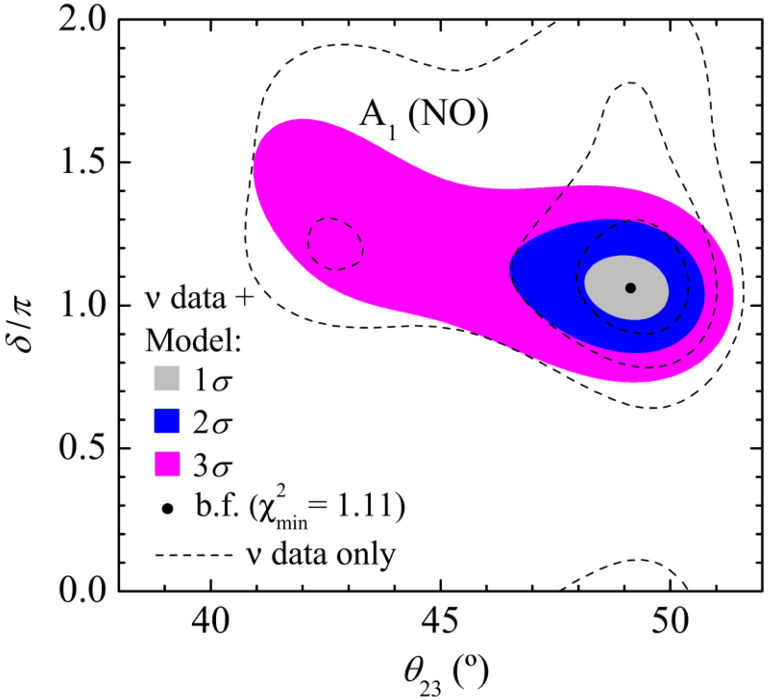


- Selects **second octant for θ_{23}** (2 σ).
- Predicts a CP-violating phase $\boldsymbol{\delta \sim [0.8, 1.6]\pi}$ (3 σ).

Neutrino sector predictions: A1 case

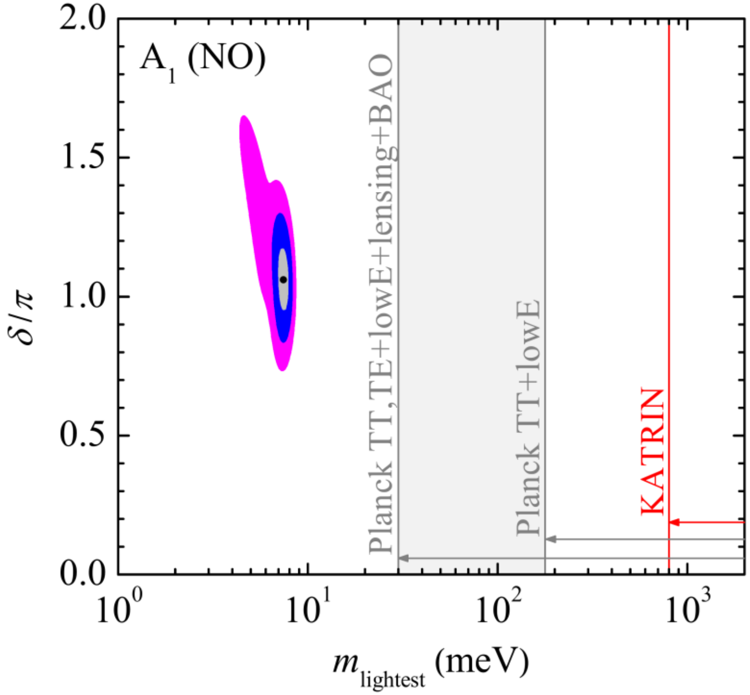
$$\mathcal{Z}_8^{\mu-\tau} \to \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ . & \times & \times \\ . & . & \times \end{pmatrix} \quad (\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{11} = 0$$

δ and θ_{23}



- Selects **second octant for θ_{23}** (2 σ).
- Predicts a CP-violating phase $\boldsymbol{\delta \sim [0.8, 1.6]\pi}$ (3 σ).

Lightest neutrino mass



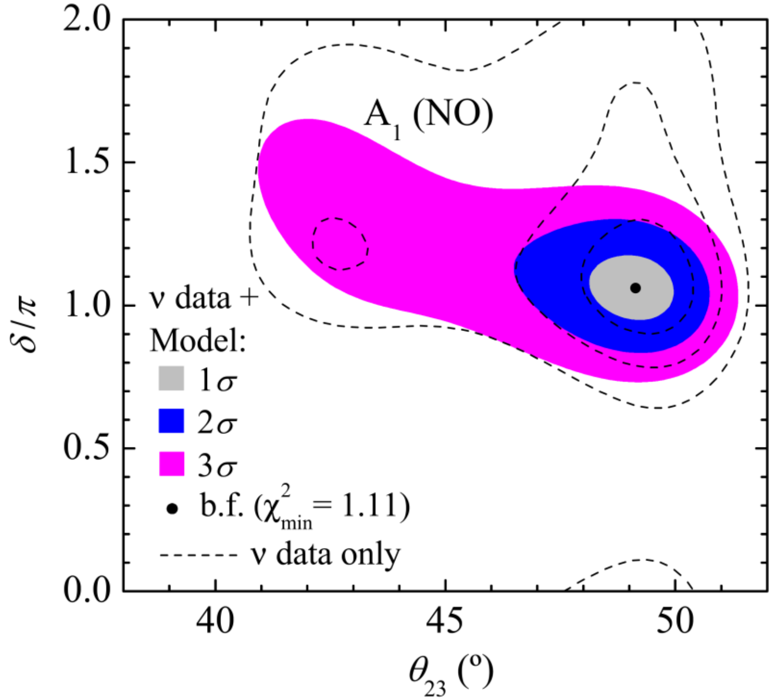
- Lower and upper limit ~ $[4,9]$ meV (3 σ)
- **Well below the limits from cosmology (Planck) and KATRIN**

Neutrino sector predictions: A1 case

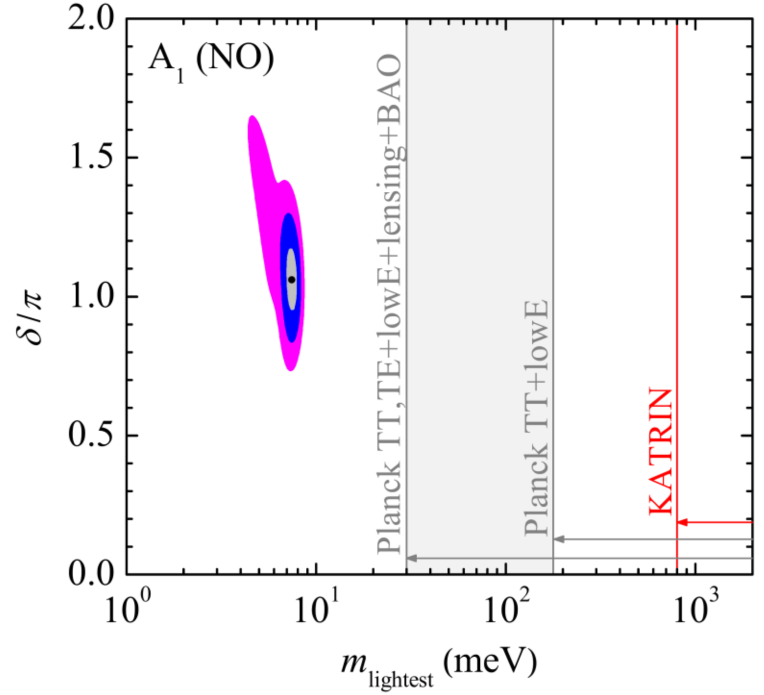
$$\mathcal{Z}_8^{\mu-\tau} \rightarrow \mathrm{A}_1 : \begin{pmatrix} 0 & 0 & \times \\ \cdot & \times & \times \\ \cdot & \cdot & \times \end{pmatrix} \qquad (\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{11} = 0$$

$\boldsymbol{m_{\beta\beta} = 0}$

δ and θ_{23}



Lightest neutrino mass



- Selects **second octant for θ_{23}** (2 σ).
- Predicts a CP-violating phase $\boldsymbol{\delta \sim [0.8, 1.6]\pi}$ (3 σ).

- Lower and upper limit ~ $[4{,}9]$ meV (3 σ)
- **Well below the limits from cosmology (Planck) and KATRIN**

Neutrino sector predictions: B3 and B4 case

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

$$(\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{22} = 0$$

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

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

Neutrino sector predictions: B3 and B4 case

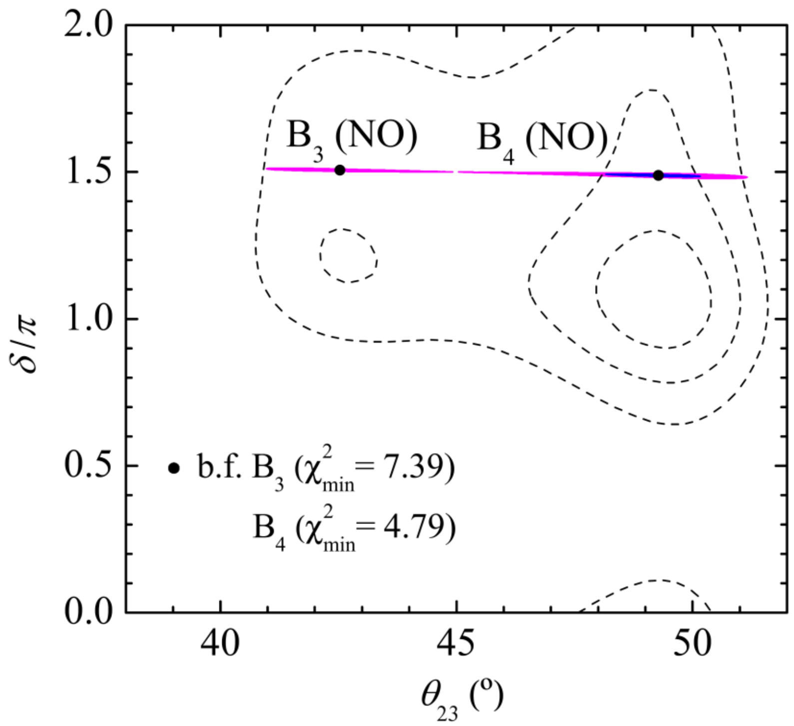
$$\mathcal{Z}_8^{e-\tau} \rightarrow \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ . & 0 & \times \\ . & . & \times \end{pmatrix}$$

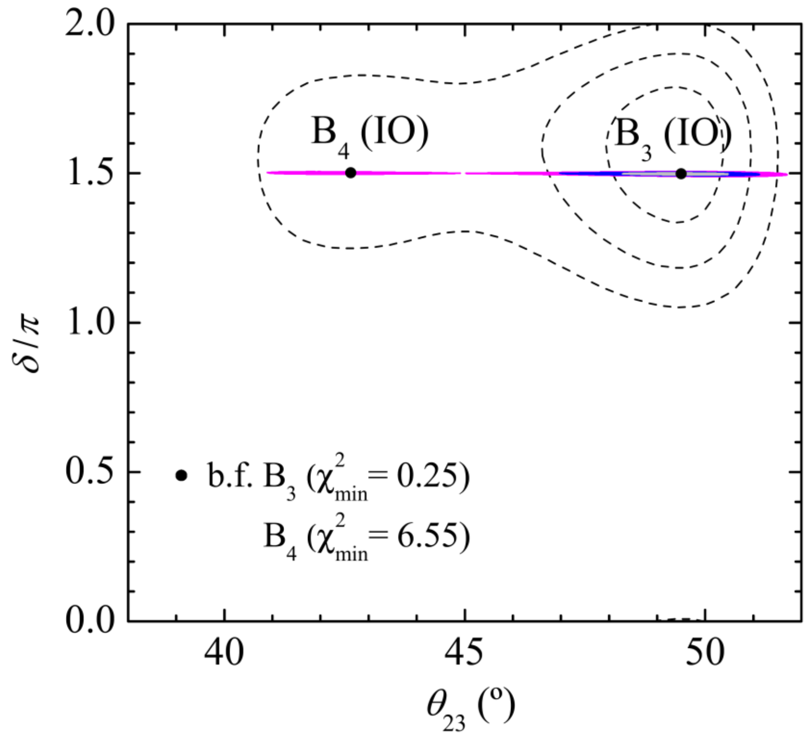
$$(\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{22} = 0$$

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

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}





Neutrino sector predictions: B3 and B4 case

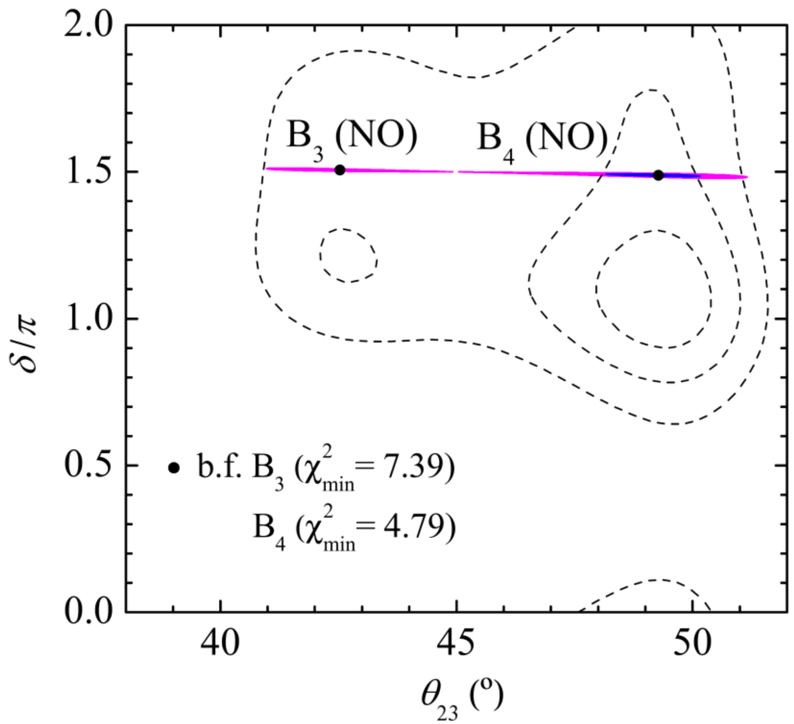
$$\mathcal{Z}_8^{e-\tau} \rightarrow \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ . & 0 & \times \\ . & . & \times \end{pmatrix}$$

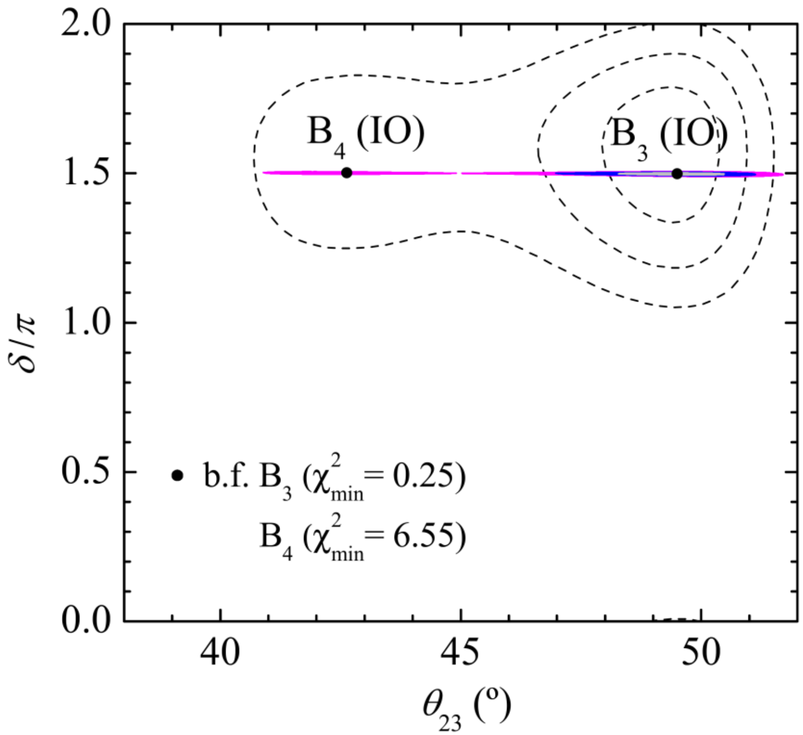
$$(\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{22} = 0$$

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

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}





- B3 NO: selects **first octant for θ_{23}**
- B4 NO: selects **second octant for θ_{23}**

Neutrino sector predictions: B3 and B4 case

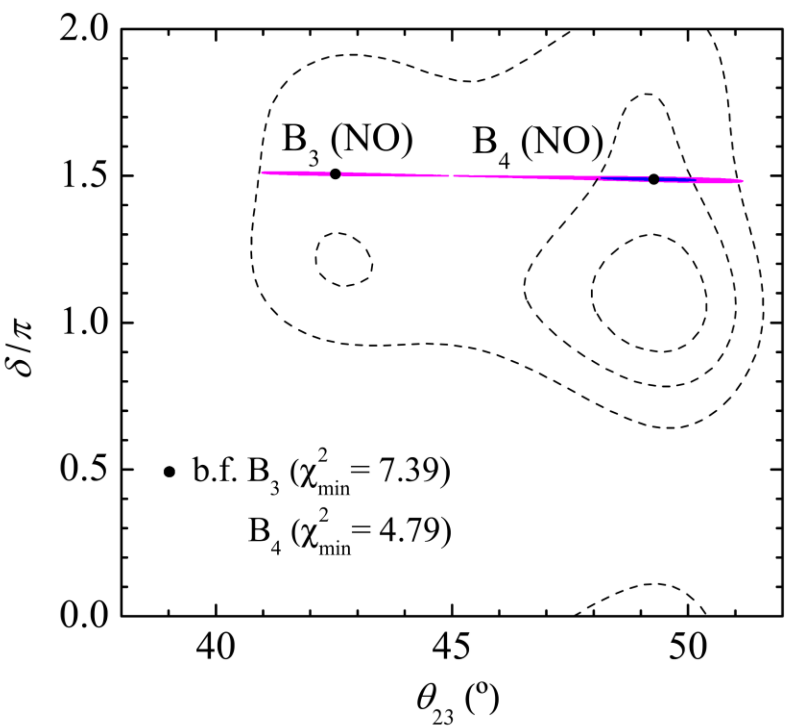
$$\mathcal{Z}_8^{e-\tau} \to \mathrm{B}_3 : \begin{pmatrix} \times & 0 & \times \\ . & 0 & \times \\ . & . & \times \end{pmatrix}$$

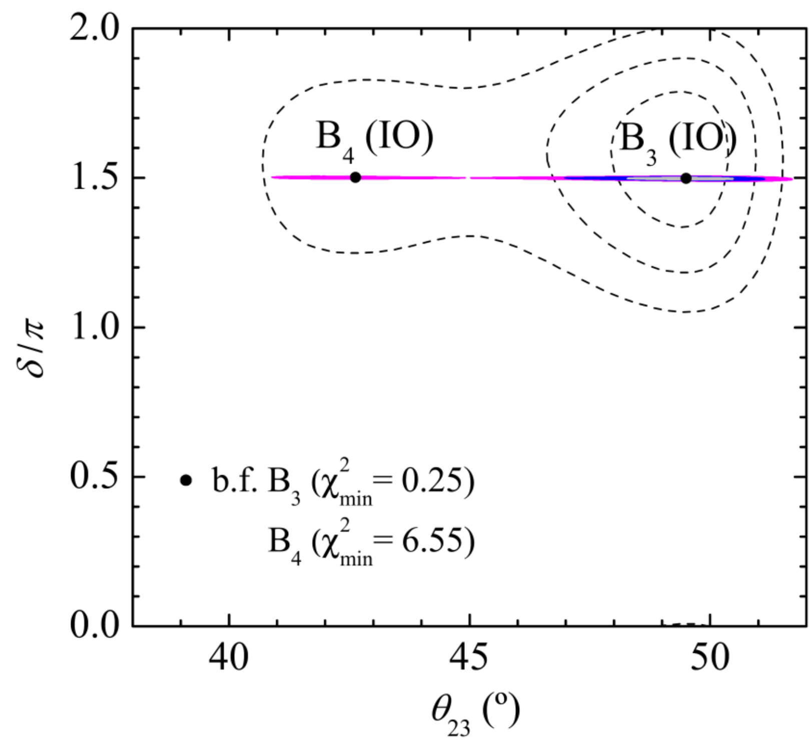
$$(\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{22} = 0$$

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

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}





- B3 NO: selects **first octant for θ_{23}**
- B4 NO: selects **second octant for θ_{23}**

- B3 IO: selects **second octant for θ_{23}**
- B4 IO: selects **first octant for θ_{23}**

Neutrino sector predictions: B3 and B4 case

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

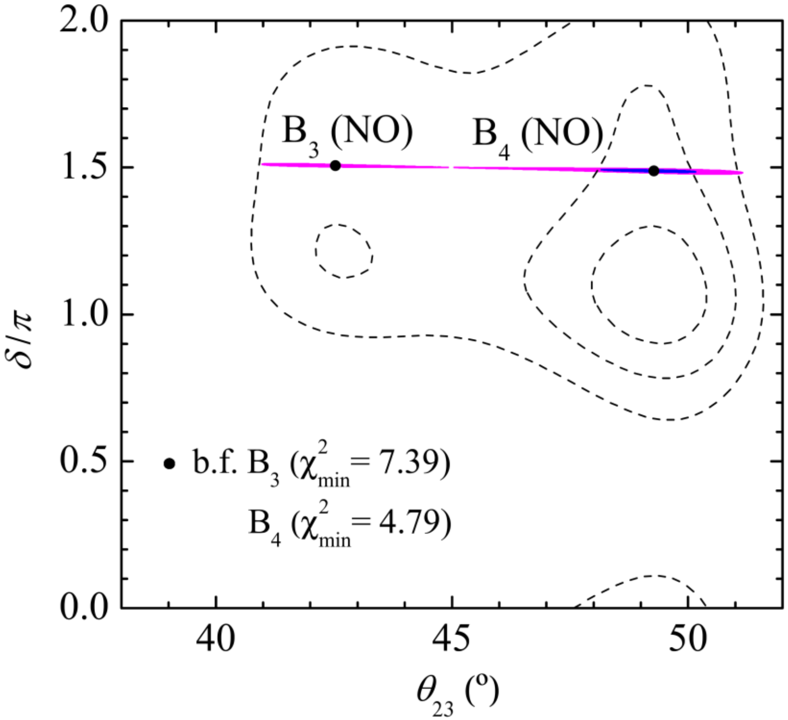
$$(\mathbf{M}_\nu)_{12} = (\mathbf{M}_\nu)_{22} = 0$$

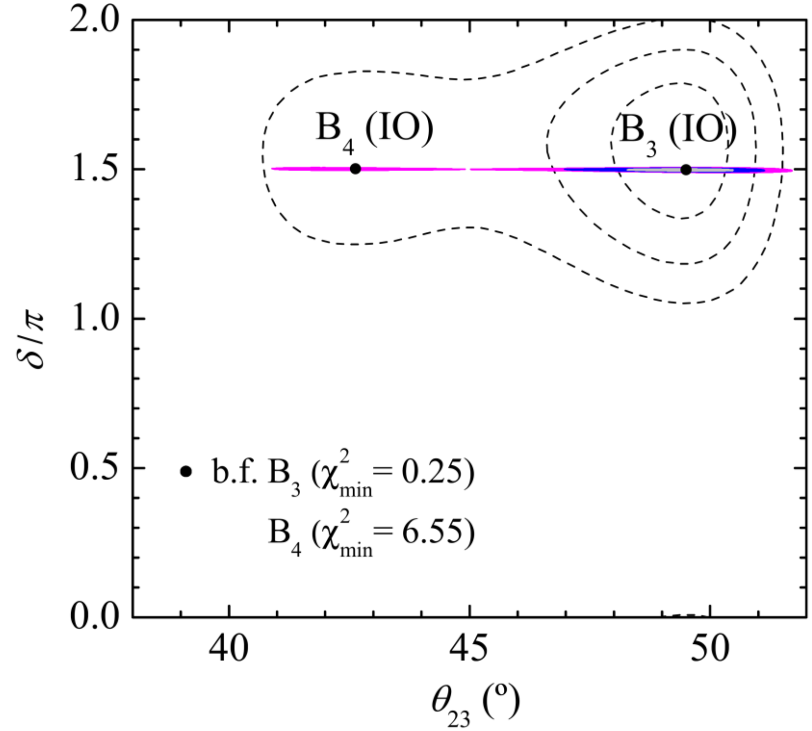
$$\mathcal{Z}_8^{e-\mu} \to \mathrm{B}_4 : \begin{pmatrix} \times & \times & 0 \\ . & \times & \times \\ . & . & 0 \end{pmatrix}$$

$$(\mathbf{M}_\nu)_{13} = (\mathbf{M}_\nu)_{33} = 0$$

δ and θ_{23}

- Both cases sharply predict $\delta \sim 3\pi/2$

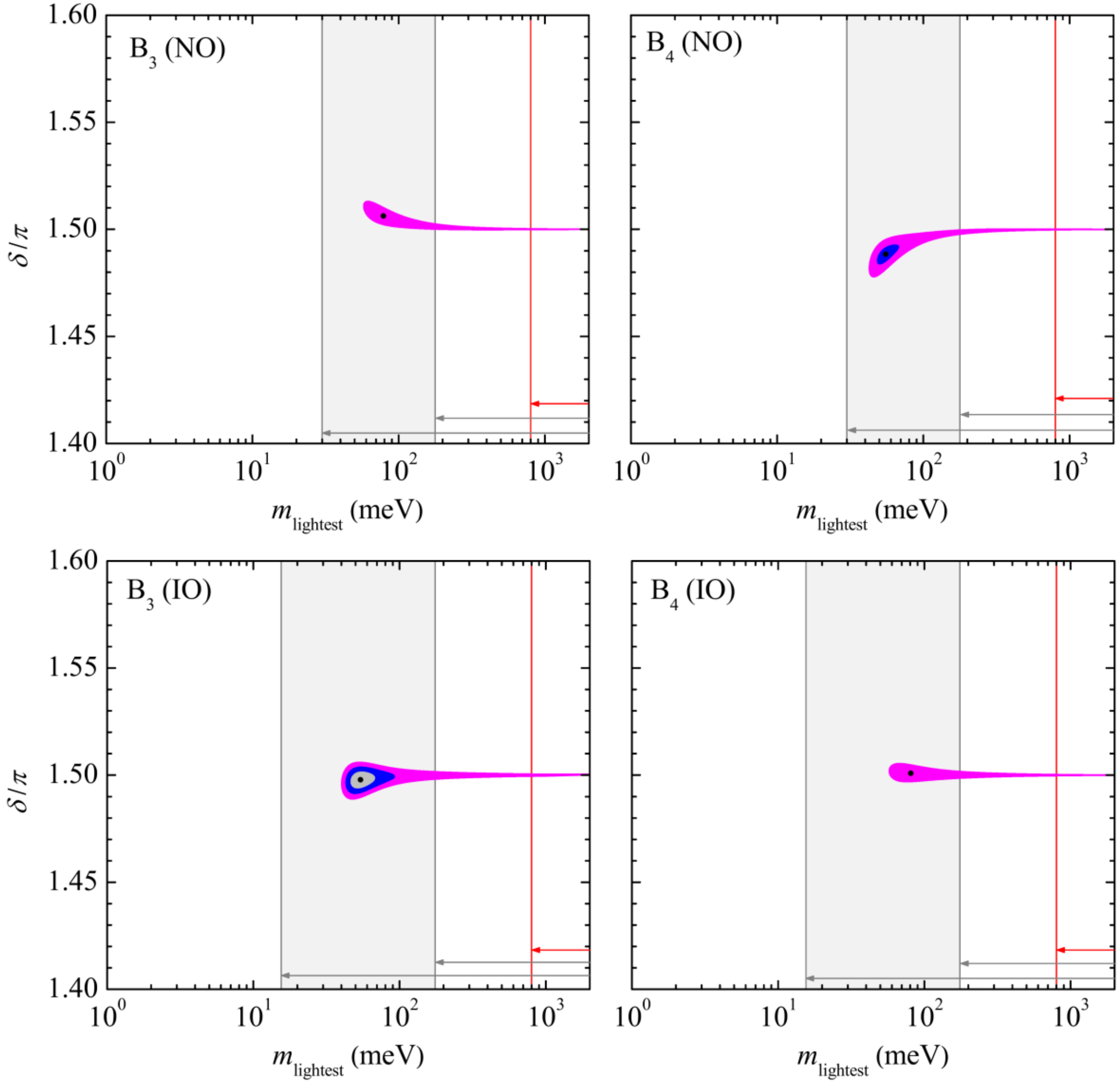




- B3 NO: selects **first octant for θ_{23}**
- B4 NO: selects **second octant for θ_{23}**
- B3 IO: selects **second octant for θ_{23}**
- B4 IO: selects **first octant for θ_{23}**

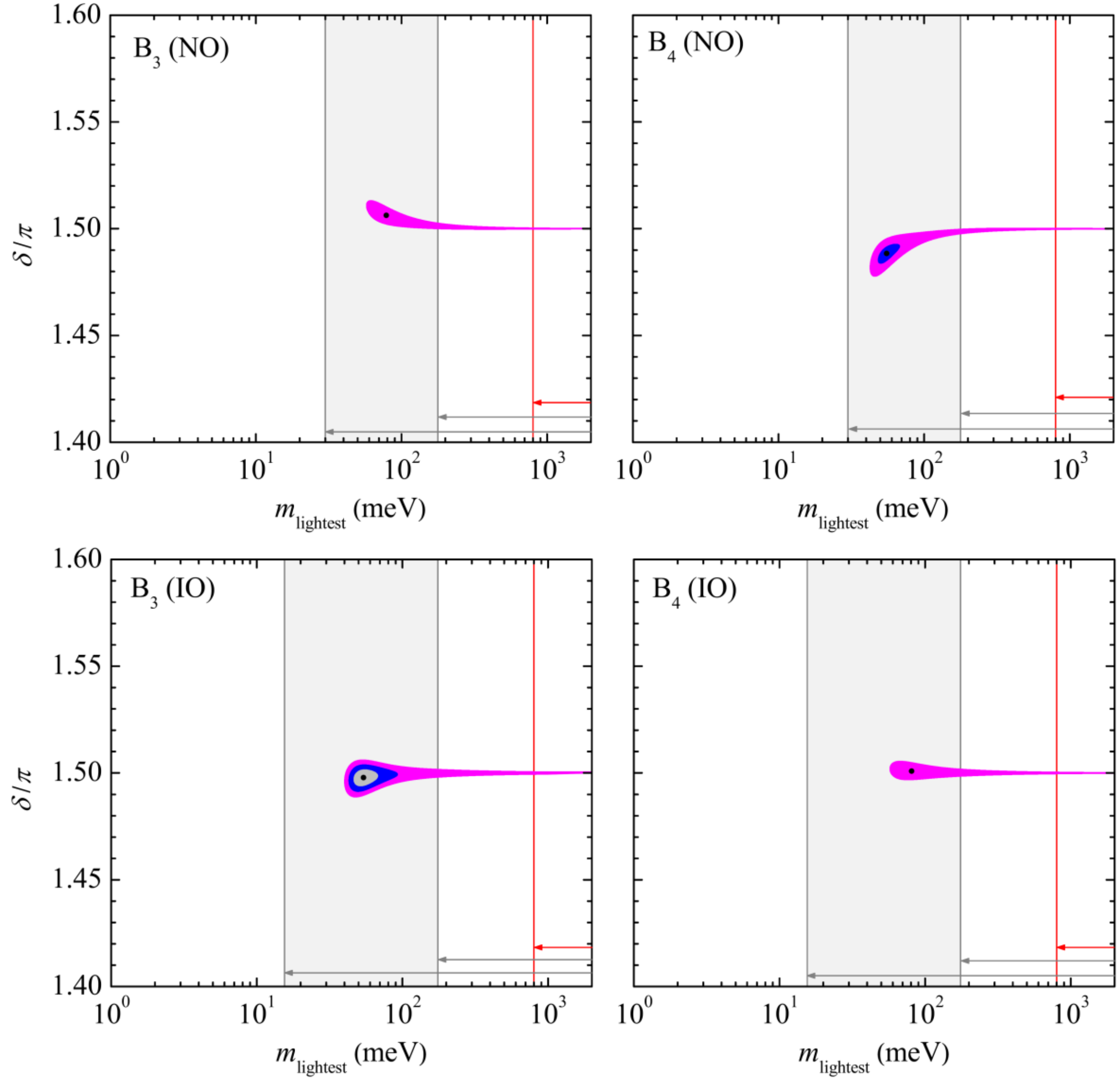
Neutrino sector predictions: B3 and B4 case

Lightest neutrino mass



Neutrino sector predictions: B3 and B4 case

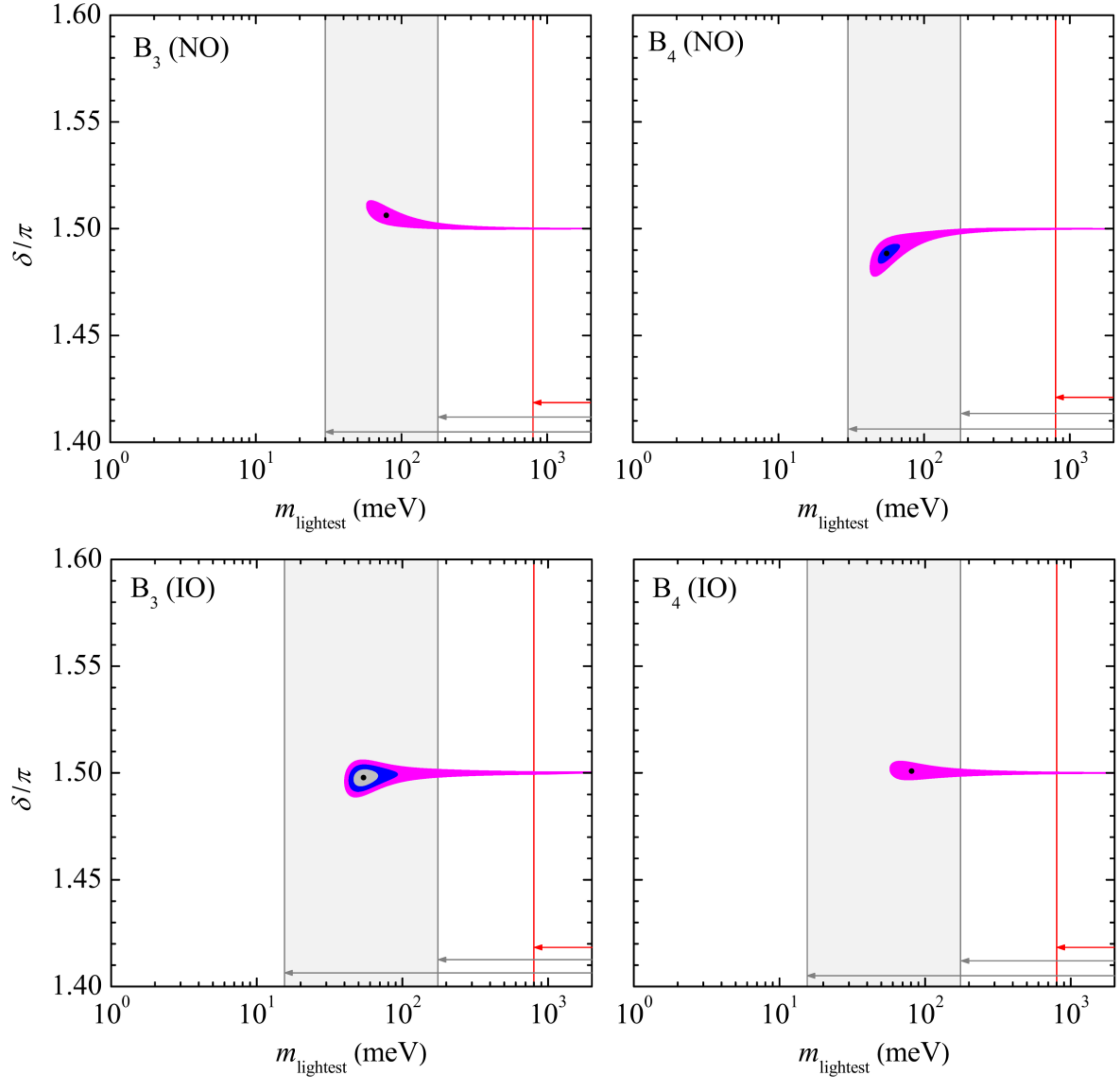
Lightest neutrino mass



- B3 NO: Lower limit ~ 40 meV (3 σ)
- B4 NO: Lower limit ~ 40 meV (3 σ)
  Upper limit ~ 60 meV (2 σ)

Neutrino sector predictions: B3 and B4 case

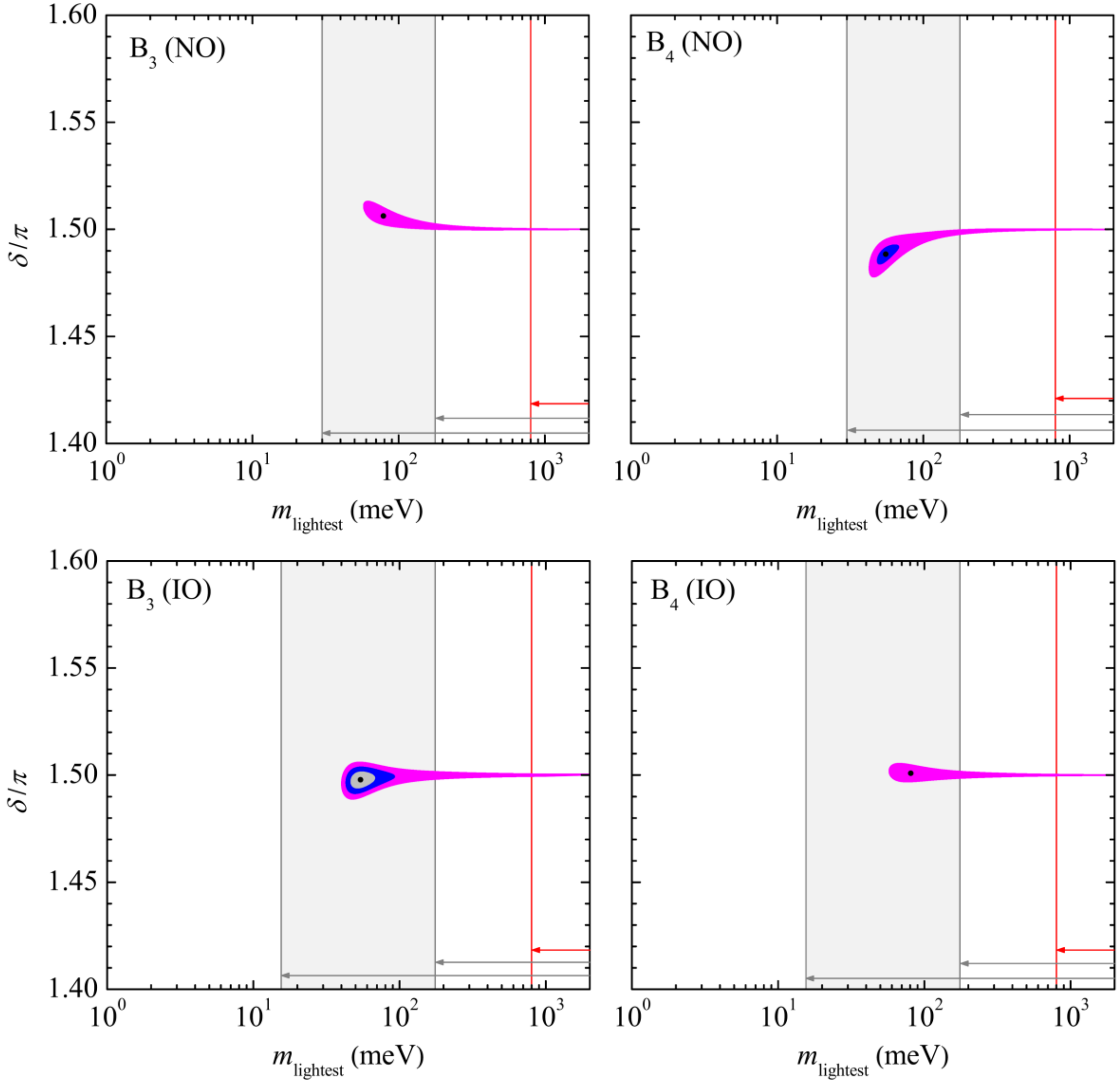
Lightest neutrino mass



- B3 NO: Lower limit ~ 40 meV (3 σ)
- B4 NO: Lower limit ~ 40 meV (3 σ) Upper limit ~ 60 meV (2 σ)
- B3 IO: Lower limit ~ 40 meV (3 σ) Upper limit ~ 100 meV (2 σ)
- B4 IO: Lower limit ~ 40 meV (3 σ)

Neutrino sector predictions: B3 and B4 case

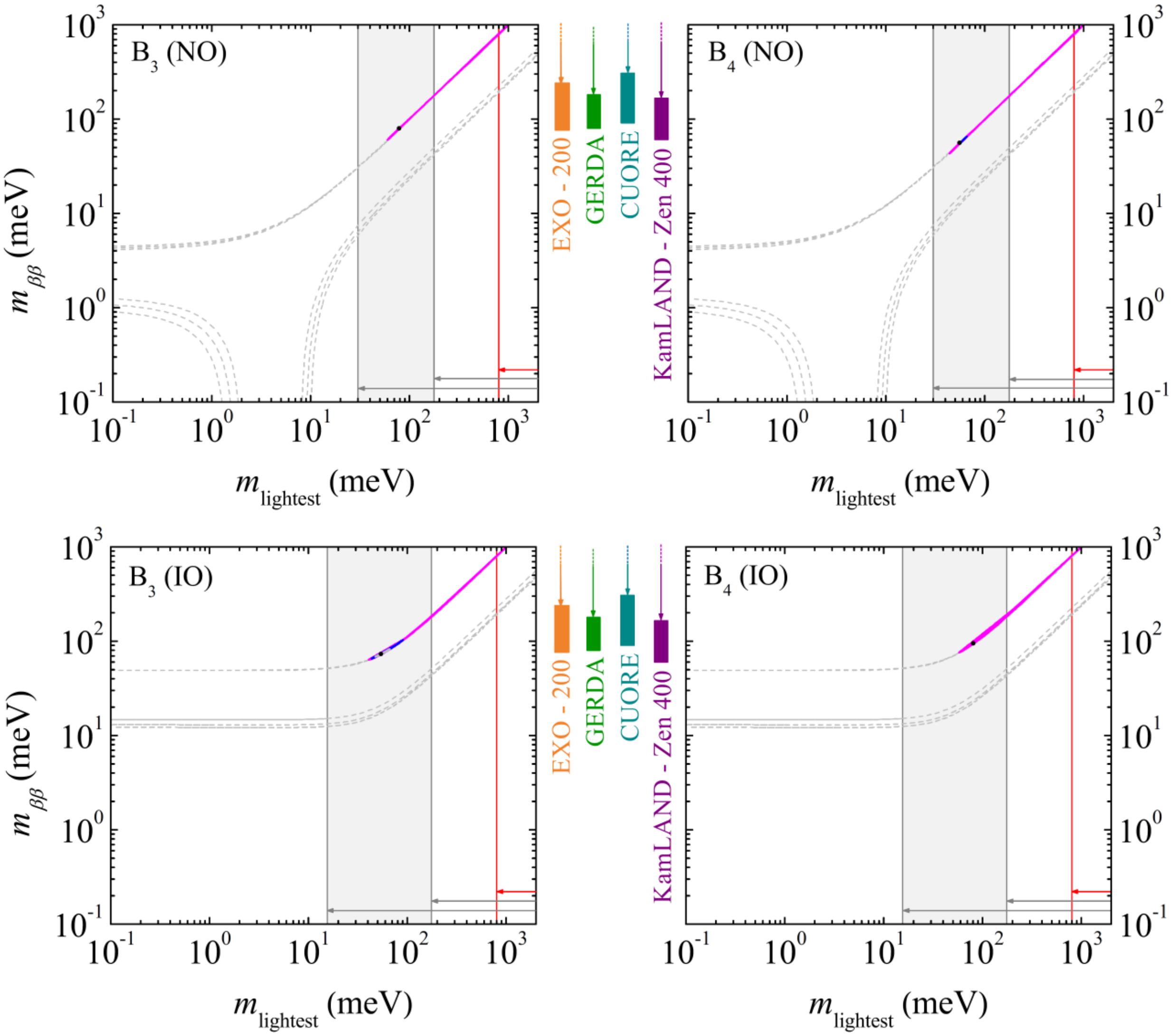
Lightest neutrino mass



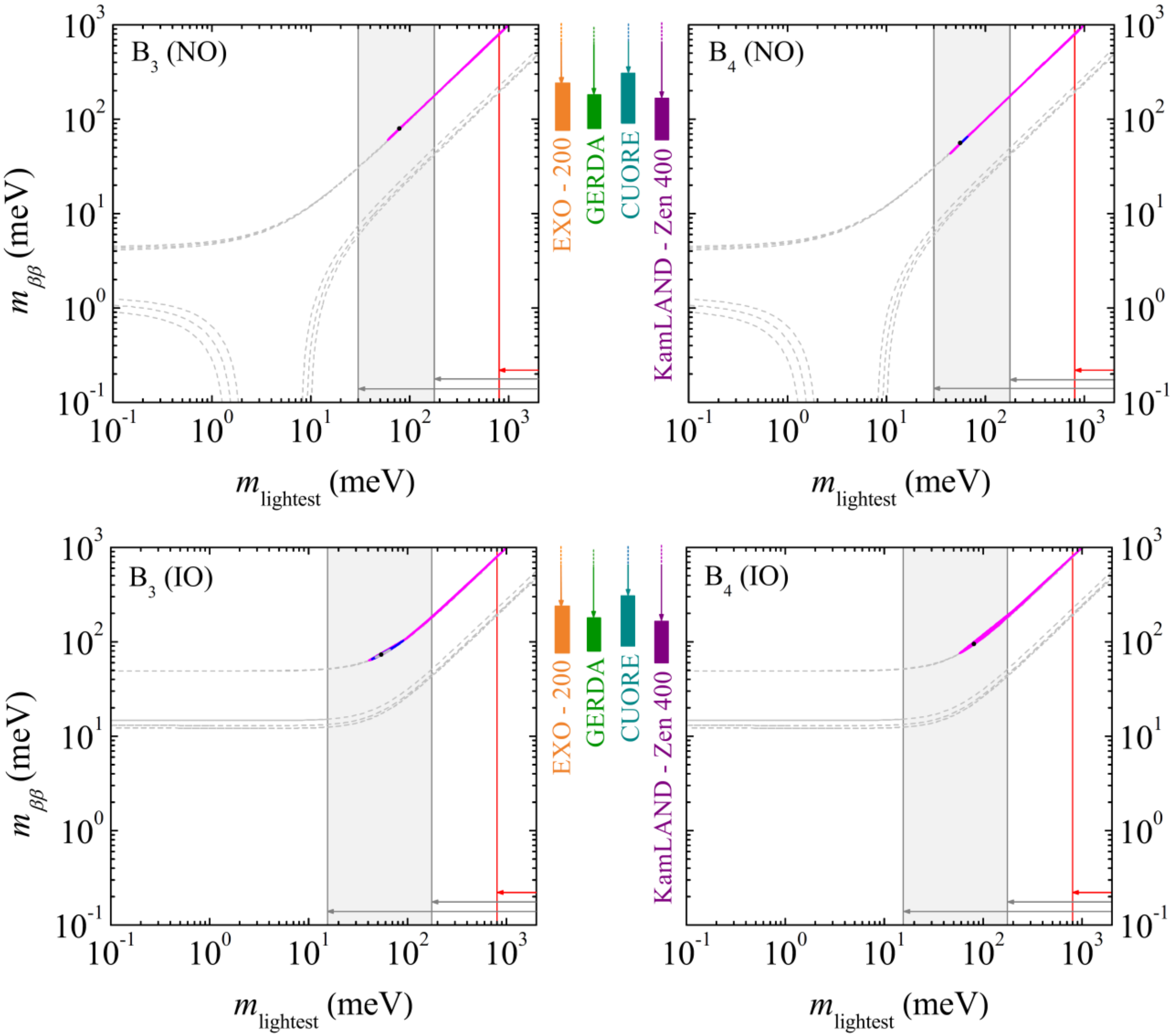
- B3 NO: Lower limit ~ 40 meV (3 σ)
- B4 NO: Lower limit ~ 40 meV (3 σ)
  Upper limit ~ 60 meV (2 σ)
- **Now being probed by cosmology**
- B3 IO: Lower limit ~ 40 meV (3 σ)
  Upper limit ~ 100 meV (2 σ)
- B4 IO: Lower limit ~ 40 meV (3 σ)

Neutrino sector predictions: B3 and B4 case

$m_{\beta\beta}$



$m_{\beta\beta}$



- **Current KamLAND-Zen 400 excludes B3 and B4 IO**
- B4 NO still viable and will be **tested by near-future $0\nu\beta\beta$ experiments**

Flavour

Charged-lepton flavour violation (cLFV)

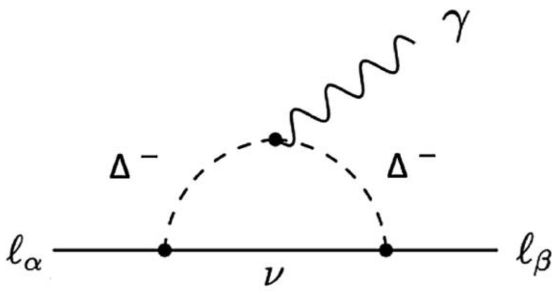
cLFV process	Present limit (90% CL)	Future sensitivity
$\text{BR}(\mu \to e\gamma)$	4.2×10^{-13} (MEG)	6×10^{-14} (MEG II)
$\text{BR}(\tau \to e\gamma)$	3.3×10^{-8} (BaBar)	3×10^{-9} (Belle II)
$\text{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar)	10^{-9} (Belle II)
$\text{BR}(\mu^- \to e^- e^+ e^-)$	1.0×10^{-12} (SINDRUM)	10^{-16} (Mu3e)
$\text{BR}(\tau^- \to e^- e^+ e^-)$	2.7×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\text{BR}(\tau^- \to e^- \mu^+ \mu^-)$	2.7×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\text{BR}(\tau^- \to e^+ \mu^- \mu^-)$	1.7×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\text{BR}(\tau^- \to \mu^- e^+ e^-)$	1.8×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\text{BR}(\tau^- \to \mu^+ e^- e^-)$	1.5×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\text{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	2.1×10^{-8} (Belle)	4×10^{-10} (Belle II)
$\text{CR}(\mu - e, \text{Al})$	–	3×10^{-17} (Mu2e)
		$10^{-15} - 10^{-17}$ (COMET I-II)
$\text{CR}(\mu - e, \text{Ti})$	4.3×10^{-12} (SINDRUM II)	10^{-18} (PRISM/PRIME)
$\text{CR}(\mu - e, \text{Au})$	7×10^{-13} (SINDRUM II)	–
$\text{CR}(\mu - e, \text{Pb})$	4.6×10^{-11} (SINDRUM II)	–

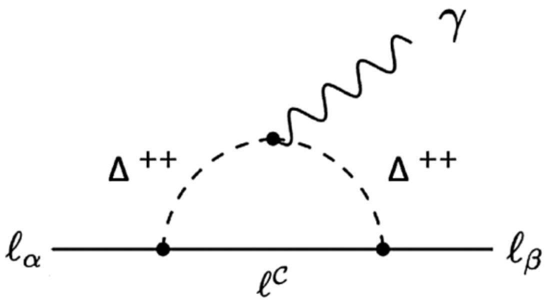
Charged-lepton flavour violation (cLFV)

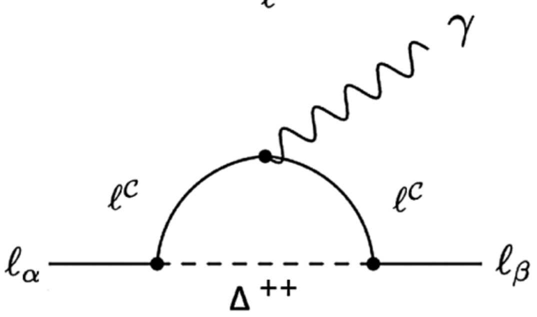
cLFV process	Present limit (90% CL)	Future sensitivity
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13} (MEG)	6×10^{-14} (MEG II)
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8} (BaBar)	3×10^{-9} (Belle II)
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar)	10^{-9} (Belle II)
$\mathrm{BR}(\mu^- \to e^- e^+ e^-)$	1.0×10^{-12} (SINDRUM)	10^{-16} (Mu3e)
$\mathrm{BR}(\tau^- \to e^- e^+ e^-)$	2.7×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\mathrm{BR}(\tau^- \to e^- \mu^+ \mu^-)$	2.7×10^{-8} (Belle)	5×10^{-10} (Belle II)
$\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-)$	1.7×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\mathrm{BR}(\tau^- \to \mu^- e^+ e^-)$	1.8×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\mathrm{BR}(\tau^- \to \mu^+ e^- e^-)$	1.5×10^{-8} (Belle)	3×10^{-10} (Belle II)
$\mathrm{BR}(\tau^- \to \mu^- \mu^+ \mu^-)$	2.1×10^{-8} (Belle)	4×10^{-10} (Belle II)
$\mathrm{CR}(\mu - e, \mathrm{Al})$	–	3×10^{-17} (Mu2e)
		$10^{-15} - 10^{-17}$ (COMET I-II)
$\mathrm{CR}(\mu - e, \mathrm{Ti})$	4.3×10^{-12} (SINDRUM II)	10^{-18} (PRISM/PRIME)
$\mathrm{CR}(\mu - e, \mathrm{Au})$	7×10^{-13} (SINDRUM II)	–
$\mathrm{CR}(\mu - e, \mathrm{Pb})$	4.6×10^{-11} (SINDRUM II)	–

Contributions to cLFV: Higgs triplet

$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$

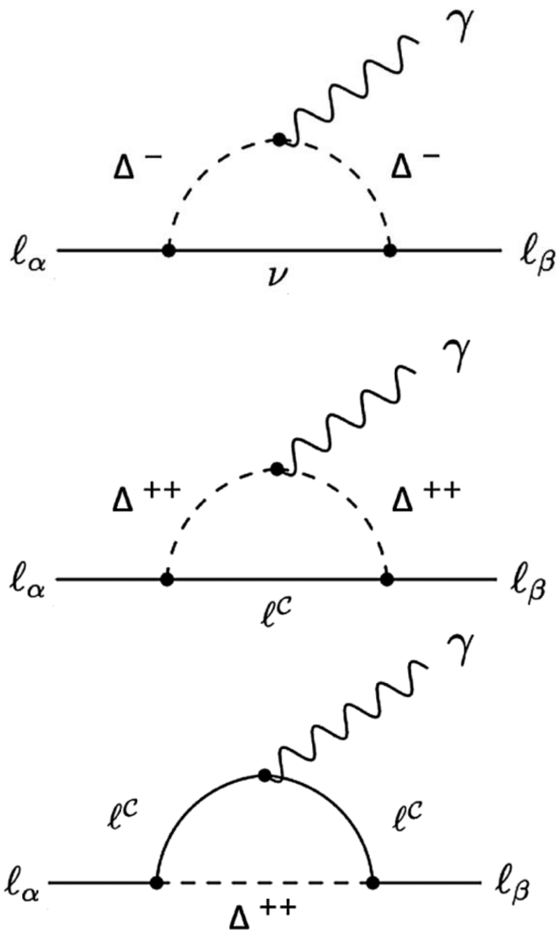






Contributions to cLFV: Higgs triplet

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

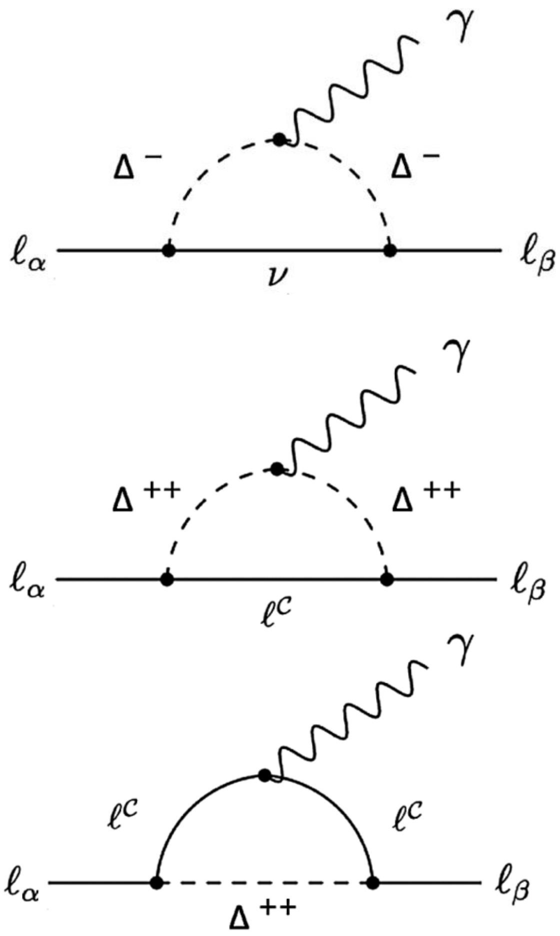


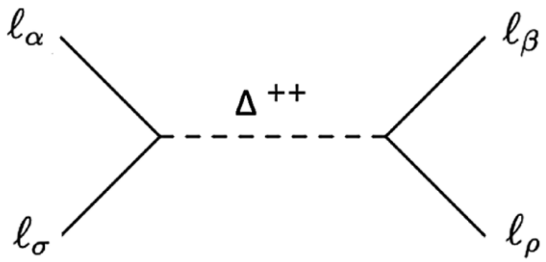
$$\propto \left|(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}\right|^2$$

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

$$\mathrm{BR}(\ell_\alpha^- \to \ell_\beta^- \ell_\sigma^+ \ell_\rho^-)$$

Diagrams from: 2203.06362

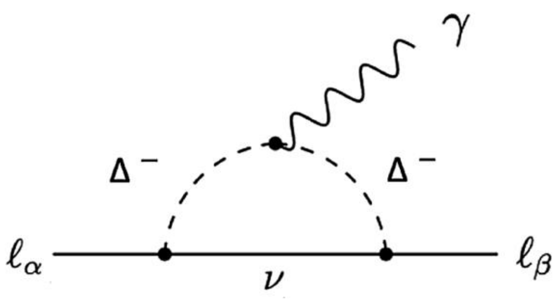


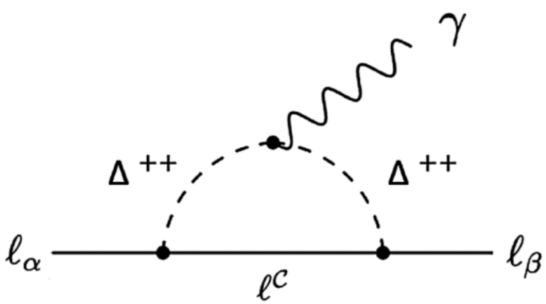


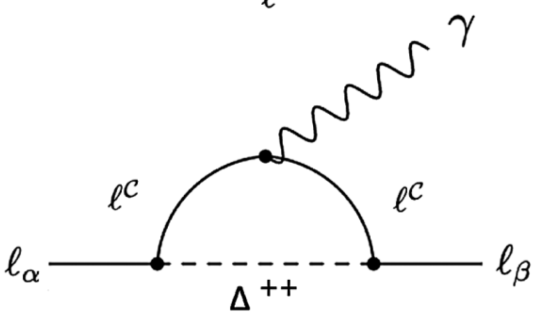
$$\propto \left|(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}\right|^2$$

Contributions to cLFV: Higgs triplet

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

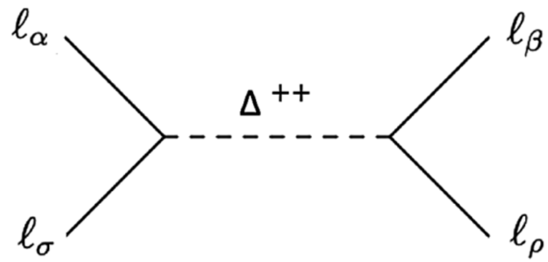






$$\propto \left|(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}\right|^2$$

$$\mathrm{BR}(\ell_\alpha^- \to \ell_\beta^- \ell_\sigma^+ \ell_\rho^-)$$

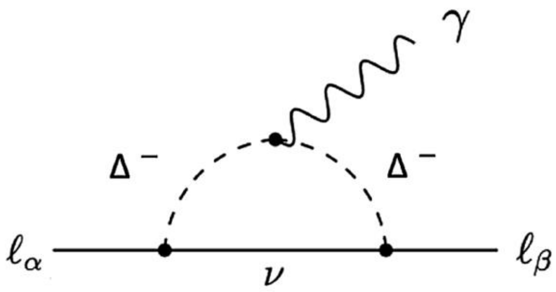


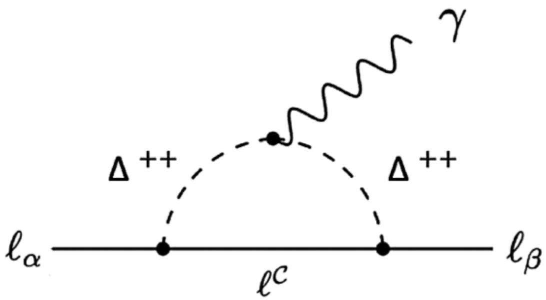
Diagrams from: 2203.06362

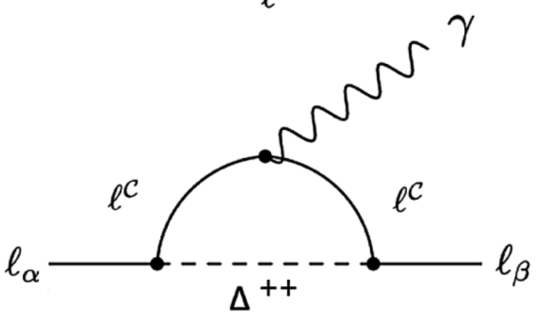
$$\propto \left|(\mathbf{Y}_\Delta)_{\alpha\sigma}\right|^2 \left|(\mathbf{Y}_\Delta)_{\beta\rho}\right|^2$$

Contributions to cLFV: Higgs triplet

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

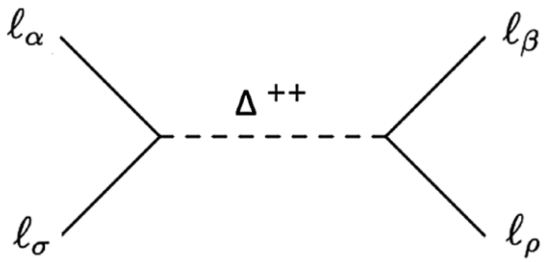






$$\propto |(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}|^2$$

$$\mathrm{BR}(\ell_\alpha^- \to \ell_\beta^- \ell_\sigma^+ \ell_\rho^-)$$



Diagrams from: 2203.06362

$$\propto |(\mathbf{Y}_\Delta)_{\alpha\sigma}|^2 |(\mathbf{Y}_\Delta)_{\beta\rho}|^2$$

- For all symmetry cases:

$$\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger \sim \begin{pmatrix} \times & 0 & 0 \\ . & \times & 0 \\ . & . & \times \end{pmatrix}$$

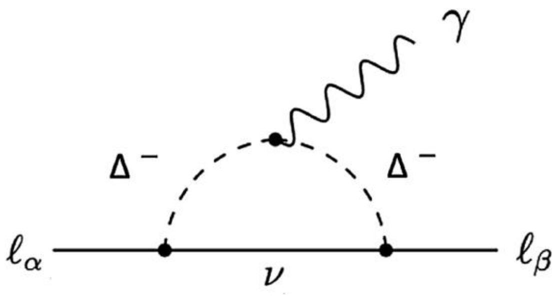
Diagonal

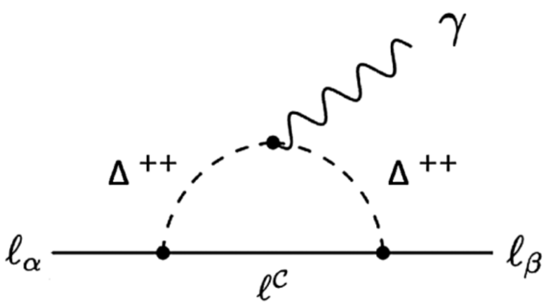
$$(\mathbf{Y}_\Delta)_{\alpha\beta}$$

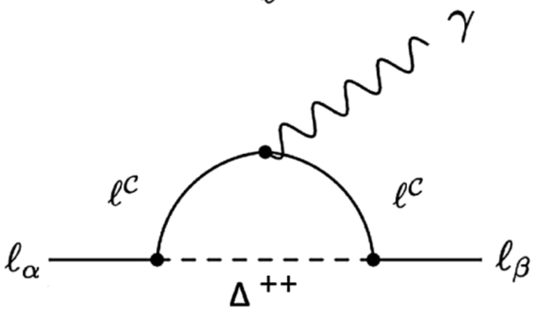
The two couplings in $\mathbf{Y}_\Delta$ have no common index

Contributions to cLFV: Higgs triplet

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

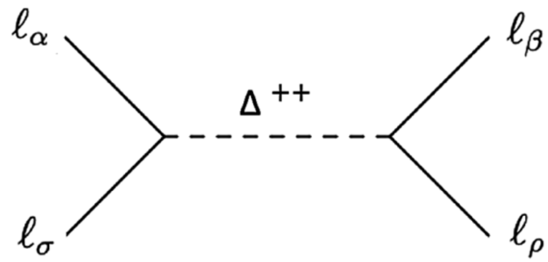






$$\propto |(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}|^2$$

$$\mathrm{BR}(\ell_\alpha^- \to \ell_\beta^- \ell_\sigma^+ \ell_\rho^-)$$



Diagrams from: 2203.06362

$$\propto |(\mathbf{Y}_\Delta)_{\alpha\sigma}|^2 |(\mathbf{Y}_\Delta)_{\beta\rho}|^2$$

- For all symmetry cases:

$$\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger \sim \begin{pmatrix} \times & 0 & 0 \\ . & \times & 0 \\ . & . & \times \end{pmatrix}$$

Diagonal

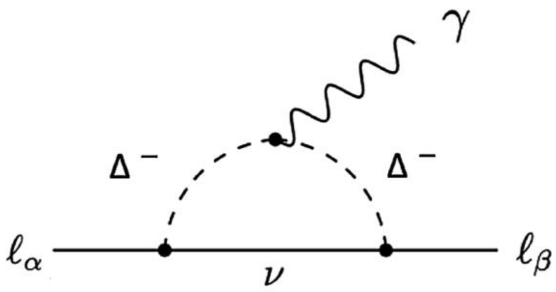
$$(\mathbf{Y}_\Delta)_{\alpha\beta}$$

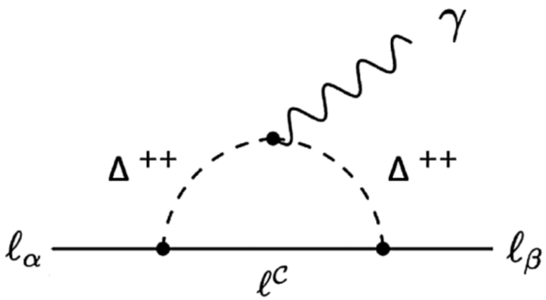
The two couplings in $\mathbf{Y}_\Delta$ have no common index

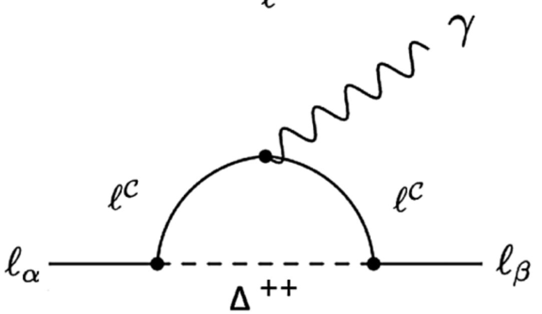
There is no radiative decay, μ-e conversion, nor $l_\alpha \longrightarrow 3\ l_\beta$

Contributions to cLFV: Higgs triplet

$$\mathrm{BR}\left(\ell_\alpha \to \ell_\beta \gamma\right)$$

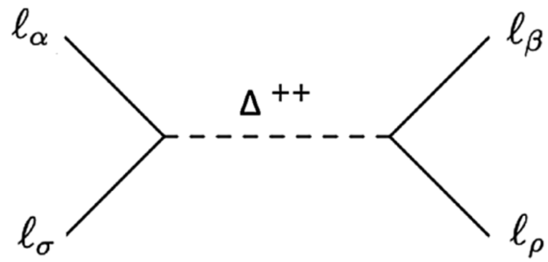






$$\propto \left|(\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger)_{\alpha\beta}\right|^2$$

$$\mathrm{BR}(\ell_\alpha^- \to \ell_\beta^- \ell_\sigma^+ \ell_\rho^-)$$



Diagrams from: 2203.06362

$$\propto \left|(\mathbf{Y}_\Delta)_{\alpha\sigma}\right|^2 \left|(\mathbf{Y}_\Delta)_{\beta\rho}\right|^2$$

- For all symmetry cases:

$$\mathbf{Y}_\Delta \mathbf{Y}_\Delta^\dagger \sim \begin{pmatrix} \times & 0 & 0 \\ . & \times & 0 \\ . & . & \times \end{pmatrix}$$

Diagonal

$$(\mathbf{Y}_\Delta)_{\alpha\beta}$$

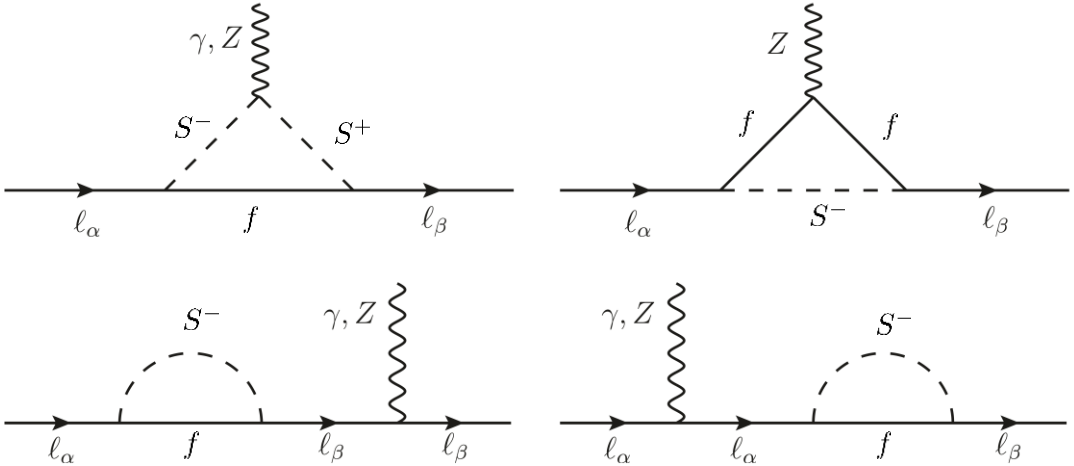
The two couplings in $\mathbf{Y}_\Delta$ have no common index

There is no radiative decay, μ-e conversion, nor $l_\alpha \longrightarrow 3\ l_\beta$

$$\frac{\mathrm{BR}(\tau^- \to \mu^+ e^- e^-)}{1.5 \times 10^{-8}} \approx 35.28 \left(\frac{10\ \mathrm{TeV}}{m_{\Delta^{++}}}\right)^4 \left|(\mathbf{Y}_\Delta)_{ee}\right|^2 \left|(\mathbf{Y}_\Delta)_{\mu\tau}\right|^2$$

$$\frac{\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-)}{1.7 \times 10^{-8}} \approx 29.40 \left(\frac{10\ \mathrm{TeV}}{m_{\Delta^{++}}}\right)^4 \left|(\mathbf{Y}_\Delta)_{\mu\mu}\right|^2 \left|(\mathbf{Y}_\Delta)_{e\tau}\right|^2$$

Contributions to cLFV: Inert doublets

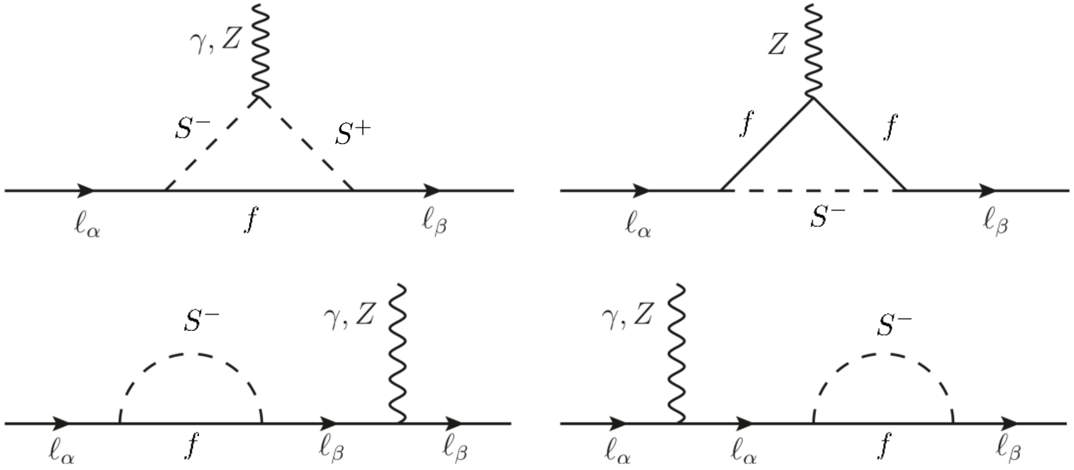


Contributions to cLFV: Inert doublets

Each symmetry case has only two Yukawas and dark charged scalars mix

$$\mathcal{Z}_8^{e-\mu} \qquad \mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \; \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \qquad \begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = \mathbf{R} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}$$

$$\widetilde{\mathbf{Y}}_f^1 = \mathbf{Y}_f^1 \cos\varphi + \mathbf{Y}_f^2 \sin\varphi \; , \; \widetilde{\mathbf{Y}}_f^2 = -\mathbf{Y}_f^1 \sin\varphi + \mathbf{Y}_f^2 \cos\varphi$$

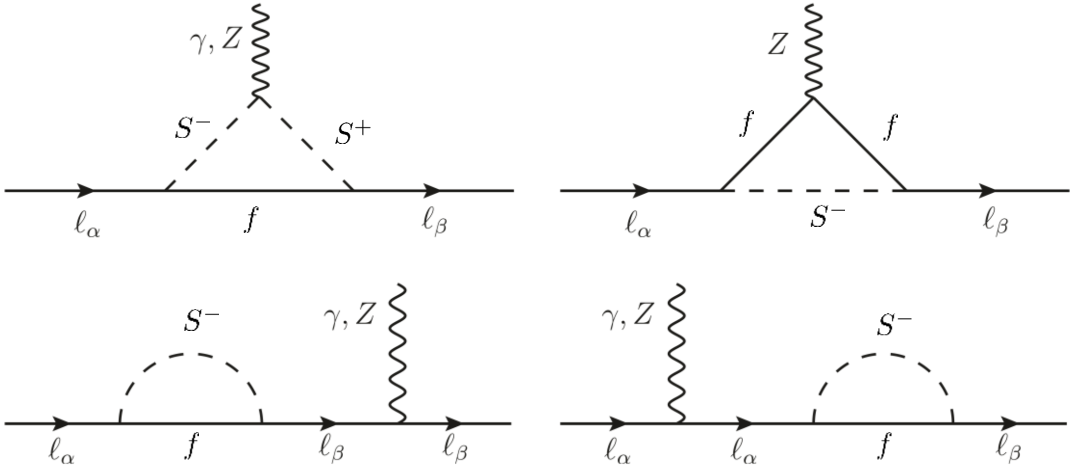


Contributions to cLFV: Inert doublets

Each symmetry case has only two Yukawas and dark charged scalars mix

$$\mathcal{Z}_8^{e-\mu} \qquad \mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \; \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \qquad \begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = \mathbf{R} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}$$

$$\widetilde{\mathbf{Y}}_f^1 = \mathbf{Y}_f^1 \cos\varphi + \mathbf{Y}_f^2 \sin\varphi \;, \; \widetilde{\mathbf{Y}}_f^2 = -\mathbf{Y}_f^1 \sin\varphi + \mathbf{Y}_f^2 \cos\varphi$$



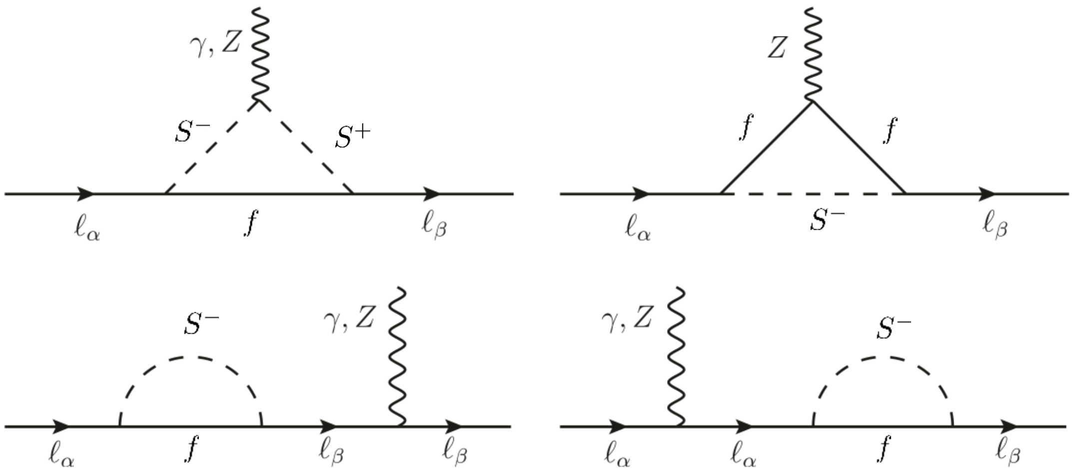
For each $Z_8^{\alpha-\beta}$ only $l_\alpha \to 3\, l_\beta$, $l_\alpha \to l_\beta\, \gamma$, and μ-e conversion for $Z_8^{e-\mu}$

Contributions to cLFV: Inert doublets

Each symmetry case has only two Yukawas and dark charged scalars mix

$$\mathcal{Z}_8^{e-\mu} \qquad \mathbf{Y}_f^1 = \begin{pmatrix} y_e \\ 0 \\ 0 \end{pmatrix} \; \mathbf{Y}_f^2 = \begin{pmatrix} 0 \\ y_\mu \\ 0 \end{pmatrix} \qquad \begin{pmatrix} \eta_1^+ \\ \eta_2^+ \end{pmatrix} = \mathbf{R} \begin{pmatrix} S_1^+ \\ S_2^+ \end{pmatrix}$$

$$\widetilde{\mathbf{Y}}_f^1 = \mathbf{Y}_f^1 \cos\varphi + \mathbf{Y}_f^2 \sin\varphi \; , \; \widetilde{\mathbf{Y}}_f^2 = -\mathbf{Y}_f^1 \sin\varphi + \mathbf{Y}_f^2 \cos\varphi$$



For each $Z_8^{\alpha-\beta}$ only $l_\alpha \to 3\, l_\beta$, $l_\alpha \to l_\beta\, \gamma$, and μ-e conversion for $Z_8^{e-\mu}$

Due to flavour symmetry the allowed contributions to cLFV from both sectors do not overlap

Cases	Type-II seesaw	Scotogenic
$\mathcal{Z}_8^{e-\mu}$ (B_4)	$\tau^- \to \mu^+ e^- e^-$	$\mu \to e\gamma,\ \mu \to 3e,\ \mu - e$ conversion
$\mathcal{Z}_8^{e-\tau}$ (B_3)	$\tau^- \to \mu^+ e^- e^-$	$\tau \to e\gamma,\ \tau \to 3e$
$\mathcal{Z}_8^{\mu-\tau}$ (A_1)	$\tau^- \to e^+ \mu^- \mu^-$	$\tau \to \mu\gamma,\ \tau \to 3\mu$

Numerical analysis

Packages

Numerical analysis

Packages

SARAH — **Model implementation**

Numerical analysis

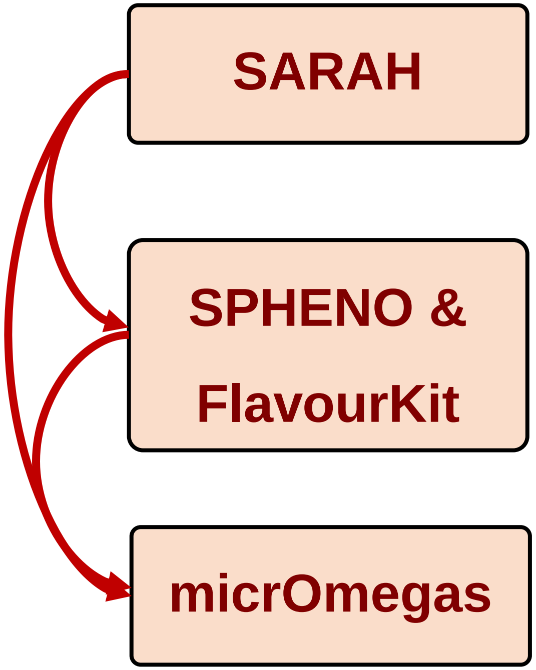
Packages

SARAH — **Model implementation**

SPHENO & FlavourKit — **Masses, mixing, BRs, CRs, flavour**

Numerical analysis

Packages



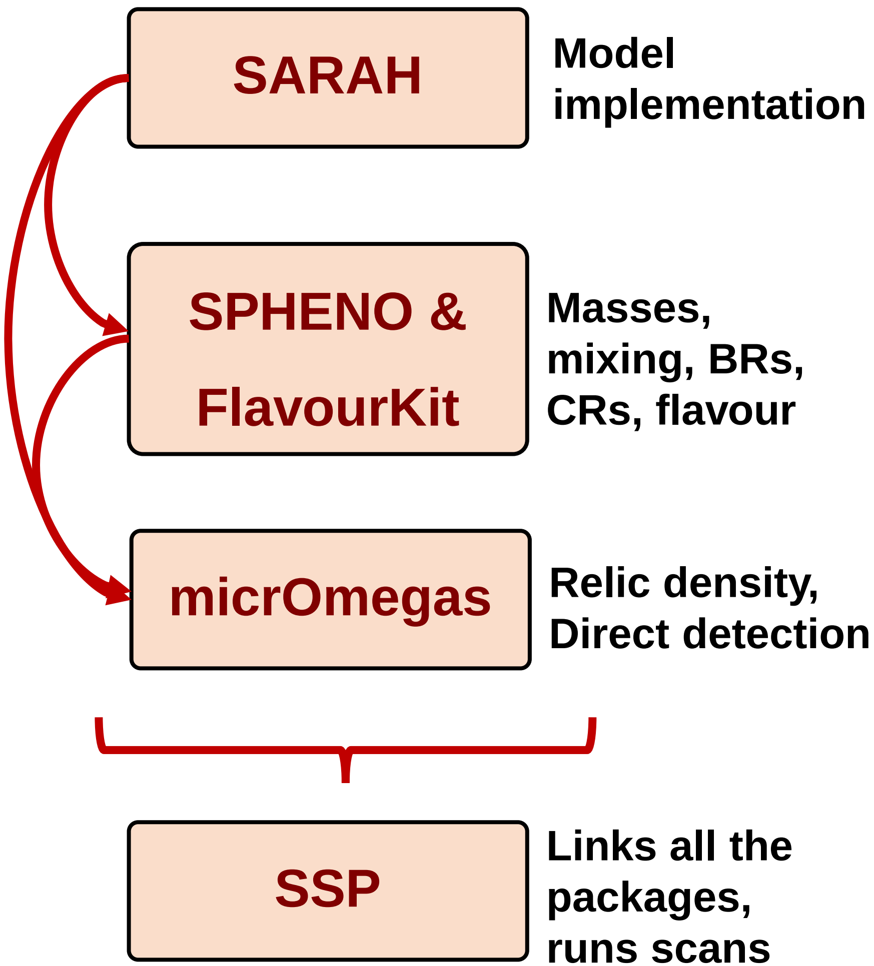
Model implementation

Masses, mixing, BRs, CRs, flavour

Relic density, Direct detection

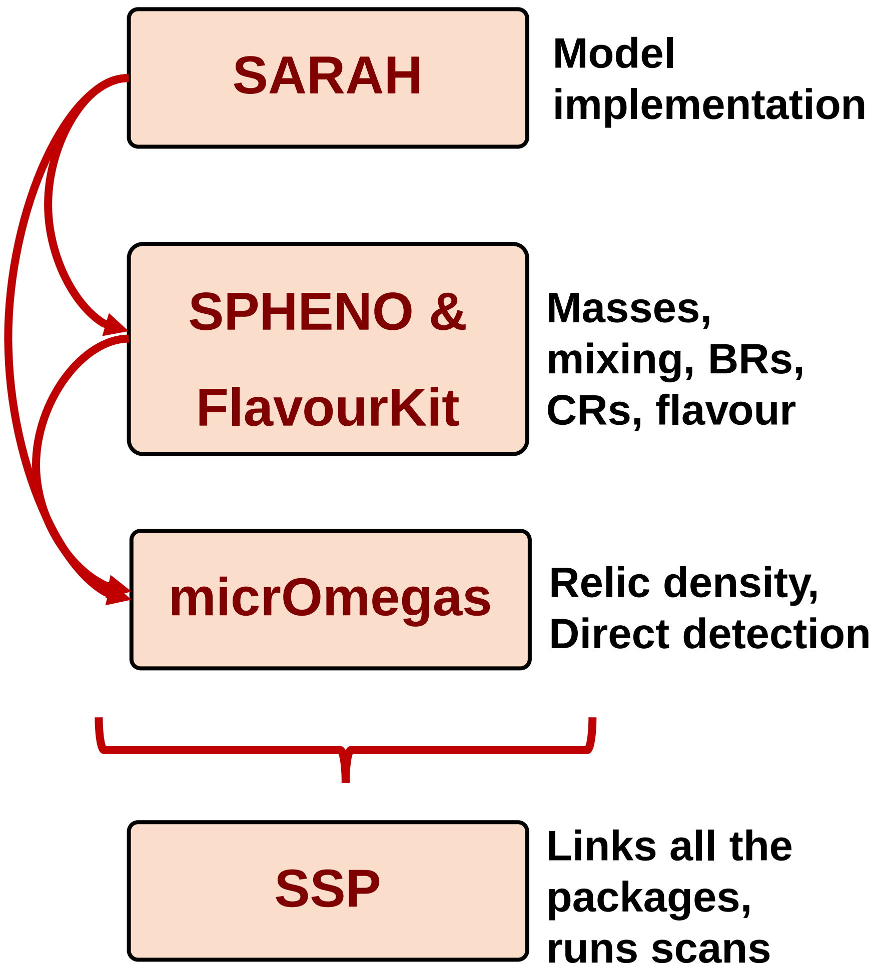
Numerical analysis

Packages



Numerical analysis

Packages

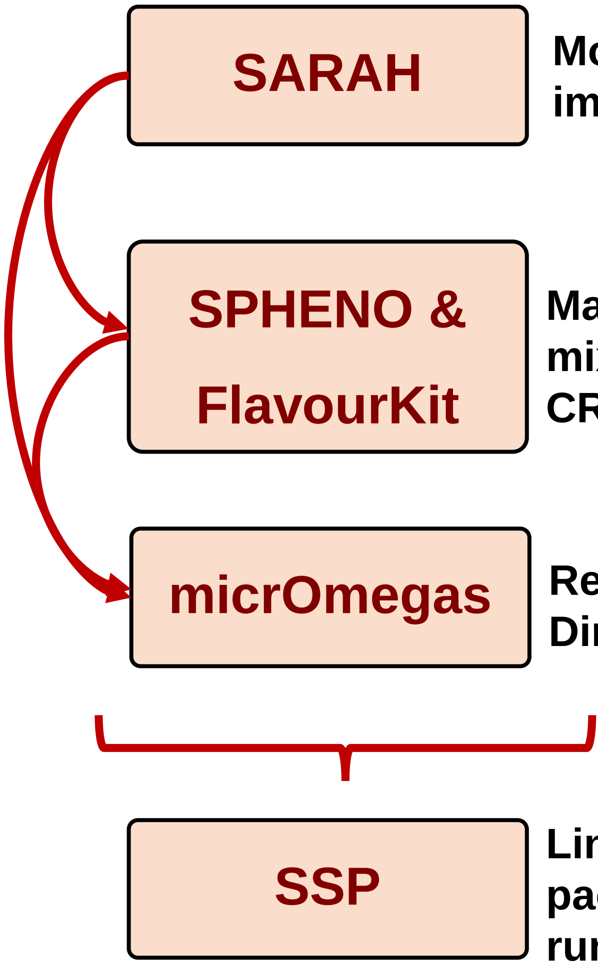


Parameter scan and constraints

Parameters	Scan range
M_f	$[10, 1000]$ (GeV)
$m^2_{\eta_1}, m^2_{\eta_2}$	$[10^2, 1000^2]$ (GeV^2)
$\lvert\mu_{12}\rvert$	$[10^{-6}, 10^3]$ (GeV)
$\lvert\lambda_3\rvert,\ \lvert\lambda_4\rvert,\ \lvert\lambda'_3\rvert,\ \lvert\lambda'_4\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-12}, 1]$

Numerical analysis

Packages



SARAH: **Model implementation**

SPHENO & FlavourKit: **Masses, mixing, BRs, CRs, flavour**

micrOmegas: **Relic density, Direct detection**

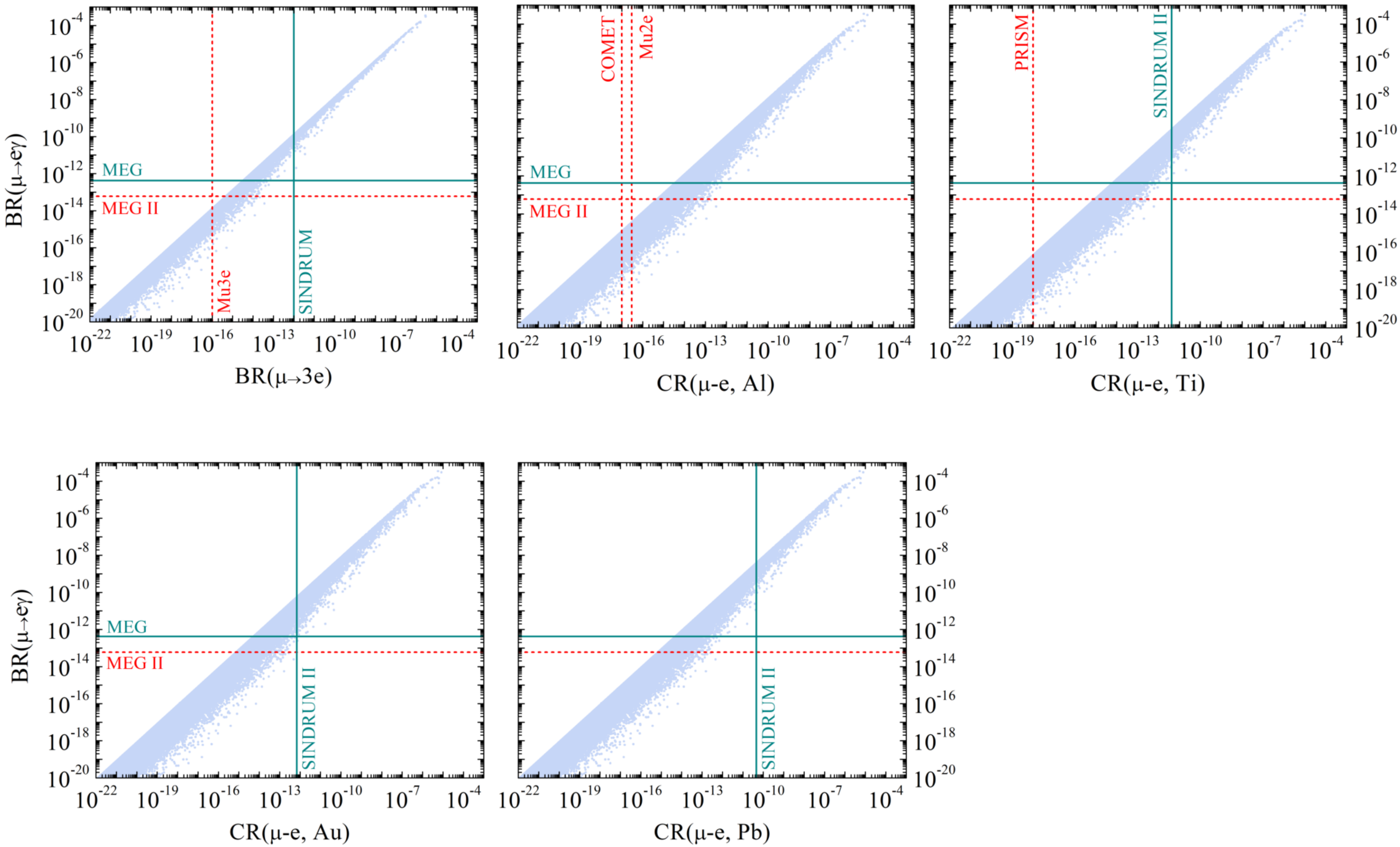
SSP: **Links all the packages, runs scans**

Parameter scan and constraints

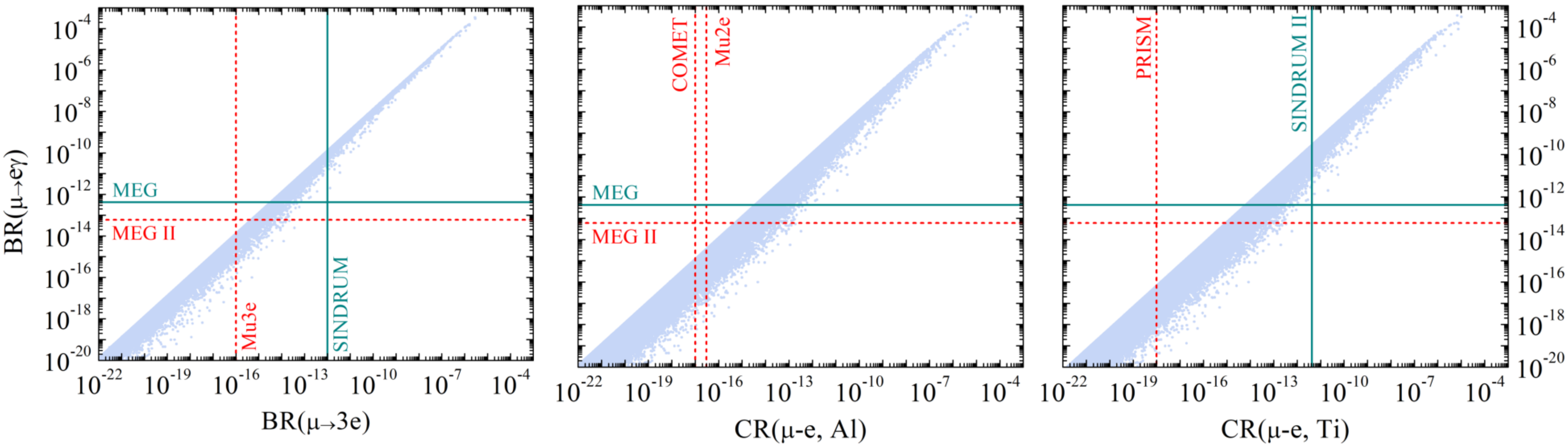
Parameters	Scan range
M_f	$[10, 1000]$ (GeV)
$m^2_{\eta_1}, m^2_{\eta_2}$	$[10^2, 1000^2]$ (GeV^2)
$\lvert\mu_{12}\rvert$	$[10^{-6}, 10^3]$ (GeV)
$\lvert\lambda_3\rvert,\ \lvert\lambda_4\rvert,\ \lvert\lambda'_3\rvert,\ \lvert\lambda'_4\rvert$	$[10^{-5}, 1]$
$\lvert\lambda_5\rvert$	$[10^{-12}, 1]$

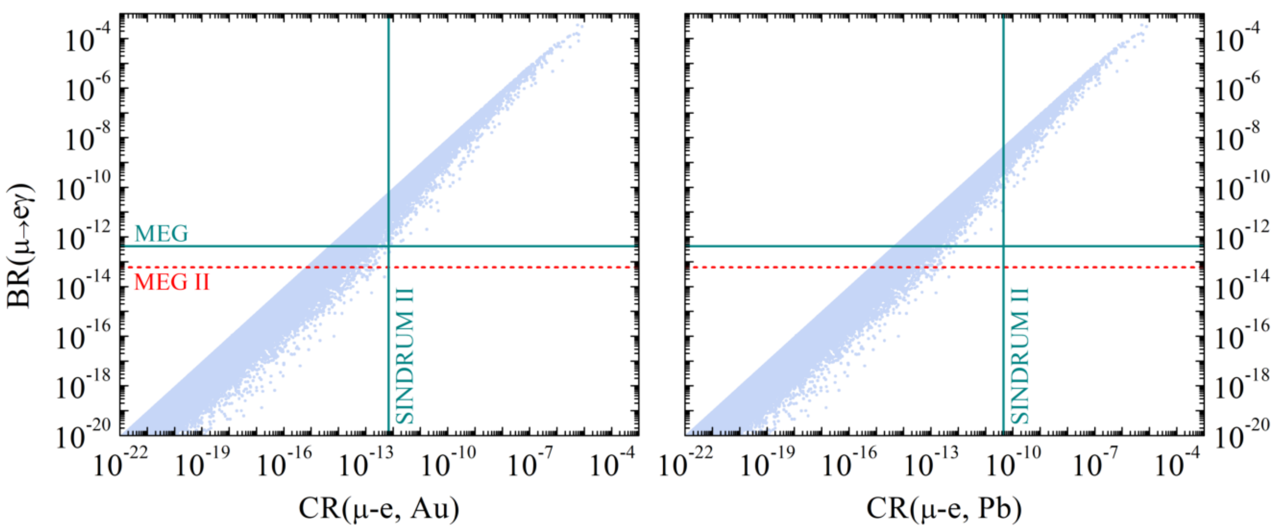
- Perturbativity of couplings
- Higgs triplet decoupled and does not mix
- Compatibility with neutrino data through parameter reconstruction
- **Focus on case $Z_8^{e-\mu}$ NO**

Scotogenic sector contribution to muon cLFV



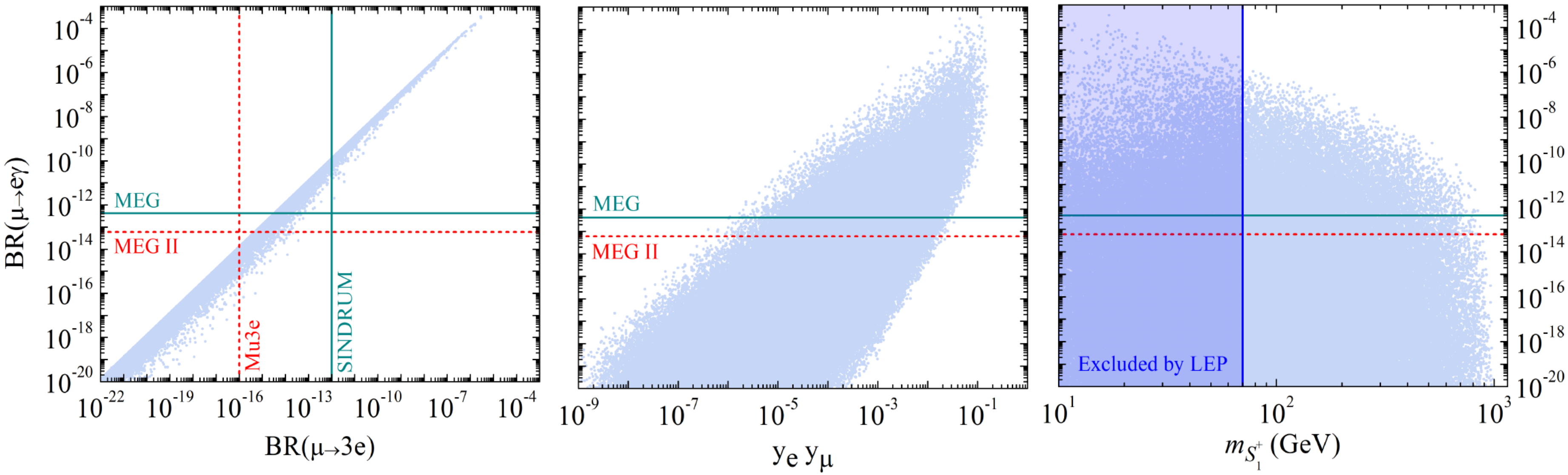
Scotogenic sector contribution to muon cLFV



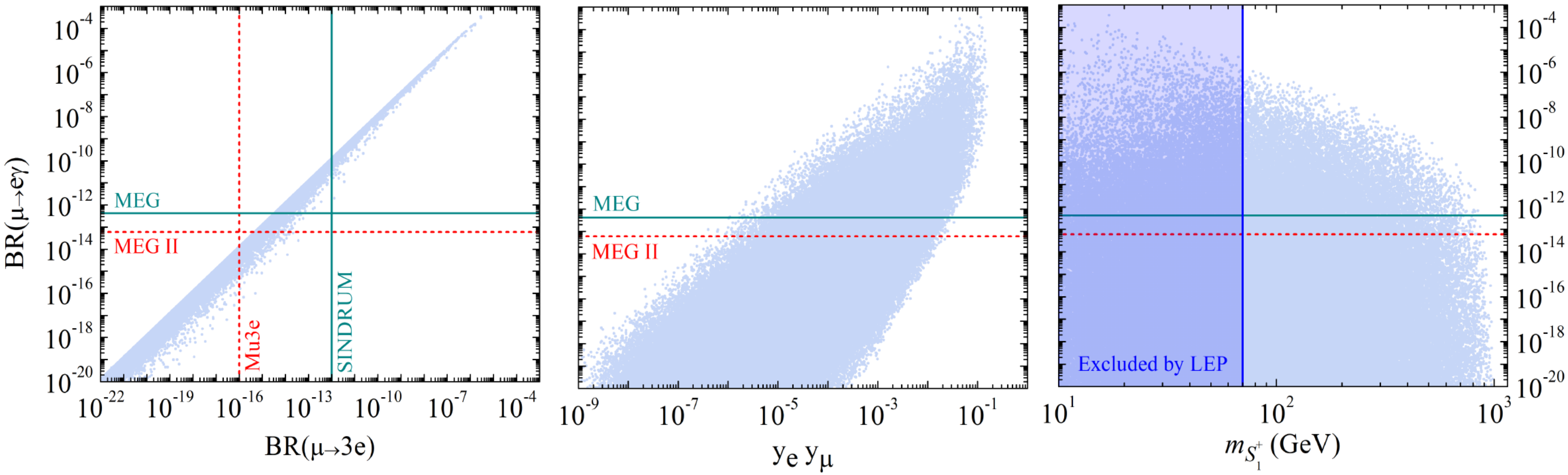


- Large fraction of **parameter space is excluded by current cLFV constraints**
- There is still a large number of points that evade current and future bounds

Scotogenic sector contribution to muon cLFV

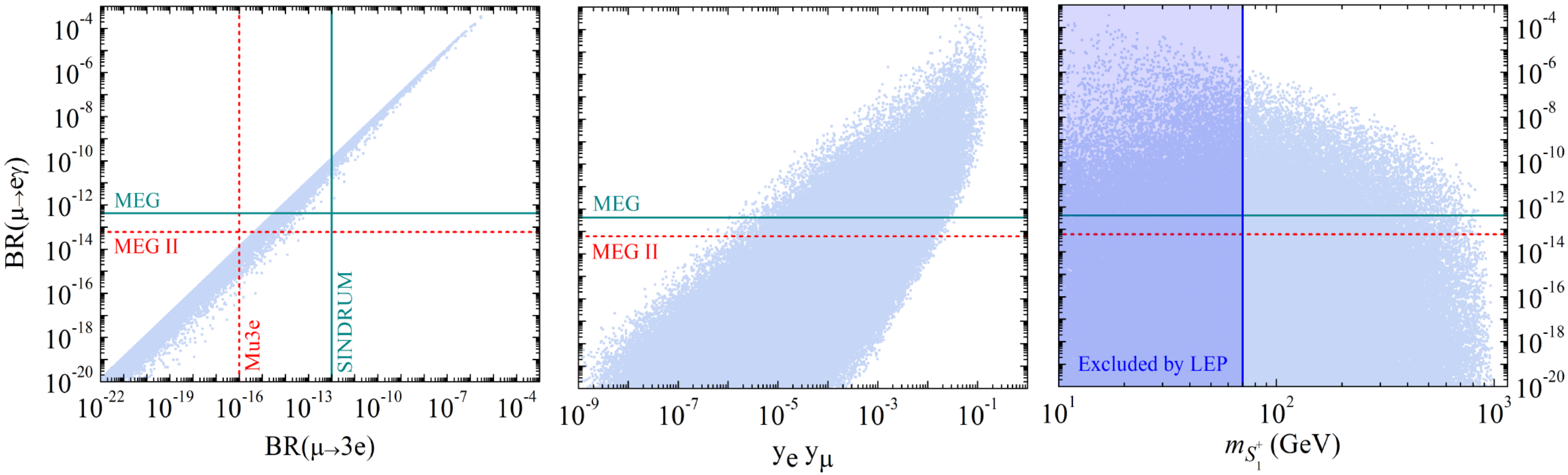


Scotogenic sector contribution to muon cLFV



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

Scotogenic sector contribution to muon cLFV



- Scotogenic cLFV processes are **mediated at loop level by dark charged scalars**

$$\frac{\mathrm{BR}(\mu\to e\gamma)}{4.2\times10^{-13}} \approx 1.98\times10^{10}\left(\frac{70\ \mathrm{GeV}}{m_{S_1^+}}\right)^4 \sin^2(2\varphi)\,y_e^2 y_\mu^2 \left|g\left(\frac{M_f^2}{m_{S_1^+}^2}\right)-\frac{m_{S_1^+}^2}{m_{S_2^+}^2}\,g\left(\frac{M_f^2}{m_{S_2^+}^2}\right)\right|^2$$

- Quadratic dependence on the product of Yukawa couplings and BR decreases with increasing dark charged scalar mass

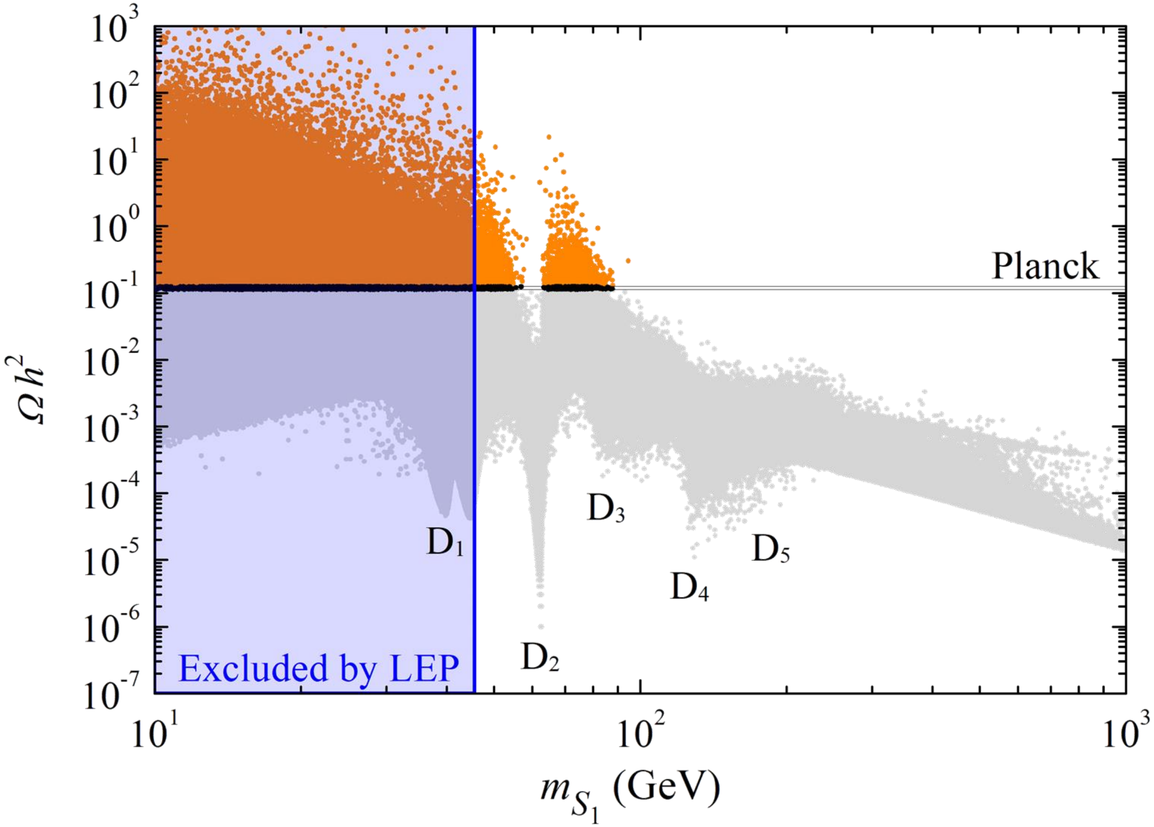
- **Only non-zero thanks to mixing between inert doublets**

Dark matter

Scalar Dark Matter: Relic density

The case of **scalar DM:**

lightest neutral scalar S_1



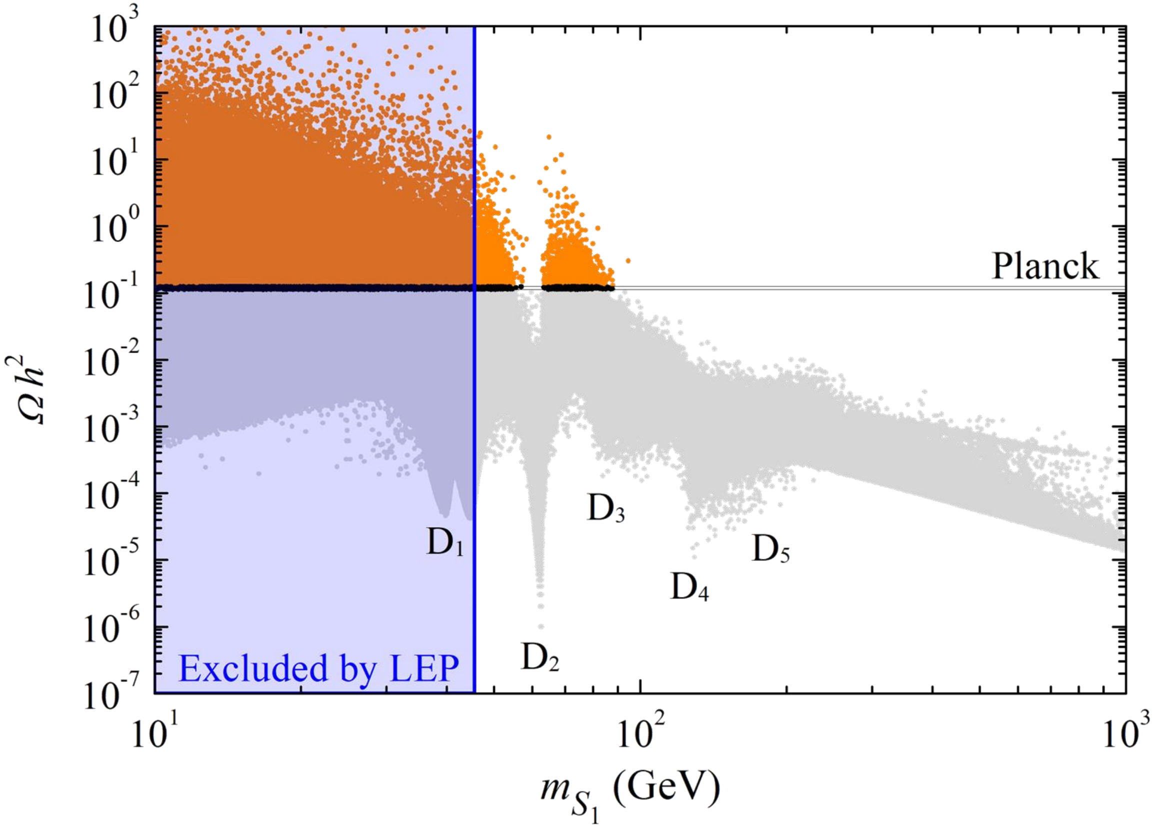
Scalar Dark Matter: Relic density

The case of **scalar DM:**

lightest neutral scalar S_1

LEP constraint Z-boson decay width

$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$



Scalar Dark Matter: Relic density

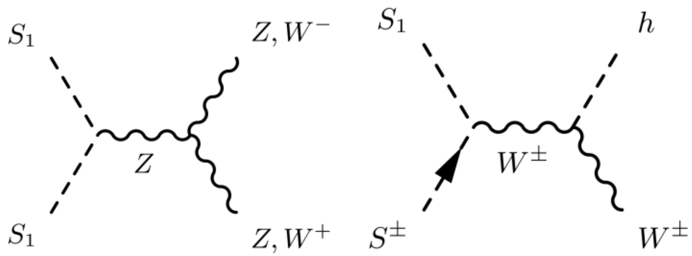
The case of **scalar DM:**

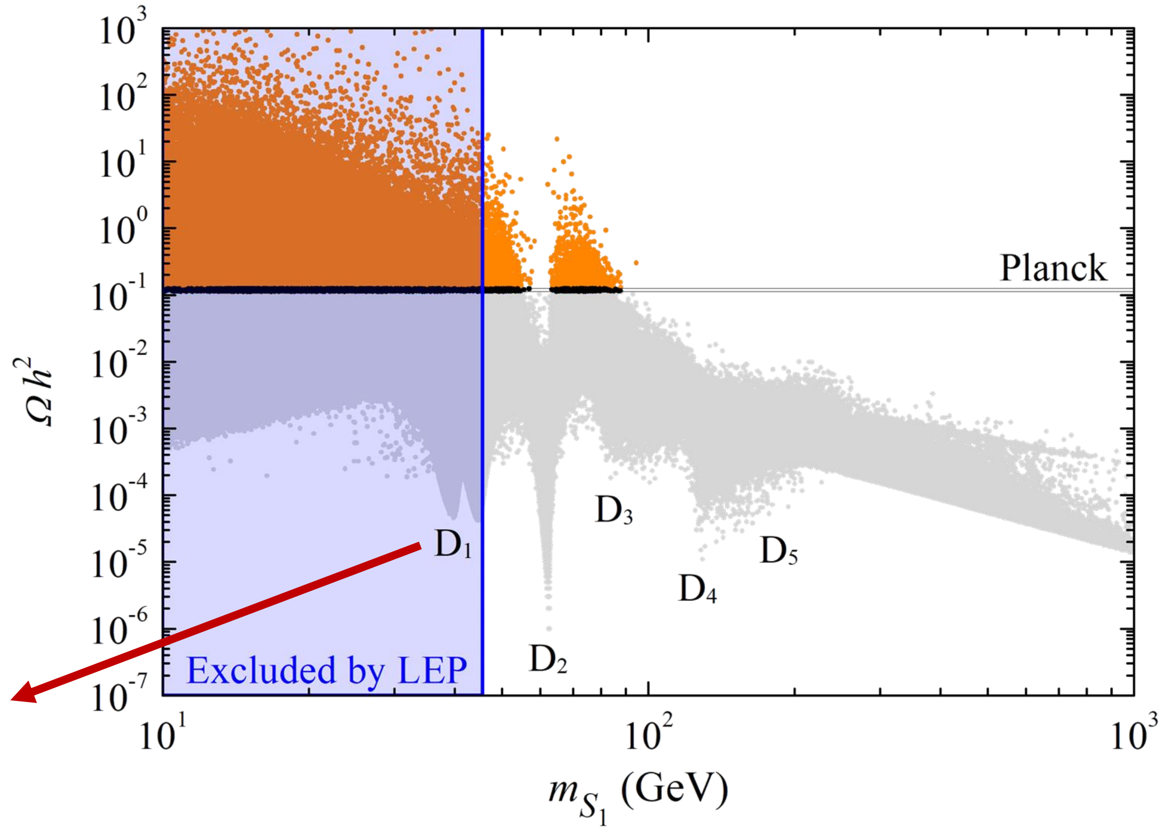
lightest neutral scalar S_1

LEP constraint Z-boson decay width

$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$

Z,W-boson s-channel





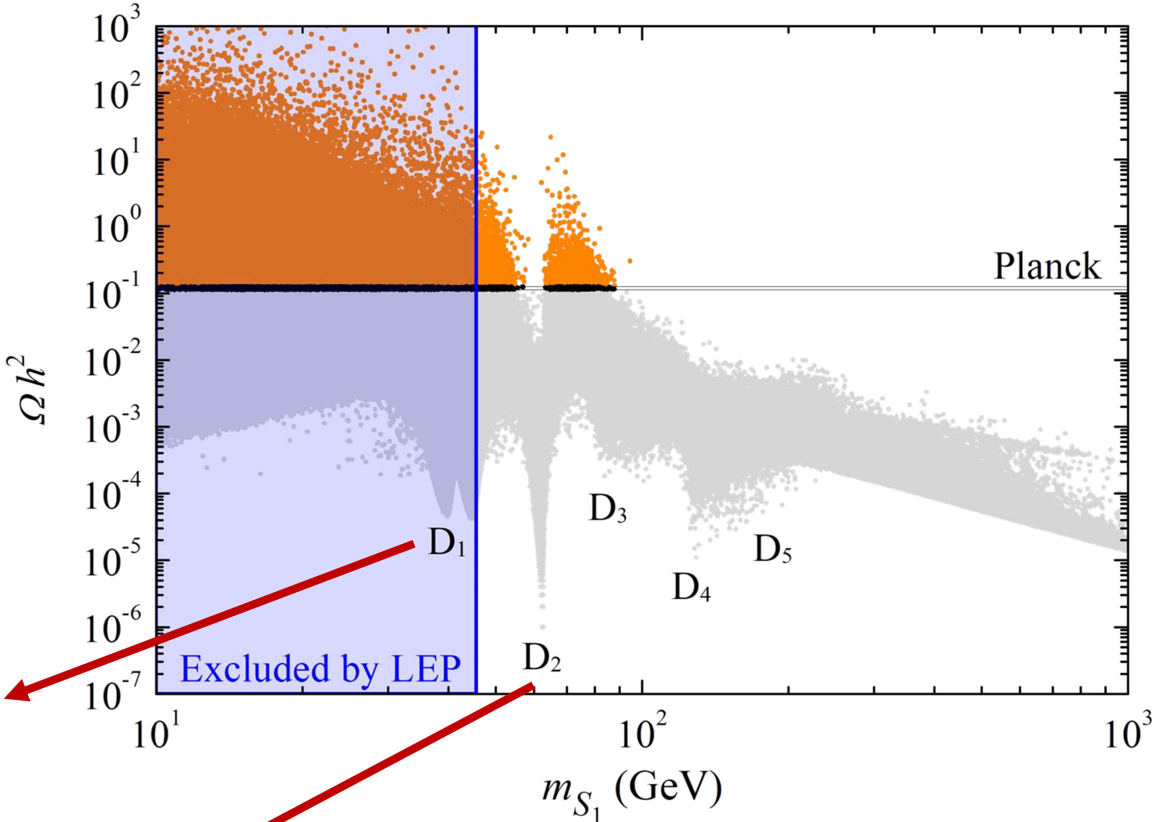
Scalar Dark Matter: Relic density

The case of **scalar DM:**

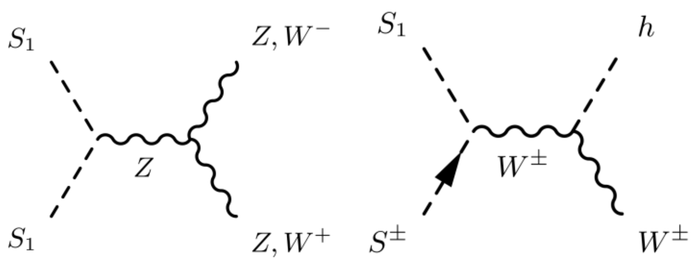
lightest neutral scalar S_1

LEP constraint Z-boson decay width

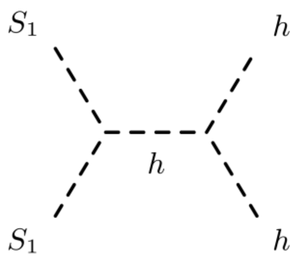
$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$



Z,W-boson s-channel



Higgs s-channel



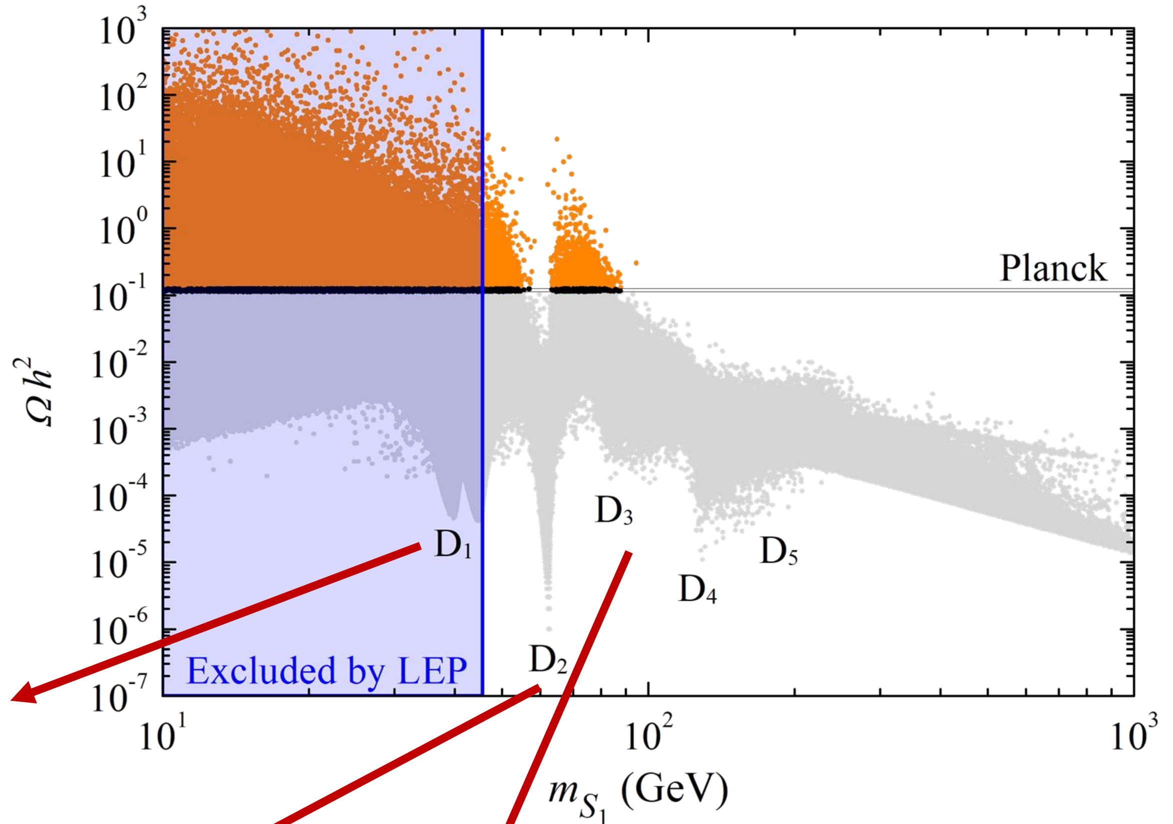
Scalar Dark Matter: Relic density

The case of **scalar DM:**

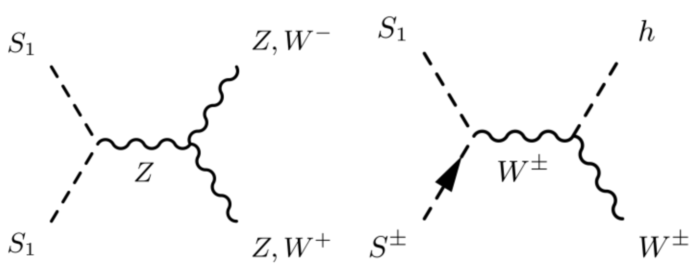
lightest neutral scalar S_1

LEP constraint Z-boson decay width

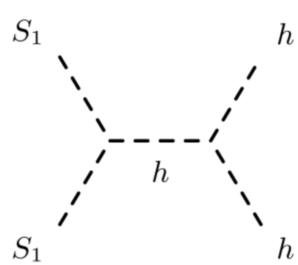
$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$

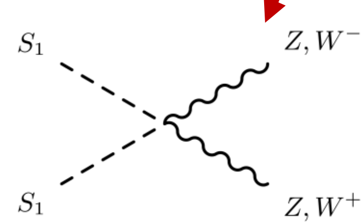


Z,W-boson s-channel



Higgs s-channel





Quartic ínto EW boson

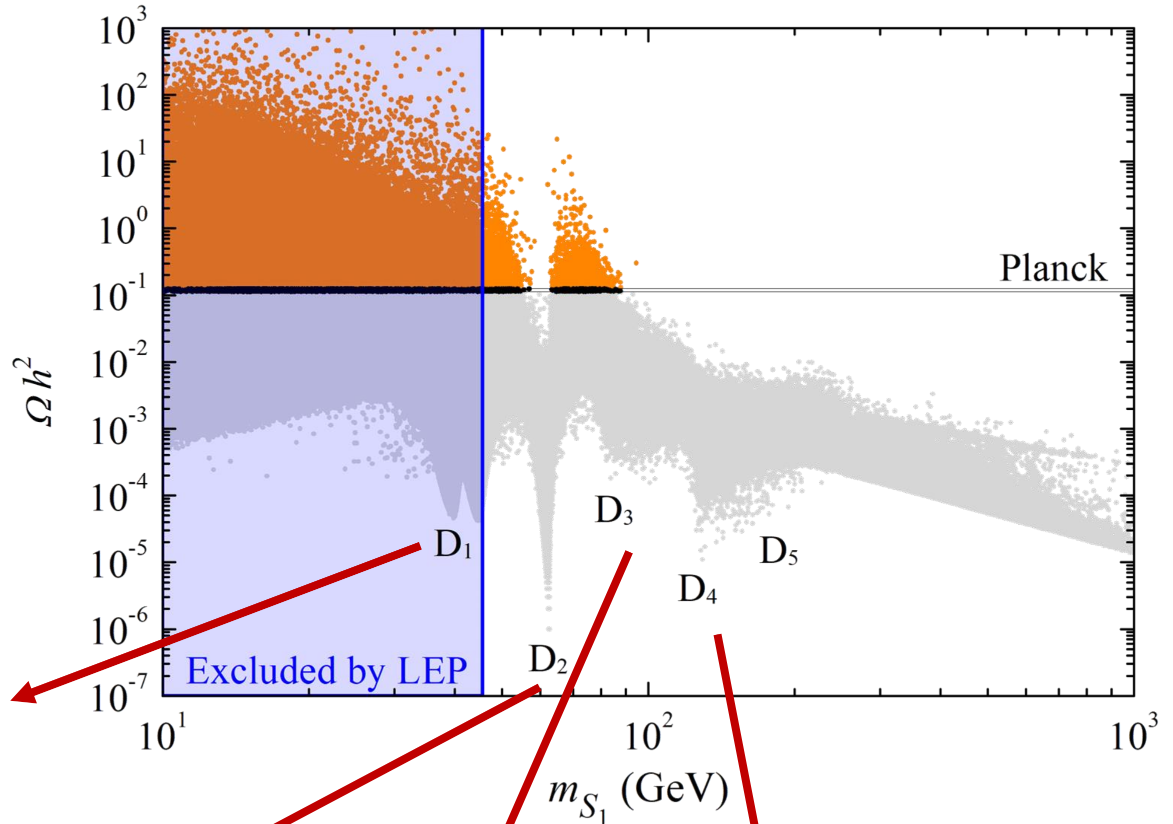
Scalar Dark Matter: Relic density

The case of **scalar DM:**

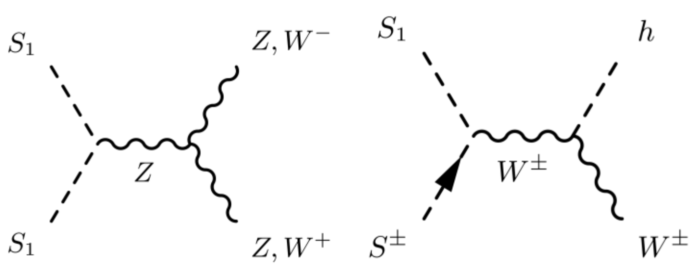
lightest neutral scalar S_1

LEP constraint Z-boson decay width

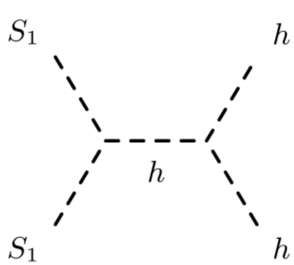
$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$

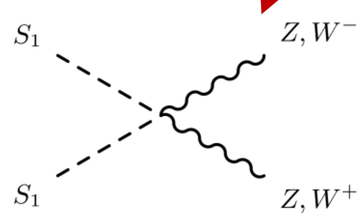


Z,W-boson s-channel

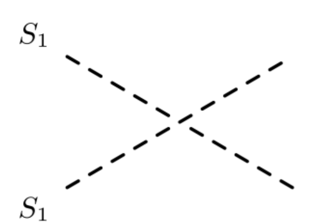


Higgs s-channel





Quartic ínto EW boson



Quartic into Higgs boson

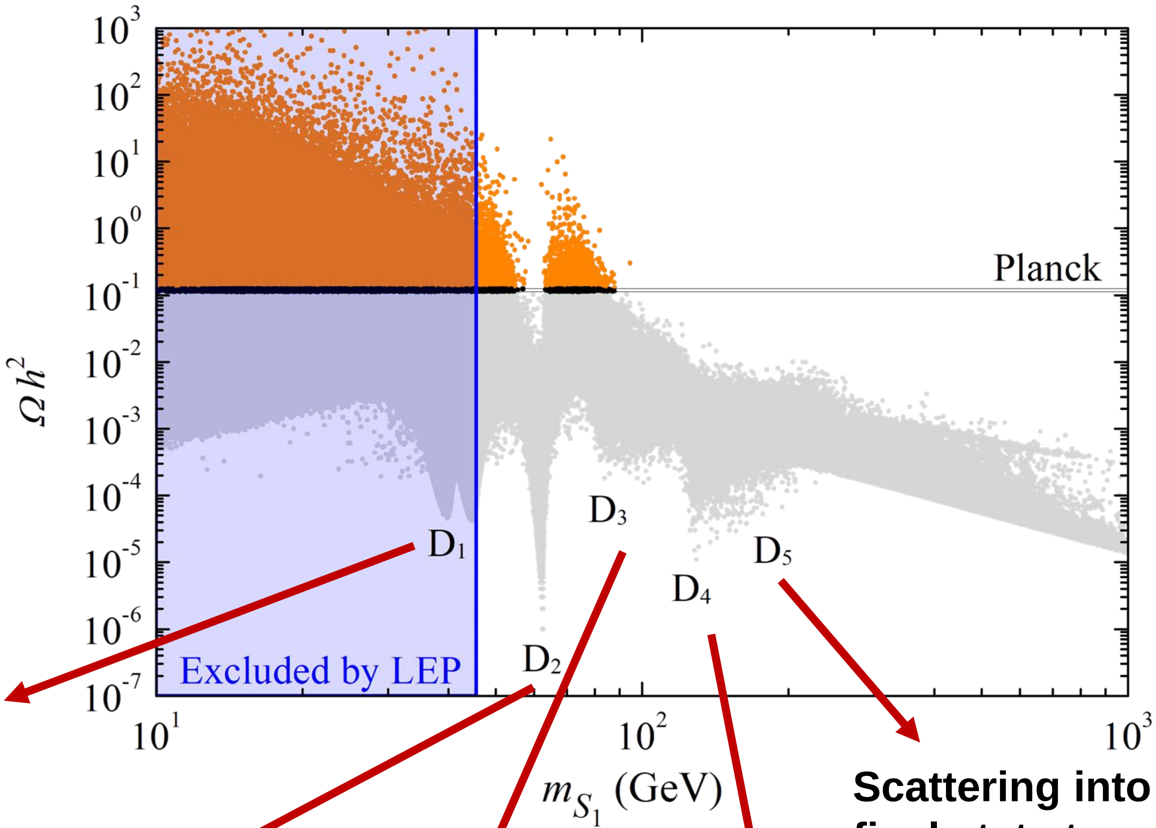
Scalar Dark Matter: Relic density

The case of **scalar DM:**

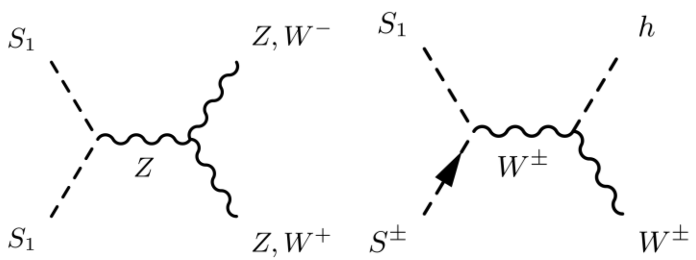
lightest neutral scalar S_1

LEP constraint Z-boson decay width

$$m_{S_1} > m_Z/2 \simeq 45.6 \text{ GeV}$$

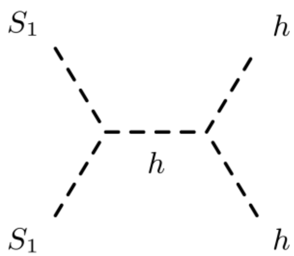


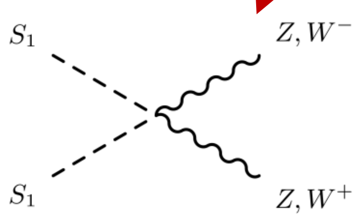
Z,W-boson s-channel



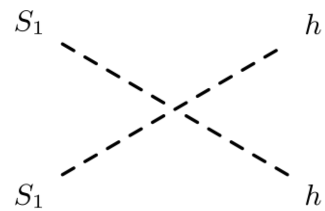
Scattering into final state top quarks

Higgs s-channel





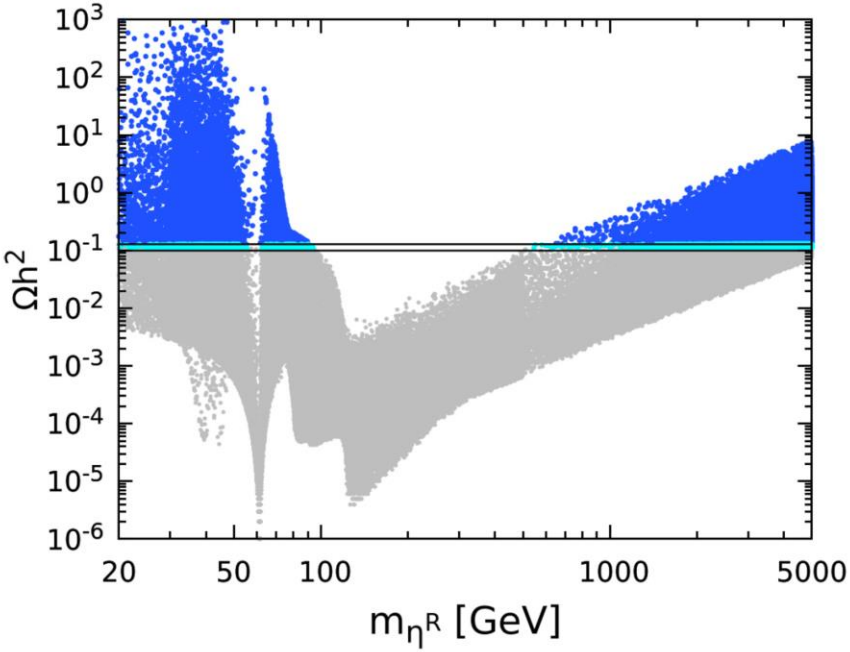
Quartic ínto EW boson

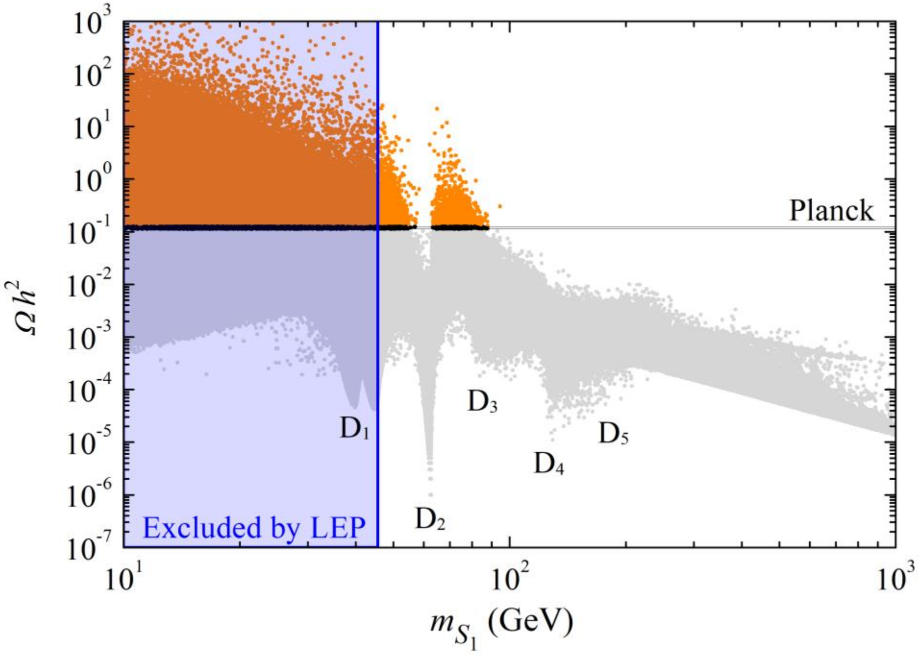


Quartic into Higgs boson

Scalar Dark Matter: Relic density

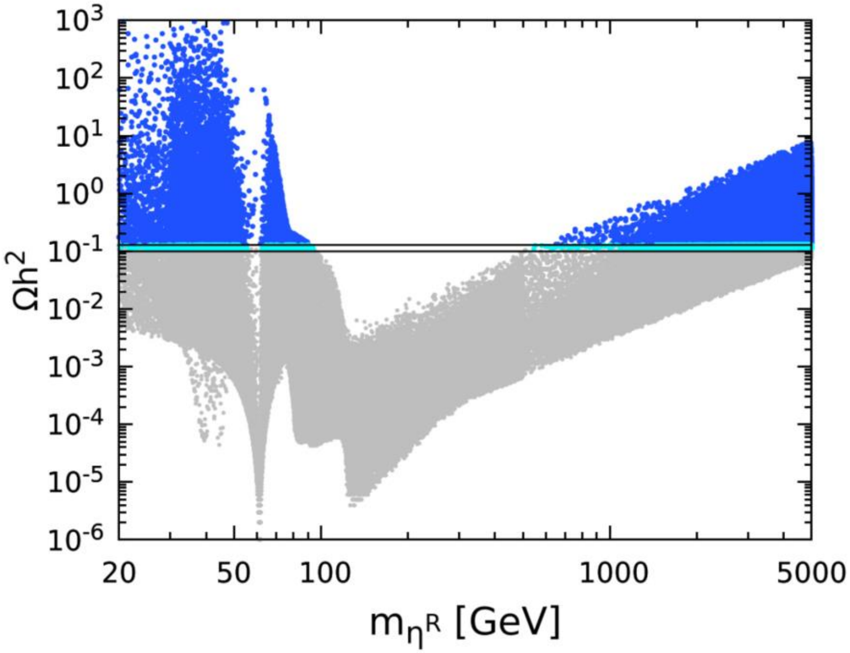
Mandal, Srivastava and Valle 2104.13401

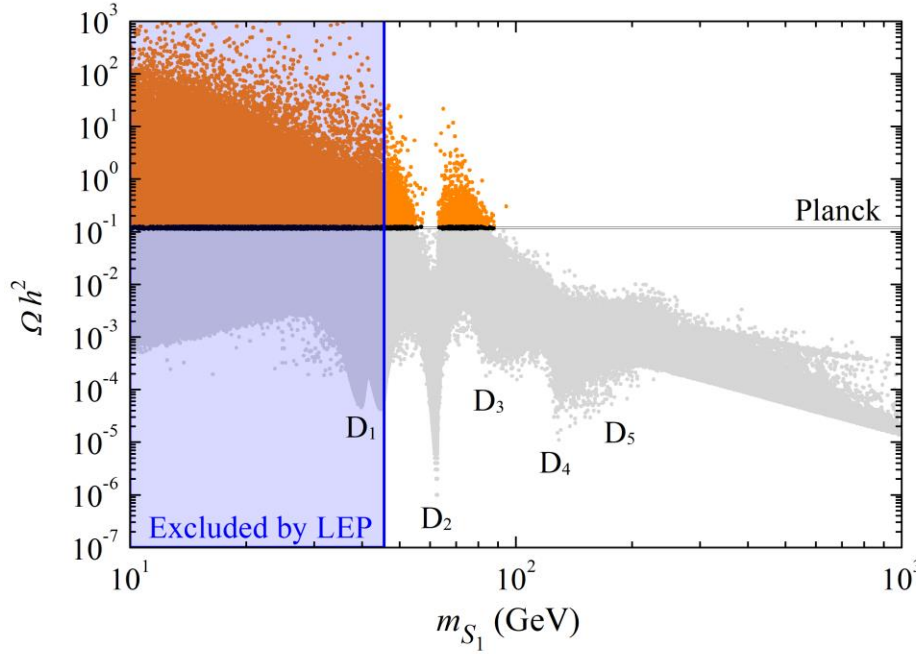




Scalar Dark Matter: Relic density

Mandal, Srivastava and Valle 2104.13401

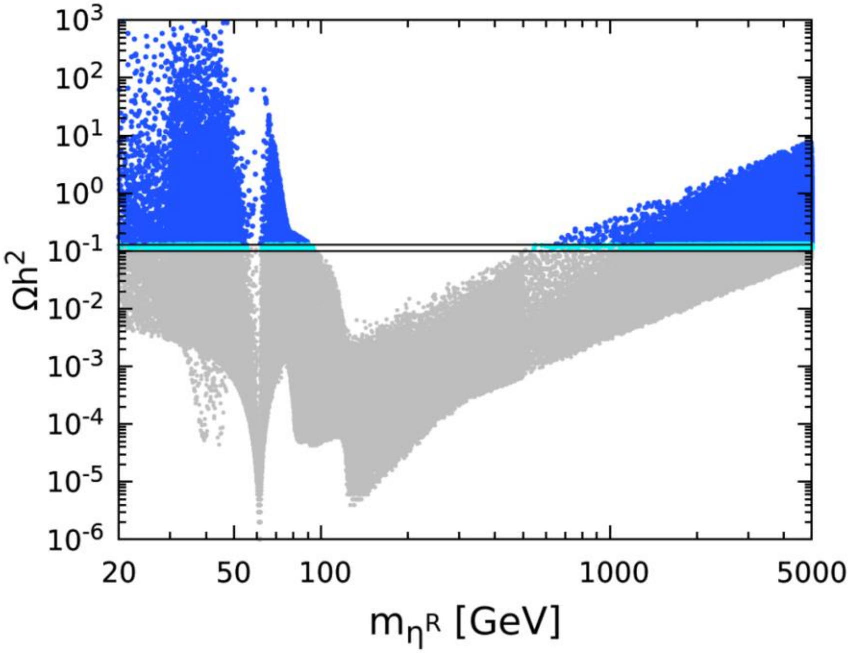


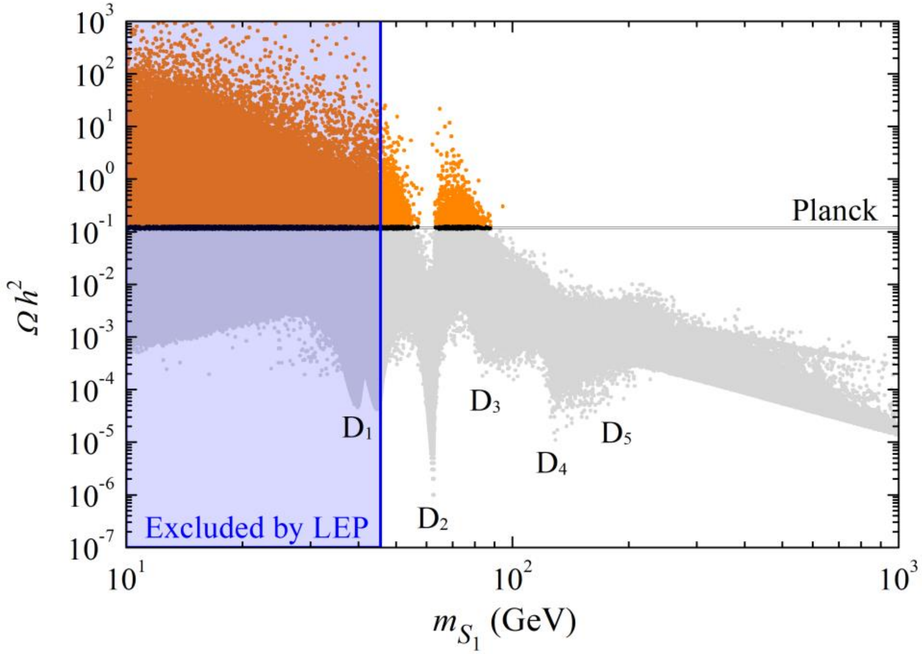


- In **scoto-type-I seesaw and inert doublet model** a high-mass region **above 500 GeV allows for correct relic density** since the thermally averaged cross section drops with $\boldsymbol{\alpha\ 1/m_{\mathrm{DM}}^2}$

Scalar Dark Matter: Relic density

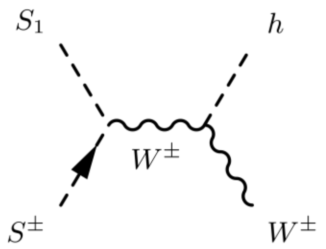
Mandal, Srivastava and Valle 2104.13401

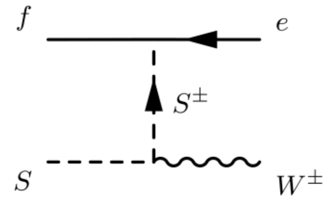




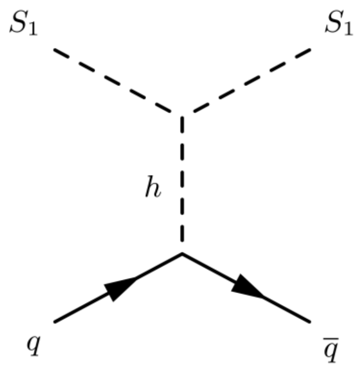
- In **scoto-type-I seesaw and inert doublet model** a high-mass region **above 500 GeV allows for correct relic density** since the thermally averaged cross section drops with $\boldsymbol{\alpha\ 1/m_{\rm DM}^2}$

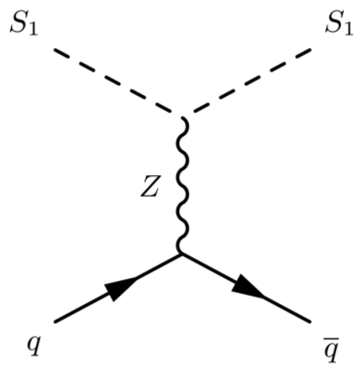
- In our scenario we have **two-inert doublets** leading to **co-annihilation channels** increasing the thermally averaged cross section e.g.



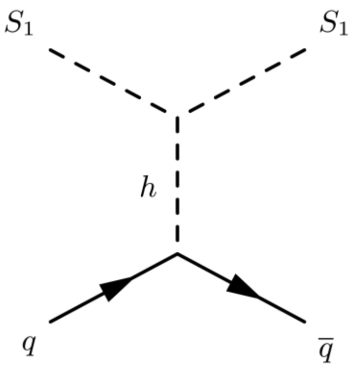


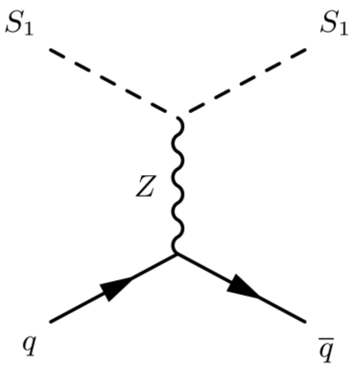
Scalar Dark Matter: Direct detection





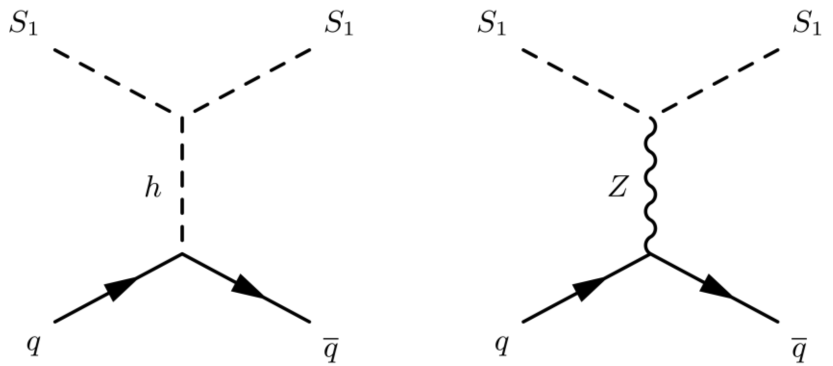
Scalar Dark Matter: Direct detection



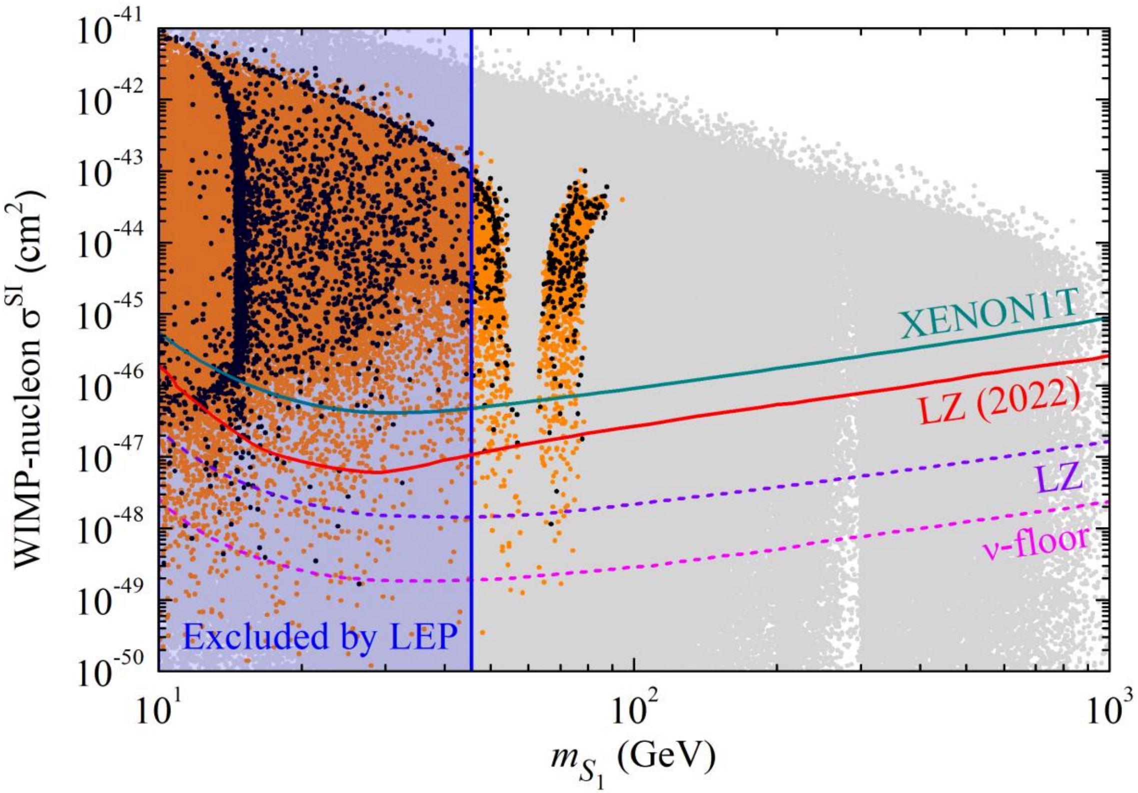


- Tree-level contribution to **WIMP-nucleon spin-independent elastic cross section**

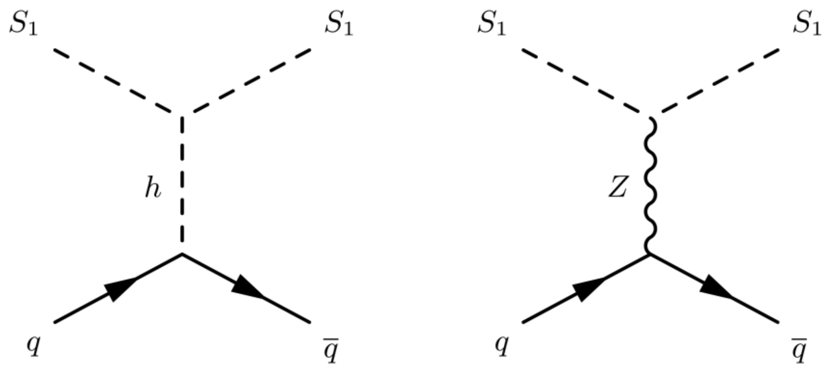
Scalar Dark Matter: Direct detection



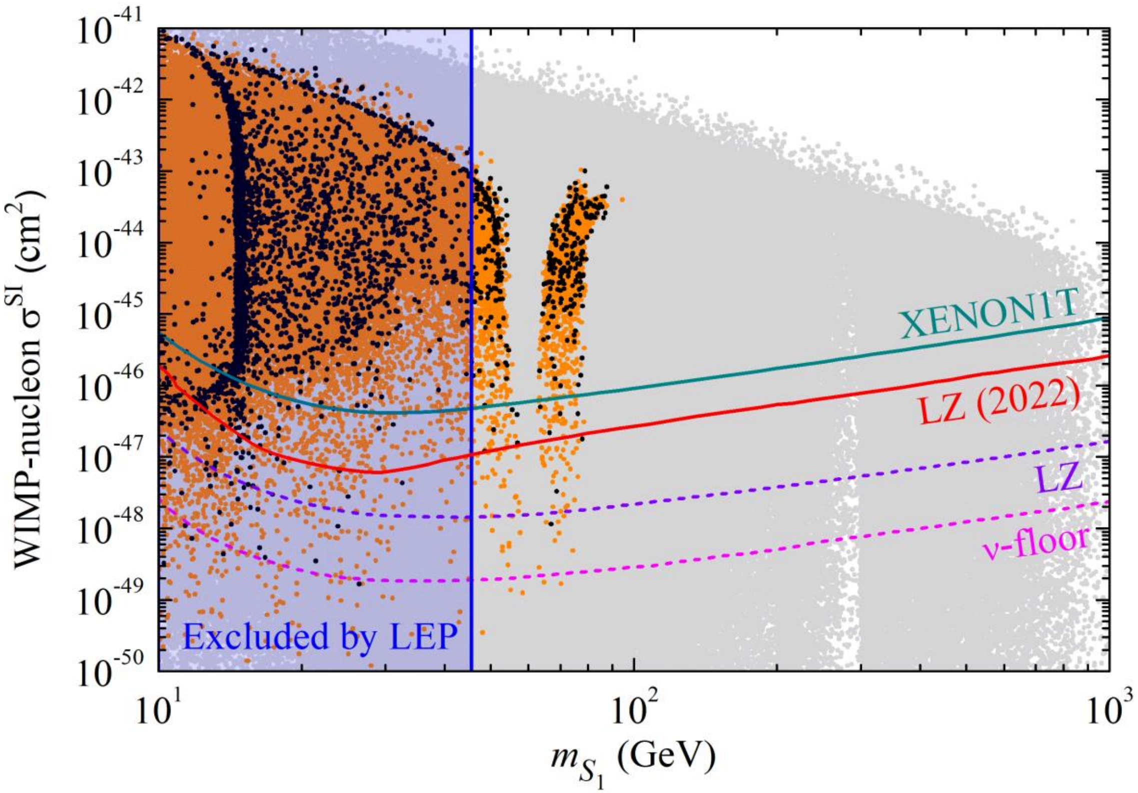
- Tree-level contribution to **WIMP-nucleon spin-independent elastic cross section**



Scalar Dark Matter: Direct detection



- Tree-level contribution to **WIMP-nucleon spin-independent elastic cross section**



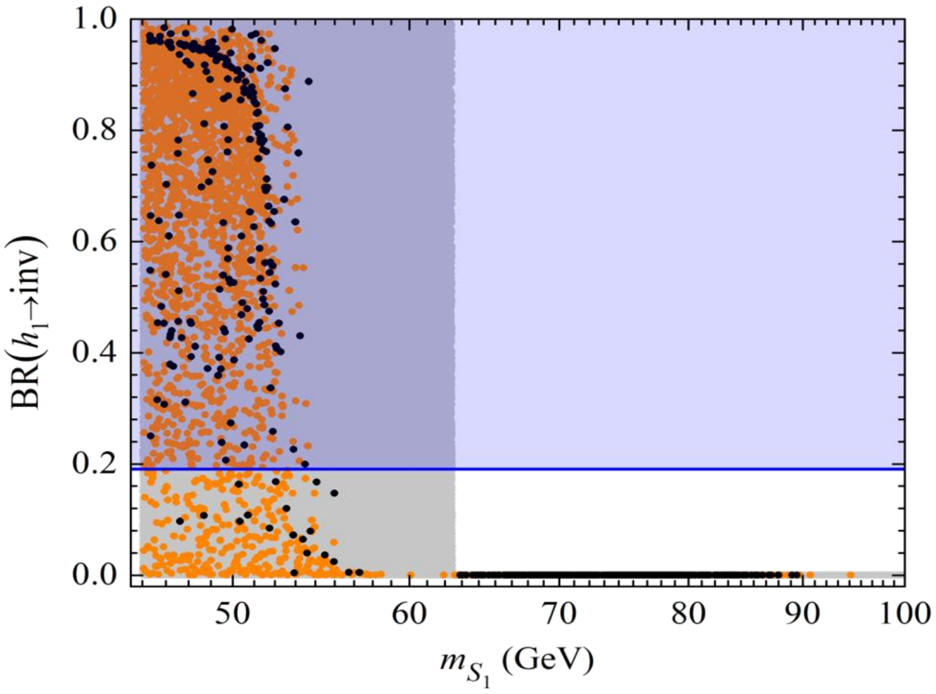
- **Updated result:**

-The current most stringent constraint from WIMP direct detection experiment on spin-independent elastic cross section comes from **Lux-Zeplin (LZ) collaboration 2022**

- **Rules out the mass region between 46 and 61 GeV**

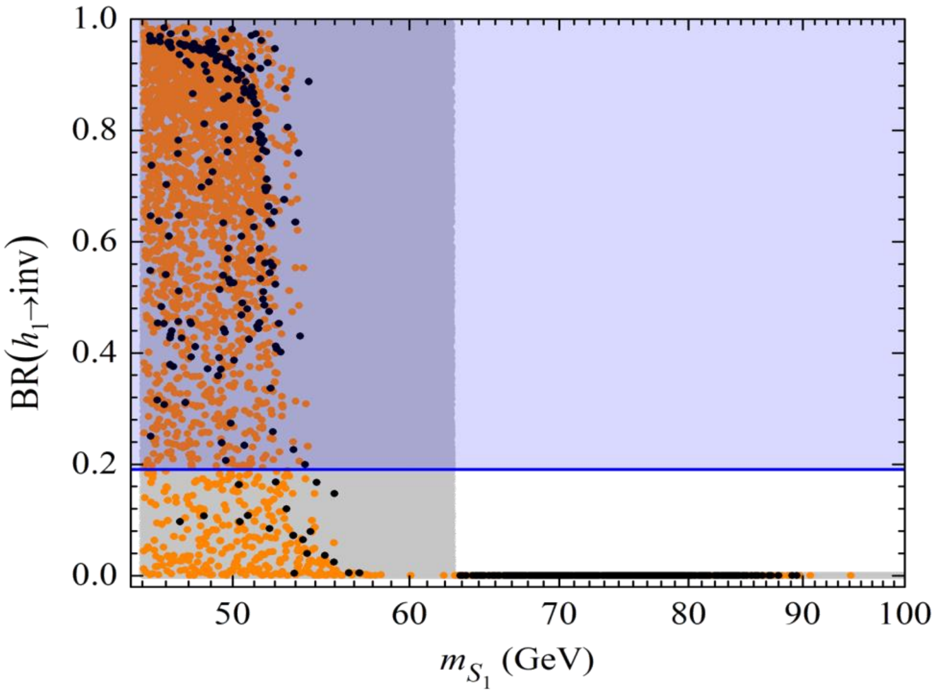
Scalar Dark Matter: LHC Higgs data

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

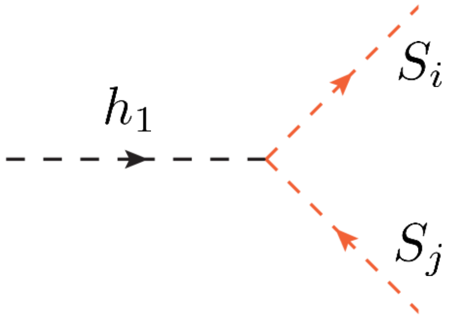


Scalar Dark Matter: LHC Higgs data

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

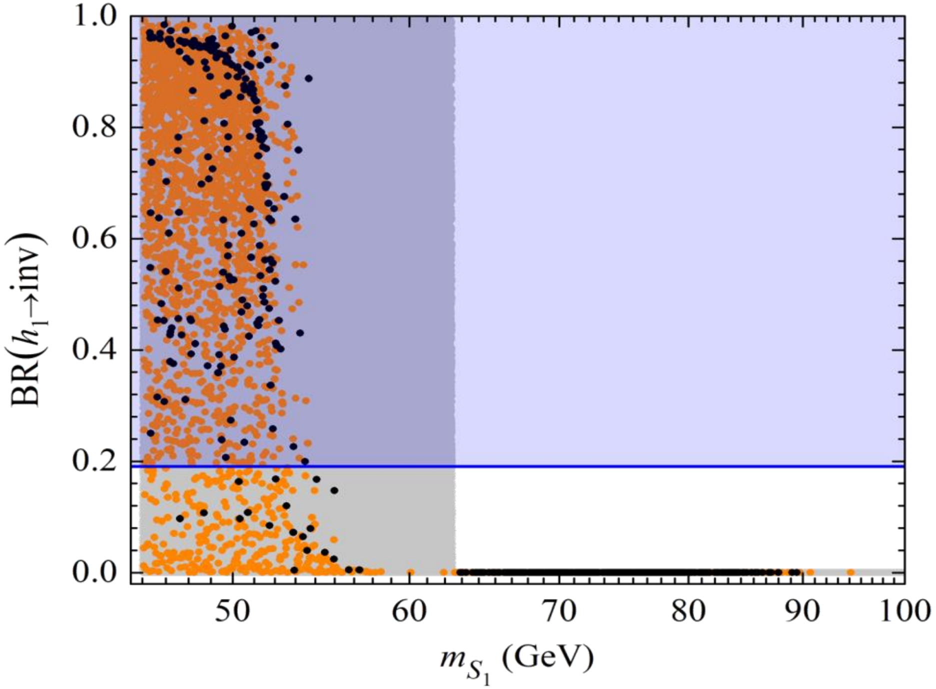


$$\Gamma(h_1 \to \mathrm{inv}) = \frac{1}{2}\sum_{i,j=1}^{4}\Gamma(h_1 \to S_i S_j)$$

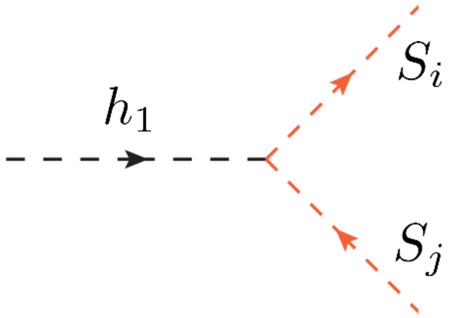


Scalar Dark Matter: LHC Higgs data

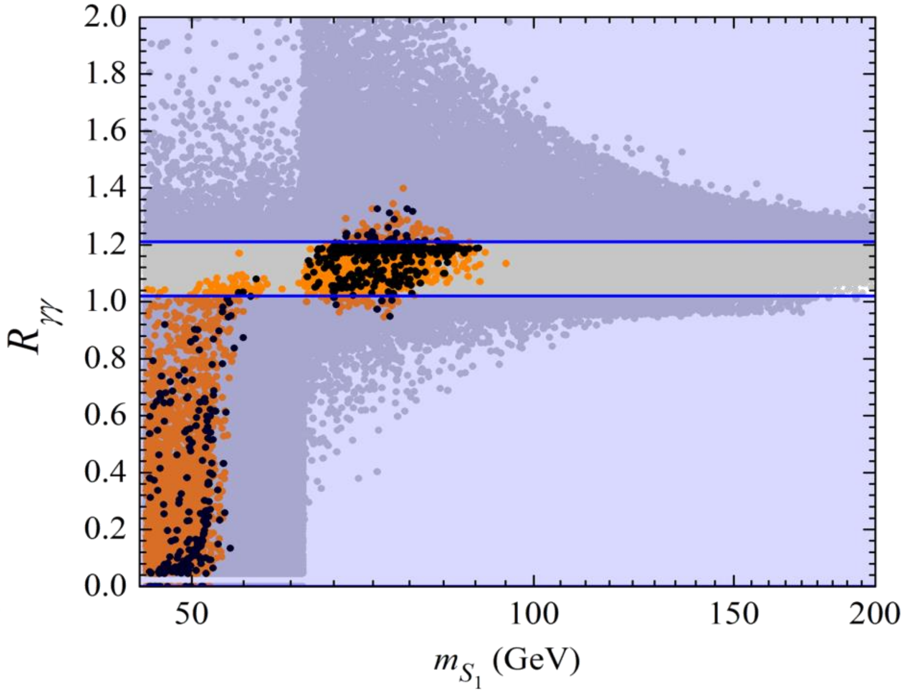
Higgs invisible decay $\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$



$$\Gamma(h_1 \to \mathrm{inv}) = \frac{1}{2}\sum_{i,j=1}^{4}\Gamma(h_1 \to S_i S_j)$$

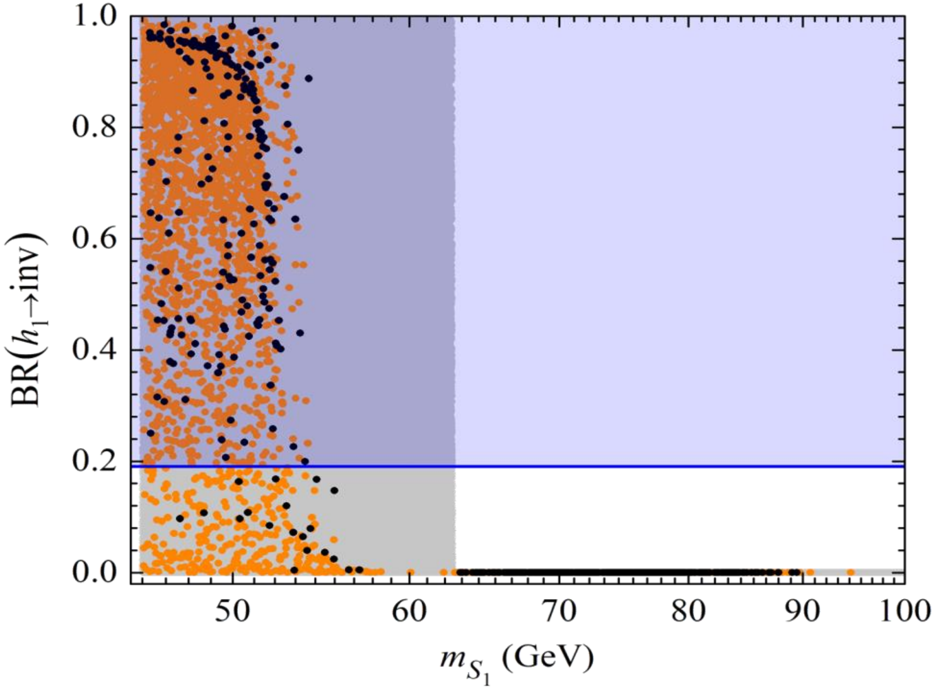


Higgs to photon-photon $R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$

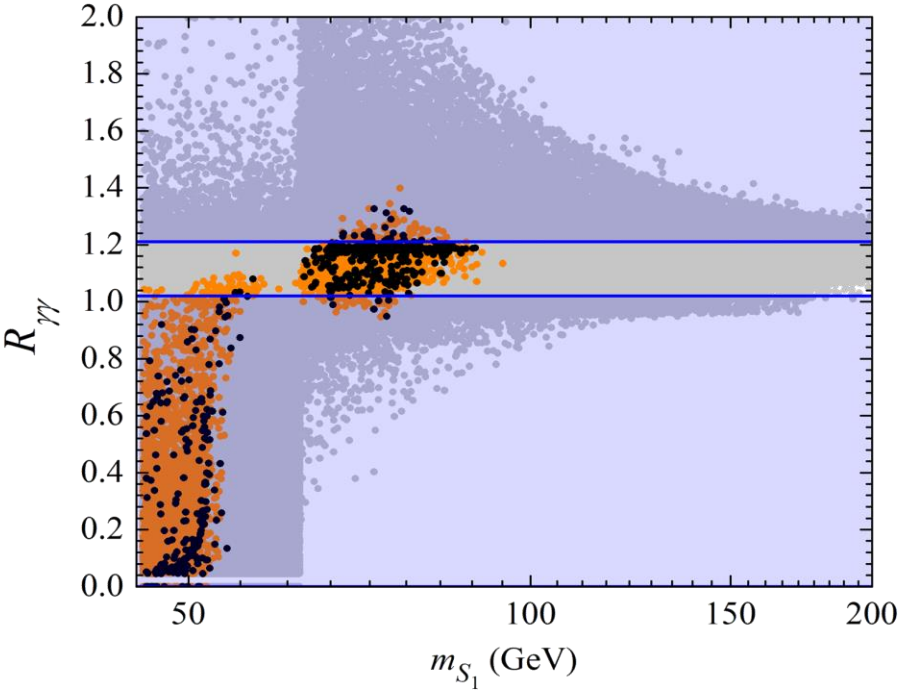


Scalar Dark Matter: LHC Higgs data

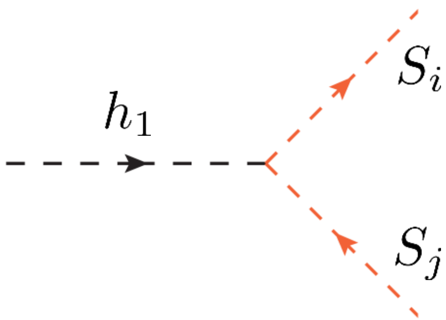
Higgs invisible decay $\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$

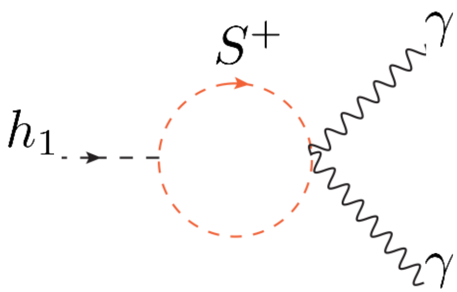


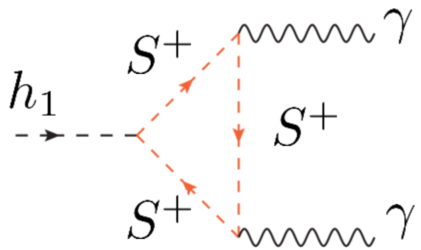
Higgs to photon-photon $R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$



$$\Gamma(h_1 \to \mathrm{inv}) = \frac{1}{2}\sum_{i,j=1}^{4} \Gamma(h_1 \to S_i S_j)$$

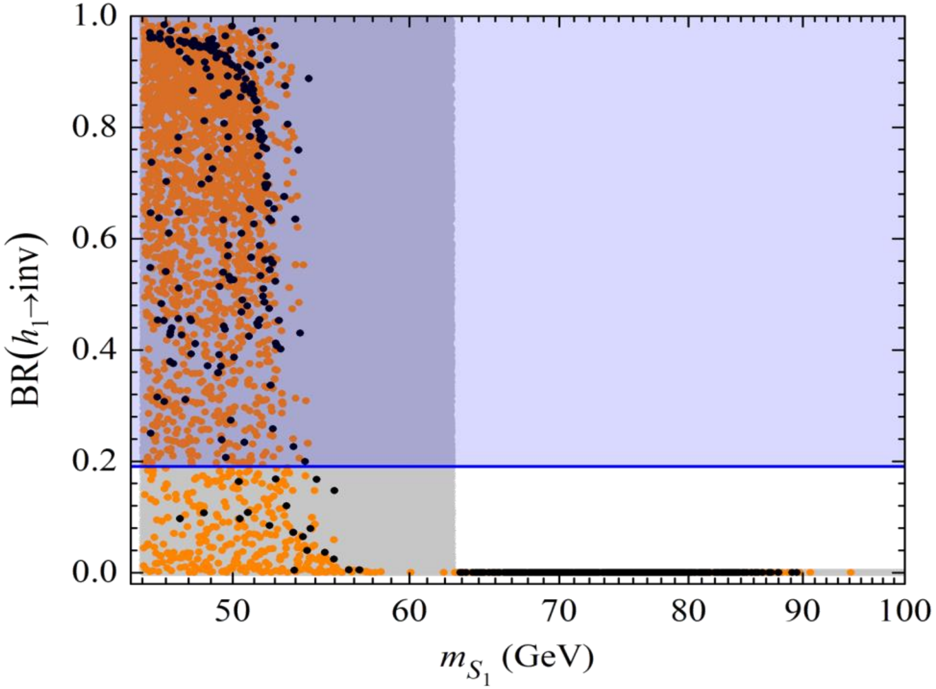




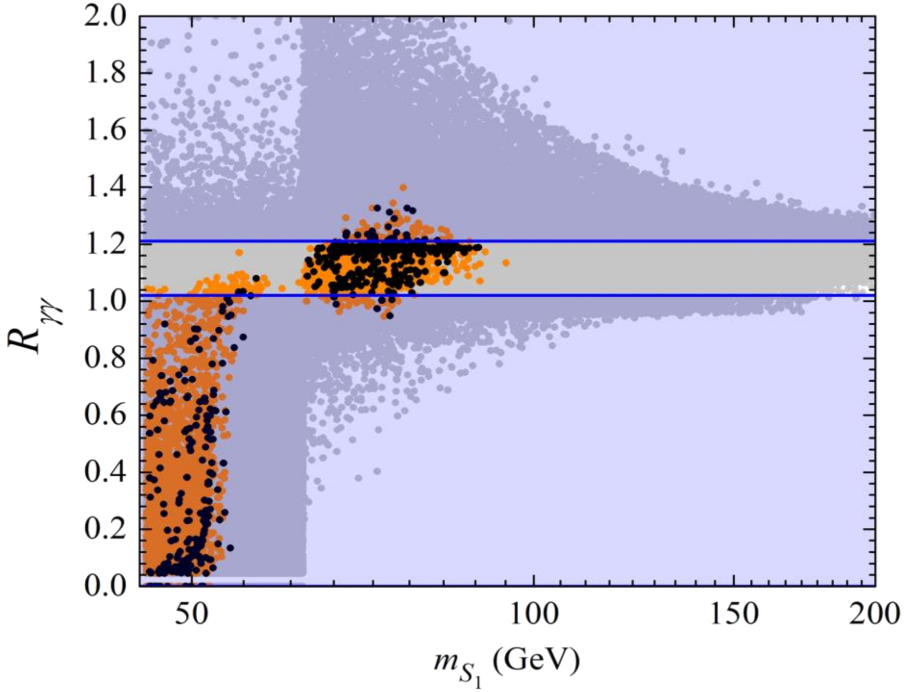


Scalar Dark Matter: LHC Higgs data

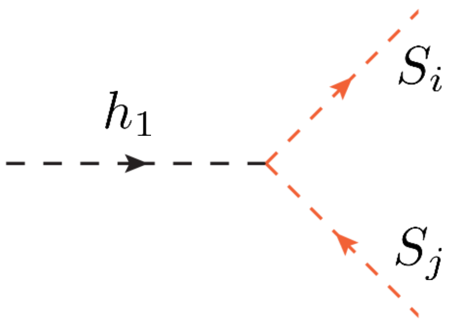
Higgs invisible decay $\mathrm{BR}(h_1 \to \mathrm{inv}) \leq 0.19$

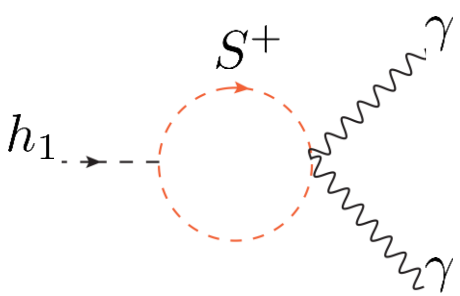


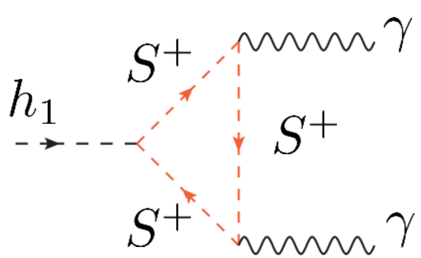
Higgs to photon-photon $R_{\gamma\gamma} = 1.11^{+0.10}_{-0.09}$



$$\Gamma(h_1 \to \mathrm{inv}) = \frac{1}{2}\sum_{i,j=1}^{4} \Gamma(h_1 \to S_i S_j)$$





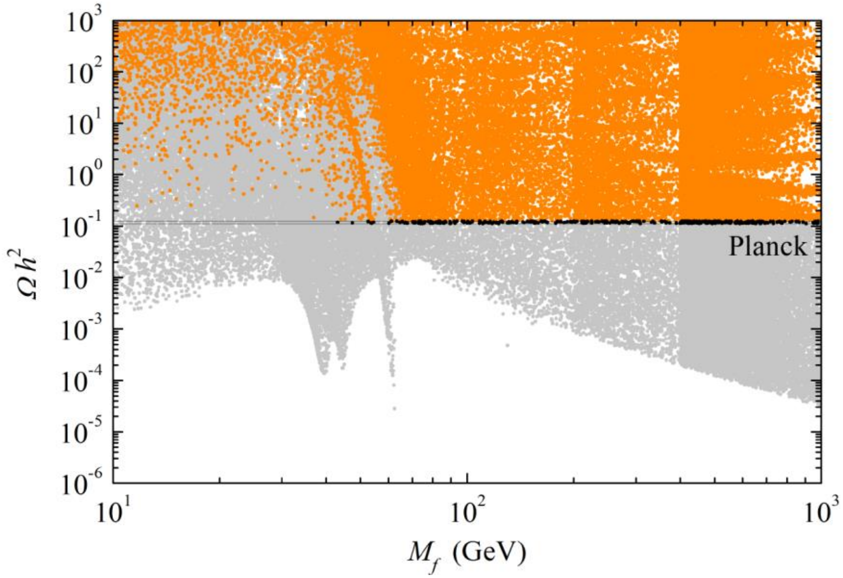


Allowed mass region: 68 to 90 GeV

Fermion Dark Matter: Relic density

Fermion Dark Matter: Relic density

Relic density



The case of **fermionic DM:**

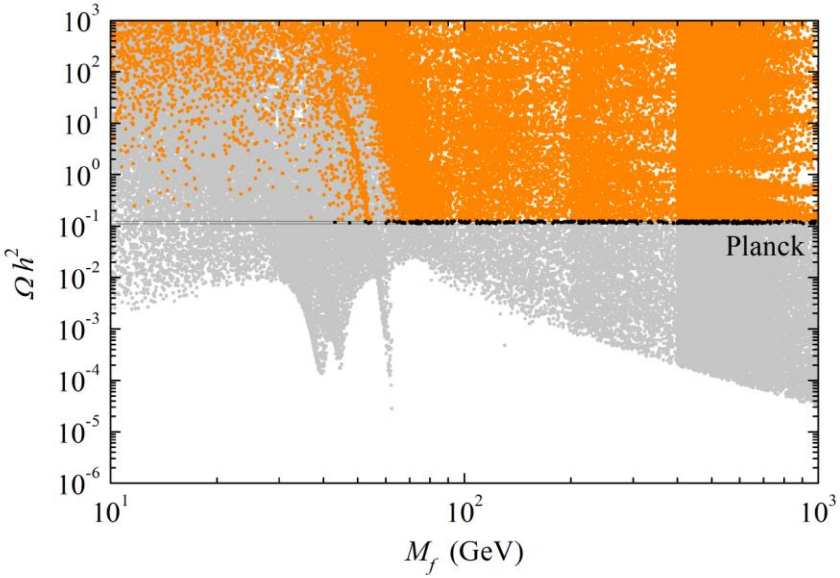
fermion f

Allowed mass region:

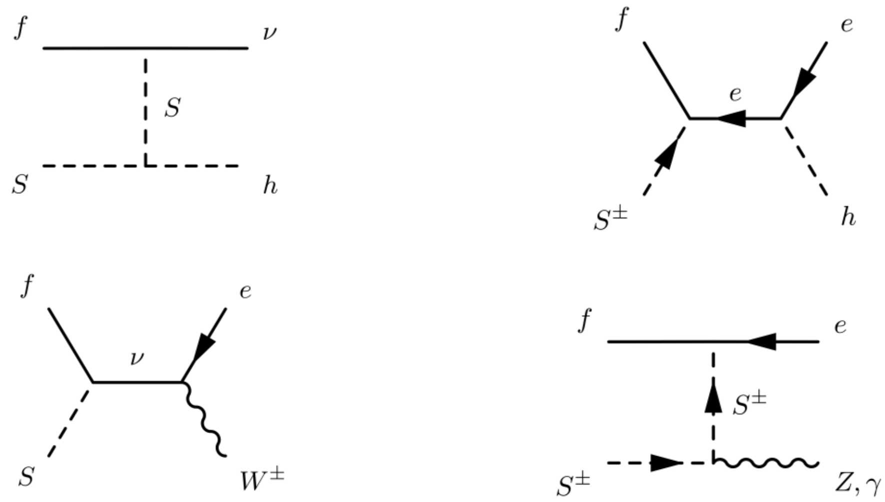
above 45 GeV

Fermion Dark Matter: Relic density

Relic density



Co-annihilation channels, e.g. :



The case of **fermionic DM:**

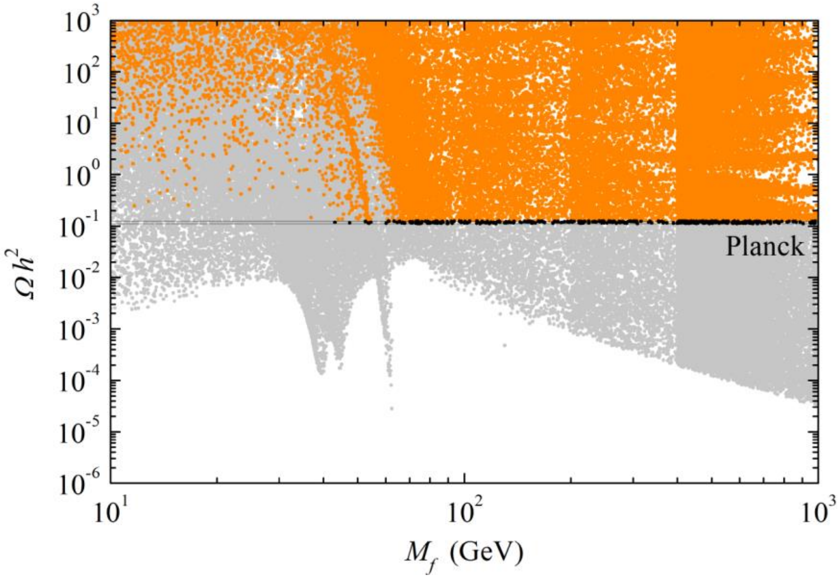
fermion f

Allowed mass region:

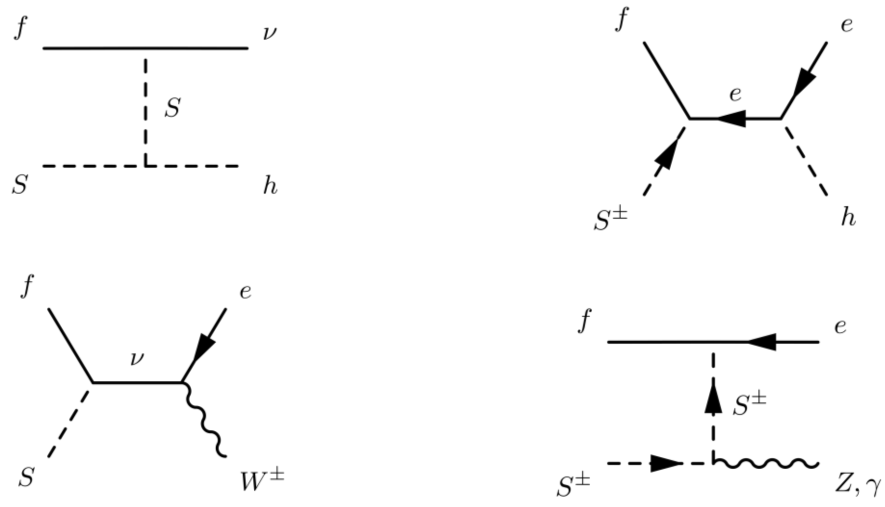
above 45 GeV

Fermion Dark Matter: Relic density

Relic density

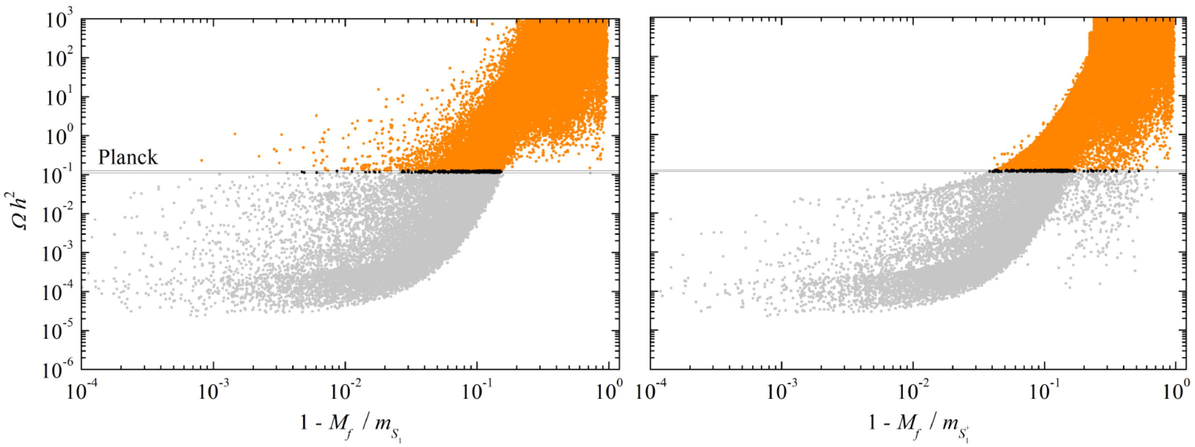


Co-annihilation channels, e.g. :



The case of **fermionic DM:**

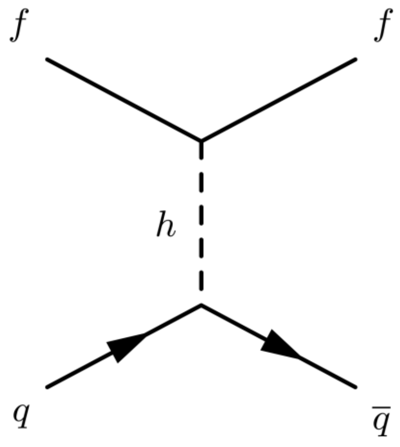
fermion f



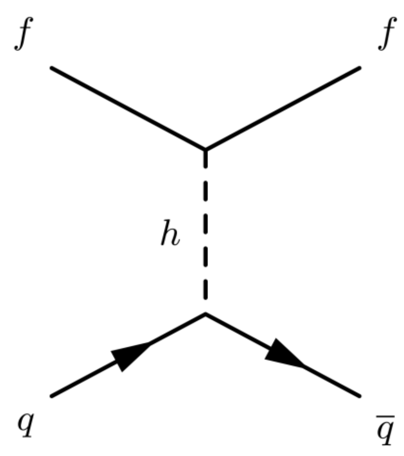
Allowed mass region:

above 45 GeV

Fermion Dark Matter: Direct detection

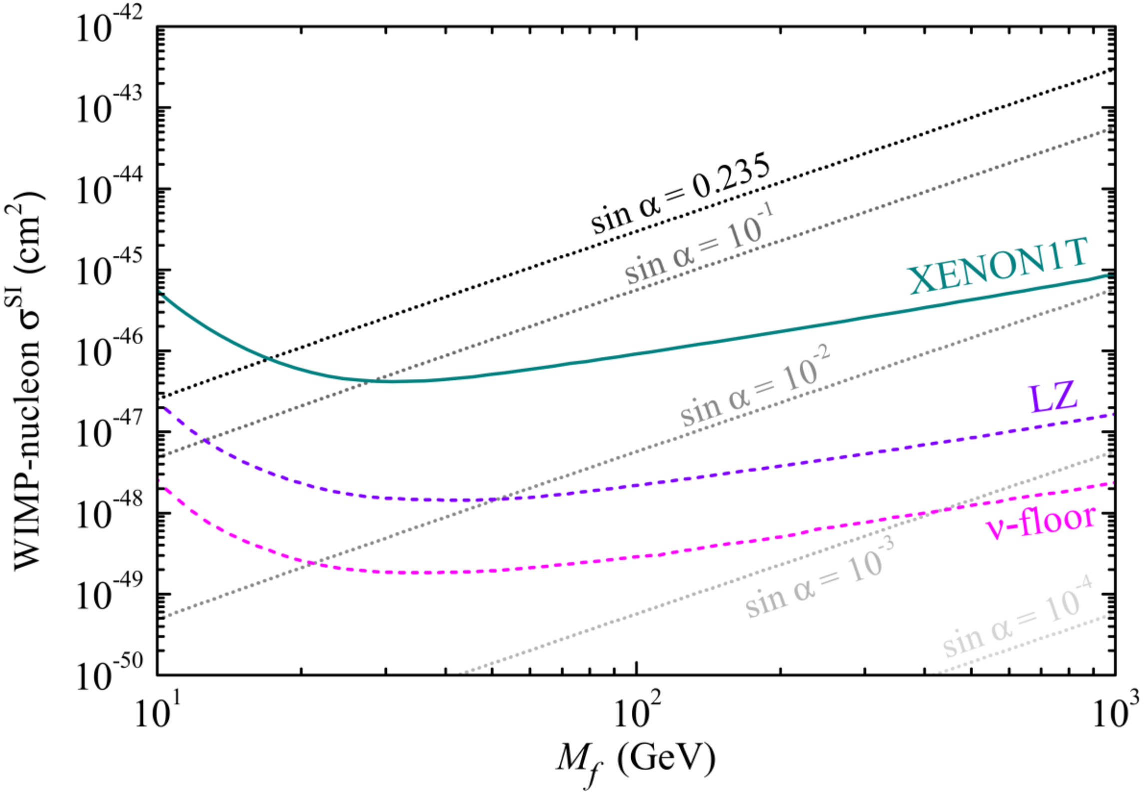


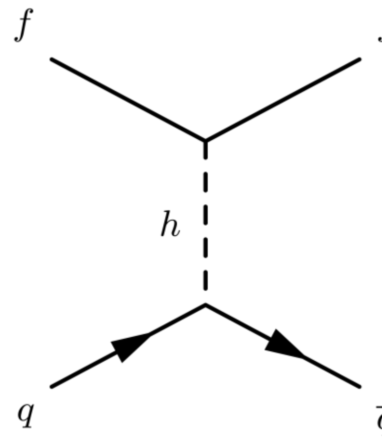
Fermion Dark Matter: Direct detection



- For WIMP DM Majorana-type fermions, with bare mass term only, there is no tree-level nor one-loop contributions to the spin independent cross section
- In our model the **fermion *f* mass is dynamically generated via the singlet VEV**
- Since the **singlet mixes with the Higgs** there is a **contribution at tree-level to** the spin independent cross section controlled by the **mixing angle** between the scalars

Fermion Dark Matter: Direct detection





- For WIMP DM Majorana-type fermions, with bare mass term only, there is no tree-level nor one-loop contributions to the spin independent cross section
- In our model the **fermion *f* mass is dynamically generated via the singlet VEV**
- Since the **singlet mixes with the Higgs** there is a **contribution at tree-level to** the spin independent cross section controlled by the **mixing angle** between the scalars

Conclusion

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints**, resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments

- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single Z_8 **symmetry is broken down to a dark** Z_2 by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** θ_{23} **octant with** $\delta \sim 3\pi/2$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $0\nu\beta\beta$**-decay** experiments

- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single Z_8 **symmetry is broken down to a dark** Z_2 by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** θ_{23} **octant with** $\delta \sim 3\pi/2$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $0\nu\beta\beta$**-decay** experiments

- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**

- **Fermion DM:** masses **above 45 GeV** are compatible with observed **relic density**

Conclusion

- Neutrino masses are generated via the **interplay** between **type-II seesaw** and **scotogenic** mechanisms

- A single $\boldsymbol{Z_8}$ **symmetry is broken down to a dark** $\boldsymbol{Z_2}$ by the **complex VEV of a scalar singlet**, leading to **observable CP-violating effects** in the lepton sector and **low-energy constraints,** resulting in **two-texture zero patterns in the effective neutrino mass matrix**

- For most cases the **model selects one** $\boldsymbol{\theta_{23}}$ **octant with** $\boldsymbol{\delta \sim 3\pi/2}$, predictions for the lightest neutrino mass are in the range probed by **cosmology** and will be tested by near future $\boldsymbol{0\nu\beta\beta}$**-decay** experiments

- A large fraction of **our model's parameter space is excluded by current cLFV constraints** while other regions will be probed by future experiments

- **Scalar DM:** one viable mass region **between 68 GeV and 90 GeV** is compatible with the observed **DM relic density, current DD constraints and collider bounds** (LEP and Higgs data), this region will be **probed by future DD searches**

- **Fermion DM:** masses **above 45 GeV** are compatible with observed **relic density**

Thank you !