Production of dark matter in association with a Higgs via exclusive photon fusion

XV Latin American Symposium on High Energy Physics

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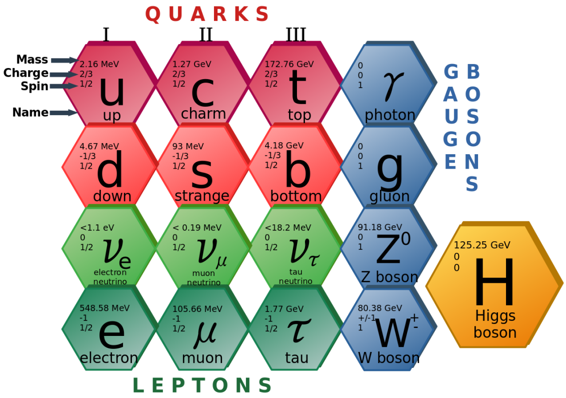
Outline

Standard Model

- Quantum Field Theory: Electromagnetic + Weak + Strong Forces
- Symmetry group: $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
- Self-consistent. Free of anomalies. Consistent perturbative scheme for systems at very high energies (LHC at 13 TeV)
- Higgs: last piece of the theory discovered in 2012, $M_H = 125\ GeV$.



Dark matter: observational evidence

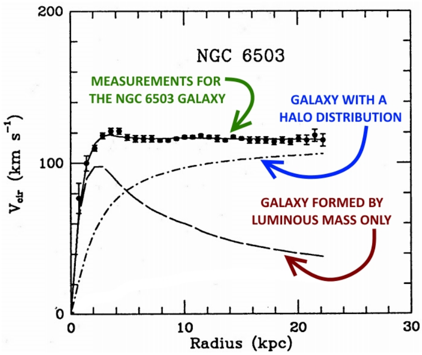


Figure: Rotation curve for the galaxy NGC6503 (Doroshkevich et. al., 2012).

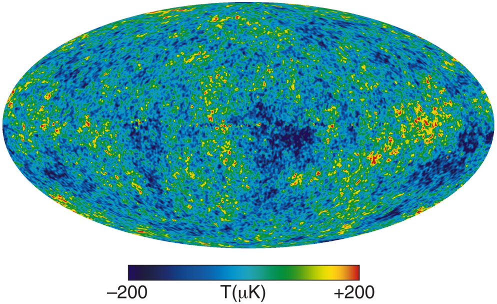
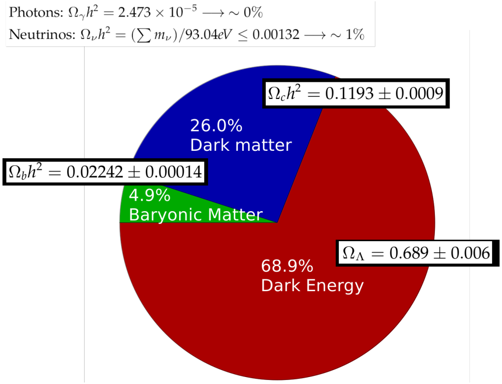


Figure: Internal Linear Combination Map (ILC), which is a linear combination of the WMAP (Wilkinson Microwave Anisotropy Probe) maps, at five different frequencies. This map shows the anisotropy of the CMB. (Bennett et. al., 2013).

Dark matter: observational evidence

Fixing Planck's data: ΛCDM scheme + CMB anisotropies + baryon acoustic oscilations (BAO) distance measurements + Planck lensing (Plack 2018 results):

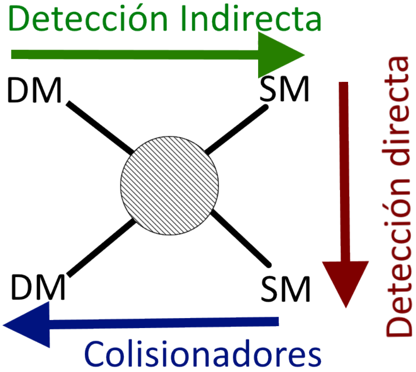
$$\rho_{tot}/\rho_c \equiv \Omega_{tot} \equiv \sum_i \Omega_i + \Omega_\Lambda = 0.9993 \pm 0.0019. \quad (1)$$



Dark Matter Properties

- Relic density observed: $\Omega_c h^2 = 0.1193 \pm 0.0009$.
- Cold: non-relativistic before the matter dominated era to form the cosmological structures we see today. *Hot dark matter* is not sufficient to account for the DM content of the Universe. *Warm dark matter* is a possibility.
- Effectively neutral: interact very weakly with electromagnetic radiation. Effectively a singlet of the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ group.
- Leave stellar evolution and Big Bang Nucleosynthesis predictions unchanged. The Tully-Fisher relation is another strong cosmological constraint.
- Consistent with current experimental bounds.

Dark Matter Searches



DM search approaches:

- Model based (*WIMPs, axion, ...*)
- Signal based (*fuzzy DM, astrophysics...*)

The Inert Higgs Doublet Model

The Inert Higgs Doublet Model (IDM) [1] is a simple way to introduce a DM candidate via a Lorentz scalar $SU(2)$ doublet (Φ_2), in addition to the Standard Model Higgs doublet (Φ_1).

What distinguishes the IDM to more general models with two Higgs doublets is that its potential has a $\mathcal{Z}_2$ symmetry unbroken by the vaccum state[2]. The unbroken discrete symmetry implies no Yukawa couplings between Φ_2 and fermions (hence called *inert*).

The most general CP conserving Higgs potential for this case is:

$$
\begin{aligned}
V &= \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 \\
&+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \lambda_5 Re\left[\left(\Phi_1^\dagger\Phi_2\right)\right]^2
\end{aligned} \tag{2}
$$

Inert Doublet Model plus a complex Scalar (IDMS)

The IDMS[1] [3] incorporates to the SM gauge symmetry a local $U(1)_\chi$ gauge symmetry and a second $SU(2)$ scalar doublet, where the DM candidate arises.

Stability of DM

- The second scalar doublet must have a VEV equal to zero.
- Either we impose a discrete $\mathcal{Z}_2$ symmetry or a $U(1)_\chi$ symmetry.

The scalar fields and their assignments under the $G_{\text{SM}} \otimes U(1)_X$ group are given by:

$$\begin{aligned} \Phi_1 &\sim (\mathbf{1}, \mathbf{2}, 1/2, x_1), \\ \Phi_2 &\sim (\mathbf{1}, \mathbf{2}, 1/2, x_2), \\ \mathcal{S}_X &\sim (\mathbf{1}, \mathbf{1}, 0, x). \end{aligned} \tag{3}$$

[1] Eur. Phys. J. C, 80(8):788, 2020

Scalar fields

The scalar fields are written as follows:

$$
\begin{aligned}
\Phi_1 &= \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(\upsilon + \phi_1 + i\eta_1) \end{pmatrix}, \\
\Phi_2 &= \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\phi_2 + i\eta_2) \end{pmatrix}, \\
\mathcal{S}_X &= \frac{1}{\sqrt{2}}(\upsilon_x + s_x + i\eta_x).
\end{aligned} \tag{4}
$$

The spontaneous symmetry breaking (SSB) occurs as follows

$$
G_{\mathrm{SM}} \times U(1)_X \xrightarrow{\langle S_X \rangle} G_{\mathrm{SM}} \xrightarrow{\langle \Phi_1 \rangle} SU(3)_C \times U(1)_{\mathrm{EM}}, \tag{5}
$$

where $\langle S_X \rangle = v_x/\sqrt{2}$ and $\langle \Phi_1 \rangle^T = (0, v/\sqrt{2})$ with $v = 246.22$ GeV.

Higgs potential

The most general, renormalizable and gauge invariant potential is

$$
\begin{aligned}
V &= \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \mu_x^2\mathcal{S}_X^*\mathcal{S}_X + \left[\mu_{12}^2\Phi_1^\dagger\Phi_2 + h.c.\right] \\
&+ \lambda_x\left(\mathcal{S}_X^*\mathcal{S}_X\right)^2 + \lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2 \\
&+ \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \left[\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2\right. \\
&+ \left.\lambda_6\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_1^\dagger\Phi_2\right) + \lambda_7\left(\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + h.c.\right] \\
&+ \left(\mathcal{S}_X^*\mathcal{S}_X\right)\left[\lambda_{1x}\left(\Phi_1^\dagger\Phi_1\right) + \lambda_{2x}\left(\Phi_2^\dagger\Phi_2\right)\right] \\
&+ \left[\lambda_{12x}\left(\Phi_1^\dagger\Phi_2\right)\left(\mathcal{S}_X^*\mathcal{S}_X\right) + h.c.\right],
\end{aligned}
\tag{6}
$$

where $\mu_{1,2}^2$, $\lambda_{1,2,3,4,1x,2x}$ are real parameters and μ_{12}^2, $\lambda_{5,6,7,12x}$ can be complex parameters. Note that $\mu_2^2 > 0$ because the DM candidate arises from Φ_2, which has $<\Phi_2>= 0$.

Mass matrix

By considering the $\{\phi_1, s_x, \phi_2, \xi_2\}$ basis, and after the SSB, the scalar mass matrix can be written as follows

$$\mathbf{M_0^2} = \begin{pmatrix} \mathrm{M}_{11} & \mathrm{M}_{12} & \mathrm{M}_{13} & 0 \\ \mathrm{M}_{12} & \mathrm{M}_{22} & \mathrm{M}_{23} & 0 \\ \mathrm{M}_{13} & \mathrm{M}_{23} & \mathrm{M}_{33} & \mathrm{M}_{34} \\ 0 & 0 & \mathrm{M}_{34} & \mathrm{M}_{44} \end{pmatrix}, \tag{7}$$

where

$$\begin{aligned}
\mathrm{M}_{11} &= 2\lambda_1 \upsilon^2, \quad \mathrm{M}_{12} = \lambda_{1\mathrm{x}} \upsilon\, \upsilon_{\mathrm{x}}, \quad \mathrm{M}_{13} = \frac{1}{2}\lambda_6 \upsilon^2, \\
\mathrm{M}_{22} &= 2\lambda_x \upsilon_x^2, \quad \mathrm{M}_{23} = \frac{1}{2}\lambda_{12\mathrm{x}} \upsilon \upsilon_{\mathrm{x}}, \\
\mathrm{M}_{33} &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 + \mathrm{Re}[\lambda_5])\upsilon^2 + \frac{1}{2}\lambda_{2x}\upsilon_x^2, \\
\mathrm{M}_{34} &= -\mathrm{Im}[\lambda_5]\upsilon^2, \\
\mathrm{M}_{44} &= \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4 - \mathrm{Re}[\lambda_5])\upsilon^2 + \frac{1}{2}\lambda_{2x}\upsilon_x^2.
\end{aligned} \tag{8}$$

Mass matrix

The mass matrix for the neutral scalar is diagonalized by

$$\begin{pmatrix} h \\ S \end{pmatrix} = \begin{pmatrix} \cos\alpha_1 & -\sin\alpha_1 \\ \sin\alpha_1 & \cos\alpha_1 \end{pmatrix} \begin{pmatrix} \phi_1 \\ s_x \end{pmatrix} \tag{9}$$

and

$$\begin{pmatrix} \chi \\ A \end{pmatrix} = \begin{pmatrix} \cos\alpha_2 & -\sin\alpha_2 \\ \sin\alpha_2 & \cos\alpha_2 \end{pmatrix} \begin{pmatrix} \phi_2 \\ \xi_2 \end{pmatrix}, \tag{10}$$

where $\tan\alpha_{1,2} = \frac{\rho_{1,2}}{1+\sqrt{1+\rho_{1,2}^2}}$ with $\rho_1 = \frac{\lambda_{1x} v v_x}{\lambda_1 v^2 - \lambda_x v_x^2}$ and $\rho_2 = \frac{-\mathrm{Im}[\lambda_5]}{\mathrm{Re}[\lambda_5]}$ [4].

The scalar masses are given by

$$\begin{aligned} M_{S,h}^2 &= \lambda_1 v^2 + \lambda_x v_x^2 \pm (\lambda_1 v^2 + \lambda_x v_x^2)\sqrt{1+\rho_1^2}, \\ M_{H^\pm}^2 &= \mu_2^2 + \frac{1}{2}(\lambda_3 v^2 + \lambda_{2x} v_x^2), \\ M_{A,\chi}^2 &= M_{H^\pm}^2 + \left(\frac{\lambda_4}{2} \pm |\lambda_5|\right) v^2. \end{aligned} \tag{11}$$

Couplings

The IDMS couplings involved in the calculations of this work are as follows:

Coupling	Expression
$hf_i\bar{f}_i$	$\frac{m_{f_i}}{\upsilon}\cos\alpha_1$
hH^-H^+	$(\lambda_3\cos\alpha_1+\lambda_{2x}/2)\upsilon$
$hW^-_\mu W^+_\nu$	$gm_W\cos\alpha_1 g_{\mu\nu}$
$h\chi\chi$	$(\lambda_{345}\cos\alpha_1+\lambda_{2x}/2)\upsilon$
$Z'_\mu f_i\bar{f}_i$	$\frac{g_x}{2}\left(1-\gamma^5\right)\gamma^\mu$
$Z'_\mu\chi\chi$	$\frac{g_x}{2}(p_{Z'_\mu}-p_\chi)^\mu$
$Sf_i\bar{f}_i$	$\frac{m_{f_i}}{\upsilon}\sin\alpha_1$
$SW^-_\mu W^+_\nu$	$gm_W\sin\alpha_1 g_{\mu\nu}$
$S\chi\chi$	$\lambda_{2x}\upsilon_x\cos\alpha_1-\lambda_{345}\upsilon\sin\alpha_1$
$\chi(A)H^\pm W^\mp_\mu$	$i\frac{g}{\sqrt{2}}(p_{H^\pm}-p_{\chi(A)})^\mu\cos\alpha_2$
$S\chi h$	$\frac{\lambda_{12x}\cos\alpha_1}{2}\left(\frac{\upsilon_x}{\cos\alpha_2}\right)$

To avoid a decay of DM candidate into $H^\pm W^\mp$ or two neutral scalars, we require that $v_x>\sqrt{\frac{2M_h^2+2\mu_2^2}{4\lambda_x-\lambda_{2x}}}$ and $m_\chi<\sqrt{2\lambda_x}v_x$. We define $\lambda_{345}=\lambda_3+\lambda_4+2\lambda_5$.

IDMS Dark Matter Stability

To enforce dark matter stability (χ), we can take the following approaches:

- Impose a discrete $\mathcal{Z}_2$ symmetry, then the terms proportional to $\phi_1^\dagger \phi_2$ are eliminated ($\mu_{12} = \lambda_6 = \lambda_7 = \lambda_{12x} = 0$). No interactions with Higgs!

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- Impose a discrete $\mathcal{Z}_2$ symmetry AND allow a lightly parity violating term, $\lambda_{12x} \neq 0$

Central Exclusive Production

In proton-proton collisions, a colorless exchange (γ, color neutralized gluons or a pomeron, $\mathbb{P}$) could result in a $p + p \to p + X + p$ process, where the protons remain intact after the collision.

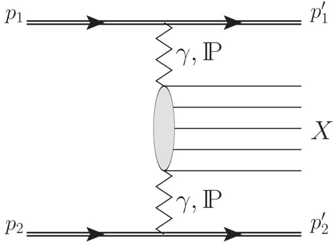

Figure: Central Exclusive Production diagram ($p + p \to p + X + p$) [5].

Central Exclusive Production

The outgoing protons can be captured by near beam detectors, such as the CMS-TOTEM Precision Proton Spectrometer (PPS) or the ATLAS Forward Proton detectors (AFP).

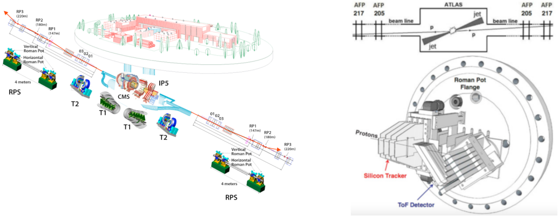

Figure: CMS-TOTEM PPS (left) and AFP (right).

Each proton loses a fraction of its longitudinal momentum, $\xi_{1,2} = \Delta p_{1,2}/p_{1,2}$, and the mass of the X state can be reconstructed, $M(X) = M(pp) \sim \sqrt{\xi_1 \xi_2 s}$.

Dark Matter associated with a Higgs in γ-fusion CEP

The process of interest is $pp \to h\chi pp$, where the DM particle χ is produced along side a Higgs in photon-fusion induced CEP. The proton kinematics allows for the reconstruction of the scalar S, while measurements of the central objects would allow the reconstructions of the χ kinematics.

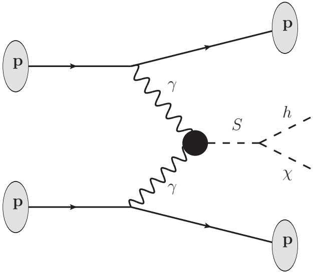

Figure: Diagram of the process $pp \to h\chi pp$.

Preliminary Results

IDMS model implemented using LanHEP 4.0. We calculate the $pp \to h\chi pp$ cross-section using MadGraph5_aMC ver. 3.5. The photon-fusion to S vertex is done at an effective level.

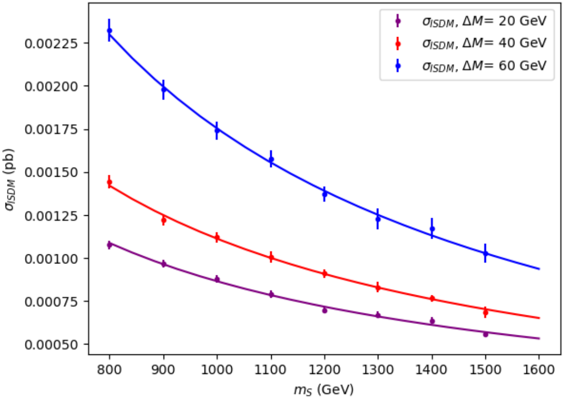

Figure: Cross-section of the $pp \to h\chi pp$ process for different masses of m_S and for $\Delta M = m_S - m_h - m_\chi = 20$, 40 and 60 GeV.

Conclusions

- The analysis of the Central Exclusive Production opens the door to searches for physics beyond the Standard Model, where processes with a dark matter candidate alongside an SM particle are of particular interest.
- We explore the possibility that a DM candidate can come from an extension of the SM with a local $U(1)_\chi$ gauge symmetry and a second $SU(2)$ scalar doublet.
- We calculate the cross section of the $pp \to h\chi pp$ process, where the scalar S is produced through a photon-fusion induced CEP and subsequently decays into $h + \chi$, for different values of the m_S and for $\Delta M = m_S - m_h - m_\chi = 20$, 40 and 60 GeV.
- More calculations of the cross-section as well as the missing mass spectrum need to be done. The particular characteristics of the near-beam proton detectors also need to be taken into account to determine the expected signatures of the process.

References I

[1] Nilendra G. Deshpande and Ernest Ma. Pattern of symmetry breaking with two higgs doublets. *Phys. Rev. D*, 18:2574–2576, Oct 1978. doi: 10.1103/PhysRevD.18.2574. URL `https://link.aps.org/doi/10.1103/PhysRevD.18.2574`.

[2] Michael Gustafsson. The Inert Doublet Model and Its Phenomenology. *PoS*, CHARGED2010:030, 2010. doi: 10.22323/1.114.0030.

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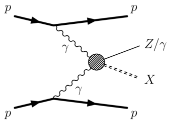
[5] The CMS Precision Proton Spectrometer at the HL-LHC – Expression of Interest. 3 2021.

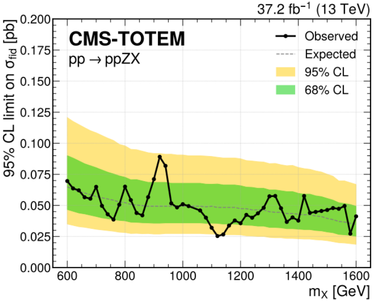
THANK YOU!

Auxiliary Slides

Search for New Physics in CEP



Search for new physics in CEP using the missing mass technique with the CMS-TOTEM PPS detector (Eur. Phys. J. C, 83:827, 2023).



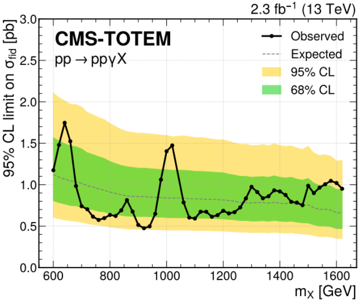


Figure: Upper limits on the $pp \to ppZ/\gamma + X$ cross section at 95% CL, as a function of m_X found by the CMS-TOTEM study.

Constraints on IDMS free model parameters

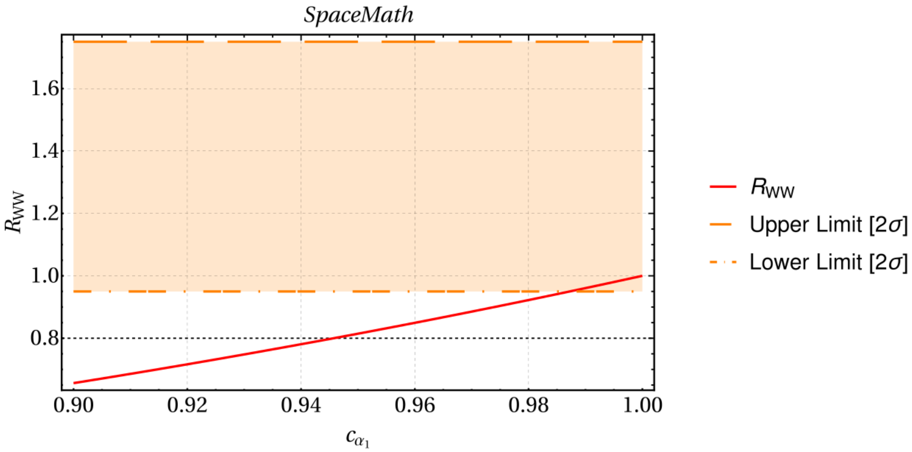


Figure: $\mathcal{R}_{WW^*}$ as a function of $\cos\alpha_1$. The shadowed area represents the allowed region by the signal from collider experiments at 2σ.

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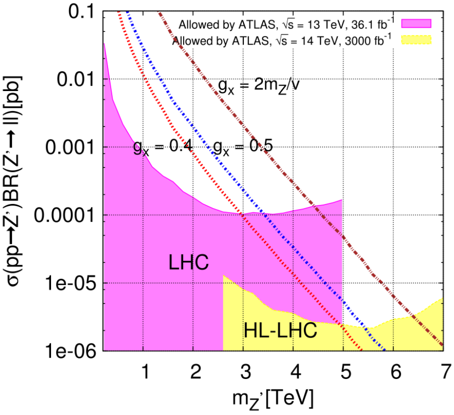

Figure: $\sigma_{Z'}\mathcal{B}_{Z'}$ as a function of the Z' gauge boson mass for g_x =0.4, 0.5 and $2m_Z/v$. Dark areas correspond to allowed regions by ATLAS Collaboration.

Constraints on IDMS free model parameters

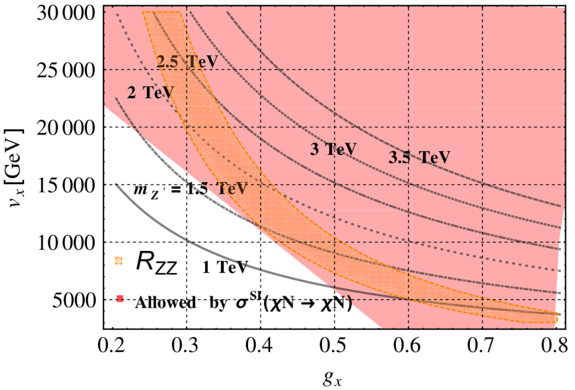

Figure: The inclined and curved orange area represents the consistent region with R_{ZZ^*} while the large area (light red) indicates the allowed values by the upper limit on $\sigma_{SI}(\chi N \to \chi N)$.