ICTP-SAIFR Program on Particle Physics

Dark Universe Workshop – Early Universe Cosmology, Baryogenesis and Dark Matter

Dark Matter and Vector fields in non-trivial representations of SU(2)_L

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Content

Why consider vector fields ?

Why consider vector fields ?

- Vector fields are wild animals

- Usually they are tamed introducing gauge symmetries (like in the SM)

- However vectors play different roles in Nature
  - In the hadronic sector we have some examples:
    - Rho-meson can be seen as an emergent gauge boson (HLS)
    - The a1 axial-vector behaves like a matter field (transforming homogeneously under HLS)

- Of course this example comes from a effective non-fundamental sector, but nothing prevents its realization in other (dark?) sectors of Nature

A Vector Resonance in the Dark Sector

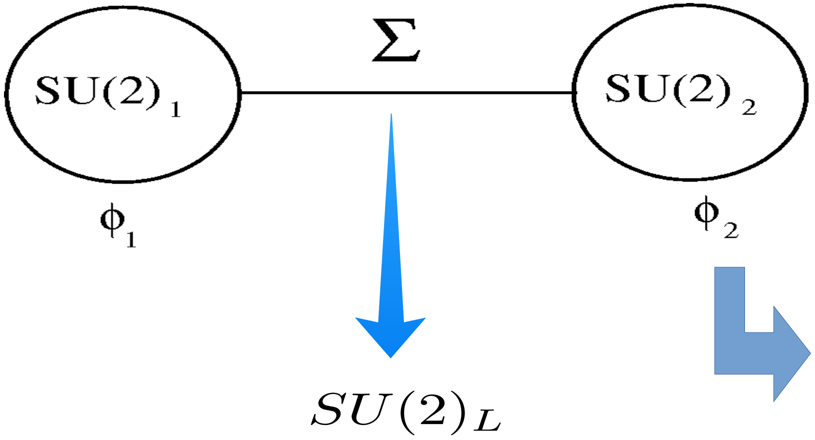
Based on:

- Phys.Rev. D96 (2017), 095025 *M. Mora, F. Rojas-Abatte, J. Urbina, AZ*
- Chin.Phys. C43 (2019), 063102 *C. Callender, AZ*

IDM + Vector Resonance

Model Based on $SU(2)_1 \times SU(2)_2 \times U(1)_Y$

Symmetry Breaking Pattern



Inert doublet

Hypothesis: $g_1 \ll g_2$

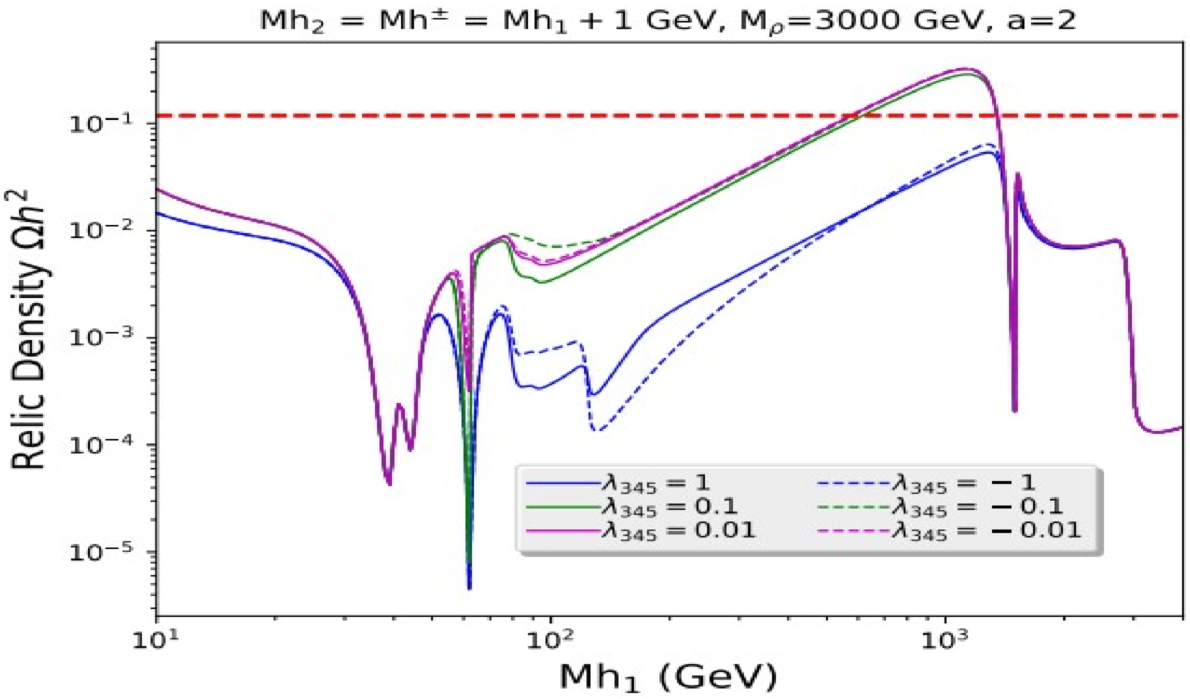
Spectrum

$\rho_\mu^{0,\pm}$	$M_\rho = 2 - 4.5\ \mathrm{TeV}$
$h^\pm$	
h_1	DM candidate
h_2	
H	Standard-like Higgs

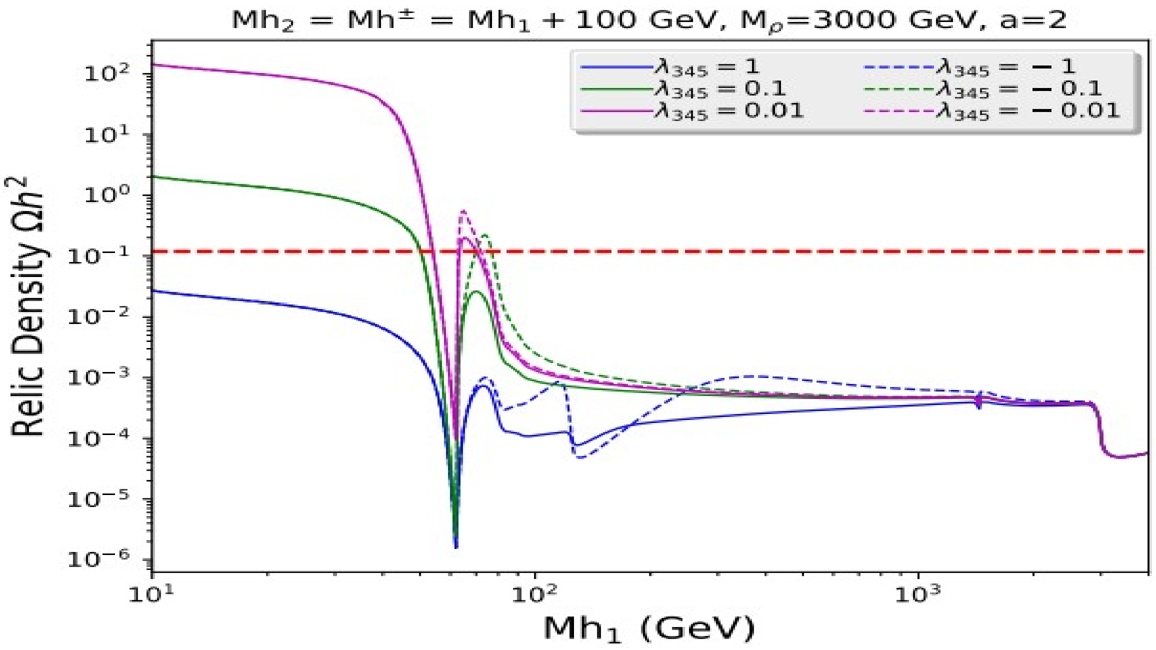
Parameters

a	$\frac{u}{v}$	$a = 3, 4, 5$
λ_2		ϕ_2 Self Interaction
λ_{345}	$\lambda_3 + \lambda_4 + \lambda_5$	Higgs-New Scalars interaction
M_ρ		
$M_{h^\pm}$		
M_{h1}		
M_{h2}		

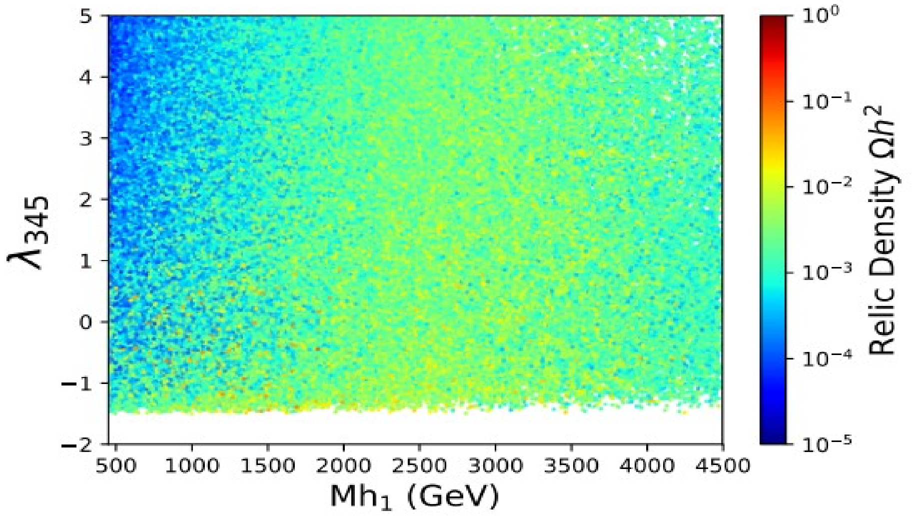
Relic density

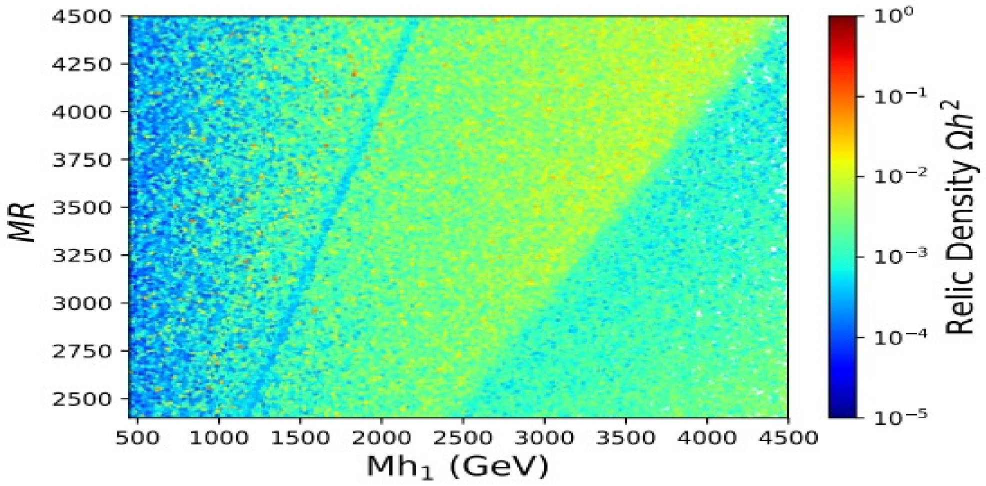


Relic density

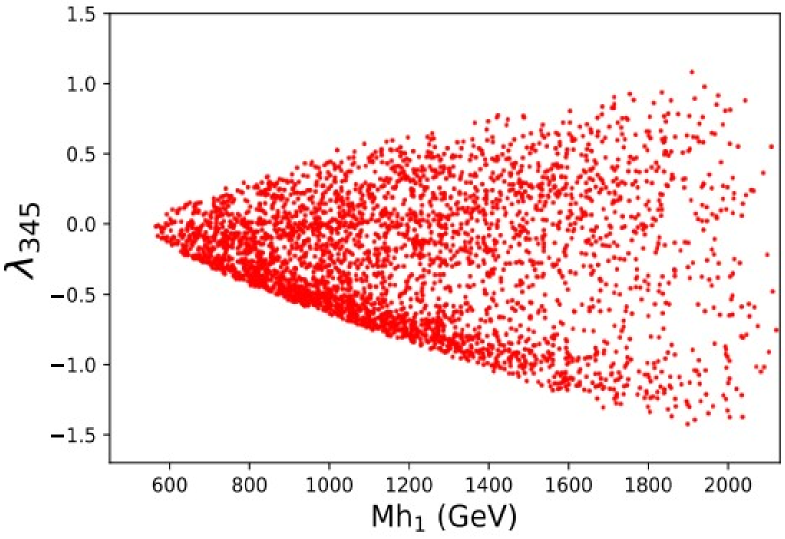


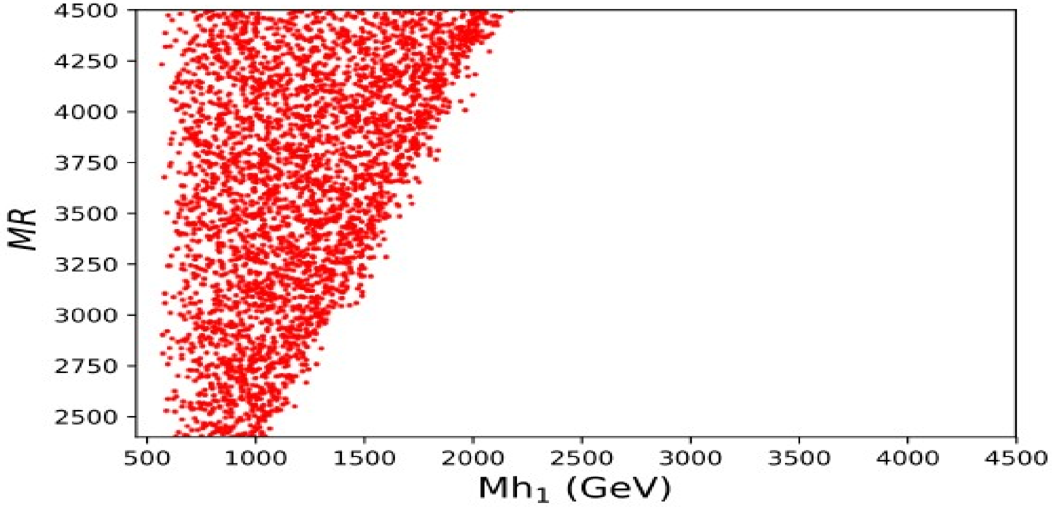
Relic density



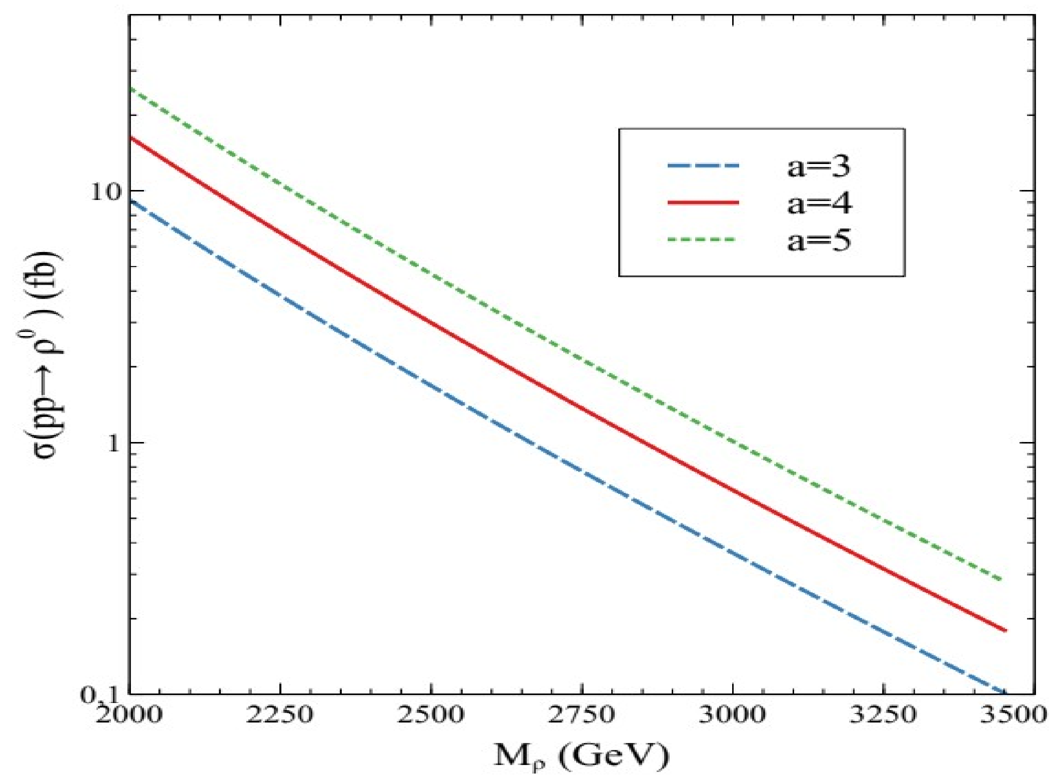


Relic density

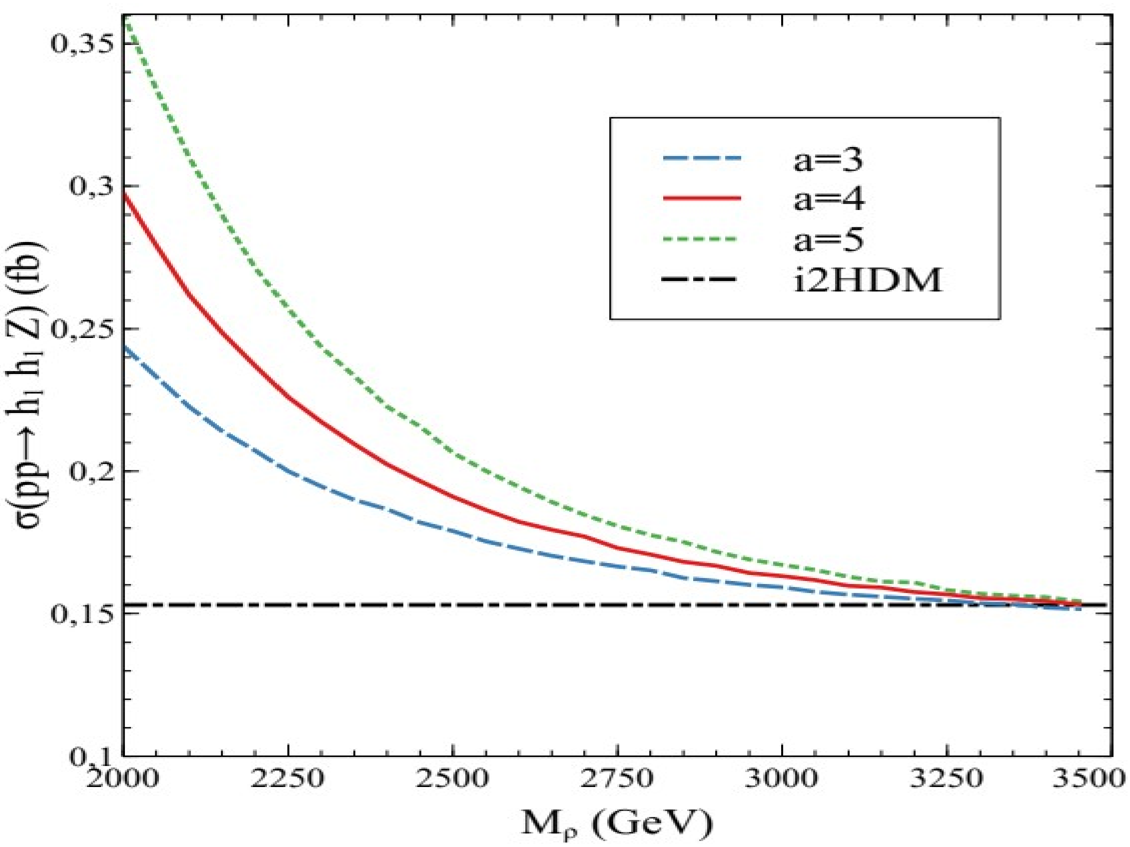




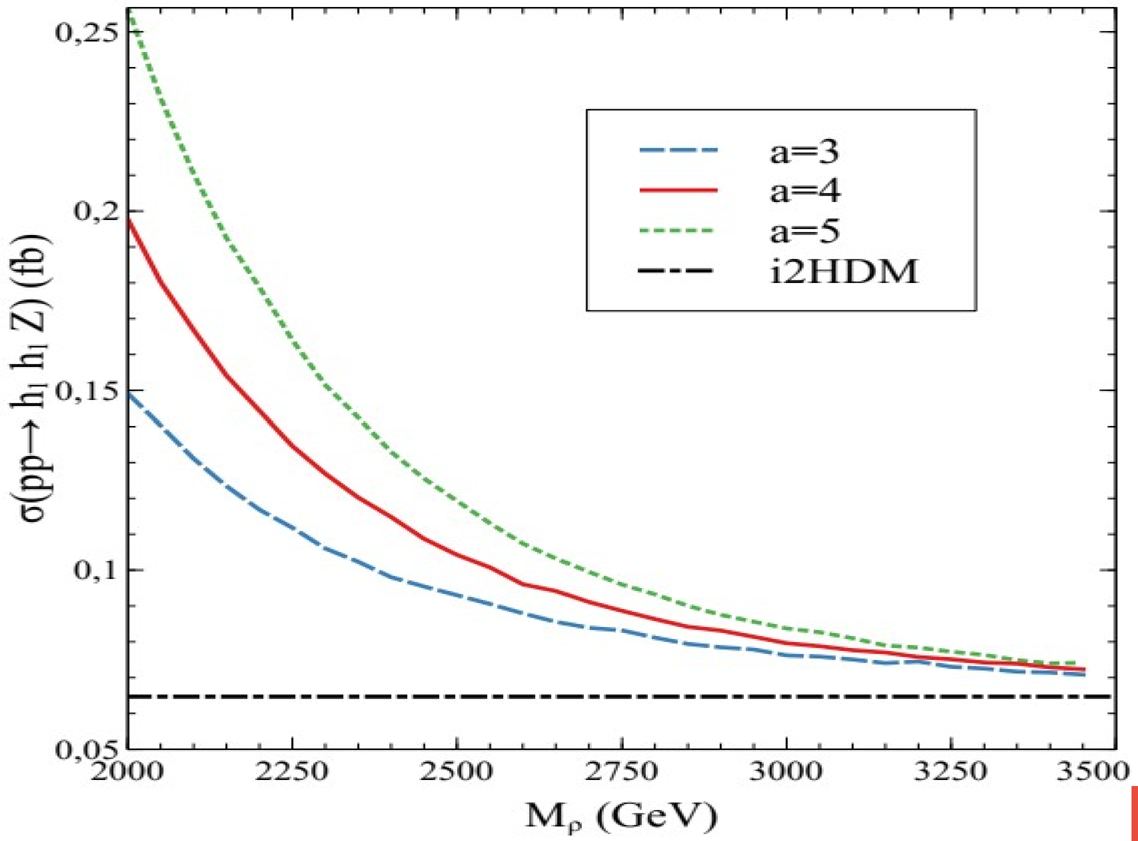
Neutral vector production at LHC



Mono-Z at the LHC



Mono-Z at the LHC

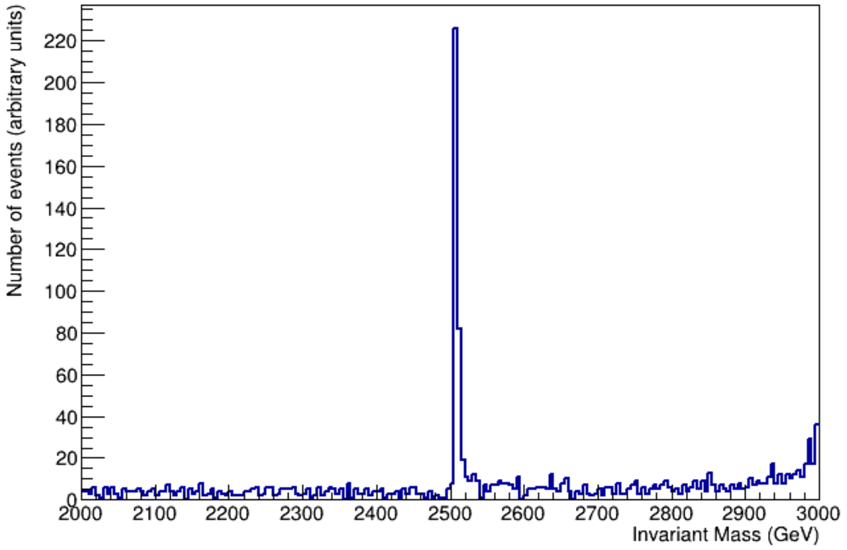


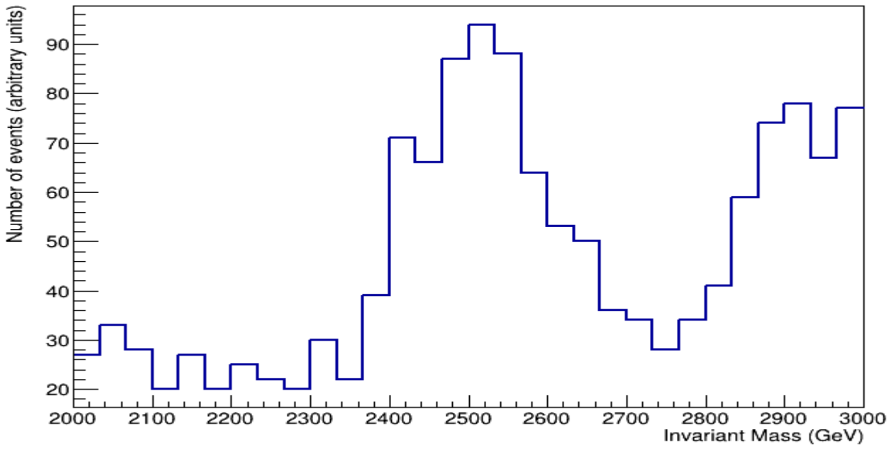
Resonance Searches at CIIC (Heavy Scalars)

$$M_{h1}, M_{h2}, M_{h\pm} > M_\rho/2$$

$$e^+e^- \to \mu^+\mu$$

$$\sqrt{s} = 3 \text{ TeV}$$

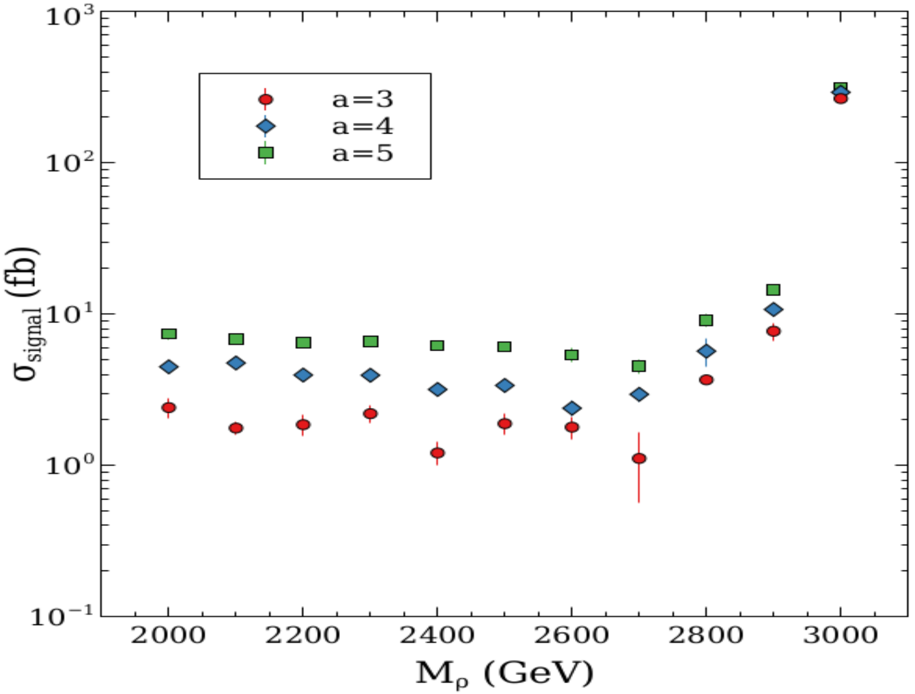


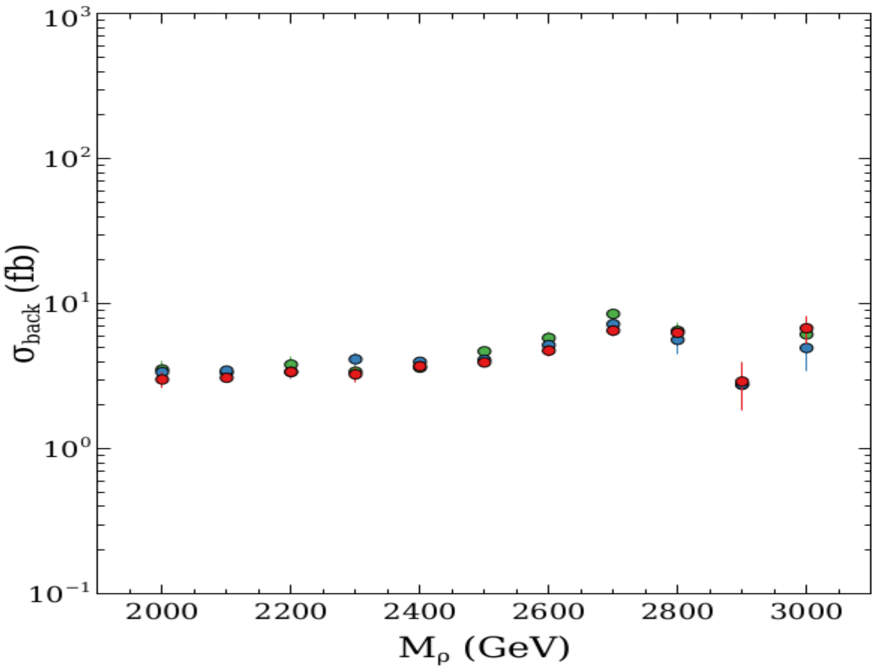


Resonance Searches at CllC (Heavy Scalars)

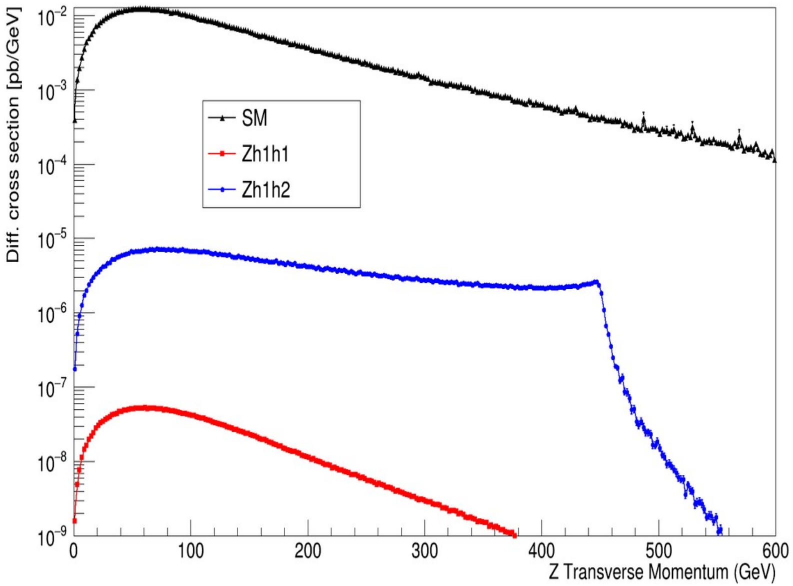
$$M_{h1}, M_{h2}, M_{h\pm} > M_\rho/2$$

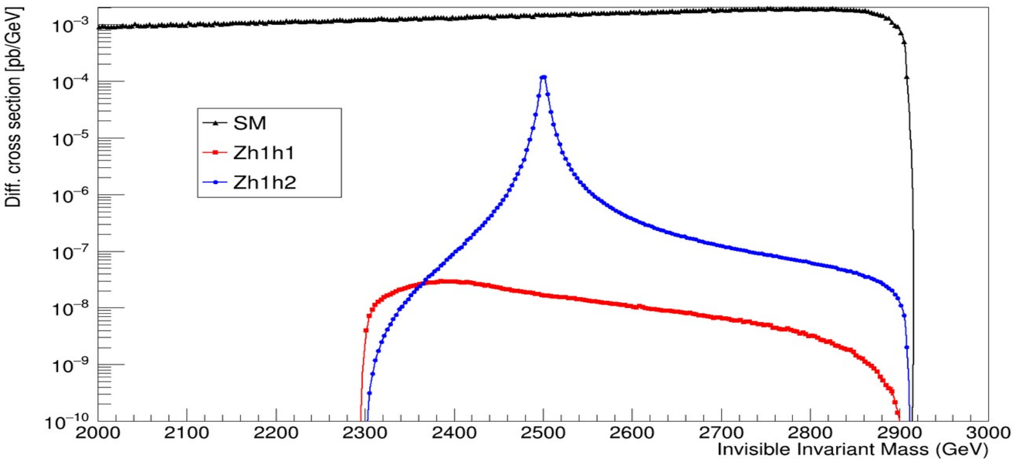
$$e^+e^- \to \mu^+\mu$$





Mono-Z at CLIC





Vector Dark Matter

Vector Dark Matter

Vector Dark Matter Candidates

- **Kaluza-Klein photon**
- **T-odd heavy photon in Little Higgs with T-parity**
- **(Abelian) Z’ with Z_2 symmetry**
- **Vector part of propagating torsion [A. Belyaev and I. Shapiro]**
- **Vectors fields in SU(2)_L representations**

Minimal Isotriplet Vector Dark Matter

Based on:

- Phys.Rev. D99 (2019), 115003 *A.Belyaev, G. Cacciapaglia, J. McKey, D. Marin and AZ*

$$\begin{aligned}\mathcal{L} \;=\;& -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\ & -\frac{g^2}{2}Tr\left\{[V_\mu, V_\nu]\,[V^\mu, V^\nu]\right\} \\ & -igTr\left\{G_{\mu\nu}\,[V^\mu, V^\nu]\right\} + M^2 Tr\{V_\nu V^\nu\}\end{aligned}$$

V is a massive vector field in the adjoint representation of a local SU(N)

This Lagrangian is consistent with perturbative unitarity at tree level due to two crucial facts:

- It has an accidental Z_2 symmetry
- There is only one coupling constant: the gauge coupling constant

$$\begin{aligned} G_\mu &\rightarrow UG_\mu U^{-1} - \frac{1}{g}\left(\partial_\mu U\right)U^{-1} \\ V_\mu &\rightarrow UV_\mu U^{-1}\end{aligned}$$

A. Zerwekh Int.J.Mod.Phys. A28 (2013) 1350054

A simple rotation

$$G = \frac{1}{\sqrt{2}}(A1 + A2)$$

$$V = \frac{1}{\sqrt{2}}(A1 - A2)$$

$$\mathcal{L} = -\frac{1}{2}Tr\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}Tr\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}Tr\left[\left(A_{1\mu} - A_{2\mu}\right)^2\right]$$

$$F_{1\mu\nu} = \partial_\mu A_{1\nu} - \partial_\nu A_{1\mu} - i\sqrt{2}g\left[A_{1\mu}, A_{1\nu}\right]$$

Same coupling constant

(pseudo-) T-parity

$$F_{2\mu\nu} = \partial_\mu A_{2\nu} - \partial_\nu A_{2\mu} - i\sqrt{2}g\left[A_{2\mu}, A_{2\nu}\right]$$

$$A_{i\mu} \rightarrow U A_{i\mu} U^{-1} - \frac{1}{\sqrt{2}g}\left(\partial_\mu U\right) U^{-1} \qquad (i = 1, 2)$$

A simple rotation

$$G = \frac{1}{\sqrt{2}}(A1 + A2)$$

$$V = \frac{1}{\sqrt{2}}(A1 - A2)$$

Bigauge theory

$$\mathcal{L} = -\frac{1}{2}Tr\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}Tr\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}Tr\left[(A_{1\mu} - A_{2\mu})^2\right]$$

This is the Yang-Mills analog of Bigravity (Thanks to Max Bañados)

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-f}R(f) + m^2 M_g^2\int d^4x\sqrt{-g}\sum_{n=0}^{4}\beta_n e_n(\mathbb{X}) -$$

$$\mathbb{X} = \sqrt{g^{-1}f}$$

$$e_0(\mathbb{X}) = 1,$$
$$e_1(\mathbb{X}) = [\mathbb{X}],$$
$$e_2(\mathbb{X}) = \frac{1}{2}\left([\mathbb{X}]^2 - [\mathbb{X}^2]\right),$$
$$e_3(\mathbb{X}) = \frac{1}{6}\left([\mathbb{X}]^3 - 3[\mathbb{X}][\mathbb{X}^2] + 2[\mathbb{X}^3]\right),$$
$$e_4(\mathbb{X}) = \det \mathbb{X},$$

$$
\begin{aligned}
\mathcal{L} \quad = \quad & \mathcal{L}_{SM} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
& - \frac{g^2}{2} Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
& - igTr\left\{W_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + \tilde{M}^2 Tr\{V_\nu V^\nu\} \\
& + a\left(\Phi^\dagger \Phi\right) Tr\{V_\nu V^\nu\}
\end{aligned}
$$

Higgs doublet

D_μ is the covariant derivative of SU(2) in the adjoint representation

Only two free parameters: a and M

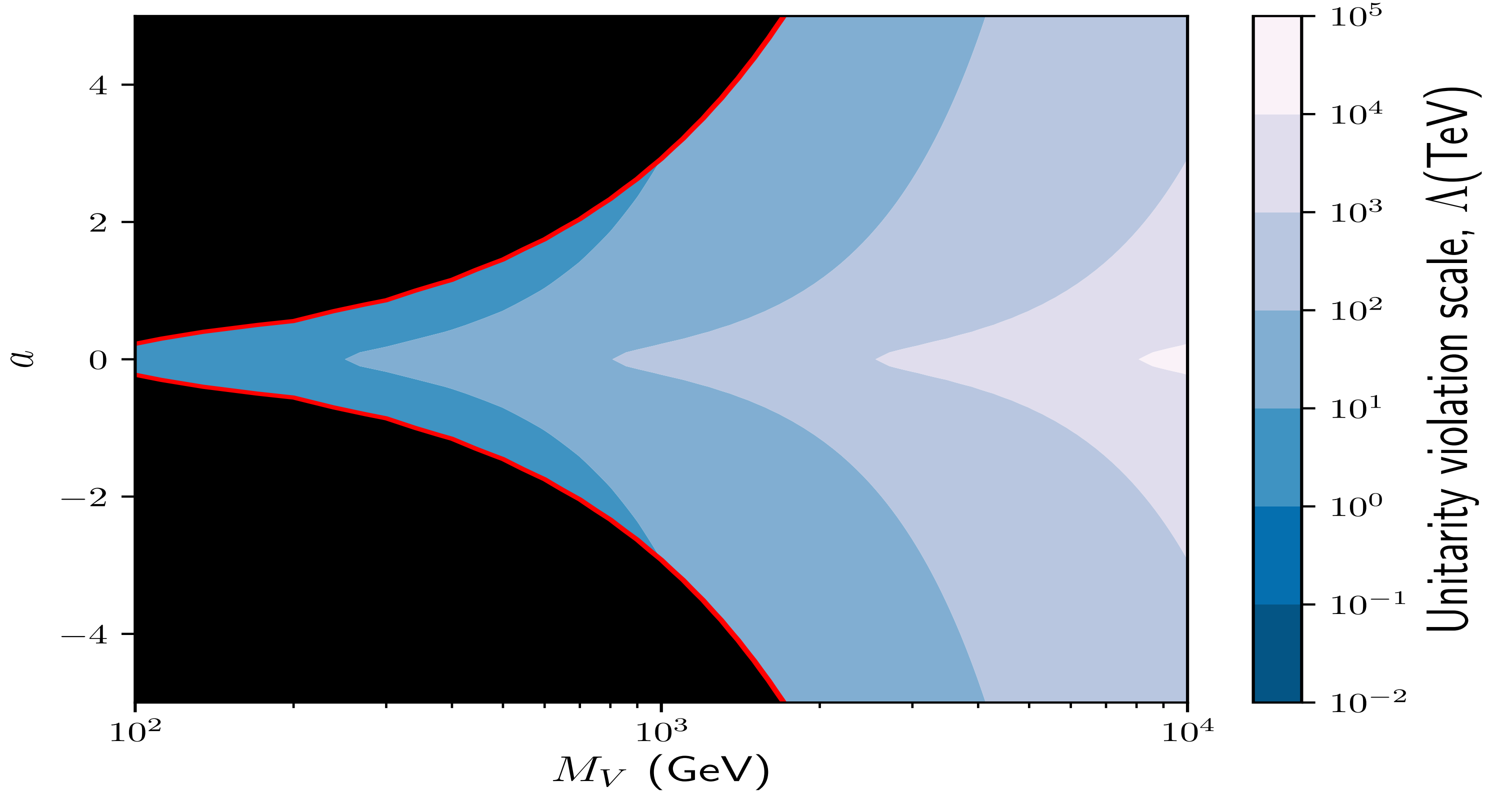
$$
a^{1-\mathrm{loop}} = -3 \frac{\alpha^2}{\sin \theta_W^4} \ln \frac{\Lambda}{M_V} \approx -0.0037 \; \ln \frac{\Lambda}{M_V}
$$

Unitarity

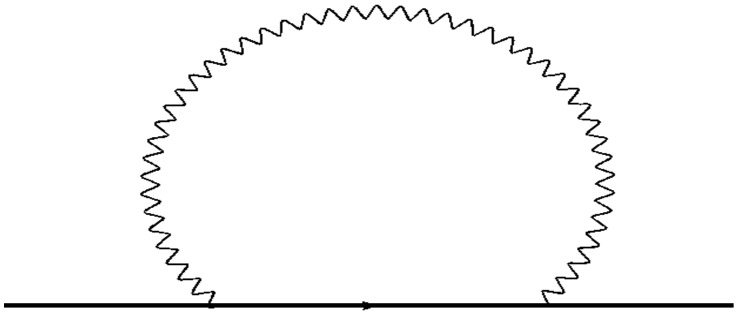
$$\sigma_l(k) \leq \frac{4\pi\,(2l+1)}{k^2}$$

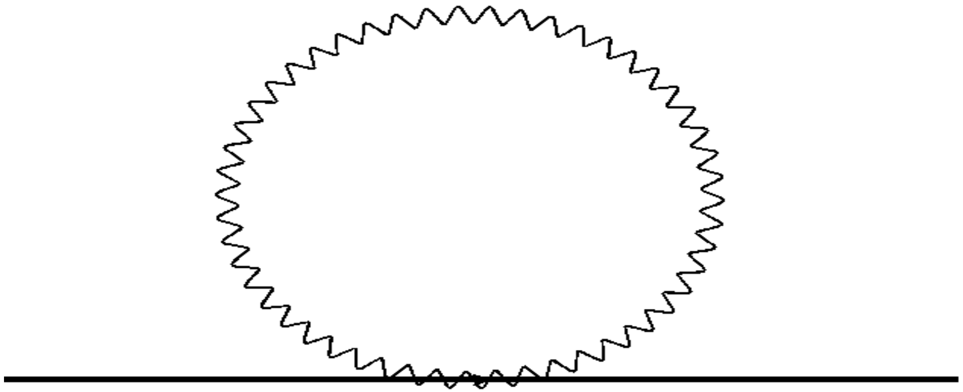
$$\Lambda \approx \frac{8\sqrt{\pi}M_V^2}{\sqrt{4a^2v^2 + 3g^2M_W^2}}$$

Unitarity violation scale



Radiative corrections produce mass splitting

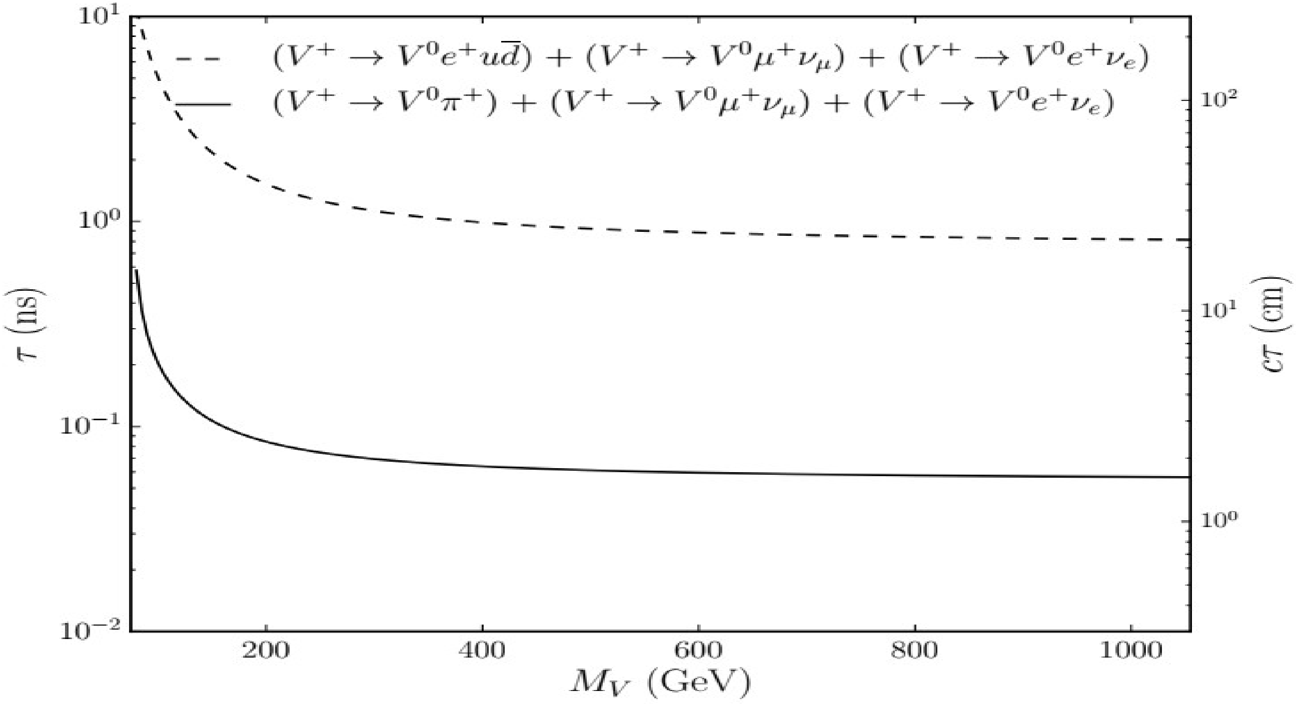


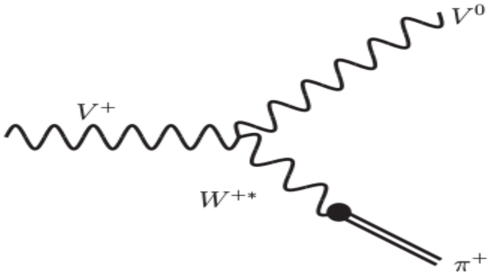


$$\Delta M \approx 210 MeV$$

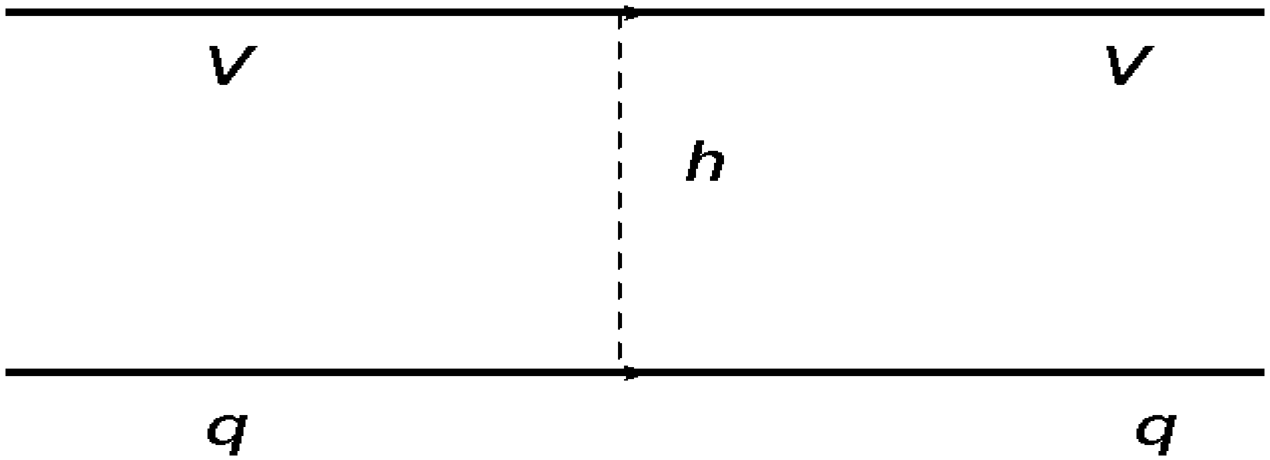
$$V^{\pm} \to V^{0} e^{\pm} \nu \qquad V^{\pm} \to V^{0} \pi^{\pm}$$

Lifetime of the charged components

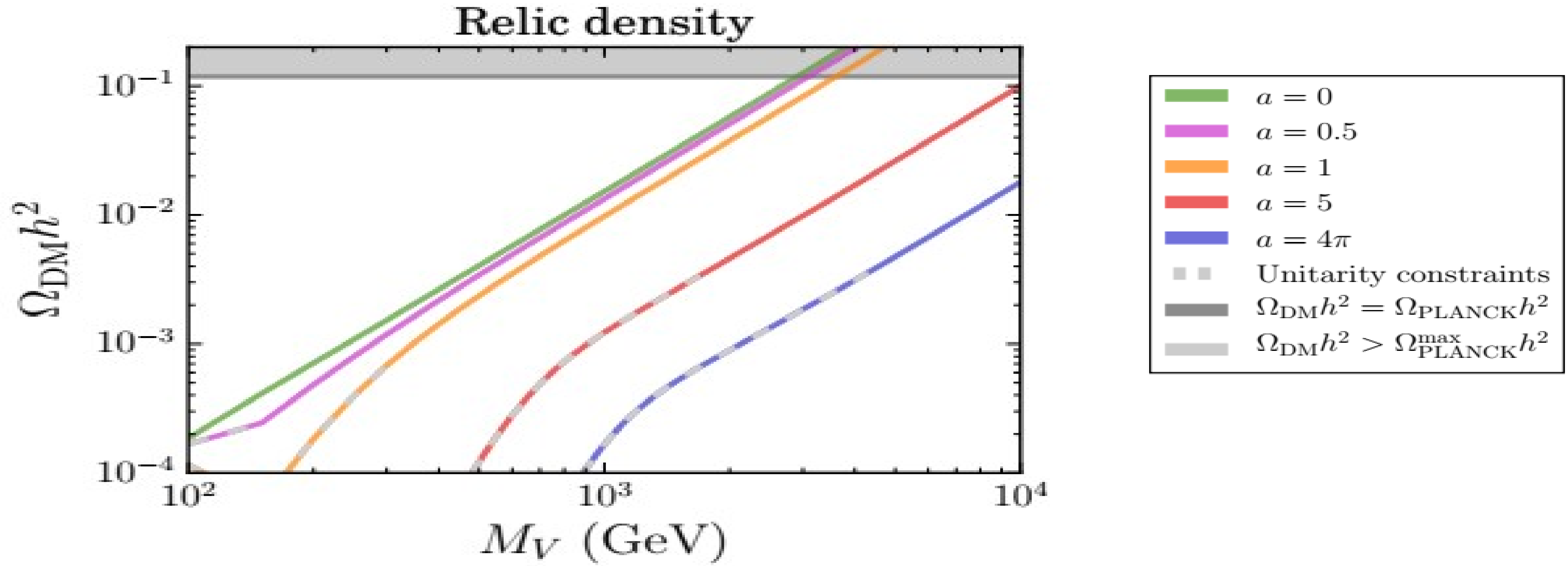




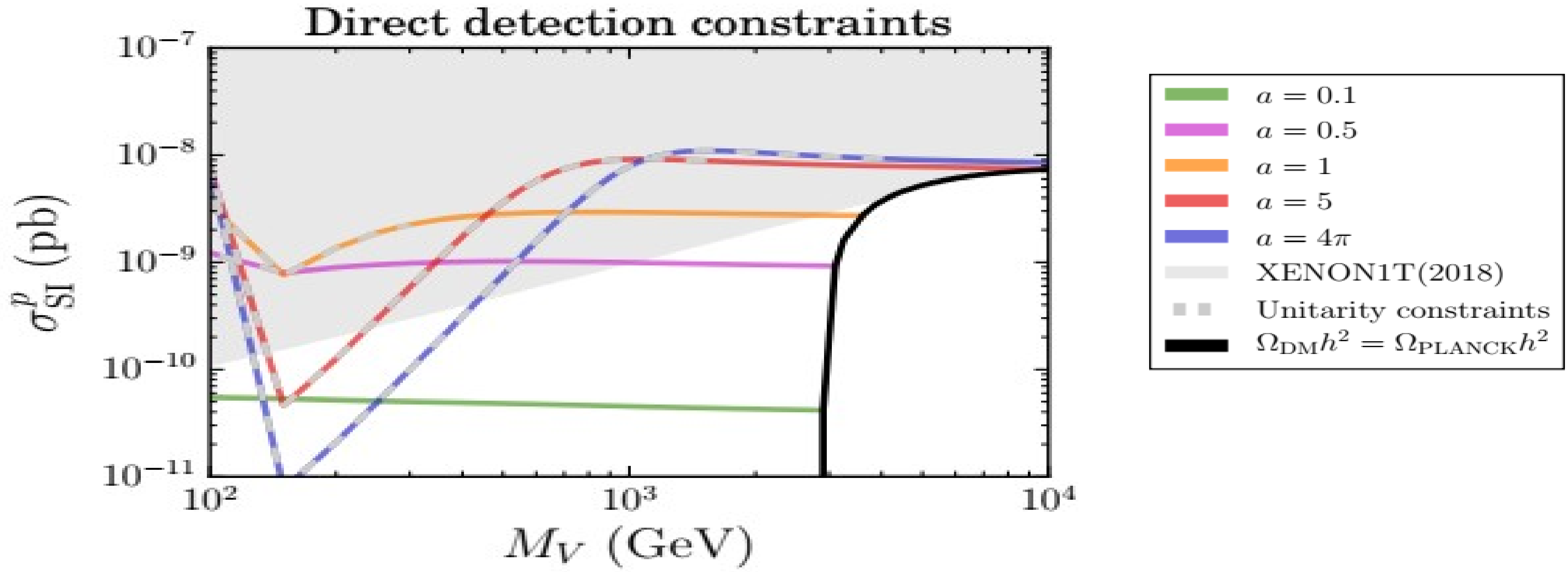
Interaction between V^0 and quarks (low energy)



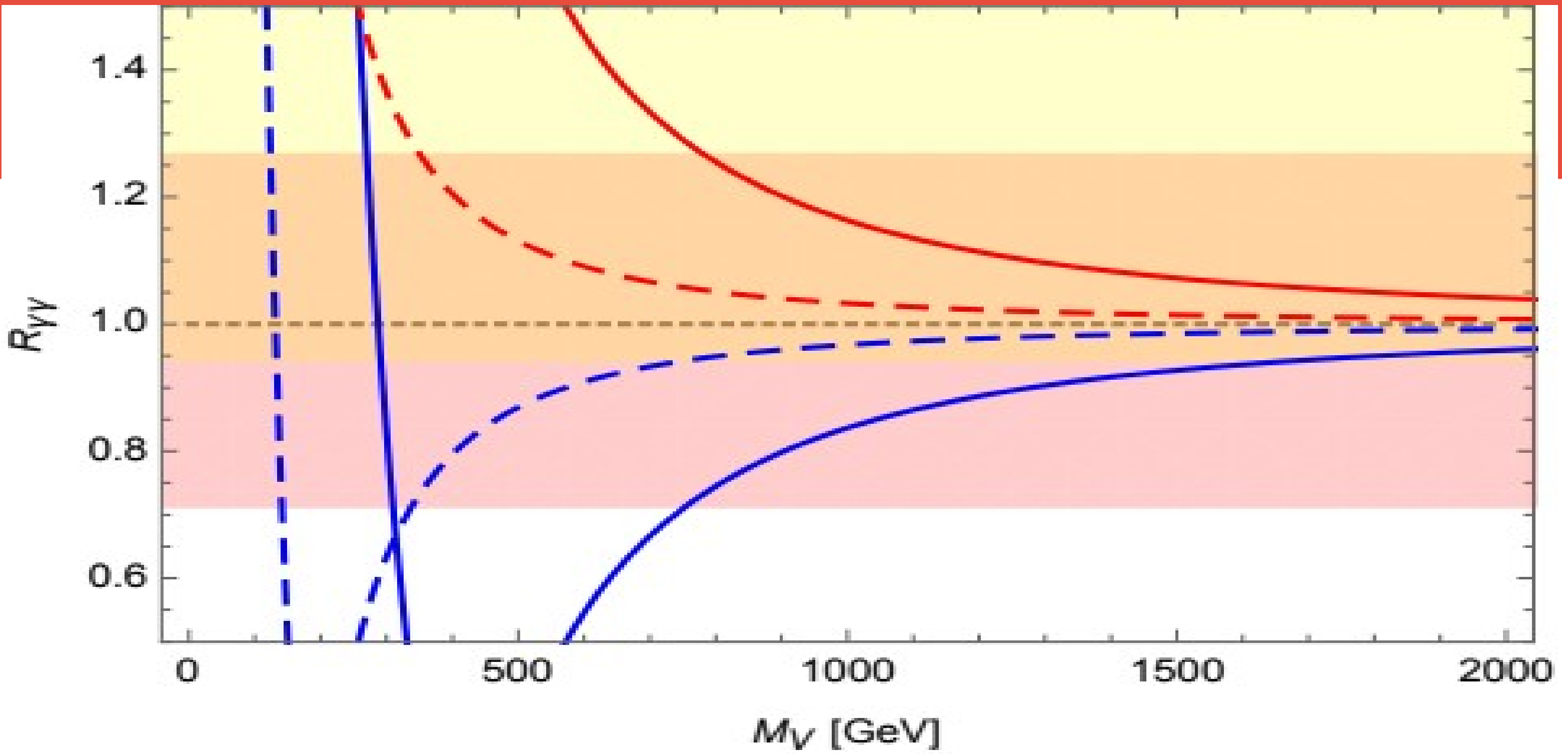
Experimental Constrains



Relic density
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\Omega_{\rm DM}h^2$
10^2
10^3
10^4
M_V (GeV)
$a = 0$
$a = 0.5$
$a = 1$
$a = 5$
$a = 4\pi$
Unitarity constraints
$\Omega_{\rm DM}h^2 = \Omega_{\rm PLANCK}h^2$
$\Omega_{\rm DM}h^2 > \Omega_{\rm PLANCK}^{\rm max}h^2$

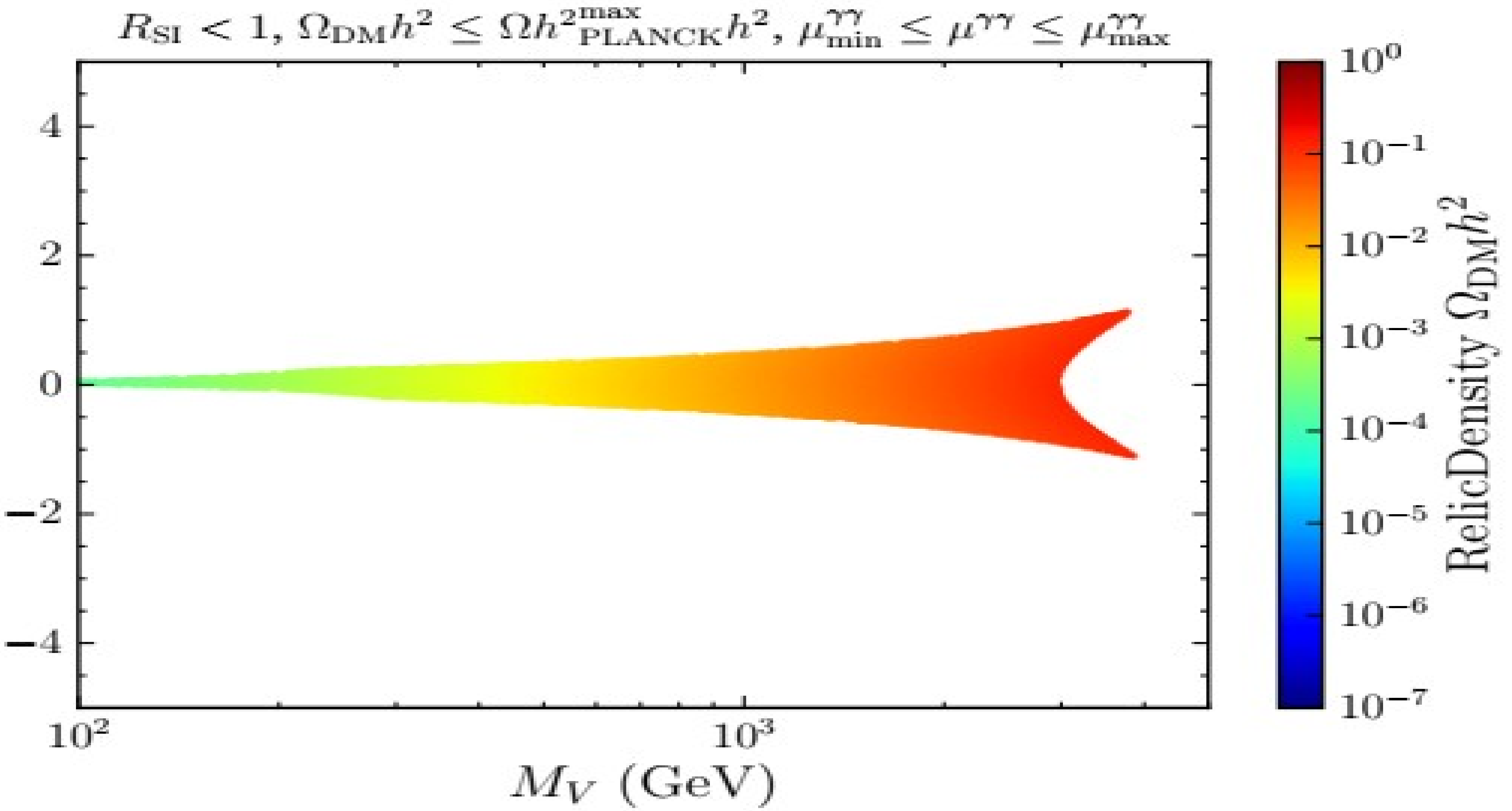


Direct detection constraints
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
$\sigma^p_{\rm SI}$ (pb)
10^2
10^3
10^4
M_V (GeV)
$a = 0.1$
$a = 0.5$
$a = 1$
$a = 5$
$a = 4\pi$
XENON1T(2018)
Unitarity constraints
$\Omega_{\rm DM}h^2 = \Omega_{\rm PLANCK}h^2$

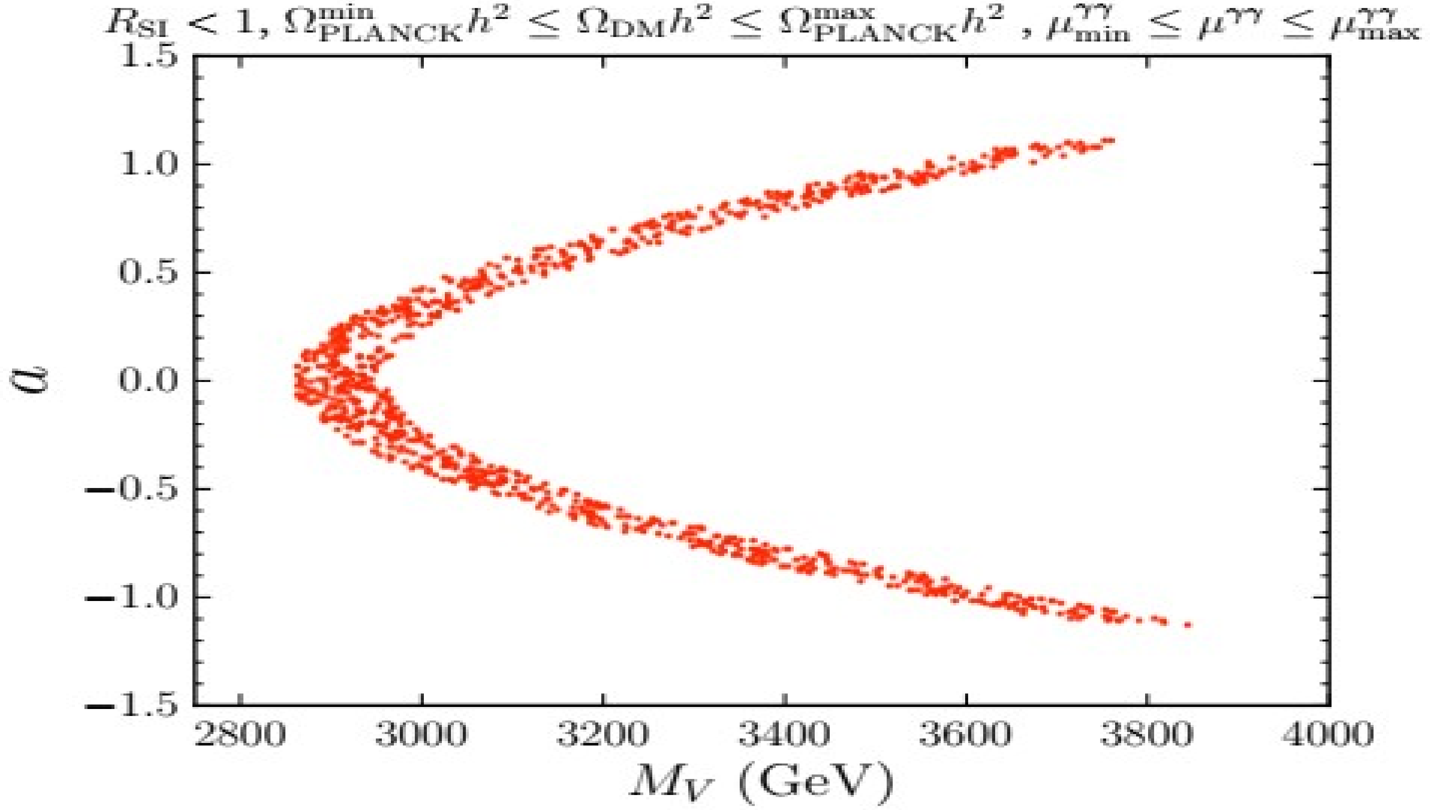


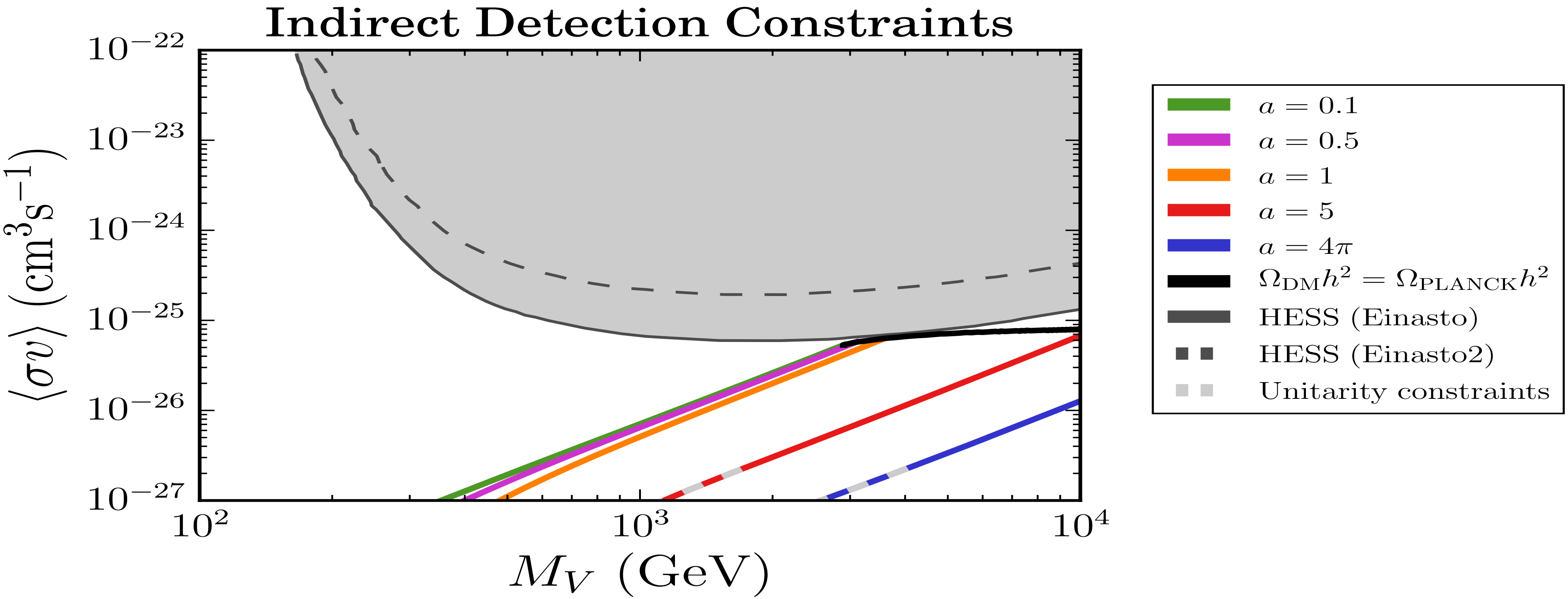
a = +/- 1(dashed) and a = +/- 5

The colour code uses red for positive values and blue for negative. The coloured bands are the experimentally allowed regions at 95 % CL from ATLAS (pink) and CMS (yellow), while the orange band shows the overlap



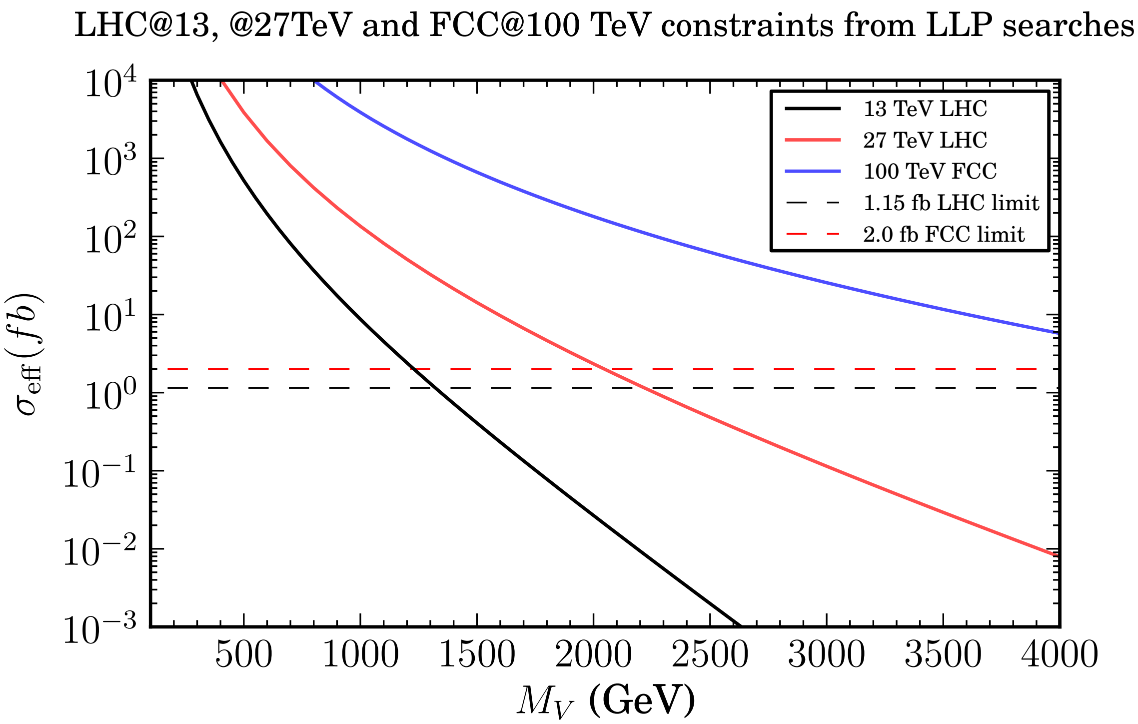
$R_{SI} < 1,\ \Omega_{DM}h^2 \le \Omega h^{2\,max}_{PLANCK} h^2,\ \mu^{\gamma\gamma}_{min} \le \mu^{\gamma\gamma} \le \mu^{\gamma\gamma}_{max}$
4
2
0
−2
−4
10^2
10^3
M_V (GeV)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
RelicDensity $\Omega_{DM}h^2$


$R_{SI} < 1, \Omega^{min}_{PLANCK} h^2 \leq \Omega_{DM} h^2 \leq \Omega^{max}_{PLANCK} h^2$, $\mu^{\gamma\gamma}_{min} \leq \mu^{\gamma\gamma} \leq \mu^{\gamma\gamma}_{max}$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
a
2800
3000
3200
3400
3600
3800
4000
M_V (GeV)



Indirect Detection Constraints
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
$\langle \sigma v \rangle$ (cm^{3}s^{-1})
10^2
10^3
10^4
M_V (GeV)
$a = 0.1$
$a = 0.5$
$a = 1$
$a = 5$
$a = 4\pi$
$\Omega_{\rm DM} h^2 = \Omega_{\rm PLANCK} h^2$
HESS (Einasto)
HESS (Einasto2)
Unitarity constraints

What about the LHC ?



$$\sigma_{eff} = \sigma\left(pp \to V^{\pm}V^{0}\right) + 2\sigma\left(pp \to V^{+}V^{-}\right)$$

Dark Matter from a Vector Field in the Fundamental Representation of SU(2)_L

Based on:

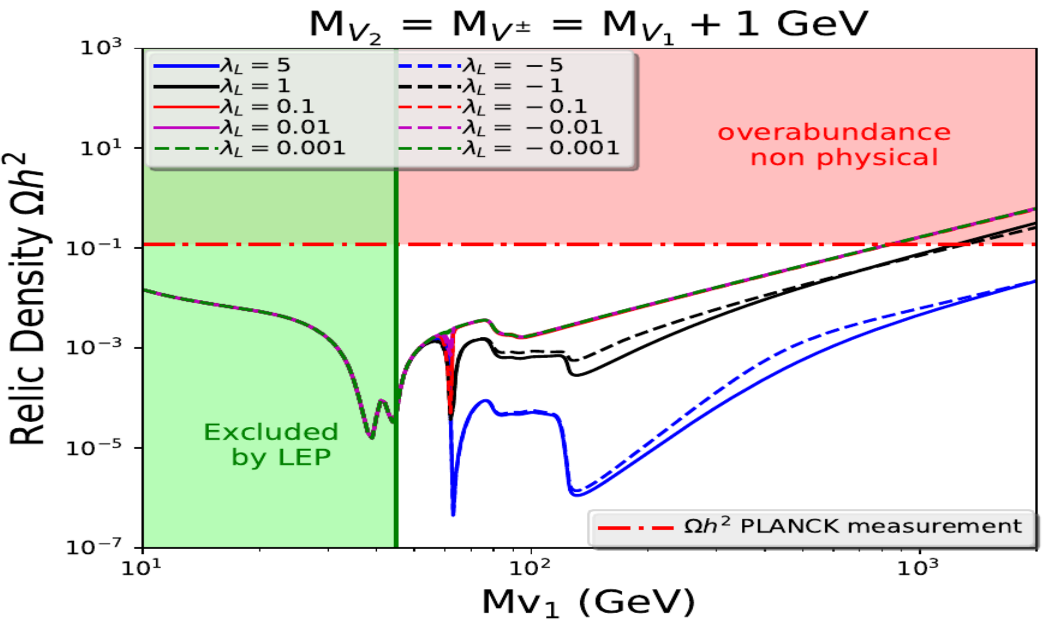
- Phys.Rev. D99 (2019) no.7, 075026 *Bastián Díaz, Felipe Rojas-Abatte, A. Z.*

$$
\begin{aligned}
L = & (D_\mu V_\nu - D_\nu V_\mu)^\dagger (D^\mu V^\nu - D^\nu V^\mu) \\
& + \frac{1}{2} M^2 V_\mu^\dagger V^\mu + \lambda_2 (\phi^\dagger \phi)(V_\mu^\dagger V^\mu) \\
& + \lambda_3 (\phi^\dagger V_\mu)(V^{\mu\dagger} \phi) + \lambda_4 (V_\mu^\dagger \phi)(\phi^\dagger V^\mu) \\
& + \alpha_1 \left[\phi^\dagger D_\mu V^\mu + (D_\mu V^\mu)^\dagger \phi\right] + \alpha_2 \left[V_\mu^\dagger (D^\mu \phi) + (D_\mu \phi)^\dagger V^{\mu\dagger}\right] \\
& + \alpha_3 (V_\mu^\dagger V^\mu)(V_\nu^\dagger V^\nu) + \alpha_4 (V_\mu^\dagger V^\nu)(V_\nu^\dagger V^\mu)
\end{aligned}
$$

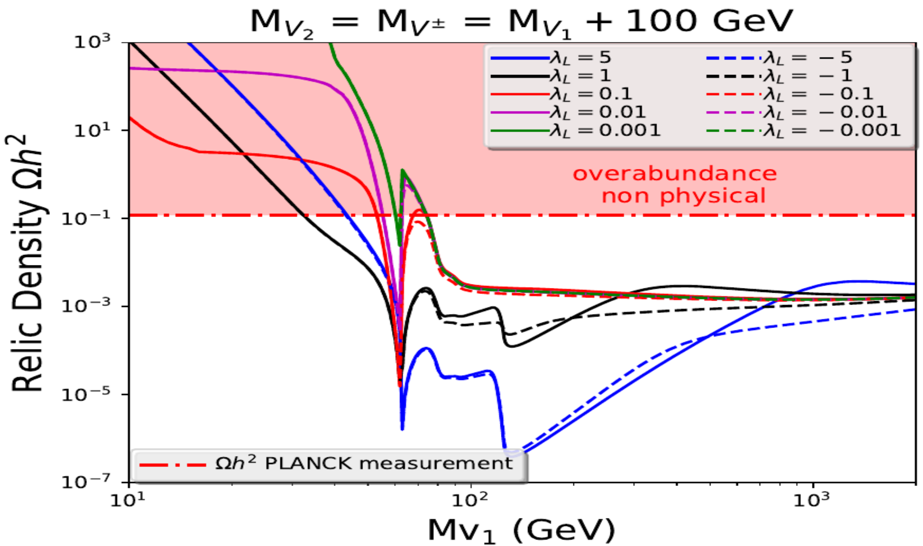
$$
V_\mu = \begin{pmatrix} V_\mu^+ \\ V_\mu^0 + i V_\mu^1 \end{pmatrix}
$$

It is not possible to couple V to standard fermions without introducing exotic vector-like fermions

Very nice but already invented by M.V. Chizhov and G. Dvali, PLB 703 (2011) 593

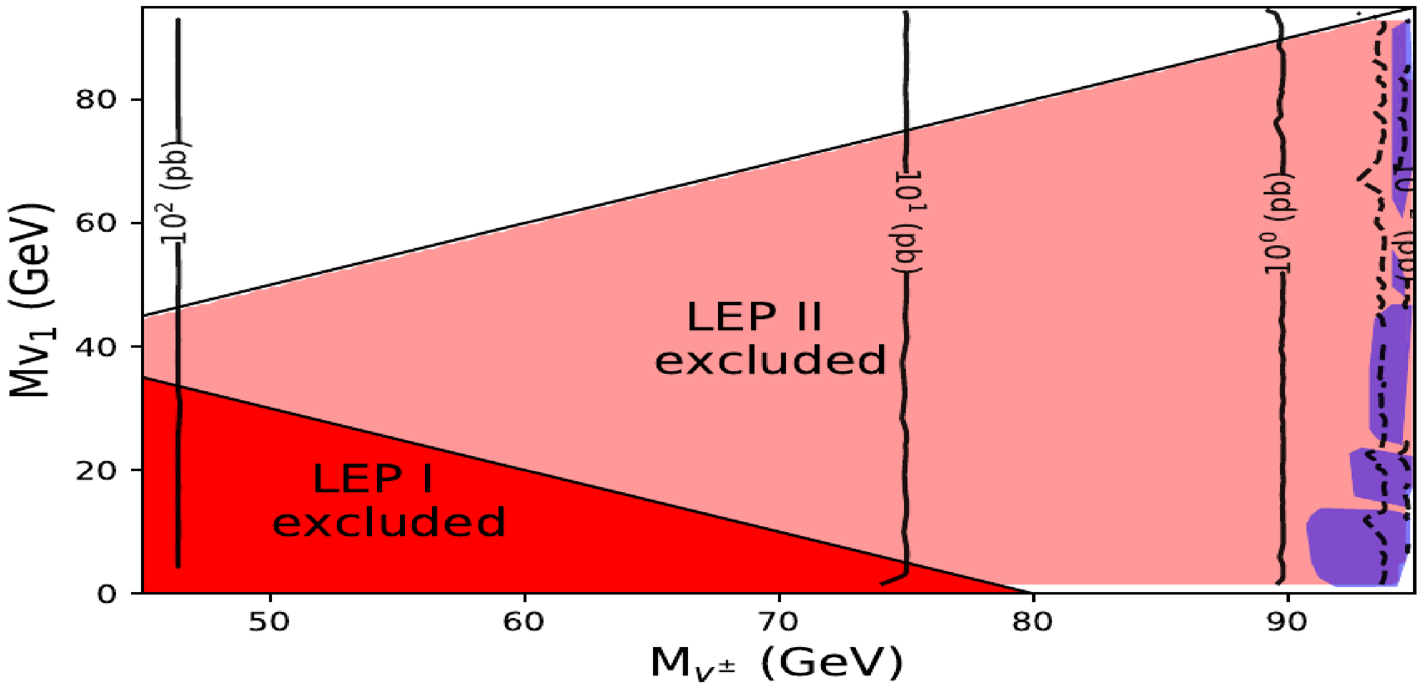


$M_{V_2} = M_{V^\pm} = M_{V_1} + 1$ GeV
$\lambda_L = 5$
$\lambda_L = 1$
$\lambda_L = 0.1$
$\lambda_L = 0.01$
$\lambda_L = 0.001$
$\lambda_L = -5$
$\lambda_L = -1$
$\lambda_L = -0.1$
$\lambda_L = -0.01$
$\lambda_L = -0.001$
overabundance
non physical
Excluded
by LEP
Ωh^2 PLANCK measurement
Relic Density Ωh^2
Mv_1 (GeV)



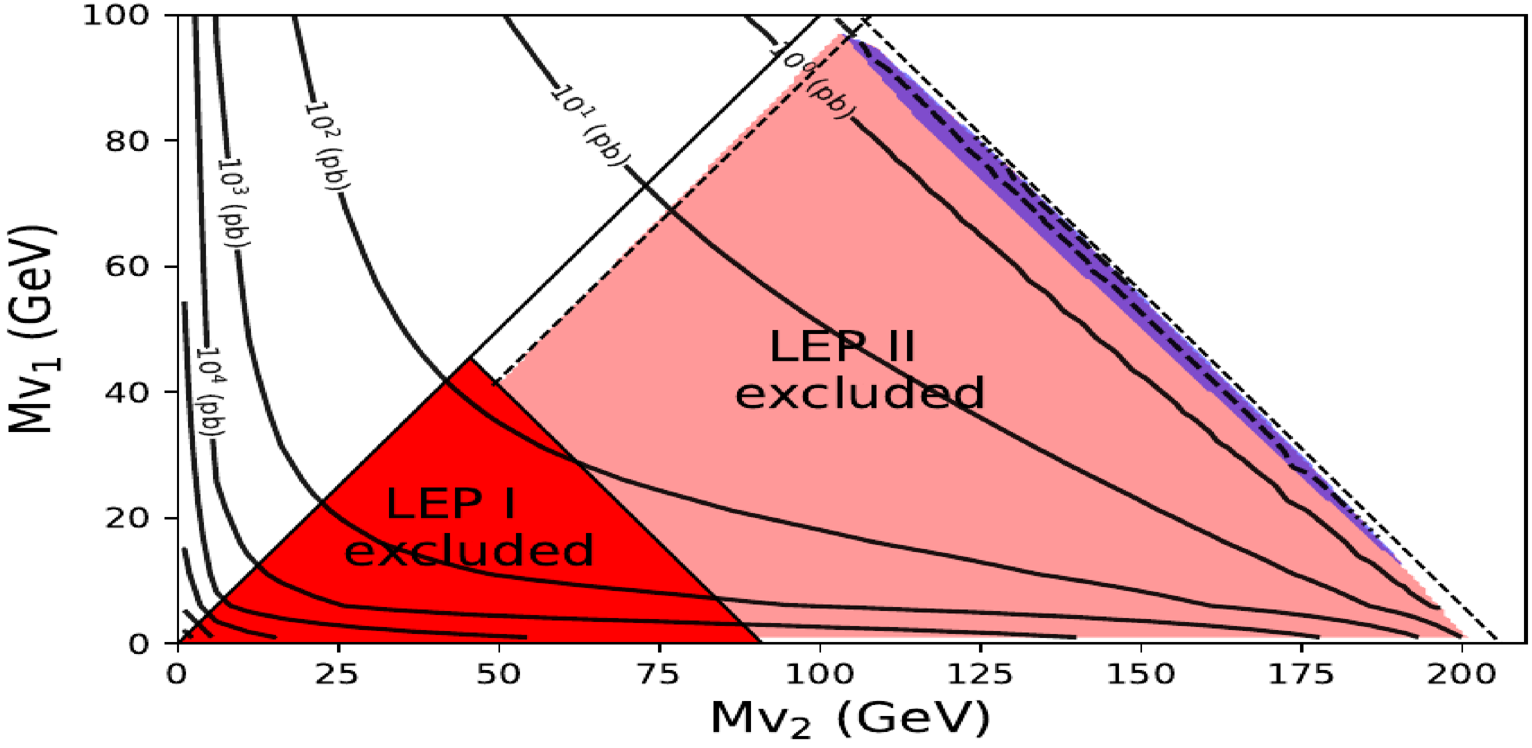
$M_{V_2} = M_{V^\pm} = M_{V_1} + 100$ GeV
$\lambda_L = 5$
$\lambda_L = 1$
$\lambda_L = 0.1$
$\lambda_L = 0.01$
$\lambda_L = 0.001$
$\lambda_L = -5$
$\lambda_L = -1$
$\lambda_L = -0.1$
$\lambda_L = -0.01$
$\lambda_L = -0.001$
overabundance
non physical
Ωh^2 PLANCK measurement
Relic Density Ωh^2
Mv_1 (GeV)

LEP

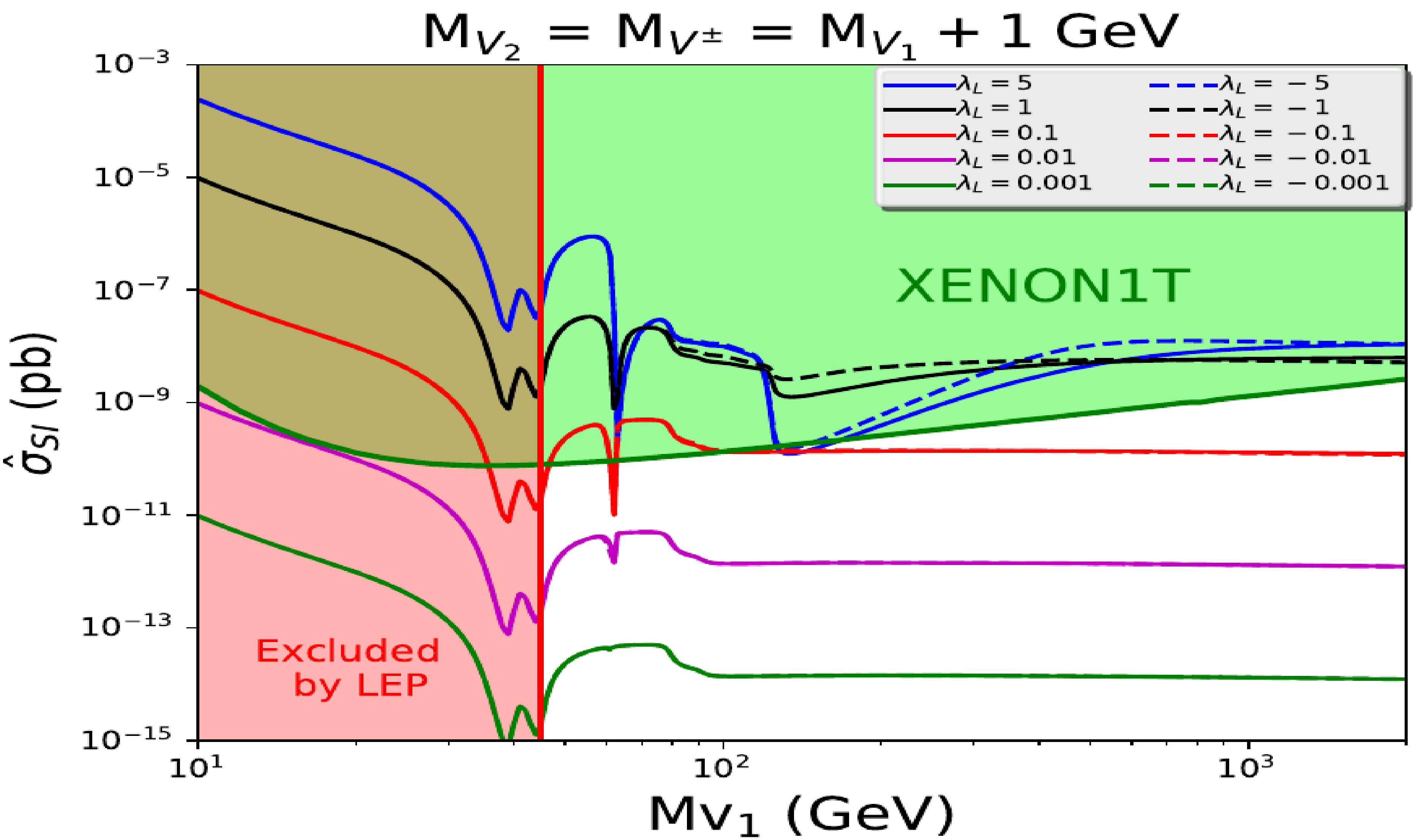


LEP II
excluded
LEP I
excluded
10^2 (pb)
10^1 (pb)
10^0 (pb)
M_{V_1} (GeV)
$M_{V^\pm}$ (GeV)
0
20
40
60
80
50
60
70
80
90

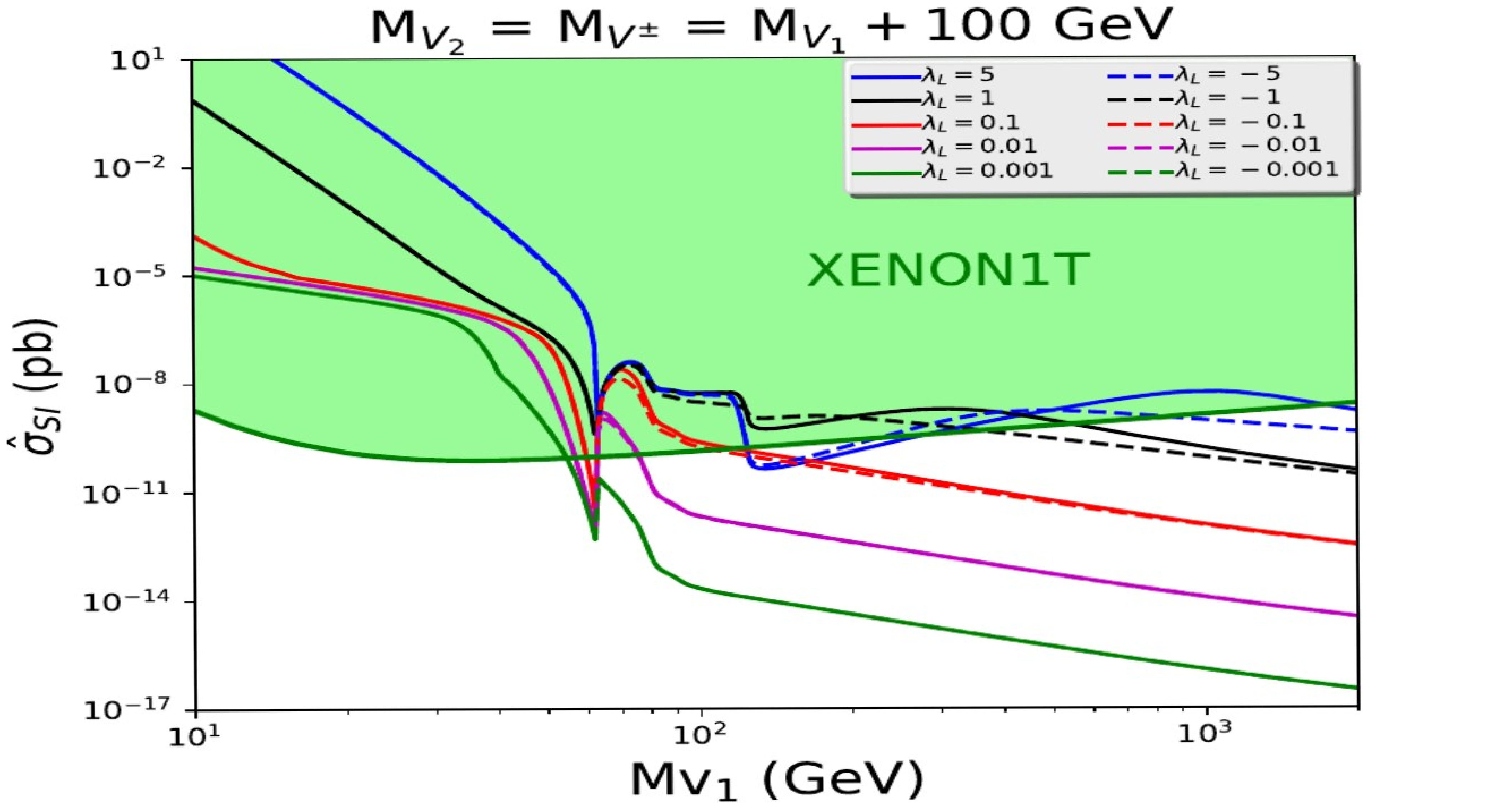
LEP



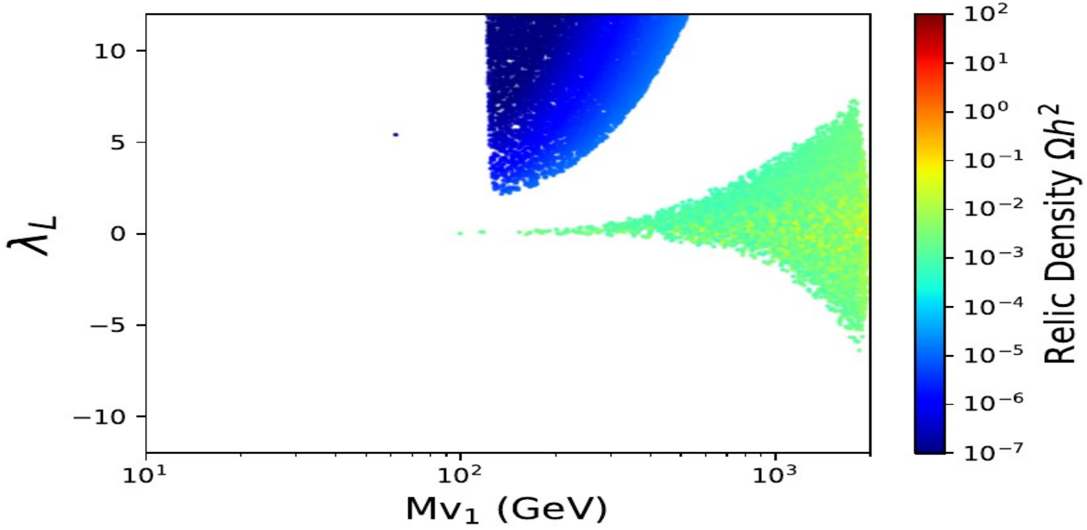
LEP I excluded
LEP II excluded
10^4 (pb)
10^3 (pb)
10^2 (pb)
10^1 (pb)
10^0 (pb)
M_{V_1} (GeV)
M_{V_2} (GeV)
0
20
40
60
80
100
0
25
50
75
100
125
150
175
200



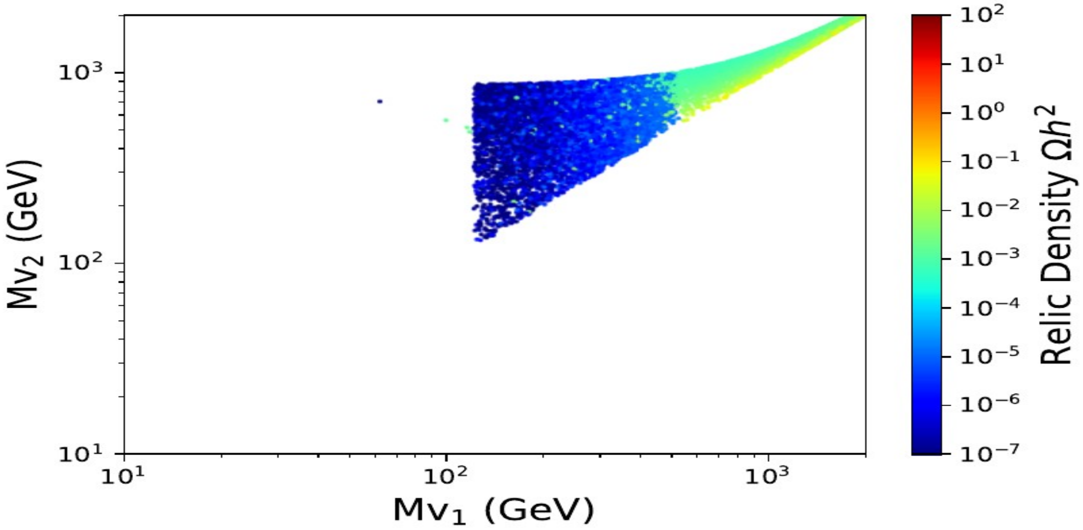
$M_{V_2} = M_{V^\pm} = M_{V_1} + 1$ GeV
$\hat{\sigma}_{SI}$ (pb)
M_{V_1} (GeV)
$\lambda_L = 5$
$\lambda_L = 1$
$\lambda_L = 0.1$
$\lambda_L = 0.01$
$\lambda_L = 0.001$
$\lambda_L = -5$
$\lambda_L = -1$
$\lambda_L = -0.1$
$\lambda_L = -0.01$
$\lambda_L = -0.001$
XENON1T
Excluded by LEP



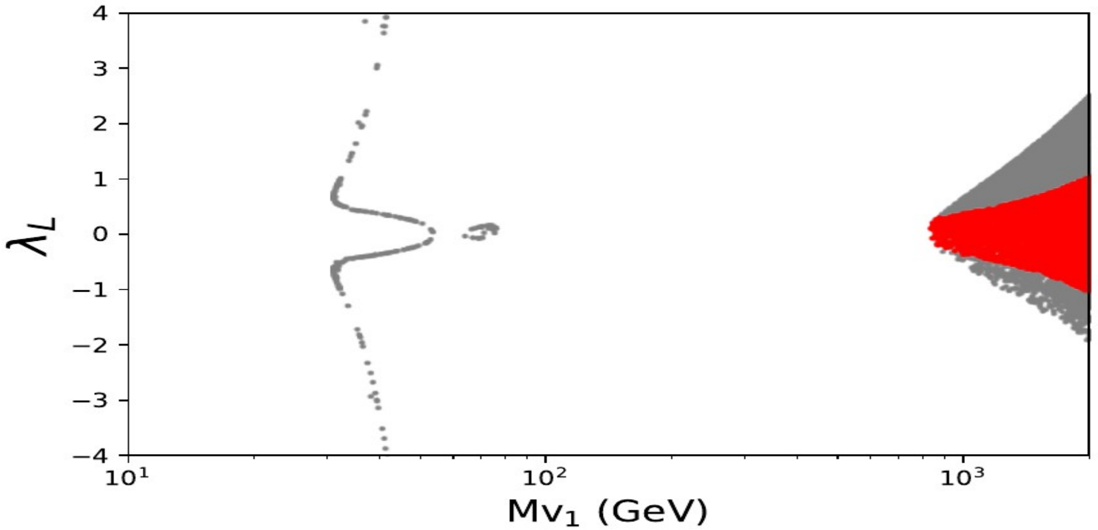
$M_{V_2} = M_{V^\pm} = M_{V_1} + 100$ GeV
$\lambda_L = 5$
$\lambda_L = -5$
$\lambda_L = 1$
$\lambda_L = -1$
$\lambda_L = 0.1$
$\lambda_L = -0.1$
$\lambda_L = 0.01$
$\lambda_L = -0.01$
$\lambda_L = 0.001$
$\lambda_L = -0.001$
XENON1T
$\hat{\sigma}_{SI}$ (pb)
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-11}
10^{-14}
10^{-17}
10^{1}
10^{2}
10^{3}
M_{V_1} (GeV)



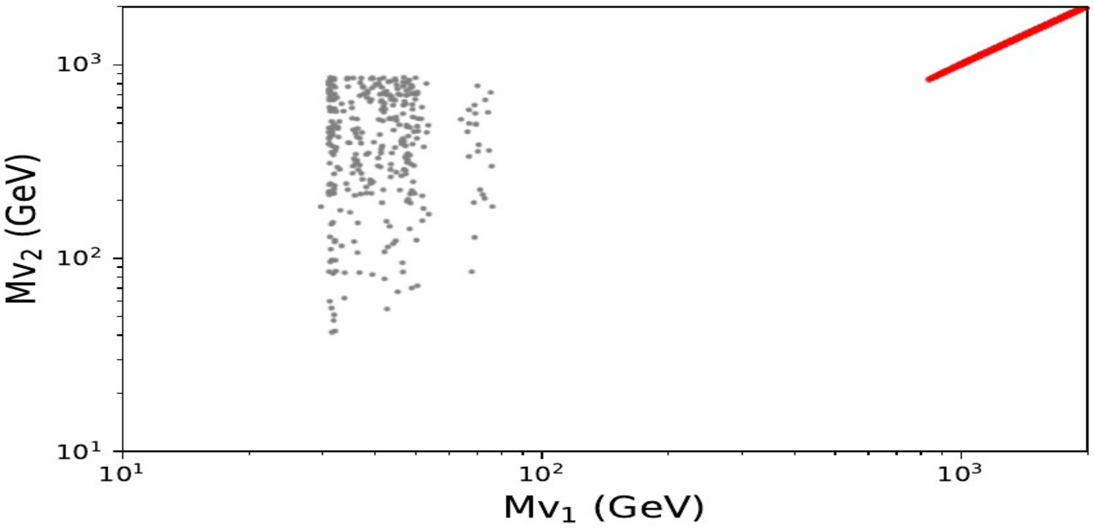
10
5
0
−5
−10
λ_L
10^1
10^2
10^3
Mv_1 (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Relic Density Ωh^2



10^3
10^2
10^1
Mv_2 (GeV)
10^1
10^2
10^3
Mv_1 (GeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Relic Density Ωh^2



4
3
2
1
0
−1
−2
−3
−4
λ_L
10^1
10^2
10^3
Mv_1 (GeV)



10^3
10^2
10^1
Mv_2 (GeV)
10^1
10^2
10^3
Mv_1 (GeV)

Conclusions

- **Vectors fields can play crucial roles in the dark sector**
- **We built extensions of the SM incorporating the new vector matter field in SU(2) multiplets and the models contain natural dark matter candidates.**
- **In both models a new Z_2 symmetry appears motivated by theory and not imposed by hand (specially in the isotriplet case).**
- **The models are consistent with collider and cosmological data**
- **A Vector in the Fundamental Representation offers a nice DM candidate but the model is strongly challenged by data and by unitarity constrains**
- **The model with isotriplet vector fields seems to be more robust.**
- **The models can be completely rule out (or discovered) at a 100 TeV collider**

People's demand....

Backup

Intriguing Questions

- How do we construct a consistent theory containing only a gauge boson and a massive vector field ?

- Is it possible to avoid the introduction of scalar fields ?

Poor Man (phenomenologist) Approach

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{1}{2} Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} \\
& + (1+a)\, Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
& + a_1 Tr\left\{\left(D_\mu V_\nu - D_\nu V_\mu\right)\left[V^\mu, V^\nu\right]\right\} \\
& + \frac{a_2}{2} Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
& + i a_3 Tr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}
\end{aligned}
$$

$$
\begin{aligned}
G_\mu \quad & \rightarrow \quad U G_\mu U^{-1} - \frac{1}{g}\left(\partial_\mu U\right) U^{-1} \\
V_\mu \quad & \rightarrow \quad U V_\mu U^{-1}
\end{aligned}
$$

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Compute $V_L V_L \to V_L V_L \qquad GG \to V_L V_L$

$$
\begin{aligned}
\mathcal{M} \quad = \quad & \frac{\left(a_2+g^2+a_1^2\right)\left(t^2-2tu-2u^2\right)(t+u)^2\, itu}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^4} f^{abe} f^{cde} \\
& + \frac{\left(a_2+g^2+a_1^2\right)\left(t^2+4tu+u^2\right)(t+u)^2\, itu}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^4} f^{ace} f^{bde} \\
& - \frac{\left(a_2+g^2\right)\left(t^4+11t^3u-23t^2u^2-28tu^3-2u^4\right)(t+u)\, i}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{abe} f^{cde} \\
& - \frac{6i\,(t+u)^2\, ag^2t^2u}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{abe} f^{cde} \\
& - \frac{\left(t^4+14t^3u-20t^2u^2-28tu^3-2u^4\right)a_1^2\,(t+u)\, i}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{abe} f^{cde} \\
& - \frac{\left(t^4+14t^3u+40t^2u^2+14tu^3+u^4\right)a_1^2\,(t+u)\, i}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{ace} f^{bde} \\
& + \frac{6i\,(t+u)^3\, ag^2tu}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{ace} f^{bde} \\
& - \frac{\left(a_2+g^2\right)\left(t^4+17t^3u+46t^2u^2+17tu^3+u^4\right)(t+u)\, i}{4s\left(M^2-s\right)\left(M^2-t\right)\left(M^2-u\right)M^2} f^{ace} f^{bde} \\
& + \mathcal{O}\left(\frac{M^2}{s}\right)
\end{aligned}
$$

If we choose :

$$
\begin{aligned}
a &= 0 \\
a_1 &= 0 \\
a_2 &= -g^2 \\
a_3 &= -g
\end{aligned}
$$

The unitary-violating terms disappear

$$\mathcal{M}(V_L V_L \to V_L V_L) = 0$$

$$\mathcal{M}(GG \to V_L V_L) = \text{constant} + \mathcal{O}\left(\frac{M^2}{s}\right)$$

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$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{1}{2}Tr\left\{G_{\mu\nu}G^{\mu\nu}\right\} - Tr\left\{D_\mu V_\nu D^\mu V^\nu\right\} + Tr\left\{D_\mu V_\nu D^\nu V^\mu\right\} \\
& -\frac{g^2}{2}Tr\left\{\left[V_\mu, V_\nu\right]\left[V^\mu, V^\nu\right]\right\} \\
& -igTr\left\{G_{\mu\nu}\left[V^\mu, V^\nu\right]\right\} + M^2 Tr\{V_\nu V^\nu\}
\end{aligned}
$$

V is a massive vector field in the adjoint representation of a local SU(N)

This Lagrangian is consistent with perturbative unitarity at tree level due to two crucial facts:

- It has an accidental Z_2 symmetry
- There is only one coupling constant: the gauge coupling constant

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A simple rotation

$$G = \frac{1}{\sqrt{2}}(A1 + A2)$$
$$V = \frac{1}{\sqrt{2}}(A1 - A2)$$

$$\mathcal{L} = -\frac{1}{2}Tr\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}Tr\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}Tr\left[(A_{1\mu} - A_{2\mu})^2\right]$$

$$F_{1\mu\nu} = \partial_\mu A_{1\nu} - \partial_\nu A_{1\mu} - i\sqrt{2}g\left[A_{1\mu}, A_{1\nu}\right]$$

Same coupling constant

(pseudo-) T-parity

$$F_{2\mu\nu} = \partial_\mu A_{2\nu} - \partial_\nu A_{2\mu} - i\sqrt{2}g\left[A_{2\mu}, A_{2\nu}\right]$$

$$A_{i\mu} \rightarrow U A_{i\mu} U^{-1} - \frac{1}{\sqrt{2}g}(\partial_\mu U)U^{-1} \quad (i = 1, 2)$$

A simple rotation

$$G = \frac{1}{\sqrt{2}}(A1 + A2)$$

$$V = \frac{1}{\sqrt{2}}(A1 - A2)$$

Bigauge theory

$$\mathcal{L} = -\frac{1}{2}Tr\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}Tr\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}Tr\left[(A_{1\mu} - A_{2\mu})^2\right]$$

This is the Yang-Mills analog of Bigravity (Thanks to Max Bañados)

$$S = -\frac{M_g^2}{2}\int d^4x\sqrt{-g}R(g) - \frac{M_f^2}{2}\int d^4x\sqrt{-f}R(f) + m^2M_g^2\int d^4x\sqrt{-g}\sum_{n=0}^{4}\beta_n e_n(\mathbb{X})$$

$$\mathbb{X} = \sqrt{g^{-1}f}$$

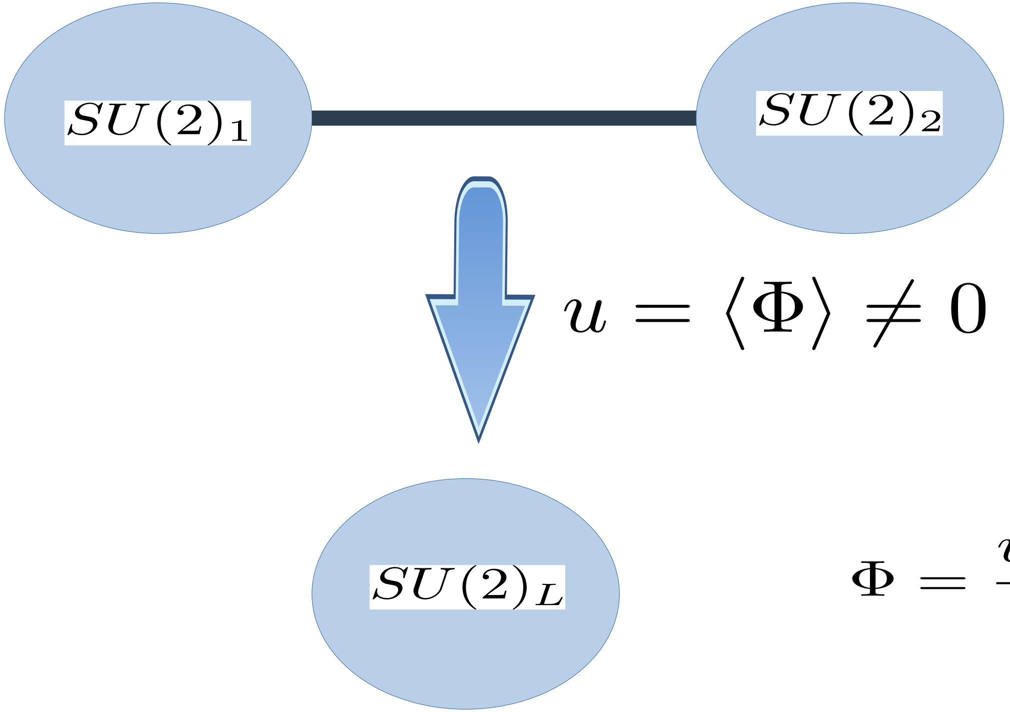
$$e_0(\mathbb{X}) = 1,$$
$$e_1(\mathbb{X}) = [\mathbb{X}],$$
$$e_2(\mathbb{X}) = \frac{1}{2}\left([\mathbb{X}]^2 - [\mathbb{X}^2]\right),$$
$$e_3(\mathbb{X}) = \frac{1}{6}\left([\mathbb{X}]^3 - 3[\mathbb{X}][\mathbb{X}^2] + 2[\mathbb{X}^3]\right),$$
$$e_4(\mathbb{X}) = \det\mathbb{X},$$

Let’s start from the gauge-like representation

$$\mathcal{L} = -\frac{1}{2}\,\mathrm{Tr}\left[F_{1\mu\nu}F_1^{\mu\nu}\right] - \frac{1}{2}\,\mathrm{Tr}\left[F_{2\mu\nu}F_2^{\mu\nu}\right] + \frac{M^2}{2}\,\mathrm{Tr}\left[\left(A_{1\mu} - A_{2\mu}\right)^2\right]$$

We have to reproduce this particular structure

The idea is to describe both vector fields as gauge fields and to break down the symmetry to SM



$$\Phi \rightarrow U_1 \Phi U_2^\dagger$$

$$D\Phi = \partial\Phi - i\frac{g}{\sqrt{2}}A_1\Phi + i\frac{g}{\sqrt{2}}\Phi A_2$$

$$\Phi = \frac{u + \widetilde{\sigma}(x)}{\sqrt{2}}\Sigma$$

Same coupling constant!
(T-parity)

But…

- SU(2)XSU(2) has the same algebra than SO(4)
- There is only one coupling constant
- Maybe the underlying theory is based on $SO(4)_L \times U(1)_Y$

A simple idea for coupling the matter fields

(toy model)

- Make the standard left-handed fermions doublets of both SU(2)'s
- Make the SM Higgs field doublet of both SU(2)'s

$$D\psi_L = \partial\psi_L - i\frac{g}{\sqrt{2}}A_1\psi_L - i\frac{g}{\sqrt{2}}A_2\psi_L - ig'YB\psi_L$$

$$D\varphi = \partial\varphi - i\frac{g}{\sqrt{2}}A_1\varphi - i\frac{g}{\sqrt{2}}A_2\varphi - ig'YB\varphi$$

In this way, the standard fields only couple to the even combination

$$W = \frac{1}{\sqrt{2}}\left(A_1 + A_2\right)$$

Scalar Potential

$$V(\Phi,\varphi) = \frac{\mu_2^2}{2}\,\mathrm{Tr}\left[\Phi^\dagger\Phi\right] + \frac{\lambda_2}{4}\,\mathrm{Tr}\left[\Phi^\dagger\Phi\right]^2 + \mu_1^2\varphi^\dagger\varphi + \lambda_1\left(\varphi^\dagger\varphi\right)^2 + \frac{\lambda_3}{2}\left(\varphi^\dagger\varphi\right) Tr\left[\Phi^\dagger\Phi\right]$$

$$m_\sigma \approx \sqrt{2\lambda_2}u\left(1+\frac{\lambda_3^2 v^2}{32\lambda_2^2 u^2}\right)$$

$$m_h \approx \sqrt{2\lambda_1 - \frac{\lambda_3^2}{8\lambda_2}v}$$

Some prediction and results

- As M_V is about 3-4 TeV, the scale of the new symmetry breaking has to be about 10 TeV
- λ_1 has to be larger than in the SM
- The a parameter (controlling the hhVV interaction) is small because it is generated only through mixings
- The model preserves unitarity