SAPHIR Annual Research Meeting 2023

Massive Vector Fields and Dark Matter

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UTFSM-SAPHIR

Everybody Hates Massive Vector Fields
(especially except me and my students)

WARNING

- Most of the results presented here were obtained using the approximation

$$\varepsilon_L^\mu \approx \frac{p^\mu}{M} + \mathcal{O}\left(\frac{M^2}{E^2}\right)$$

- This is an usual approximation which appears in textbooks

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- So far so good...

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- . . . as it was recently (a few days ago) discovered by Gonzalo Benítez

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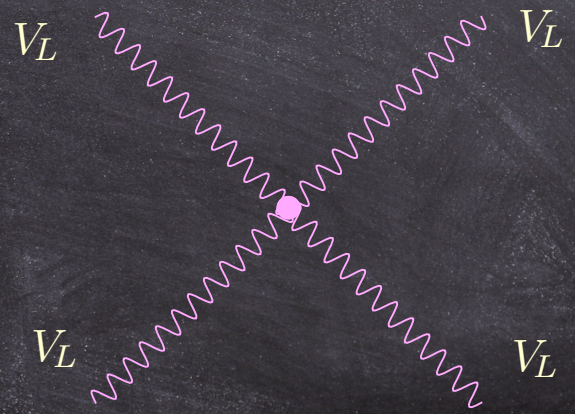

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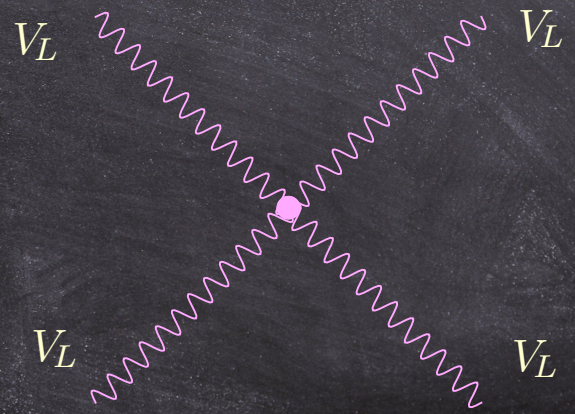

The Minimal Dark Matter Paradigm

- The " WIMP Miracle" stands on two main characteristics:
  - DM mass in the [few GeV's, few TeV's] range
  - DM interaction with SM $\rightarrow$ weak interaction
- Idea: The DM may be the neutral component of a $SU(2)_L$ multiplet
- This idea was advanced by Cirelli, Fornengo and Strumio (2006) for scalars and fermions
- For lower representations it is needed to enforce a Z_2 symmetry in order to stabilize DM
- For higher representations the Z_2 symmetry is automatic

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What About Vectors ?

- As stated before, everybody hates massive vectors because (in the non-Abelian case)[1]
  - They induce perturbative untitarity violation
  - They make the theory non-renormalizable
- However Massive Vectors (which are not gauge bosons) may legitimately appear in Effective Theories.

1. Remark for Dark Photon fans: the Abelian massive vector (Proca theory) is renormalizable via the Stückelberg trick: you don't need Dark Higgs

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A Little Hope...

In 2013 I showed that a theory defined by this simple Lagrangian

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

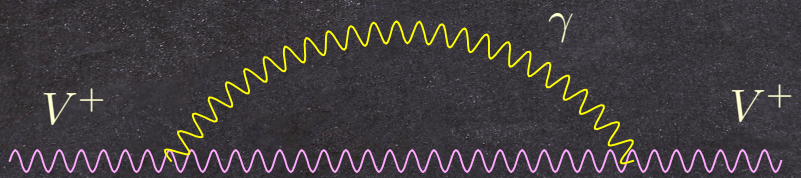
with G_μ a gauge boson of $\mathrm{SU}(N)$ and V_μ a massive vector in the adjoint of $\mathrm{SU}(N)$, is unitary at tree level

Remark. Unitarity requires that V_μ appears in pairs $\Rightarrow$ an accidental Z_2 emerges

The Minimal Vector Dark Matter Model

A. Belyaev, G. Cacciapaglia, J.Mckay, D. Marin, AZ Phys.Rev.D 99 (2019) 11, 115003

$$(V^+, V^0, V^-)^T$$

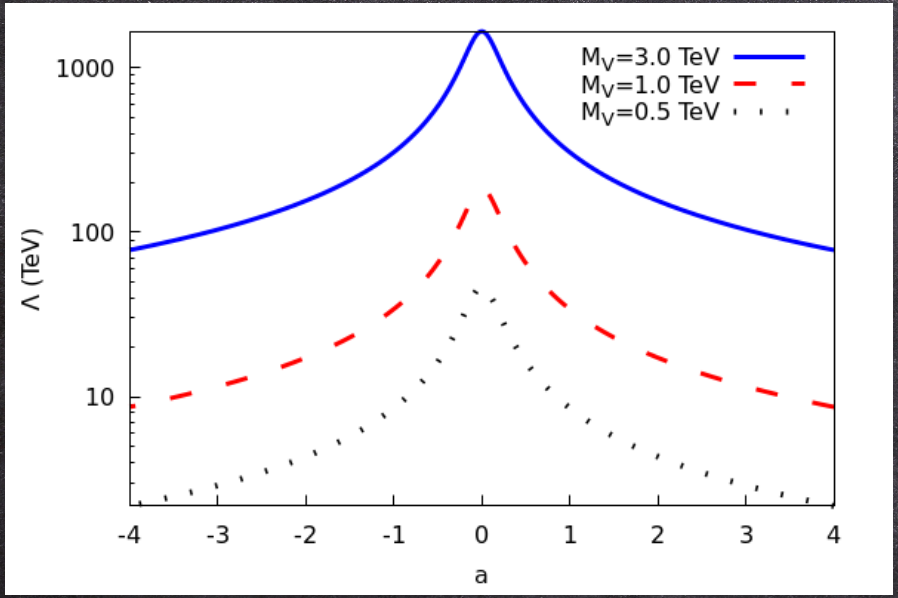


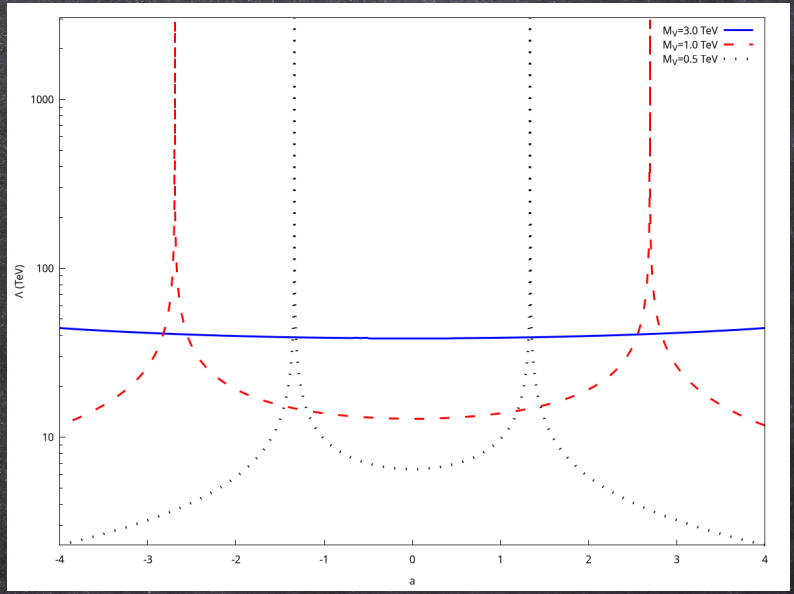
Radiative corrections make V^0 lighter than the charged vectors

$$M_{V^+} - M_{V^0} \approx 200\,\mathrm{MeV}$$

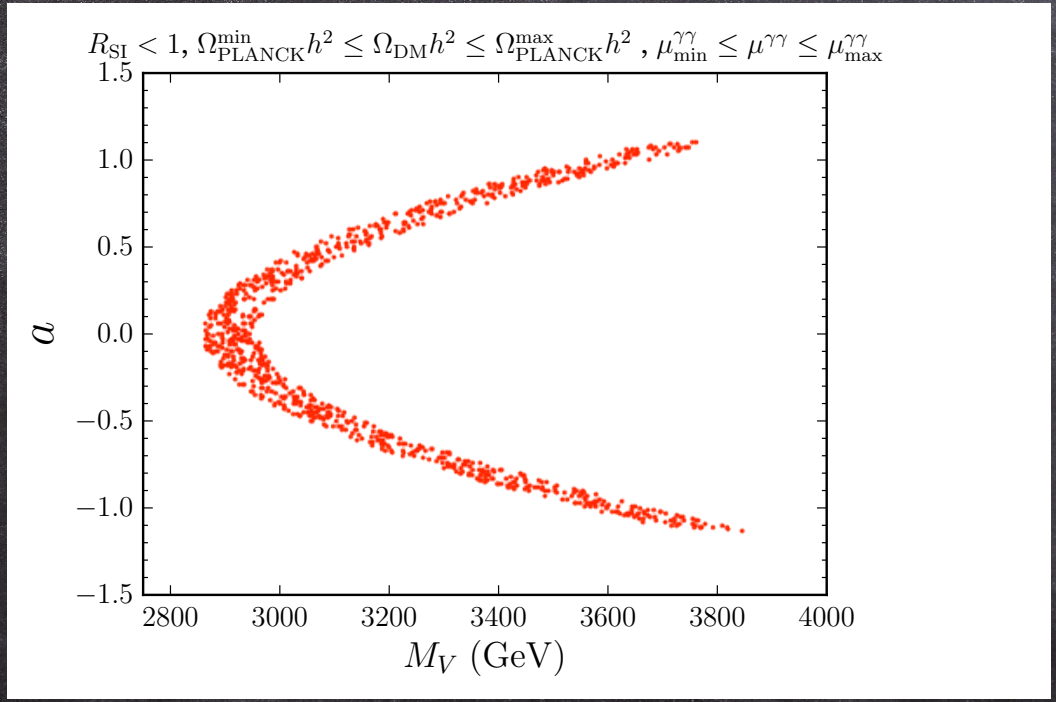
$$V^+ \to V^0\,\pi^+$$

MVDM: Unitarity

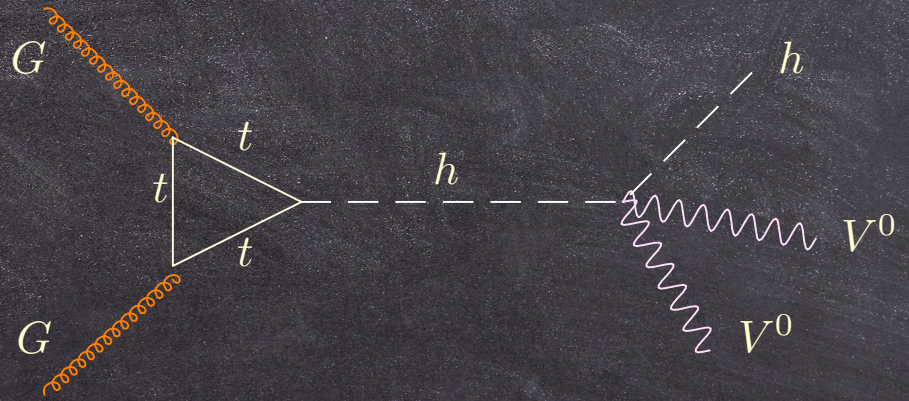


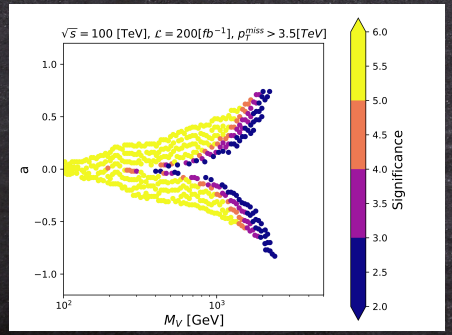


MVDM: Dark Matter Results



Mono-h in the MVDM Model





G.Benitez and A.Z.

Work in progress

MVDM: Ultraviolet Completion

Zexi Hu, Chengfeng Cai,Yi-Lei Tang, Zhao-Huan Yu, Hong-Hao Zhang JHEP 07 (2021), 089

$$\mathrm{SU}(2)_0 \times \mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times U(1)_Y$$

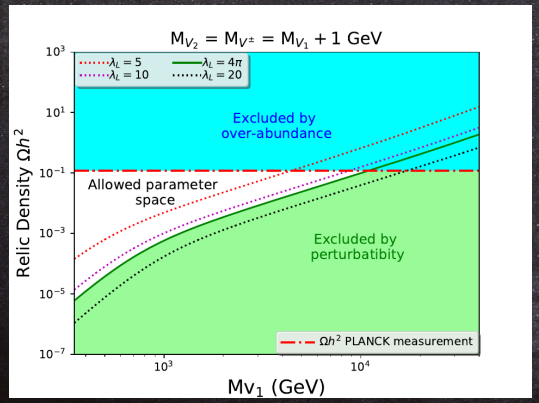
with interchange symmetry between $\mathrm{SU}(2)_0$ and $\mathrm{SU}(2)_2$

A Vector in the Fundamental

B. Díaz, F. Rojas-Abatte, AZ. Phys.Rev.D 99 (2019) 7, 075026

$$V_\mu = \begin{pmatrix} V_\mu^+ \\ V_{1\mu}^0 + i V_{2\mu}^0 \end{pmatrix}$$

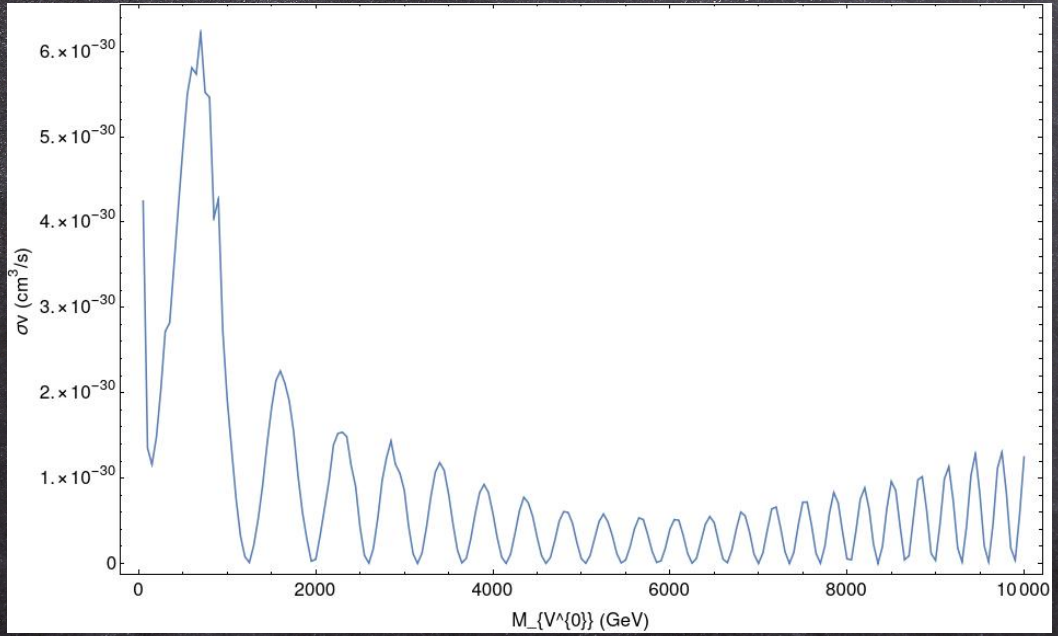
- The Z_2 symmetry is automatic
- It is not possible to couple V_μ to standard fermions
- Unitarity $\Rightarrow$ nearly degenerated components



The model can, in principle, be embeded in non-minimal 331 models

Sommerfeld Enhancement

Sebastián Acevedo and AZ, work in progress



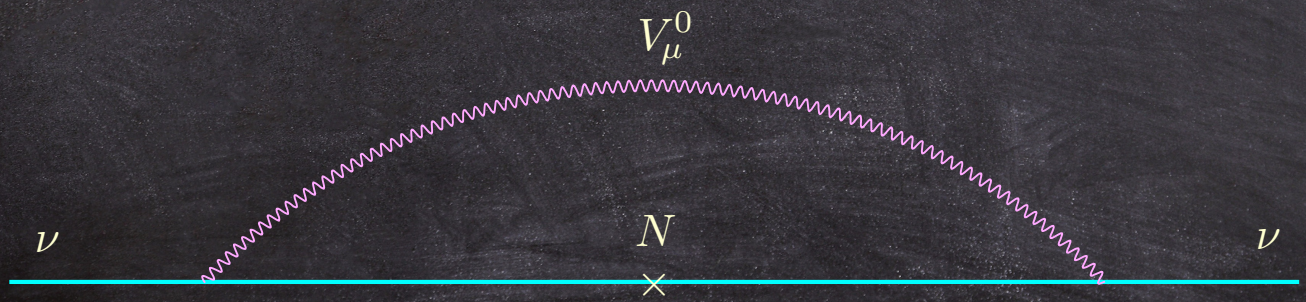
The Vector Scotogenic Model

$$\mathcal{L}_{\rm int} = \beta\, \bar{L} \not{V} N_L + h.c.$$

N_L massive left-handed sterile neutrino odd under Z_2 to prevent Yukawa interaction terms

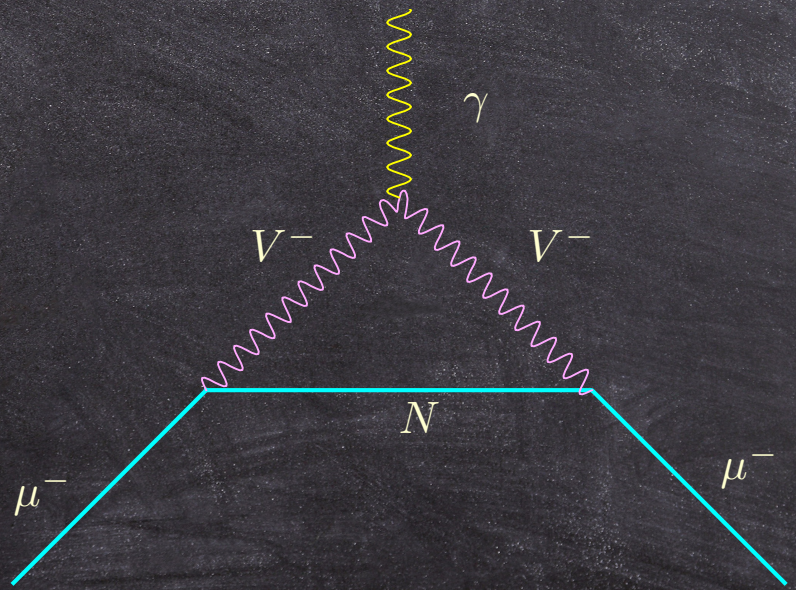
Neutrino Mass Generation

J. Vignatti, A. Cárcamo and AZ, *J.Phys.G* 46 (2019) 11, 115007



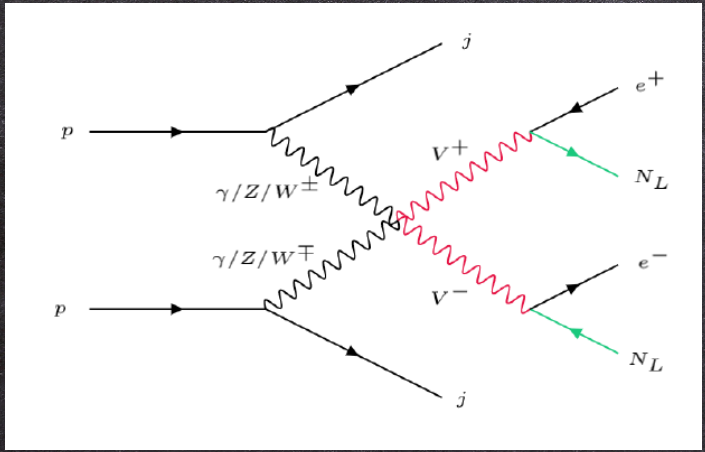
VSM: $(g-2)_\mu$

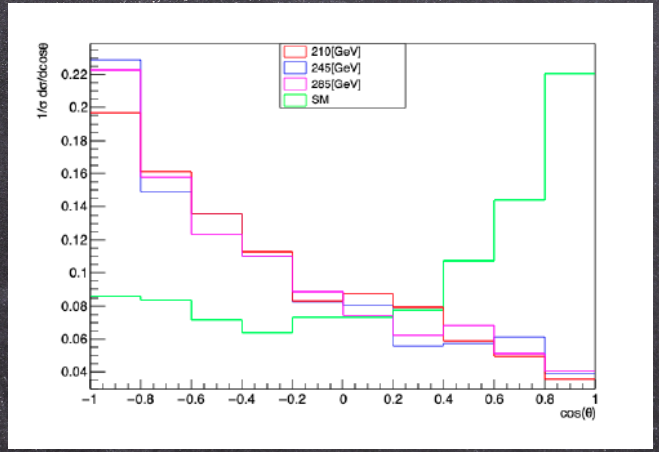
Phung Van Dong, Duong Van Loi, Le Duc Thien, Pham Ngoc Thu Phys.Rev.D 104 (2021) 3, 035001



VSM: Searching for N_L

Paulo Areyuna, Jilberto Zamora, AZ arXiv:2211.09753





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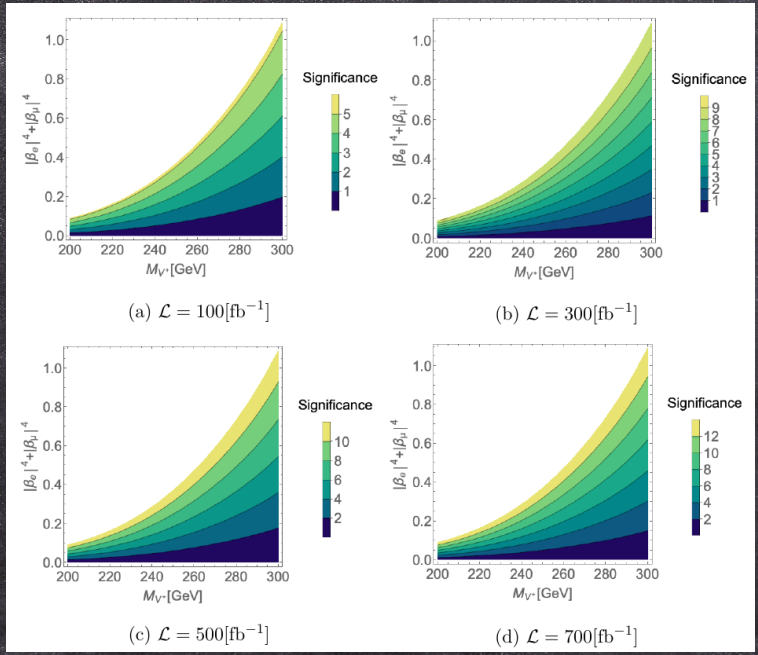


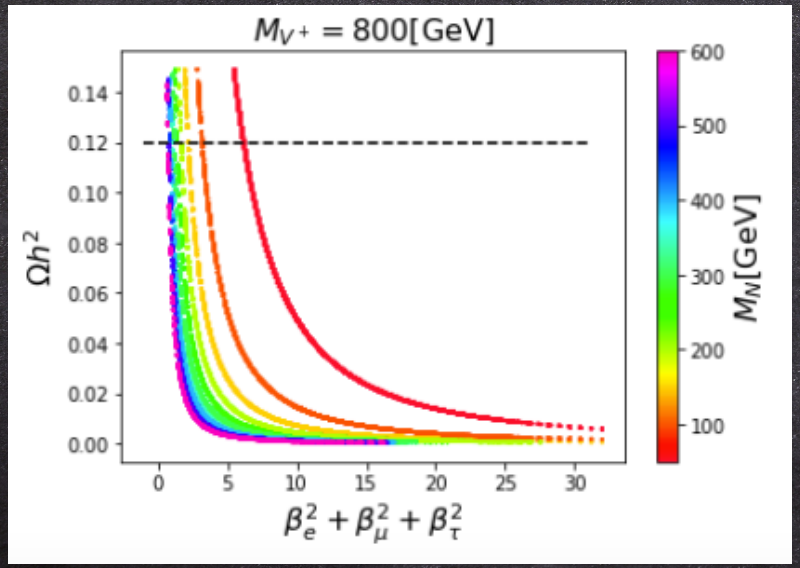
(a) $\mathcal{L} = 100[\text{fb}^{-1}]$ (b) $\mathcal{L} = 300[\text{fb}^{-1}]$

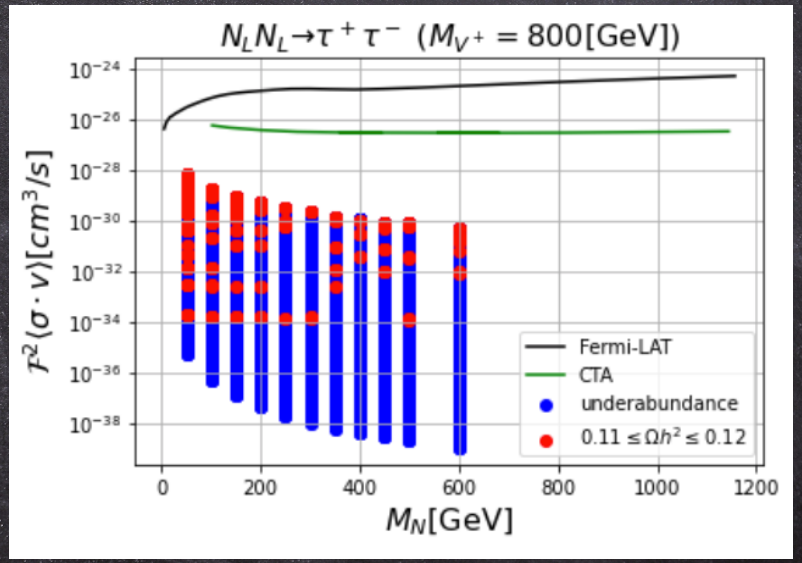
(c) $\mathcal{L} = 500[\text{fb}^{-1}]$ (d) $\mathcal{L} = 700[\text{fb}^{-1}]$

$M_N \approx 50\,\text{GeV}$ HL-LHC

VSM: N_L as Dark Matter

P. Areyuna, J. Zamora and AZ, work in progress





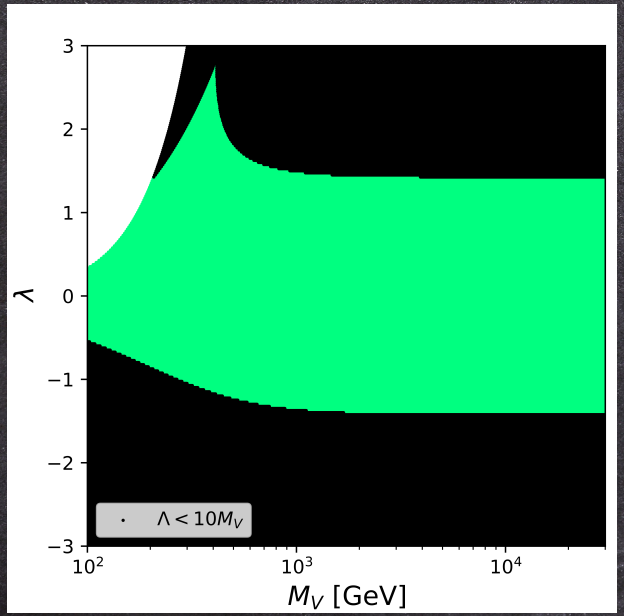
The Quintuplet

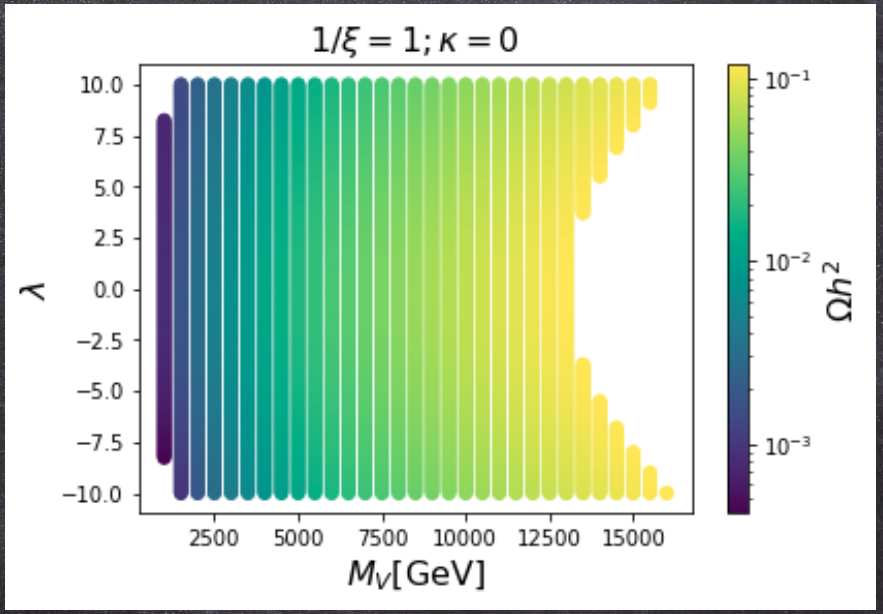
P. Escalona, S. Acevedo, P. Areyuna, G. Benitez, P. Solar, AZ, Work in progress

$(V^{++}, V^{+}, V^{0}, V^{-}, V^{--})^{T}$

- This complete the Minimal DM program
- Unitarity violation starts ti be wild
- Z_2 automatic
- $Y = 0 \Rightarrow$ can escape Direct Dtection
- Mass splitting radiactively generated
- A lot of (co-)anihilation channels $\Rightarrow M_{V^0} \sim 10\,\mathrm{TeV}$

The Quintuplet





Possible Ways Out from the Unitarity Hell

Two solutions:

- To poromote the massive vector fields into (or component of) gauge fields
- Go to the non-perturbative sector
  - Anamaria Hell, JHEP 03 (2022), 167
  - The non-Abelian Proca theory is unitary and renormalizable in the non-pertubative regime
  - The $M_V \to 0$ limit is smooth
  - Is it possible to make phenomenology ? A. Hell, A. Belyaev and A.Z., work in progress

Conclusions

- We are completing the Minimal Dark Matter program
- Massive Vectors have provided good effective theories with rich phenomenology
- These models provide good DM candidates and can be viewed as the low energy limit of more complex theories
- The unitarity problem exists but can be kept under control
- Maybe the good theory is realized in the non pertubative regime: this is a novel idea (and we need novel ideas) worth to be explored

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Conclusions

Please
Don't hate massive vectors !
They want to be your friends

Thank You