Minimal SU(N) Vector Dark Matter

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SD, Kimmo Tuominen; arXiv:1506.xxxxx

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Motivations

SM fits all collider data but:

- No viable Dark Matter (DM) candidate
- $m_{\rm Higgs} = 125$ GeV $\Rightarrow$ metastable potential
- Fine tuning
- Baryon asymmetry
- ...

Possible solution: new SU(N) gauge group & new scalar to make vector bosons massive $=$ DM candidates and eventually solve other problems

Hambye'08, Hambye & Strumia'13, Carone & Ramos'13

SU(N) Vector DM

Take scalar matrix field Φ in bi-adjoint of $\mathrm{SU}(N)_L \times \mathrm{SU}(N)_R$ and gauge only $\mathrm{SU}(N)_L \equiv \mathrm{SU}(N)_D$

$$\Phi = \frac{\sigma}{\sqrt{N^2-1}} I + i \frac{\phi_a}{\sqrt{2N}} T^a \,, \quad \Phi' = \exp\left[-i g_D \alpha_a T^a\right] \Phi \,, \quad a = 1, \ldots, N^2-1$$

All SM fields singlets of $\mathrm{SU}(N)_D$, Φ singlet of $\mathcal{G}_{SM}$, then minimal (no mass terms) potential is

$$V = \frac{\lambda_h}{2} \left(H^\dagger H\right)^2 + \frac{\lambda_\phi}{2} \mathrm{Tr} \left(\Phi^\dagger \Phi\right)^2 - \lambda_p H^\dagger H \mathrm{Tr} \Phi^\dagger \Phi \,, \quad H = \frac{1}{\sqrt{2}} \begin{pmatrix} \pi^+ \\ h + i\pi^0 \end{pmatrix}$$

Potential minimum at

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_h \end{pmatrix} \,, \quad \langle \Phi \rangle = \frac{v_\phi}{\sqrt{N^2-1}} I \quad \Rightarrow \quad m_A = \frac{g_D}{\sqrt{N - N^{-1}}}$$

Residual $\mathrm{SO}(N)$ global symmetry makes massive vector bosons A^a stable
$\Rightarrow$ viable DM candidates

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Classical Conformality

Mass terms generated radiatively via dimensional transmutation $\Rightarrow$ quantum corrections to m_H^2 depend on $\log \Lambda_{\rm UV}$: no fine tuning needed; f.t. problem traded with that of justifying zero tree level mass terms

$$\Delta V = \sum_{p \in \{\varphi, \psi, A\}} (-1)^{2s_p} \frac{2s_p + 1}{4} m_p^4 \left(\log \frac{m_p^2}{\Lambda^2} - k_p \right) \ , \ k_{\varphi(\psi)} = \frac{3}{2} \, , \ k_A = \frac{5}{2}$$

Coleman & Weinberg'73, Bardeen'95, Farina et al.'13, Heikinheimo et al'13

SM Potential Stabilization

The only SM beta function that is modified in the present model is

$$16\pi^2 \frac{d\lambda_h}{dt} = 16\pi^2 \left(\frac{d\lambda_h}{dt}\right)_{SM} + N^2 \lambda_p^2$$

Extra positive contribution lifts λ_h from negative values at $\Lambda_{\rm Planck}$. Mixing $h - \sigma$ in physical h_1 also can give larger than SM λ_h at EW scale:

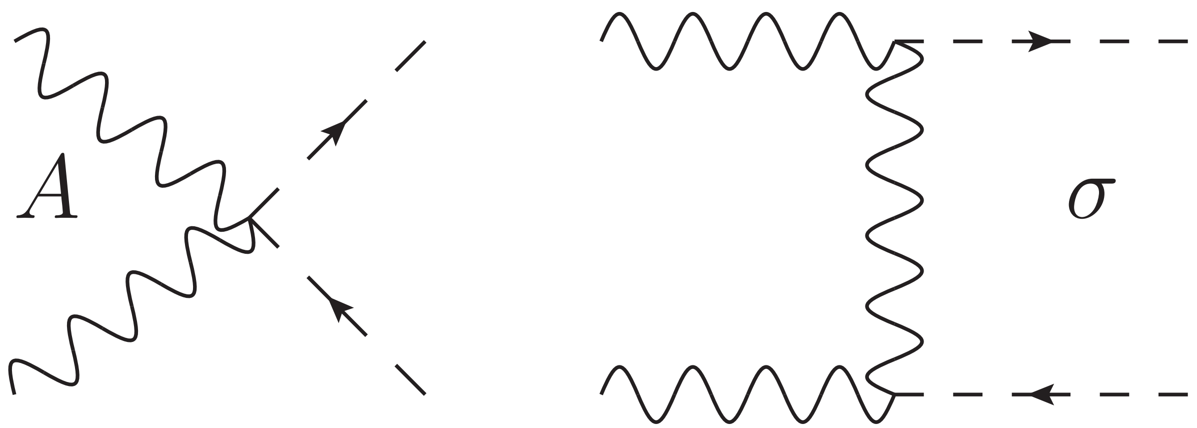
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \sigma \end{pmatrix}$$

Also the σ direction is stable

$$16\pi^2 \frac{d\lambda_\phi}{dt} \sim r_{2,N} g_D^4; \quad r_{2,N} = \frac{41}{6}, \frac{51}{16}, \frac{353}{150}, \text{ for } N = 2, 3, 4$$

DM Abundance

Higgs couplings are SM-like $\Rightarrow \cos\alpha \sim 1$. In the limit of no-mixing, the dark vector annihilation process is



with $\sigma \sim h_2$ eventually decaying to h_1. In semi-annihilation process one σ replaced by A. Thermally averaged cross sections

$$\langle v\sigma_{\rm ann}\rangle = \frac{11 m_A^2}{144\,(N^2-1)\,\pi v_\phi^4}\,, \quad \langle v\sigma_{\rm semi-ann}\rangle = \frac{3 m_A^2}{8\,(N^2-1)\,\pi v_\phi^4}\,,$$

and DM relic abundance

$$\Omega h^2 \simeq \frac{1.07\times 10^9 {\rm GeV}^{-1} x_f}{\sqrt{g_*(x_f)} M_{Pl}\langle\sigma v\rangle}\,, \quad \langle\sigma v\rangle = \langle\sigma_{\rm ann} v\rangle + \frac{1}{2}\langle\sigma_{\rm semi-ann} v\rangle\,.$$

LHC Pheno Viability

All SM couplings (except λ_h) and v_h set to SM values; λ_h & λ_ϕ set by V minimization conditions; v_ϕ set by requiring $m_{h_1} = 125$ GeV; Only two free parameters: g_D, λ_s. We collect 10^5 random data points in interval

$$0 < g_D < 1.4,\ 0 < \lambda_p < 0.12$$

For each data point we calculate Higgs coupling strengths to $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$, then use LHC data to calculate χ^2, and select data points satisfying

$$p\left(\chi^2 > \chi_j^2\right) > 0.05\ , \quad 1 \leqslant j \leqslant 10^5.$$

Averaging over all the viable data points, $\overline{\cos\alpha} = 0.95$, and

$$N = \begin{cases} 2 \\ 3 \\ 4 \end{cases} , \quad \overline{\lambda_p} = \begin{matrix} 0.063 \\ 0.064 \\ 0.059 \end{matrix} , \quad \overline{g_D} = \begin{matrix} 0.58 \\ 0.64 \\ 0.66 \end{matrix} , \quad \overline{v_\phi}/\mathrm{GeV} = \begin{matrix} 1335 \\ 1310 \\ 1328 \end{matrix} .$$

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Stability & Perturbativity

We calculate the 1L betas for $N = 2, 3, 4$, evaluate all the couplings at 100 scales between v_h and $\Lambda_{\rm Planck}$, and require at all scales perturbativity as well as

$$\lambda_h, \lambda_\phi > 0$$

About 5% of the LHC viable data points are stable and perturbative with free parameter values

$$N = \begin{cases} 2 \\ 3 \\ 4 \end{cases} , \quad \lambda_p = \begin{matrix} 0.020 \pm 0.011 \\ 0.019 \pm 0.011 \\ 0.019 \pm 0.010 \end{matrix} , \quad g_D = \begin{matrix} 0.55 \pm 0.11 \\ 0.60 \pm 0.12 \\ 0.63 \pm 0.12 \end{matrix} ,$$

and dark Higgs and vector boson masses

$$N = \begin{cases} 2 \\ 3 \\ 4 \end{cases} , \quad m_{h_2}/{\rm GeV} = \begin{matrix} 175 \pm 10 \\ 175 \pm 10 \\ 175 \pm 9 \end{matrix} , \quad m_A = \begin{matrix} 580 \pm 99 \\ 480 \pm 66 \\ 420 \pm 63 \end{matrix} .$$

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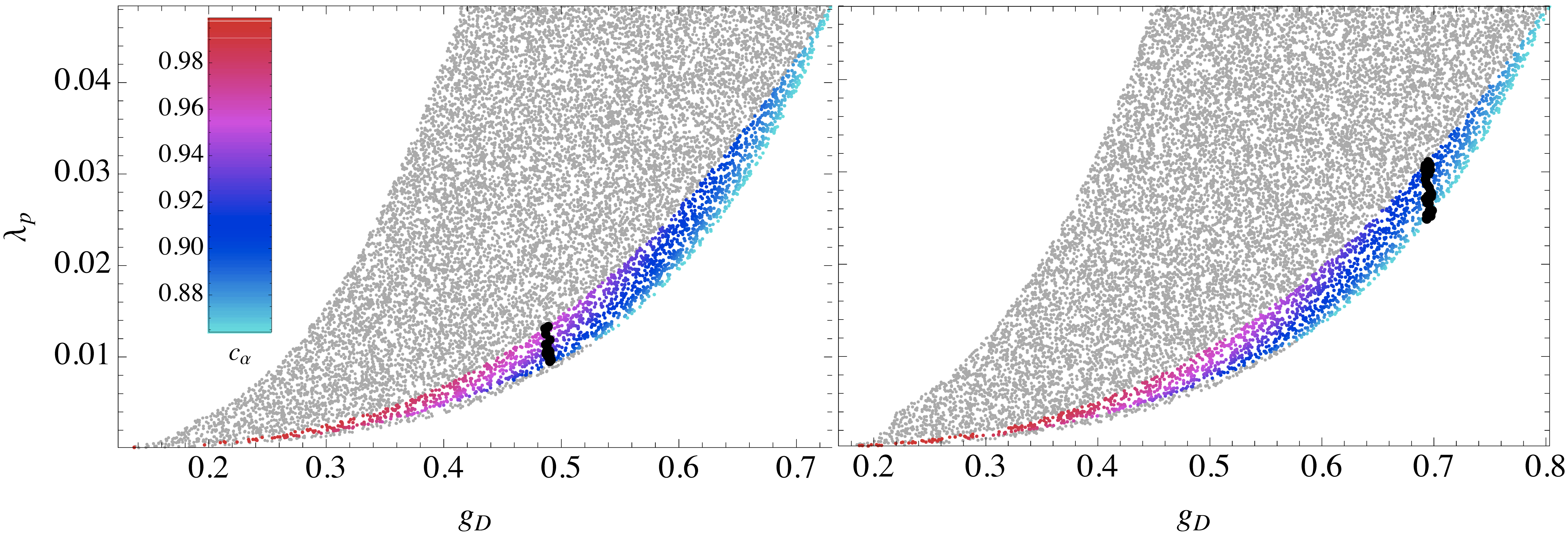
N=2,3 viable regions

Portal coupling vs "dark" gauge coupling for $N = 2$ (left panel), $N = 3$ (right panel), in gray for viable $c_\alpha \equiv \cos\alpha$ only, in color[c_α] for stable V as well, and in black also for DM abundance within 95%CL of Planck+WMAP result

$$\Omega h^2 = 0.193 \pm 0.0028$$



N=2,3 Mass Spectrum

Heavy Higgs mass vs "dark" gauge boson mass for $N = 2$ (left panel), $N = 3$ (right panel), in gray for viable $c_\alpha \equiv \cos\alpha$ only, in color[c_α] for stable V as well, and in black also for DM abundance within 95%CL of Planck+WMAP result

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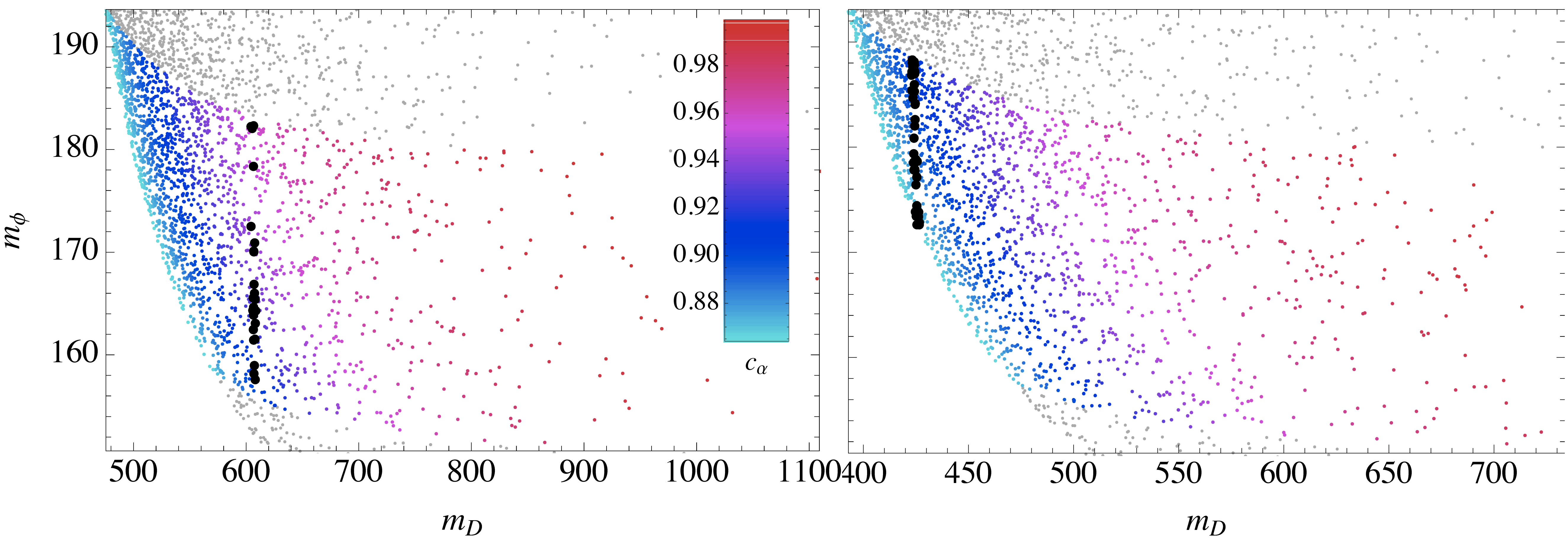
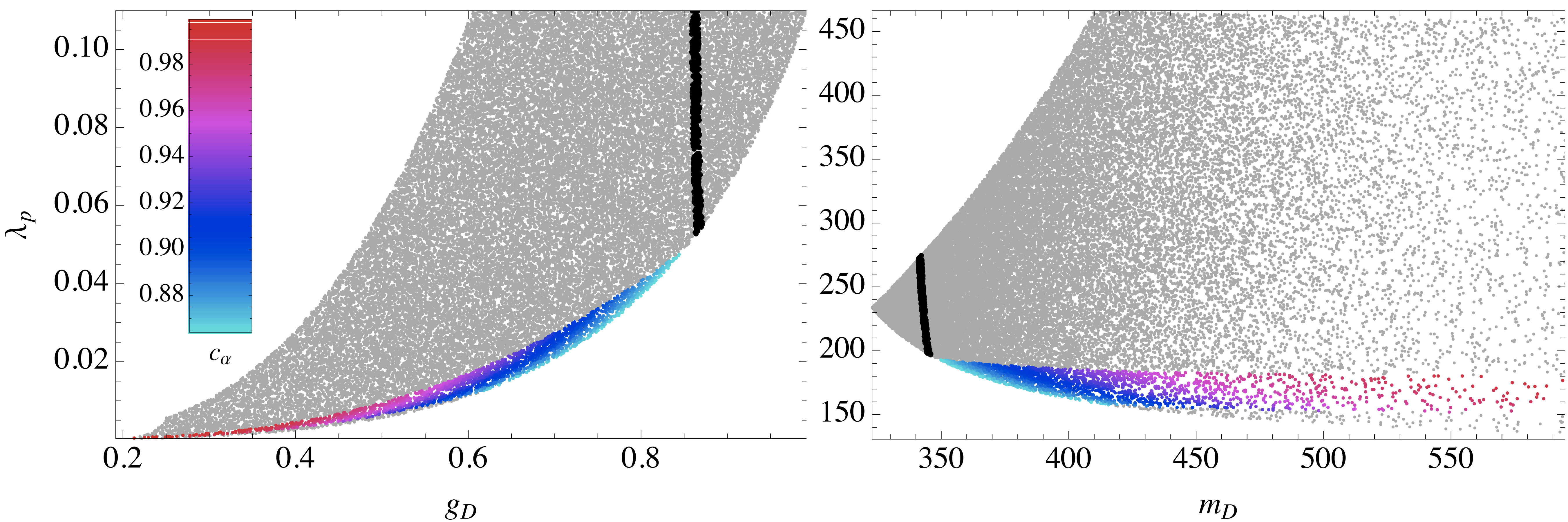


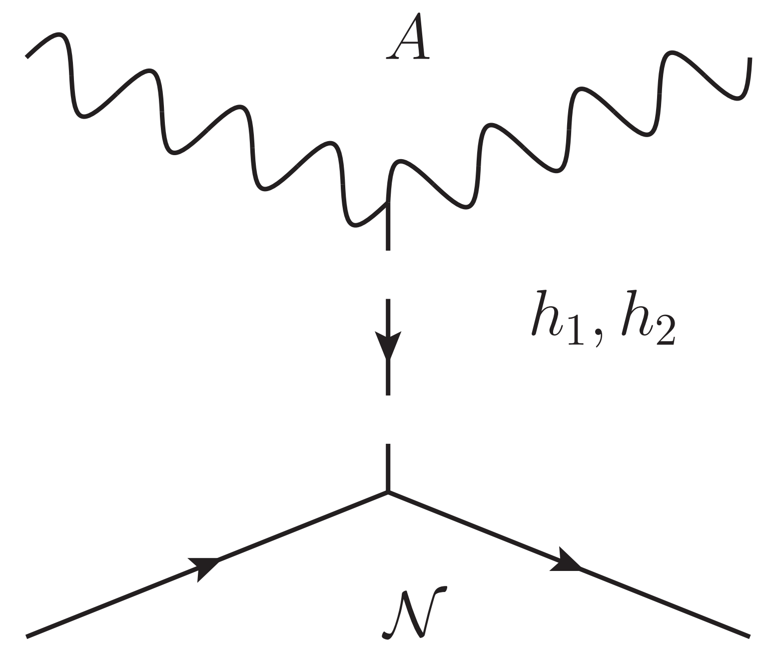
No Viable DM for N=4

Portal coupling vs "dark" gauge coupling (left panel) & heavy Higgs mass vs "dark" gauge boson mass (right panel) for $N = 4$, in gray for viable $c_\alpha \equiv \cos\alpha$ only, in color[c_α] for stable V as well, and in black instead for DM abundance within 95%CL of Planck+WIMAP result (too much DM for stable V)



DM Direct Detection

Spin independent cross section for A^a elastic scattering off a nucleon $\mathcal{N}$, with $f = 0.303$



$$\sigma_{SI} = \frac{f^2 m_{\mathcal{N}}^2 m_A^2}{64\pi v_h^2 v_\phi^2} \sin^2 2\alpha \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right)^2$$

Result for LHC viable data points

$$N = \begin{cases} 2 \\ 3 \end{cases} , \quad \sigma_{SI}\left(\mathcal{N} A \to \mathcal{N} A\right) = \begin{array}{l} (5 \pm 4) \times 10^{-46}\ \mathrm{cm}^2 \\ (3 \pm 3) \times 10^{-46}\ \mathrm{cm}^2 \end{array} .$$

Experimental upper constraint (LUX 2013) is about an order larger.

SU$(3)_D$ model favored by experiment over SU$(2)_D$ (2% vs 1% of stable V data points have also viable DM abundance)

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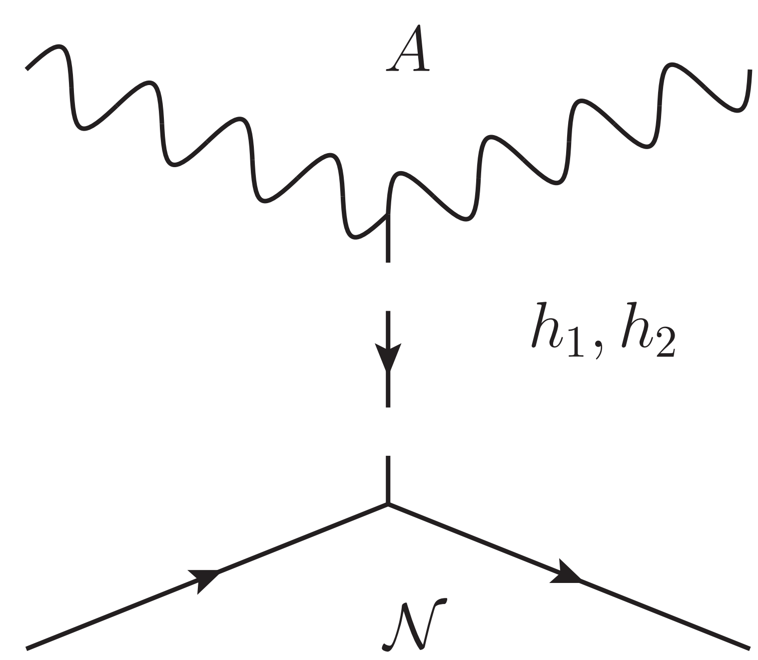

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Conclusions

Minimal (2 new parameters/particles) SU(N) extension of SM for

- Viable vector DM candidate
- Stabilizing SM potential
- LHC viability
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T h a n k   y o u !

Backup Slides

One Loop V minimization

One loop effective potential correction

$$\Delta V = \sum_{p\in\{\varphi,\psi,A\}} (-1)^{2s_p} \frac{2s_p+1}{4} m_p^4 \left(\log \frac{m_p^2}{\Lambda^2} - k_p \right) \ , \ k_{\varphi(\psi)} = \frac{3}{2} \ , \ k_A = \frac{5}{2}$$

One loop effective potential is at minimum if quartics satisfy

$$V_{1L} = V + \Delta V : \quad \left. \frac{\partial V}{\partial \varphi_i} \right|_{vev} = 0 \ ; \ \varphi_i = h, \sigma \quad \Rightarrow \quad \lambda_\phi = \frac{v_w^2}{v_\phi^2} \lambda_p \ , \ \lambda_h = \frac{v_\phi^2}{v_w^2} \lambda_p$$

Scalar squared mass matrix then defined by

$$\left(\mathcal{M}_\varphi^2\right)_{ij} = \left. \frac{\partial^2 V_{1L}}{\partial \varphi_i \partial \varphi_j} \right|_{vev} - \frac{\delta_{ij}}{v_i} \left. \frac{\partial \Delta V}{\partial \varphi_i} \right|_{vev}$$