# A minimal model for SU(N) vector dark matter


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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 broken spontaneously by new scalar vev provides DM candidate and eventually solves other problems

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

# Minimal Matter Extension

Take scalar matrix field $\Phi$ in bi-adjoint of $\mathrm{SU}(N)_L \times \mathrm{SU}(N)_R$:

$$\Phi = \frac{\sigma}{\sqrt{2\left(N^2-1\right)}} I + i \frac{\phi_a}{\sqrt{2N}} T^a \,, \quad \left(T^a\right)^{bc} = -i f^{abc} \,, \quad a = 1, \ldots, N^2-1$$

with $\sigma$,$\phi_a \in \Re$, and gauge only $\mathrm{SU}(N)_L \equiv \mathrm{SU}(N)_D$. Under $\mathrm{SU}(N)_D$ transformation

$$\Phi \to \Phi' = \exp\left[-i g_D \alpha_a T^a\right] \Phi = \frac{\sigma'}{\sqrt{2\left(N^2-1\right)}} I + i \frac{\phi'_a}{\sqrt{2N}} T^a ,$$

with $\sigma', \phi'_a \in \Re$ because $\mathrm{Tr} T^a \{T^b, T^c\} = 0$ (true for real and semireal reps: bifundamental scalar is gauge invariant only for $N = 2$)

For $\langle \Phi \rangle \neq 0$ pseudoscalars $\phi_a$ absorbed by the $\mathrm{SU}(N)_D$ vectors: only one physical scalar left!

# Classically Conformal Potential

All SM fields singlets under $\mathrm{SU}(N)_D$, $\Phi$ singlet of $\mathcal{G}_{SM}$, then classically conformal (no tree level dimensionful couplings) potential is

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

Mass terms generated radiatively via dimensional transmutation

$$\Delta V = \sum_{p\in\{\varphi,\psi,A\}} (-1)^{2s_p}\frac{2s_p+1}{64\pi^2} m_p^4\left(\log\frac{m_p^2}{\Lambda^2} - k_p\right), \; k_\varphi = k_\psi = \frac{3}{2}, \; k_A = \frac{5}{6}$$

Quantum corrections to $m_H^2$ depend on $\log\Lambda_{\mathrm{UV}}$: no fine tuning needed; f.t. problem traded with that of justifying initial conditions giving zero tree level mass terms at EW scale. One loop effective potential:

$$V_{1L} = V + \Delta V$$

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

# SU(N) Vector DM

Dark sector

$$\mathcal{L} \supset \mathrm{Tr}\left[D_\mu \Phi\right]^\dagger D^\mu \Phi - V \ , \quad D^\mu = \partial^\mu - i g_D A_a^\mu T^a \ .$$

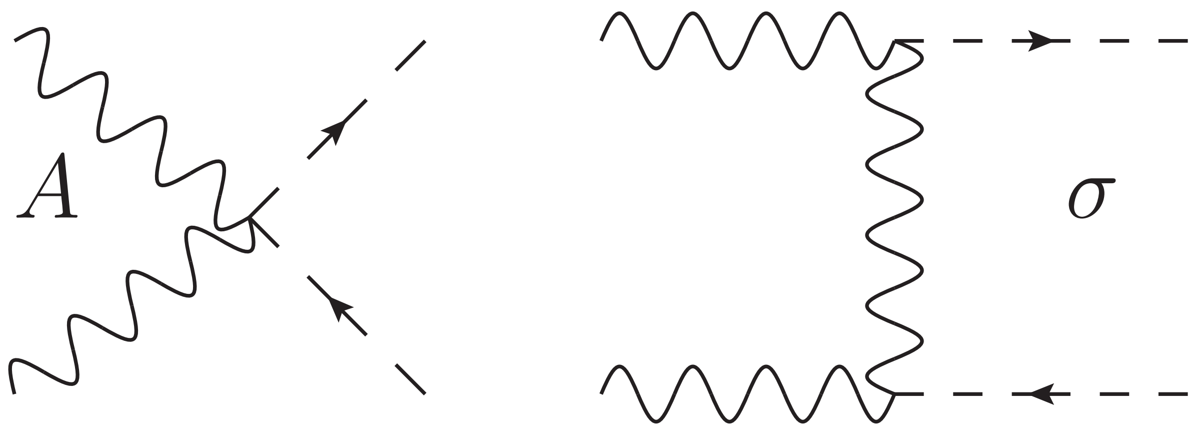
Potential minimum at

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

Pseudoscalars $\phi_a$ provide longitudinal d.o.f. to $A_a$, $\pi^0$ and $\pi^\pm$ to $Z$ and $W^\pm$, respectively. Residual SO$(N)$ global symmetry makes massive vector bosons $A^a$ stable $\Rightarrow$ $A^a$ = viable DM candidates.

# DM Relic Abundance

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 $\sigma$ replaced by $A$. Thermally averaged cross sections

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

and DM relic abundance

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

# Potential Minimization

Minimization conditions for the tree level potential,

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

The scalar mass matrix at the minimum of the potential is then defined as

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

where the last term represents the one loop correction to the zero tree level mass terms. Scalar mass eigenstate mixing parametrized by angle $\alpha$ according to

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

# Scalar Mass Matrix

Elements of the scalar mass matrix at one loop in the $(h,\sigma)$ basis:

$$\begin{aligned}
(\mathcal{M}_\varphi^2)_{11} &= \lambda_p v_\phi^2 + \frac{1}{32\pi^2}\left\{\log\left[\left(1+\frac{v_\phi^2}{v_h^2}\right)\lambda_p\right]\left(v_h^2+\frac{9v_\phi^4}{v_h^2}\right)\lambda_p^2 - 6\lambda_p^2 v_\phi^2 + 16\left[1+3\log\left(\frac{m_W}{v_h}\right)\right]\frac{m_W^4}{v_h^2}\right. \\
&\qquad \left. 8\left[1+3\log\left(\frac{m_Z}{v_h}\right)\right]\frac{m_Z^4}{v_h^2} - 96\log\left(\frac{m_b}{v_h}\right)\frac{m_b^4}{v_h^2} - 96\log\left(\frac{m_t}{v_h}\right)\frac{m_t^4}{v_h^2}\right\}, \\
(\mathcal{M}_\varphi^2)_{12} &= (\mathcal{M}_\varphi^2)_{21} = -\lambda_p v_h v_\phi + \frac{1}{32\pi^2}\left\{6\lambda_p v_h v_\phi - \log\left[\left(1+\frac{v_\phi^2}{v_h^2}\right)\lambda_p\right]\left(\frac{3v_h^3}{v_\phi} - 4v_\phi v_h + \frac{3v_\phi^3}{v_h}\right)\lambda_p^2\right\}, \\
(\mathcal{M}_\varphi^2)_{22} &= \lambda_p v_h^2 + \frac{1}{32\pi^2}\left\{\log\left[\left(1+\frac{v_\phi^2}{v_h^2}\right)\lambda_p\right]\left(v_\phi^2+\frac{9v_h^4}{v_\phi^2}\right)\lambda_p^2 - 6\lambda_p^2 v_h^2 + \right. \\
&\qquad \left. 8\left(N^2-1\right)\left[1+3\log\left(\frac{m_A}{v_h}\right)\right]\frac{m_A^4}{v_\phi^2}\right\}
\end{aligned}$$

# LHC Pheno Viability

All SM couplings (except $\lambda_h$) and $v_h$ set to SM values; $\lambda_h$ & $\lambda_\phi$ set by $V$ minimization conditions; $v_\phi$ set by requiring $m_{h_1} = 125$ GeV; Only two free parameters: $g_D, \lambda_s$. 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 $\chi^2$, and select data points (about 40% of the total) 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

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

# Higgs Signal Strengths

Parametrization of Lagrangian sector relevant for Higgs physics at LHC:

$$\mathcal{L}_{\text{eff}} = a_V \frac{2m_W^2}{v_w} h W_\mu^+ W^{-\mu} + a_V \frac{m_Z^2}{v_w} h Z_\mu Z^\mu - a_f \sum_{\psi=t,b,\tau} \frac{m_\psi}{v_w} h \bar{\psi}\psi$$

Fit performed minimizing $\chi^2$ of signal strengths with respect to $a_V, a_f$

$$\chi^2 = \sum_i \left( \frac{\hat{\mu}_{ij}^{\text{exp}} - \hat{\mu}_{ij}^{\text{th}}}{\Delta^{\text{exp}}} \right)^2 , \quad \hat{\mu}_{ij} = \frac{\sigma_{\text{tot}} \text{Br}_{ij}}{\sigma_{\text{tot}}^{\text{SM}} \text{Br}_{ij}^{\text{SM}}} , \quad \text{Br}_{ij}^{\text{SM}} = \frac{\Gamma_{h\to ij}}{\Gamma_{\text{tot}}} .$$

The new physics predictions are obtained from the SM ones

$$\hat{\Gamma}_{ij} \equiv \frac{\Gamma_{h\to ij}}{\Gamma_{h_{\text{SM}}\to ij}^{\text{SM}}} , \quad \hat{\sigma}_\Omega \equiv \frac{\sigma_{\omega\to\Omega}}{\sigma_{\omega\to\Omega}^{\text{SM}}},$$

in terms of the coupling coefficients in the effective Lagrangian:

$$\hat{\sigma}_{hqq} = \hat{\sigma}_{hA} = \hat{\Gamma}_{AA} = |a_V|^2 , \quad \hat{\sigma}_{ht\bar{t}} = \hat{\sigma}_h = \hat{\Gamma}_{gg} = \hat{\Gamma}_{\psi\psi} = |a_f|^2$$

# Higgs Decay to Diphoton

$$\Gamma_{h\to\gamma\gamma} = \frac{\alpha_e^2 m_h^3}{256\pi^3 v_w^2} \left| \sum_i N_i e_i^2 F_i \right|^2 ,$$

where $N_i$ is the number of colors, $e_i$ the electric charge, and

$$\begin{aligned} F_W &= [2 + 3\tau_W + 3\tau_W (2 - \tau_W) f(\tau_W)] a_V \ , \quad \tau_i = \frac{4m_i^2}{m_h^2} \ ; \\ F_\psi &= -2\tau_\psi [1 + (1 - \tau_\psi) f(\tau_\psi)] a_f \ , \quad \psi = t, b, \tau, \ldots \ , \end{aligned}$$

with

$$f(\tau_i) = \begin{cases} \arcsin^2 \sqrt{1/\tau_i} & \tau_i \geq 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi\right]^2 & \tau_i < 1 \end{cases} .$$

# 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 $\lambda_h$ from negative values at $\Lambda_{\mathrm{Planck}}$. Mixing $h$-$\sigma$ in physical $h_1$ also can give larger than SM $\lambda_h$ at EW scale

# Stability & Perturbativity

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

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

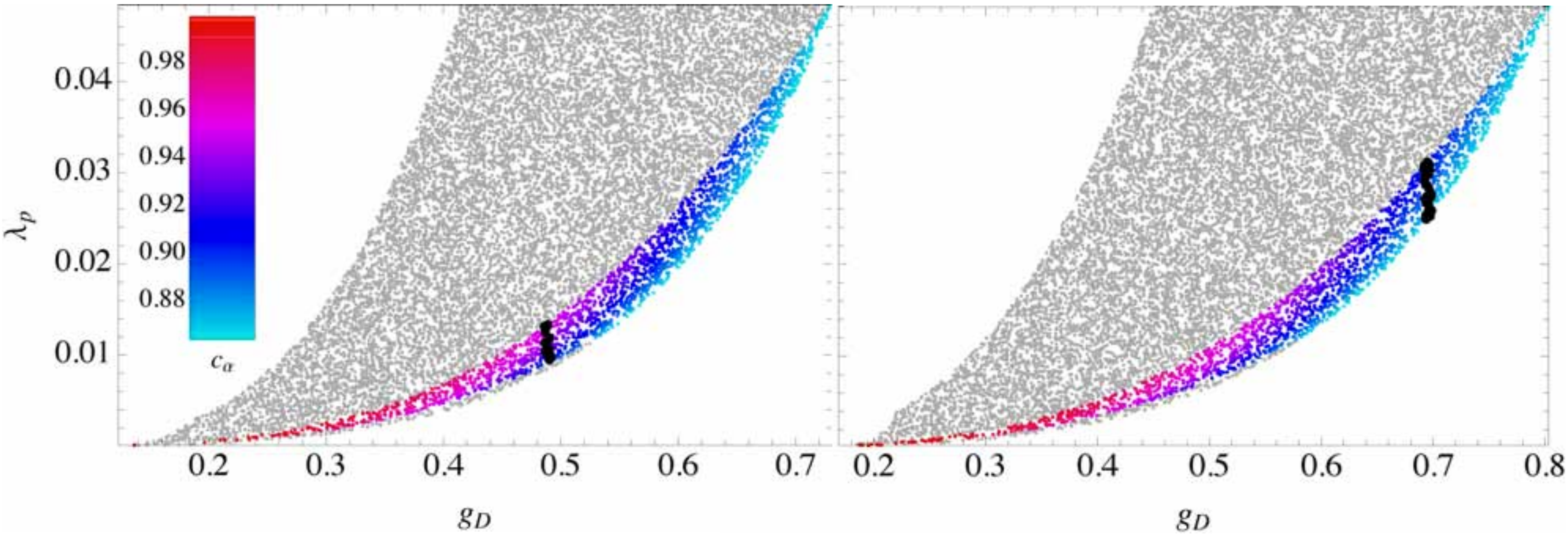
and dark Higgs and vector boson masses

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

# N=2,3 viable regions

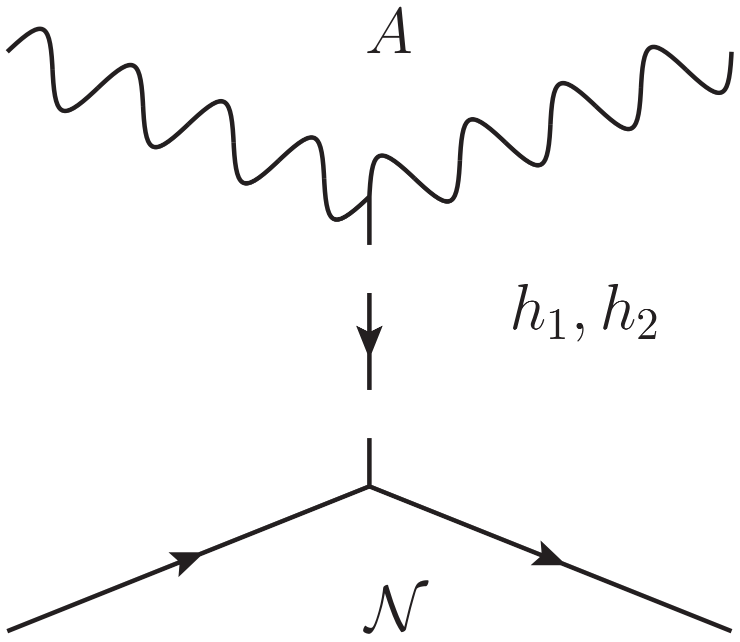
Portal coupling vs "dark" gauge coupling for $N = 2$ (left panel), $N = 3$ (right panel), in gray for viable $c_\alpha \equiv \cos\alpha$ only, in color[$c_\alpha$] for stable $V$ as well, and in black also for DM abundance within 95%CL of Planck+WMAP result

$$\Omega h^2 = 0.1193 \pm 0.0028$$



# DM Direct Detection

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




$$\sigma_{SI} = \frac{f_{\mathcal{N}}^2 m_{\mathcal{N}}^4 m_A^2}{4\pi v_h^2 v_\phi^2} \sin^2 2\alpha \left( \frac{1}{m_1^2} - \frac{1}{m_2^2} \right)^2$$

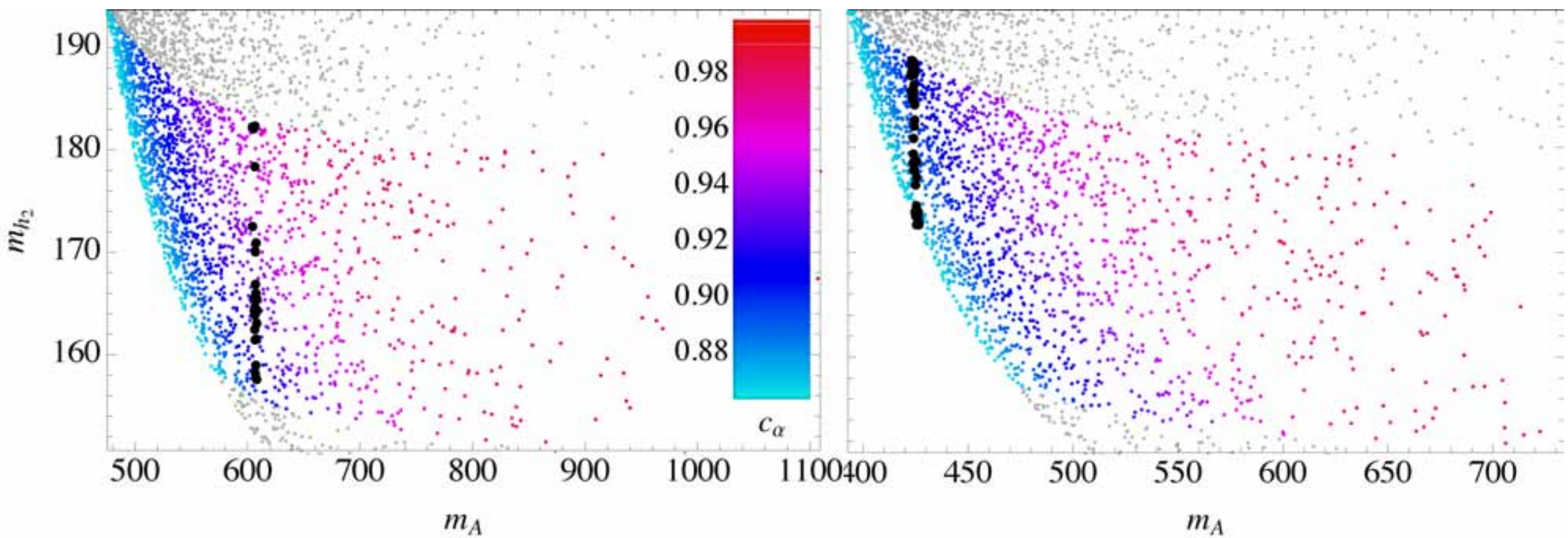
Result for universally viable data points

$$N = \begin{cases} 2 \\ 3 \end{cases}, \quad \sigma_{SI}(\mathcal{N}A \to \mathcal{N}A) = \begin{matrix} (1.9 \pm 6.2) \times 10^{-45}\ \mathrm{cm}^2 \\ (4.5 \pm 4.3) \times 10^{-45}\ \mathrm{cm}^2 \end{matrix}$$

Experimental upper constraint (LUX 2013) for $N = 2\ (3)$ is on average 70% (10%) larger.

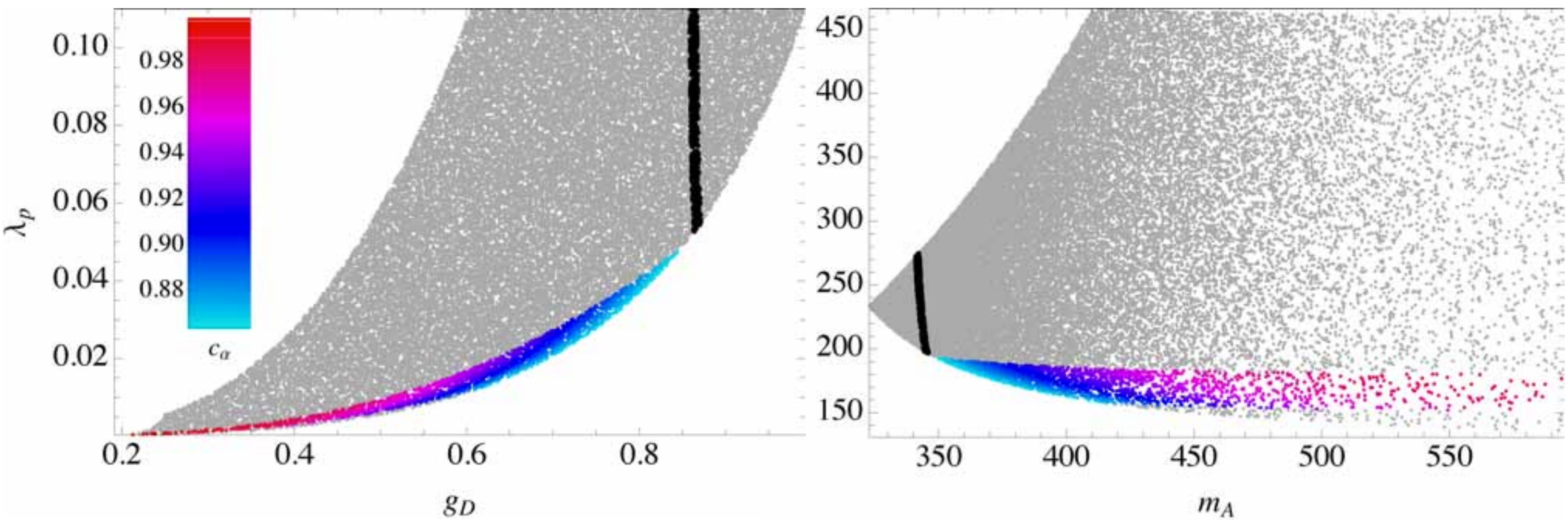
# N=2,3 Mass Spectrum

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[$c_\alpha$] for stable $V$ as well: Planck constraint on DM relic abundance fixes DM candidate mass



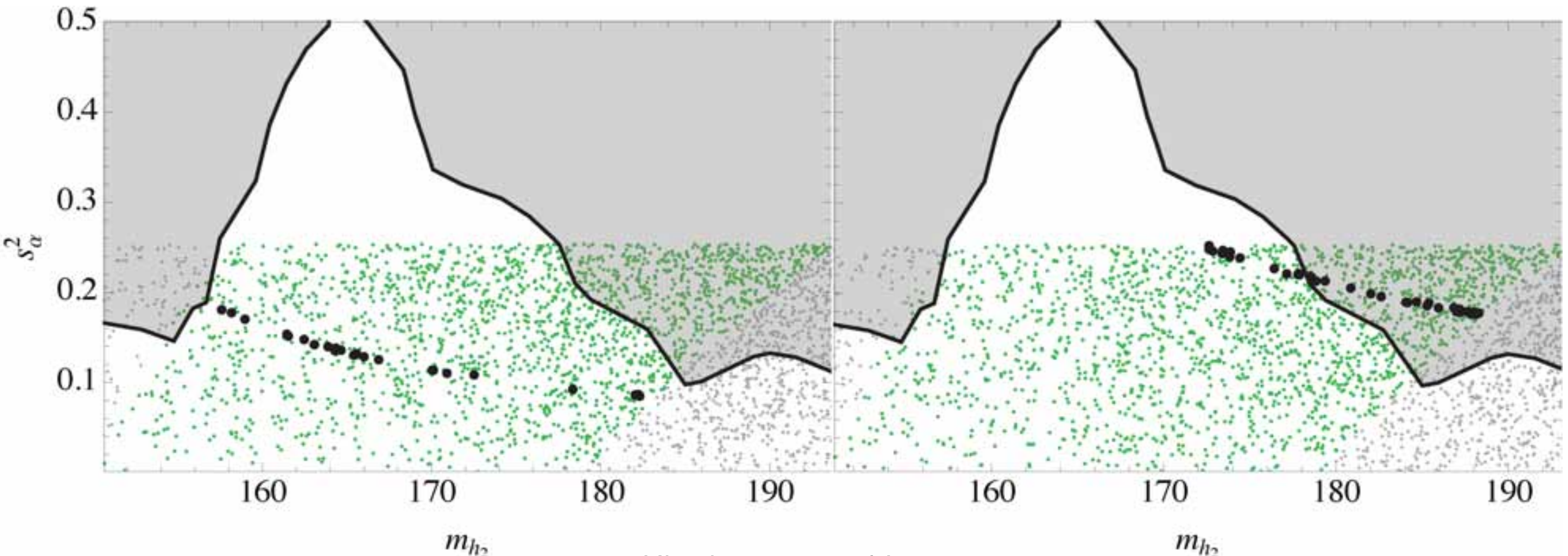
# No Viable DM for N=4

For $N = 4$ predicted DM relic abundance is too large (too many vector DM components): model is ruled out



# Constraint on Heavy Higgs Mass

CMS constraint (shaded region ruled out at 95%CL) on $s_\alpha^2 = \sin^2\alpha$ in function of heavy Higgs mass with viable data points (in green those stable and with viable light Higgs couplings, in black those that satisfy also DM constraints), for $N = 2$ (left panel) and $N = 3$ (right panel).



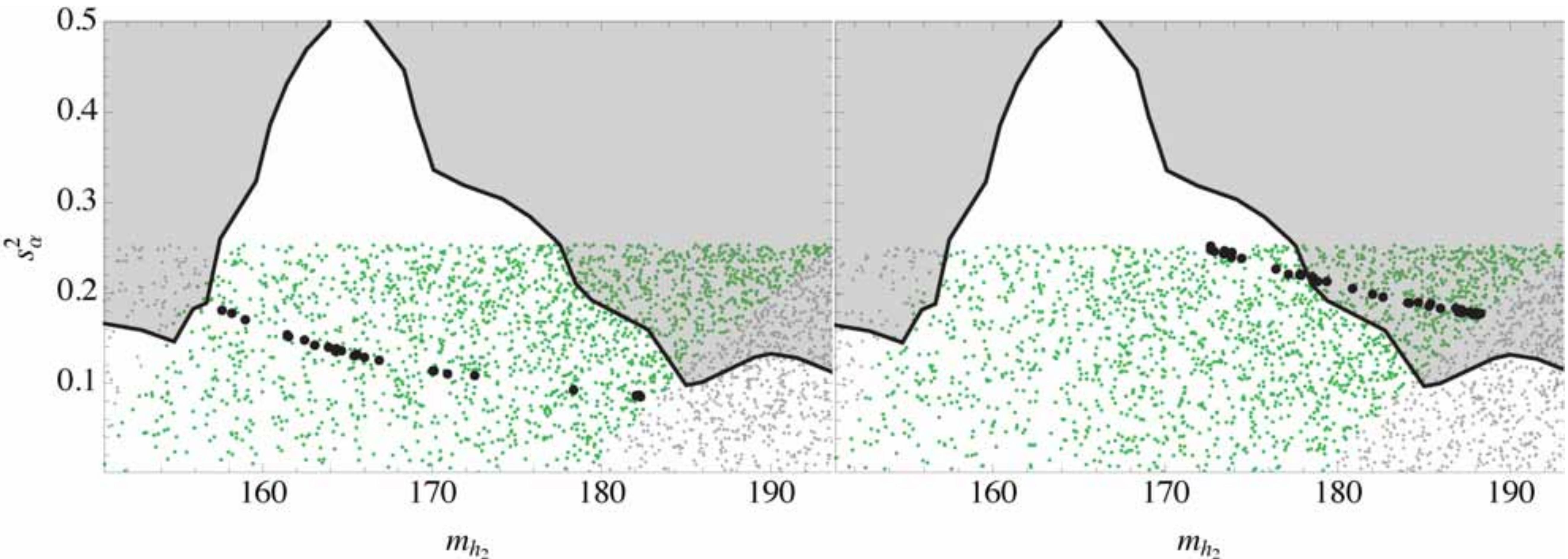

Khachatryan et al.'15

# LHC Prospects

Assuming constraint to be dominated by data statistical uncertainty, change inversely proportional to

$$\sqrt{\mathrm{N}} = \sqrt{\sigma_{h_2}\epsilon_{eff}L_{tot}}$$

For total integrated luminosity at the end of Run II in 2019 equal to 150 fb$^{-1}$ the upper bound on $\sin\alpha$ reduces by a factor of 1/2



# Conclusions

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

- Provides viable vector DM candidate
- Stabilizes SM potential
- Solves SM fine tuning problem?
- SU$(3)$ DM model ruled out if no heavy H discovery at RUN II

T h a n k  y o u !