

# SCALE INVARIANT EXTENSION OF THE SM WITH QCD-LIKE HIDDEN SECTOR

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Based on the work in progress  
with  
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- 1 INTRODUCTION
- 2 MODEL DESCRIPTION
- 3 DM PHENOMENOLOGY
- 4 SUMMARY AND PROSPECTS

# INTRODUCTION

- Two major problems of the particle physics,

## *Hierarchy problem* & **Dark Matter**

# INTRODUCTION

- Strategy for HP : Dimensional Transmutation

$$\Lambda/Q = e^{-\frac{\pi}{b_1 \alpha(Q)}},$$

where  $\alpha(\Lambda) = \infty$ .

- Strategy for DM : Place them in the hidden sector!

→ Scale Invariant SM + Hidden (SI) QCD + messenger sector.

HUR, DWJ, KO AND LEE, PLB696(2011) 262-265

HUR, KO, PRL106(2011) 141802

- Model lagrangian:

$$\mathcal{L} \supset - \frac{\lambda_H}{2} (H^\dagger H)^2 + \frac{\lambda_{HS}}{2} S^2 H^\dagger H - \frac{\lambda_S}{8} S^4$$

$$- \frac{1}{4} \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{h,f}} (\bar{Q}_k i \not{D} \cdot \gamma - \lambda_k S) Q_k.$$

1. scale invariant  $\rightarrow$  no intrinsic scales.
2. singlet scalar  $S$  mediate two sectors.
3. HP is solved by hidden quark condensates.
4. Hidden meson/baryon : DMs.

# LOGICAL STRUCTURE

1.  $\langle \bar{Q}_k Q_k \rangle$  condensate.
  2. Linear  $S$  term generated,
  3. Nontrivial vacuum for  $S$  and  $H$ ,
  4. EWSB and hidden quark mass term,
  5. Go to 1.
- ◇ n.b.) All scales are generated by hidden confinement scale  $\Lambda_h$  !!

# CAN YOU SOLVE THE STRONGLY-INTERACTING THEORY?

- No. ( at least for me) :

Then, how to treat the problem?

- low energy effective theory :

1. (non) linear  $\sigma$  model,

Hur, DWJ, Ko and Lee, PLB696 (2011) 262-265

Hur, Ko, PRL106 (2011) 141802

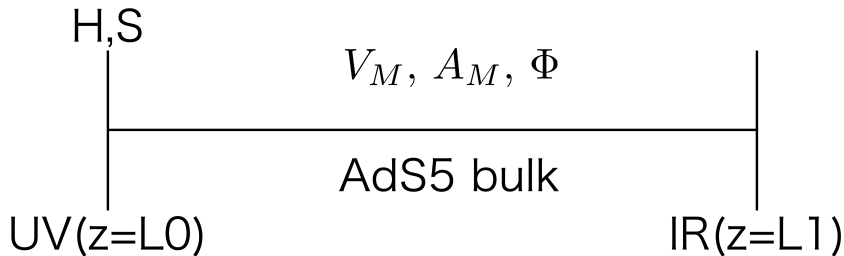
2. Nambu–Jona-Lasinio approach,

Holthausen, Kubo, Lim and Lindner, JHEP 1312 (2013) 076

# WE ADOPT AdS/CFT (AdS/QCD) APPROACH!

DA ROLD AND POMAROL, NPB721 (2005) 79-97, JHEP01 (2006) 157

- Spontaneously broken global symmetry in 4D  
= Spontaneously broken local symmetry in 5D





# $SU(N_{hf})_L \times SUN(N_{hf})_R$ GAUGE SYMMETRY IN $AdS_5$ .

- 5D action :

$$S_5 = \int d^4x \int_{L_0}^{L_1} \sqrt{g} M_5 L \times \text{Tr} \left[ -\frac{1}{4} L_{MN} L^{MN} - \frac{1}{4} R_{MN} R^{MN} + \frac{1}{2} |D_M \Phi|^2 - \frac{1}{2} M_\Phi^2 |\Phi|^2 \right],$$

where  $M_\Phi^2 = -3/L^2$ .

- chiral sym. breaks with  $\langle \Phi \rangle \propto \mathbf{1}_{N_f}$ .

- EOM with boundary conditions,

$$\frac{L}{L_0} v|_{L_0} = M_q, \quad Lv|_{L_1} = \xi$$

$$\mathcal{L}_{IR} = -\frac{L^4}{z^4} V(\Phi)|_{L_1}, \quad V(\Phi) = -\frac{1}{2} m_b^2 \text{Tr}|\Phi|^2 + \lambda \text{Tr}|\Phi|^4.$$

gives

$$v(z) = c_1 z + c_3 z^3, \quad c_1 \simeq \frac{M_q L_1^3 - \xi L_0^2}{L L_1^3}, \quad c_3 \simeq \frac{\xi - M_q L_1}{L L_1^3}.$$

- 5 parameters :  $M_q, M_5, L_1, \xi$  and  $\lambda$ .
- Calculating correlation functions and fitting with exp.data,

$$M_5 L = \frac{N_c}{12\pi^2} \equiv \tilde{N}_c, \quad \frac{2.4}{L_1} \simeq M_\rho (\simeq 770 \text{ MeV}), \quad \xi \simeq 4(w / M_{a1} \simeq 1230 \text{ MeV}).$$

## LET'S GET BACK TO OUR MODEL.

- Effective lagrangian is written as

$$\begin{aligned}
 -\mathcal{L} \supset & \frac{\lambda_H}{2} (H^\dagger H)^2 - \frac{\lambda_{HS}}{2} S^2 H^\dagger H + \frac{\lambda_S}{8} S^4 \\
 & - \frac{1}{2} \mu_\sigma^2 [\sigma^2 + \pi^2] + \frac{1}{4} \mu_\sigma^2 [\sigma^2 + \pi^2]^2 - m_{S\sigma}^2 S \sigma.
 \end{aligned}$$

- From AdS/QCD, we have a relation

$$\begin{aligned}
 m_{S\sigma}^2 &= \text{Tr}[\lambda_k] f_\sigma m_\sigma = \frac{f_\pi^2 m_\pi^2}{v_s \langle \bar{Q} Q \rangle} f_\sigma m_\sigma = \frac{f_\pi m_\pi^2}{v_s} \\
 \rightarrow \frac{f_\sigma m_\sigma}{f_\pi^2} &= \frac{B_0}{f_\pi} \simeq 17.5.
 \end{aligned}$$

★ ★ ★ We assume  $SU(2)$ , so we have **3** copies of hidden pions with same physical properties.

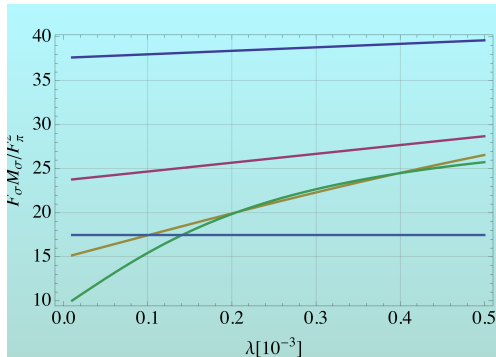
- Numerical calculation :

$$\lambda \simeq 1 \times 10^{-4},$$

which gives

$$m_\sigma \simeq 436 \text{ MeV}.$$

- It also gives  $m_\sigma \simeq 5f_\pi$ .



$$\frac{F_\sigma M_\sigma}{F_\pi^2} \text{ and } \frac{B_0}{F_\pi} = 17.5$$



- After symmetry breaking,

$$\begin{aligned}
 -\mathcal{L} \supset & \frac{\lambda_H}{8} (v_H + h)^4 - \frac{\lambda_{HS}}{4} (v_S + s)^2 (v_H + h)^2 \\
 & + \frac{\lambda_S}{8} (v_S + s)^4 \\
 & - \frac{1}{2} \mu_\sigma^2 (v_\sigma + \tilde{\sigma})^2 + \frac{1}{4} \lambda_\sigma (v_\sigma + \tilde{\sigma})^4 \\
 & - m_{S\sigma}^2 (v_\sigma + \tilde{\sigma}) (v_S + s).
 \end{aligned}$$

- 9** parameters reduces to **3** parameters by
  - ◇ 3 vacuum conditions,
  - ◇ 2 observations :  $v_H = 246$  GeV and  $m_h = 125$  GeV,
  - ◇ AdS/QCD relation :  $M_\sigma \simeq 5f_\pi$ .

$$\text{3 free parameters : } m_\pi, f_\pi, \tan \beta = \frac{v_S}{v_H}$$

- mass<sup>2</sup> matrix :

$$\mathbf{M}^2 = \begin{pmatrix} t_\beta^2 v_H^2 \lambda_{HS} & -t_\beta v_H^2 \lambda_{HS} & 0 \\ -t_\beta v_H^2 \lambda_{HS} & \frac{3f_\pi^2 m_\pi^2}{t_\beta^2 v_H^2} + v_H^2 \lambda_{HS} & -\frac{f_\pi m_\pi^2}{t_\beta v_H} \\ 0 & -\frac{f_\pi m_\pi^2}{t_\beta v_H} & f_\pi^2 \xi_\sigma^2 \end{pmatrix}$$

- Diagonalizing with fixed eigenvalue  $m_h^2 = (125 \text{ GeV})^2$ ,

$$\det [\mathbf{M}^2 - m_h^2 \cdot \mathbf{I}] = 0,$$

analytic form of  $\lambda_{HS}$  is derived as

$$\lambda_{HS} = \frac{m_h^2}{t_\beta^2 v_H^2} \frac{m_h^4 t_\beta^2 v_H^2 + 3f_\pi^4 m_\pi^2 \xi_\sigma^2 - f_\pi^2 (3m_h^2 m_\pi^2 + m_\pi^4 + m_h^2 t_\beta^2 v_H^2 \xi_\sigma^2)}{m_h^4 (1 + t_\beta^2) v_H^2 + 3f_\pi^4 m_\pi^2 \xi_\sigma^2 - f_\pi^2 (3m_h^2 m_\pi^2 + m_\pi^4 + m_h^2 (1 + t_\beta^2) v_H^2 \xi_\sigma^2)}.$$

## A FEW COMMENTS

- For large  $t_\beta$ ,  $\lambda_{HS} \sim \frac{m_h^2}{t_\beta^2 v_H^2}$ .
  - ◊ (1,1) component is approximately  $\sim m_h^2$ .
  - ◊ (1,2) components are suppressed with  $t_\beta \rightarrow$  small mixing.
- For small  $t_\beta$ , (1,2) components are less suppressed  $\rightarrow$  mixing is enhanced.
- If  $t_\beta$  is too small, perturbativity can break down for  $\lambda_S$ .

$$\lambda_S = \frac{\lambda_{HS}}{t_\beta^2} + \frac{2m_\pi^2 f_\pi^2}{v_H^4 t_\beta^4}.$$

## MIXING

$$\begin{pmatrix} h \\ s \\ \tilde{\sigma} \end{pmatrix} = \begin{pmatrix} V_{h0} & V_{hX} & V_{hY} \\ V_{s0} & V_{sX} & V_{sY} \\ V_{\sigma0} & V_{\sigma X} & V_{\sigma Y} \end{pmatrix} \begin{pmatrix} h_0 \\ h_X \\ h_Y \end{pmatrix}$$

- $\mathbf{V}^T \cdot \mathbf{M} \cdot \mathbf{V} = \mathbf{M}_{\text{diag}}$ .
- $h$  couples to SM sector,  $\sigma$  couples to Hidden sector (hidden pions) and  $s$  mediates two.
- $h_0, h_X, h_Y$  are mass eigenstates with  $m_{h_0} = 125$  GeV.
- Masses, mixing angles and relevant lagrangian are calculated analytically as functions of  $(f_\pi, m_\pi, t_\beta)$ .



# NUMERICAL RESULTS (PRELIMINARY!)

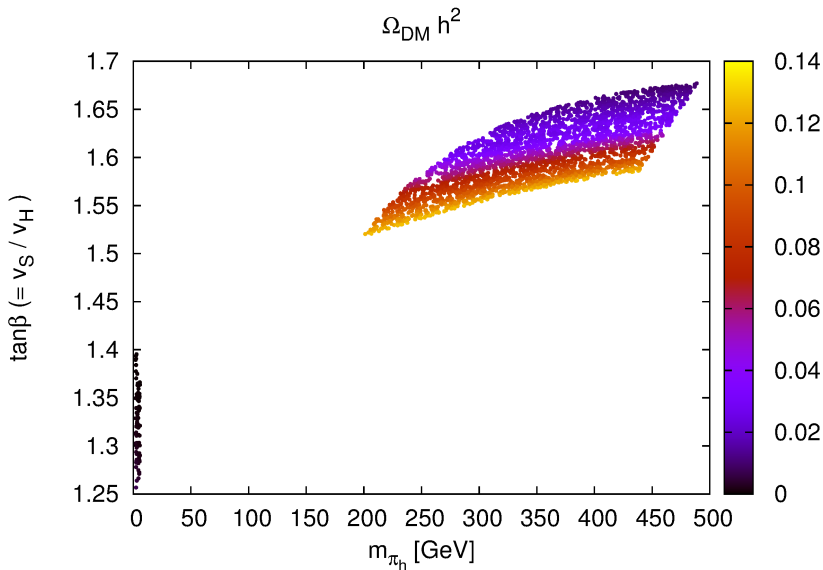
With MicrOMEGAs,

- Exp. constraints :

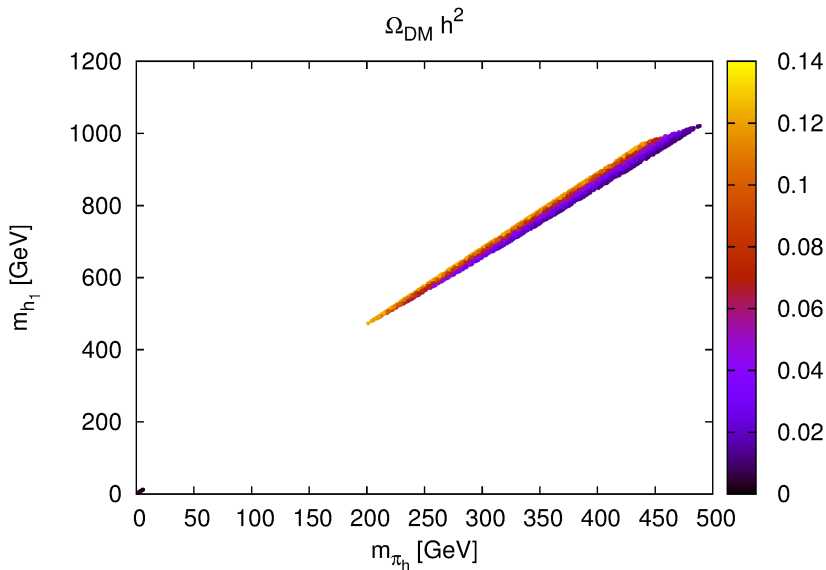
1. Signal strength :  $\hat{\mu} = 1.00 \pm 0.13$  (CMS)  $\rightarrow$  constrains  $|V_{h_0}|^2$
2. LEP bound for extra scalar (lighter than 125 GeV ).
3. CMS and ATLAS bounds for extra scalars.
4. Relic density :  $\Omega_{DM} h^2 = 0.1198 \pm 0.0026$ .
5. SK bounds for upward muon flux.
6. Icecube neutrino flux.
7. Fermi LAT : 6-year results for DM annihilations.
8. Higgs invisible width : 0.75 for ATLAS and 0.58 for CMS.
9. Direct detections : LUX+SuperCDMS+CRESST-II 2014 + ...

- Also perturbative bound for  $\lambda_S$  and stability bound for  $\lambda_{HS}$ .

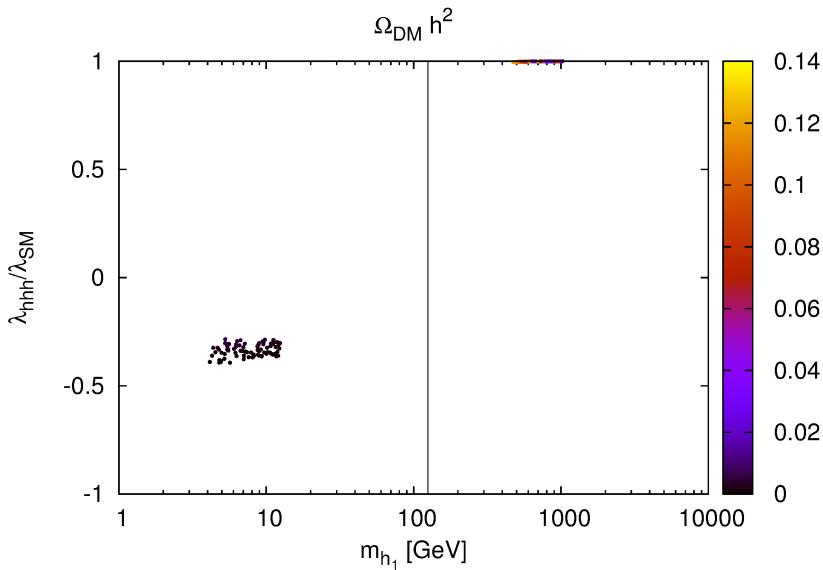
$f_\pi = 500 \text{ GeV}$ , (PRELIMINARY!)



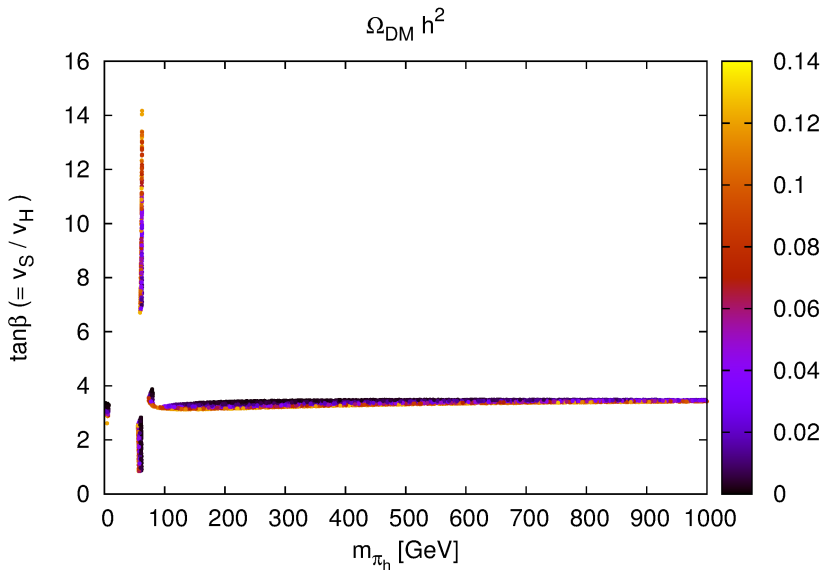
$f_\pi = 500$  GeV, (PRELIMINARY!)



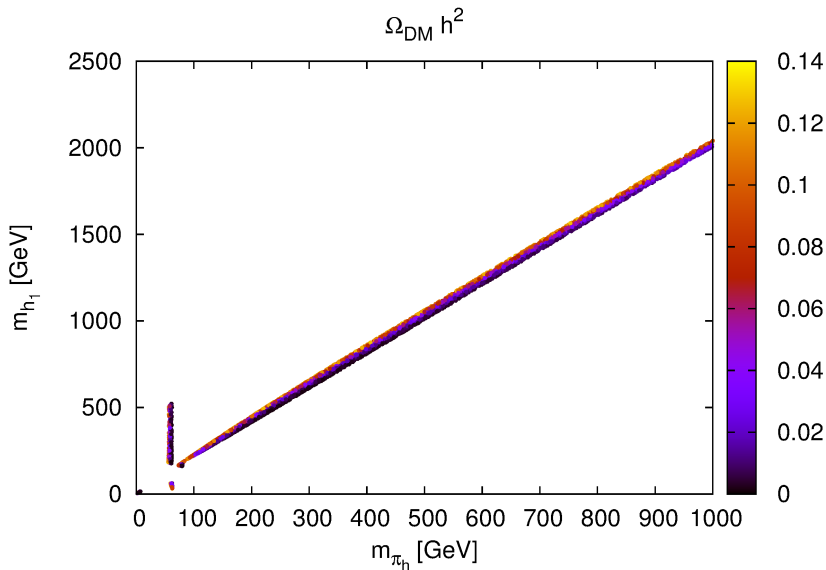
$f_\pi = 500$  GeV, (PRELIMINARY!)



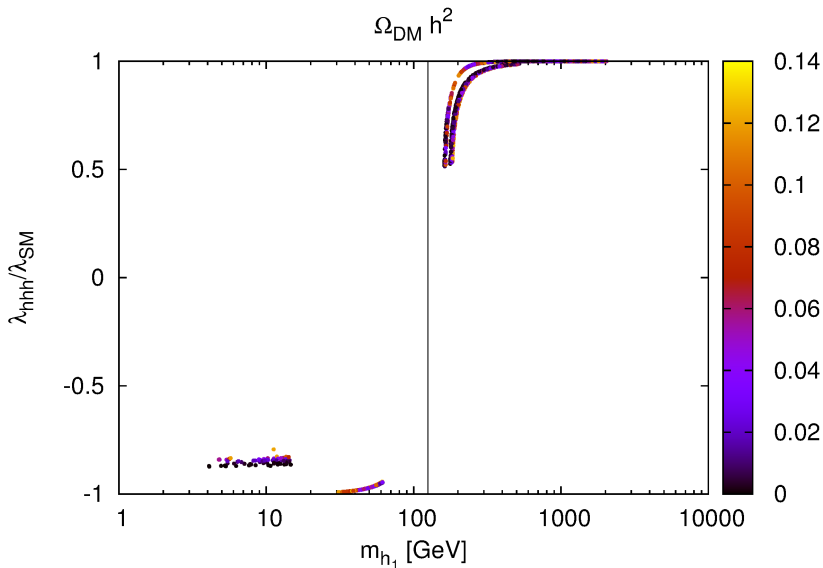
$f_\pi = 1000 \text{ GeV}$ , (PRELIMINARY!)



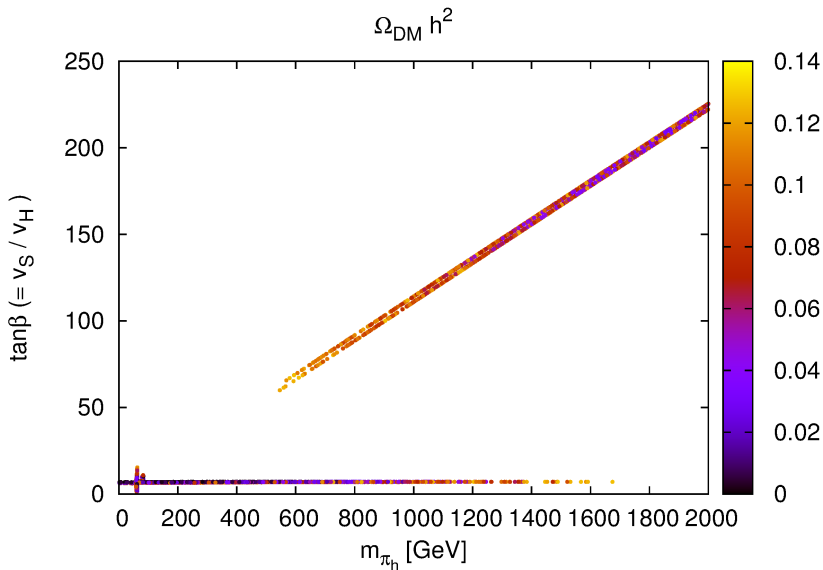
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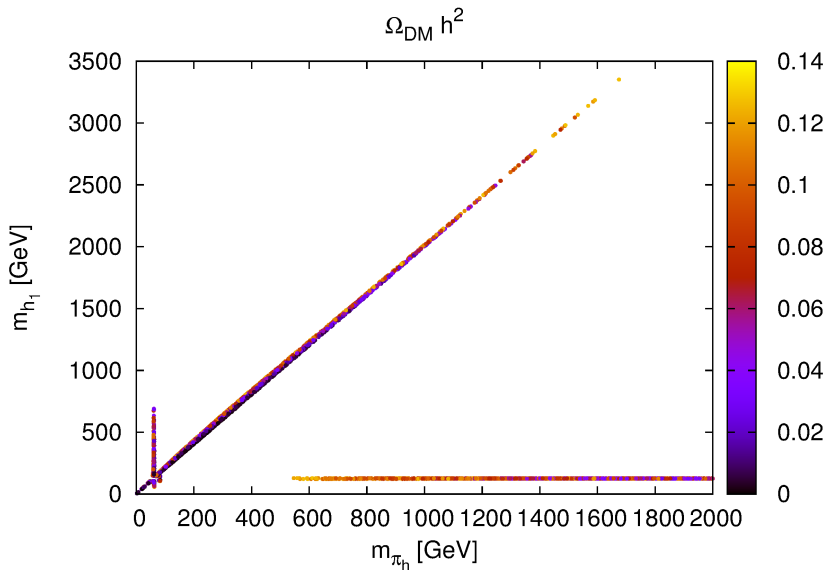


$$f_\pi = 2000 \text{ GeV}, \text{ (PRELIMINARY!)}$$

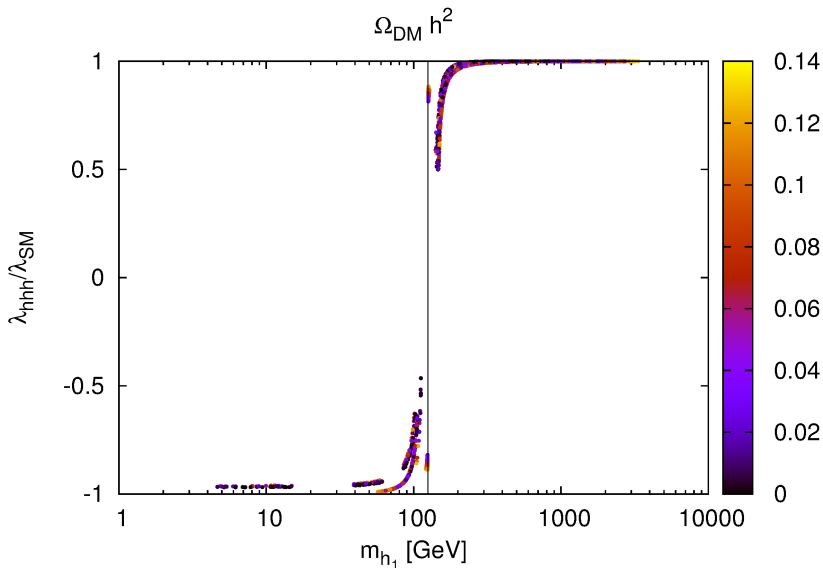




$f_\pi = 2000 \text{ GeV}$ , (PRELIMINARY!)



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# SUMMARY AND PROSPECTS

- Scale Invariant model with QCD-like hidden sectors provide the resolution of long-standing problems in particle physics.
- AdS/QCD is used effectively to reduce the undeterminacy of the model parameters.
- Together with many experimental endeavors, the model can have sharp predictability.
- DM problem can be resolved either by resonance of extra scalars or enhancement of the coupling via mixing.
- More thorough pheno. studies are on-going, including the possible deviations from the SM results (ex. Higgs triple coupling etc.), considering hidden baryonic DM etc.