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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Introduction

- Two major problems of the particle physics,

Hierarchy problem

&

Dark Matter

Introduction

- Strategy for HP : Dimensional Transmutaion

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

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

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

$\rightarrow$ Scale Invariant SM + Hidden (SI) QCD + messenger sector.

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

Hur, Ko, PRL106(2011) 141802

- Model largrangian:

$$\mathcal{L} \supset -\frac{\lambda_H}{2}\left(H^\dagger H\right)^2 + \frac{\lambda_{HS}}{2} S^2 H^\dagger H - \frac{\lambda_S}{8} S^4 - \frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{h,f}} \left(\bar{\mathcal{Q}}_k iD\cdot\gamma - \lambda_k S\right)\mathcal{Q}_k .$$

1. scale invaraint → 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. $\langle \bar{\mathcal{Q}}_k \mathcal{Q}_k \rangle$ condendate.
2. Linear S term generated,
3. Nontrivial vaccum for S and H,
4. EWSB and hidden quark mass term,
5. Go to 1.

⋄ n.b.) All scales are generated by hidden confinment scale Λ_h !!

Can you solve the strongly-interacting theory?

- No. (at least for me) :

  Then, how to treat the problem?

- low energy effective theory :

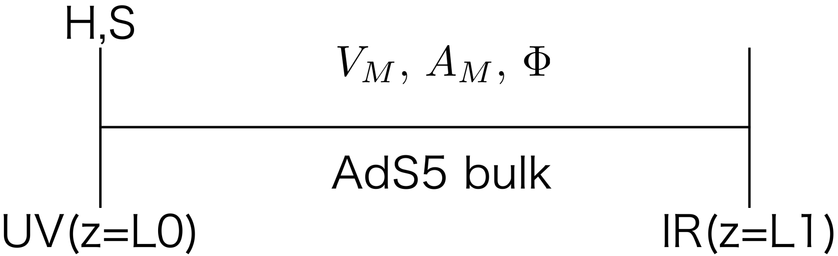
  1. (non) linear σ model,
  Hur, DWJ, Ko and Lee, PLB696 (2011) 262-265
  Hur, Ko, PRL106 (2011) 141802

  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

- Spontaneouly 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 :

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

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

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

- EOM with boundary conditions,

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

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

gives

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

- 5 parameters : M_q, M_5, L_1, ξ and λ.

- 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

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

- From AdS/QCD, we have a relation

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

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

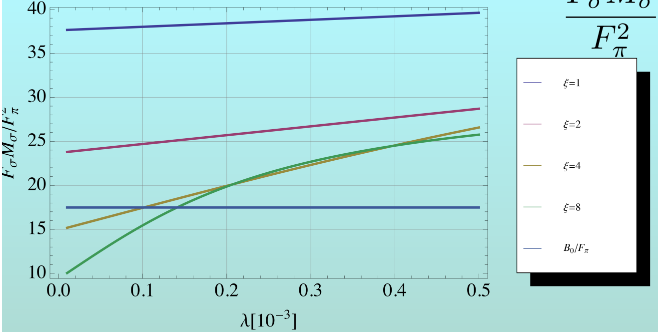
- Numerical calculation :

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

which gives

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

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



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

- After symmetry breaking,

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

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

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

- mass^2 matrix :

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

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

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

analytic form of λ_{HS} is derived as

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

A FEW COMMENTS

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

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

Mixing

$$\begin{pmatrix} h \\ s \\ \tilde{\sigma} \end{pmatrix} = \begin{pmatrix} V_{h0} & V_{hX} & V_{hY} \\ V_{s0} & V_{sX} & V_{sY} \\ V_{\sigma 0} & V_{\sigma X} & V_{\sigma Y} \end{pmatrix} \begin{pmatrix} h_0 \\ h_X \\ h_Y \end{pmatrix}$$

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

Numerical results (Preliminary!)

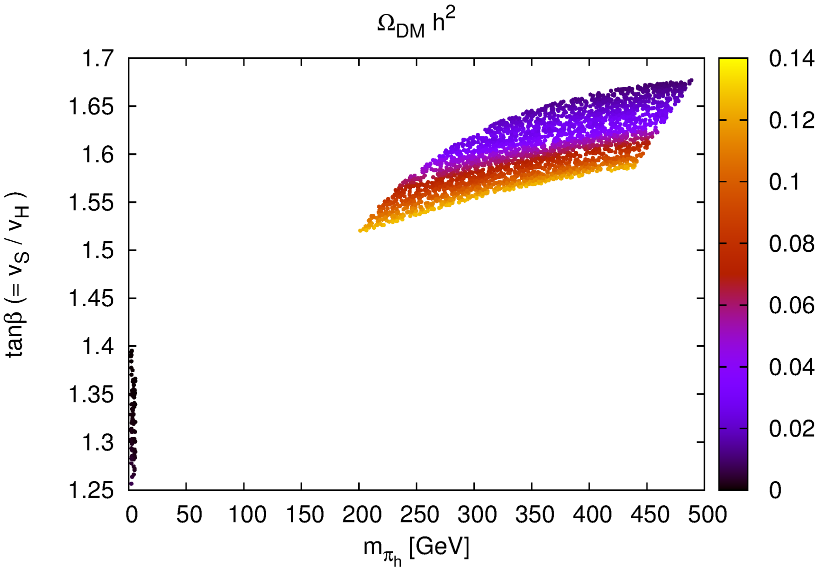
With MicrOMEGAs,

- 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 + $\cdots$

- Also perturbative bound for λ_S and stability bound for λ_{HS}.

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



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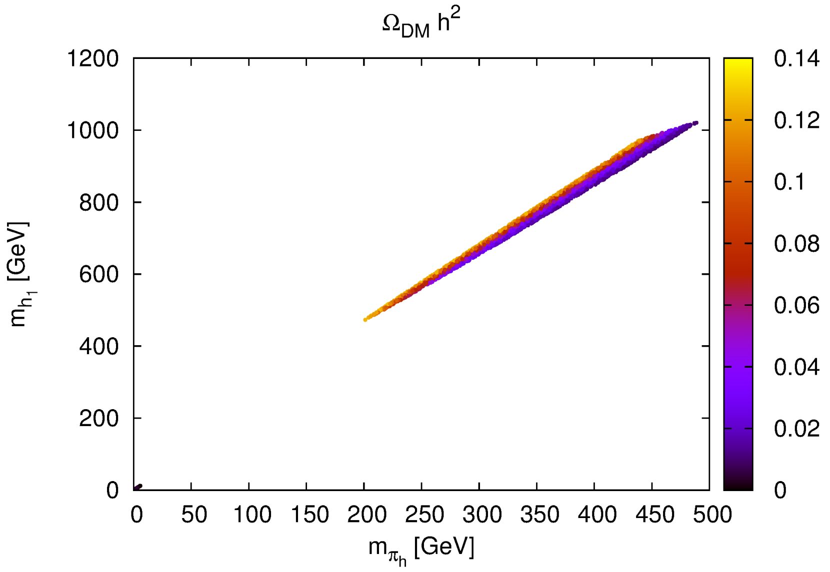

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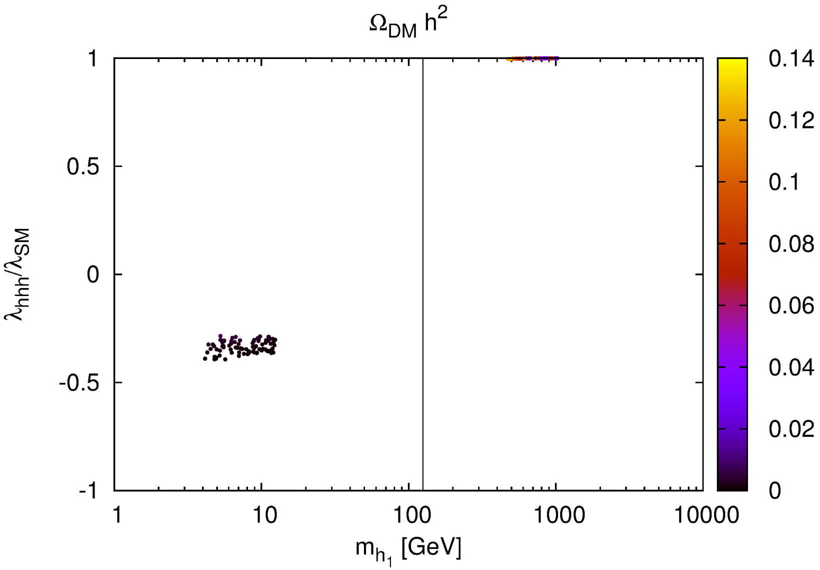
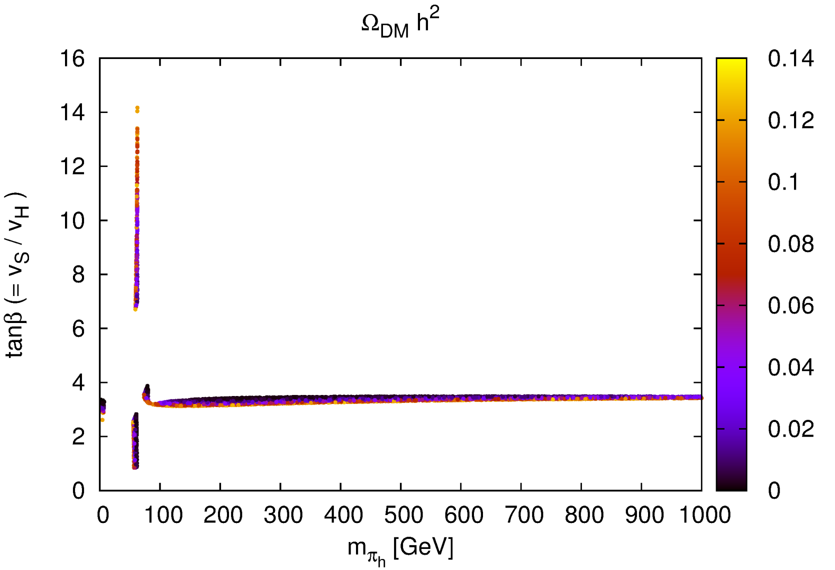


$f_\pi = 1000$ GeV, (Preliminary!)



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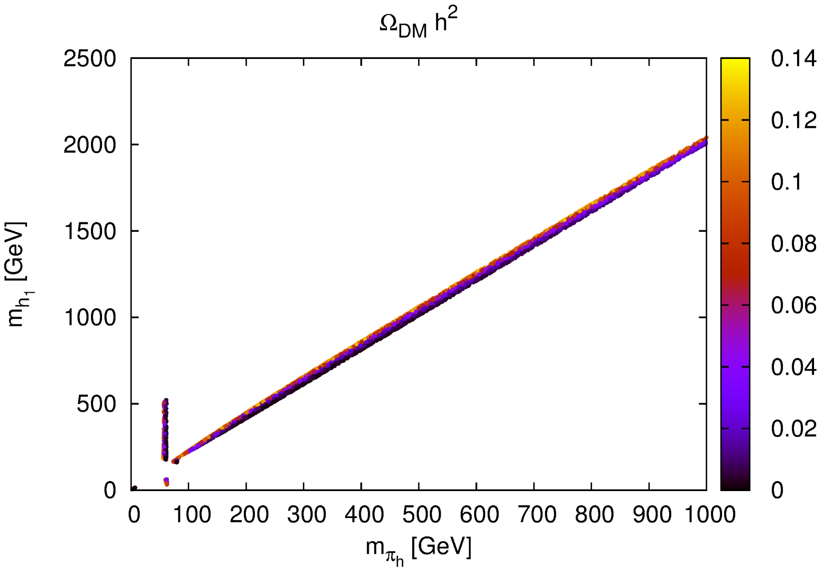

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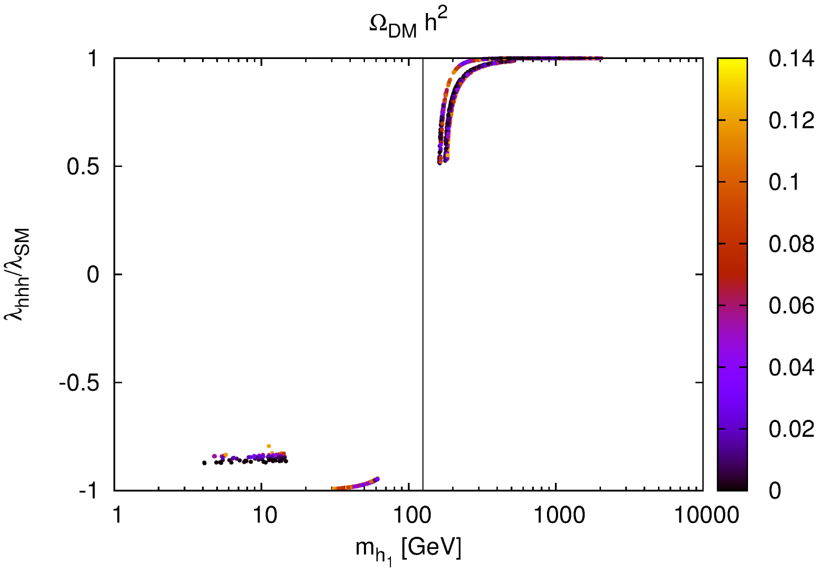
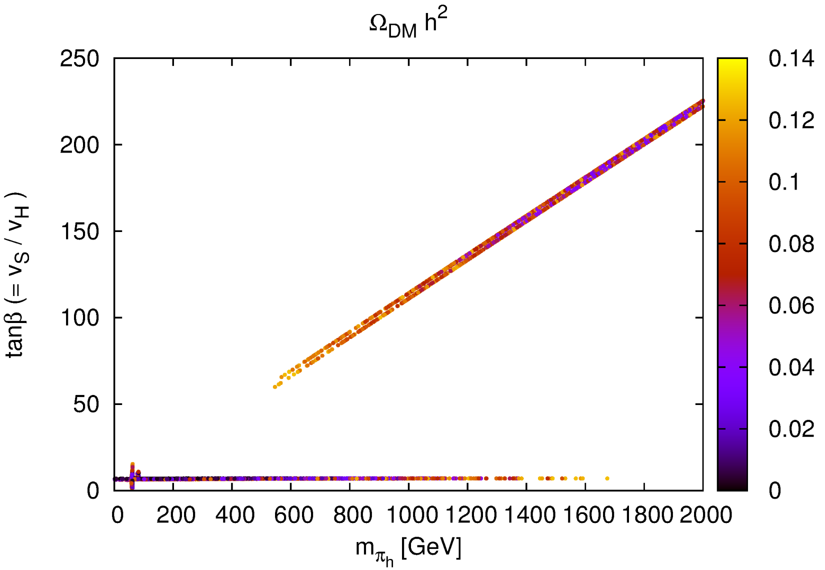
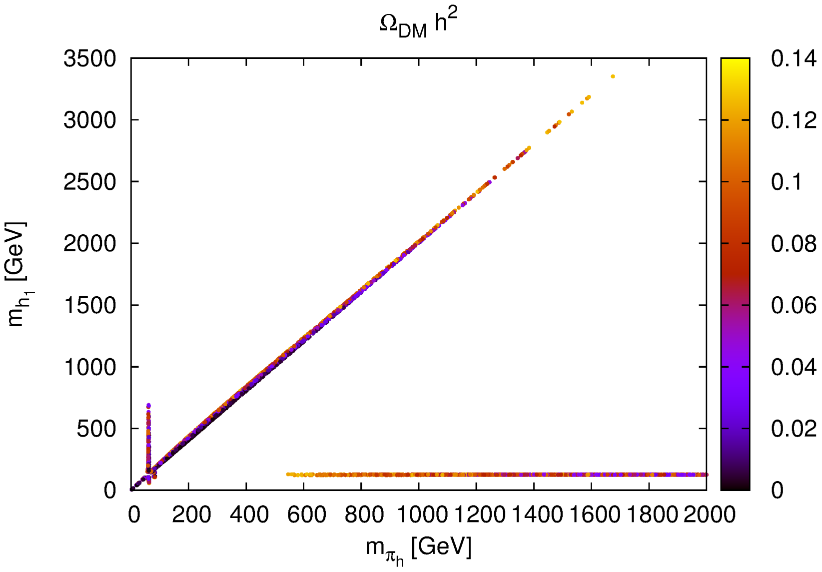


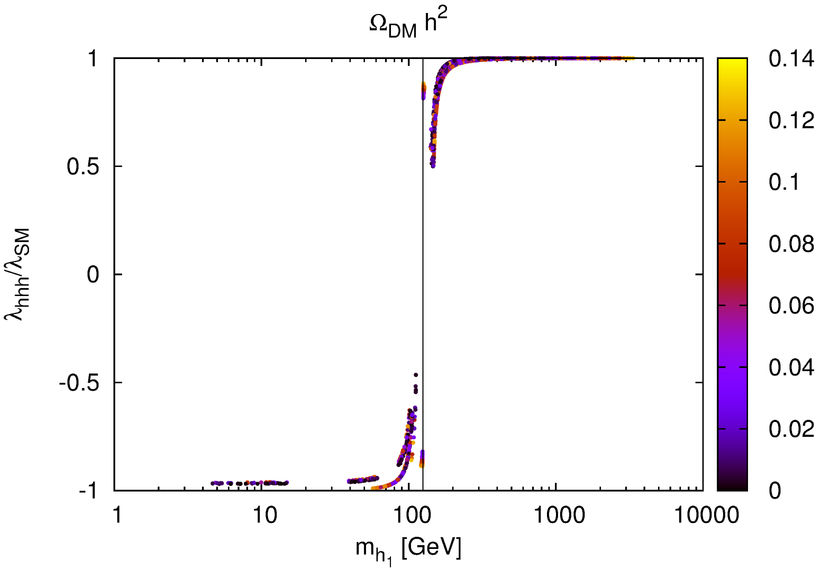
$f_\pi = 2000$ GeV, (Preliminary!)



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



$f_\pi = 2000$ GeV, (Preliminary!)



Summary and Prospects

- Scale Invaraint 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 resoance of extra scalars or enhancement of the coupling via mixing.
- More thorough pheno. studies are on-going, including the possible deviaions from the SM results (ex. Higgs triple coupling etc.), considering hidden baryonic DM etc.