EWSB and CDM from Strongly Interacting Hidden Sector

Pyungwon Ko (KIAS)

(Based on arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee, and papers in preparation with T. Hur and S. Baek)

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Contents

Current Status of the SM

SO GOOD with all the data, EWPT, CKM
except for

1. Unseen Higgs so far
2. Neutrino masses and mixings
3. Baryon Number Asymmetry
4. Nature of CDM

- LHC designed to discover SM Higgs (Item 1)
- Seesaw + Leptogenesis (Items 2+3)
- Many models for Item 4

What's next ?

- Understanding of

  I ignore here

  - Origin of EWSB
  - Origin of families (Flavors)
  - Many fine tuning problems

- Usual arguments for new physics around TeV scale based on quadratic divergence of (Higgs mass)^2

- Real Fine tuning problem with EWPT & CKM

- New physics could be insensitive to the SM interaction, but has something to do with CDM & EWSB

Motivations

- Forget about fine tuning problem of Higgs mass, and consider a hidden sector (neutral under SM gauge group) at EW scale
- Introduce new particles neutral under the SM gauge group (Hidden Sector)
- Less constrained by EWPT and CKMology, because new particlers are SM singlets, could be light
- Hidden sector : Generic in many BSM's & Why not ? (e.g. SUSY is broken in a hidden sector)

Hidden sector ?

- Usually the hidden sector breaks SUSY spontaneously, and then does nothing else
- Could play an important role in phenomenology at TeV scale, especially in Higgs phenomenology (Invisible Higgs decay into a pair of CDM's)
- Many possibilities for the choice of gauge groups and matter contents of the hidden sector (e.g.# of colors and flavors in the hidden QCD)
- Phenomenology depends on mediators between the SM and a hidden sector

Can we understand

- the stability of DM without ad hoc Z2 symmetry ?
- the generation of mass scales from quantum mechanics ?
- other effects of a hidden sector, if it exists ?
- Answer to these seemingly unrelated questions is YES !

Stability of DM

- Usually guaranteed by ad hoc Z2 symmetry
- Or life time of DM made very long by fine tuning of couplings
- Note that quark flavor is conserved within renormalizable QCD (accidental symmetry)
- Can we find a similar reason for the DM stability ?

Can we understand the origin of all the masses ?

- In massless QCD, all the masses originate from dimensional transmutation
- Proton mass dynamically generated by quarks and gluons, not by the quark masses
- A similar mechanism for elementary particles ?
- Questions by Coleman and Weinberg, F. Wilczek, C. Hill, W. Bardeen, ...

Related Works & Talks (as of 2007)

- Foot, Volkas, et al (Mirror World)
- Berezhiani et al (Mirror World)
- Strassler, Zurek, et al (Hidden Valley)
- Wilczek (Higgs portal & Phantom)
- Cheung, Ng, et al (Shadow)
- Ko et al (Hidden Sector strong interaction)
- More works afterwards

Weakly Interacting Hidden Sector

- Perturbation applicable & easy to analyze
- Many CDM models (including leptophilic Dirac Fermion DM) are this type with "Higgs portal"
- Gauge boson mass is generated by Higgs mechanism
- Origin of mass scale remains unclear, just like in SM

Strongly Interacting Hiddens Sector

- Perturbation not applicable & difficult to analyze
- Construct relevant Effective Field Theory (EFT) depending on the physics problems
- Can address dynamical generation of mass scale, like in massless QCD
- Chiral lagrangian technique for the Nambu-Goldstone boson (the hidden sector pion = CDM)

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Can we build a model for EWSB and CDM similar to QCD ?

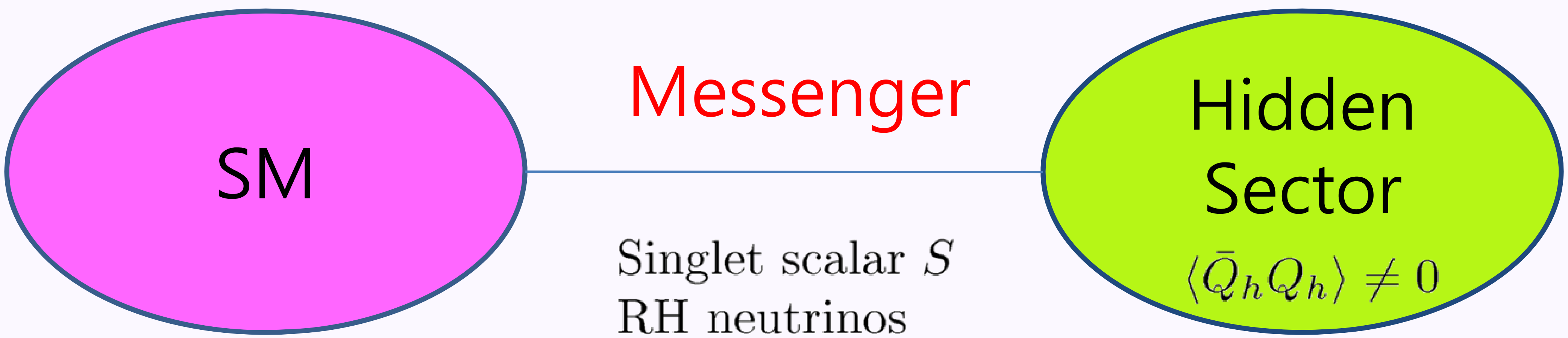
Can we build a model for EWSB and CDM similar to QCD ?

Yes !

Toy model : Hidden Sector Pion as CDM

(arXiv:0709.1218 with T.Hur, D.W.Jung and J.Y.Lee)

Basic Picture



Singlet scalar S
RH neutrinos
etc.

SM
Quarks
Leptons
Gauge Bosons
Higgs boson

Hidden Sector
Quarks Q_h
Gluons g_h
Others

Similar to ordinary QCD

Hidden Sector Pion as a CDM

- CDM in most models stable due to ad hoc Z2 symmetry
- In our models I&II, the hidden sector pion is stable due to flavor conservation in hQCD (accidental symmetry of the underlying gauge theory), which is a nice aspect of our model
- Remember pion is stable under strong interaction in ordinary hadronic world, decays only through em or weak interaction

Warming up with a toy model

(Reinterpretation of 2 Higgs doublet model)

- Consider a hidden sector with QCD like new strong interaction, with two light flavors
- Approximate SU(2)L X SU(2)R chiral symmetry, which is broken spontaneously
- Lightest meson π_h : Nambu-Goldstone boson -> Chiral lagrangian applicable
- Flavor conservation makes π_h stable -> CDM

- Potential for H_1 and H_2

$$V(H_1,H_2) = -\mu_1^2(H_1^\dagger H_1) + \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \mu_2^2(H_2^\dagger H_2)$$
$$+\frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3(H_1^\dagger H_1)(H_2^\dagger H_2) + \frac{a v_2^3}{2}\sigma_h$$

Not present in the two-Higgs Doublet model

- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

$$H_1 = \begin{pmatrix} 0 \\ \frac{v_1 + h_{\rm SM}}{\sqrt{2}} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} \pi_h^+ \\ \frac{v_2 + \sigma_h + i\pi_h^0}{\sqrt{2}} \end{pmatrix}$$

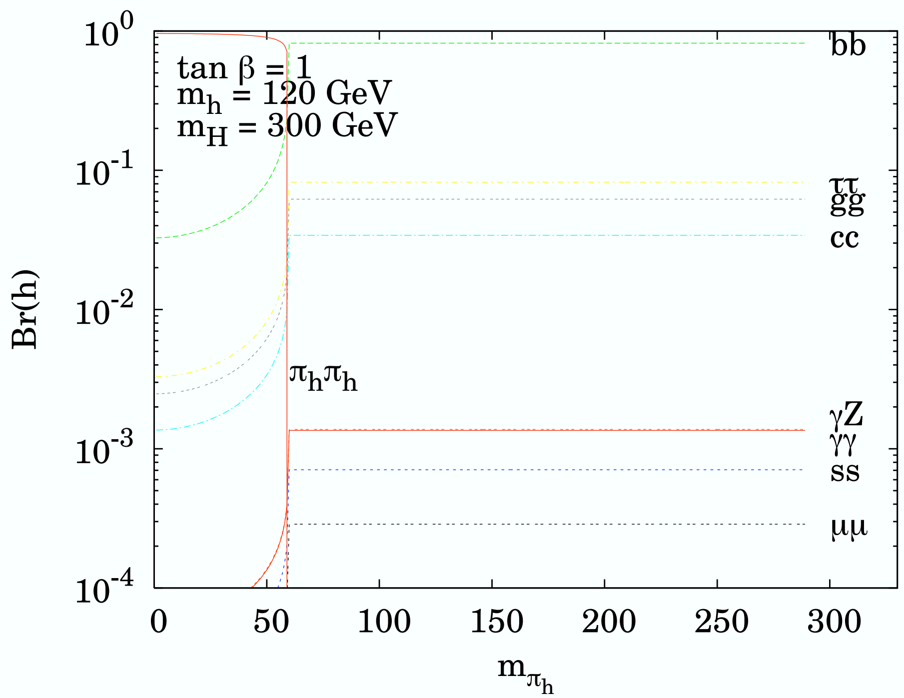
- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1\lambda_2' > \lambda_3^2$

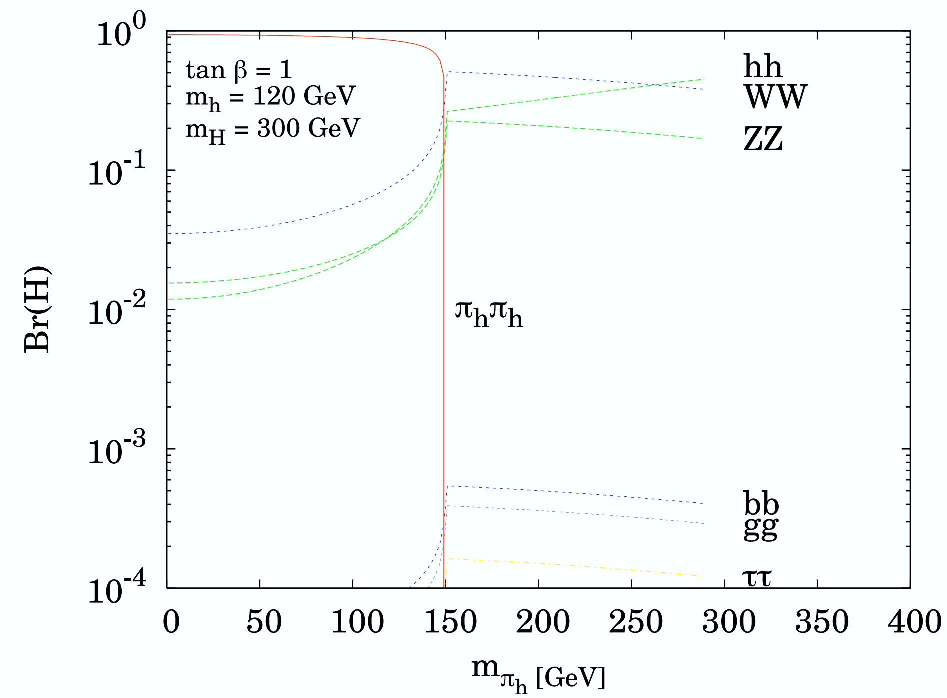
Similar to the usual two-Higgs doublet model, except that

- H2 : SM singlet, no contribution to W,Z, or fermion masses -> Less problem with EWPT or Higgs mediated CPV
- "a" term gives hidden sector pion mass ->CDM
- Charges of hidden pion : Not electric charge, but the hidden sector isospin (I3)
- Higgs sector <> Gell-Mann Levy sigma model <> Low Energy Effective Theory of QCD

- h and H are mixtures of $h_{\rm SM}$ and σ_h: partially composite
- $h(H) - V - V$ couplings : the same as the $H_{\rm SM} - V - V$ couplings modulo $\cos\alpha$ and $\sin\alpha$
- the same is true for the $h(H) - f - \bar{f}$ with SM fermions f couplings
- Productions of h and H at colliders are suppressed by $\cos^2\alpha$ and $\sin^2\alpha$, relative to the production of the SM Higgs with the same mass
- $h(H) - \pi_h - \pi_h$ couplings contribute to the invisible decays $h(H) \to \pi_h \pi_h$
- 4 parameters for $\mu_1^2 = 0$: $\tan\beta$, m_{π_h}, λ_1 and λ_2 or trade the last two with m_h and m_H

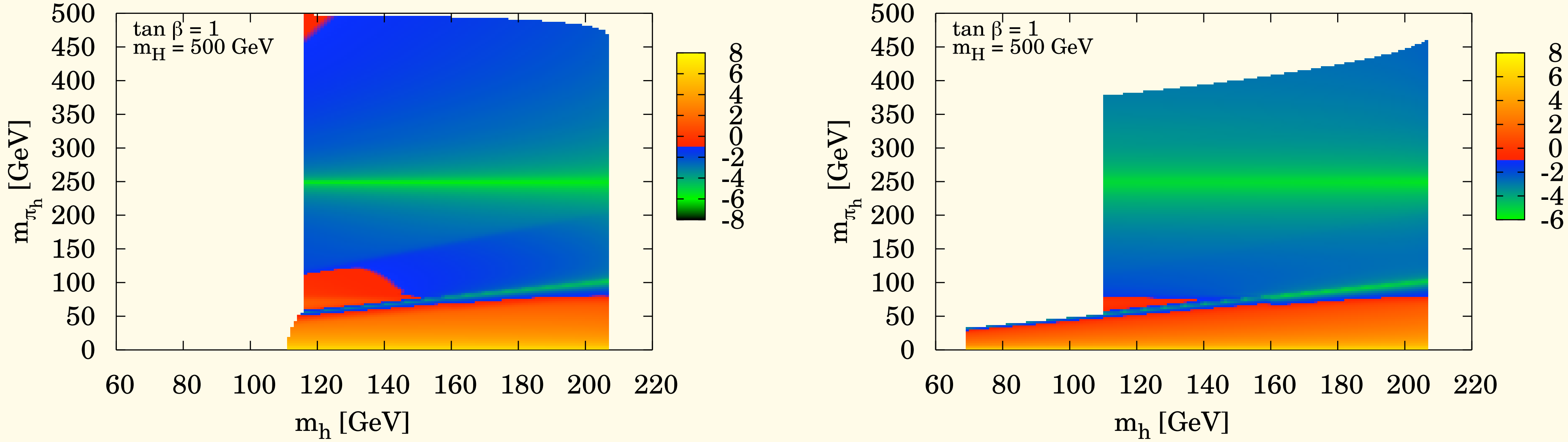
Br of h and H





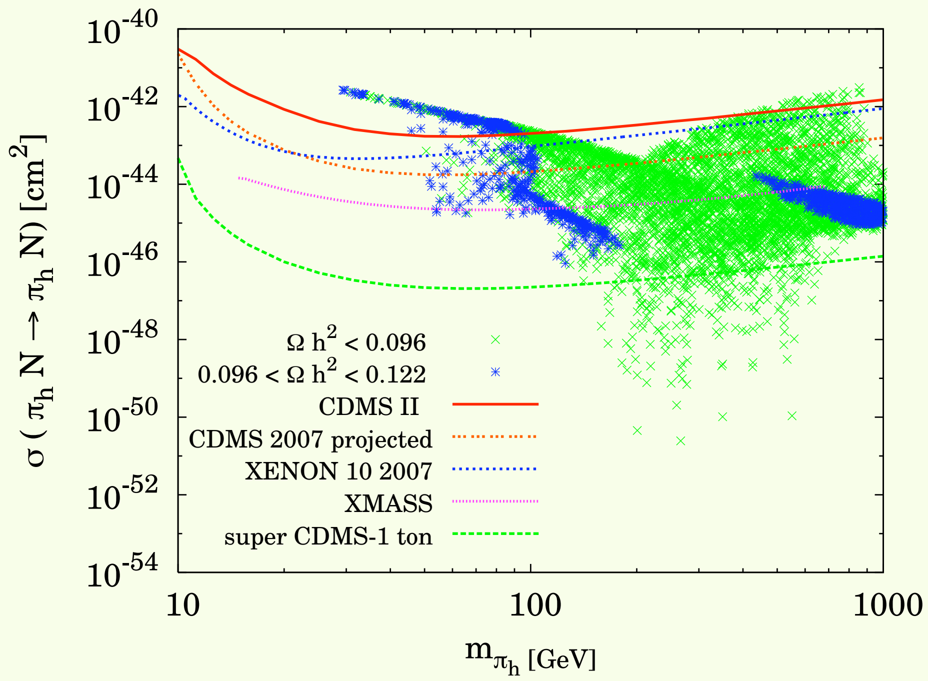
- Branching ratios of h and H as functions of m_{π_h} for $\tan\beta = 1$, $m_h = 120$ GeV and $m_H = 300$ GeV.
- $h, H \rightarrow \pi_h \pi_h$: invisible decay branching ratios make difficult to detect them at colliders

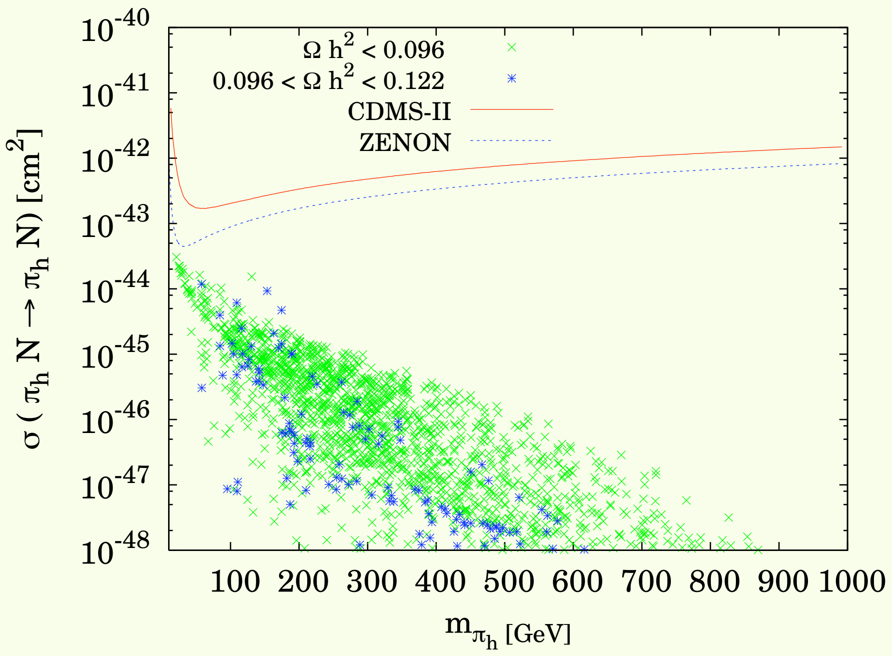
Relic Density



- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate



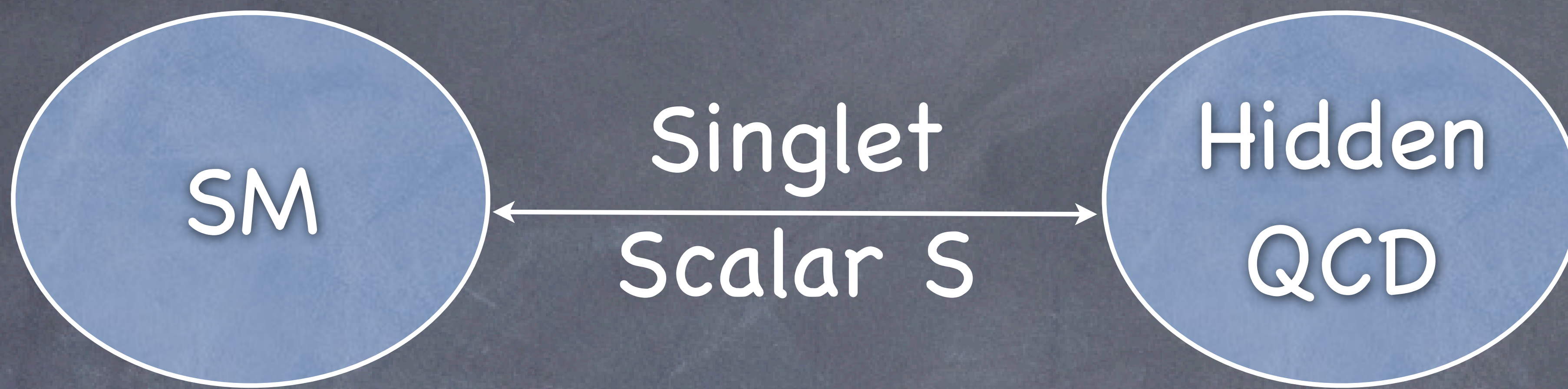


- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be probed to some extent at Super CDMS

Model I : Scalar Messenger

Work in preparation

Model I (Scalar Messenger)



- SM - Messenger - Hidden Sector QCD
- Assume classically scale invariant lagrangian --> No mass scale in the beginning
- Chiral Symmetry Breaking in the hQCD generates a mass scale, which is injected to the SM by "S"

Modified SM with classical scale symmetry

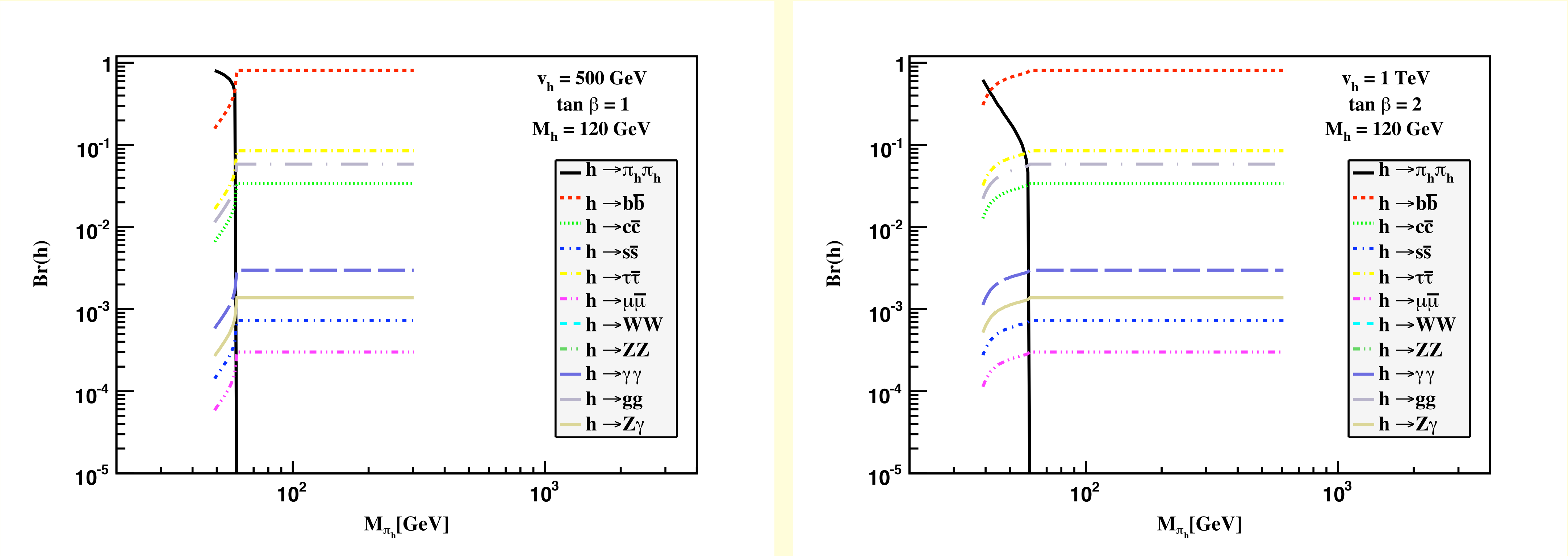
$$
\begin{aligned}
\mathcal{L}_{\rm SM} &= \mathcal{L}_{\rm kin} - \frac{\lambda_H}{4}\,(H^\dagger H)^2 - \frac{\lambda_{SH}}{2}\,S^2\,H^\dagger H - \frac{\lambda_S}{4}\,S^4 \\
&+ \Big(\overline{Q}^i H Y^D_{ij} D^j + \overline{Q}^i \tilde{H} Y^U_{ij} U^j + \overline{L}^i H Y^E_{ij} E^j \\
&+ \overline{L}^i \tilde{H} Y^N_{ij} N^j + S N^{iT} C Y^M_{ij} N^j + h.c. \Big)
\end{aligned}
$$

Hidden sector lagrangian with new strong interaction

$$
\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k
$$

- Hidden sector condensate develops a linear potential for S -> Nonzero VEV for S
- Hidden sector quarks get massive by <S>
- Nonzero Higgs mass parameter form <S>
- EWSB occurs if the sign is correct
- Therefore, all the mass scales from hidden sector quark condensates
- Construct effective chiral lagrangian for the hidden sector pion
- Calculate the relic density, (in)direct detection rate etc.

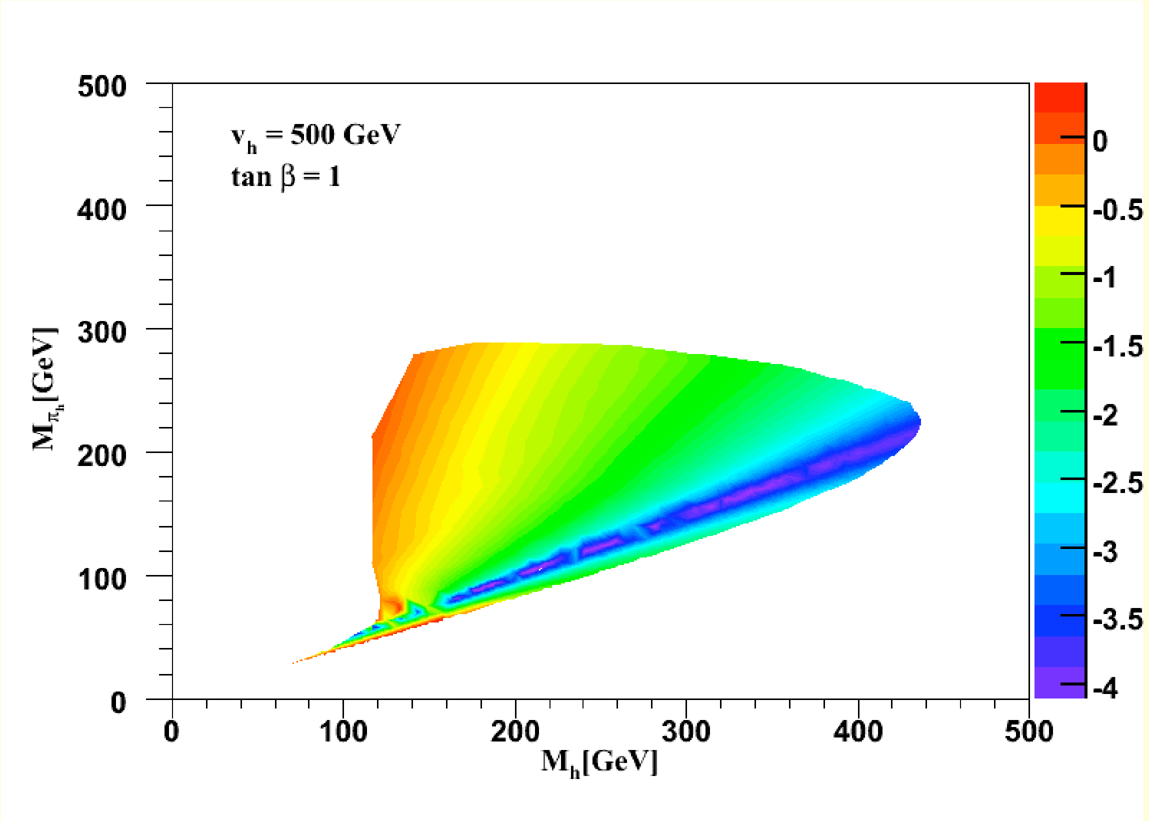
Br for lighter Higgs h

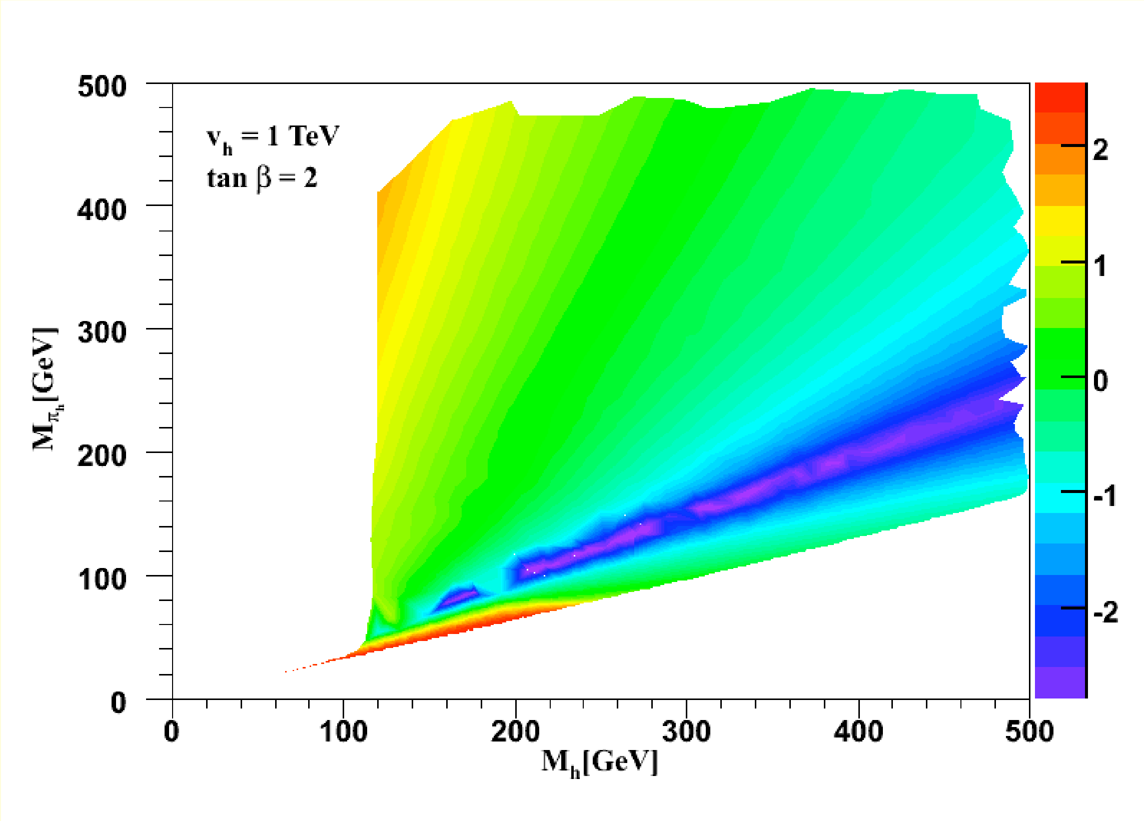


Br's of h owith $m_h = 120$ GeV as functions of m_{π_h} for (a)$v_h = 500$ GeV and $\tan\beta = 1$

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Relic density



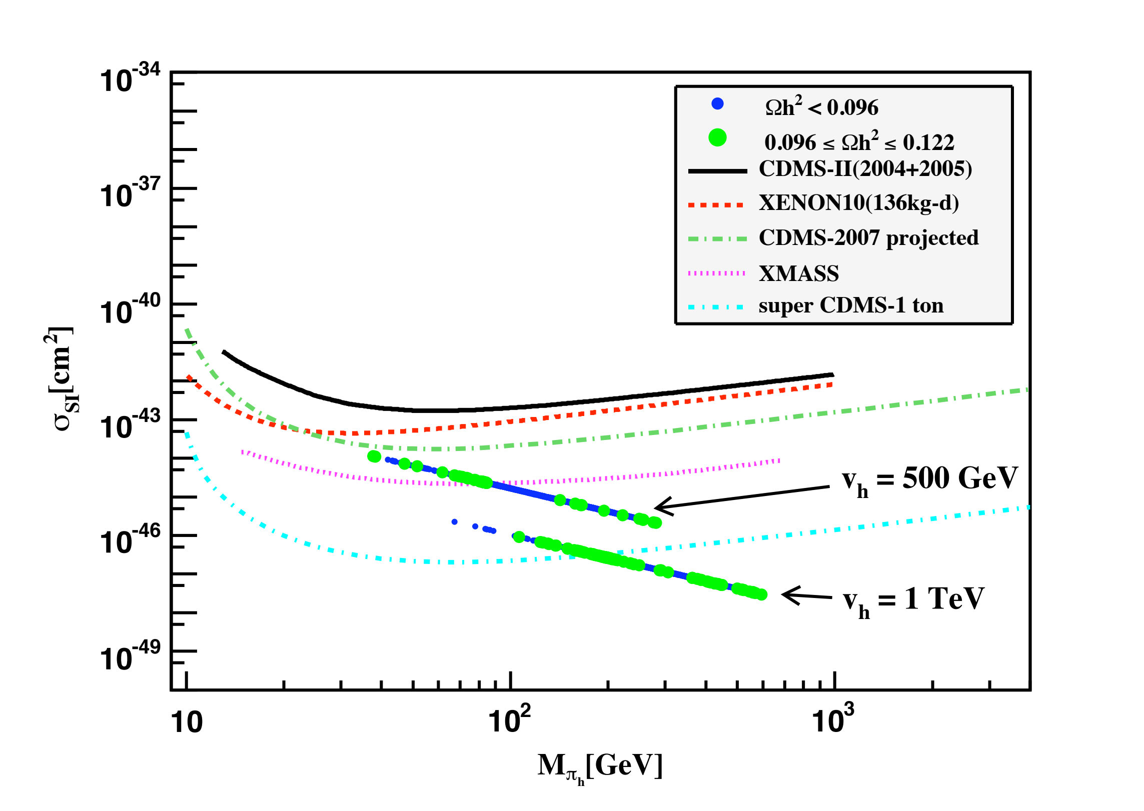


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(a) $v_h = 500$ GeV and $\tan\beta = 1$,

(b) $v_h = 1$ TeV and $\tan\beta = 2$.

Direct Detection Rate



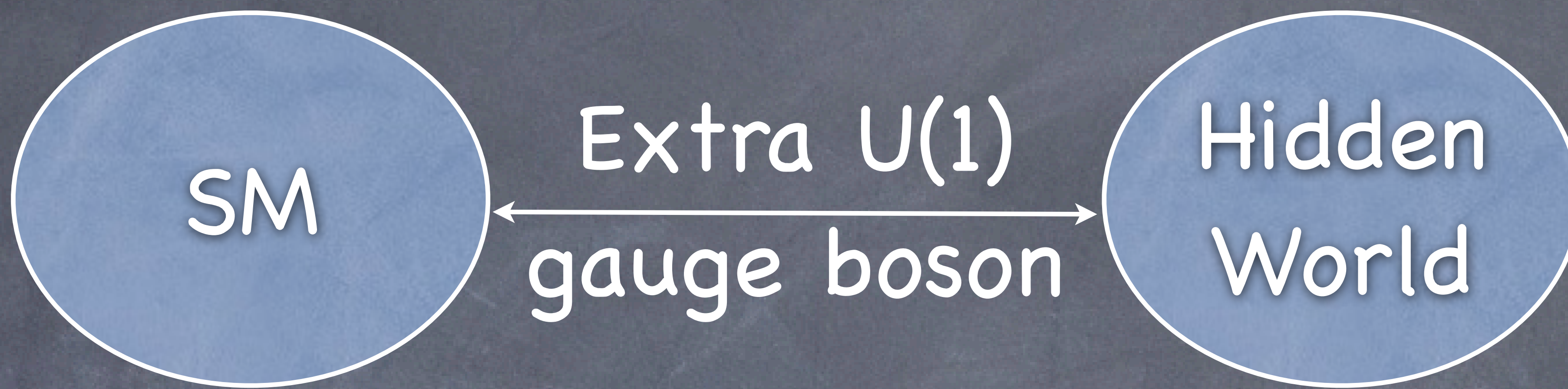
$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.
the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

the lower one: $v_h = 1$ TeV and $\tan\beta = 2$.

U(1) model by Strassler et al. (Hidden Valley)

Work in preparation
(with S. Baek & Taeil Hur)

Model II & III (Extra U(1))



- We consider two models
- U(1) model by Strassler et al. (Hidden valley scenario) : with hidden sector QCD
- Leptophilic U(1) motivated by PAMELA and FERMI data (Baek and Ko) : with hidden sector DM Dirac fermion

Model II with Extra U(1)

- Assume extra U(1) under which both SM and hQCD matters are charged [Hidden Valley Scenarios by Strassler et al.]
- Hidden sector pion as CDM [Cassel, Ghilencea, Ross]
- hidden-Higgs and SM Higgs mix with each other
- Relic density of CDM is dominated by Higgs exchanges
- Direct Detection Rates close to the current/future experiments

	q_{Li}	u_{Ri}	d_{Ri}	ℓ_{Li}	e_{Ri}	N_{Ri}	U_{hL}	U_{hR}	D_{hL}	D_{hR}	H	Φ
$SU(3)$	**3**	**3**	**3**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**1**
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	0	0	0	$\frac{1}{2}$	0
$U(1)_X$	$-\frac{1}{5}$	$\frac{1}{5}$	$-\frac{3}{5}$	$\frac{3}{5}$	$\frac{1}{5}$	1	q_+	$-q_-$	$-q_+$	q_-	$\frac{2}{5}$	2
$SU(n_h)$	**1**	**1**	**1**	**1**	**1**	**1**	$\mathbf{n_h}$	$\mathbf{n_h}$	$\mathbf{n_h}$	$\mathbf{n_h}$	**1**	**1**
# of gen.	3	3	3	3	3	3	1	1	1	1	1	1

Table 1: Charge assignments for the model : $q_+ + q_- = -2$

The full renormalizable Lagrangian above the confinement scale Λ_h is given by

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L'}_{\rm SM} + \mathcal{L}_{\rm hidden}^{\rm Kinetic} + \mathcal{L}_{\rm hidden}^{\rm Yukawa} + \mathcal{L}_{\rm hidden}^{\rm Scalar} \\
\mathcal{L}_{\rm hidden}^{\rm Kinetic} &= -\frac{1}{4}[(F_h)^a_{\mu\nu}(F_h)^{a\mu\nu}] - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{\sin\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} \\
&\quad +(D_\mu\Phi^*)(D_\mu\Phi) + i\,\overline{N_{Ri}}\not{D}\,N_{Ri} \\
&\quad +i\,\overline{U_{hL}}\not{D}\,U_{hL} + i\,\overline{U_{hR}}\not{D}\,U_{hR} + i\,\overline{D_{hL}}\not{D}\,D_{hL} + i\,\overline{D_{hR}}\not{D}\,D_{hR} \\
\mathcal{L}_{\rm hidden}^{\rm Yukawa} &= -y_{N_{RL}}\overline{N_{Ri}}\widetilde{H}^\dagger\ell_{Lj} + h.c. \\
&\quad -y_{U_h}\overline{U_{hR}}U_{hL}\Phi - y_{D_h}\overline{D_{hR}}D_{hL}\Phi^* - y_{N_Rij}\overline{N^c_{Ri}}N_{Rj}\Phi^* + h.c. \\
\mathcal{L}_{\rm hidden}^{\rm Scalar} &= +\mu_2^2\Phi^*\Phi - \lambda_{12}(H^\dagger H)(\Phi^*\Phi) - \frac{\lambda_2}{2}(\Phi^*\Phi)^2,
\end{aligned}
$$

In the low energy below Λ_h scale, the Lagrangian involving hidden sector quarks Q_h can be replaced by

$$\mathcal{L}_{chial}^{eff} = \frac{v_h^2}{4}\mathrm{Tr}[D_\mu \Sigma_h D^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}\mathrm{Tr}[\mu_h(M_{Q_h}\Sigma_h + \Sigma_h^\dagger M_{Q_h}^\dagger], \tag{2.8}$$

where

$$\Sigma_h(x) = e^{2i\Pi(x)/v_h}, \quad \Pi(x) = \pi_a \frac{\sigma_a}{2} = \begin{pmatrix} \frac{\pi^0}{2} & \frac{\pi^+}{\sqrt{2}} \\ \frac{\pi^-}{\sqrt{2}} & -\frac{\pi^0}{2} \end{pmatrix}. \tag{2.9}$$

The mass matrix of hidden quarks is given by

$$M_{Q_h} = \begin{pmatrix} y_{U_h}\Phi & 0 \\ 0 & y_{D_h}\Phi^* \end{pmatrix}. \tag{2.10}$$

The covariant derivative of Σ field is defined by

$$D_\mu \Sigma_h = \partial_\mu \Sigma_h + i\frac{g_X}{\cos\chi}(Q_L \Sigma_h - \Sigma_h Q_R)X_\mu, \tag{2.11}$$

where

$$Q_L = \begin{pmatrix} q_+ & 0 \\ 0 & -q_+ \end{pmatrix} \text{ and } Q_R = \begin{pmatrix} -q_- & 0 \\ 0 & q_- \end{pmatrix}. \tag{2.12}$$

The scalar potential is given by

$$V(H,\Phi) = -\mu_1^2 H^\dagger H - \mu_2^2 \Phi^*\Phi + \rho^3(\Phi^* + \Phi)/\sqrt{2} \tag{2.14}$$

$$+\frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Phi^*\Phi)^2 + \lambda_{12}(H^\dagger H)(\Phi^*\Phi). \tag{2.15}$$

The coefficient of the linear terms, which come from the second term of Eq. 2.8, is defined by $\rho^3 \equiv -(y_{U_h} + y_{D_h})\mu_h v_h^2/\sqrt{2}$. If we define components of the scalar fields like this :

$$H = \begin{pmatrix} 0 \\ (h+v_1)/\sqrt{2} \end{pmatrix}, \quad \Phi = (\phi + v_2 + i\phi_I)/\sqrt{2}, \tag{2.16}$$

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

For simplicity, we assume $y_{N_R} = 0$ (ignore neutrino part), $\mu_h = v_h$, and $M_{U_h} = M_{D_h}$. The remaining free parameters are g_X, χ, q_+, α, $\tan\beta \equiv \frac{v_2}{v_1}$, $M_{Z'}$, $M_{\pi^\pm}$, M_{H_1}, M_{H_2}.

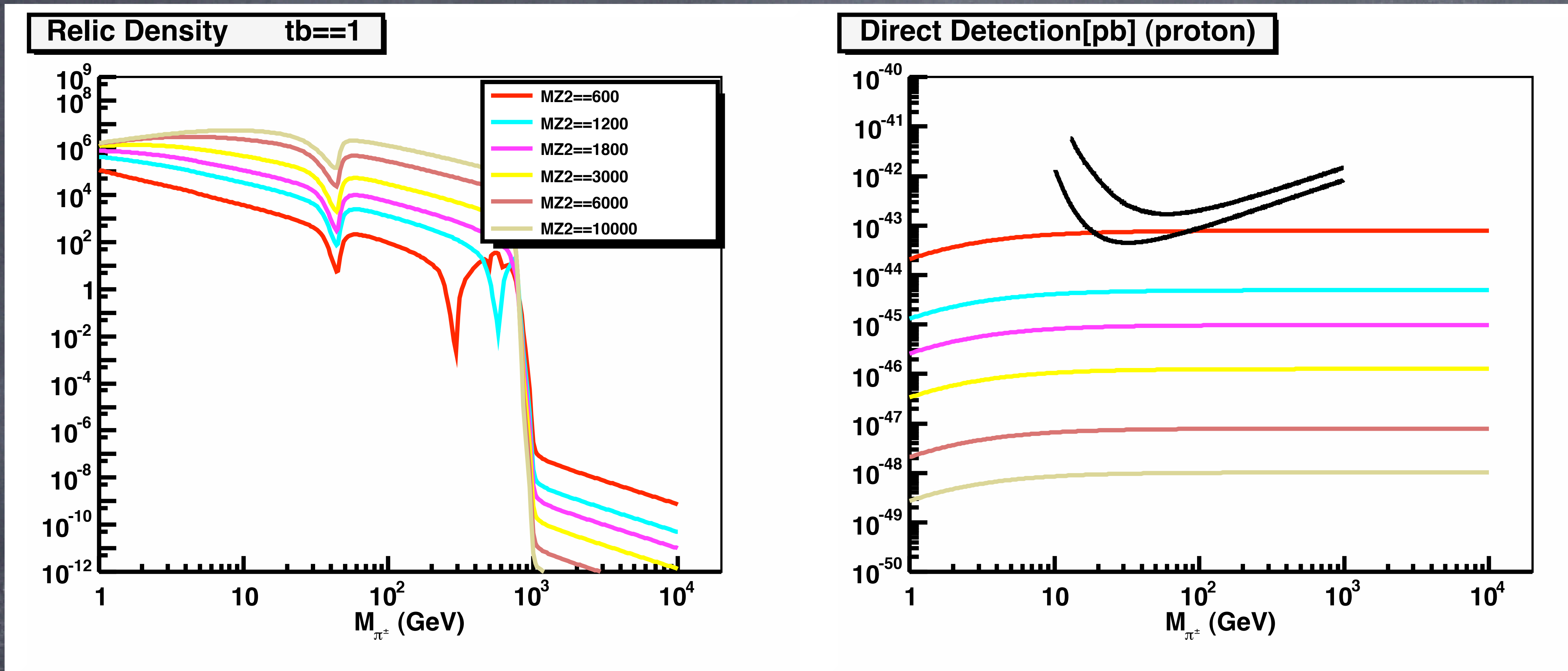


Figure 2: The DM relic density (left panel), the spin-independent cross section of the DM scattering off a proton (right panel) as a function of the DM mass $M_{\pi_h^\pm}$ for $\tan\beta = 1, q_+ - q_- = 2$, and various choices of the Z' masses, $M_{Z'} = 600, 1200, 1800, 3000, 6000, 10000$ GeV. We fixed $g_X = 0.1121, \chi = 0,$ $M_{H_1} = 300(\text{GeV}), \mathrm{M_{H_2}} = 1000(\text{GeV})$.

alpha = 0 for simplicity

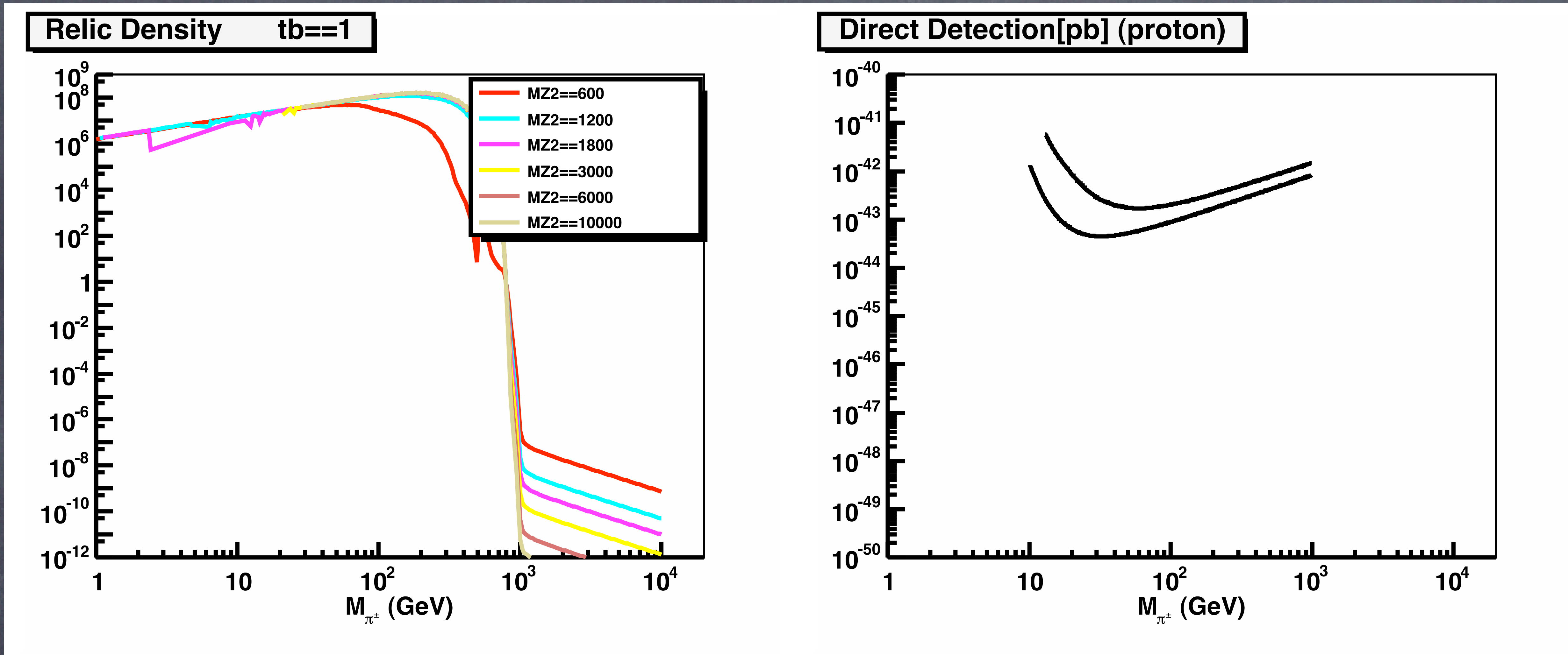


Figure 3: The same with Fig. 2, but with $q_+ - q_- = 0$.

q+ - q- = 0 :
No coupling
between DM and Z'

alpha=0 : no couplings
for DM-DM-H1,
and q-qbar-H2

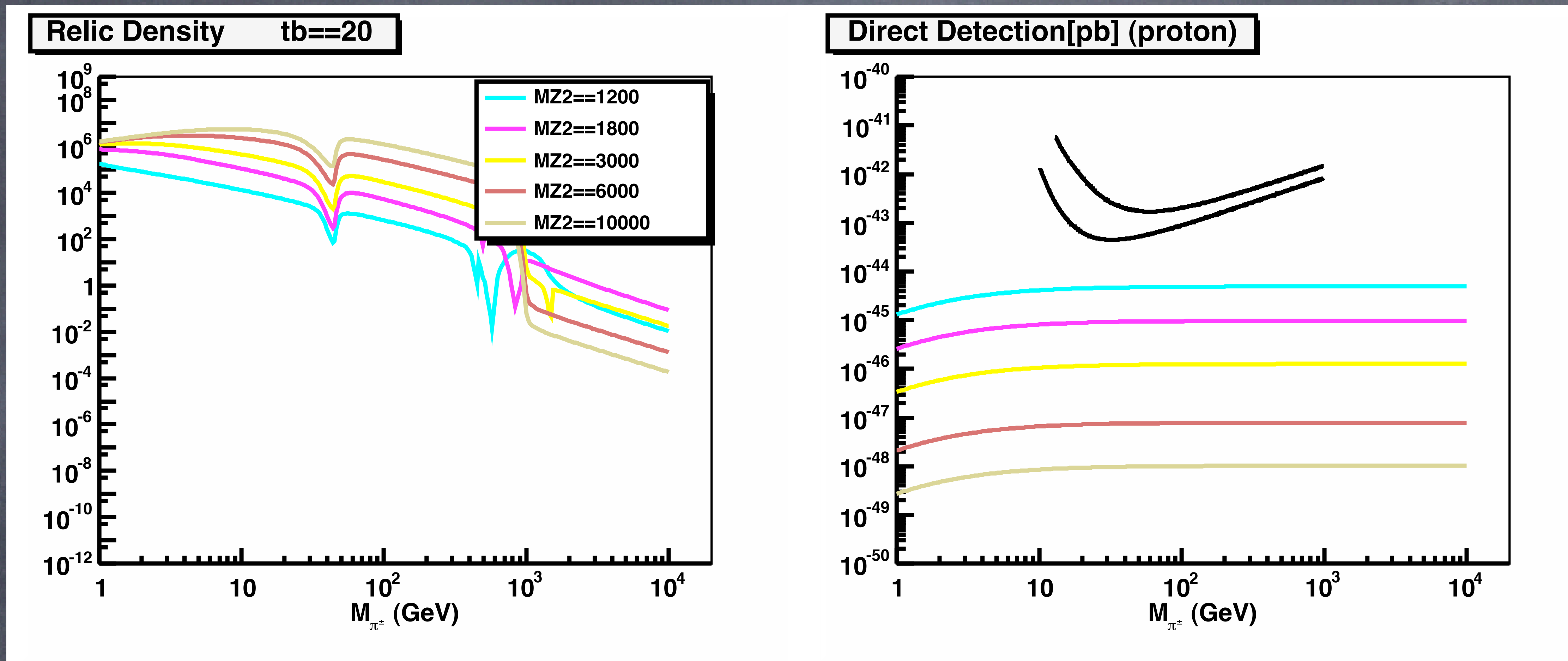


Figure 6: The same with Fig. 2, but with $\tan\beta = 20$.

q+ - q- = 2 : Higgs coupling to DM decreases for large tan(beta)

Collider Signatures

- Two scalar Higgs h_1 and h_2
- New $Z^{'}$ gauge boson
- DM (complex scalars) : $\pi_h^{\pm}$
- $\pi_h^0 \to h_1 Z_1, h_1 Z_2, h_2 Z_1, h_2 Z_2$
- $h_{1,2}$ decay like the SM Higgs boson, except that $h_2 \to h_1 h_1$ and $h_{1,2} \to DM + DM$ can be open if they are kinematically allowed
- $Z_{1,2}$ decays into SM particles or DM pairs

Conclusions

- Hidden sector could be generic, is less constrained by EWPT and CKMology, and could be important in EWSB and CDM
- All the masses (including CDM mass) can come from dimensional transmutation in the hidden sector QCD
- (In)Direct Detection Exp.t's of CDM may be able to find some signatures
- Higgs phenomenology can be affected a lot (Invisible Br, Reduced productions at colliders, multi scalars partially composite, etc.)
- SUSY extension, loop corrections etc. for future study