EWSB and CDM from Scale Invariant Extensions of the SM with Strongly Interacting Hidden Sector

Pyungwon Ko (KIAS)

PASCOS 2013, Taipei, Taiwan
(Nov 20 - Nov 26, 2013)

(1) EWSB and CDM from strongly interacting hidden sector

arXiv:0709.1218, PLB (2010) with T. Hur, D.W.Jung, J.Y.Lee

(2) Scale invariant extension of the SM with strongly interacting hidden sector

arXiv:1103.2571, PRL (2011) with T. Hur
and more in preparation with S.Baek, T.Hur

Contents

- Motivations
- Toy model: Hidden Sector Pion as CDM
- Model I with a scalar messenger
- Conclusions

Current Status of the SM

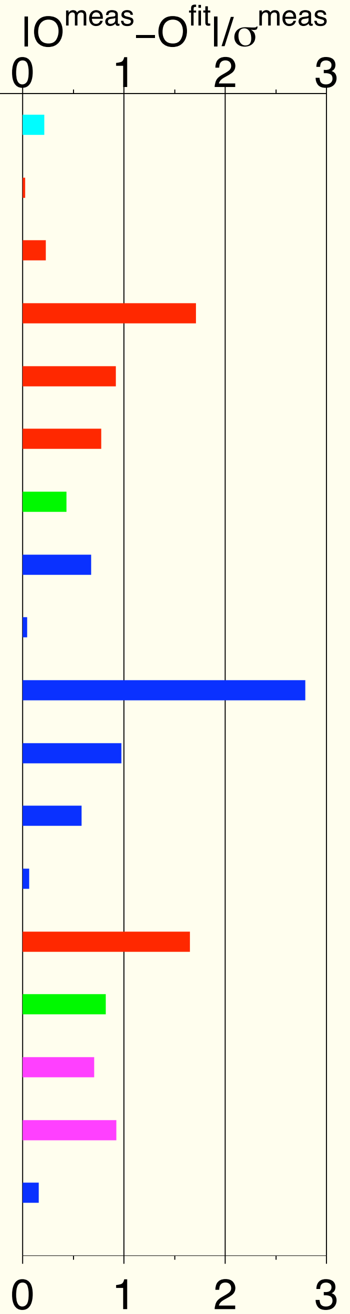
SO GOOD with all the data, EWPT, CKM
except for

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

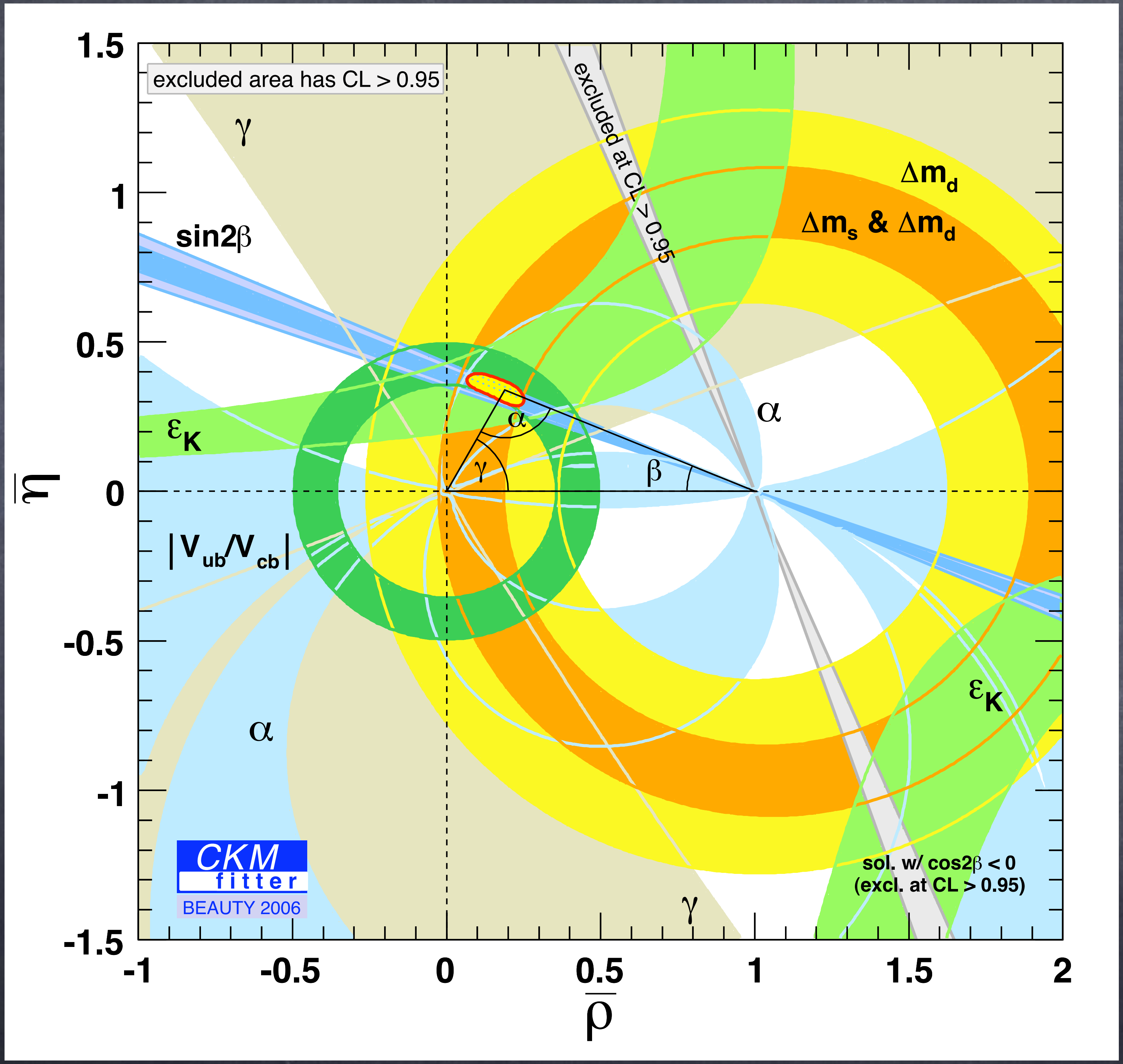
Overall features of EWPT

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



$$\Lambda_{\rm NP} > O(10)\,{\rm TeV}$$

CKM Fit



$$\Lambda_{\rm NP} > O(100)\,{\rm TeV}$$

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 better insensitive to the SM interaction, but has something to do with CDM & EWSB

K. Wilson "The origin of lattice gauge theory" hep-lat/0412043

5. BLUNDERS AND A BIZARRE EPISODE

In the early 1970's, I committed several blunders that deserve a brief mention. The blunders all occurred in the same article [27]: a 1971 article about the possibility of applying the renormalization group to strong interactions, published before the discovery of asymptotic freedom. My first blunder was not recognizing the theoretical possibility of asymptotic freedom. In my 1971 article, my intent was to identify all the distinct alternatives for the behavior of the Gell-Mann–Low function β(g), which is negative for small g in the case of asymptotic freedom. But I ignored this possibility. The only

exactly at threshhold for binding, and the di-neutron also [28].

The final blunder was a claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies unless they were associated with some kind of broken symmetry [23]. The claim was that, otherwise, their masses were likely to be far higher than could be detected. The claim was that it would be unnatural for such particles to have masses small enough to be detectable soon. But this claim makes no sense when one becomes familiar with the history of physics. There have been a number of cases where numbers arose that were unexpectedly small or large.

Wise and Manohar,
Hep-ph/0606172

Most of the extensions of the standard model with new physics at the TeV scale have been motivated by the hierarchy puzzle, i.e., why is the weak scale so small compared with the Planck or unification scales. However, the measured value of the cosmological constant suggests that a fine tuning that is qualitatively similar to that needed to achieve the smallness of the weak scale is needed for the cosmological constant. Perhaps we are not looking at this issue correctly.

If one does not adopt the hierarchy puzzle as the criteria for motivating extensions of the standard model then one can take a more general point of view. Certainly the

Motivations

- Ignore 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)
- Hidden sector : Generic in many BSM's & Why not ?   (e.g. SUSY is broken in a hidden sector)
- Less constrained by EWPT and CKMology, because new particles are SM singlets, and good CDM

Can we understand

- the stability of DM without ad hoc Z2 symmetry ?
- the generation of mass scales from quantum mechanics ?
- the 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 and baryon numbers 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, ...

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) and mediators between the SM and a hidden sector

Hidden sector

- Any new physics @ TeV scale is strongly constrained by EWPT and CKMology
- Hidden sector made of SM gauge singlets is less constrained and could be CDM
- Generic in many BSM's including SUSY and string models
- E8 x E8': natural setting for SM X Hidden sector
- SO(32) may be broken into SM X Hidden sector

G. Shiu et al. arXiv:1302.5471, PRL for millicharged DM from string theory

Hidden sector

- Hidden sector gauge group can stabilize hidden sector CDM
- Very often there appear extra SM singlet scalars which stabilize the EW vac unto Planck scale
- Can address "QM generation of all the mass scales including CDM masses from strong dynamics in the hidden sector" (alternative to the Coleman-Weinberg) : Hur and Ko, PRL (2011) and earlier paper and proceedings

How to specify hidden sector ?

- Gauge group Gh : Abelian or Nonabelian
- Strength of gauge coupling : weak or strong
- Matter contents : singlet, fundamental or higher dim of Gh
- All of these are not known : can we make any useful predictions out of it ?
- But there are some generic features in Higgs phenomenology and dark radiation

Known facts on hCDM

For confining vectorlike Gh,

- hCDM : hidden sector composite hadrons (mesons and baryons)
- hCDM : absolutely stable or long lived
- All the mass scales can be generated from hidden sector strong dynamics (similar to BCS or NJL)
- No long range dark force or dark radiation

T. Hur, D. -W. Jung, P. Ko and J. Y. Lee, Phys. Lett. B **696**, 262 (2011) [arXiv:0709.1218 [hep-ph]]; T. Hur and P. Ko, Phys. Rev. Lett. **106**, 141802 (2011) [arXiv:1103.2571 [hep-ph]].

P. Ko, Int. J. Mod. Phys. A **23**, 3348 (2008) [arXiv:0801.4284 [hep-ph]]; P. Ko, AIP Conf. Proc. **1178**, 37 (2009); P. Ko, PoS ICHEP **2010**, 436 (2010) [arXiv:1012.0103 [hep-ph]]; P. Ko, AIP Conf. Proc. **1467**, 219 (2012).

- For weakly interacting hidden sector,
  - Long range dark force if Gh is unbroken
  - If Gh is unbroken and h-scalar is CDM, no extra scalar is needed (*)
  - If Gh is broken, hDM can be still stable or long lived depending on the charge assignments of hD
- More than one neutral Higgs-like scalar with signal strength equal to or smaller than "1" (indep. of production and decay) except for (*)
- EW stable up to Planck scale

S.Baek, P.Ko, W.I.Park, E.Senaha, JHEP (2012), and in preparation

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)
- Many works after 2007

Weakly Interacting Hidden Sector

- Perturbation applicable & easy to analyze,
- Gauge boson mass is generated by Higgs mechanism
- Origin of mass scale remains unclear (or by ordinary Higgs mechanism), just like in SM
- Leptophilic Dirac Fermion DM (Baek and Ko, arXiv: 0811.1646, JCAP 0910:011 (2009))

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)

--> This talk

Nicety of QCD

- Renormalizable : Valid to very high energy scale
- Asymtotic feedom : No Landau pole below $M_{\rm Planck}$
- QM dimensional transmutation :

$$g_s \to \Lambda_{\rm QCD} \ll M_{\rm Planck}$$

- Trace anomaly breaks scale sym. of massless QCD
- Chiral symmetry breaking (spontaneous & explicit)
- Light hadron mass dominantly from chiral sym breaking
- Flavor conservation : accidental symmetry of QCD

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

Yes !

Toy Model

(arXiv:0709.1218, Phys. Lett. B696, 262 (2011)
with T.Hur, D.W.Jung and J.Y.Lee)

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 sym of the underlying gauge theory), which is a very nice aspect of our model
- Remember pion is stable under strong interaction in ordinary hadronic world, decays only through em or weak interaction
- These can decay by nonrenormalizable interactions, but cna live long enough if they are light (< mhiggs)

Comments

- Hidden sector baryons also good CDM, like technibaryons
- Their dynamics is not easy to describe, as in QCD where p pbar-> pions can not be described reliably
- It is possible that both hidden sector pions and baryons are good CDM's, with very long life time for hidden sector pions
- Then WMAP data on CDM will be a combined result of h-pions and h-baryons

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

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:

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

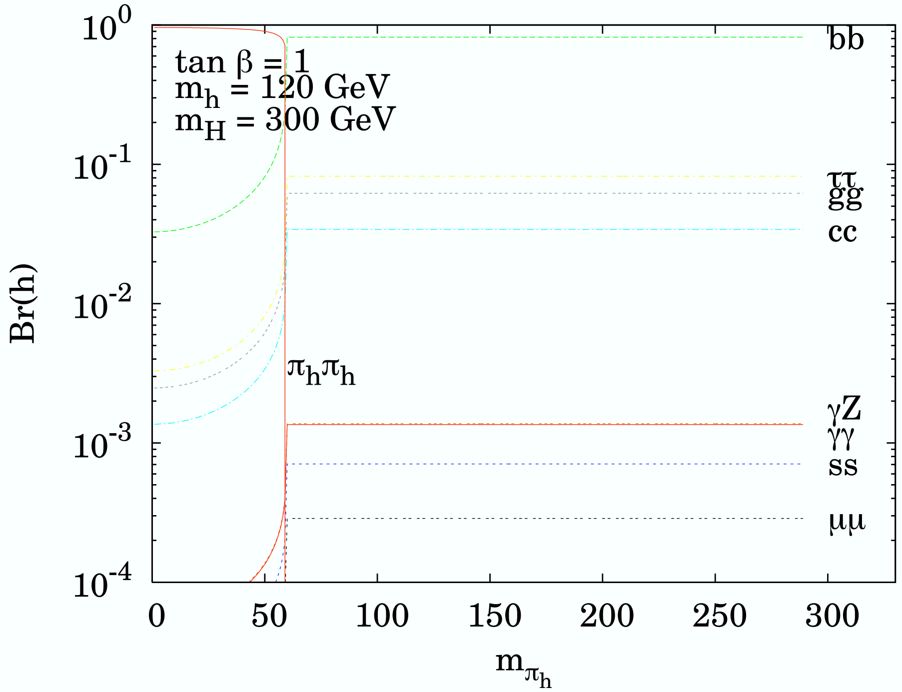
- Correct EWSB : $\lambda_1(\lambda_2 + a/2) \equiv \lambda_1 \lambda_2' > \lambda_3^2$

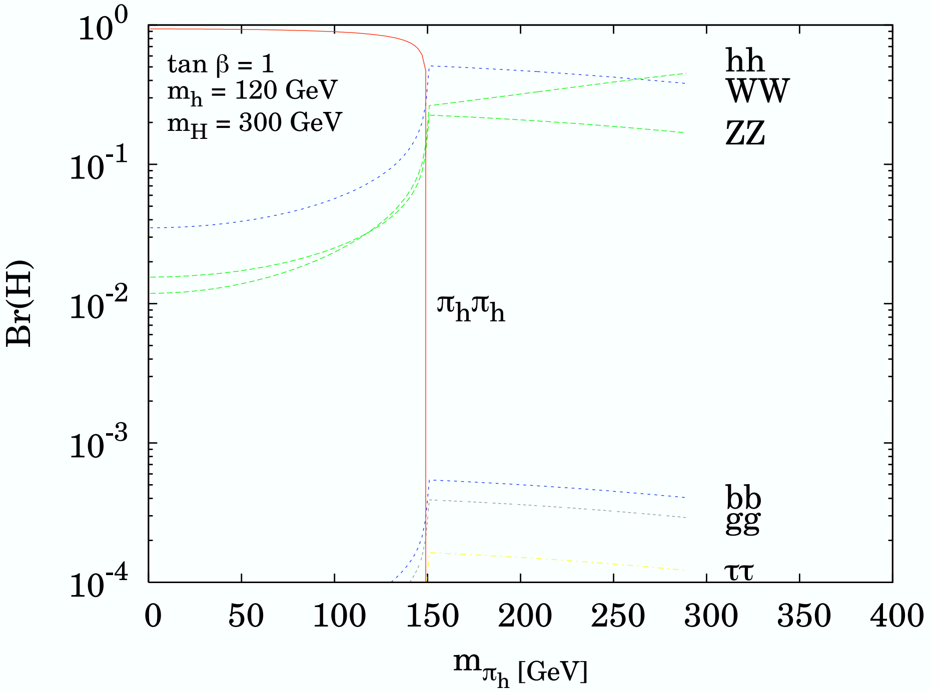
Similar to the usual two-Higgs doublet model, except that

- 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)

- 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

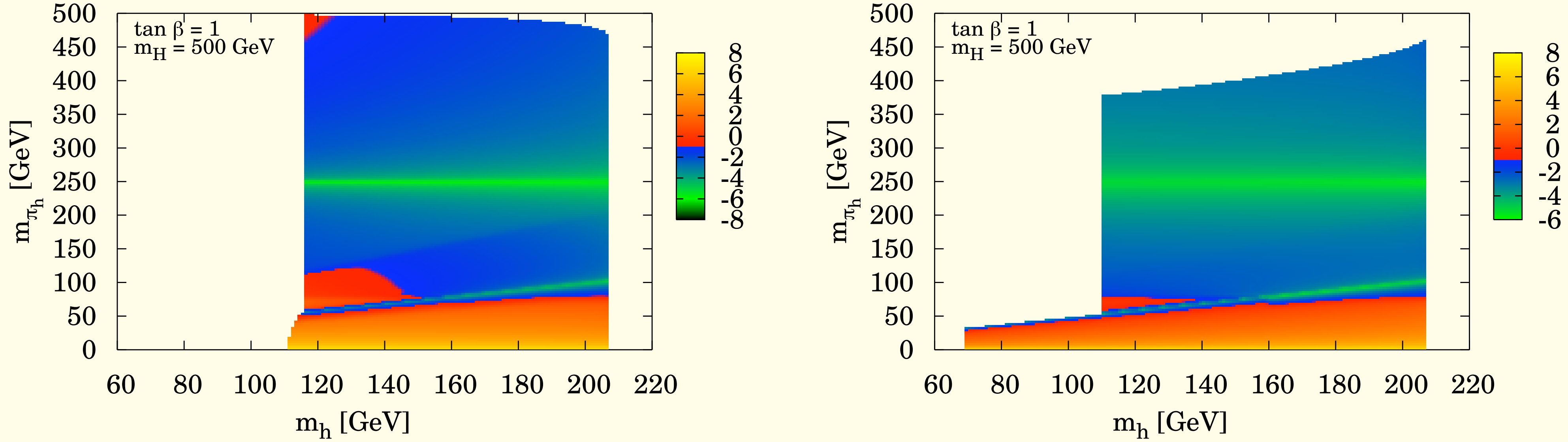
Br of h and H





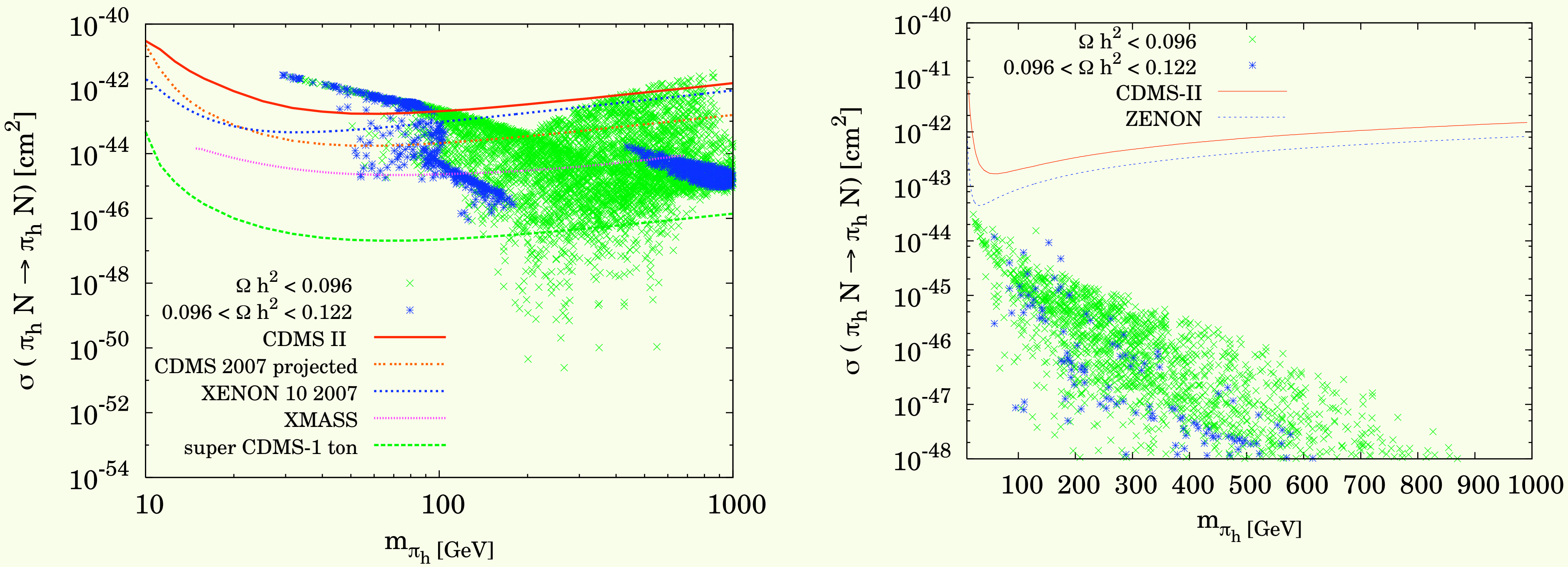
- Branching ratios of h and H as functions of m_{π_h} for $\tan\beta = 1$, $m_h = 120$ GeV and $m_H = 300$ GeV.
- $h, H \to \pi_h \pi_h$: invisible decay branching ratios make difficult to detect them at colliders

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

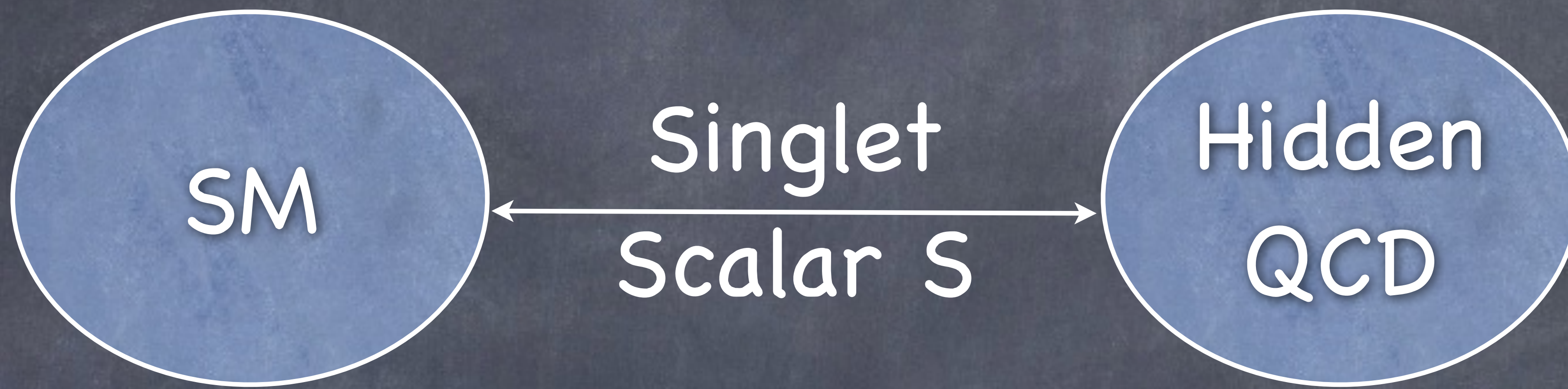


- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be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

Model I : Scalar Messenger (Scale invariant extension of the standard model)

arXiv:1103.2571 [hep-ph] (with Taeil Hur)
PRL 106: 141802 (2011)

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

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

Hidden sector lagrangian with new strong interaction

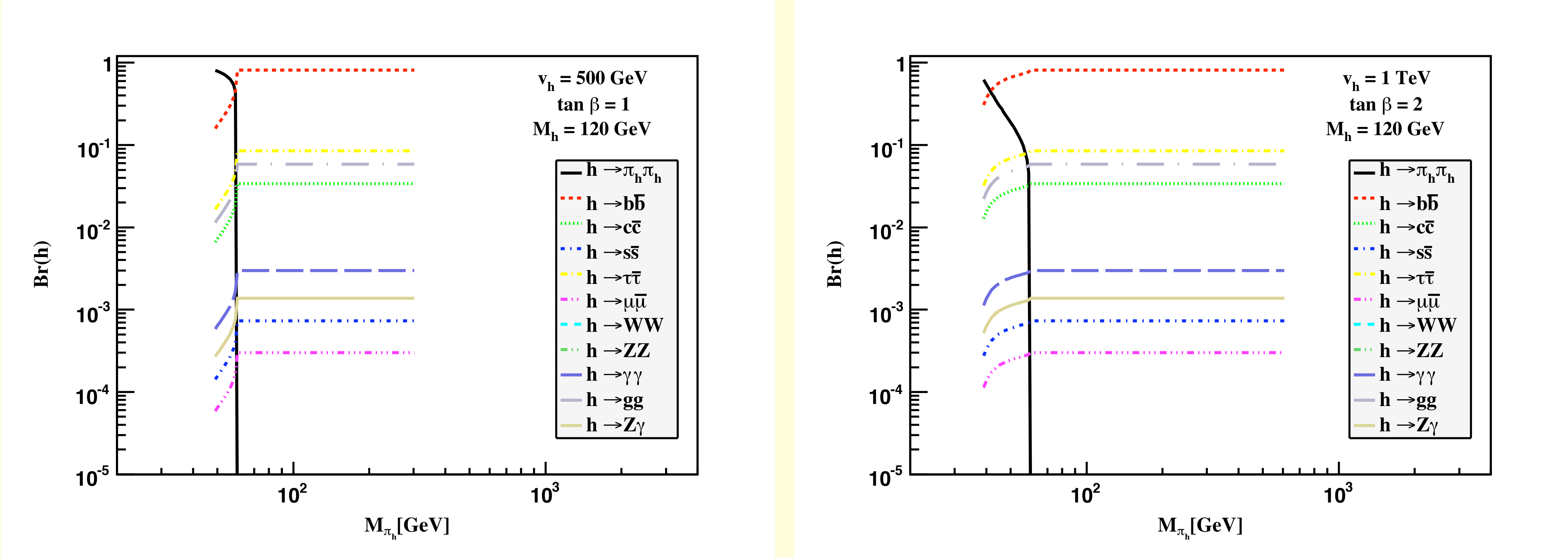
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k(i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

- 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.

Effective lagrangian far below $\Lambda_{h,\chi} \approx 4\pi\Lambda_h$

$$
\begin{aligned}
\mathcal{L}_{\text{full}} &= \mathcal{L}^{\text{eff}}_{\text{hidden}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
\mathcal{L}^{\text{eff}}_{\text{hidden}} &= \frac{v_h^2}{4}\text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2}\text{Tr}[\lambda S \mu_h (\Sigma_h + \Sigma_h^\dagger)] \\
\mathcal{L}_{\text{SM}} &= -\frac{\lambda_1}{2}(H_1^\dagger H_1)^2 - \frac{\lambda_{1S}}{2} H_1^\dagger H_1 S^2 - \frac{\lambda_S}{8} S^4 \\
\mathcal{L}_{\text{mixing}} &= -v_h^2 \Lambda_h^2 \left[\kappa_H \frac{H_1^\dagger H_1}{\Lambda_h^2} + \kappa_S \frac{S^2}{\Lambda_h^2} + \kappa'_S \frac{S}{\Lambda_h} \right. \\
&+ \left. O(\frac{S H_1^\dagger H_1}{\Lambda_h^3}, \frac{S^3}{\Lambda_h^3}) \right] \\
&\approx -v_h^2 \left[\kappa_H H_1^\dagger H_1 + \kappa_S S^2 + \Lambda_h \kappa'_S S \right]
\end{aligned}
$$

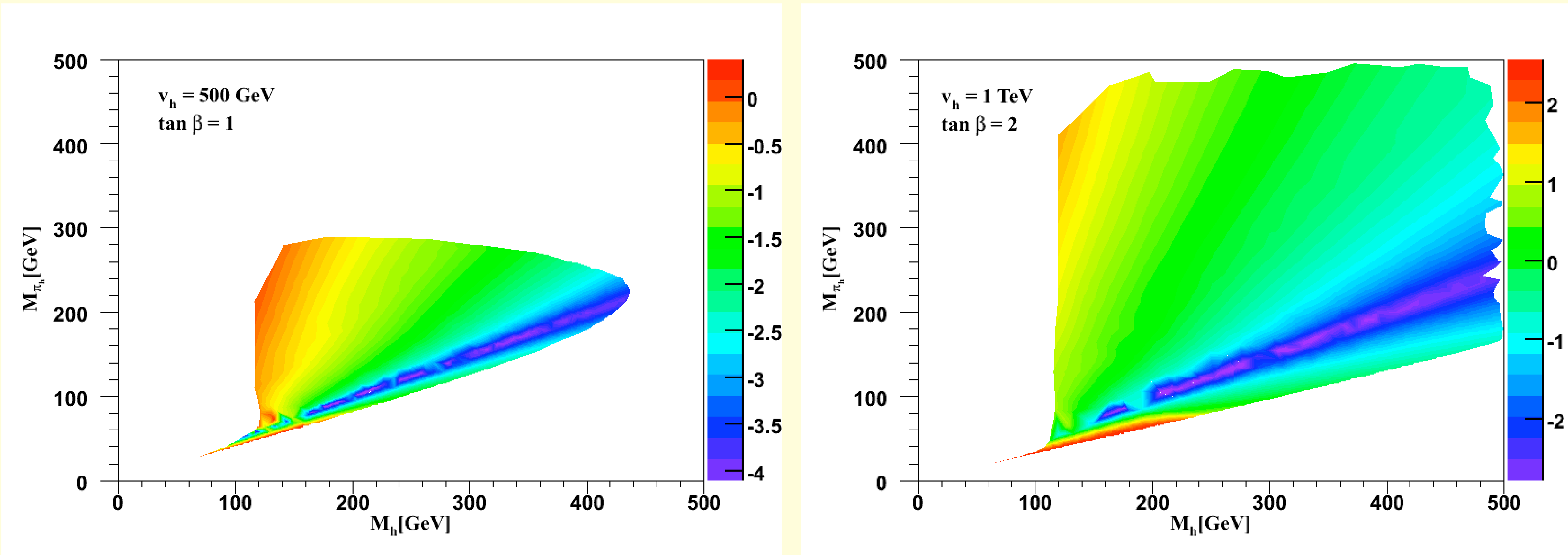
Br for lighter Higgs h



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

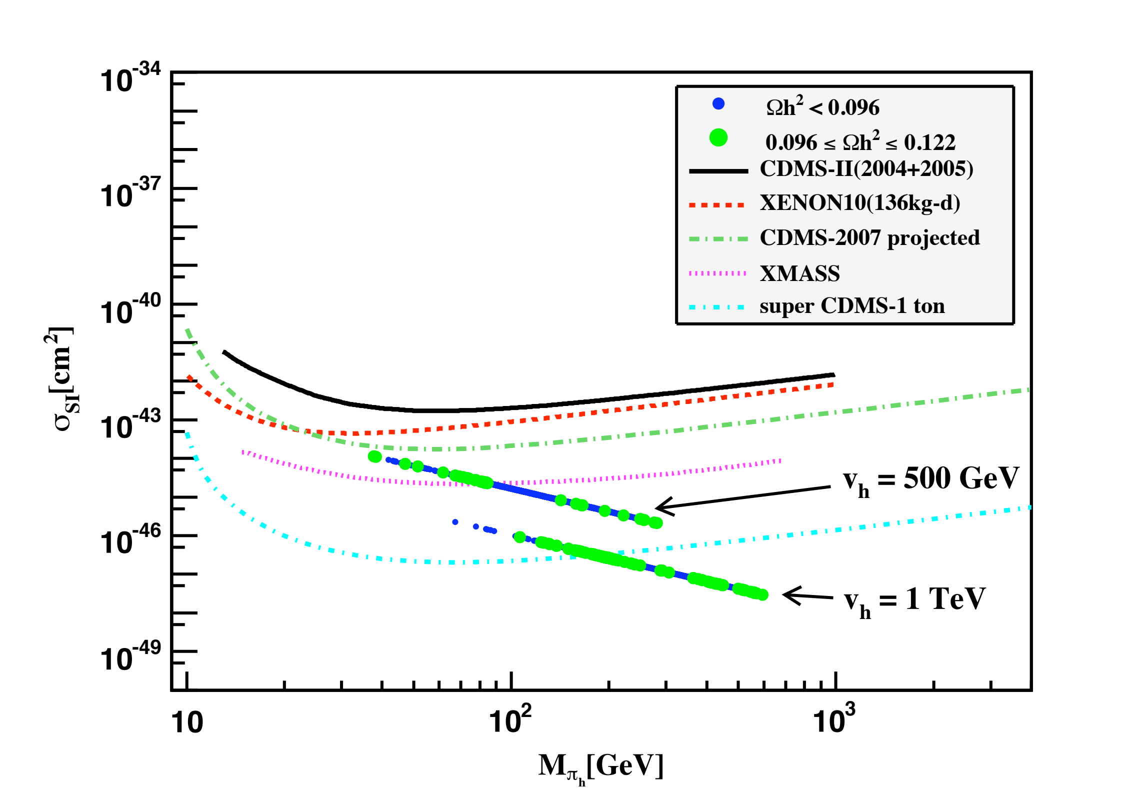


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(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 $\tan\beta = 2$.

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 strongly interacting hidden sector (hidden sector Technicolor, or Dark TC) (recent works by Kubo, Lindner et al; Raidal et al)
- (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.)

Future Directions

- SUSY version ?
- Weakly interacting (non)abelian hidden sector ?
- Connection between Baryon/DM ratio ? --> Natural setting for asymmetric dark matter
- Gauge coupling unification and embedding into GUT or String Model ?

Works afterwards with S. Baek, W.I.Park, W. Senaha

- Singlet fermion DM with Higgs portal ; Vac structures and stability therein
- Higgs portal Vector DM
- Singlet portal extensions of the standard seesaw model with a dark sector w/ local dark gauge symmetry
- Hidden sector monopole, VDM and dark radiation with Higgs portal
- And works in preparation

Higgs signal strength/Dark radiation/DM

Models	Unbroken U(1)X	Local Z2	Unbroken SU(N)	Unbroken SU(N) (confining)
Scalar DM	1 0.08 complex scalar	<1 ~0 real scalar	1 ~0.08*# complex scalar	1 ~0 composite hadrons
Fermion DM	<1 0.08 Dirac fermion	<1 ~0 Majorana	<1 ~0.08*# Dirac fermion	<1 ~0 composite hadrons

: The number of massless gauge bosons