Global Analysis of the Higgs Signal Strength Data

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arXiv: 1307.3948, JHEP 1310(2013)225
with Sunghoon Jung and Suyong Choi

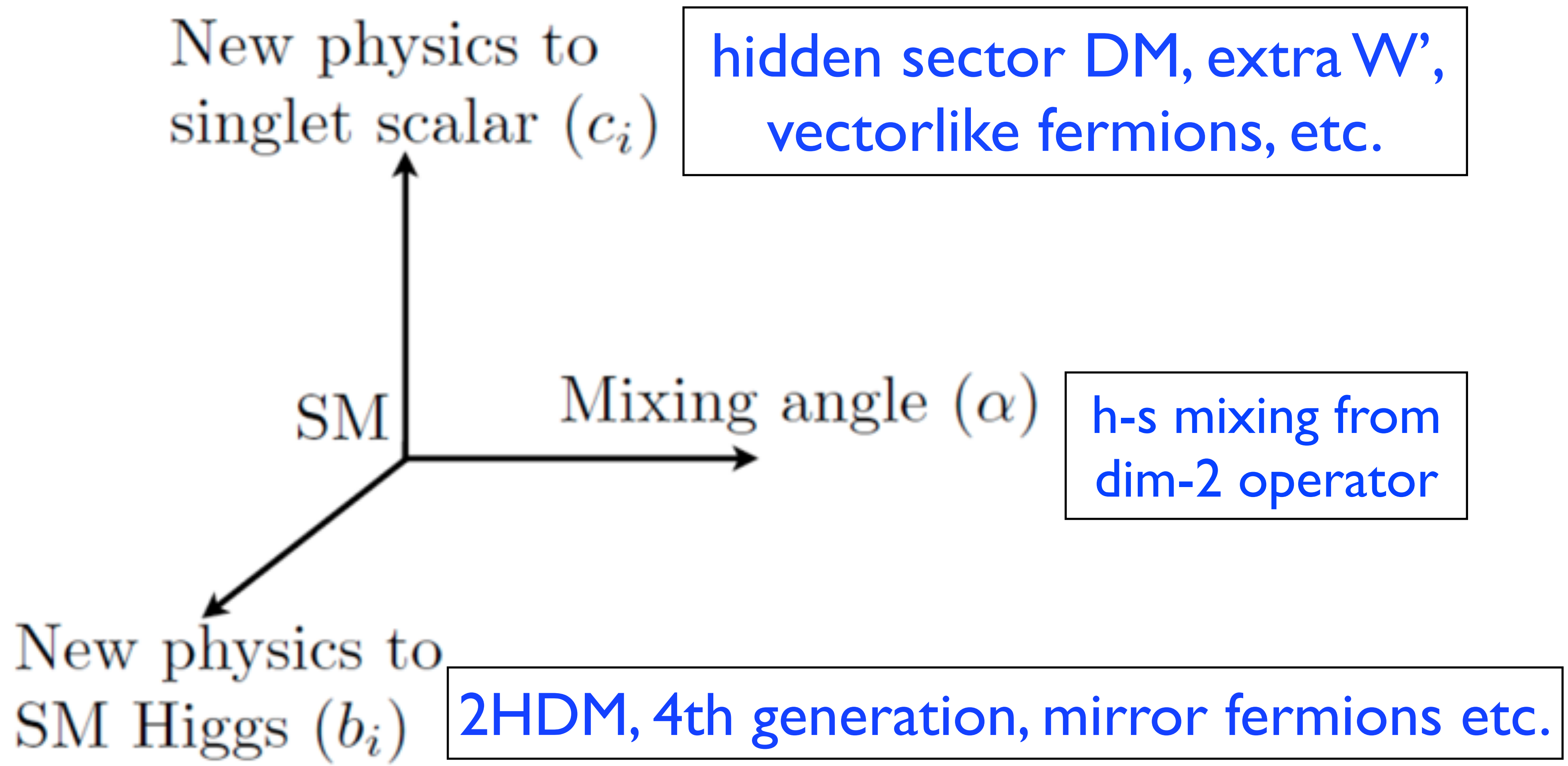
What can we learn about BSM from Higgs properties ?

- Higgs signal strength ~ SM like
- H to diphoton may require new charged particles at EW scale
- There could be an additional singlet scalar that mixes with the SM Higgs boson (especially motivated by hidden sector DM with Higgs portal or singlet portal)
- We include "S" explicitly in Eff Lagrangian

Basic Picture

Assumptions

- Impose the full SM gauge symmetry, not just its unbroken subgroup
- Assume there is an additional SM singlet scalar, extra vector-like fermions, hDM etc
- "S" could be a remnant of the spontaneous breaking of extra gauge symmetry such as U(1) B-L
- Our assumptions encompass a large class of BSMs



- Orthogonal ways to modify the same observable.
- Information on individual direction will be lost/hidden if no proper basis is used. Interpretation of data depends on basis.
- Our framework is suitable to get insight on singlet mixing, singlet couplings as well as Higgs couplings.

SM Higgs

$$
\begin{aligned}
-\mathcal{L}_{\rm h,int} \;=\; & \sum_f b_f \frac{m_f}{v} h\bar{f}f - \left\{2b_W \frac{h}{v} + b_W^{'} \left(\frac{h}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{b_Z \frac{h}{v} + \frac{1}{2}b_Z^{'} \left(\frac{h}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
+ \; & \frac{\alpha}{8\pi} r_{\rm sm}^{\gamma} \left\{b_\gamma \frac{h}{v} + \frac{1}{2}b_\gamma^{'} \left(\frac{h}{v}\right)^2\right\} F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\rm sm}^{g} \left\{b_g \frac{h}{v} + \frac{1}{2}b_g^{'} \left(\frac{h}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \\
+ \; & \frac{\alpha_2}{\pi} \left\{2b_{dW} \frac{h}{v} + b_{dW'} \left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi} \left\{2b_{dZ} \frac{h}{v} + b_{dZ'} \left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu} Z^{\mu\nu} \\
+ \; & \frac{\alpha_2}{\pi} \left\{2\widetilde{b_{dW}} \frac{h}{v} + \widetilde{b_{dW'}} \left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi} \left\{2\widetilde{b_{dZ}} \frac{h}{v} + \widetilde{b_{dZ'}} \left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu} \widetilde{Z^{\mu\nu}} \\
+ \; & \frac{\alpha}{\pi} \left\{2b_{Z\gamma} \frac{h}{v} + b_{Z\gamma'} \left(\frac{h}{v}\right)^2\right\} F_{\mu\nu} Z^{\mu\nu} \qquad (2.1)
\end{aligned}
$$

Singlet Scalar S

$$
\begin{aligned}
-\mathcal{L}_{\rm s,int} \;=\; & \sum_f c_f \frac{m_f}{v} s\bar{f}f - \left\{2c_W \frac{s}{v} + c_W^{'} \left(\frac{s}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{c_Z \frac{s}{v} + \frac{1}{2}c_Z^{'} \left(\frac{s}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
+ \; & \frac{\alpha}{8\pi} r_{\rm sm}^{\gamma} \left\{c_\gamma \frac{s}{v} + \frac{1}{2}c_\gamma^{'} \left(\frac{s}{v}\right)^2\right\} F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\rm sm}^{g} \left\{c_g \frac{s}{v} + \frac{1}{2}c_g^{'} \left(\frac{s}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \qquad (2.10) \\
+ \; & \frac{\alpha_2}{\pi} \left\{2c_{dW} \frac{s}{v} + c_{dW'} \left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi} \left\{2c_{dZ} \frac{s}{v} + c_{dZ'} \left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu} Z^{\mu\nu} \\
+ \; & \frac{\alpha_2}{\pi} \left\{2\widetilde{c_{dW}} \frac{s}{v} + \widetilde{c_{dW'}} \left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi} \left\{2\widetilde{c_{dZ}} \frac{s}{v} + \widetilde{c_{dZ'}} \left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu} \widetilde{Z^{\mu\nu}} \\
+ \; & \frac{\alpha}{\pi} \left\{2c_{Z\gamma} \frac{s}{v} + c_{Z\gamma'} \left(\frac{s}{v}\right)^2\right\} F_{\mu\nu} Z^{\mu\nu} \quad - \mathcal{L}_{nonSM} \qquad (2.11)
\end{aligned}
$$

Typical Sizes of b,c's

$$b_i \sim \text{``1''} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{or} \quad \text{``1''} + \frac{g^2 m^2}{M^2}$$

Most of dim-6 operators lead to the definite relation, $b_i = b_i^{'}$, since they involve $H^\dagger H$ which yields $(v+h)^2$. But this is not the case for b_f and $b_f^{'}$. For example, the following operators ($q_L \equiv (t_L, b_L)$), which are invariant under the full SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$,

$$\overline{q_L} D_\mu b_R D^\mu H, \;\; \overline{q_L} D_\mu t_R D^\mu \widetilde{H},$$

$$c_i \sim \text{``0''} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{``0''} + \frac{g^2 m^2}{M^2},$$

All the c_i's from nonrenormalizable operators

- 125GeV Higgs (mass-eigenstate) is

$$H = h\cos\alpha - s\sin\alpha$$

h: SU(2) doublet interaction eigenstate
s: SU(2) singlet interaction eigenstate
alpha: mixing angle (alpha=0 means SM-like)

- h and s effective couplings are parameterized by {b_i}, {c_i}. Some terms are shown below.

$$-\mathcal{L}_{\mathrm{h,int}} = \sum_f b_f \frac{m_f}{v} h\bar{f}f - \left(2b_W \frac{h}{v} + b'_W \left(\frac{h}{v}\right)^2\right) m_W^2 W_\mu^+ W^{-\mu} - \left(b_Z \frac{h}{v} + \frac{1}{2} b'_Z \left(\frac{h}{v}\right)^2\right) m_Z^2 Z_\mu Z^\mu + \frac{\alpha}{8\pi} r_{\mathrm{sm}}^\gamma \left(b_\gamma \frac{h}{v} + \frac{1}{2} b'_\gamma \left(\frac{h}{v}\right)^2\right) F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\mathrm{sm}}^g \left(b_g \frac{h}{v} + \frac{1}{2} b'_g \left(\frac{h}{v}\right)^2\right) G_{\mu\nu}^a G^{a\mu\nu} \qquad (2.2)$$

NB: b_i=1, c_i=0 mean SM-like

- Models are ubiquitous, and singlet scalar is versatile:
- If Hidden fermion is DM, s is needed for correct thermal relic density.

Model	Nonzero c_F's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ, c_{h^2}
Dilaton	$c_g, c_W, c_Z, c_\gamma, c_{h^2}$
Vectorlike Quarks	$c_g, c_\gamma, c_{Z\gamma}, c_{h^2}$
Vectorlike Leptons	$c_\gamma, c_{Z\gamma}, c_{h^2}$
New Charged Vector bosons	c_γ, c_{h^2}
Extra charged scalar bosons	

$$\mathcal{L}_{\text{hidden}} = \mathcal{L}_S + \mathcal{L}_\psi - \lambda S \overline{\psi}\psi,$$
$$\mathcal{L}_{\text{portal}} = -\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H,$$

- If an extra vector exists, s should break gauge symmetry. Gauge symmetry may needed for various reasons: just another force, or ensuring DM stability, etc...
- Condensation can provide new mass scale.

Building Blocks of SM

- Lorentz/Poincare Symmetry
- Local Gauge Symmetry : Gauge Group + Matter Representations from Experiments
- Higgs mechanism for masses of weak gauge bosons and SM chiral fermions
- These principles lead to unsurpassed success of the SM in particle physics

Lessons for Model Building

- Specify local gauge sym, matter contents and their representations under local gauge group
- Write down all the operators upto dim-4
- Check anomaly cancellation
- Consider accidental global symmetries
- Look for nonrenormalizable operators that break/conserve the accidental symmetries of the model

- If there are spin-1 particles, extra care should be paid : need an agency which provides mass to the spin-1 object
- Check if you can write Yukawa couplings to the observed fermion
- One may have to introduce additional Higgs doublets with new gauge interaction if you consider new chiral gauge symmetry (Ko, Omura, Yu on chiral U(1)' model for top FB asymmetry)
- Impose various constraints and study phenomenology

(3,2,1) or SU(3)cXU(1)em ?

- Well below the EW sym breaking scale, it may be fine to impose SU(3)c X U(1)em
- At EW scale, better to impose (3,2,1) which gives better description in general after all
- Majorana neutrino mass is a good example
- For example, in the Higgs + dilaton (radion) system, and you get different results (work in with D.W.Jung, in PLB)

Issue here is whether we use

$$\mathcal{L}_{\rm int} \simeq -\frac{\phi}{f_\phi}\, T^{\mu}_{\ \mu} = -\frac{\phi}{f_\phi}\left[m_H^2 H^\dagger H - 2m_W^2 W^+ W^- - m_Z^2 Z_\mu Z^\mu + \sum_f m_f \bar{f} f + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}\right], \tag{1}$$

OR

$$T^{\mu}_{\ \mu}({\rm SM}) = 2\mu_H^2 H^\dagger H + \sum_G \frac{\beta_G}{g_G} G_{\mu\nu} G^{\mu\nu}.$$

arXiv:1401.5586 with D.W.Jung
Phys.Lett. B in press

In the usual earlier approach, one has

$$\mathcal{L}(f, \bar{f}, \phi) = -\frac{m_f}{f_\phi} \bar{f} f \phi \, \mathrm{e}^{-\bar{\phi}/f_\phi}.$$

In the new approach, one has

$$\mathcal{L}(f, \bar{f}, H_{i=1,2}) = -\frac{m_f}{v} \overline{f} f h = -\frac{m_f}{v} \overline{f} f (H_1 c_\alpha + H_2 s_\alpha),$$

These two lead to very different predictiontions for the Higgs phenomenology at the LHC, especially for H to diphoton, and gg fusion for H productions (see the paper for the details)

Digression on Higgs portal DM models

Based on the works

(with S.Baek, Suyong Choi, P. Gondolo, T. Hur, D.W.Jung, Sunghoon Jung, J.Y.Lee, W.I.Park, E.Senaha, Yong Tang in various combinations)

- Strongly interacting hidden sector (0709.1218 PLB, 1103.2571 PRL)
- Light DM in leptophobic Z' model (1106.0885 PRD)
- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Singlet portal extensions of the standard seesaw models with unbroken dark symmetry (1303.4280 JHEP)
- Hidden sector Monopole, VDM and DR (1311.1035)
- Self-interacting scalar DM with local Z3 sum (1402.6449)

Main Motivations

- Origin of Mass (including DM, RHN) ?
- Understanding DM Stability or Longevity ?
- Assume the standard seesaw for neutrino masses and mixings, and leptogenesis for baryon number asymmetry of the universe
- Assume minimal inflation models : Higgs(+singlet scalar) inflation, Starobinsky inflation

Origin of Mass

- Massive SM particles get their masses from Higgs mechanism or confinement in QCD
- How about DM particles ? Where do their masses come from ?
- SM Higgs ? SUSY Breaking ? Extra Dim ?
- Can we generate all the masses as in proton mass from dim transmutation in QCD ? (proton mass in massless QCD)

- There are basically three different approaches on the origin of masses
- Standard Higgs mechanism with fundamental scalars (SM, MSSM etc.)
- Dynamical Symmetry Breaking : Technicolor, BCS (Hur and Ko; Kubo and Lindner et al)
- Radiative Symmetry Breaking : Coleman-Weinberg mechanism (Recently renewed interests in this approach : Meissner & Nicolai; Okada & Iso et al; Lindner et al; and many more)
- NB : If we consider extra dim, more options

Questions about DM

- Electric Charge/Color neutral
- How many DM species are there ?
- Their masses and spins ?
- Are they absolutely stable or very long lived ?
- How do they interact with themselves and with the SM particles ?
- Where do their masses come from ? Another (Dark) Higgs mechanism ? Dynamical SB ?
- How to observe them ?

Underlying Principles

- Hidden Sector CDM
- Singlet Portals (including Higgs portal)
- Renormalizability (with some caveats)
- Local Dark Gauge Symmetry (unbroken or spontaneously broken) : Dark matter feels gauge force like most of other particles & DM is stable for the same reason as electron is stable

(Alternative models by Asaka, Shaposhnikov et al.)

DM is stable because...

- Symmetries

  - (ad hoc) Z_2 symmetry
  - R-parity
  - Topology (from a broken sym.)

- Very small mass and weak coupling

  e.g: QCD-axion ($m_a \sim \Lambda_{QCD}^2/f_a$; $f_a \sim 10^{9\text{-}12}$ GeV)

  ⇨ $$\Gamma_a \sim \mathcal{O}(10^{-5})\frac{m_a^3}{f_a^2} \ll H_0 \sim 10^{-42}\mathrm{GeV}$$

But for WIMP ...

- Global sym. is not enough since

$$-\mathcal{L}_{\rm int} = \begin{cases} \lambda \frac{\phi}{M_{\rm P}} F_{\mu\nu} F \mu\nu & \text{for boson} \\ \lambda \frac{1}{M_{\rm P}} \bar{\psi}\gamma^\mu D_\mu \ell_{Li} H^\dagger & \text{for fermion} \end{cases}$$

Observation requires [M. Ackermann et al. (LAT Collaboration), PRD 86, 022002 (2012)]

$$\tau_{\rm DM} \gtrsim 10^{26-30}{\rm sec} \Rightarrow \begin{cases} m_\phi \lesssim \mathcal{O}(10){\rm keV} \\ m_\psi \lesssim \mathcal{O}(1){\rm GeV} \end{cases}$$

⇒ WIMP is unlikely to be stable

- SM is guided by gauge principle

It looks natural and may need to consider a gauge symmetry in dark sector, too.

Hidden Sector

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

Hidden Sector

- Hidden sector gauge symmetry can stabilize hidden DM
- There could be some contributions to the dark radiation from unbroken dark sector
- Consistent with GUT in a broader sense
- Can address "QM generation of all the mass scales 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 (G_h) : Abelian or Nonabelian
- Strength of gauge coupling : strong or weak
- Matter contents : singlet, fundamental or higher dim representations of G_h
- All of these can be freely chosen at the moment : Any predictions possible ?
- But there are some generic testable features in Higgs phenomenology and dark radiation

Known facts for hCDM

- Strongly interacting hidden sector
  - CDM : composite h-mesons and h-baryons
  - All the mass scales can be generated from hidden sector
  - No long range dark force
  - CDM can be absolutely stable or long lived

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).

- Weakly interacting hidden sector
  - Long range dark force if Gh is unbroken
  - If Gh is unbroken and CDM is DM, then no extra scalar boson is necessary (*)
  - If Gh is broken, hDM can be still stable or decay, depending on Gh charge assignments
- More than one neutral scalar bosons with signal strength = 1 or smaller (indep. of decays) except for the case (*)
- Vacuum is stable up to Planck scale

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

Higgs signal strength/Dark radiation/DM

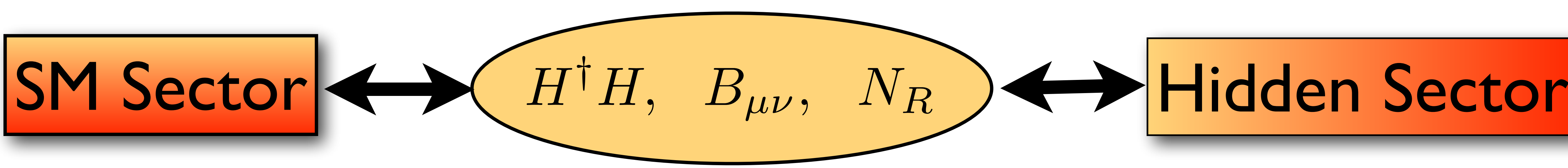
in preparation with Baek and W.I. Park

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

Singlet Portal

- If there is a hidden sector, then we need a portal to it in order not to overclose the universe
- There are only three unique gauge singlets in the SM + RH neutrinos



$$\boxed{N_R \leftrightarrow \widetilde{H} l_L}$$

General Comments

- Many studies on DM physics using EFT
- However we don't know the mass scales of DM and the force mediator
- Sometimes one can get misleading results
- Better to work in a minimal renormalizable and anomaly-free models
- Explicit examples : singlet fermion Higgs portal DM, vector DM, Z2 scalar CDM

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu}V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

A. Djouadi, et.al. 2011

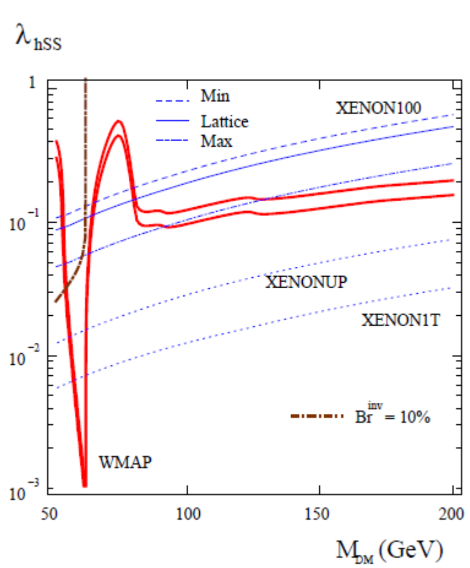


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{\rm inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

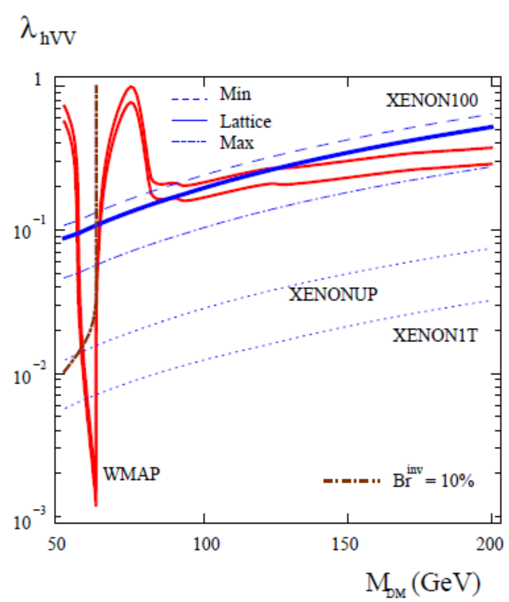


FIG. 2. Same as Fig. 1 for vector DM particles.

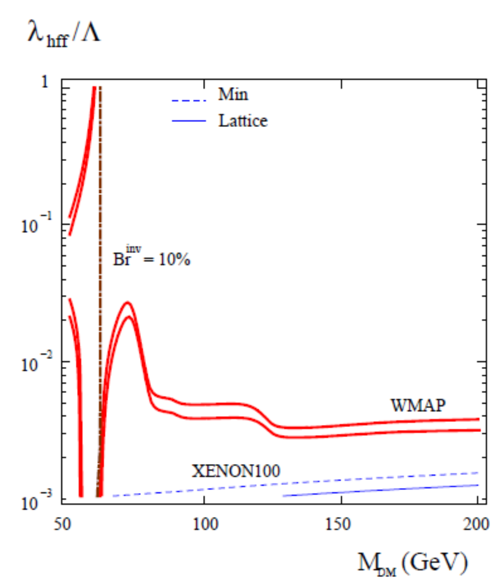


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_{HS}}{2} H^\dagger H S^2 - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi \right]\psi - \frac{\lambda_{H\psi}}{\Lambda} H^\dagger H \, \overline{\psi}\psi$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV} H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

- Scalar CDM : looks OK, renorm. .. BUT .....
- Fermion CDM : nonrenormalizable
- Vector CDM : looks OK, but it has a number of problems (in fact, it is not renormalizable)

Usual story within EFT

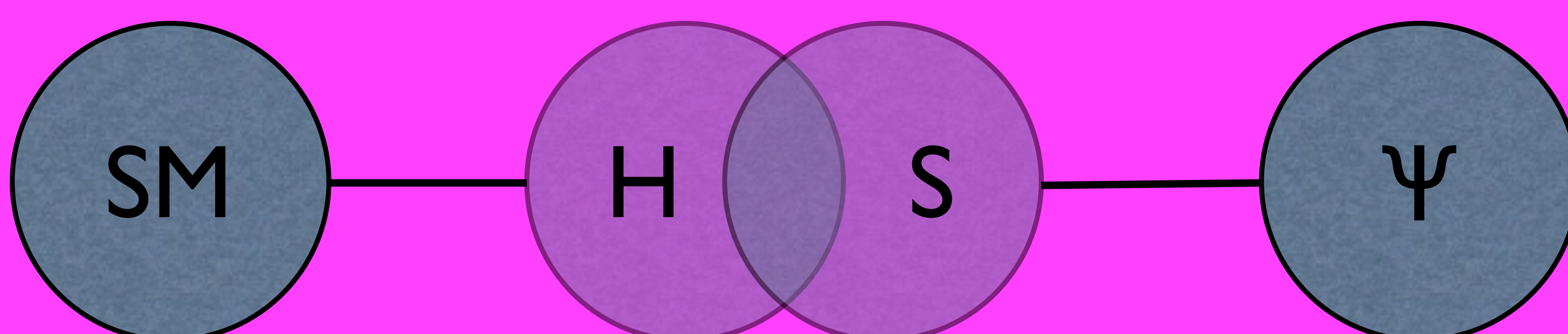
- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced in the full theories (renormalizable) however

Singlet fermion CDM

$$
\begin{aligned}
\mathcal{L} \;=\; & \mathcal{L}_{\rm SM} - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\
& + \frac{1}{2}(\partial_\mu S \partial^\mu S - m_S^2 S^2) - \mu_S^3 S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4 \\
& + \overline{\psi}(i \not{\partial} - m_{\psi_0})\psi - \lambda S \overline{\psi}\psi
\end{aligned}
$$

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Ratiocination

- Mixing and Eigenstates of Higgs-like bosons

$$\mu_H^2 = \lambda_H v_H^2 + \mu_{HS} v_S + \frac{1}{2}\lambda_{HS} v_S^2,$$
$$m_S^2 = -\frac{\mu_S^3}{v_S} - \mu'_S v_S - \lambda_S v_S^2 - \frac{\mu_{HS} v_H^2}{2v_S} - \frac{1}{2}\lambda_{HS} v_H^2,$$

at vacuum

$$M^2_{\text{Higgs}} \equiv \begin{pmatrix} m^2_{hh} & m^2_{hs} \\ m^2_{hs} & m^2_{ss} \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

$$H_1 = h\cos\alpha - s\sin\alpha,$$
$$H_2 = h\sin\alpha + s\cos\alpha.$$

⇐ Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \, \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \, \mathrm{Br}(h \to \mathrm{SM})}$$

$$r_1 = \frac{\cos^4\alpha \, \Gamma_{H_1}^{\mathrm{SM}}}{\cos^2\alpha \, \Gamma_{H_1}^{\mathrm{SM}} + \sin^2\alpha \, \Gamma_{H_1}^{\mathrm{hid}}}$$

$$r_2 = \frac{\sin^4\alpha \, \Gamma_{H_2}^{\mathrm{SM}}}{\sin^2\alpha \, \Gamma_{H_2}^{\mathrm{SM}} + \cos^2\alpha \, \Gamma_{H_2}^{\mathrm{hid}} + \Gamma_{H_2 \to H_1 H_1}}$$

$0 < \alpha < \pi/2 \Rightarrow r_1(r_2) < 1$

Invisible decay mode is not necessary!

If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

- EW precision observables

Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)

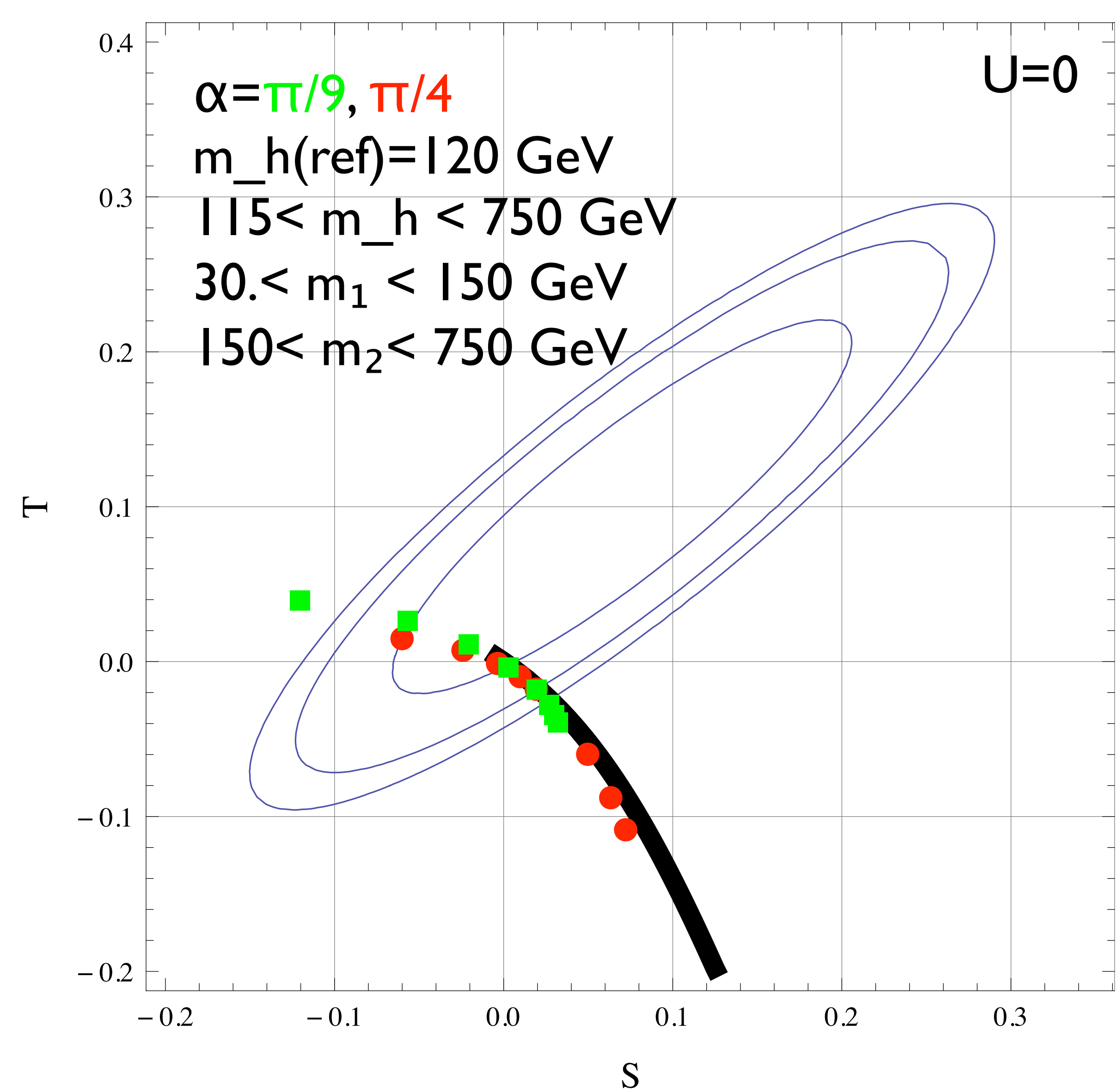
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

$$\alpha_{\rm em} T = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}$$

$$\alpha_{\rm em} U = 4 s_W^2 \left[\frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2} \right]$$

$$S = \cos^2\alpha \; S(m_1) + \sin^2\alpha \; S(m_2)$$

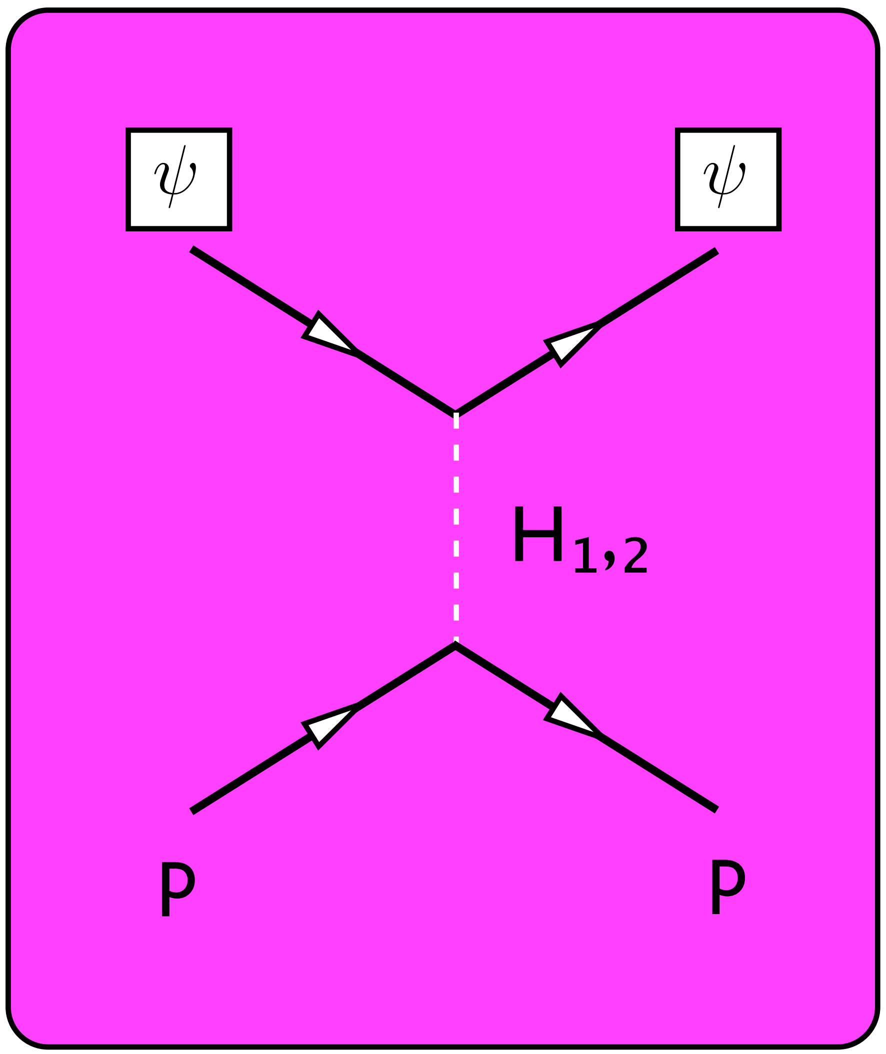
Same for T and U

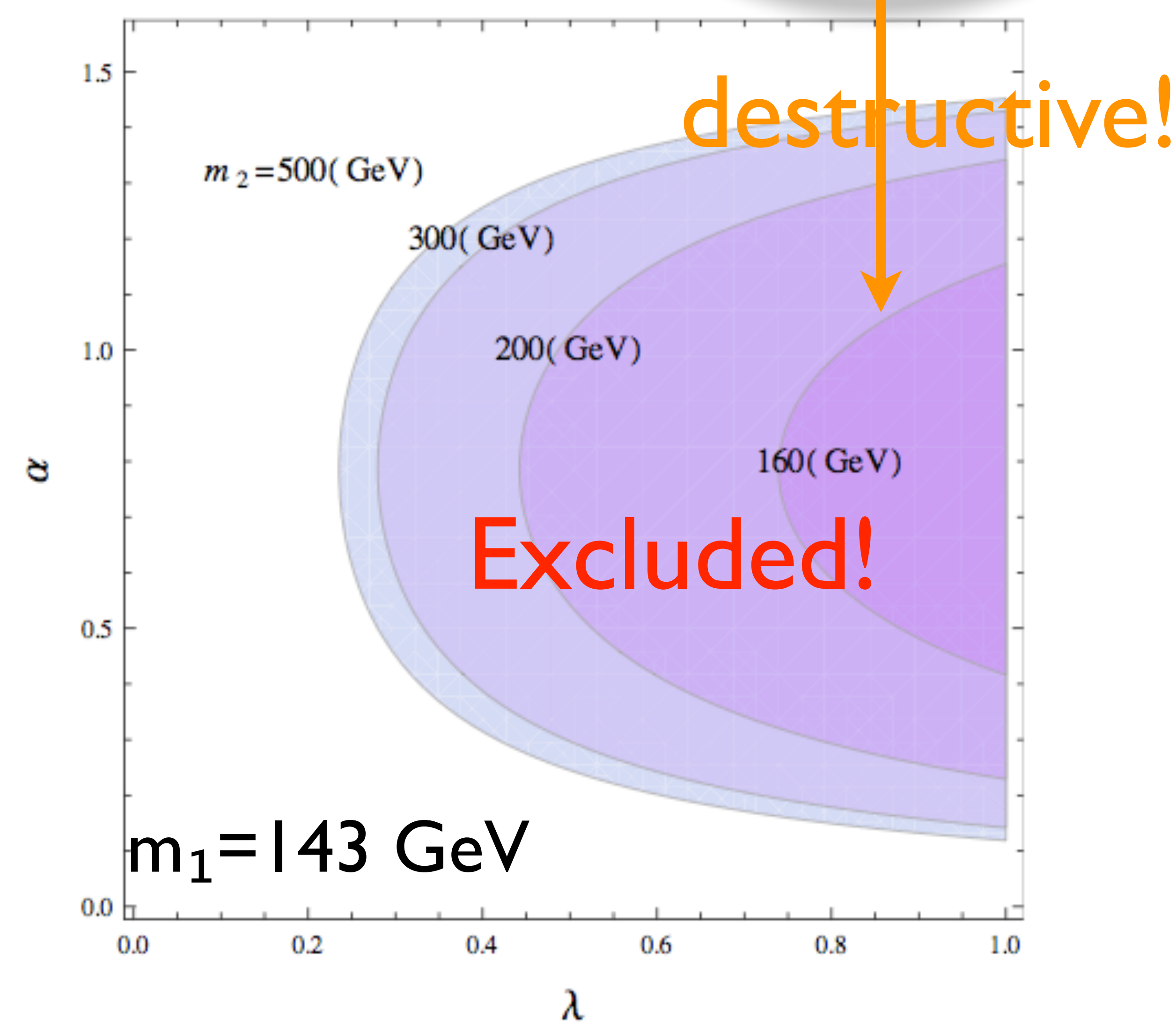


Constraints

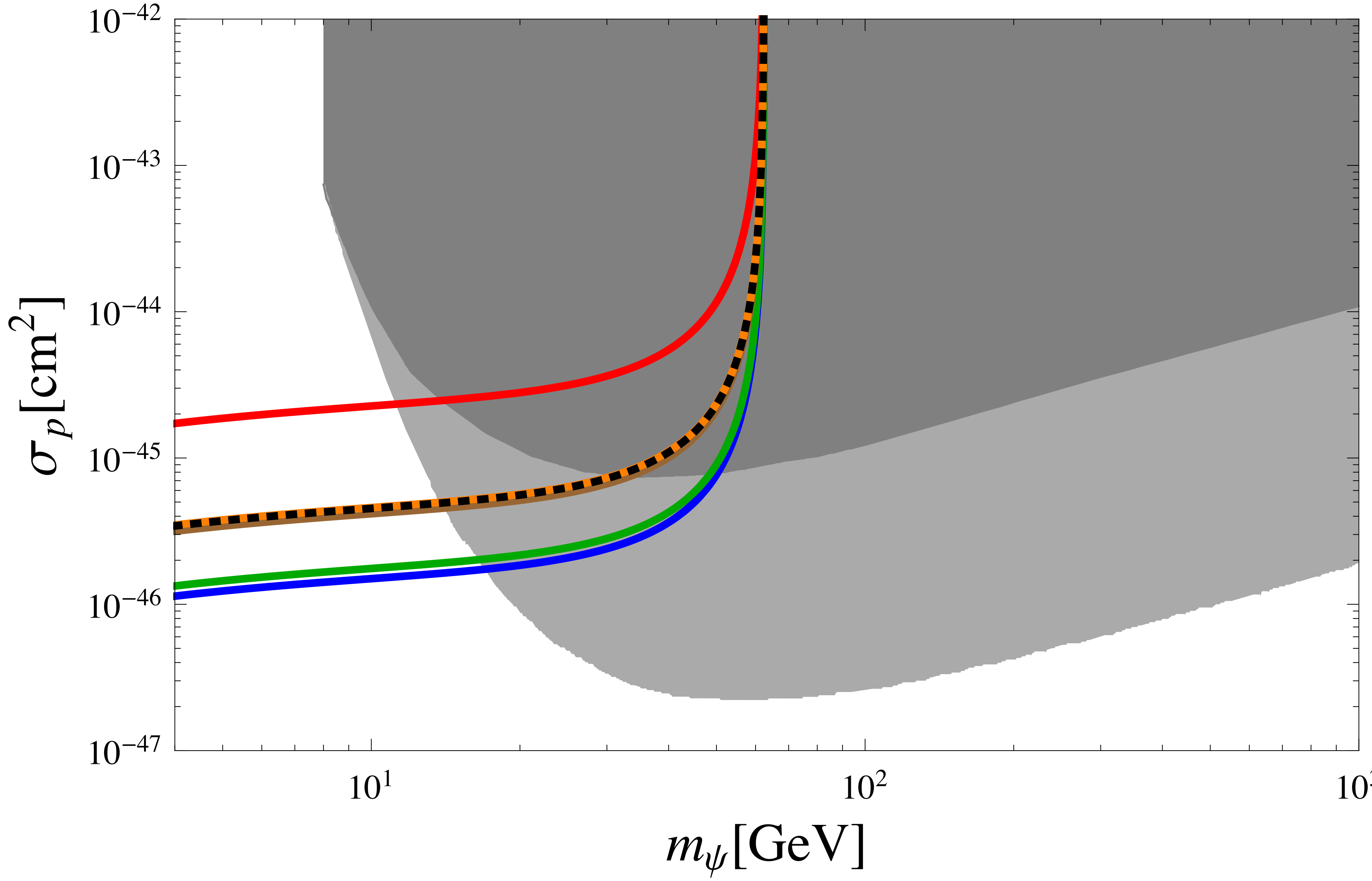
- Dark matter to nucleon cross section (constraint)

$$\sigma_p \approx \frac{1}{\pi}\mu^2\lambda_p^2 \simeq 2.7\times 10^{-2}\frac{m_p^2}{\pi}\left|\left(\frac{m_p}{v}\right)\lambda\sin\alpha\cos\alpha\left(\frac{1}{m_1^2}-\frac{1}{m_2^2}\right)\right|^2$$





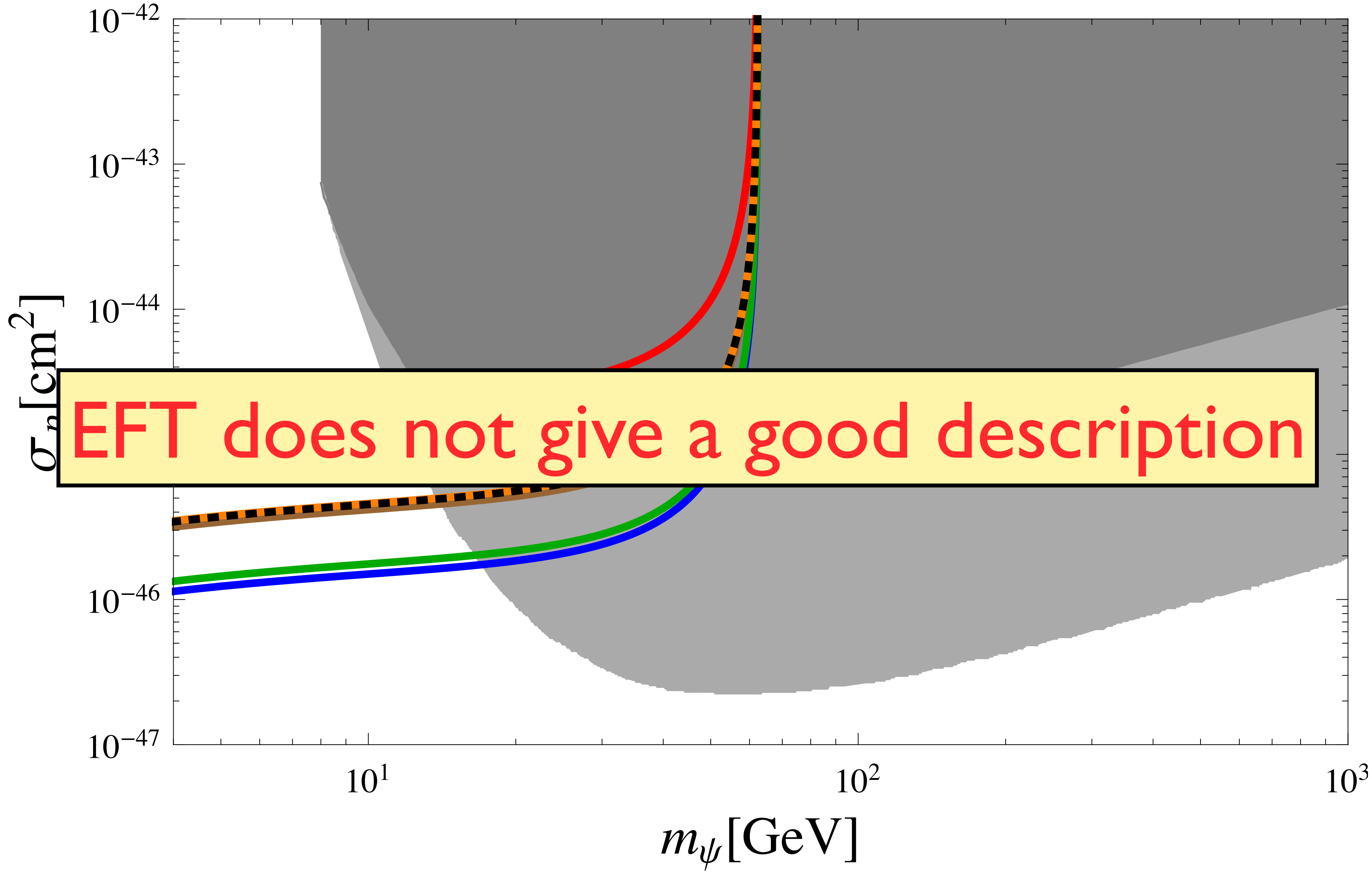
Invisible Higgs decay vs SI DD x-section (preliminary)



m_phi = 70 (red), 100 (blue), 200 (green), 500 (brown), 1000 (orange) GeV for solid lines.

The black dashed line is for EFT result.

Invisible Higgs decay vs SI DD x-section (preliminary)



m_phi = 70 (red), 100 (blue), 200 (green), 500 (brown), 1000 (orange) GeV for solid lines.

The black dashed line is for EFT result.

- We don't use the effective lagrangian approach (nonrenormalizable interactions), since we don't know the mass scale related with the CDM

$$\mathcal{L}_{\text{eff}} = \overline{\psi}\left(m_0 + \frac{H^\dagger H}{\Lambda}\right)\psi. \qquad \text{or} \qquad \lambda h \overline{\psi}\psi$$

- Only one Higgs boson (alpha = 0)

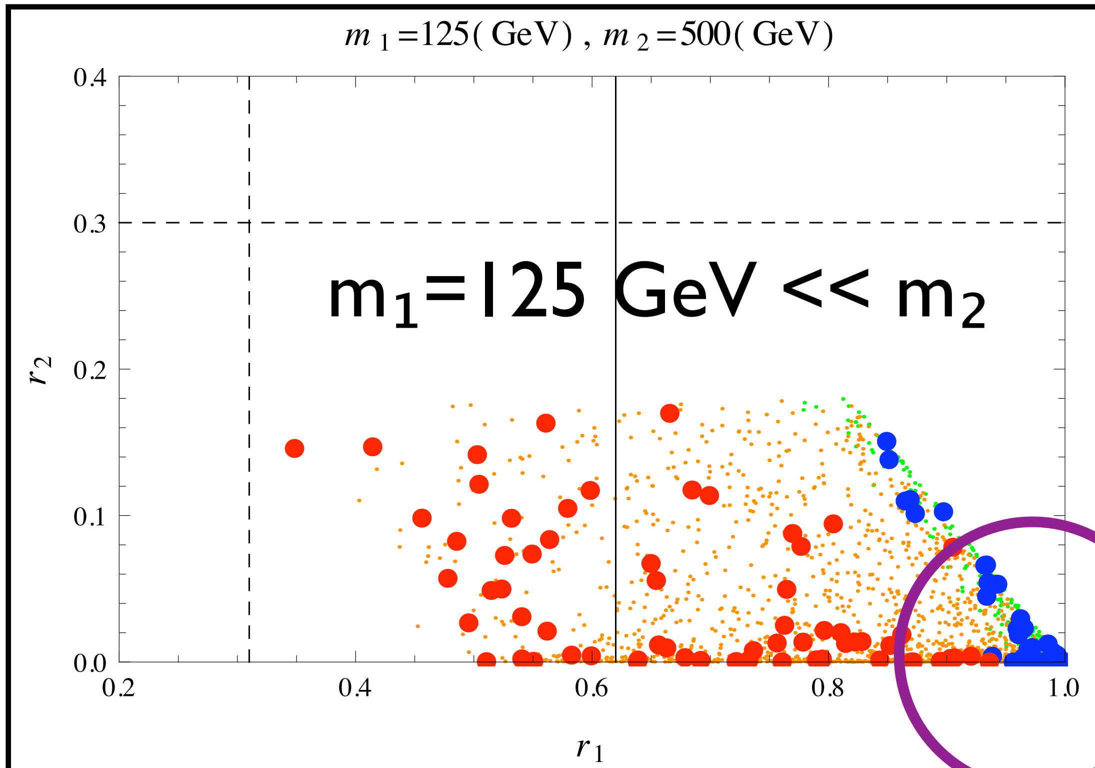
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

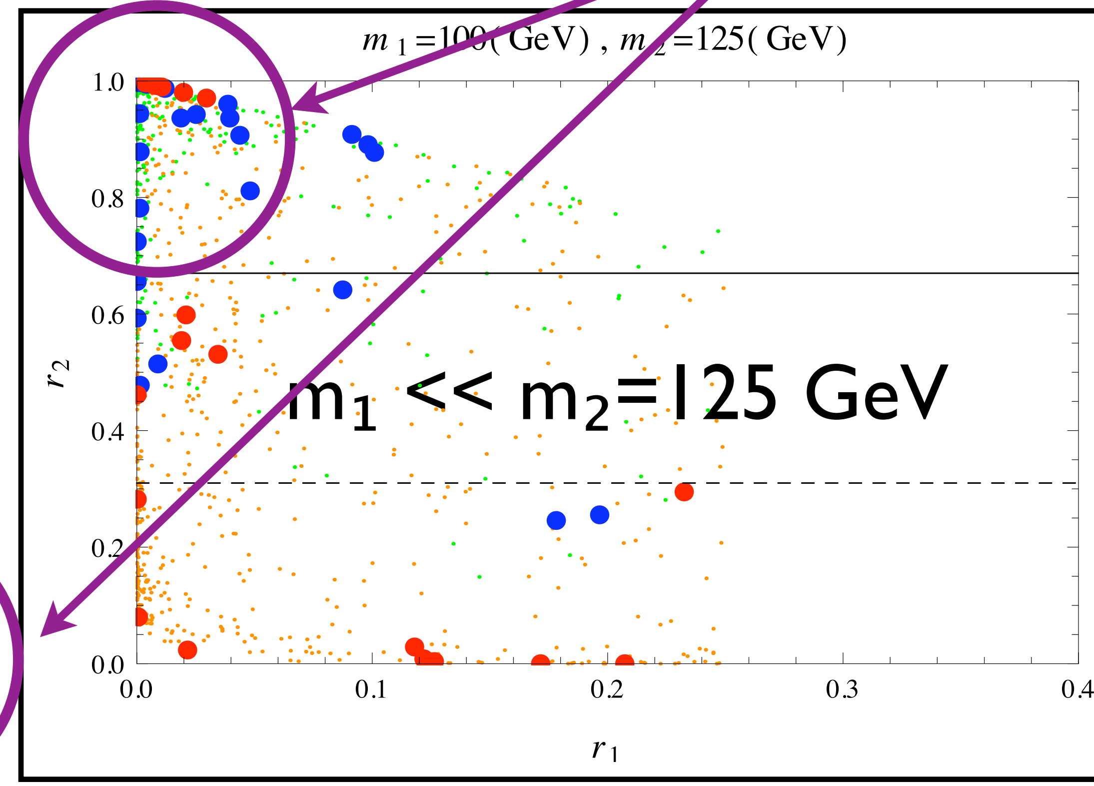
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

- Signal strength (r_2 vs r_1)

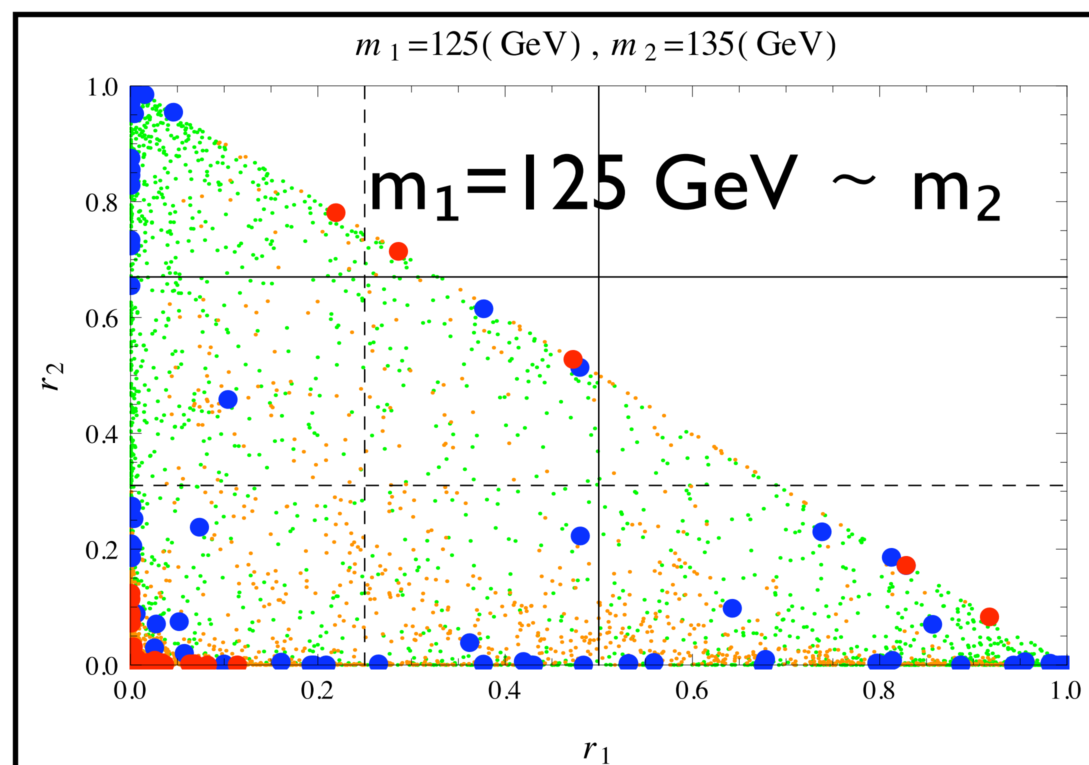
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.

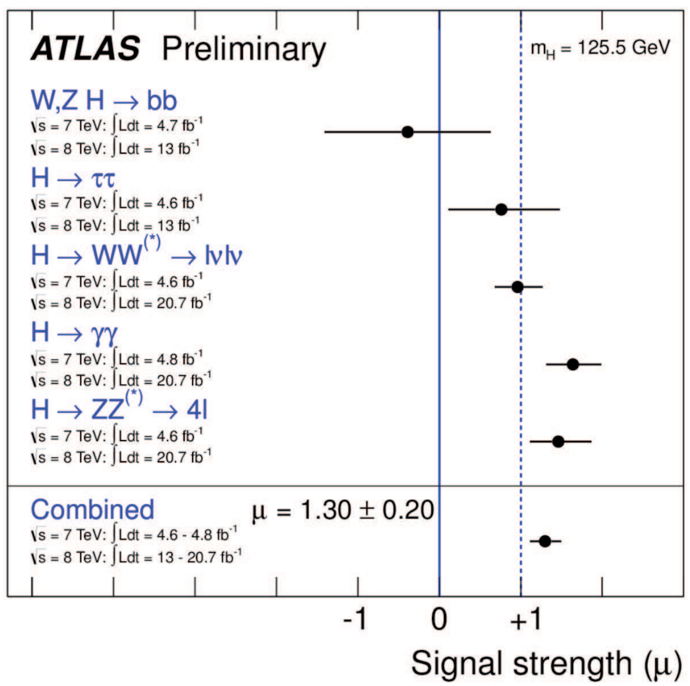


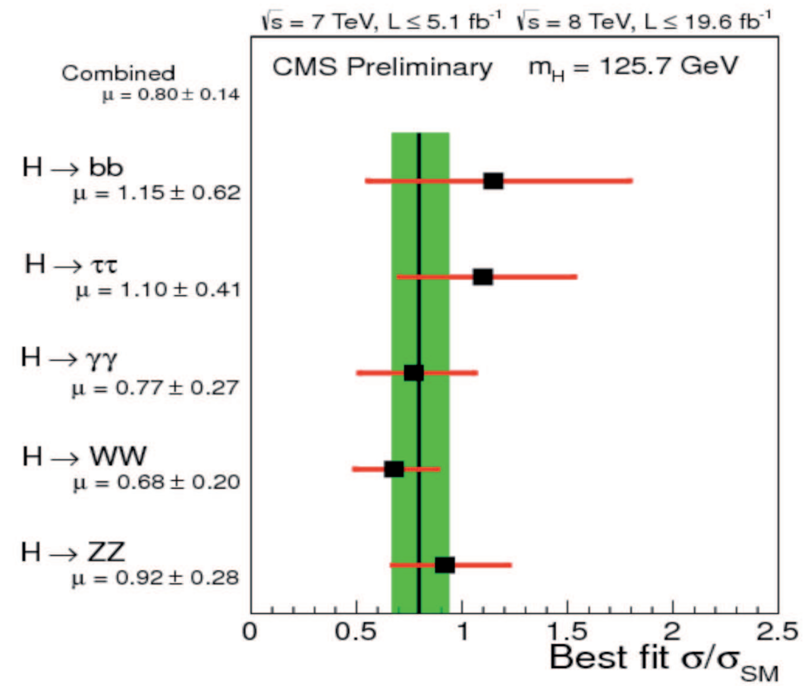
- : Ω(x),σ_p(x)
- : Ω(x),σ_p(o)
- : Ω(o),σ_p(x)
- : Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$



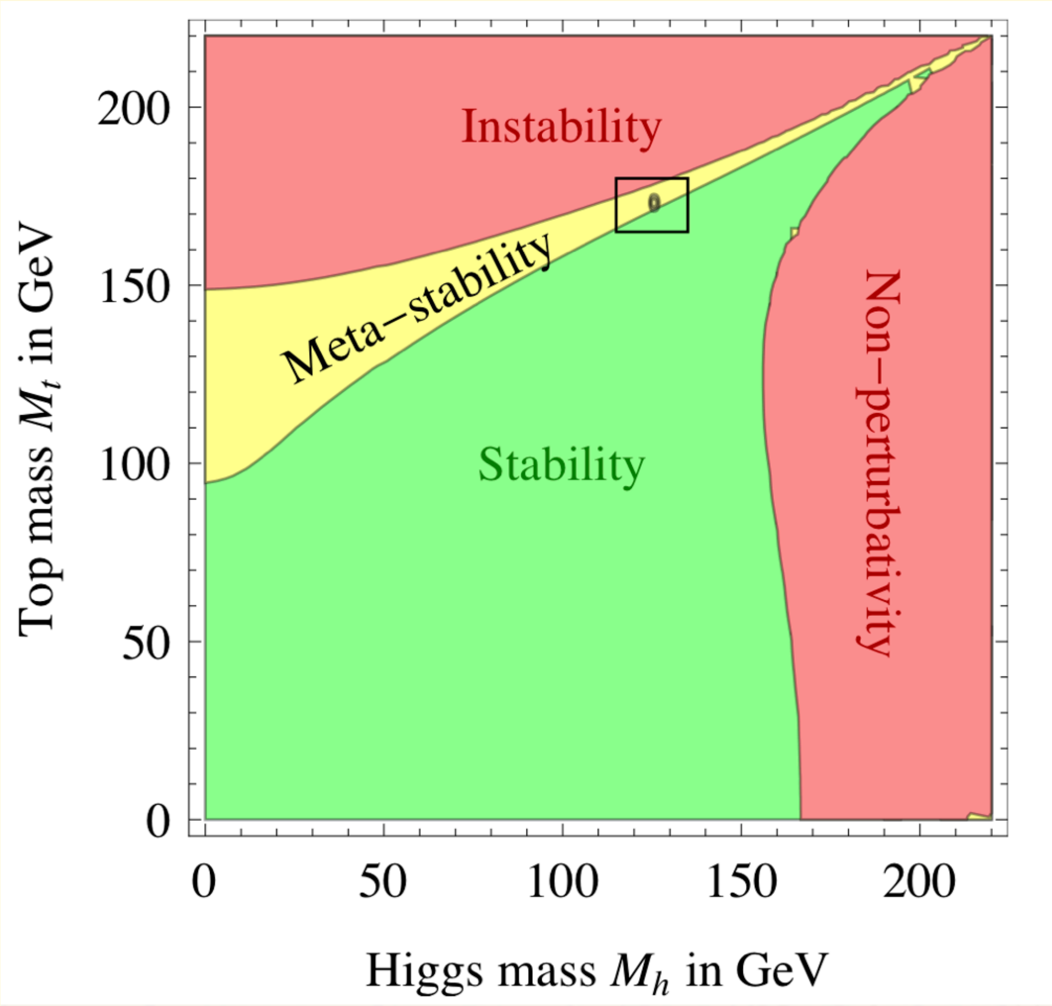


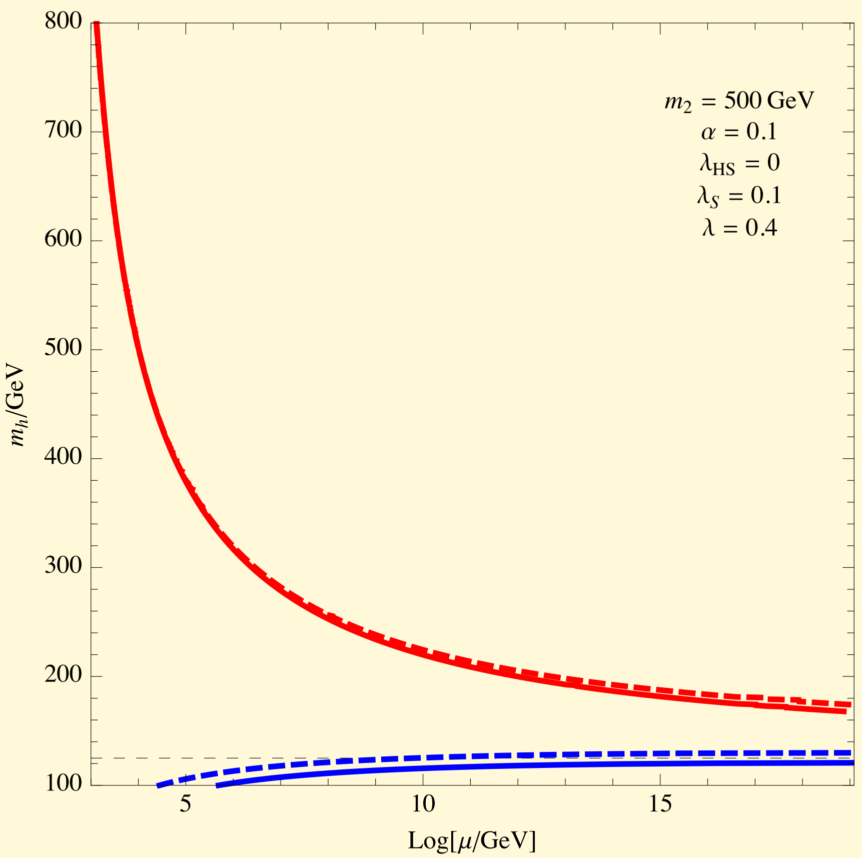
Decay Mode	ATLAS (M_H = 125.5 GeV)	CMS (M_H = 125.7 GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

$$\langle \mu \rangle = \mathbf{0.96 \pm 0.12}$$

Getting smaller

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Similar for Higgs portal Vector DM

$$\mathcal{L} = -m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{4} H^\dagger H V_\mu V^\mu - \frac{\lambda_V}{4} (V_\mu V^\mu)^2$$

- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- Stueckelberg mechanism ?? (work in progress)
- A complete model should be something like this:

$$\mathcal{L}_{VDM} = -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{\lambda_\Phi}{4} \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right)^2$$
$$-\lambda_{H\Phi} \left(H^\dagger H - \frac{v_H^2}{2} \right) \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2} \right) ,$$

$$\langle 0 | \phi_X | 0 \rangle = v_X + h_X(x)$$

- There appear a new singlet scalar h_X from phi_X , which mixes with the SM Higgs boson through Higgs portal
- The effects must be similar to the singlet scalar in the fermion CDM model
- Important to consider a minimal renormalizable model to discuss physics correctly
- Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)

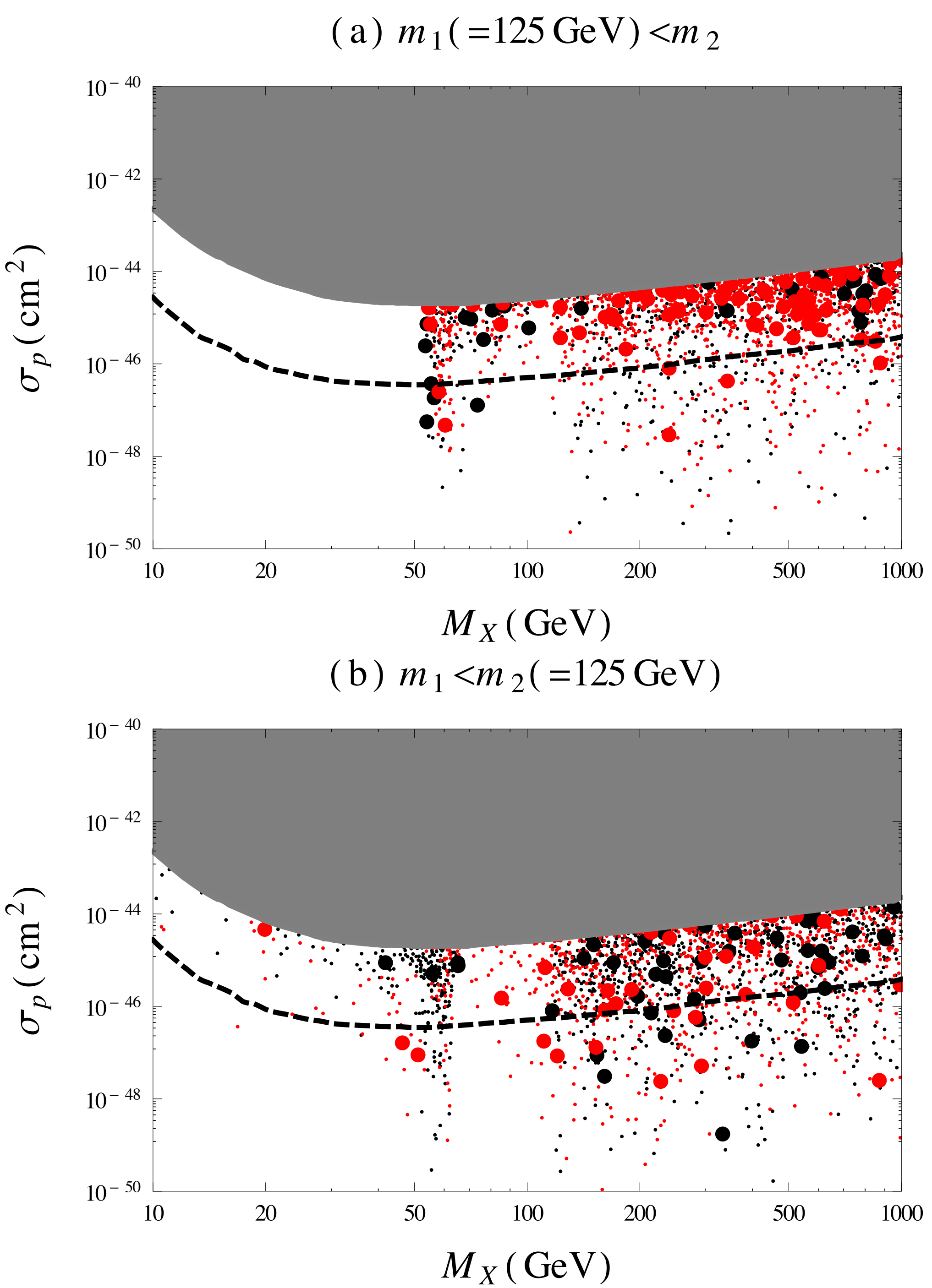


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7(r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity of the next XENON experiment, XENON1T.

New scalar improves EW vacuum stability

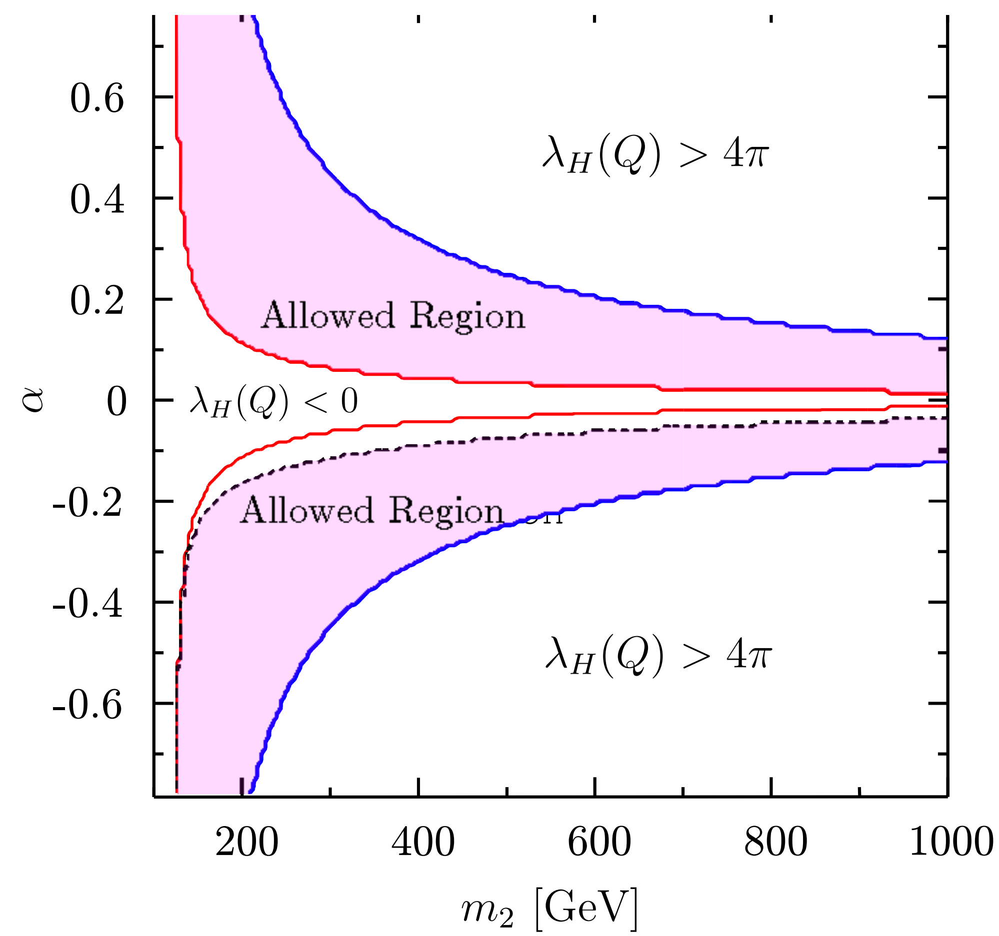


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

- SFDM scenario is ruled out in the EFT
- We may lose imformation in DM pheno.

A. Djouadi, et.al. 2011

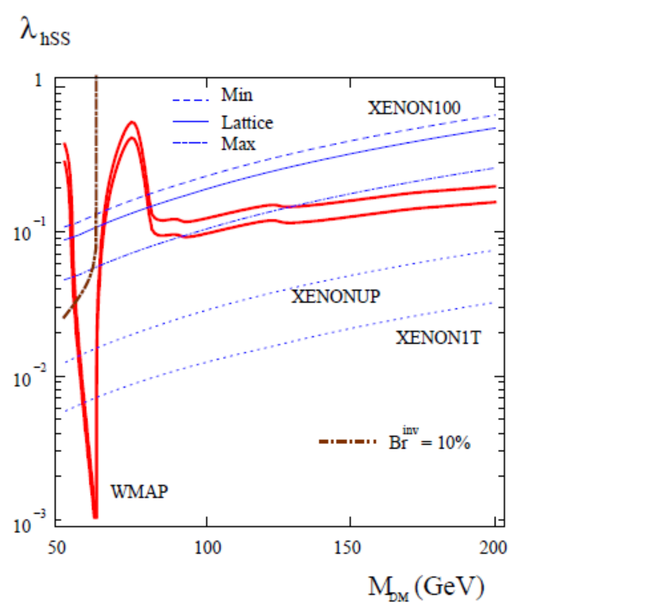


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

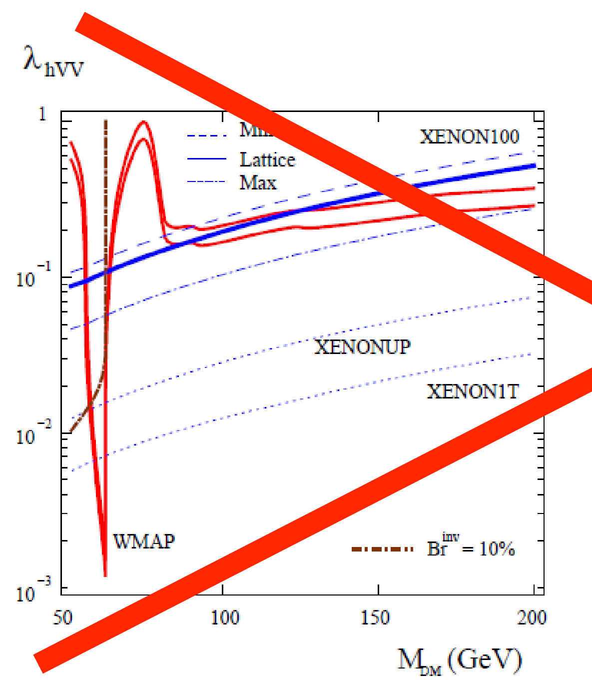


FIG. 2. Same as Fig. 1 for vector DM particles.

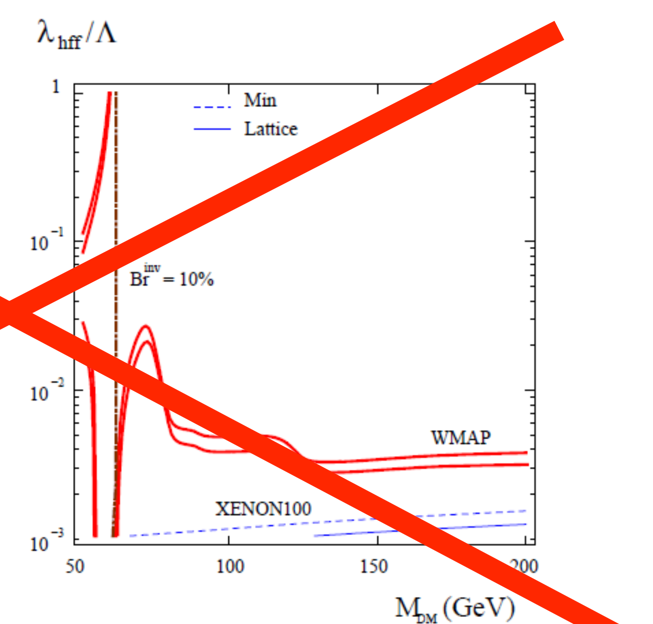
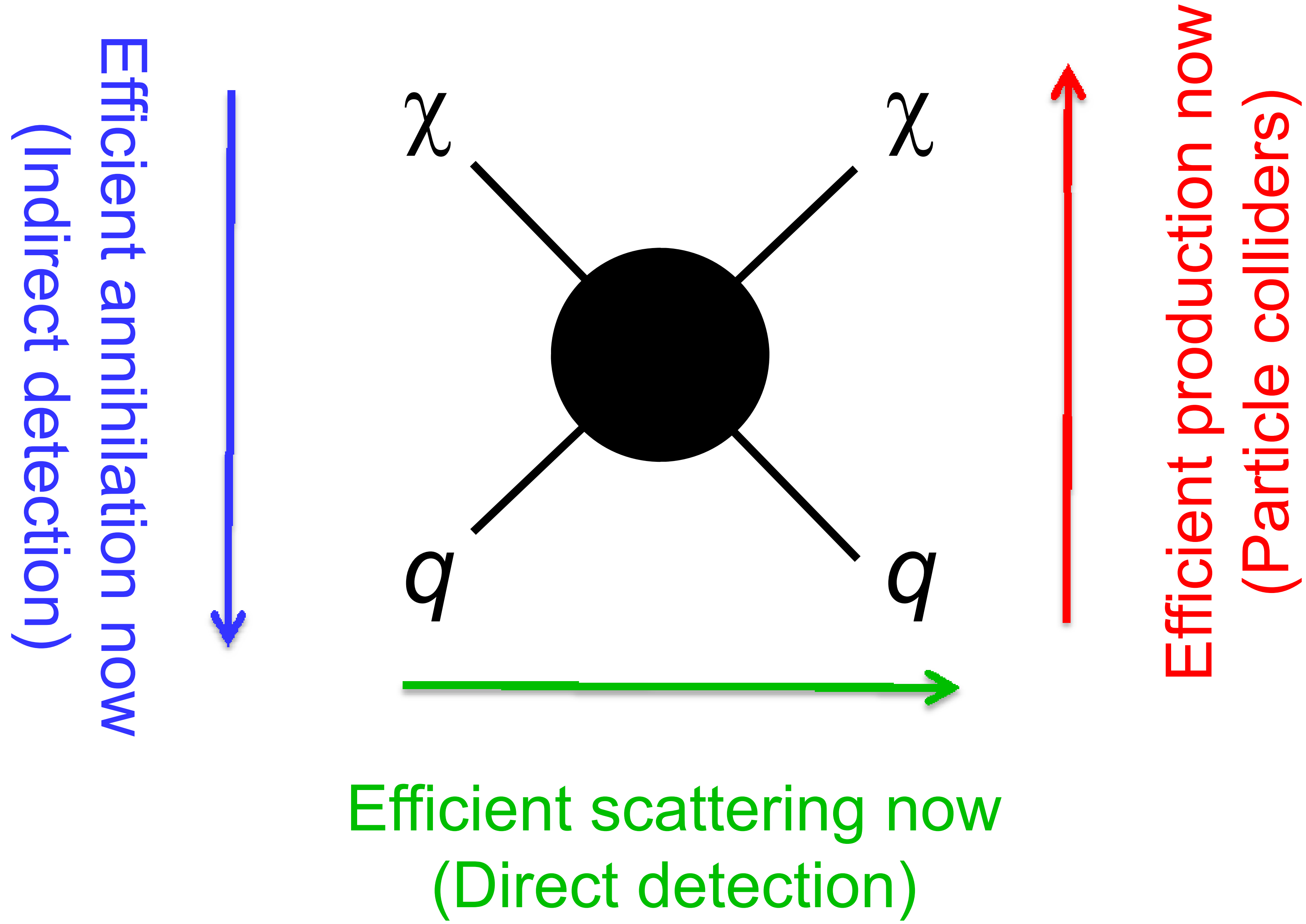


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian,
we get different results !

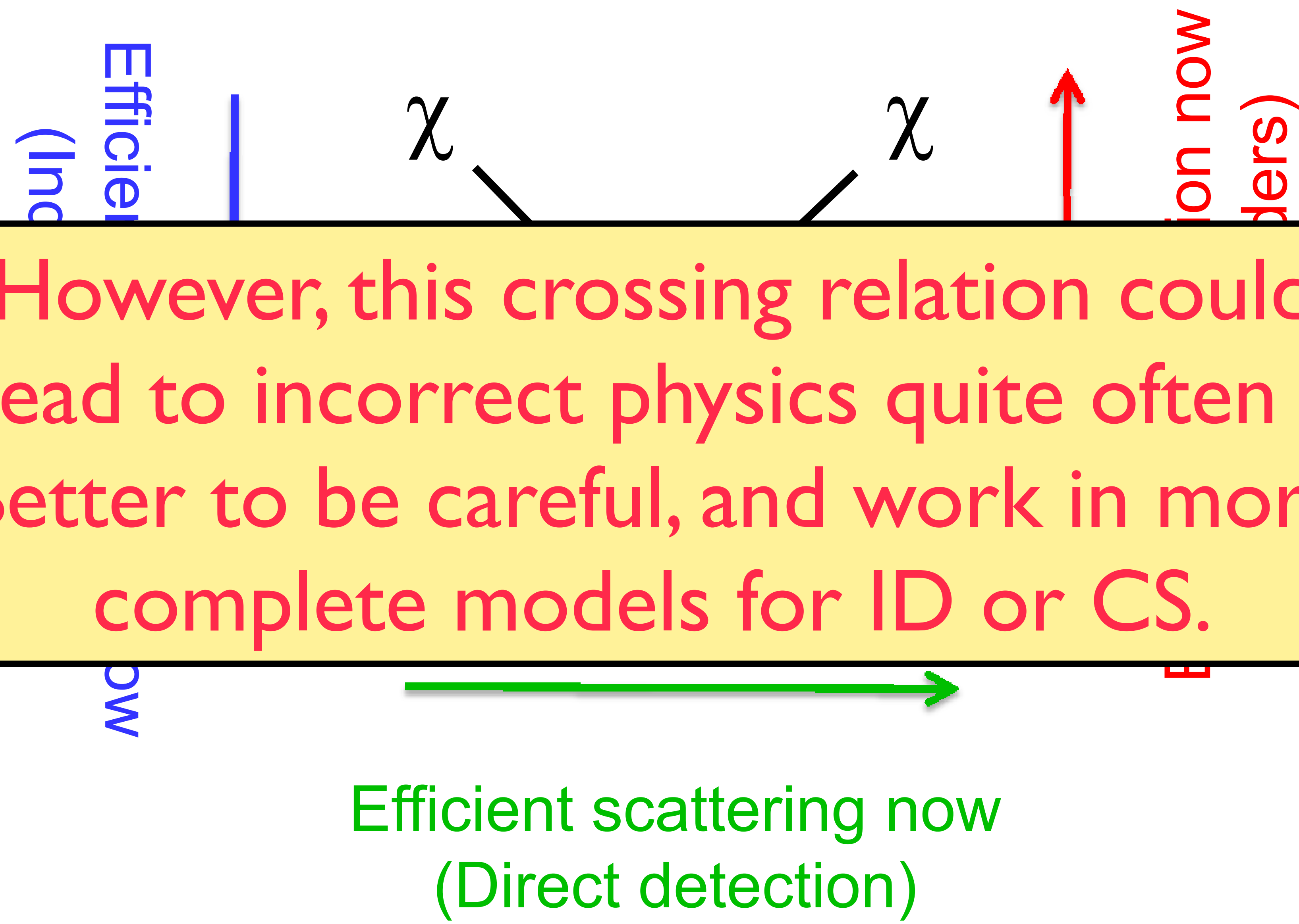
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then

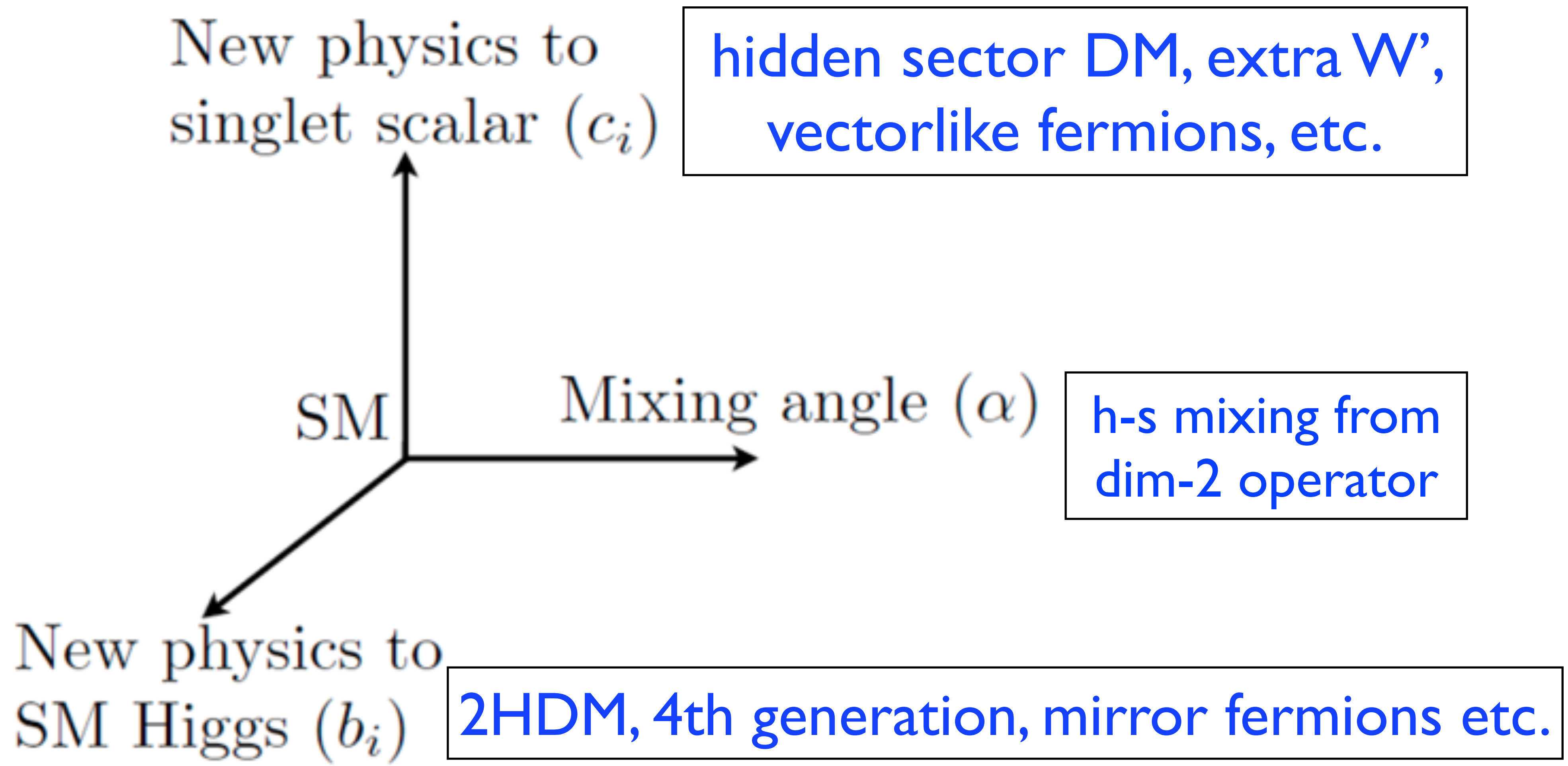


However, this crossing relation could lead to incorrect physics quite often ! Better to be careful, and work in more complete models for ID or CS.

General Remarks

- Sometimes we need new fields beyond the SM ones and the CDM, in order to make DM models realistic and theoretically consistent
- If there are light fields in addition to the CDM, the usual Eff. Lag. with SM+CDM would not work
- Better to work with minimal renormalizable model
- See papers by Ko, Omura, Yu on the top FB asym with leptophobic Z' coupling to the RH up-type quarks only : new Higgs doublets coupled to Z' are mandatory in order to make a realistic model

Back to the main theme



- Orthogonal ways to modify the same observable.
- Information on individual direction will be lost/hidden if no proper basis is used. Interpretation of data depends on basis.
- Our framework is suitable to get insight on singlet mixing, singlet couplings as well as Higgs couplings.

SM Higgs

$$
\begin{aligned}
-\mathcal{L}_{\rm h,int} &= \sum_f b_f \frac{m_f}{v} h\bar{f}f - \left\{2b_W \frac{h}{v} + b_W^{'} \left(\frac{h}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{b_Z \frac{h}{v} + \frac{1}{2} b_Z^{'} \left(\frac{h}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
&+ \frac{\alpha}{8\pi} r_{\rm sm}^\gamma \left\{b_\gamma \frac{h}{v} + \frac{1}{2} b_\gamma^{'} \left(\frac{h}{v}\right)^2\right\} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\rm sm}^g \left\{b_g \frac{h}{v} + \frac{1}{2} b_g^{'} \left(\frac{h}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \\
&+ \frac{\alpha_2}{\pi} \left\{2b_{dW} \frac{h}{v} + b_{dW'} \left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi} \left\{2b_{dZ} \frac{h}{v} + b_{dZ'} \left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu} Z^{\mu\nu} \\
&+ \frac{\alpha_2}{\pi} \left\{2\widetilde{b_{dW}} \frac{h}{v} + \widetilde{b_{dW'}} \left(\frac{h}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi} \left\{2\widetilde{b_{dZ}} \frac{h}{v} + \widetilde{b_{dZ'}} \left(\frac{h}{v}\right)^2\right\} Z_{\mu\nu} \widetilde{Z^{\mu\nu}} \\
&+ \frac{\alpha}{\pi} \left\{2b_{Z\gamma} \frac{h}{v} + b_{Z\gamma'} \left(\frac{h}{v}\right)^2\right\} F_{\mu\nu} Z^{\mu\nu} \qquad (2.1)
\end{aligned}
$$

Singlet Scalar S

$$
\begin{aligned}
-\mathcal{L}_{\rm s,int} &= \sum_f c_f \frac{m_f}{v} s\bar{f}f - \left\{2c_W \frac{s}{v} + c_W^{'} \left(\frac{s}{v}\right)^2\right\} m_W^2 W_\mu^+ W^{-\mu} - \left\{c_Z \frac{s}{v} + \frac{1}{2} c_Z^{'} \left(\frac{s}{v}\right)^2\right\} m_Z^2 Z_\mu Z^\mu \\
&+ \frac{\alpha}{8\pi} r_{\rm sm}^\gamma \left\{c_\gamma \frac{s}{v} + \frac{1}{2} c_\gamma^{'} \left(\frac{s}{v}\right)^2\right\} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\rm sm}^g \left\{c_g \frac{s}{v} + \frac{1}{2} c_g^{'} \left(\frac{s}{v}\right)^2\right\} G_{\mu\nu}^a G^{a\mu\nu} \qquad (2.10) \\
&+ \frac{\alpha_2}{\pi} \left\{2c_{dW} \frac{s}{v} + c_{dW'} \left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ W^{-\mu\nu} + \frac{\alpha_2}{\pi} \left\{2c_{dZ} \frac{s}{v} + c_{dZ'} \left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu} Z^{\mu\nu} \\
&+ \frac{\alpha_2}{\pi} \left\{2\widetilde{c_{dW}} \frac{s}{v} + \widetilde{c_{dW'}} \left(\frac{s}{v}\right)^2\right\} W_{\mu\nu}^+ \widetilde{W^{-\mu\nu}} + \frac{\alpha_2}{\pi} \left\{2\widetilde{c_{dZ}} \frac{s}{v} + \widetilde{c_{dZ'}} \left(\frac{s}{v}\right)^2\right\} Z_{\mu\nu} \widetilde{Z^{\mu\nu}} \\
&+ \frac{\alpha}{\pi} \left\{2c_{Z\gamma} \frac{s}{v} + c_{Z\gamma'} \left(\frac{s}{v}\right)^2\right\} F_{\mu\nu} Z^{\mu\nu} \quad - \mathcal{L}_{nonSM} \qquad (2.11)
\end{aligned}
$$

Typical Sizes of b,c's

$$b_i \sim \text{“1”} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{or} \quad \text{“1”} + \frac{g^2 m^2}{M^2}$$

Most of dim-6 operators lead to the definite relation, $b_i = b_i^{'}$, since they involve $H^\dagger H$ which yields $(v+h)^2$. But this is not the case for b_f and $b_f^{'}$. For example, the following operators ($q_L \equiv (t_L, b_L)$), which are invariant under the full SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$,

$$\overline{q_L} D_\mu b_R D^\mu H, \quad \overline{q_L} D_\mu t_R D^\mu \widetilde{H},$$

$$c_i \sim \text{“0”} + \frac{g^2 m^2}{(4\pi)^2 M^2}, \quad \text{“0”} + \frac{g^2 m^2}{M^2},$$

All the c_i's from nonrenormalizable operators

Mixing with a singlet scalar

$$H_1 = h\cos\alpha - s\sin\alpha$$

$$H_2 = h\sin\alpha + s\cos\alpha$$

$$\mathcal{M}(H_1F) = \mathcal{M}(hF)_{\rm SM} \times (b_F\cos\alpha - c_F\sin\alpha) \equiv \kappa_{1F}\mathcal{M}(hF)_{\rm SM}$$

$$\mathcal{M}(H_2F) = \mathcal{M}(hF)_{\rm SM} \times (-b_F\sin\alpha + c_F\cos\alpha) \equiv \kappa_{2F}\mathcal{M}(hF)_{\rm SM}$$

Model	Nonzero c's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ
Dilaton	$c_{h^2}, c_g, c_W, c_Z, c_\gamma$
Vectorlike Quarks	c_g, c_γ
Vectorlike Leptons	c_γ
New Charged Vector bosons	c_γ

Other c's are all zeros !

- 125GeV Higgs (mass-eigenstate) is

$$H = h\cos\alpha - s\sin\alpha$$

h: SU(2) doublet interaction eigenstate
s: SU(2) singlet interaction eigenstate
alpha: mixing angle (alpha=0 means SM-like)

- h and s effective couplings are parameterized by {b_i}, {c_i}. Some terms are shown below.

$$-\mathcal{L}_{\rm h,int} = \sum_f b_f \frac{m_f}{v} h\bar{f}f - \left(2b_W\frac{h}{v} + b'_W\left(\frac{h}{v}\right)^2\right) m_W^2 W_\mu^+ W^{-\mu} - \left(b_Z\frac{h}{v} + \frac{1}{2}b'_Z\left(\frac{h}{v}\right)^2\right) m_Z^2 Z_\mu Z^\mu$$
$$+ \frac{\alpha}{8\pi} r_{\rm sm}^\gamma \left(b_\gamma\frac{h}{v} + \frac{1}{2}b'_\gamma\left(\frac{h}{v}\right)^2\right) F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{16\pi} r_{\rm sm}^g \left(b_g\frac{h}{v} + \frac{1}{2}b'_g\left(\frac{h}{v}\right)^2\right) G_{\mu\nu}^a G^{a\mu\nu} \qquad (2.2)$$

NB: b_i=1, c_i=0 mean SM-like

- Models are ubiquitous, and singlet scalar is versatile:

Model	Nonzero c_F's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ, c_{h^2}
Dilaton	$c_g, c_W, c_Z, c_\gamma, c_{h^2}$
Vectorlike Quarks	$c_g, c_\gamma, c_{Z\gamma}, c_{h^2}$
Vectorlike Leptons	$c_\gamma, c_{Z\gamma}, c_{h^2}$
New Charged Vector bosons	c_γ, c_{h^2}
Extra charged scalar bosons	

- If Hidden fermion is DM, s is needed for correct thermal relic density.

$$\mathcal{L}_{\rm hidden} = \mathcal{L}_S + \mathcal{L}_\psi - \lambda S \overline{\psi}\psi,$$
$$\mathcal{L}_{\rm portal} = -\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H,$$

- If an extra vector exists, s should break gauge symmetry. Gauge symmetry may needed for various reasons: just another force, or ensuring DM stability, etc...

- Condensation can provide new mass scale.

- Singlet-Higgs mixing is just gauge invariant, renormalizable.

$$\mathcal{L}_{\text{portal}} = -\mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H,$$

- S and Mixing eventually modify Higgs properties!
- Many interesting examples are built to enhance Higgs-to-diphoton rate.

$$l_4 = \begin{pmatrix} \nu_4 \\ e_4 \end{pmatrix} \sim (1,2,-1/2),\ e_4^c \sim (1,1,1),$$

$$\tilde{l}_4 = \begin{pmatrix} \tilde{e}_4 \\ \tilde{\nu}_4 \end{pmatrix} \sim (1,\bar{2},1/2),\ \ \tilde{e}_4^c \sim (1,1,-1),$$

$$\begin{aligned} -\mathcal{L} = &\, M_l l_4 \tilde{l}_4 + M_e e_4^c \tilde{e}_4^c + M \\ &+ y_e H l_4 e_4^c + \tilde{y}_e \tilde{l}_4 H^\dagger \tilde{e}_4^c - \\ &+ \frac{x_l}{\sqrt{2}} S l_4 \tilde{l}_4 + \frac{x_e}{\sqrt{2}} S e_4^c \tilde{e}_4^c \end{aligned}$$

$$\mathcal{M}_e' = \begin{pmatrix} M_l + x_l w/\sqrt{2} & \tilde{y}_e v/\sqrt{2} \\ y_e v/\sqrt{2} & M_e + x_e w/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L} \supset \frac{\alpha}{16\pi v} b_{EM} \left(\frac{\partial}{\partial \log v} \log\det \mathcal{M}\mathcal{M}^\dagger \right) h F_{\mu\nu} F^{\mu\nu}$$

Mixing

Direct coupling to Higgs

inherit from singlet coupling

$$\mu_{\gamma\gamma} = \left| c_\theta + \frac{v}{\sqrt{2}A_\gamma^{SM}} \left[y c_\theta \left(\frac{A_{1/2}(m_{e_1})}{m_{e_1}} - \frac{A_{1/2}(m_{e_2})}{m_{e_2}} \right) + x s_\theta \left(\frac{A_{1/2}(m_{e_1})}{m_{e_1}} + \frac{A_{1/2}(m_{e_2})}{m_{e_2}} \right) \right] \right|^2 \quad (27$$

- After all, signal is modified by three sources.
- This structure can’t be revealed by just measuring single mu_gamma and fit any Higgs parameter to it.
- Our lagrangian actually has mixing angle, y, x as free parameters to fit. Although not perfect and too early to say conclusively, we will see what we can do.

- Production times BR is measured: signal strength. So hard to extract info on individual couplings.

$$R\left(\sigma(i \to h)\frac{\Gamma(h \to j)}{\Gamma^{tot}}\right) = \frac{\kappa_i^2\kappa_j^2}{\kappa_H^2} \qquad \kappa_i^2 = \frac{\Gamma(h \to i)}{\Gamma(h \to i)_{SM}} \quad \kappa_H^2 = \frac{\Gamma^{tot}}{\Gamma^{tot}_{SM}}$$

- Unknown width leaves overall normalization undetermined.

$$\frac{\kappa_i^2\kappa_j^2}{\kappa_H^2} \equiv \hat{\kappa}_i^2\hat{\kappa}_j^2,$$

- If nonSM decay width exists, generally no unique solution of global fit is found. But statistically useful info can still be obtained, and built-in restrictions may further provide info.

- Higgs is produced via several channel. They are properly weighted-summed by couplings and density.

$$R(\sigma(pp \to h)) = \kappa_g^2 \mathcal{A}_g + \kappa_W^2 \mathcal{A}_W + \kappa_Z^2 \mathcal{A}_Z$$

$$\mathcal{A}_g = \frac{\sigma(ggF)}{(\sigma(ggF) + \sigma(VBF))} \simeq 0.925,$$

$$R(\sigma(pp \to Vh)) = \kappa_W^2 \mathcal{A}'_W + \kappa_Z^2 \mathcal{A}'_Z$$

How to parameterize modifications to loop-induced gg fusion will be discussed later.

- How is decay width ratio, kappa, parameterized in terms of {alpha, b_i, c_i}?
- Tree-level decay to WW, ZZ, ff:

$$\kappa_i^2 = \frac{\Gamma(h \to i)}{\Gamma(h \to i)_{SM}} = (b_i c_\alpha - c_i s_\alpha)^2$$

- Loop induced decay to gg, gamma gamma:

$$\kappa_g^2 = (b_g c_\alpha - c_g s_\alpha)^2 = (c_\alpha(b_t \mathcal{C}_t + \Delta b_g) - c_g s_\alpha)^2$$

$$\kappa_\gamma^2 = (b_\gamma c_\alpha - c_\gamma s_\alpha)^2 = (c_\alpha(b_W \mathcal{B}_W + b_t \mathcal{B}_t + \Delta b_\gamma) - c_\gamma s_\alpha)^2$$

Scalar mixing

modification of W, top coupling

modification of diphoton coupling

inherit from singlet

- NB: b, Delta b, c are norm. to SM coupling.

$$\mathcal{B}_W = \frac{A_1(\tau_W)}{A_1(\tau_W) + N_c Q_t^2 A_{1/2}(\tau_t)} \simeq 1.283,$$

	channel	luminosity (fb^{-1})	μ	ref.
CMS	$\gamma\gamma$	24.7	$0.78^{+0.28}_{-0.26}$	[15]
	ZZ	24.7	$0.91^{+0.30}_{-0.24}$	[16]
	WW	24.7	$0.76^{+0.21}_{-0.21}$	[17]
	$\tau\tau$	24.3	$1.1^{+0.4}_{-0.4}$	[18]
	$b\bar{b}$	17	$1.3^{+0.7}_{-0.6}$	[19]
ATLAS	$\gamma\gamma$	25	$1.65^{+0.35}_{-0.30}$	[20]
	ZZ	25	$1.7^{+0.50}_{-0.40}$	[21]
	WW	25	$1.01^{+0.31}_{-0.31}$	[22]
	$\tau\tau$	18	$0.7^{+0.7}_{-0.7}$	[23]
	$b\bar{b}$	18	$-0.4^{+1.06}_{-1.06}$	[24]

- Moriond 2013 data used.
- Best fit values of each channel is used. The minimum of each channel occurs at slightly different mh.

- All signal strengths are *universally modified* if just scalar mixing(alpha) and/or non-SM width(kappa_H).

$\{\alpha, BR_{nonSM}\}$: In this case,

$$\kappa_{univ}^2 = c_\alpha^2, \qquad \kappa_H^2 = \frac{c_\alpha^2}{1 - BR_{nonSM}}.$$

- Data is parameterized by one while theory has two.

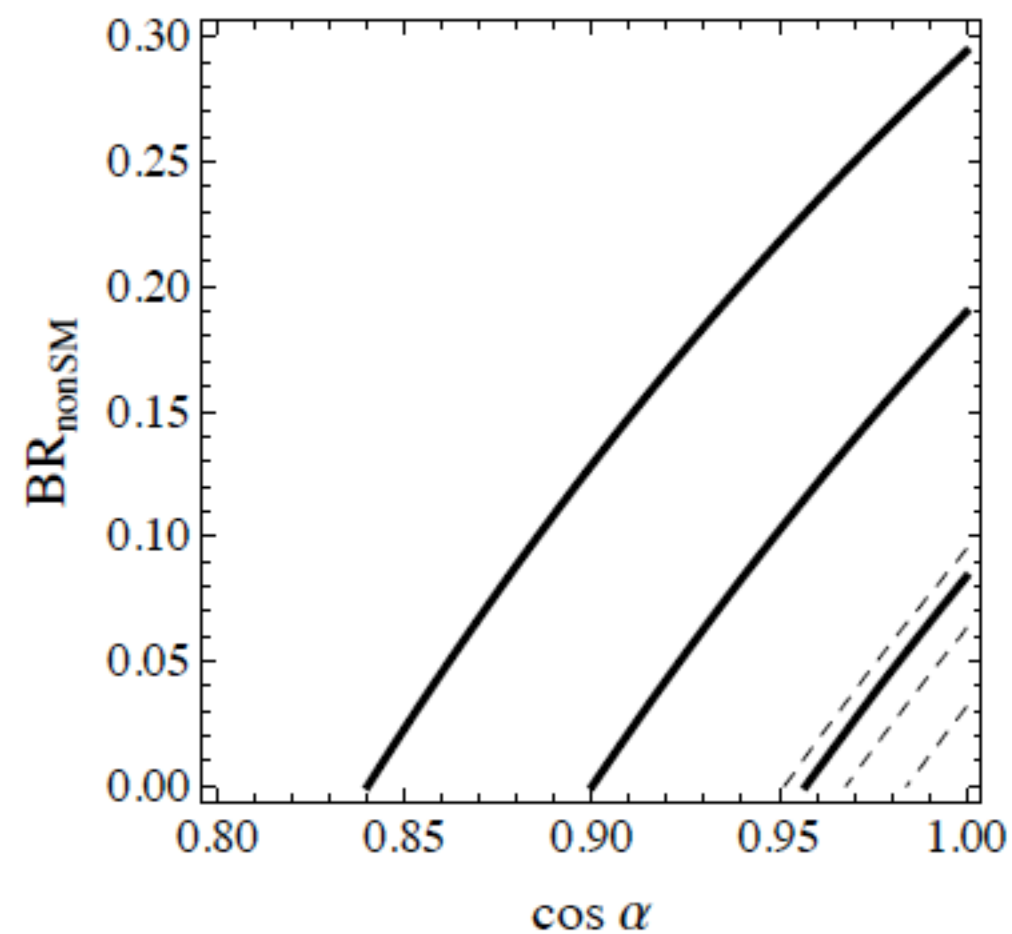
$$\mu_i = \kappa_{univ}^2 \frac{\kappa_{univ}^2}{\kappa_H^2} = \hat{\kappa}_{univ}^2 \hat{\kappa}_{univ}^2.$$

- Overall, enhancement is slightly preferred although not significant

$$\hat{\kappa}_{univ}^2 = 1.012^{+0.0517}_{-0.0549},$$

$BR_{nonSM} \leq 18.8\%$ at 95%C.L. if $c_\alpha = 1$ fixed

$c_\alpha \geq 0.904$ at 95%C.L. if $BR_{nonSM} = 0$ fixed



bi's only

	both	CMS	ATLAS
SM	$\chi^2/\nu = 12.01/10 = 1.20$	$2.33/5 = 0.466$	$9.69/5 = 1.94$
(Δb_γ)	(0.090) 11.19/9=1.24	(-0.117) 1.71/4=0.428	(0.28) 4.99/4=1.25
$(\Delta b_g, \Delta b_\gamma)$	(-0.018, 0.107) $11.13/8 = 1.39$	(-0.078, -0.048) $0.859/3 = 0.286$	(0.11, 0.17) $4.14/3 = 1.38$
(b_V, b_f)	(1.031, 0.962) $11.74/8 = 1.47$	(0.898, 1.021) 0.808/3=0.27	(1.345, 0.808) 4.52/3=1.51
$(b_V \leq 1, b_u, b_d)$	(1.0, 0.969, 0.938) $11.86/7 = 1.69$		
$(\Delta b_g, \Delta b_\gamma, b_V, b_f)$	(0.041, 0.117, 0.941, 0.961) $11.07/6 = 1.85$		

Table 5. Best-fit results using b_i only from both CMS and ATLAS data as well as individual. Errors are shown in text.

General Cases

Models	Best-fit results	χ^2/ν
SM		$12.01/10 = 1.20$
universal modification $(\hat{\kappa}^2_{univ})$ (BR_{nonSM}) $(\cos\alpha)$	 (1.012) $\leq 18.8\%$ at 95%CL ≥ 0.904 at 95%CL	 $11.96/9 = 1.33$
VL lepton, W', S' (c_α, c_γ)	 (0.98, -0.55)	 $11.1/8 = 1.39$
VL quark $(c_\alpha, c_g, c_\gamma)$	 (0.947, -0.128, -0.313)	 $11.1/7 = 1.58$
$(c_\alpha, c_\gamma, Br_{nonSM})$	$BR_{nonSM} \leq 24\%$ at 95%CL	$11.1/8 = 1.39$
$(c_\alpha, c_g, c_\gamma, Br_{nonSM})$	$BR_{nonSM} \leq 39\%$ at 95%CL	$11.1/7 = 1.58$
singlet mixed-in $\hat{\kappa}$ $(\hat{\kappa}^2_g, \hat{\kappa}^2_\gamma, \hat{\kappa}^2_{mix})$	 (1.03, 1.15, 0.942)	 $11.1/7 = 1.58$
singlet mixed-in theory $(\hat{c}_g, \hat{c}_\gamma, \hat{c}_\alpha)$	 (-0.176, -0.432, 0.971)	 $11.1/7 = 1.58$

Table 7. Summary of best-fit results with scalar mixing. If BR_{nonSM} is included in fit, no unique solution is found, and its upper bound at 95%CL is presented. Only central values of best-fit are shown, and errors can be found in text.

Results

- Although it is premature to draw a definitive conclusion due to large uncertainties, the SM gives the best fit in terms of the chi^2/d.o.f.
- Even if we include more parameters with new physics, it does not improve the overall fit very much
- Mixing with an extra singlet scalar is slightly disfavored now, but the CMS data alone favors such a scenario

Important to seek for

- The 2nd singlet-like scalar boson (which might couple to the DM)
- This scalar is very generic in any DM models with hidden sector (with local dark gauge symmetries)
- And can solve some puzzles in CDM models with DM self-interaction from light mediator (2nd scalar or dark gauge boson)