Scale Inv. Extension of the SM with Strongly Interacting Hidden Sector

EWSB and CDM from hQCD

P. Ko (KIAS)

SUSY : Model Building and Phenomenology
IPMU, Dec. 2-4 (2013)

SM Chapter is being closed

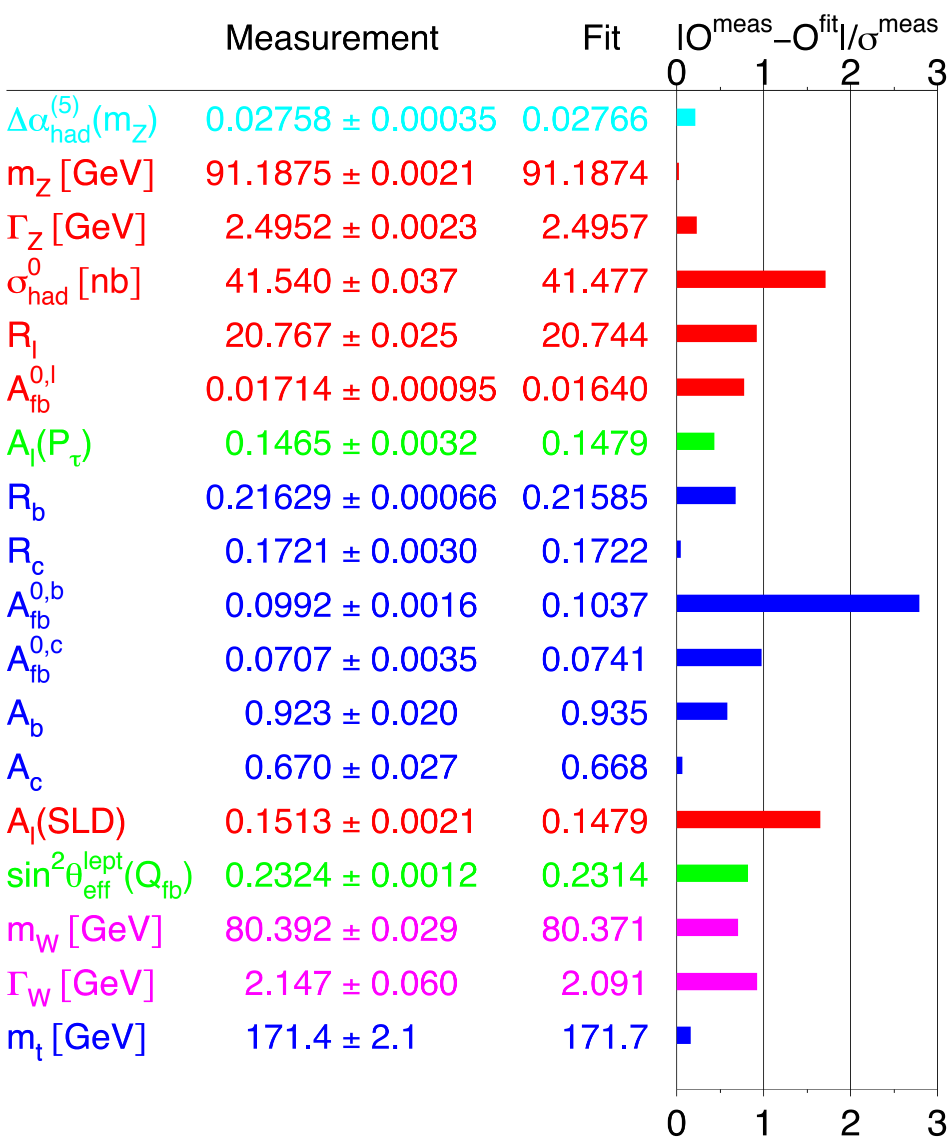
- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

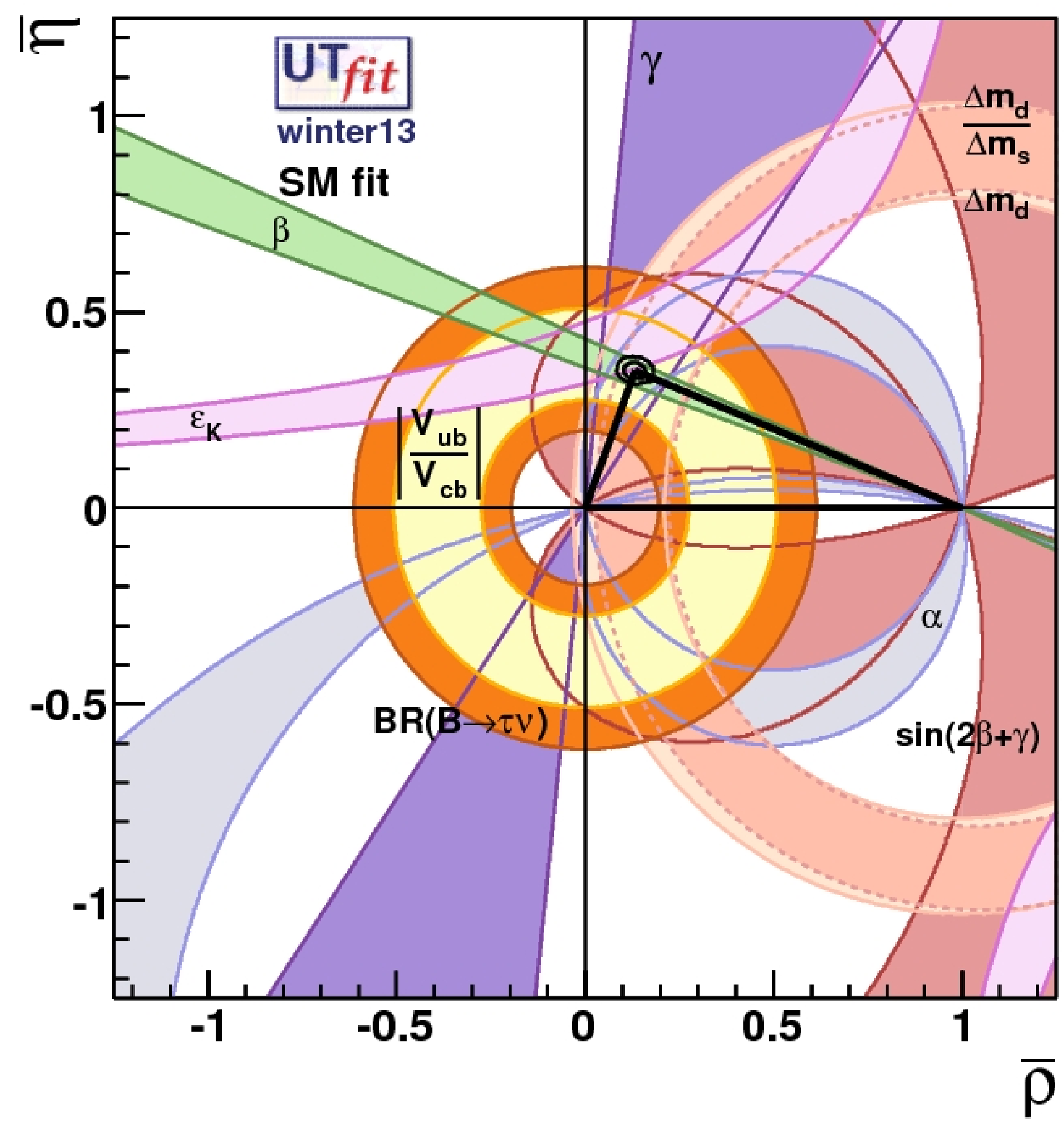
SM Lagrangian

$$
\begin{aligned}
\mathcal{L}_{MSM} = & -\frac{1}{2g_s^2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2g^2}\mathrm{Tr}W_{\mu\nu}W^{\mu\nu} \\
& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} + i\frac{\theta}{16\pi^2}\mathrm{Tr}G_{\mu\nu}\tilde{G}^{\mu\nu} + M_{Pl}^2 R \\
& +|D_\mu H|^2 + \bar{Q}_i i\not{D} Q_i + \bar{U}_i i\not{D} U_i + \bar{D}_i i\not{D} D_i \\
& +\bar{L}_i i\not{D} L_i + \bar{E}_i i\not{D} E_i - \frac{\lambda}{2}\left(H^\dagger H - \frac{v^2}{2}\right)^2 \\
& -\left(h_u^{ij} Q_i U_j \tilde{H} + h_d^{ij} Q_i D_j H + h_l^{ij} L_i E_j H + c.c.\right) . (1)
\end{aligned}
$$

Based on local gauge principle

EWPT & CKM



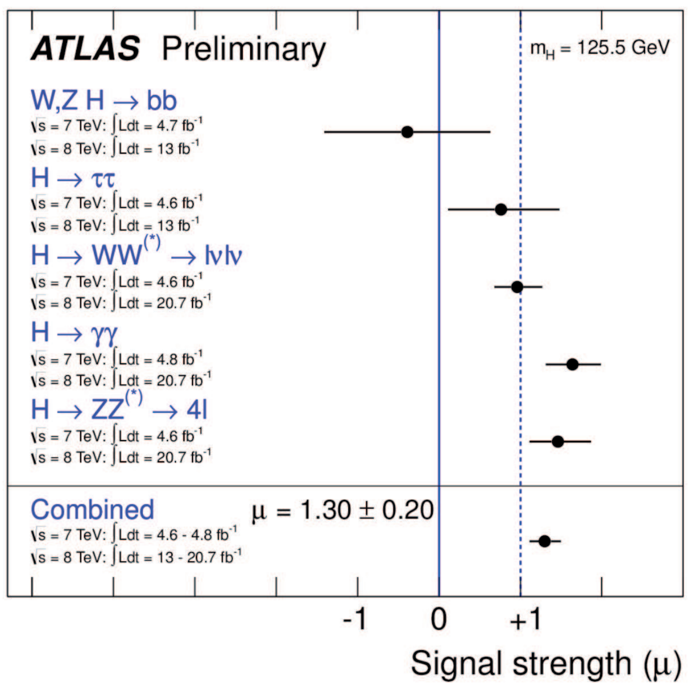


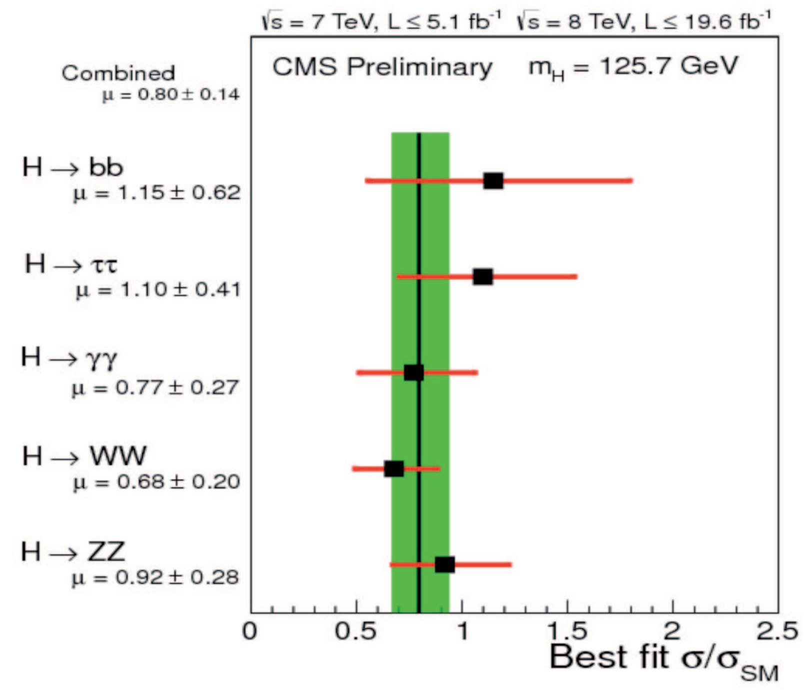
Almost Perfect !

Updates@LHCP

Signal Strengths

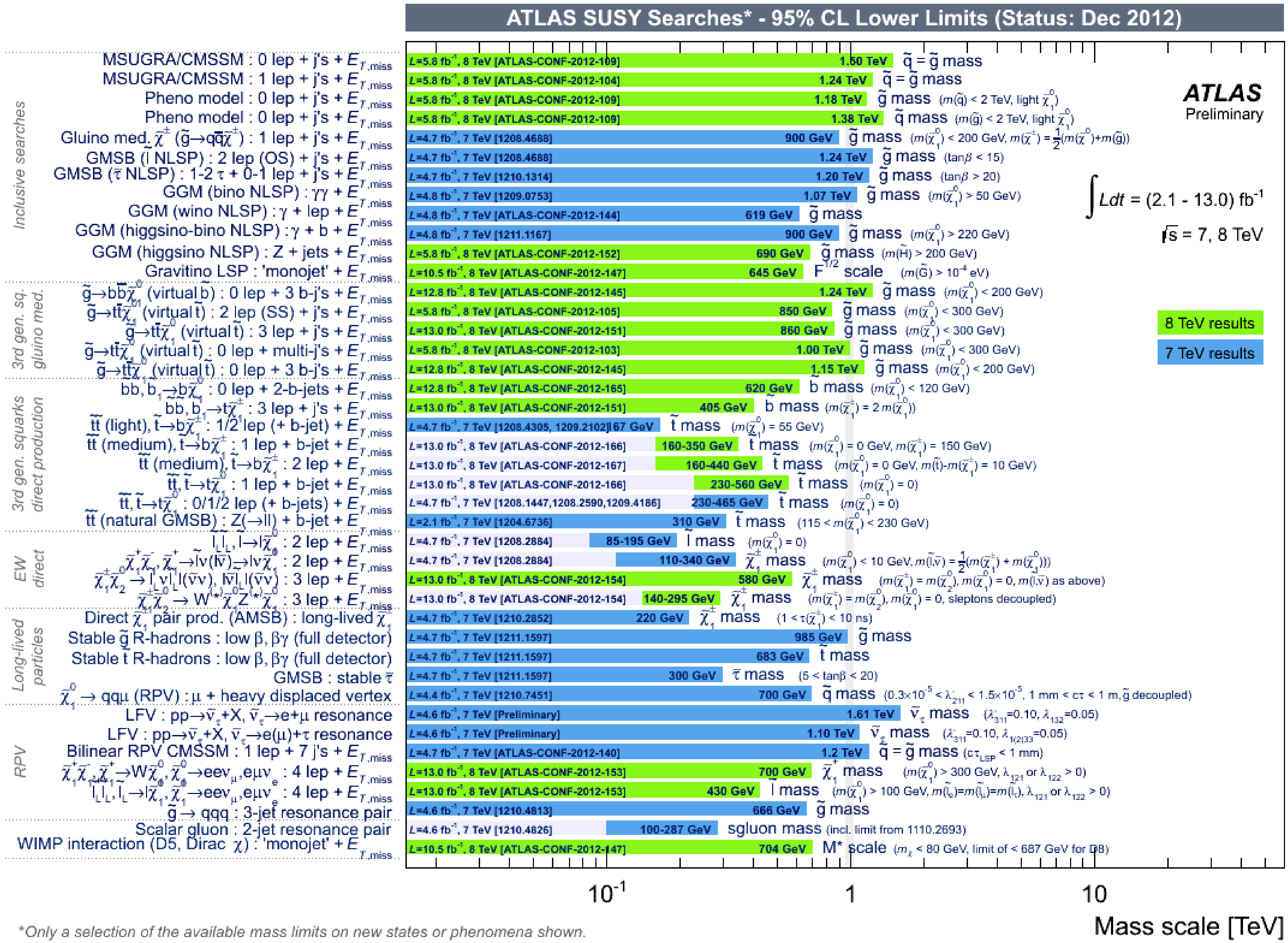
$$\mu \equiv \frac{\sigma \cdot \mathrm{Br}}{\sigma_{\mathrm{SM}} \cdot \mathrm{Br}_{\mathrm{SM}}}$$





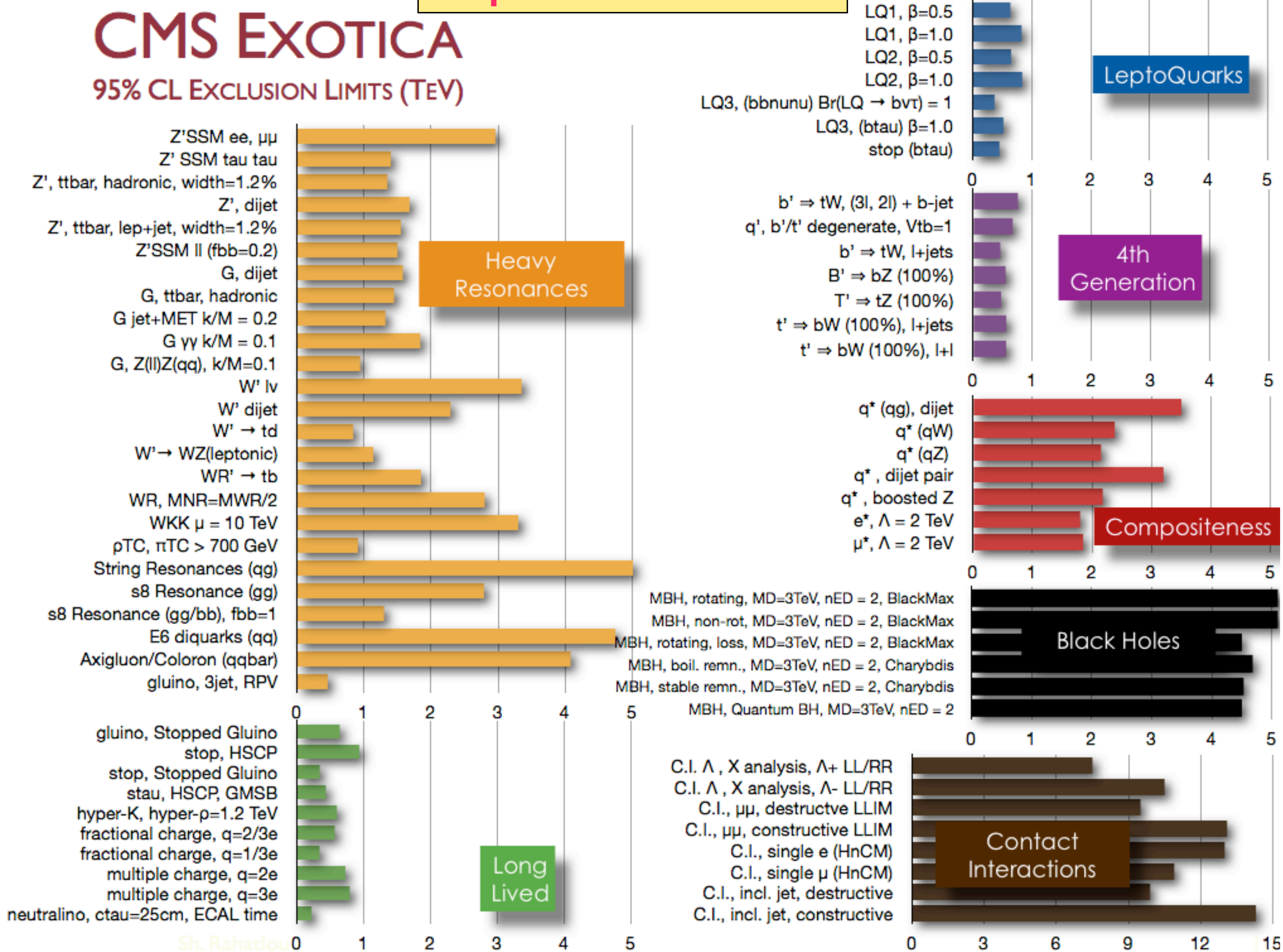
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

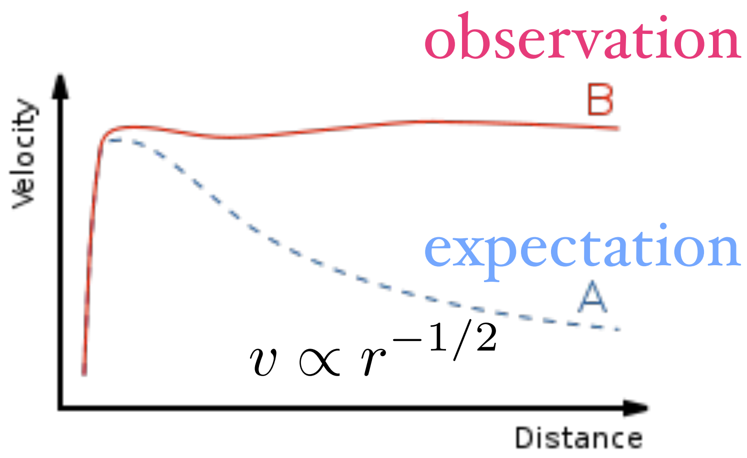


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Aspen this March



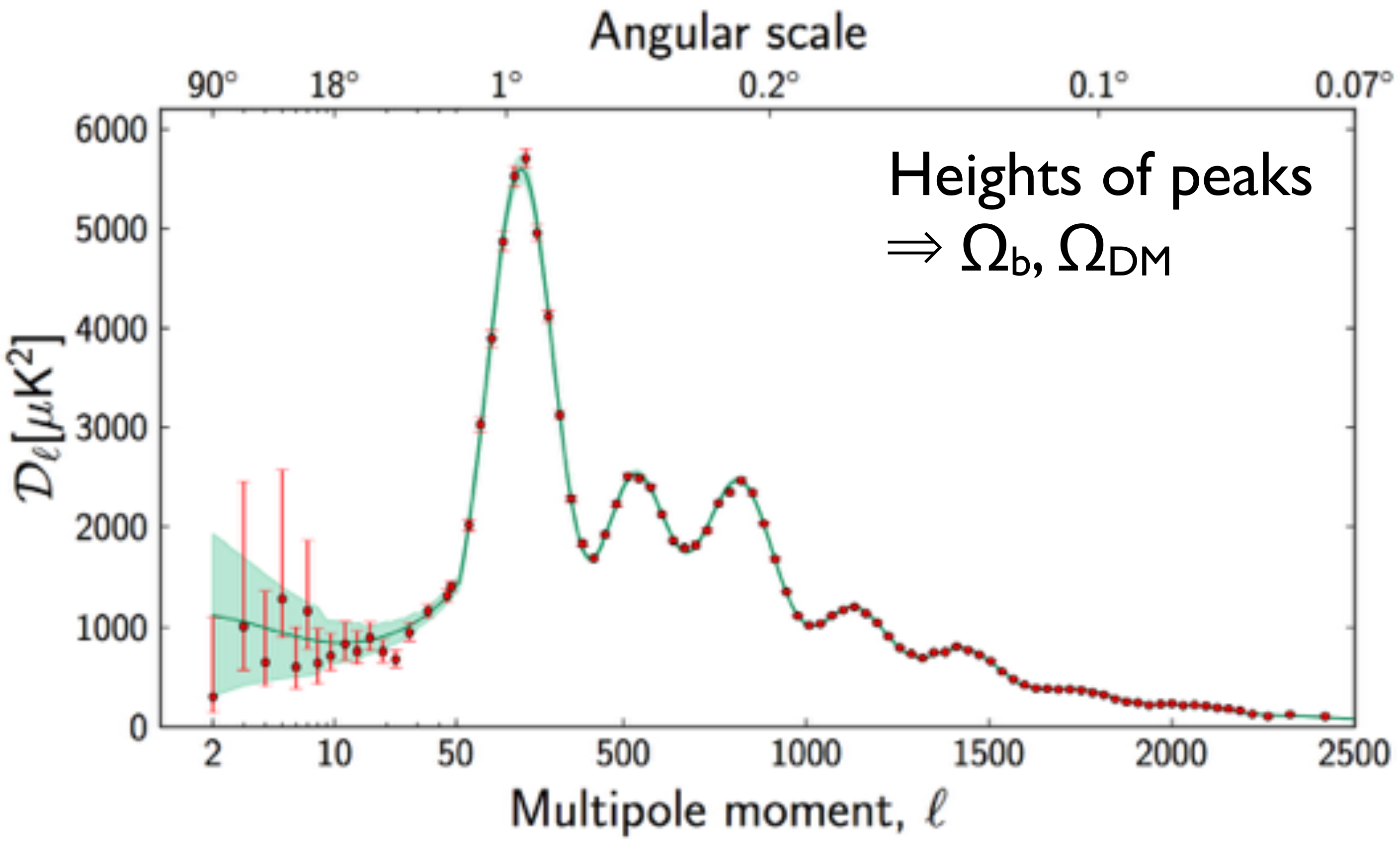
- Dark & visible matter and dark energy, neutrinos



Jan Oort (1932), Fritz Zwicky (1933)

Bullet cluster

Strong gravitational lensing in Abell 1689

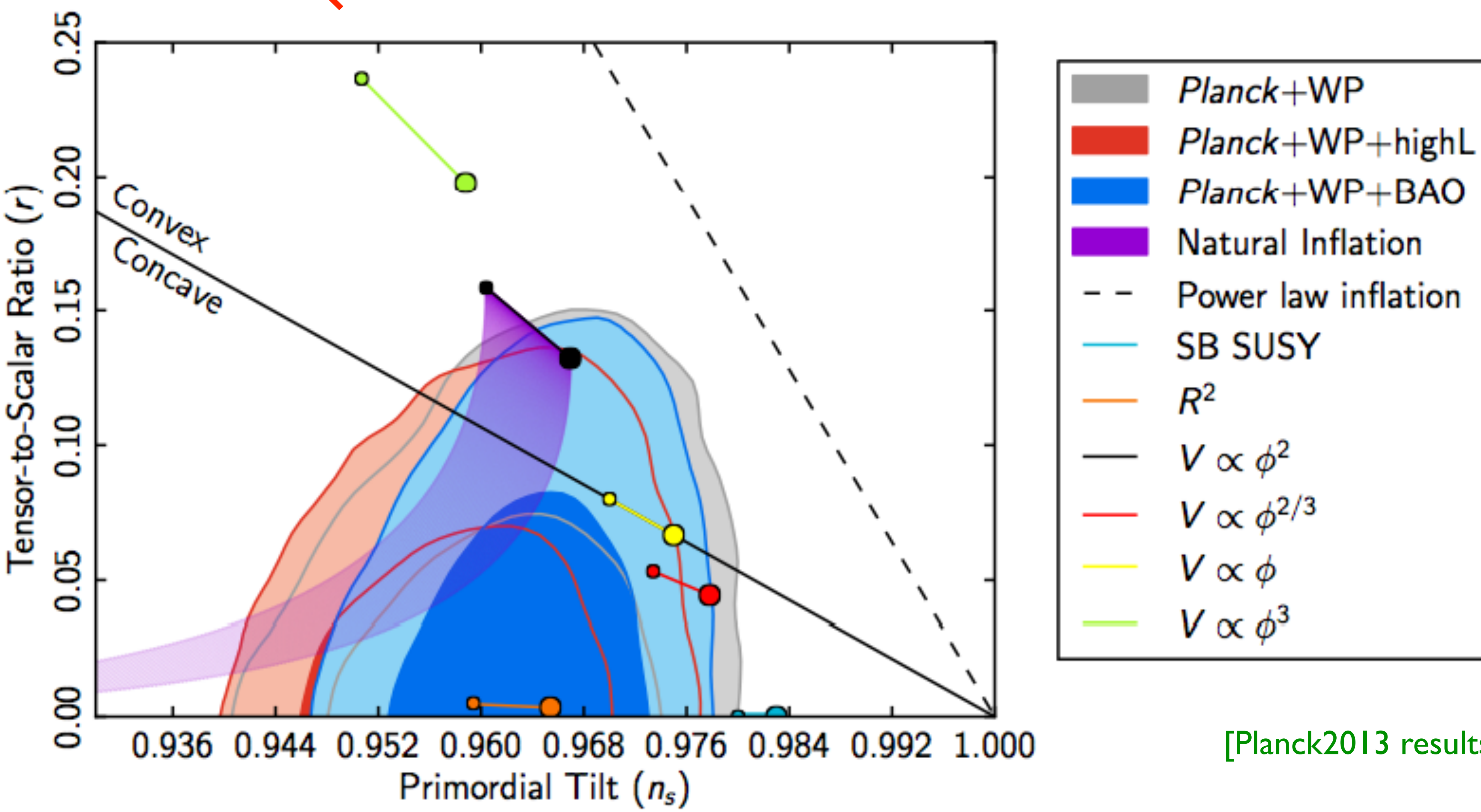


$$\Omega_b \simeq 0.048$$
$$\Omega_{DM} \simeq 0.259$$
$$\Omega_\Lambda \simeq 0.691$$

(Planck+WP+highL+BAO)

Inflation models in light of Planck2013 data

$\Rightarrow V \propto \phi^4$



[Planck2013 results]

Maybe it is right time to think about what LHC and Planck data tells us about New Physics@EW 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 preparation with D.W.Jung)
- Singlet mixing with SM Higgs

Contents

- Underlying Principles : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
- Scale Inv Extension of the SM with strongly Interacting Hidden Sector : EWSB and CDM from hQCD; All Masses including DM mass from Dim Transmutation in hQCD
- Unbroken $U(1)_X$: Singlet Portal and Dark Radiation
- Higgs Phenomenology & Dark Radiation : Universal Suppression of Higgs signal strength and extra neutral scalar, dark radiation, etc.

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 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)

(And a few works in preparation)

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; Linder 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
- Renormalizability (with some caveats)
- Local Dark Gauge Symmetry (unbroken or spontaneously broken) : Dark matter feels gauge force like most of other particles

Common Guiding Principles

- Fine tuning problems : Higgs mass, Strong CP, Cosmological Constant
- Data driven problems : New particles or new phenomena (Muon g-2, Top FBA, Wjj excess, Top FBA, H2digamma, Fermi/LAT 130 GeV gamma rays, etc.)
- Theoretical problems : Violation of fundamental principles of QFT [Unitarity, Anomaly Cancellation, (Renormalizability)]

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 $\beta(g)$, 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

New Physics Scale ?

- No theory for predicting new physics scale, if our renormalizable model predictions agree well with the data
- Only data can tell where the NP scales are
- Given models working up to some energy scale, we can tell new physics scale if Unitarity is violated, or Landau pole or Vacuum Instability appears
- Otherwise we don't know for sure where is new physics scale

Neutral Kaon System

- Often said that the charm is predicted in order to solve the quadratic divergence in Delta MK
- This is not really true, since this comes from anomalous model (SM with three quarks and leptons are anomalous)
- If we imposed anomaly cancellation, we would have no quadratic div in Delta MK and no large FCNC from the beginning
- Important to work within theoretically consistent model Lagrangian to get correct phenomenology

Guiding Principles

- Data driven problems : New particles or new phenomena (DM, Neutrino masses and mixings, baryon # asymmetry, etc)
- Theoretical problems : Unitarity, Anomaly Cancellation, (Renormalizability) Very important to keep them
- Fine tuning problems : Higgs mass, Strong CP, Cosmological Constant, etc >> << Let me postpone considering these problems for the moment, since it does not violate any theoretical principles >> Anthropic principle (?) >><< We may miss some interesting possibilities if we stick to this principle too much in this era of LHC and many other expt's>>

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

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

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

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

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]].

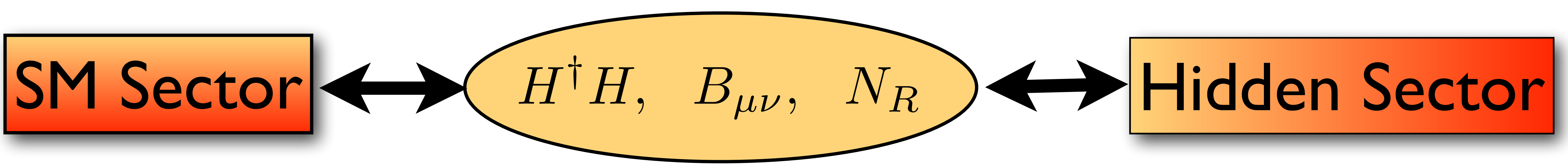
P. Ko, Int. J. Mod. Phys. A **23**, 3348 (2008) [arXiv:0801.4284 [hep-ph]]; P. Ko, AIP Conf. Proc. **1178**, 37 (2009); P. Ko, PoS ICHEP **2010**, 436 (2010) [arXiv:1012.0103 [hep-ph]]; P. Ko, AIP Conf. Proc. **1467**, 219 (2012).

- 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)

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



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

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

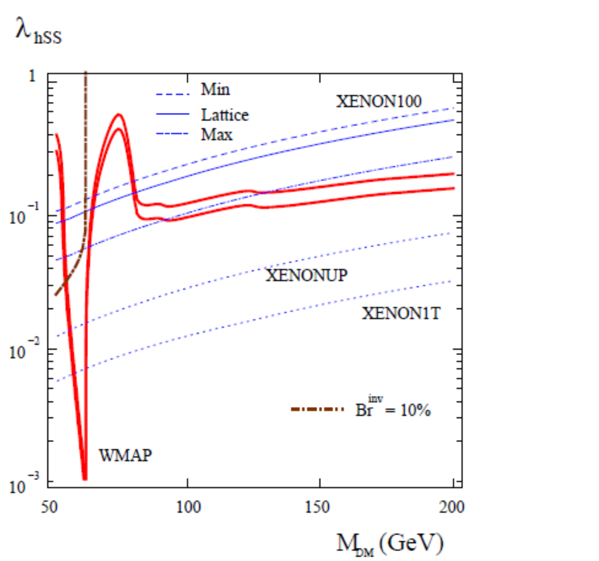


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

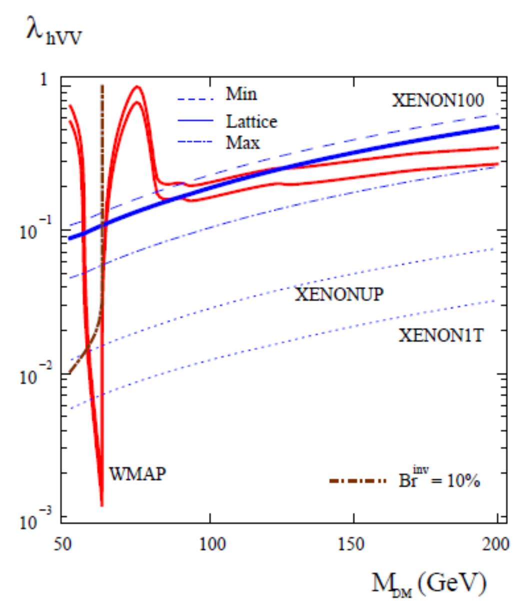


FIG. 2. Same as Fig. 1 for vector DM particles.

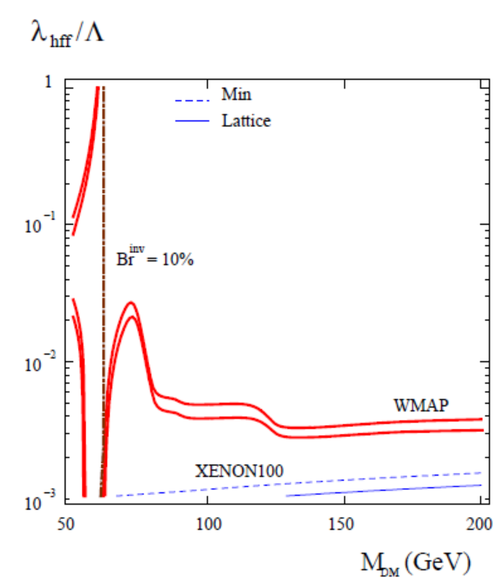


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

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

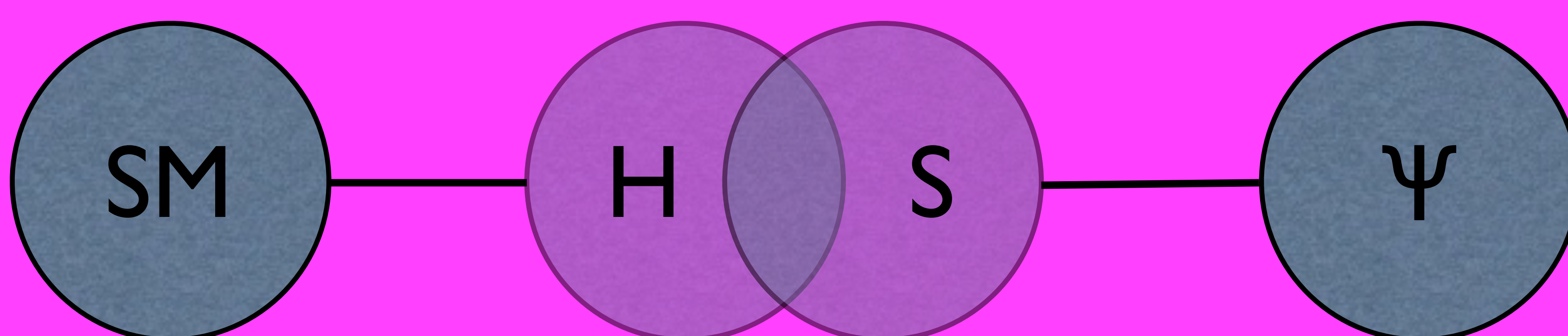
- Strong bounds from direct detection exp's put stringent bounds on the Higgs coupling to the dark matters
- So, the invisible Higgs decay is suppressed
- There is only one SM Higgs boson with the signal strengths equal to ONE if the invisible Higgs decay is ignored
- All these conclusions are not reproduced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

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

at vacuum

$$M_{\rm Higgs}^2 \equiv \begin{pmatrix} m_{hh}^2 & m_{hs}^2 \\ m_{hs}^2 & m_{ss}^2 \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$$

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

⇐ Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

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

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

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

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

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)

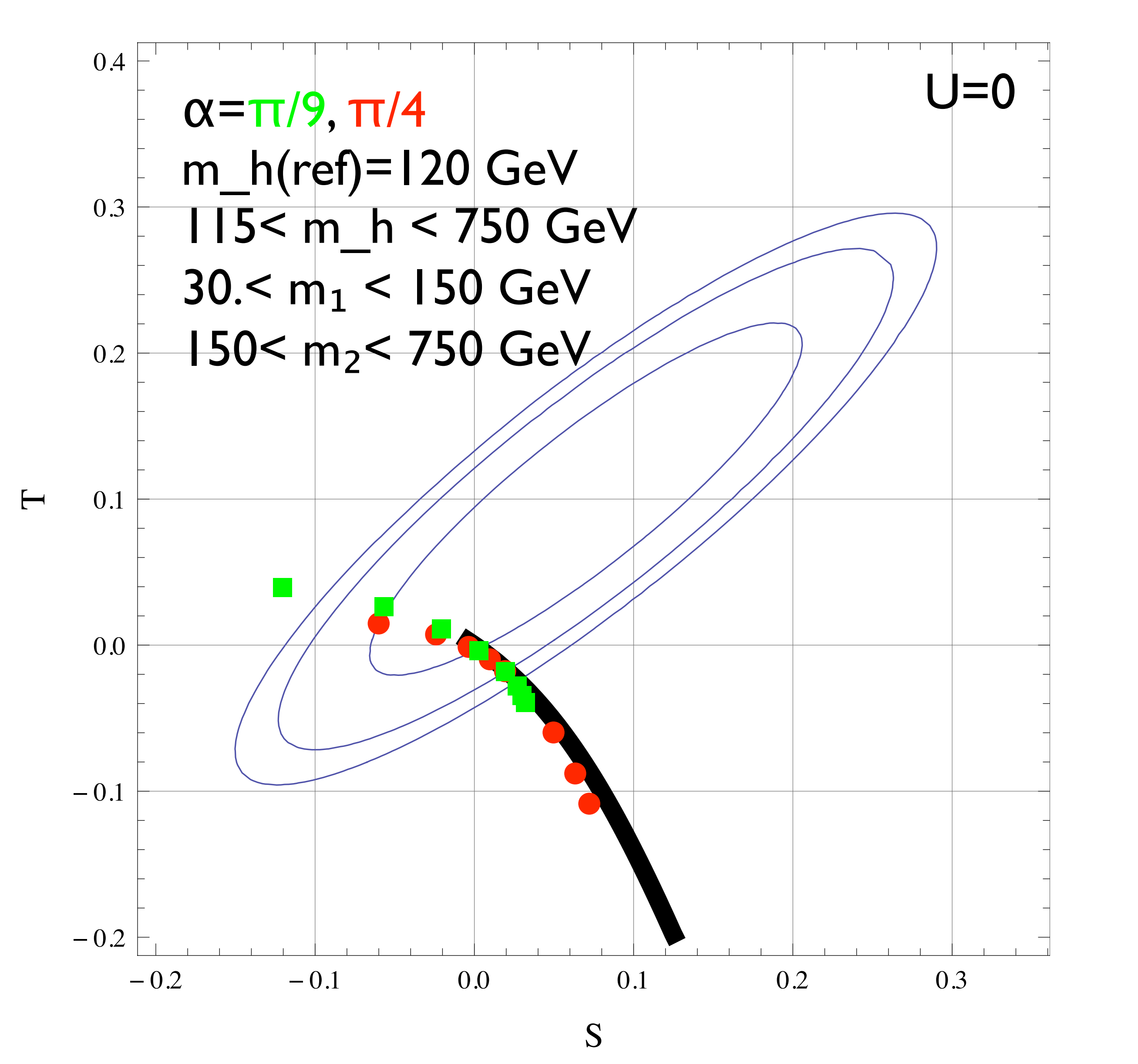
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right]$$

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

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

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

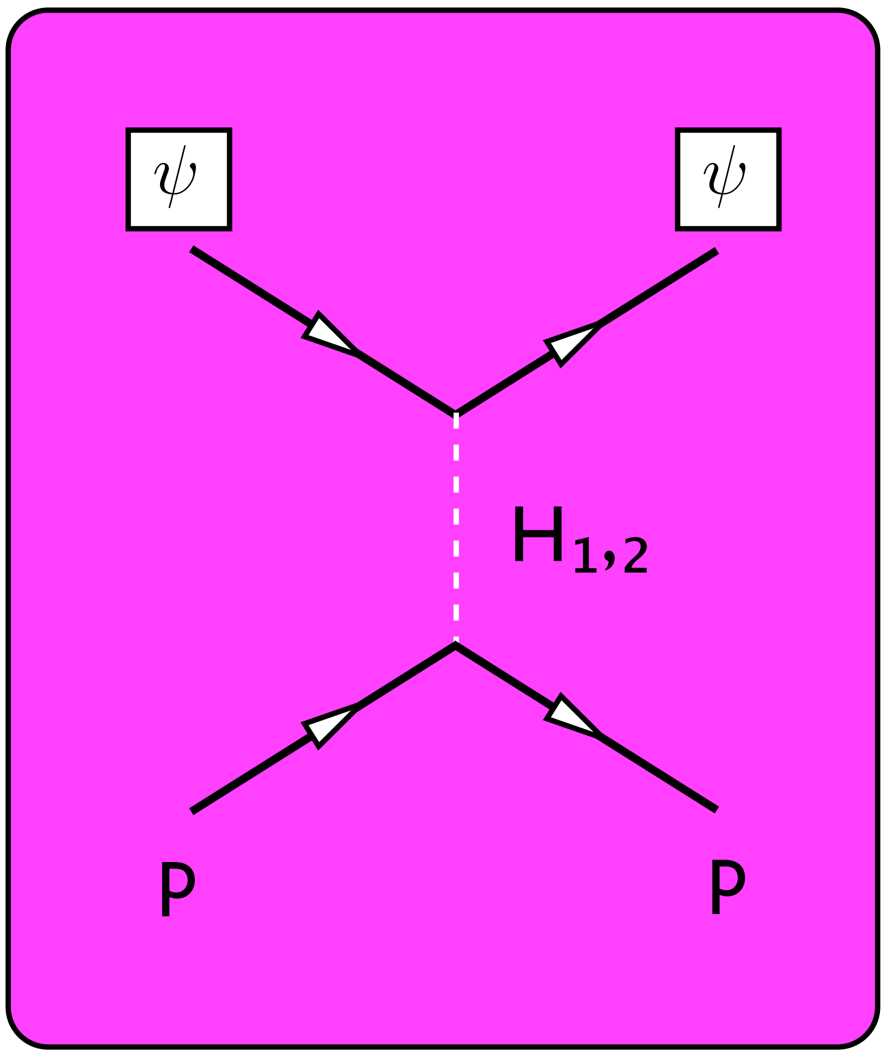
Same for T and U

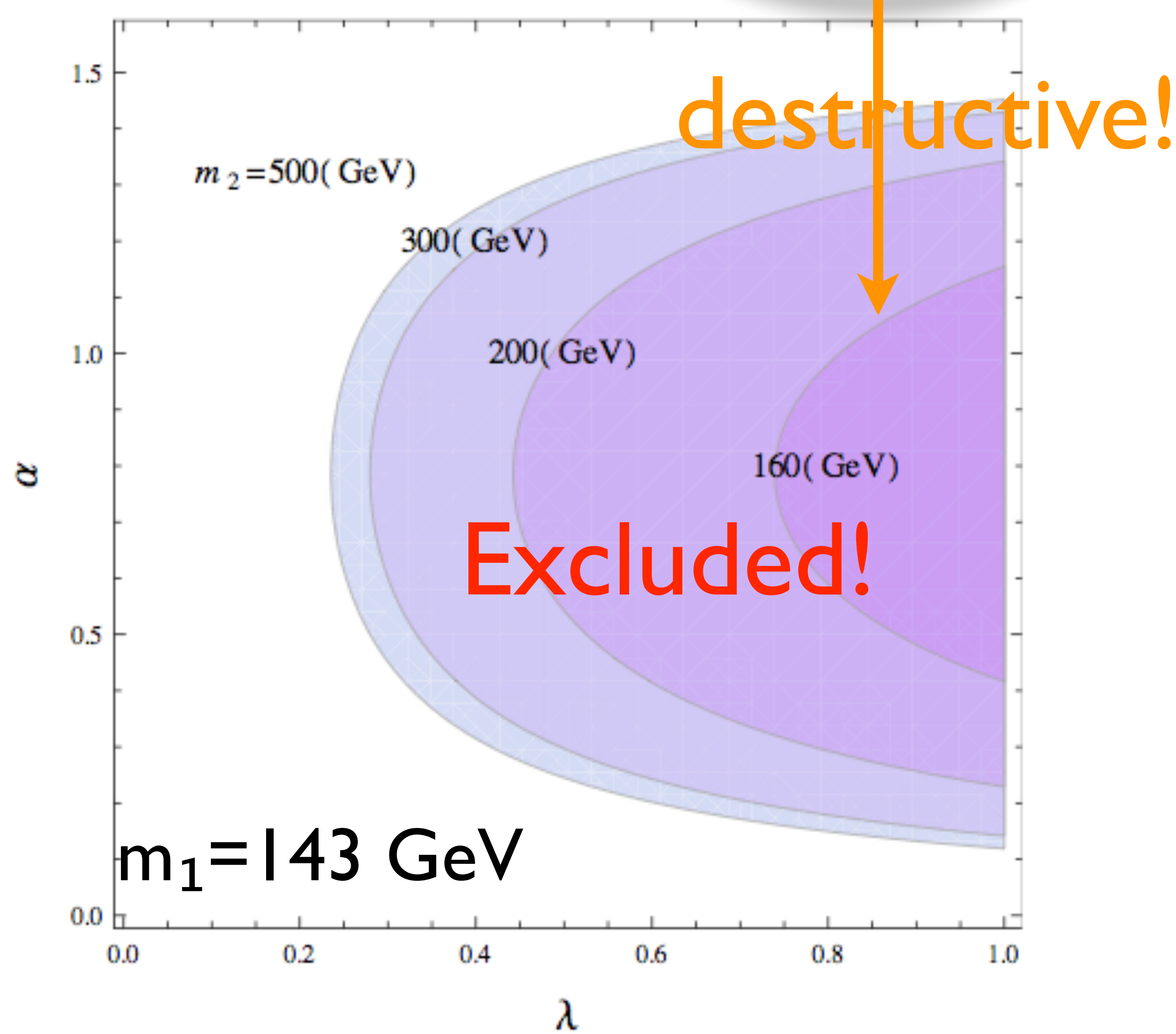


Constraints

- Dark matter to nucleon cross section (constraint)

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





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

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

- Only one Higgs boson (alpha = 0)

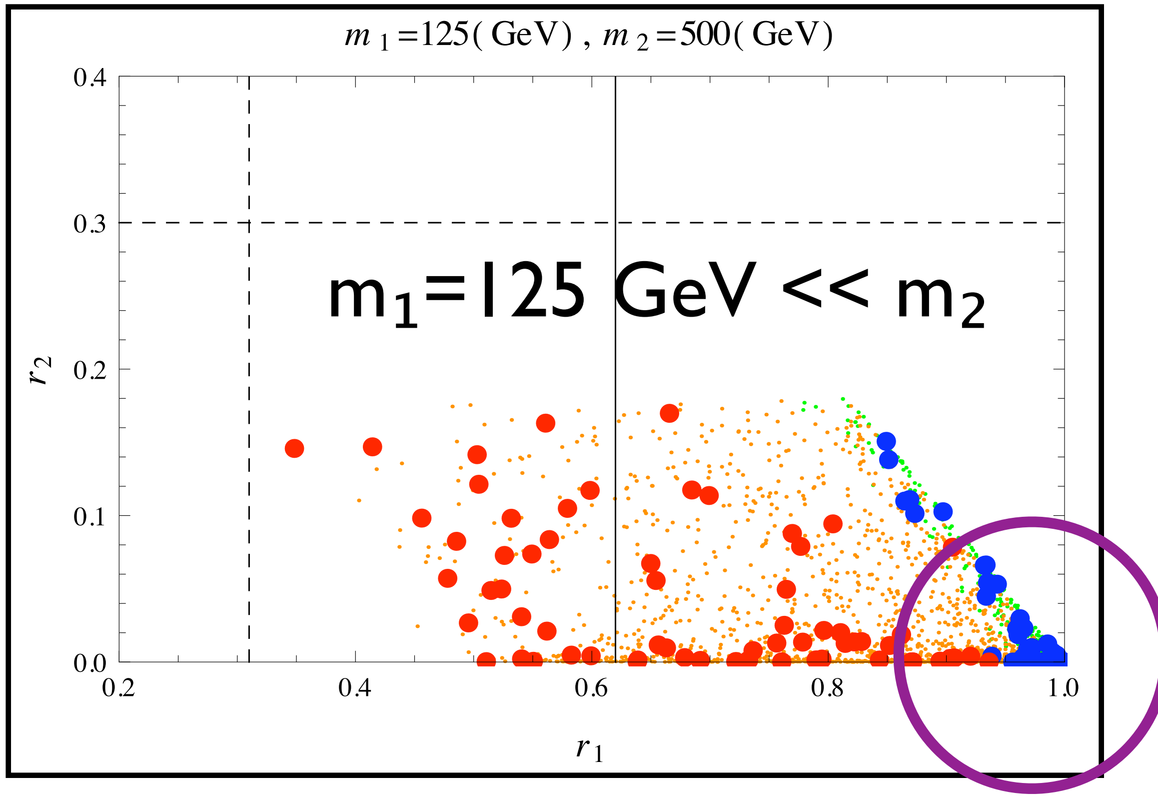
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

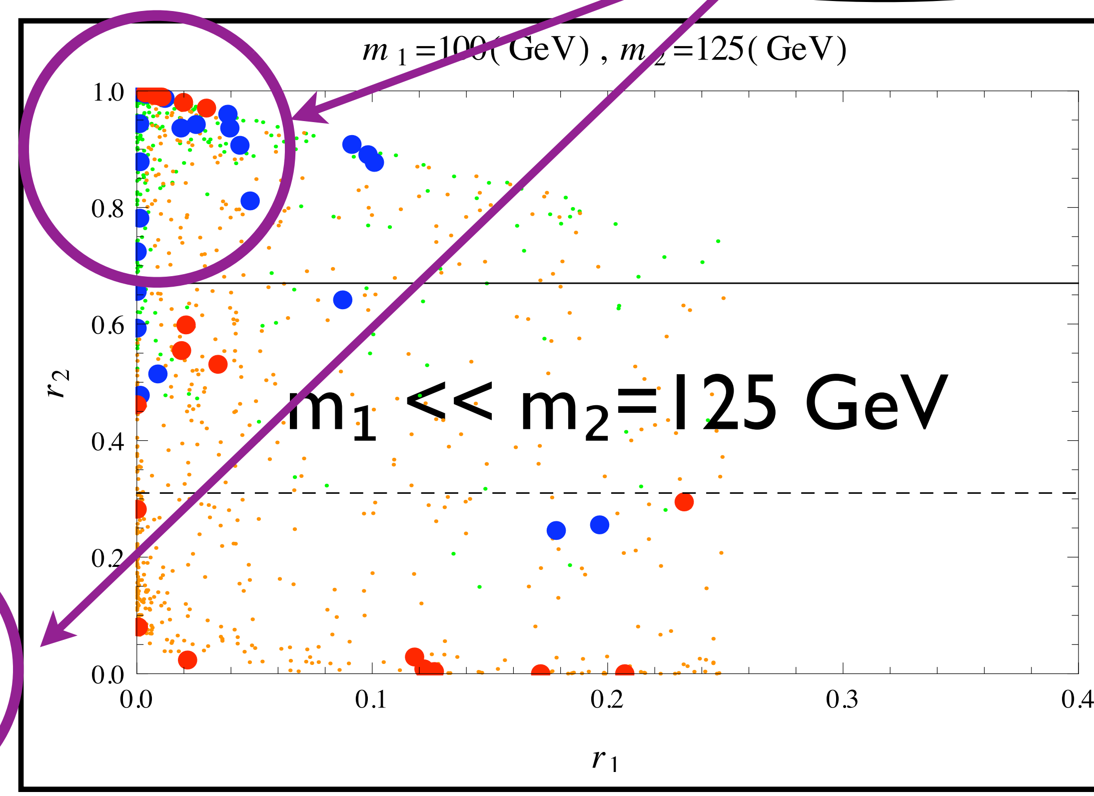
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

Discovery possibility

LHC data for 125 GeV resonance

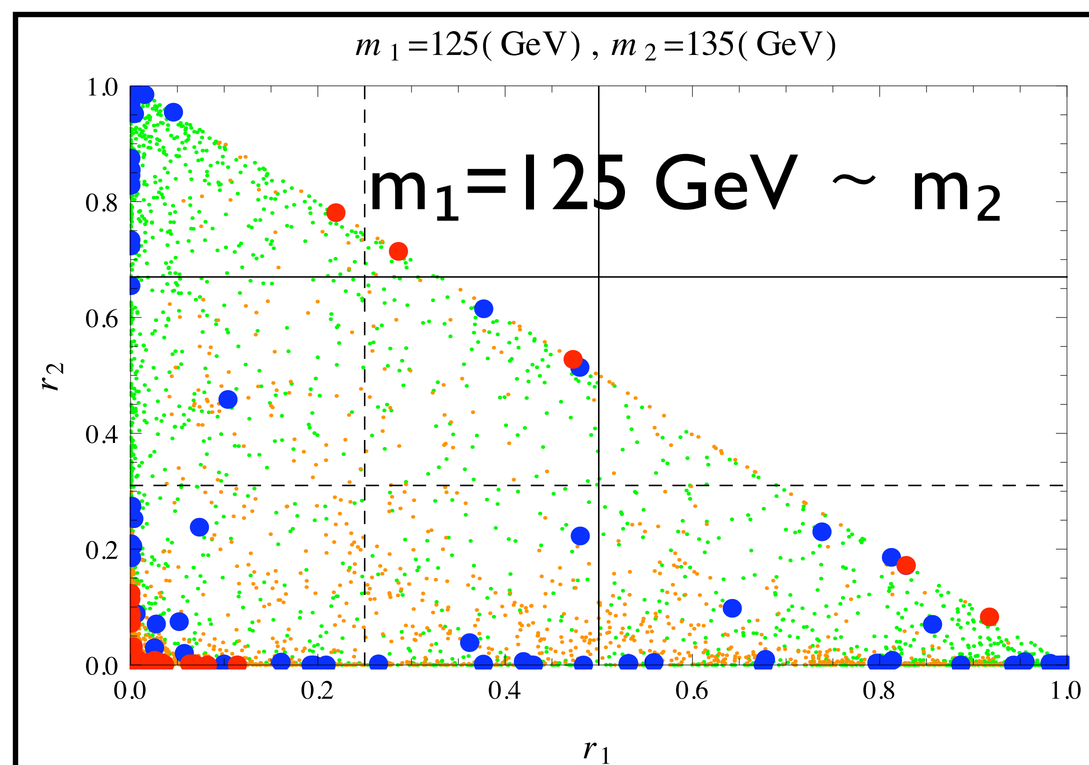
- Signal strength (r_2 vs r_1)





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.

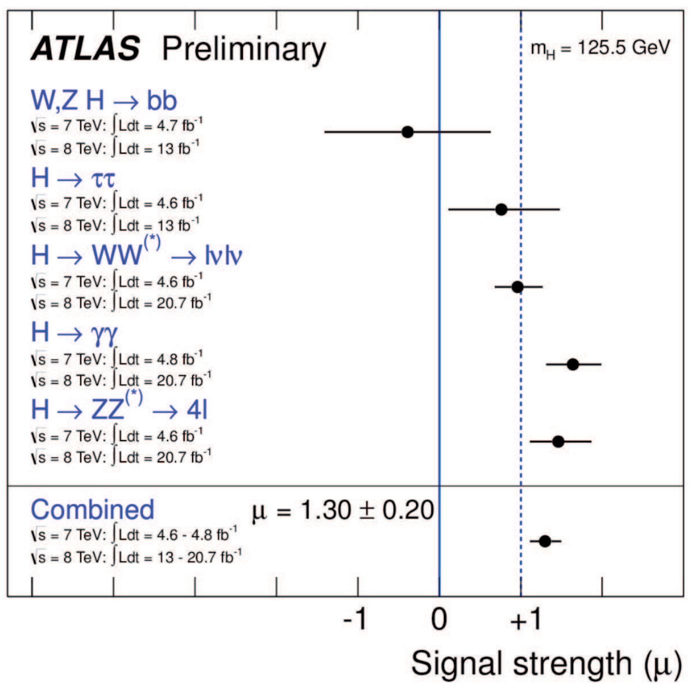


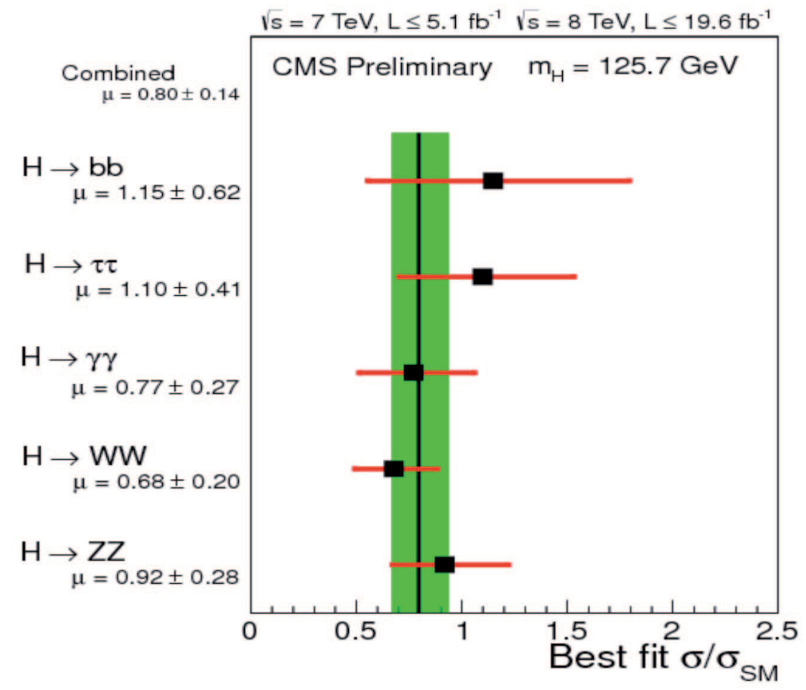
- : Ω(x),σ_p(x)
- : Ω(x),σ_p(o)
- : Ω(o),σ_p(x)
- : Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

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



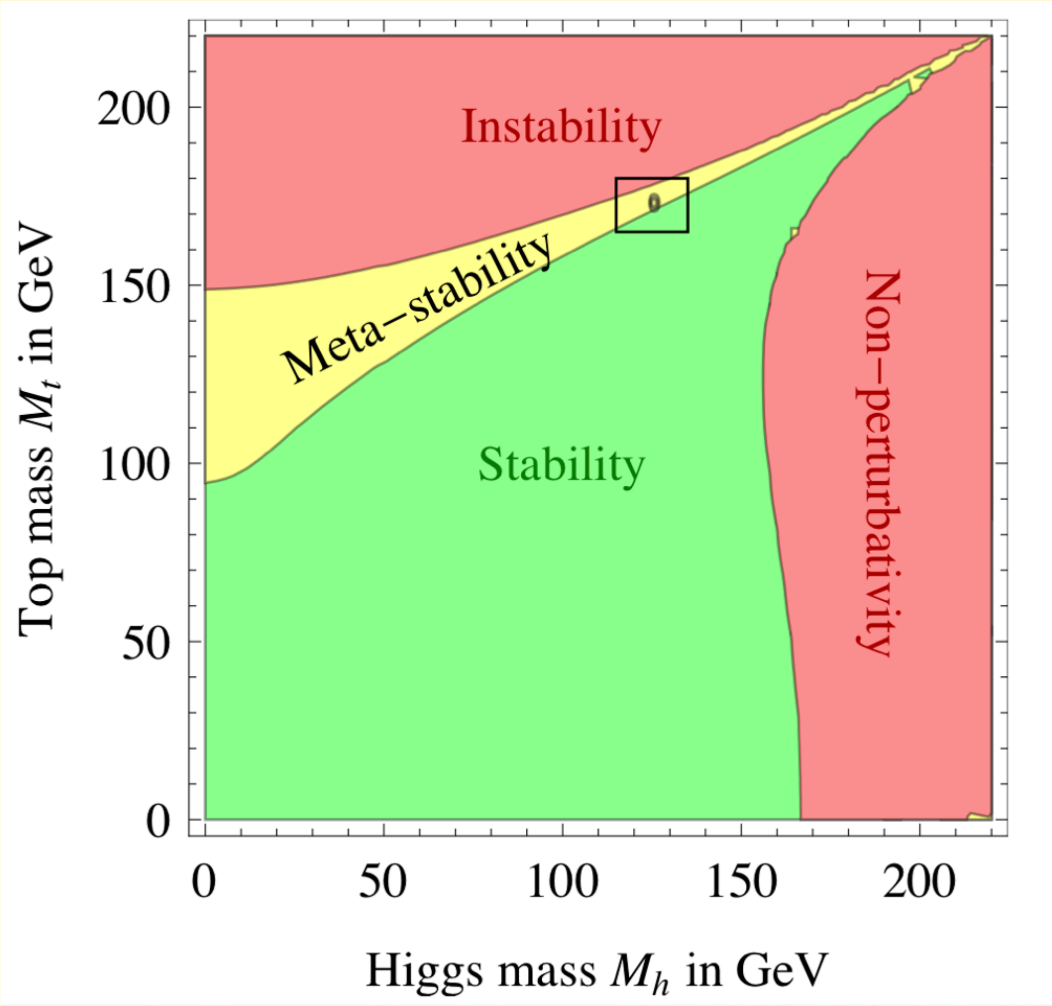


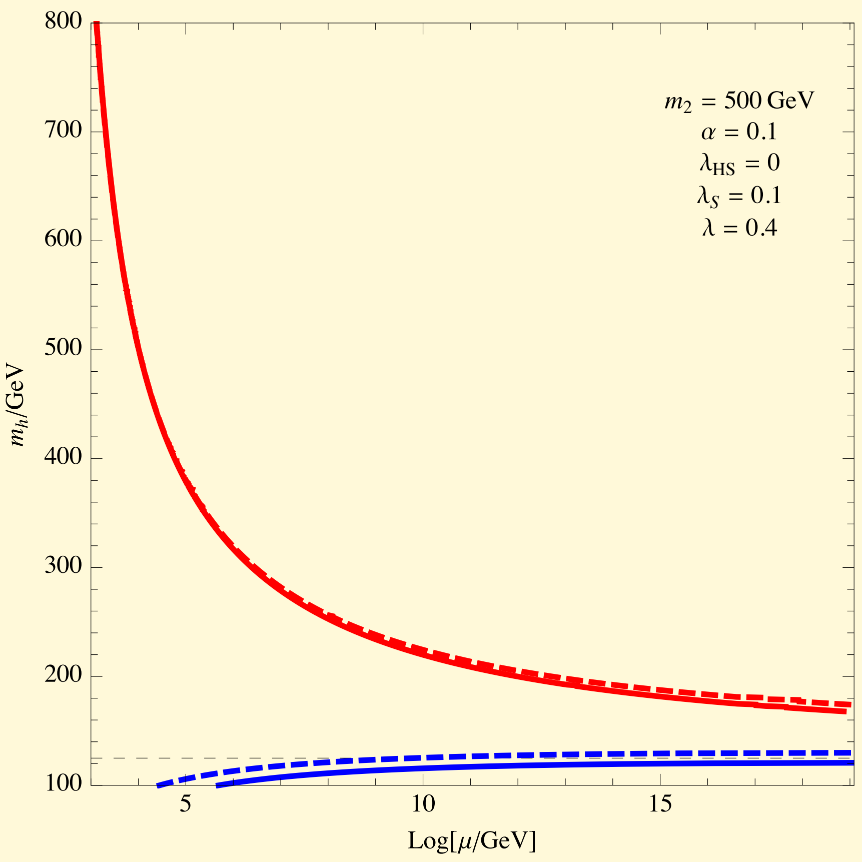
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

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)

New scalar improves EW vacuum stability

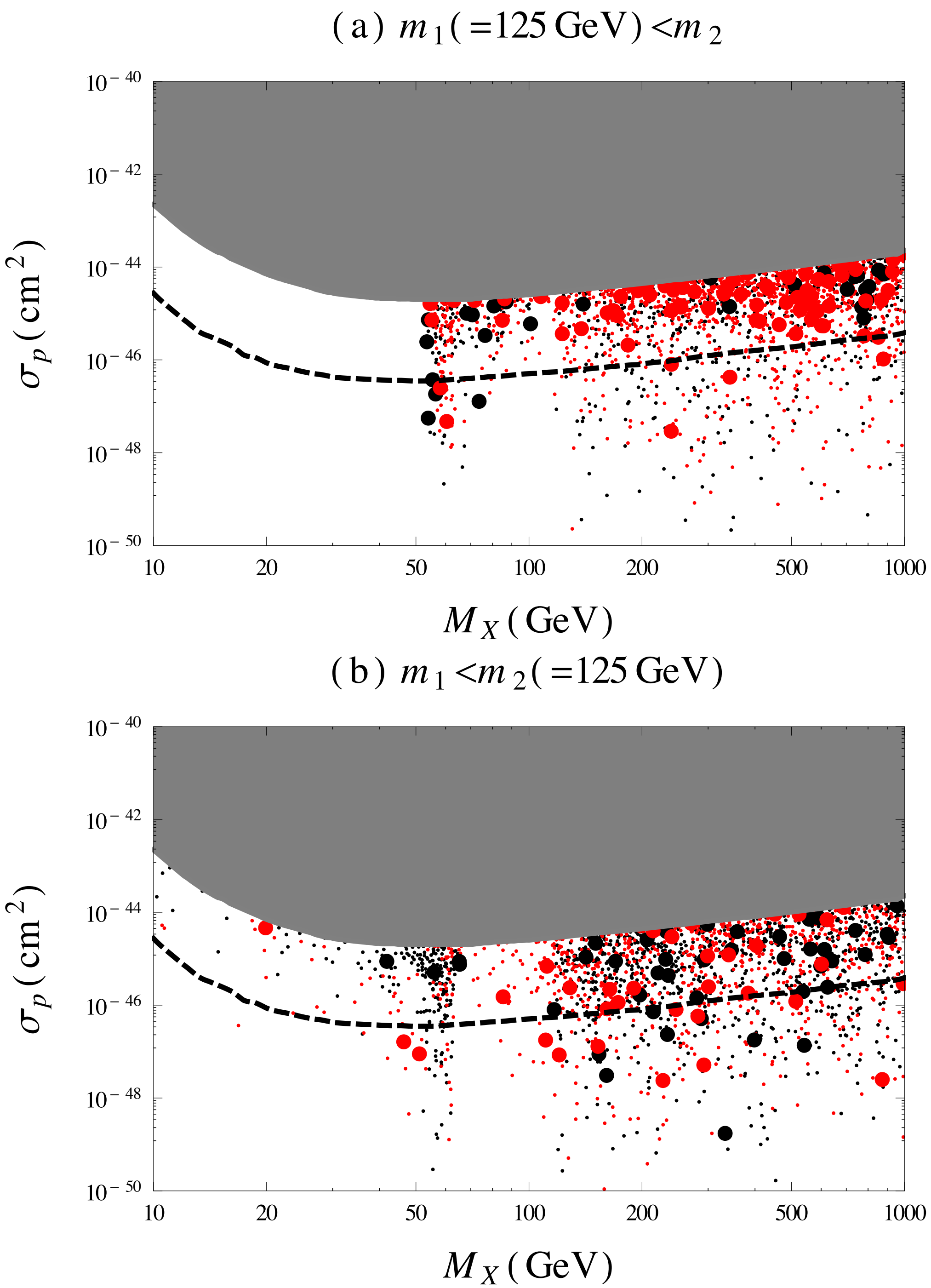


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7$($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

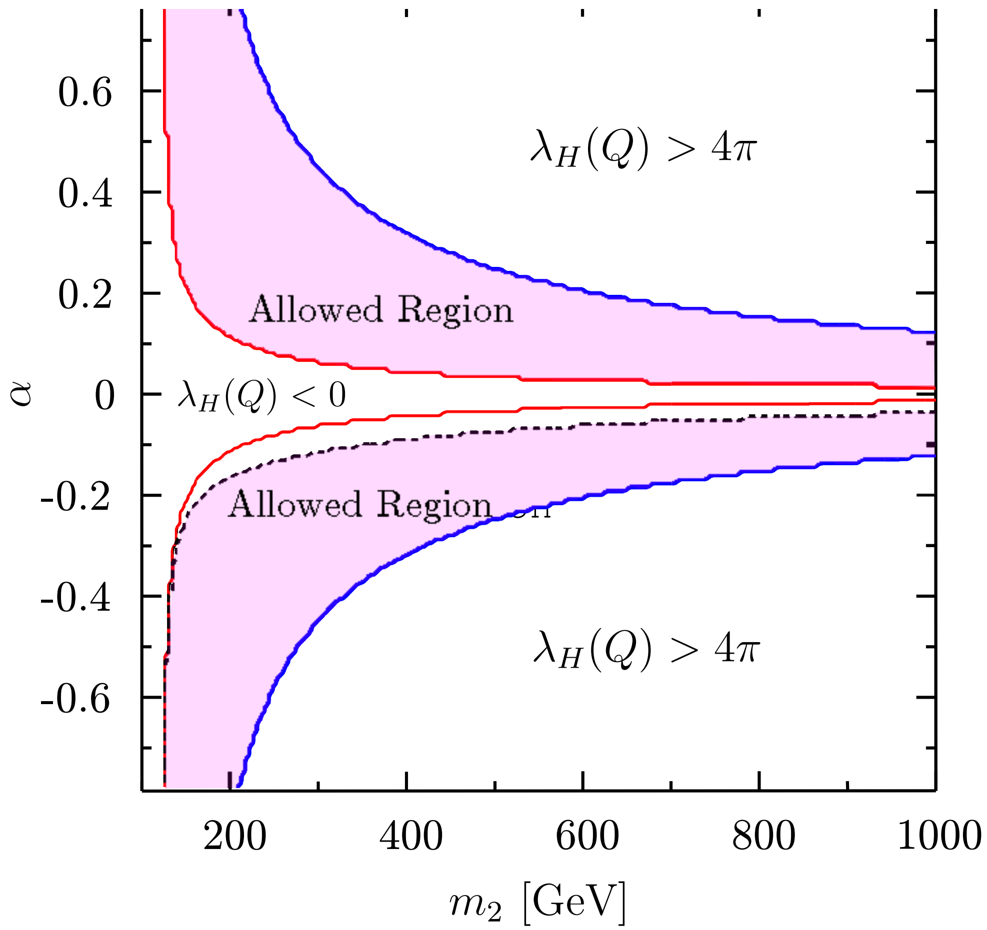


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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

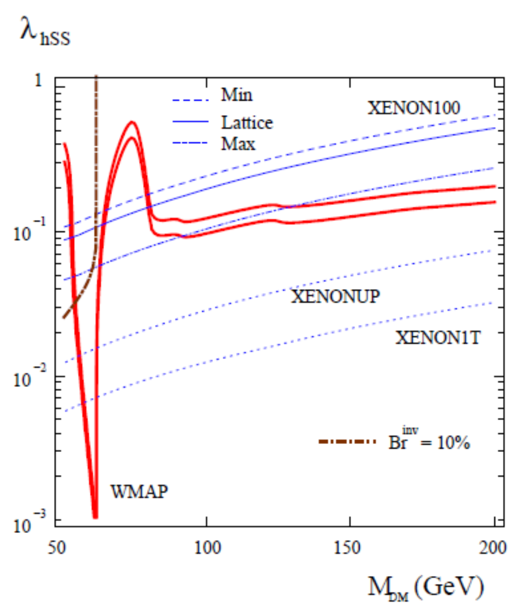


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

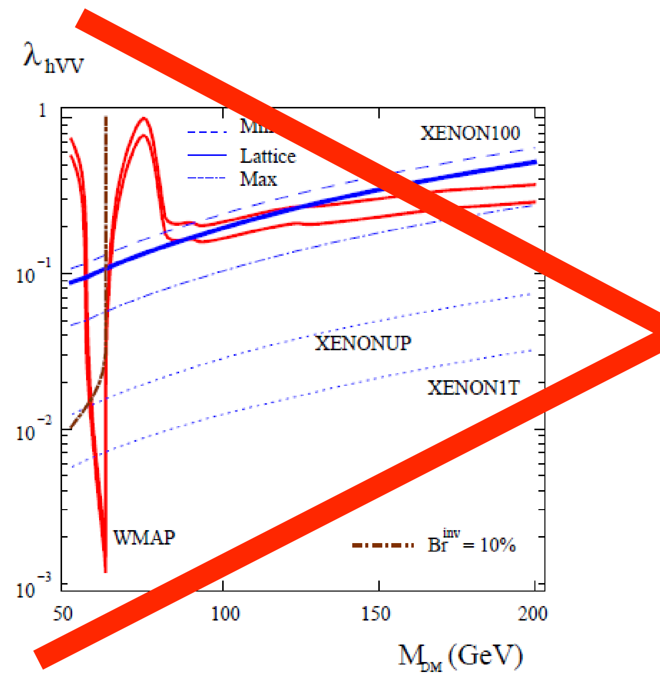


FIG. 2. Same as Fig. 1 for vector DM particles.

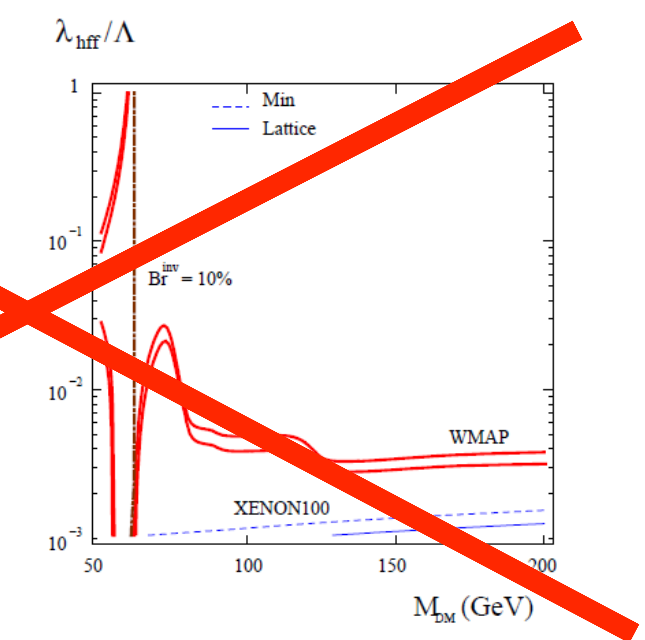
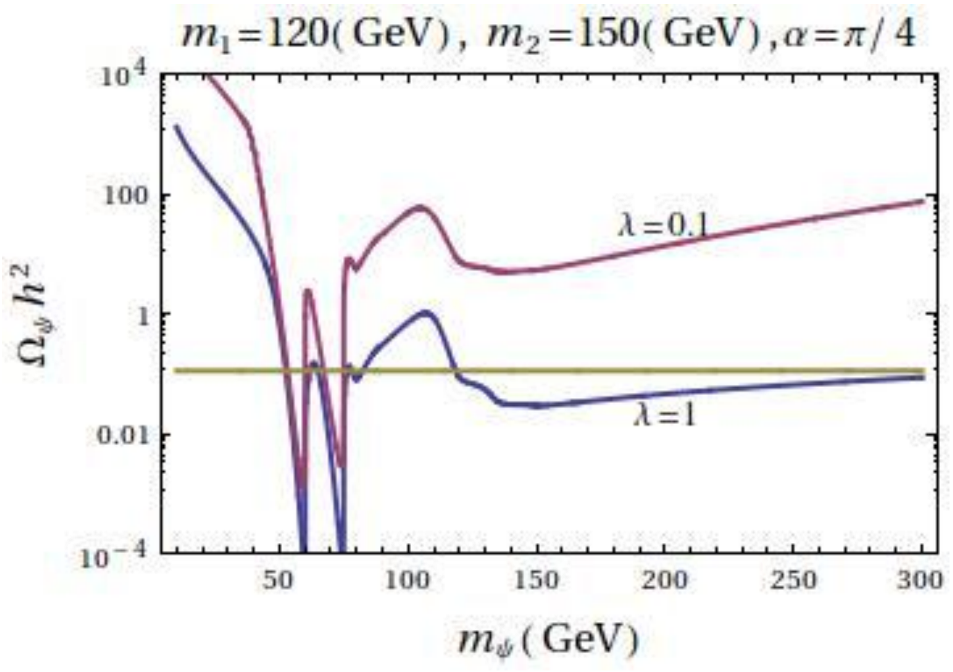


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian, we get different results !

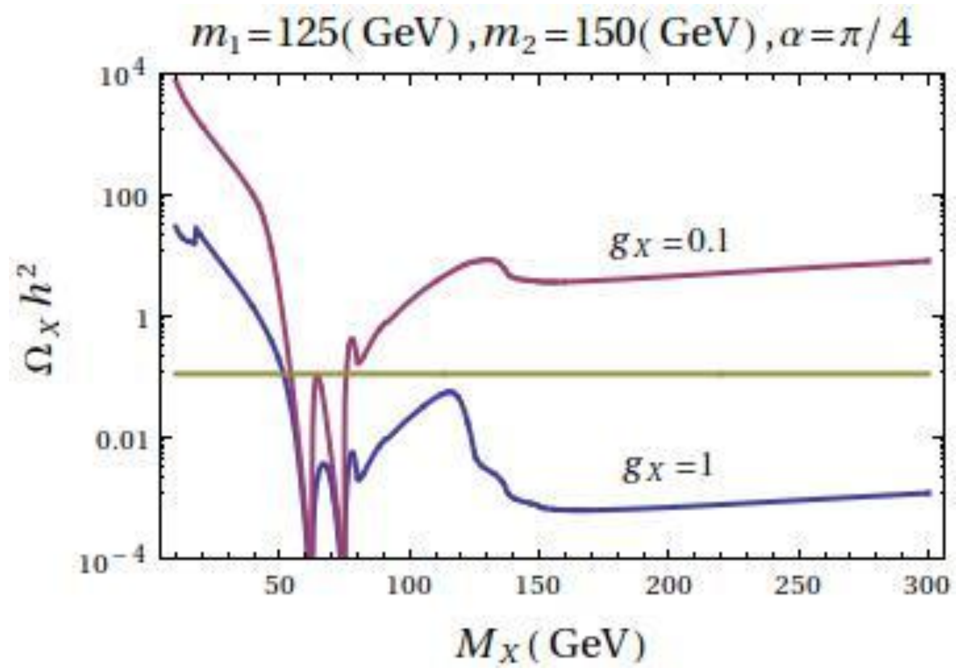
DM relic density

SFDM



P-wave annihilation

VDM

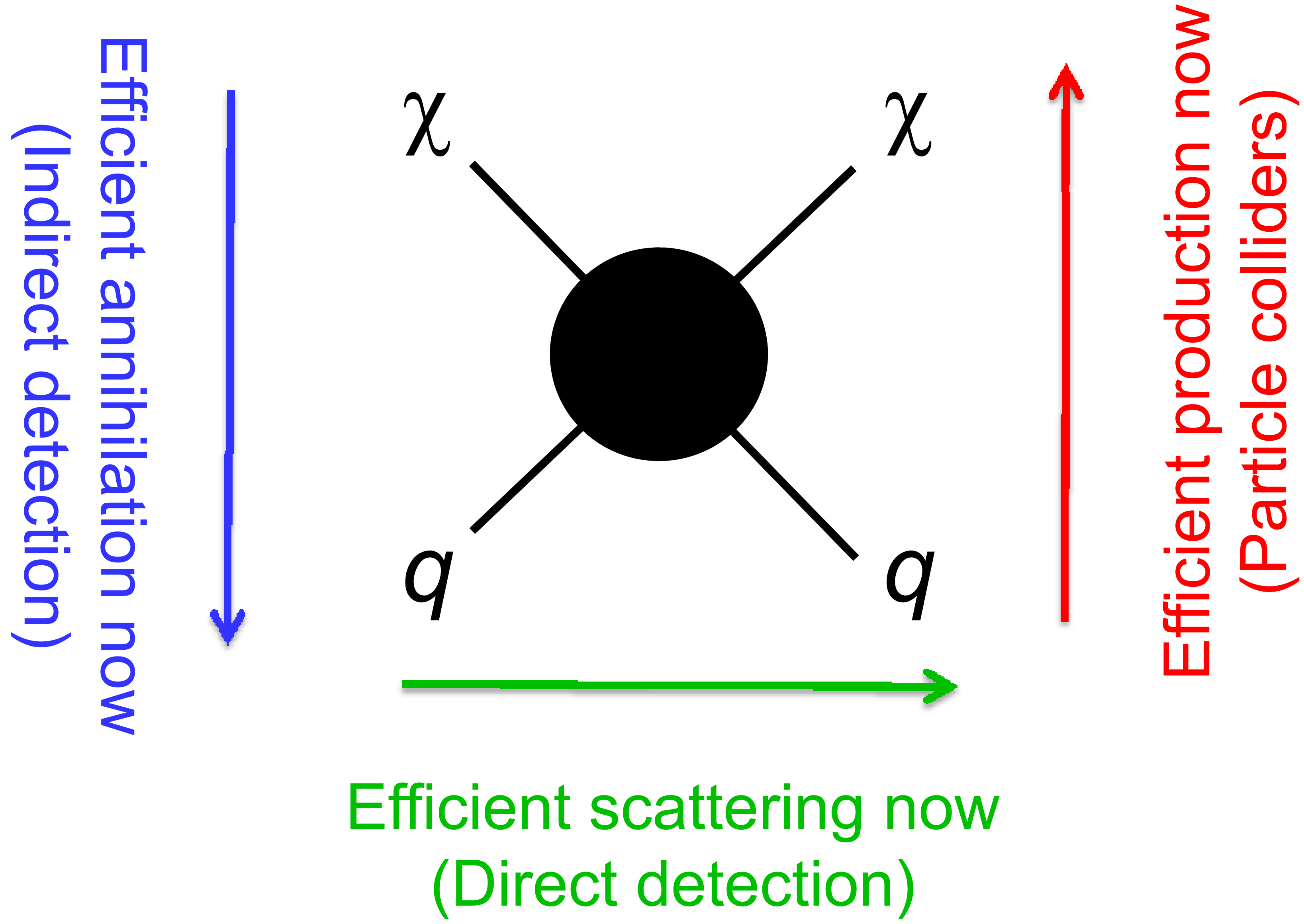


S-wave annihilation

Higgs-DM couplings less constrained due to the GIM-like cancellation mechanism

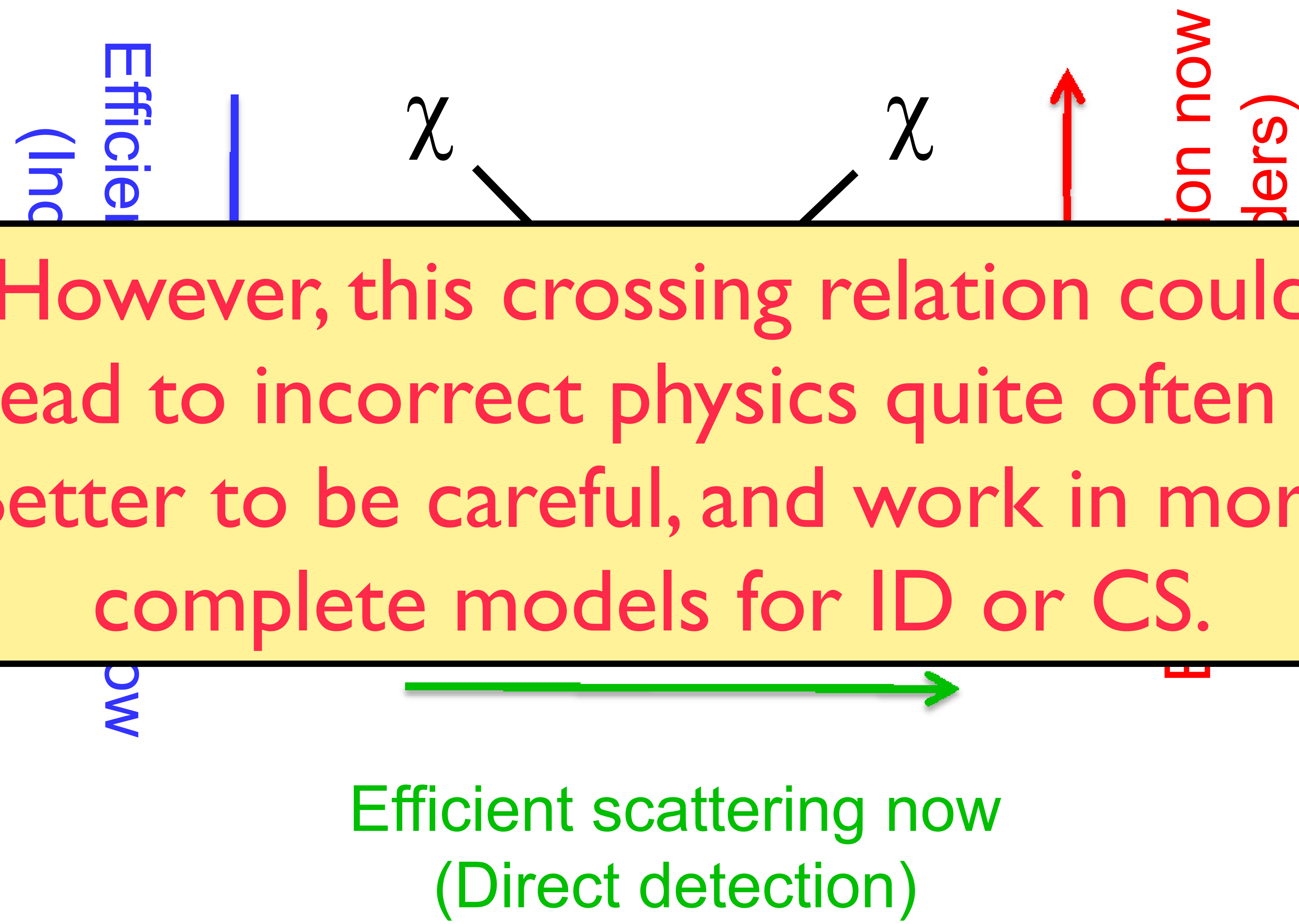
Crossing & WIMP detection

Correct relic density → Efficient annihilation then



Crossing & WIMP detection

Correct relic density → Efficient annihilation then



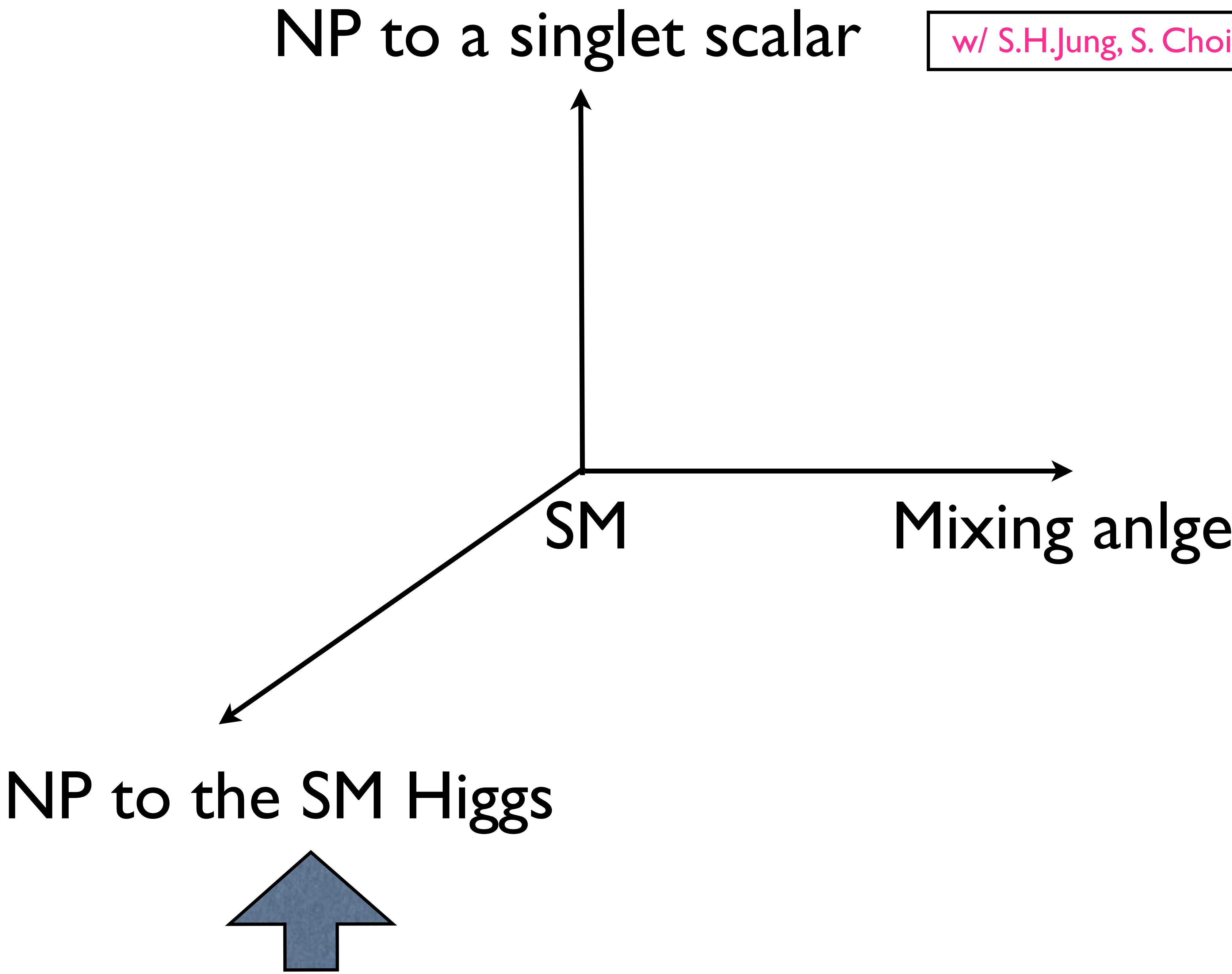
However, this crossing relation could lead to incorrect physics quite often ! Better to be careful, and work in more complete models for ID or CS.

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

Short digression on the mixing between the SM Higgs and a singlet scalar

w/ S.H.Jung, S. Choi, JHEP (2013)



Considered by the usual approaches based on effective Lagrangian

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

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

Mixing with a singlet scalar

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

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

$$\mathcal{M}(H_1 F) = \mathcal{M}(hF)_{\rm SM} \times (b_F\cos\alpha - c_F\sin\alpha) \equiv \kappa_{1F}\mathcal{M}(hF)_{\rm SM}$$

$$\mathcal{M}(H_2 F) = \mathcal{M}(hF)_{\rm SM} \times (-b_F\sin\alpha + c_F\cos\alpha) \equiv \kappa_{2F}\mathcal{M}(hF)_{\rm SM}$$

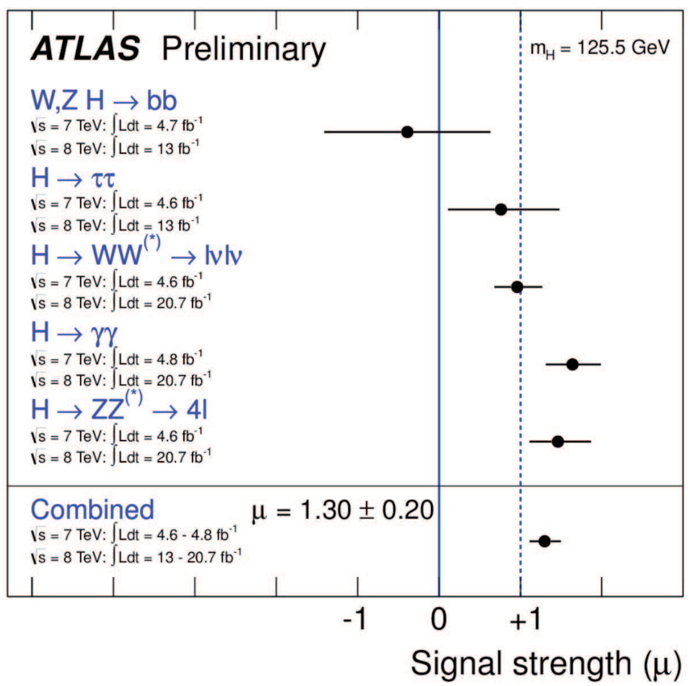
Model	Nonzero c's
Pure Singlet Extension	c_{h^2}
Hidden Sector DM	c_χ
Dilaton	$c_{h^2}, c_g, c_W, c_Z, c_\gamma$
Vectorlike Quarks	c_g, c_γ
Vectorlike Leptons	c_γ
New Charged Vector bosons	c_γ

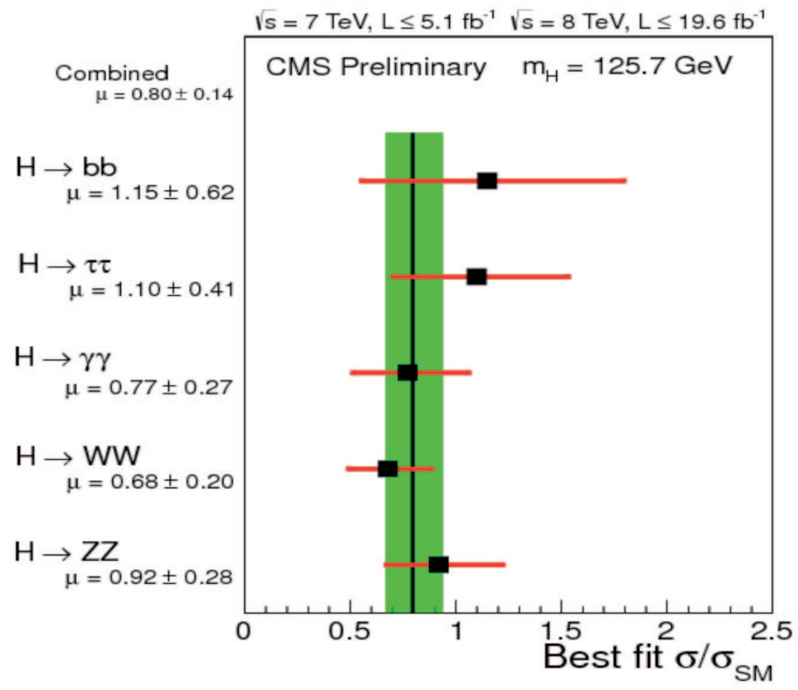
Other c's are all zeros !

Updates@LHCP by Pich

Signal Strengths

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





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$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
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Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Constraint on the mixing and Br_inv

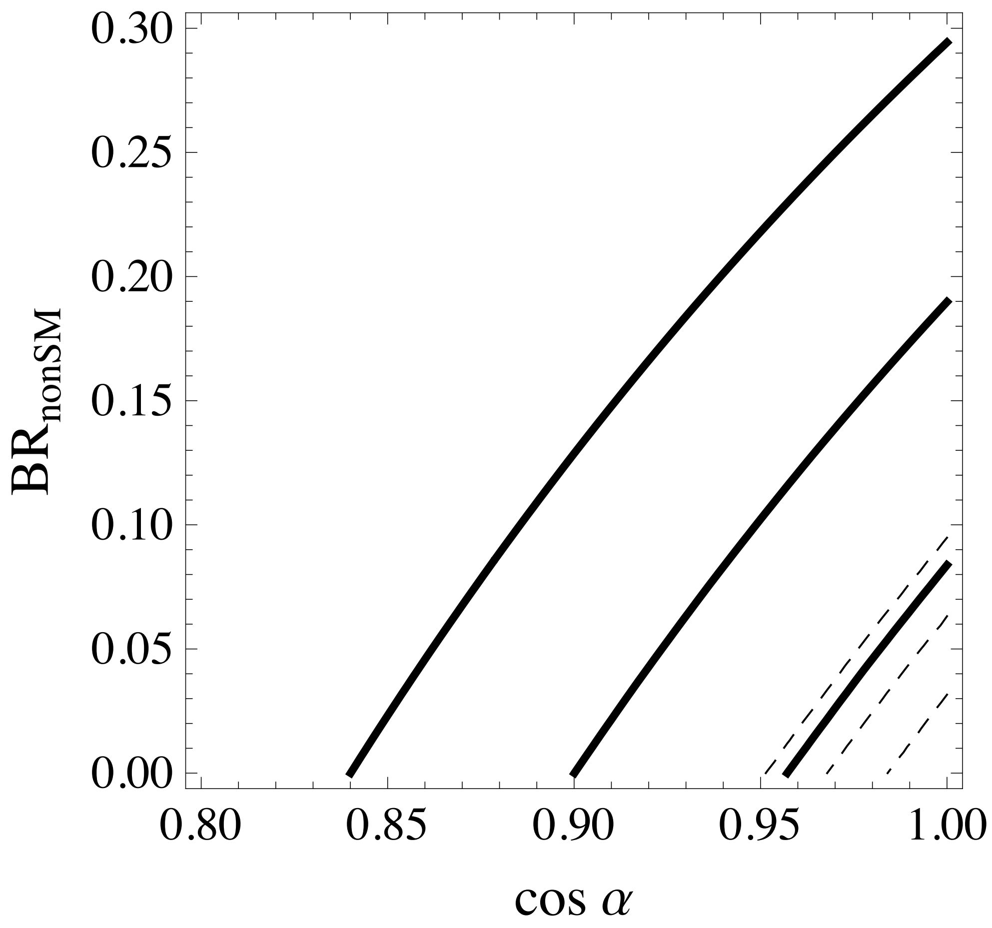


Figure 2. $1, 2, 3\sigma$ ranges of best-fit is shown for the case of universal modification. Best-fit is given by eq.(5.5) as well as eq.(5.9) and eq.(5.10). Dashed lines are expected if all future data are $R^i_j = 1.0 \pm 0.1$.

Why Dark Symmetry ?

- Is DM absolutely stable or very long lived ?
- If DM is absolutely stable, one can assume it carries a new conserved dark charge, associated with unbroken dark gauge sym
- DM can be long lived (lower bound on DM lifetime is much weaker than that on proton lifetime) if dark sym is spontaneously broken

Higgs is harmful to DM stability

Z2 sym scalar DM

$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{\lambda_S}{4!} S^4 - \frac{\lambda_{SH}}{2} S^2 H^\dagger H.$$

- Very popular alternative to SUSY LSP
- Simplest in terms of the # of new dof's
- But, where does this Z2 symmetry come from ?
- Is it Global or Local ?

Fate of CDM with Z2 sym

- Global Z2 cannot save DM from decay with long enough lifetime

Consider Z_2 breaking operators such as

$$\frac{1}{M_{\rm Planck}} S O_{\rm SM}$$

keeping dim-4 SM operators only

The lifetime of the Z_2 symmetric scalar CDM S is roughly given by

$$\Gamma(S) \sim \frac{m_S{}^3}{M^2_{\rm Planck}} \sim (\frac{m_S}{100{\rm GeV}})^3 10^{-37} GeV$$

The lifetime is too short for 100 GeV DM

Fate of CDM with Z2 sym

- Spontaneously broken local U(1)x can do the job to some extent, but there is still a problem

Let us assume a local $U(1)_X$ is spontaneously broken by $\langle \phi_X \rangle \neq 0$ with

$$Q_X(\phi_X) = Q_X(X) = 1$$

Then, there are two types of dangerous operators:

$\phi_X^\dagger X H^\dagger H,$ and $\phi_X^\dagger X O_{\rm SM}^{(dim-4)}$

Problematic ! | Perfectly fine !

- These arguments will apply to all the CDM models based on ad hoc Z_2 symmetry, global or local it may be

- One way out is to implement Z_2 symmetry as local U(1) symmetry (Work in progress with Seungwon Baek and Wan-Il Park@ KIAS)

In preparation w/ WIPark and SBaek

$$Q_X(\phi) = 2, \quad Q_X(X) = 1$$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2}\epsilon X_{\mu\nu} B^{\mu\nu} + D_\mu \phi_X^\dagger D^\mu \phi_X - \frac{\lambda_X}{4}\left(\phi_X^\dagger \phi_X - v_\phi^2\right)^2 + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X$$
$$- \frac{\lambda_X}{4}\left(X^\dagger X\right)^2 - \left(\mu X^2 \phi^\dagger + H.c.\right) - \frac{\lambda_{XH}}{4} X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4} \phi_X^\dagger \phi_X H^\dagger H - \frac{\lambda_{XH}}{4} X^\dagger X \phi_X^\dagger \phi_X$$

The lagrangian is invariant under $X \to -X$ even after $U(1)_X$ symmetry breaking.

Unbroken Local Z2 symmetry

$$X_R \to X_I \gamma_h^* \text{ followed by } \gamma_h^* \to \gamma \to e^+ e^-$$ etc.

The heavier state decays into the lighter state

The local Z2 model is not that simple as the usual Z2 scalar DM model (also for the fermion CDM)

Unbroken Local Dark Sym

- Local dark symmetry can be either confining (like QCD) or not
- For confining dark symmetry, gauge fields will confine and there is no long range dark force, and DM will be composite baryons/mesons in the hidden sector
- Otherwise, there could be a long range dark force that is constrained by large/small structures, and contributes to dark radiation

Spon. Broken local dark sym

- If dark sym is spont. broken, DM will decay in general, if there is no discrete gauge symmetry
- There will be a singlet scalar after spontaneous breaking of dark gauge symmetry, which mixes with the SM Higgs boson
- There will be at least two neutral scalars (and no charged scalars) in this case
- Vacuum stability is improved by the new scalar
- Higgs Signal strengths universally reduced from "ONE"

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics

Hur, Jung, Ko, Lee : 0709.1218, PLB (2011)
Hur, Ko : arXiv:1103.2517,PRL (2011)
Proceedings for workshops/conferences during 2007-2011 (DSU,ICFP,ICHEP etc.)

Nicety of QCD

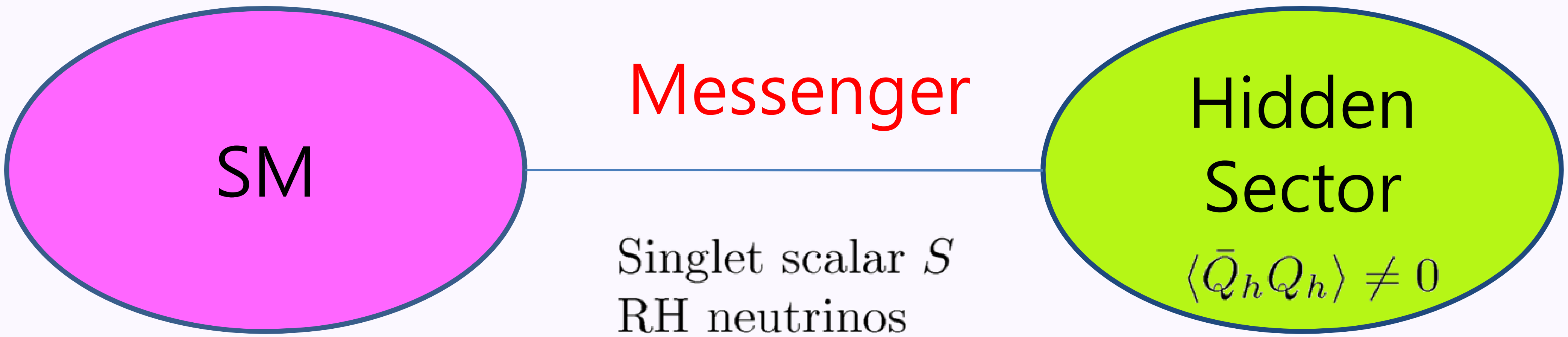
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

h-pion & h-baryon DMs

- In most WIMP DM models, DM is stable due to some ad hoc Z_2 symmetry
- If the hidden sector gauge symmetry is confining like ordinary QCD, the lightest mesons and the baryons could be stable or long-lived >> Good CDM candidates
- If chiral sym breaking in the hidden sector, light h-pions can be described by chiral Lagrangian in the low energy limit

(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

Key Observation

- If we switch off gauge interactions of the SM, then we find
- Higgs sector ~ Gell-Mann-Levy's linear sigma model which is the EFT for QCD describing dynamics of pion, sigma and nucleons
- One Higgs doublet in 2HDM could be replaced by the GML linear sigma model for hidden sector 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

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

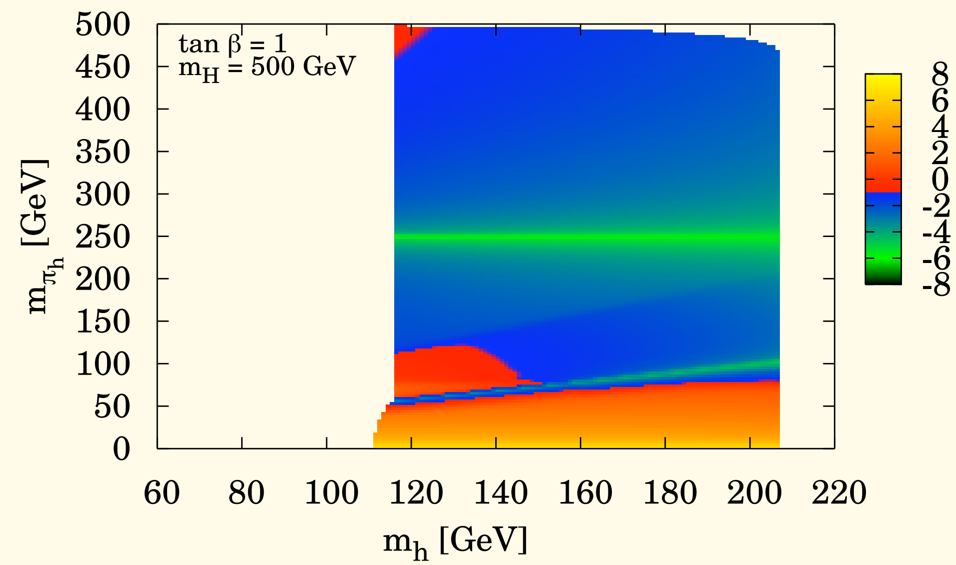
Not present in the two-Higgs Doublet model

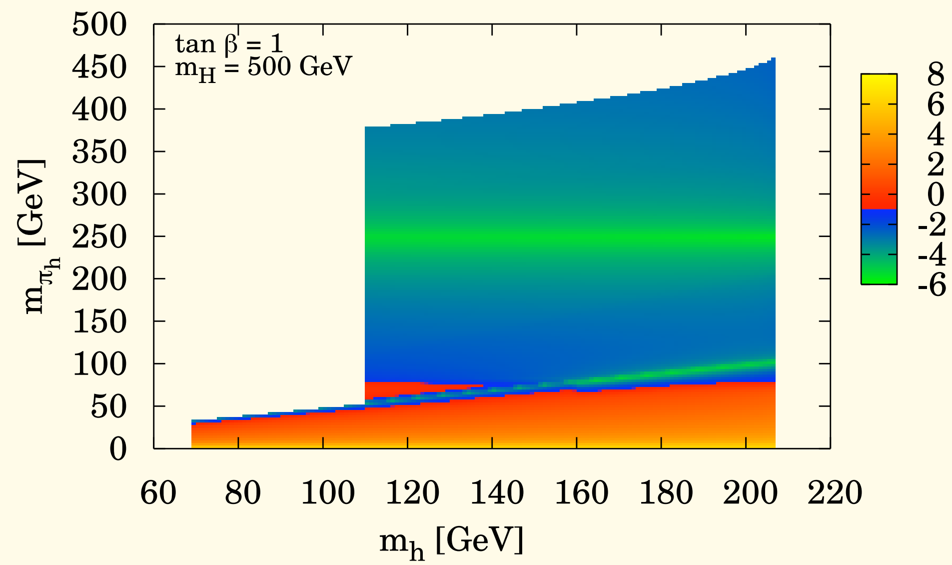
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

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

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

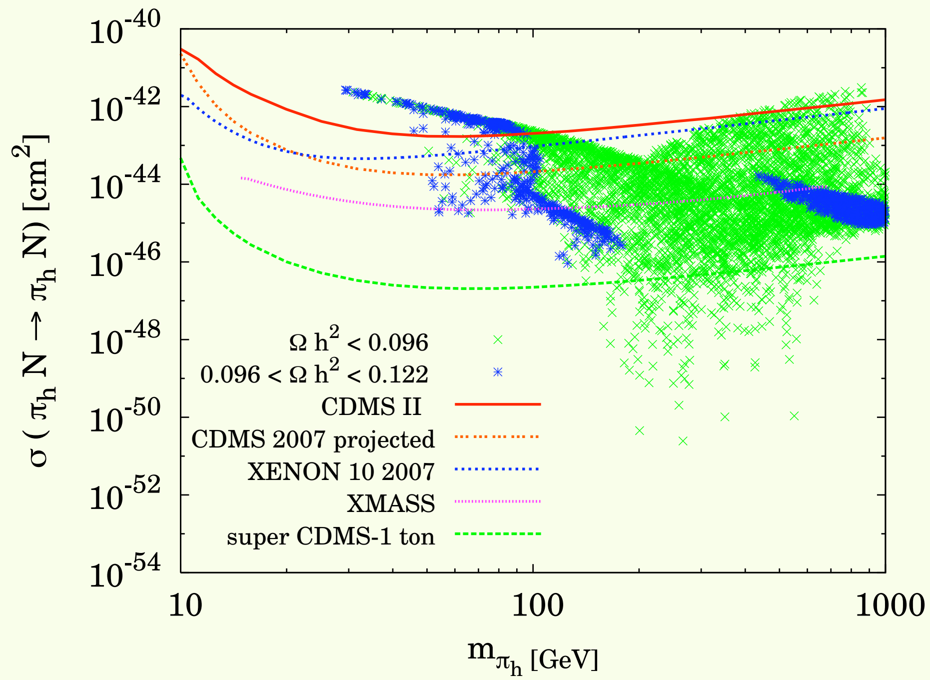
Relic Density

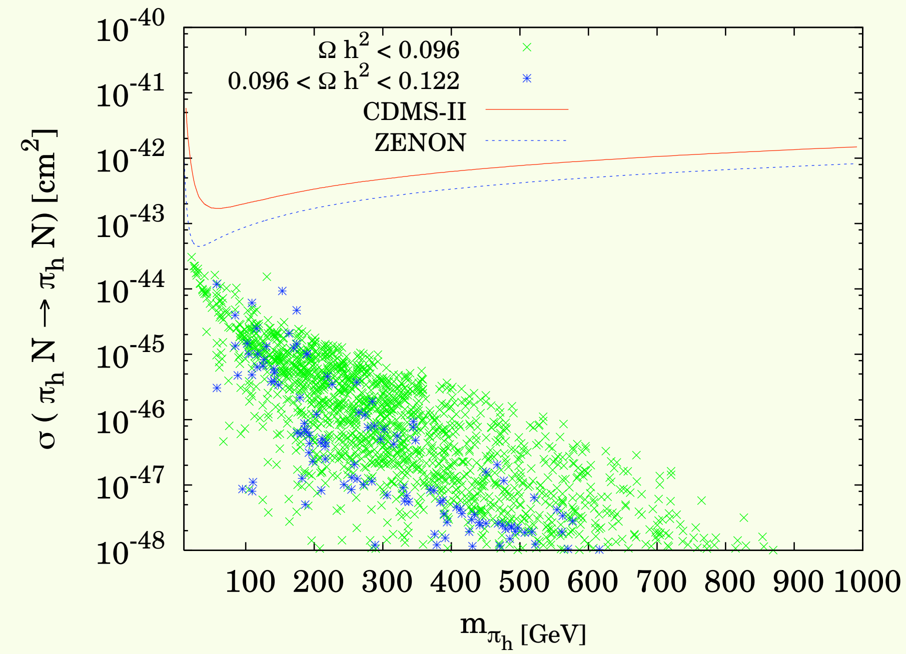




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

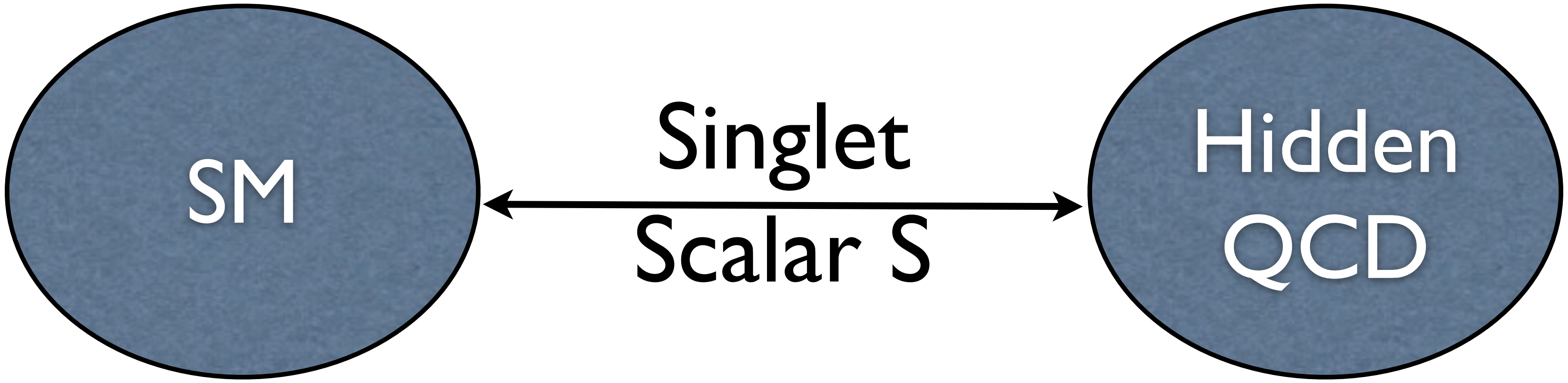




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be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

Model I (Scalar Messenger)

Hur, Ko, PRL (2011)



- 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"

Scale invariant extension of the SM with strongly interacting hidden sector

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

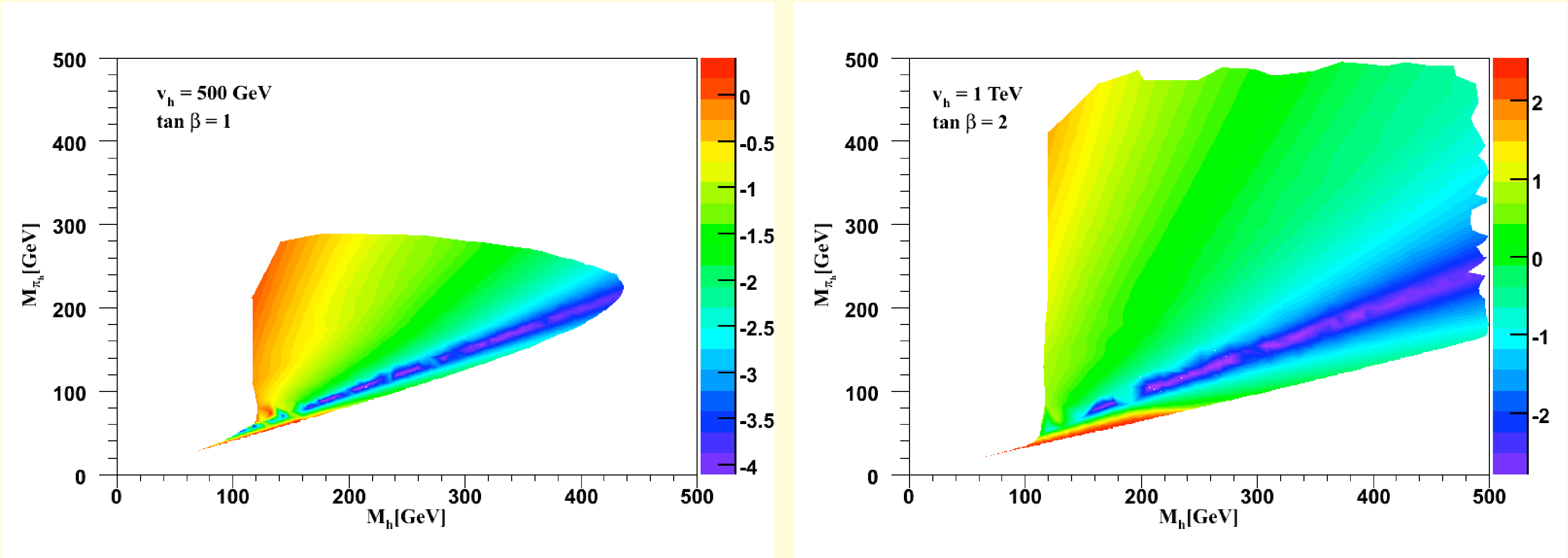
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

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

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

Relic density

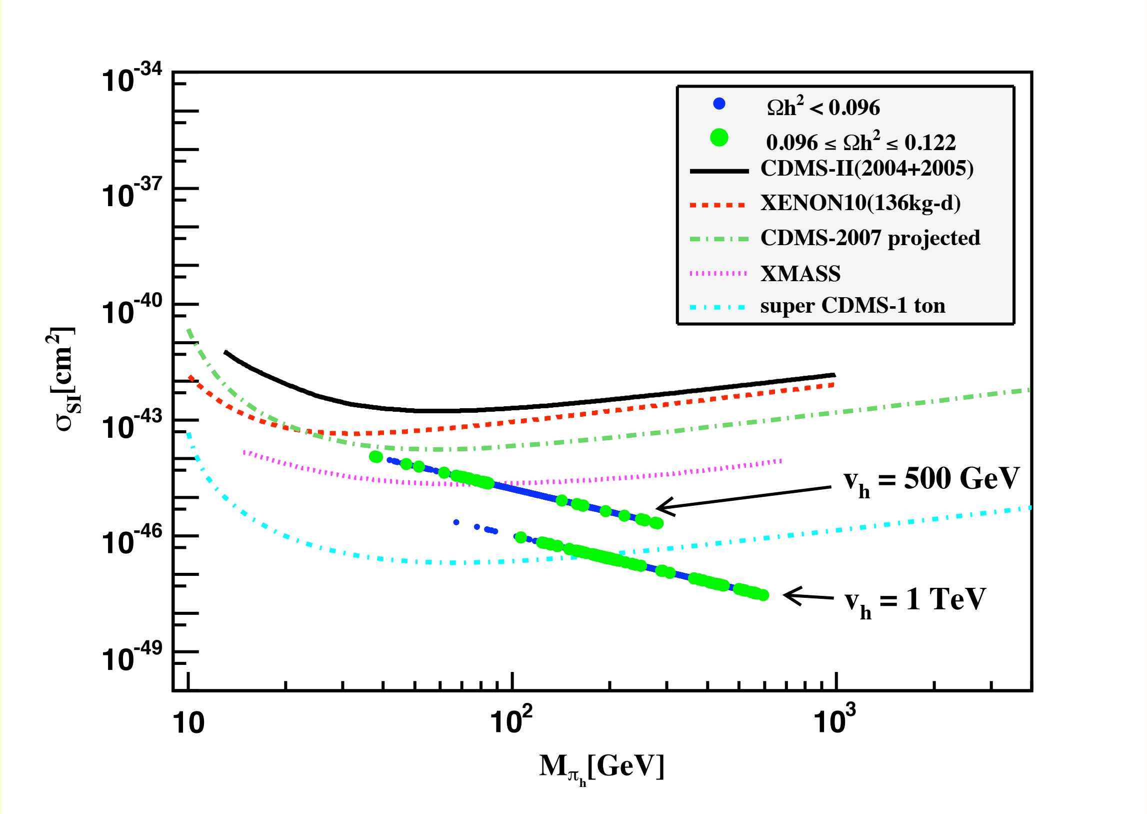


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

(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 $\tan\beta = 2$.

Naturalness Problem ?

- Scale Symmetry is explicitly broken only by dim-4 operators (beta functions)
- Our model is renormalizable when dim regularization is used, and no quadratic divergence
- Logarithmic sensitivity to high energy scale
- OK up to Planck scale as long as no new particles at high energy scale

Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is absolutely stable), but confining like QCD (No long range dark force and no Dark Radiation)
- DM : composite hidden hadrons (mesons and baryons)
- All masses including CDM masses from dynamical sym breaking in the hidden sector
- Singlet scalar is necessary to connect the hidden sector and the visible sector
- Higgs Signal strengths : universally reduced from one

- Similar to the massless QCD with the physical proton mass without finetuning problem
- Similar to the BCS mechanism for SC, or Technicolor idea
- Eventually we would wish to understand the origin of DM and RH neutrino masses, and this model is one possible example
- Could consider SUSY version of it

More issues to study

- DM : strongly interacting composite hadrons in the hidden sector >> self-interacting DM >> can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations (T. Asaka's talk)
- Better approach for hQCD ? (For example, Kugo, Lindner et al use NJL approach)

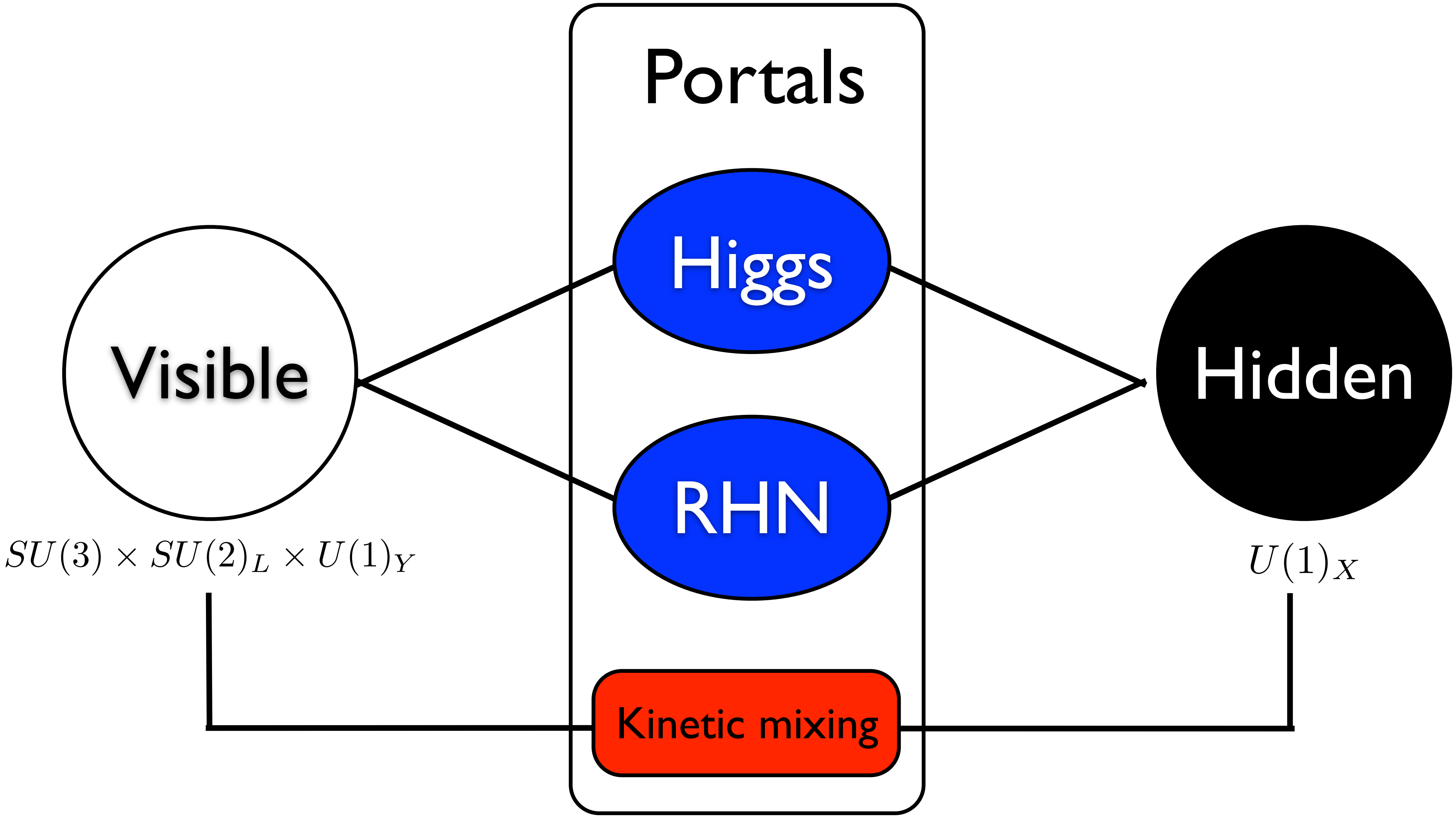
Singlet Portal Extension of the Standard Seesaw Model with Unbroken Dark Sym

An Alternative to the new minimal SM

(based on a work with S. Baek, P. Ko, 1303.4280, JHEP)

A minimal(?) model

- The structure of the model



- **Symmetry**

$$SU(3) \times SU(2)_L \times U(1)_Y \times U(1)_X$$

(SM is neutral under U(1)_X)

- **Lagrangian**

$$\mathcal{L} = \mathcal{L}_{\rm Kinetic} + \mathcal{L}_{\rm H-portal} + \mathcal{L}_{\rm RHN-portal} + \mathcal{L}_{\rm DS}$$

$$\mathcal{L}_{\rm Kinetic} = i\bar{\psi}\gamma^\mu D_\mu \psi + |D_\mu X|^2 - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}B^{\mu\nu}$$

$$-\mathcal{L}_{\rm H-portal} = \frac{1}{2}\lambda_{HX}|X|^2 H^\dagger H$$

$$-\mathcal{L}_{\rm RHN-portal} = \frac{1}{2}M_i \bar{N^C_{Ri}} N_{Ri} + \left[Y_\nu^{ij}\bar{N_{Ri}}\ell_{Lj}H^\dagger + \lambda^i \bar{N_{Ri}}\psi X^\dagger + {\rm H.c.}\right]$$

$$-\mathcal{L}_{\rm DS} = m_\psi \bar{\psi}\psi + m_X^2|X|^2 + \frac{1}{4}\lambda_X |X|^4$$

$$(q_L, q_X):\quad N = (1, 0),\ \ \psi = (1, 1),\ \ X = (0, 1)$$

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

Constraints

Our model can address

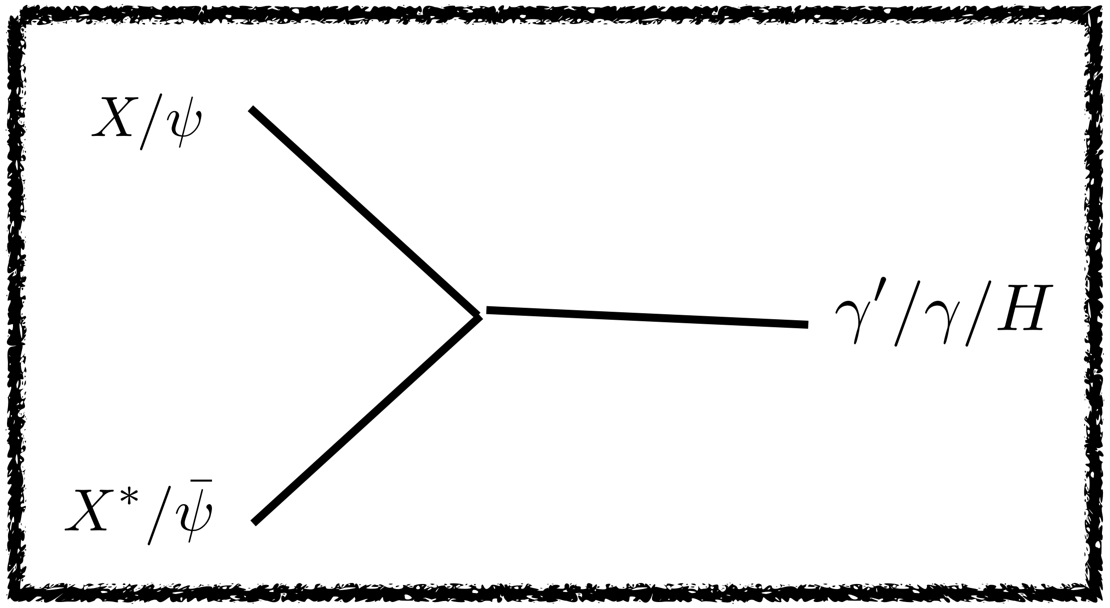
* Some small scale puzzles of CDM (Dark matter self-interaction) (α_X, m_X)
* CDM relic density (Unbroken dark $U(1)_X$) (λ, λ_{hx}, m_X,)
* Vacuum stability of Higgs potential (Positive scalar loop correction) (λ_{hx})
* Direct detection (Photon and Higgs exchange)(ε, λ_{hx})
* Dark radiation (Massless photon)(α_X)
* Lepto/darkogenesis (Asymmetric origin of dark matter) (Y_ν, λ, M_1, m_X)
* Inflation (Higgs inflation type) (λ_{hx}, λ_X)

In other words, the model is highly constrained.

- Interaction vertices of dark particles (X, ψ)

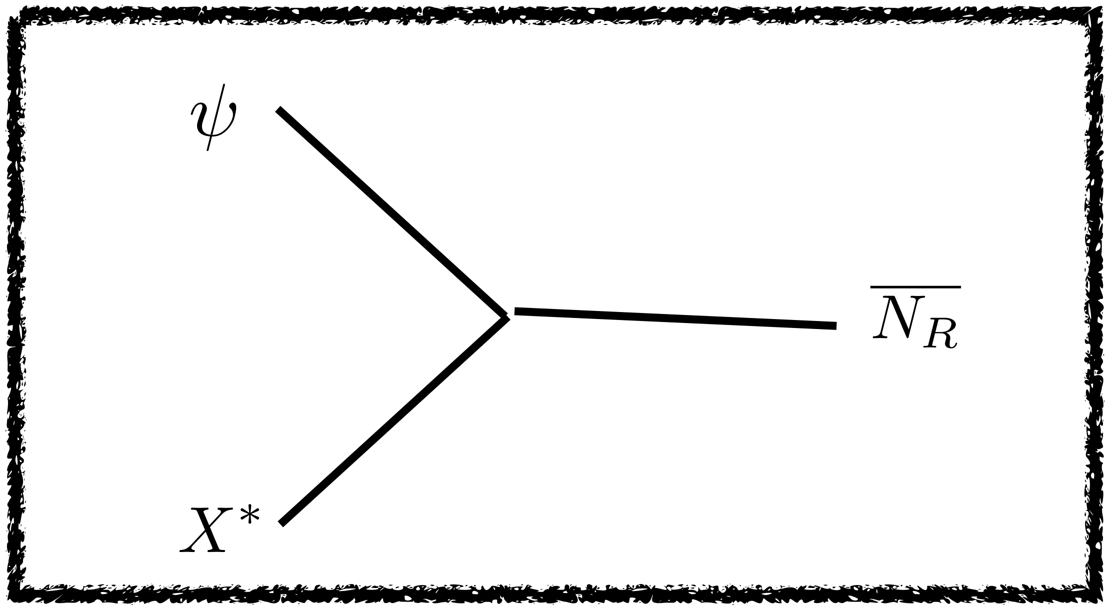
Kinetic term diagonalization: $\begin{pmatrix} \hat{B}^\mu \\ \hat{X}^\mu \end{pmatrix} = \begin{pmatrix} 1/\cos\epsilon & 0 \\ -\tan\epsilon & 1 \end{pmatrix} \begin{pmatrix} B^\mu \\ X^\mu \end{pmatrix}$

$$\Longrightarrow \mathcal{L}_{\rm DS-SM} = g_X q_X t_\epsilon \bar{\psi}\gamma^\mu\psi\left(c_W A_\mu - s_W Z_\mu\right) + \left|\left[\partial_\mu - i g_X q_X t_\epsilon \left(c_W A_\mu - s_W Z_\mu\right)\right] X\right|^2$$



Annihilation
or
scattering

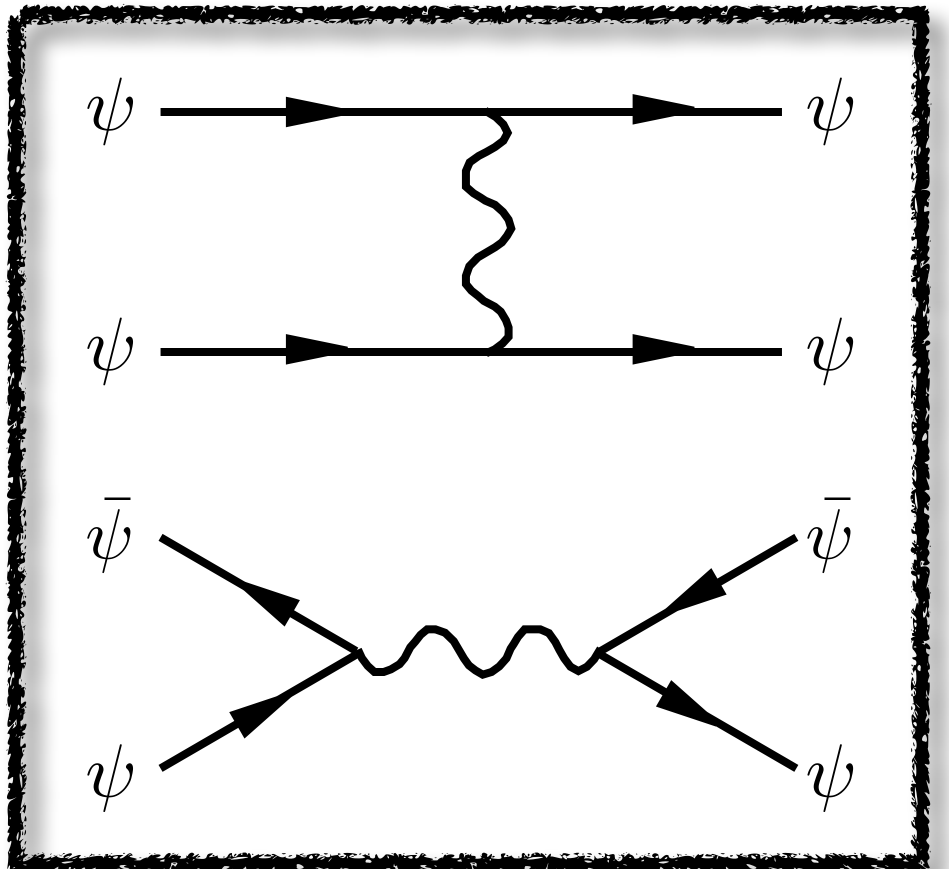
(⇒ Relic density, direct/indirect searches)



Decay of N_R and ψ or X

(⇒ Lepto/darkogenesis?)

• Constraints on dark gauge coupling



$$\sigma_T \sim \frac{16\pi\alpha_X^2}{m_{X(\psi)}^2}\frac{1}{v^4}\ln\left[\frac{m_{X(\psi)}^2 v^3}{\sqrt{4\pi\rho_{X(\psi)}\alpha_X^3}}\right]$$

From inner structure and kinematics of dwarf galaxies,

$$\sigma_T^{\rm max}/m_{\rm dm} \lesssim 35\ {\rm cm}^2/{\rm g}$$

[Vogelsberger, Zavala and Leb, 1201.5892]

$$\Longrightarrow \quad \alpha_X \lesssim 5\times 10^{-5}\left(\frac{m_{X(\psi)}}{300{\rm GeV}}\right)^{3/2}$$

☛ If stable, $\Omega_\psi \sim 10^4\,(300{\rm GeV}/m_\psi) \gg \Omega_{\rm CDM}^{\rm obs} \simeq 0.26$.

"$m_\Psi > m_X$" $\Rightarrow$ Ψ decays.

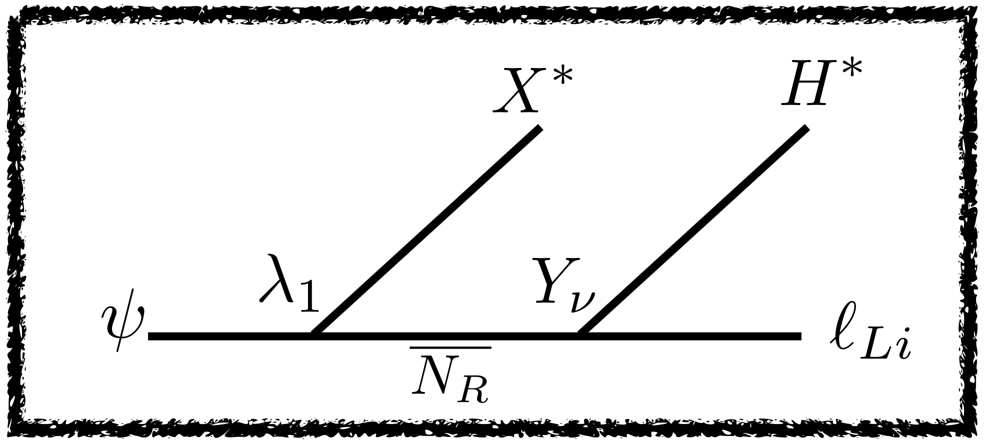
"X"(the scalar dark field) = CDM

☛ For α_X close to its upper bound, X-X* can explain some puzzles of collisionless CDM:

(i) cored profile of dwarf galaxies.

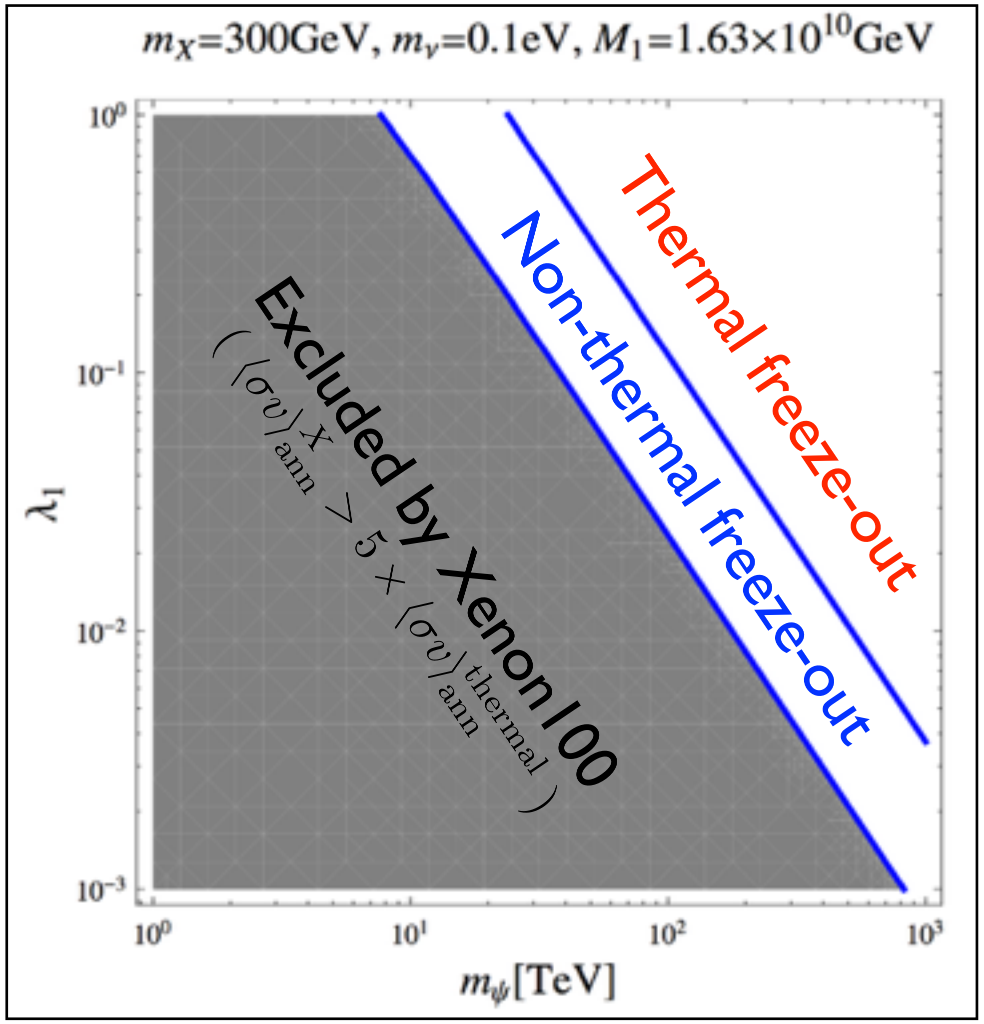
(ii) low concentration of LSB galaxies and dwarf galaxies. [Vogelsberger, Zavala and Leb, 1201.5892]

• CDM relic density



The late-time decay of ψ

X forms a symmetric DM.
(Non-) thermal freeze-out of X via Higgs portal



$$\text{Thermal}(T_{\rm d}^{\psi} > T_{\rm fz}^{X}): \ \langle\sigma v\rangle^X_{\rm ann} = \langle\sigma v\rangle^{\rm thermal}_{\rm ann}$$

$$\text{Nonthermal}(T_{\rm d}^{\psi} < T_{\rm fz}^{X}): \ \langle\sigma v\rangle^X_{\rm ann} \sim \Gamma^{\psi}_{\rm d}/n^{\rm obs}_X$$

$$\lambda_1 = \lambda_1(m_\psi, \langle\sigma v\rangle^X_{\rm ann}, \cdots)$$

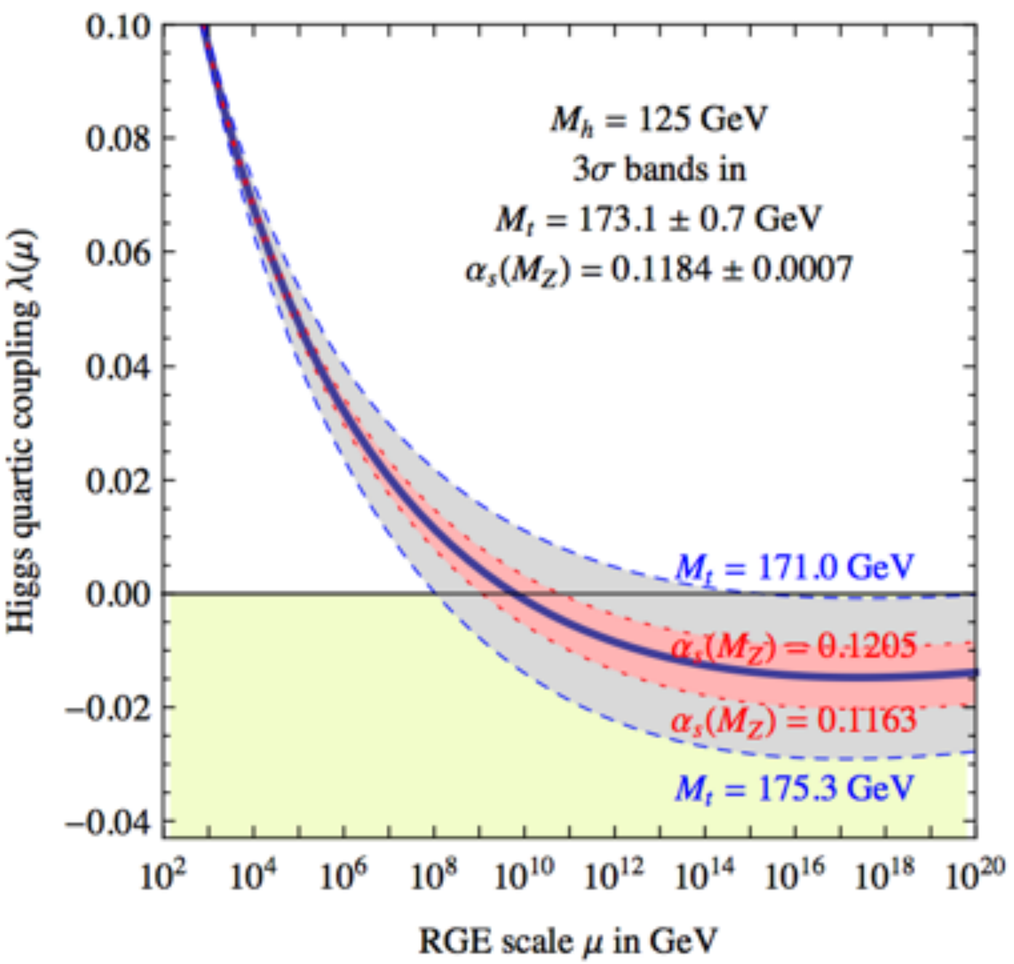
- **Vacuum stability (λ_{hx})** [S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

$$\beta^{(1)}_{\lambda_H} = \frac{1}{16\pi^2}\left[24\lambda_H^2 + 12\lambda_H\lambda_t^2 - 6\lambda_t^4 - 3\lambda_H\left(3g_2^2+g_1^2\right) + \frac{3}{8}\left(2g_2^4 + \left(g_2^2+g_1^2\right)^2\right) + \frac{1}{2}\lambda_{HS}^2\right]$$

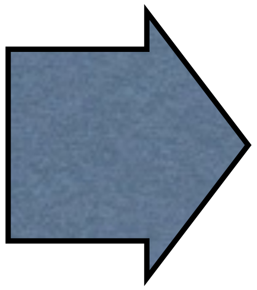
$$\beta^{(1)}_{\lambda_{HS}} = \frac{\lambda_{HS}}{16\pi^2}\left[2\left(6\lambda_H + 3\lambda_S + 2\lambda_{HS}\right) - \left(\frac{3}{2}\lambda_H\left(3g_2^2+g_1^2\right) - 6\lambda_t^2 - 4\lambda^2\right)\right],$$

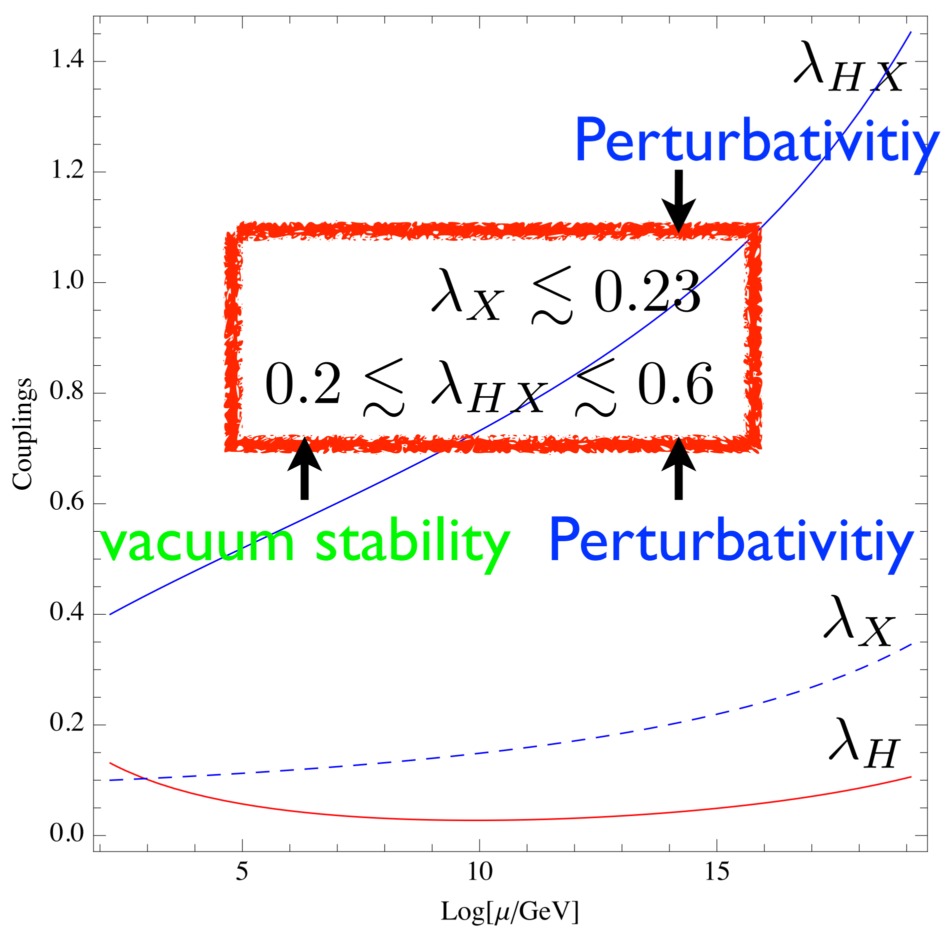
$$\beta^{(1)}_{\lambda_S} = \frac{1}{16\pi^2}\left[2\lambda_{HS}^2 + 18\lambda_S^2 + 8\lambda_S\lambda^2 - 3\lambda^4\right],$$

with $\lambda_{HS} \to \lambda_{HX}/2$ and $\lambda_S \to \lambda_X$

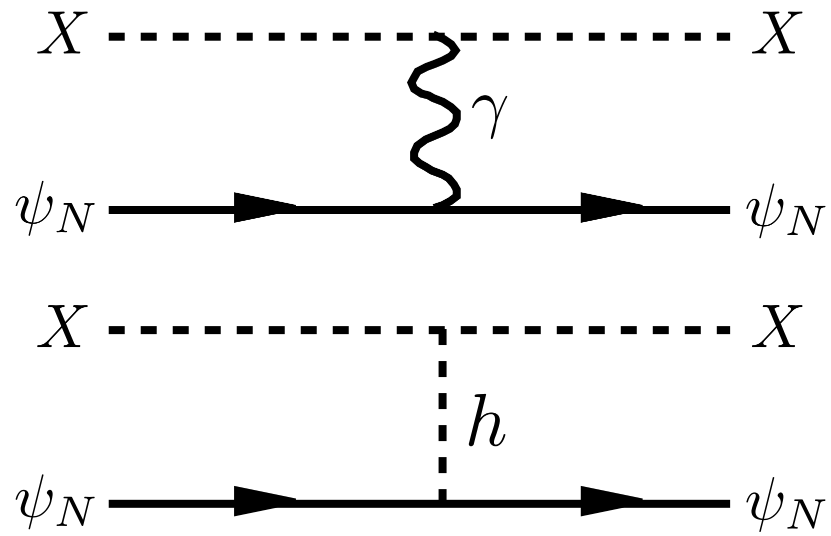


[G. Degrassi et al., 1205.6497]



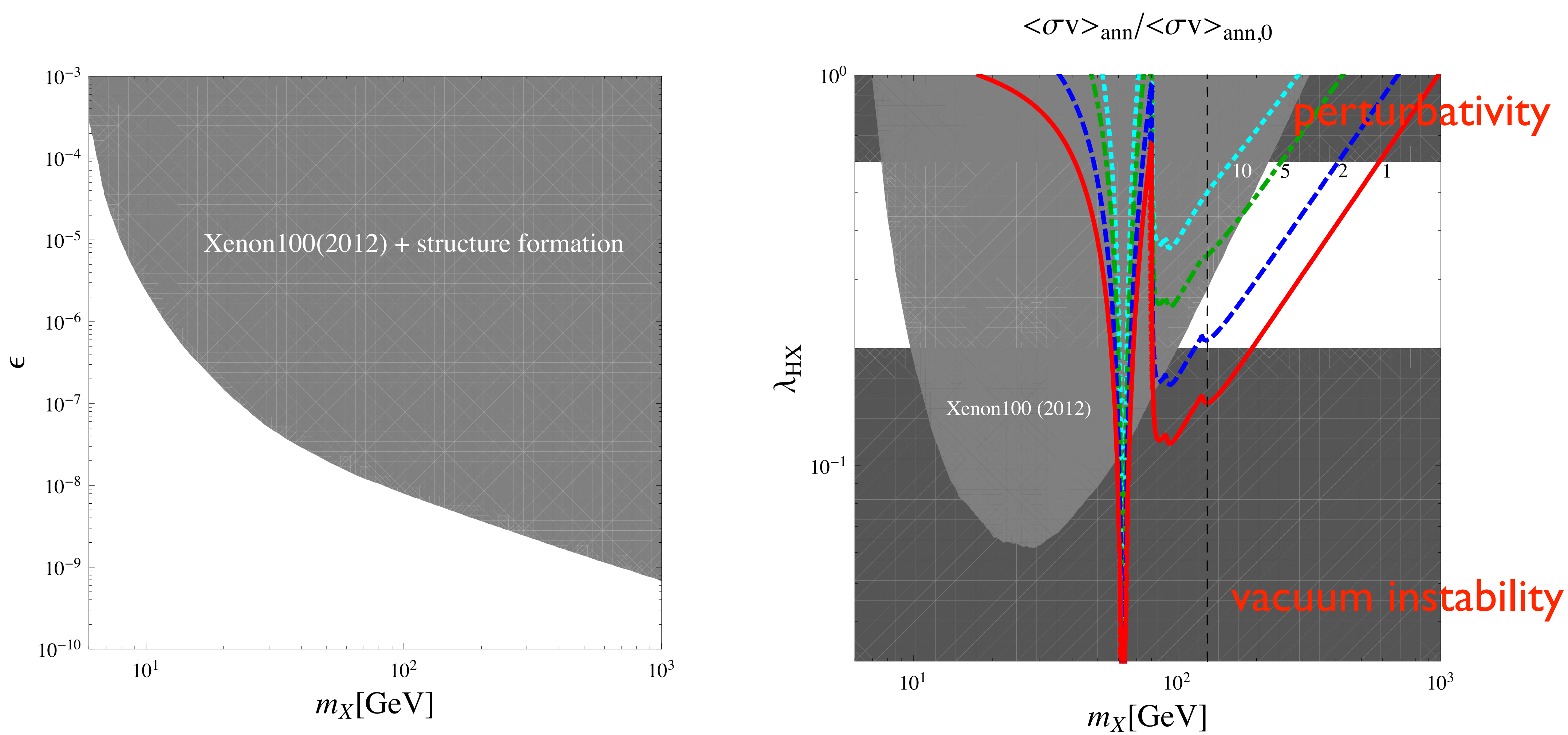


• DM direct search (ϵ, λ_{hx}, m_X)



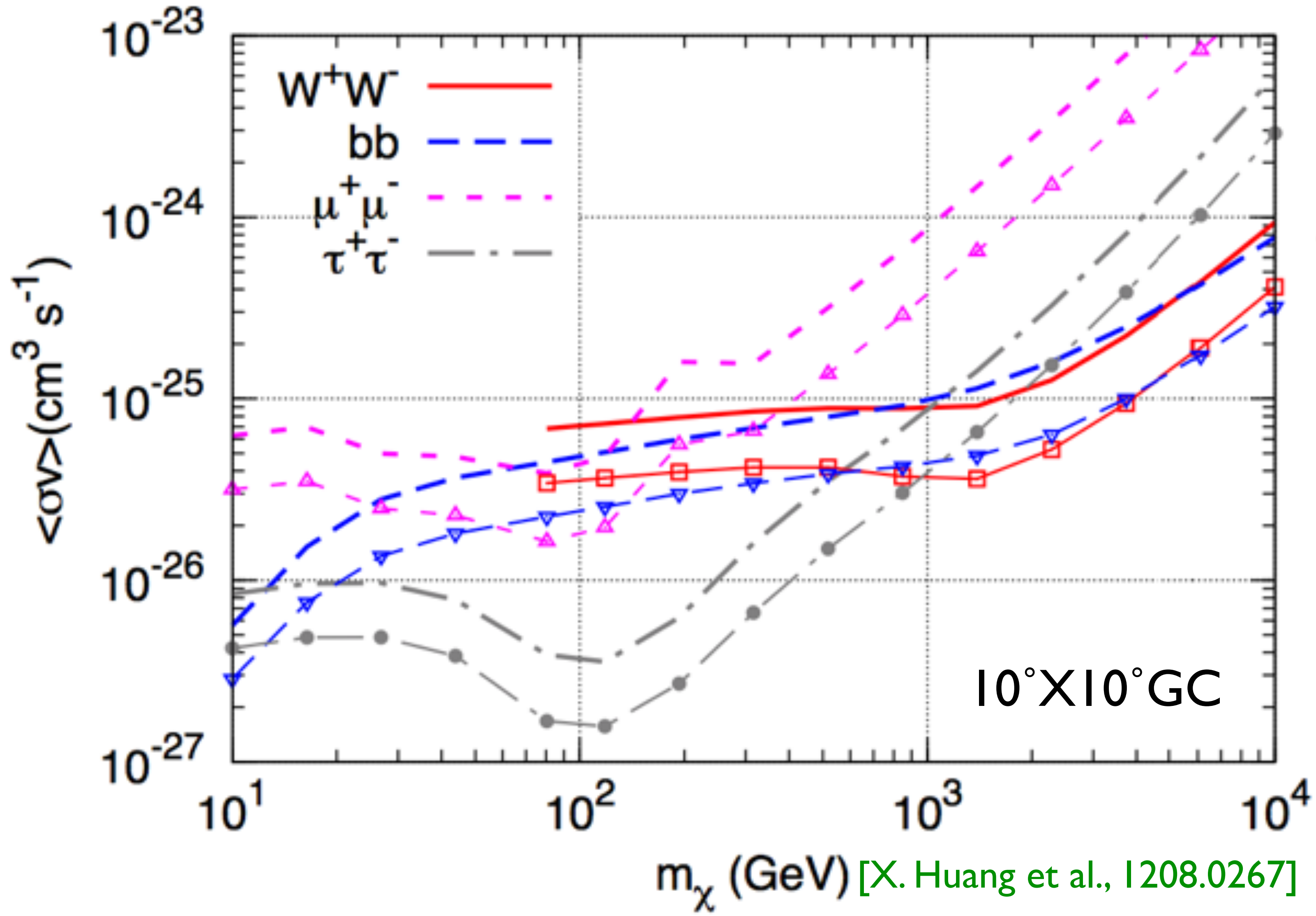
$$\frac{d\sigma_A}{dE_r} = \frac{2\pi\epsilon_e^2\alpha_{em}^2 Z^2}{m_A E_r^2 v^2}\mathcal{F}_A^2(qr_A)$$

$$\sigma_{\mathcal{N},h}^{SI} = \frac{\lambda_{HX}^2}{64\pi}\frac{m_r^2 m_{\mathcal{N}}^2}{m_X^2 m_h^4} f_{q,h}^2$$



• Indirect search (λ_{hx}, m_X)

- DM annihilation via Higgs produces a continum spectrum of γ-rays
- Fermi-LAT γ-ray search data poses a constraint



[X. Huang et al., 1208.0267]

In our model,

$$\langle\sigma v\rangle^{\rm obs}_{XX^\dagger\to W^+W^-} \lesssim 2\times 7.4\times 10^{-26}{\rm cm}^3/{\rm sec}$$

$$\Rightarrow \langle\sigma v\rangle^X_{\rm ann} \lesssim \frac{2\times 7.4\times 10^{-26}{\rm cm}^3/{\rm sec}}{{\rm Br}(XX^\dagger\to W^+W^-)}$$

$$\Rightarrow \quad 1\le \frac{\langle\sigma v\rangle^X_{\rm ann}}{\langle\sigma v\rangle^{\rm th}_{\rm ann}} \lesssim 5$$

☛ Monochromatic γ-ray spectrum?

$$\langle\sigma v\rangle^{\gamma\gamma}_{\rm ann} \sim 10^{-4}\langle\sigma v\rangle^X_{\rm ann} \lesssim 10^{-29}{\rm cm}^3/{\rm sec}$$

Too weak to be seen!

• Collider phenomenology (λ_{hx}, m_X)

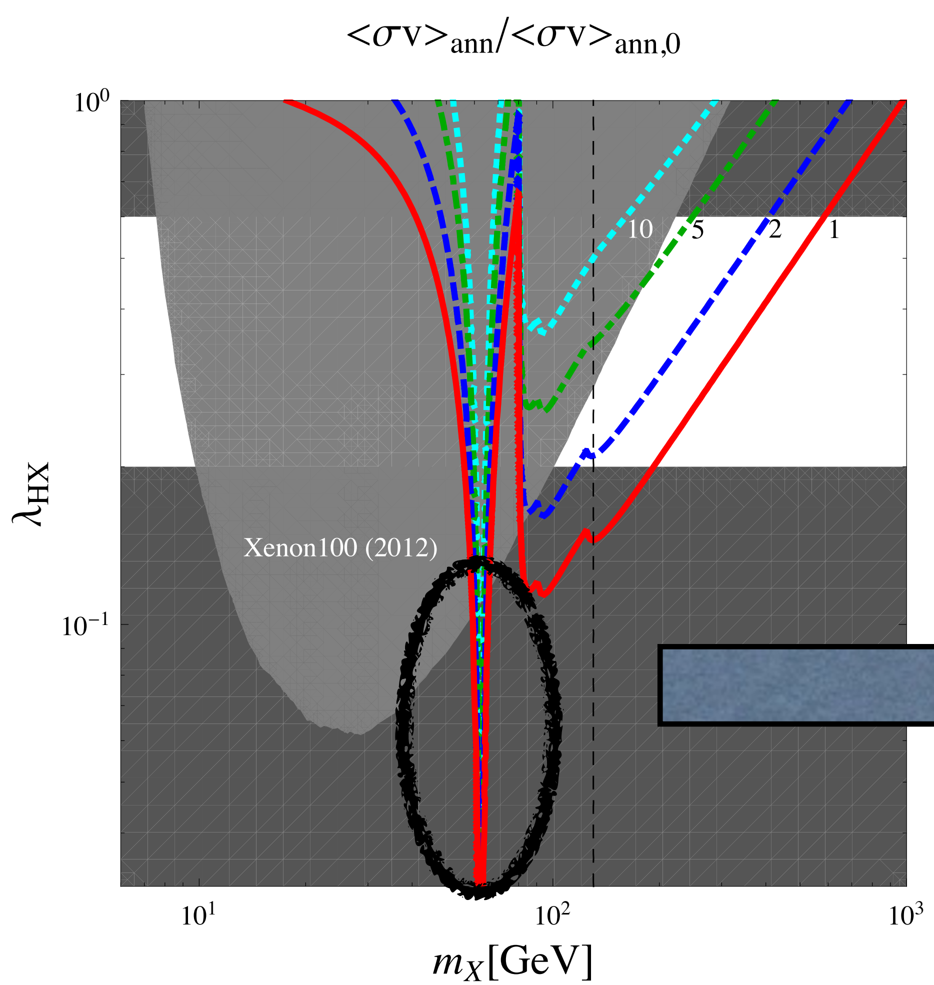
Invisible decay rate of Higgs is

$$\Gamma_{h\to XX^\dagger} = \frac{\lambda_{HX}^2}{128\pi}\frac{v^2}{m_h}\left(1-\frac{4m_X^2}{m_h^2}\right)^{1/2}$$

SM signal strength at collider is

$$\mu = 1 - \frac{\Gamma_{h\to XX^\dagger}}{\Gamma_h^{\rm tot}}$$

(cf., $\mu_{\rm ATLAS} = 1.43 \pm 0.21$ for $m_h = 125.5\,{\rm GeV}$
$\mu_{\rm CMS} = 0.8 \pm 0.14$ for $m_h = 125.7\,{\rm GeV}$)



We may need $\mathrm{Br}(h\to XX^\dagger) \ll \mathcal{O}(10)\%$, i.e.,

$$\lambda_{HX} \ll 0.1$$

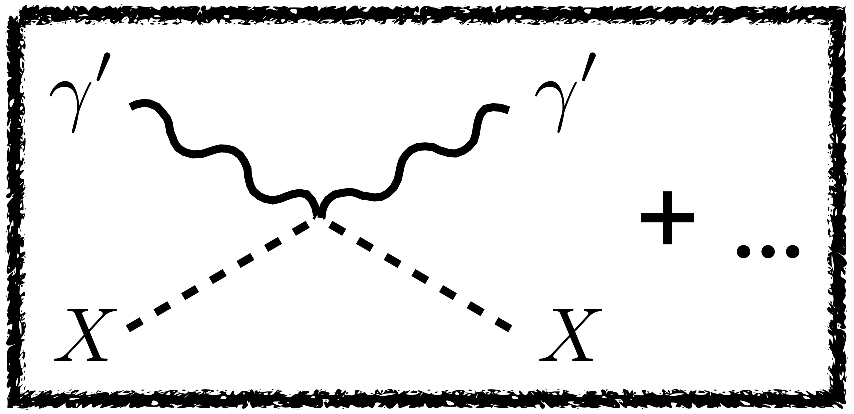
or

$$m_h - 2m_X \lesssim 0.5\,\mathrm{GeV}$$

or kinematically forbidden

• Dark radiation

Decoupling of dark photon



$$\Rightarrow \begin{cases} \Gamma(T_{\gamma'}) = \dfrac{32\pi^3 \alpha_X^2 T_{\gamma'}^4}{45 m_X^3} \Rightarrow T_{\mathrm{dec},\gamma'-X} \gtrsim 16\mathrm{MeV} \\ T_{\mathrm{dec},X-\mathrm{SM}} \sim 1\mathrm{GeV} \Rightarrow T_{\mathrm{dec},\gamma'-\mathrm{SM}} \sim 1\mathrm{GeV} \end{cases}$$

# of extra relativistic degree of freedom

$$\Delta N_{\mathrm{eff}} = \frac{\rho_{\gamma'}}{\rho_\nu} = \frac{g_{\gamma'}}{(7/8)g_\nu} \left(\frac{T_{\gamma,0}}{T_{\nu,0}}\right)^4 \left(\frac{T_{\gamma',\mathrm{dec}}}{T_{\gamma,\mathrm{dec}}}\right)^4 \left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\gamma,\mathrm{dec}})}\right)^{4/3}$$

$$\frac{T_{\nu,0}}{T_{\gamma,0}} = \begin{cases} \left(\frac{4}{11}\right)^{1/3} & \text{for} \quad T_{\mathrm{dec}} \gtrsim 1\mathrm{MeV} \\ 1 & \text{for} \quad T_{\mathrm{dec}} \lesssim 1\mathrm{MeV} \end{cases}$$

$\Delta N_{\mathrm{eff}} = 0.474^{+0.48}_{-0.45}$ at 95% CL (Planck+WP+highL+H_0+BAO)

[Planck Collaboration, arXiv:1303.5076]

Unbroken SU(N) dark sym

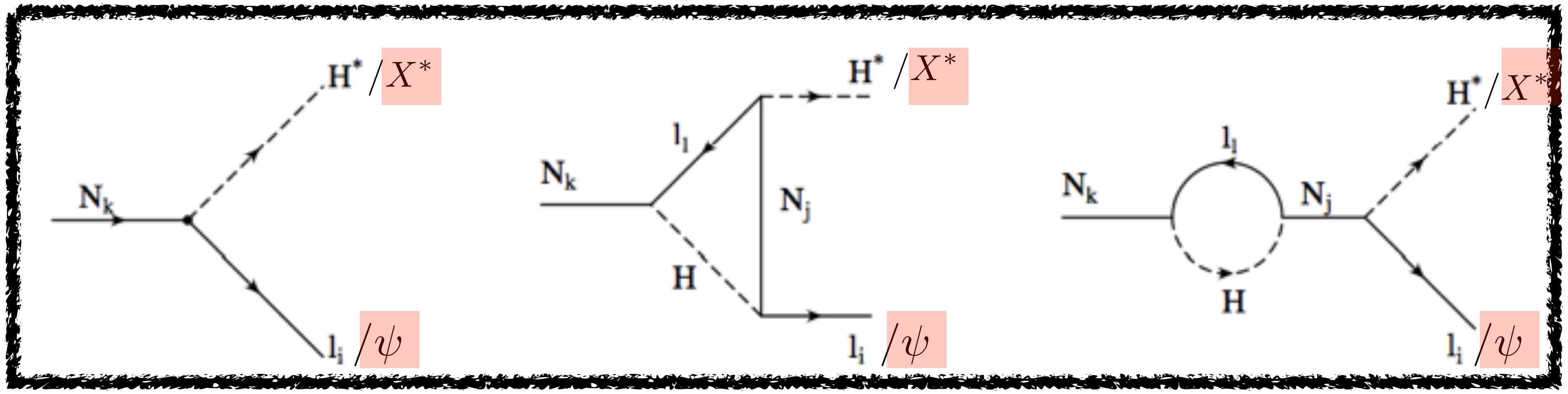
$$\Delta N_{\mathrm{eff}}(N=2) = 0.253,$$
$$\Delta N_{\mathrm{eff}}(N=3) = 0.675,$$
$$\Delta N_{\mathrm{eff}}(N=4) = 1.265.$$

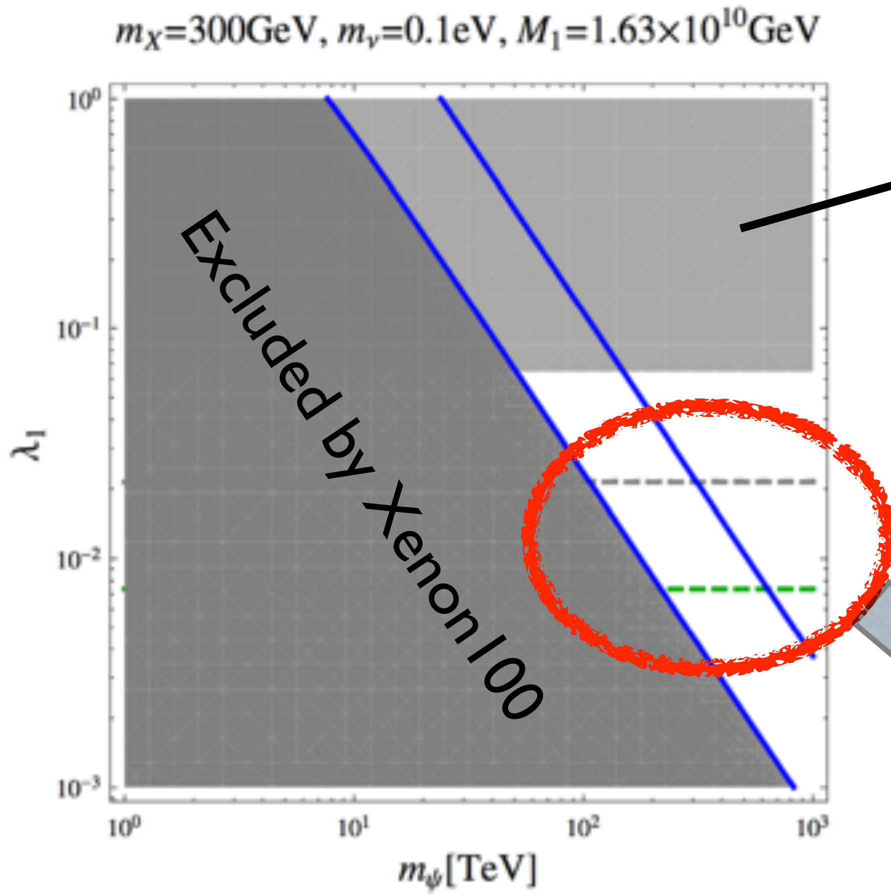
(In preparation)

$$T_{\mathrm{dec},\gamma'-\mathrm{SM}} \sim 1\mathrm{GeV} \Rightarrow \Delta N_{\mathrm{eff}} = \frac{2}{2\frac{7}{8}} \left(\frac{11}{4}\right)^{4/3} \left(\frac{g_{*S}(T_{\gamma,0})}{g_{*S}(T_{\mathrm{dec},X_\mu})}\right)^{4/3} \sim 0.06$$

- # Lepto/darkogenesis (1/2)

(Genesis from the decay of RHN)





Light gray: narrow width approx. is invalid

White between blue lines:

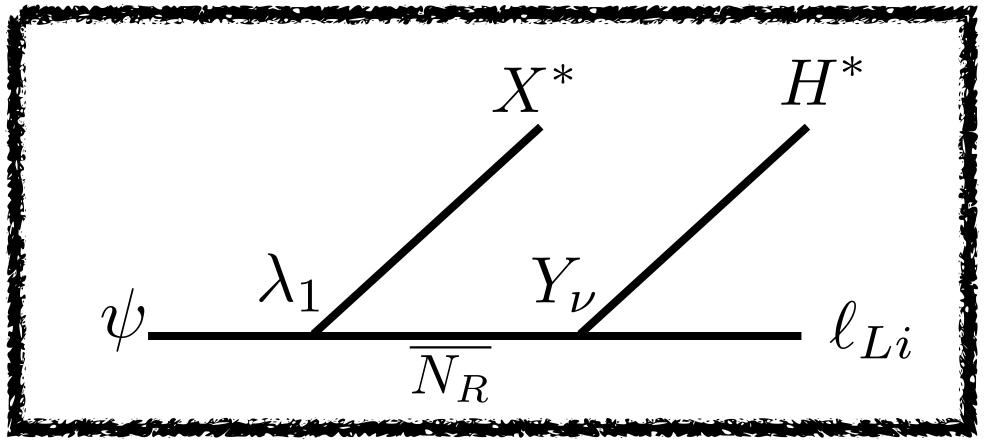
$$1 \leq \langle \sigma v \rangle^{\rm tot}_{\rm ann} / \langle \sigma v \rangle^{\rm th}_{\rm ann} \lesssim 5$$

Green lines: $Y_{\nu 1} = \lambda_1$

Correct BAU and CDM relic can be obtained.

• Lepto/darkogenesis (2/2)

(Genesis from the late-time decay of ψ &ψ-bar)



Late-time decay of ψ → $\Delta(Y_{\Delta L}) \neq 0$

$T_{\rm d}^{\psi} \ll m_\psi$ → No wash-out!

$$\Delta(Y_{\Delta L}) = 2\epsilon_L Y_\psi(T_{\rm fz}^{\psi})$$

$$Y_\psi(T_{\rm fz}^{\psi}) = \frac{3.79\left(\sqrt{8\pi}\right)^{-1} g_*^{1/2}/g_{*S}x_{\rm fz}^{\psi}}{m_\psi M_{\rm P}\langle\sigma v\rangle_{\rm ann}^{\psi}} \simeq 0.05\frac{x_{\rm fz}^{\psi}}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}$$

$$\frac{\Delta(Y_{\Delta L})}{Y_{\Delta L}} \simeq 2\times 10^7\frac{x_{\rm fz}^{\psi}}{\alpha_X^2}\frac{m_\psi}{M_{\rm P}}\frac{M_1 m_\nu^{\rm max}}{v_H^2}\times\begin{cases}1 & \text{for } {\rm Br}_L \gg {\rm Br}_\psi\\ \sqrt{\lambda_2^2 M_1/\lambda_1^2 M_2} & \text{for } {\rm Br}_L \ll {\rm Br}_\psi\end{cases}$$

$$\left({\rm e.g}: \epsilon_L \sim 10^{-7}, \alpha_X \sim 10^{-5}, m_\psi \sim 10^3{\rm TeV} \to \frac{\Delta(Y_{\Delta L})}{Y_{\Delta L}} \sim 0.3\right)$$

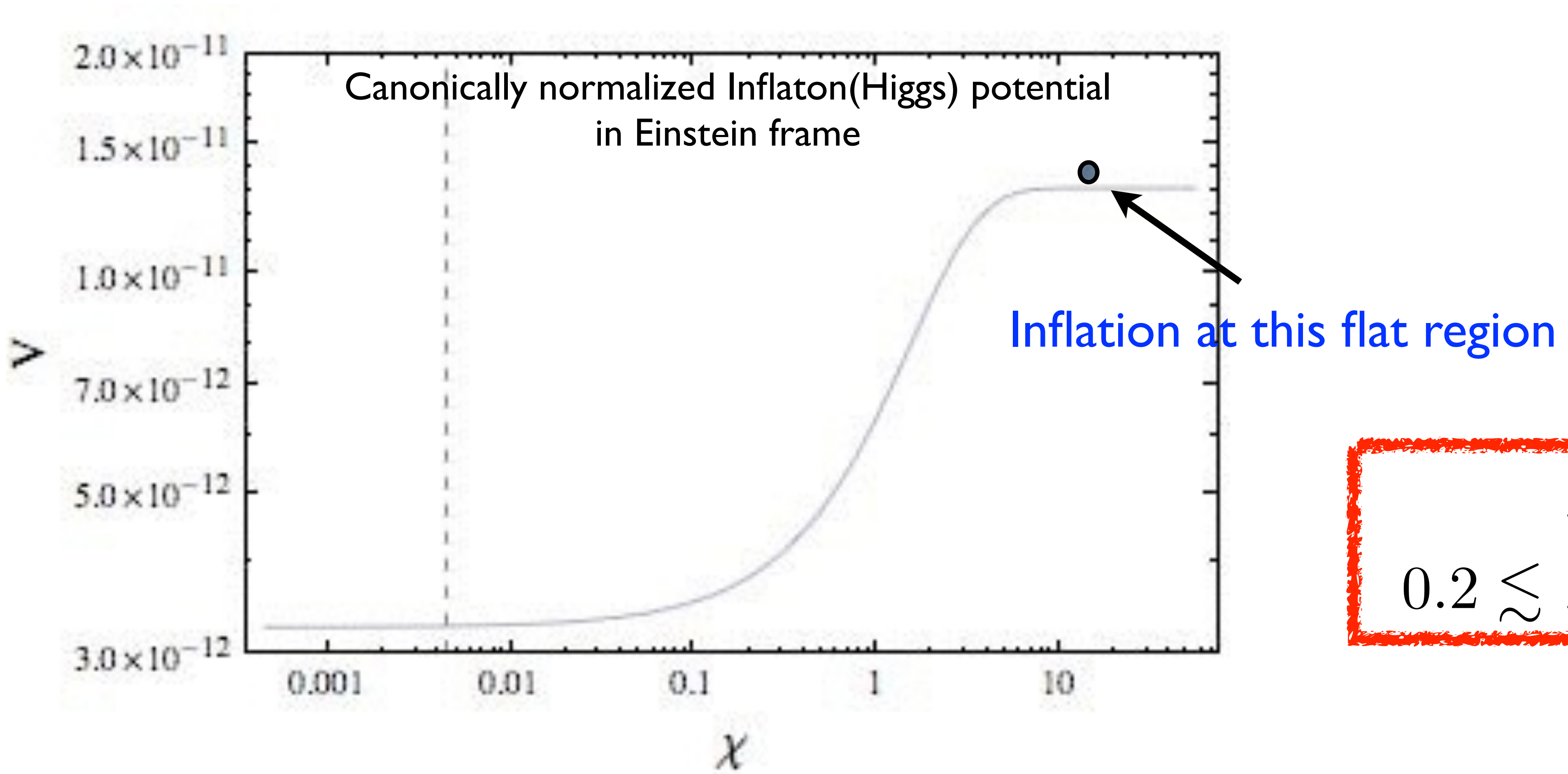
* Late-time decays of symmetric ψ and ψ-bar can generate a sizable amount of lepton number asymmetry.

- # Higgs inflation in Higgs-singlet system

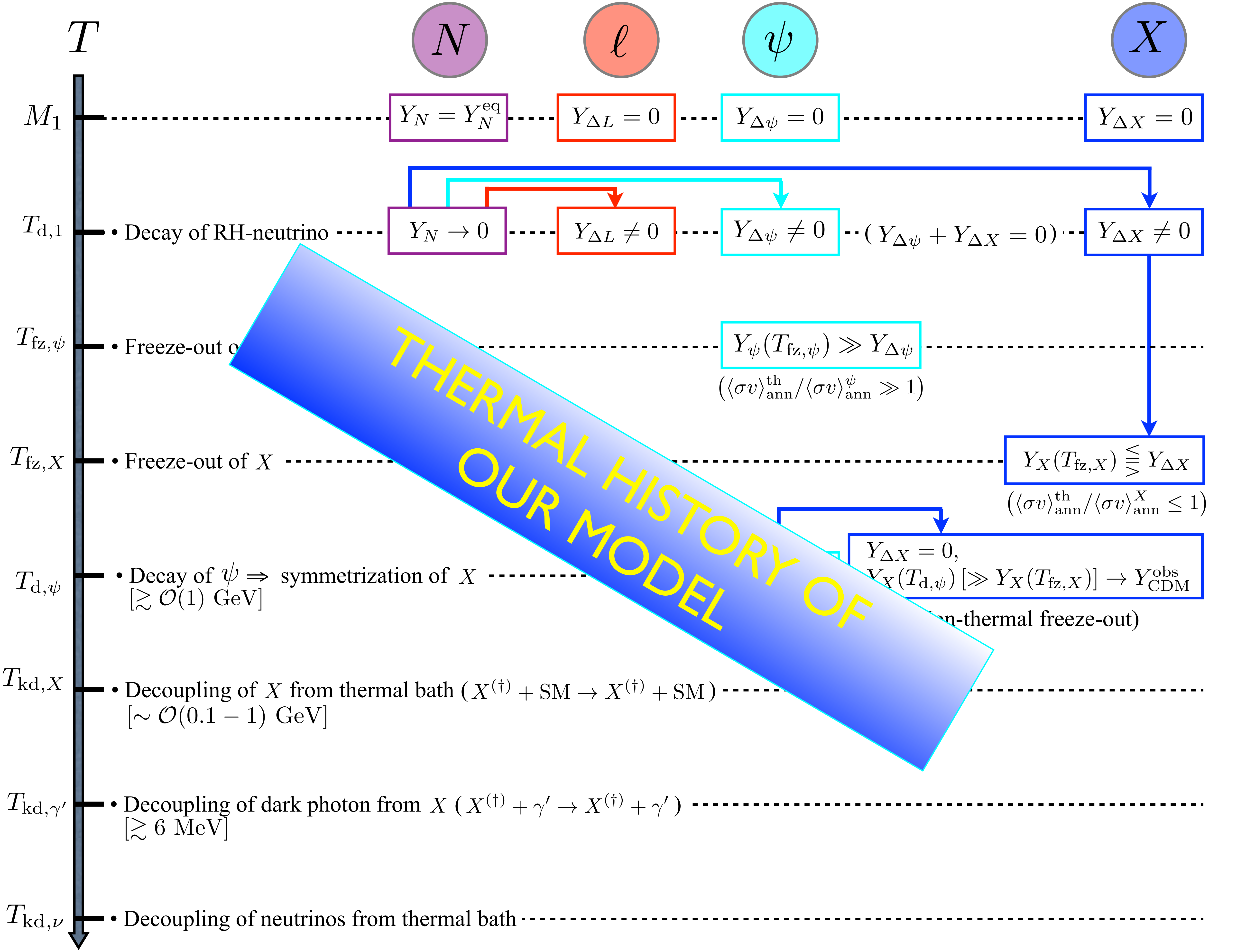
[Lebedev,1203.0156]

$$\frac{\mathcal{L}_{\rm scalar}}{\sqrt{-g}} = -\frac{1}{2}M_{\rm P}^2 R - \frac{1}{2}\left(\xi_h h^2 + \xi_x x^2\right) R + \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{2}(\partial_\mu x)^2 - V(h,x)$$

where $\xi_h,\ \xi_x \gg 1$



$$\lambda_X \lesssim 0.23$$
$$0.2 \lesssim \lambda_{HX} \lesssim 0.6$$


THERMAL HISTORY OF OUR MODEL
T
N
ℓ
ψ
X
M_1
$Y_N = Y_N^{\rm eq}$
$Y_{\Delta L} = 0$
$Y_{\Delta\psi} = 0$
$Y_{\Delta X} = 0$
$T_{\rm d,1}$
• Decay of RH-neutrino
$Y_N \to 0$
$Y_{\Delta L} \neq 0$
$Y_{\Delta\psi} \neq 0$
$(\,Y_{\Delta\psi} + Y_{\Delta X} = 0)$
$Y_{\Delta X} \neq 0$
$T_{{\rm fz},\psi}$
• Freeze-out o
$Y_\psi(T_{{\rm fz},\psi}) \gg Y_{\Delta\psi}$
$(\langle\sigma v\rangle_{\rm ann}^{\rm th}/\langle\sigma v\rangle_{\rm ann}^{\psi} \gg 1)$
$T_{{\rm fz},X}$
• Freeze-out of X
$Y_X(T_{{\rm fz},X}) \lesseqqgtr Y_{\Delta X}$
$(\langle\sigma v\rangle_{\rm ann}^{\rm th}/\langle\sigma v\rangle_{\rm ann}^{X} \leq 1)$
$T_{{\rm d},\psi}$
• Decay of $\psi \Rightarrow$ symmetrization of X
$[\gtrsim \mathcal{O}(1)\ {\rm GeV}]$
$Y_{\Delta X} = 0,$
$Y_X(T_{{\rm d},\psi})\, [\gg Y_X(T_{{\rm fz},X})] \to Y_{\rm CDM}^{\rm obs}$
n-thermal freeze-out)
$T_{{\rm kd},X}$
• Decoupling of X from thermal bath $(\,X^{(\dagger)} + {\rm SM} \to X^{(\dagger)} + {\rm SM}\,)$
$[\sim \mathcal{O}(0.1-1)\ {\rm GeV}]$
$T_{{\rm kd},\gamma'}$
• Decoupling of dark photon from X $(\,X^{(\dagger)} + \gamma' \to X^{(\dagger)} + \gamma'\,)$
$[\gtrsim 6\ {\rm MeV}]$
$T_{{\rm kd},\nu}$
• Decoupling of neutrinos from thermal bath

Local Gauge Principle
Enforced to DM Physics
in the models presented

We got a set of predictions
consistent with all the
observations available so far

Nontrivial and Interesting possibility

Variations

Signal strength

Assume the decay of Higgs to DMs is forbidden.

Dark sector fields	$U(1)_X$	Messenger	DM	Extra DR	μ_i
$\hat{B}'_\mu, X, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X	~ 0.06	$1\ (i=1)$
$\hat{B}'_\mu, X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0.06	$1\ (i=1)$
$\hat{B}'_\mu, \psi_X$	Unbroken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0.06	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \psi_X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, N_R$	X or ψ_X	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, X, \phi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}$	X	~ 0	$< 1\ (i=1,2)$
$\hat{B}'_\mu, \psi_X$	Broken	$H^\dagger H, \hat{B}'_{\mu\nu}\hat{B}^{\mu\nu}, S$	ψ_X	~ 0	$< 1\ (i=1,2,3)$

○ = a singlet real scalar

because of mixing in Higgs sector

* Fermion dark matter requires a real scalar mediator which is mixed with SM Higgs.
* Unbroken U(1)x allows a sizable contribution to the extra radiation.

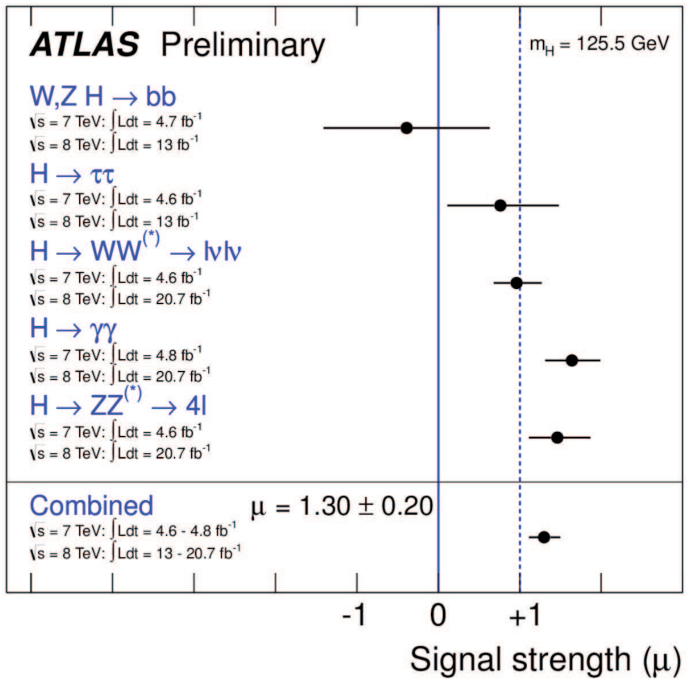
Note that "mu < 1" if CDM is fermion, whether U(1)x is broken or not

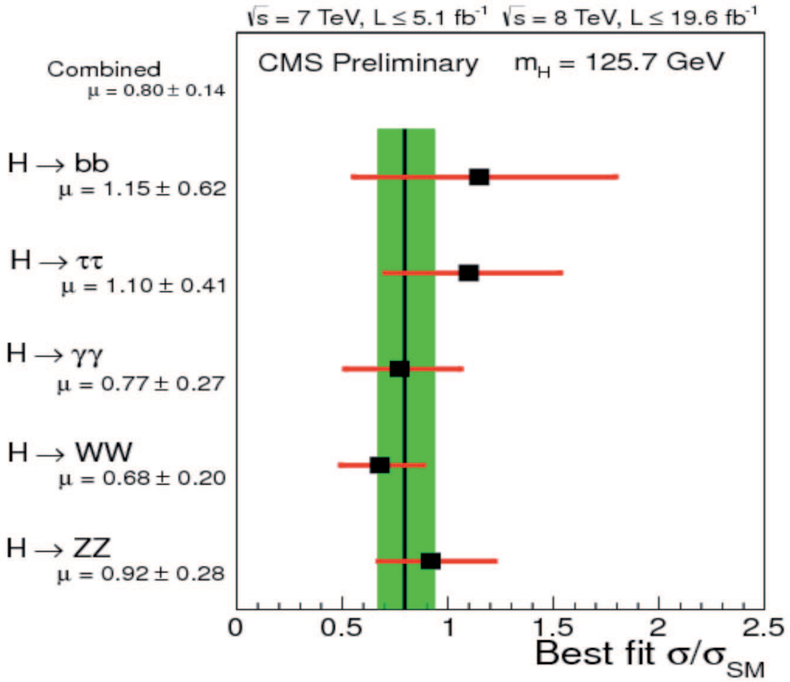
And Universal Suppression

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	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Summary of the 2nd part

- Stability of weak scale dark matter requires a local symmetry.
- The simplest extension of SM with a local U(1) has a unique set of renormalizable interactions.
- The model can be an alternative of NMSM, address following issues.

  * Some small scale puzzles of standard CDM scenario
  * Vacuum stability of Higgs potential
  * CDM relic density (thermal or non-thermal)
  * Dark radiation
  * Lepto/darkogenesis
  * Inflation (Higgs inflation type)

Conclusion

- Two examples of hidden sector DM models with local DM symmetry
- Strongly Interacting Case : EWSB and CDM mass from dim transmutation in hidden sector
- Weakly Interacting Case : Dark Radiation Constrained by Planck
- In either case, the Higgs signal strengths are universally suppressed

- Stability or longevity of a hCDM is closely related with the SM Higgs sector (amusing !)
- Whatever you do for CDM stabilization or longevity, unlikely to avoid extra singlet scalar(s) which mix w/ the SM Higgs boson
- Universal suppressions of the signal strengths of Higgs productions/decays @ LHC
- Precise measurements of the signal strengths @ LHC can test the hCDM hypothesis

- The signal strength of Higgs boson is universally reduced from “one”If dark sym is unbroken and DM is scalar, there could be only one SM Higgs boson with signal strengths = ONE (and dark radiation)
- LHC Higgs data probes the hidden sector DM
- Dark radiation begins to constrain the number of massless dark gauge bosons that stabilize the EW scale DM

- The 2nd scalar is very very elusive
- Small mixing limit is the interesting region
- How can we find the 2nd scalar at experiments ?
- We will see if this class of DM can survive the LHC Higgs data in the coming years

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

Loopholes & Ways Out

- DM could be very light and long lived (Totalitarian principle)
- More than one Higgs doublet playing the singlet portals to the hidden sector (against Occam's razor principle)
  - SUSY needs 2HDM's
  - New chiral Gauge Sym needs new Higgs Doublets