Impacts of Dark Higgs on Particle Physics & Cosmology

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Key Ideas

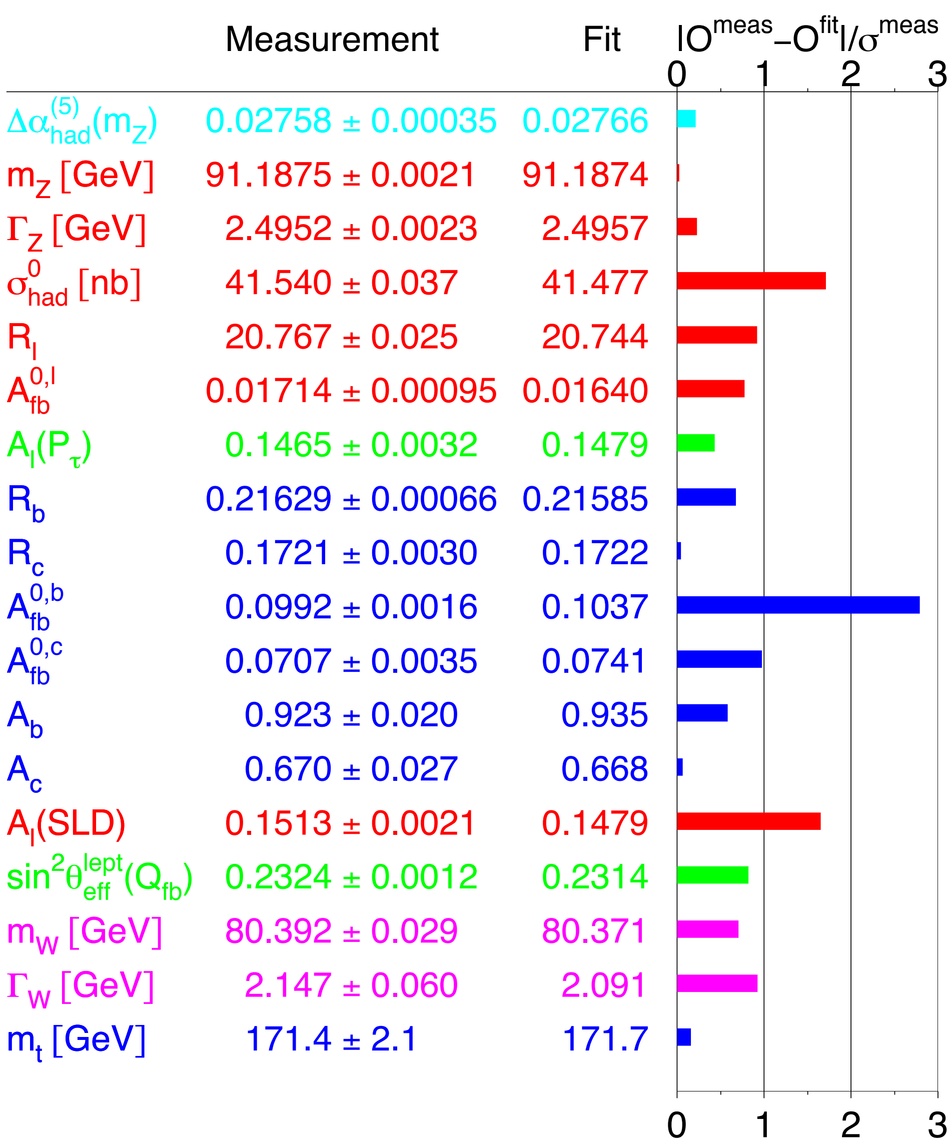
- Stability/Longevity of Dark Matter (DM)
- Local Dark Gauge Symmetry
- Thermal DM through Singlet Portals (especially Higgs Portal)
- Connections between Higgs, DM and Higgs Inflation, especially the role of "Dark Higgs"

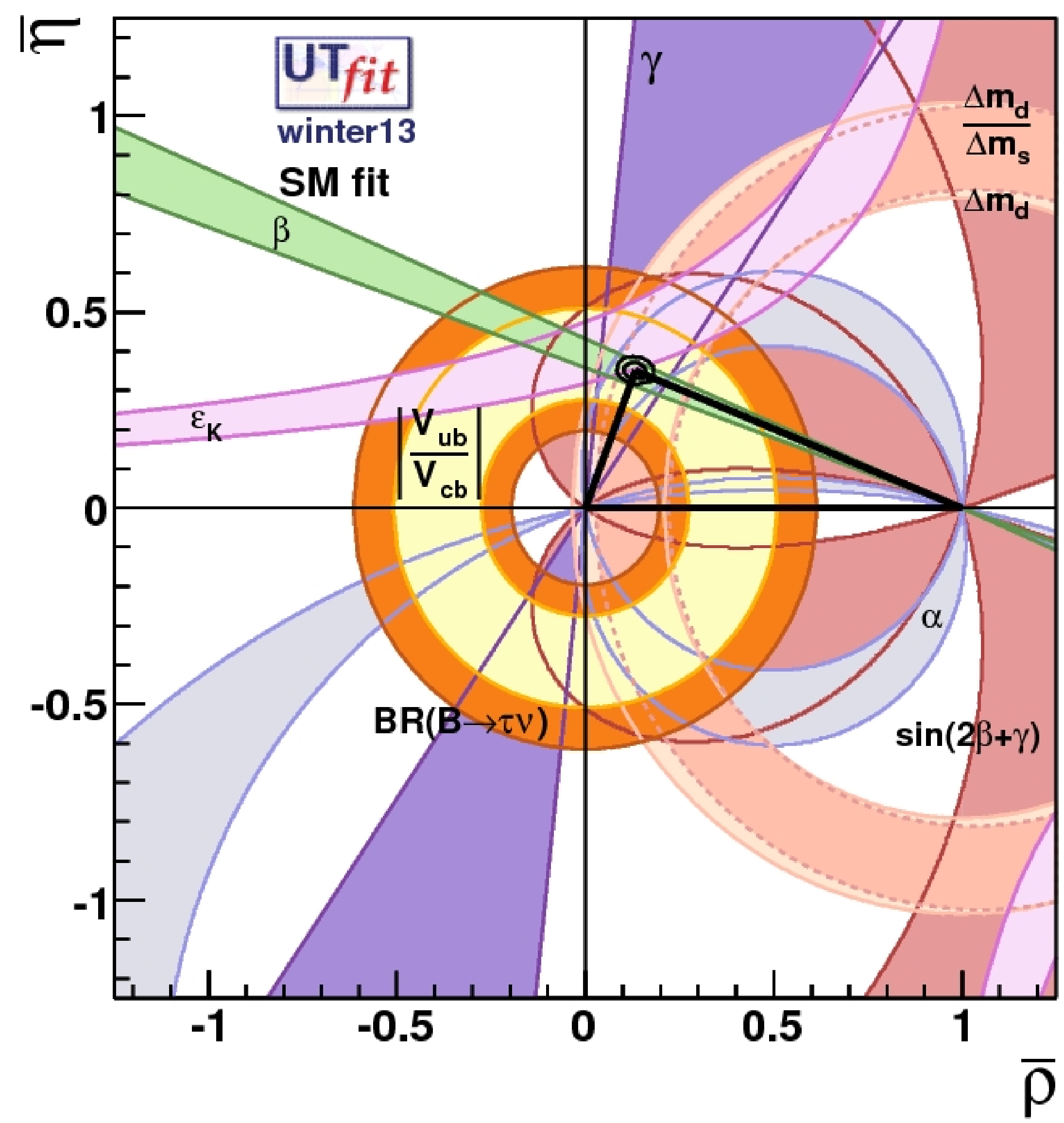
SM Lagrangian

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

Based on local gauge principle

EWPT & CKM





Almost Perfect !

Theory vs. Data on $(g-2)_\mu$

Table 1: Summary at Tau06 Workshop

Contribution	Value $\times 10^{10}$	Error $\times 10^{10}$	Comment
QED	11 658 471.9	0.1	4 loops; 5th estin
Had. vac. pol.	690.9	4.4	Only CM D-2 anc
Had. light by light	12.0	3.5	Value from Ref. [
Had., other 2nd or.	-9.8	0.1	
Weak	15.4	0.22	2 loops
Total theory	11 659 180.4	5.6	0.48 ppm
Experiment (BNL E821)	11 659 208.0	6.3	0.54 ppm
Expt. - Thy.	27.6	8.4	3.3 standard dev

Only Higgs (~SM) and Nothing Else So Far at the LHC

All the interactions except for gravity are described by Qunaum Gauge Theories !

Motivations for BSM

- Neutrino masses and mixings
- Baryogenesis
- Inflation (inflaton)
- Nonbaryonic DM
- Origin of EWSB and Cosmological Const ?

Leptogenesis

Starobinsky ? Higgs Inflations

Many candidates

Can we attack these problems ?

Main Motivations

- Understanding DM Stability or Longevity ?
- Origin of Mass (including DM, RHN) ?
- 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)

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 ?

- Most studies on DM were driven by some anomalies: 511 keV gamma ray, PAMELA/AMS02 positron excess, DAMA/CoGeNT, Fermi/LAT 135 GeV gamma ray, 3.5 keV Xray, Gamma ray excess from GC etc
- On the other hand, not so much attention given to DM stability/longevity in nonSUSY DM models
- Also extra particles (the so-called mediators, scalar, vector etc) are introduced to have strong DM self-interaction, rather ad hoc
- Any good organizing principle ?

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- Any good organizing principle ? YES !

In QFT

- DM could be absolutely stable due to unbroken local gauge symmetry (DM with local Z_2, Z_3 etc.) or topology (hidden sector monopole + vector DM + dark radiation)
- Longevity of DM could be due to some accidental symmetries (hidden sector pions and baryons)
- I will mainly talk about local Z_2 + EWSB & CDM from strongly interacting hidden sector (backup for monopole DM)

Contents

- Underlying Principles : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
- Scalar DM with local Z2 : comparison with global models, limitation of EFT approach, and phenomenology
- Scale Inv Extension of the SM with strongly Int. Hidden Sector : EWSB and CDM from hQCD; All Masses including DM mass from Dim Transmutation in hQCD, DM stable due to accidental sym
- Higgs Phenomenology & Higgs Inflation with extra singlet (dark Higgs) : Universal Suppression of Higgs signal strength and extra neutral scalar, Higgs inflation, etc.
- (un)broken $U(1)_X$: Singlet Portal and Dark Radiation; h-monopole
- Tight bond between DM-sterile nu's with $U(1)_X$: Dark Radiation

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 local dark symmetry (1303.4280 JHEP)
- Hidden sector Monopole, VDM and DR (1311.1035)
- Self-interacting scalar DM with local Z3 symmetry (1402.6449)
- And a few more, including Higgs-portal assisted Higgs inflation, Higgs portal VDM for gamma ray excess from GC, and DM-sterile nu's etc.

Analogy with weak int

- Fermi's theory of weak interaction (EFT)>>Michelle parameters >>(V-A)>> MVB(W)>>Higgs mechanism>>SM
- DM signatures >>EFT>>…..>>DM models
- EFT for DM: simple, intuitive, but can be misleading, wrong or useless
- Eventually one has to go through all the possibilities one-by-one (as in the weak interaction where all possible Lorentz structure): inevitably model dependent

Principles for DM Physics

- Local Gauge Symmetry for DM
  - can make DM absolutely stable or long lived
  - all the known particles feel gauge force
- Renormalizability with some caveat
  - does not miss physics which EFT can not catch.
- Singlet portals
  - allows communication of DS to SM (thermalization, detectability, ...)

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

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

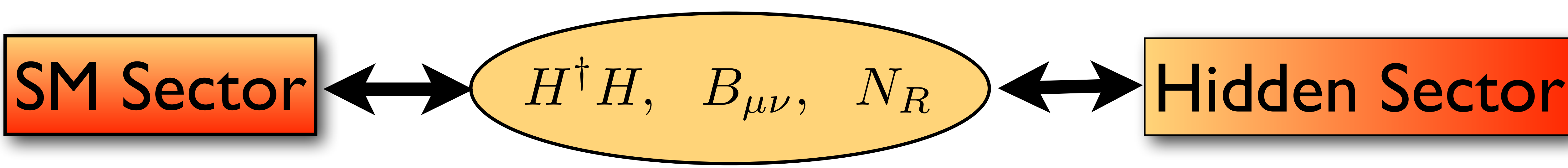
- Hidden sector gauge symmetry can stabilize hidden DM
- There could be some contributions to the dark radiation (dark photon or sterile neutrinos)
- Consistent with GUT in a broader sense
- Can address "QM generation of all the mass scales from strong dynamics in the hidden sector" (alternative to the 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

Singlet Portal

- If there is a hidden sector and DM is thermal, then we need a portal to it
- There are only three unique gauge singlets in the SM + RH neutrinos



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

Generic Aspects

- Two types of force mediators :
  - Higgs-Dark Higgs portals (Higgs-singlet mixing)
  - Kinetic portal to dark photon for U(1) dark gauge sym (absent for non-Abelian dark gauge sym@renor. level)
  - Naturally there due to underlying dark gauge symmetry
- RH neutrino portal if it is a gauge singlet (not in the presence of U(1) B-L gauge sym)
- These (especially Higgs portal which has been often neglected) can thermalize CDM efficiently

General Comments

- Many studies on DM physics using EFT
- However we don't know the mass scales of DM and the force mediator, and also dark sym
- 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

Why renormalizable models ?
&
Limitation of EFT for DM

Higgs portal DM as examples

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

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

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

All invariant under ad hoc Z2 symmetry

arXiv:1112.3299, … 1402.6287, etc.

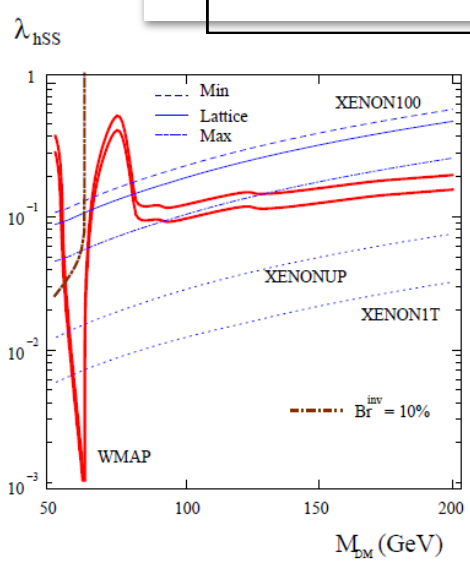


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

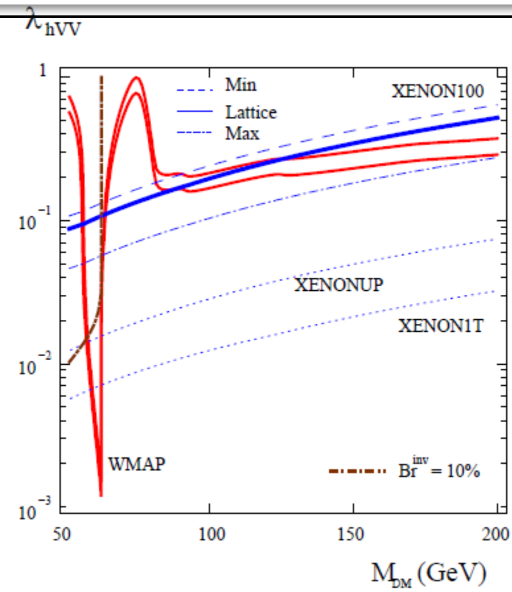


FIG. 2. Same as Fig. 1 for vector DM particles.

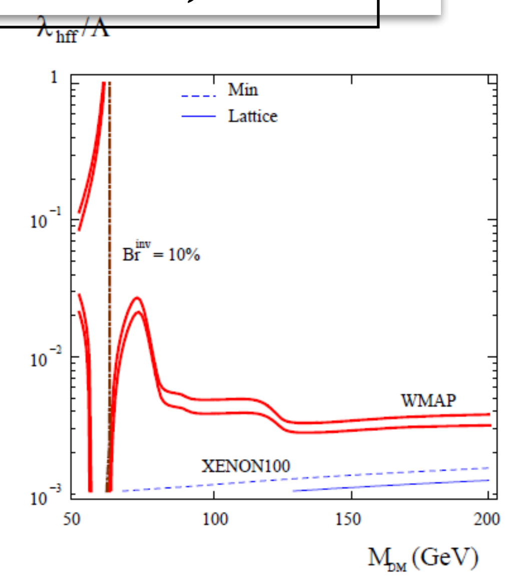


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

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

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

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

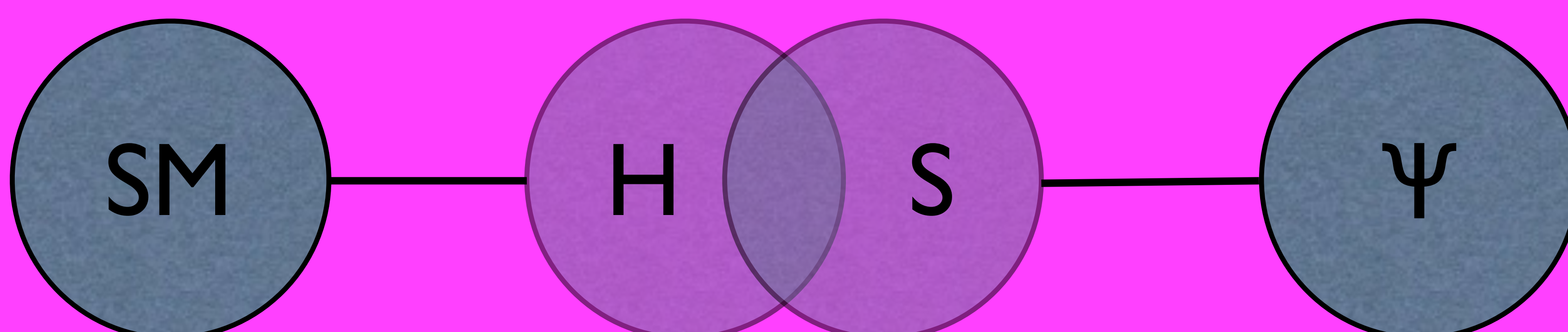
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

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

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

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

← Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

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

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

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

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

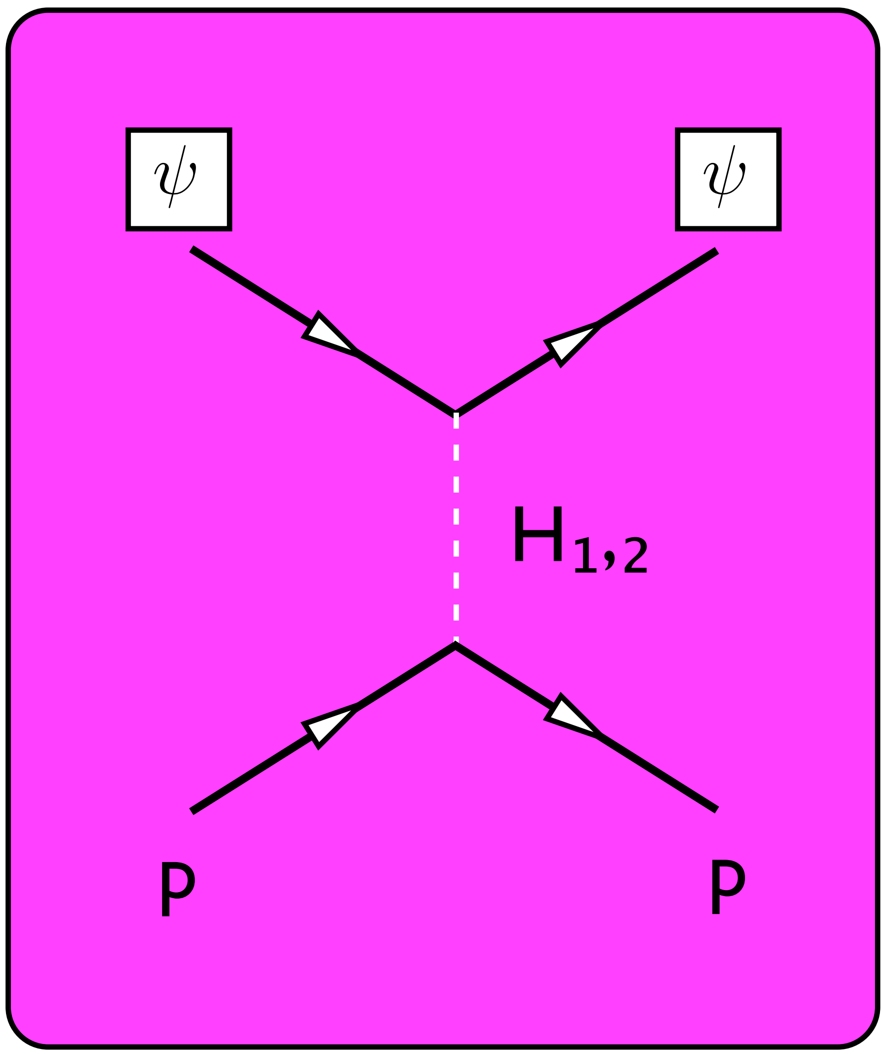
Invisible decay mode is not necessary!

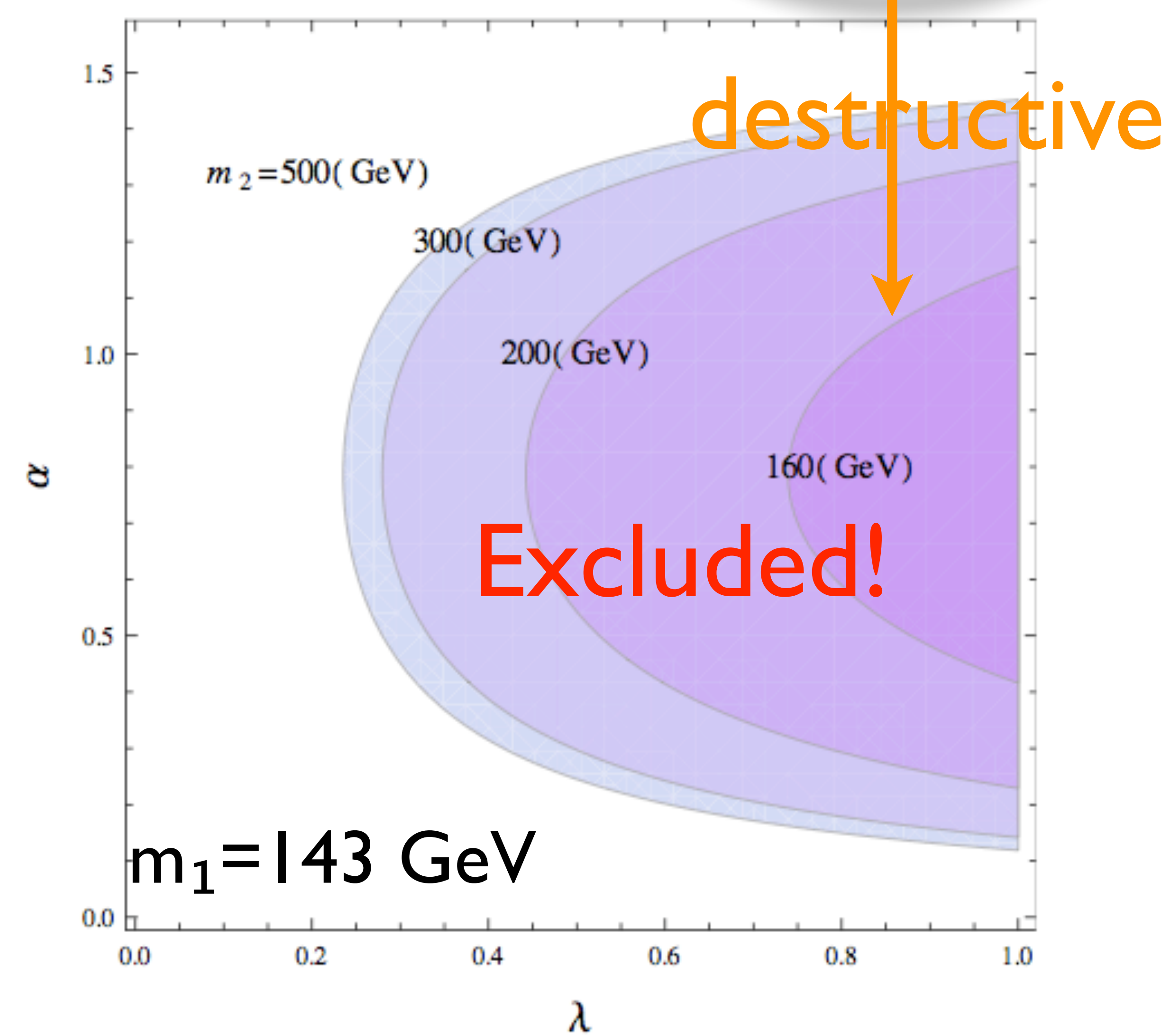
If r_i > 1 for any single channel,
this model will be excluded !!

Constraints

- 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

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

Breaks SM gauge sym

- Only one Higgs boson (alpha = 0)

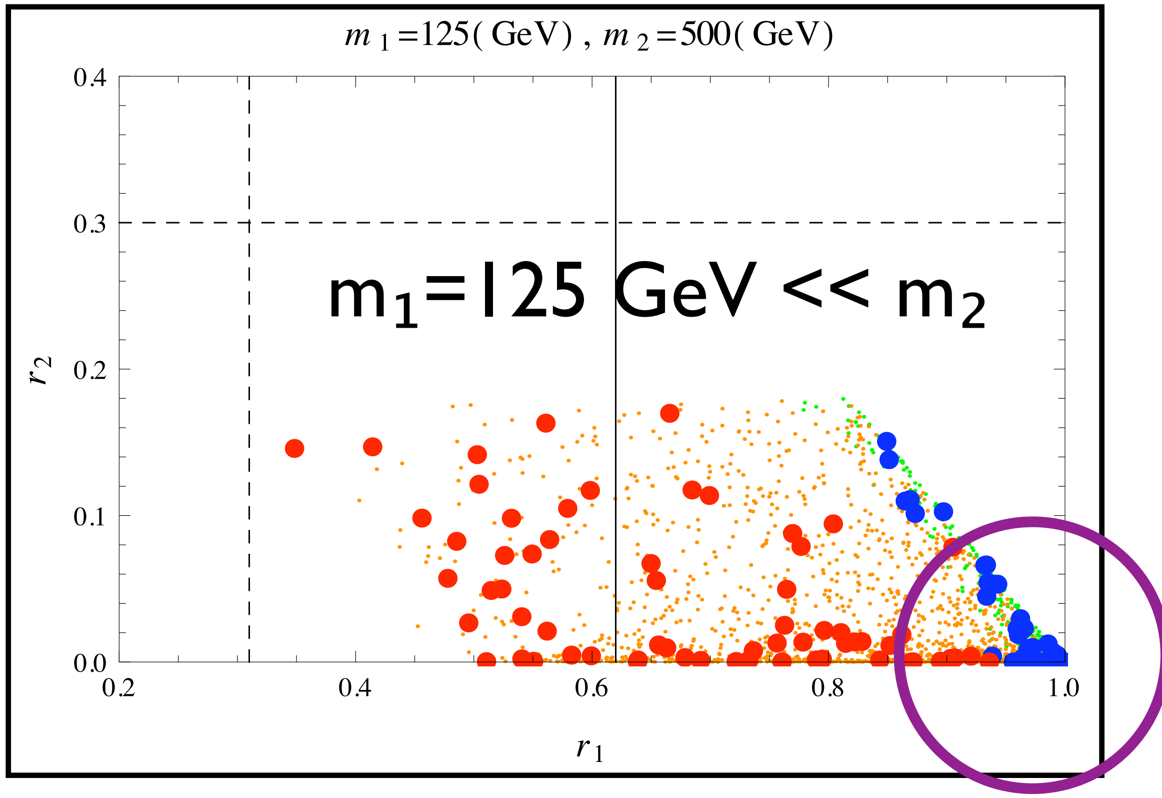
- We cannot see the cancellation between two Higgs scalars in the direct detection cross section, if we used the above effective lagrangian

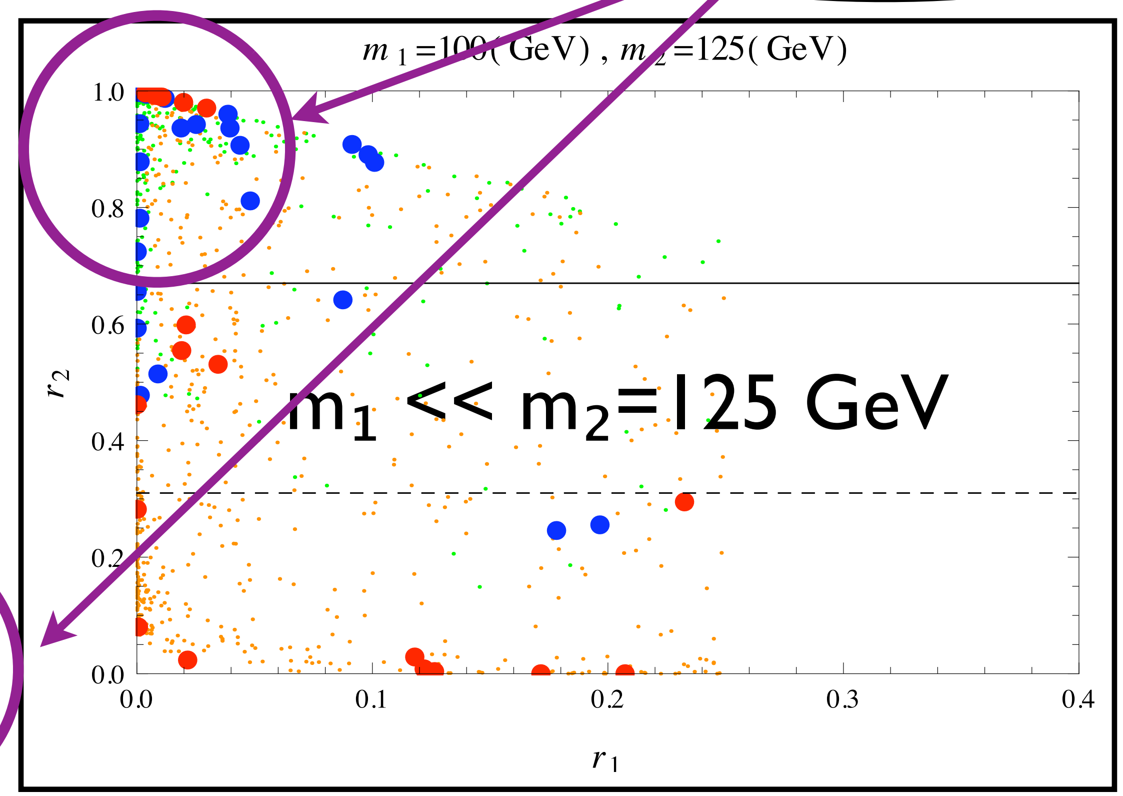
- The upper bound on DD cross section gives less stringent bound on the possible invisible Higgs decay

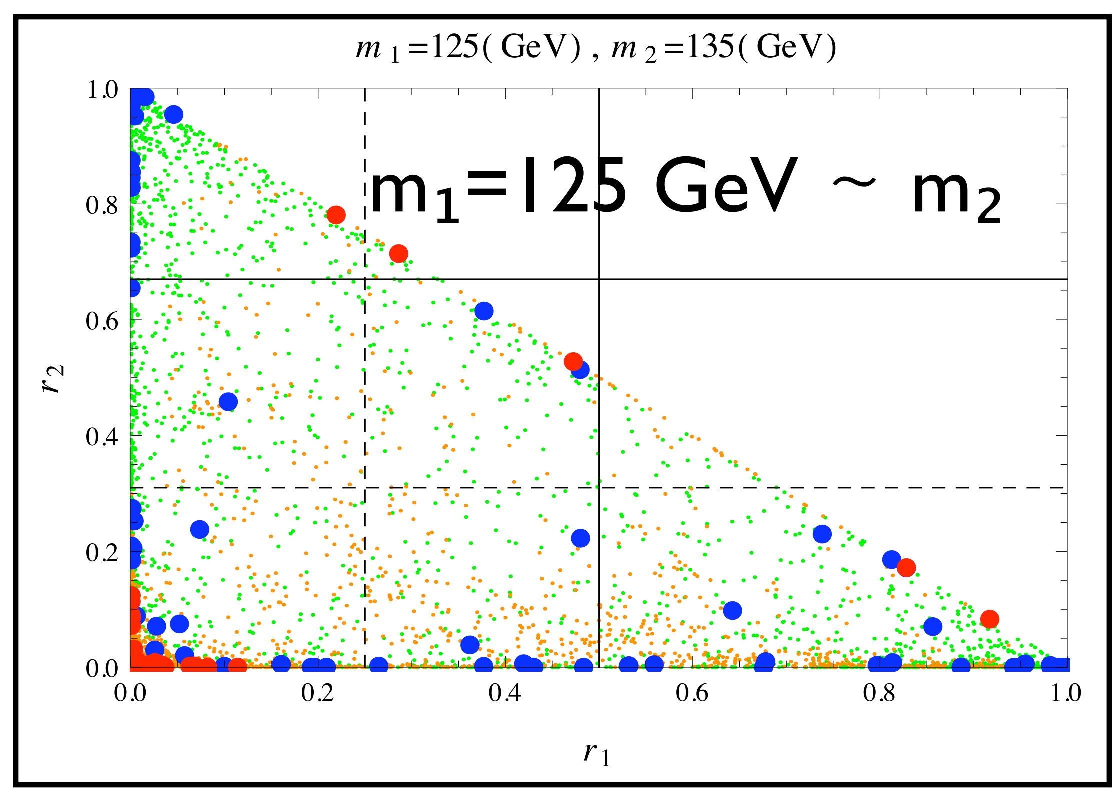
Discovery possibility

- Signal strength (r_2 vs r_1)

LHC data for 125 GeV resonance





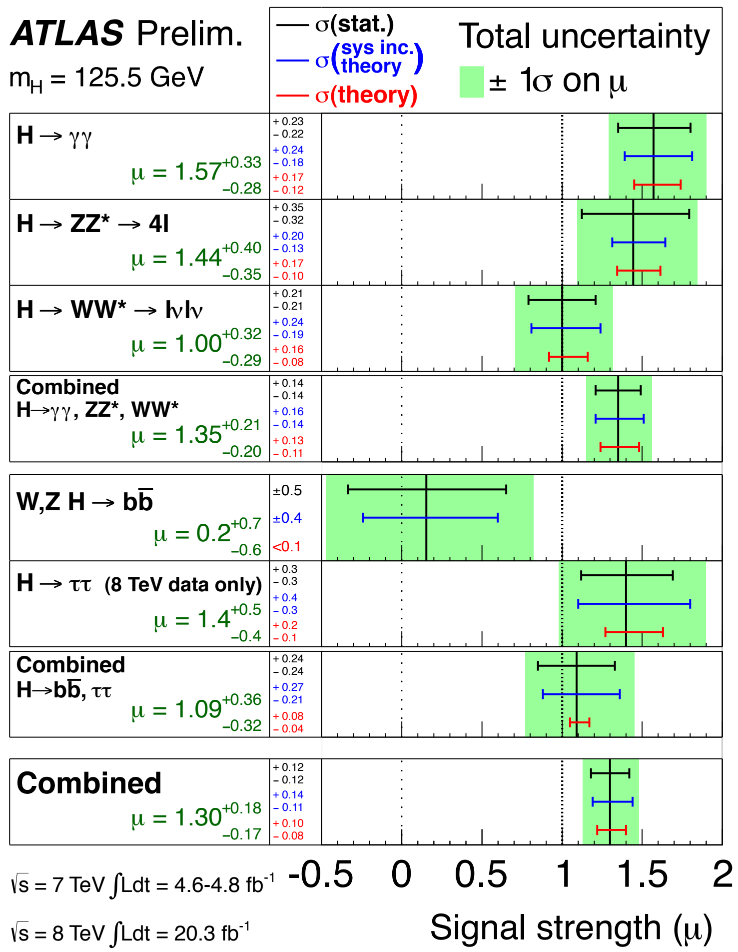


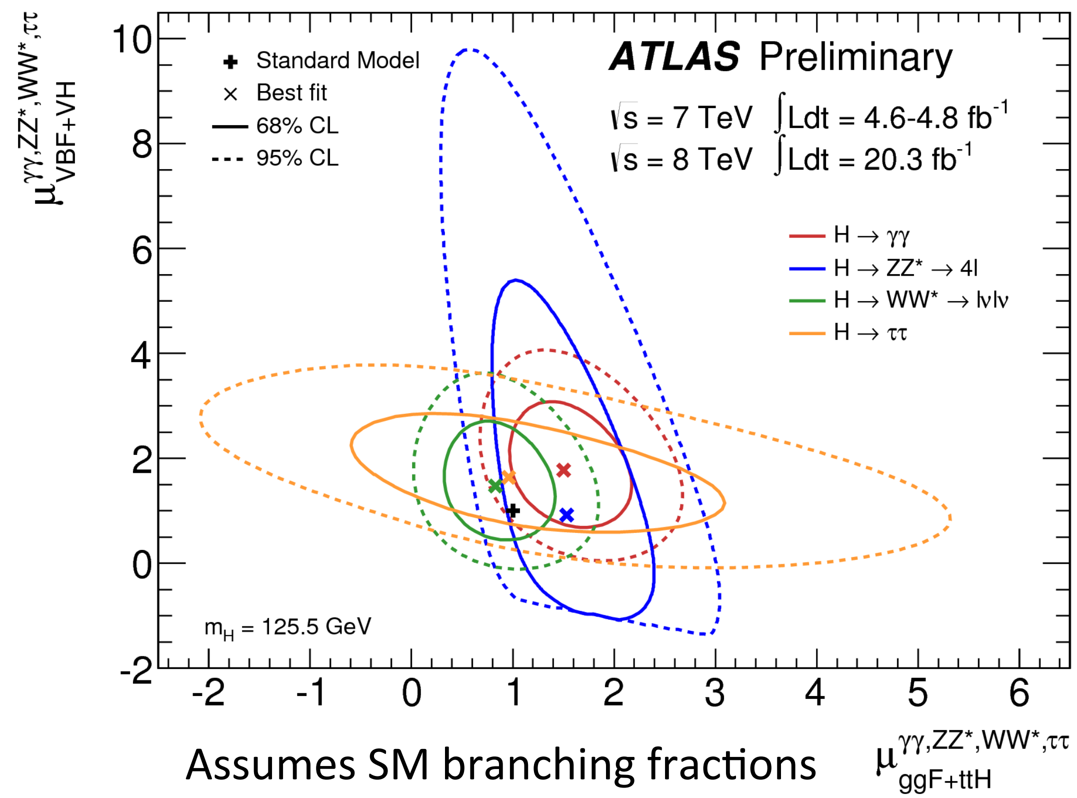
: $L = 5\ \mathrm{fb}^{-1}$ for 3σ Sig.

: $L = 10\ \mathrm{fb}^{-1}$ for 3σ Sig.

- (green) : Ω(x),σ_p(x)
- (orange) : Ω(x),σ_p(o)
- (blue) : Ω(o),σ_p(x)
- (red) : Ω(o),σ_p(o)

Main Decay and Production Modes





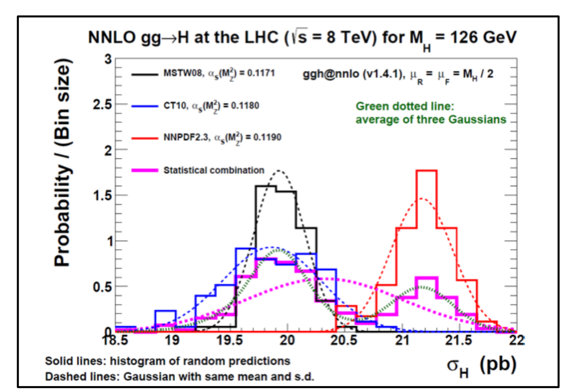
Assumes SM branching fractions and production modes

Compatible with SM (at 14%)

$$\mu = 1.30 \pm 0.12\ (\text{stat})\ \pm 0.10\ (\text{th})\ \pm 0.09\ (\text{syst})$$

All channels couplings updated soon

Stay tuned !

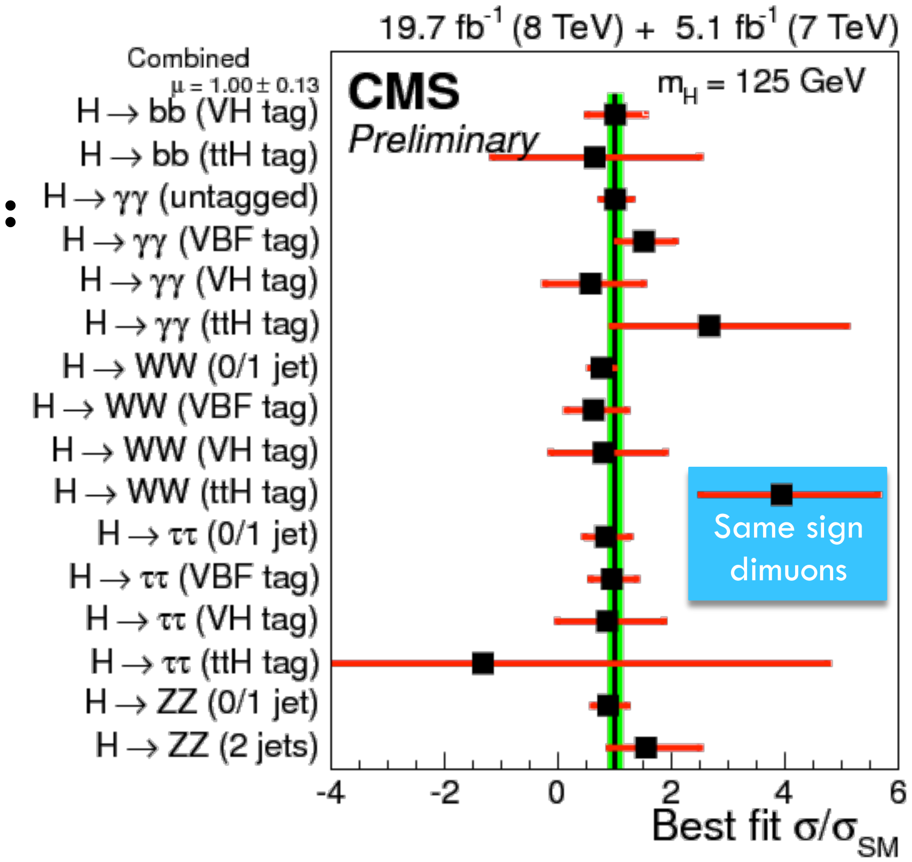


Signal strength

[CMS-PAS-HIG-14-009]

$$\sigma/\sigma_{\mathrm{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo.}) \pm 0.07(\mathrm{syst.})\right]$$

- Grouped by production tag and dominant decay:
  - $\chi^2/\mathrm{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**

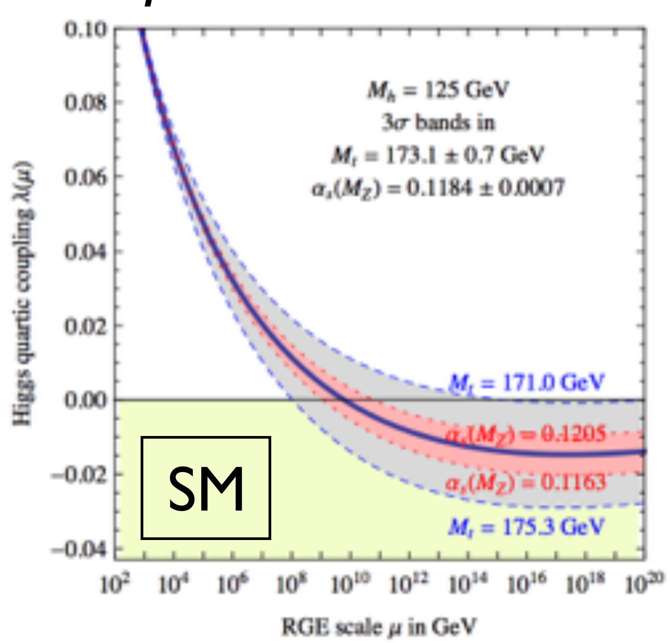


Low energy pheno.

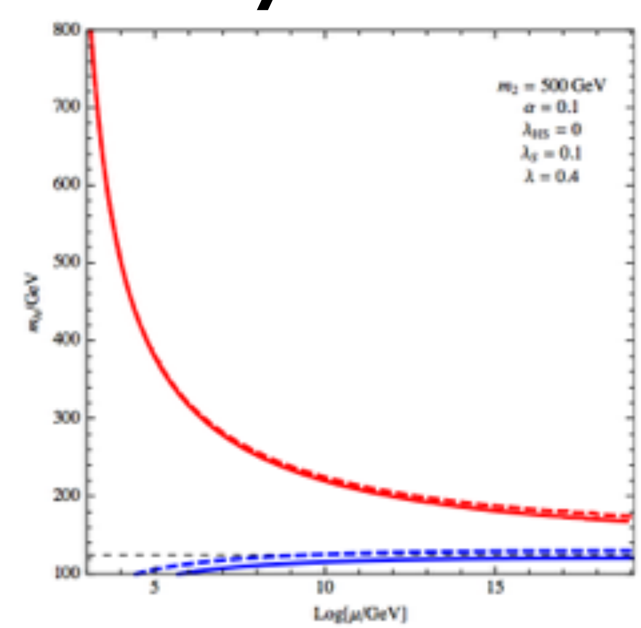
- Universal suppression of collider SM signals
  [See 1112.1847, Seungwon Baek, P. Ko & WIP]
- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{\rm SM}$$

⇨ If "$m_\phi > m_h$", vacuum instability can be cured.

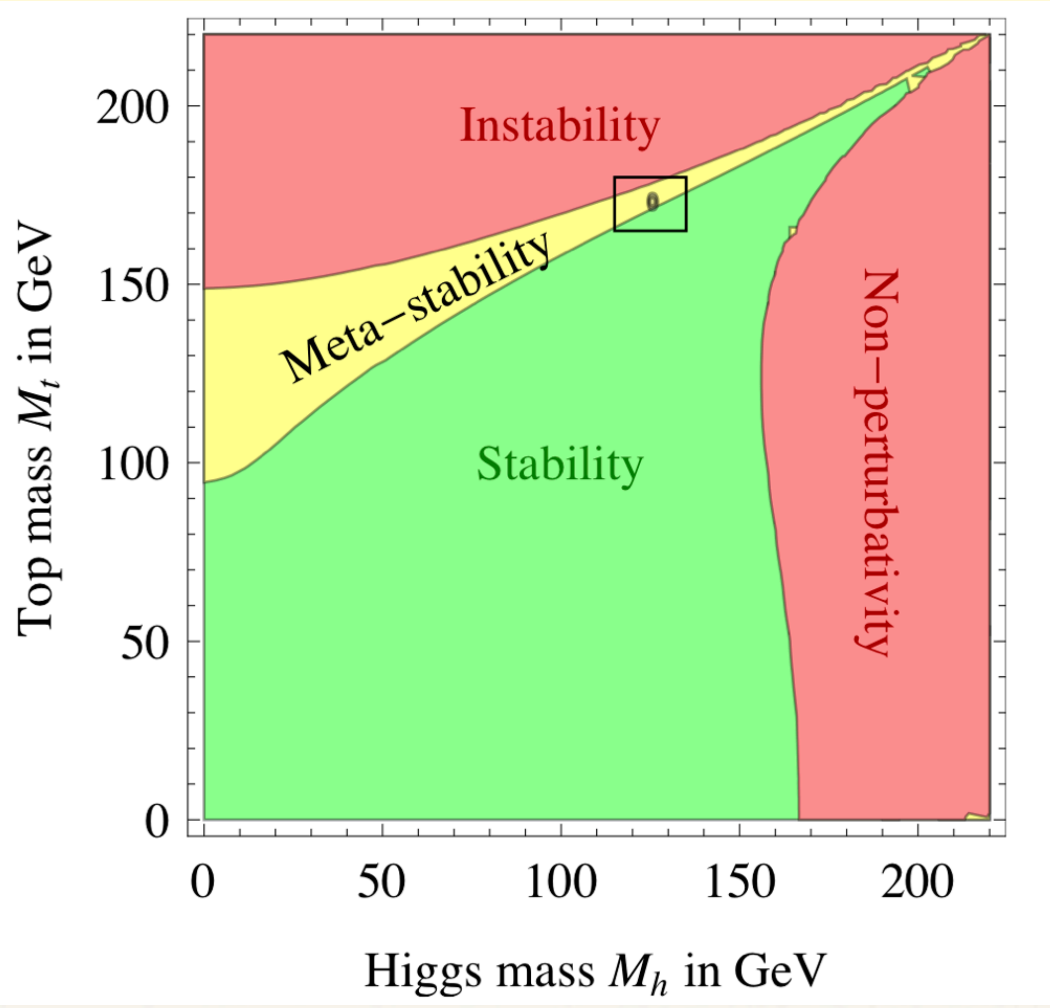


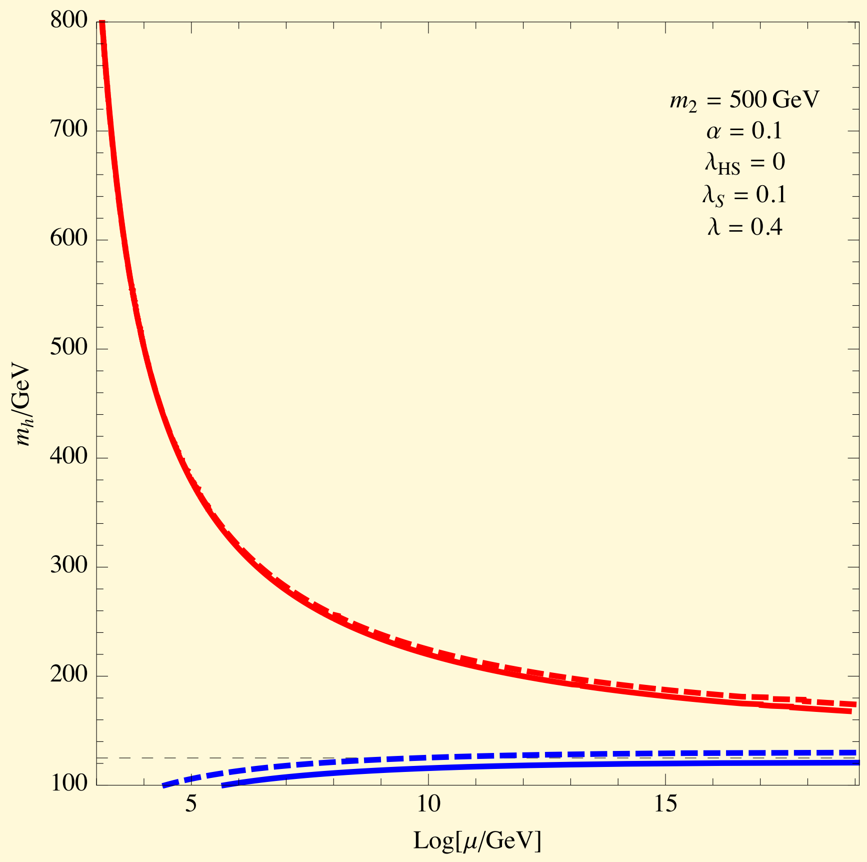
[G. Degrassi et al., 1205.6497]



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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 and unitary model to discuss physics correctly [Baek, Ko, Park and Senaha, arXiv:1212.2131 (JHEP)]

- Can accommodate GeV scale gamma ray excess from GC (Yong Tang's talk on Feb. 11)

New scalar improves EW vacuum stability

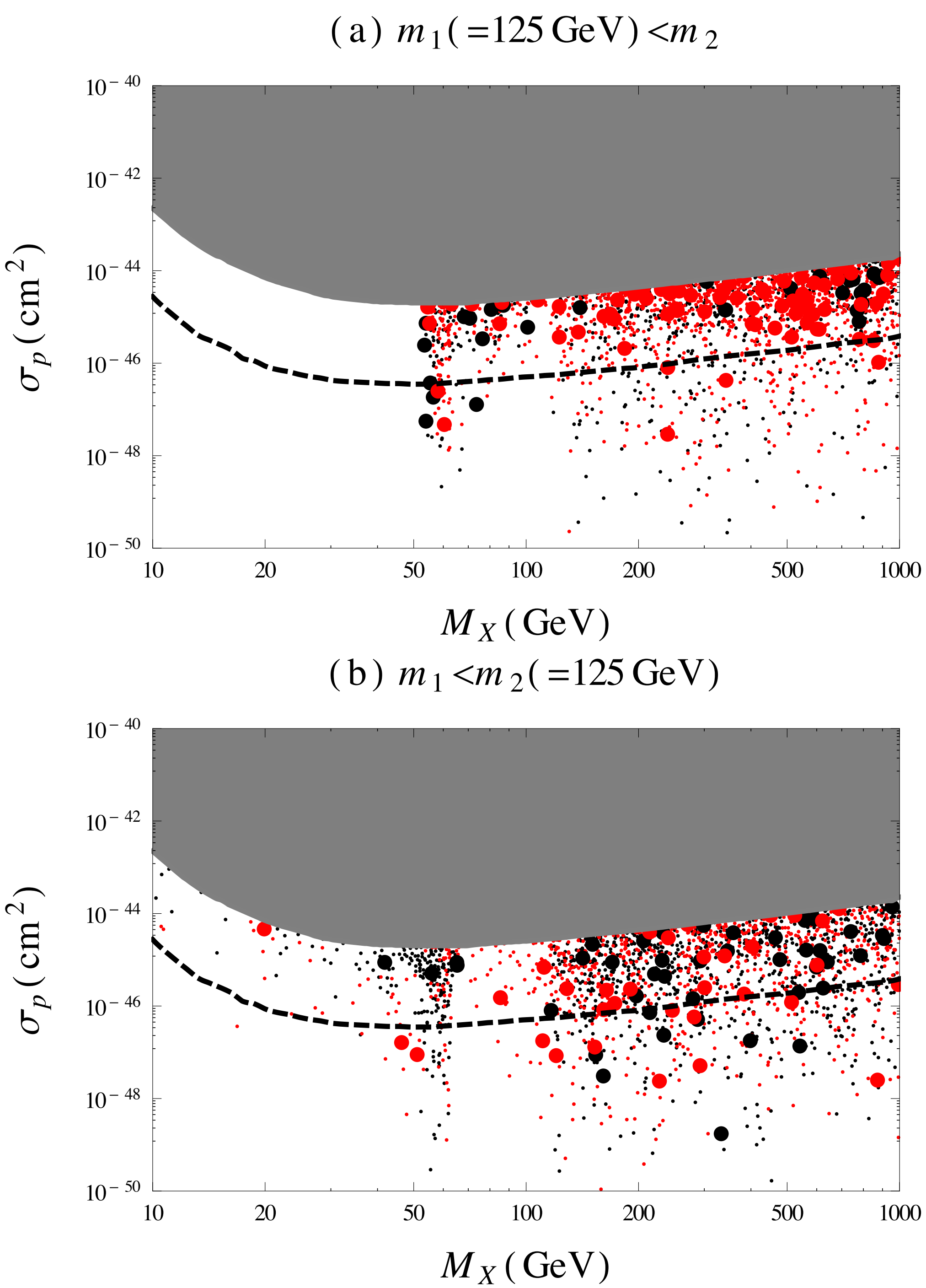


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7(r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

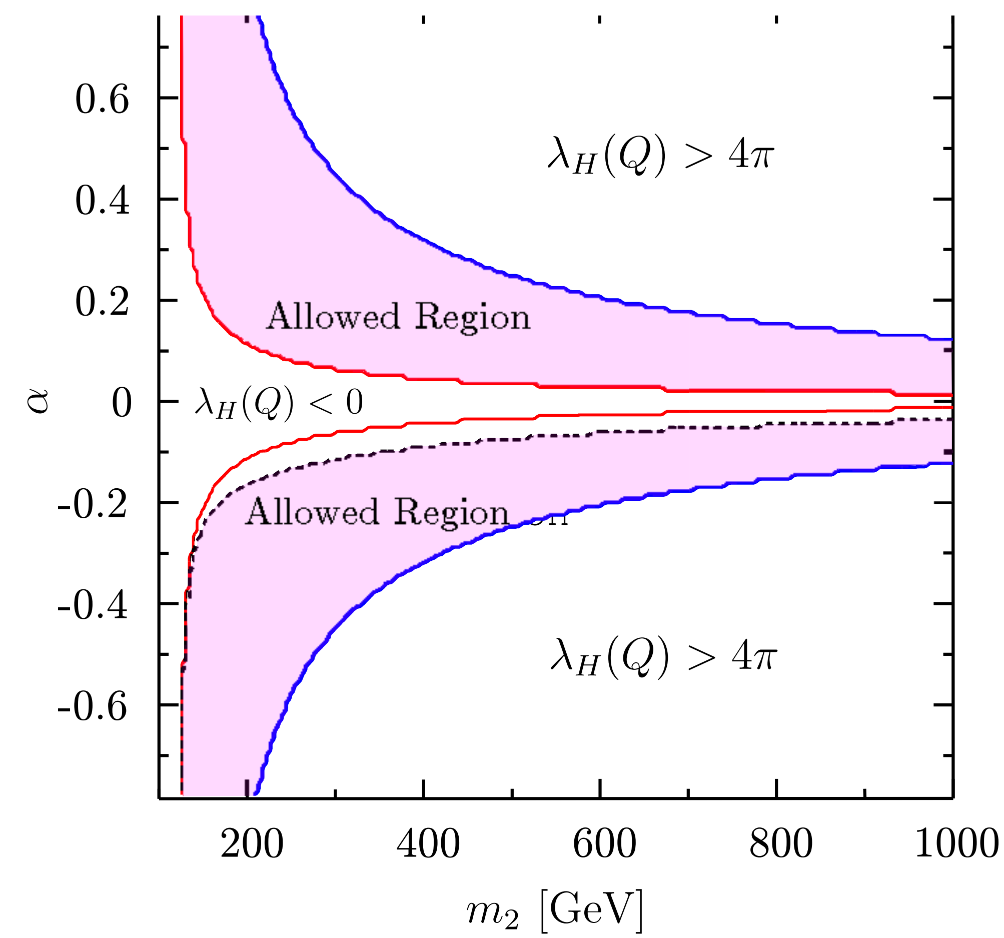


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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

arXiv:1112.3299, … 1402.6287, etc.

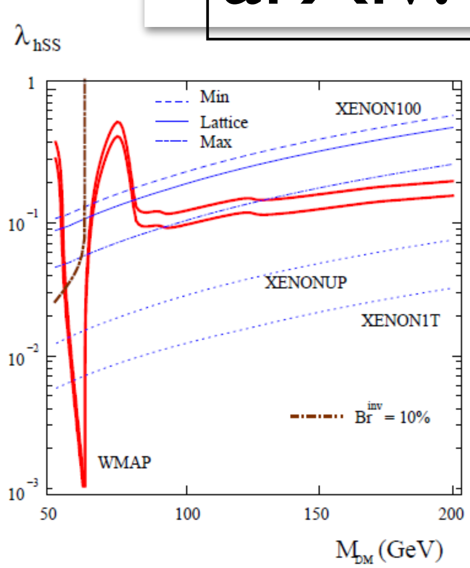


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

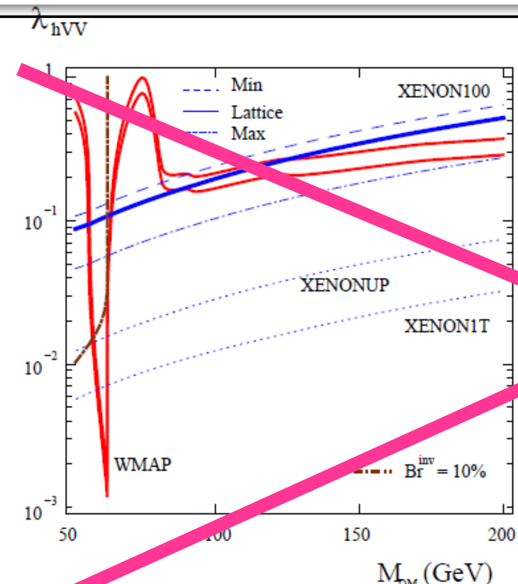


FIG. 2. Same as Fig. 1 for vector DM particles.

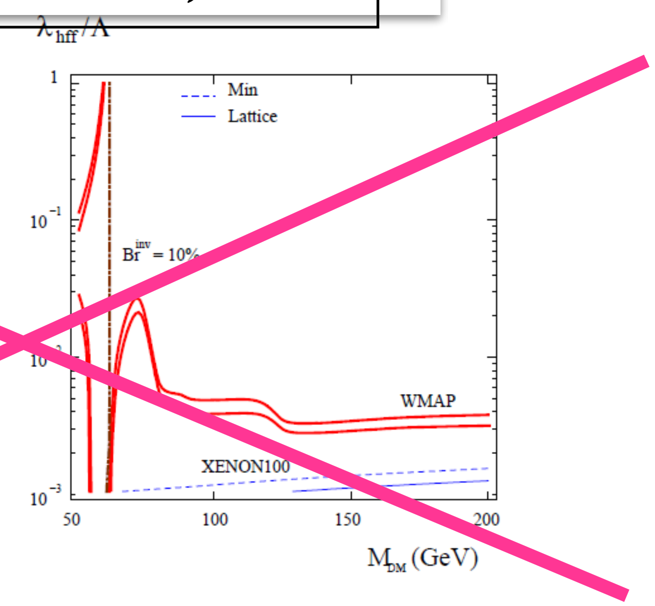
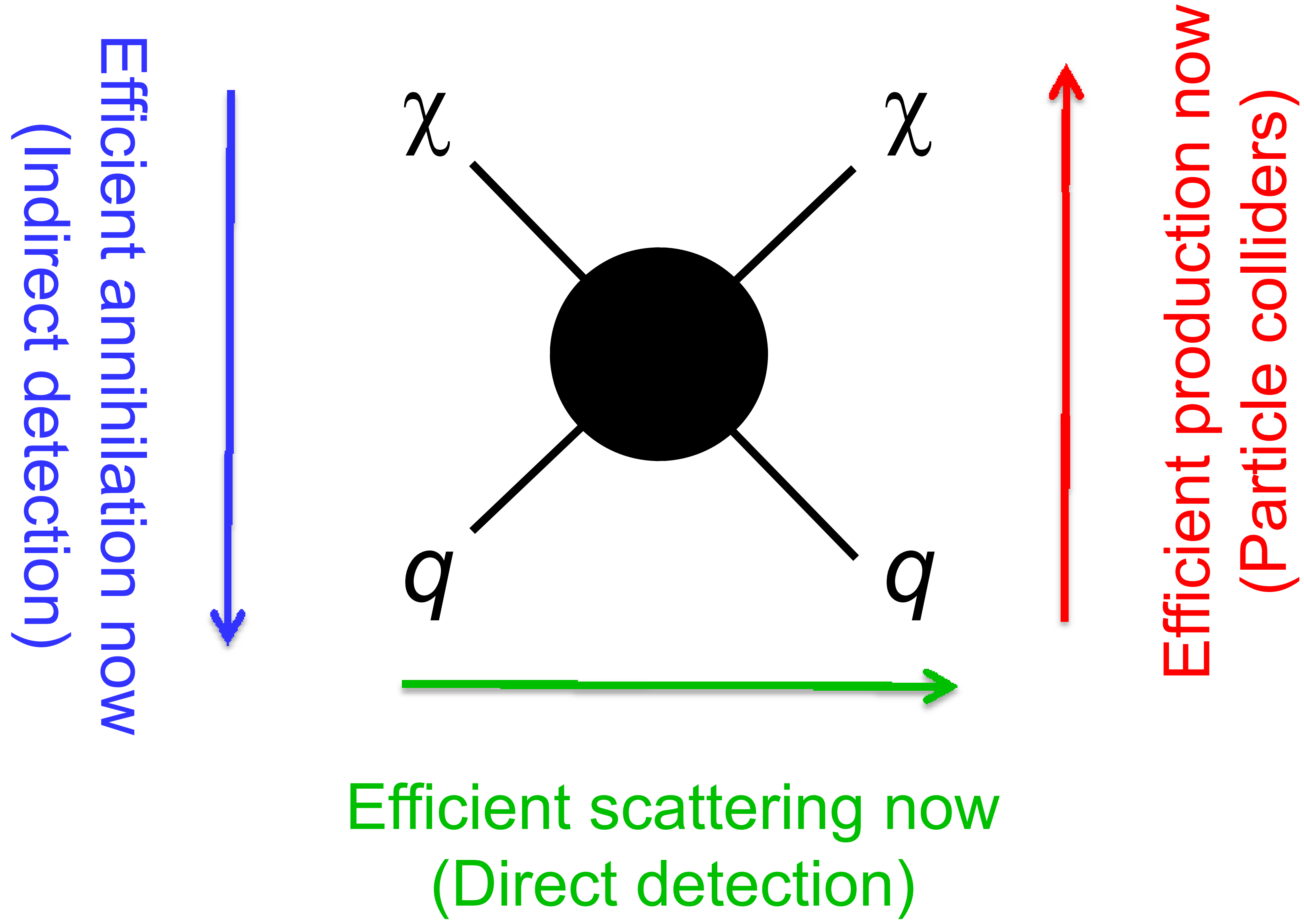


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

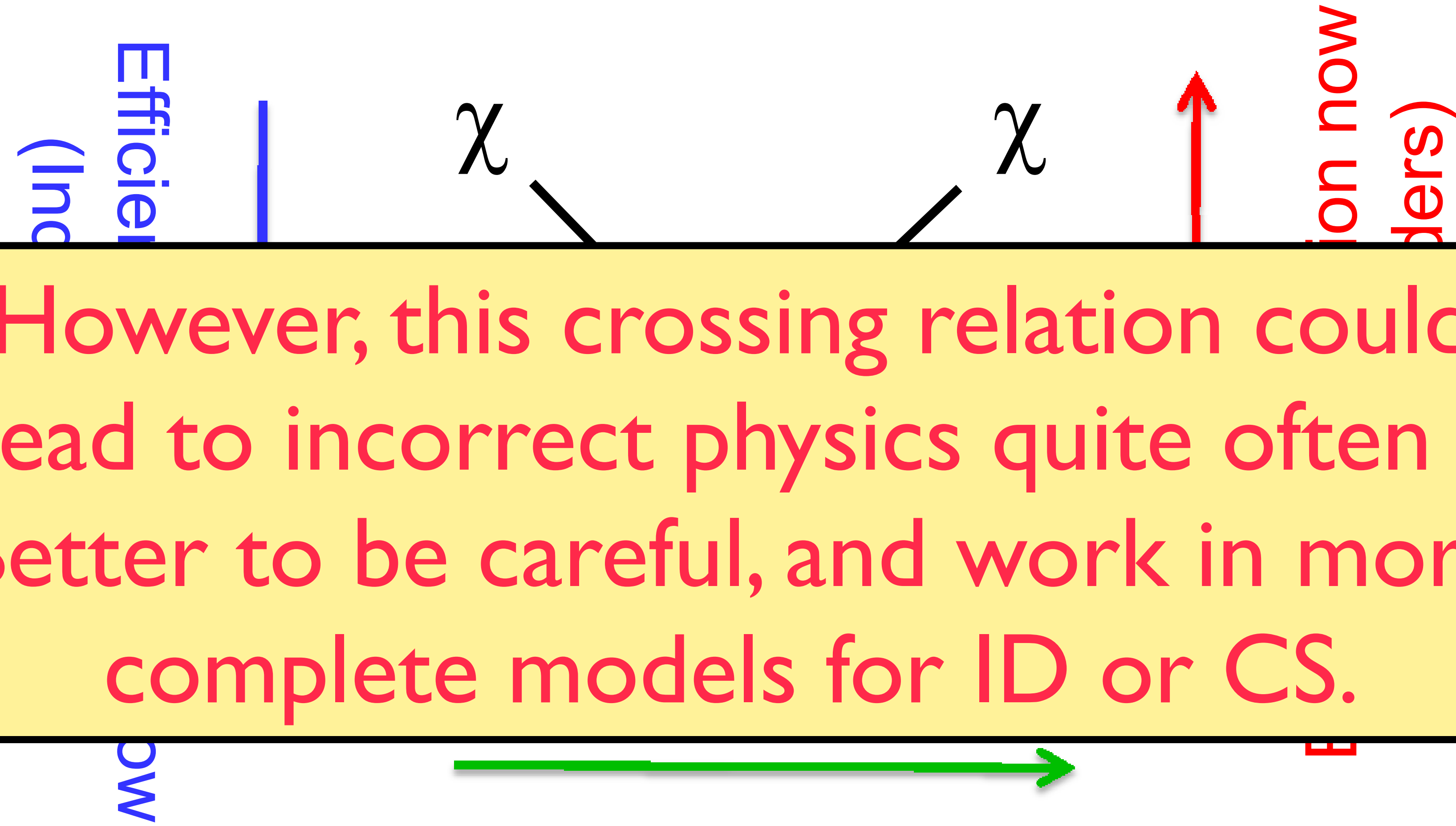
Crossing & WIMP detection

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.

Efficient scattering now
(Direct detection)

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 models
- 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

DM is stable/long lived 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)

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

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.

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 can be harmful to weak scale 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

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

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:

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

Problematic !

Perfectly fine !

- These arguments will apply to all the CDM models based on ad hoc Z_2 symmetry

- One way out is to implement Z_2 symmetry as local U(1) symmetry (arXiv:1407.6588 with Seungwon Baek and Wan-Il Park);(also works by Kubo et al; Chiang and Nomura in local B-L model)

- See a paper by Ko and Tang on local Z_3 scalar DM (Yong Tang's talk on Feb. 11), and another by Ko, Omura and Yu on inert 2HDM with local U(1)_H

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

arXiv:1407.6588 w/ WIPark and SBaek

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

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

Unbroken Local Z2 symmetry

Gauge models for excited DM

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

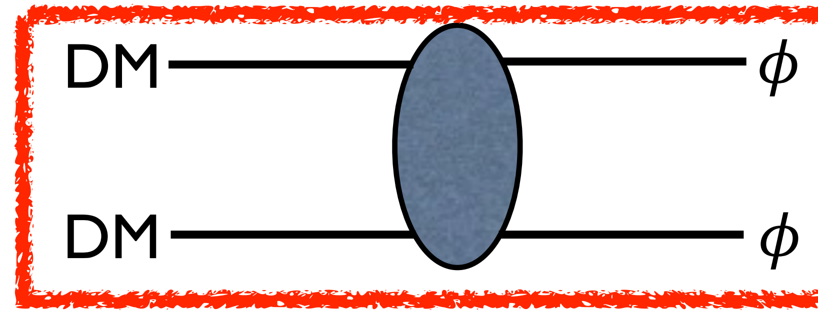
The heavier state decays into the lighter state

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

- Some DM models with Higgs portal

➢ Vector DM with Z2 [1404.5257, P. Ko, WIP & Y. Tang]

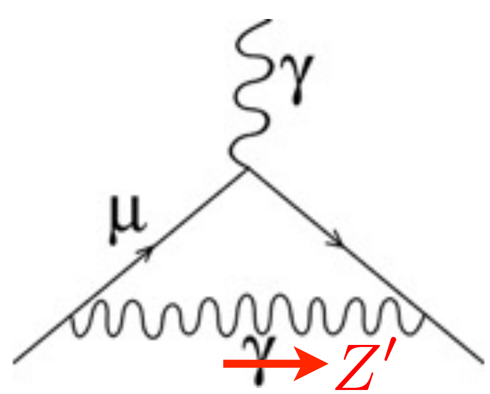
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 -\lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



➢ Scalar DM with local Z2 [1407.6588, Seungwon Baek, P. Ko & WIP]

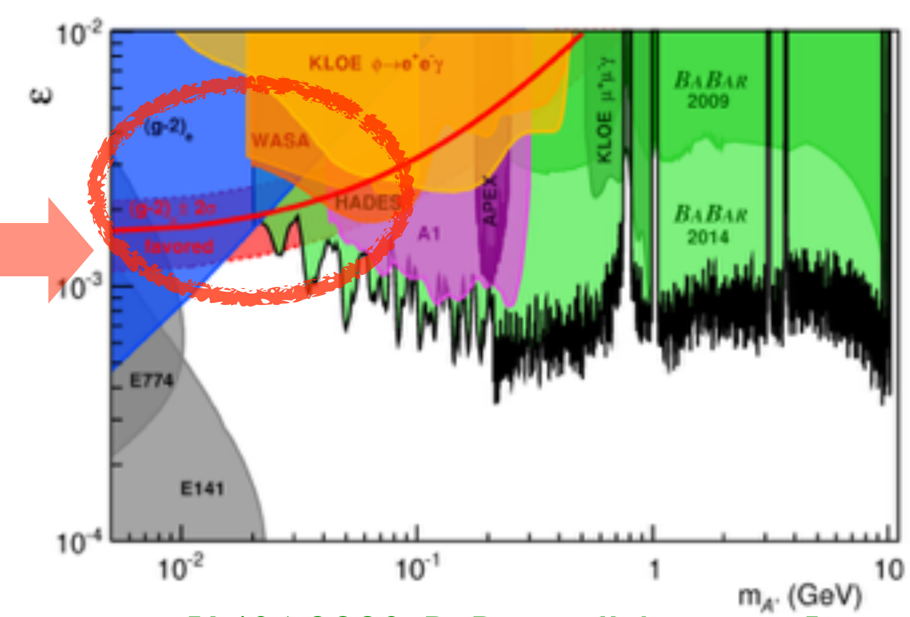
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi -\lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger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

- muon (g-2) as well as GeV scale gamma-ray excess explained
- natural realization of excited state of DM
- free from direct detection constraint even for a light Z'



$$\Delta a_\mu \approx \frac{\alpha_{\rm em}\epsilon^2}{2\pi\cos\theta_W^2}$$

$(\text{for } m_{Z'} \lesssim m_\mu)$



[1406.2980, BaBar collaboration]

Model Lagrangian

$$q_X(X,\phi) \; = \; (1,2)$$

[1407.6588, Seungwon Baek, P. Ko & WIP]

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

- X : scalar DM (XI and XR, excited DM)
- phi : Dark Higgs
- X_mu : Dark photon
- 3 more fields than Z2 scalar DM model
- Z2 Fermion DM can be worked out too

Gamma ray from GC

$$\frac{m_h}{2} < m_I \lesssim 80\,\mathrm{GeV}\,, \quad \frac{m_I - m_\phi}{m_I} \ll \mathcal{O}(0.1)$$

- Possible to satisfy thermal relic density, (in)direct detection constraints
- For light Z' with small kinetic mixing, muon g-2 can be accommodated
- Similar to the excited DM models by Weiner et al, etc. except for dark Higgs field

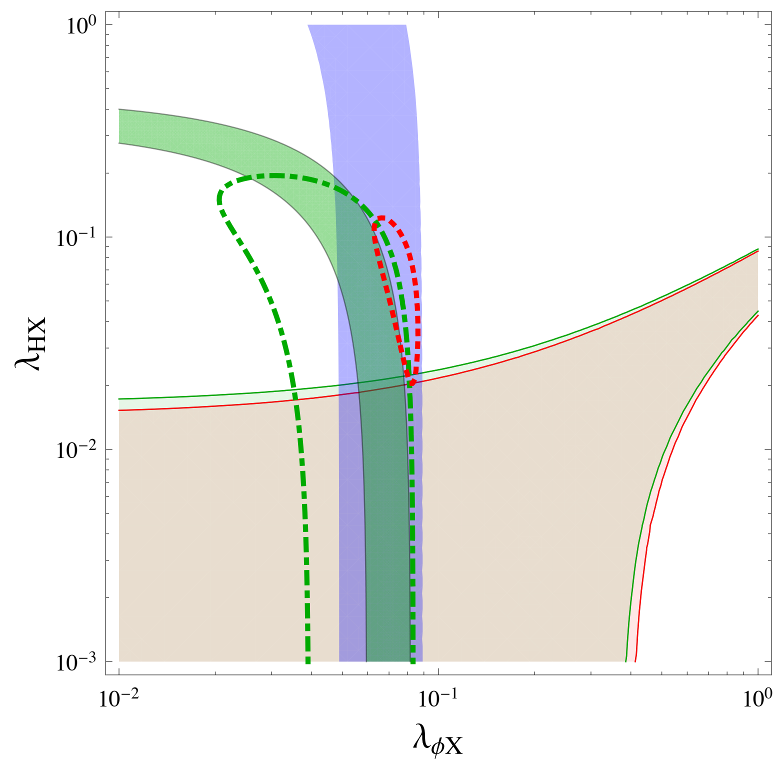


FIG. 3: Parameter space for $m_I = 80$, $m_\phi = 75\,\mathrm{GeV}$ with $\alpha = 0.1$, $v_\phi = 100\,\mathrm{GeV}$, satisfying constraints from LUX direct search experiment (Green region between thin green lines: $\mu = 5\,\mathrm{GeV}$. Red region between thin red lines: $\mu = 7\,\mathrm{GeV}$), $\langle\sigma v_{\rm rel}\rangle_{\rm tot}/\langle\sigma v_{\rm rel}\rangle_{26} = 1$ (Dot-dashed green line: $\mu = 5\,\mathrm{GeV}$. Dotted red line: $\mu = 7\,\mathrm{GeV}$), and $1/3 \le \langle\sigma v_{\rm rel}\rangle_{\phi\phi}/\langle\sigma v_{\rm rel}\rangle_{26} \le 1$ (Blue region). In the dark green region, $\langle\sigma v_{\rm rel}\rangle_{Z'Z'}/\langle\sigma v_{\rm rel}\rangle_{26} \le 0.1$, so the contribution of Z'-decay to GeV scale excess of γ-ray may be safely ignored.

Other possible phenomenology

- Another possibility was to use this model for 511 keV gamma ray and PAMELA/AMS02 positron excess (strong tension with CMB constraints, however)
- 3.55 keV Xray using endo(exo)thermic scattering : for future work
- In any case, the local Z_2 model has new fields with interesting important own roles, and can modify phenomenology a lot

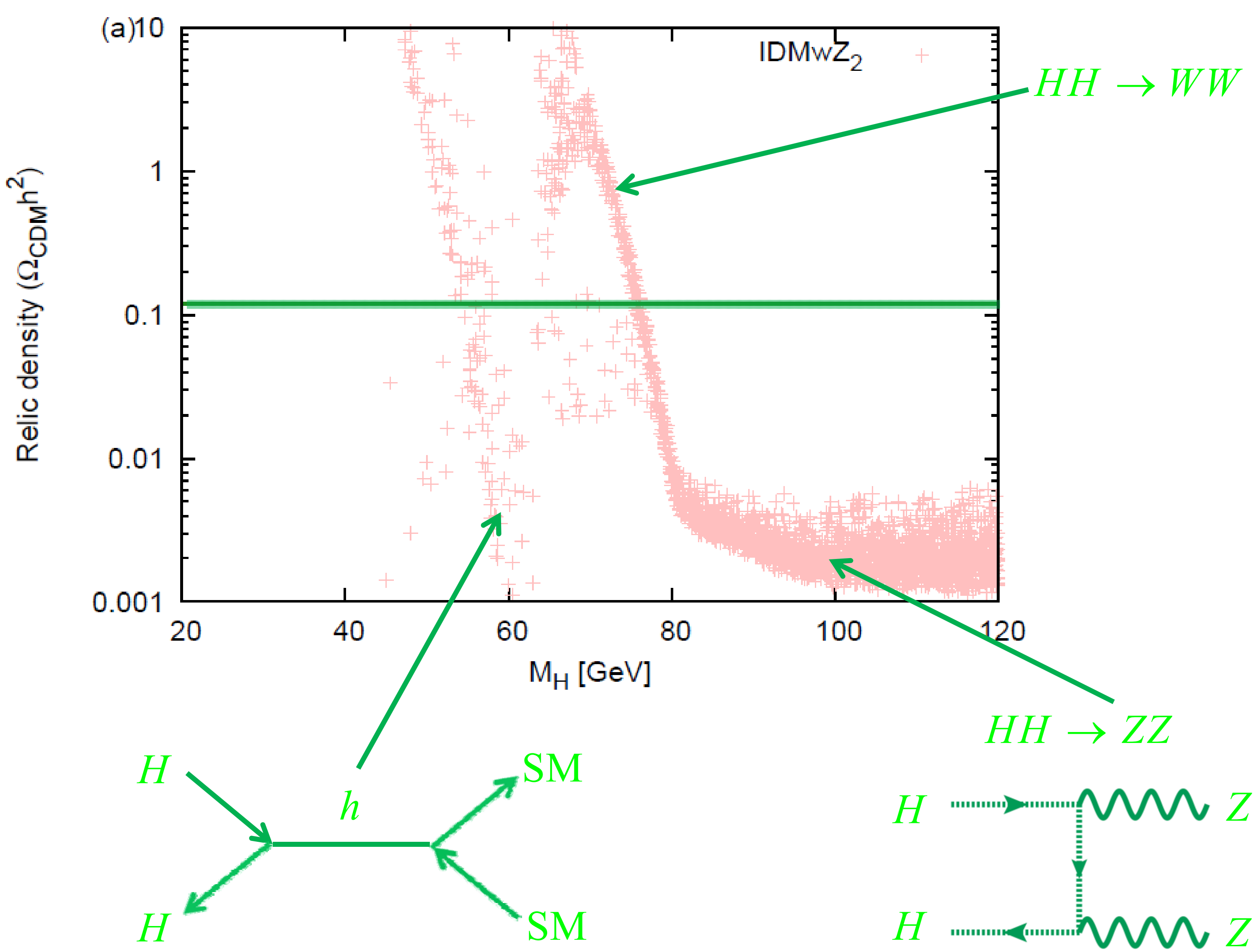
Main points

- Local Dark Gauge Symmetry can guarantee the DM stability (or longevity, see later discussion)
- Minimal models have new fields other than DM (Dark Higgs and Dark Gauge Bosons) for theoretical consistency
- Can solve many puzzles in CDM by large self-interactions, and also muon g-2, and also calculable amount of Dark Radiation

Inert 2HDM model

Relic density (low mass)

$\Omega_{\text{CDM}} h^2 = 0.1199 \pm 0.0027$



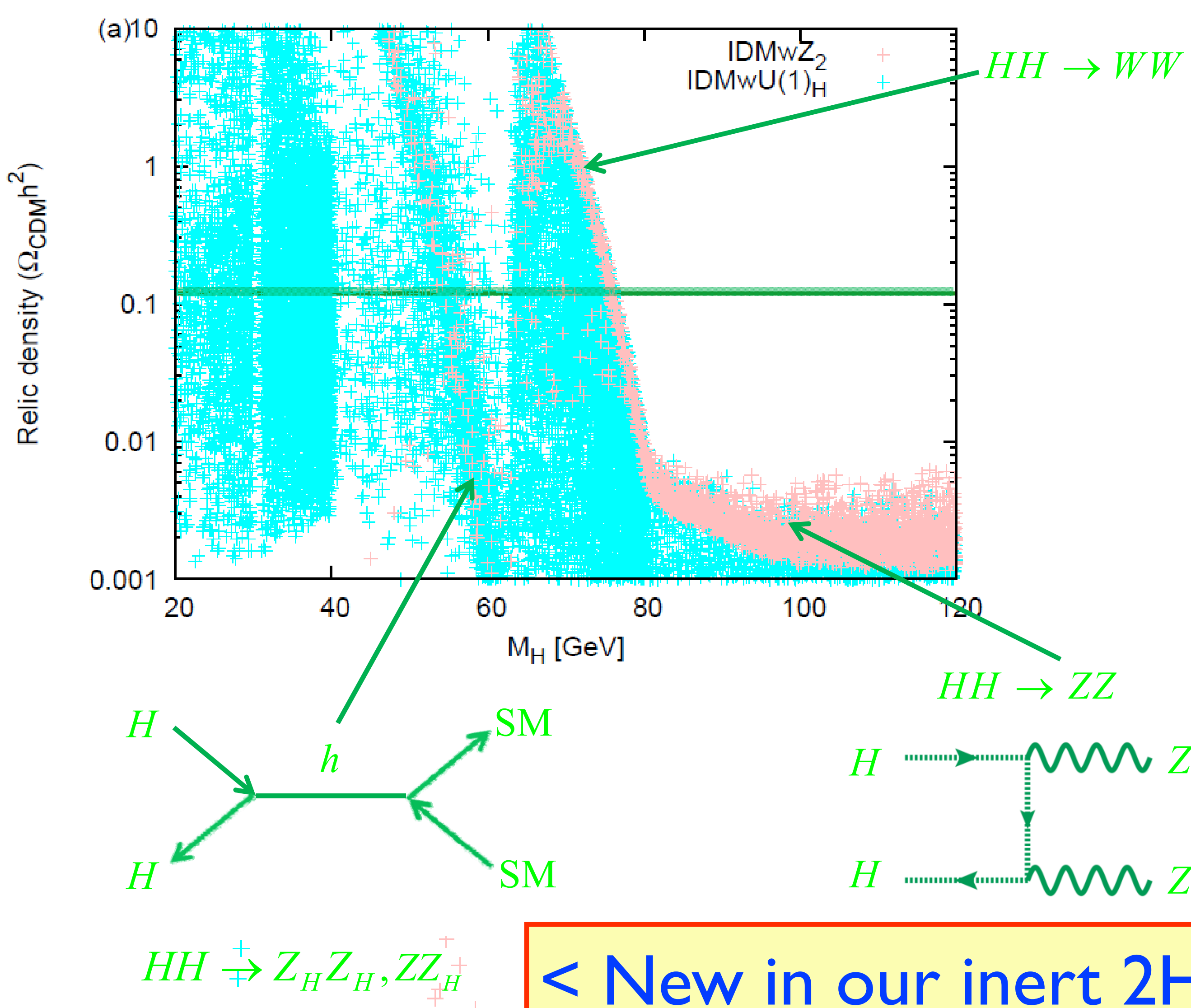
+ IDMwZ$_2$

LUX bound is satisfied.

Inert 2HDM with U(1)H gauge symmetry

Relic density (low mass)

$\Omega_{\mathrm{CDM}} h^2 = 0.1199 \pm 0.0027$



+ IDMwZ$_2$
+ IDMwU(1)$_H$

LUX bound is satisfied.

Ko, Omura, Yu
arXiv:1405.2138

< New in our inert 2HDM with U(1)$_H$ gauge sym

AMS02 positron excess from decaying fermionic thermal DM

Work in preparation with Yong Tang
arXiv:1410.xxxx [hep-ph]

Basics

$$\delta\mathcal{L} = \lambda_{\rm eff}\bar{\chi}\phi\nu, \qquad \text{with} \qquad \lambda_{\rm eff} \sim 10^{-26}$$

If we use the SM Higgs for phi, strong contraints from gamma ray and antiproton flux data

Can we make use of light dark Higgs instead ?

YES !

Model

Ko and Tang, 1404.0236
Published in PLB

We consider a local dark gauge symmetry $U(1)_X$ with dark Higgs Φ and two different Dirac fermions in the dark sector, χ and ψ. Assign $U(1)_X$ charges to the dark fields as follows:

$$(Q_\chi, Q_\psi, Q_\Phi) = (2, 1, 1),$$

we can write down the possible renormalizable interactions including singlet right-handed neutrinos N for the model,

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N}_I i\partial\!\!\!/ N_I - \left(\frac{1}{2} m_{NI} \bar{N}_I^c N_I + y_{\alpha I} \bar{L} H N_I + h.c\right) \\ & - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{1}{2} \sin\epsilon X_{\mu\nu} F_Y^{\mu\nu} + (D_\mu \Phi)^\dagger D^\mu \Phi - V(\phi, H) \\ & + \bar{\chi}\left(iD\!\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - m_\psi\right)\psi - \left(f\bar{\chi}\Phi\psi + g_I \bar{\psi}\Phi N_I + h.c\right),\end{aligned} \quad (2.1)$$

with Higgs portal interactions

$$V = \lambda_H \left(H^\dagger H - \frac{v_H^2}{2}\right)^2 + \lambda_{\phi H}\left(H^\dagger H - \frac{v_H^2}{2}\right)\left(\Phi^\dagger \Phi - \frac{v_\phi^2}{2}\right) + \lambda_\phi \left(\Phi^\dagger \Phi - \frac{v_\phi^2}{2}\right)^2.$$

Feynman Diagrams

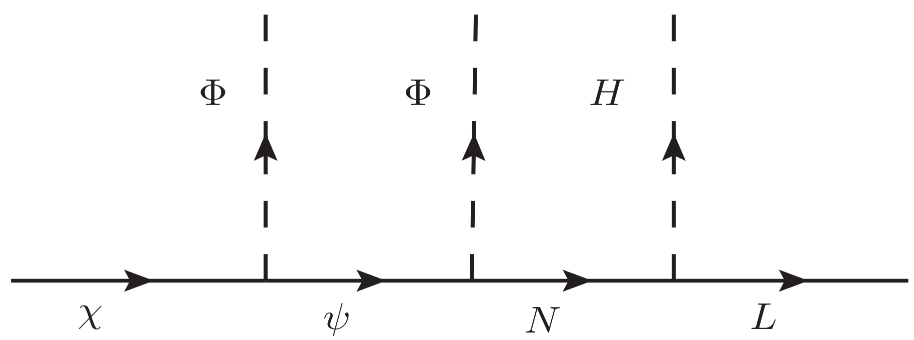


FIG. 1: Feynman diagram that generates the effector operator $\bar{\chi}\Phi\Phi\tilde{H}L$.

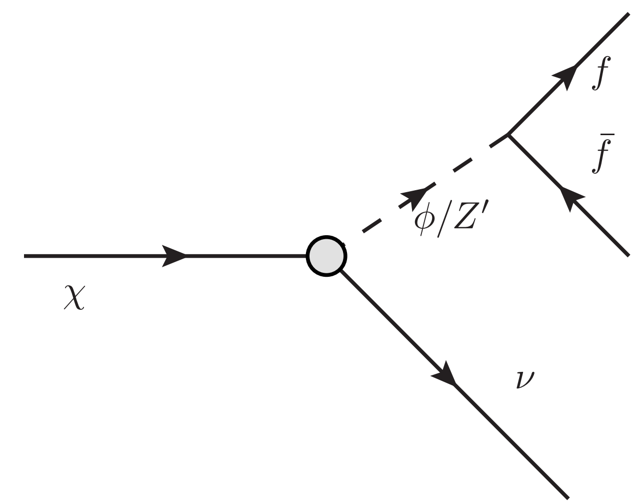


FIG. 2: Dominant decaying process.

In this model, we can estimate

$$\lambda_{\rm eff} \sim \frac{yfg}{4\sqrt{2}}\frac{v_\phi}{m_\psi}\frac{v_H}{m_N} \sim 10^{-26}.$$

This can be easily achieved if we chose the parameters as

$$v_\phi \sim O(100)\text{MeV},\ m_N \sim m_\chi \sim 10^{14}\text{GeV},\ yfg \sim 1.$$

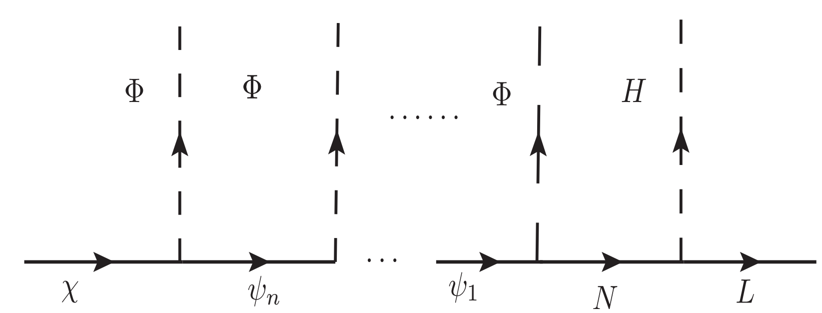


FIG. 4: Feynman diagram that generates the effector operator $\bar{\chi}\Phi^{n+1}\tilde{H}L$.

$$Br(\chi \to \phi\nu) : Br(\chi \to Z'\nu) = n^2 : 1.$$

Fit to the data

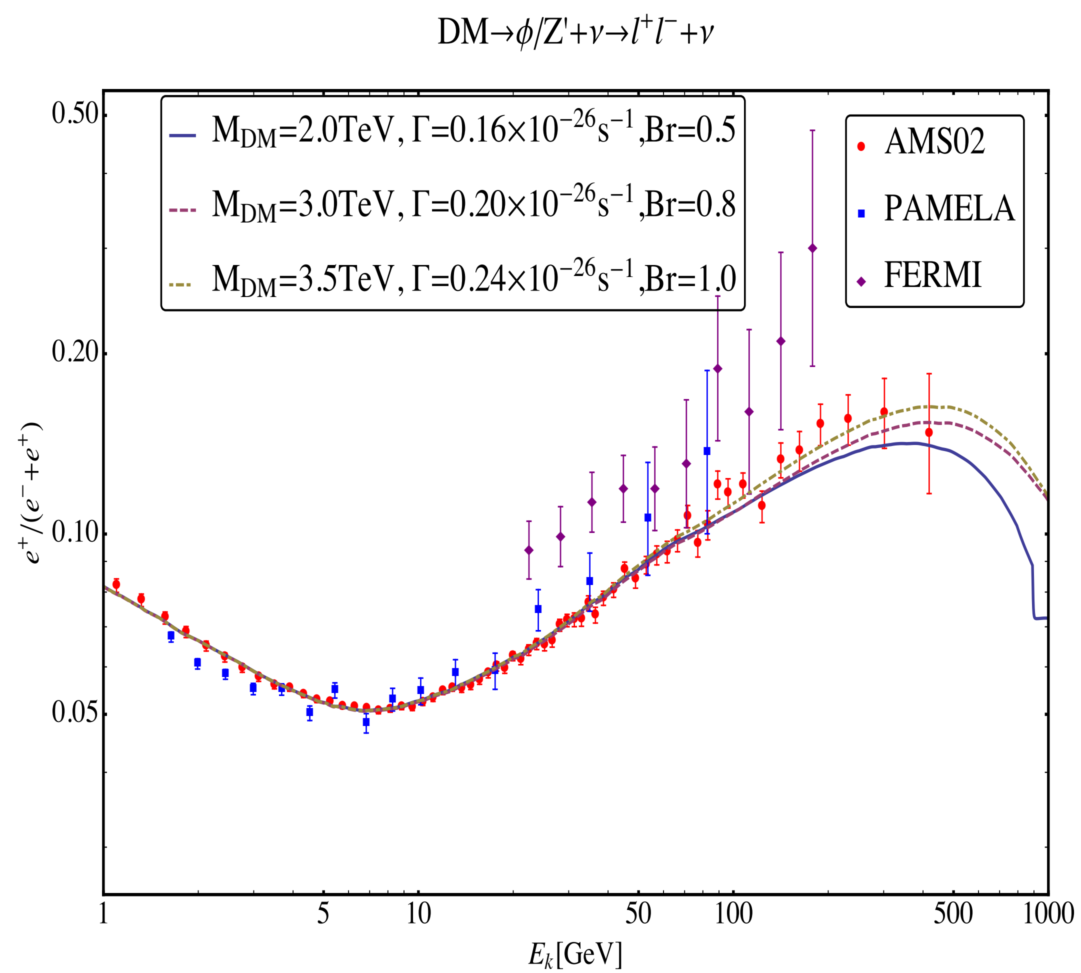


FIG. 5: Positron fraction in three different sets of parameters. $M_{\rm DM}$ and total decay width Γ are chosen to visually match the positron fraction data. Data are extracted from Ref. [58].

Dark Higgs and Z' below pi pi threshold

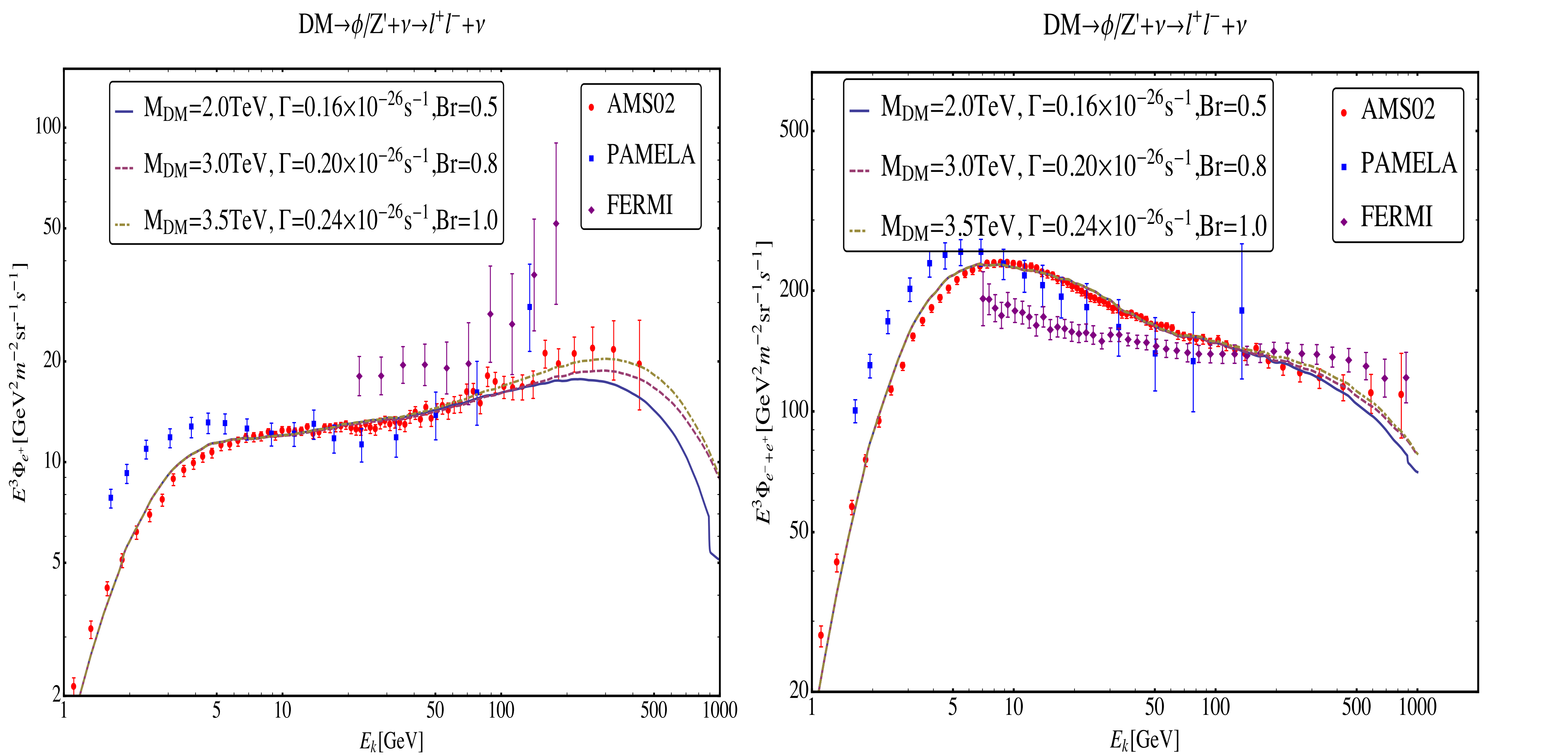


FIG. 6: Positron flux (left) and electron+positron flux (right) [59–61] for three different sets of parameters described in the text, Eqs. (5.6)-(5.8).

Both absolute fluxes and the ratio could be fit in a reasonable way

EWSB and CDM from Strongly Interacting Hidden Sector

All the masses (including CDM mass) from hidden sector strong dynamics, and CDM long lived by accidental sym

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

- Potential for H_1 and H_2

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

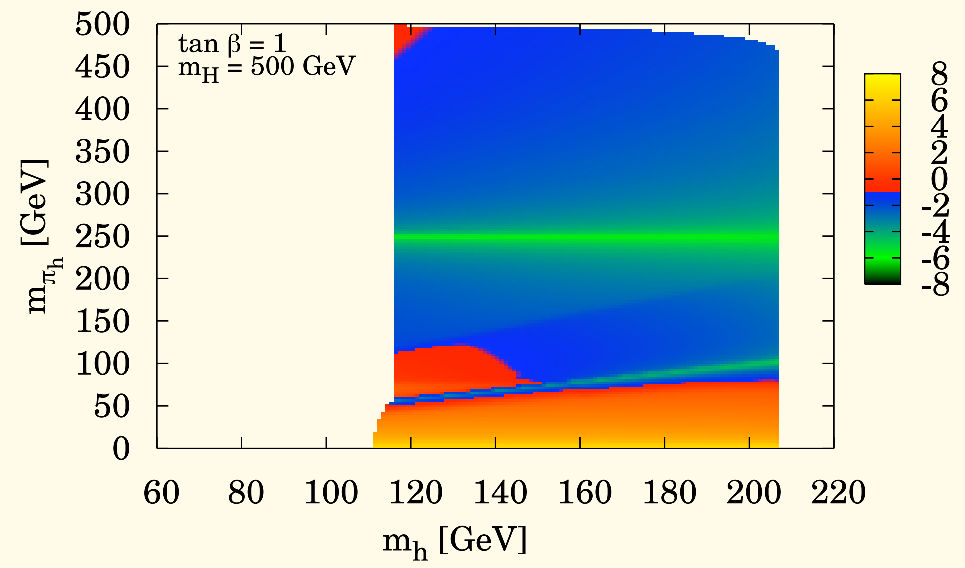
Not present in the two-Higgs Doublet model

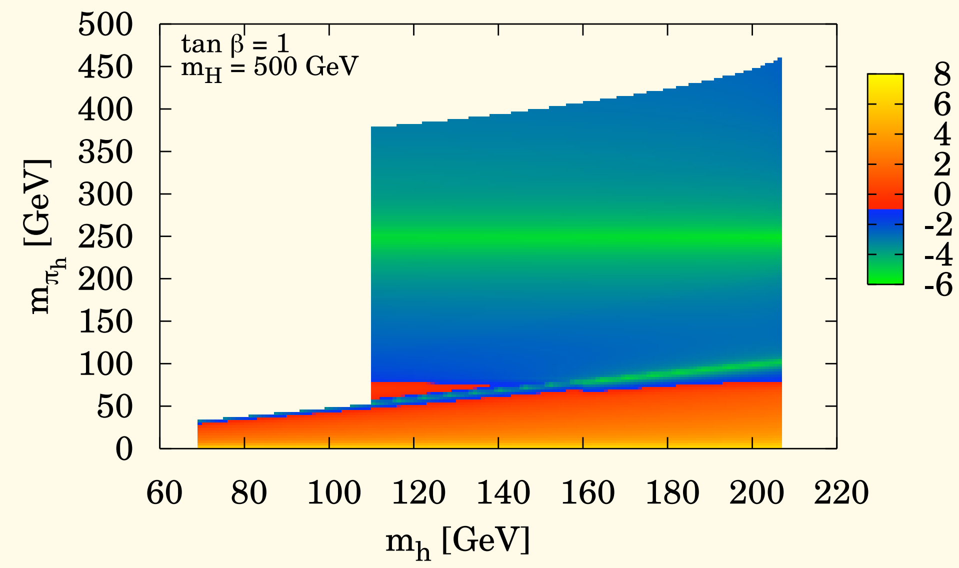
- Stability : $\lambda_{1,2} > 0$ and $\lambda_1 + \lambda_2 + 2\lambda_3 > 0$
- Consider the following phase:

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

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

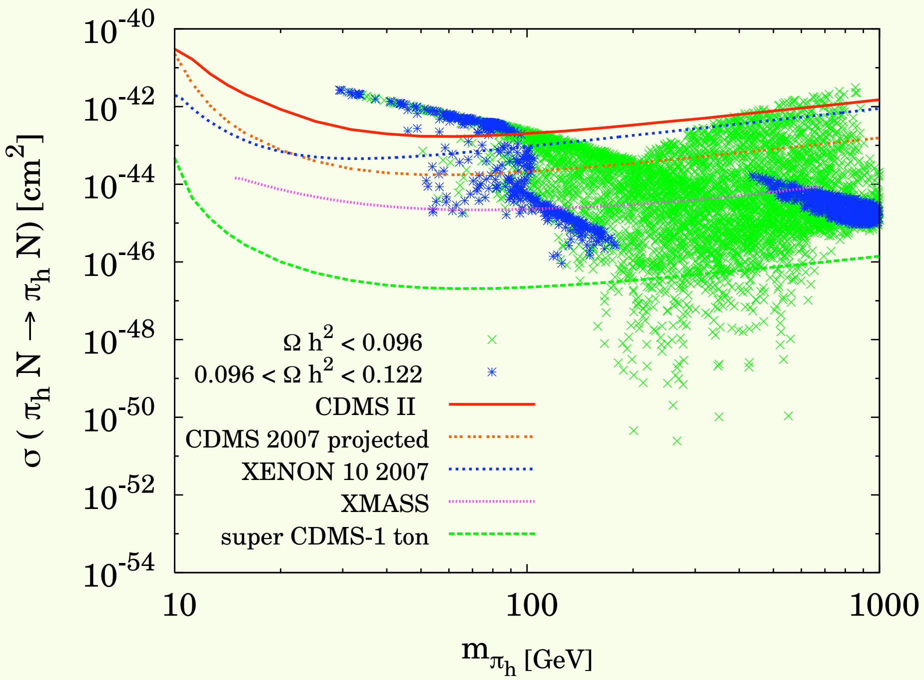
Relic Density

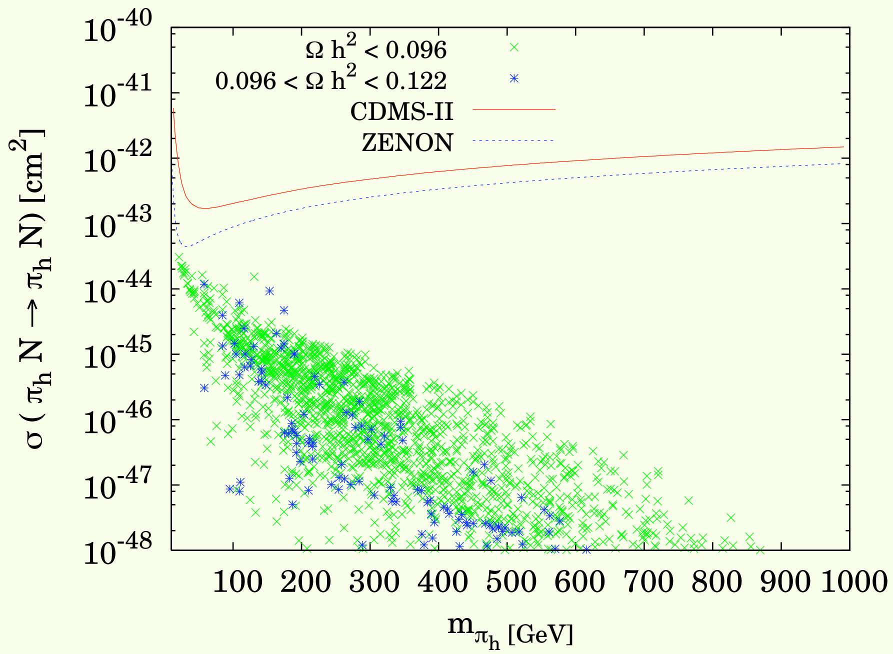




- $\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for $\tan\beta = 1$ and $m_H = 500$ GeV
- Labels are in the $\log_{10}$
- Can easily accommodate the relic density in our model

Direct detection rate

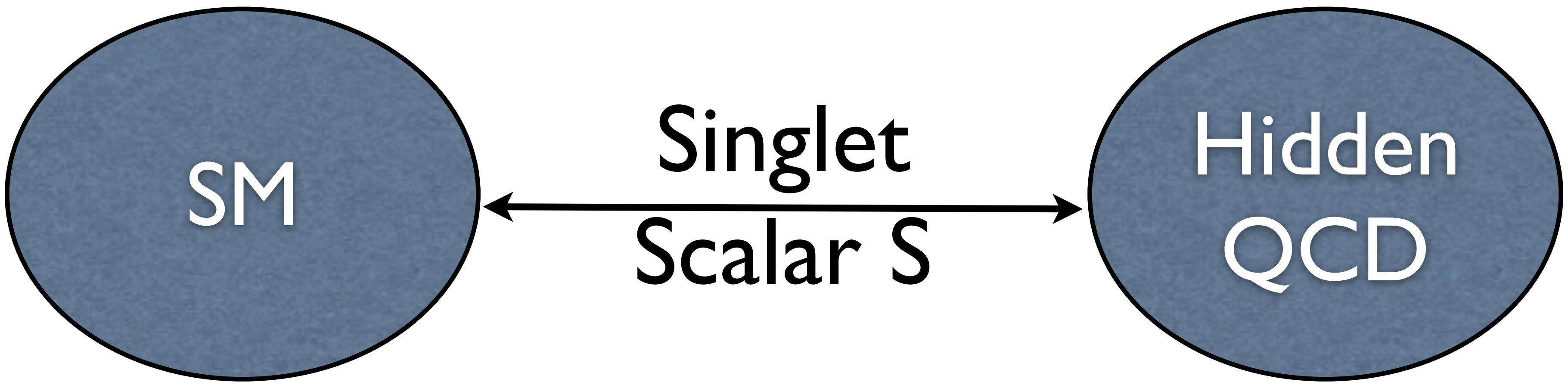




- $\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h} for $\tan\beta = 1$ and $\tan\beta = 5$.
- σ_{SI} for $\tan\beta = 1$ is very interesting, partly excluded by the CDMS-II and XENON 10, and als can be probed by future experiments, such as XMASS and super CDMS
- $\tan\beta = 5$ case can be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

Appraisal of Scale Invariance

- May be the only way to understand the origin of mass dynamically (including spontaneous sym breaking)
- Without it, we can always write scalar mass terms for any scalar fields, and Dirac mass terms for Dirac fermions, the origin of which is completely unknown
- Probably only way to control higher dimensional op's suppressed by Planck scale

Scale invariant extension of the SM with strongly interacting hidden sector

Modified SM with classical scale symmetry

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

Hidden sector lagrangian with new strong interaction

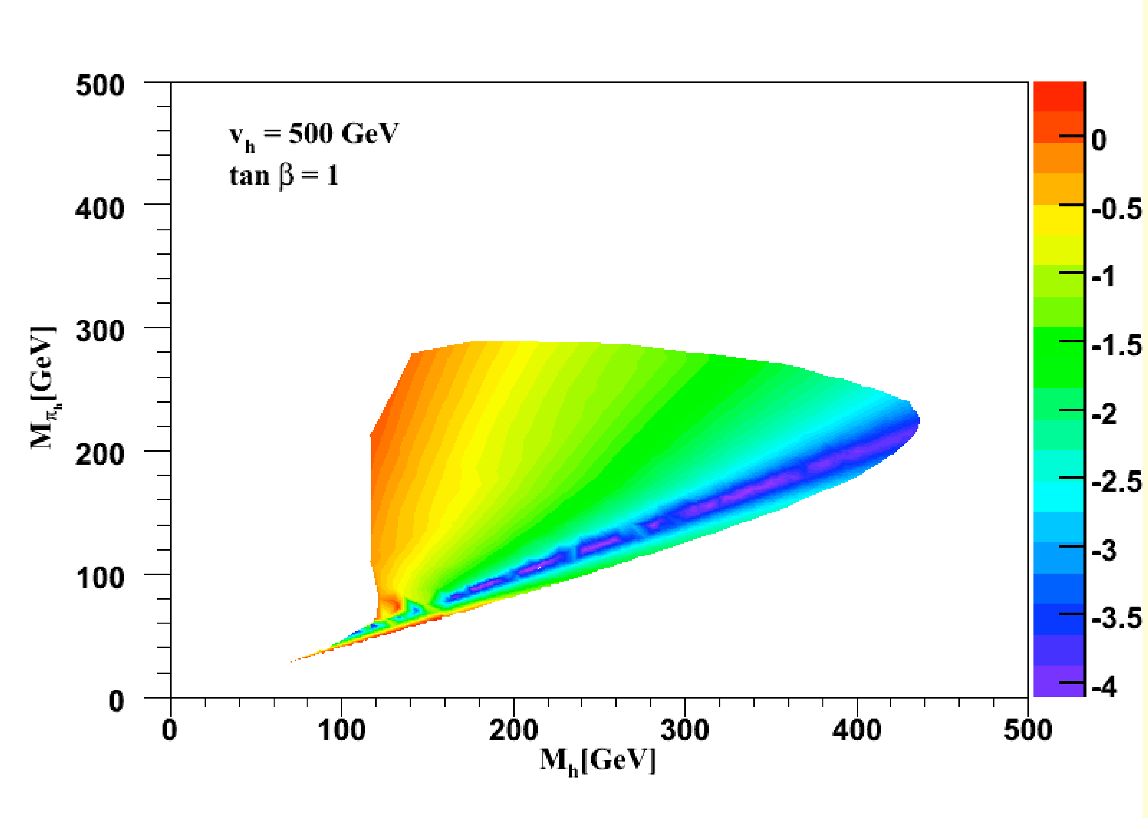
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

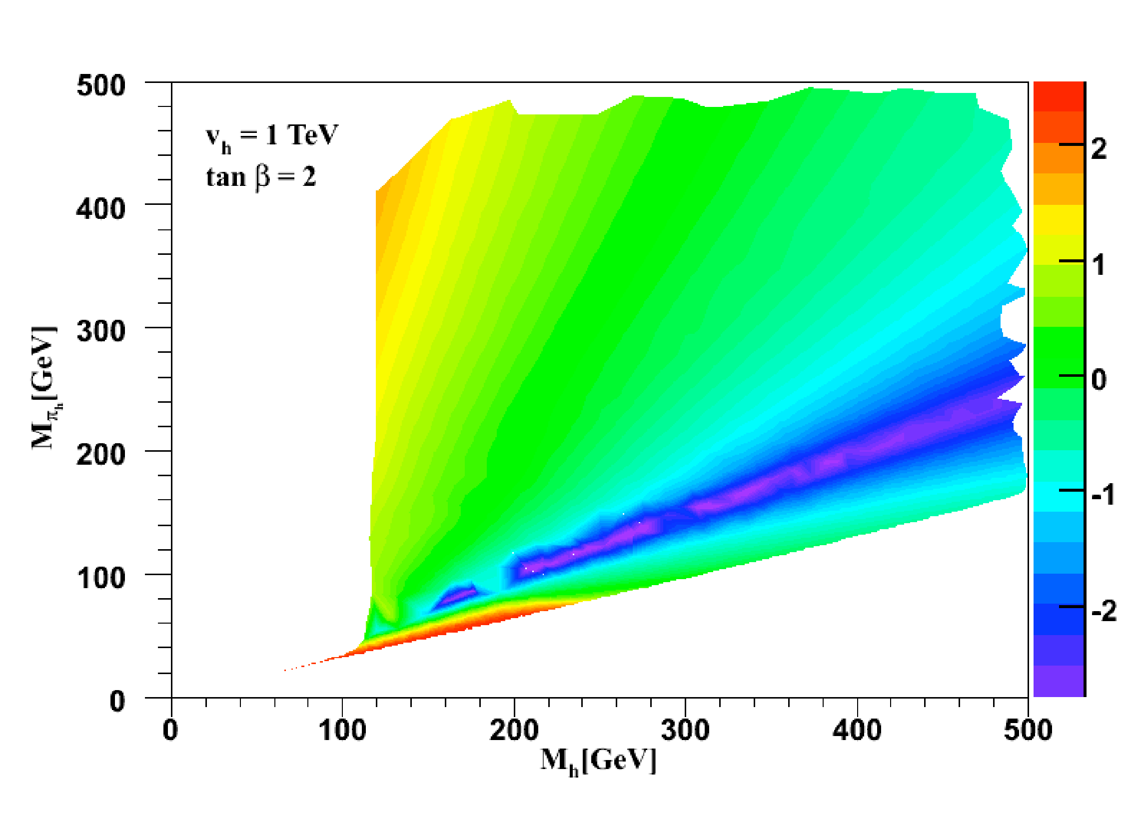
3 neutral scalars : h, S and hidden sigma meson
Assume h-sigma is heavy enough for simplicity

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



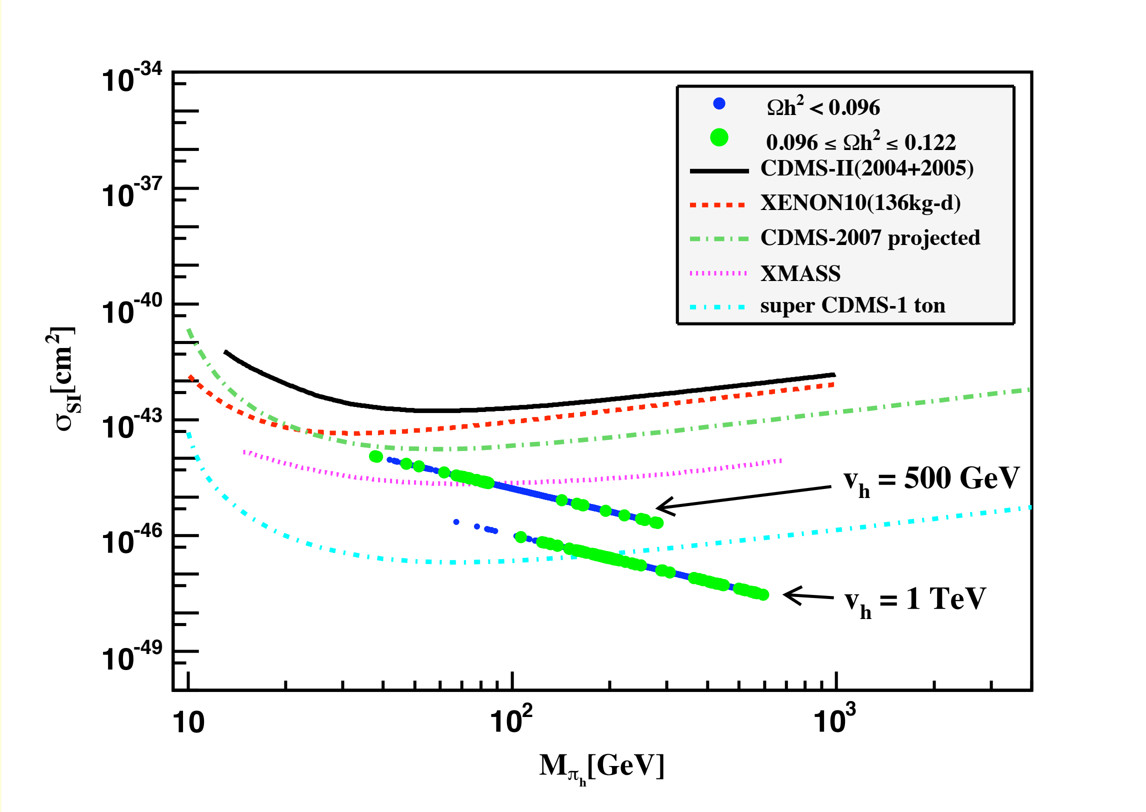


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

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

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

Direct Detection Rate

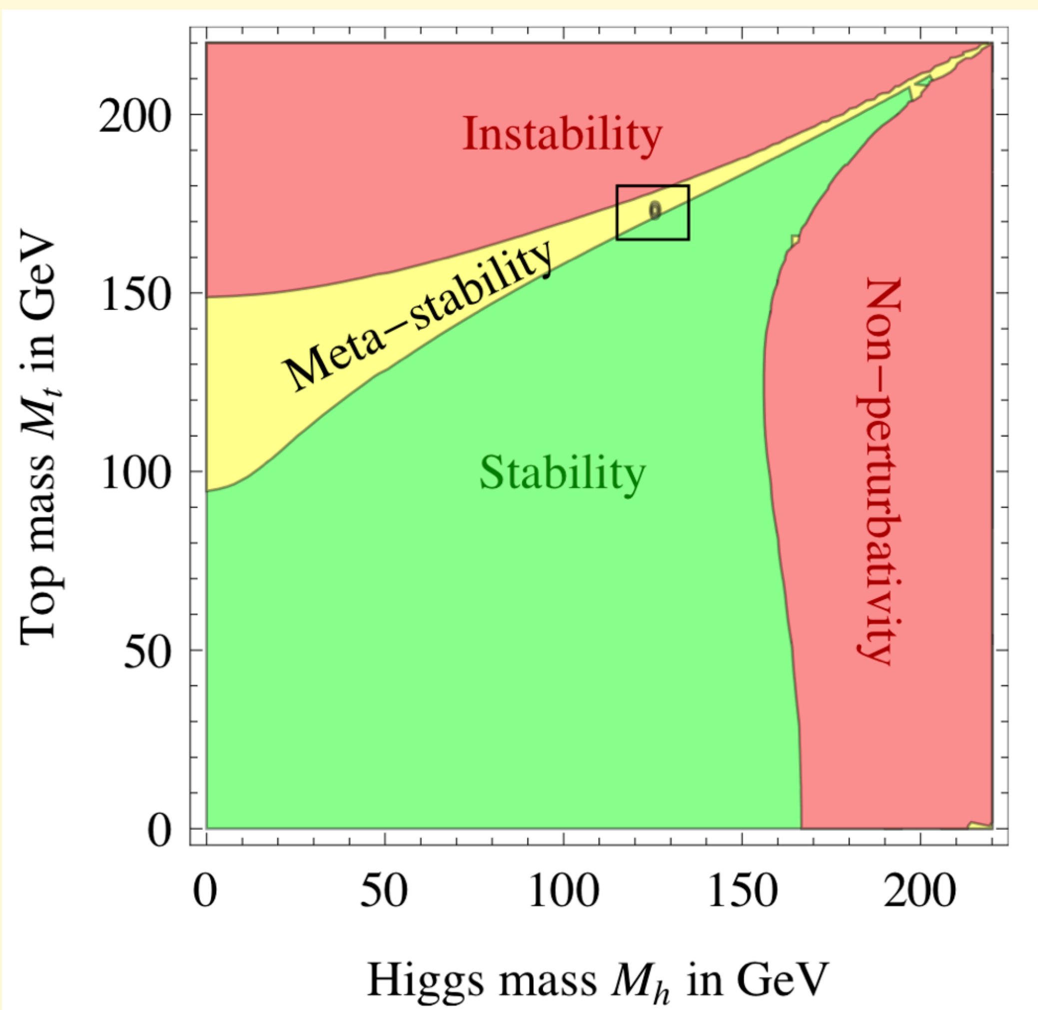


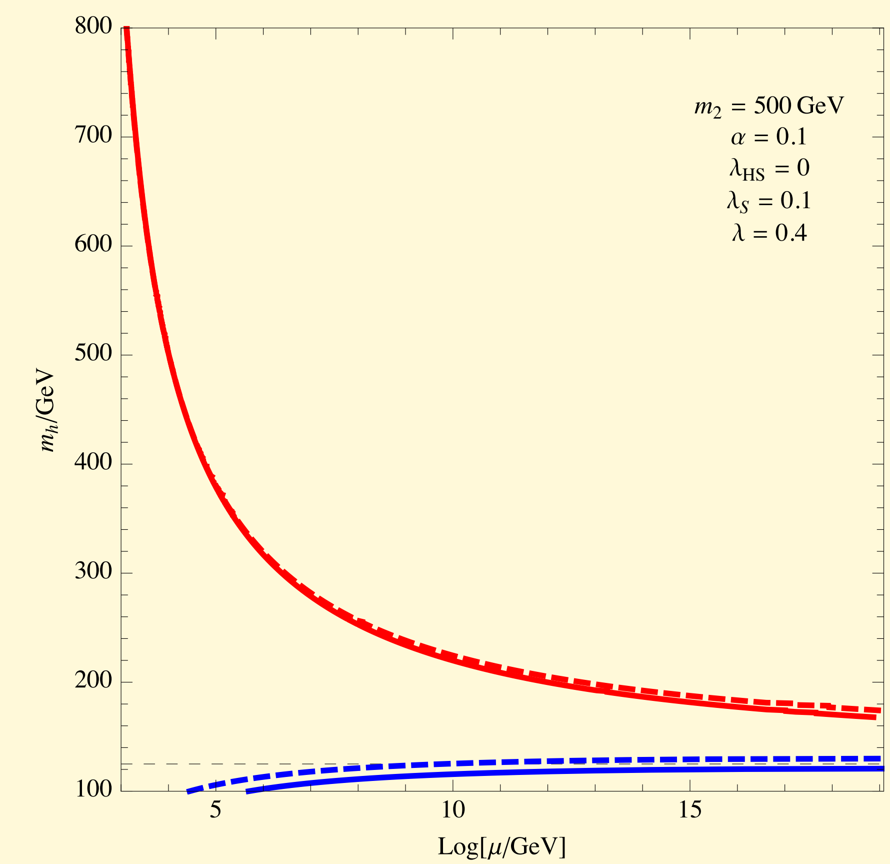
$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

the upper one: $v_h = 500$ GeV and $\tan\beta = 1$,

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

Vacuum Stability Improved by the singlet scalar S

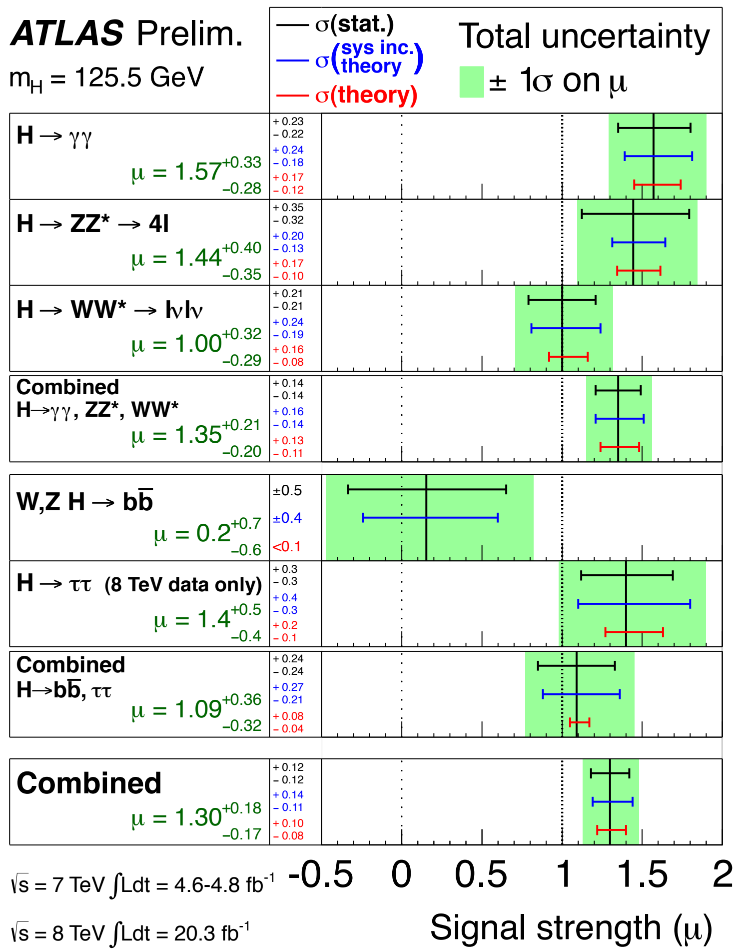


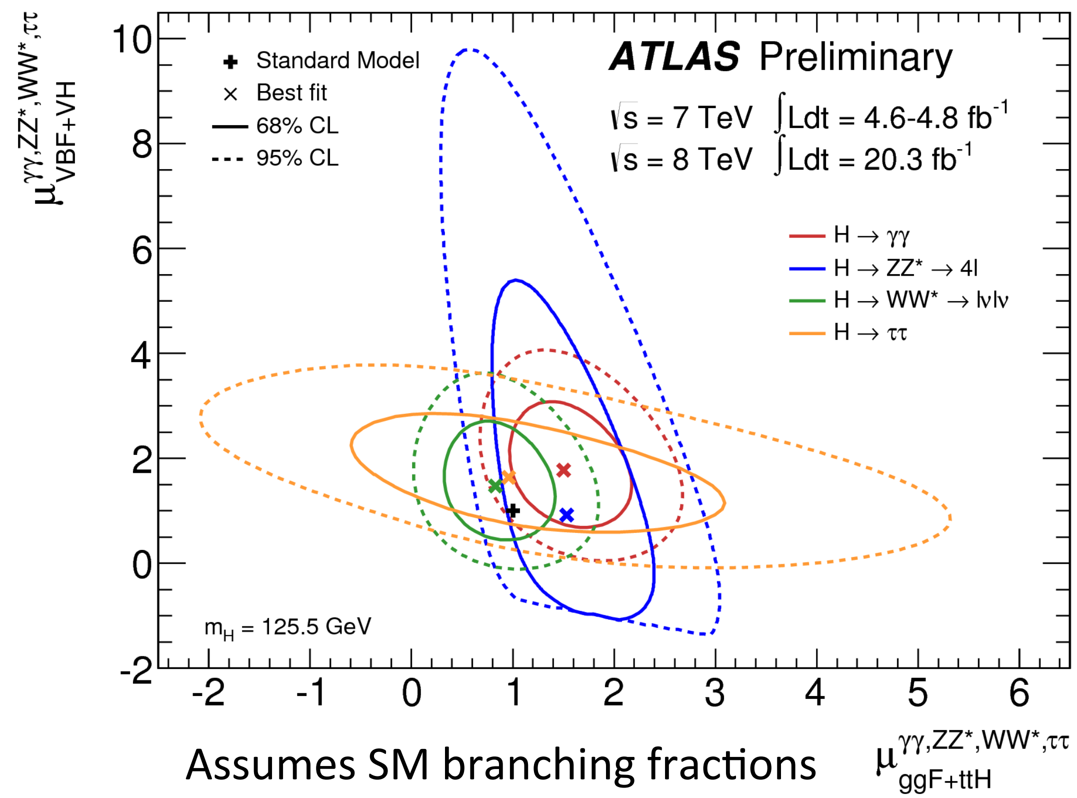


A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Main Decay and Production Modes





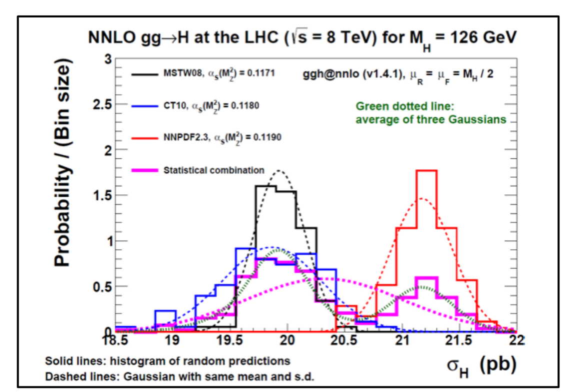
← Assumes SM branching fractions and production modes

Compatible with SM (at 14%)

$$\mu = 1.30 \pm 0.12\ (\text{stat}) \ \pm 0.10\ (\text{th}) \ \pm 0.09\ (\text{syst})$$

All channels couplings updated soon

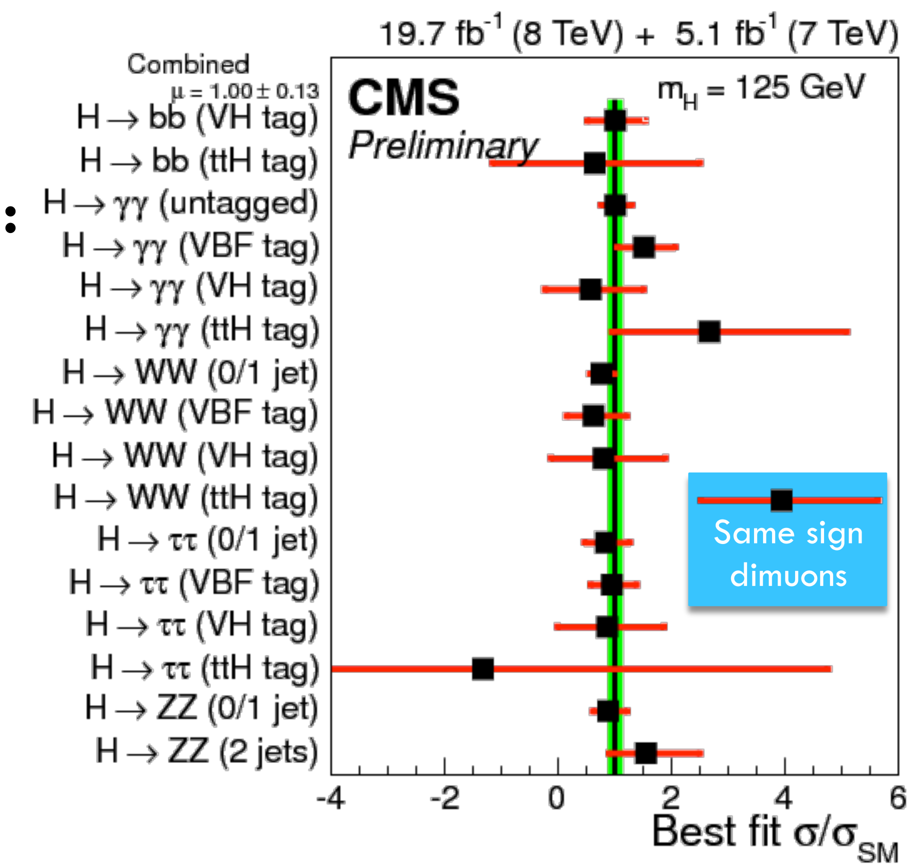
Stay tuned !



Signal strength

$$\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13 \left[\pm 0.09(\text{stat.})^{+0.08}_{-0.07}(\text{theo.}) \pm 0.07(\text{syst.})\right]$$

- Grouped by production tag and dominant decay:
  - $\chi^2/\text{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**

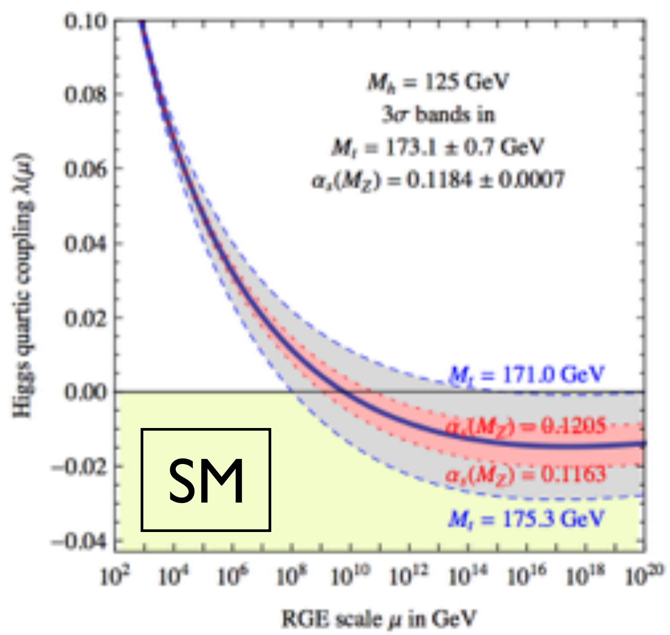


Low energy pheno.

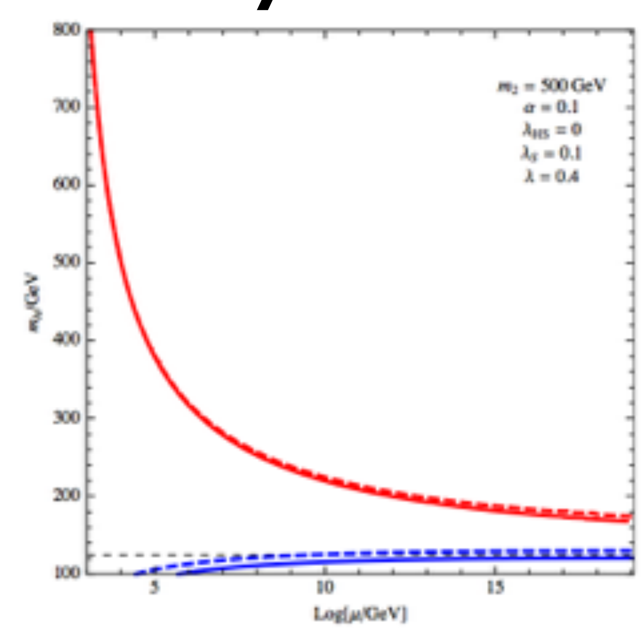
- Universal suppression of collider SM signals
  [See 1112.1847, Seungwon Baek, P. Ko & WIP]
- If "$m_h > 2\, m_\phi$", non-SM Higgs decay!
- Tree-level shift of $\lambda_{H,SM}$ (& loop correction)

$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2\alpha \right] \lambda_H^{SM}$$

If "$m_\phi > m_h$", vacuum instability can be cured.



[G. Degrassi et al., 1205.6497]



[S. Baek, P. Ko, WIP & E. Senaha, JHEP(2012)]

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
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H.Hatanaka, D.W.Jung@KIAS [poster session])

Impact of dark higgs -Cosmo.

(Higgs-portal assisted Higgs inflation)

[arXiv: 1405.1635, P. Ko & WIP]

Higgs Inflation in SM

- Largrangian

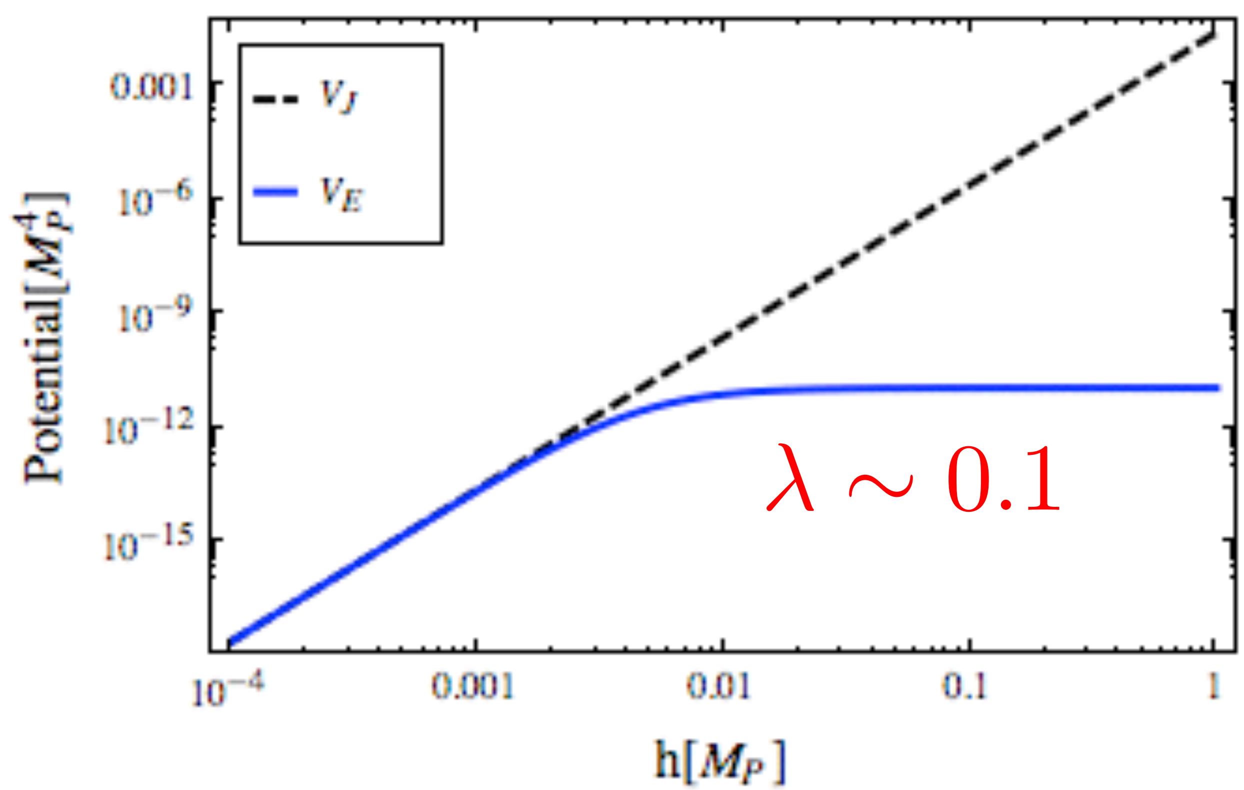
$$\mathcal{L} = -\frac{1}{2\kappa}\left(1 + \xi\frac{h^2}{M_\mathrm{P}^2}\right)R + \mathcal{L}_h, \ \text{where } \xi \gg 1$$

Conformal tr. : $g_{\mu\nu} \to \Omega^2 g_{\mu\nu}, \ \text{where } \Omega^2 = 1 + \xi\frac{h^2}{M_\mathrm{P}^2}$

$$V_J = \frac{\lambda}{4}\left(h^2 - v^2\right)^2$$

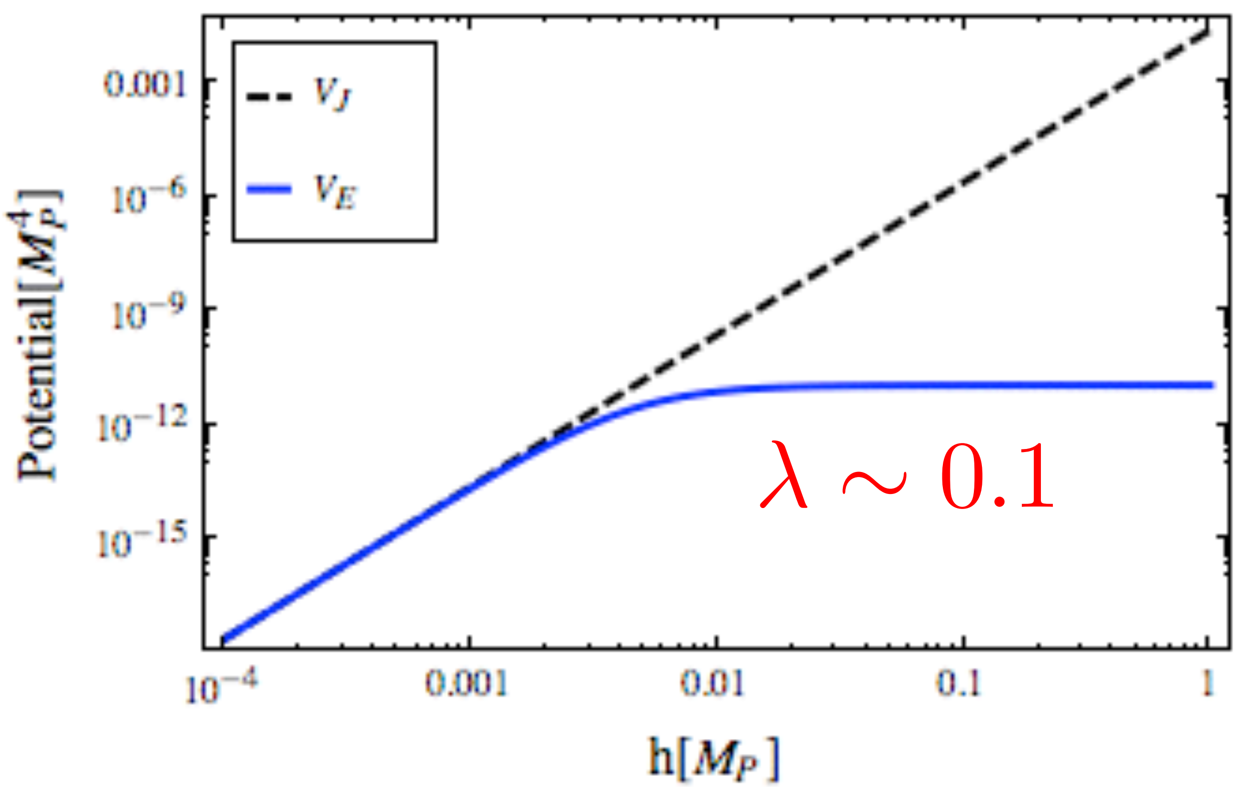
$$U(\chi) = \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}\left(h(\chi)^2 - v^2\right)^2$$

$$\frac{d\chi}{dh} = \frac{\sqrt{1 + \xi\left(1 + 6\xi\right)h^2/M_{\mathrm{Pl}}^2}}{1 + \xi h^2/M_{\mathrm{Pl}}^2}$$



- Parameters and observables of Higgs inflation

$$U(\chi) = \frac{1}{\Omega(\chi)^4}\frac{\lambda}{4}\left(h(\chi)^2 - v^2\right)^2 \quad \Rightarrow \quad \begin{cases} \epsilon = \frac{M_P^2}{2}\left(\frac{dU/d\chi}{U}\right)^2 \simeq \frac{4M_P^4}{3\xi^2 h^4} \\ \eta = M_P^2 \frac{d^2U/d\chi^2}{U} \simeq -\frac{4M_P^2}{3\xi h^2}\,, \end{cases} \quad \Rightarrow \epsilon \simeq \frac{3}{4}\eta^2$$



$$n_s = 1 - 6\epsilon + 2\eta \sim 0.96$$

$$\Rightarrow \eta \simeq \frac{1}{2}(n_s - 1)$$

$$\Rightarrow \epsilon \simeq \frac{3}{16}(n_s - 1)^2$$

$$\Rightarrow r \simeq 16\epsilon \simeq 3\,(n_s - 1)^2 \sim 5 \times 10^{-3}$$

Higgs Inflation in SM

(after BICEP2)

$r_{\mathrm{BICEP2}} \sim 0.1$ ➡ Is Higgs inflation ruled out? No!

$$U(h) = \frac{\lambda}{4\Omega^4}\left(h^2 - v_H^2\right) \to \frac{\lambda(\mu)}{4\Omega^4}\left(h^2 - v_H^2\right)$$

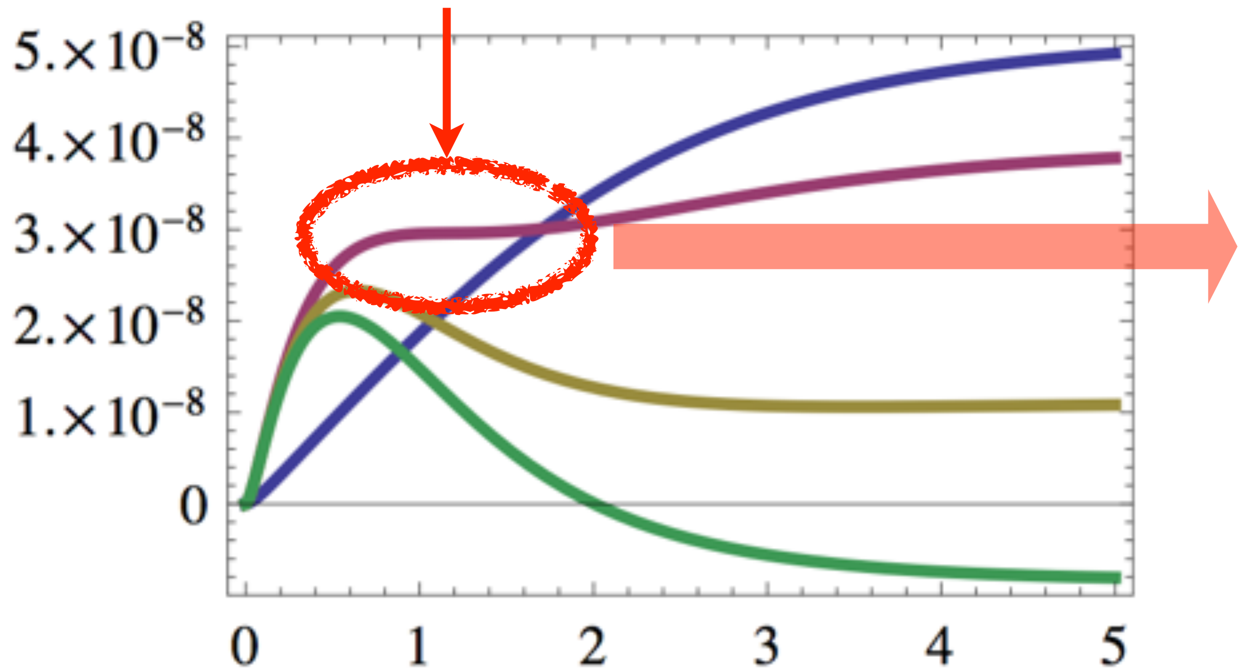
[Hamda, Kawai, Oda and Park, 1403.5043; Bezrukov and Shposhnikov, 1403.6078]

Effects of running on slow-roll parameters

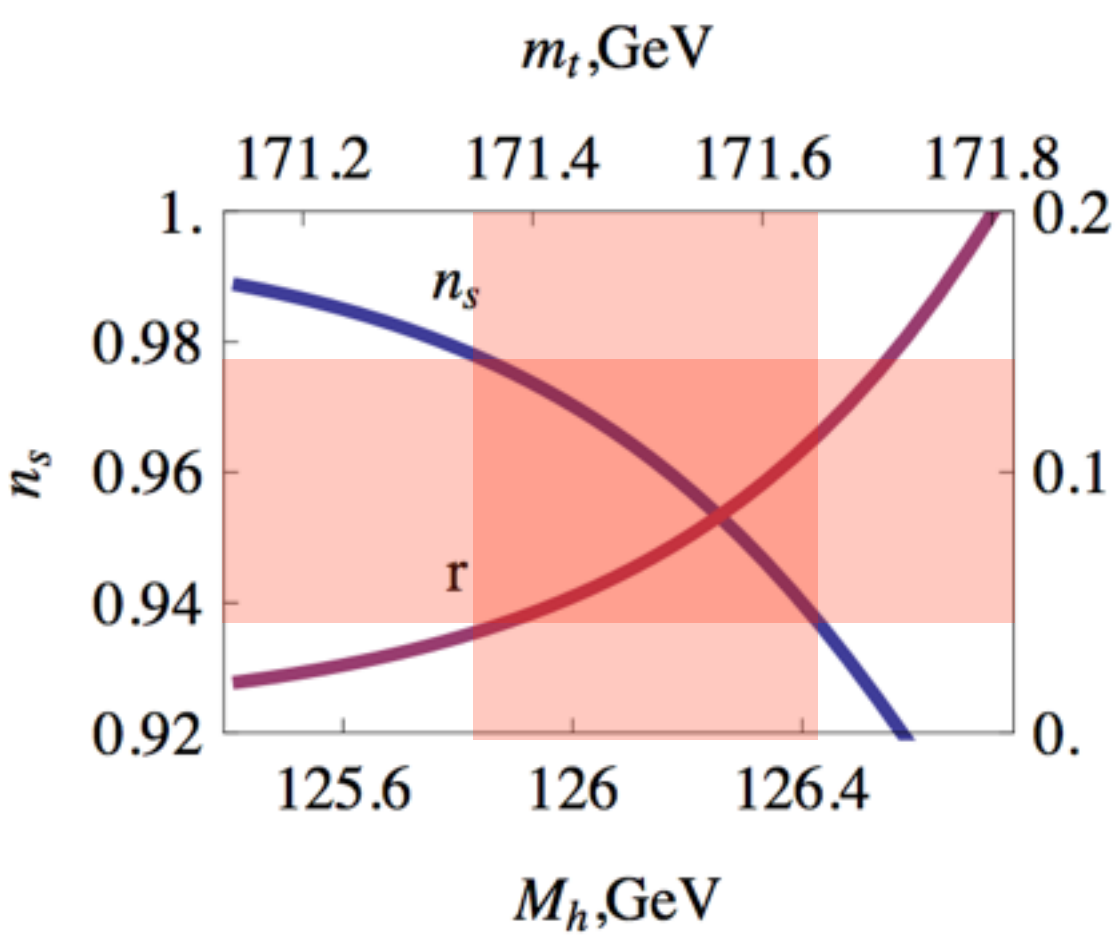
$$\epsilon = \frac{M_{\rm Pl}^2}{2}\left(\frac{dh}{d\chi}\frac{dU}{dh}\right)^2 = \frac{1}{2}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)^2 \frac{M_{\rm Pl}^2/h^2}{\sqrt{\Omega^2+6\xi^2h^2/M_{\rm Pl}^2}} \approx \frac{1}{12}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)^2\frac{M_{\rm Pl}^4}{\xi^2h^4} \quad (17)$$

$$\begin{aligned}\eta &= \frac{M_{\rm Pl}^2}{U}\frac{dh}{d\chi}\frac{d}{dh}\left(\frac{dh}{d\chi}\frac{dU}{dh}\right)\\ &= \left(4+\frac{\beta_\lambda}{\lambda_H}\right)\frac{M_{\rm Pl}^2}{h^2}\frac{\Omega^2}{\Omega^2+6\xi^2h^2/M_{\rm Pl}^2}\left\{\frac{1}{\Omega^2}\frac{\beta_\lambda}{\lambda_H}\left[1+\frac{d\ln\left(\beta_\lambda/\lambda_H\right)/d\ln\varphi}{4+\beta_\lambda/\lambda_H}\right]+3-2\frac{d\ln\Omega^2}{d\ln h}-\frac{\xi\left(1+6\xi\right)h^2/M_{\rm Pl}^2}{1+\xi\left(1+6\xi\right)h^2/M_{\rm Pl}^2}\right\}\\ &\simeq -\frac{1}{3}\left(4+\frac{\beta_\lambda}{\lambda_H}\right)\frac{M_{\rm Pl}^2}{\xi h^2}\left\{1-\frac{M_{\rm Pl}^2}{2\xi h^2}\frac{\beta_\lambda}{\lambda_H}\left[1+\frac{d\ln\beta_\lambda/d\ln\varphi-\beta_\lambda/\lambda_H}{4+\beta_\lambda/\lambda_H}\right]\right\} \quad (18)\end{aligned}$$

ϵ & η are independent



[Bezrukov and Shposhnikov, 1403.6078]



* Flat inflection points requires a precise choice of m_t and M_h, e.g.,

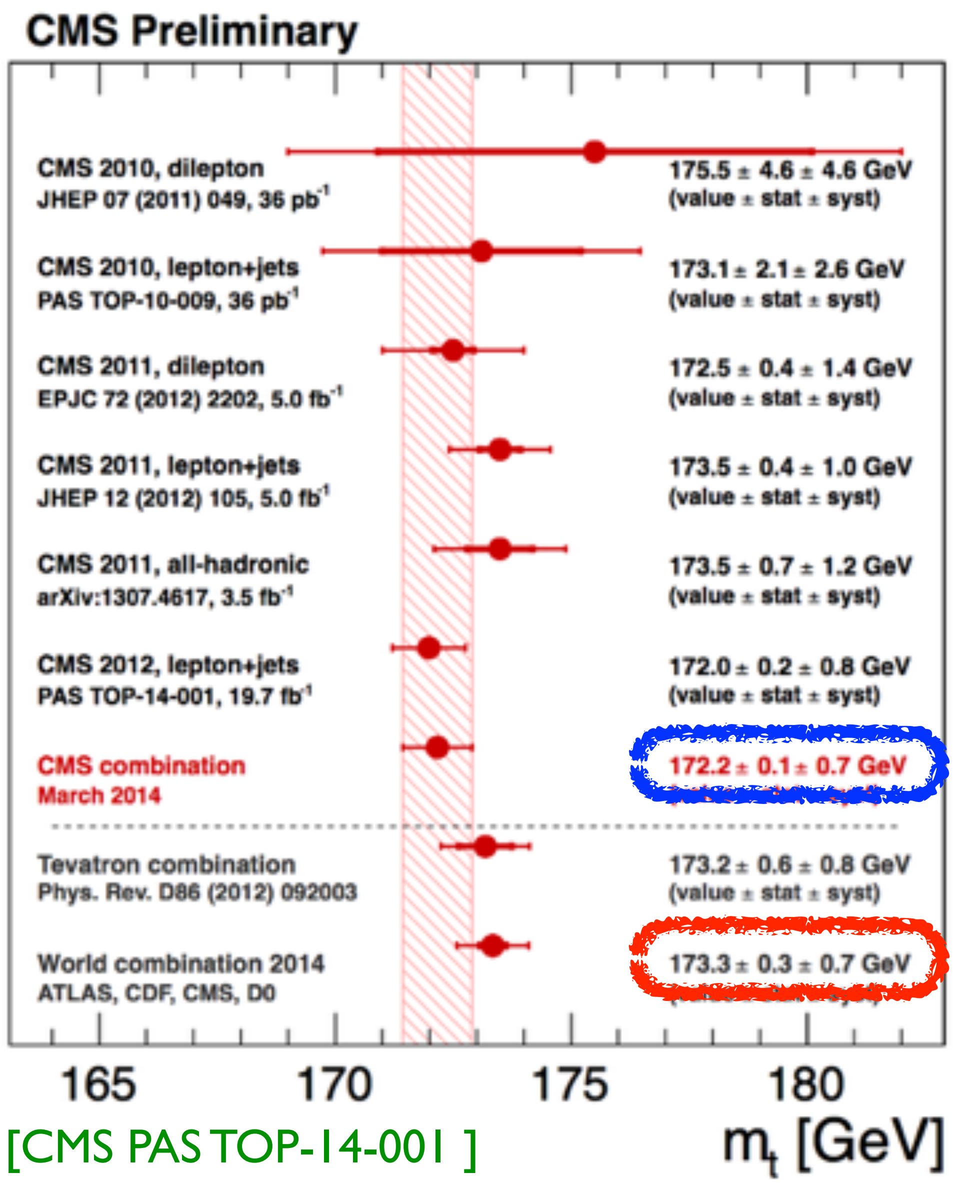
$m_t \approx 171.XXXX,\ M_h \approx 12X.XXXX$

$\Rightarrow$ $\lambda \sim$ a few 10^{-6}

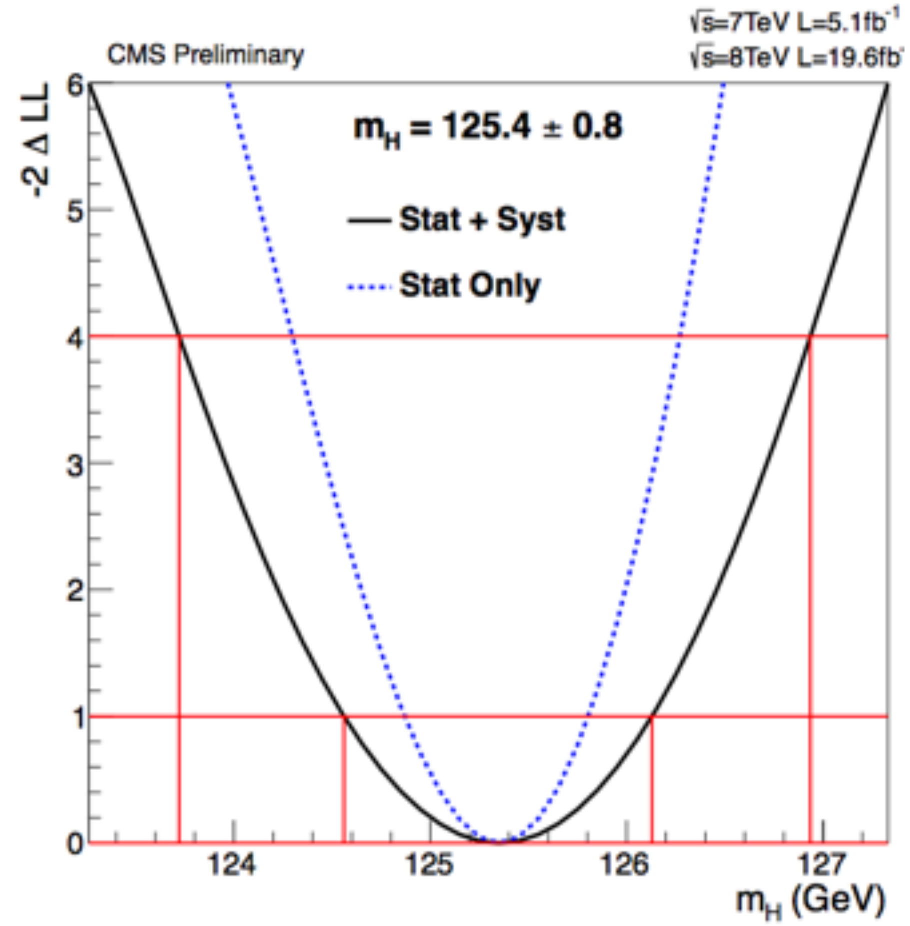
$r \sim 0.1$ with $n_s \approx 0.96$ only for

$m_t \approx 171.5XXX,\ M_h \approx 126.2XXX$

However m_t and M_h are tightly constrained!

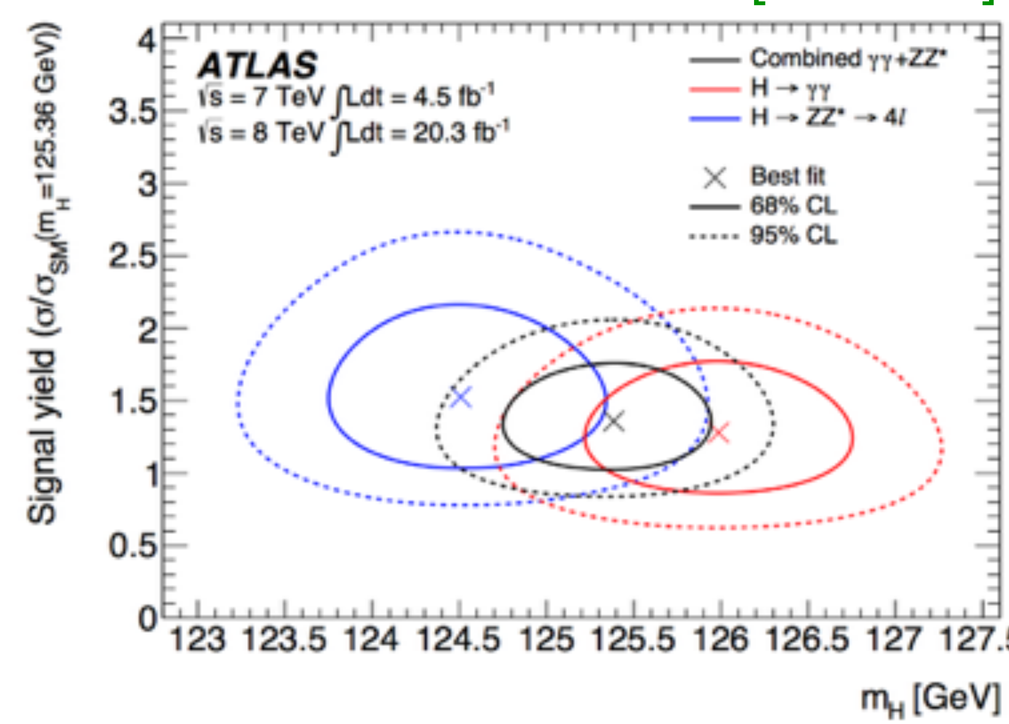


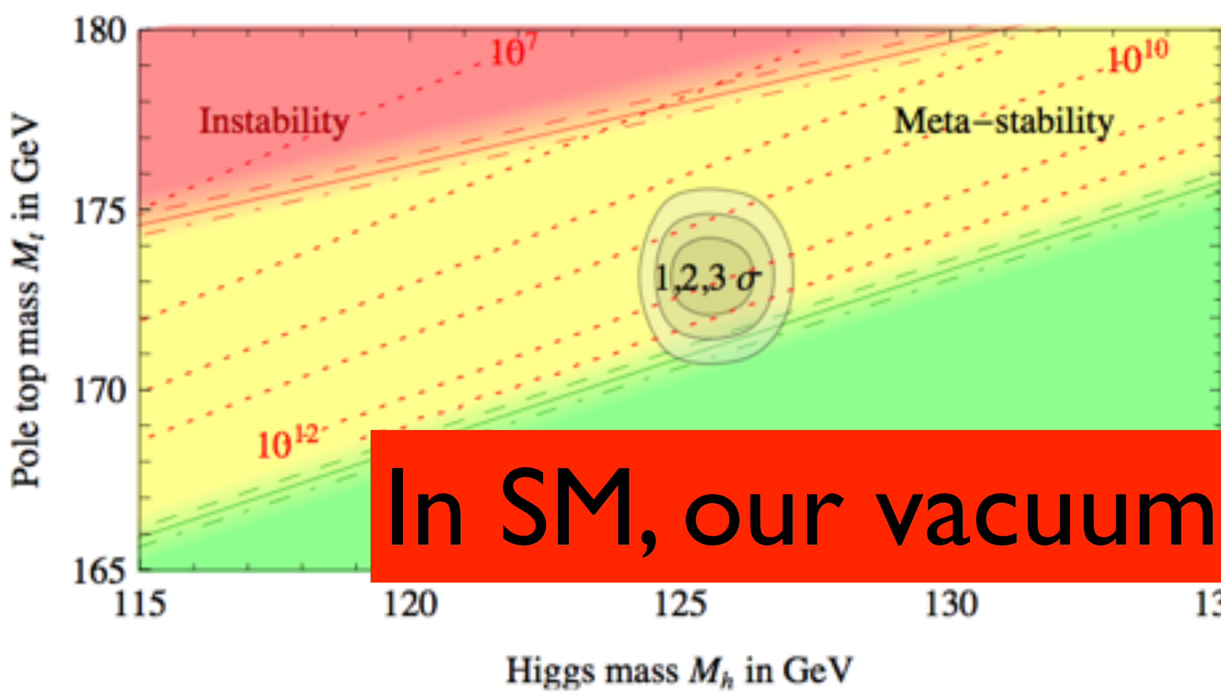
[CMS PAS TOP-14-001]



[CMS PAS HIG-13-001]

[1406.3827]





In SM, our vacuum is likely to be meta-stable.

* Higgs inflation in SM may not be possible at the first place.

* However SM seems to be extended somehow.

* Higgs portal with dark Higgs saves Higgs inflation

Higgs portal interaction

$$V \supset \lambda_{\Phi H} |\Phi|^2 H^\dagger H$$

Scalar mixing

$$\lambda_H = \left[1 - \left(1 - \frac{m_\phi^2}{m_h^2}\right) \sin^2\alpha\right] \lambda_H^{SM}$$

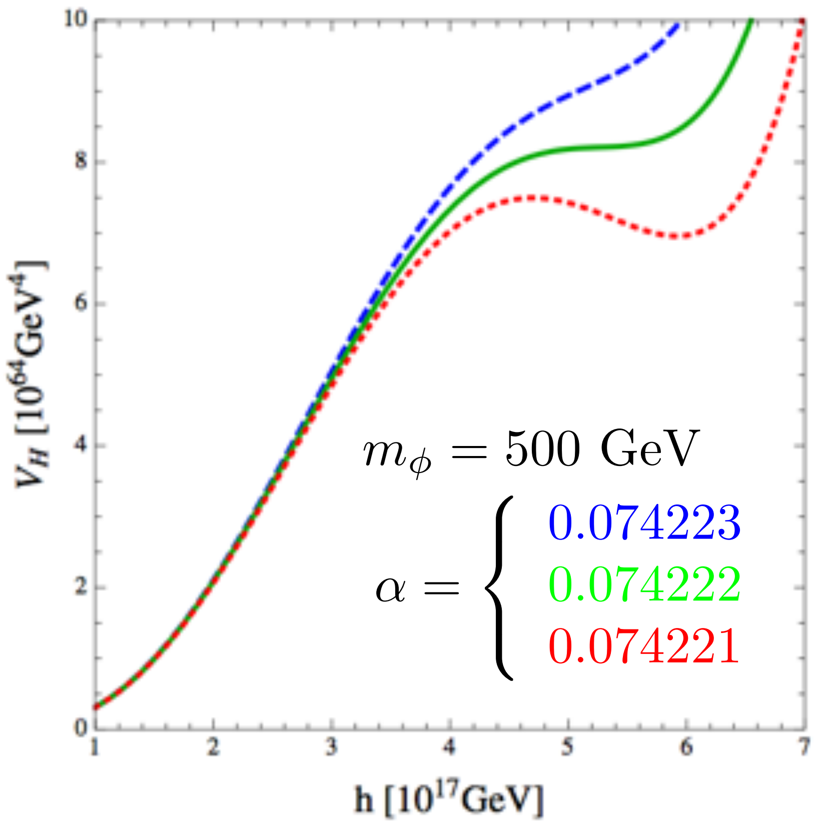
⇨ $\lambda_H > \lambda_H^{SM}$ for $m_\phi > m_h$ & $\alpha \neq 0$

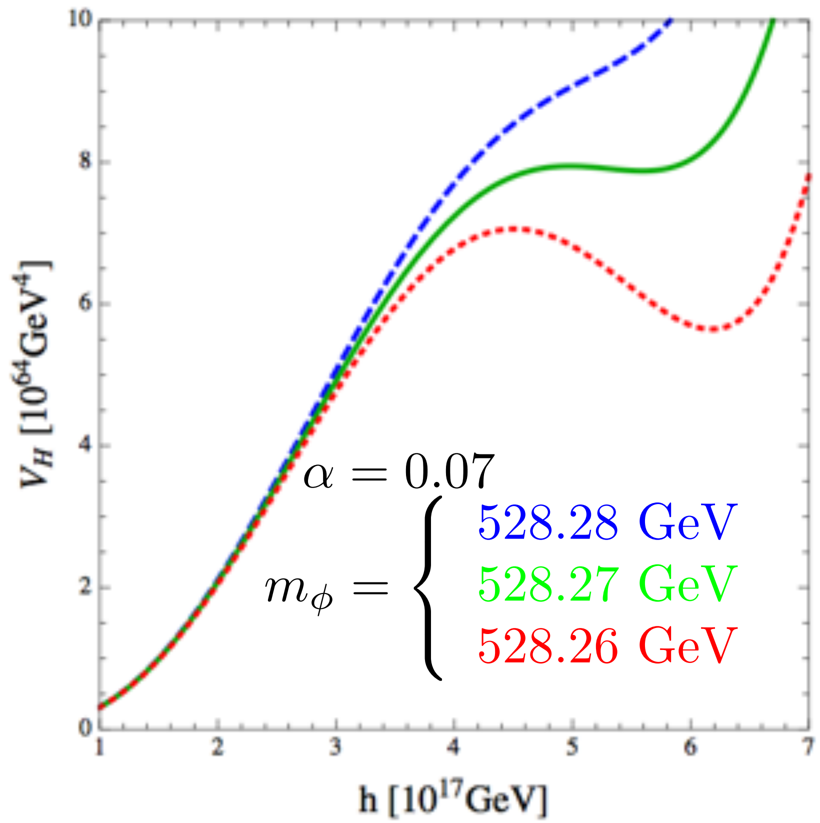
⇨ Vacuum instability is easily removed.

⇨ Higgs inflation becomes possible for a wide range of m_t and M_h

Higgs portal interaction disconnect m_t and M_h from inflationary observables.

Higgs-portal Higgs inflation

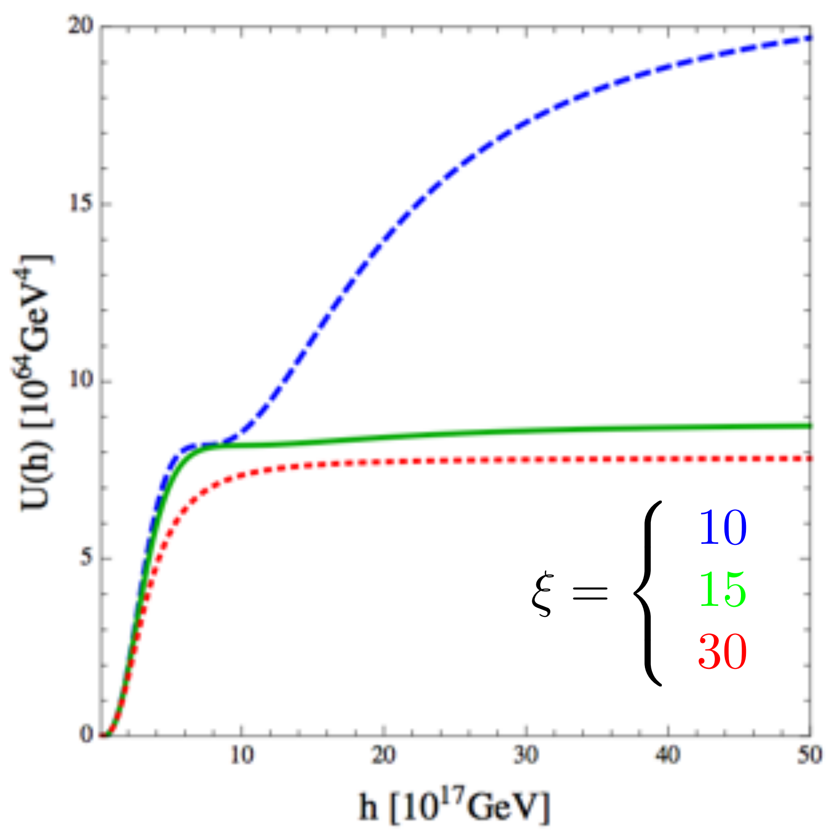




$m_t = 173.2$ GeV
$M_h = 125.5$ GeV

* Inflection point control

(α, m_ϕ) & $\lambda_{\Phi H}$



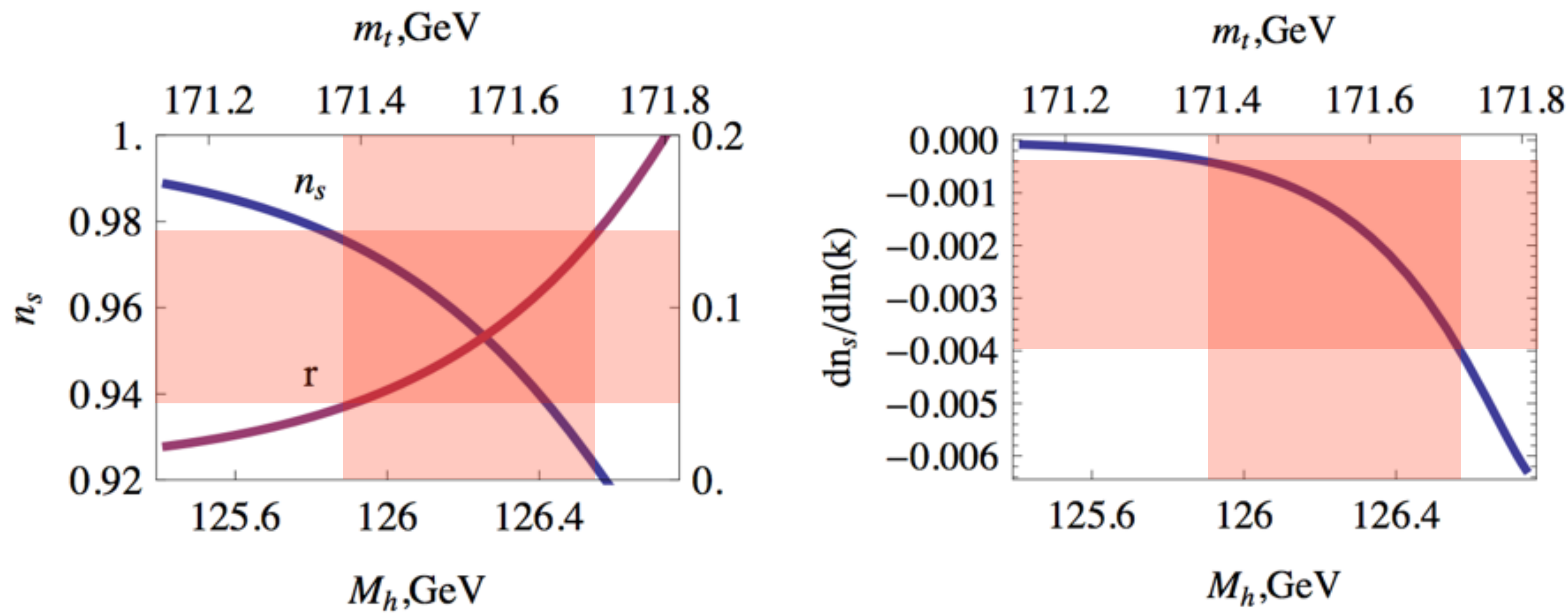
Result of numerical analysis

$k_* \times$ Mpc	N_e	$h_*/M_{\rm Pl}$	ϵ_*	η_*	$10^9 P_S$	n_s	r
0.002	59	0.83	0.00448	−0.02465	2.2639	0.9238	0.0717
0.05	56	0.72	0.00525	−0.00190	2.1777	0.9647	0.0840

- Result depends very sensitively on α, m_Φ and $\lambda_{\Phi H}$ -

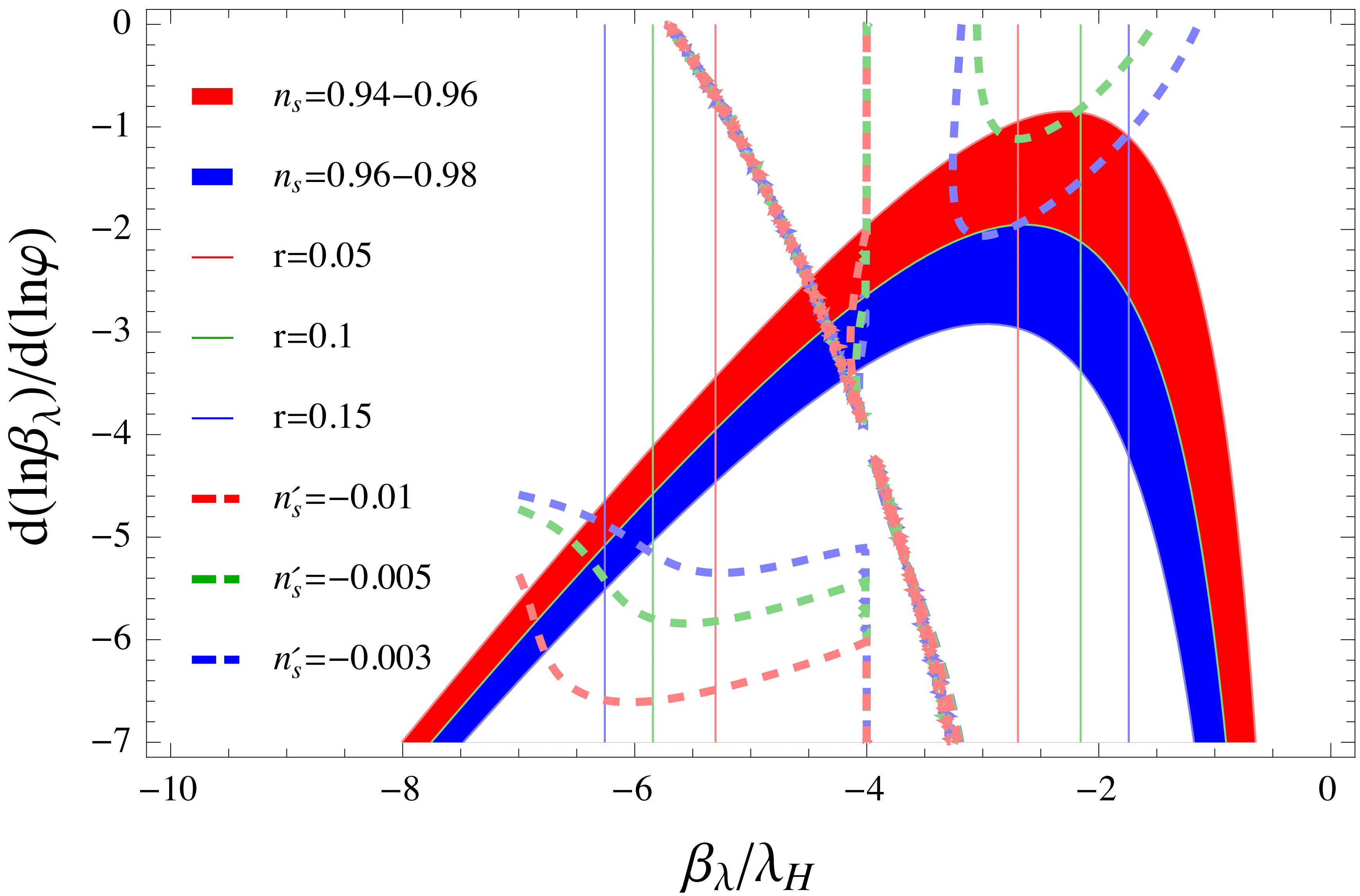
Scale dependence!

- Prediction of SM Higgs inflation



$$\frac{dn_s}{d\ln k} \sim 10^{-3}$$

Higgs portal assisted HI



possible to have r~O(0.1) with small spectral running independent of top mass

Conclusion

- Renormalizable and unitary model (with some caveat) is important for DM phenomenology (EFT can fail completely)
- Hidden sector DM with Dark Gauge Sym is well motivated, can guarantee DM stability, solves some puzzles in CDM paradigm, and open a new window in DM models
- Especially a wider region of DM mass is allowed due to new open channels

- DM Dynamics dictated by local gauge symmetry
- Invisible Higgs decay into a pair of DM
- Non Standard Higgs decays into a pair of light dark Higgs bosons, or dark gauge bosons, etc.
- Additional singlet-like scalar "S" : generic, can play important roles in DM phenomenology, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio >> Should be actively searched for
- Searches @ LHC & other future colliders !