

# Towards EW Scale CDM with local dark gauge sym

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# Contents

- DM models with local dark gauge symmetry
- DM EFT vs. Full theory : Higgs portal DM as examples

# 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” and “Dark Gauge Bosons” that can play a role of light mediators

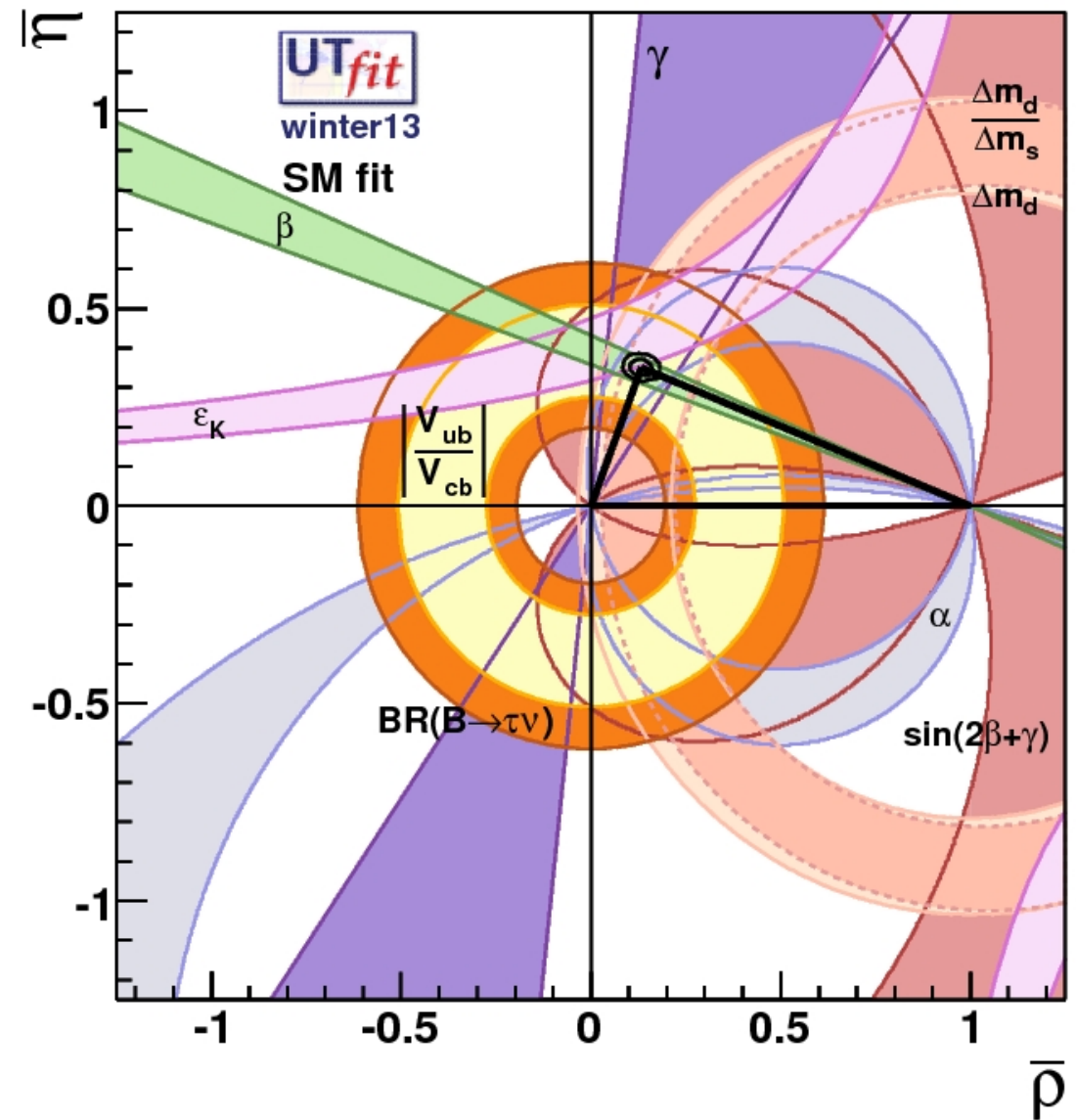
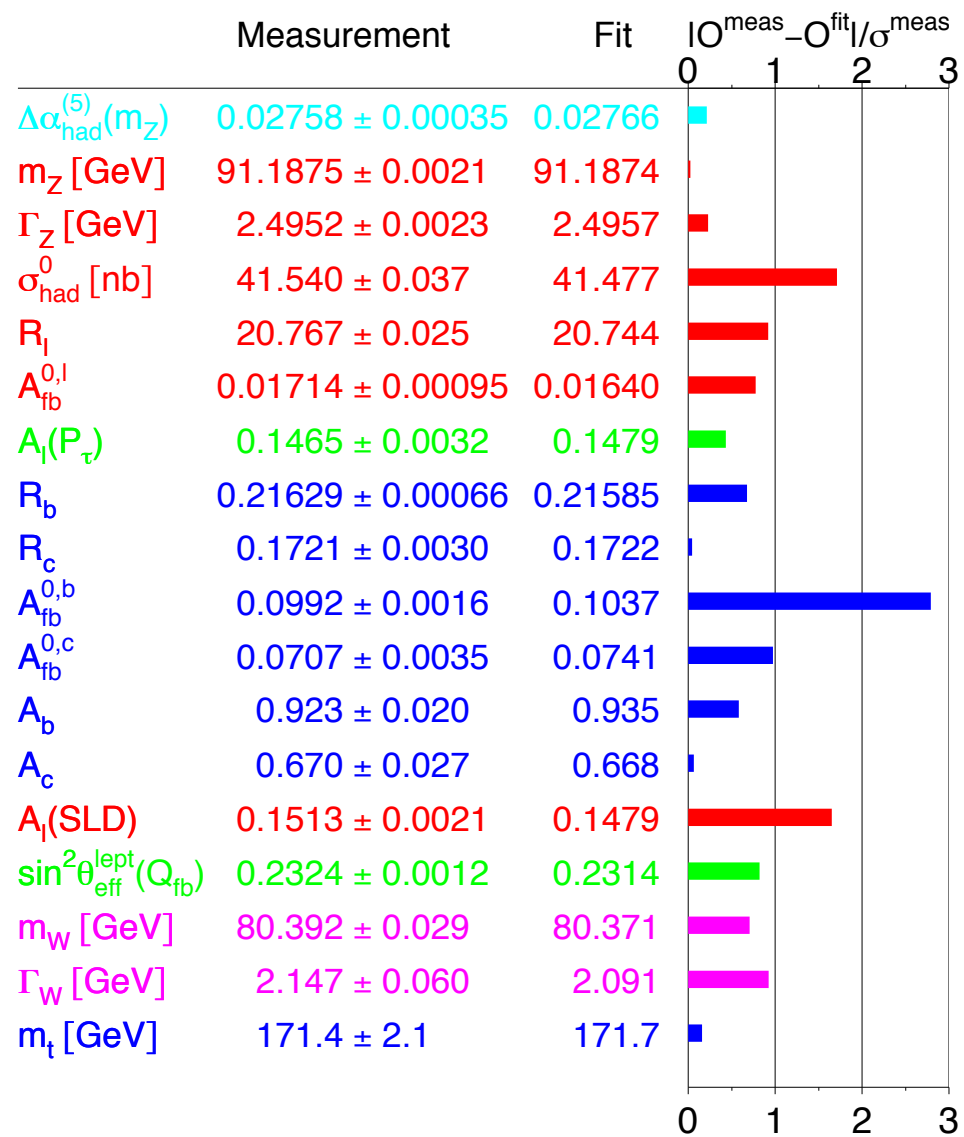
# SM Lagrangian

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

Based on local gauge principle



# EWPT & CKM



Almost Perfect !

Only Higgs ( $\sim$ SM) and Nothing  
Else So Far at the LHC

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

# Motivations for BSM

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

Leptogenesis

Starobinsky

?

Higgs Inflation

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 issue in nonSUSY DM models
- Also extra particles (the so-called mediators, scalar, vector etc) are introduced for SIDM in somewhat ad hoc way
- Any good organizing principle ?

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- Any good organizing principle ? YES !

# Local Dark Gauge Sym

- Well tested principle in the SM
- Natural for stable or long-lived DM
- Completely fix the dynamics of DM, SM
- Guarantees stability/longevity of DM
- Force mediators already present in a gauge invariant way (Only issue is the mass scale)
- Predictable amount of dark radiation



# 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  $Z_3, Z_2$  + EWSB** & CDM from strongly interacting hidden sector (**only briefly for monopole DM**)

# Contents

- **Underlying Principles** : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
  - **Scalar DM with local  $Z_2, Z_3$**  : 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  $Z_3$  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.

# Remarks

- All the models are consistent with the LHC results finding out no signatures for BSM
- Not easy to test these models at the LHC or ILC or Flavor Physics
- Most of them are not well described by the DM EFT (with complementarity)
- Very conservative approach to DM models

# 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, ...)

# 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
- $E_8 \times E_8'$  : natural setting for SM  $\times$  Hidden
- $SO(32)$  may be broken into  $G_{SM} \times G_h$

# 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

# Higgs signal strength/Dark radiation/DM

in preparation with Baek and W.I. Park

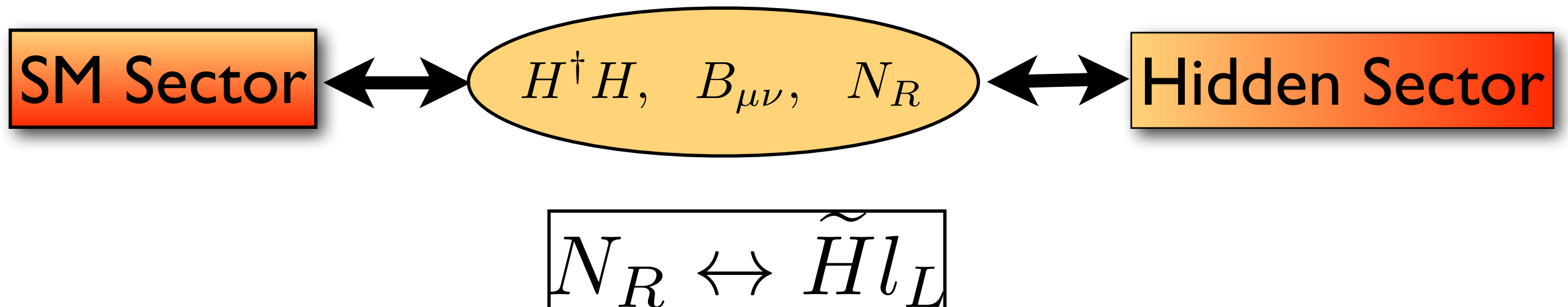
Models	Unbroken $U(1)_X$	Local $Z_2$	Unbroken $SU(N)$	Unbroken $SU(N)$ (confining)
Scalar DM	$I$ 0.08 complex scalar	$< I$ $\sim 0$ real scalar	$I$ $\sim 0.08 * \#$ complex scalar	$I$ $\sim 0$ composite hadrons
Fermion DM	$< I$ 0.08 Dirac fermion	$< I$ $\sim 0$ Majorana	$< I$ $\sim 0.08 * \#$ Dirac fermion	$< I$ $\sim 0$ composite hadrons

# : The number of massless gauge bosons



# 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



# 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, Z3, Z2, scalar CDM

# But for WIMP ...

- Global sym. is not enough since

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

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

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

$\Rightarrow$  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

# Z<sub>2</sub> 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 Z<sub>2</sub> symmetry come from ?
- Is it Global or Local ?

# Fate of CDM with $Z_2$ sym

- Global  $Z_2$  cannot save DM from decay with long enough lifetime

Consider  $Z_2$  breaking operators such as

$$\frac{1}{M_{\text{Planck}}} SO_{\text{SM}}$$

keeping dim-4 SM operators only

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

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

The lifetime is too short for  $\sim 100$  GeV DM

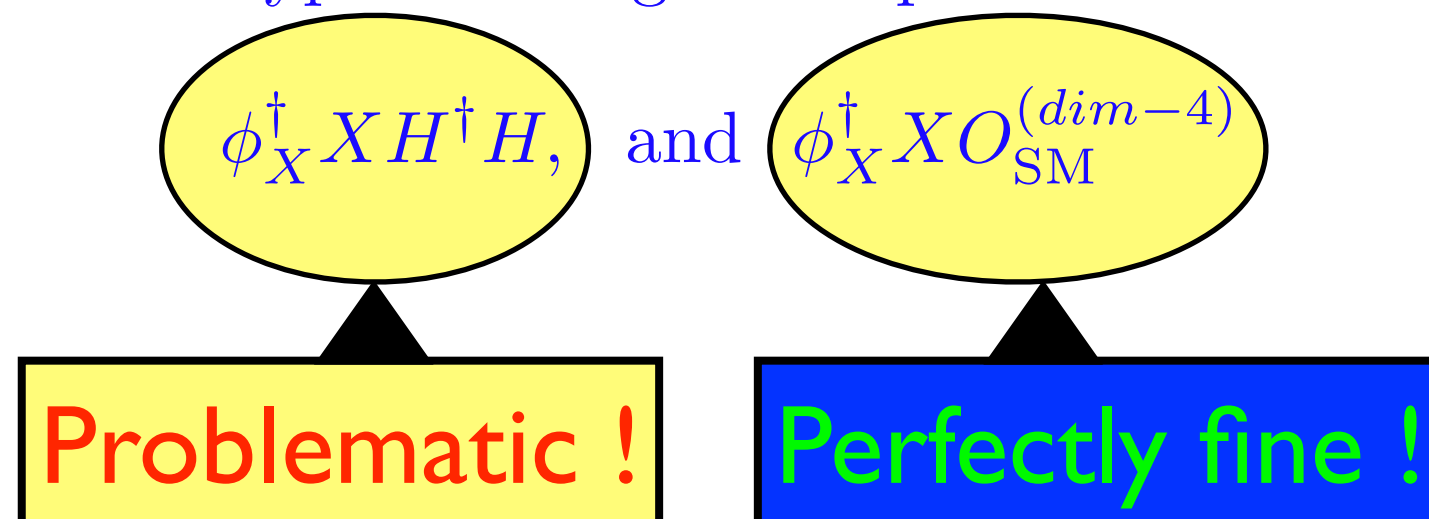
# Fate of CDM with $Z_2$ sym

- 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:





- 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, and another by Ko, Omura and Yu on inert 2HDM with local  $U(1)_H$

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

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

$$- \frac{\lambda_X}{4}(X^\dagger X)^2 - (\mu X^2\phi^\dagger + H.c.) - \frac{\lambda_{XH}}{4}X^\dagger X H^\dagger H - \frac{\lambda_{\phi_X H}}{4}\phi_X^\dagger\phi_X H^\dagger H - \frac{\lambda_{XH}}{4}X^\dagger X\phi_X^\dagger\phi_X$$

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

Unbroken Local Z2 symmetry  
Gauge models for excited DM

$X_R \rightarrow X_I\gamma_h^*$  followed by  $\gamma_h^* \rightarrow \gamma \rightarrow e^+e^-$  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)

# 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
- They can be a light mediator for SIDM
- Can solve many puzzles in CDM by large self-interactions, and also calculable amount of Dark Radiation

# Local Z<sub>3</sub> Scalar DM

P.Ko, YTang, arXiv:1402.6449

Again an extra U(1)<sub>X</sub> gauge symmetry is introduced, with scalar DM  $X$  and dark higgs with charges 1 and 3, respectively.

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{1}{2} \sin \epsilon \tilde{X}_{\mu\nu} \tilde{B}^{\mu\nu} + D_\mu \phi_X^\dagger D^\mu \phi_X + D_\mu X^\dagger D^\mu X - V$$

$$V = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 - \mu_\phi^2 \phi_X^\dagger \phi_X + \lambda_\phi (\phi_X^\dagger \phi_X)^2 + \mu_X^2 X^\dagger X + \lambda_X (X^\dagger X)^2 \\ + \lambda_{\phi H} \phi_X^\dagger \phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X \phi_X^\dagger \phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \boxed{(\lambda_3 X^3 \phi_X^\dagger + H.c.)}$$

$$X \rightarrow e^{i\frac{2\pi}{3}} X$$

$$\boxed{\text{Z}_3 \text{ symmetry}} \quad X^\dagger \rightarrow e^{-i\frac{2\pi}{3}} X^\dagger$$

$$X^3 + X^{\dagger 3}$$

# Comparison with global Z3

$$V_{\text{eff}} \simeq -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_X^2 X^\dagger X + \lambda_X (X^\dagger X)^2 + \lambda_{HX} X^\dagger X H^\dagger H + \mu_3 X^3 \\ + \text{higher order terms} + H.c,$$

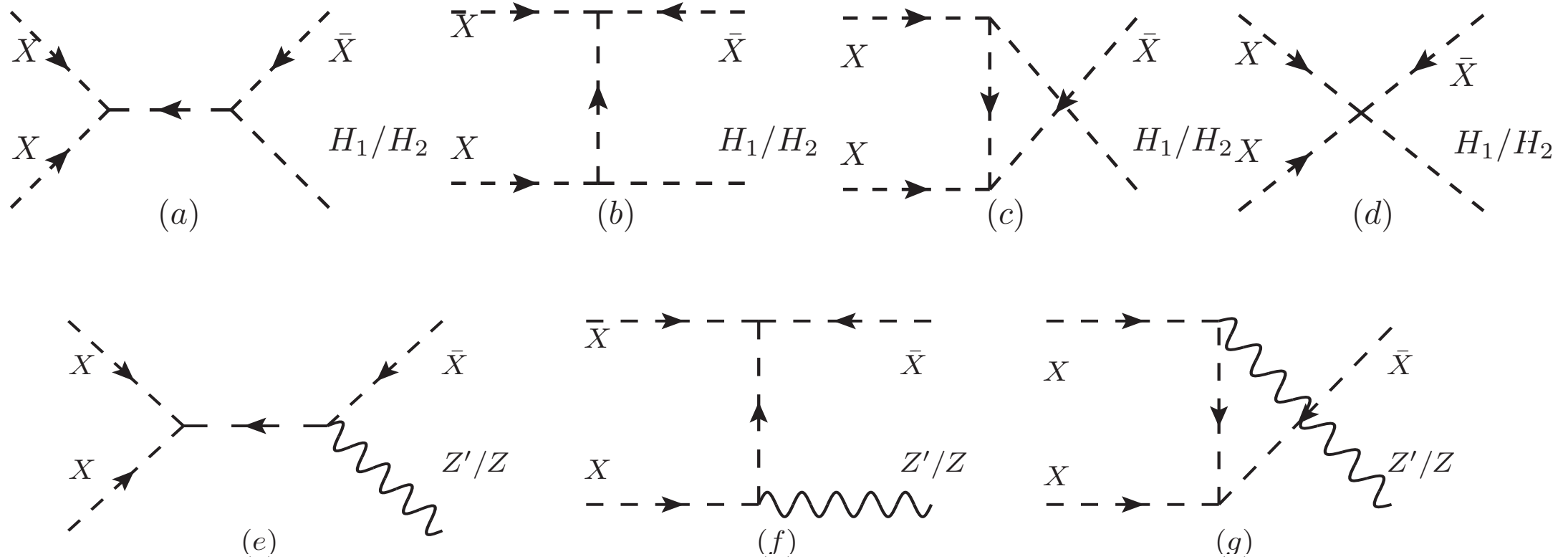
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

$$\frac{1}{\Lambda} X F_{\mu\nu} F^{\mu\nu}$$

Global Z3 “X” will decay immediately and can not be a DM

- Also particle spectra different : Z' and H2
- DM & H phenomenology change a lot

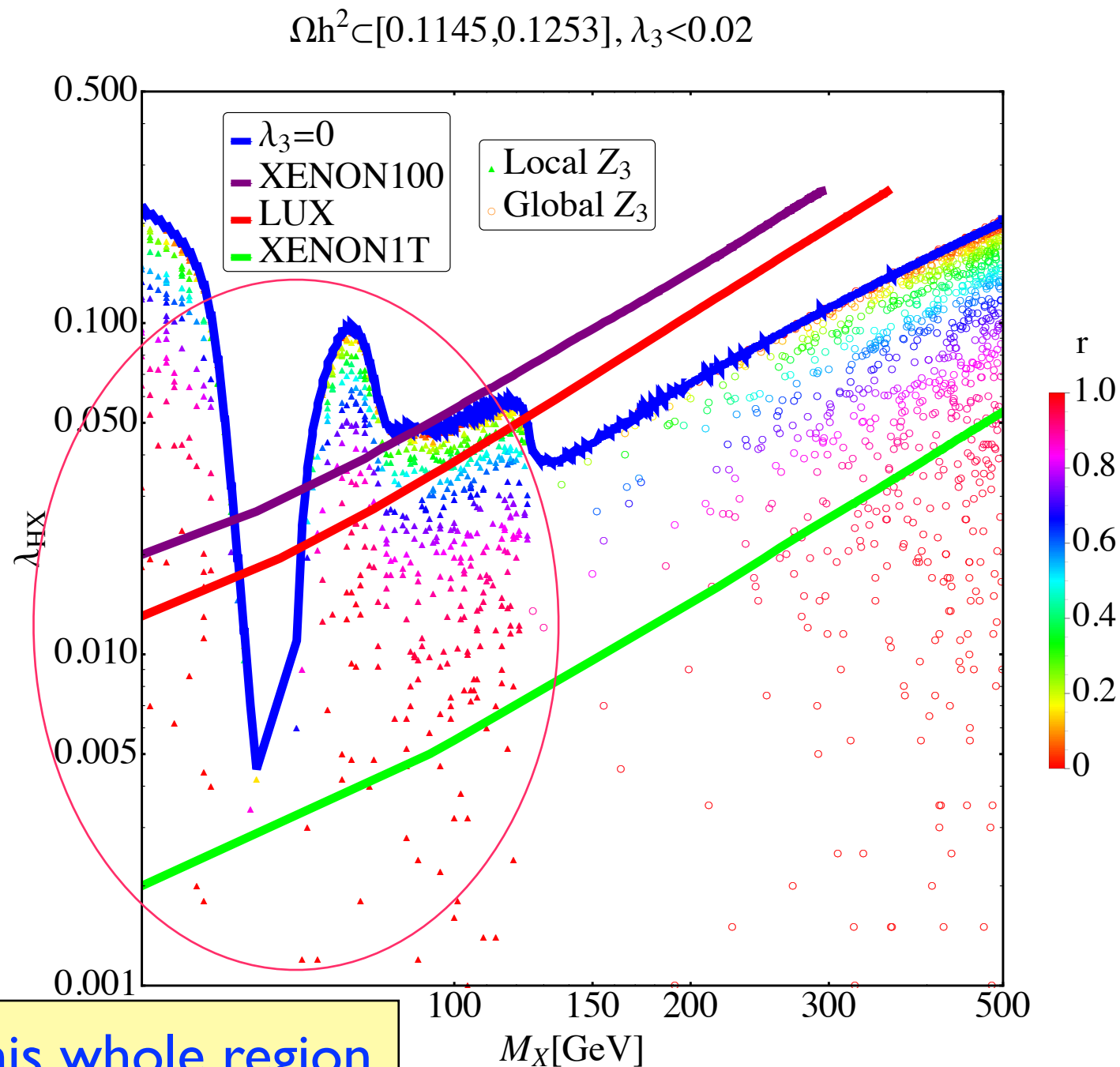
# Semi-annihilation



$$\frac{dn_X}{dt} = -v\sigma^{XX^* \rightarrow YY} (n_X^2 - n_{X \text{ eq}}^2) - \frac{1}{2}v\sigma^{XX \rightarrow X^*Y} (n_X^2 - n_X n_{X \text{ eq}}) - 3Hn_X,$$

$$r \equiv \frac{1}{2} \frac{v\sigma^{XX \rightarrow X^*Y}}{v\sigma^{XX^* \rightarrow YY} + \frac{1}{2}v\sigma^{XX \rightarrow X^*Y}}.$$

# Relic density and Direct Search



This whole region  
is allowed in  
local  $Z_3$  case

- Blue band marks the upper bound,
- All points are allowed in our local  $Z_3$  model, 1402.6449
- only circles are allowed in global  $Z_3$  model, 1211.1014

## Global Z3 (Belanger, Pukhov et al)

- SM + X
- DD & Thermal relic  $\gg$   
 $mX > 120 \text{ GeV}$
- Vacuum stability  $\gg$  DD  
cross section within  
XenonIT experiment
- No light mediators

## Local Z3 (Ko, Yong Tang)

- SM + X ,  $\phi$  ,  $Z'$
- Additional Annihilation  
Channels open
- DD constraints relaxed
- Light  $mX$  allowed
- Light mediator  $\phi$  : strong  
self interactions of X's



# Dark matter self-interactions

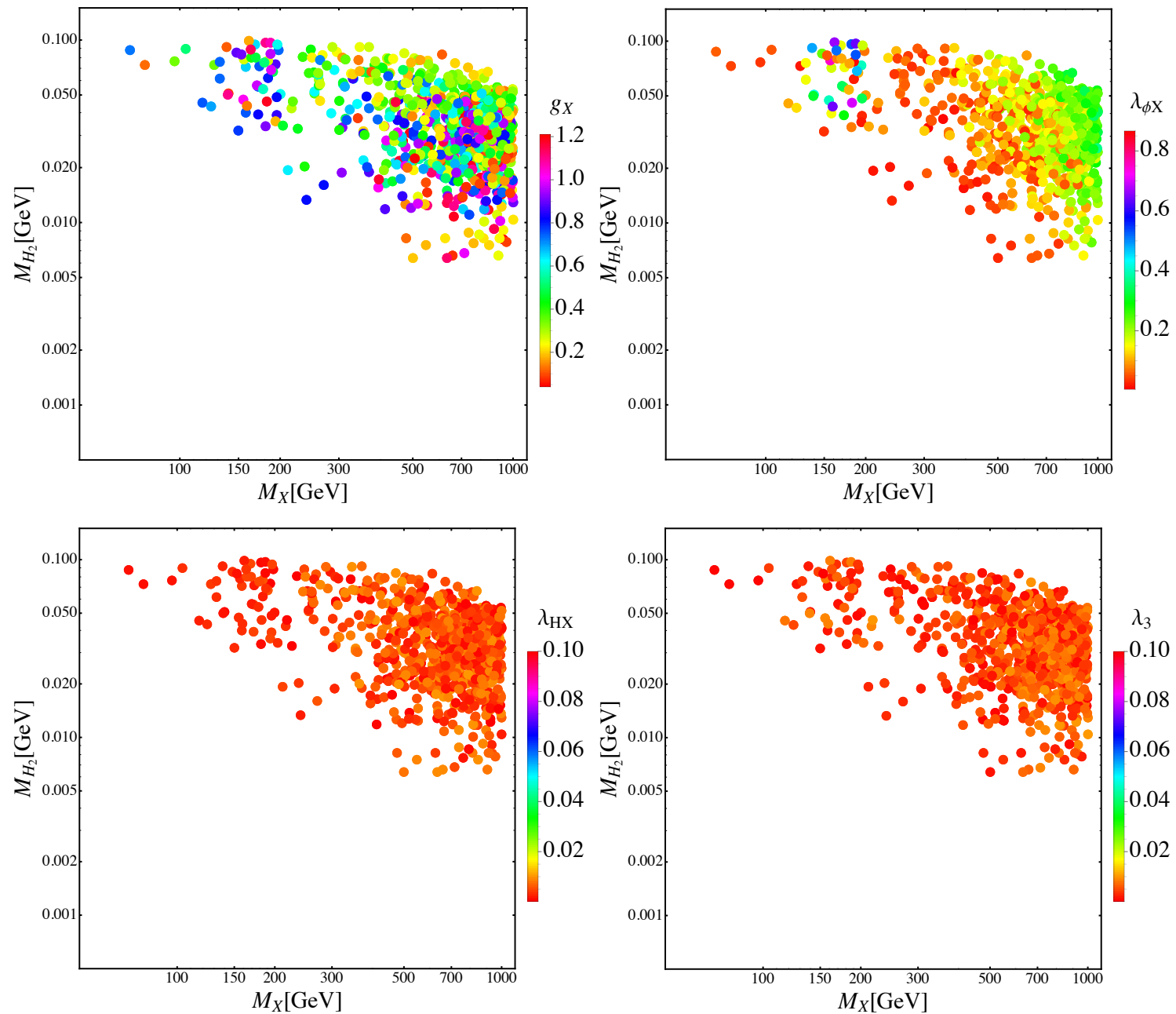


FIG. 3: Scatter plots of various parameters that are consistent with relic density, LUX direct search bound and self-interaction  $\sigma_T/M_X \in [0.1, 10] \text{ cm}^2/\text{g}$  at Dwarf galaxies scale with  $v_{\text{rel}} \simeq 10 \text{ km/s}$ , and  $\sigma_T/M_X \lesssim 0.5 \text{ cm}^2/\text{g}$  at Milky Way and cluster scales with  $v_{\text{rel}} \simeq 220 \text{ km/s}$  and  $v_{\text{rel}} \simeq 1000 \text{ km/s}$ , respectively. We have used  $M_{Z'} \simeq 200 \text{ GeV}$  and  $\epsilon \ll 0.03$  and scanned other parameters as illustration.

# Comparison with EFT

$$U(1)_X \text{ sym : } X^\dagger X H^\dagger H, \frac{1}{\Lambda^2} (X^\dagger D_\mu X) (H^\dagger D^\mu H), \frac{1}{\Lambda^2} (X^\dagger D_\mu X) (\bar{f} \gamma^\mu f), \text{ etc.} \quad (4.3)$$

$$Z_3 \text{ sym : } \frac{1}{\Lambda} X^3 H^\dagger H, \frac{1}{\Lambda^2} X^3 \bar{f} f, \text{ etc.} \quad (4.4)$$

$$(\text{or } \frac{1}{\Lambda^3} X^3 \bar{f}_L H f_R, \text{ if we imposed the full SM gauge symmetry}) \quad (4.5)$$

- There is no  $Z'$ ,  $H_2$  in the EFT, and so indirect detection or thermal relic density cal.s can be completely wrong (or different, say softly)
- Complementarity breaks down : (4.3) cannot capture semi-annihilation described by (4.4)

# Gamma ray excess from the GC

(P. Ko, Yong Tang, I407.5492, JCAP)

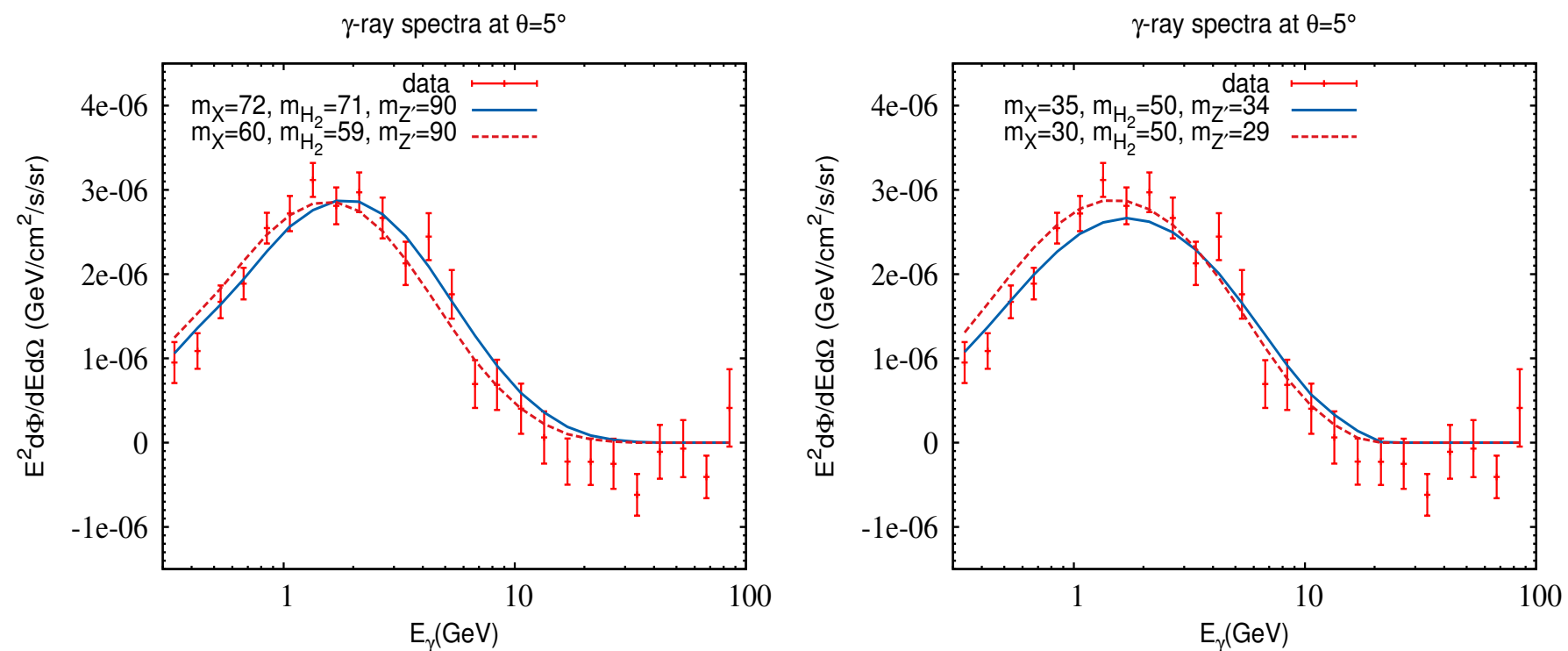


FIG. 4:  $\gamma$ -ray spectra from dark matter (semi-)annihilation with  $H_2$ (left) and  $Z'$ (right) as final states. In each case, mass of  $H_2$  or  $Z'$  is chosen to be close to  $m_X$  to avoid large lorentz boost. Masses are in GeV unit. Data points at  $\theta = 5$  degree are extracted from [1].

Possible only in local Z3  
not in global Z3 or DM EFT

# Hidden Sector Monopole, Stable VDM and Dark Radiation

$$SU(2)_h \rightarrow U(1)_h$$

+

Higgs portal

[S. Baek, P. Ko & WIP, arXiv:1311.1035]

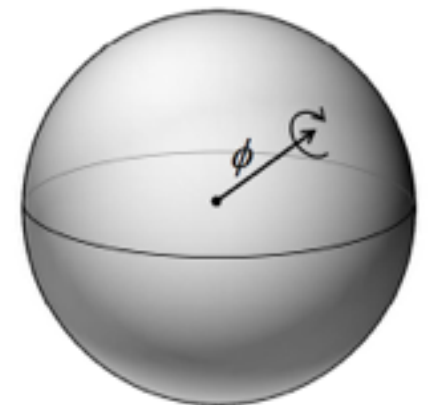
# The Model

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \underbrace{\frac{1}{4} V_{\mu\nu}^a V^{a\mu\nu} + \frac{1}{2} D_\mu \vec{\phi} \cdot D^\mu \vec{\phi} - \frac{\lambda_\phi}{4} (\vec{\phi} \cdot \vec{\phi} - v_\phi^2)^2}_{\text{'t Hooft-Polyakov monopole}} - \underbrace{\frac{\lambda_{\phi H}}{2} \vec{\phi} \cdot \vec{\phi} H^\dagger H}_{\text{Higgs portal}}$$

- Symmetry breaking

$$\phi^T = (0, 0, v_\phi) \Rightarrow SU(2) \rightarrow U(1)$$



- Particle spectra  $\left( V^\pm \equiv \frac{1}{\sqrt{2}} (V_1 \mp iV_2), \gamma' \equiv V_3, H_1, H_2 \right)$

- VDM:  $m_V = g_X v_\phi$
- Monopole:  $m_M = m_V / \alpha_X$

Stable due to topology and U(1)

- Higgses:  $m_{1,2} = \frac{1}{2} \left[ m_{hh}^2 + m_{\phi\phi}^2 \mp \sqrt{(m_{hh}^2 - m_{\phi\phi}^2)^2 + 4m_{\phi h}^4} \right]$

# Main Results

- h-Monopole is stable due to topological conservation
- h-VDM is stable due to the unbroken  $U(1)$  subgroup, even if we consider higher dim nonrenormalizable operators
- Massless h-photon contributes to the dark radiation at the level of 0.08-0.11
- Higgs portal plays an important role

# 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.)

See also the talk by M. Lindner about conformal symmetry

# 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)

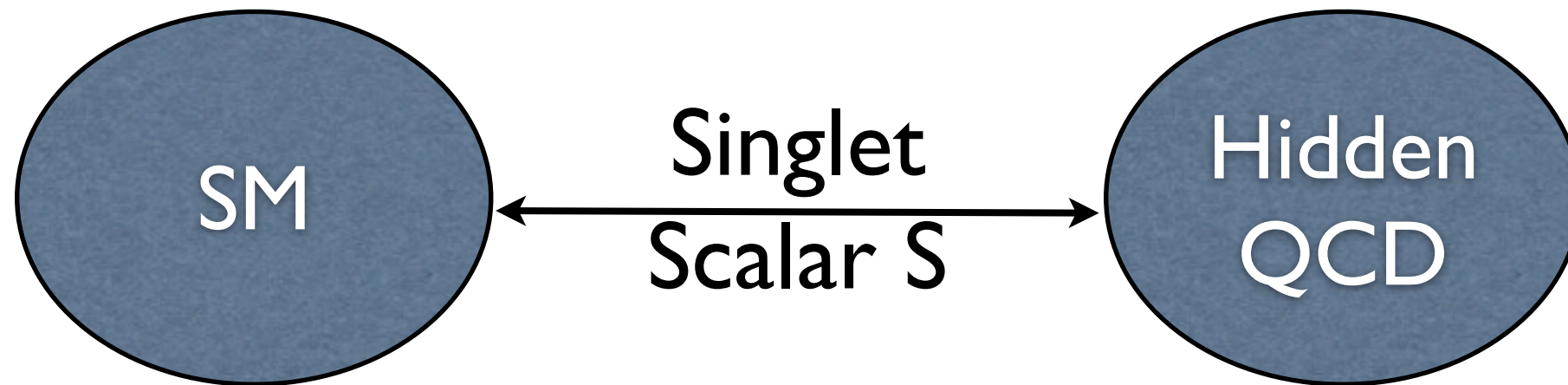


# h-pion & h-baryon DMs

- 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

# 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

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

Hidden sector lagrangian with new strong interaction

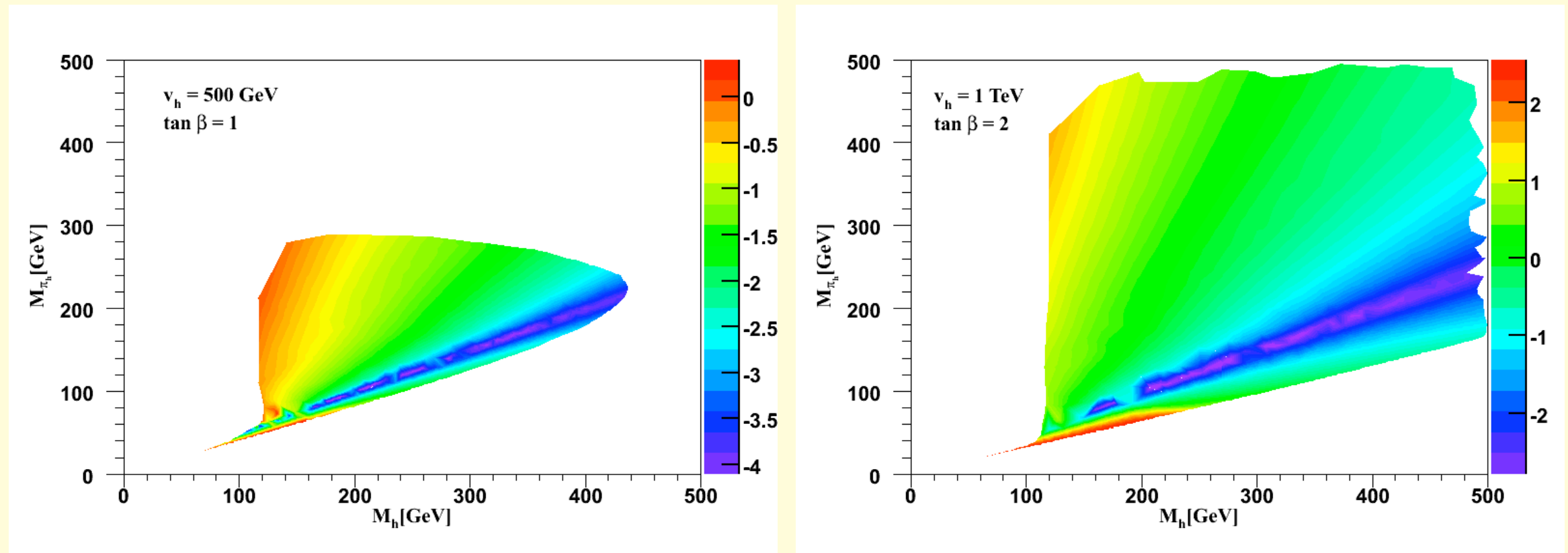
$$\mathcal{L}_{\text{hidden}} = -\frac{1}{4} \mathcal{G}_{\mu\nu} \mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \bar{\mathcal{Q}}_k (i \mathcal{D} \cdot \gamma - \lambda_k S) \mathcal{Q}_k$$

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

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

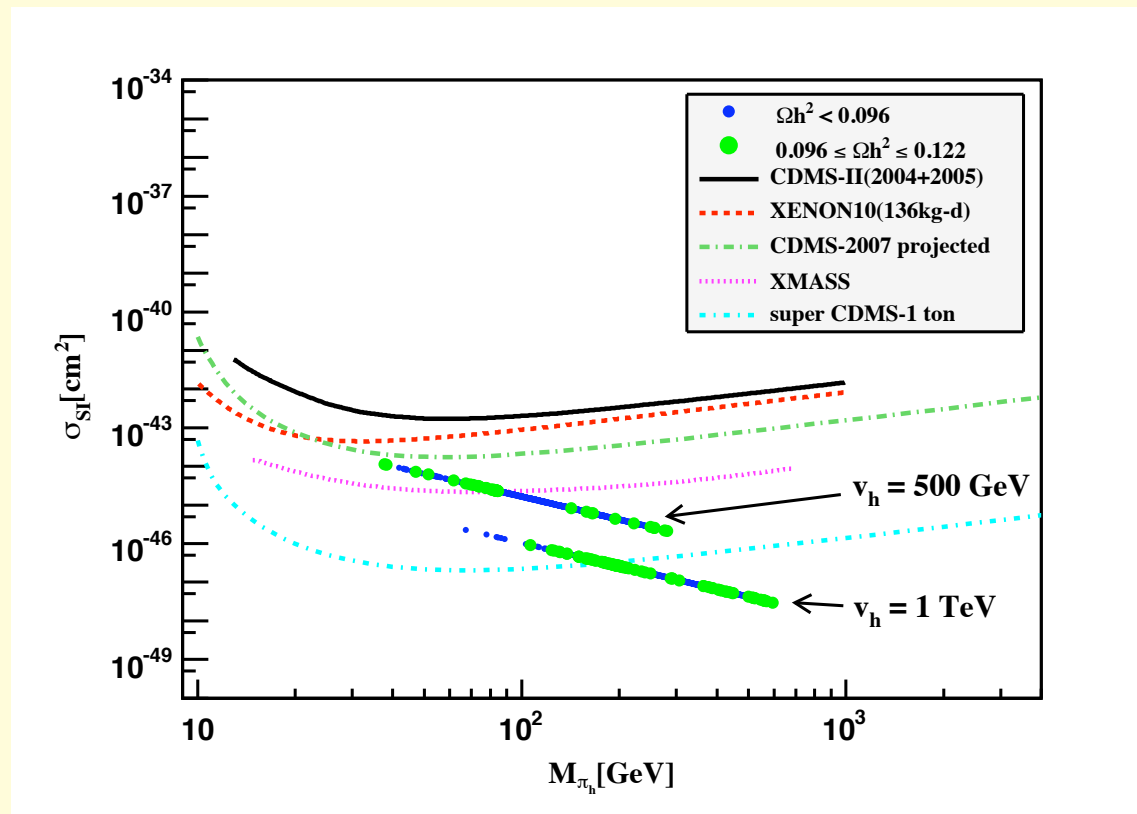
$$\begin{aligned}
 \mathcal{L}_{\text{full}} &= \mathcal{L}_{\text{hidden}}^{\text{eff}} + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mixing}} \\
 \mathcal{L}_{\text{hidden}}^{\text{eff}} &= \frac{v_h^2}{4} \text{Tr}[\partial_\mu \Sigma_h \partial^\mu \Sigma_h^\dagger] + \frac{v_h^2}{2} \text{Tr}[\lambda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

# Relic density



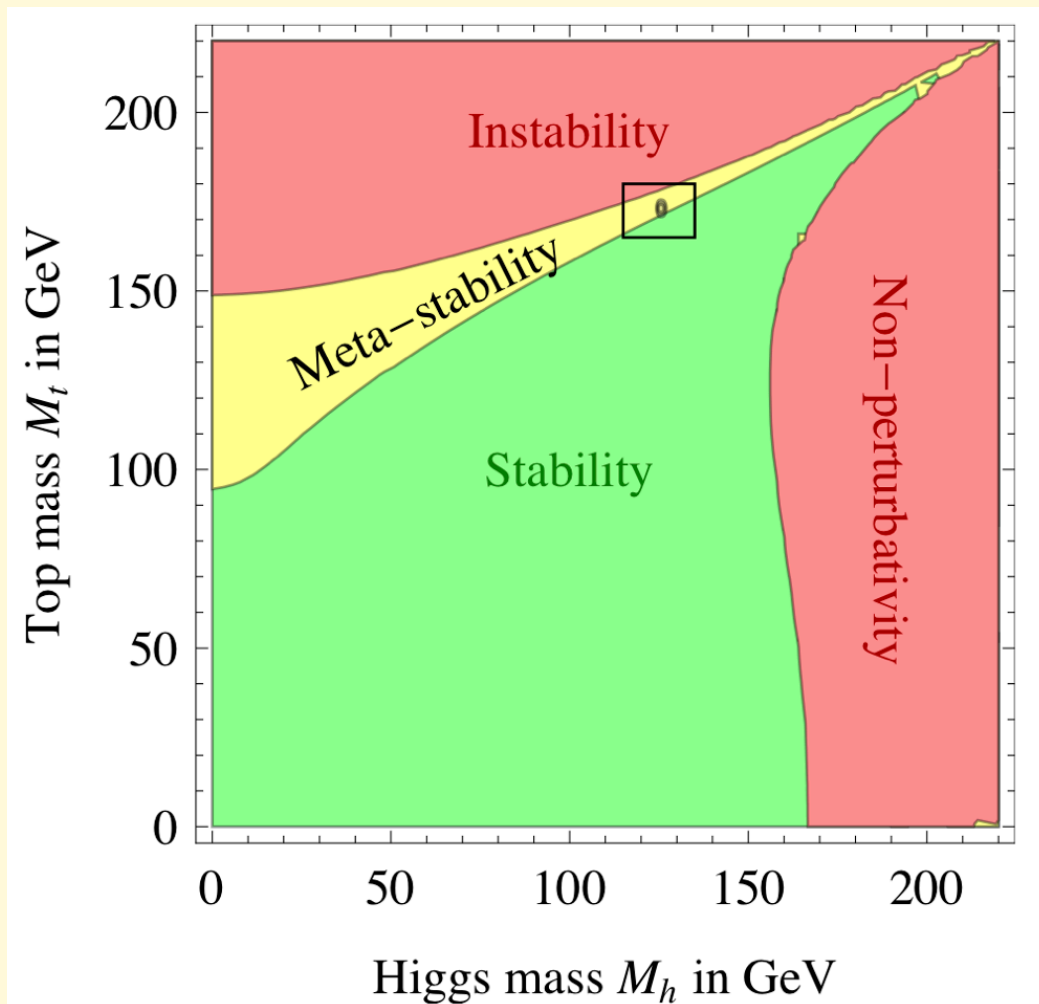
$\Omega_{\pi_h} h^2$  in the  $(m_{h_1}, m_{\pi_h})$  plane for  
(a)  $v_h = 500$  GeV and  $\tan \beta = 1$ ,  
(b)  $v_h = 1$  TeV and  $\tan \beta = 2$ .

# Direct Detection Rate

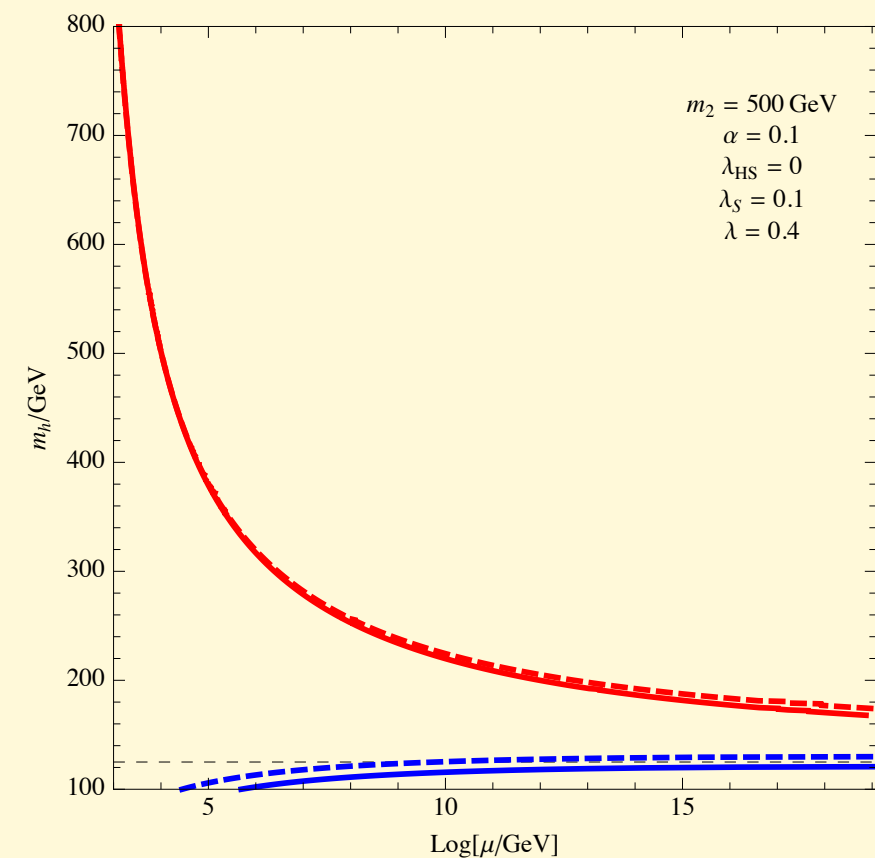


$\sigma_{SI}(\pi_h p \rightarrow \pi_h p)$  as functions of  $m_{\pi_h}$ .  
 the upper one:  $v_h = 500$  GeV and  $\tan \beta = 1$ ,  
 the lower one:  $v_h = 1$  TeV and  $\tan \beta = 2$ .

# Vacuum Stability Improved by the singlet scalar $S$

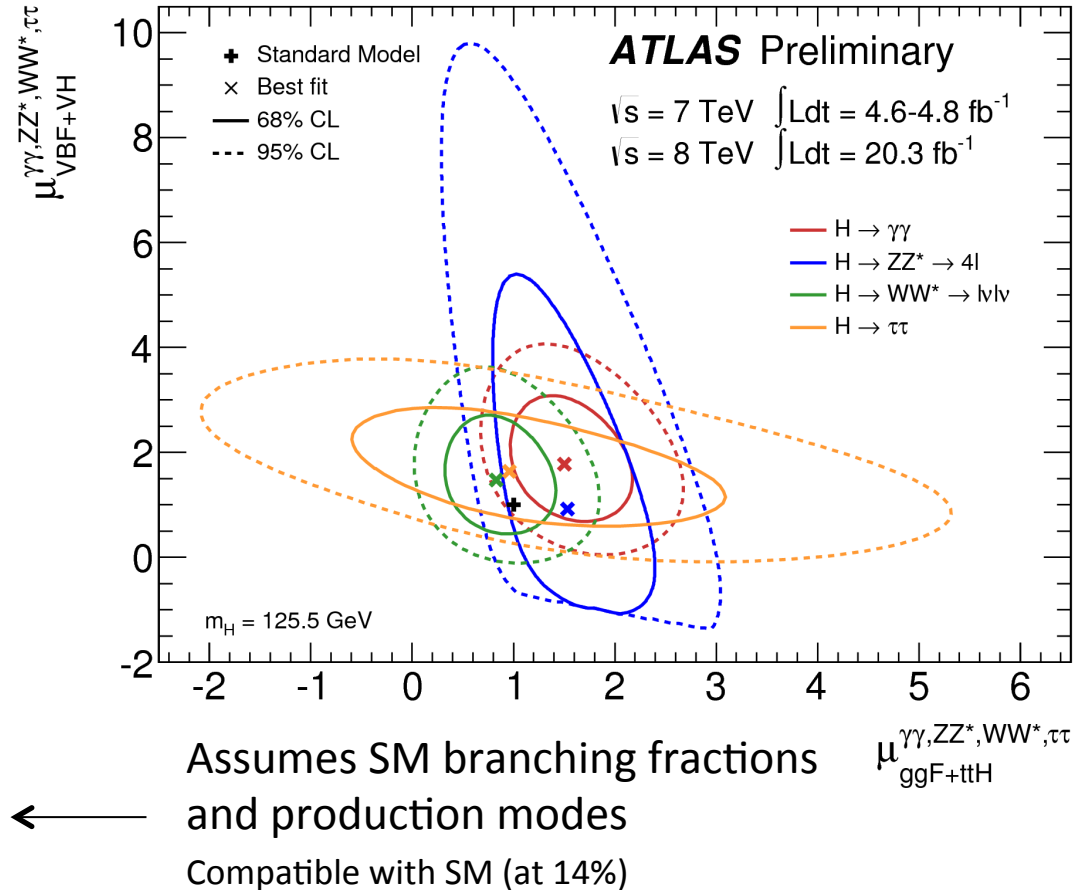
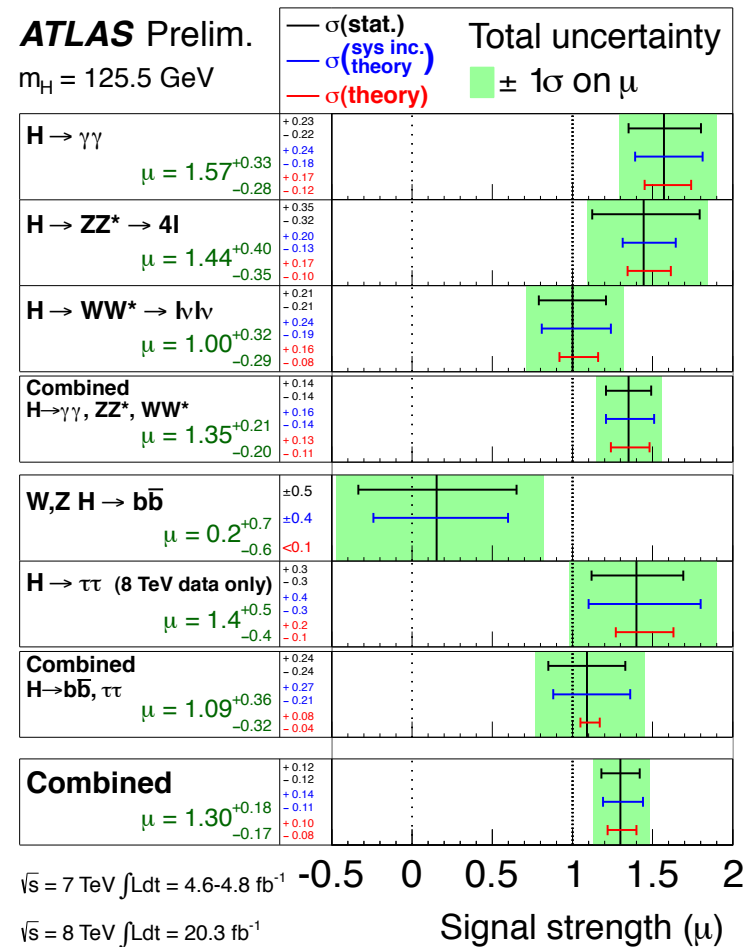


A. Strumia, Moriond EW 2013



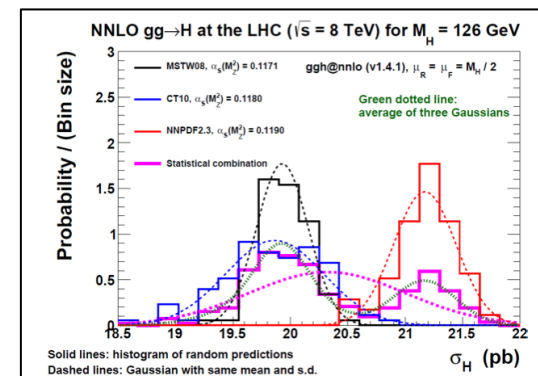
Baek, Ko, Park, Senaha (2012)

# Main Decay and Production Modes



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

All channels couplings updated soon  
Stay tuned !





# Signal strength



53

[CMS-PAS-HIG-14-009]

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

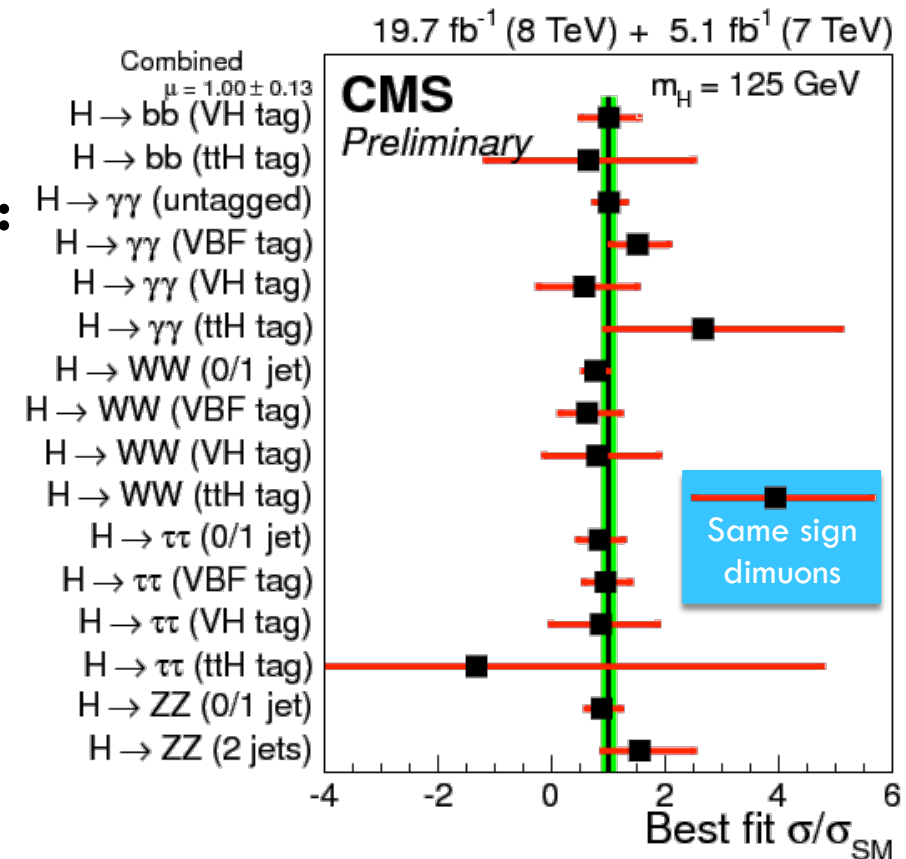
- Grouped by production tag and dominant decay:

- $\chi^2/\text{dof} = 10.5/16$

- p-value = 0.84  
(asymptotic)

- ttH-tagged  $2.0\sigma$  above SM.

- Driven by one channel.



# Low energy pheno.

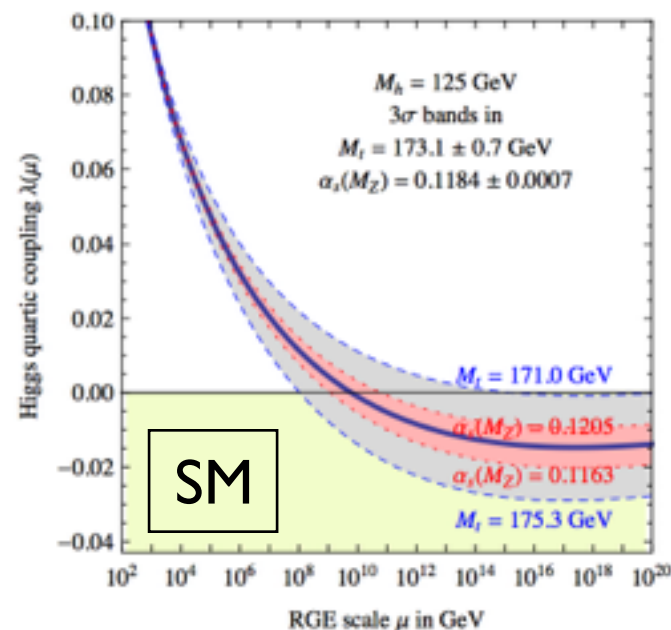
- Universal suppression of collider SM signals  
[See 1112.1847, Seungwon Baek, P. Ko & VIP]

- If “ $m_h > 2 m_\phi$ ”, non-SM Higgs decay!

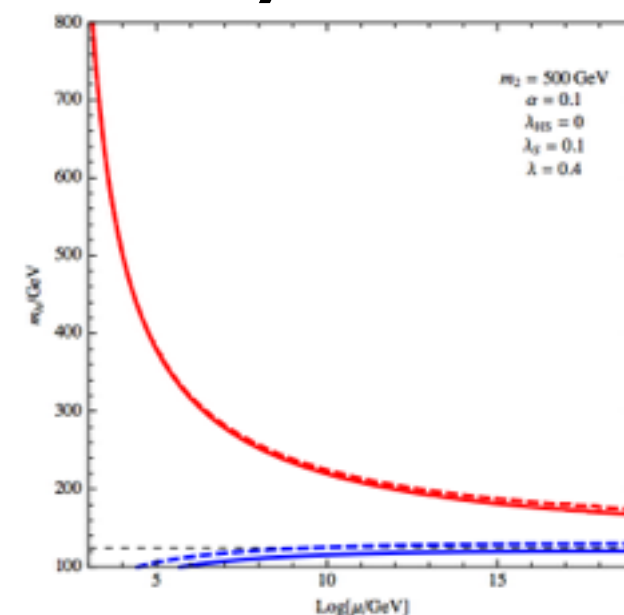
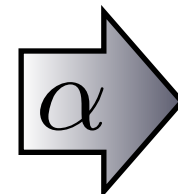
- Tree-level shift of  $\lambda_{H,SM}$  (& loop correction)

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

➔ If “ $m_\phi > m_h$ ”, vacuum instability can be cured.



[G. Degrandi et al., 1205.6497]



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

# Comparison w/ other model

- Dark gauge symmetry is unbroken (DM is long-lived because of accidental flavor symmetry), 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  $\gg$  self-interacting DM  $\gg$  can solve the small scale problem of DM halo
- TeV scale seesaw : TeV scale leptogenesis, or baryogenesis from neutrino oscillations
- Wess-Zumino term: 3  $>$  2 possible (e.g. Hochberg, Kuflik, Murayam, Volansky, Wacker for  $Sp(N)$  case)
- Another approach for hQCD ? (For example, Kubo, Lindner et al use NJL approach; and AdS/QCD approach with H. Hatanaka, D.W. Jung@KIAS)

# Conclusions

- I discussed three different types of stable or long-lived DM models with built-in (light) mediators because of the underlying local dark gauge symmetry (standard QFT)
- Light mediators can solve (some) CDM puzzles
- Dynamics (interaction between DM and SM particles and DM self interactions) is completely fixed by local gauge symmetry

- Natural Ground for Light Mediators
- Invisible Higgs decay into a pair of DM, or
- 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 (also strong 1st order ph tr)>> Should be actively searched for
- Searches @ LHC & other future colliders !

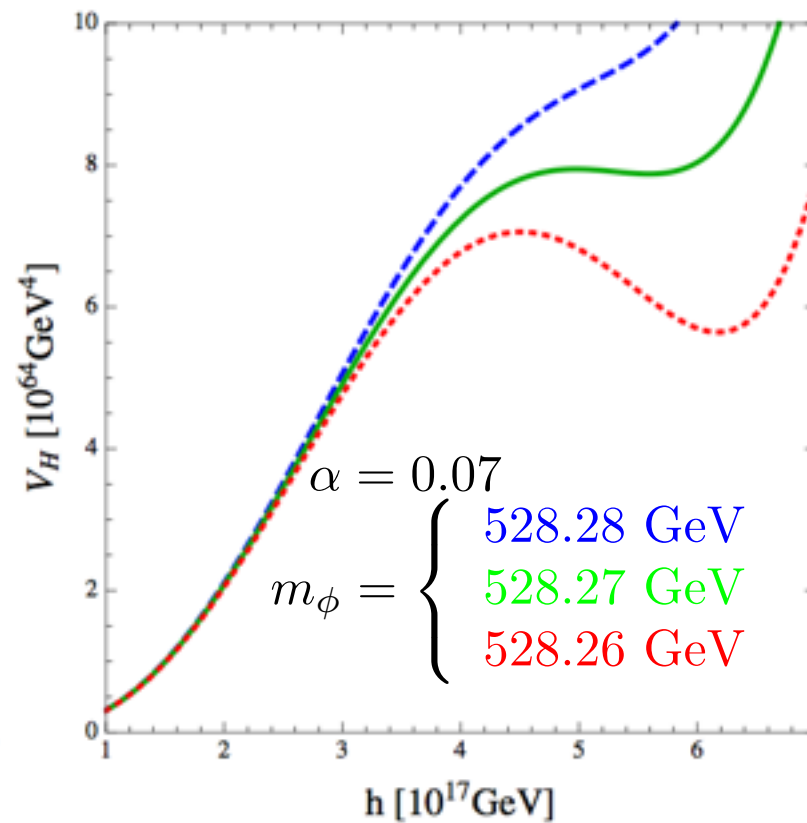
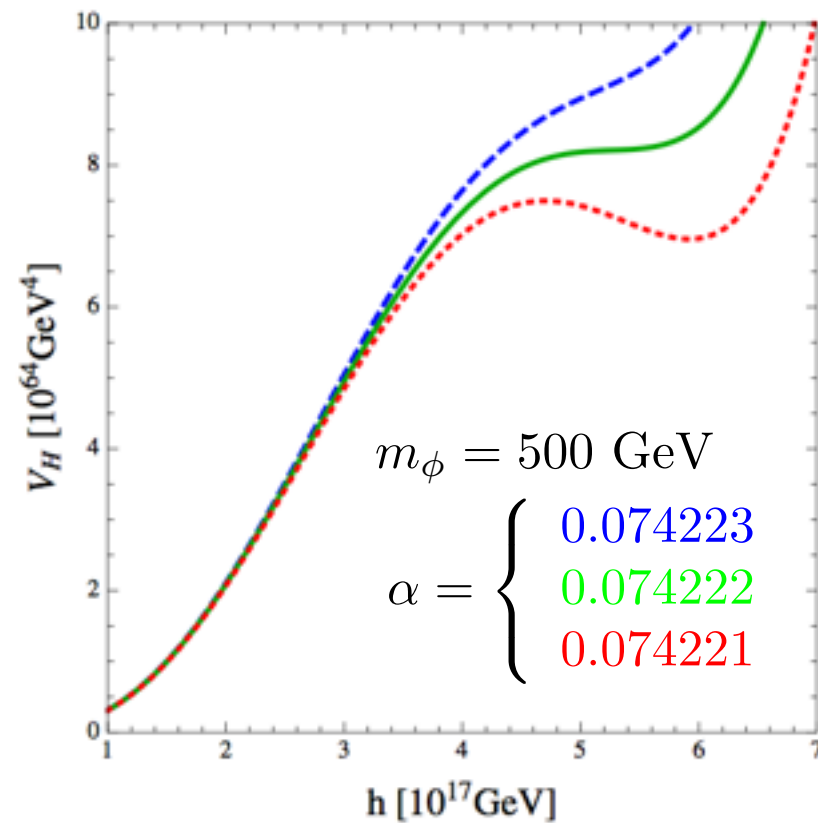
# Impact of Dark Higgs -Cosmo.

(Higgs-portal assisted Higgs inflation)

[arXiv: 1405.1635, P. Ko & WIP]



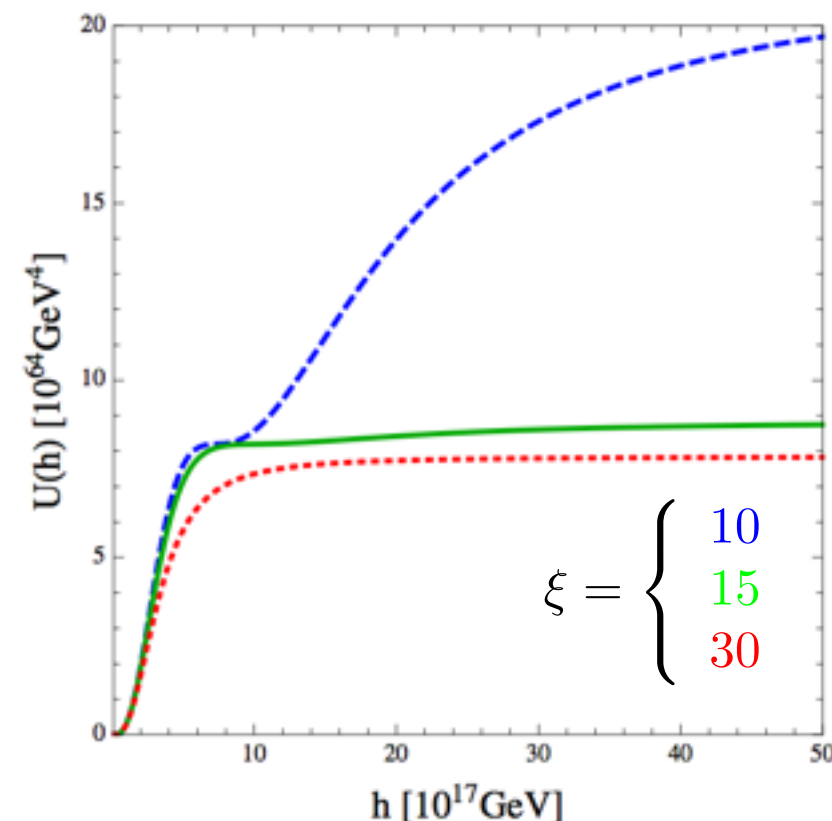
# Higgs-portal Higgs inflation



$$m_t = 173.2 \text{ GeV}$$

$$M_h = 125.5 \text{ GeV}$$

\* Inflection point control  
 $(\alpha, m_\phi)$  &  $\lambda_{\Phi H}$



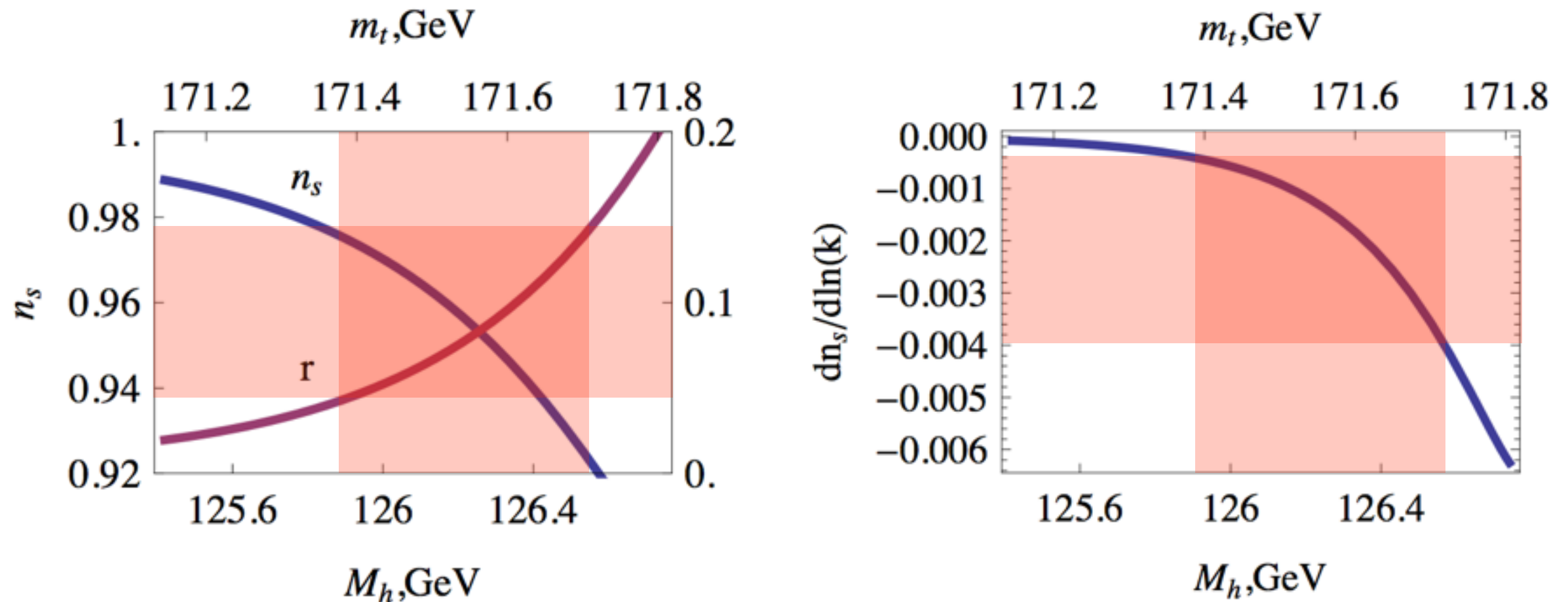
## Result of numerical analysis

$k_* \times \text{Mpc}$	$N_e$	$h_*/M_{\text{Pl}}$	$\epsilon_*$	$\eta_*$	$10^9 P_S$	$n_s$	$r$
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  $\alpha$ ,  $m_\phi$  and  $\lambda_{\Phi H}$  -

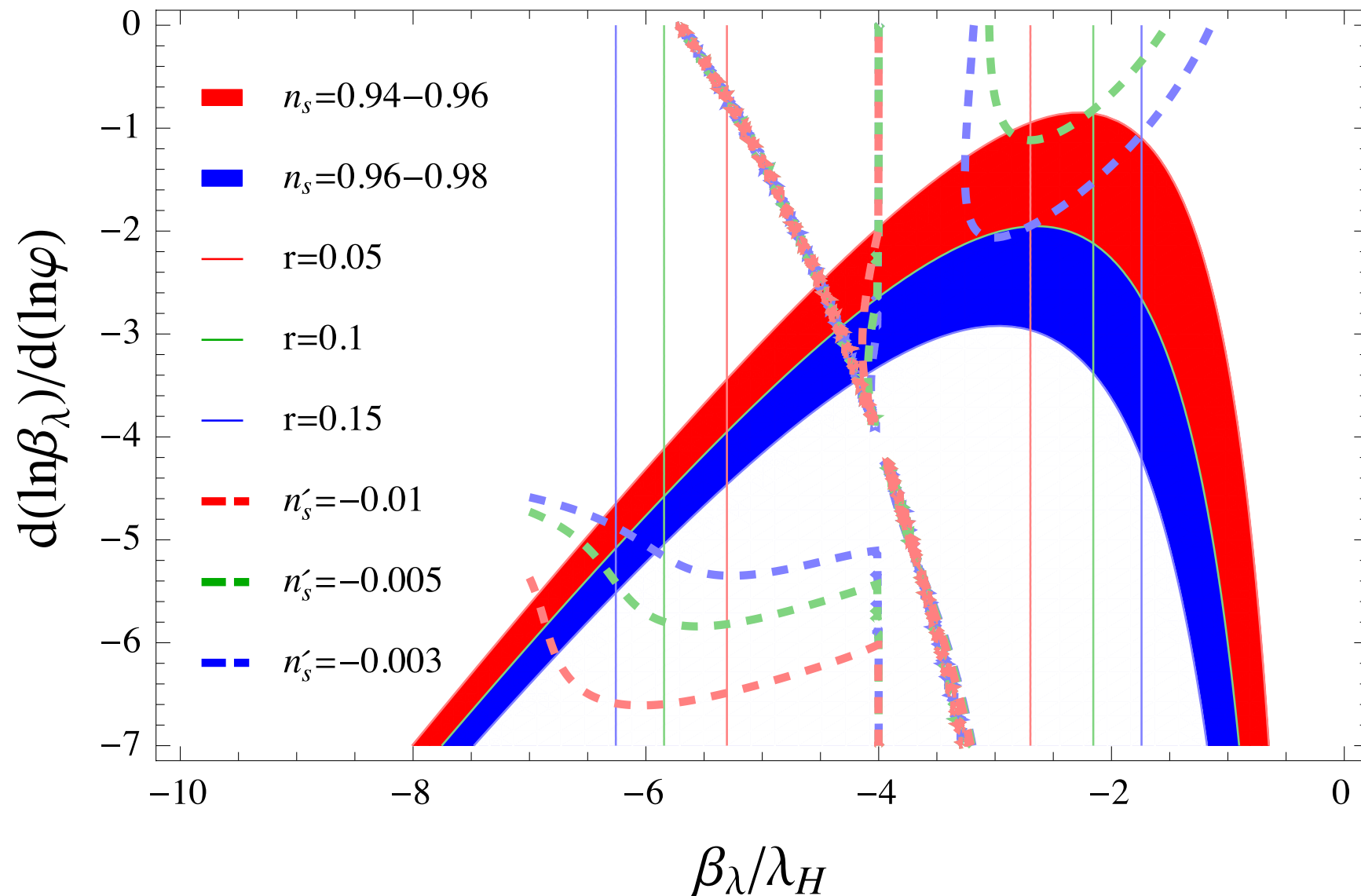
Scale dependence!

- Prediction of SM Higgs inflation



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

# Higgs portal assisted HI



possible to have  $r \sim \mathcal{O}(0.1)$  with small spectral running independent of top mass

# DM EFT vs. Full Theory:

Higgs portal DM as examples

# Principles for DM Physics

- Local Gauge Symmetry for DM
  - can make DM absolutely stable
  - 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, ...)

# Higgs portal DM as examples

All invariant  
under ad hoc  
Z2 symmetry

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

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

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

arXiv:1112.3299, 1205.3169, 1402.6287, to name a few

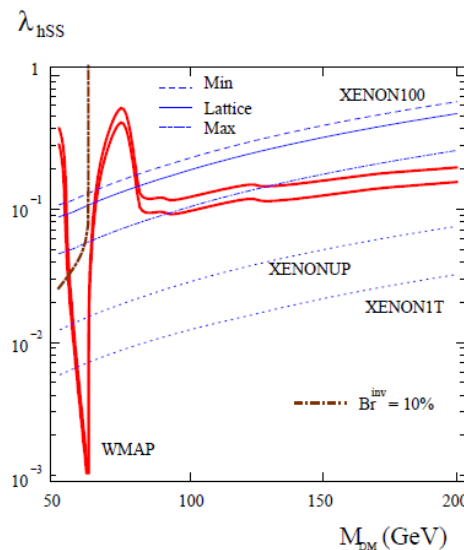


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and  $\text{BR}^{\text{inv}} = 10\%$  for  $m_h = 125$  GeV. Shown also are the prospects for XENON upgrades.

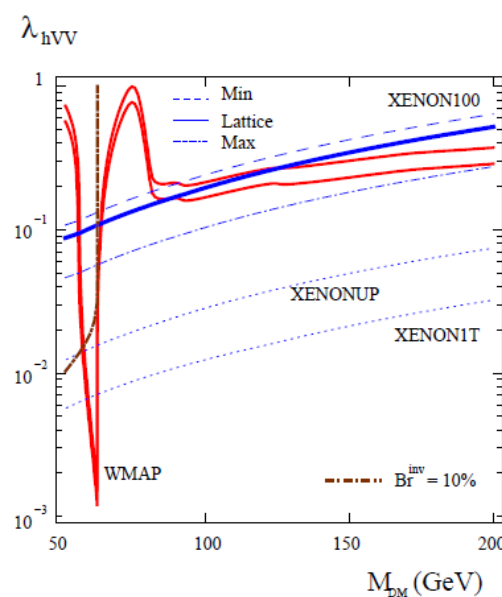


FIG. 2. Same as Fig. 1 for vector DM particles.

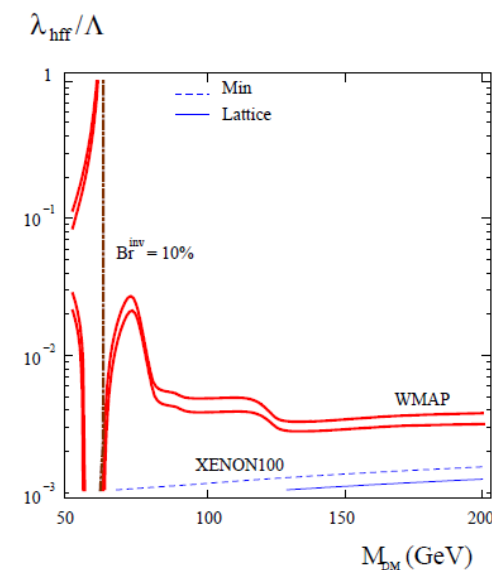


FIG. 3. Same as in Fig.1 for fermion DM;  $\lambda_{hff}/\Lambda$  is in  $\text{GeV}^{-1}$ .

# Higgs portal DM as examples

All invariant  
under ad hoc  
Z2 symmetry

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

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

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

- 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

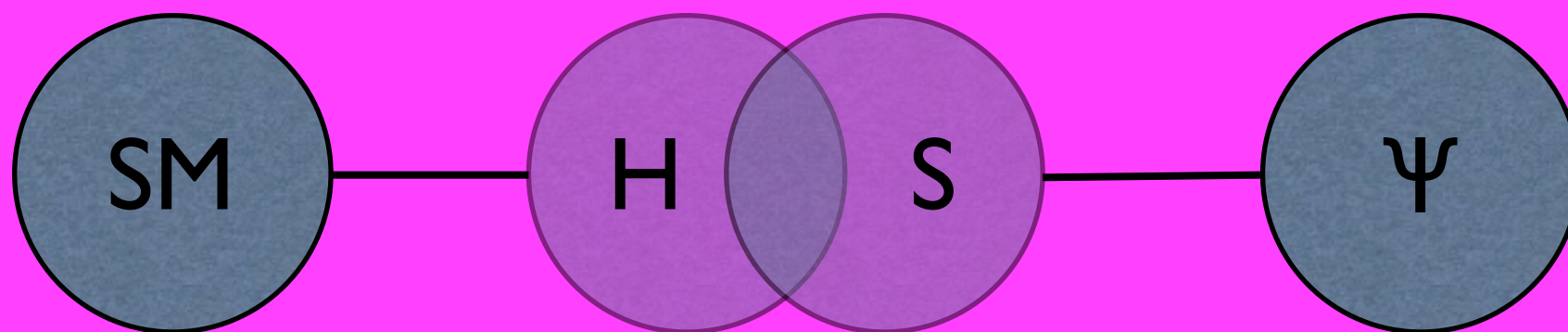


# Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

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

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

at vacuum

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

$$\begin{aligned}H_1 &= h \cos \alpha - s \sin \alpha, \\ H_2 &= h \sin \alpha + s \cos \alpha.\end{aligned}$$



Mixing of Higgs and singlet

# Ratiocination

- Signal strength (reduction factor)

$$r_i = \frac{\sigma_i \text{Br}(H_i \rightarrow \text{SM})}{\sigma_h \text{Br}(h \rightarrow \text{SM})}$$

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

$$r_2 = \frac{\sin^4 \alpha \Gamma_{H_2}^{\text{SM}}}{\sin^2 \alpha \Gamma_{H_2}^{\text{SM}} + \cos^2 \alpha \Gamma_{H_2}^{\text{hid}} + \Gamma_{H_2 \rightarrow H_1 H_1}}$$

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

Invisible decay mode is not necessary!

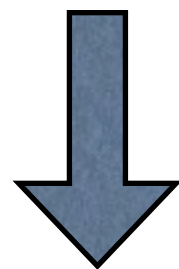
If  $r_i > 1$  for any single channel,  
this model will be excluded !!

# Constraints

## EW precision observables

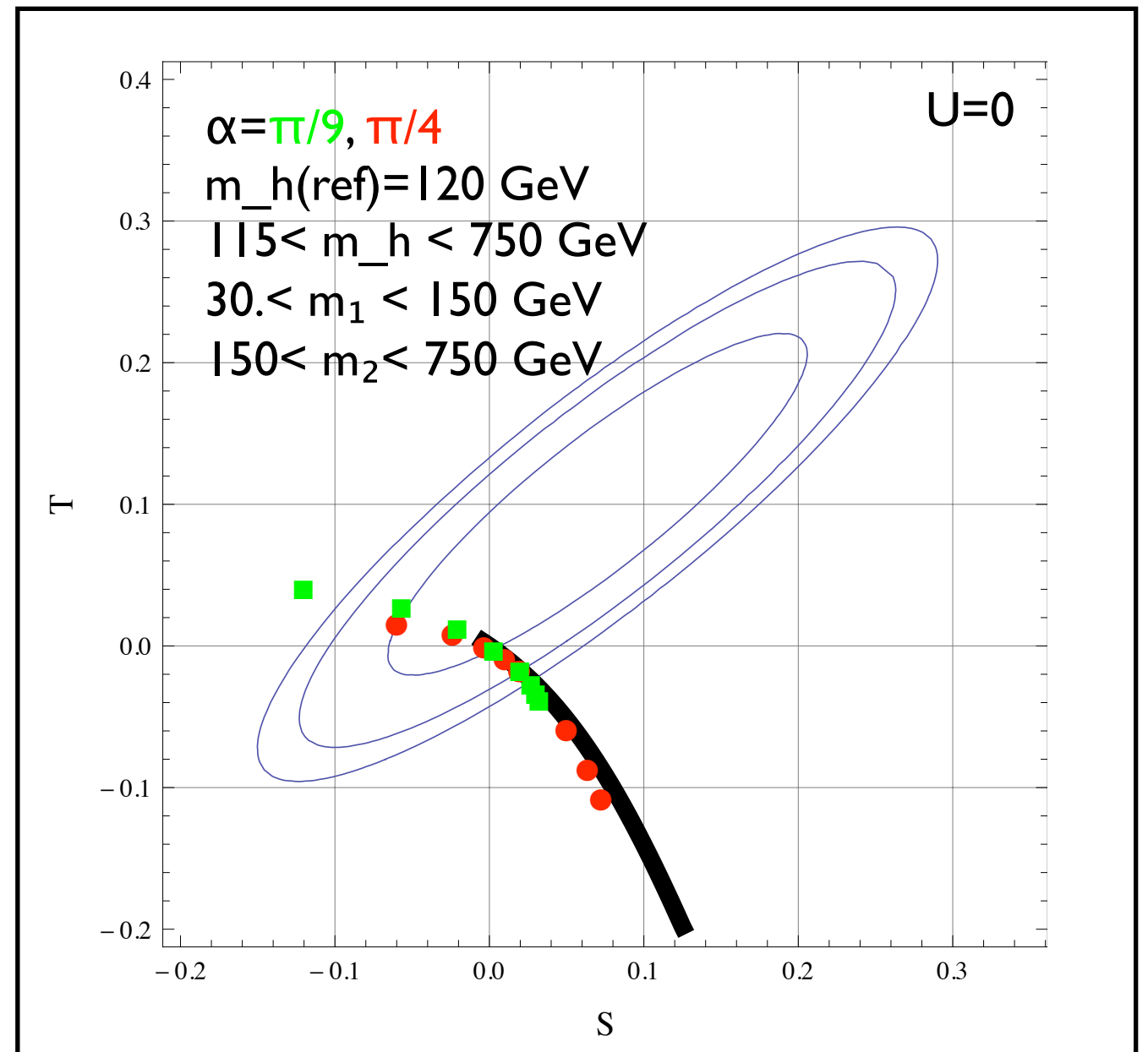
Peskin & Takeuchi, Phys.Rev.Lett.65,964(1990)

$$\begin{aligned}\alpha_{\text{em}} S &= 4s_W^2 c_W^2 \left[ \frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2} \right] \\ \alpha_{\text{em}} T &= \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} \\ \alpha_{\text{em}} U &= 4s_W^2 \left[ \frac{\Pi_{WW}(M_W^2) - \Pi_{WW}(0)}{M_W^2} \right]\end{aligned}$$



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

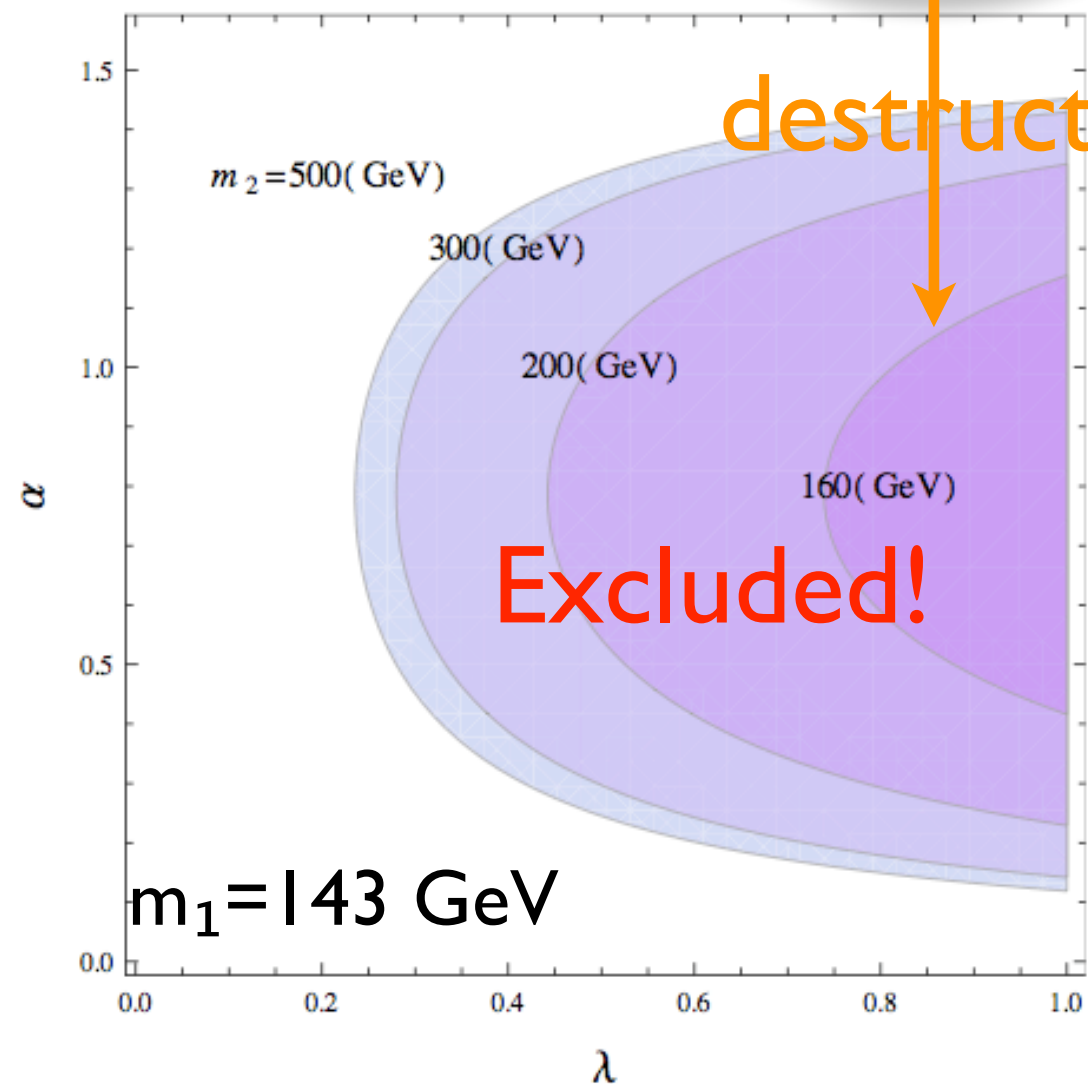
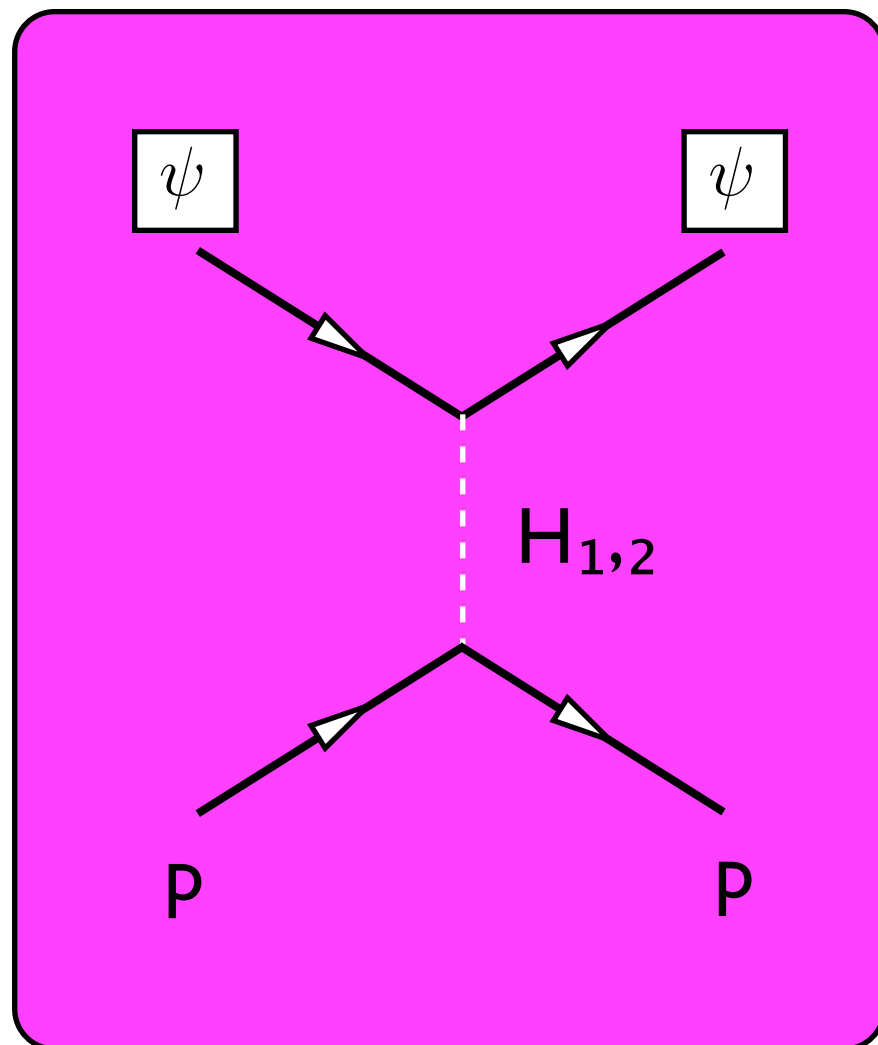
Same for T and U



# Constraints

- Dark matter to nucleon cross section (constraint)

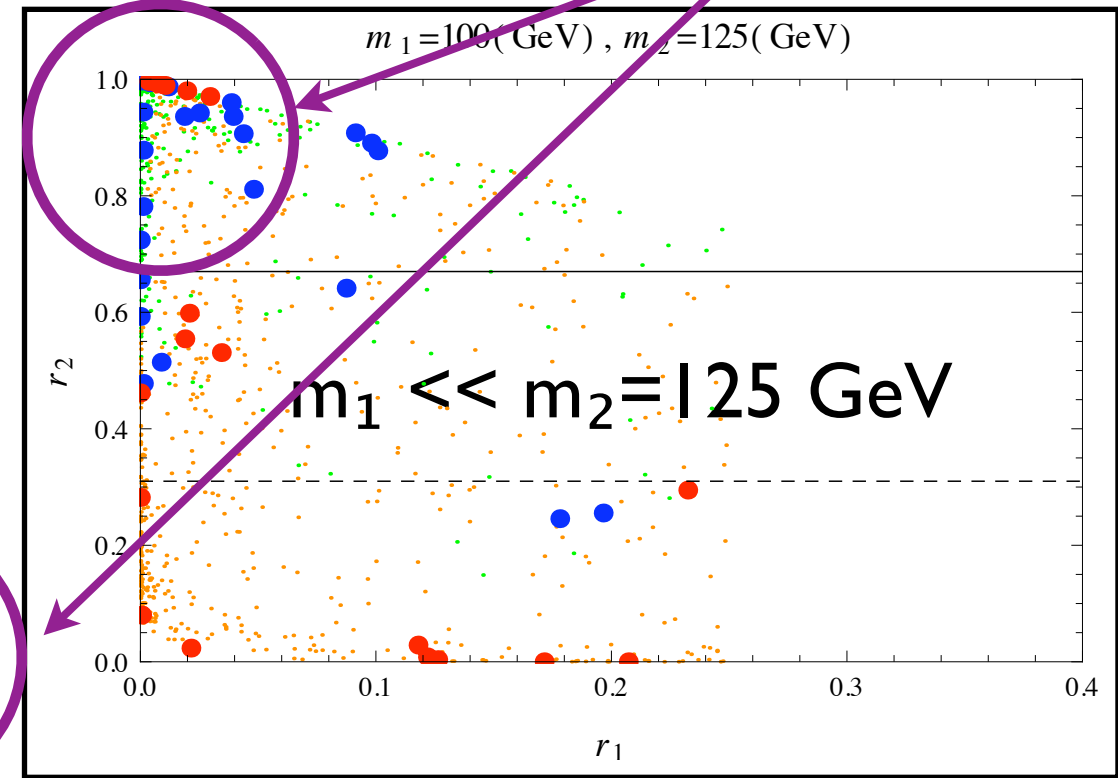
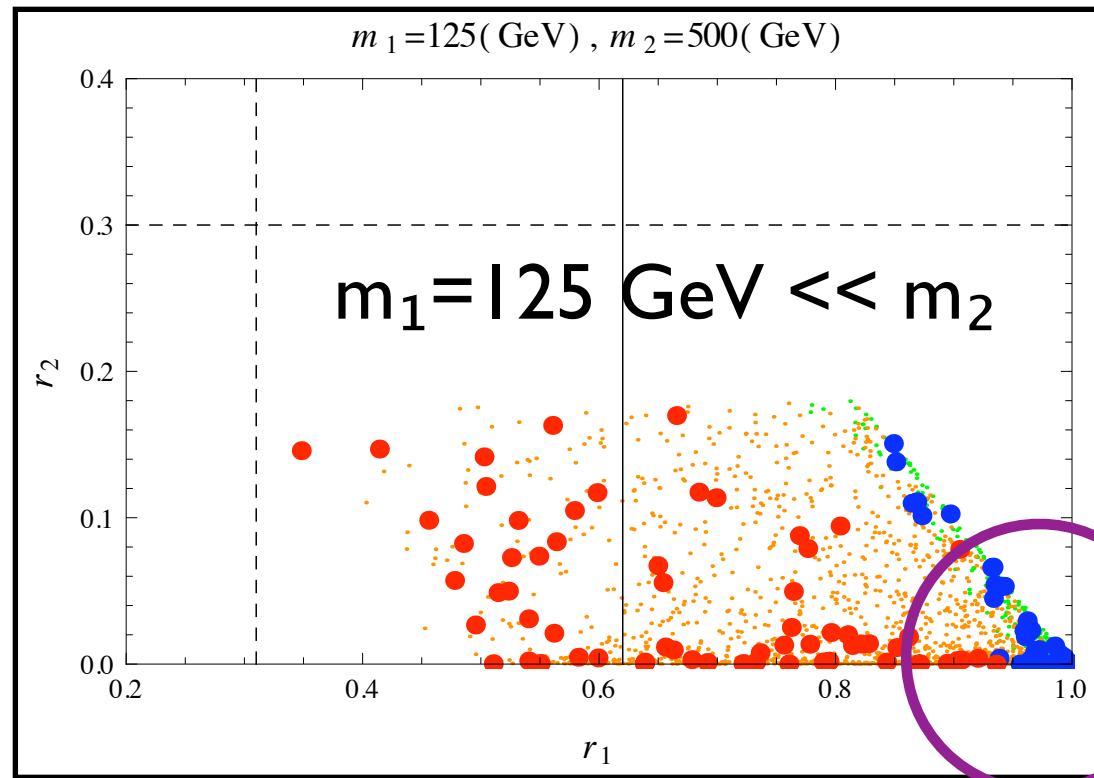
$$\sigma_p \approx \frac{1}{\pi} \mu^2 \lambda_p^2 \simeq 2.7 \times 10^{-2} \frac{m_p^2}{\pi} \left| \left( \frac{m_p}{v} \right) \lambda \sin \alpha \cos \alpha \left( \frac{1}{m_1^2} - \frac{1}{m_2^2} \right) \right|^2$$



# Discovery possibility

- Signal strength ( $r_2$  vs  $r_1$ )

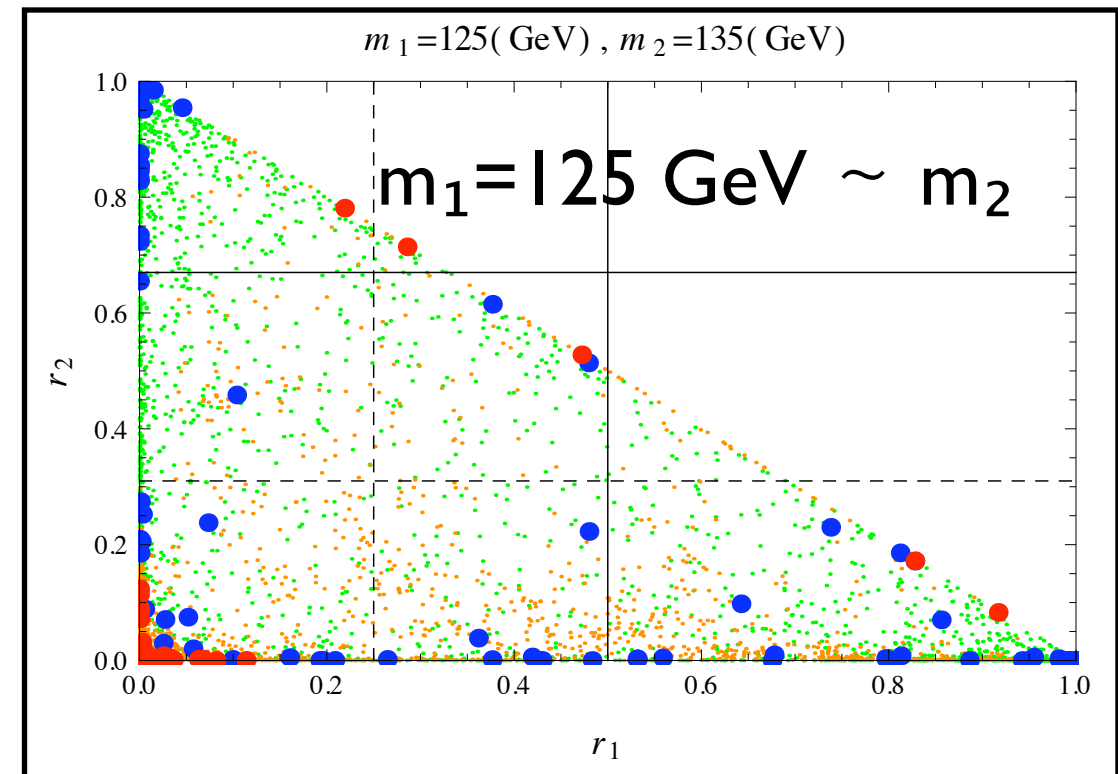
LHC data for 125 GeV resonance



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

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

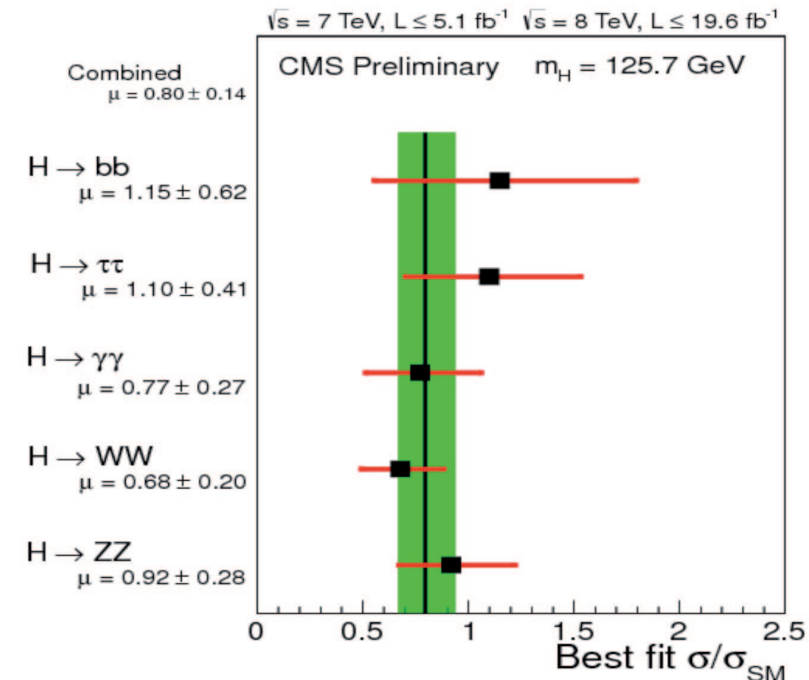
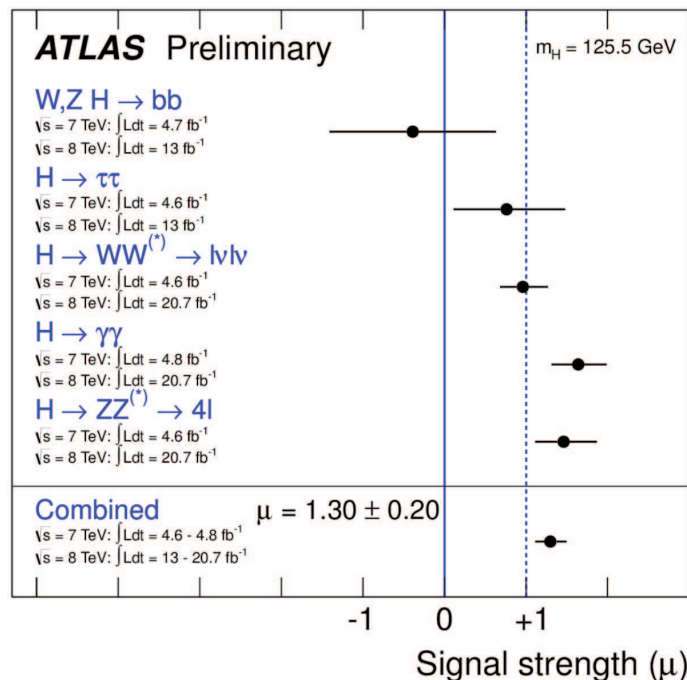
- :  $\Omega(x), \sigma_p(x)$
- :  $\Omega(x), \sigma_p(o)$
- :  $\Omega(o), \sigma_p(x)$
- :  $\Omega(o), \sigma_p(o)$



# Updates@LHCP

## Signal Strengths

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

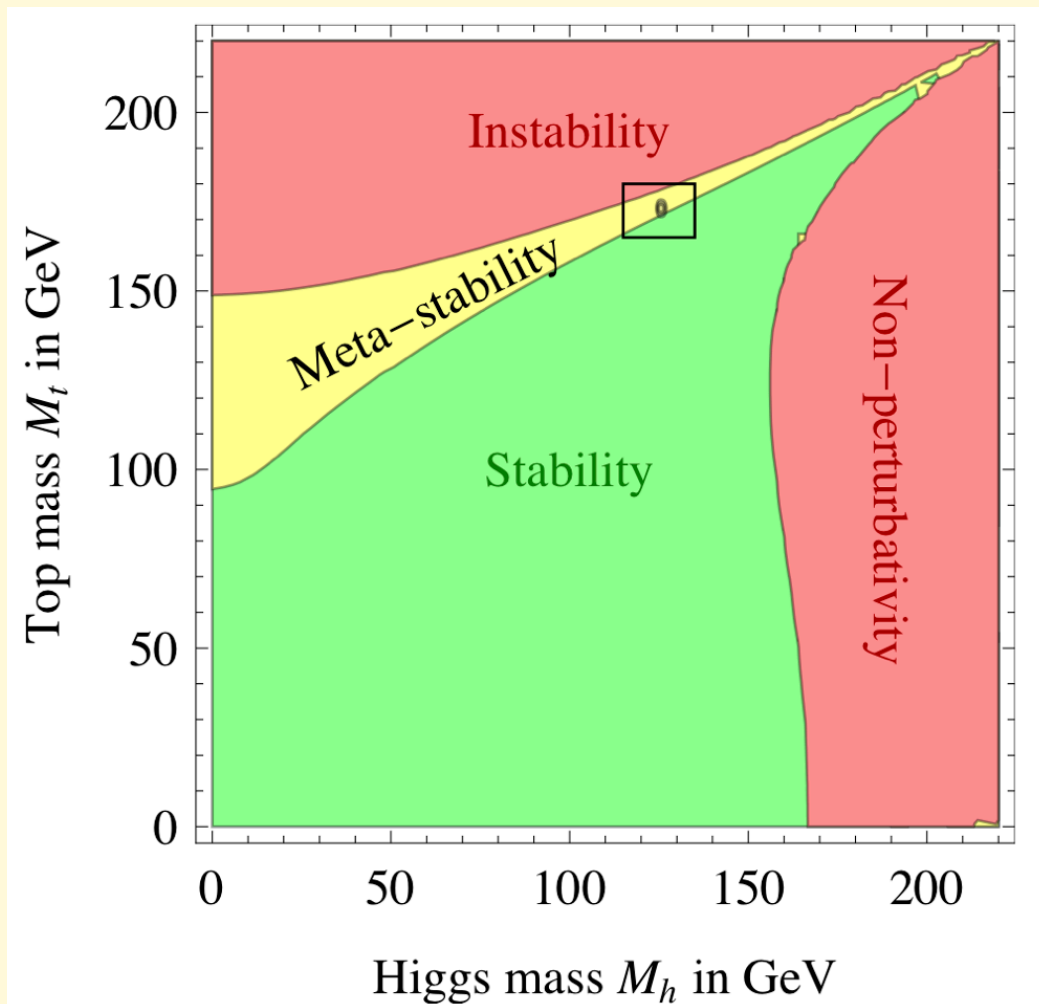


Decay Mode	ATLAS ( $M_H = 125.5 \text{ GeV}$ )	CMS ( $M_H = 125.7 \text{ GeV}$ )
$H \rightarrow b\bar{b}$	$-0.4 \pm 1.0$	$1.15 \pm 0.62$
$H \rightarrow \tau\tau$	$0.8 \pm 0.7$	$1.10 \pm 0.41$
$H \rightarrow \gamma\gamma$	$1.6 \pm 0.3$	$0.77 \pm 0.27$
$H \rightarrow WW^*$	$1.0 \pm 0.3$	$0.68 \pm 0.20$
$H \rightarrow ZZ^*$	$1.5 \pm 0.4$	$0.92 \pm 0.28$
<b>Combined</b>	<b><math>1.30 \pm 0.20</math></b>	<b><math>0.80 \pm 0.14</math></b>

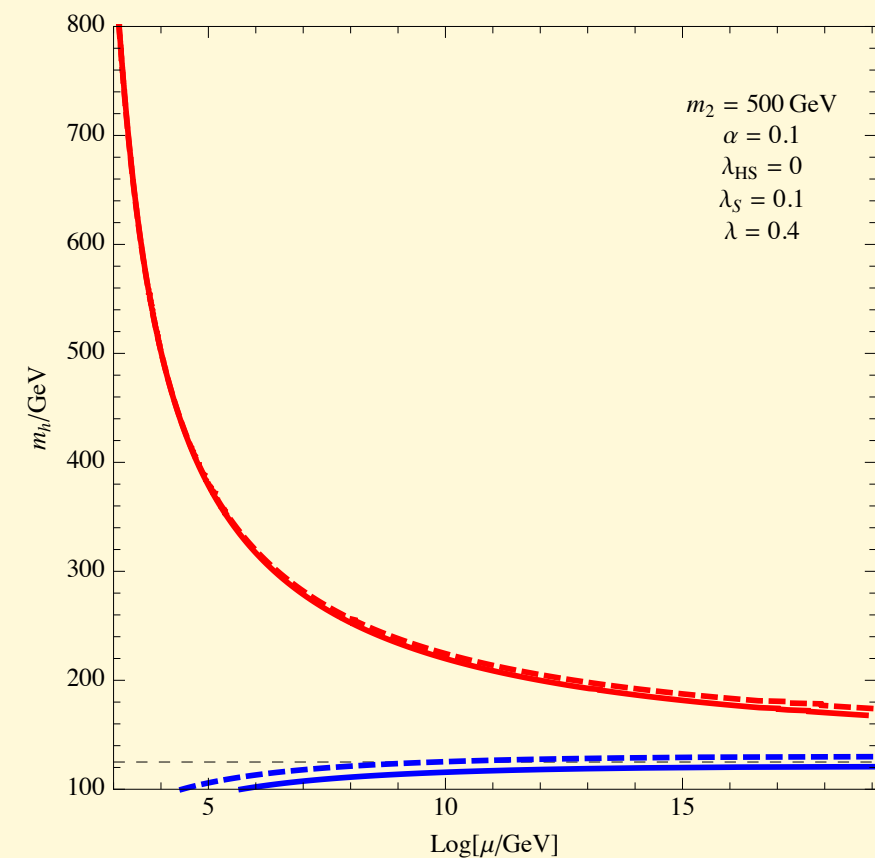
$$\langle \mu \rangle = 0.96 \pm 0.12$$

Getting smaller

# Vacuum Stability Improved by the singlet scalar $S$



A. Strumia, Moriond EW 2013



Baek, Ko, Park, Senaha (2012)



# Low energy pheno.

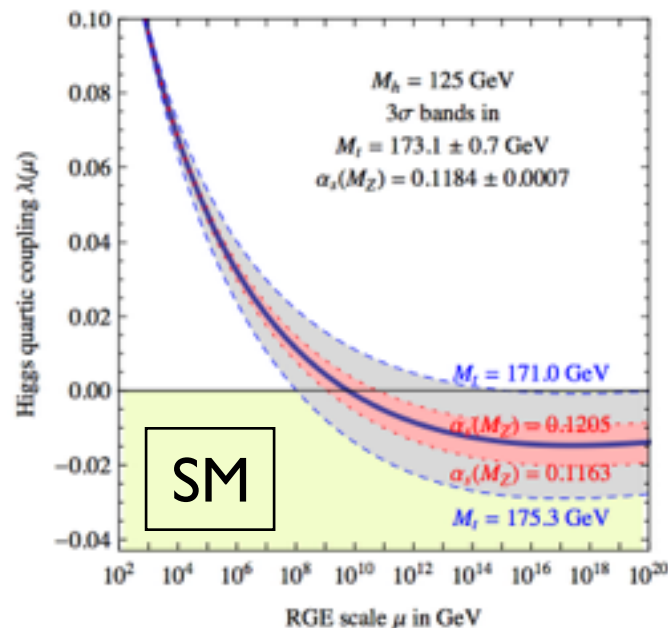
- Universal suppression of collider SM signals  
[See 1112.1847, Seungwon Baek, P. Ko & VIP]

- If “ $m_h > 2 m_\phi$ ”, non-SM Higgs decay!

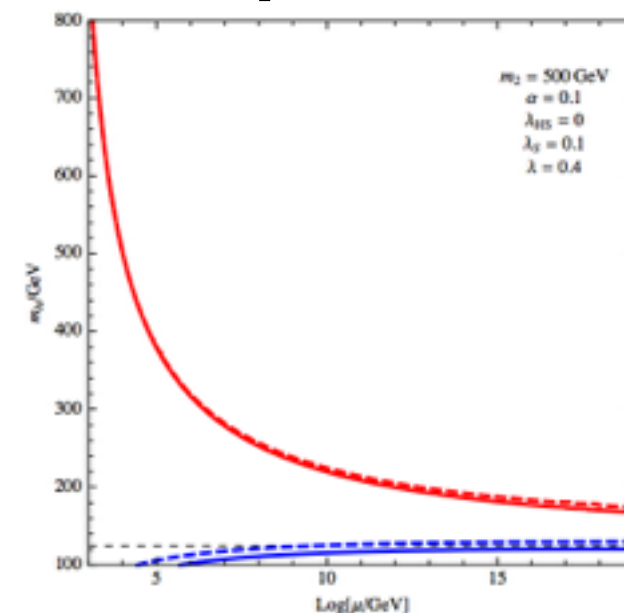
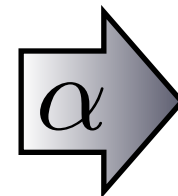
- Tree-level shift of  $\lambda_{H,SM}$  (& loop correction)

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

➡ If “ $m_\phi > m_h$ ”, vacuum instability can be cured.



[G. Degrandi et al., 1205.6497]



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

# Similar for Higgs portal Vector DM

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

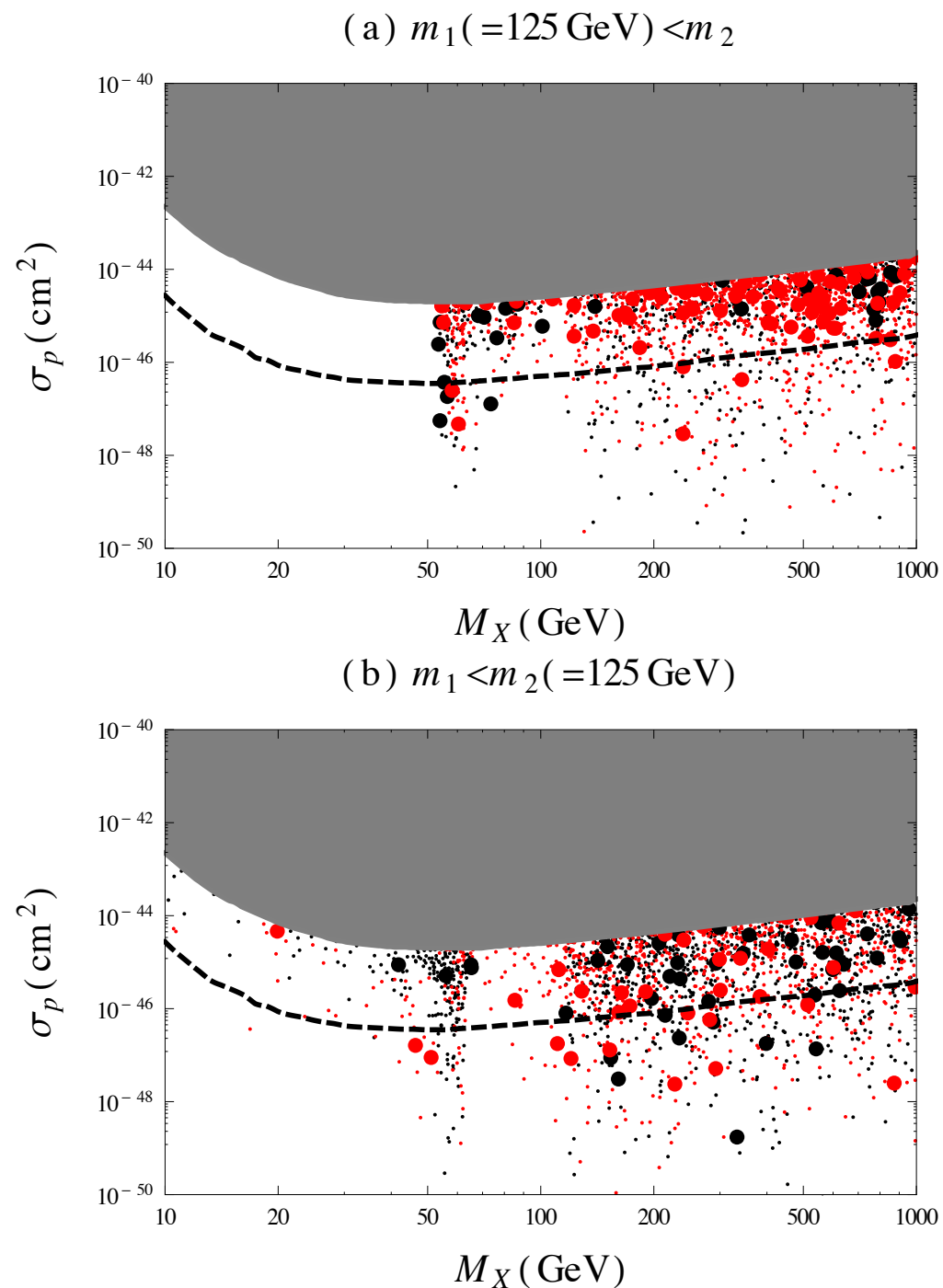
- Although this model looks renormalizable, it is not really renormalizable, since there is no agency for vector boson mass generation
- Need to a new Higgs that gives mass to VDM
- Stueckelberg mechanism ?? (work in progress)
- A complete model should be something like this:

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

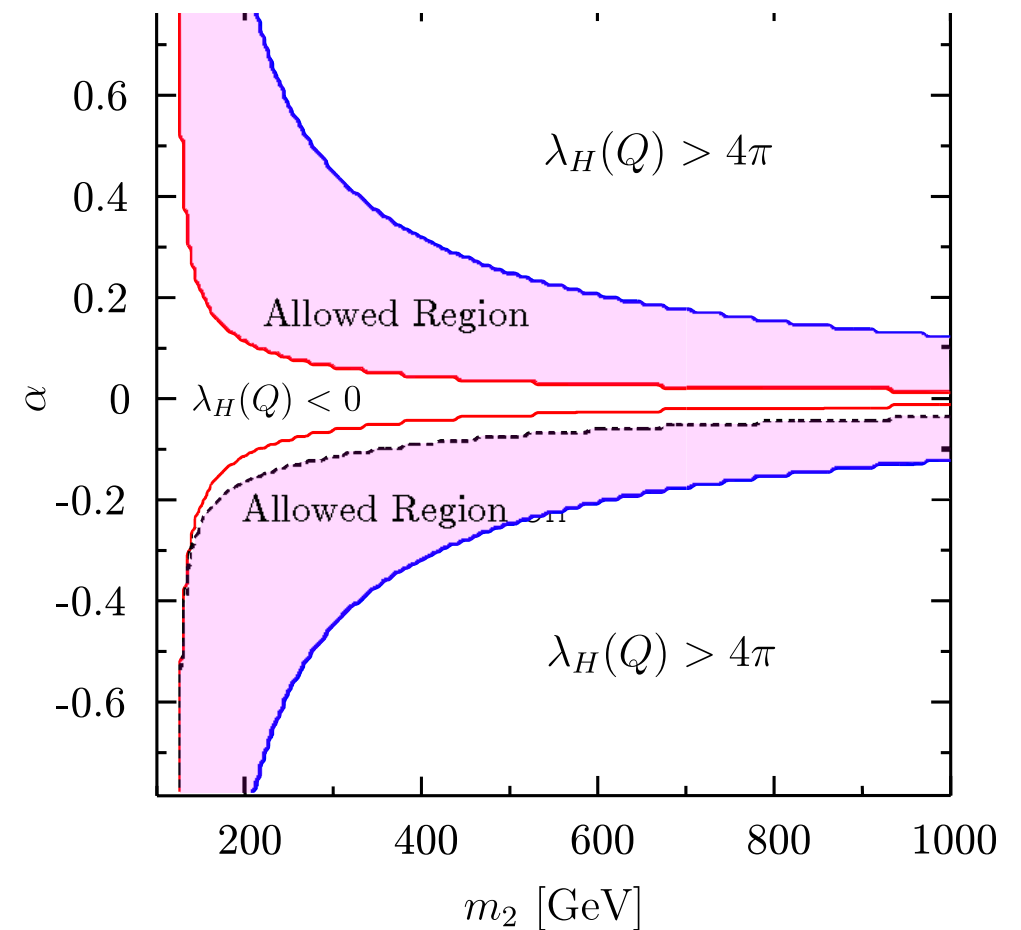
$$\langle 0|\phi_X|0\rangle = v_X + h_X(x)$$

- 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  $\sigma_p$  as a function of  $M_X$ . The big (small) points (do not) satisfy the WMAP relic density constraint within  $3\sigma$ , 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  $\alpha$ - $m_2$  plane. We take  $m_1 = 125 \text{ GeV}$ ,  $g_X = 0.05$ ,  $M_X = m_2/2$  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 information in DM pheno.

arXiv:1112.3299, 1205.3169, 1402.6287, to name a few

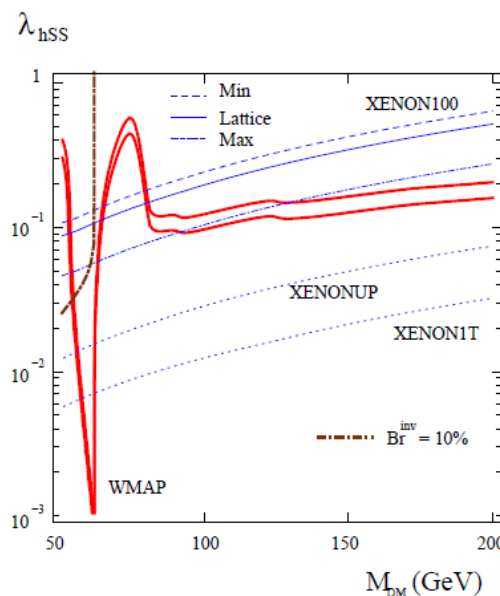


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and  $\text{Br}^{\text{inv}} = 10\%$  for  $m_h = 125$  GeV. Shown also are the prospects for XENON upgrades.

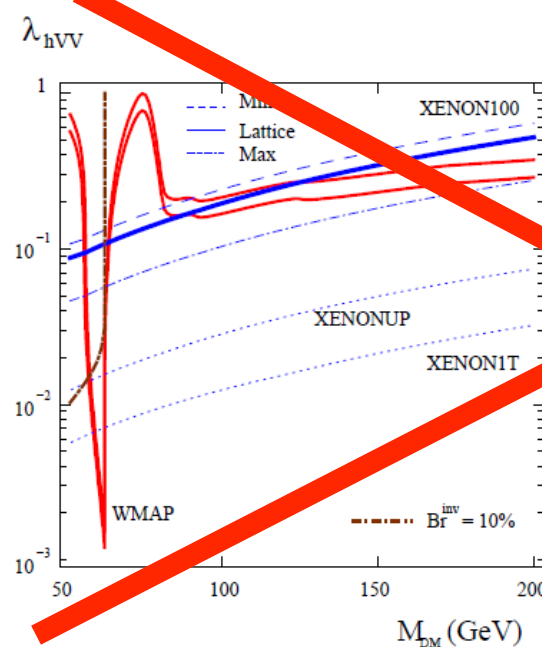


FIG. 2. Same as Fig. 1 for vector DM particles.

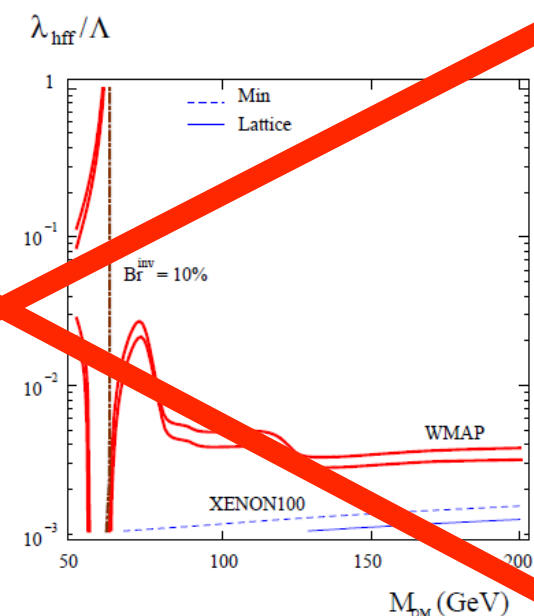


FIG. 3. Same as in Fig.1 for fermion DM;  $\lambda_{hff}/\Lambda$  is in  $\text{GeV}^{-1}$ .

With renormalizable lagrangian,  
we get different results !

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

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

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

Is this any useful in  
phenomenology ?

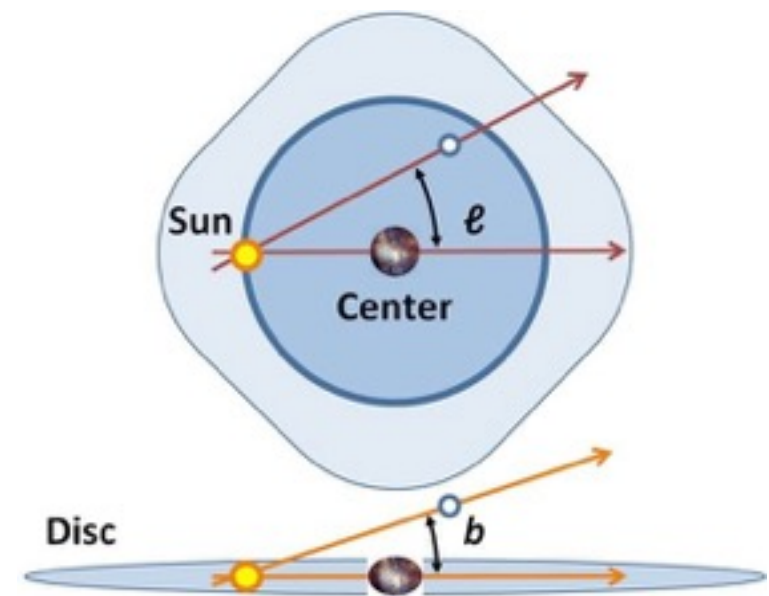
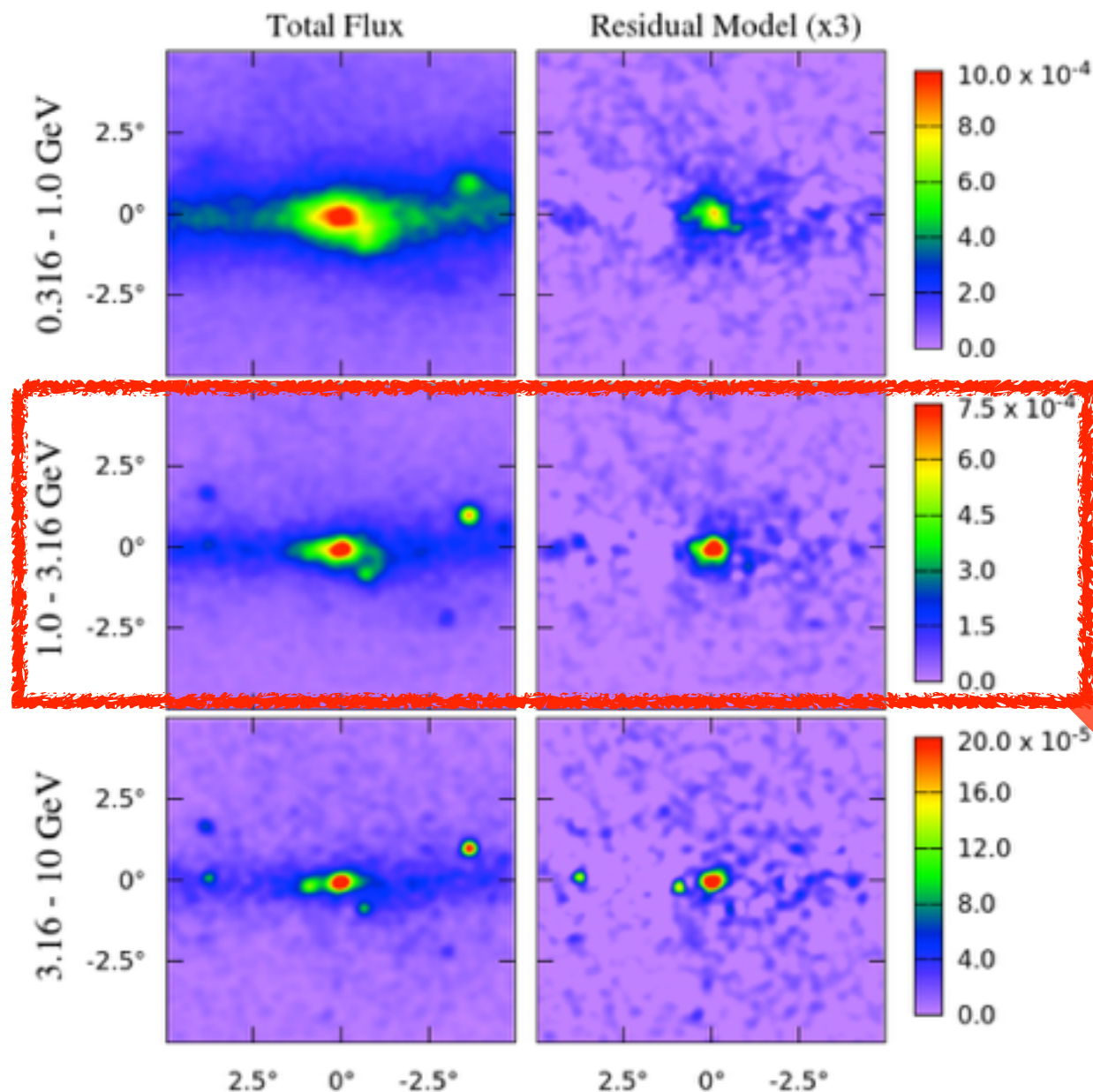
Is this any useful in  
phenomenology ?

YES !



# Fermi-LAT $\gamma$ -ray excess

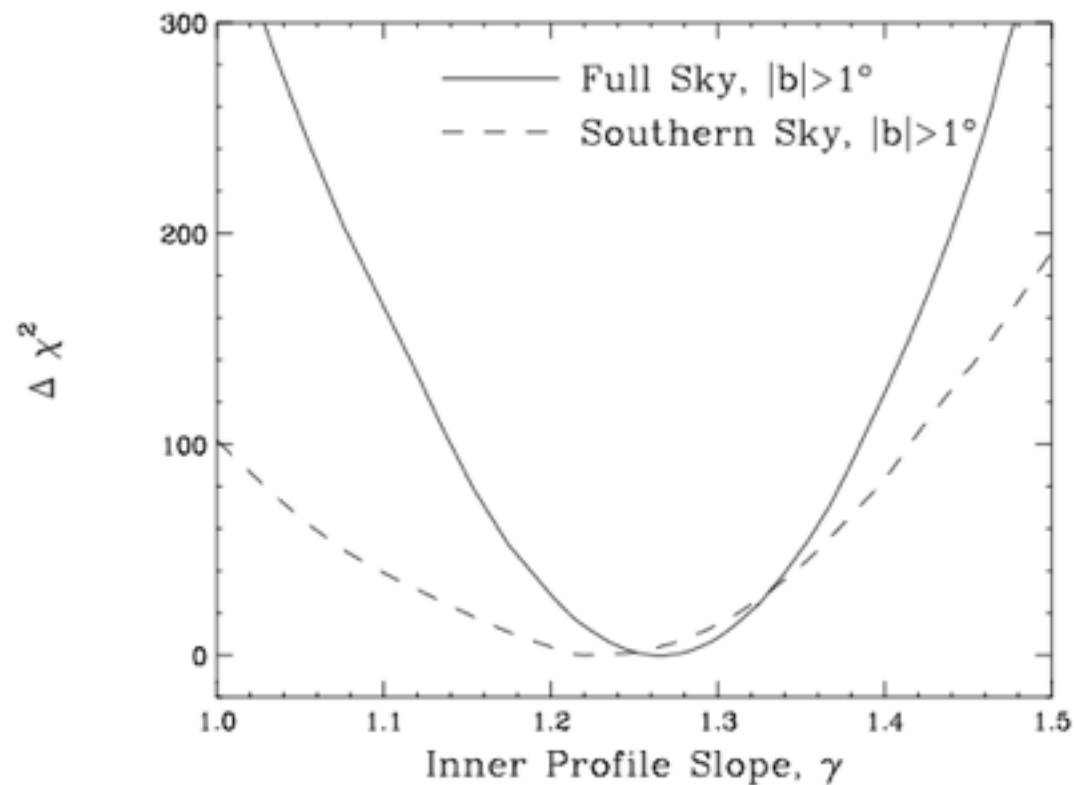
- Gamma-ray excess in the direction of GC



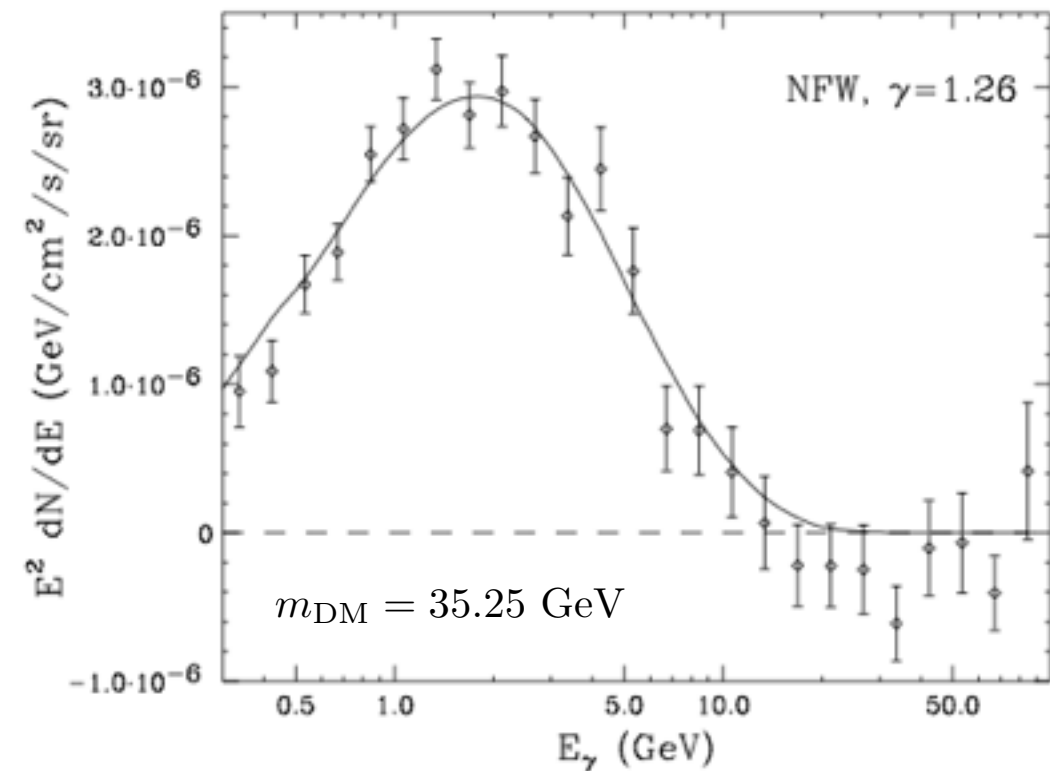
$$\text{GC} : b \sim l \lesssim 0.1^\circ$$

extended  
GeV scale excess!

## ● A DM interpretation



DM + DM  $\rightarrow b\bar{b}$  with  $\sigma v = 1.7 \times 10^{-26} \text{ cm}^3/\text{s}$



\* See “1402.6703, T. Daylan et.al.” for other possible channels

## ● Millisecond Pulsars (astrophysical alternative)

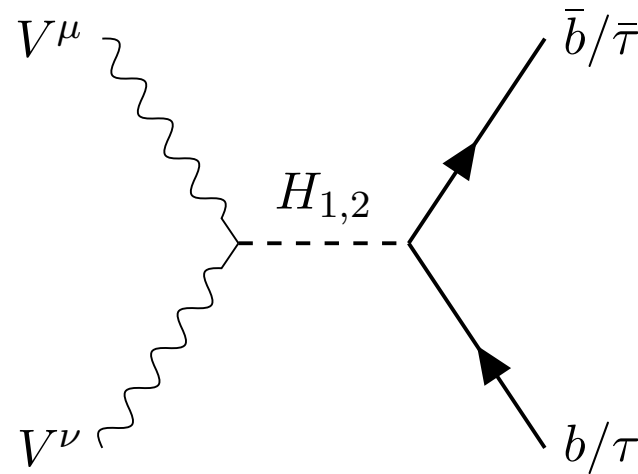
It may or may not be the main source, depending on

- luminosity func.
- bulge population
- distribution of bulge population

\* See “1404.2318, Q. Yuan & B. Zhang” and “1407.5625, I. Cholis, D. Hooper & T. Linden”

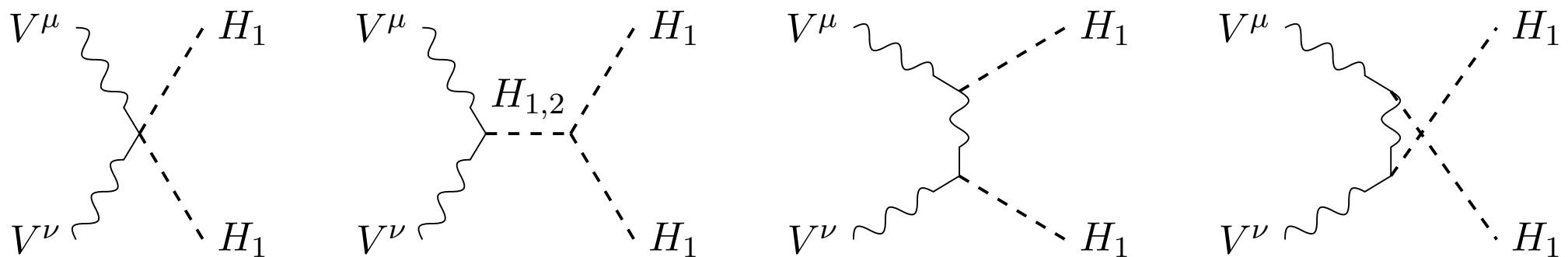
# GC gamma ray in VDM

[1404.5257, P.Ko, WIP & Y.Tang] JCAP (2014)  
(Also Celine Boehm et al. 1404.4977, PRD)



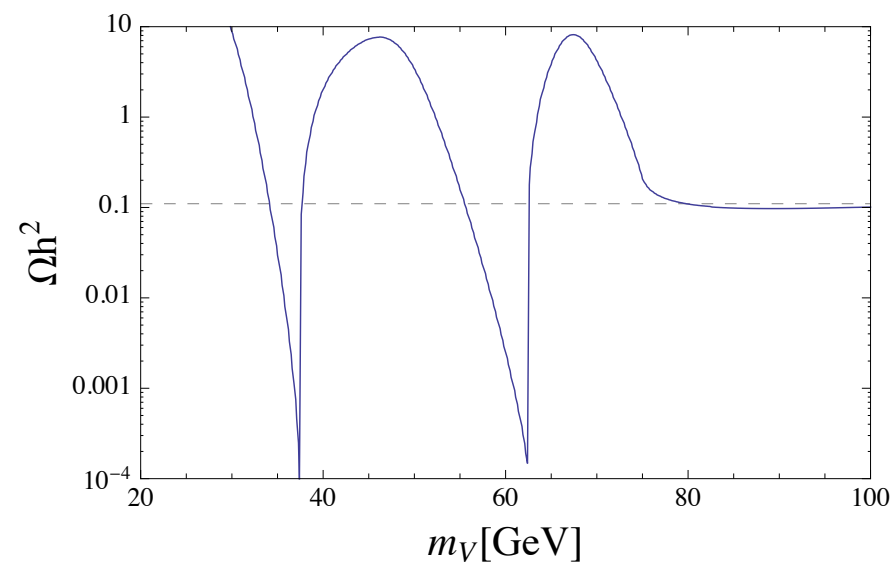
H2 : 125 GeV Higgs  
H1 : absent in EFT

**Figure 2.** Dominant  $s$  channel  $b + \bar{b}$  (and  $\tau + \bar{\tau}$ ) production

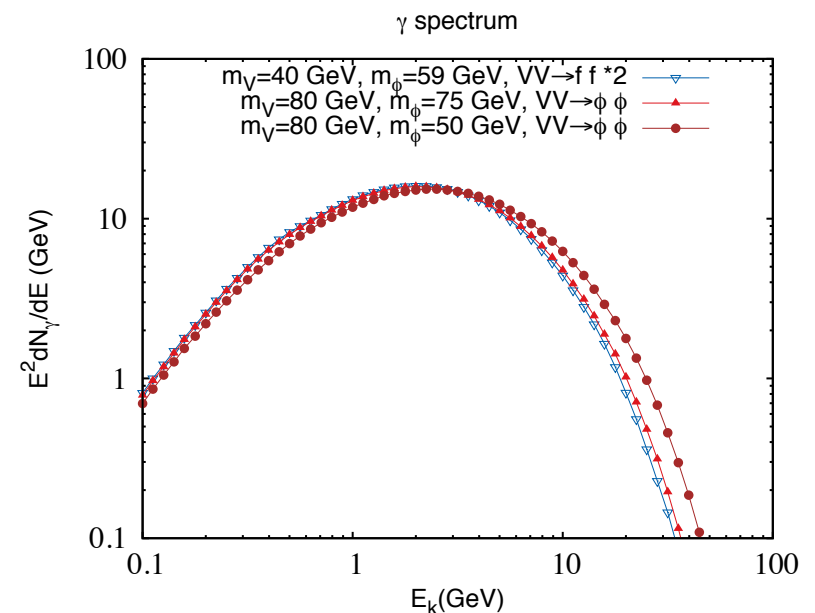


**Figure 3.** Dominant  $s/t$ -channel production of  $H_1$ s that decay dominantly to  $b + \bar{b}$

# Importance of VDM with Dark Higgs Boson



**Figure 4.** Relic density of dark matter as function of  $m_\psi$  for  $m_h = 125$ ,  $m_\phi = 75$  GeV,  $g_X = 0.2$ , and  $\alpha = 0.1$ .



**Figure 5.** Illustration of  $\gamma$  spectra from different channels. The first two cases give almost the same spectra while in the third case  $\gamma$  is boosted so the spectrum is shifted to higher energy.

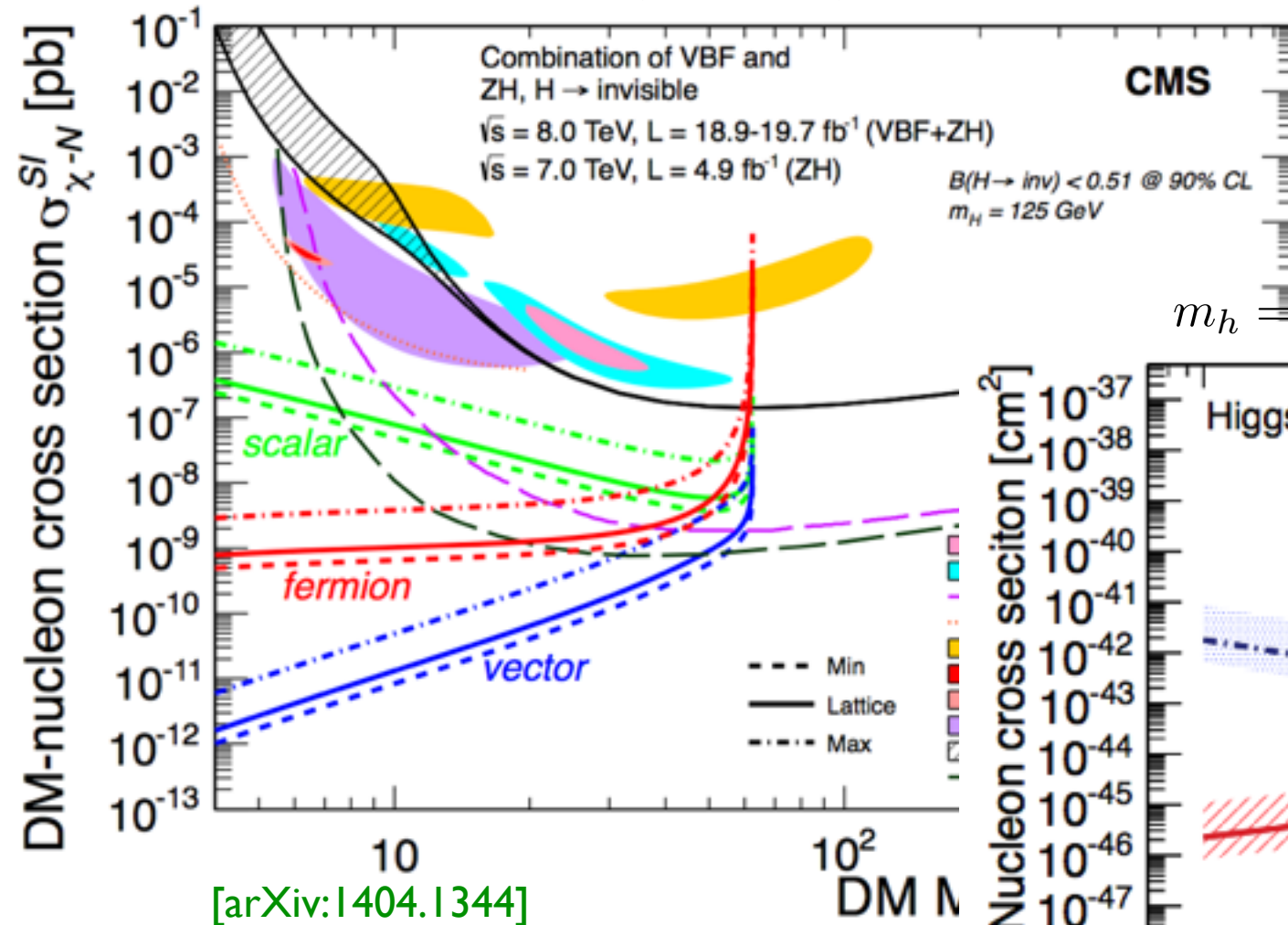
This mass range of VDM would have been  
impossible in the VDM model (EFT)

And there would be no second scalar in EFT

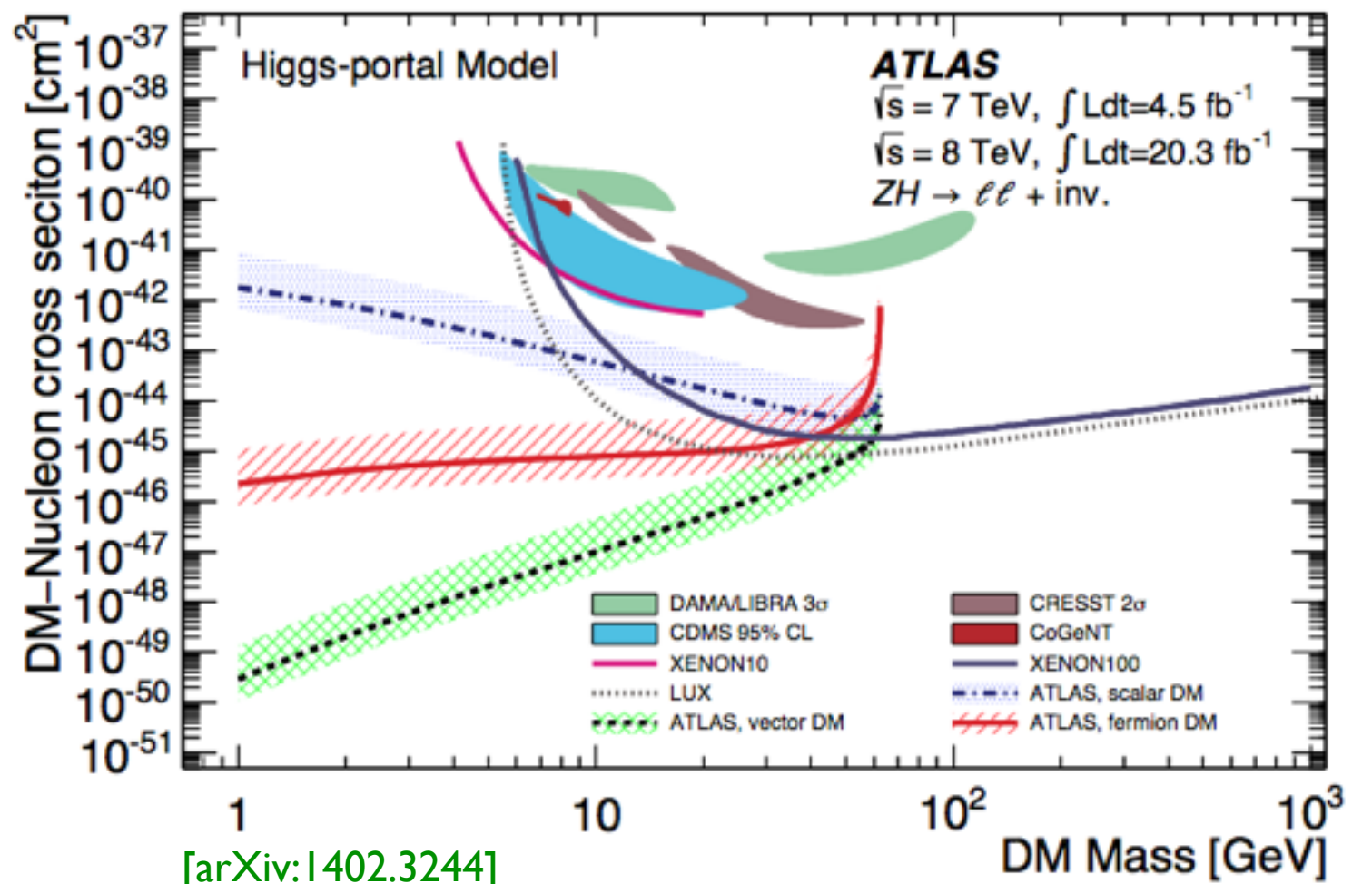
# Collider Implications

$m_h = 125\text{GeV}$ ,  $\text{Br}(H \rightarrow \text{inv}) < 0.51$  at 90% CL

Based on EFTs



$m_h = 125.5\text{GeV}$ ,  $\text{Br}(H \rightarrow \text{inv}) < 0.52$  at 90% CL





- However, in renormalizable unitary models of Higgs portals, **2 more relevant parameters**

$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H$$

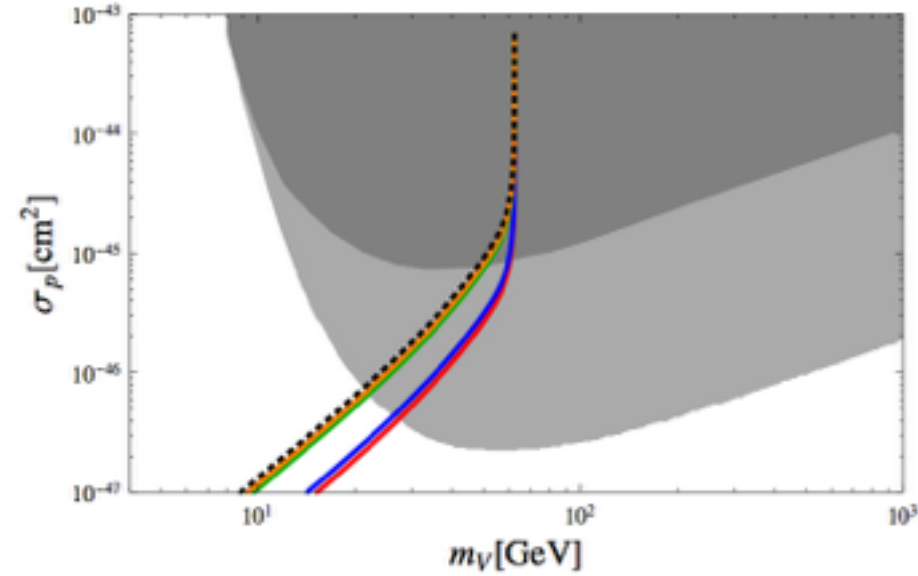
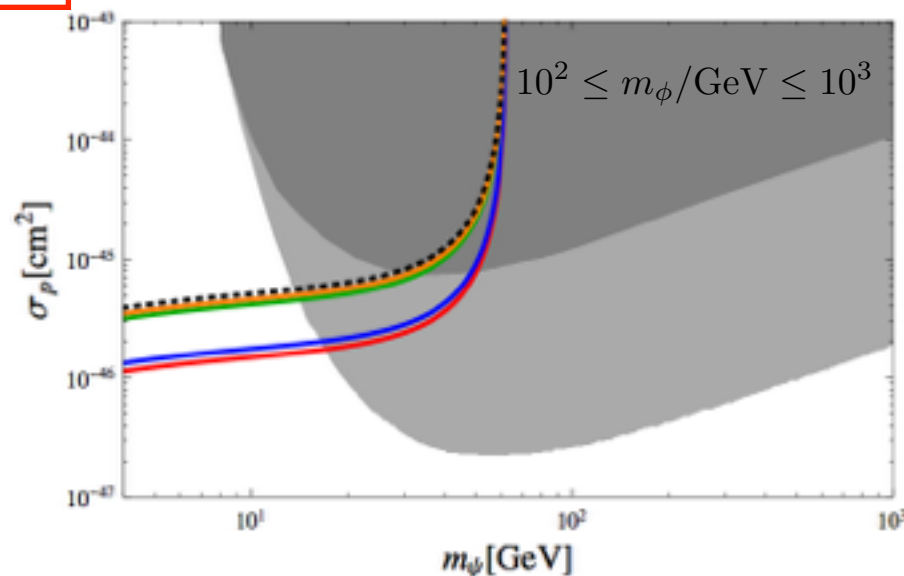
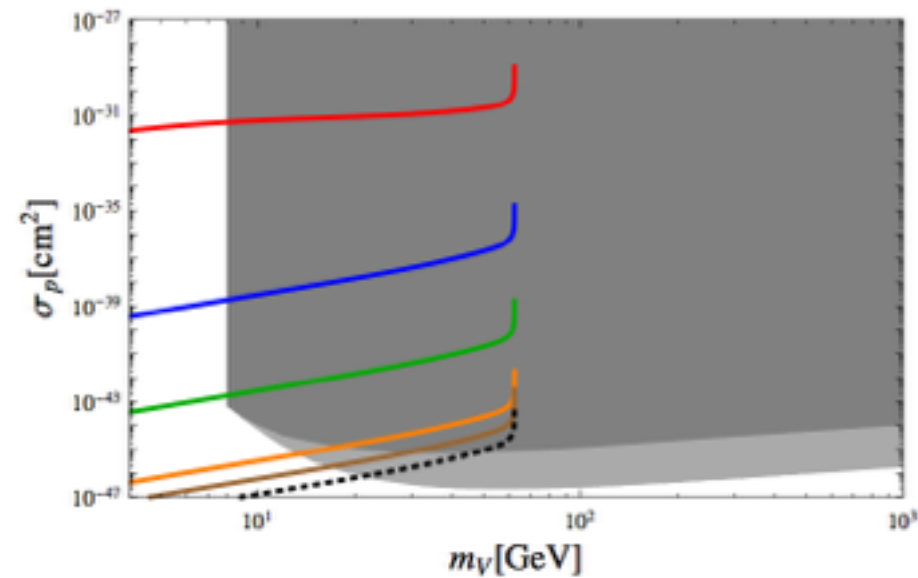
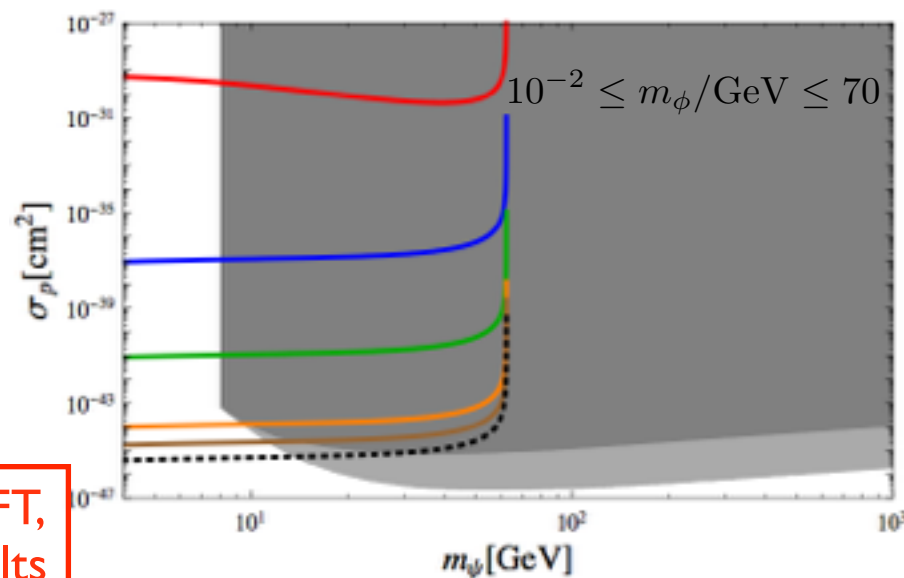
$$+ \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

$$\sigma_p^{\text{SI}} = (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 m_h^4 \mathcal{F}(m_{\text{DM}}, \{m_i\}, v)$$

$$\simeq (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

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



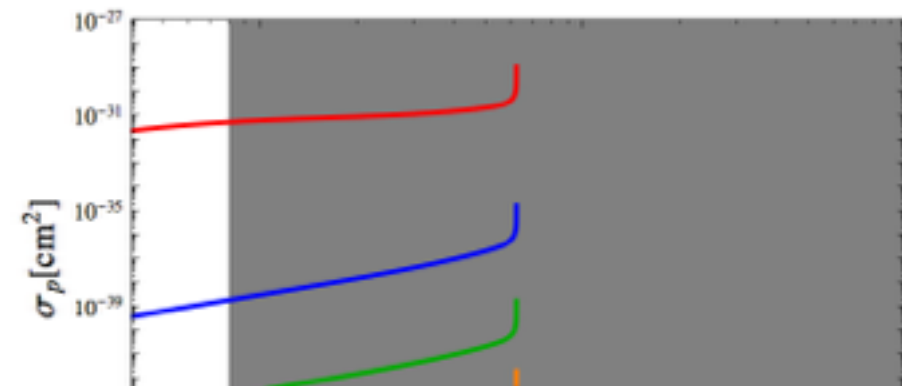
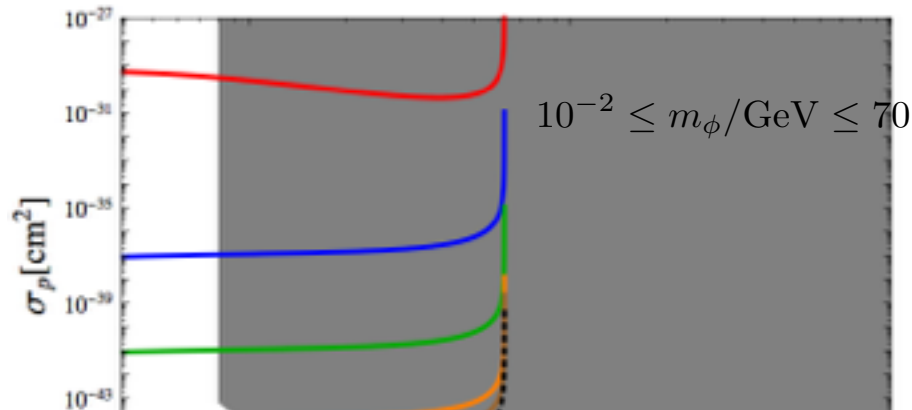
Dashed curves: EFT,  
ATLAS, CMS results

- However, in renormalizable unitary models of Higgs portals, **2 more relevant parameters**

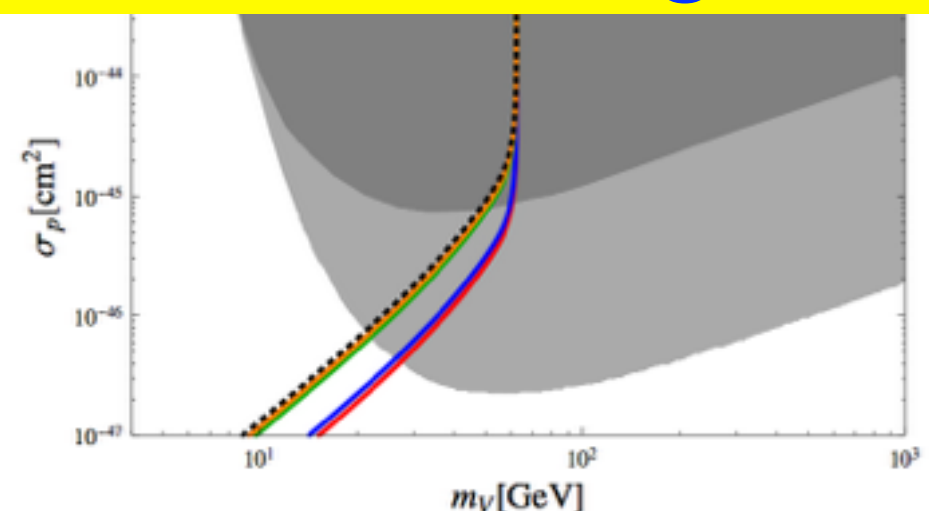
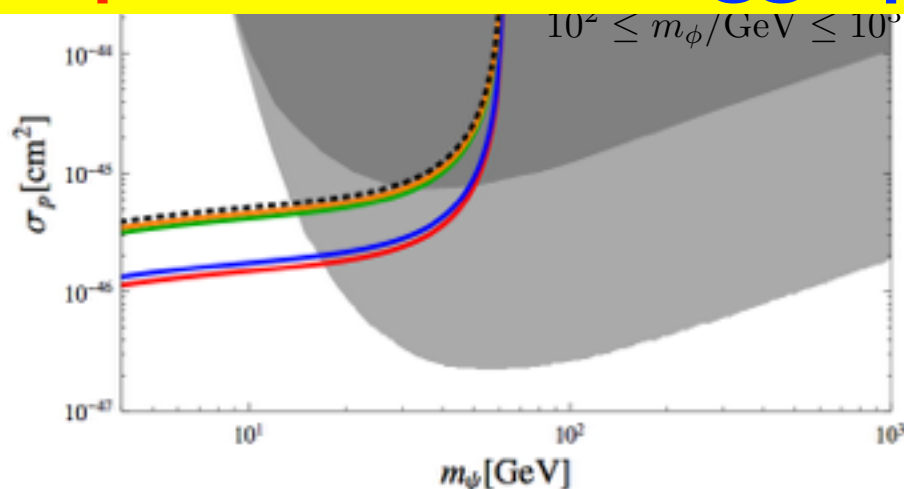
$$\mathcal{L}_{\text{SFDM}} = \bar{\psi}(i\partial - m_\psi - \lambda_\psi S) - \mu_{HS} S H^\dagger H - \frac{\lambda_{HS}}{2} S^2 H^\dagger H \\ + \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \mu'_S S - \frac{\mu'_S}{3} S^3 - \frac{\lambda_S}{4} S^4.$$

$$\sigma_p^{\text{SI}} = (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 m_h^4 \mathcal{F}(m_{\text{DM}}, \{m_i\}, v) \\ \simeq (\sigma_p^{\text{SI}})_{\text{EFT}} c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$

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

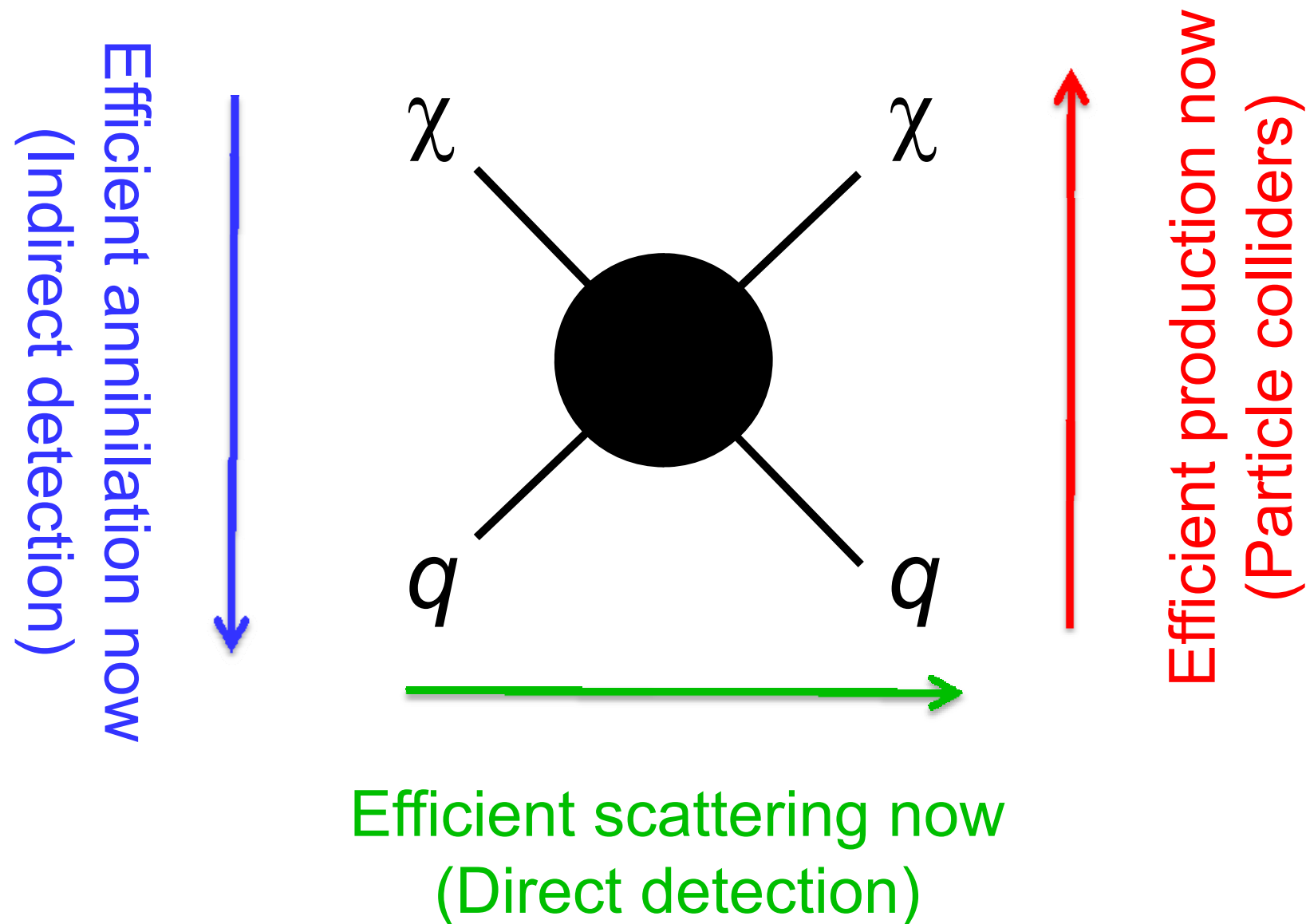


Interpretation of collider data is **quite model-dependent** in **Higgs portal DMs** and in general



# Crossing & WIMP detection

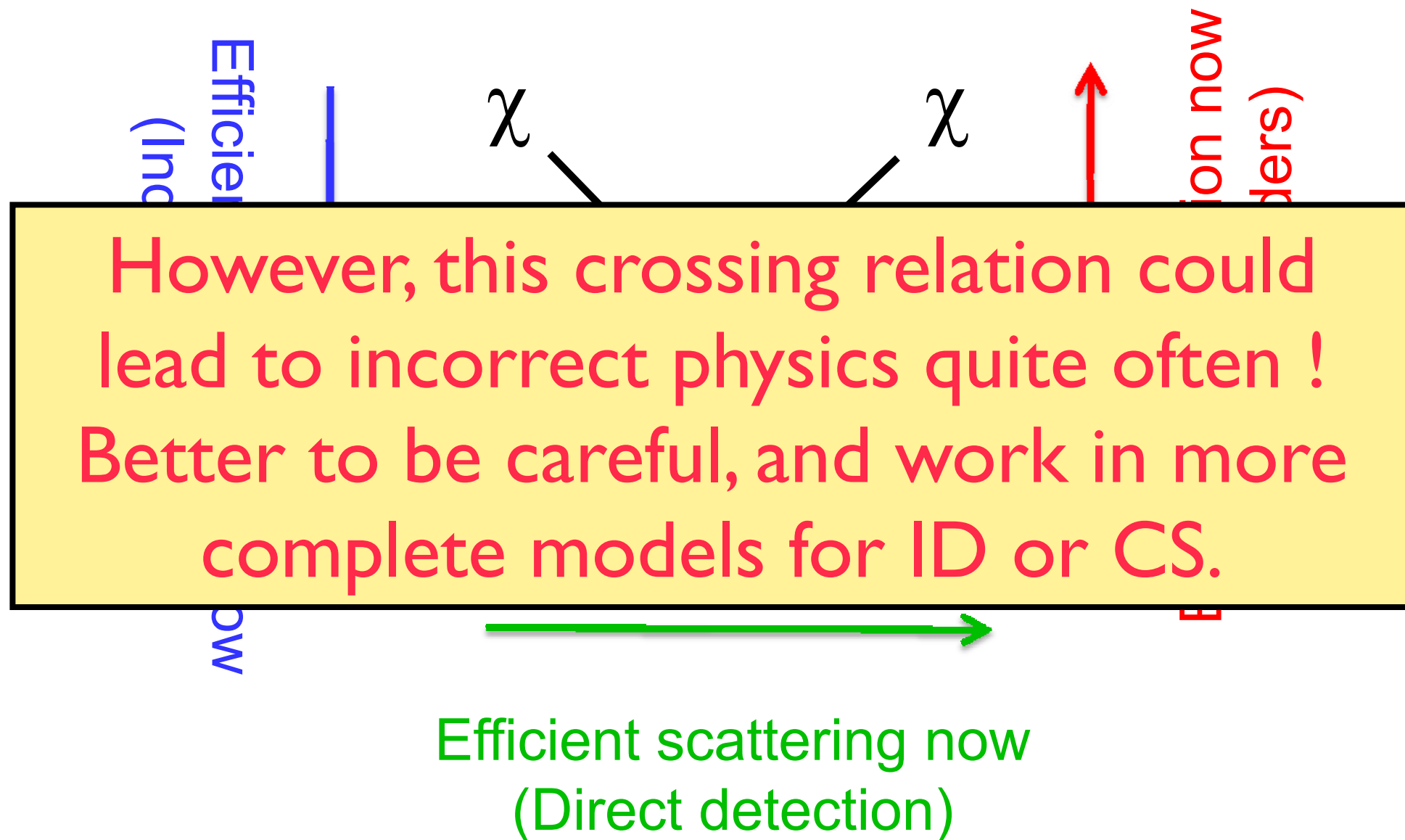
Correct relic density  $\rightarrow$  Efficient annihilation then





# Crossing & WIMP detection

Correct relic density  $\rightarrow$  Efficient annihilation then



# DD vs. Monojet : Why complementarity breaks down in EFT ?

Work in collaboration with  
S. Baek, Myeonghun Park,  
W.I.Park, Chaehyun Yu

arXiv:1506.06556;  
and works in preparation

# Why is it broken down in DM EFT ?

The most nontrivial example is  
the (scalar)x(scalar) operator  
for DM-N scattering

$$\mathcal{L}_{SS} \equiv \frac{1}{\Lambda_{dd}^2} \bar{q}q\bar{\chi}\chi \quad \text{or} \quad \frac{m_q}{\Lambda_{dd}^3} \bar{q}q\bar{\chi}\chi$$

This operator clearly violates the SM gauge  
symmetry, and we have to fix this problem

Also N.Bell, J.Dent, T.Weiler et al,  
arXiv:1503.07874

$$\overline{Q}_L H d_R \quad \text{or} \quad \overline{Q}_L \tilde{H} u_R, \quad \text{OK}$$

$$h \bar{\chi} \chi, \quad s \bar{q} q$$

Both break SM gauge invariance

$$s \bar{\chi} \chi \times h \bar{q} q \rightarrow \frac{1}{m_s^2} \bar{\chi} \chi \bar{q} q$$

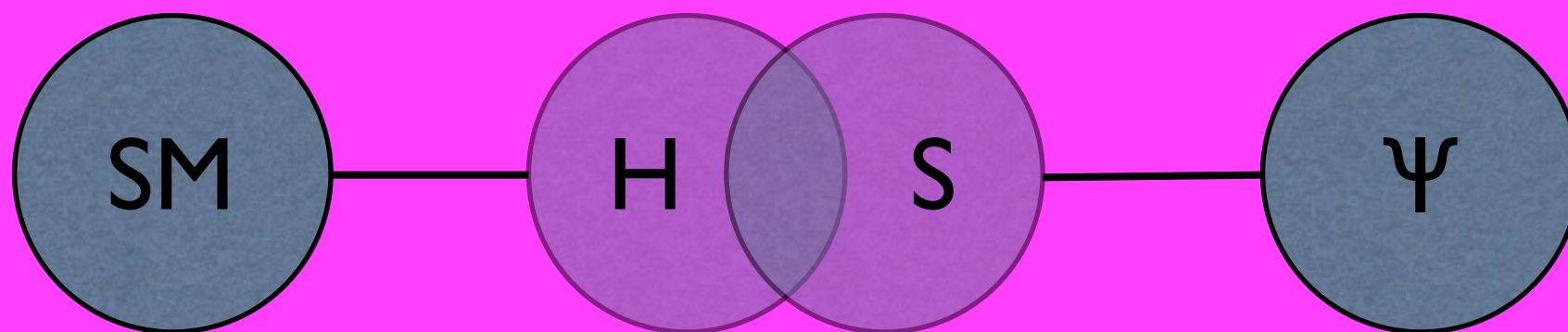
Need the mixing between s and h

# Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

mixing  
invisible decay



Production and decay rates are suppressed relative to SM.

⚠ This simple model has not been studied properly !!

# Full Theory Calculation

$$\chi(p) + q(k) \rightarrow \chi(p') + q(k')$$

$$\begin{aligned} \mathcal{M} &= \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{v} \lambda_s \sin \alpha \cos \alpha \left[ \frac{1}{t - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{1}{t - m_2^2 + im_s\Gamma_2} \right] \\ &\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v} \lambda_s \sin 2\alpha \left[ \frac{1}{m_{125}^2} - \frac{1}{m_2^2} \right] \\ &\rightarrow \overline{u(p')}u(p)\overline{u(q')}u(q) \frac{m_q}{2v} \lambda_s \sin 2\alpha \frac{1}{m_{125}^2} \equiv \frac{m_q}{\Lambda_{dd}^3} \overline{u(p')}u(p)\overline{u(q')}u(q) \end{aligned}$$

$$\Lambda_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha} \left( 1 - \frac{m_{125}^2}{m_2^2} \right)^{-1}$$

$$\bar{\Lambda}_{dd}^3 \equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}$$

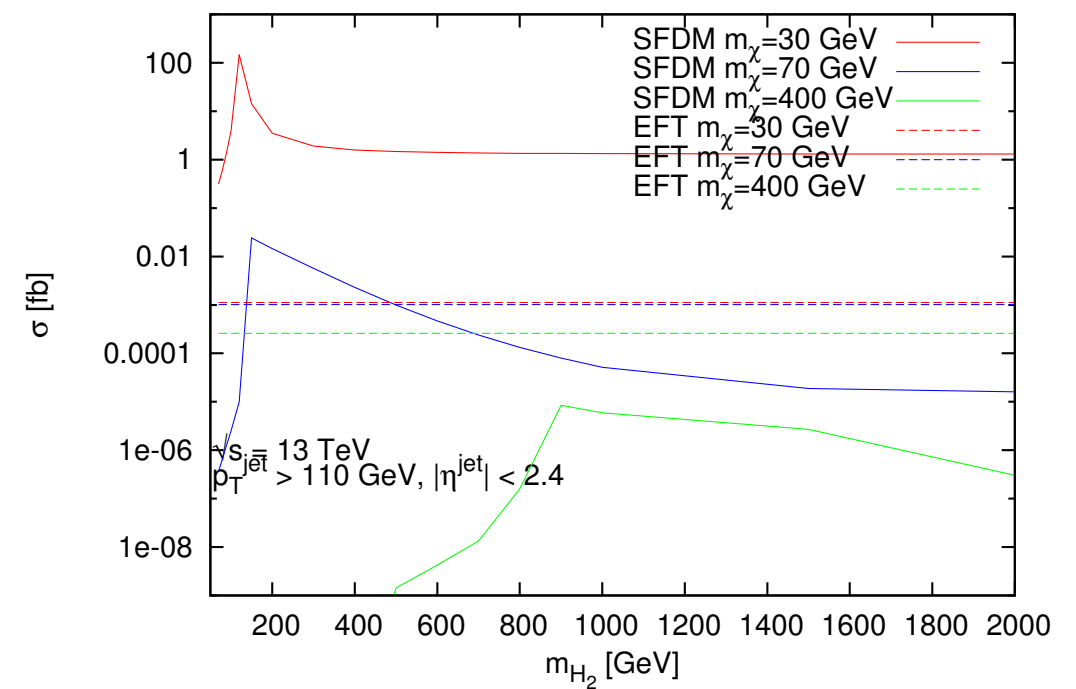
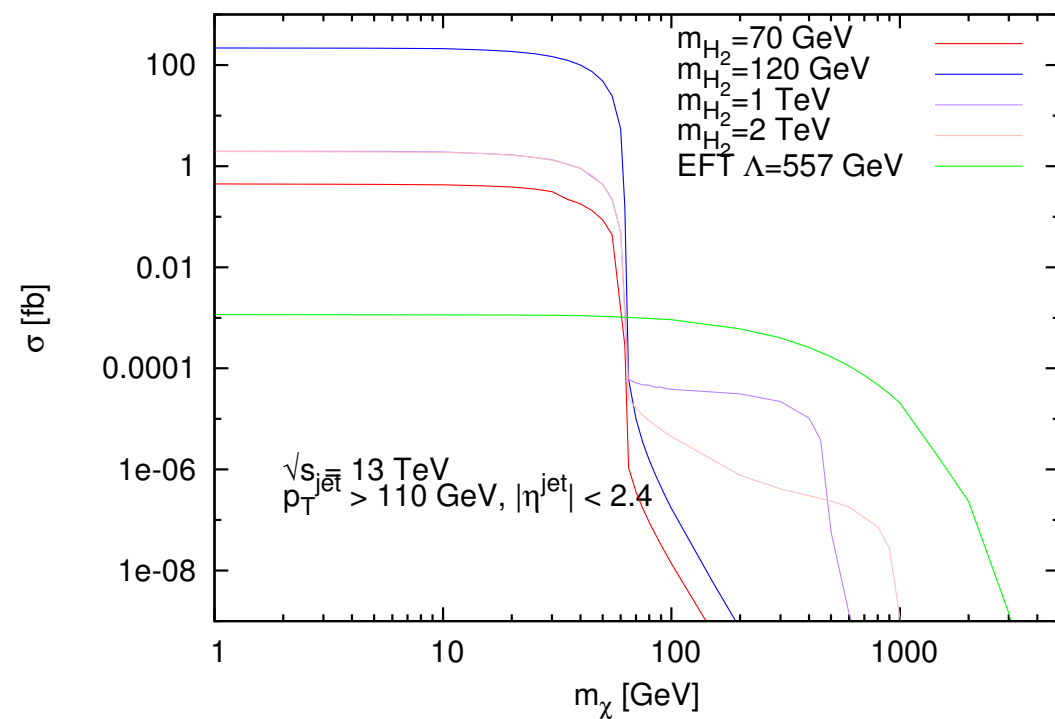
# Monojet+missing ET

Can be obtained by crossing :  $s \leftrightarrow t$

$$\frac{1}{\Lambda_{dd}^3} \rightarrow \frac{1}{\Lambda_{dd}^3} \left[ \frac{m_{125}^2}{s - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{m_{125}^2}{s - m_2^2 + im_2\Gamma_2} \right] \equiv \frac{1}{\Lambda_{col}^3(s)}$$

There is no single scale you can define  
for collider search for missing ET

# Monojet + missing ET



No similarity with the DM EFT calculation



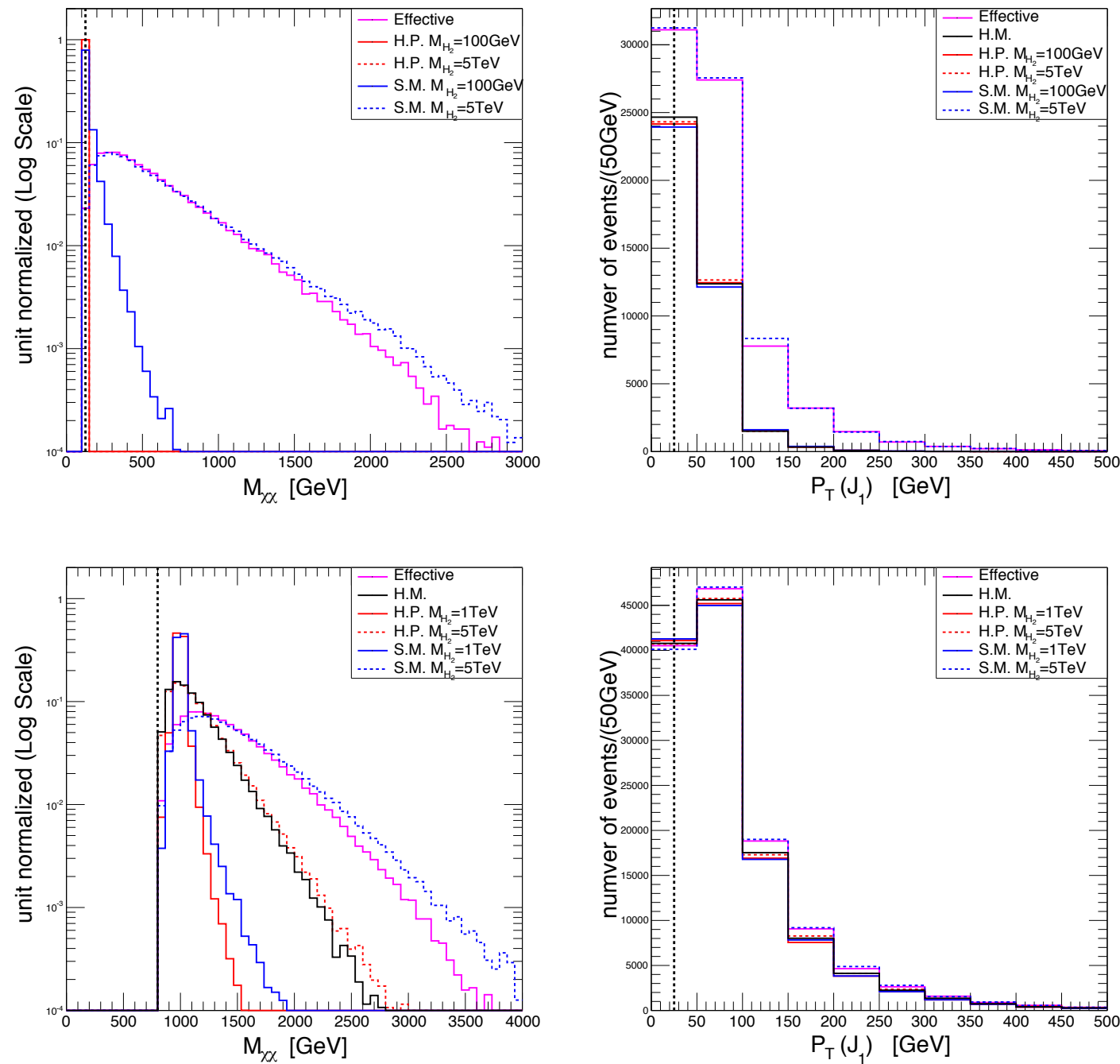


FIG. 1: In ATLAS 8TeV mono-jet+ $\cancel{E}_T$  search [6] we plot  $M_{\chi\chi}$  and the  $P_T$  of a hardest jet in a reconstruction level (after a detector simulation). Upper panels are with  $m_\chi = 50$  GeV and lower panels are of  $m_\chi = 400$  GeV.

- EFT : Effective operator  $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3} \bar{q}q\bar{\chi}\chi$
- S.M.: Simple scalar mediator  $S$  of  

$$\mathcal{L}_{int} = \left( \frac{m_q}{v_H} \sin \alpha \right) S \bar{q}q - \lambda_s \cos \alpha S \bar{\chi}\chi$$
- H.M.: A case where a Higgs is a mediator  

$$\mathcal{L}_{int} = - \left( \frac{m_q}{v_H} \cos \alpha \right) H \bar{q}q - \lambda_s \sin \alpha H \bar{\chi}\chi$$
- H.P.: Higgs portal model as in eq. (2).

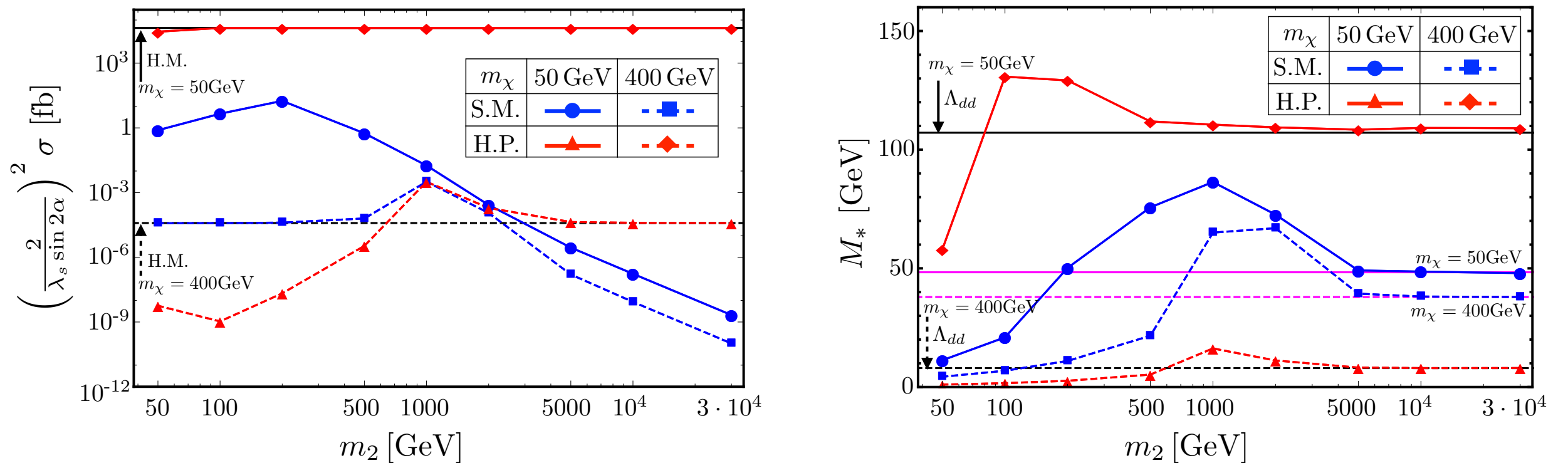


FIG. 1: We follow ATLAS 8TeV mono-jet+ $\cancel{E}_T$  searches [2]. For (a) we simulated various models for the

# $t\bar{t} + \text{missing ET}$

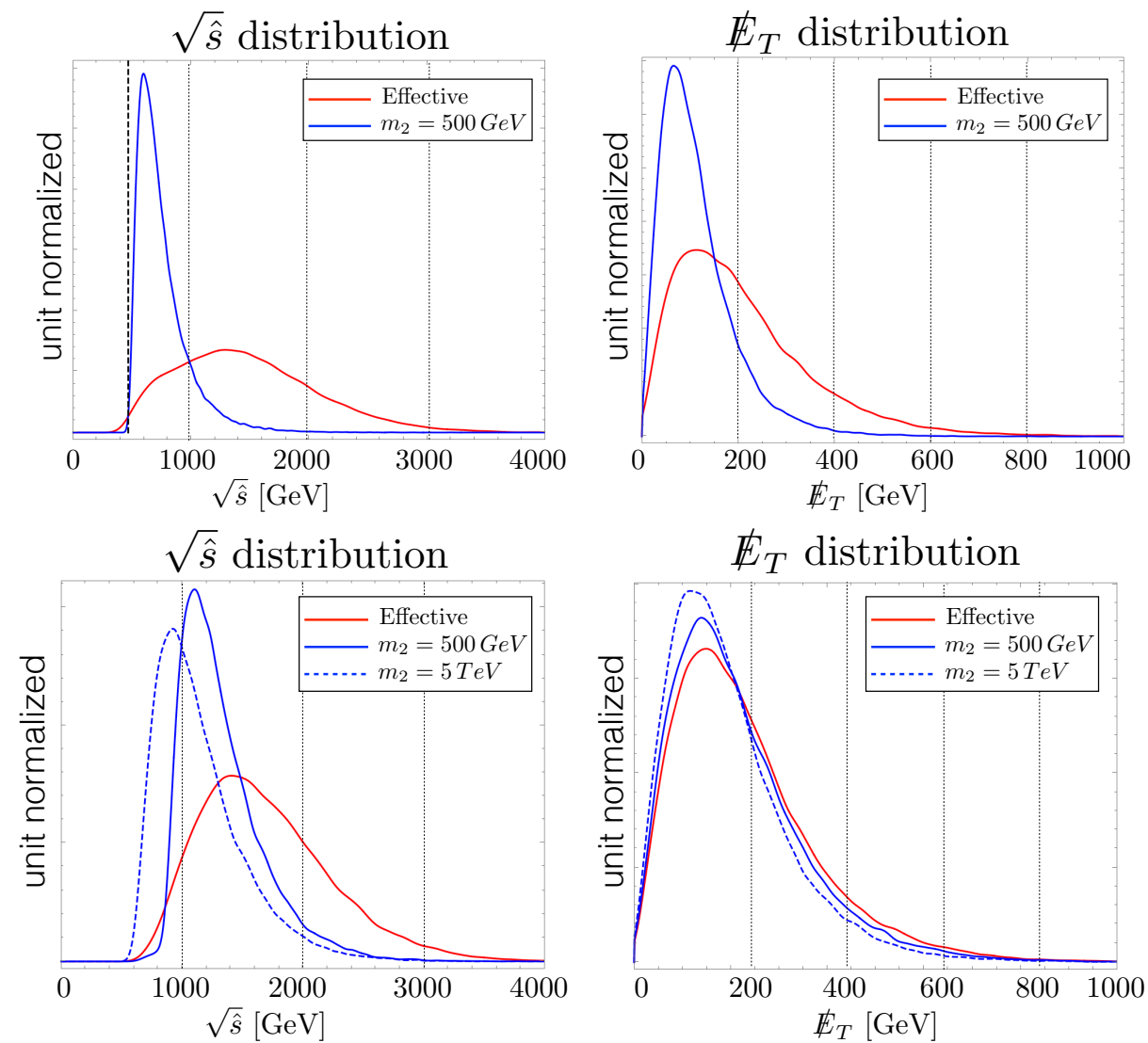


FIG. 2: Parton level distributions of various variables in a  $(t\bar{t}\chi\bar{\chi})$  channel for a dark matter's mass  $m_\chi = 10 \text{ GeV}$  (above) and  $m_\chi = 100 \text{ GeV}$  (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when  $m_2 \rightarrow \infty$  case, a missing transverse energy  $\cancel{E}_T$  of a higgs portal model shall be different from an effective operator operator case.

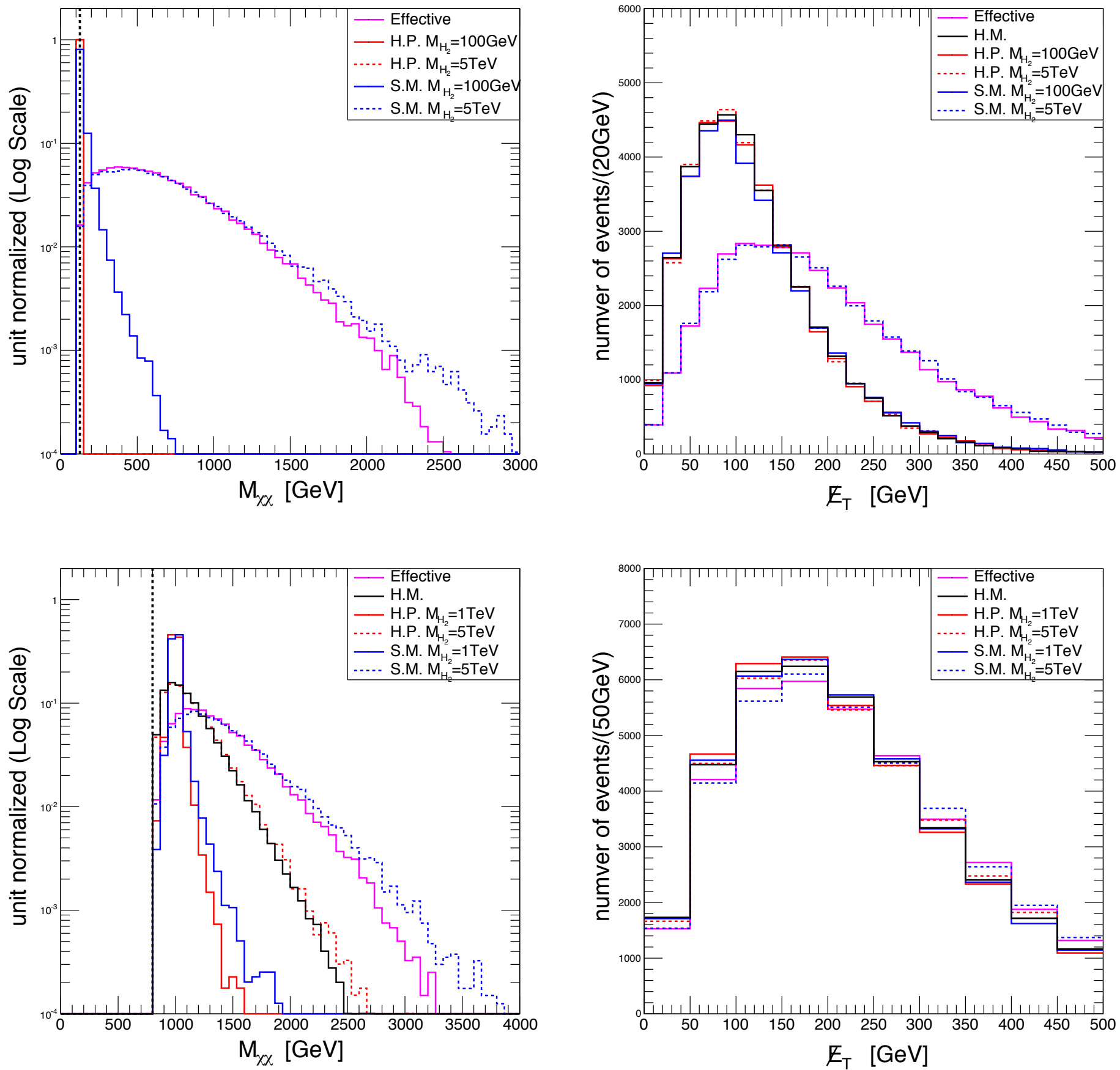


FIG. 4: With CMS 8TeV  $t\bar{t} + \cancel{E}_T$  search [6], we plot  $M_{\chi\chi}$  and the  $\cancel{E}_T$  in a reconstruction level. Upper panels are with  $M_\chi = 50$  GeV and lower panels are of  $M_\chi = 400$  GeV.

- EFT : Effective operator  $\mathcal{L}_{int} = \frac{m_q}{\Lambda_{dd}^3} \bar{q}q \bar{\chi}\chi$
- S.M.: Simple scalar mediator  $S$  of  

$$\mathcal{L}_{int} = \left( \frac{m_q}{v_H} \sin \alpha \right) S \bar{q}q - \lambda_s \cos \alpha S \bar{\chi}\chi$$
- H.M.: A case where a Higgs is a mediator  

$$\mathcal{L}_{int} = - \left( \frac{m_q}{v_H} \cos \alpha \right) H \bar{q}q - \lambda_s \sin \alpha H \bar{\chi}\chi$$
- H.P.: Higgs portal model as in eq. (2).

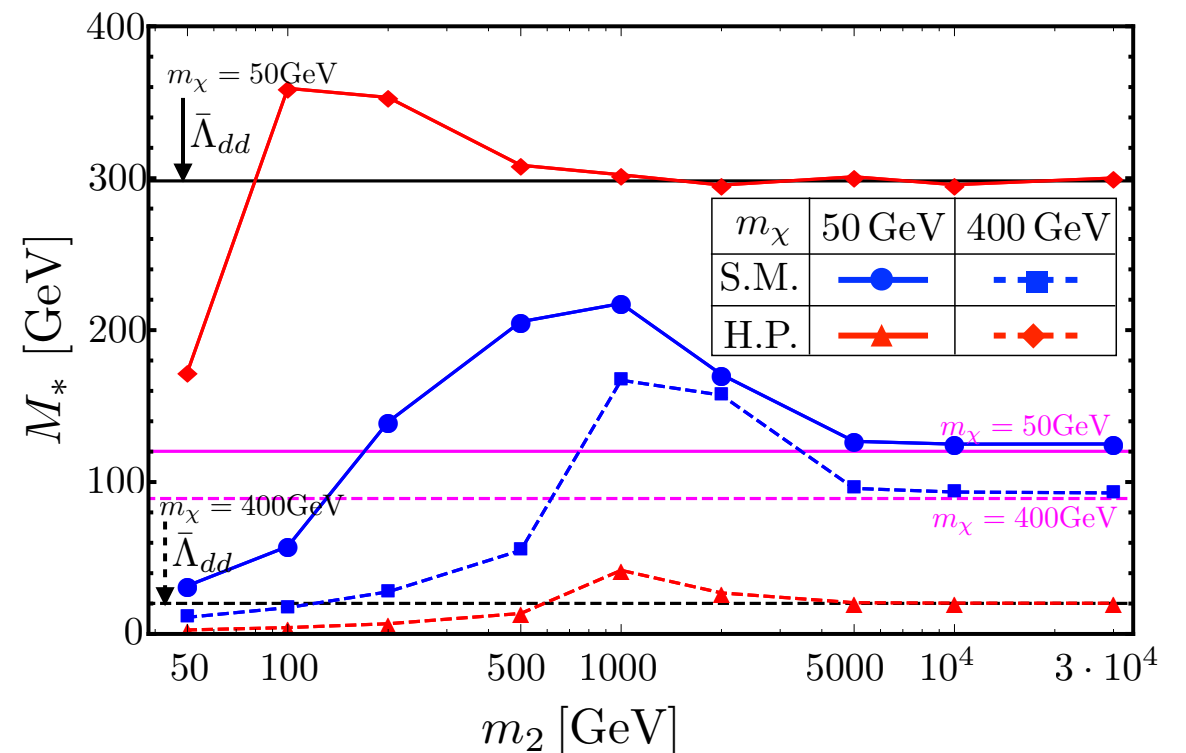
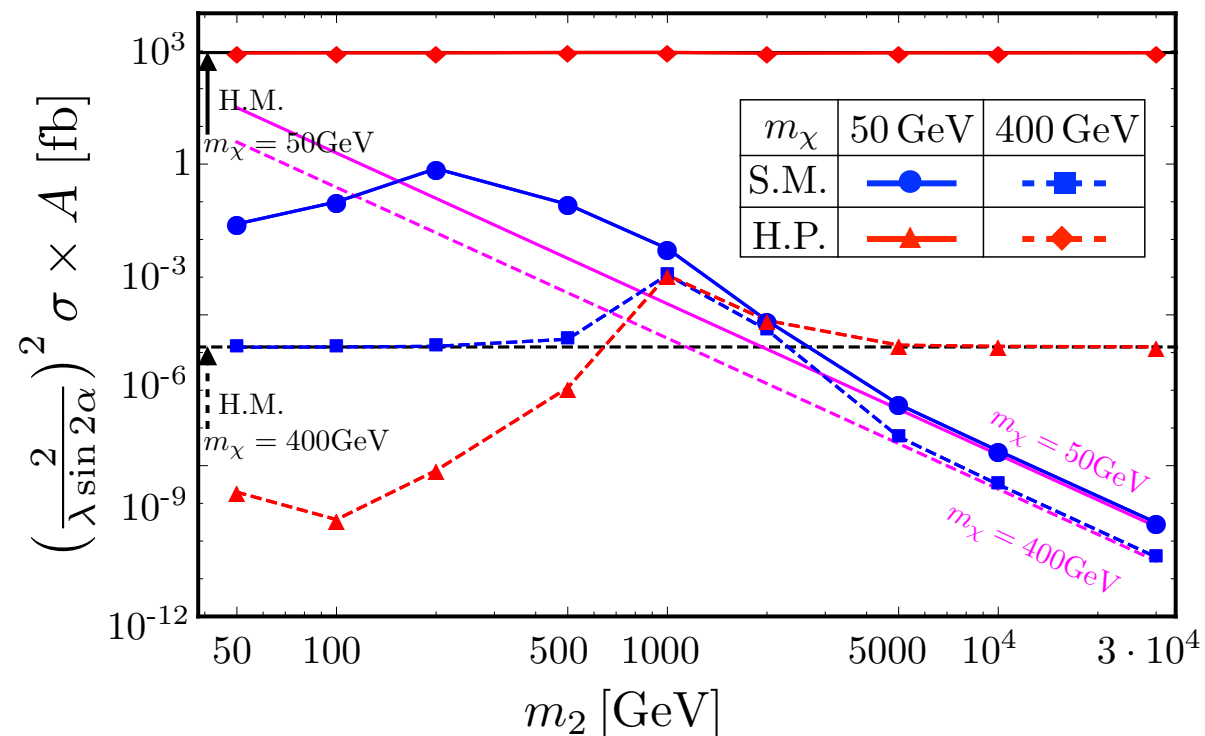


FIG. 3: We follow CMS 8TeV  $t\bar{t} + \cancel{E}_T$  search. For (a) we simulated various models for the

# A General Comment

**assume:**  $2m_\chi \ll m_{125} \ll m_2 \ll \sqrt{s}$

$$\begin{aligned}\sigma(\sqrt{s}) &= \int_0^1 d\tau \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s) \\ &= \left[ \int_{4m_\chi^2/s}^{m_{125}^2/s} d\tau + \int_{m_{125}^2/s}^{m_2^2/s} d\tau + \int_{m_2^2/s}^1 d\tau \right] \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)\end{aligned}$$

For each integration region for tau,  
we have to use different EFT

No single EFT applicable to the entire tau regions

# Indirect Detection

$$\begin{aligned}
 \left| \frac{1}{\Lambda_{ann}^3} \right| &\simeq \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + im_{125}\Gamma_{125}} - \frac{m_{125}^2}{4m_\chi^2 - m_2^2 + im_2\Gamma_2} \right| \\
 &\rightarrow \frac{1}{\Lambda_{dd}^3} \left| \frac{m_{125}^2}{4m_\chi^2 - m_{125}^2 + im_{125}\Gamma_{125}} \right| \neq \frac{1}{\Lambda_{dd}^3}
 \end{aligned}$$

- Again, no definite correlations between two scales in DD and ID
- Also one has to include other channels depending on the DM mass

# Underlying Points

- Renormalizability and unitarity
- SM gauge invariance (full SM gauge symmetry)
- Dark (gauge) symmetry equally important, although it is usually ignored (this part is also completely unknown to us as of now)
- We are working on simplified models with all these conditions



# Summary

- Using EFT for Higgs portal fermion/vector DM is not good for theoretical and phenomenological reasons
- Simply because we don't know the mass scales related with DM (and mediators) and how DM is stabilized or long lived
- Results based on EFT can be completely wrong, or misleading at best
- Better to work on the minimal unitary, renormalizable & anomaly free model