EW scale dark matter with dark gauge symmetries

Pyungwon Ko (KIAS)

DSU 2015, Kyoto
Dec 14-18 (2015)

Contents

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

Key Ideas

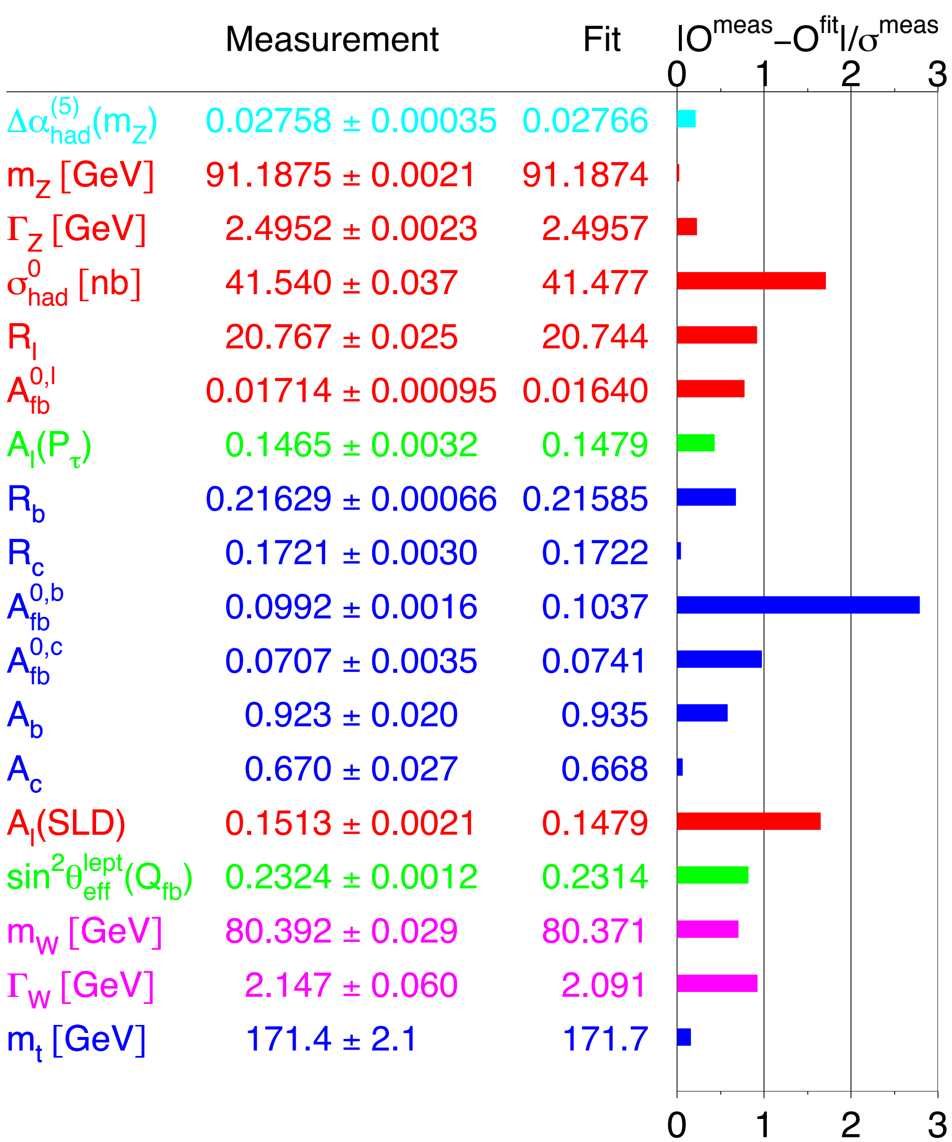
- Stability/Longevity of Dark Matter (DM)
- Local Dark Gauge Symmetry
- Thermal DM through Singlet Portals (especially Higgs Portal)
- Connections between Higgs, DM and Higgs Inflation, especially the role of "Dark Higgs" and "Dark Gauge Bosons" that can play a role of light mediators

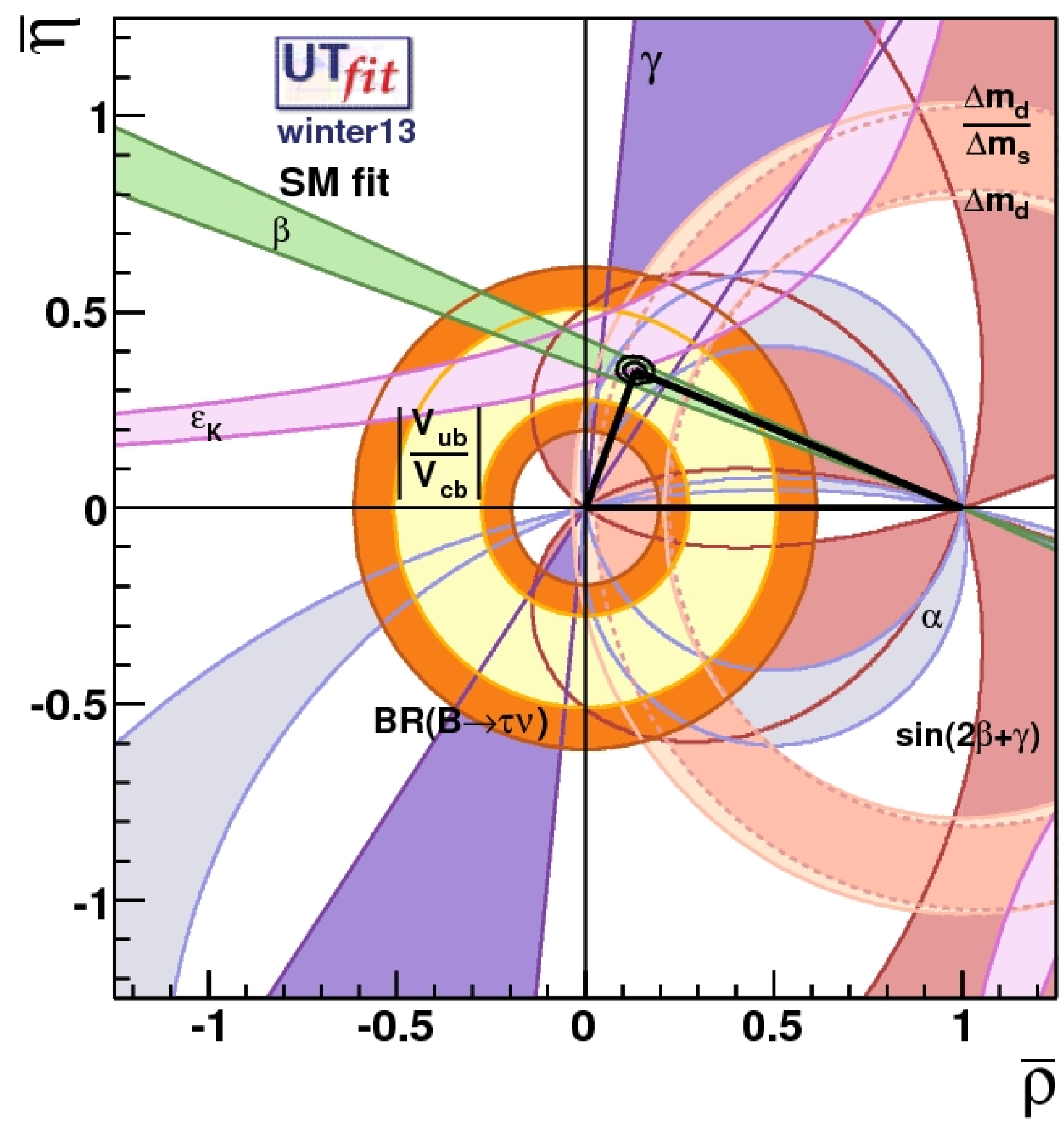
SM Lagrangian

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

Based on local gauge principle

EWPT & CKM





Almost Perfect !

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 ?

Building Blocks of SM

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

Lessons from SM

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

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

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 ?

- 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 ? 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 Z2, Z3 : 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
- AMS02, IceCube : Decaying DM with local dark gauge sym (see Yong Tang's talk at IPMU, Oct. 2015)

Talks by Arman Esmaili Taklimi, J. Kersten, Y. Mambrini

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.

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
- 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

Higgs signal strength/Dark radiation/DM

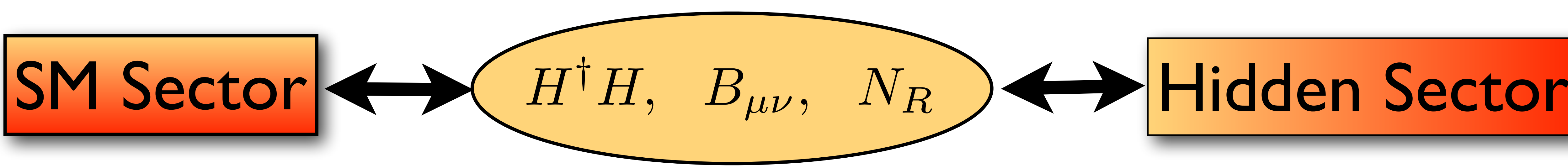
in preparation with Baek and W.I. Park

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

: The number of massless gauge bosons

Singlet Portal

- If there is a hidden sector 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, Z3, Z2, scalar CDM

But for WIMP ...

S.Baek, P.Ko, W.I.Park, arXiv:1303.4280

- 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)]

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

$\Rightarrow$ 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

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 Z_2 sym

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

Consider Z_2 breaking operators such as

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

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:

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

Problematic !

Perfectly fine !

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

- 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 arXiv:1407.6588 w/ WIPark and SBaek

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

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

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

Unbroken Local Z2 symmetry

Gauge models for excited DM

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

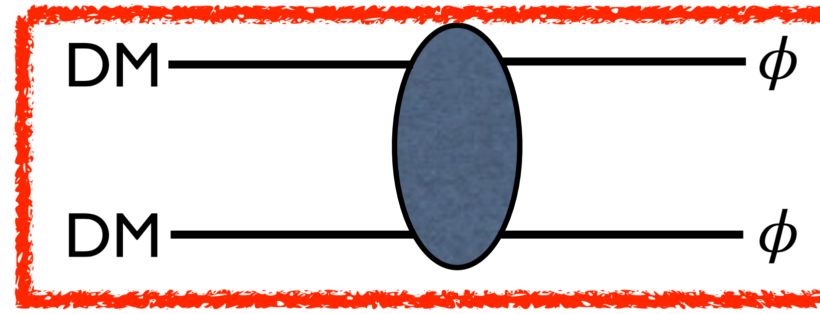
The heavier state decays into the lighter state

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]

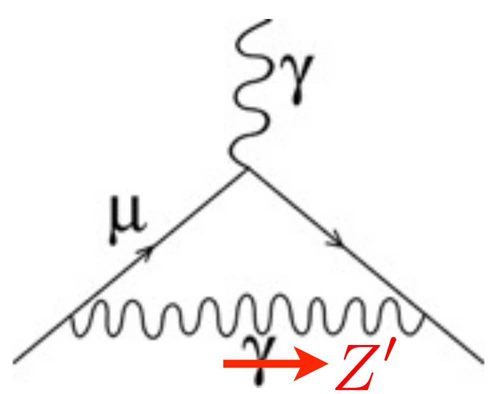
$$\mathcal{L}_{VDM} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - \lambda_\Phi\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger\Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right),$$



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

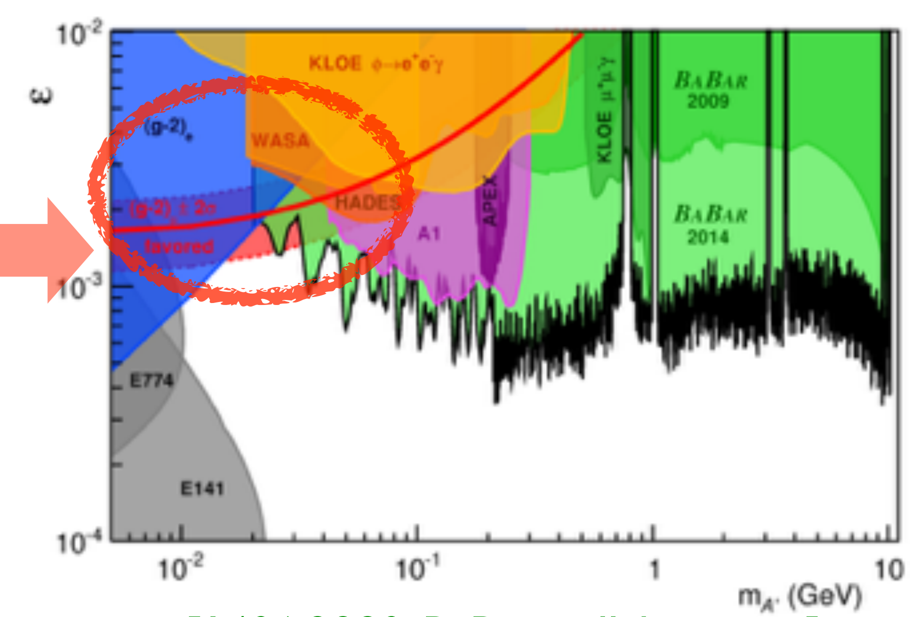
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} - \frac{1}{2}\sin\epsilon\hat{X}_{\mu\nu}\hat{B}^{\mu\nu} + D_\mu\phi D^\mu\phi + D_\mu X^\dagger D^\mu X - m_X^2 X^\dagger X + m_\phi^2\phi^\dagger\phi - \lambda_\phi\left(\phi^\dagger\phi\right)^2 - \lambda_X\left(X^\dagger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

- 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'



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

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



[1406.2980, BaBar collaboration]

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 Z3 Scalar DM

P.Ko, YTang, arXiv:1402.6449

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

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

$$V = -\mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 - \mu_\phi^2\phi_X^\dagger\phi_X + \lambda_\phi\left(\phi_X^\dagger\phi_X\right)^2 + \mu_X^2 X^\dagger X + \lambda_X \left(X^\dagger X\right)^2$$

$$+ \lambda_{\phi H}\phi_X^\dagger\phi_X H^\dagger H + \lambda_{\phi X} X^\dagger X\phi_X^\dagger\phi_X + \lambda_{HX} X^\dagger X H^\dagger H + \left(\lambda_3 X^3\phi_X^\dagger + H.c.\right)$$

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

Z3 symmetry $X^\dagger \to e^{-i\frac{2\pi}{3}} X^\dagger$

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

Comparison with global Z3

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

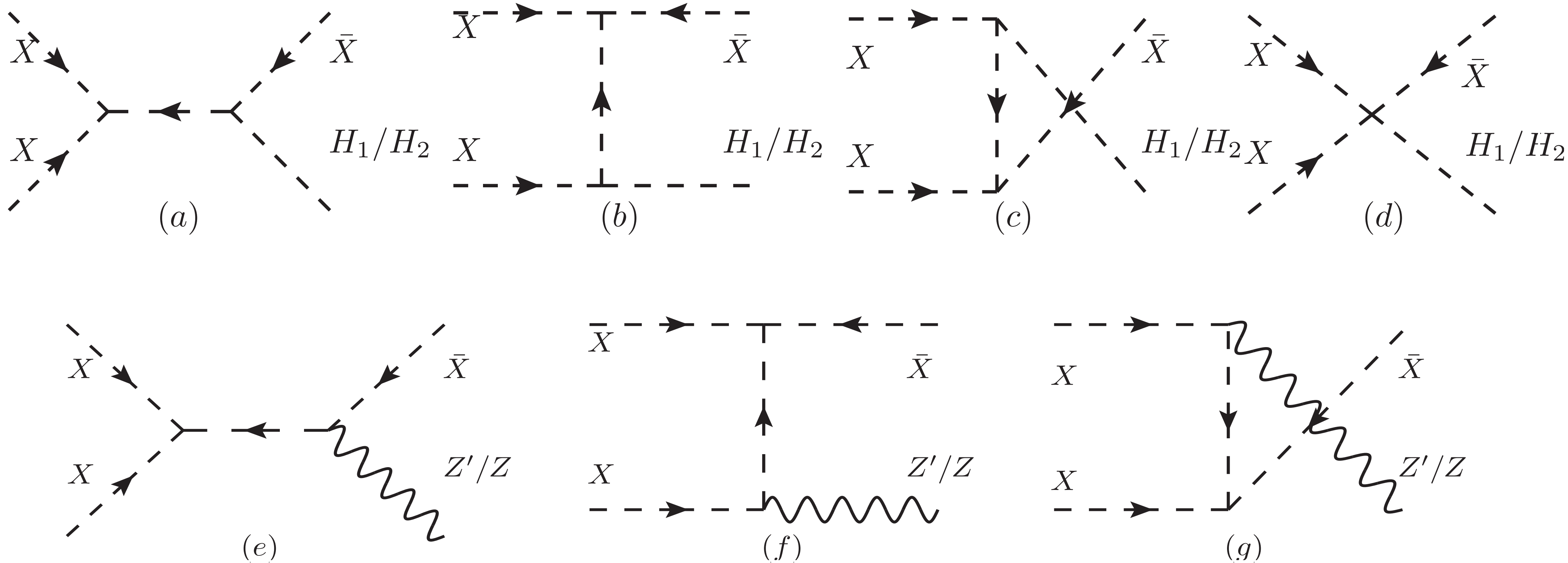
- However global symmetry can be broken by gravity induced nonrenormalizable op's:

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

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

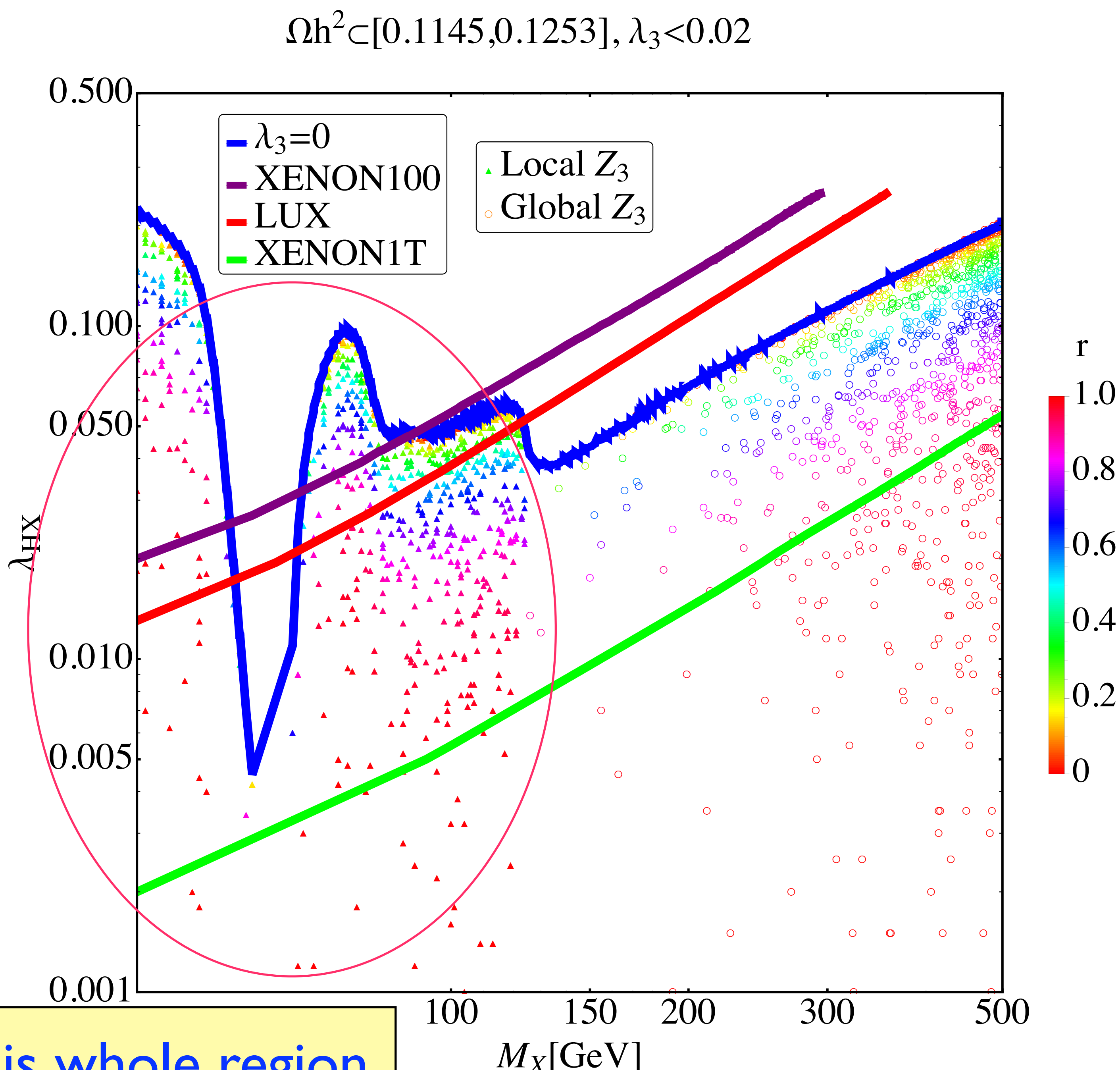


$$\frac{dn_X}{dt} = -v\sigma^{XX^*\to YY}\left(n_X^2 - n_{X\,\mathrm{eq}}^2\right) - \frac{1}{2}v\sigma^{XX\to X^*Y}\left(n_X^2 - n_X n_{X\,\mathrm{eq}}\right) - 3Hn_X,$$

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

micrOMEGAs

Relic density and Direct Search



This whole region is allowed in local Z3 case

- Blue band marks the upper bound,
- All points are allowed in our local Z3 model, 1402.6449
- only circles are allowed in global Z3 model,1211.1014

Global Z3 (Belanger, Pukhov et al)	Local Z3 (Ko, Yong Tang)
• SM + X • DD & Thermal relic >> mX > 120 GeV • Vacuum stability >> DD cross section within Xenon1T experiment • No light mediators	• 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

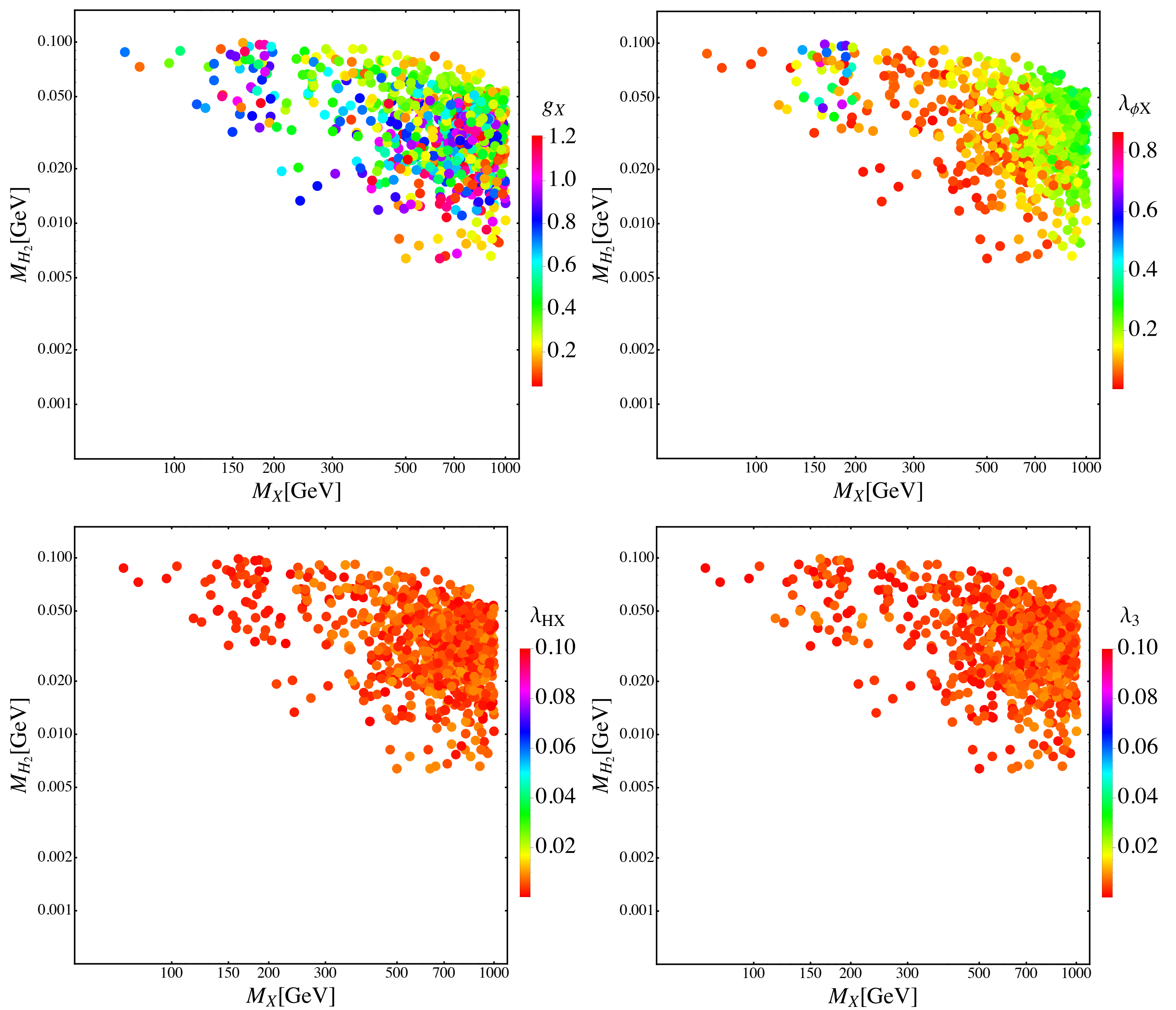


FIG. 3: Scatter plots of various parameters that are consistent with relic density, LUX direct search bound and self-interaction $\sigma_T/M_X \in [0.1, 10]$ cm^2/g at Dwarf galaxies scale with $v_{\rm rel} \simeq 10$ km/s, and $\sigma_T/M_X \lesssim 0.5$ cm^2/g at Milky Way and cluster scales with $v_{\rm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

Comparison with EFT

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

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

$$\left(\text{or } \frac{1}{\Lambda^3}X^3\overline{f_L}Hf_R, \text{if we imposed the full SM gauge symmetry}\right) \quad (4.5)$$

- There is no Z', H2 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, 1407.5492, JCAP)

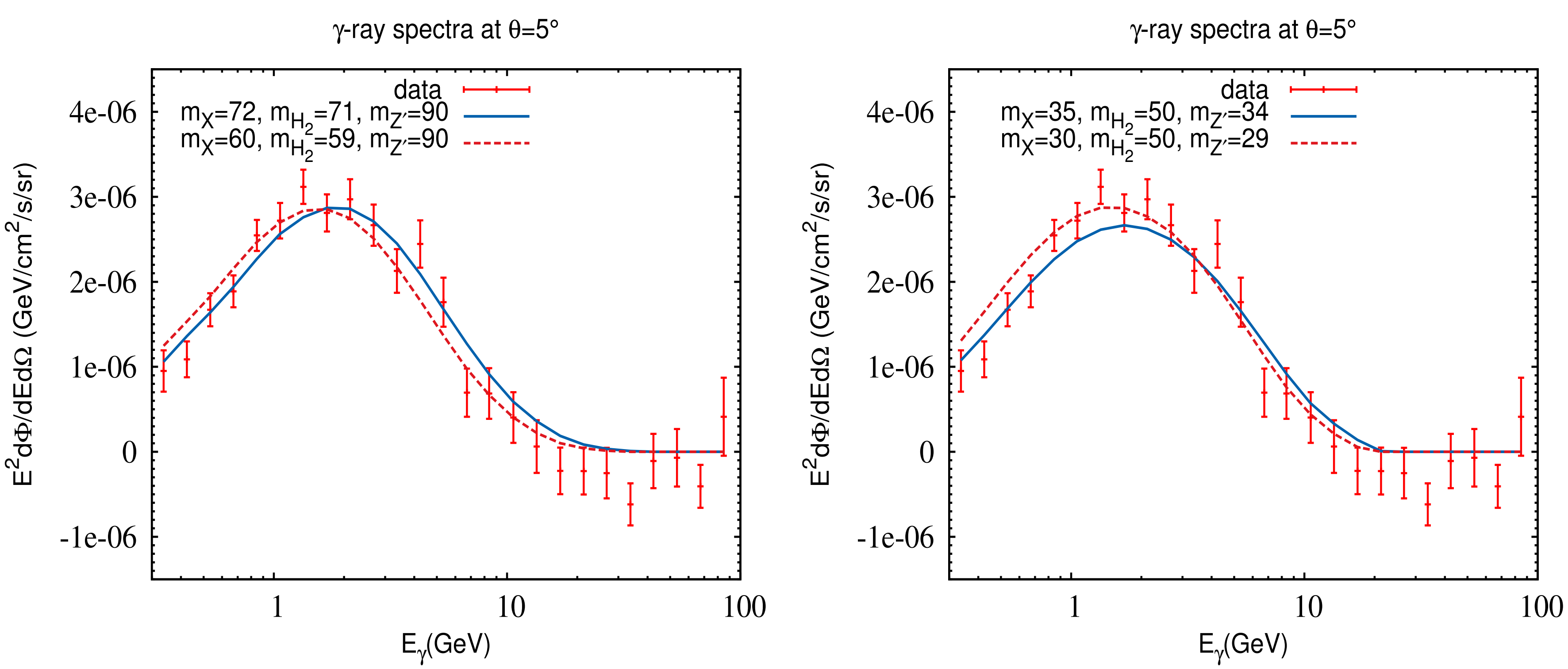


FIG. 4: γ-ray spectra from dark matter (semi-)annihilation with H_2(left) and Z'(right) as final states. In each case, mass of H_2 or Z' is chosen to be close to m_X to avoid large lorentz boost. Masses are in GeV unit. Data points at $\theta = 5$ degree are extracted from [1].

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

Hidden Sector Monopole, Stable VDM and Dark Radiation

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

+

Higgs portal

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

The Model

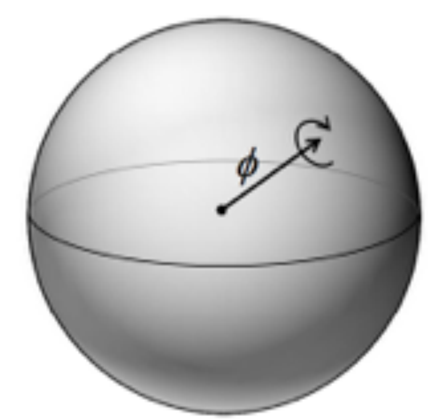
- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}V^a_{\mu\nu}V^{a\mu\nu} + \frac{1}{2}D_\mu\vec{\phi}\cdot D^\mu\vec{\phi} - \frac{\lambda_\phi}{4}\left(\vec{\phi}\cdot\vec{\phi} - v_\phi^2\right)^2 - \frac{\lambda_{\phi H}}{2}\vec{\phi}\cdot\vec{\phi}H^\dagger H$$

't Hooft-Polyakov monopole — Higgs portal

- Symmetry breaking

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



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

Stable due to topology and U(1)

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

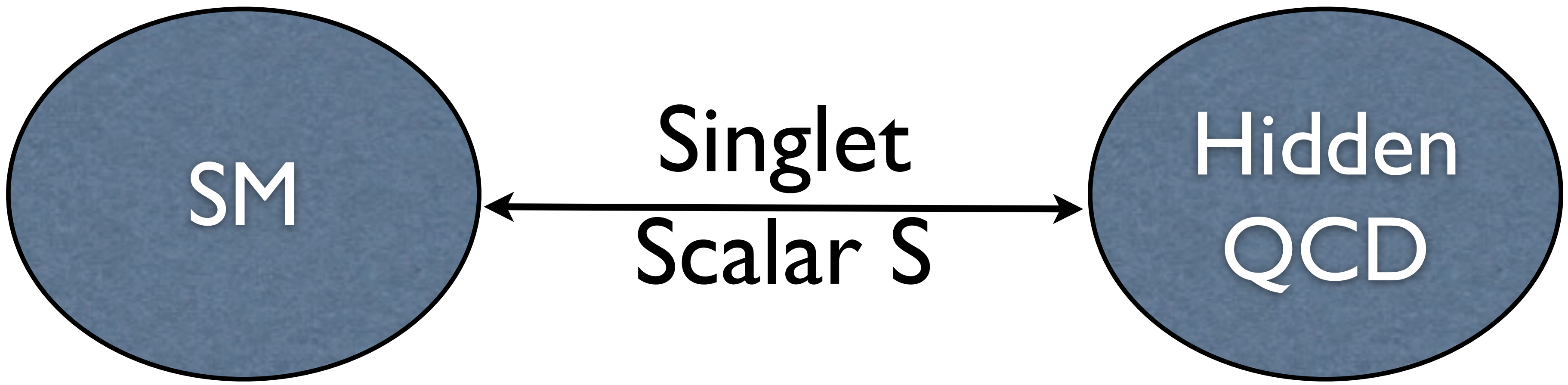
- Renormalizable
- Asymptotic freedom : no Landau pole
- QM dim transmutation :
- Light hadron masses from QM dynamics
- Flavor & Baryon # conservations : accidental symmetries of QCD (pion is stable if we switch off EW interaction; proton is stable or very long lived)

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

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

Hidden sector lagrangian with new strong interaction

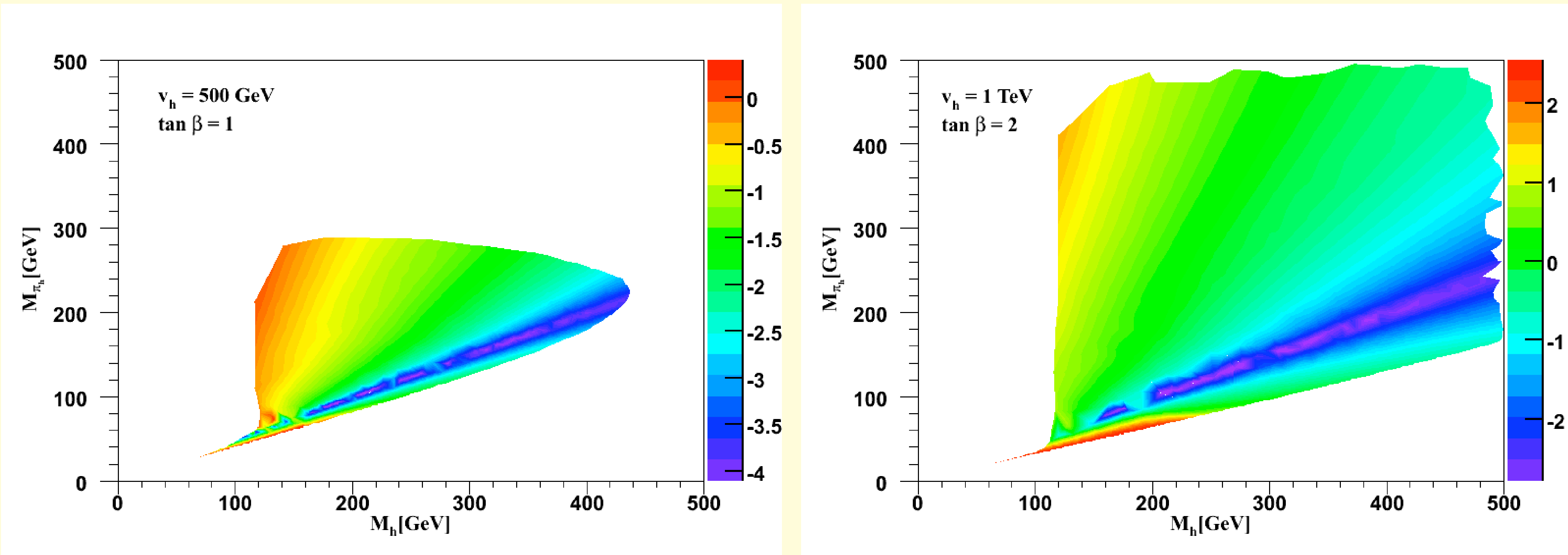
$$\mathcal{L}_{\rm hidden} = -\frac{1}{4}\mathcal{G}_{\mu\nu}\mathcal{G}^{\mu\nu} + \sum_{k=1}^{N_{HF}} \overline{\mathcal{Q}}_k (i\mathcal{D}\cdot\gamma - \lambda_k S)\mathcal{Q}_k$$

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

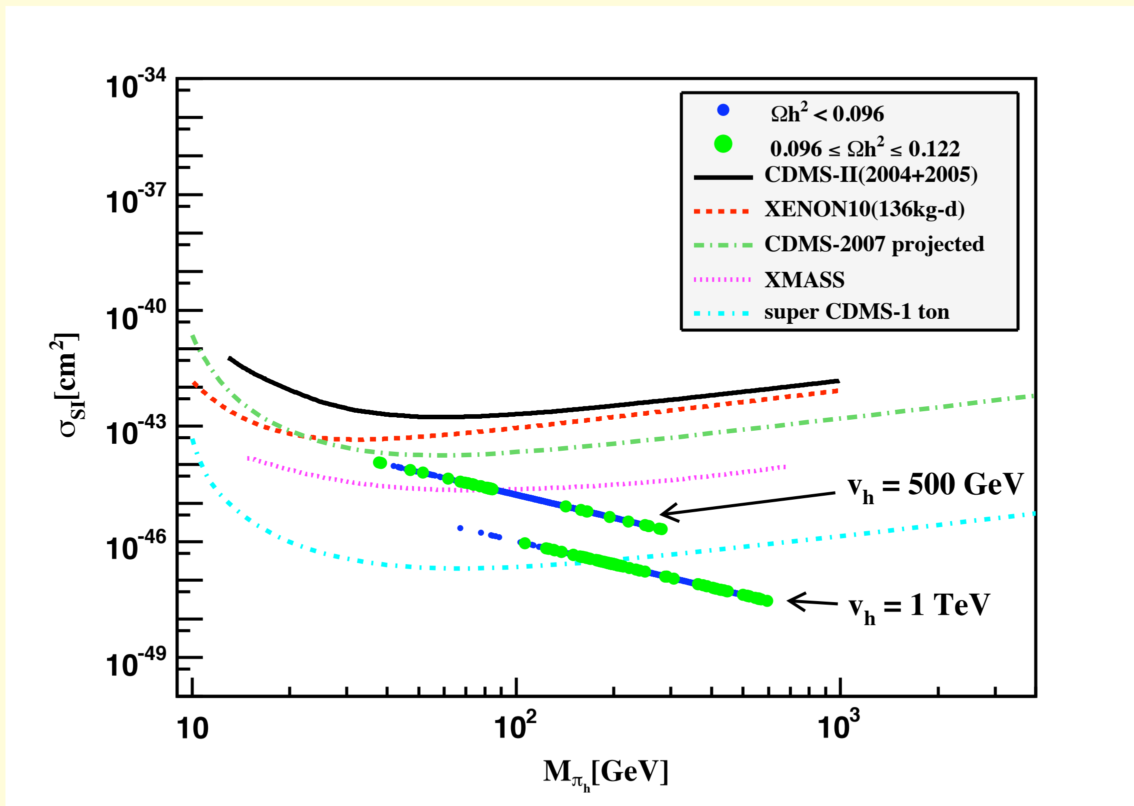


$\Omega_{\pi_h} h^2$ in the (m_{h_1}, m_{π_h}) plane for

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

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

Direct Detection Rate

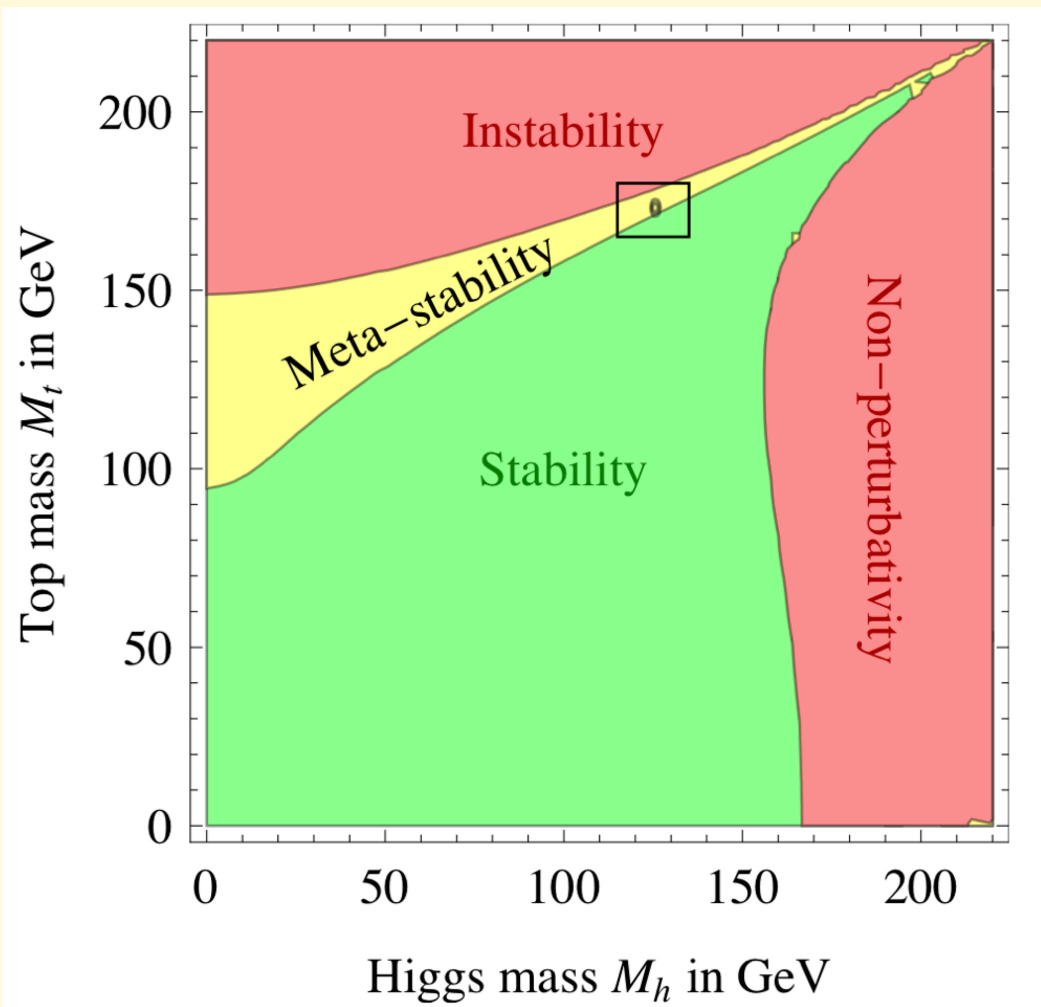


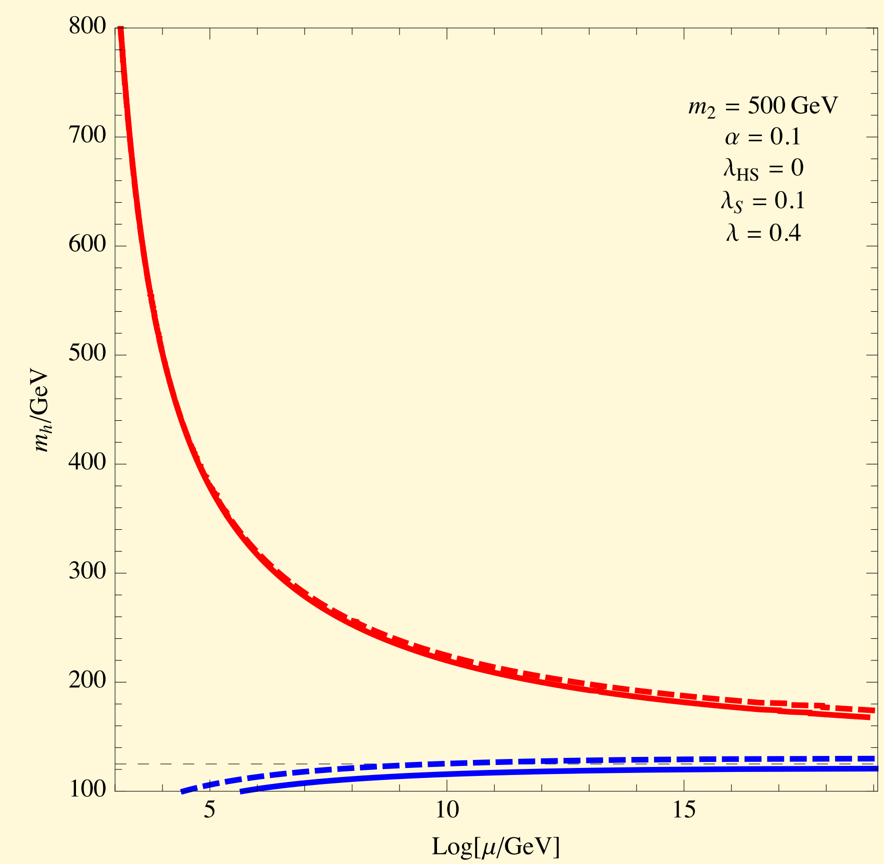
$\sigma_{SI}(\pi_h p \to \pi_h p)$ as functions of m_{π_h}.

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

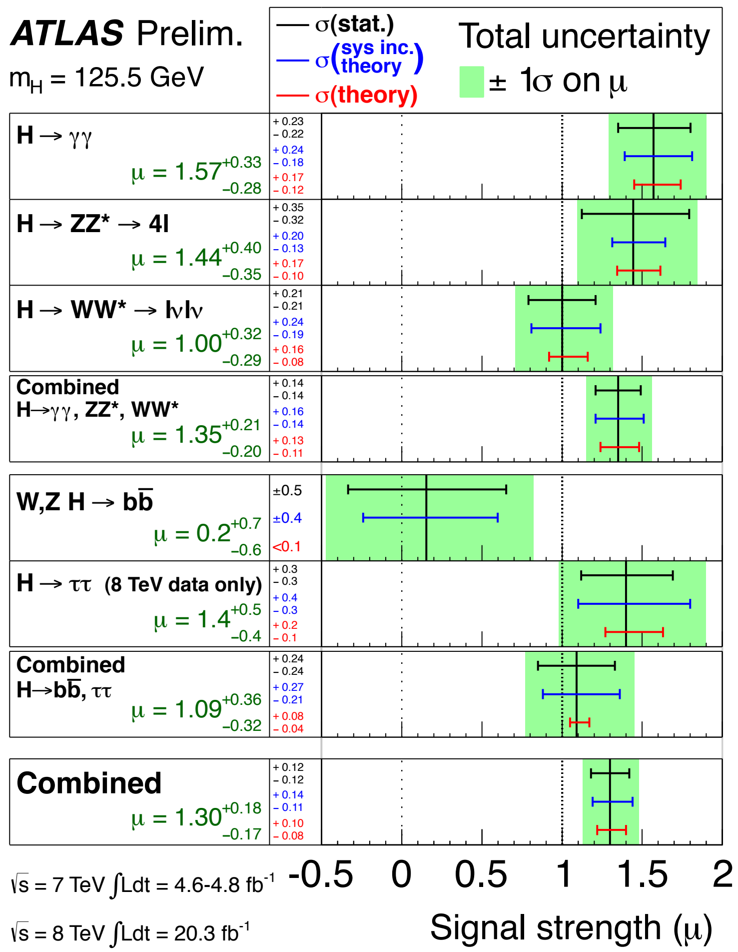


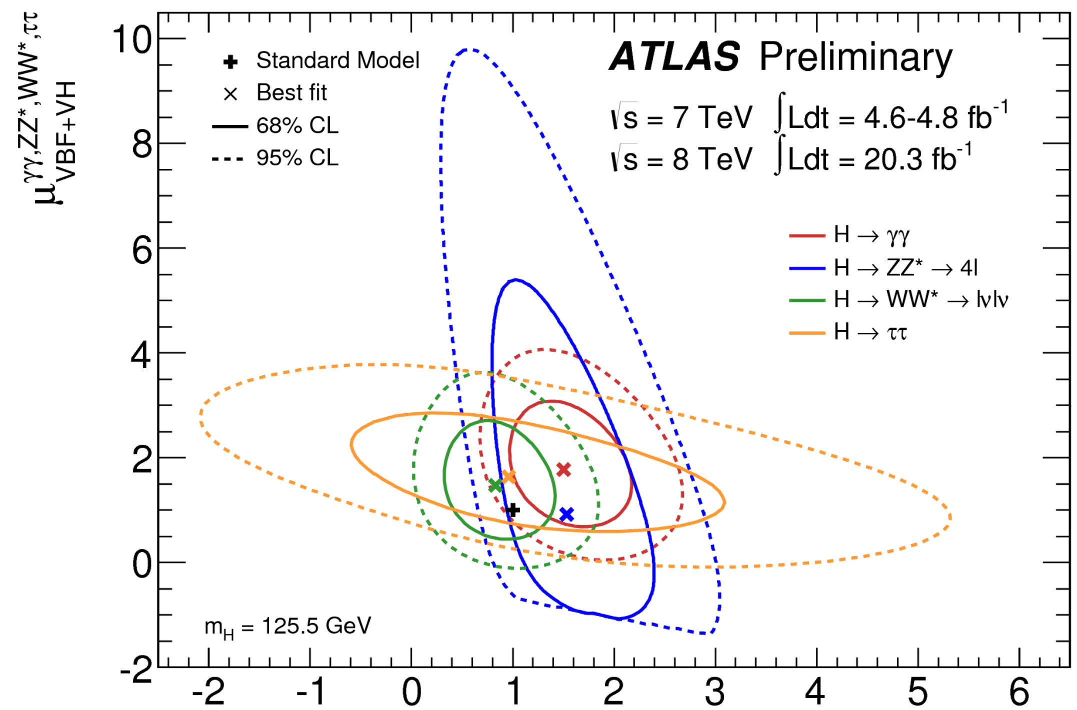


A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Main Decay and Production Modes





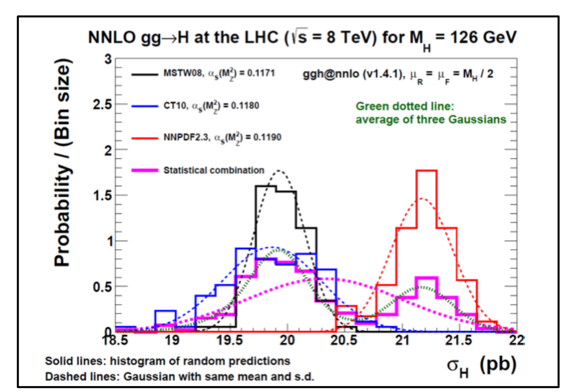
Assumes SM branching fractions and production modes

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 !

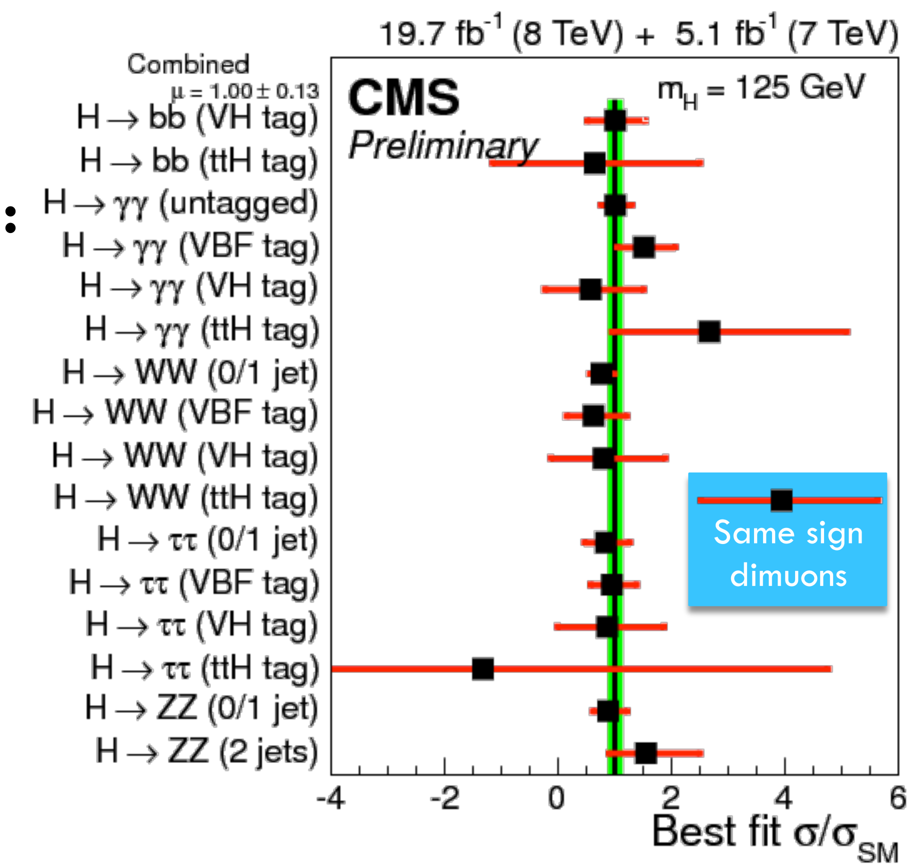


Signal strength

[CMS-PAS-HIG-14-009]

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

- 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

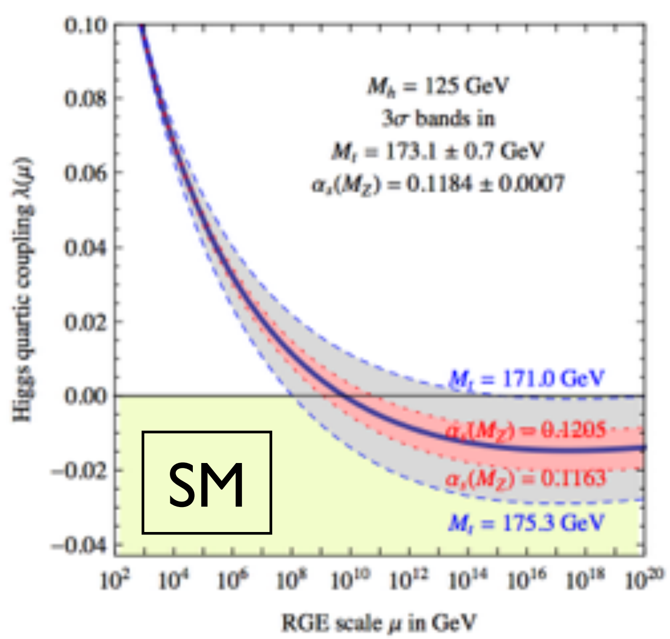
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

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

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

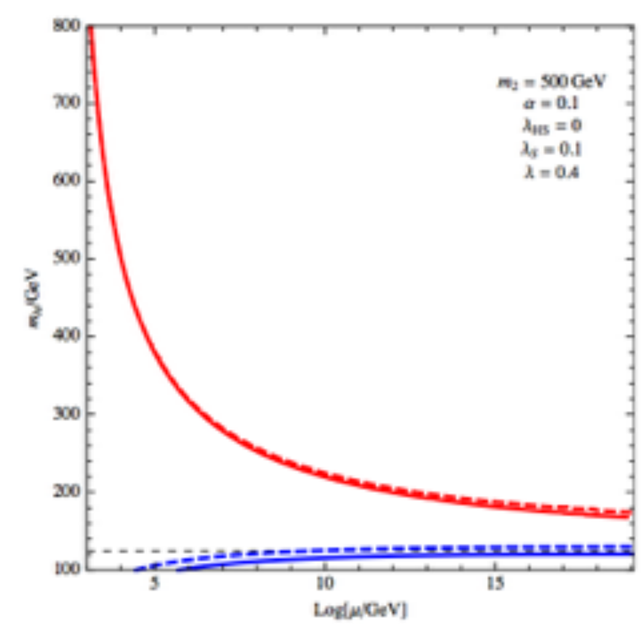
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1\right)\sin^2\alpha\right]\lambda_H^{SM}$$

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



[G. Degrassi et al., 1205.6497]

α



[S. Baek, P. Ko, WIP & 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 >> self-interacting DM >> 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

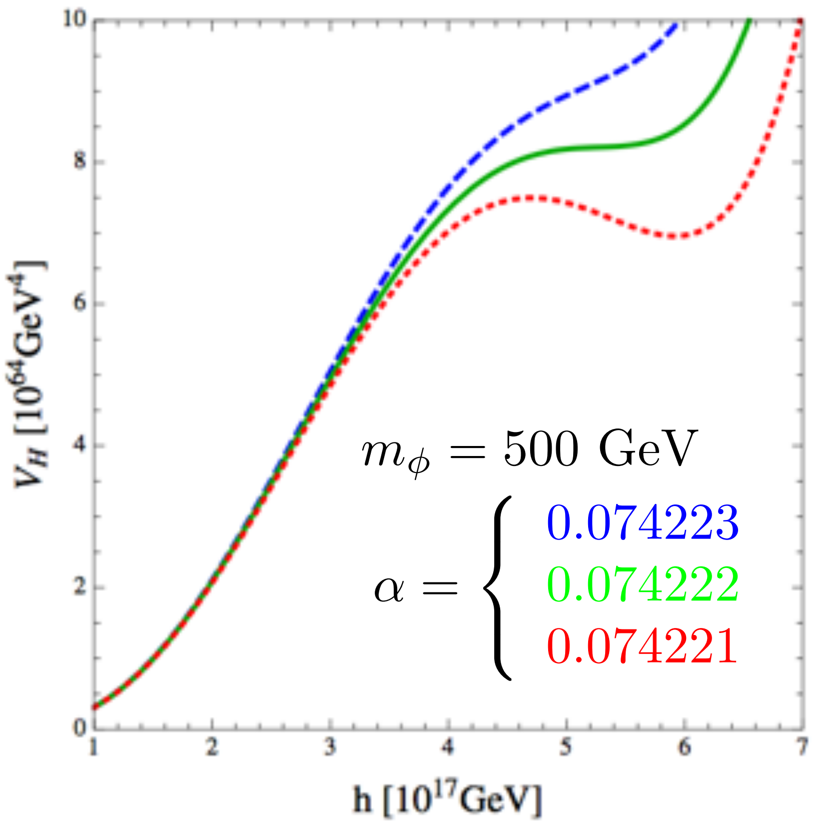
- Natural Ground for Light Mediators
- Invisible Higgs decay into a pair of DM, or
- Non Standard Higgs decays into a pair of light dark Higgs bosons, or dark gauge bosons, etc.
- Additional singlet-like scalar "S" : generic, can play important roles in DM phenomenology, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio (also strong 1st order ph tr)>> Should be actively searched for
- Searches @ LHC & other future colliders !

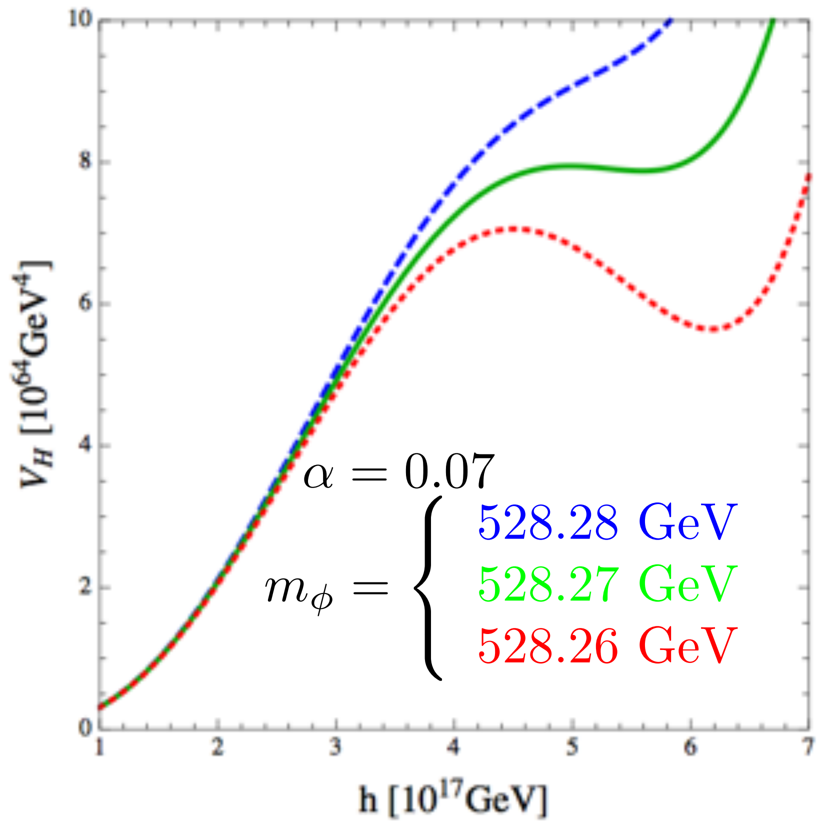
Impact of Dark Higgs -Cosmo.

(Higgs-portal assisted Higgs inflation)

[arXiv: 1405.1635, P. Ko & WIP]

Higgs-portal Higgs inflation

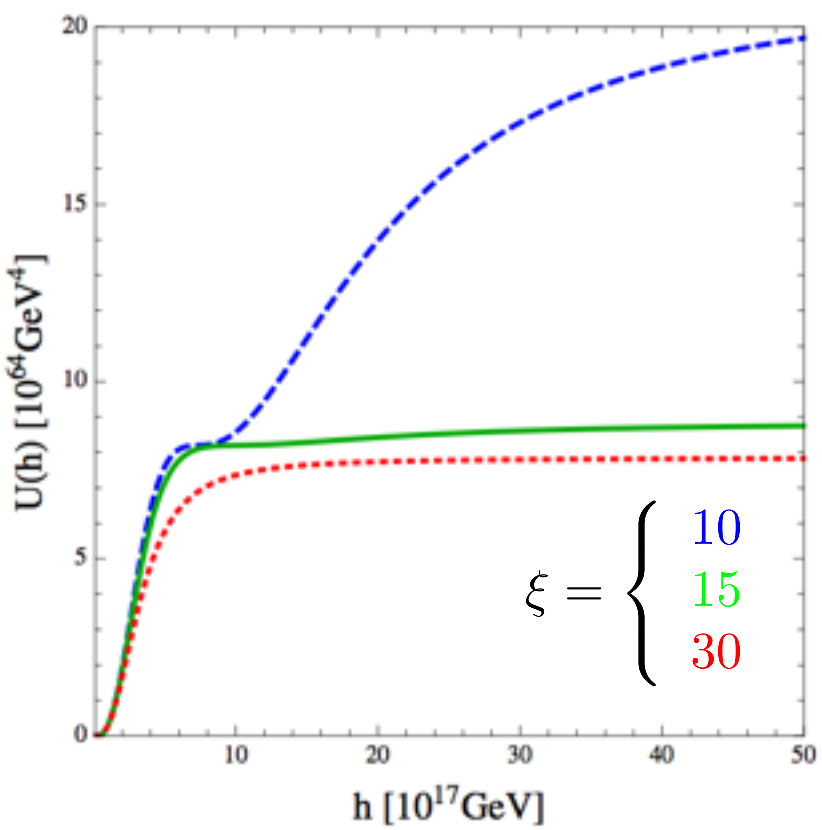




$m_t = 173.2$ GeV
$M_h = 125.5$ GeV

* Inflection point control

(α, m_ϕ) & $\lambda_{\Phi H}$



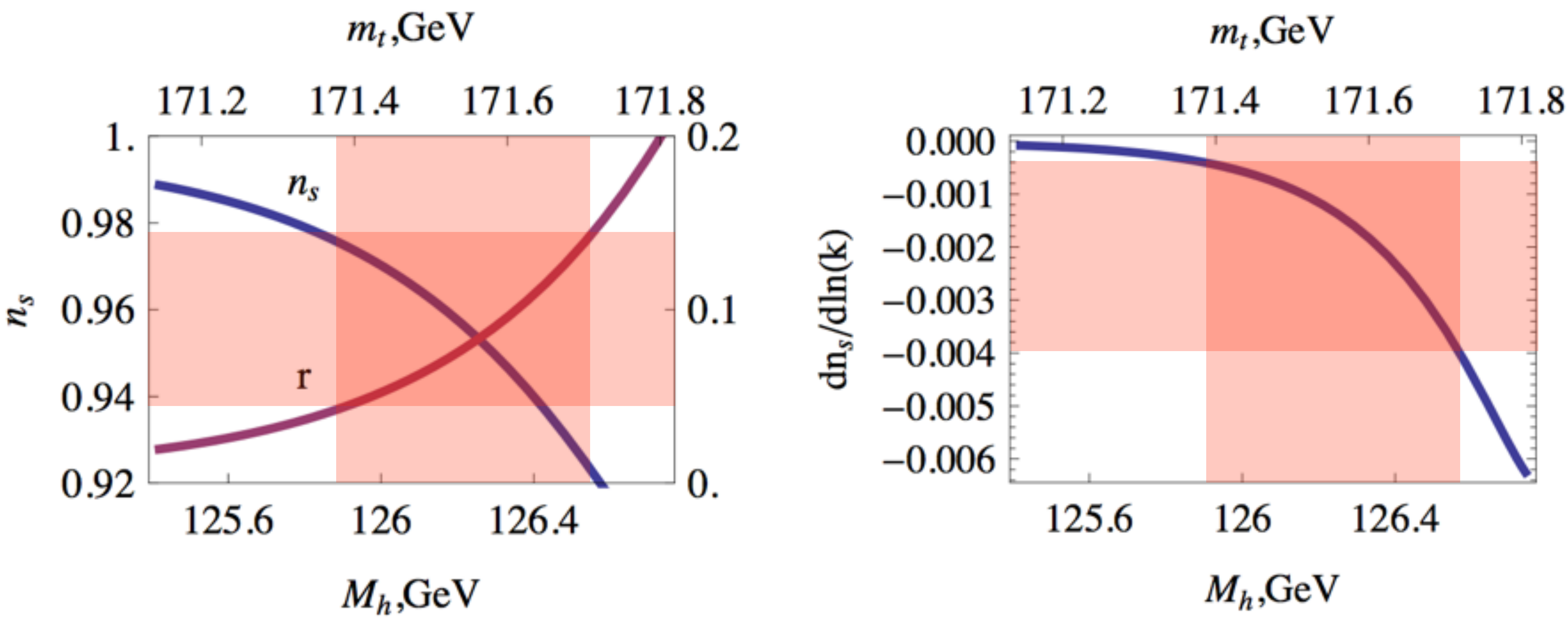
Result of numerical analysis

$k_* \times$ 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 $\lambda_{\Phi H}$ -

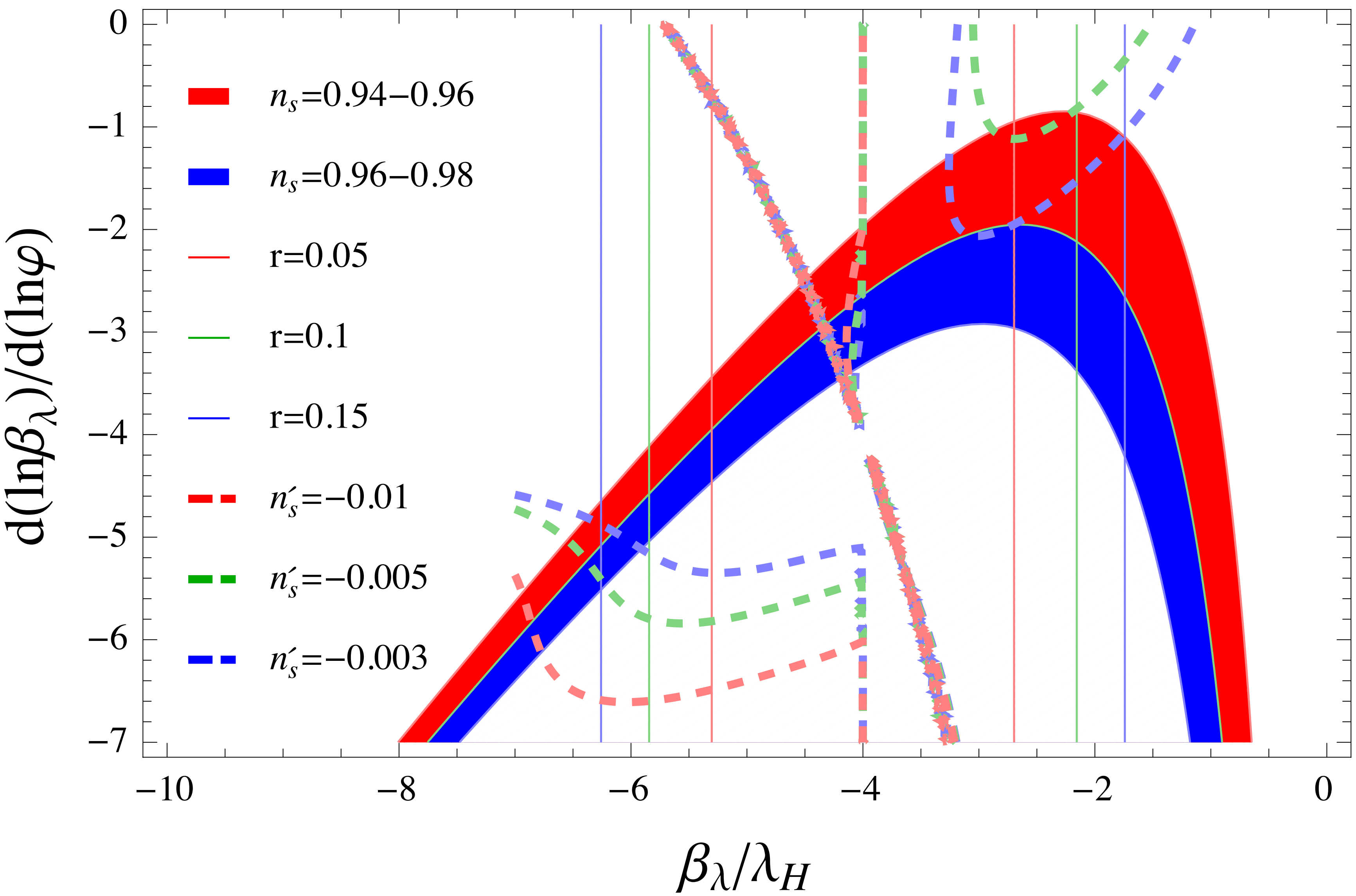
Scale dependence!

- 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

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

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

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

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

All invariant under ad hoc Z2 symmetry

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

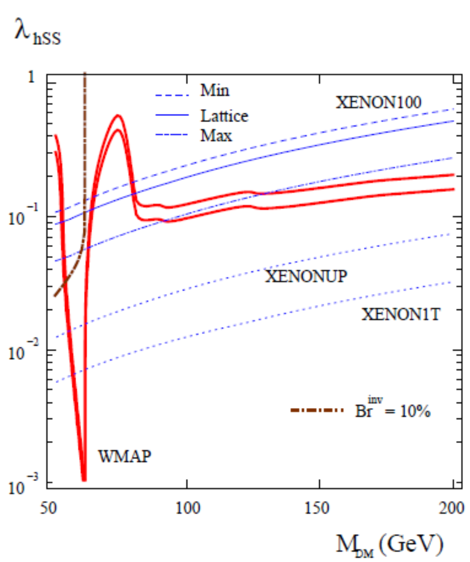


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

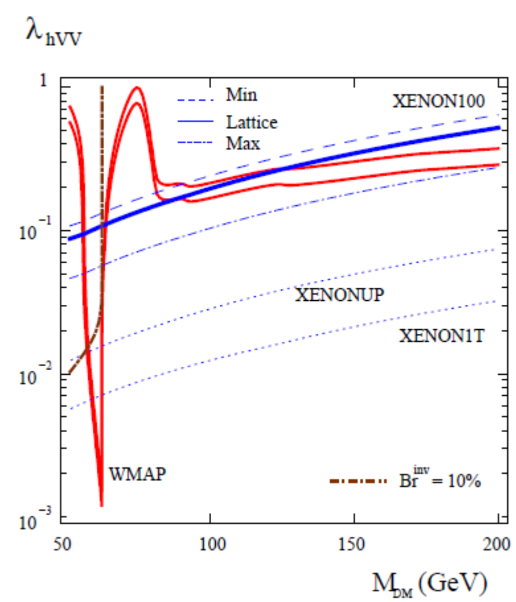


FIG. 2. Same as Fig. 1 for vector DM particles.

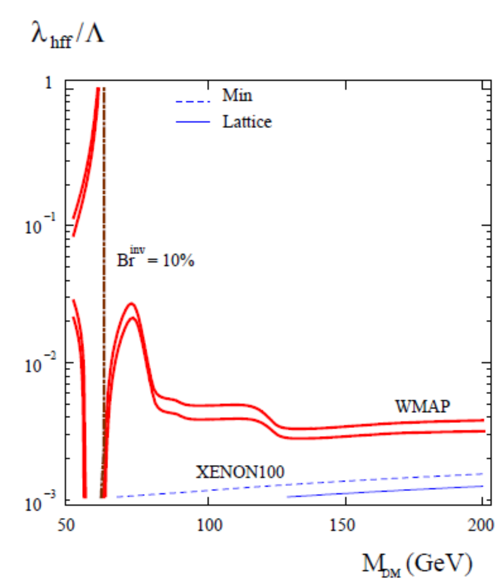


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

Higgs portal DM as examples

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_{HS}}{2}H^\dagger H S^2 - \frac{\lambda_S}{4}S^4$$
$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \frac{\lambda_{H\psi}}{\Lambda}H^\dagger H\ \overline{\psi}\psi$$
$$\mathcal{L}_{\rm vector} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{2}\lambda_{HV}H^\dagger H V_\mu V^\mu .$$

All invariant under ad hoc Z2 symmetry

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

Usual story within EFT

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

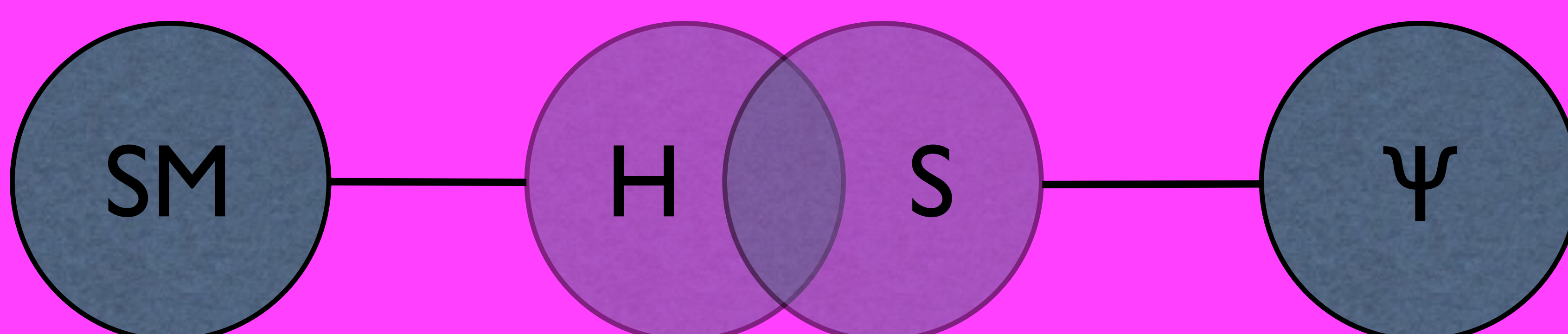
Singlet fermion CDM

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

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

at vacuum

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

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

⇐ Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

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

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

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

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

Invisible decay mode is not necessary!

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

Constraints

EW precision observables

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

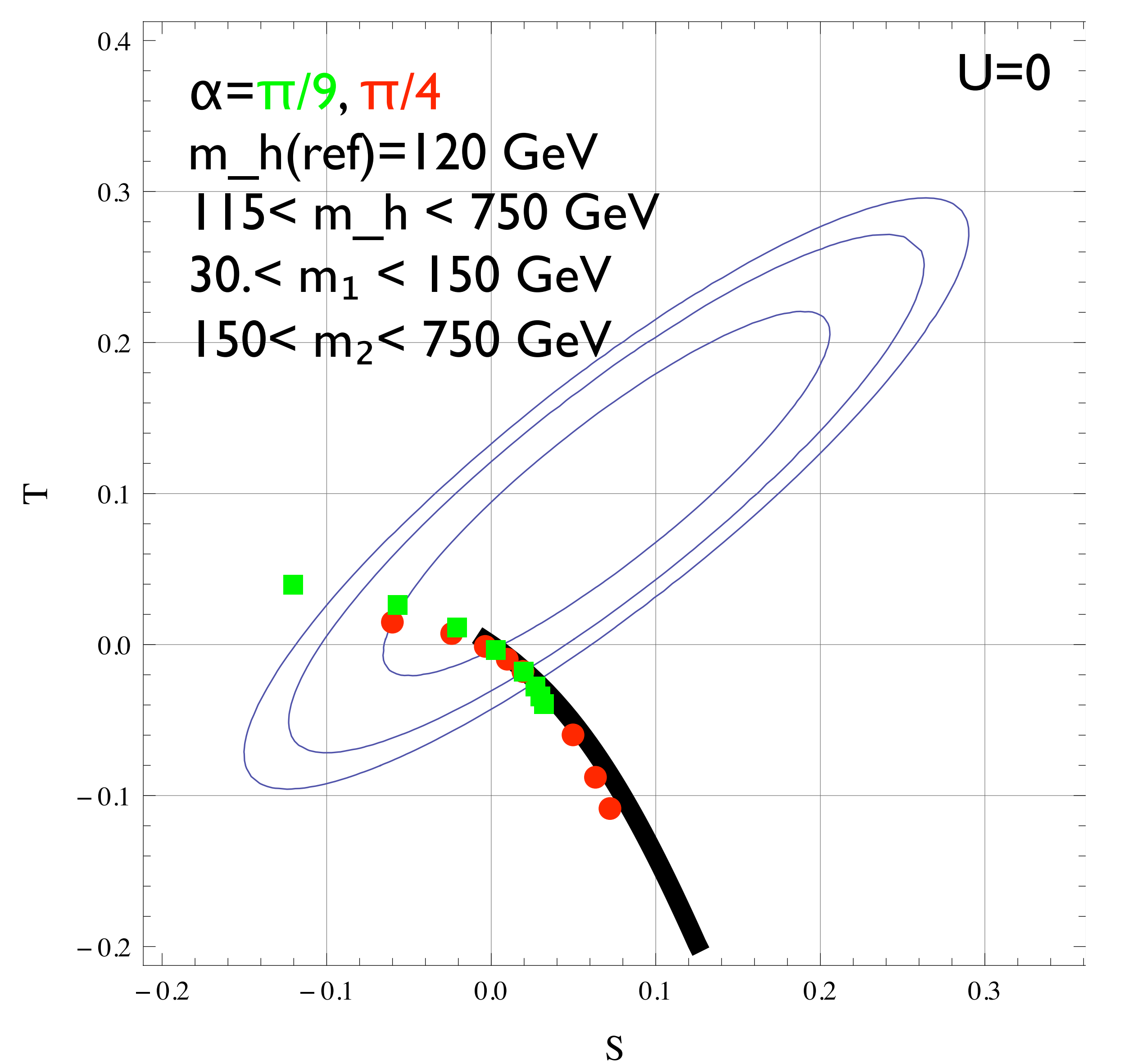
$$\alpha_{\rm em} S = 4 s_W^2 c_W^2 \left[\frac{\Pi_{ZZ}(M_Z^2) - \Pi_{ZZ}(0)}{M_Z^2}\right]$$

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

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

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

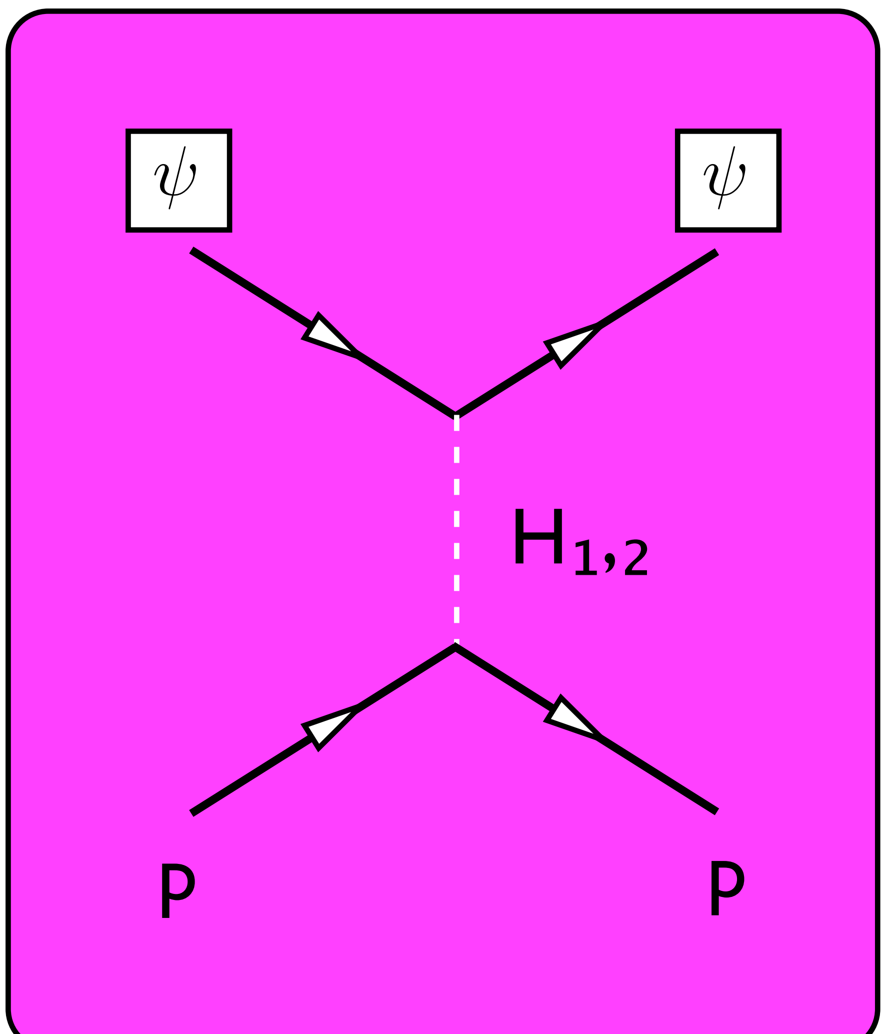
Same for T and U

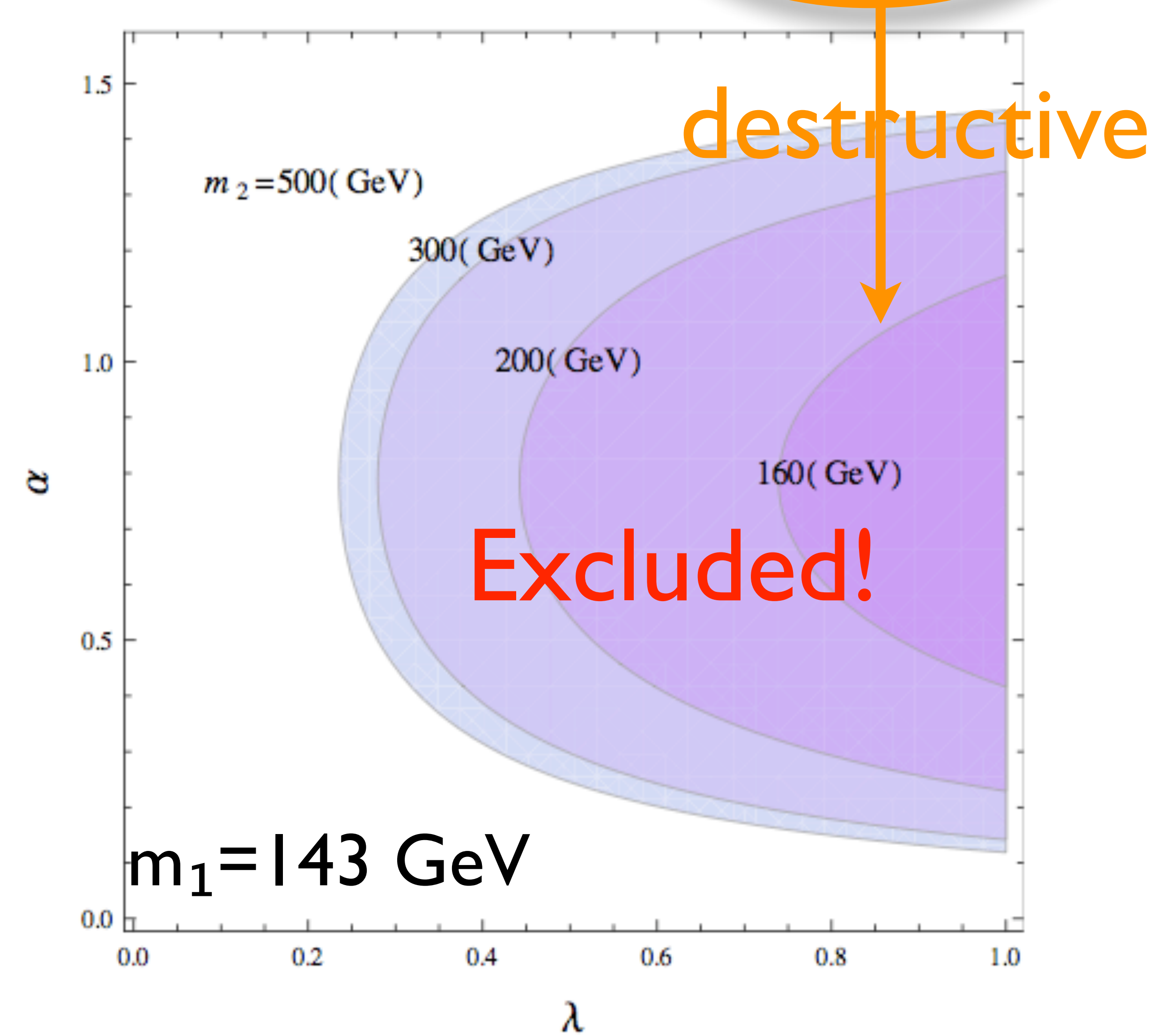


Constraints

- Dark matter to nucleon cross section (constraint)

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

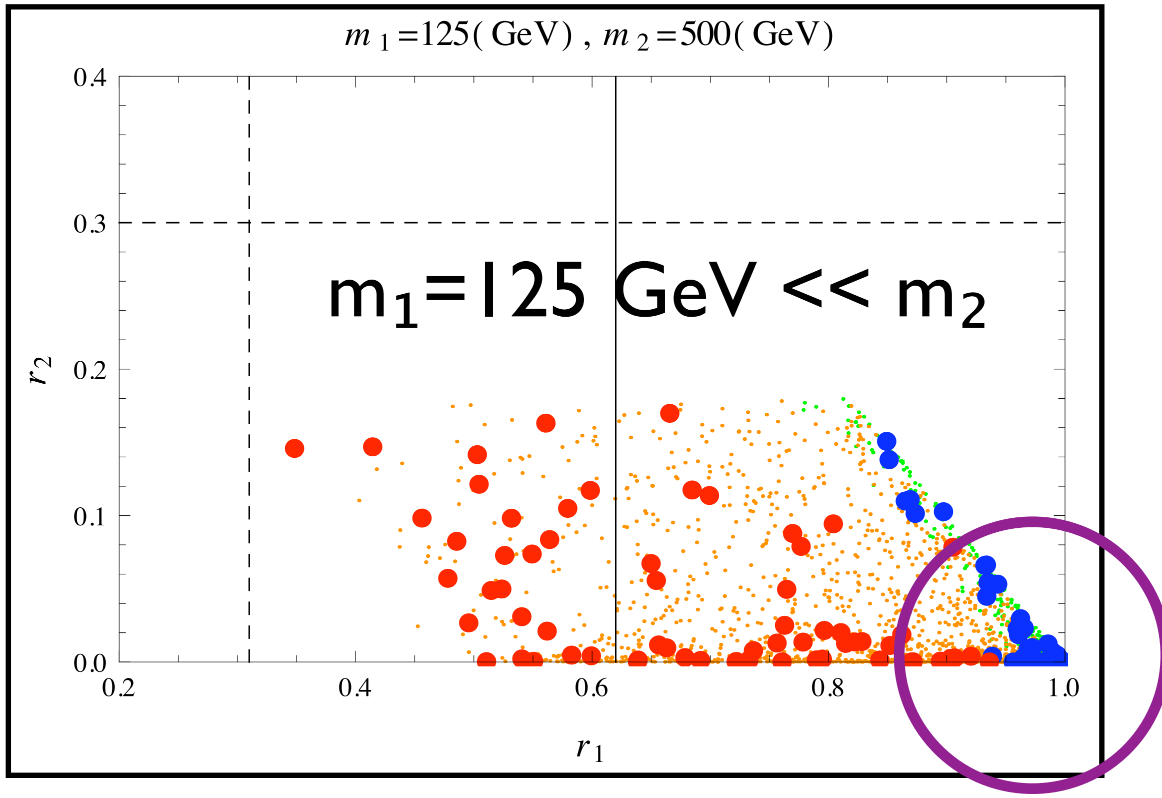


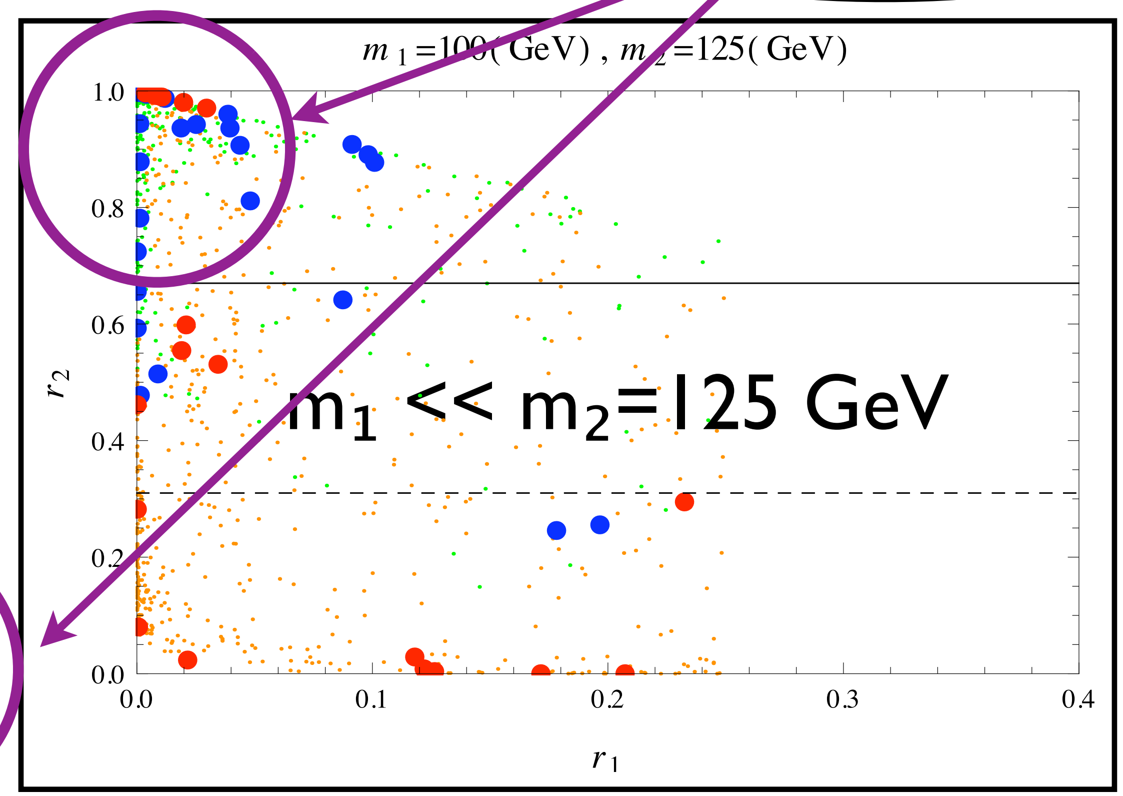


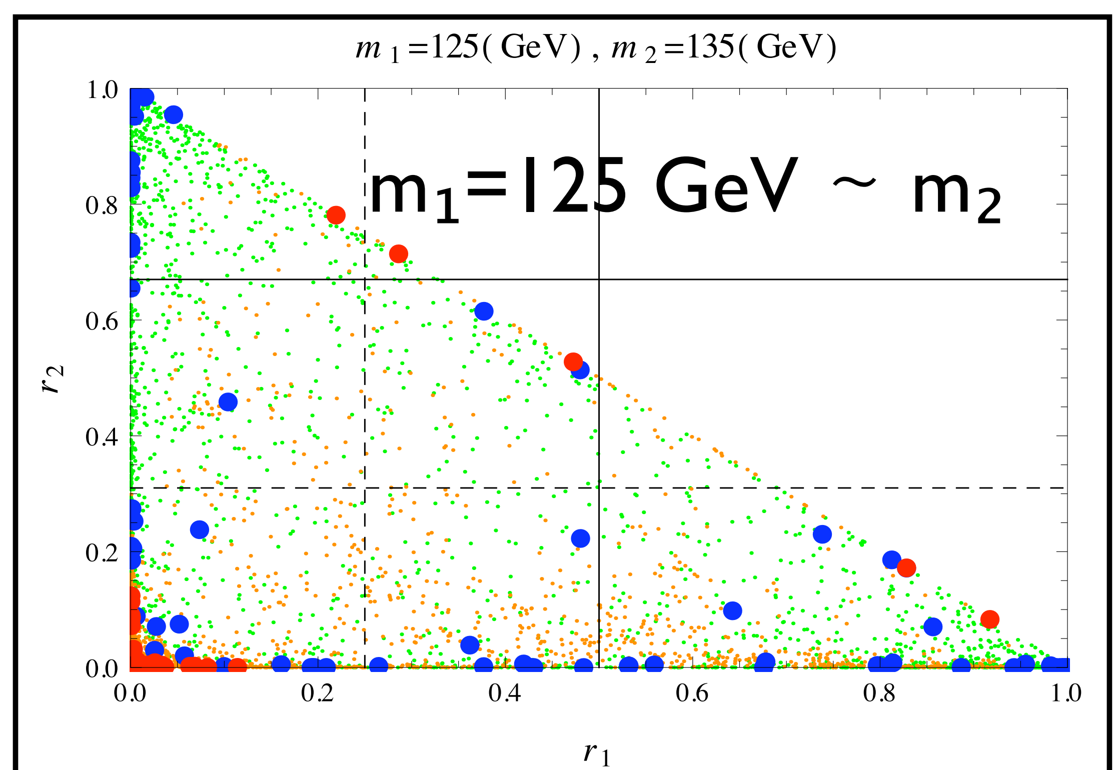
Discovery possibility

- Signal strength (r_2 vs r_1)

LHC data for 125 GeV resonance







: L= 5 fb^{-1} for 3σ Sig.

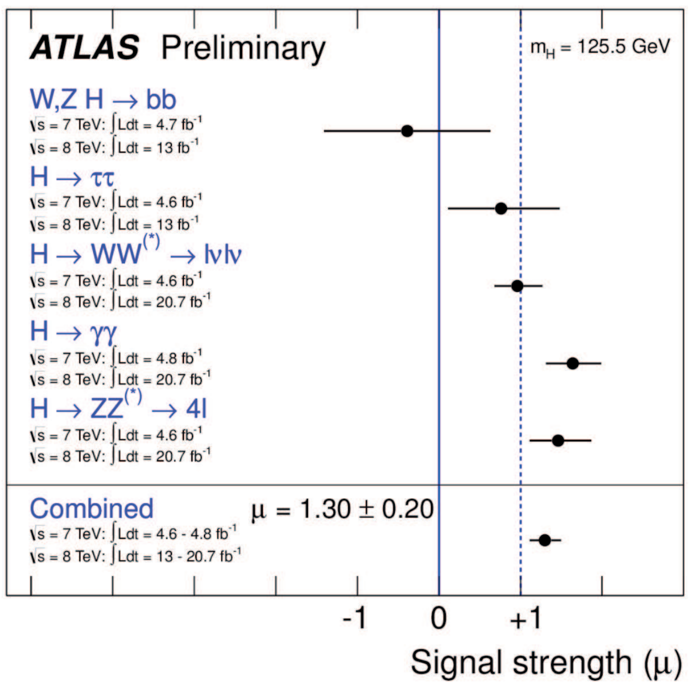
: L=10 fb^{-1} for 3σ Sig.

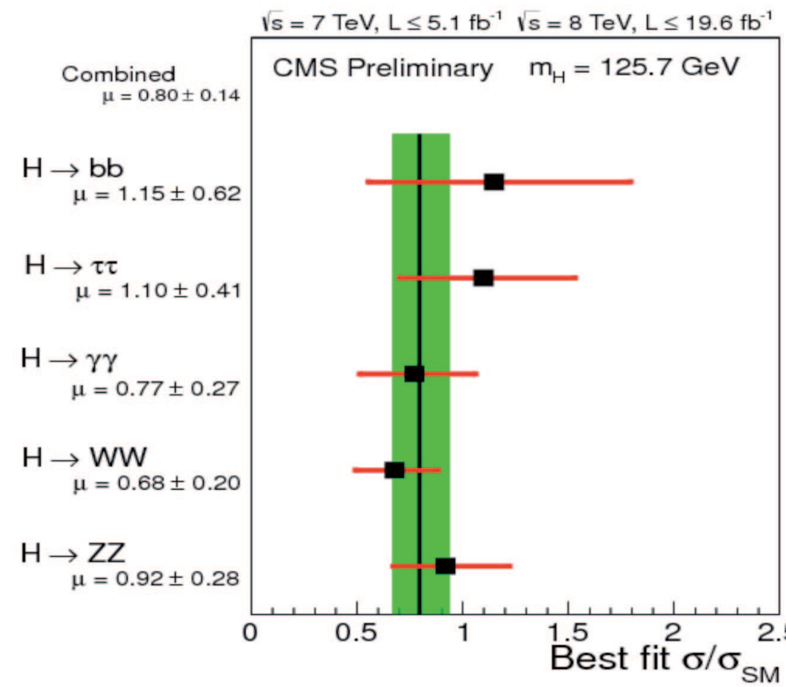
- : Ω(x),σ_p(x)
- : Ω(x),σ_p(o)
- : Ω(o),σ_p(x)
- : Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

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



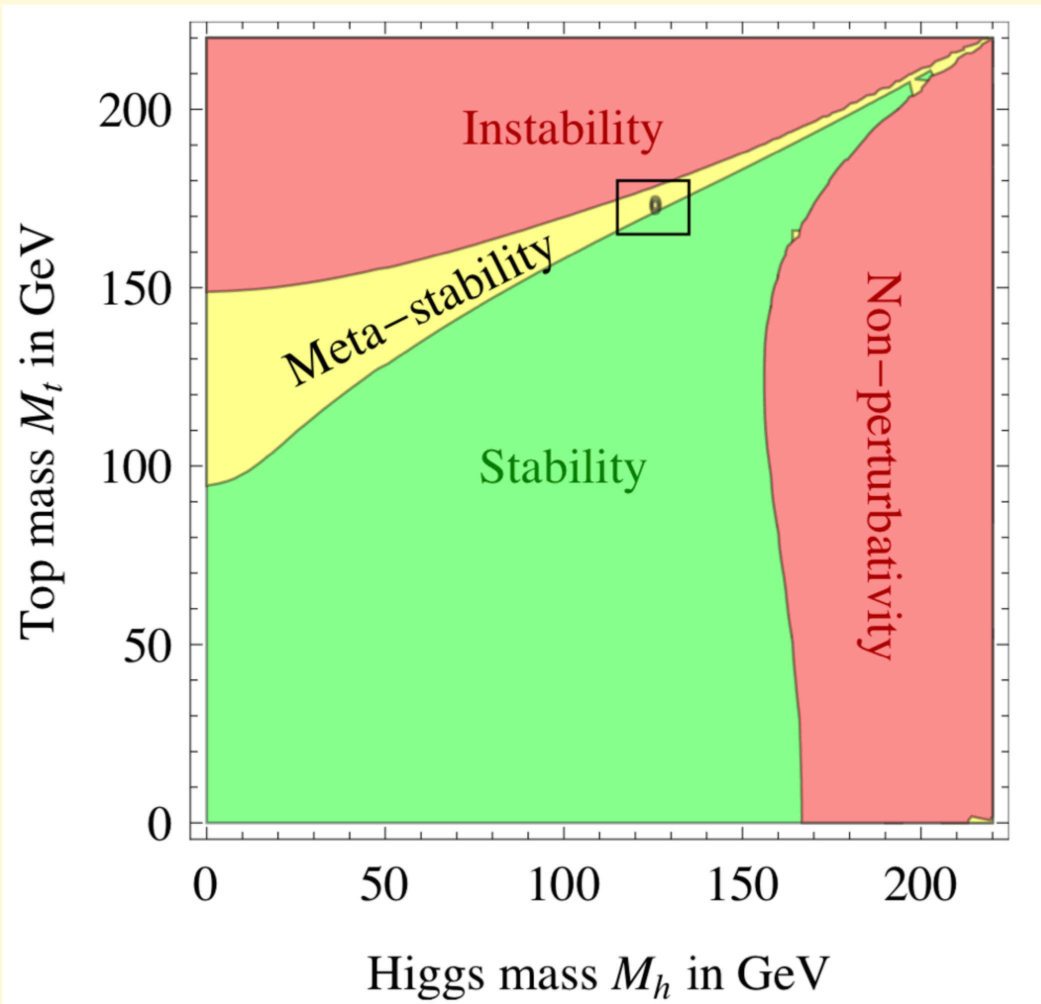


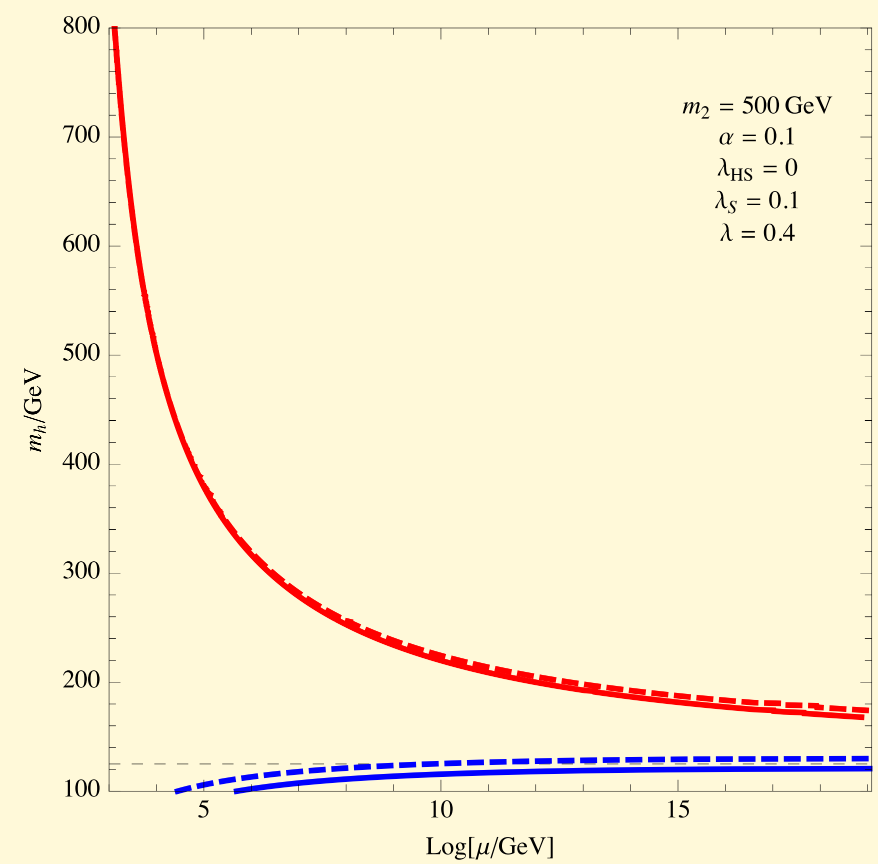
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Getting smaller

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

Baek, Ko, Park, Senaha (2012)

Low energy pheno.

- Universal suppression of collider SM signals

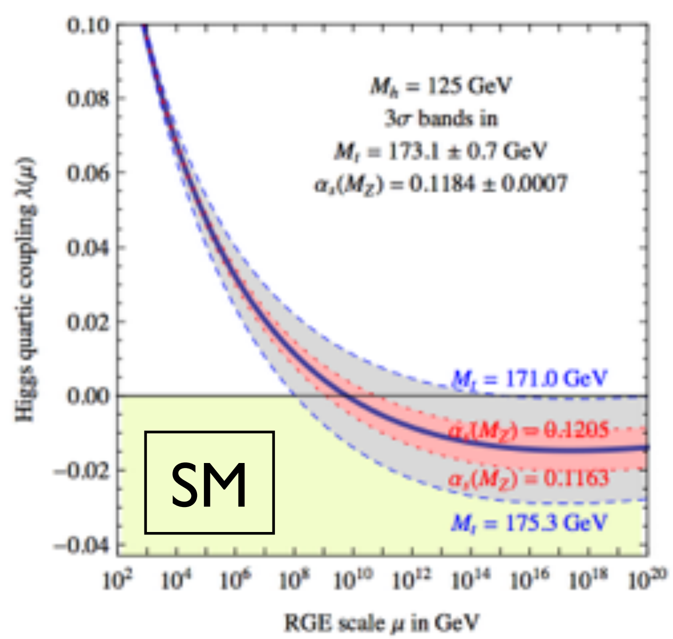
[See 1112.1847, Seungwon Baek, P. Ko & WIP]

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

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

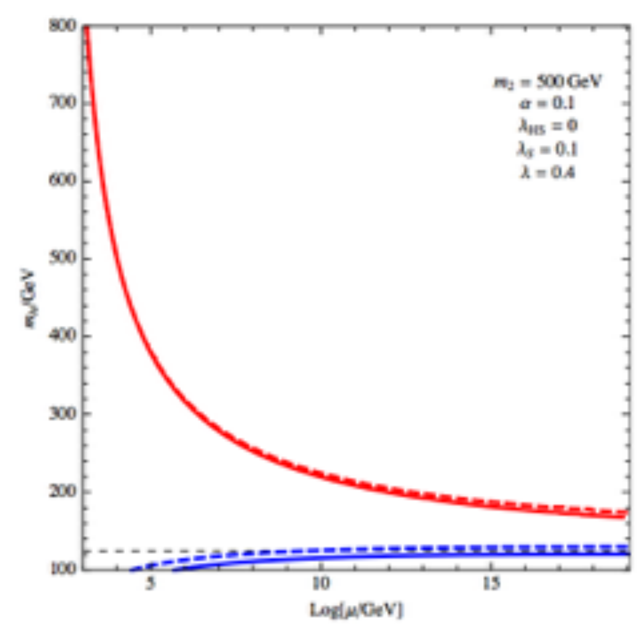
$$\lambda_{\Phi H} \Rightarrow \lambda_H = \left[1 + \left(\frac{m_\phi^2}{m_h^2} - 1 \right) \sin^2 \alpha \right] \lambda_H^{SM}$$

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



[G. Degrassi et al., 1205.6497]

α



[S. Baek, P. Ko, WIP & 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

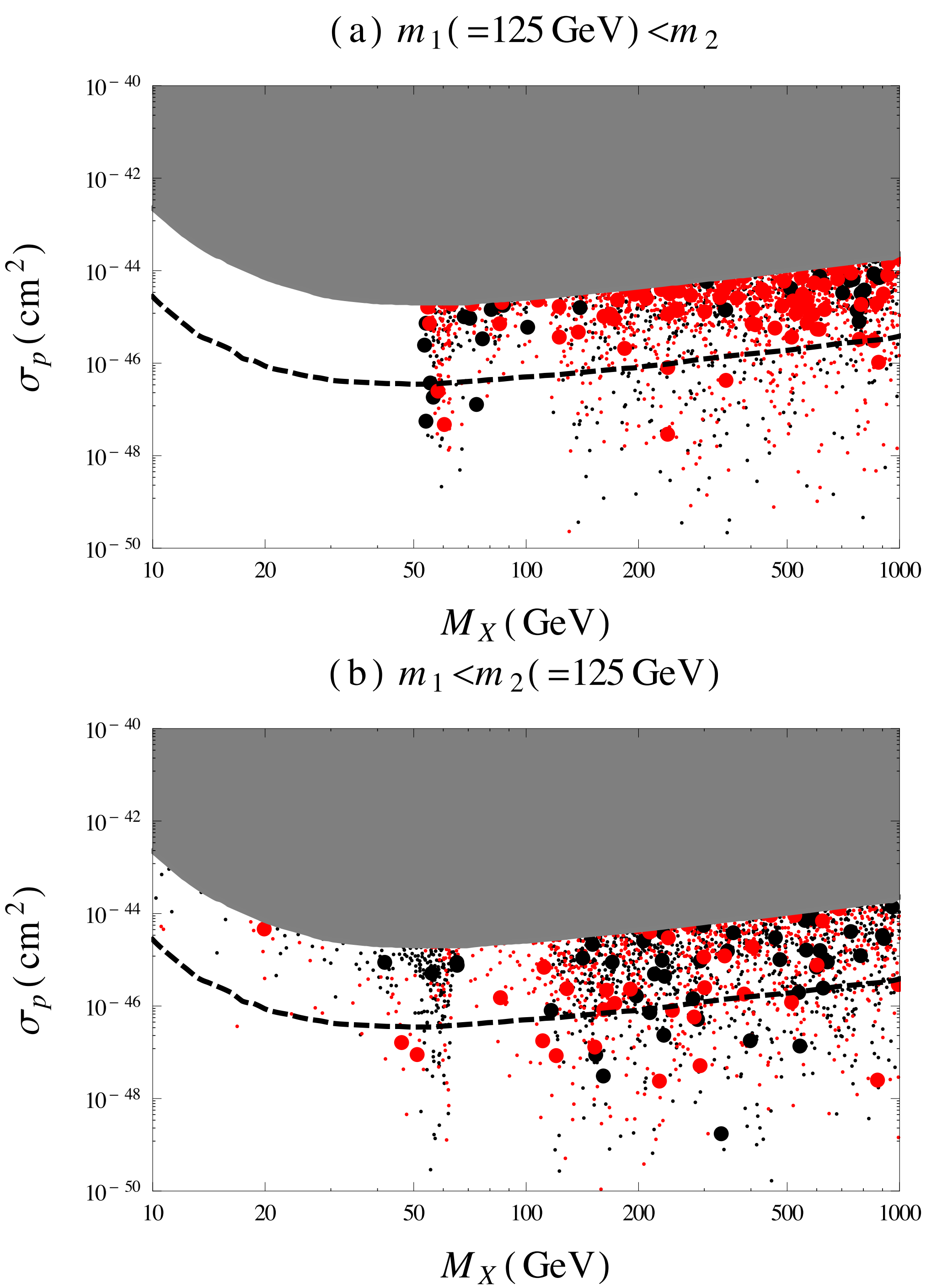


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7 (r_1 < 0.7)$. The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

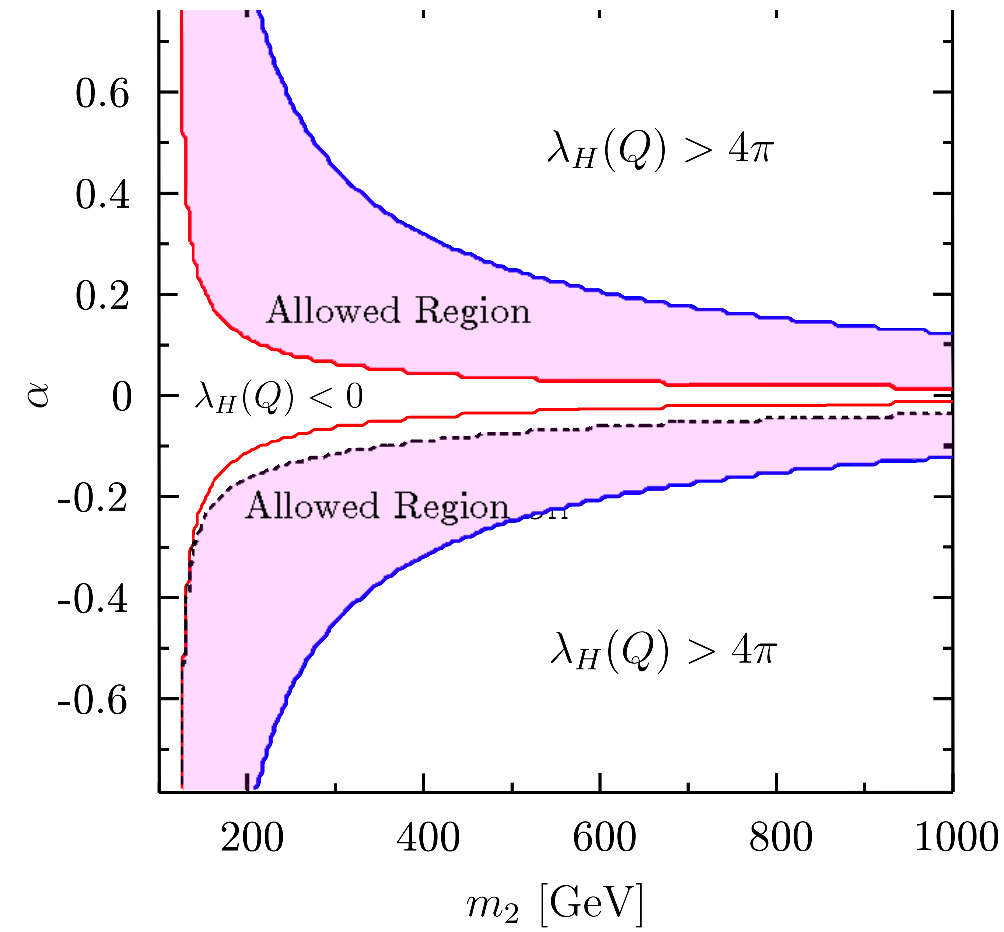


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

Comparison with the EFT approach

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

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

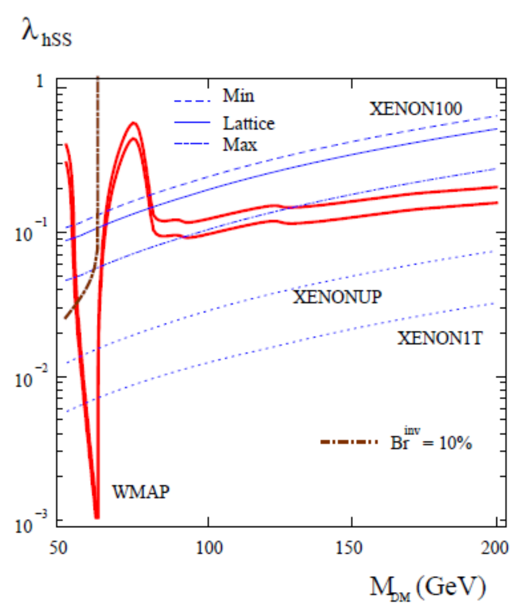


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

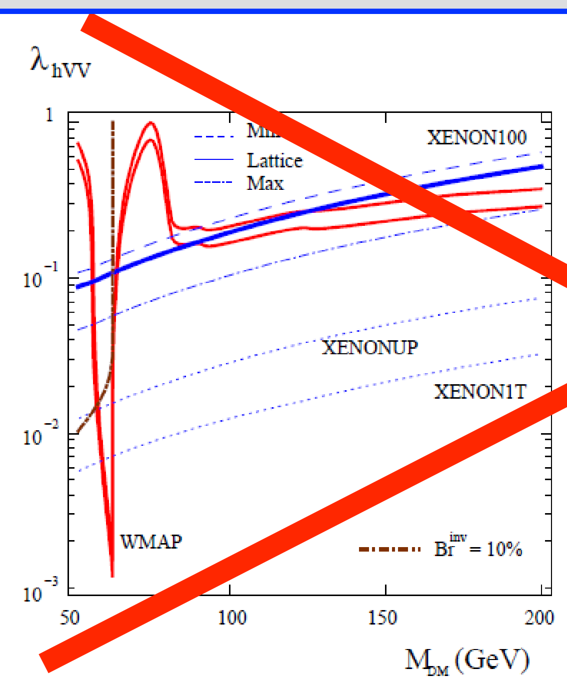


FIG. 2. Same as Fig. 1 for vector DM particles.

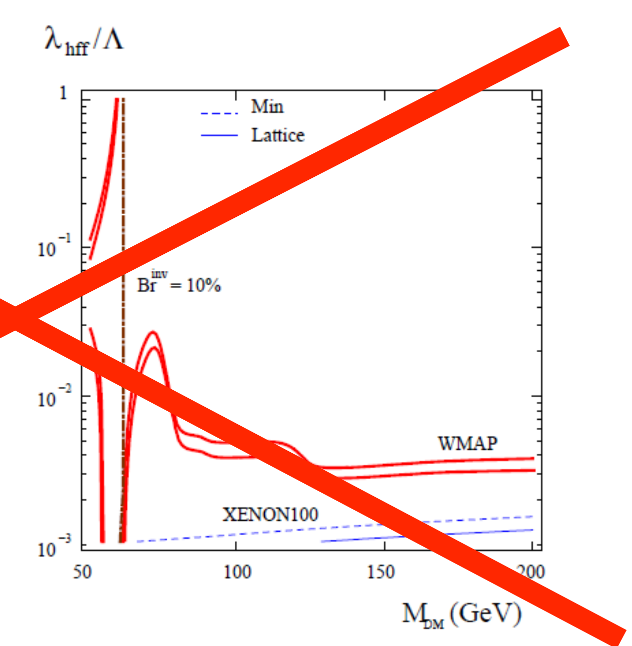


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

With renormalizable lagrangian,
we get different results !

- 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

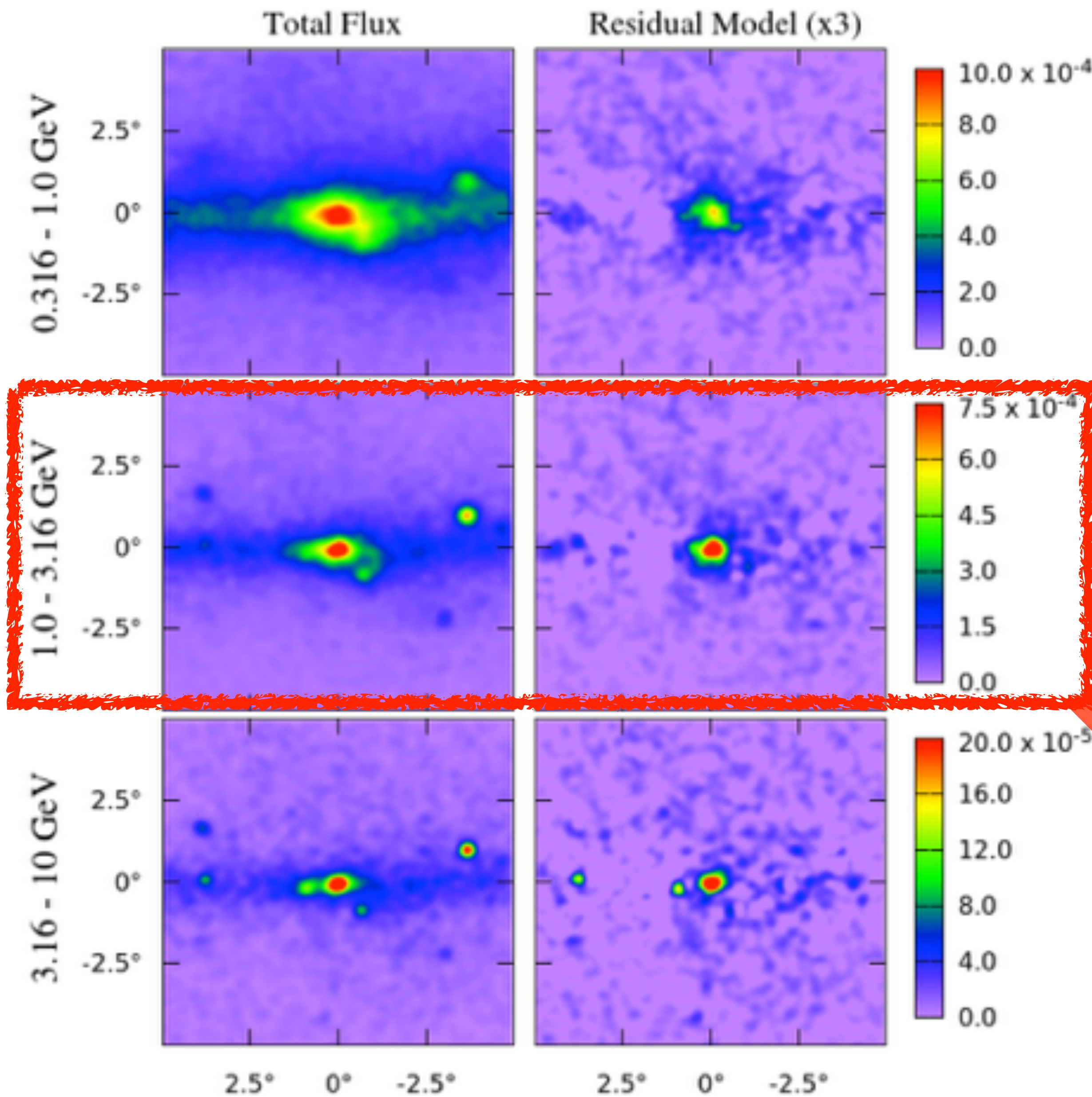
Is this any useful in phenomenology ?

Is this any useful in phenomenology ?

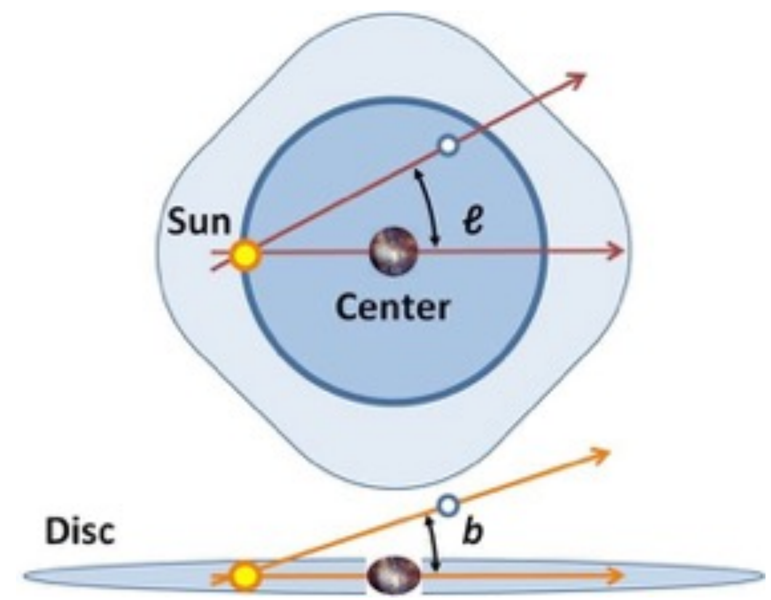
YES !

Fermi-LAT γ-ray excess

- Gamma-ray excess in the direction of GC



[1402.6703, T. Daylan et.al.]

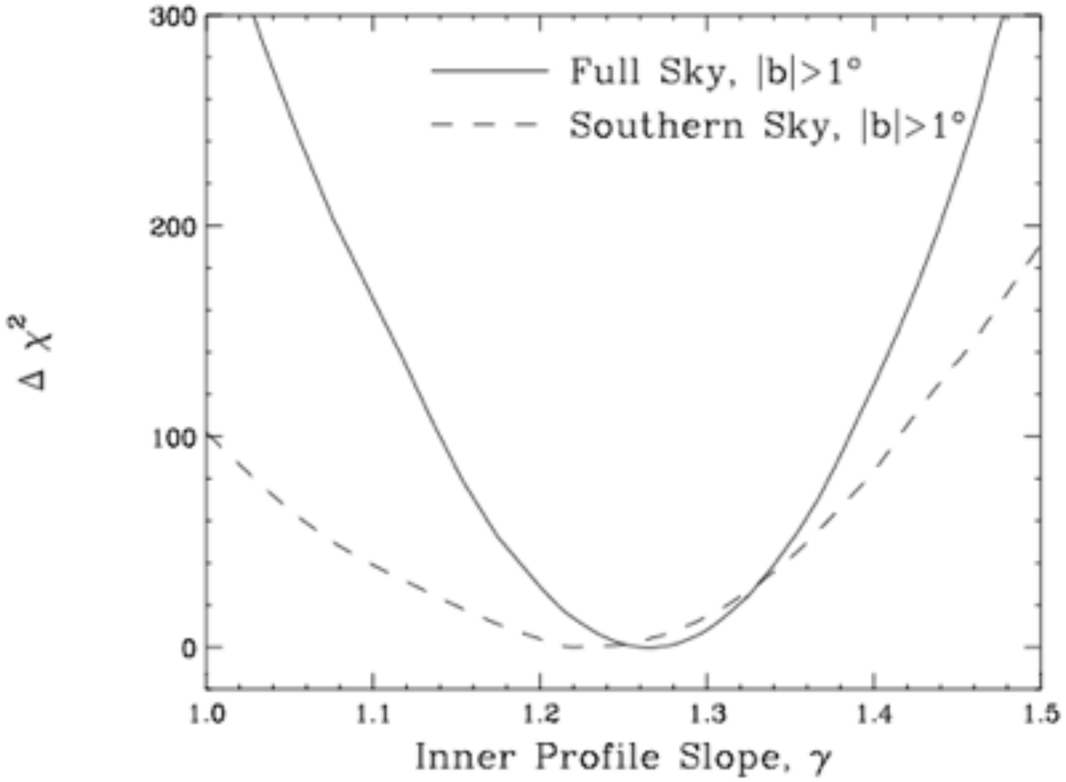


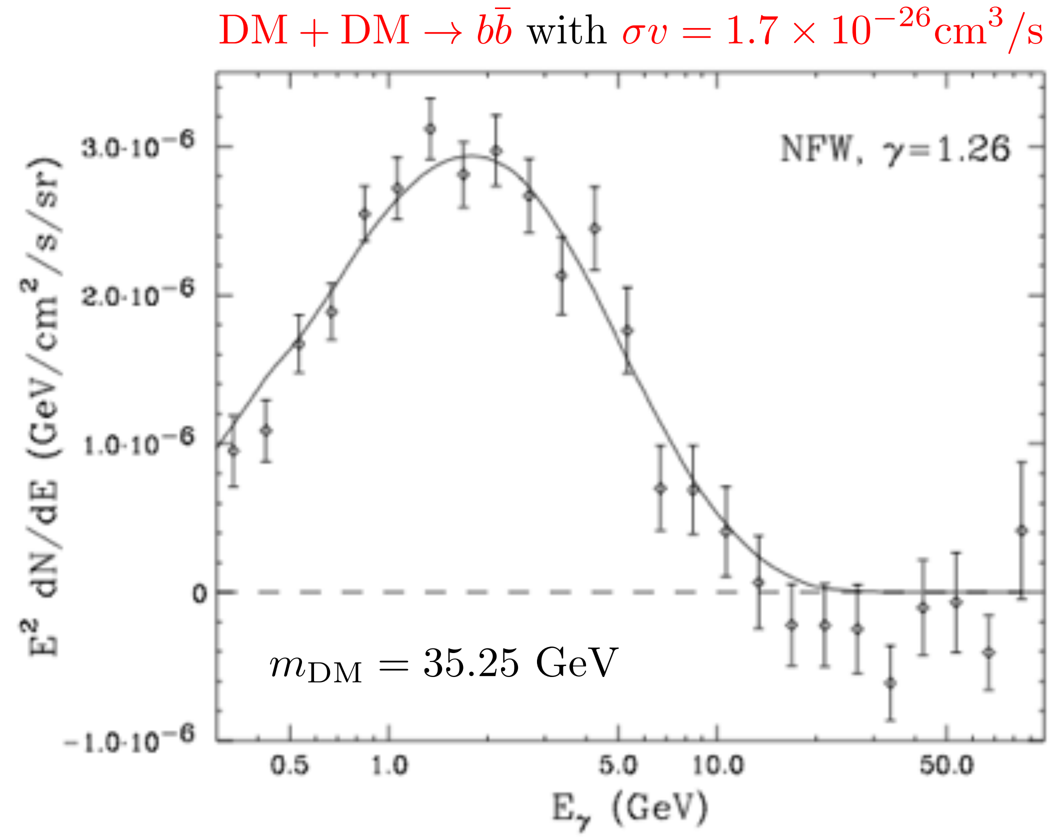
$$\text{GC} : b \sim l \lesssim 0.1^\circ$$

extended

GeV scale excess!

• A DM interpretation





* See "1402.6703, T. Daylan et.al." for other possible channels

• Millisecond Pulars (astrophysical alternative)

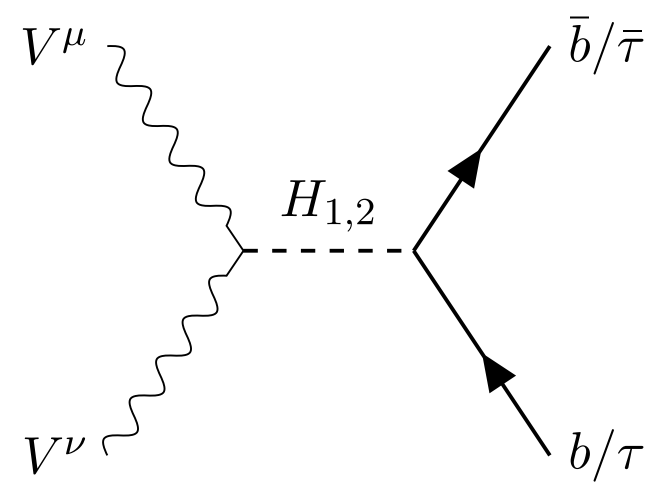
It may or may not be the main source, depending on

- 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

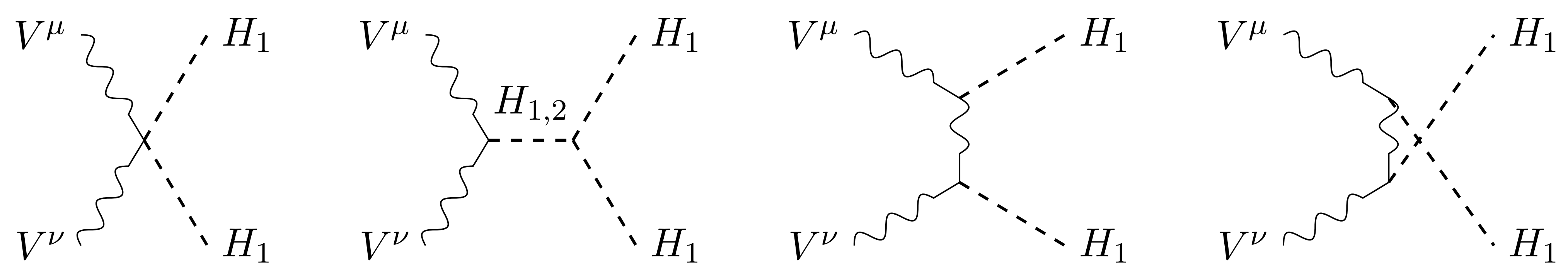


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b+\bar{b}$

Importance of VDM with Dark Higgs Boson

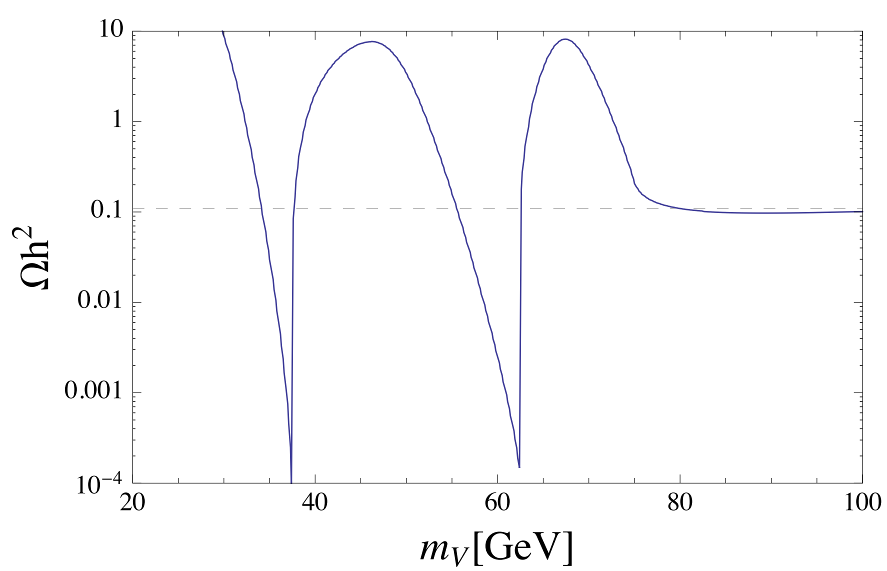


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

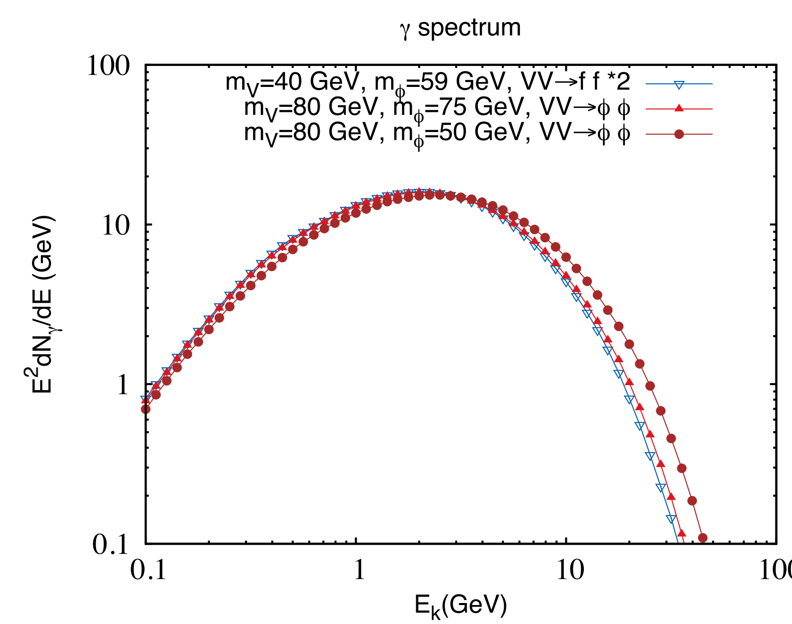
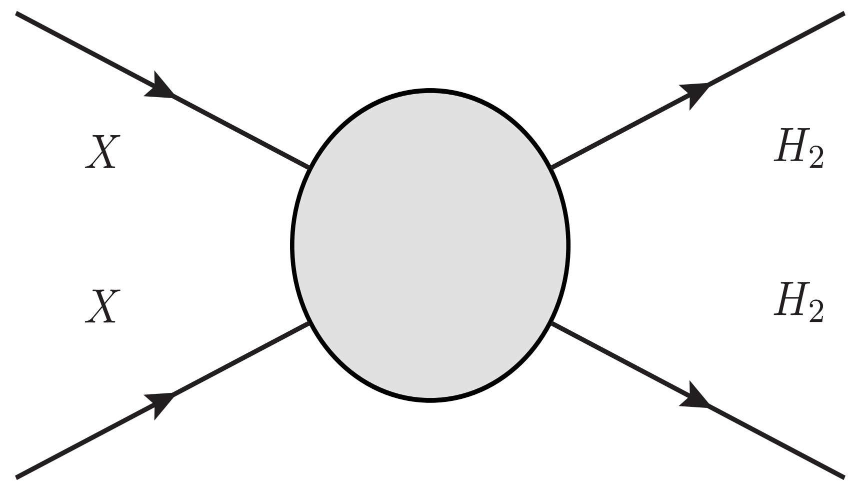


Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

And there would be no second scalar in EFT



P.Ko, Yong Tang.
arXiv:1504.03908

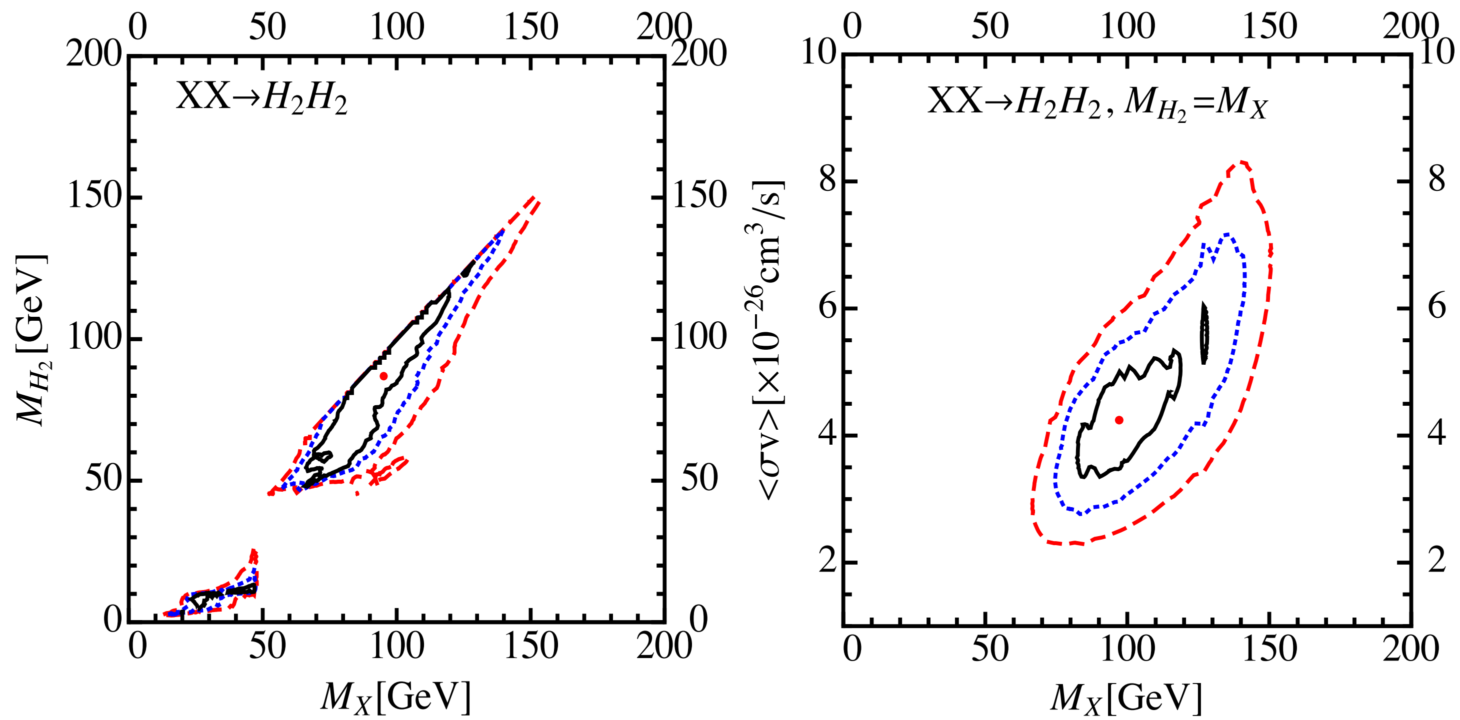


FIG. 3: The regions inside solid(black), dashed(blue) and long-dashed(red) contours correspond to 1σ, 2σ and 3σ, respectively. The red dots inside 1σ contours are the best-fit points. In the left panel, we vary freely M_X, M_{H_2} and $\langle\sigma v\rangle$. While in the right panel, we fix the mass of H_2, $M_{H_2} \simeq M_X$.

This would have never been possible within the DM EFT

P.Ko, Yong Tang.
arXiv:1504.03908

Channels	Best-fit parameters	$\chi^2_{min}/\text{d.o.f.}$	p-value
$XX \to H_2H_2$ (with $M_{H_2} \neq M_X$)	$M_X \simeq 95.0\text{GeV}, M_{H_2} \simeq 86.7\text{GeV}$ $\langle\sigma v\rangle \simeq 4.0 \times 10^{-26}\text{cm}^3/\text{s}$	$22.0/21$	0.40
$XX \to H_2H_2$ (with $M_{H_2} = M_X$)	$M_X \simeq 97.1\text{GeV}$ $\langle\sigma v\rangle \simeq 4.2 \times 10^{-26}\text{cm}^3/\text{s}$	$22.5/22$	0.43
$XX \to H_1H_1$ (with $M_{H_1} = 125\text{GeV}$)	$M_X \simeq 125\text{GeV}$ $\langle\sigma v\rangle \simeq 5.5 \times 10^{-26}\text{cm}^3/\text{s}$	$24.8/22$	0.30
$XX \to b\bar{b}$	$M_X \simeq 49.4\text{GeV}$ $\langle\sigma v\rangle \simeq 1.75 \times 10^{-26}\text{cm}^3/\text{s}$	$24.4/22$	0.34

TABLE I: Summary table for the best fits with three different assumptions.

Colliders connected to DM direct searches?

- Some scenarios of Higgs portal in EFT

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

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda}\overline{\psi}\psi H^\dagger H$$

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

Non-renormalizable
or
not gauge-invariant,
not unitary!

$m_{\rm H}$ (GeV)	Observed (expected) upper limits on $\sigma \cdot \mathcal{B}(\rm H \to inv)/\sigma_{\rm SM}$		
	VBF	ZH	VBF+ZH
115	0.63 (0.48)	0.76 (0.72)	0.55 (0.41)
125	0.65 (0.49)	0.81 (0.83)	0.58 (0.44)
135	0.67 (0.50)	1.00 (0.88)	0.63 (0.46)
145	0.69 (0.51)	1.10 (0.95)	0.66 (0.47)
200	0.91 (0.69)	—	—
300	1.31 (1.04)	—	—

[arXiv:1404.1344]

$$\sigma^{\rm SI}_{\rm S-N} = \frac{4\Gamma_{\rm inv}}{m_{\rm H}^3 v^2 \beta}\frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2},$$

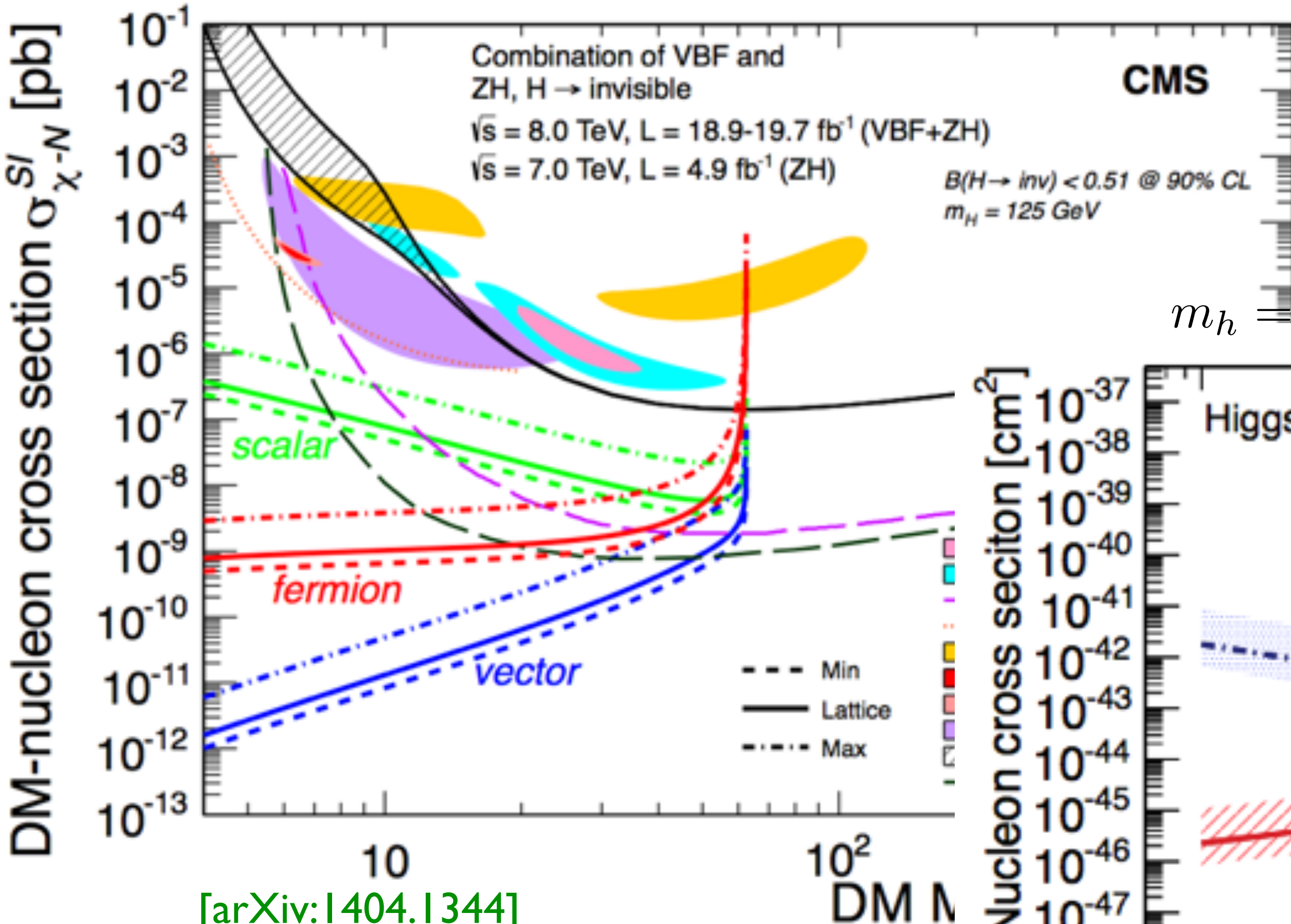
$$\sigma^{\rm SI}_{\rm V} - {\rm N} = \frac{16\Gamma_{\rm inv} M_\chi^4}{m_{\rm H}^3 v^2 \beta(m_{\rm H}^4 - 4M_\chi^2 m_{\rm H}^2 + 12M_\chi^4)}\frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2}$$

$$\sigma^{\rm SI}_{\rm f-N} = \frac{8\Gamma_{\rm inv} M_\chi^2}{m_{\rm H}^5 v^2 \beta^3}\frac{m_{\rm N}^4 f_{\rm N}^2}{(M_\chi + m_{\rm N})^2}.$$

$\Gamma_{\rm inv}$ is constraied $\Rightarrow$ So is $\sigma^{\rm SI}$

Collider Implications

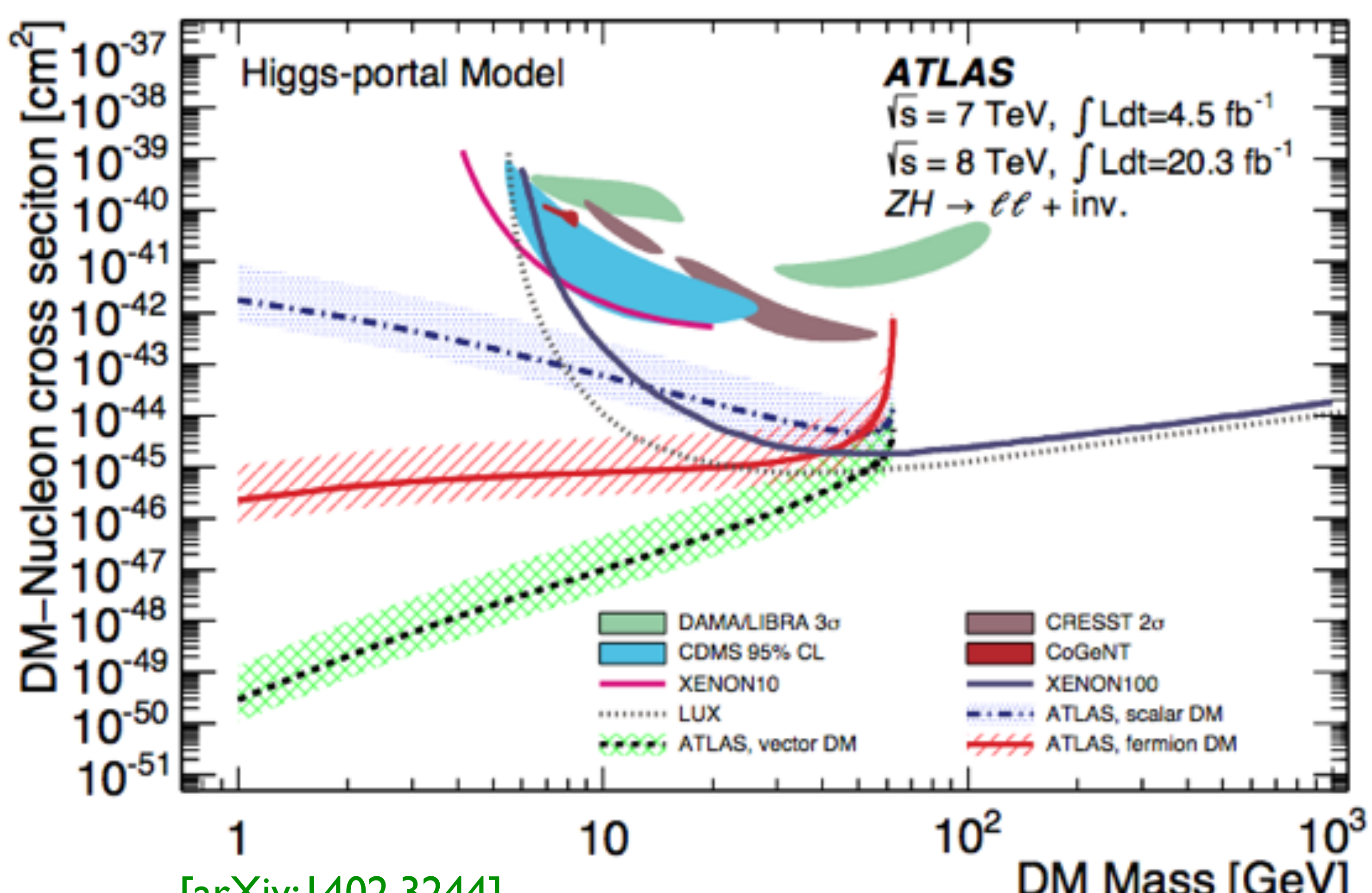
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[arXiv:1404.1344]

Based on EFTs

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



[arXiv:1402.3244]

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

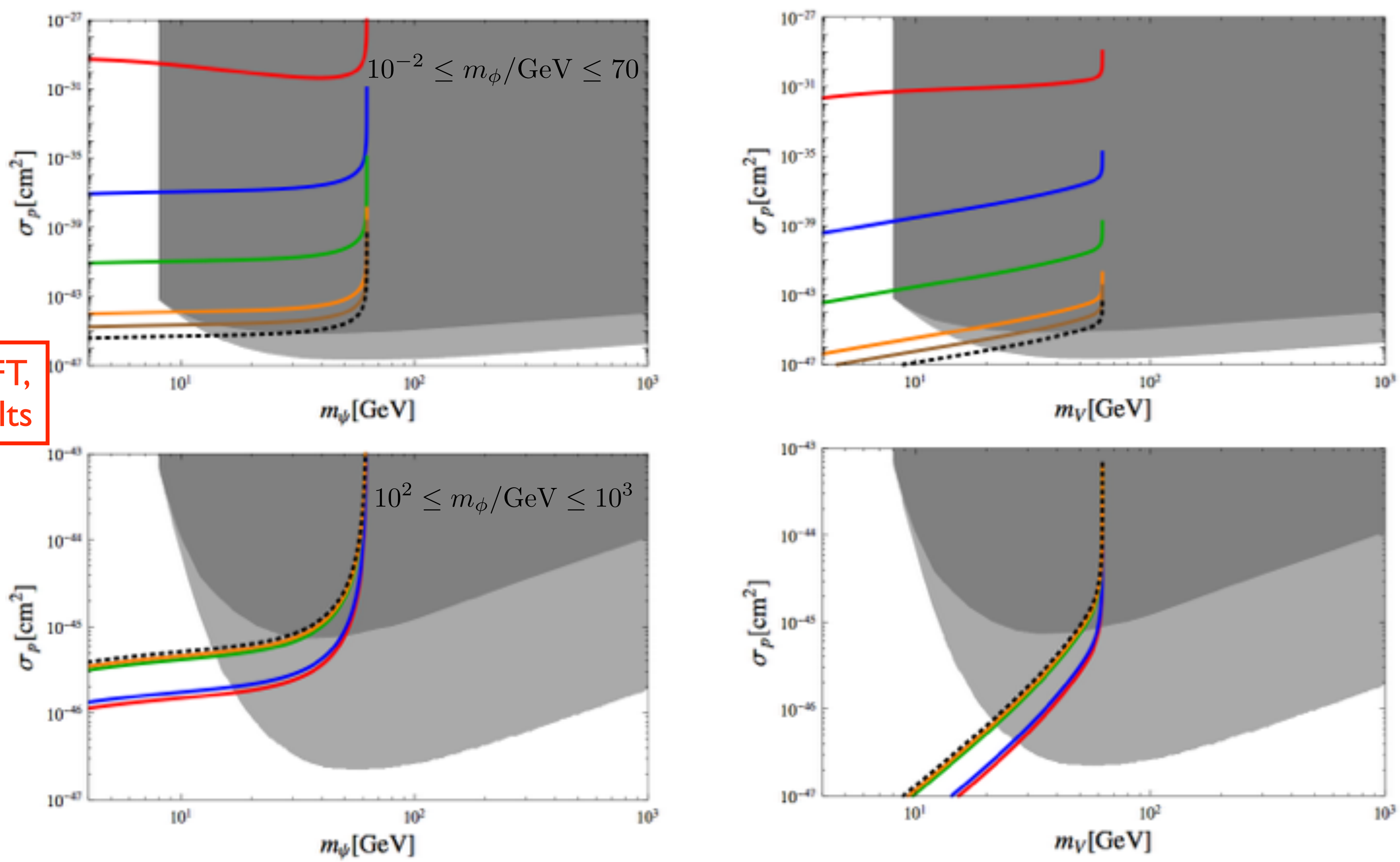
[arXiv: 1405.3530, S. Baek, P. Ko & WIPark, PRD]

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

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

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

Dashed curves:EFT, ATLAS,CMS results

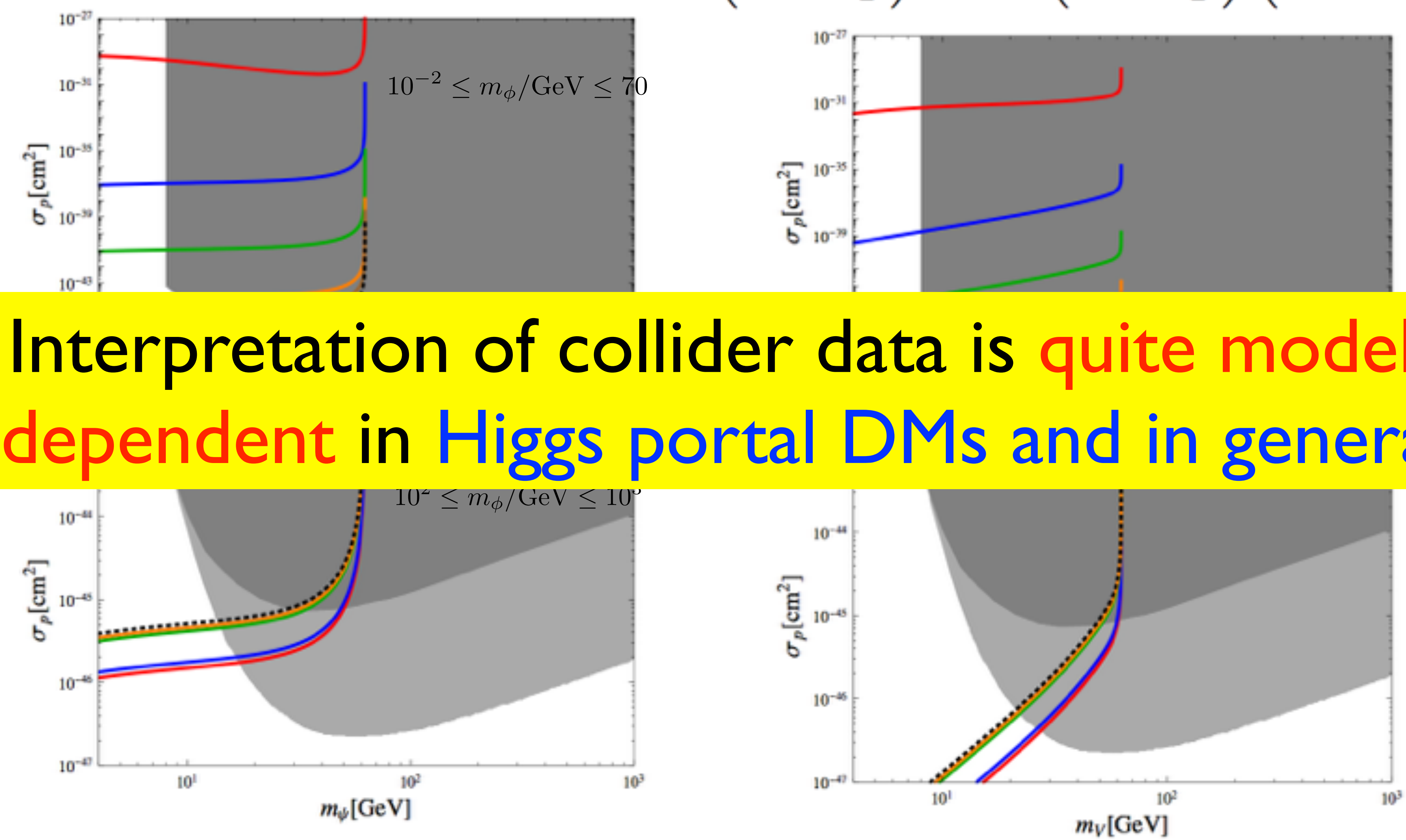


- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

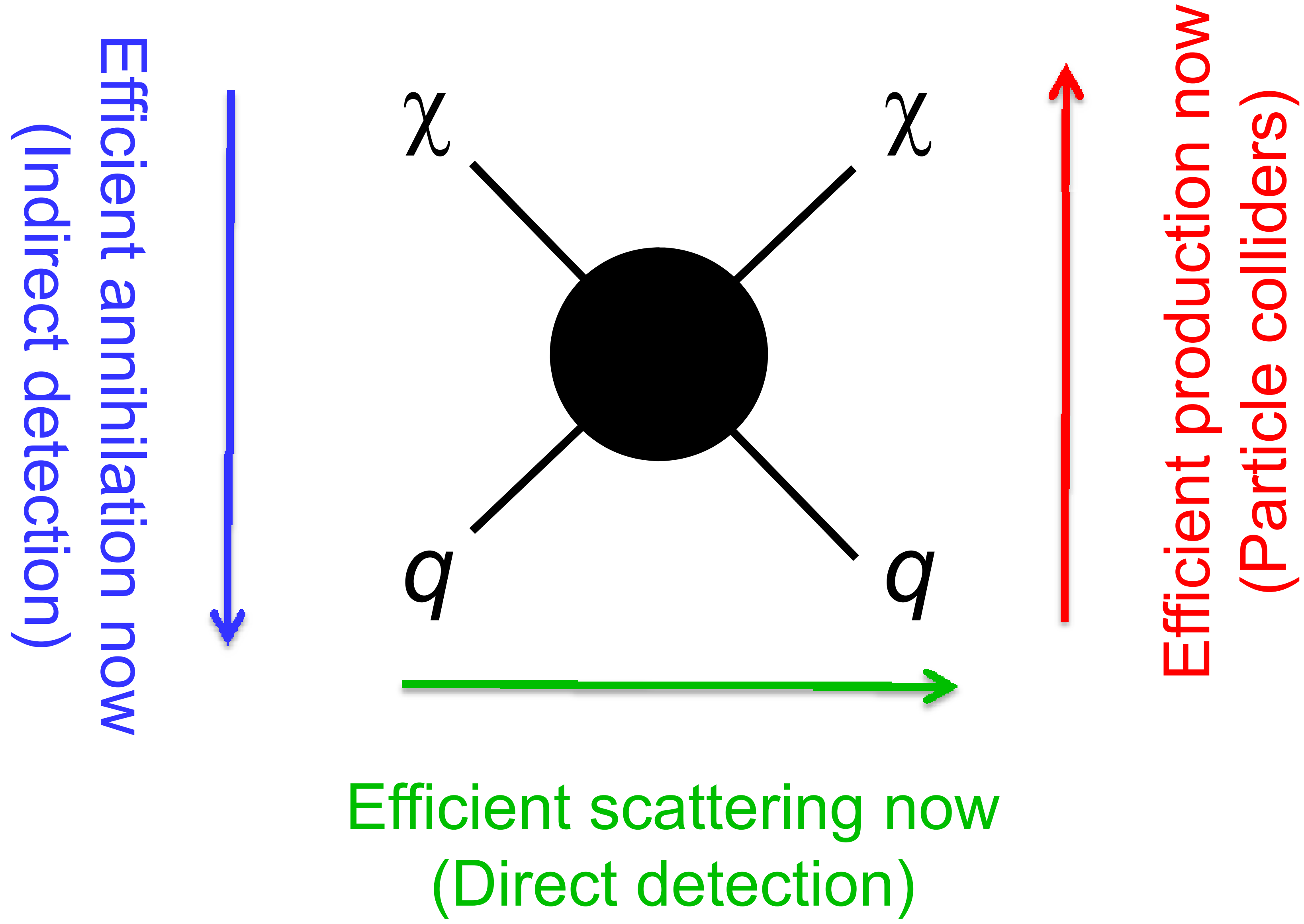
$$\sigma_p^{\rm SI} = (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 m_h^4 \mathcal{F}(m_{\rm DM}, \{m_i\}, v) \simeq (\sigma_p^{\rm SI})_{\rm EFT}\; c_\alpha^4 \left(1 - \frac{m_h^2}{m_2^2}\right)^2$$



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

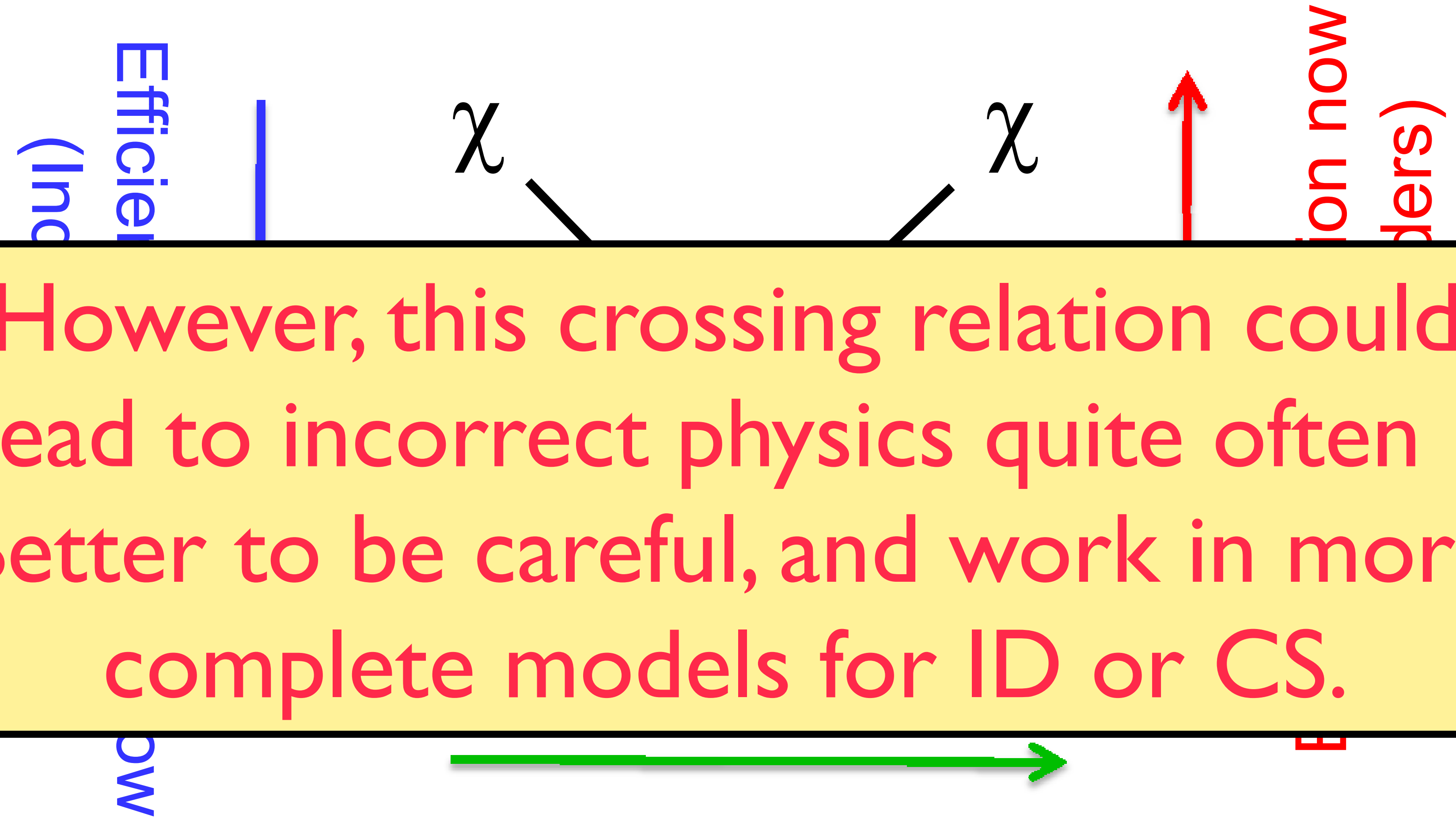
Crossing & WIMP detection

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)

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

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

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

Both break SM gauge invariance

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

Need the mixing between s and h

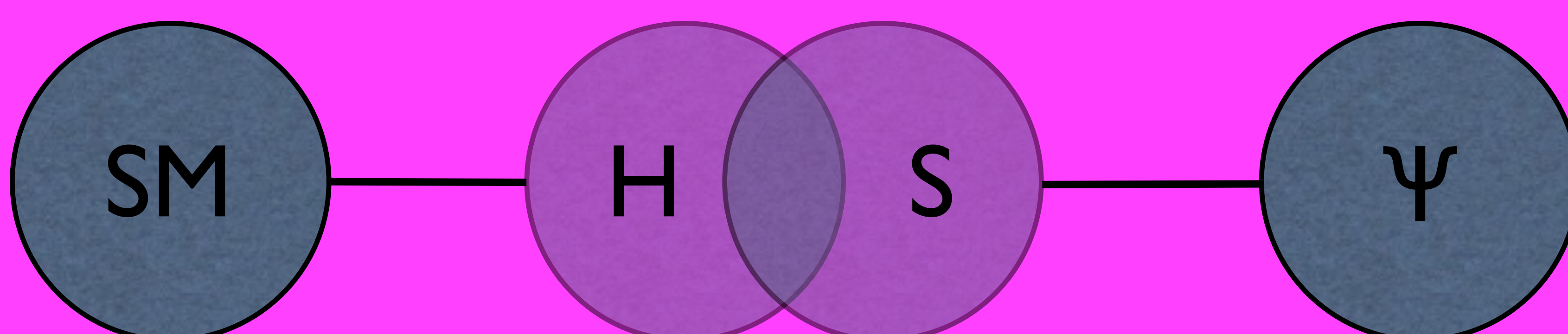
Singlet fermion CDM

Baek, Ko, Park, arXiv:1112.1847

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

mixing

invisible decay



Production and decay rates are suppressed relative to SM.

This simple model has not been studied properly !!

Full Theory Calculation

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

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

$$\begin{aligned}
\Lambda_{dd}^3 &\equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}\left(1 - \frac{m_{125}^2}{m_2^2}\right)^{-1} \\
\bar{\Lambda}_{dd}^3 &\equiv \frac{2m_{125}^2 v}{\lambda_s \sin 2\alpha}
\end{aligned}$$

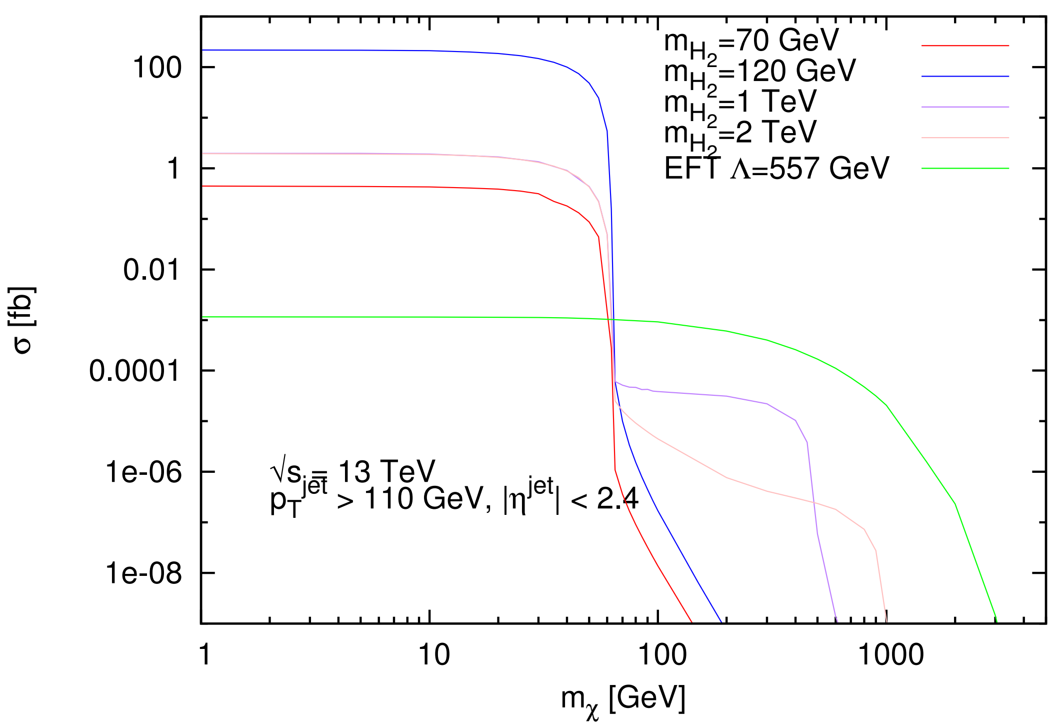
Monojet+missing ET

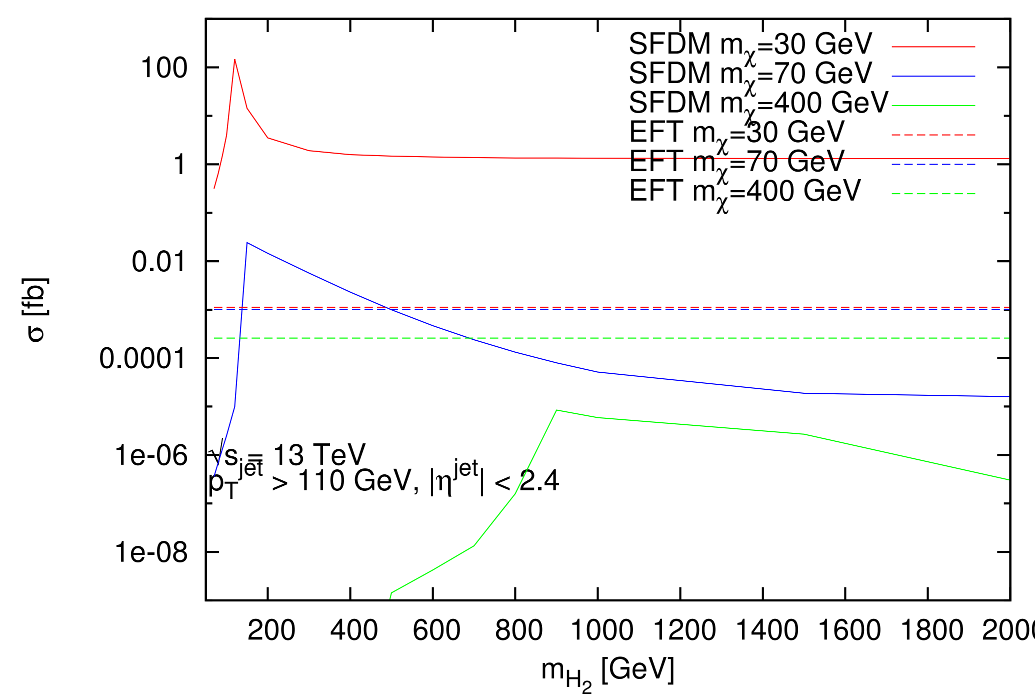
Can be obtained by crossing : s <>t

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

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

Monojet + missing ET





No similarity with the DM EFT calculation

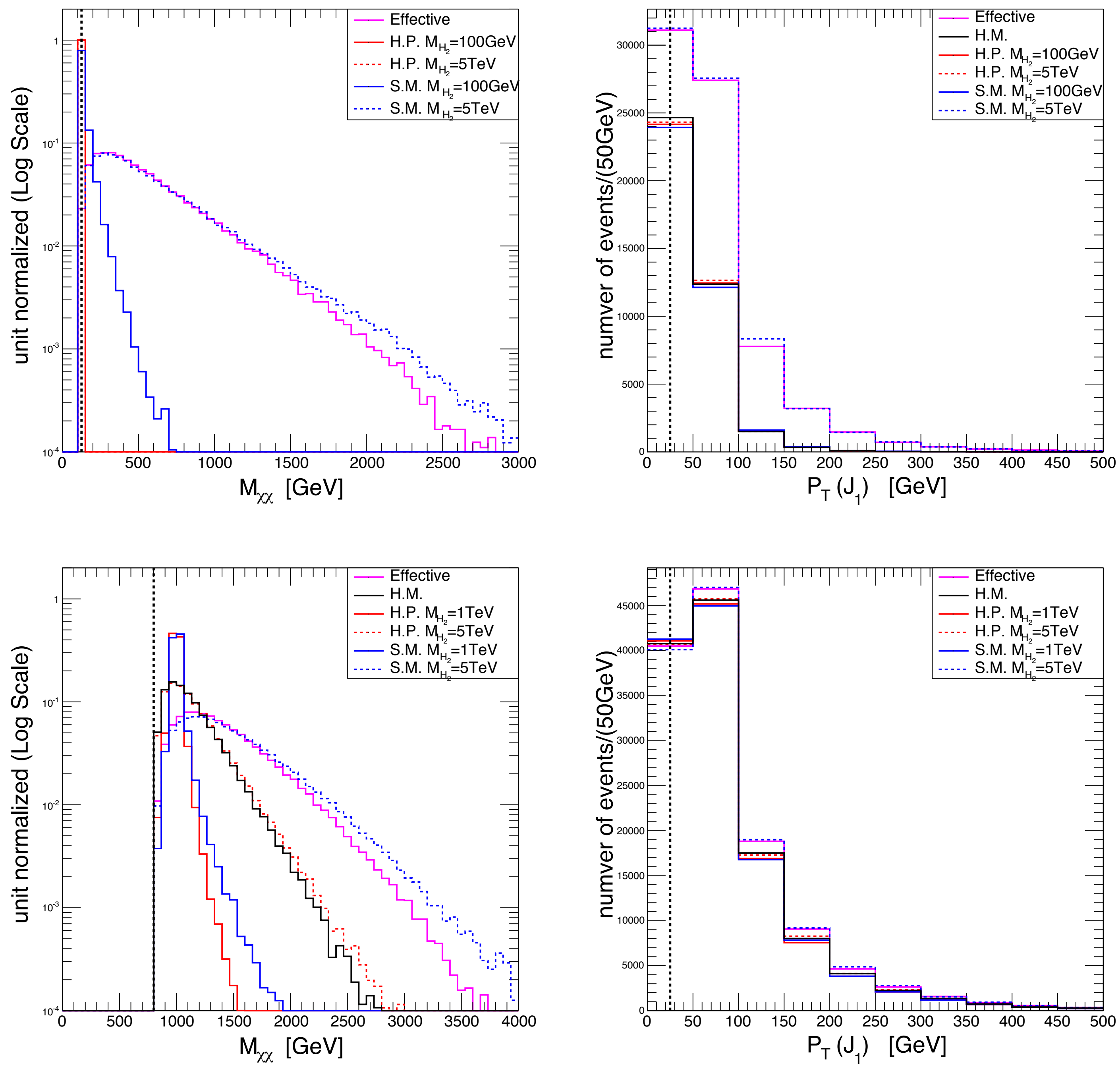


FIG. 1: In ATLAS 8TeV mono-jet+$\not{E}_T$ search [6] we plot $M_{\chi\chi}$ and the P_T of a hardest jet in a reconstruction level (after a detector simulation). Upper panels are with $m_\chi = 50\,\text{GeV}$ and lower panels are of $m_\chi = 400\,\text{GeV}$.

- 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).

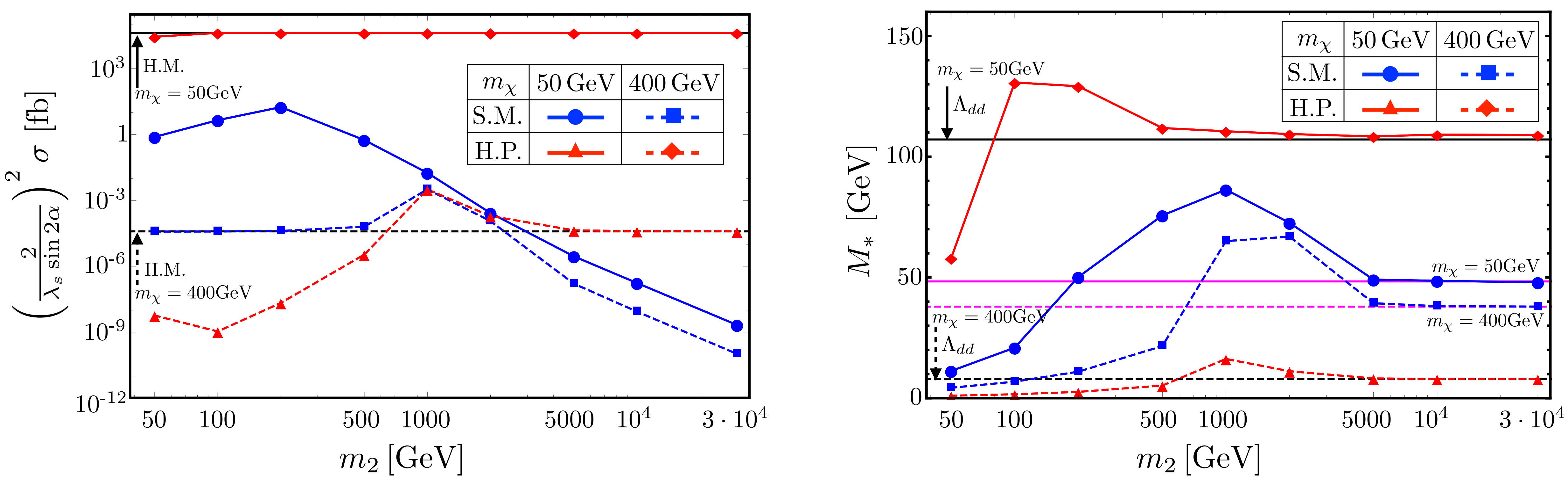


FIG. 1: We follow ATLAS 8TeV mono-jet+$\not{E}_T$ searches [2]. For (a) we simulated various models for the

tT + missing ET

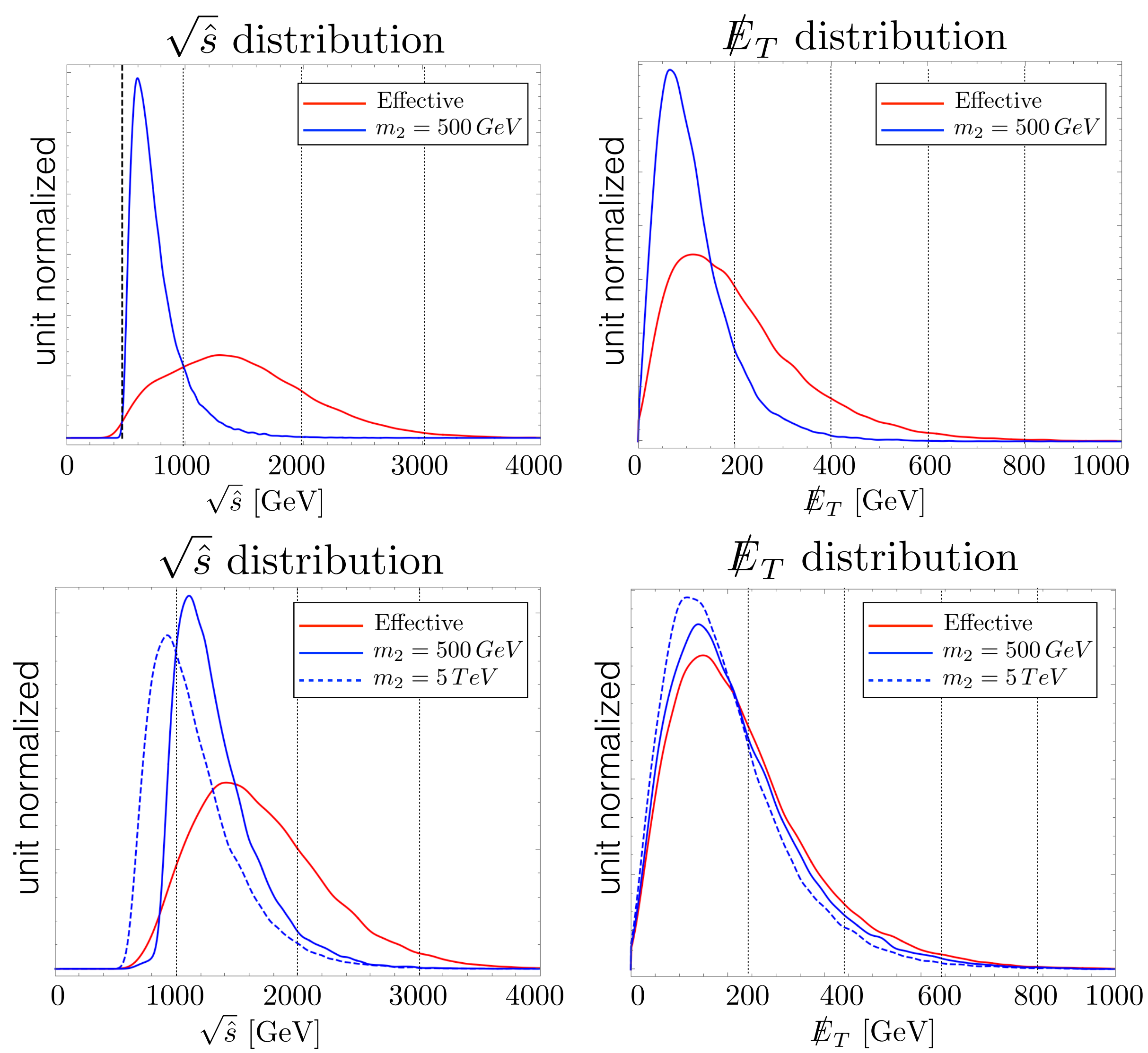


FIG. 2: Parton level distributions of various variables in a $(t\bar{t}\chi\bar{\chi})$ channel for a dark matter's mass $m_\chi = 10\,\mathrm{GeV}$ (above) and $m_\chi = 100\,\mathrm{GeV}$ (below) for LHC 8TeV. As we can see here, due to a higgs propagator, even when $m_2 \to \infty$ case, a missing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

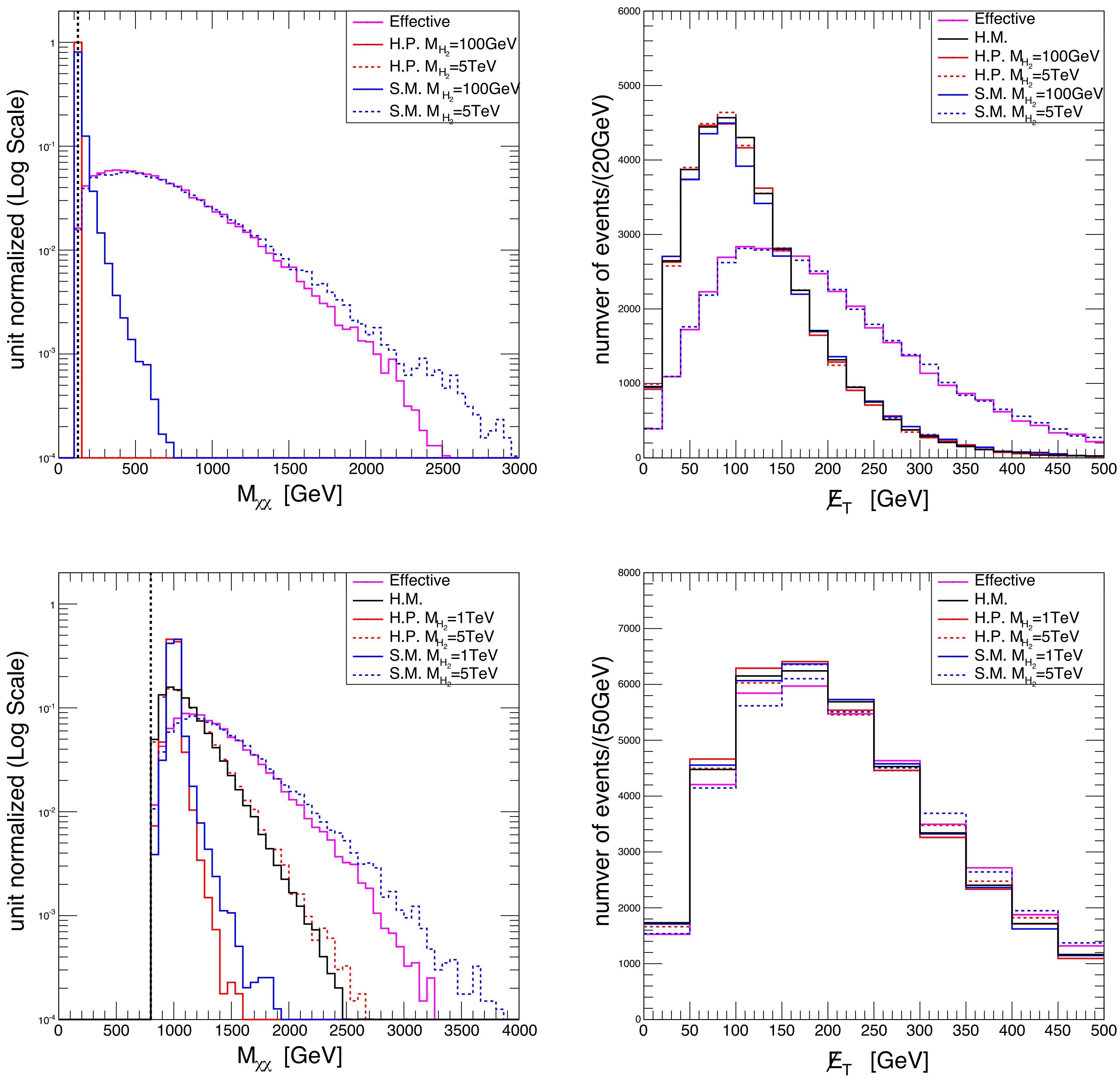


FIG. 4: With CMS 8TeV $t\bar{t} + \not{E}_T$ search [6], we plot $M_{\chi\chi}$ and the $\not{E}_T$ in a reconstruction level. Upper panels are with $M_\chi = 50\,\text{GeV}$ and lower panels are of $M_\chi = 400\,\text{GeV}$.

- 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).

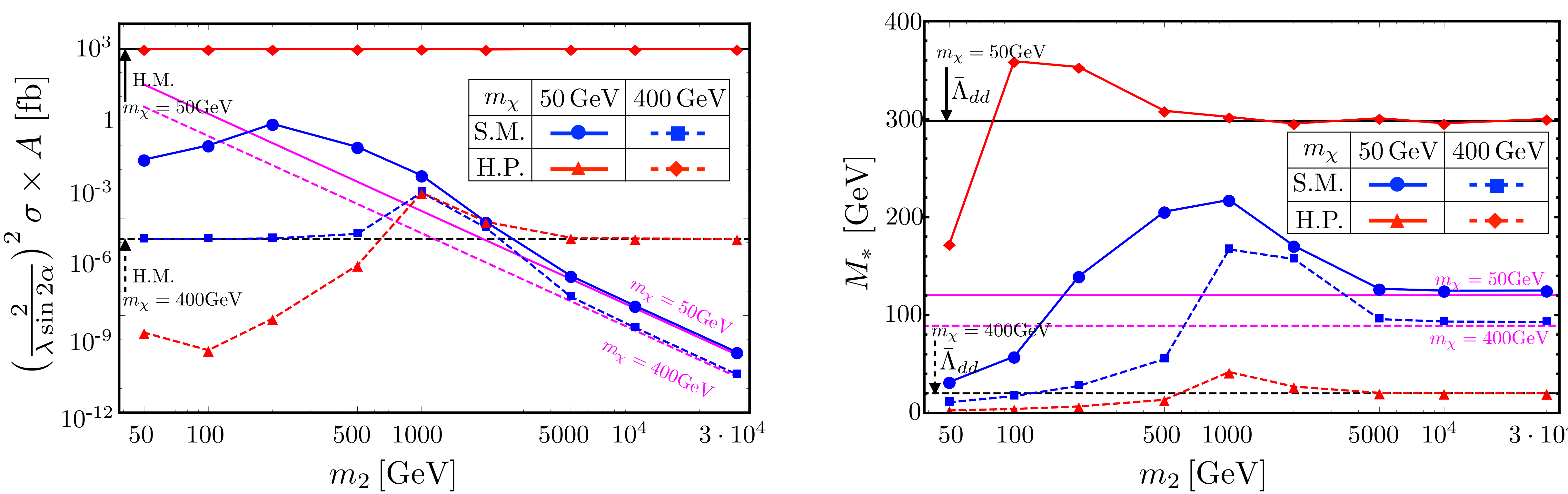


FIG. 3: We follow CMS 8TeV $t\bar{t} + \not{E}_T$ search. For (a) we simulated various models for the

A General Comment

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

$$\sigma(\sqrt{s}) = \int_0^1 d\tau \sum_{a,b} \frac{d\mathcal{L}_{ab}}{d\tau} \hat{\sigma}(\hat{s} \equiv \tau s)$$

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

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

No single EFT applicable to the entire tau regions

Indirect Detection

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

- 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

- EFT + Complementarity : No good at high energy collider
- Full SM gauge invariance, Renormalizability and Unitarity are important
- 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

Higgs portal DM at ILC ($\sqrt{s}$=500GeV)

with Hiroshi Yokoya (QUC,KIAS)

Work in progress

(Plots shown here are preliminary)

Higgs Strahlung

$$e^+(p_1) + e^-(p_2) \to h^*(q) + Z(p_Z) \to S(k_1) + S(k_2) + Z(p_Z)$$

Differential cross section

$$\boxed{\frac{d\sigma_{SD}}{dt} = \frac{1}{2\pi}\sigma_{h^*Z}(s,t)\cdot F_S(t)}$$

$$\lambda_F = y_F \sin\alpha\cos\alpha.$$

$$\mu_V = \lambda_V m_D = 2m_D^2/v_\phi \cdot \sin\alpha\cos\alpha$$

$$F_S(t) = C_S \frac{\beta_D}{8\pi}\left|\frac{2\lambda_{HS}v}{t - m_h^2 + i m_h \Gamma_h}\right|^2$$

$$F_F(t) = C_F \lambda_F^2 \cdot \frac{\beta_D^3}{8\pi} \cdot 2t \cdot \left|\frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2}\right|^2$$

$$F_V(t) = C_V \frac{\beta_D}{8\pi} \cdot \frac{\mu_V^2 t^2}{4m_D^4}\left(1 - \frac{4m_D^2}{t} + \frac{12 m_D^4}{t^2}\right) \cdot \left|\frac{1}{t - m_1^2 + i m_1 \Gamma_1} - \frac{1}{t - m_2^2 + i m_2 \Gamma_2}\right|^2$$

General Comments

- One can calculate the collider signatures at high energy scale, since the amplitudes were obtained in renormalizable and unitary models for singlet fermion DM and VDM
- There are two scalar propagators for SFDM and VDM, because of the SM gauge sym, unitarity and renormalizability
- EFT results can be obtained only if H2 is much heavier than the ILC CM energy

Asymtotic behavior in the full theory

$$\text{ScalarDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \tag{5.7}$$

$$\text{SFDM}: \quad G(t) \sim \left|\frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2}\right|^2 \left(t-4m_\chi^2\right) \tag{5.8}$$

$$\rightarrow |\frac{1}{t^2}|^2 \times t \sim \frac{1}{t^3} \text{ (as } t \rightarrow \infty) \tag{5.9}$$

$$\text{VDM}: \quad G(t) \sim \left|\frac{1}{t-m_1^2+im_1\Gamma_1} - \frac{1}{t-m_2^2+im_2\Gamma_2}\right|^2 \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right] \tag{5.10}$$

$$\rightarrow |\frac{1}{t^2}|^2 \times t^2 \sim \frac{1}{t^2} \text{ (as } t \rightarrow \infty) \tag{5.11}$$

Asymptotic behavior w/o the 2nd Higgs (EFT)

$$\text{SFDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left(t-4m_\chi^2\right)$$

$$\rightarrow \frac{1}{t} \text{ (as } t \rightarrow \infty)$$

$$\text{VDM}: \quad G(t) \sim \frac{1}{(t-m_H^2)^2 + m_H^2\Gamma_H^2} \left[2 + \frac{(t-2m_V^2)^2}{4m_V^4}\right]$$

$$\rightarrow \text{constant (as } t \rightarrow \infty)$$

Unitarity violated !

Recoil mass distribution

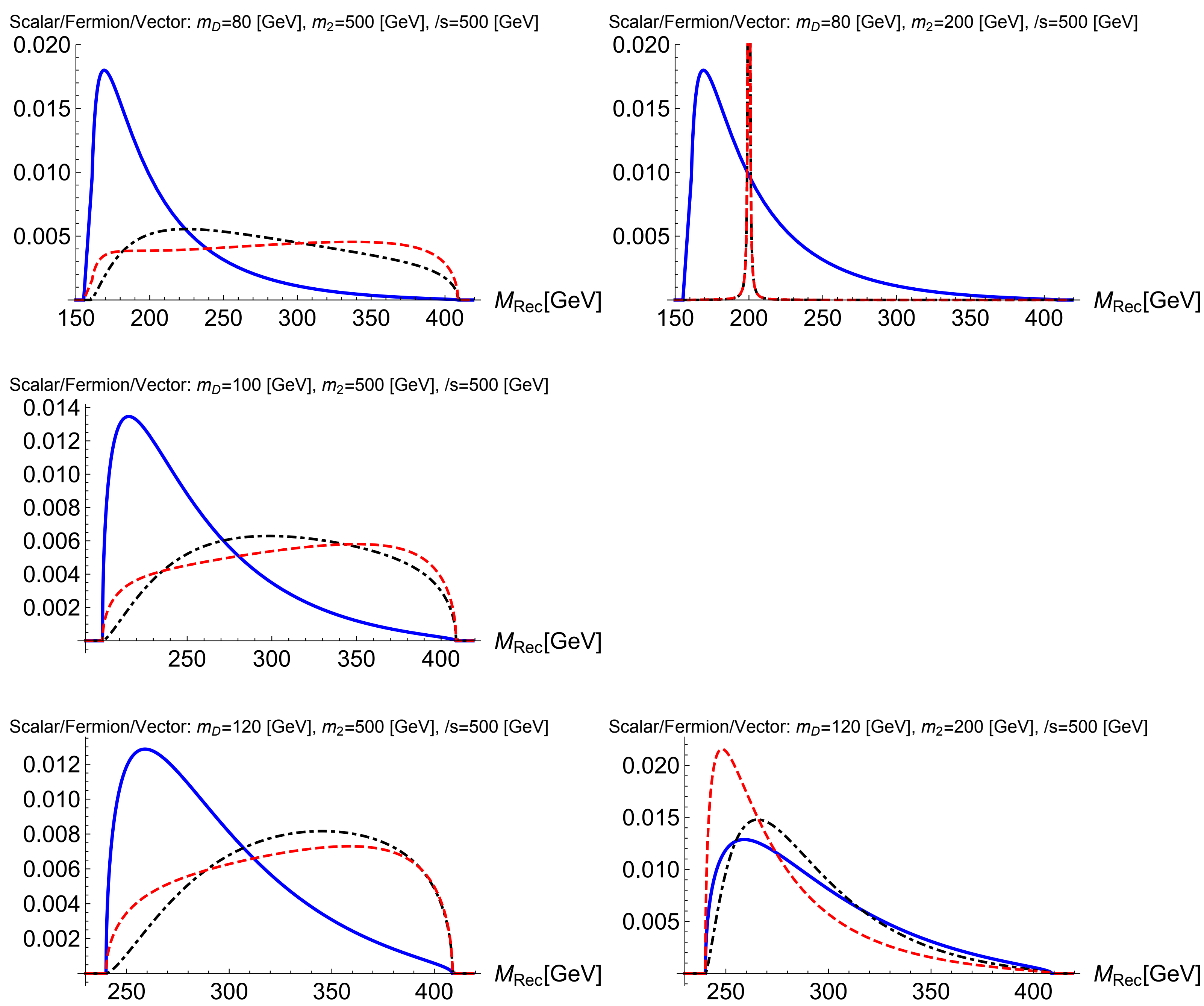


Figure 1: Normalized Distribution of the Recoil mass. Blue: Scalar DM, Black: Fermion DM, Red: Vector DM.

H2 mass dependence

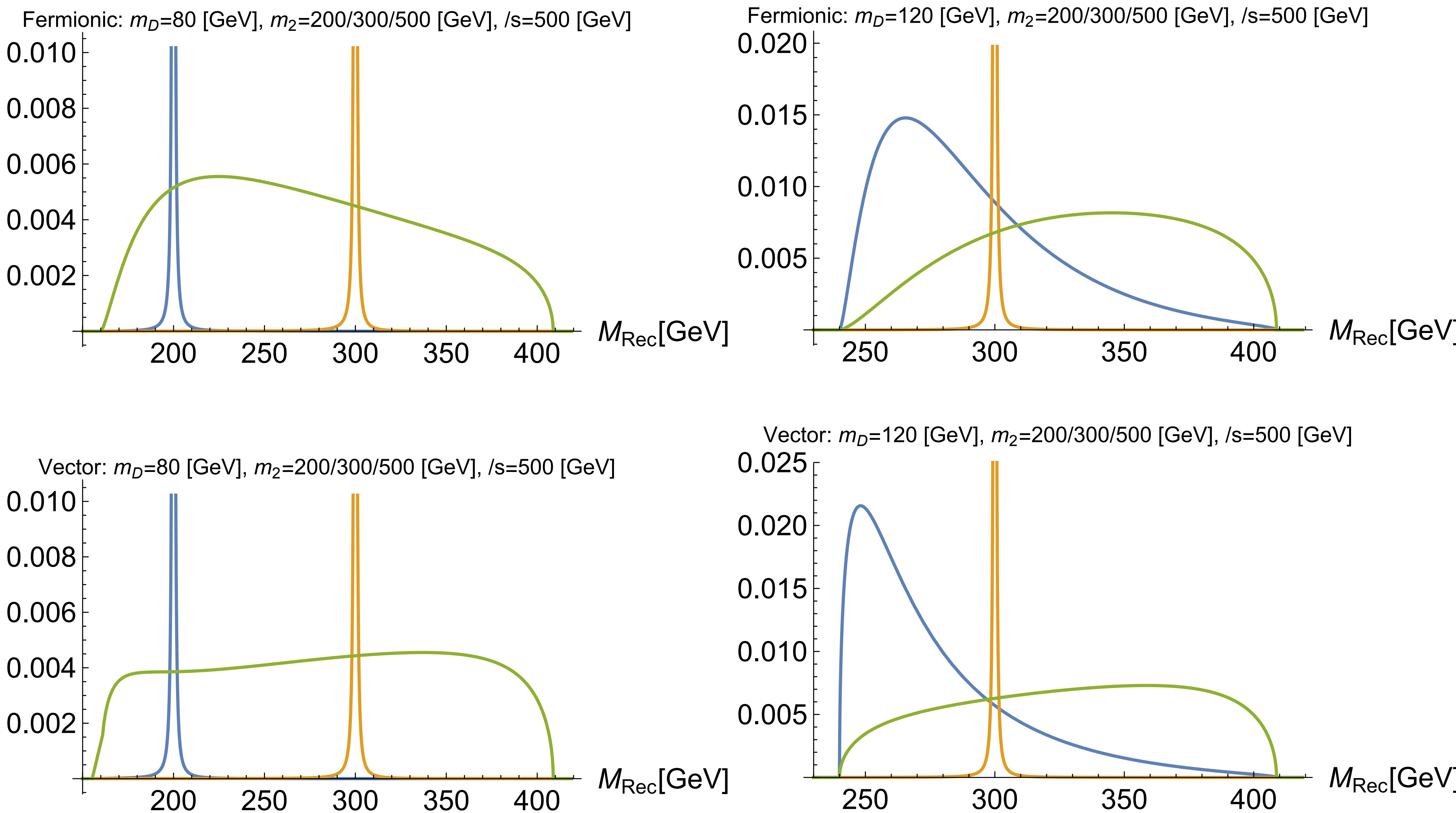


Figure 2: Normalized Distribution of the Recoil mass. Blue: $m_{H_2} = 200$ GeV, Orange: 300 GeV, Green: 500 GeV.

Total cross sections

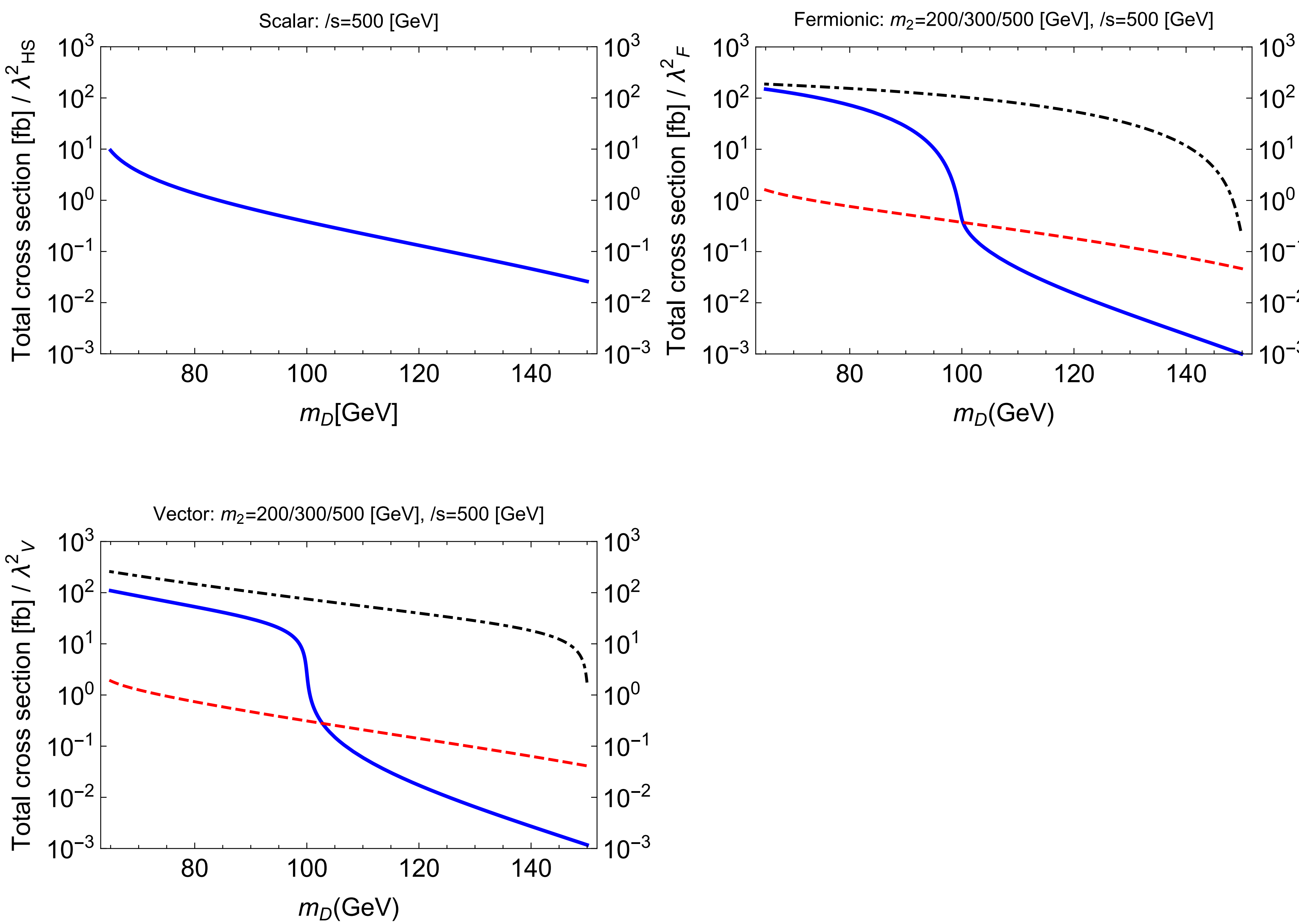


Figure 3: Total Cross sections for $e^+e^- \to ZDD$ at $\sqrt{s} = 500$ GeV. λ_{HS}, λ_F, λ_V are set to unity, and $m_{H_2} = 200$ (Blue), 300 (Black), 500 GeV (Red) are taken for Fermion and Vector DM models.

Parameter Constraints

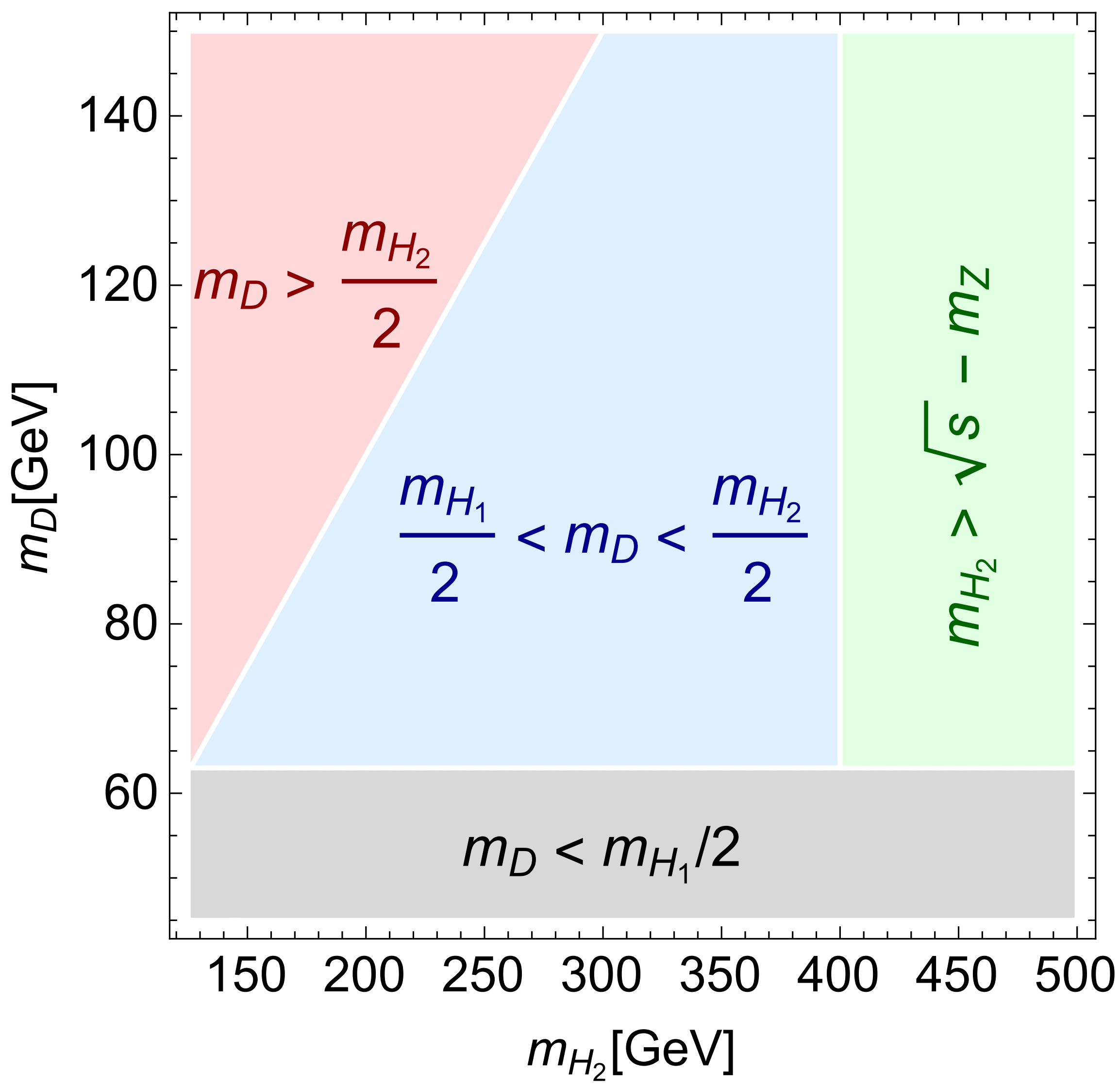


Figure 4:

Event selections

$$e^+e^- \to ZDD \to (jj \text{ or } \ell^+\ell^-) + \not{E}_T$$

$$p_T^Z \geq 100 \text{ GeV},$$

$$\left|\eta^Z\right| \leq 1.,$$
$$m_{H_2} \leq M_{\text{rec}} \leq m_{H_2} + 50 \text{ [GeV]}$$

$$S = \frac{\sigma_{ZDD}\mathcal{B}(Z \to jj)\epsilon_S\mathcal{L}}{\sqrt{\sigma_{\text{BG}}\mathcal{B}(Z \to jj)\epsilon_B\mathcal{L}}} \quad > 5$$

Discovery potential

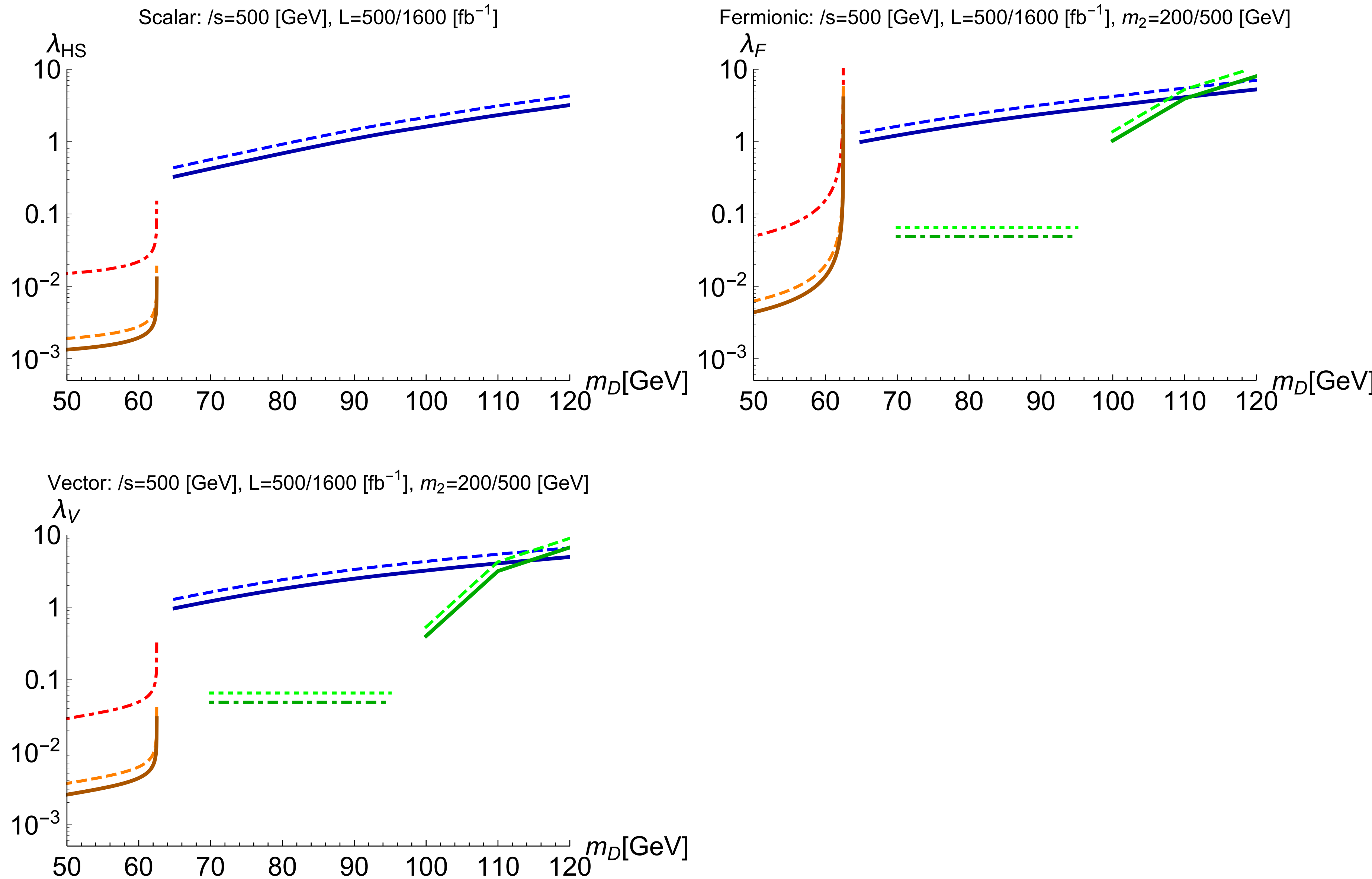


Figure 5: Contour plots for the discovery potential at 95% C.L. in $e^+e^- \to Z(\to jj)DD$ searches at the ILC with $\sqrt{s} = 500$ GeV and $\mathcal{L} = 500,\ 1600$ [fb^{-1}]. Red contour is the limit by the invisible Higgs decay search at the LHC, and orange contours are the expected limits at the ILC. Blue and green contours are the expected limit by the $Z + \not{E}_T$ searches at the ILC. For the fermion and vector DM models, blue (green) contours are for $m_{H_2} = 500$ GeV (200 GeV).

Summary of this part

- Higgs portal DM : simple viable DM models (natural if one assumes dark gauge sym)
- EFT: not reliable for collider searches for DM, and one has to consider UV completions
- Full SM gauge symmetry, unitarity and renormalizability are important when constructing UV completions
- Search for Higgs portal DM at ILC, FCC-ee, LHC and FCC-hh, SPPC being studied

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

- Dynamics dictated by local gauge principle
- 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, improves EW vac stability, helps Higgs inflation with larger tensor/scalar ratio >> Should be actively searched for
- Search for Higgs portal DM at ILC, FCC-ee, LHC and FCC-hh, SPPC being studied