Beyond DM EFT:
Higgs portal DMs as examples

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SM Chapter is being closed

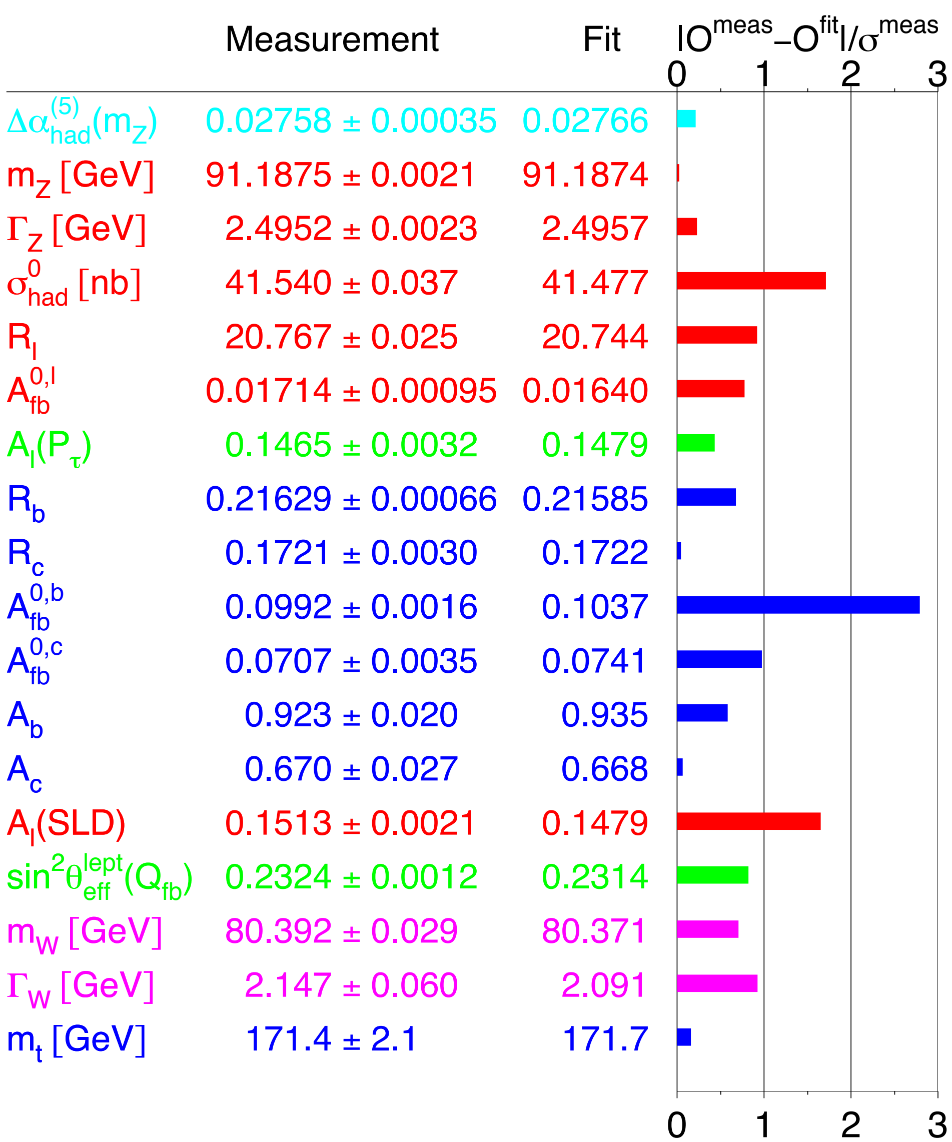
- SM has been tested at quantum level
  - EWPT favors light Higgs boson
  - CKM paradigm is working very well so far
  - LHC found a SM-Higgs like boson around 125 GeV
- No smoking gun for new physics at LHC so far

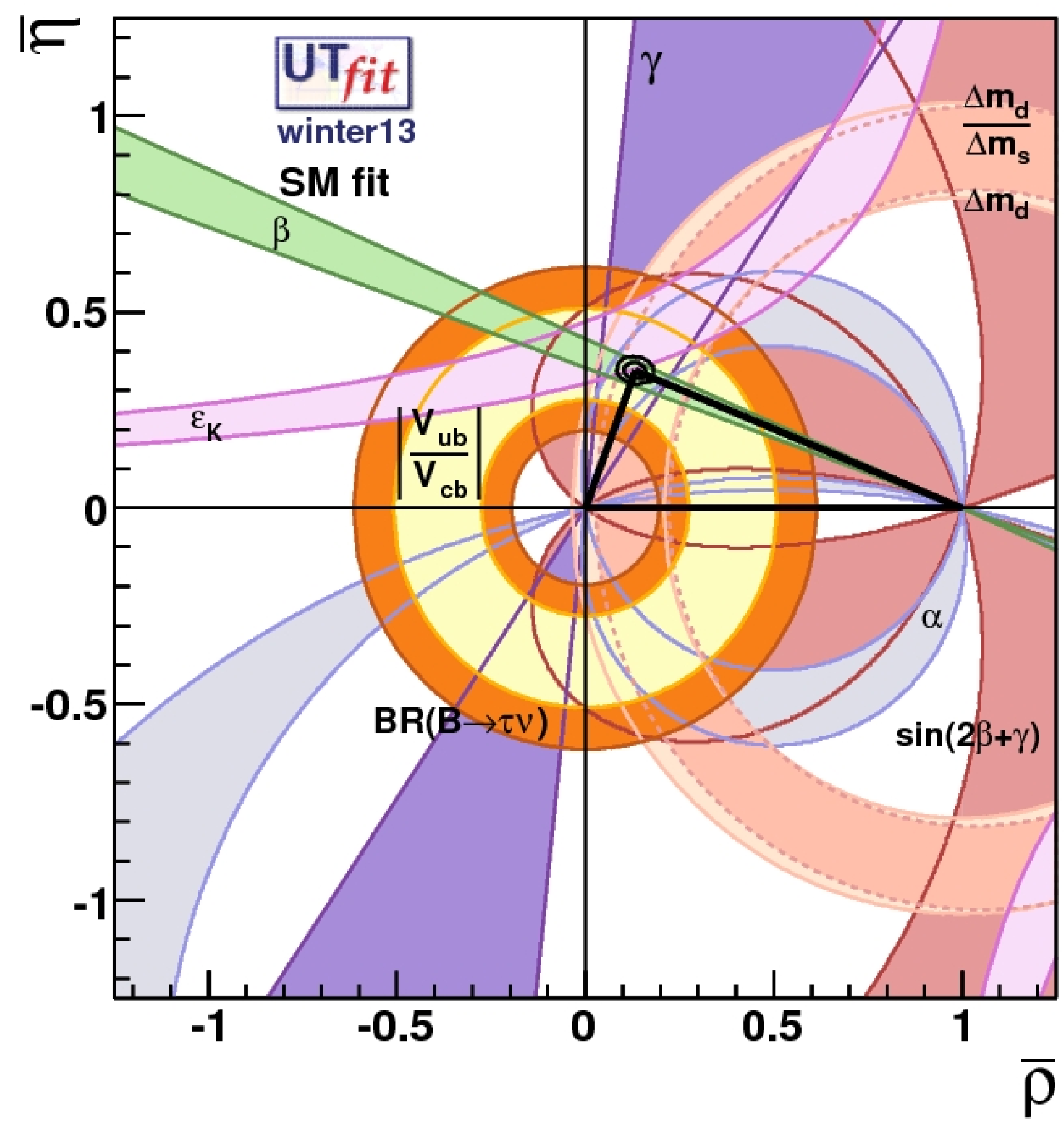
SM Lagrangian

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

Based on local gauge principle

EWPT & CKM





Almost Perfect !

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

Local Gauge Principle Works !

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

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

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

Contents

- Underlying Principles : Hidden Sector DM, Singlet Portals, Renormalizability, Local Dark Gauge Symmetry
- Scalar DM with local Z3 : comparison with global Z3, limitation of EFT approach
- h-monopole and stable VDM & dark radiation: DM stable due to topology and unbroken U(1)
- 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 : Universal Suppression of Higgs signal strength and extra neutral scalar, Higgs inflation, etc.
- (un)broken $U(1)_X$: Singlet Portal and Dark Radiation
- Tight bond between DM-sterile nu's with $U(1)_X$: Dark Radiation

see backup slides

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)

- Singlet fermion dark matter (1112.1847 JHEP)
- Higgs portal vector dark matter (1212.2131 JHEP)
- Vacuum structure and stability issues (1209.4163 JHEP)
- Higgs-portal assisted Higgs inflation, Higgs portal VDM for gamma ray excess from GC

Questions about DM

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

Underlying Principles

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

New Physics Scale ?

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

Neutral Kaon System

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

Guiding Principles

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

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

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

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

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

All invariant under ad hoc Z2 symmetry

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

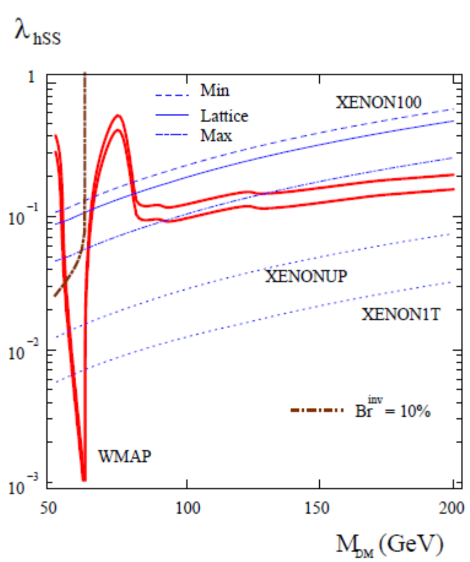


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

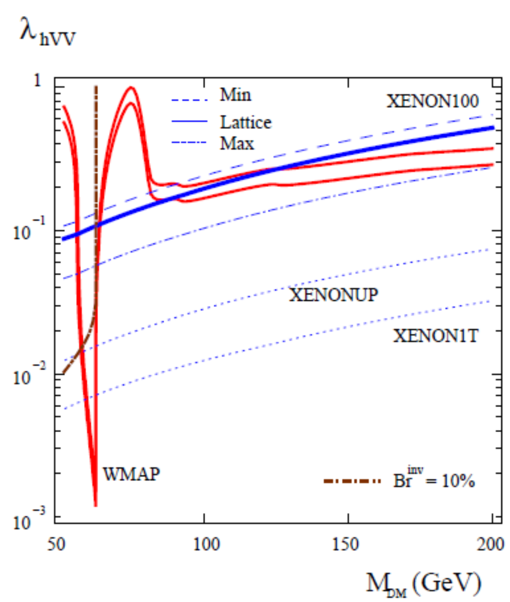


FIG. 2. Same as Fig. 1 for vector DM particles.

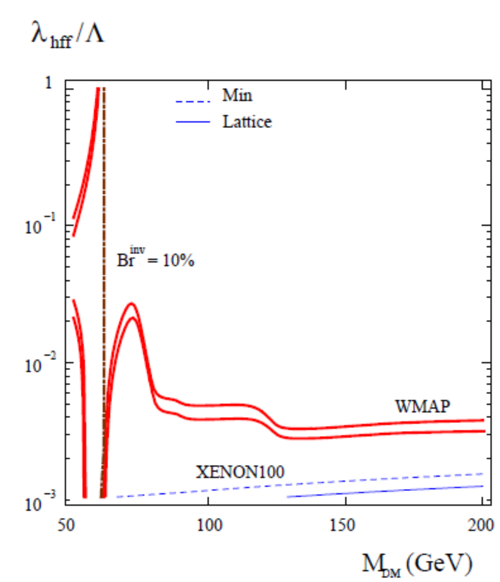


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

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

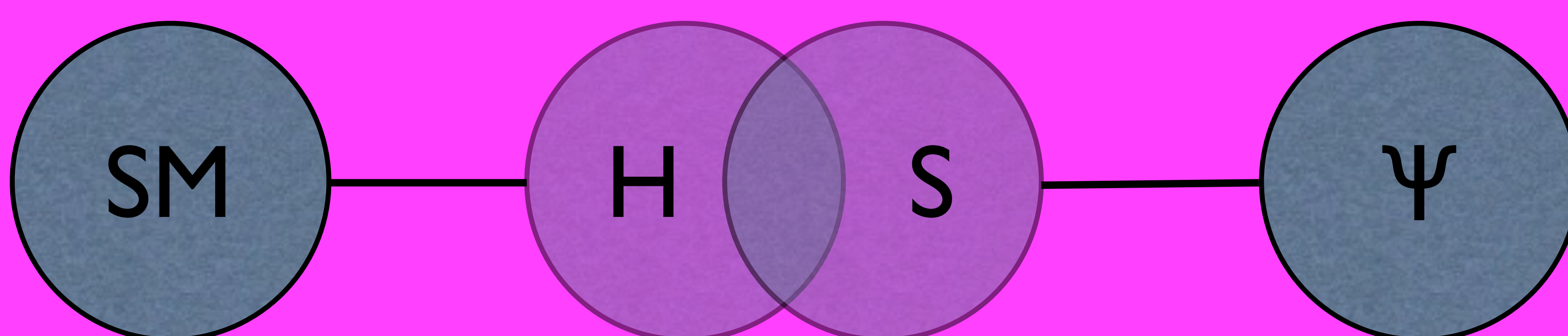
Singlet fermion CDM

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

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

at vacuum

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

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

Mixing of Higgs and singlet

Ratiocination

- Signal strength (reduction factor)

$$
\begin{aligned}
r_i &= \frac{\sigma_i \; \mathrm{Br}(H_i \to \mathrm{SM})}{\sigma_h \; \mathrm{Br}(h \to \mathrm{SM})} \\
r_1 &= \frac{\cos^4\alpha \; \Gamma^{\mathrm{SM}}_{H_1}}{\cos^2\alpha \; \Gamma^{\mathrm{SM}}_{H_1} + \sin^2\alpha \; \Gamma^{\mathrm{hid}}_{H_1}} \\
r_2 &= \frac{\sin^4\alpha \; \Gamma^{\mathrm{SM}}_{H_2}}{\sin^2\alpha \; \Gamma^{\mathrm{SM}}_{H_2} + \cos^2\alpha \; \Gamma^{\mathrm{hid}}_{H_2} + \Gamma_{H_2 \to H_1 H_1}}
\end{aligned}
$$

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

Invisible decay mode is not necessary!

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

Constraints

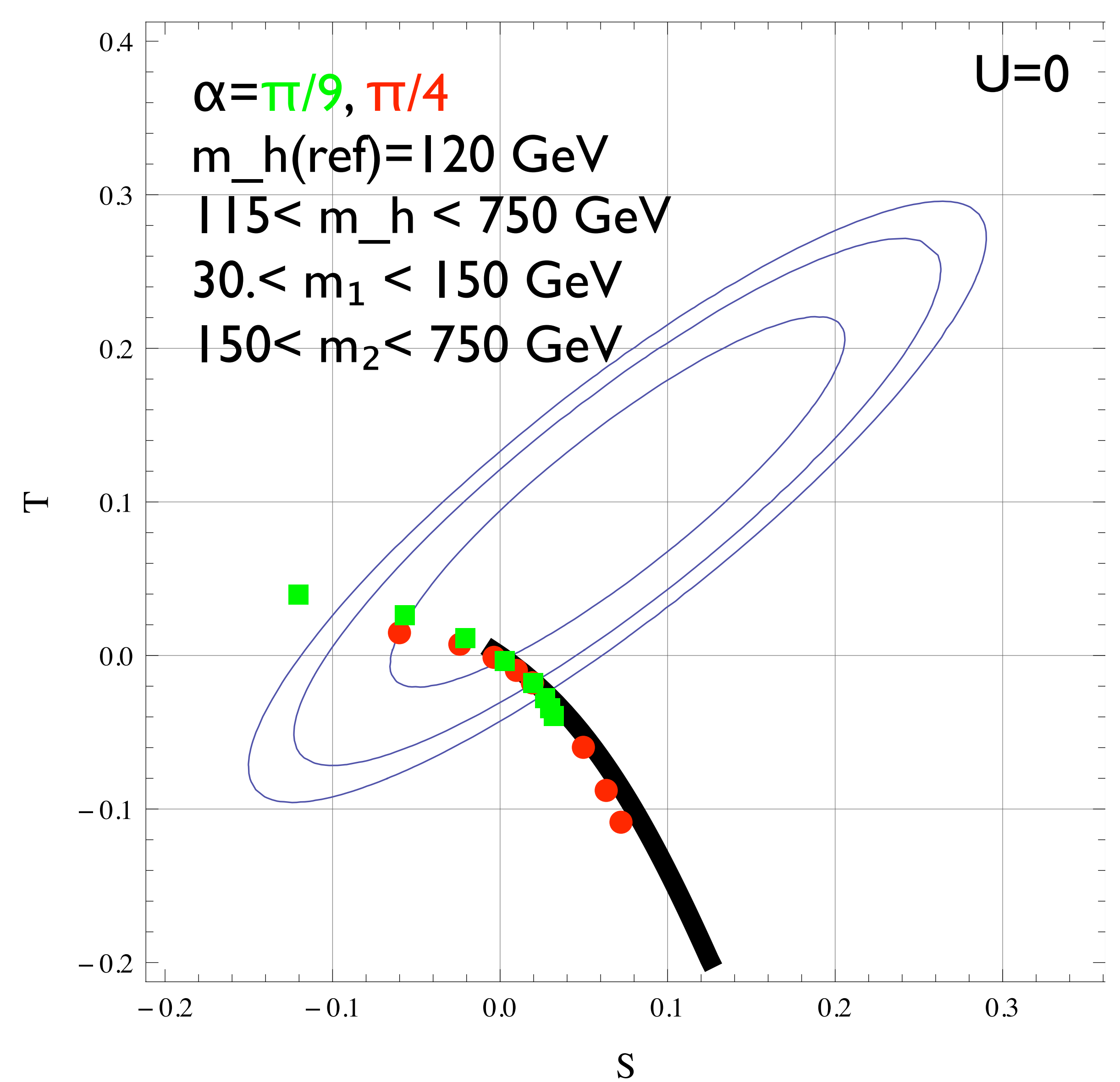
EW precision observables

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

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

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

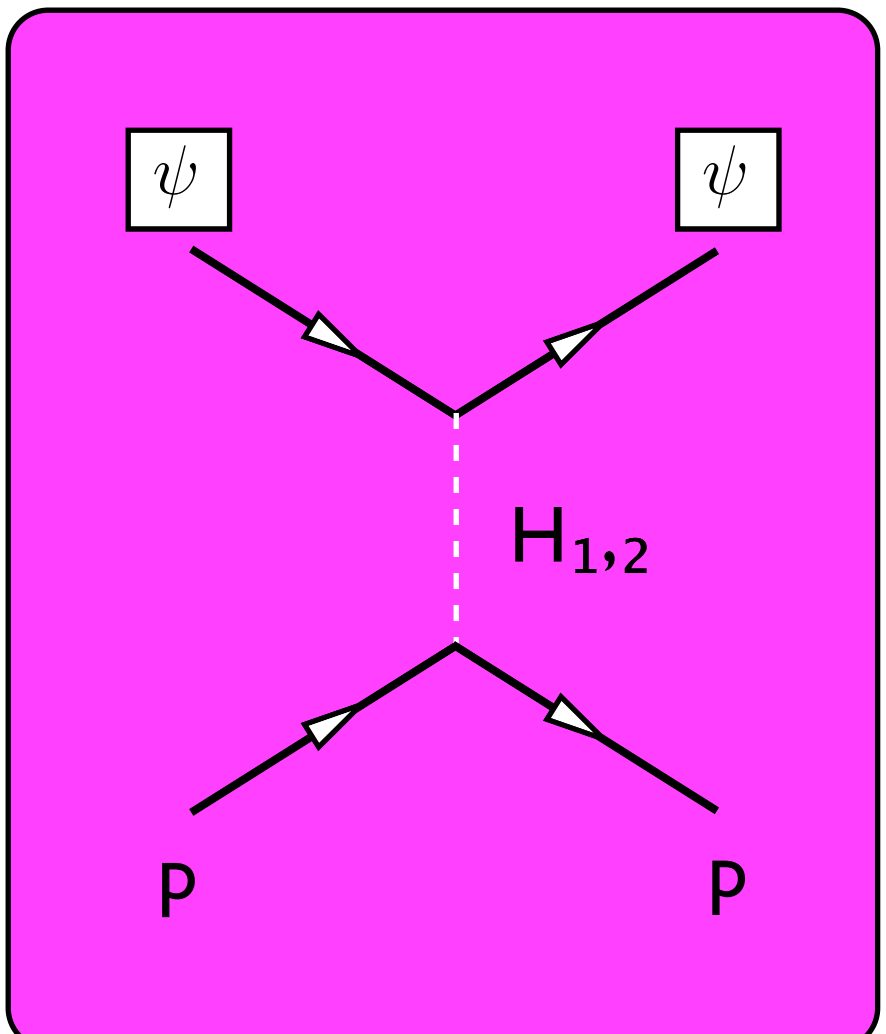
Same for T and U

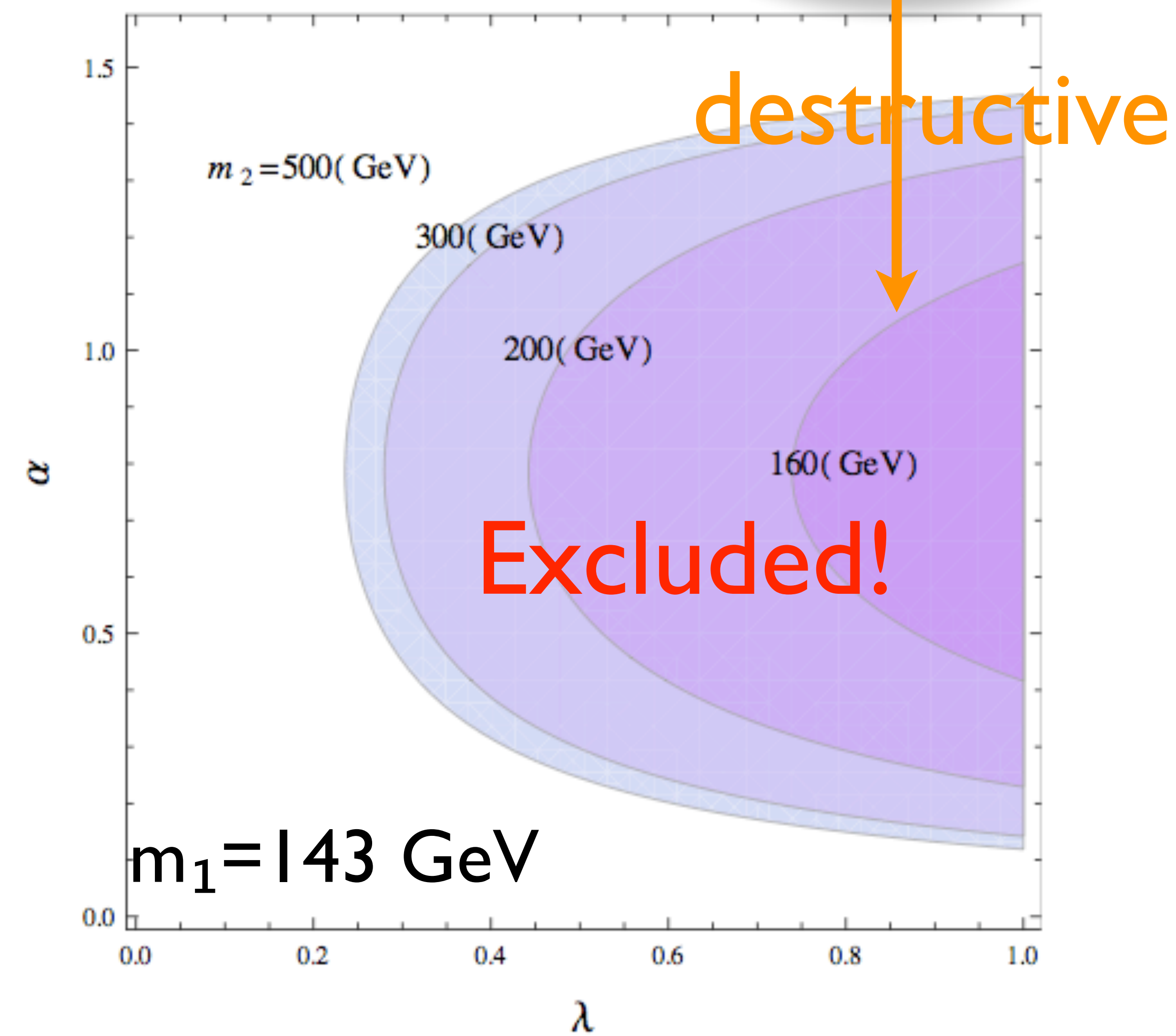


Constraints

- Dark matter to nucleon cross section (constraint)

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

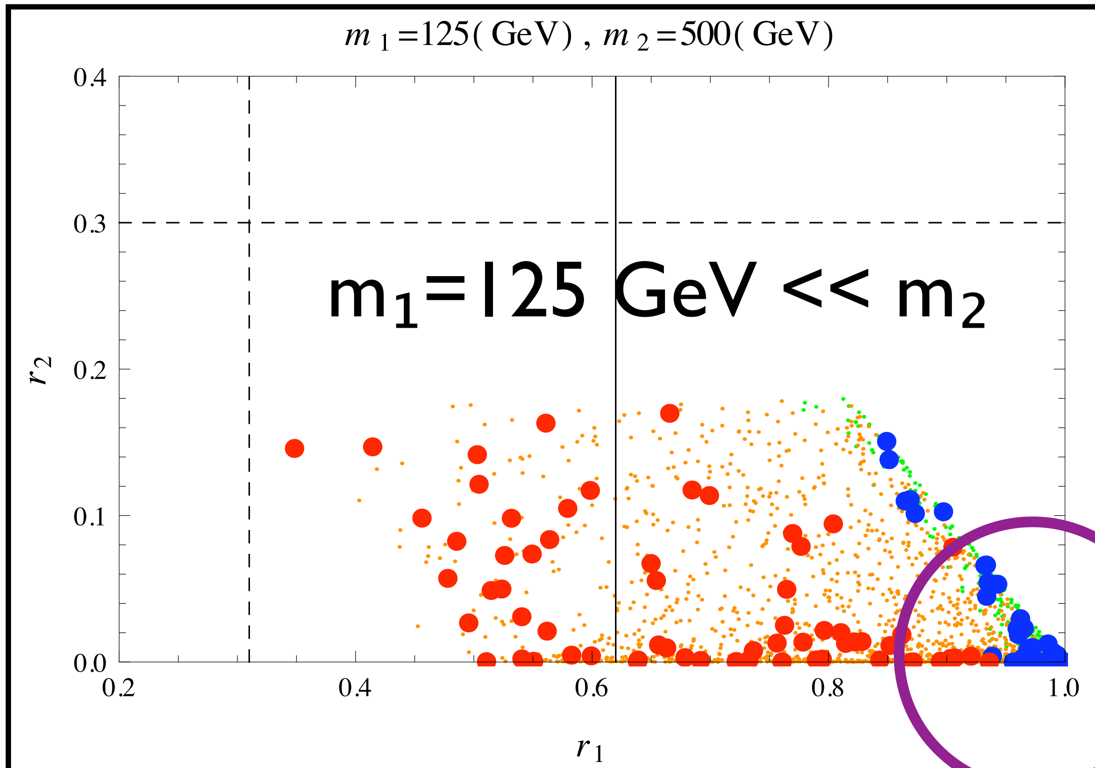


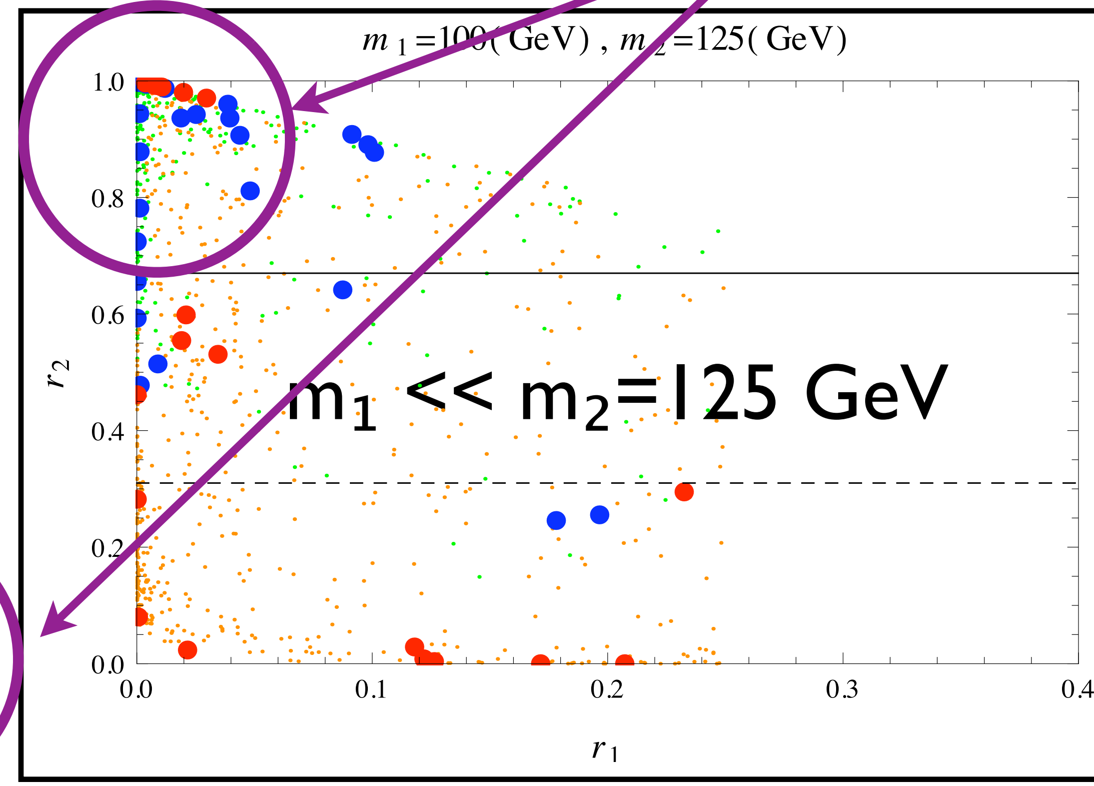


Discovery possibility

- Signal strength (r_2 vs r_1)

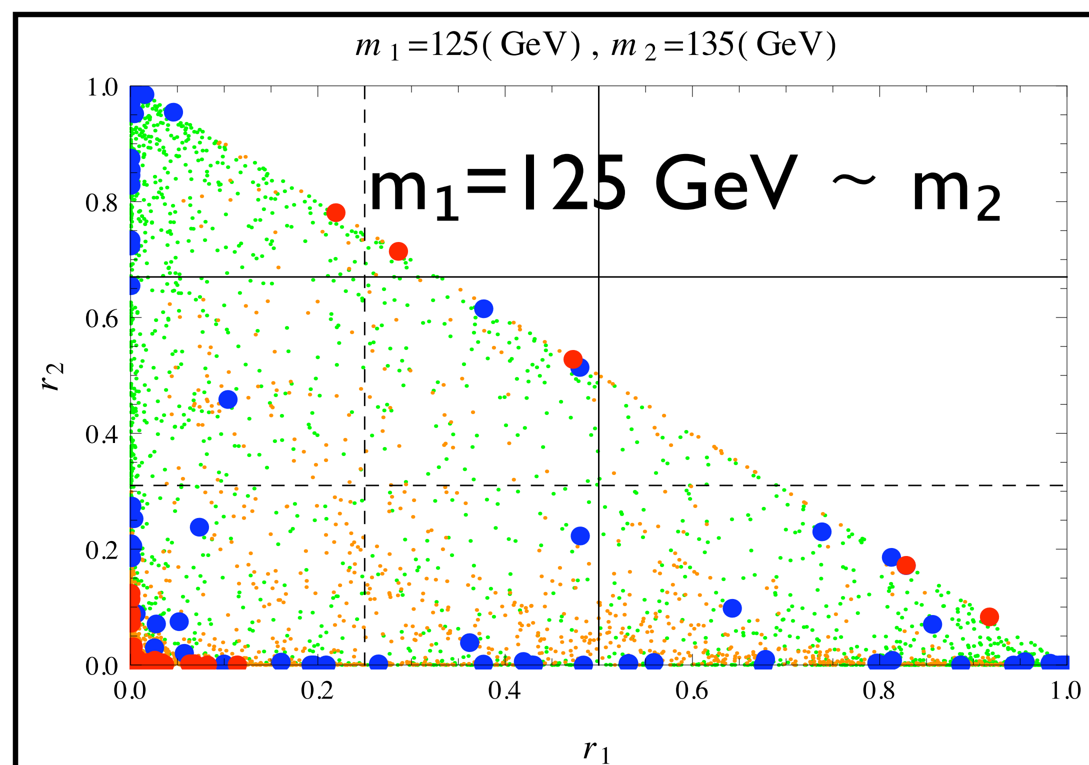
LHC data for 125 GeV resonance





: L= 5 fb^{-1} for 3σ Sig.

: L=10 fb^{-1} for 3σ Sig.



: Ω(x),σ_p(x)

: Ω(x),σ_p(o)

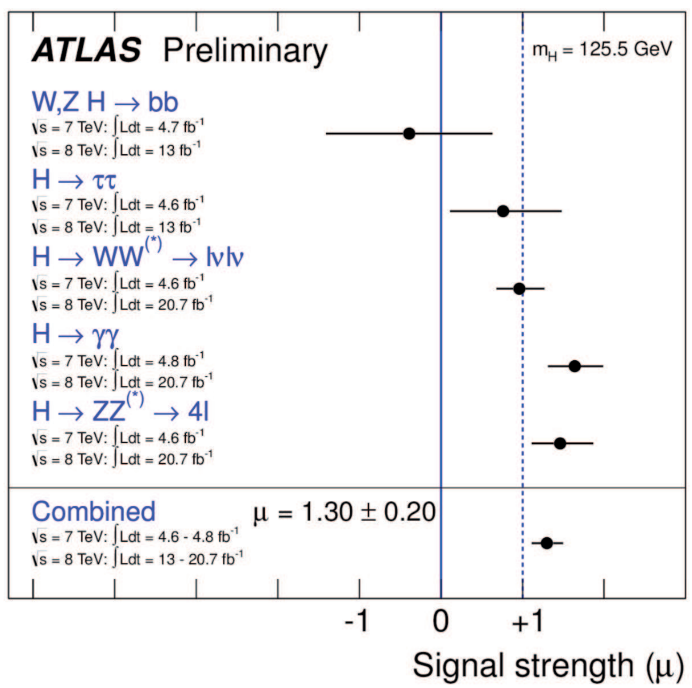
: Ω(o),σ_p(x)

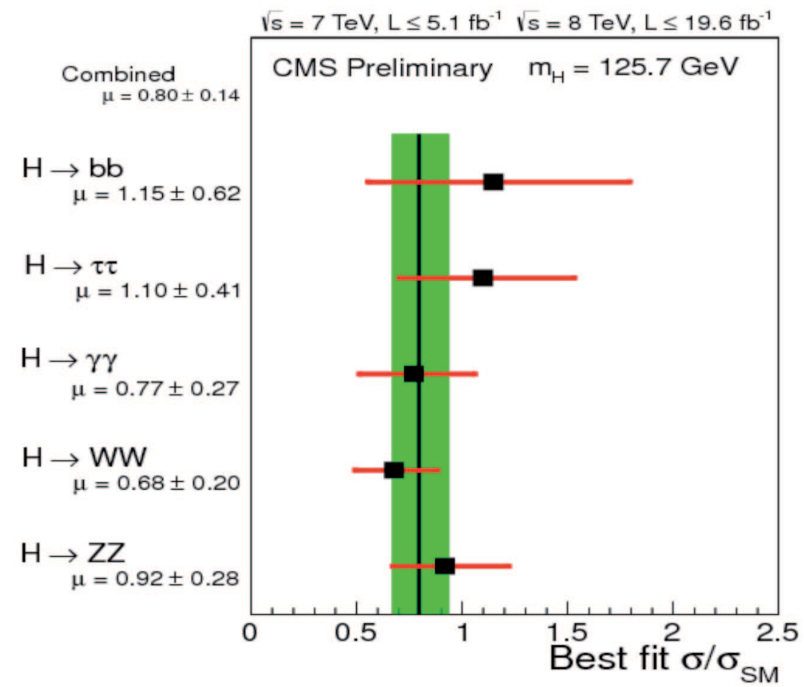
: Ω(o),σ_p(o)

Updates@LHCP

Signal Strengths

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



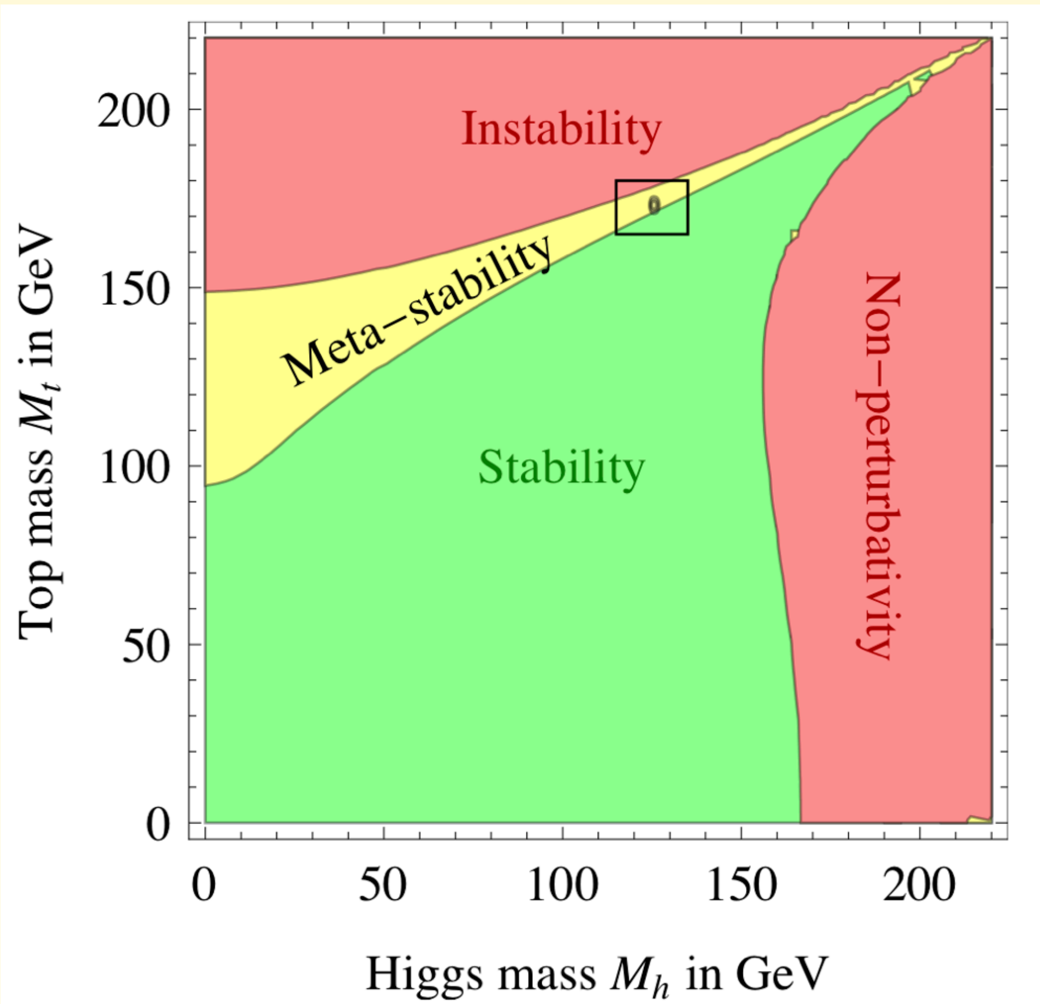


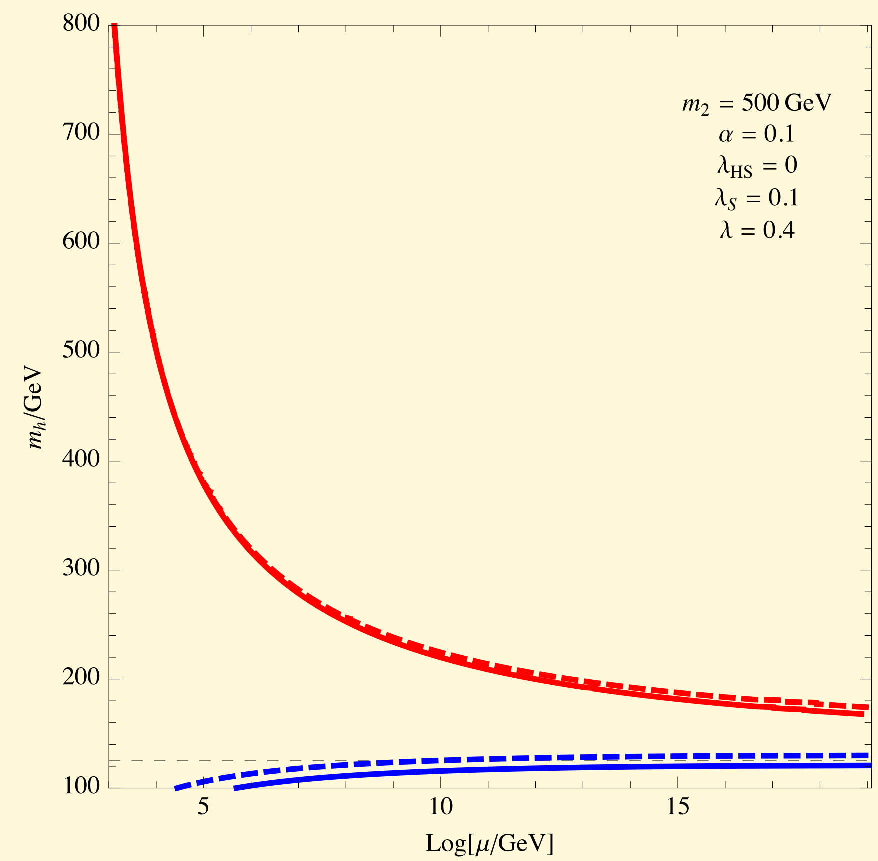
Decay Mode	ATLAS ($M_H = 125.5$ GeV)	CMS ($M_H = 125.7$ GeV)
$H \to bb$	-0.4 ± 1.0	1.15 ± 0.62
$H \to \tau\tau$	0.8 ± 0.7	1.10 ± 0.41
$H \to \gamma\gamma$	1.6 ± 0.3	0.77 ± 0.27
$H \to WW^*$	1.0 ± 0.3	0.68 ± 0.20
$H \to ZZ^*$	1.5 ± 0.4	0.92 ± 0.28
Combined	$\mathbf{1.30 \pm 0.20}$	$\mathbf{0.80 \pm 0.14}$

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

Getting smaller

Vacuum Stability Improved by the singlet scalar S





A. Strumia, Moriond EW 2013

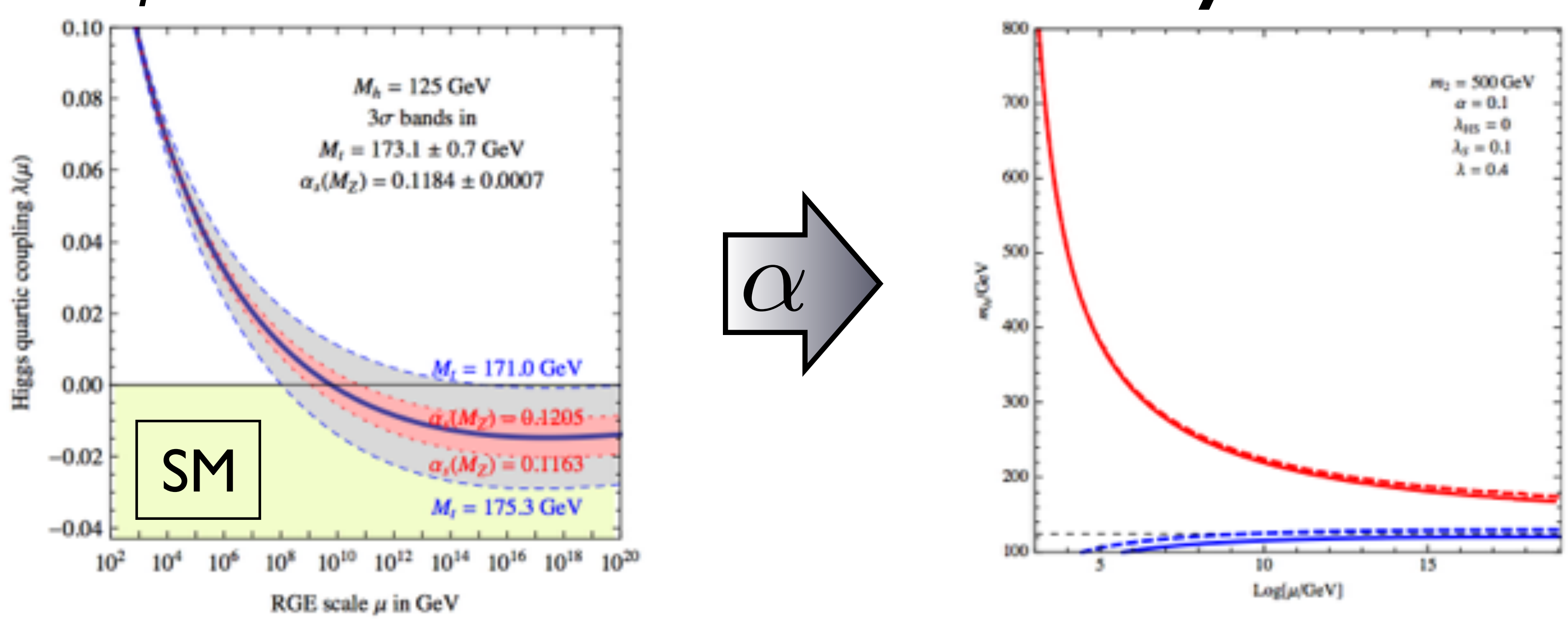
Baek, Ko, Park, Senaha (2012)

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]

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

Another UV completion

Work in progress (with S.Baek,
Wan-Il Park, Chaehyun Yu @ KIAS)

$$\mathcal{L}_{\rm new} = \overline{L}(i \not{D} - m_L)L + \overline{\psi}(i \not{\partial} - m_\psi)\psi - (\lambda_{L\psi}\overline{L}H\psi + H.c.)$$

$$L \equiv (L^+, L^0)^T$$

After EWSB, ψ and L^0 mix with each other. The mass matrix $\mathcal{M}$ in the (L^0, ψ) basis is given by

$$\mathcal{M} = \begin{pmatrix} m_L & \lambda_{L\psi}v/\sqrt{2} \\ \lambda_{L\psi}v/\sqrt{2} & m_\psi \end{pmatrix} \tag{6}$$

- Direct detection constraint satisfied with small mixing angle < 10^{-3}
- Relic dencity, indirect detection, EWPT, etc.
- Collider signature similar to the Higgsino LSP in SUSY models : More interesting than the UV completion with a singlet scalar “S”
- Comparison with EFT and the other UV completion
- Work in progress

$$L^+ \to L^0_{1,2} + W^{(*)}, \quad L^0_2 \to L^0_1 + Z^{(*)},$$

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

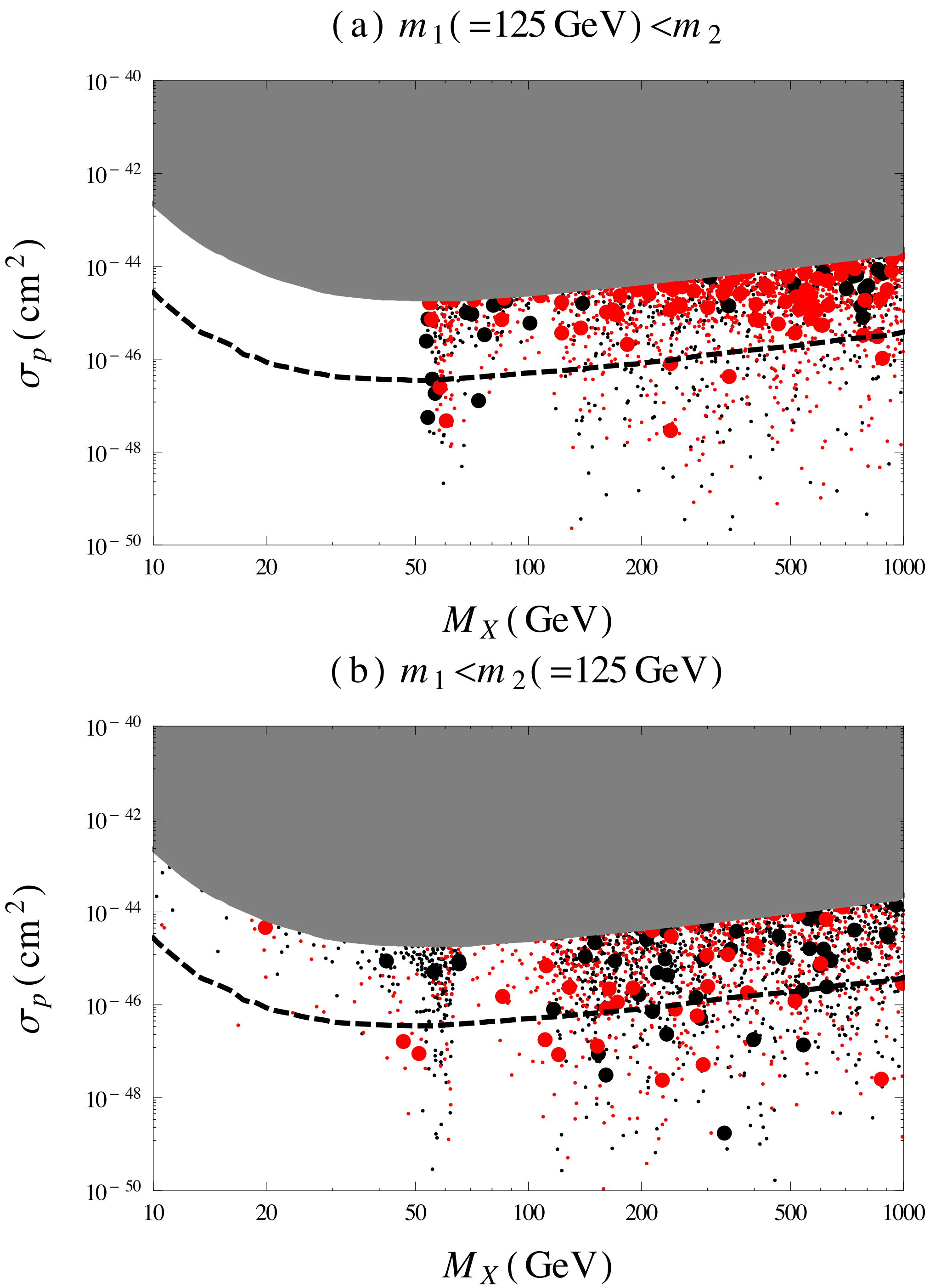


Figure 6. The scattered plot of σ_p as a function of M_X. The big (small) points (do not) satisfy the WMAP relic density constraint within 3 σ, while the red-(black-)colored points gives $r_1 > 0.7$($r_1 < 0.7$). The grey region is excluded by the XENON100 experiment. The dashed line denotes the sensitivity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

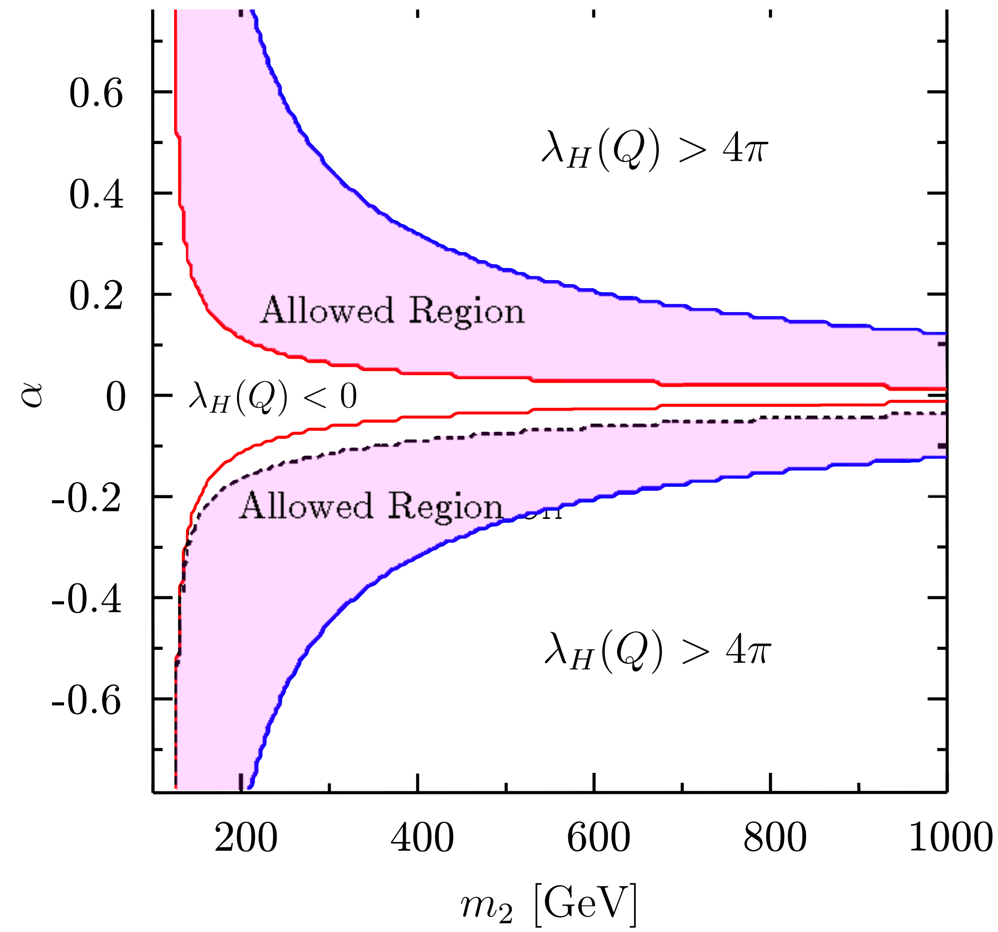


Figure 8. The vacuum stability and perturbativity constraints in the α-m_2 plane. We take $m_1 = 125$ GeV, $g_X = 0.05$, $M_X = m_2/2$ and $v_\Phi = M_X/(g_X Q_\Phi)$.

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

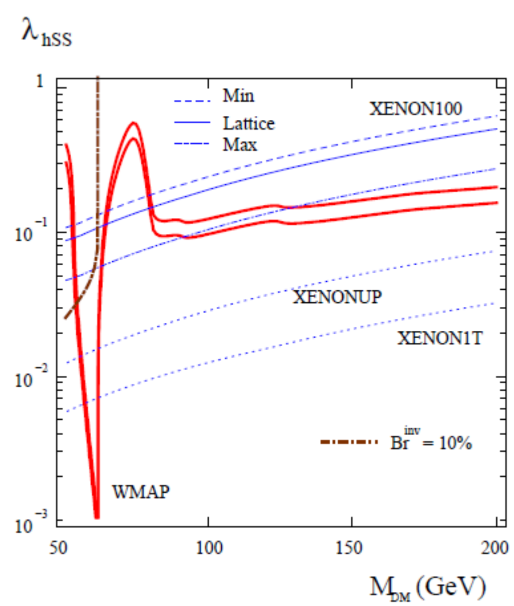


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

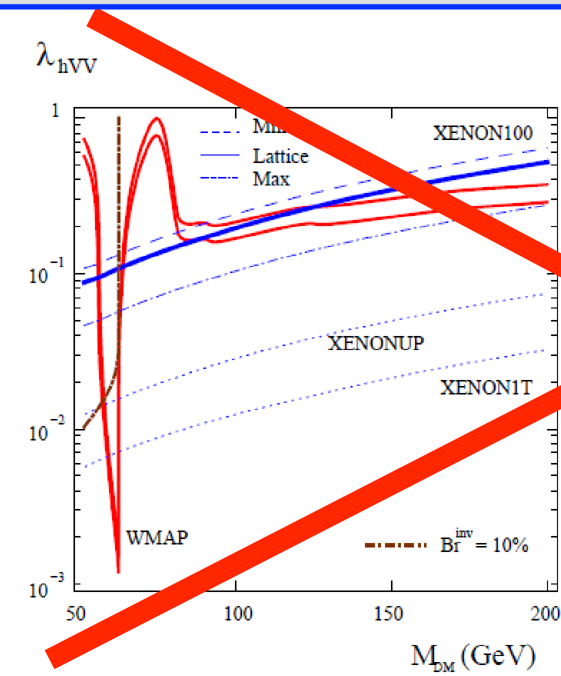


FIG. 2. Same as Fig. 1 for vector DM particles.

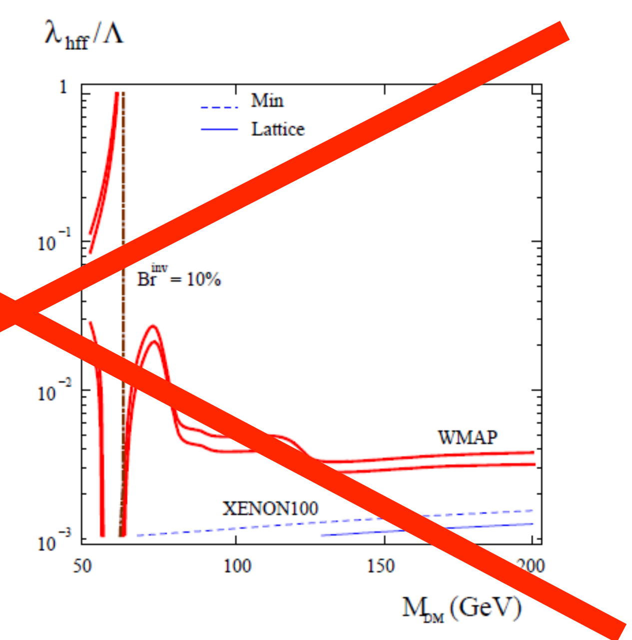


FIG. 3. Same as in Fig.1 for fermion DM; λ_{hff}/Λ is in GeV^{-1}.

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

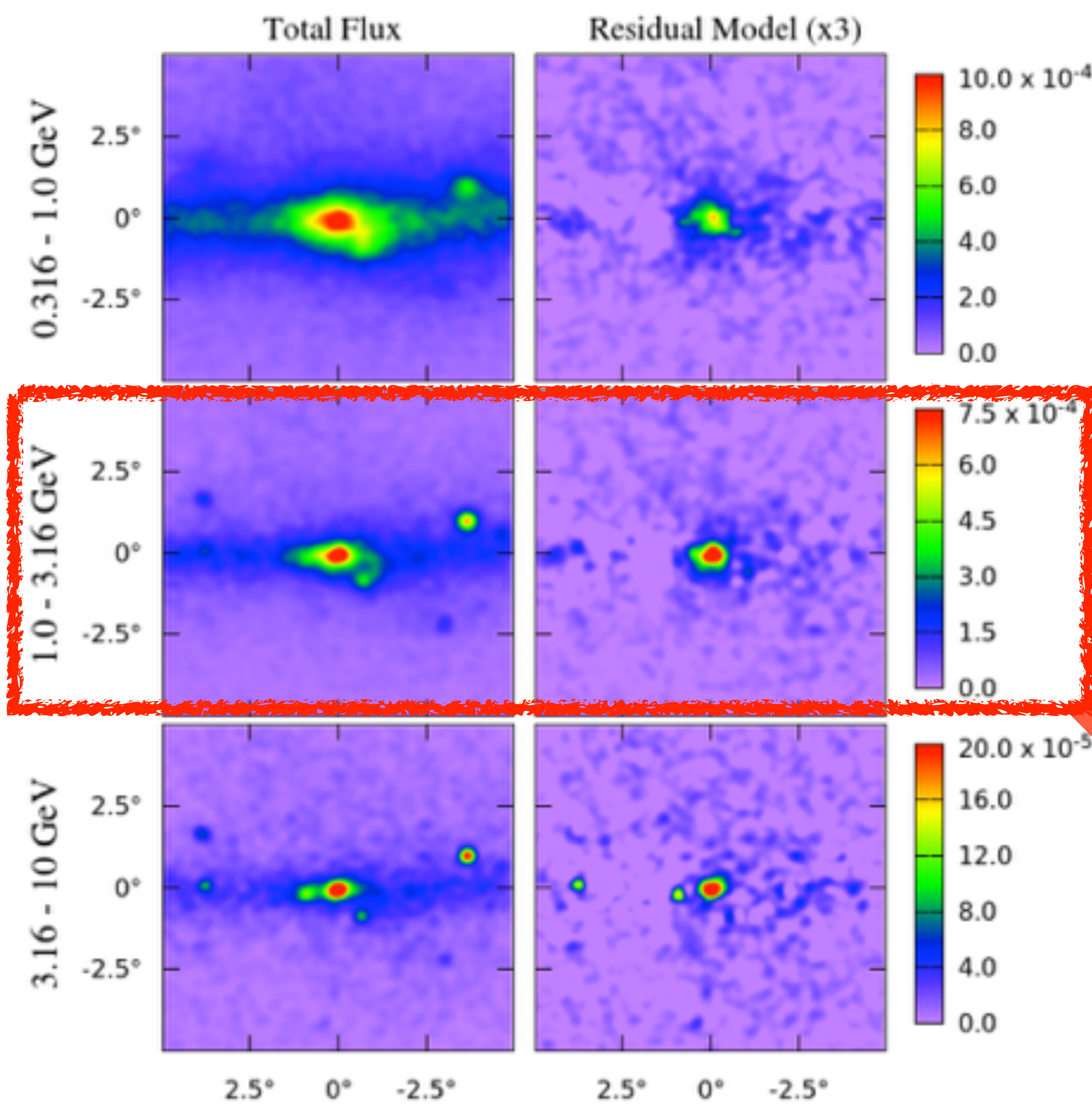
Is this any useful in phenomenology ?

Is this any useful in phenomenology ?

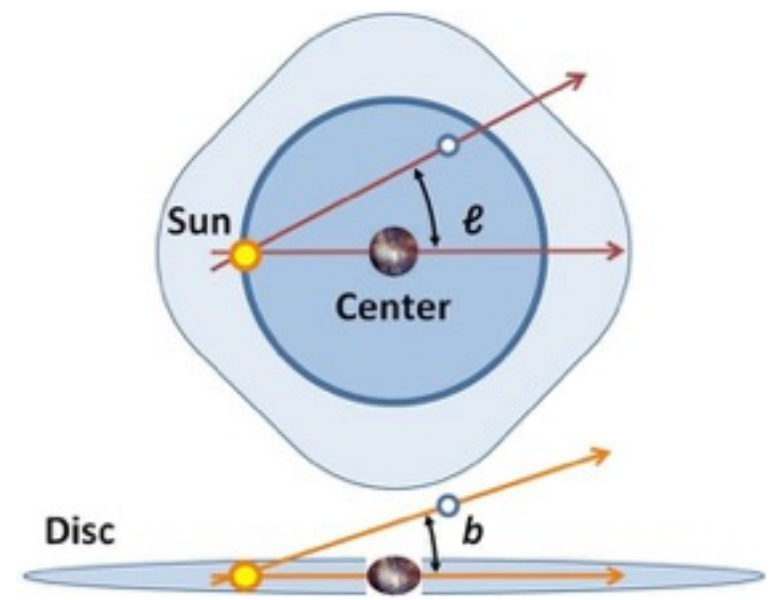
YES !

Fermi-LAT γ-ray excess

- Gamma-ray excess in the direction of GC



[1402.6703, T. Daylan et.al.]

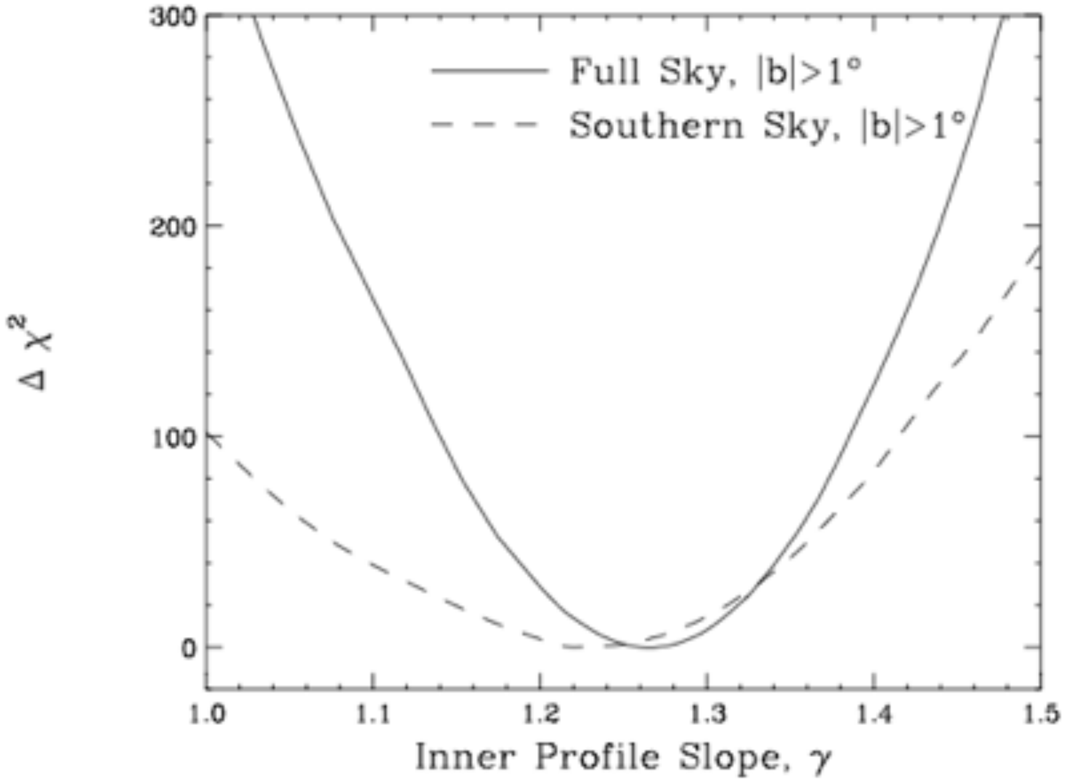


$$\mathrm{GC} : b \sim l \lesssim 0.1^\circ$$

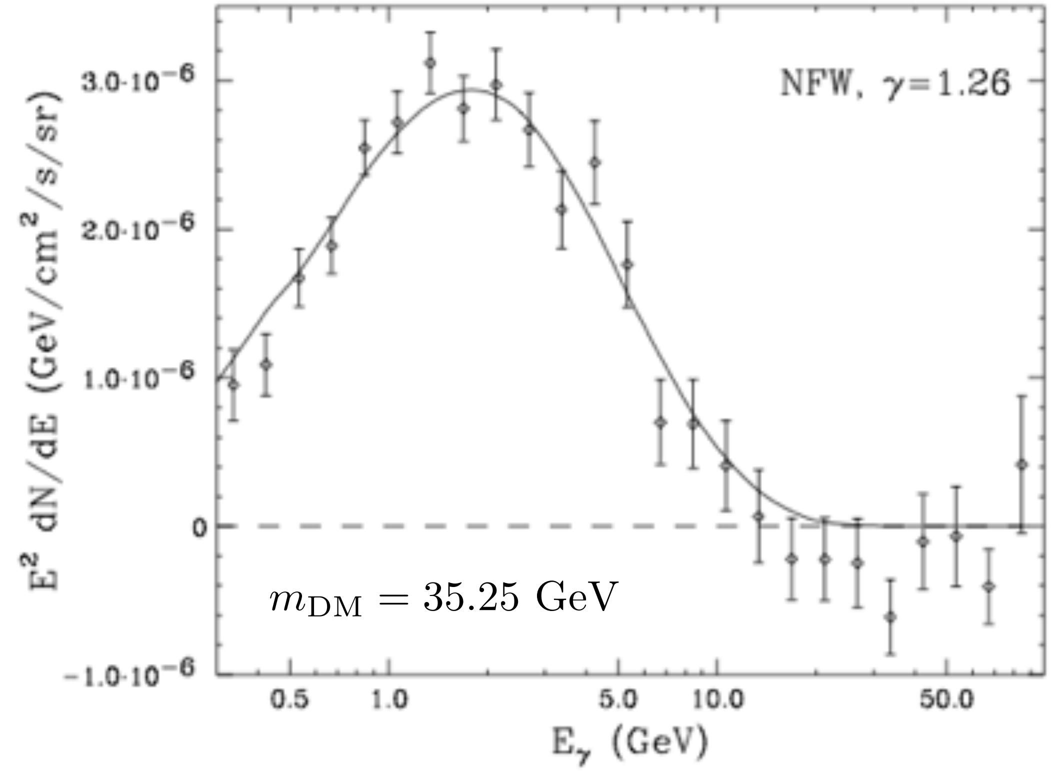
extended

$\boxed{\text{GeV scale excess!}}$

• A DM interpretation



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



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

• Millisecond Pulars (astrophysical alternative)

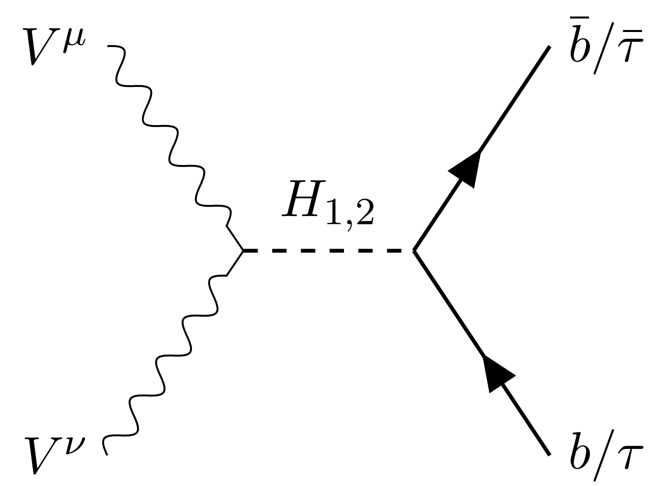
It may or may not be the main source, depending on

- 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

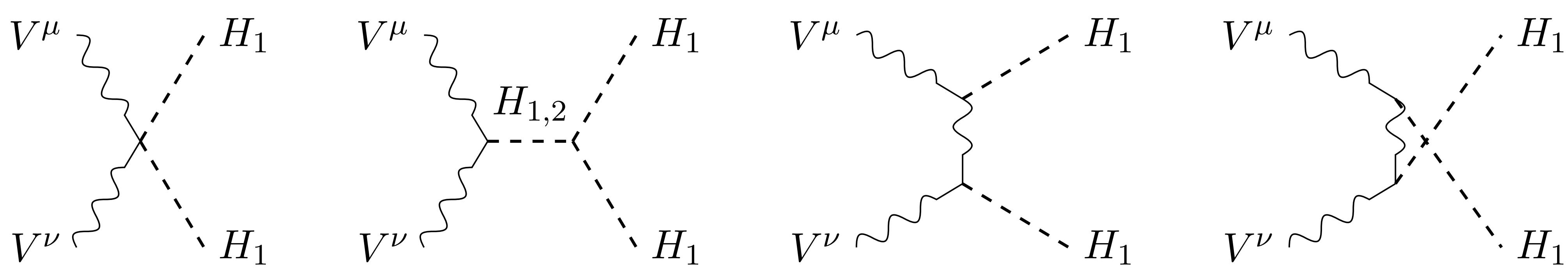


Figure 3. Dominant s/t-channel production of H_1s that decay dominantly to $b+\bar{b}$

Importance of VDM with Dark Higgs Boson

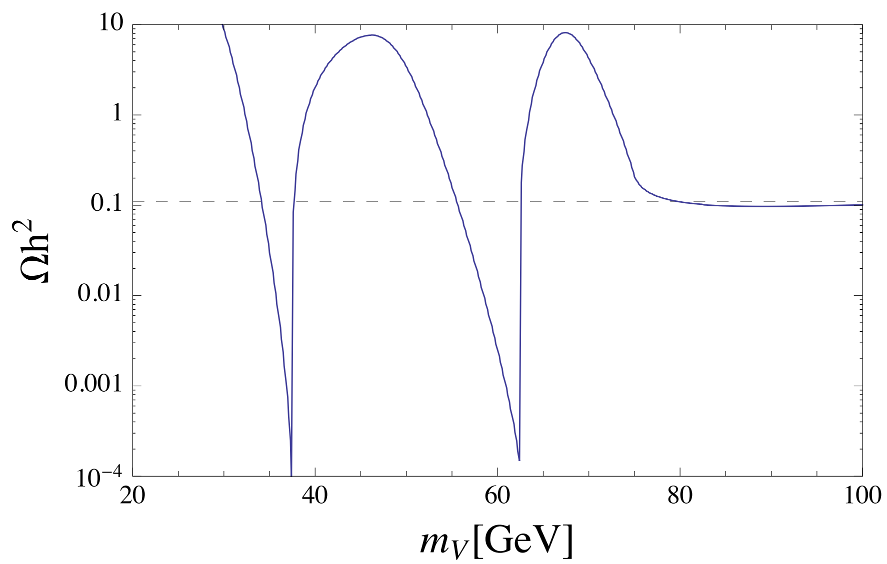


Figure 4. Relic density of dark matter as function of m_ψ for $m_h = 125$, $m_\phi = 75\,\mathrm{GeV}$, $g_X = 0.2$, and $\alpha = 0.1$.

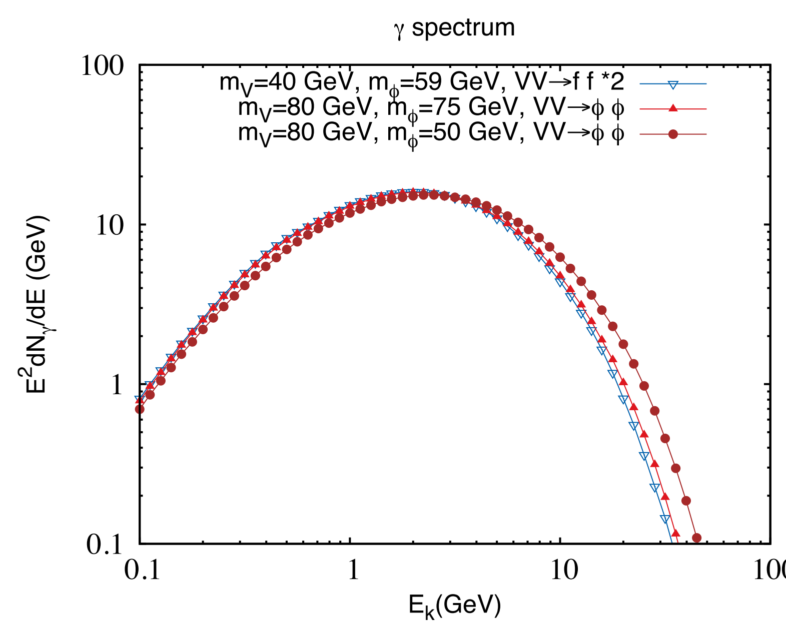


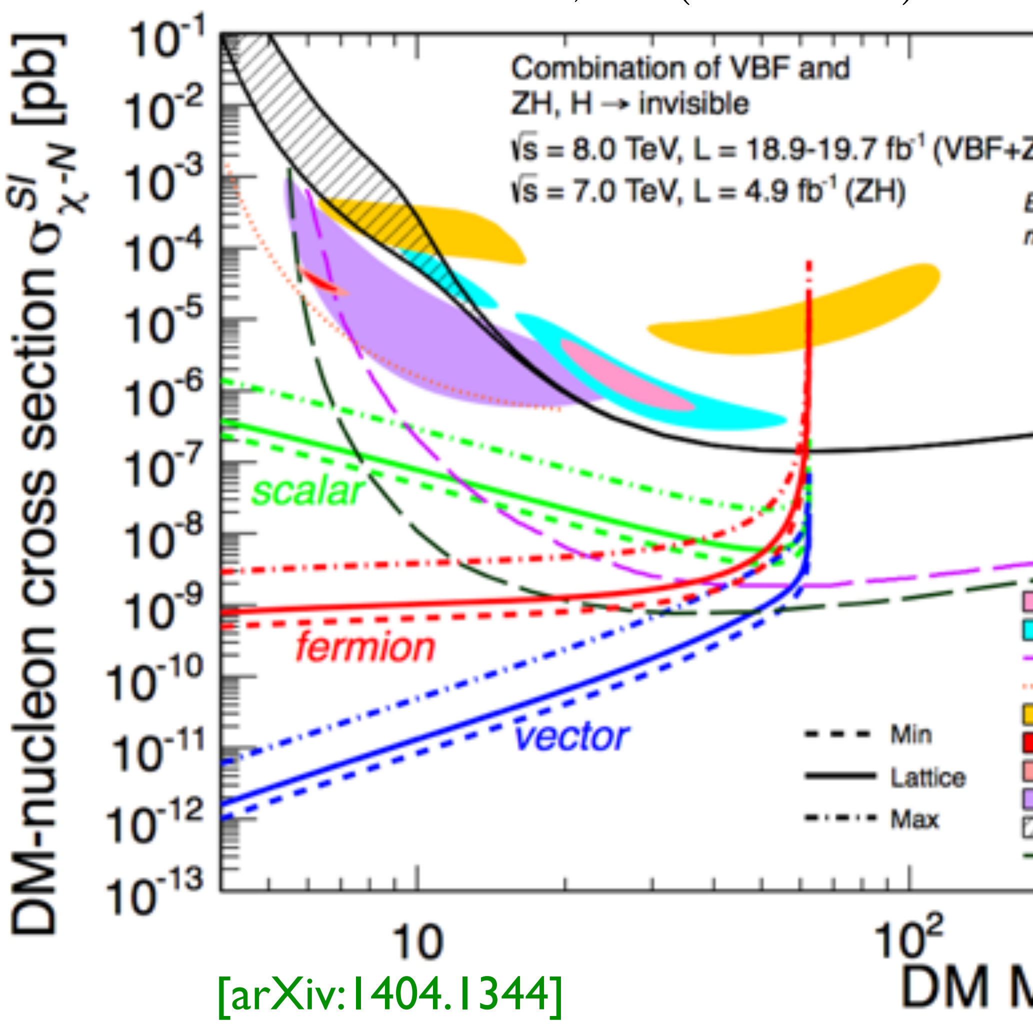
Figure 5. Illustration of γ spectra from different channels. The first two cases give almost the same spectra while in the third case γ is boosted so the spectrum is shifted to higher energy.

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

And there would be no second scalar in EFT

Collider Implications

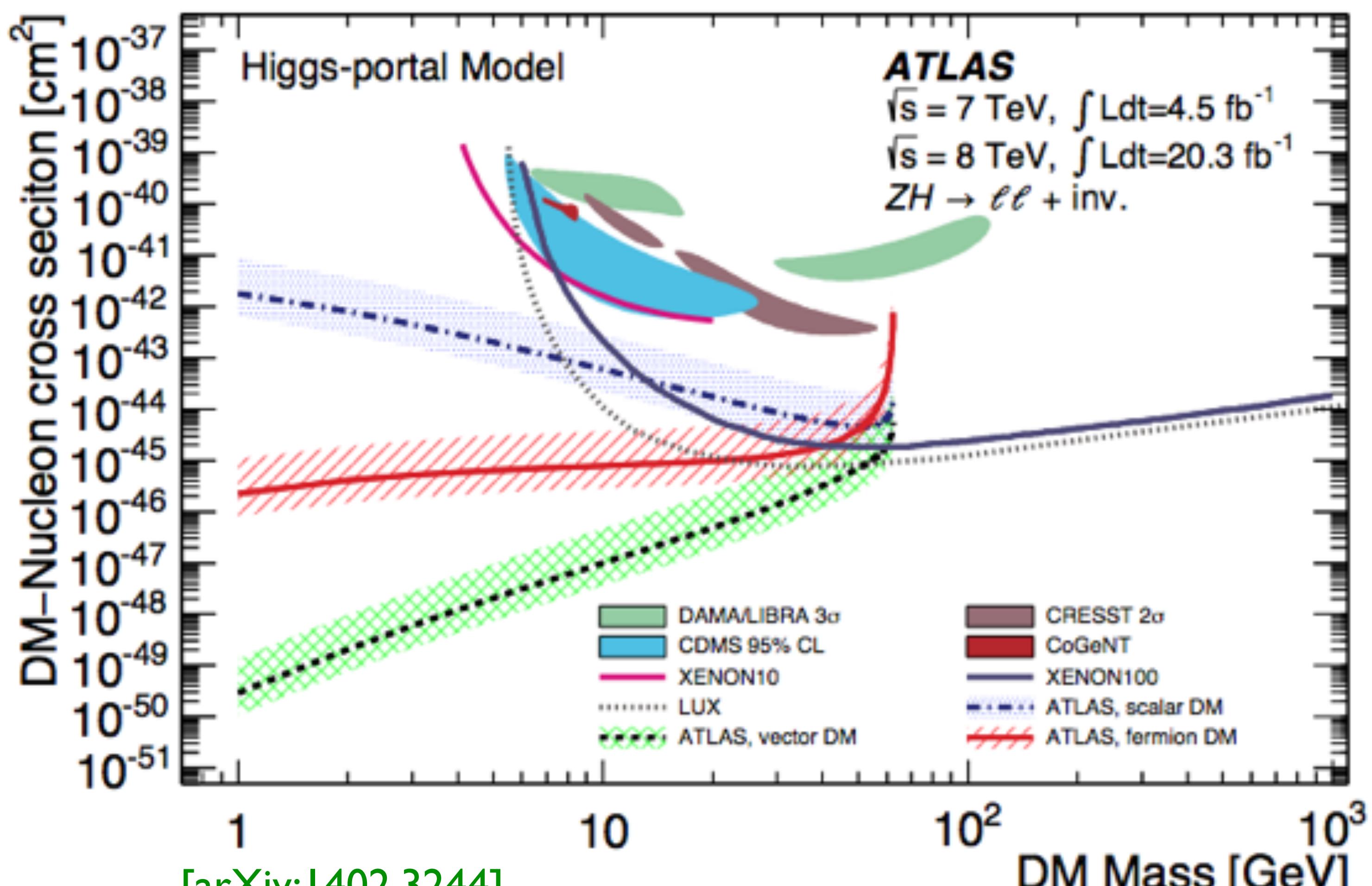
$m_h = 125\text{GeV},\ \text{Br}(H \to \text{inv}) < 0.51 \text{ at } 90\% \text{ CL}$



[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]

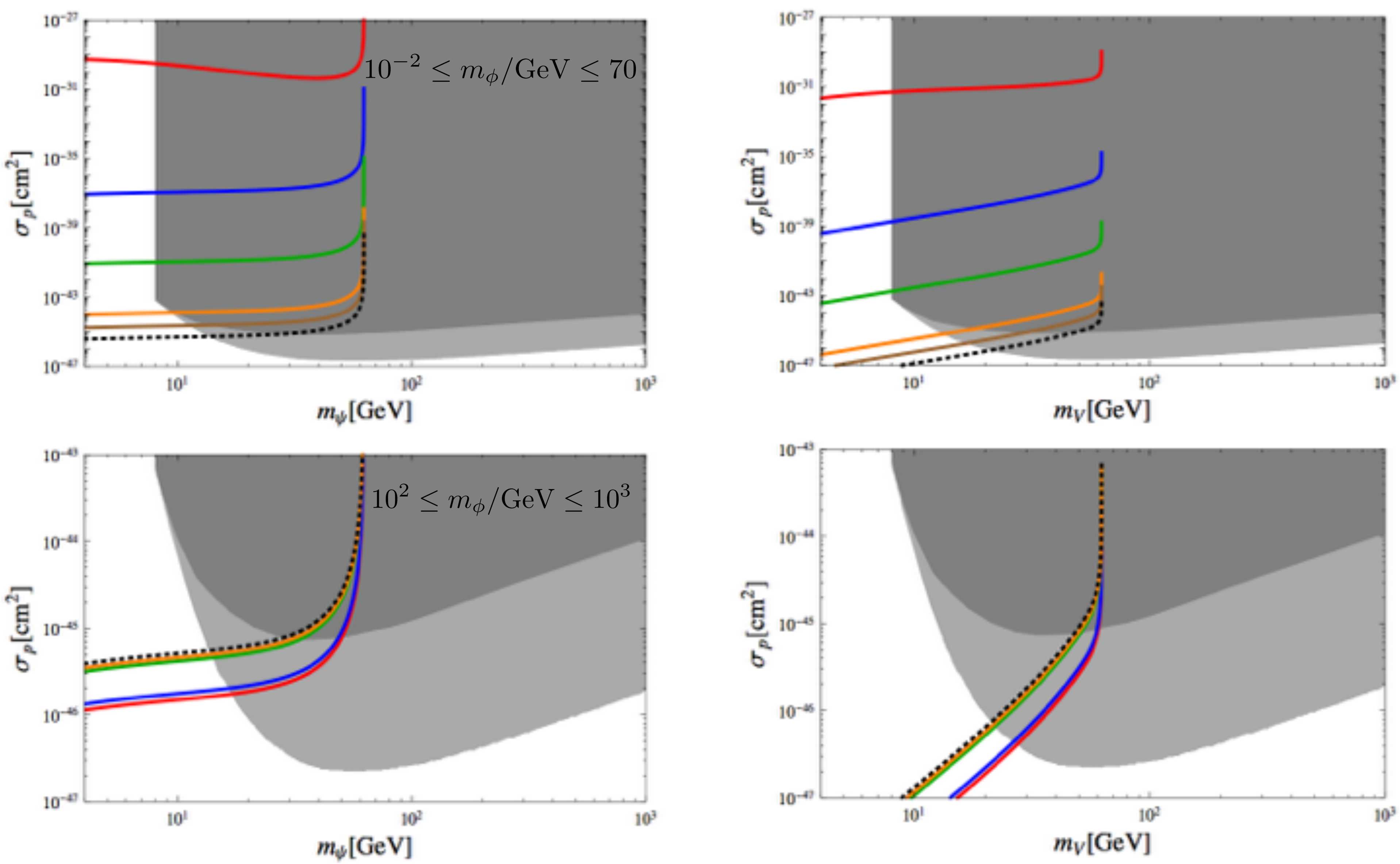
- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

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

Dashed curves:EFT, ATLAS,CMS results

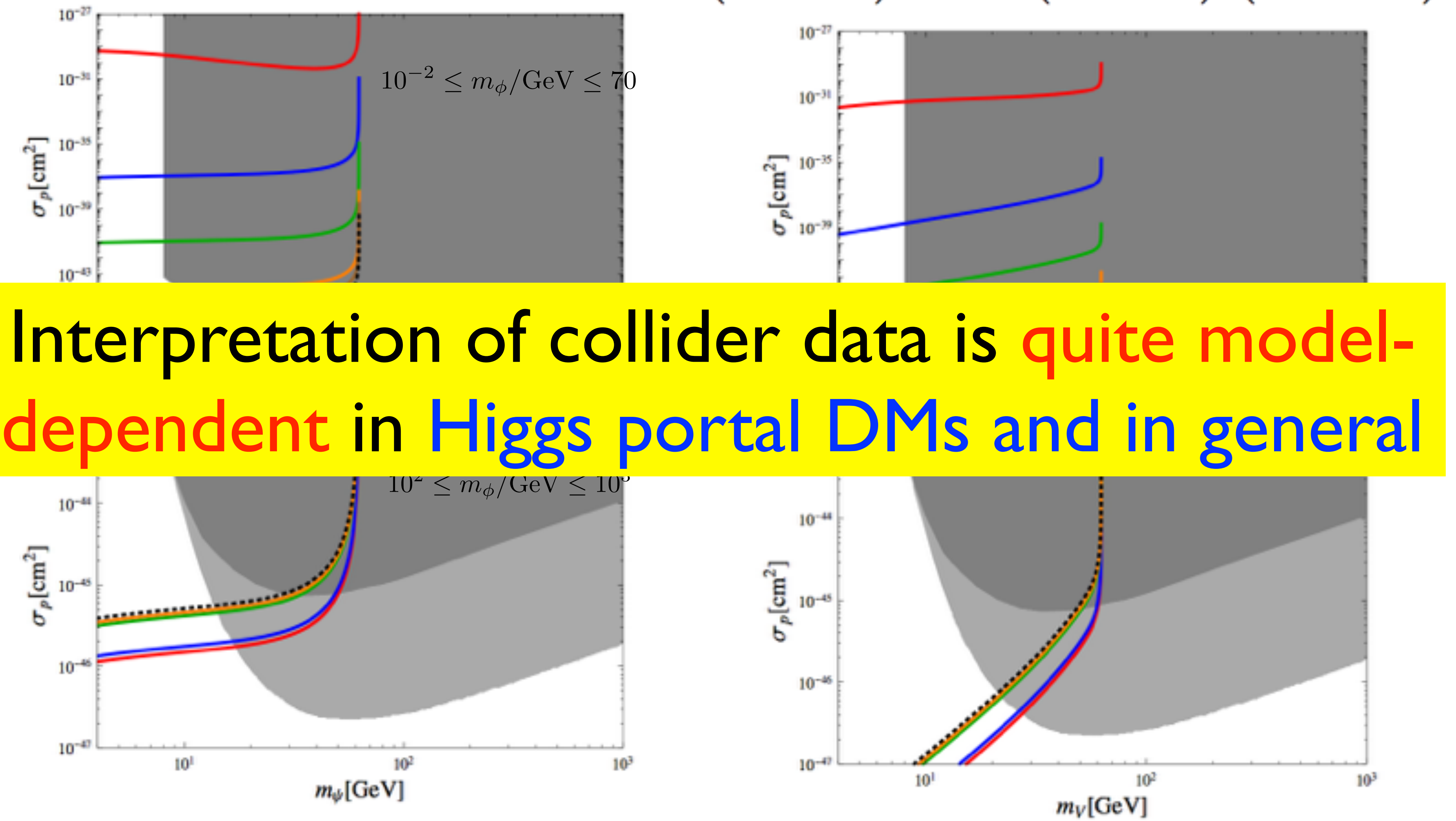


- However, in renormalizable unitary models of Higgs portals, 2 more relevant parameters

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

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

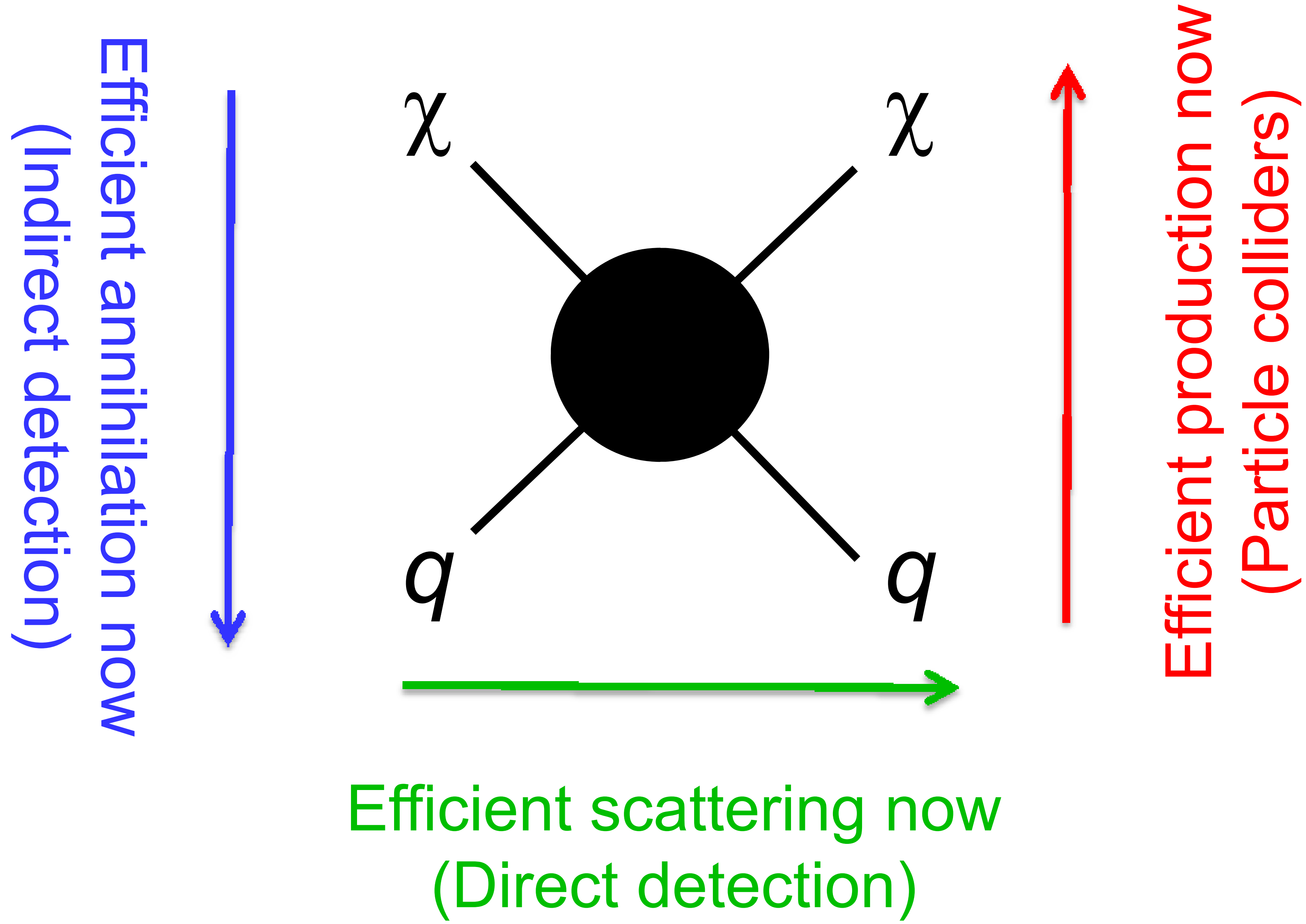
$$\mathcal{L}_{\rm VDM} = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)^2 - \lambda_{\Phi H}\left(\Phi^\dagger \Phi - \frac{v_\Phi^2}{2}\right)\left(H^\dagger H - \frac{v_H^2}{2}\right)$$



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

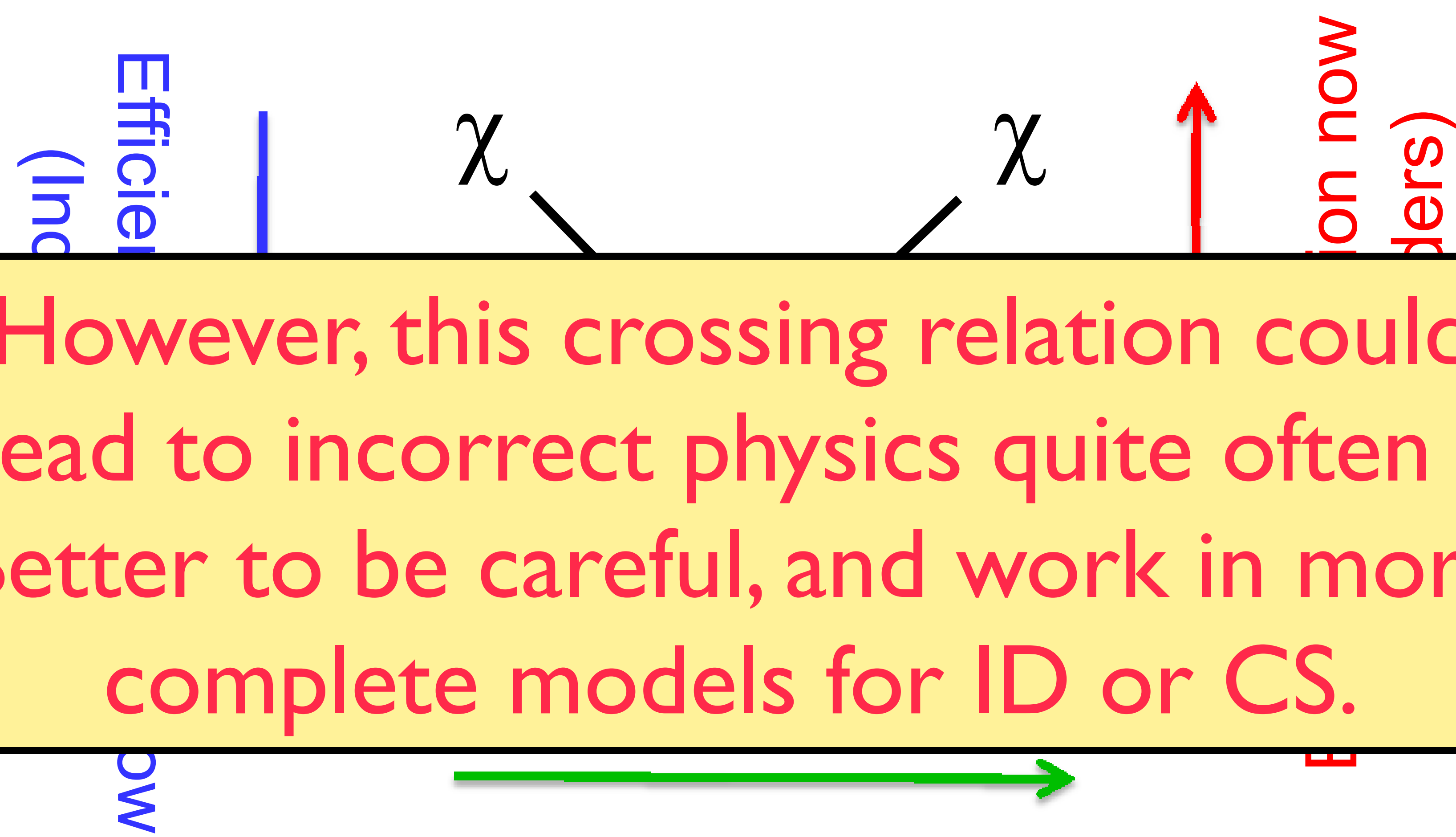
Crossing & WIMP detection

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)

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 renorm and unitary (anomaly free) model

Backup on generic cancellation in direct detection x-section

General Aspects of Higgs portal to a hidden sector

- A singlet acalar S and/or scalar ϕ_X charged under hidden sector gauge group can appear with the couplings with the SM $H^\dagger H$ operators:

$$H^\dagger HS, H^\dagger HS^2, H^\dagger H\phi_X^\dagger\phi_X, S\phi_X^\dagger\phi_X, S^2\phi_X^\dagger\phi_X$$

- Both S and ϕ_X can develop nonzero VEV's: v_S and v_ϕ, and the fluctuations around these vacuum will be additional real singlet scalars from the viewpoint of SM gauge interactions.

- There will be generic mixings among $h_{\rm SM}$, s and ϕ_X, resulting a number of neutral scalar bosons. Only $h_{\rm SM}$ couples to the SM fermions and the weak gauge bosons

- More than one neutral scalar bosons with reduced couplings to the SM fermions and weak gauge bosons
- No extra charged scalar bosons
- Invisible Higgs (or scalar boson) decays

Let us consider the mixing between $h_\alpha \equiv (h, s, \phi_{\alpha=1,...,n})$. The mass eigenstates $h_i \equiv (h_1, h_2, ..., h_{n+2})$ will be linear combinations of h_α in terms of $SO(n+2)$ matrix O: $h_i = O_i{}^\alpha h_\alpha$ with $OO^T = O^T O = 1$. Then the couplings between h_i and the SM fermions $f\bar{f}$ and the SM weak gauge boson $V = W, Z^0$ are given by

$$G_{if\bar{f}} = \frac{m_f}{v} O_{1j}, \tag{6}$$

$$G_{iVV} = g_V \frac{m_V^2}{v} O_{1j}. \tag{7}$$

$$G_{i\psi_X\overline{\psi_X}} = \lambda_X O_{2i}$$

Then, DM-N scattering amplitude behaves as

$$\text{amp} \sim \lambda_X \sum_i O_{1i} \frac{1}{t - m_i^2} O_{2i} \simeq -\lambda_X \sum_i O_{1i} \frac{1}{m_i^2} O_{i2}^T$$

$$\rightarrow -\frac{1}{m^2} \sum_i \left(O_{1i} O_{i2}^T = (OO^T)_{12} = 0 \right)$$

- The cancellation in the DD scattering cross section in the degenerate H_i's is generic (at tree level)
- Similar to the GIM cancellation at one loop level
- It cannot be seen if we included only the SM Higgs
- This would be also true for other Higgs portal models
- No spin-dependent DD cross section
- If there are new gauge interactions, this conclusion may be not true, because there would be extra contributions from new gauge bosons