Degenerate scalar scenario in a singlet scalar extension of the Standard Model

Gi-Chol Cho
(Ochanomizu U.)

in collaboration with
Sachiho Abe (Ocha→), Chikako Idegawa (Ocha), Kentarou Mawatari (Iwate U.)
Eibun Senaha (Van Lang U., Vietnam), Rio Sugihara (Ocha →)

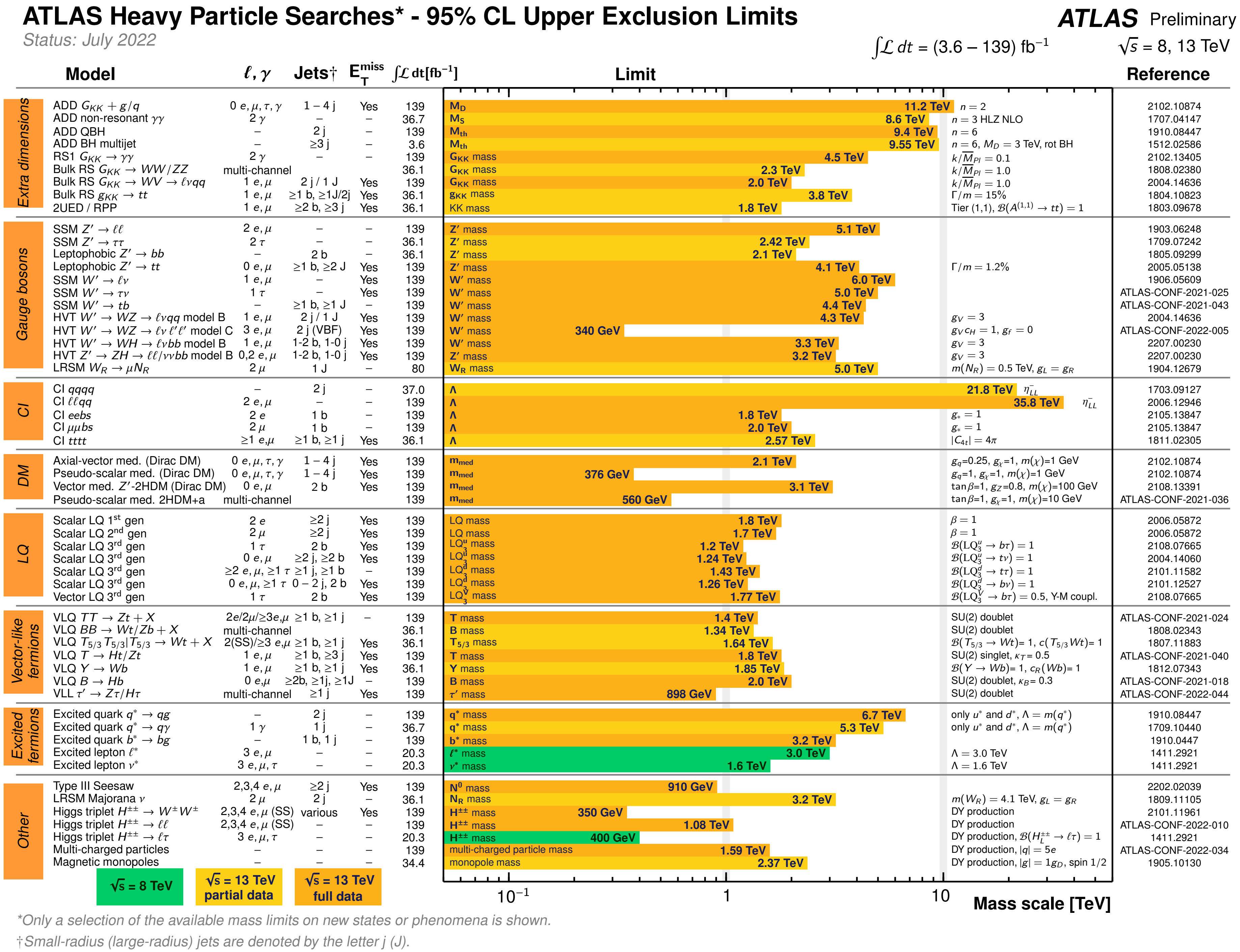
based on
PRD104, 035023, PLB 823, 136787, PRD106,115012, PLB 839, 137757
arXiv:2101.04887, 2105.11830, 2205.12046, 2212.13029)

NITEP 素粒子現象論研究会 2022

2023/Mar/16-18, 大阪公立大学

お茶の水女子大学
Ochanomizu University

Search for BSM particles (heavy)



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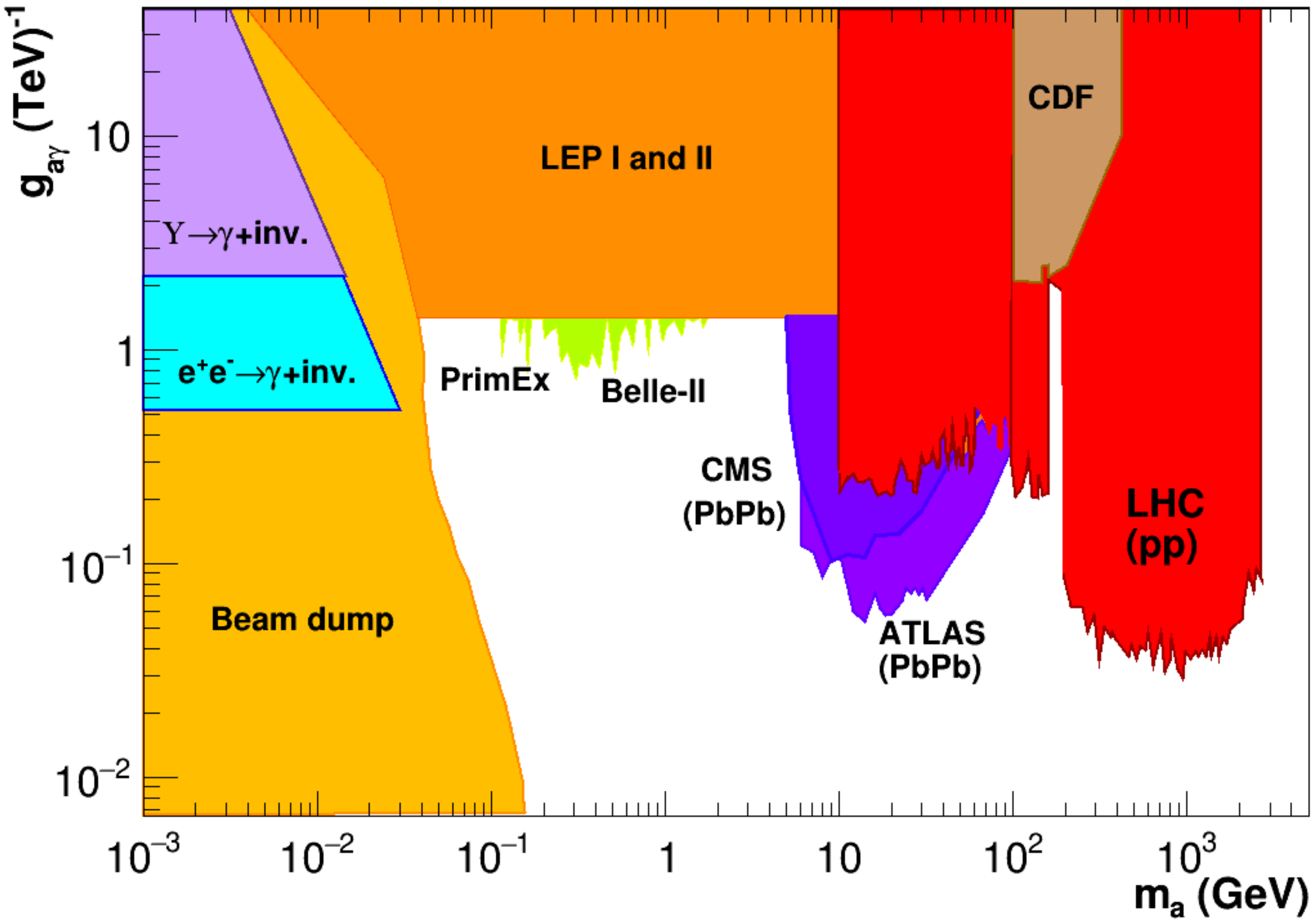
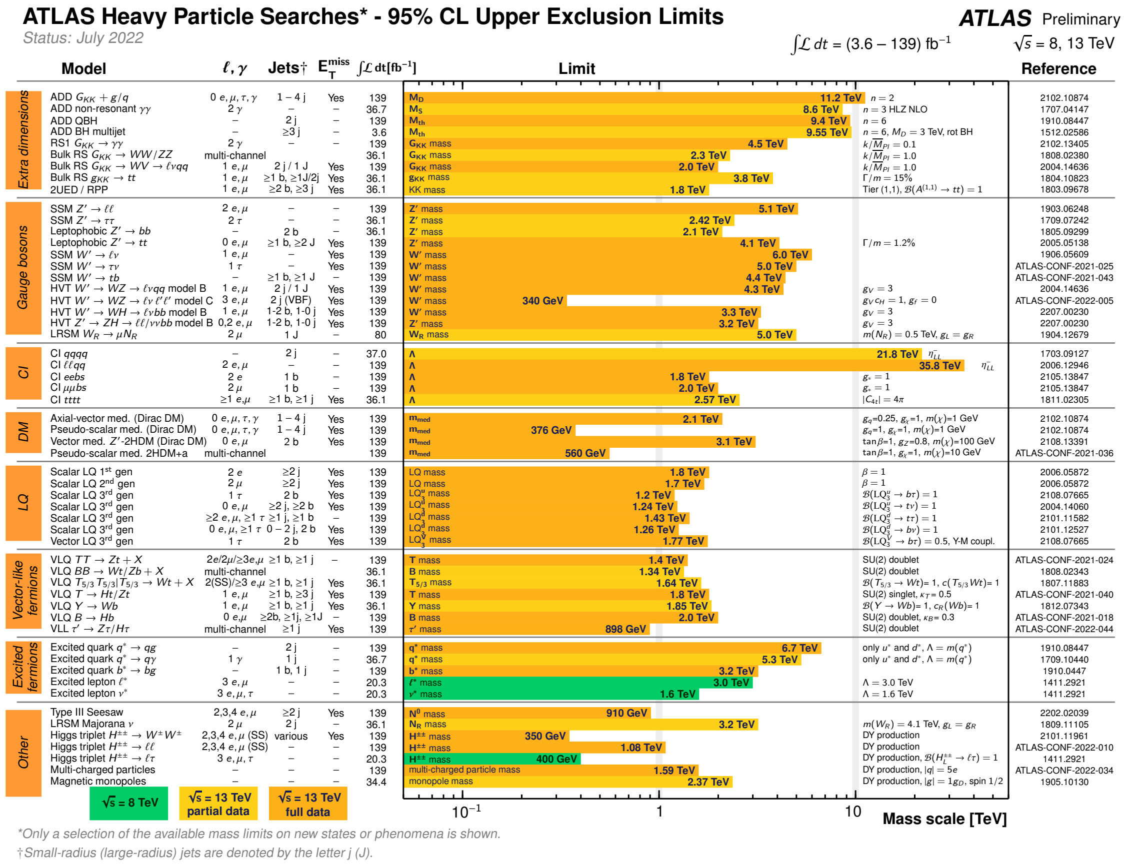
G.C.Cho

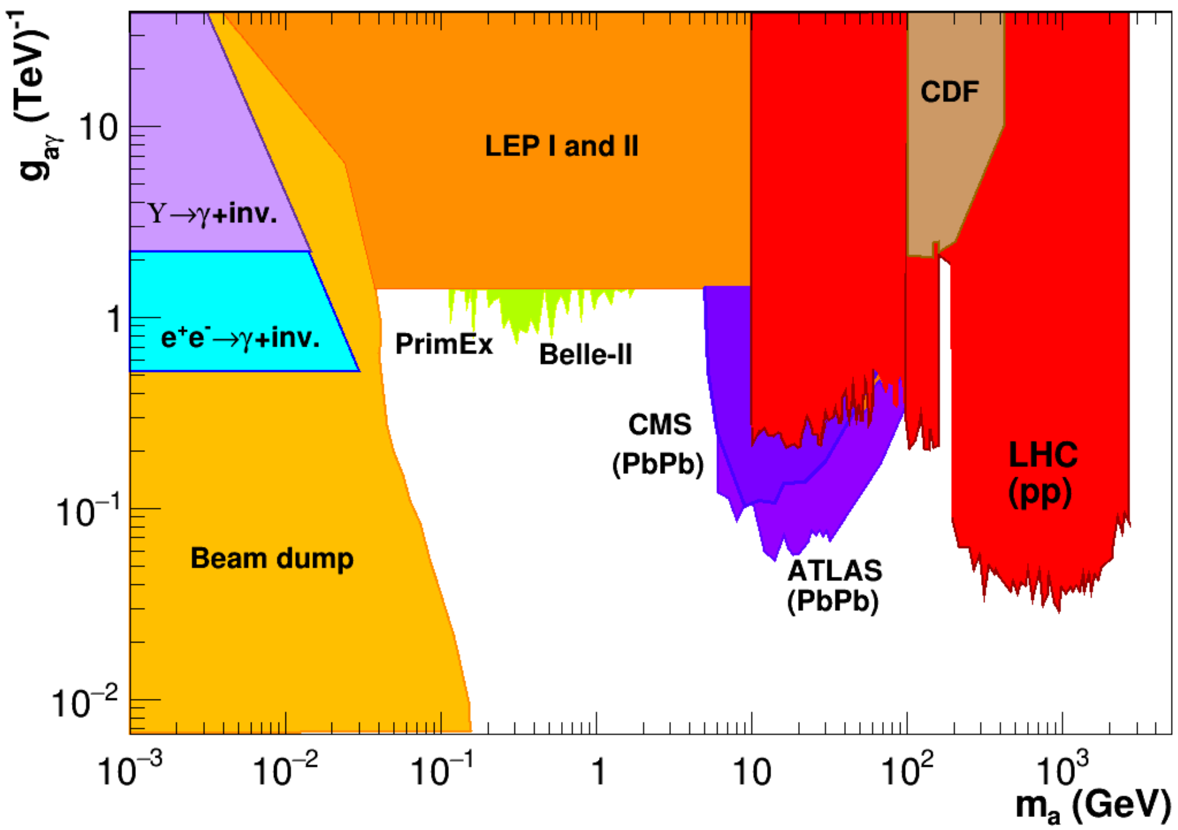
Search for BSM particles (light)



d'Enterria, 2102.08971

Current status





BSM particles →decoupled from the SM?

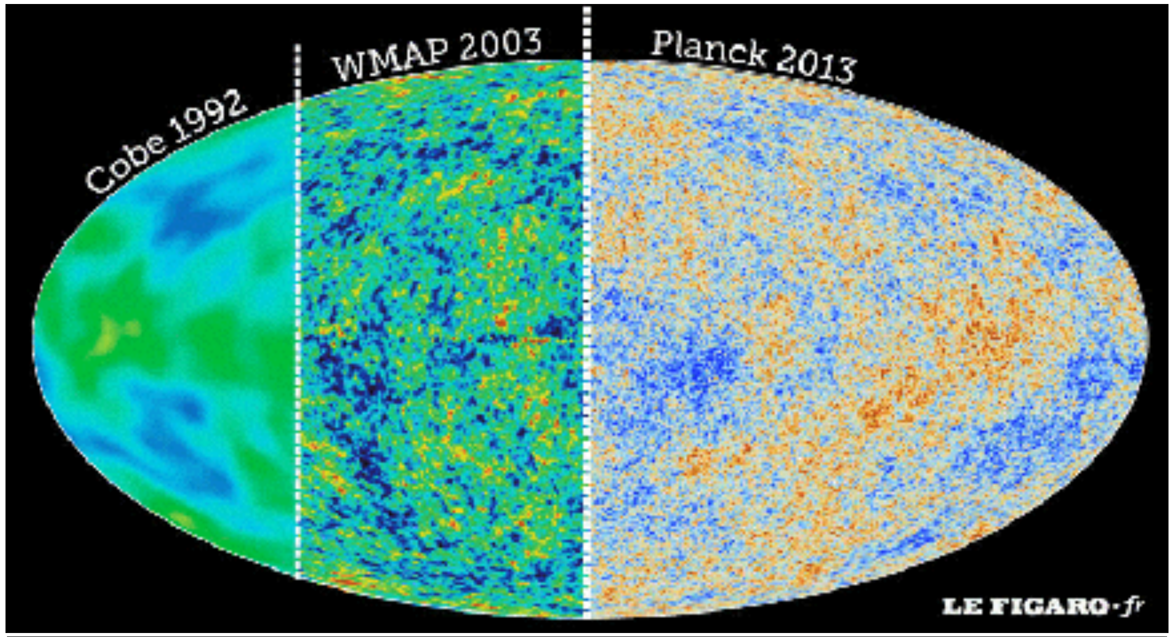
(1) too heavy

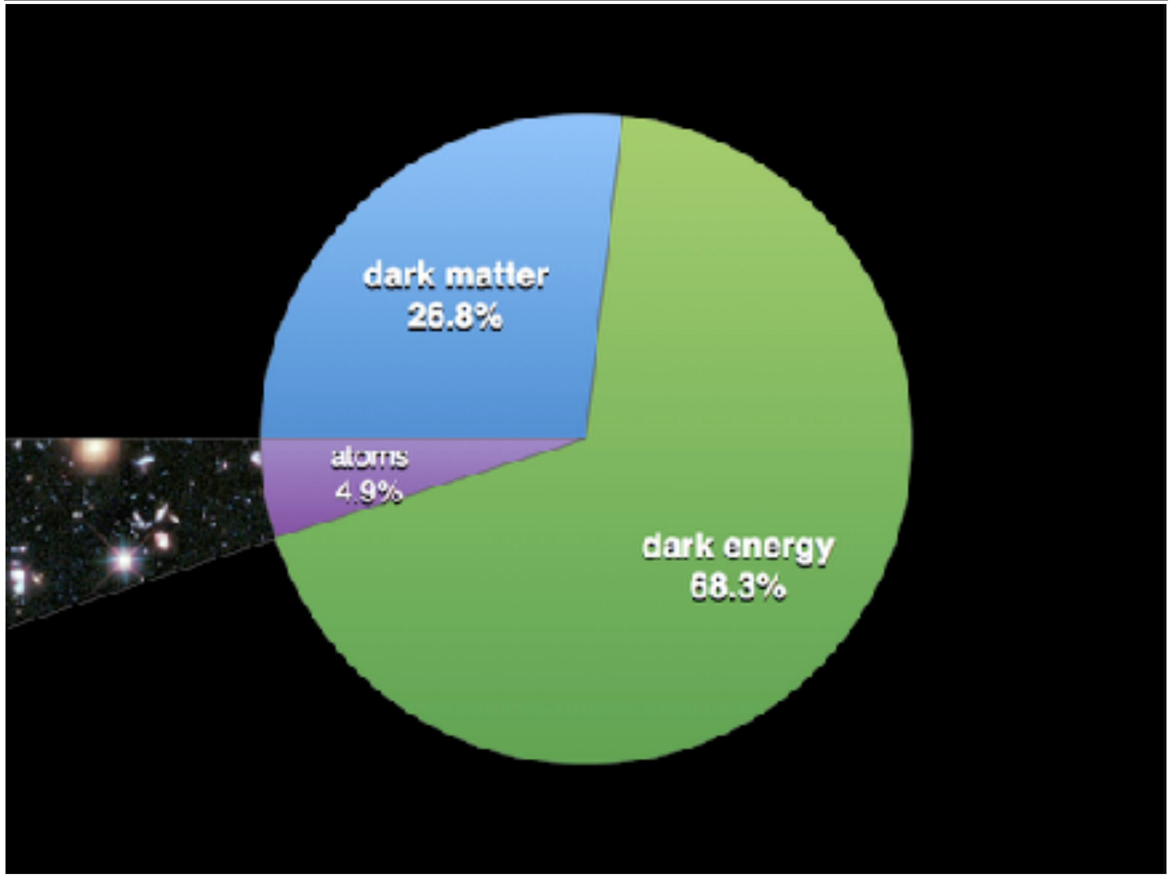
(2) light but tiny coupling

Introduction

dark matter in the universe

→ direct evidence of physics beyond the SM





Introduction

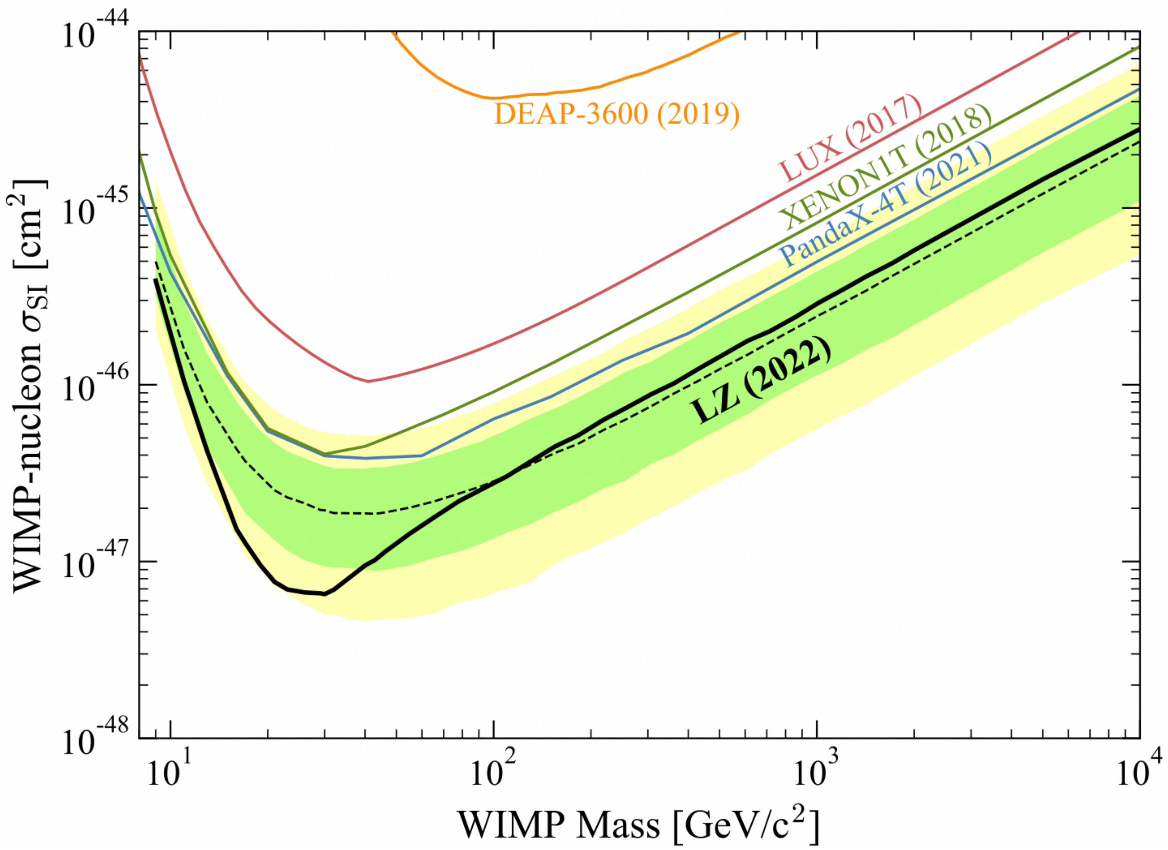
However…

no DM signature has been found yet at

colliders

direct detections

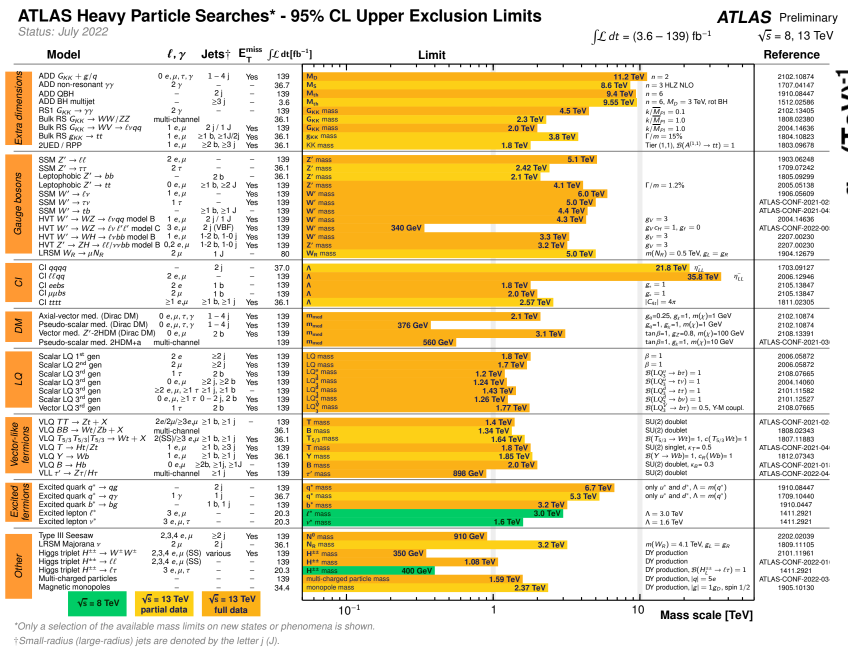
indirect detections

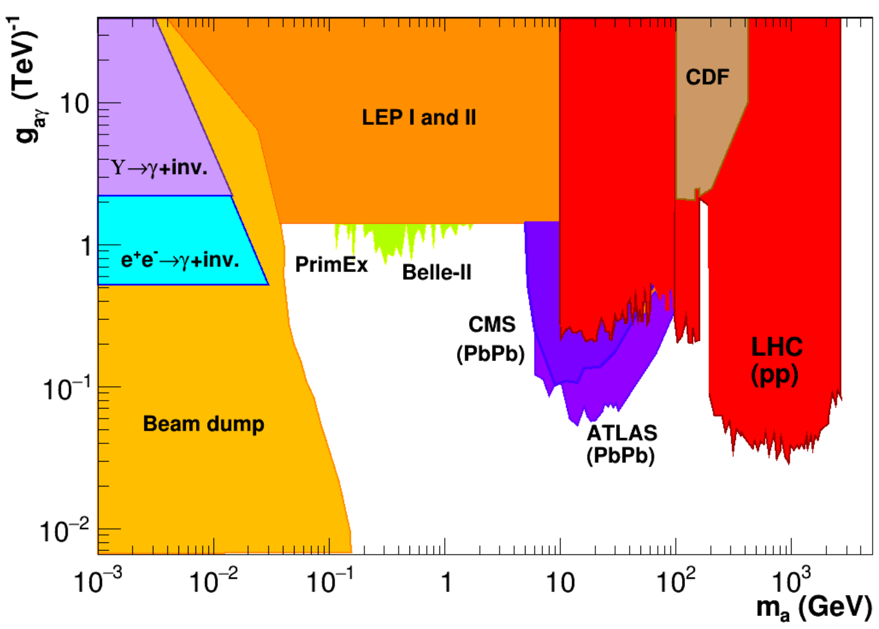


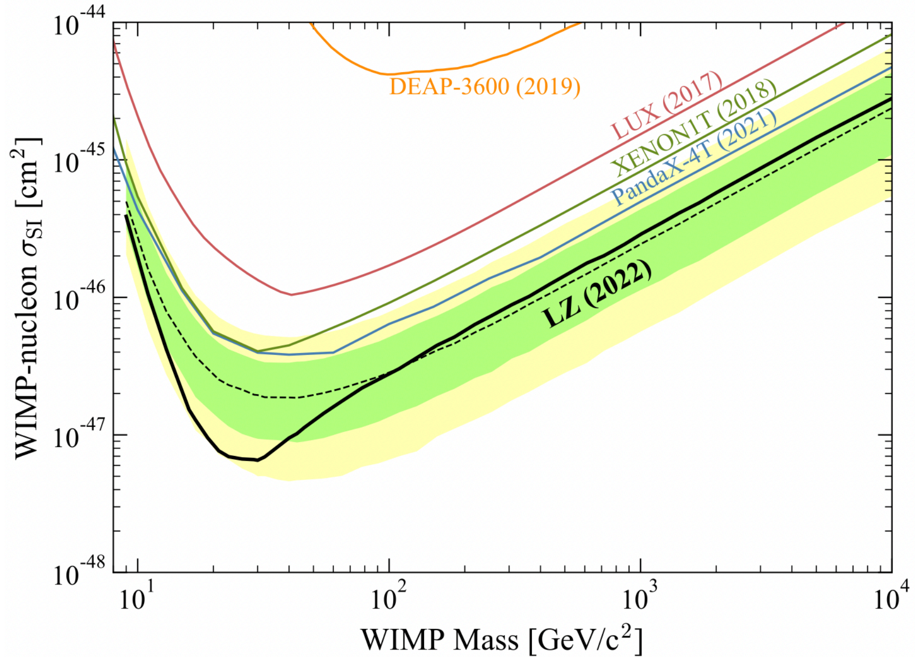
arXiv: 2207.03764

why is DM not observed at those experiments, although it is found in astronomical observations?

Introduction





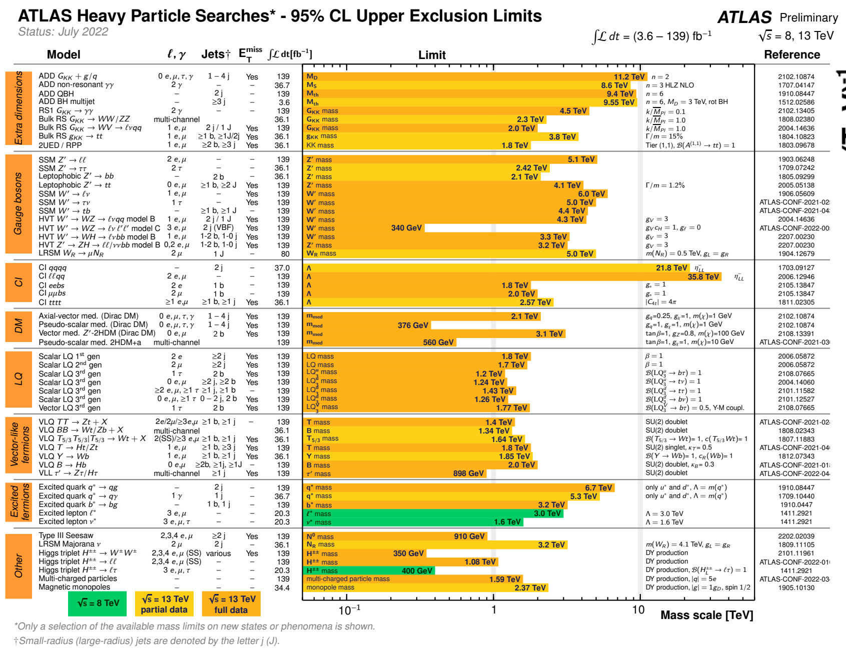


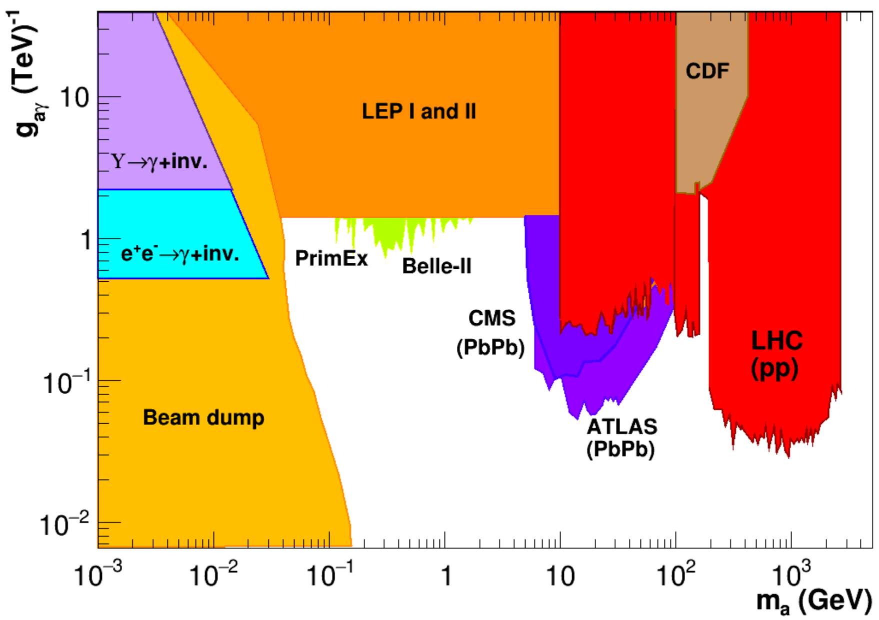
BSM particles → decoupled from the SM?

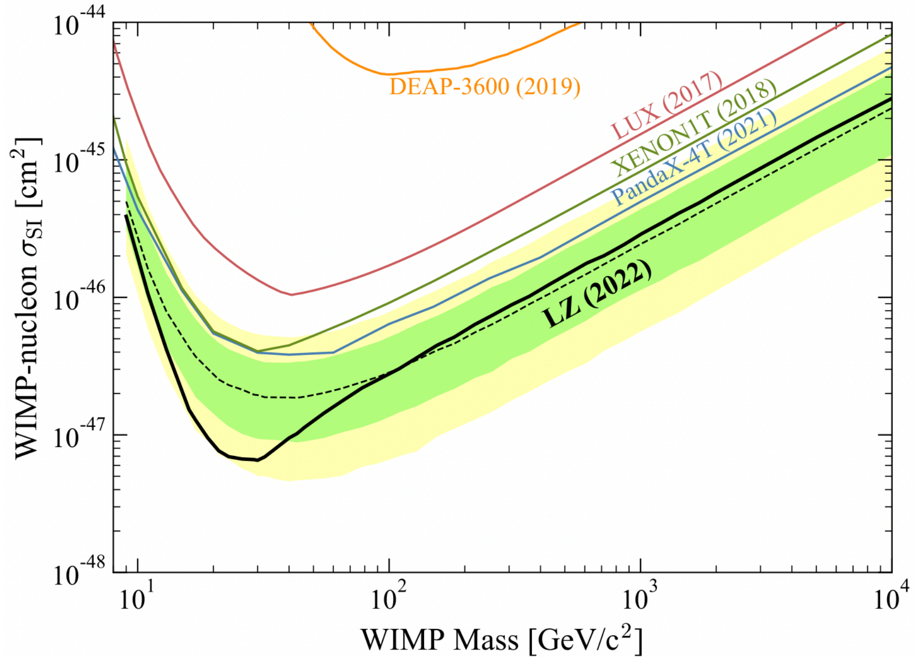
(1) too heavy

(2) light but tiny coupling

Introduction







BSM particles → decoupled from the SM?

(1) too heavy

(2) light but tiny coupling

(3) accessible, but…

Introduction

Suppression mechanisms of DM-quark scattering

fermion DM + pseudo scalar portal model

(coupling vanishes at low E.)

Ipek, McKeen, Nelson (2014)

Escudero, Berlin, Hooper, Lin (2016)

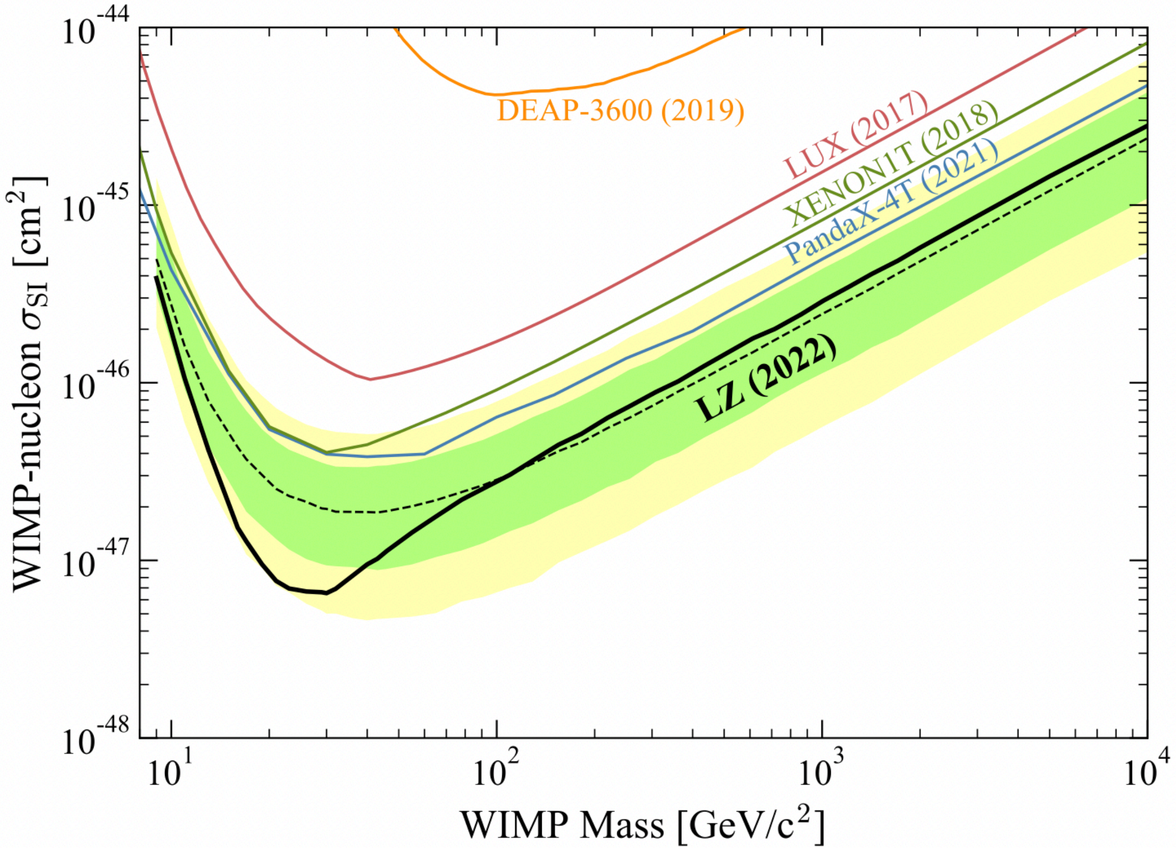
Abe, Fujiwara, Hisano (2019)

pseudo Nambu-Goldstone DM

Gross, Lebedev, Toma (2017)

pNG DM with degenerate scalars

Abe, GCC, Mawatari (2021)



arXiv: 2207.03764

Plan

Introduction

Degenerate scalar scenario in CxSM

- Singlet scalar extension of the SM
- Suppression of DM-quark scattering
- Bounds on degenerate scalar scenario
- Search for degenerate scalars@ILC
- EW phase transition and gravitational waves (→ Idegawa's talk)

phenomenological implication of degenerate scalar scenario

Multi-critical point principle and the degenerate scalar scenario

Origin of the suppression mechanism

attempt to understanding degenerate scalar scenario

Summary

Singlet scalar extension of the SM

SM + complex S (CxSM)   Barger etal, arXiv:0811.0393

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{c.c.}\right)$$

(pNG DM: $S \to -S$)

global U(1) and soft breaking terms
(minimal set of operators to realize pNG DM w/o domain wall)

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = (v_S + s + i\chi)/\sqrt{2}$$

χ ← DM   (DM stability ↔ CP sym.)

Singlet scalar extension of the SM

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{c.c.}\right)$$

mass matrix $(h,\ s)$

$$M^2 = \begin{pmatrix} \frac{\lambda}{2}v^2 & \frac{\delta_2}{2}vv_S \\ \frac{\delta_2}{2}vv_S & \Lambda^2 \end{pmatrix}$$

$$\Lambda^2 \equiv \frac{d_2}{2}v_S^2 - \sqrt{2}\frac{a_1}{v_S}$$

mass eigenvalues $m_{h_1} \to m(125)$@LHC

$(h_1,\ h_2)$

$$m^2_{h_1,h_2} = \frac{1}{2}\left(\frac{\lambda}{2}v^2 + \Lambda^2 \mp \sqrt{\left(\frac{\lambda}{2}v^2 - \Lambda^2\right)^2 + 4\left(\frac{\delta_2}{2}vv_S\right)^2}\right)$$

(DM)

$$m_\chi^2 = -b_1 - \sqrt{2}\frac{a_1}{v_S}$$

mass eigenstates $(h_1,\ h_2) \leftrightarrow (h,\ s)$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

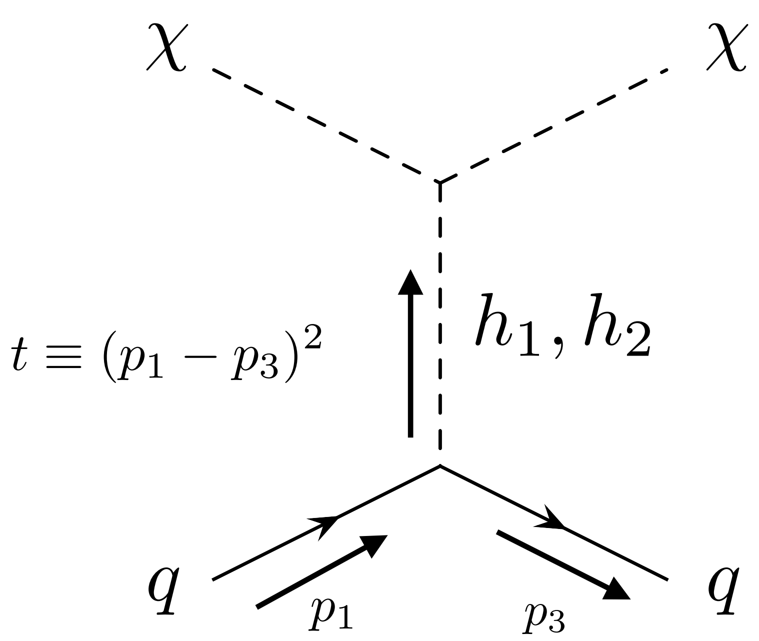
Suppression of DM-quark scattering

scalar trilinear interactions

$$\mathcal{L}_S = g_{h_1\chi\chi} h_1 \chi^2 + g_{h_2\chi\chi} h_2 \chi^2$$

$$g_{h_1\chi\chi} \equiv \frac{m_{h_1}^2 + \frac{a_S}{2v_S}}{2v_S} \sin\alpha$$

$$g_{h_2\chi\chi} \equiv - \frac{m_{h_2}^2 + \frac{a_S}{2v_S}}{2v_S} \cos\alpha$$



Yukawa interactions

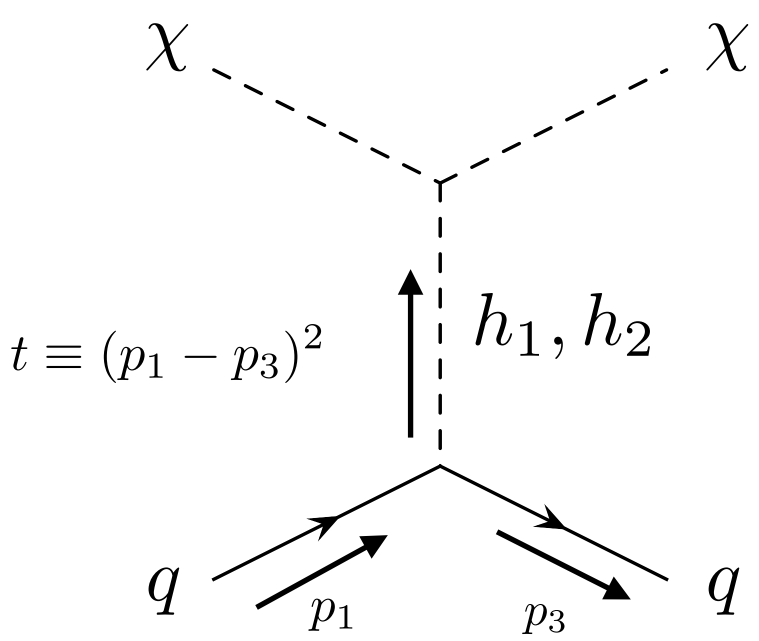
$$\mathcal{L}_Y = \frac{m_f}{v} \bar{f} f (h_1 \cos\alpha + h_2 \sin\alpha)$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Suppression of DM-quark scattering

$$i\mathcal{M}_{h_1} = -i\frac{m_f}{v v_S}\frac{m_{h_1}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_1}^2}\sin\alpha\cos\alpha\ \bar{u}(p_3)u(p_1),$$

$$i\mathcal{M}_{h_2} = +i\frac{m_f}{v v_S}\frac{m_{h_2}^2 + \frac{\sqrt{2}a_1}{v_S}}{t - m_{h_2}^2}\sin\alpha\cos\alpha\ \bar{u}(p_3)u(p_1),$$



sum of scatt. amplitudes:

$$i\left(\mathcal{M}_1 + \mathcal{M}_2\right) = i\frac{m_f}{v v_S}\bar{u}(p_3)u(p_1)\sin\alpha\cos\alpha$$

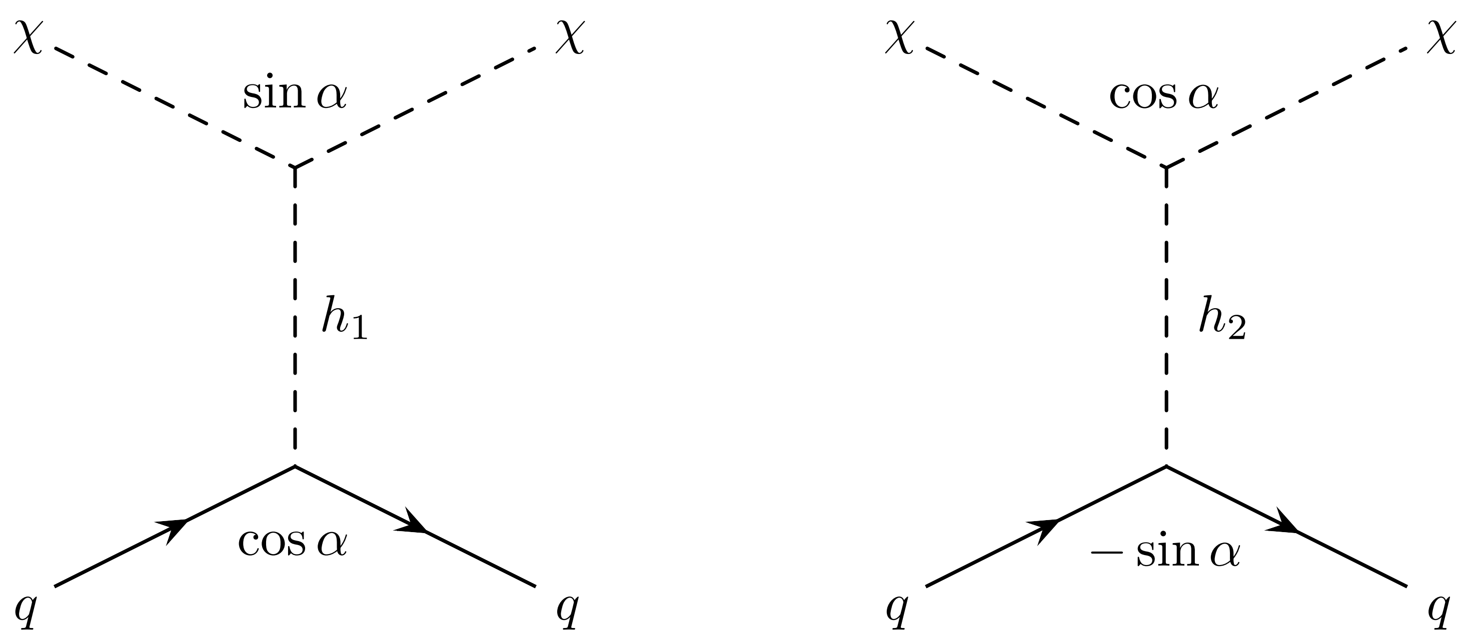
$$\times\left\{\left(-\frac{m_{h_1}^2}{t - m_{h_1}^2} + \frac{m_{h_2}^2}{t - m_{h_2}^2}\right) \simeq 0 \quad @t \to 0\right.$$

Gross, Lebedev, Toma (2017)

$$\left. + \frac{\sqrt{2}a_1}{v_S}\left(-\frac{1}{t - m_{h_1}^2} + \frac{1}{t - m_{h_2}^2}\right)\right\} \simeq 0 \quad @m_{h_1} \sim m_{h_2}$$

Abe, GCC, Mawatari (2021)

Suppression of DM-quark scattering



$$i\left(\mathcal{M}_1+\mathcal{M}_2\right)=i\frac{m_f}{v v_S}\bar{u}(p_3)u(p_1)\sin\alpha\cos\alpha$$

$$\times\left\{\left(-\frac{m_{h_1}^2}{t-m_{h_1}^2}+\frac{m_{h_2}^2}{t-m_{h_2}^2}\right)+\frac{\sqrt{2}a_1}{v_S}\left(-\frac{1}{t-m_{h_1}^2}+\frac{1}{t-m_{h_2}^2}\right)\right\}\simeq 0 \quad @m_{h_1}\sim m_{h_2}$$

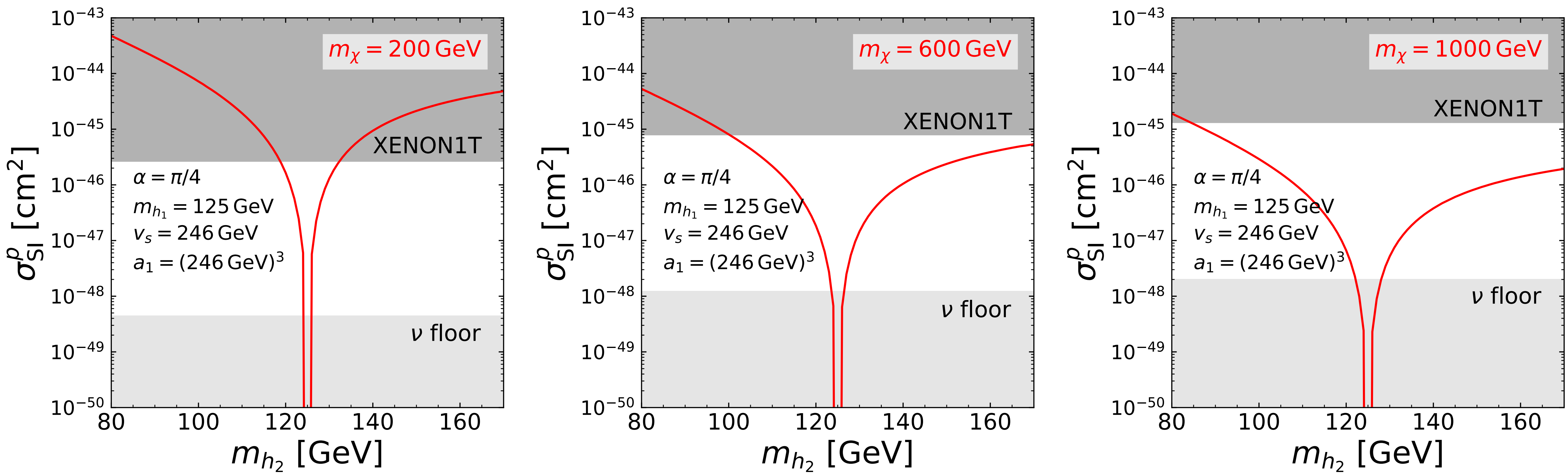
a la GIM mechanism

degenerate scalar scenario

Bounds on degenerate scalar scenario

σ_{SI}^{p} vs. m_{h_2}

Abe, GCC, Mawatari (2021)

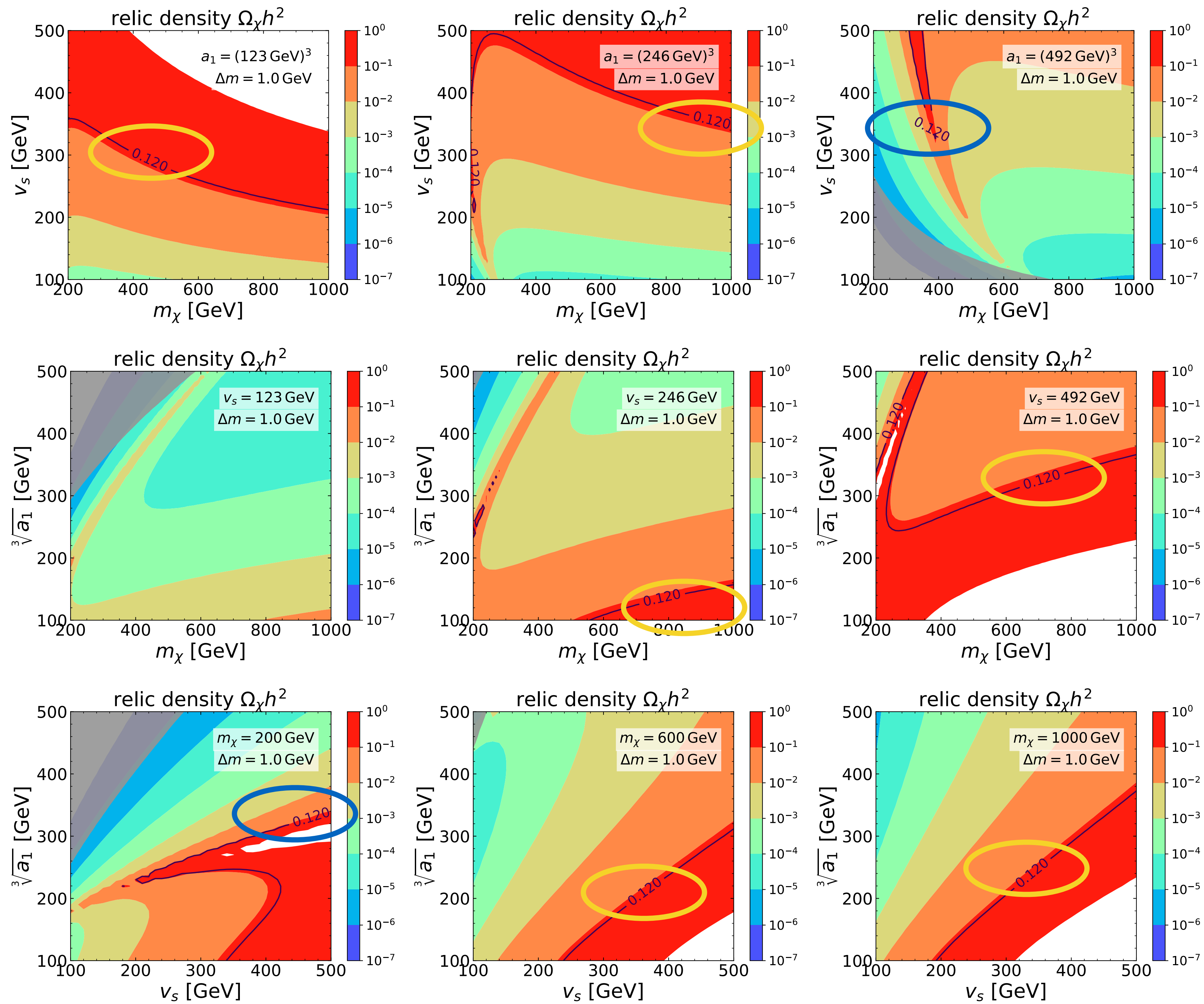


$$\alpha = \frac{\pi}{4},\ v = v_S = 246\ \text{GeV},\ a_1 = (246\ \text{GeV})^3$$

perturbativity $\lambda, d_2 < \frac{16\pi}{3}$

stability $\lambda\left(d_2 + \frac{2\sqrt{2}a_1}{v_S^3}\right) > \delta_2^2$

Bounds on degenerate scalar scenario



$(a_1,\ v_S,\ m_\chi)$

$\Omega_{\rm DM} h^2 = 0.120$

gray: XENON1T

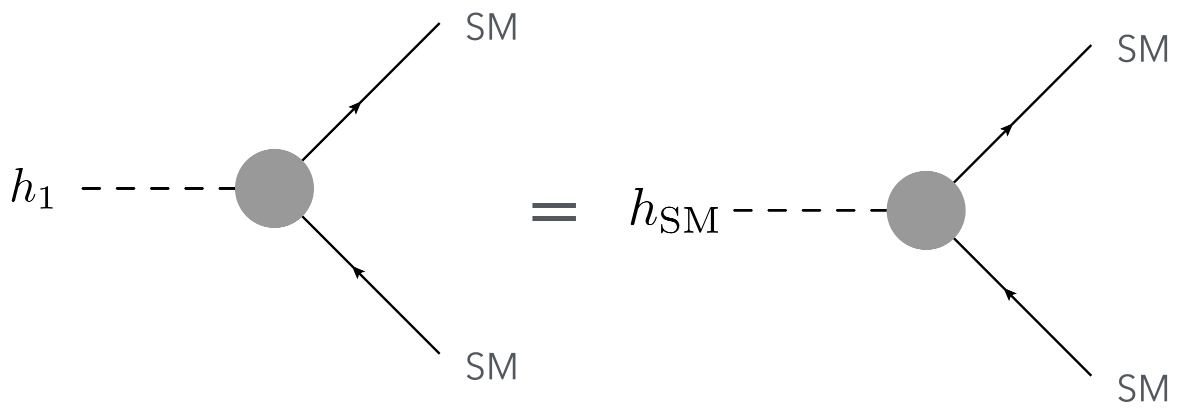
Abe, GCC, Mawatari (2021)

Bounds on degenerate scalar scenario

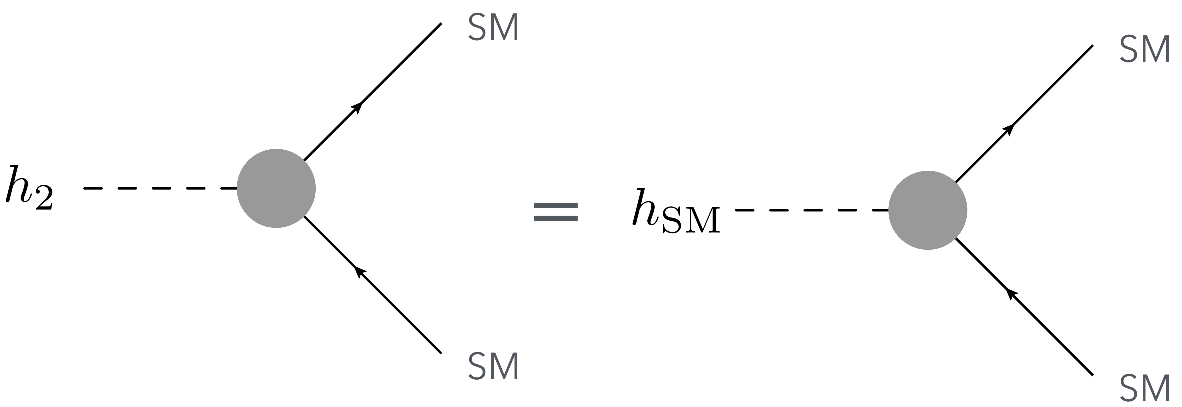
$$h_1 = h_{\rm SM}\cos\alpha - s\sin\alpha \qquad h_2 = -h_{\rm SM}\sin\alpha + s\cos\alpha$$

(125 GeV)

(invisible)



$\times \cos\alpha$

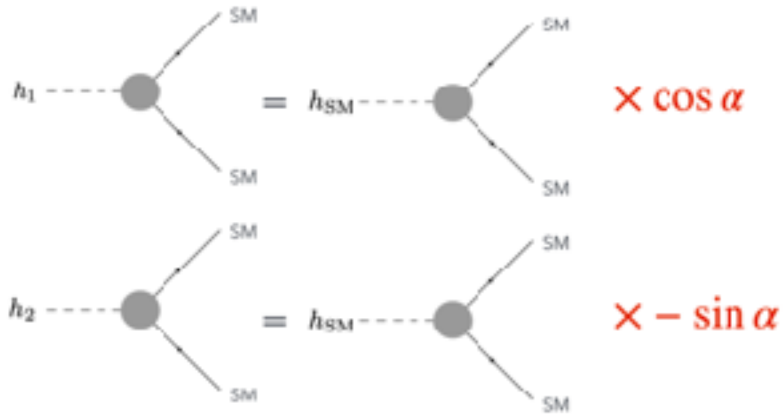


$\times - \sin\alpha$

Bounds on degenerate scalar scenario

$$h_1 = h_{\rm SM}\cos\alpha - s\sin\alpha \qquad h_2 = -h_{\rm SM}\sin\alpha + s\cos\alpha$$

(invisible)

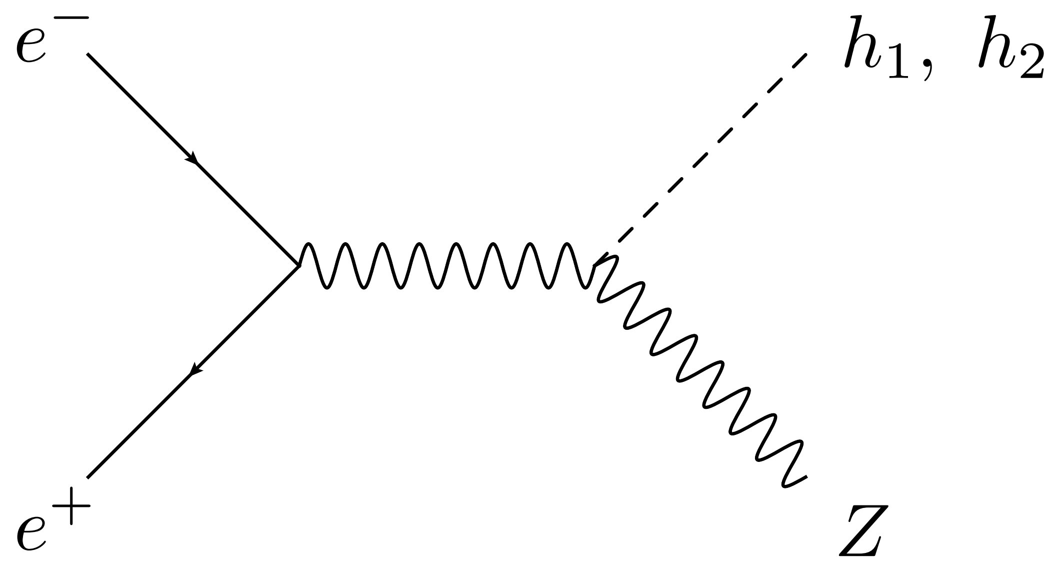


$$\Gamma(h_1 \to {\rm SM}) = \Gamma(h_{\rm SM} \to {\rm SM})(m_{h_1}) \times \cos^2\alpha$$

$$\Gamma(h_2 \to {\rm SM}) = \Gamma(h_{\rm SM} \to {\rm SM})(m_{h_2}) \times \sin^2\alpha$$

$$\Gamma(h_1 \to {\rm SM}) + \Gamma(h_2 \to {\rm SM}) \simeq \Gamma(h_{\rm SM} \to {\rm SM}) \ \text{ for } \ m_{h_1} \simeq m_{h_2}$$

Search for degenerate scalars@ILC



($\ell\ell = e$ or μ pairs)

LHC@Run-I: $\Delta m \geq 3$ GeV

CMS, arXiv:1407.0558

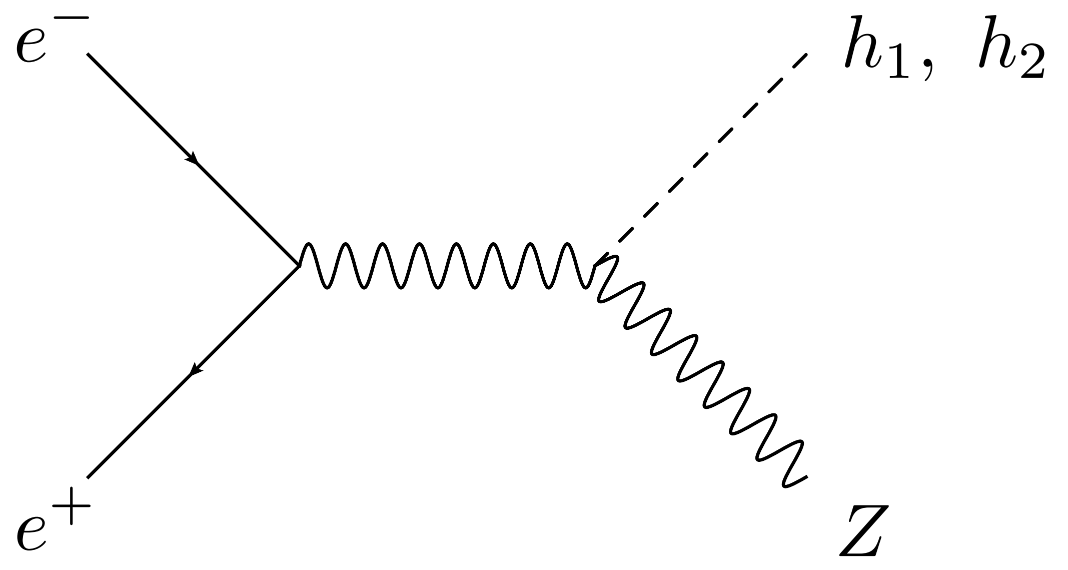
recoil mass

$$m^2_{\rm recoil} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

$$m_{h_1,h_2} = \left(125 \pm \frac{\Delta m}{2}\right)\ {\rm GeV}$$

$$\alpha = \pi/4$$

Search for degenerate scalars@ILC

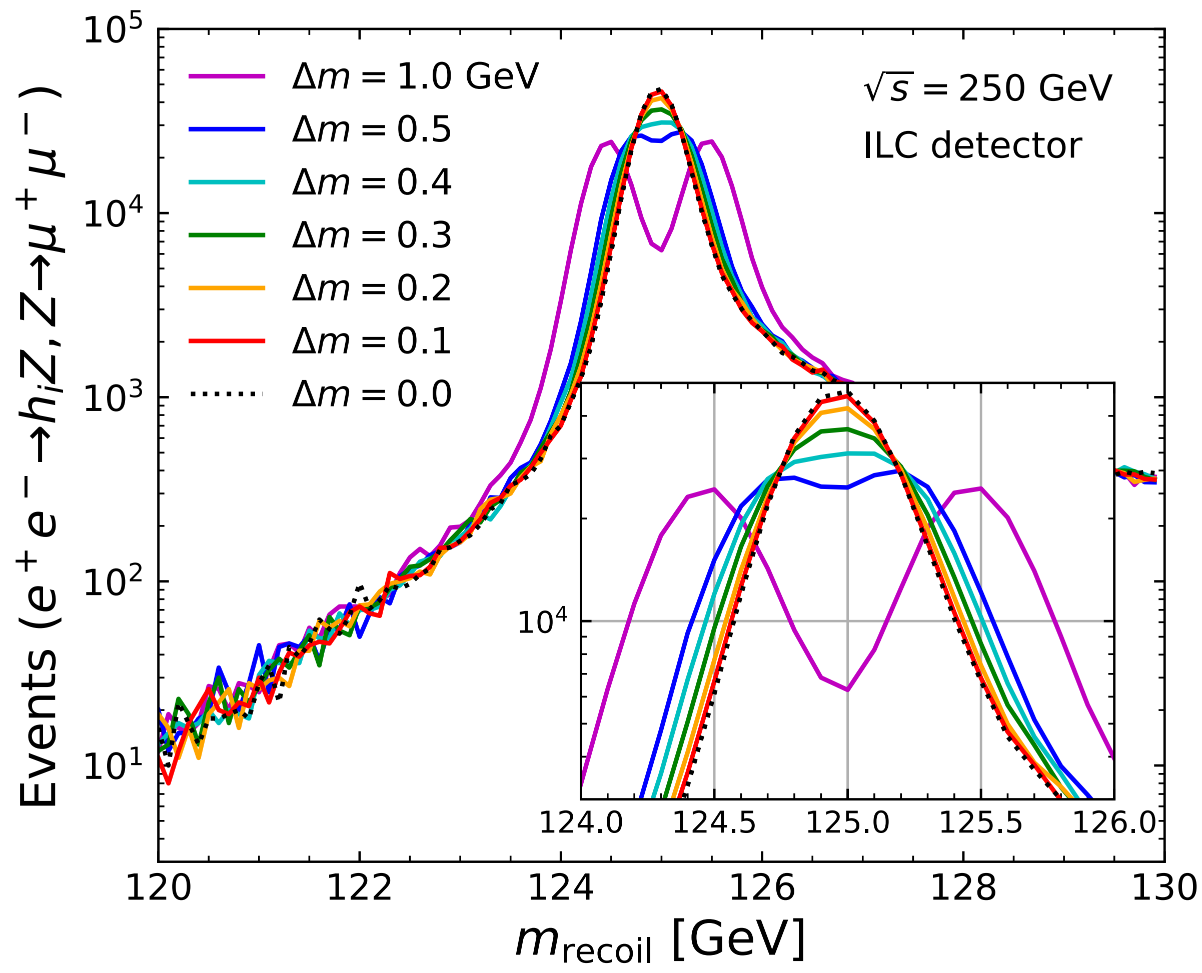


(e or μ pairs)

$$m_{h_1,h_2} = \left(125 \pm \frac{\Delta m}{2}\right)\ \mathrm{GeV}$$

$$\alpha = \pi/4$$

Abe, GCC, Mawatari (2021)

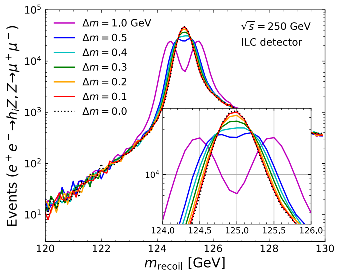


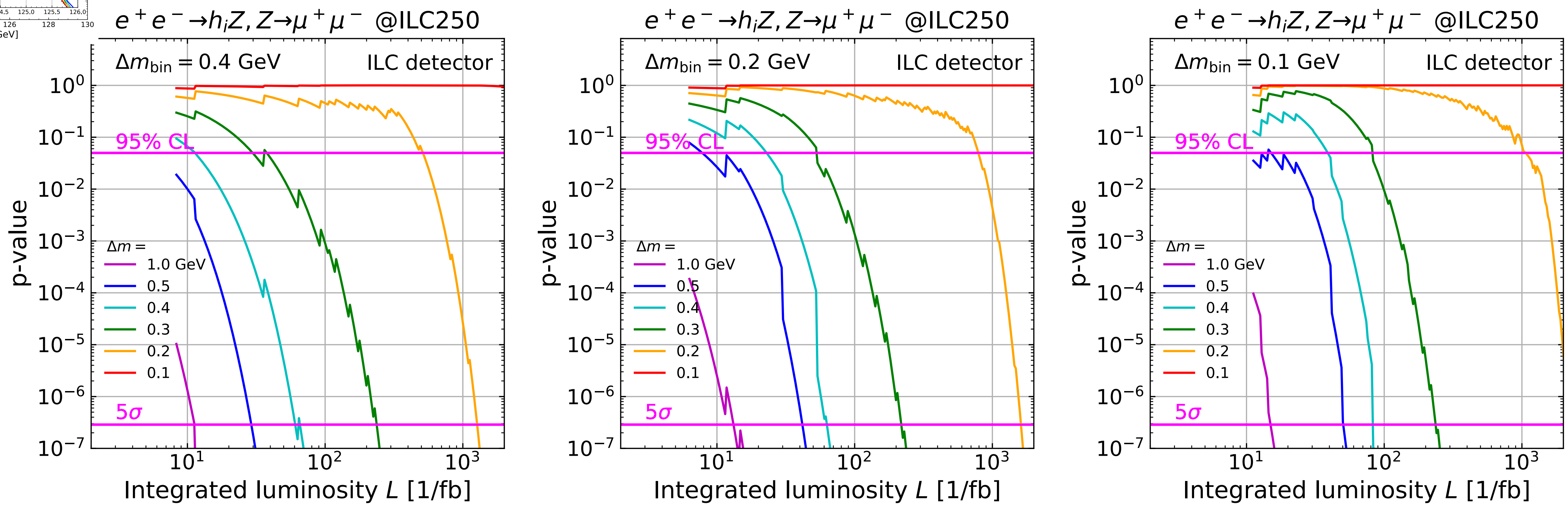
recoil mass

$$m^2_{\mathrm{recoil}} = (\sqrt{s} - E_{\ell\ell})^2 - |\vec{p}_{\ell\ell}|^2$$

MadGraph5_aMC@NLO
Pythia 8.2
Delphes (ILCDelphes card)

Search for degenerate scalars@ILC



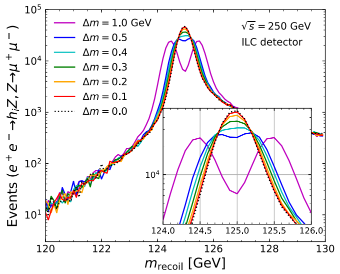


(large) ← bin size → (small)

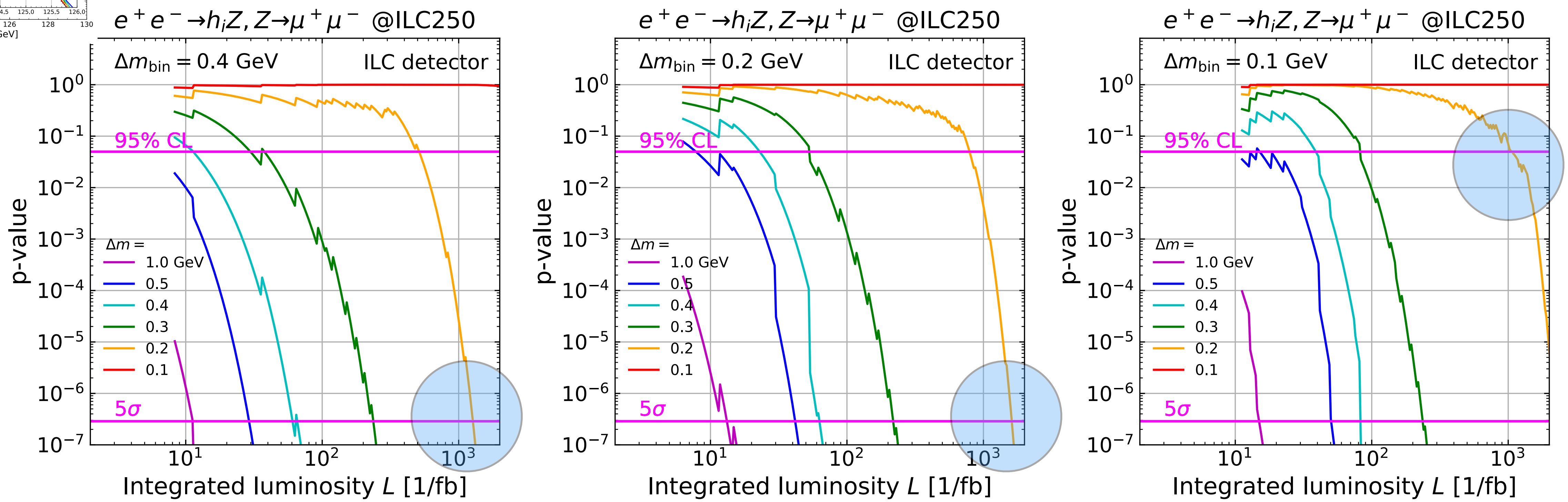
total # of events=int.L x 10 fb $(\sigma(e^+e^- \to hZ) \times \mathrm{Br}(Z \to \mu^+\mu^-))$

for $m_h = 125$ GeV w/ $\mathrm{P}(e^-, e^+) = (-0.8, 0.3)$

$$\chi^2 = \sum_{i=1}^{N} \frac{(n^i - n^i_{\rm SM})^2}{n^i_{\rm SM}}$$ w/ n^i (# of events in the i-th bin) ≥ 10



Search for degenerate scalars@ILC



(large) ← bin size → (small)

degenrate scalar scenario w/ $\Delta m \geq 0.2$ GeV might be tested at ILC with 2 ab^{-1}

* Interference effects could be important when $|m_{h_1} - m_{h_2}| \lesssim \Gamma_{h_1} + \Gamma_{h_2}$

Fuchs, Thewes, Weiglein, 1411.4652

Das, Moretti, Munir, Poulose, 1704.02941

Sakurai, Yin, 2204.01739

Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)

Multi-critical point principle (MPP)

…Nature fine-tunes couplings to their values at the multiple point

@SM

$$V_{\rm eff}(\phi) = \mu^2(\phi)\phi^2 + \frac{\lambda(\phi)}{8}\phi^4$$

$$V_{\rm eff}(\langle\phi\rangle_1) = V_{\rm eff}(\langle\phi\rangle_2)$$

($\langle\phi\rangle_1$: M_{EW}, $\langle\phi\rangle_2$: M_{pl})

$$\longrightarrow \quad 0 = \left.\frac{dV_{\rm eff}(\phi)}{d\phi}\right|_{\langle\phi\rangle_2} \approx \left.\frac{1}{8}\beta_\lambda\phi^3\right|_{\langle\phi\rangle_2}$$

$$\downarrow$$

$$m_t \approx 173\ \text{GeV},\ \ m_h \approx 135\ \text{GeV}$$

Froggatt, Nielsen, PLB368 (1996) 96

Application

2HDM: Frogatt etal (2004), Maniatis etal (2020)

SM+singlet scalars: Haruna, Kawai (2019), Hamada etal (2022)

Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)

Tree-level MPP   Kannike, Koivunen, Raidal, NPB968 (2021) 115441

…multiple vacua@tree level in multi scalar models

However, pNG-DM model does not have degenerate vacua

$$V = \frac{m^2}{2}|H|^2 + \frac{\lambda}{4}|H|^4 + \frac{\delta_2}{2}|H|^2|S|^2 + \frac{b_2}{2}|S|^2 + \frac{d_2}{4}|S|^4 + \left(a_1 S + \frac{b_1}{4}S^2 + \text{c.c.} \right)$$

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = (v_S + s + i\chi)/\sqrt{2}$$

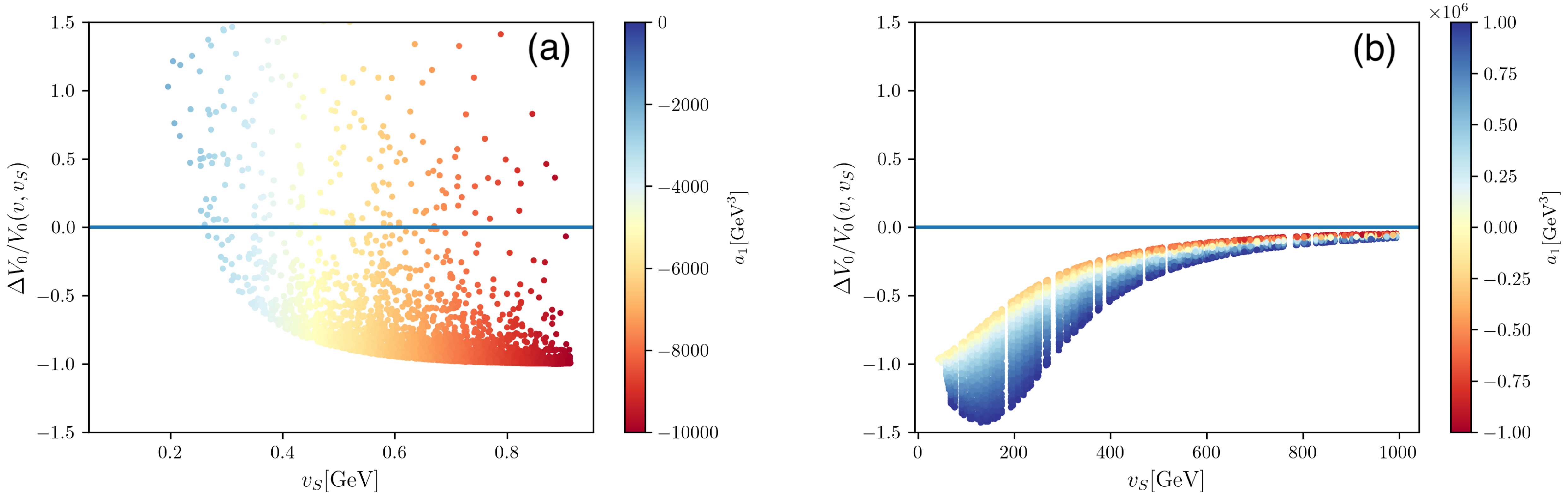
$$\longrightarrow \quad V(v, v_S) \neq V(0, v_S')$$

No Multi-critical point (when $a_1 \neq 0$)

How about in the degenerate scalar scenario?

Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)



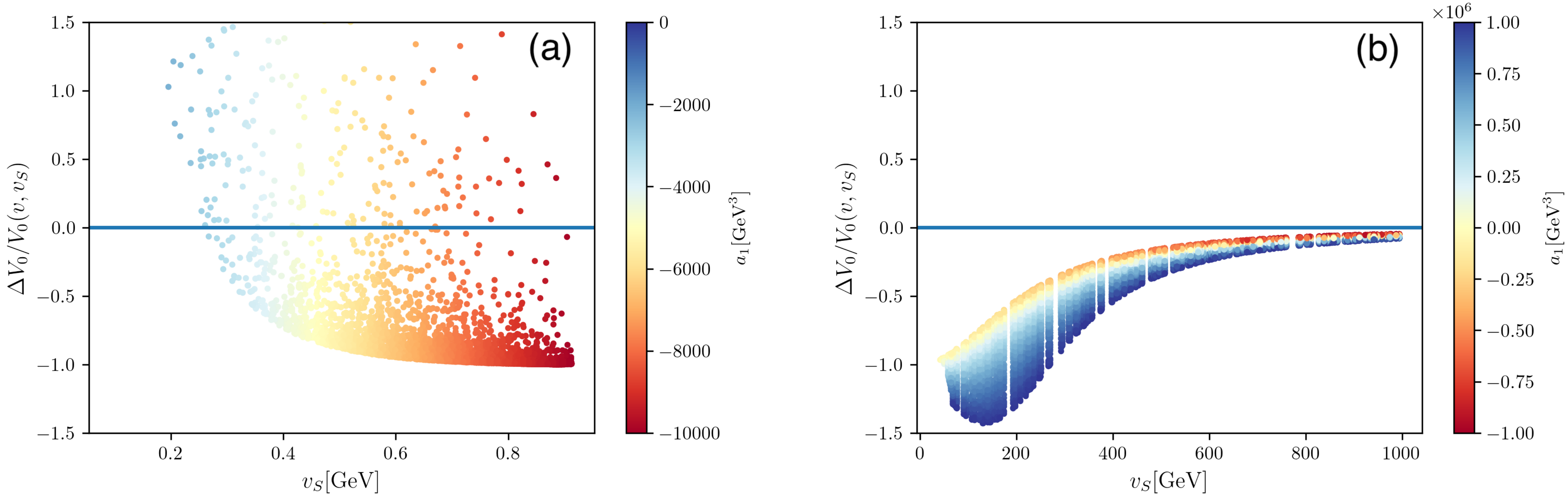
$$\Delta V_0 \equiv V_0(v, v_S) - V_0(0, v_S')$$

$$= \frac{m^2}{8}v^2 + \frac{3\sqrt{2}a_1}{4}(v_S - v_S') + \frac{b_1 + b_2}{8}(v_S^2 - v_S'^2)$$

$$\left(\propto -\frac{1}{\lambda d_2 - \delta_2^2}\frac{1}{d_2} \times \left[\delta_2\left(b_2 + b_1\right) - d_2 b_2\right]^2 < 0 \quad \text{for } a_1 = 0 \right)$$

Multi-critical point principle and the degenerate scalar scenario

GCC, Idegawa, Sugihara (2022)



$$\Delta V_0 \equiv V_0(v, v_S) - V_0(0, v'_S)$$

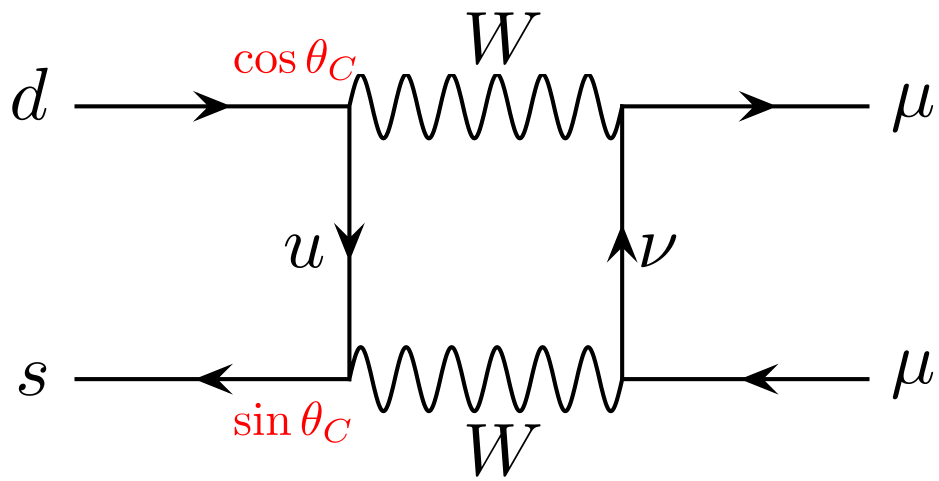
$$= \frac{m^2}{8} v^2 + \frac{3\sqrt{2} a_1}{4}(v_S - v'_S) + \frac{b_1 + b_2}{8}(v_S^2 - v_S'^2)$$

For compatibility of 1st order EWPT and tree-level MPP → Idegewa's talk

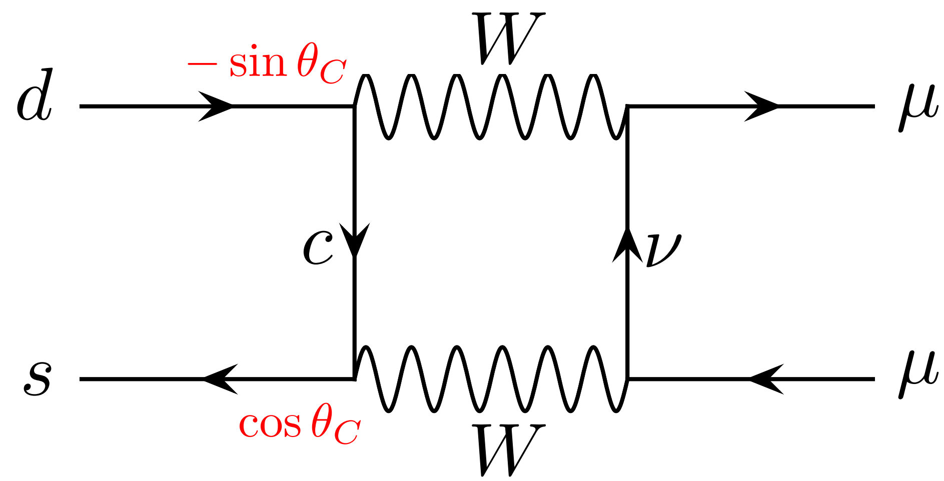
Origin of the suppression mechanism

Lesson from the GIM mechanism

$$K \to \mu^+ \mu^-$$



$$\sim \cos\theta_C \sin\theta_C f(m_u)$$



$$\sim -\cos\theta_C \sin\theta_C f(m_c)$$

amp $\sim \cos\theta_C \sin\theta_C \{f(m_u) - f(m_c)\} \simeq 0 \quad @m_u \sim m_c$

*3generation → unitarity of CKM matrix

Origin of the suppression mechanism

GCC, Idegawa, in progress

Origin of the cancellation of DM-quark amplitudes at the degenerate limit of scalar masses

Formulation $$-\mathcal{L}_{\text{int}} = C_{ijkl}\phi_i\phi_j\phi_k\phi_l$$

$$\begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} C_{hh} & C_{hs} \\ C_{hs} & C_{ss} \end{pmatrix} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} = \begin{pmatrix} C_{h_1h_1} & 0 \\ 0 & C_{h_2h_2} \end{pmatrix}$$

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

$$-\mathcal{L}_{\text{Yukawa}} = C_{h_1ff}\overline{\psi}_L\psi_R h_1 + C_{h_2ff}\overline{\psi}_L\psi_R h_2 + \text{h.c.}$$

Origin of the suppression mechanism

GCC, Idegawa, in progress

amplitudes@tree-level

$$i(\mathcal{M}_1 + \mathcal{M}_2) \propto \sum_{i=1,2} C_{h_i\chi\chi} C_{h_i ff} \frac{1}{t - m_{h_i}^2}$$

cancellation@$t \to 0$

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2} \cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2} \sin\alpha = 0$$

$$C_{h_1\chi\chi} = C_{h\chi\chi} \cos\alpha + C_{s\chi\chi} \sin\alpha$$
$$C_{h_2\chi\chi} = -C_{h\chi\chi} \sin\alpha + C_{s\chi\chi} \cos\alpha$$

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

($H - S$ mixing)

Origin of the suppression mechanism

GCC, Idegawa, in progress

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

($H - S$ mixing)

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2}\cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2}\sin\alpha = \frac{A}{v_s}\left[\sin\alpha\cos\alpha\left\{\frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2}\right\} + \Delta_h\left(\frac{\cos^2\alpha}{m_{h_1}^2} + \frac{\sin^2\alpha}{m_{h_2}^2}\right)\right]$$

$= 0$ if $\Delta_h = 0$ at $m_{h_1} = m_{h_2}$

mixing term of H and S is important

(In addition, $\Delta_s = 0$ is necessary in the pNG-DM model)

Origin of the suppression mechanism

GCC, Idegawa, in progress

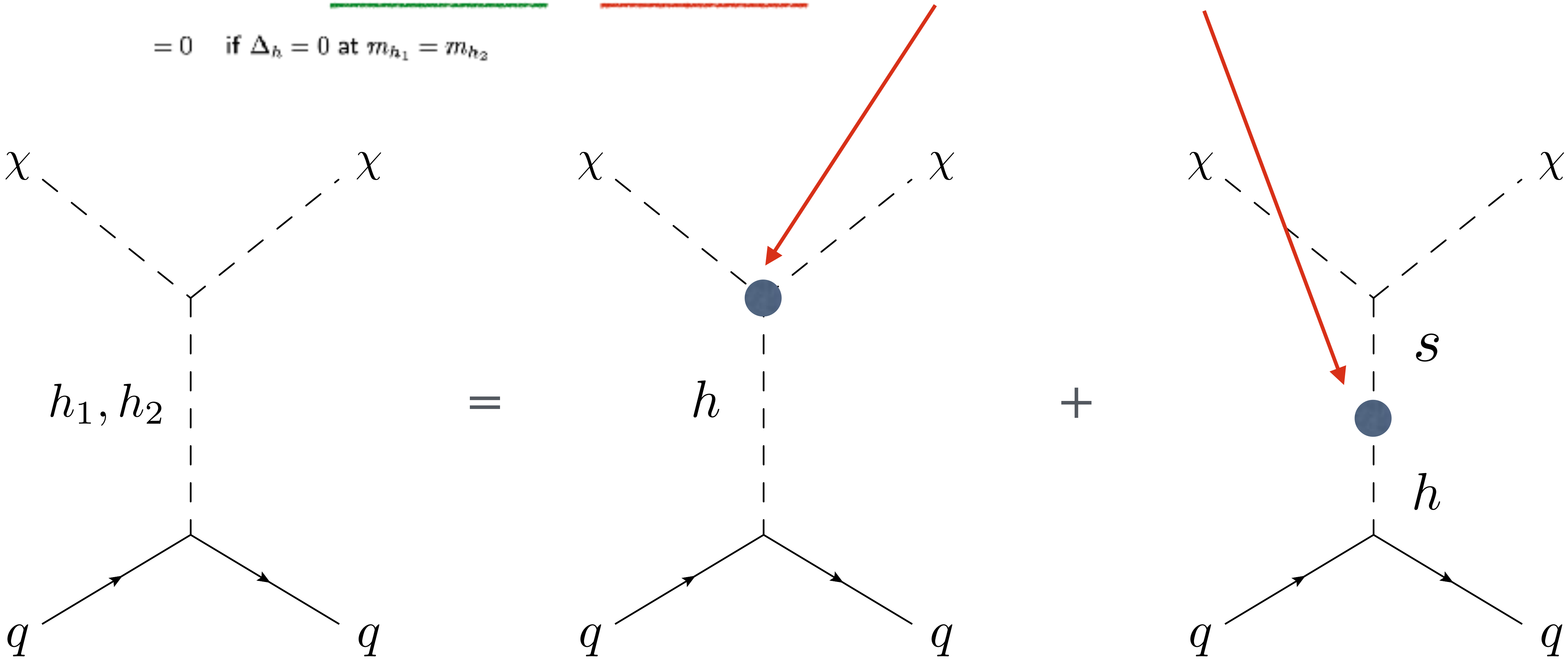
$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

($H - S$ mixing)

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2}\cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2}\sin\alpha = \frac{A}{v_s}\left[\sin\alpha\cos\alpha\left\{\frac{m_{h_1}^2 + \Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2 + \Delta_s}{m_{h_2}^2}\right\} + \Delta_h\left(\frac{\cos^2\alpha}{m_{h_1}^2} + \frac{\sin^2\alpha}{m_{h_2}^2}\right)\right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

mixing term of H and S is important



G.C.Cho

Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2}\cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2}\sin\alpha = \frac{A}{v_s}\left[\sin\alpha\cos\alpha\left\{\frac{m_{h_1}^2+\Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2+\Delta_s}{m_{h_2}^2}\right\} + \Delta_h\left(\frac{\cos^2\alpha}{m_{h_1}^2} + \frac{\sin^2\alpha}{m_{h_2}^2}\right)\right]$$

$$= 0 \quad \text{if } \Delta_h = 0 \text{ at } m_{h_1} = m_{h_2}$$

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

($H - S$ mixing)

In our case

$$V \supset \frac{\delta_2}{2}|H|^2|S|^2 = C_{h\chi\chi}h\chi^2 + C_{hs}hs$$

$$C_{h\chi\chi} = \frac{\delta_2}{4}v = \frac{1}{2v_S}C_{hs} \quad \rightarrow A = \frac{1}{2}, \quad \Delta_h = 0$$

Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2}\cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2}\sin\alpha = \frac{A}{v_s}\left[\sin\alpha\cos\alpha\left\{\frac{m_{h_1}^2+\Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2+\Delta_s}{m_{h_2}^2}\right\} + \Delta_h\left(\frac{\cos^2\alpha}{m_{h_1}^2} + \frac{\sin^2\alpha}{m_{h_2}^2}\right)\right]$$

$= 0$ if $\Delta_h = 0$ at $m_{h_1} = m_{h_2}$

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

($H - S$ mixing)

most general scalar potential

soft breaking terms

$$V \supset \frac{\delta_2}{2}|H|^2|S|^2 + \left(\frac{\delta_1}{4}|H|^2 S + \frac{\delta_3}{4}|H|^2 S^2 + \text{c.c.}\right) = C_{h\chi\chi} h\chi^2 + C_{hs} hs$$

$$C_{h\chi\chi} = \frac{\delta_2 - \delta_3}{4}v, \quad C_{hs} = \frac{v}{2}\left(\frac{\delta_1}{\sqrt{2}} + \delta_2 v_S + \delta_3 v_S\right)$$

$\Delta_h \neq 0$ unless $\delta_1 = \delta_3 = 0$ or $\delta_1 = \delta_2 = 0$

Origin of the suppression mechanism

GCC, Idegawa, in progress

$$\frac{C_{h_1\chi\chi}}{m_{h_1}^2}\cos\alpha - \frac{C_{h_2\chi\chi}}{m_{h_2}^2}\sin\alpha = \frac{A}{v_s}\left[\sin\alpha\cos\alpha\left\{\underline{\frac{m_{h_1}^2+\Delta_s}{m_{h_1}^2} - \frac{m_{h_2}^2+\Delta_s}{m_{h_2}^2}}\right\} + \Delta_h\left(\underline{\frac{\cos^2\alpha}{m_{h_1}^2} + \frac{\sin^2\alpha}{m_{h_2}^2}}\right)\right]$$

$= 0$ if $\Delta_h = 0$ at $m_{h_1} = m_{h_2}$

$$C_{h\chi\chi} = \frac{A}{v_s}(C_{hs} + \Delta_h), \quad C_{s\chi\chi} = \frac{A}{v_s}(C_{ss} + \Delta_s)$$

$(H - S$ mixing)

the degenerate scalar scenario works only for limited H-S mixing term (not in general)

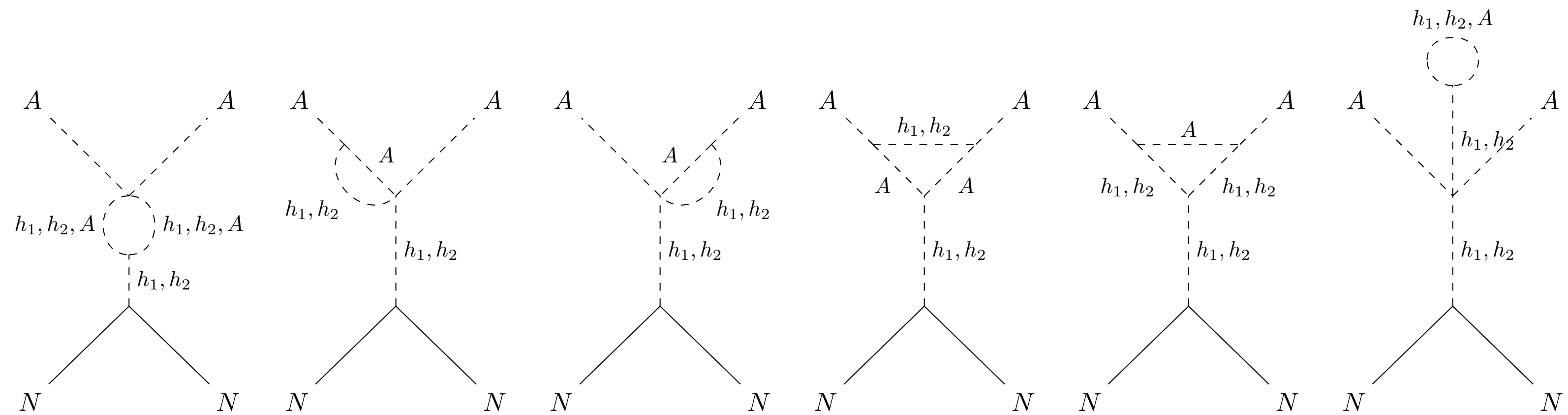
Origin of the suppression mechanism

GCC, Idegawa, in progress

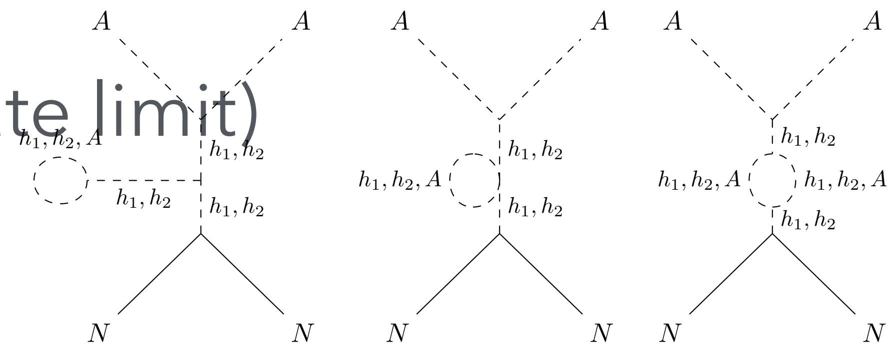
Does cancellation of DM-quark amplitudes still work beyond the leading order?

cf. pNG DM models → suppression mechanism does not work at 1-loop level

Azevedo etal, 1810.06105
Ishiwata, Toma, 1810.08139
Alanne etal, 2008.09605
Glaus etal, 2008.12985
Abe, Hamada, 2205.11919



no renormalization is required (at degenerate limit)



finite contribution?

Summary

degenerate scalar scenario → an alternative of "*Nightmare scenario*"@LHC besides super-heavy particles/ultra-weak int.

DM-quark scattering amplitudes are cancelled when $m_{h_1} \sim m_{h_2}$

recoil mass dist. @ILC w/ 2 ab^{-1} → chance to test a degenerate scalar scenario w/ $\Delta m \geq 0.2$ GeV

degenerate scalar scenario restricts soft breaking terms w/ D ≥ 3

$$(|H|^2 S,\ |H|^2 S^2)$$

cancellation of DM-quark amplitudes in the degenerate scalar scenario@1-loop level?