W-boson mass with singlet scalars

Mainly based on 2204.04770 to appear in PLB, in collaboration with
Kodai Sakurai (Tohoku -> Warsaw), Fuminobu Takahashi.

@23th July, 北陸合宿

殷　文　(東北大学)

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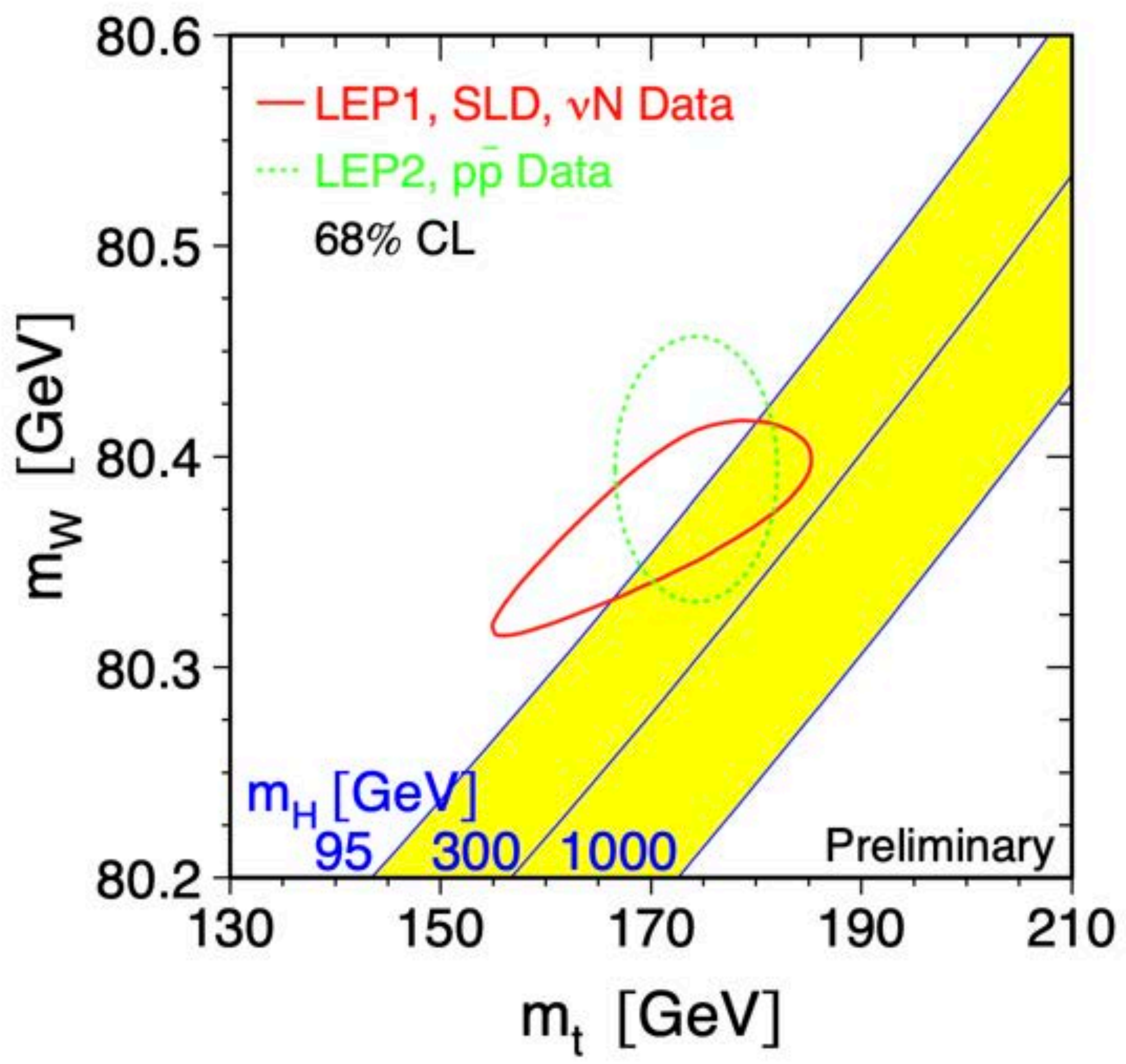
An example of the success of the SM

EW fit ->Higgs boson discovery

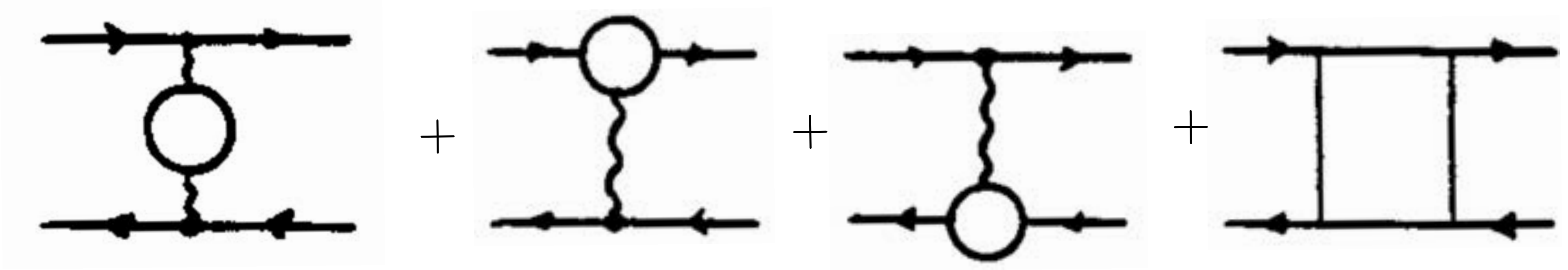


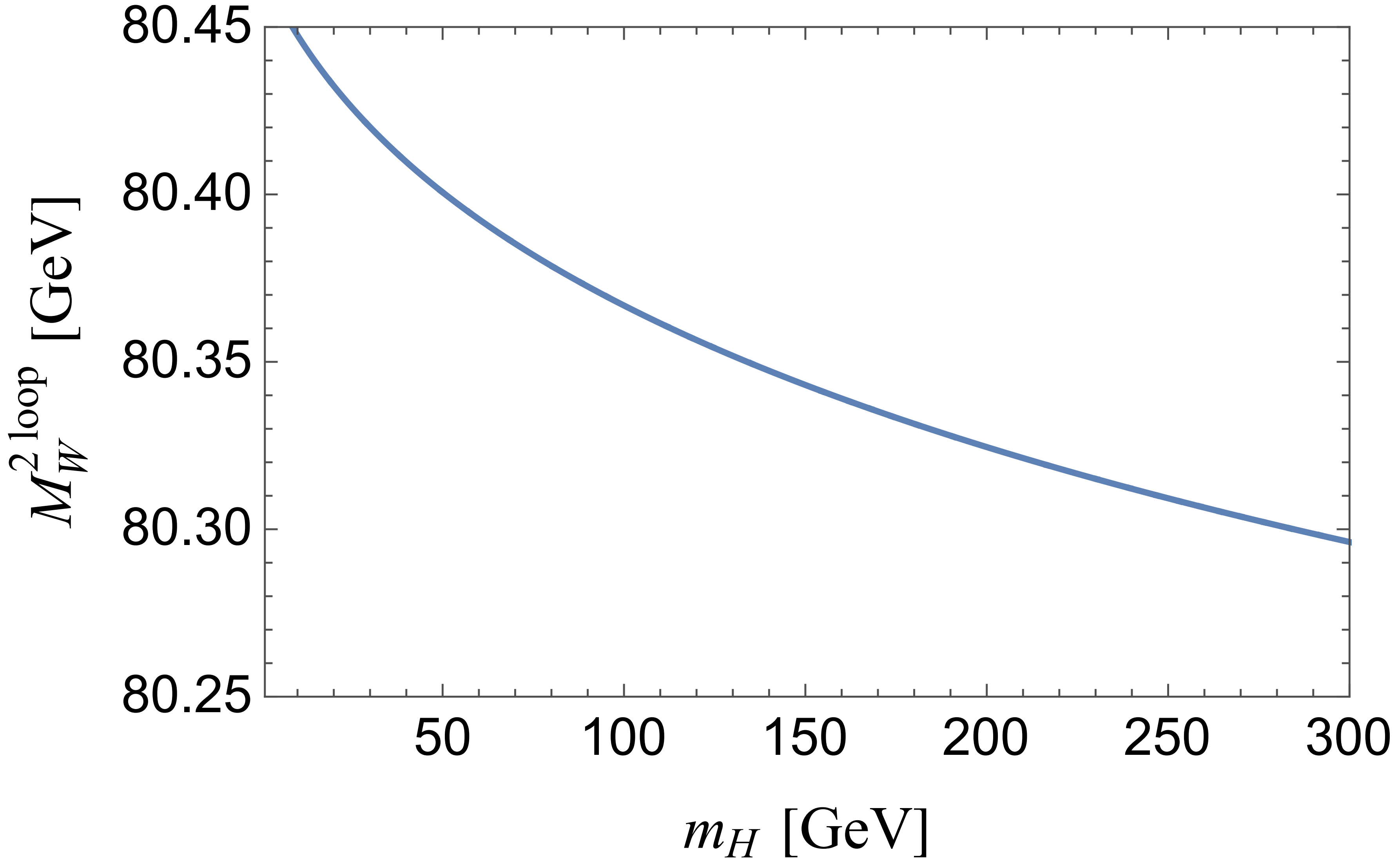
LEP EW WG summer 99 conference
http://lepewwg.web.cern.ch/lepewwg/plots/summer1999/

Matching the Fermi theory and SM prediction of muon life-time we get

$$M_W = \frac{M_Z}{2}\left(1+\sqrt{1-\frac{4\pi\alpha_{\rm em}}{\sqrt{2}G_F M_Z^2(1-\Delta r)}}\right),$$

Δr includes the effects

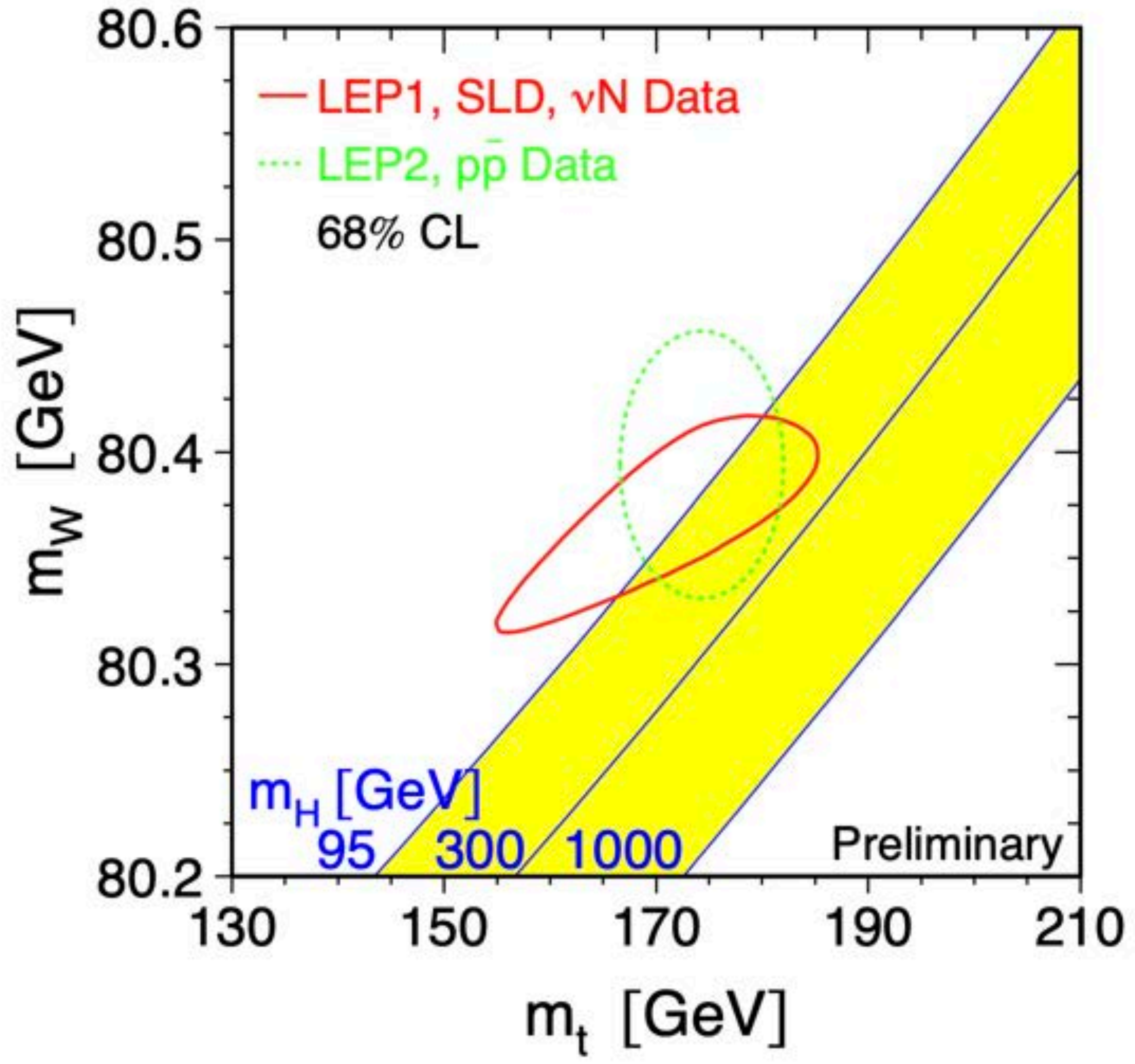




ここの図や式はKodai Sakurai’s slideから持ってきました🫢

An example of the success of the SM

EW fit ->Higgs boson discovery



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$80433.4 \pm 9.4 MeV$ (CDFII collaboration 2022)

まぐれだった！？😱

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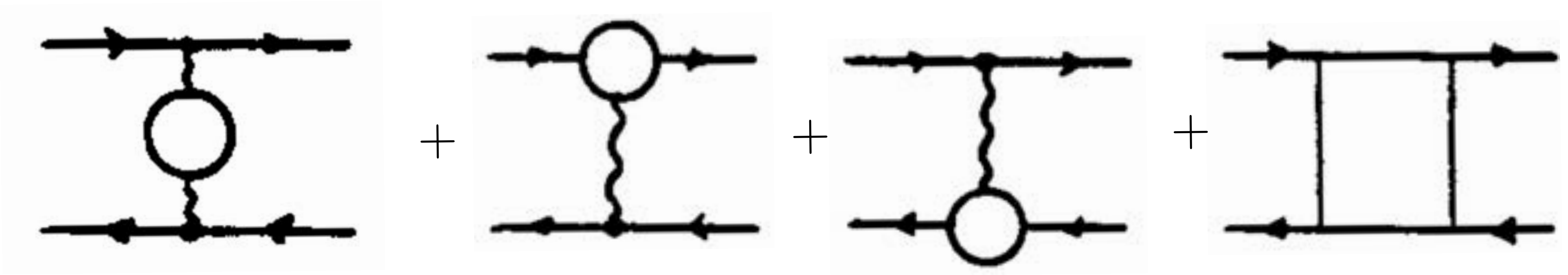

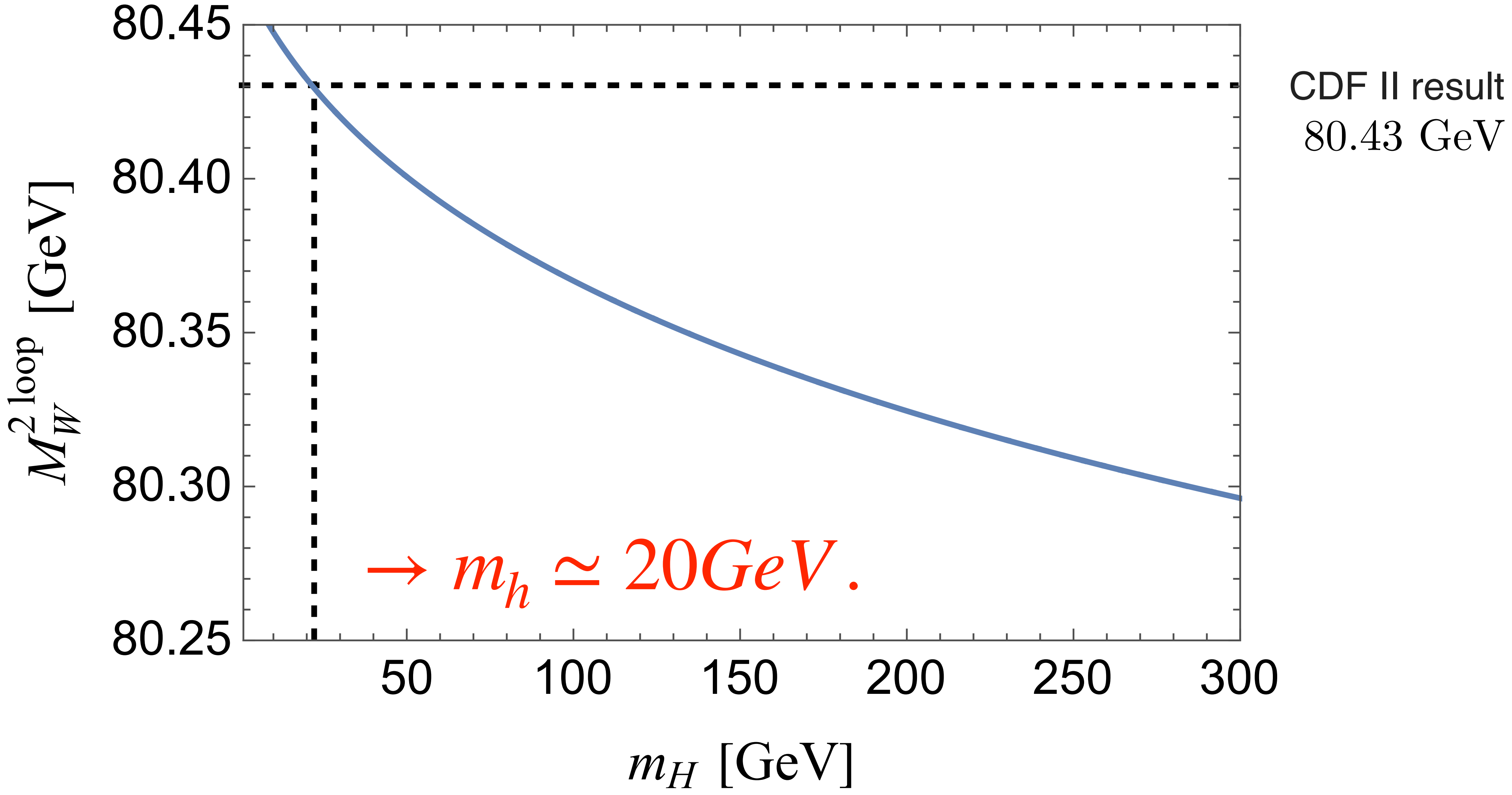

$\rightarrow m_h \simeq 20 GeV.$

ここの図や式はKodai Sakurai's slideから持ってきました🫢

W-boson mass shiftの意味することとは？

Success of SM

VS

待ちに待った
BSM 但し
SM success
は一部諦める。

$80376 \pm 23 MeV$ (D0 II)

$80370 \pm 19 MeV$ (Atlas)

~2-3σ

$80433.4 \pm 9.4 MeV$

(CDFII collaboration. 2022)

一つのBSM解としてFundamental constant の時空変化の可能性は今日は話さない。

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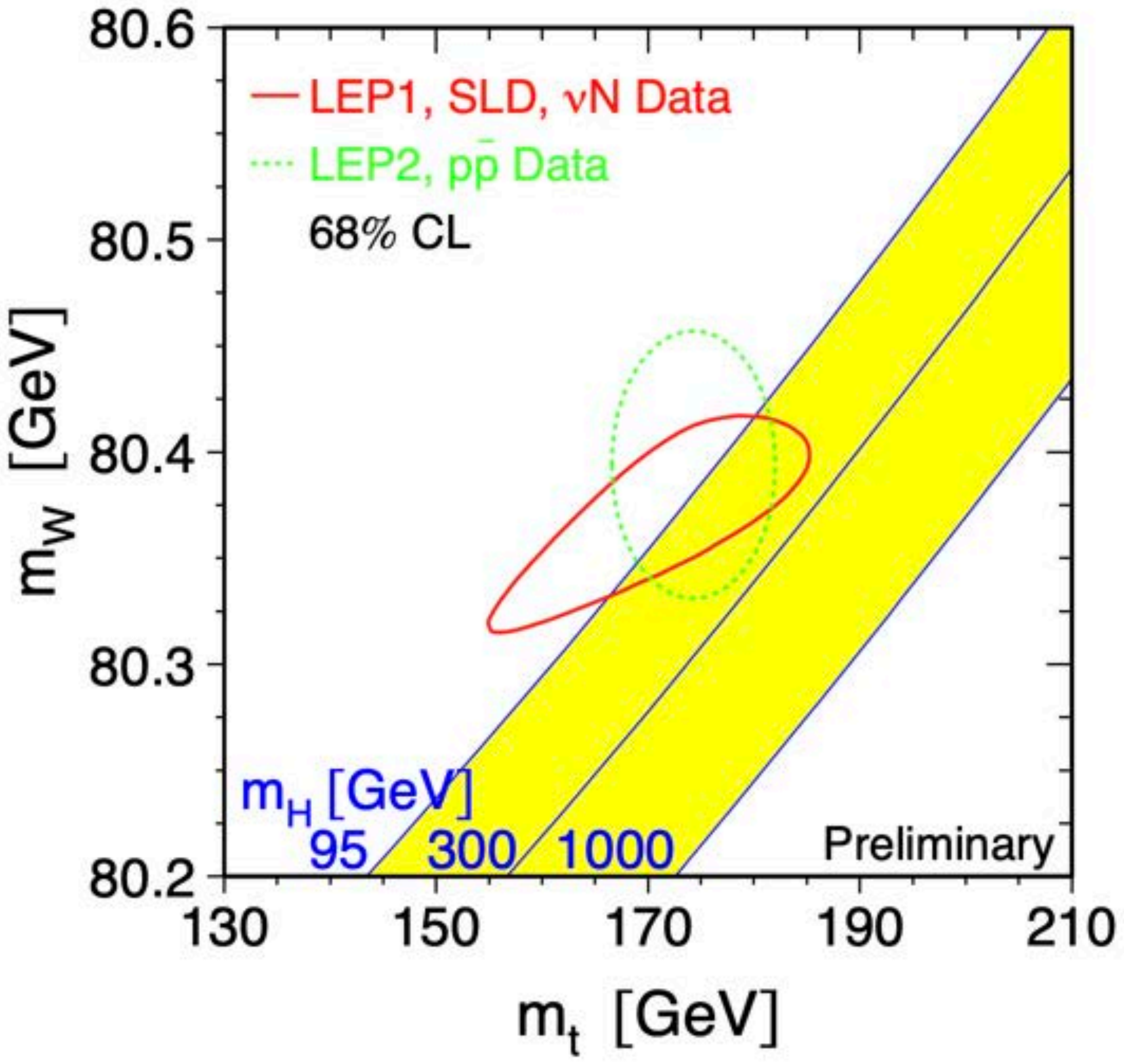
A few examples of the success of the SM

EW fit ->Higgs boson discovery



LEP EW WG summer 99 conference
http://lepewwg.web.cern.ch/lepewwg/plots/summer1999/

$80433.4 \pm 9.4 MeV$ (CDFII collaboration 2022)

$\to m_h \simeq 20 GeV$. まぐれだと認めよう。

Prediction

Suppressed flavor violation!

Suppressed CP violation!

Proton stability!

They are predicted from particle contents + renormalizability.

I would like to consider BSM with this structure.

まぐれと認めたくない。

BSMs with similar properties.

Singlet scalar (dark sector) extensions

$$\delta V = V(|H|^2, s)$$

Silveira, 1985; Burgess et al 0011335

s can be thought to be CP-even if renormalizable, i.e. the potential is accidentally CP-conserving. Flavor violation, proton decay are suppressed as in the SM.

Massive dark gauge boson (SM is not charged) also belong to this category since we need a dark higgs.

This talk

Non-trivially charged particles
*Real adjoint Higgs field

*Field with very large representation etc

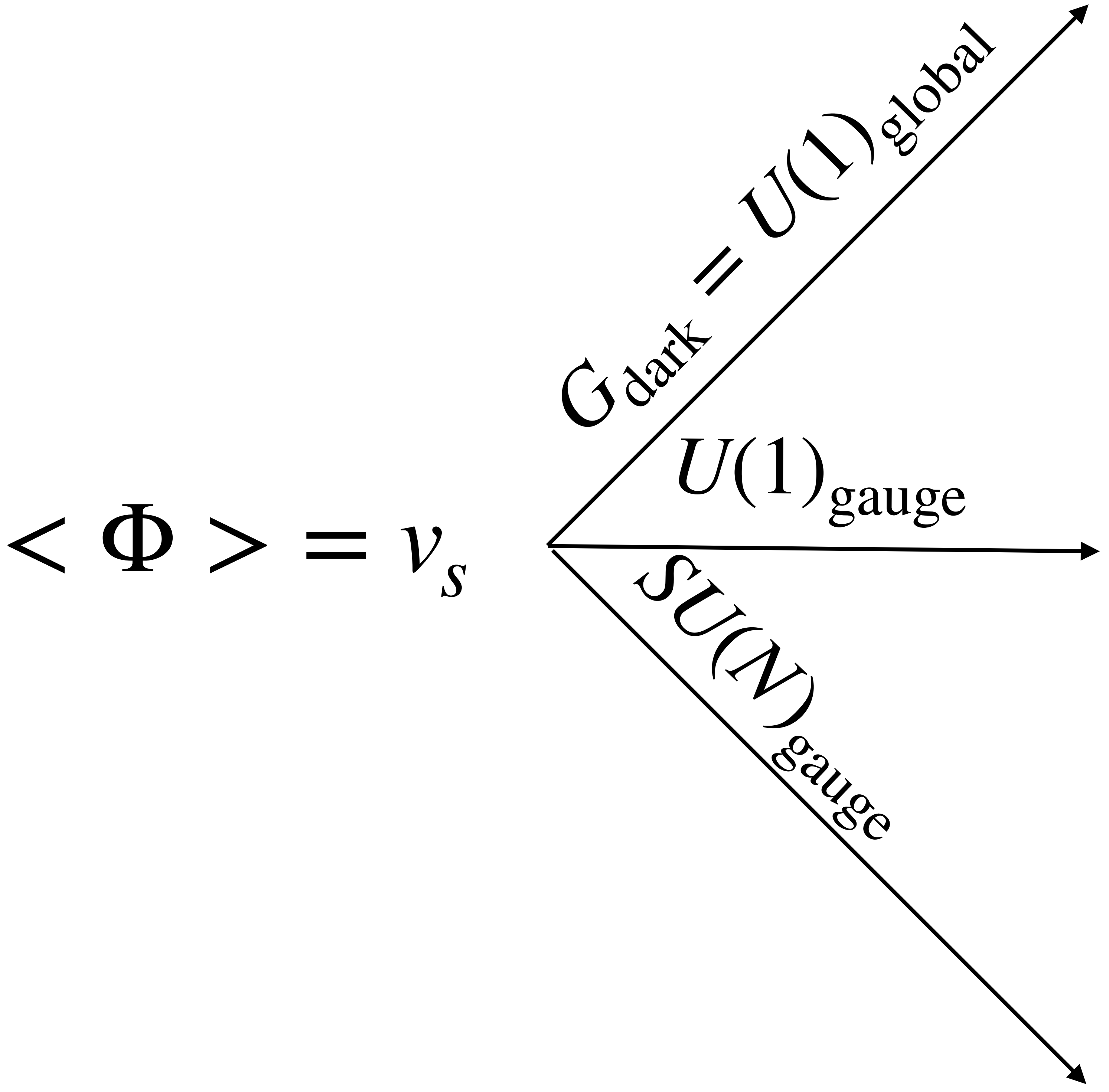
Others, including the case that BSMs are heavy.

Singlet scalar extensions can connect light dark sector:

$G_{\rm dark}$ symmetry extension. $\Phi \supset s$

See CxSM Barger et al, 0811.0393

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|\Phi|^2|H|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$



(CP-even) axion DM

Sakurai, WY, 2111.03653;

Hidden photon DM

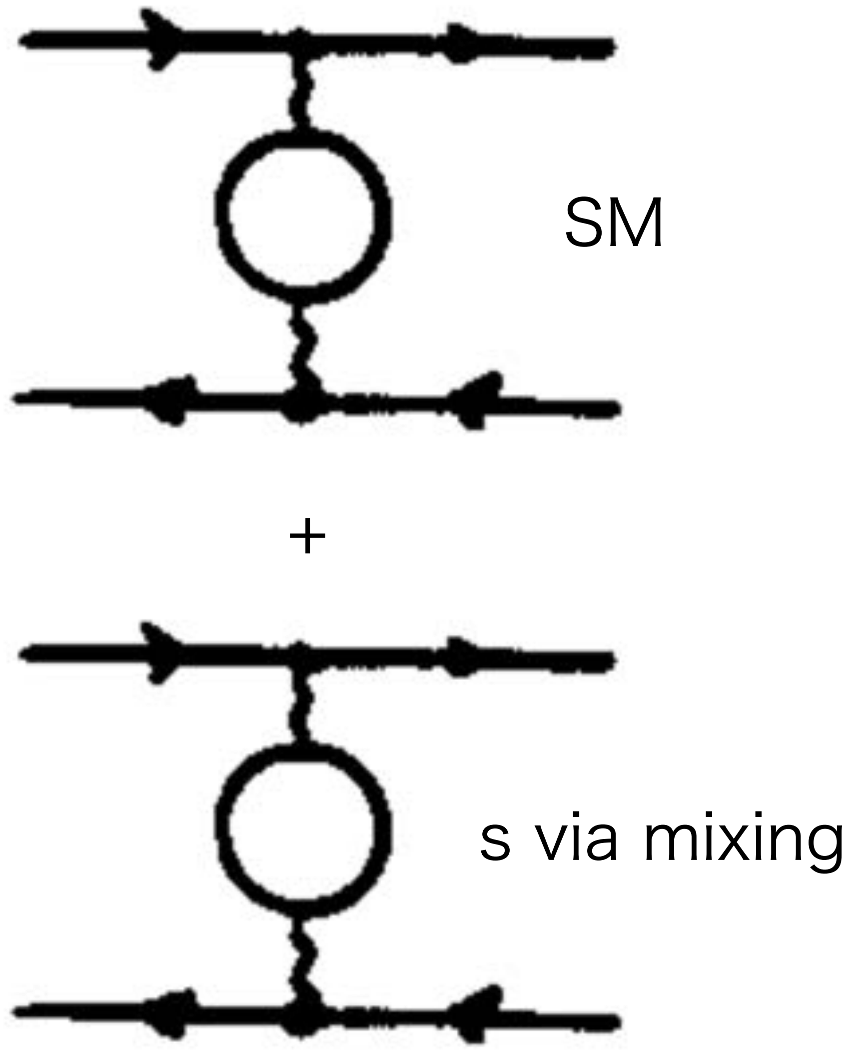
e.g. Jaeckel, and Ringwald 1002.0329;

Self-interacting
dark radiation

Takahashi, Sakurai, WY 2204.04770
see also Jeong, Takahashi, 1305.6521

いずれもh-s mixingが予言。

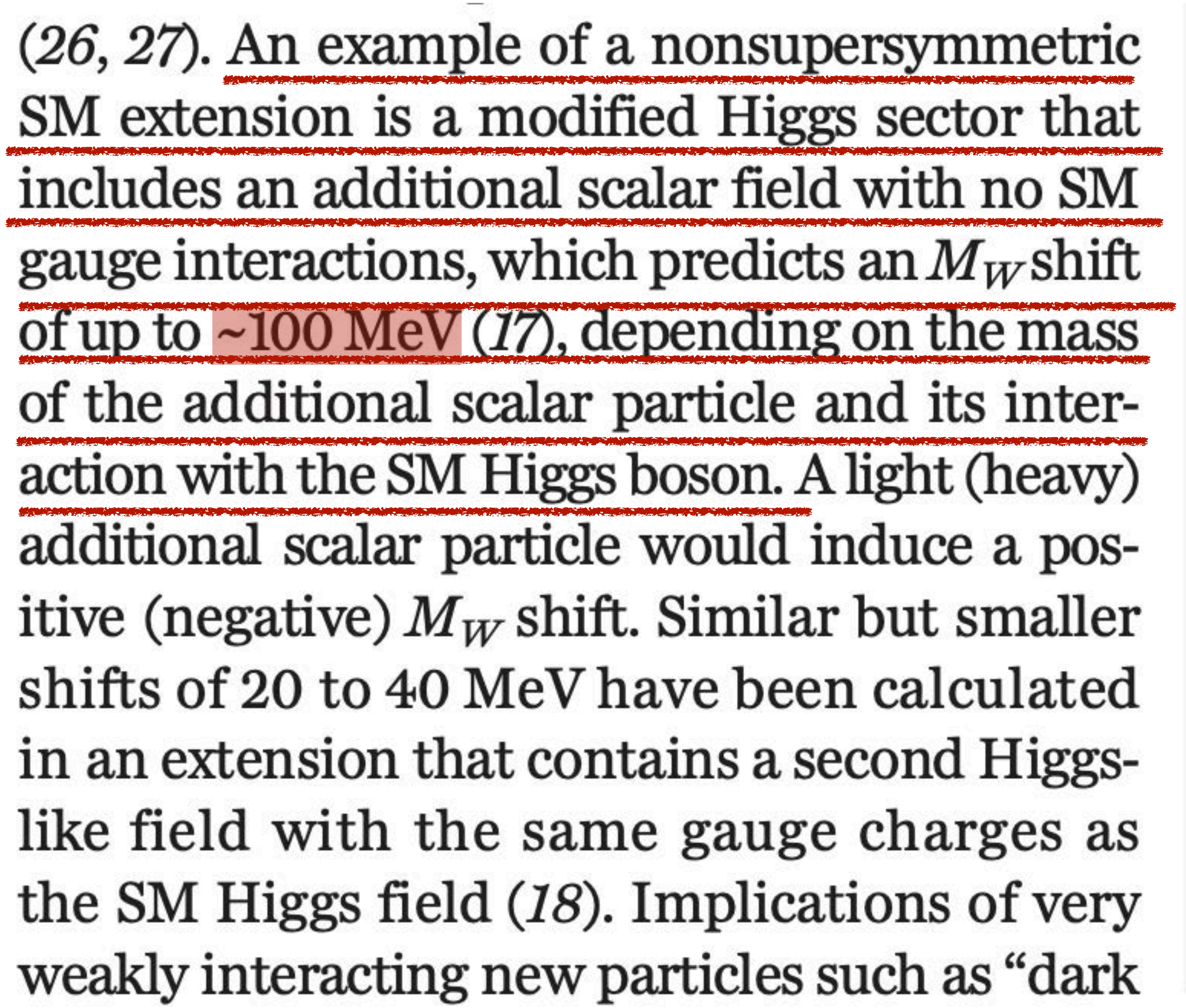
$\Delta r \supset$



A good news?

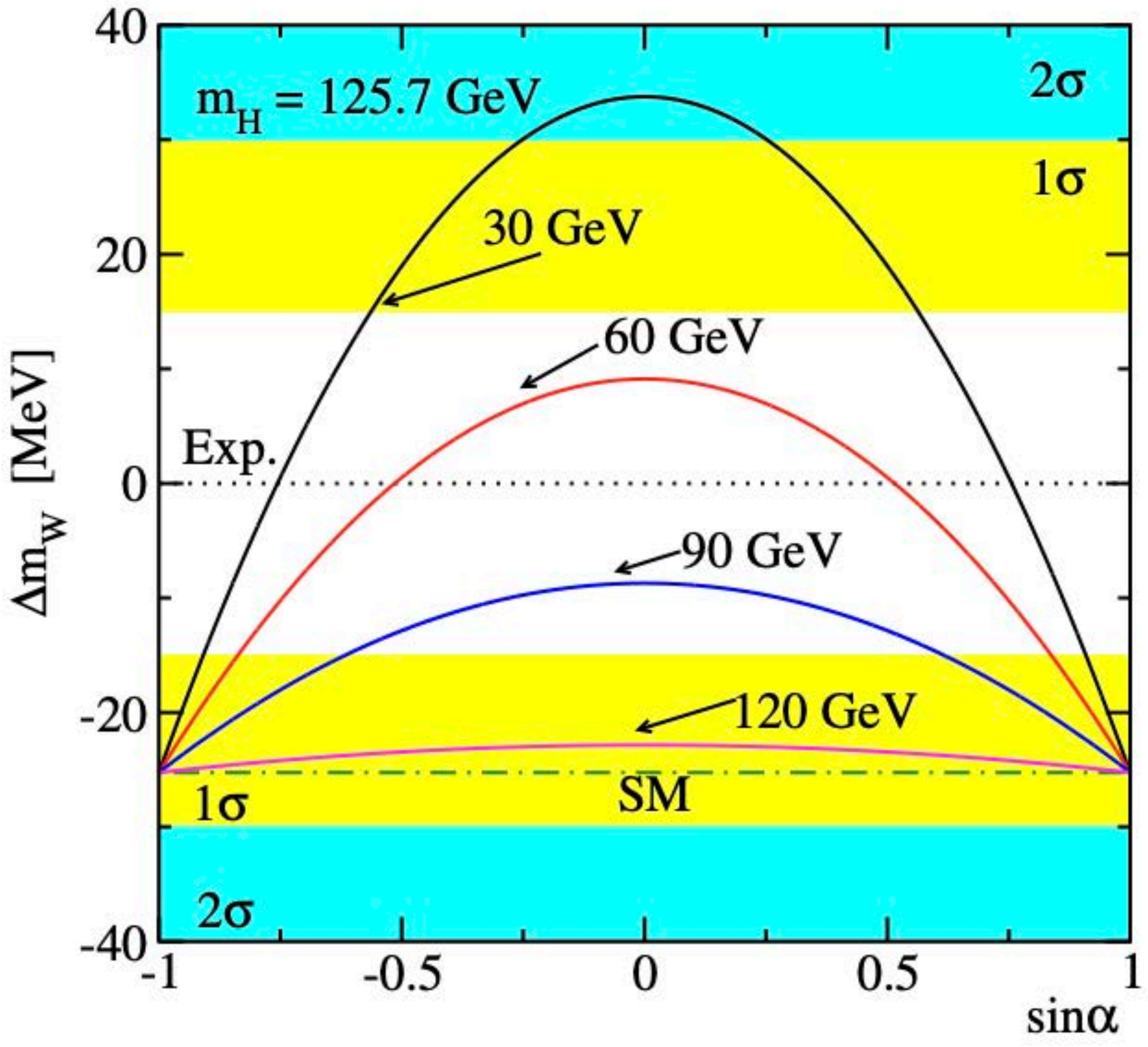
$$V \simeq m_{\rm mix}^2 sh + m_1^2\frac{s^2}{2} + m_2^2\frac{h^2}{2}, \cos\alpha \equiv m_{mix}^2/|m_1^2 - m_2^2|$$

CDF collaboration, Science 376, 170–176 (2022)



(*26*, *27*). An example of a nonsupersymmetric SM extension is a modified Higgs sector that includes an additional scalar field with no SM gauge interactions, which predicts an M_W shift of up to ~100 MeV (*17*), depending on the mass of the additional scalar particle and its interaction with the SM Higgs boson. A light (heavy) additional scalar particle would induce a positive (negative) M_W shift. Similar but smaller shifts of 20 to 40 MeV have been calculated in an extension that contains a second Higgs-like field with the same gauge charges as the SM Higgs field (*18*). Implications of very weakly interacting new particles such as "dark

[ref 17] L´opez-Val , Robens 1406.1043

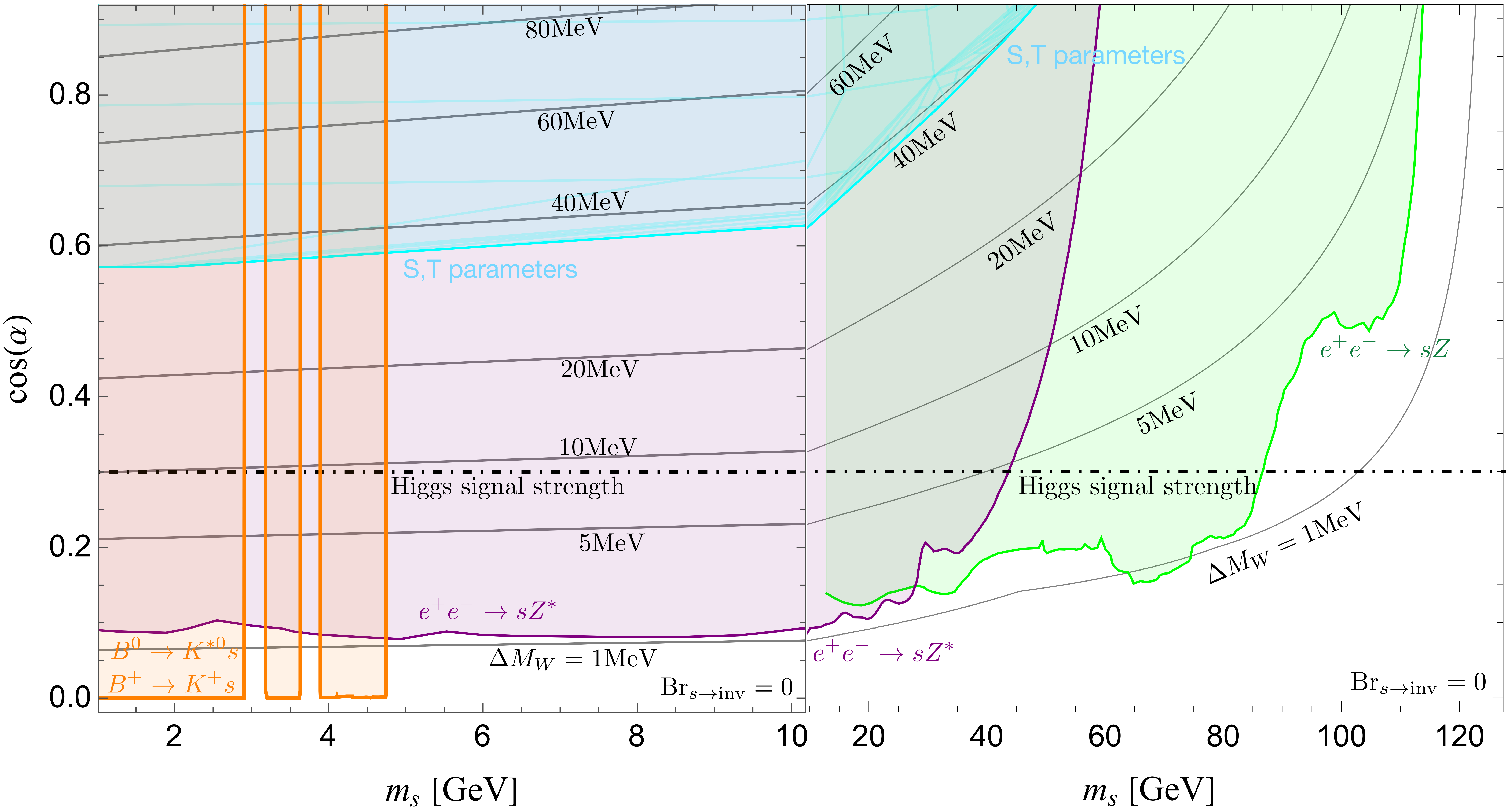


Compatibility with the LHC signal strength measurements requires | sin α| > 0.91.

2. Singlet scalar extension cannot explain the CDF-II result at all.

Sakurai, Takahashi, WY 2204.04770

W-boson mass shift is at most 2 MeV because of $e + \bar{e} \to sZ^{(*)} \to SMs$ at LEP and signal strength constraints.



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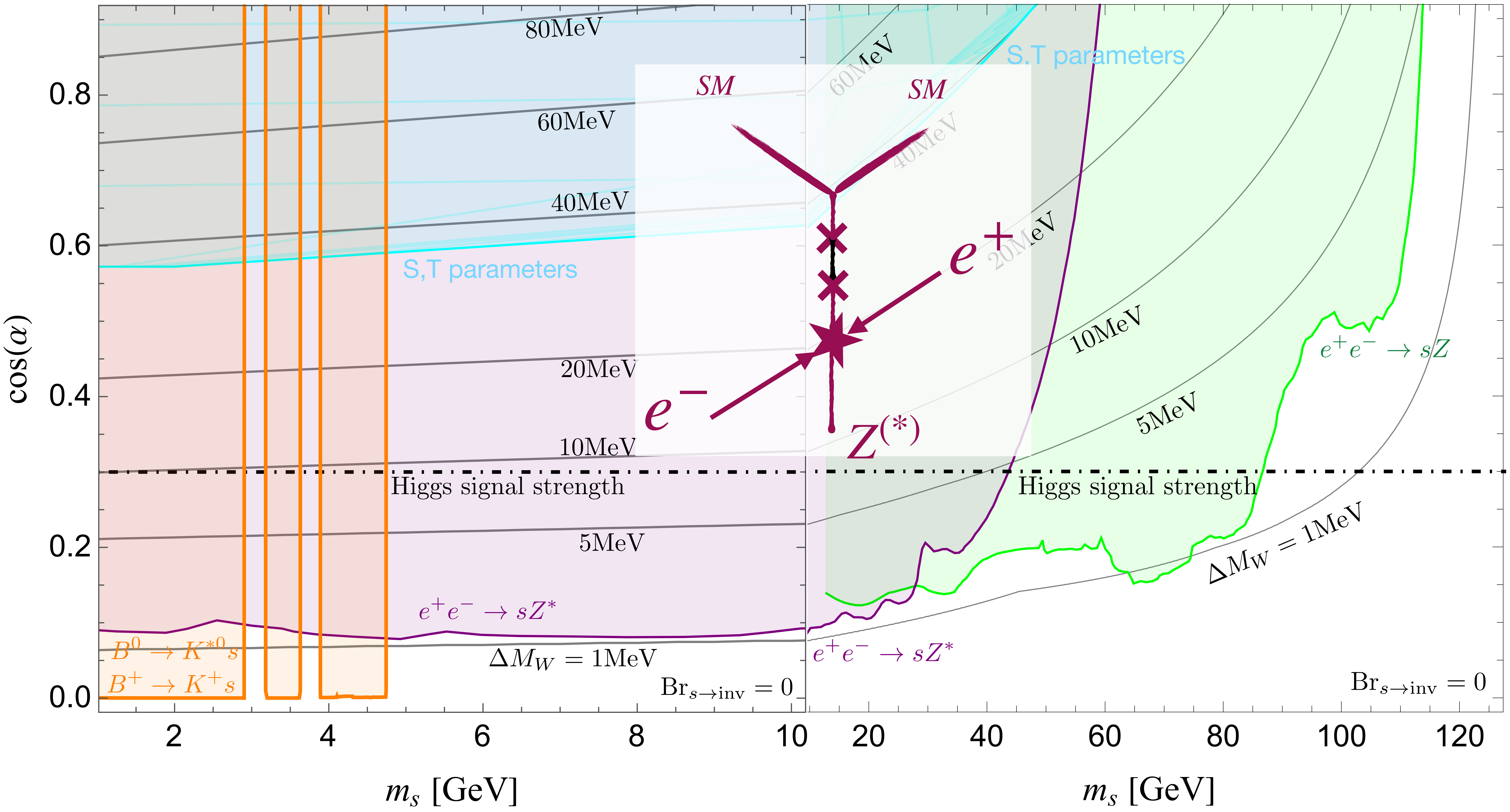
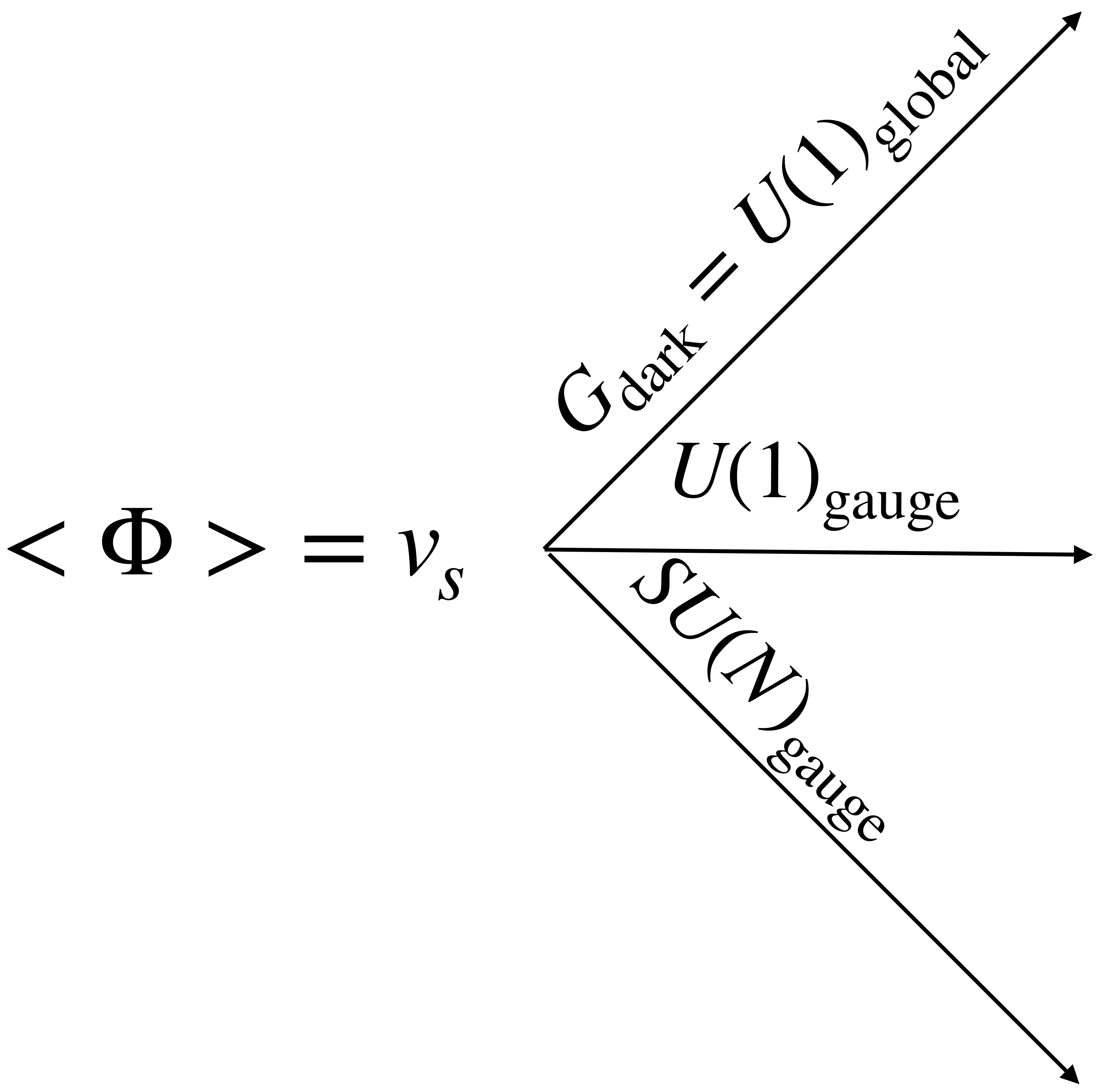


s invisible decay も prediction.

$$V = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \lambda_P |\Phi|^2 |H|^2 + \lambda_H |H|^4 - \mu_H^2 |H|^2 .$$



$< \Phi > = v_s$

$G_{\rm dark} = U(1)_{\rm global}$ → (CP-even) axion DM

Sakurai, WY, 2111.03653;

$U(1)_{\rm gauge}$ → Hidden photon DM

e.g. Jaeckel, and Ringwald 1002.0329;

$SU(N)_{\rm gauge}$ → Self-interacting dark radiation

Takahashi, Sakurai, WY 2204.04770
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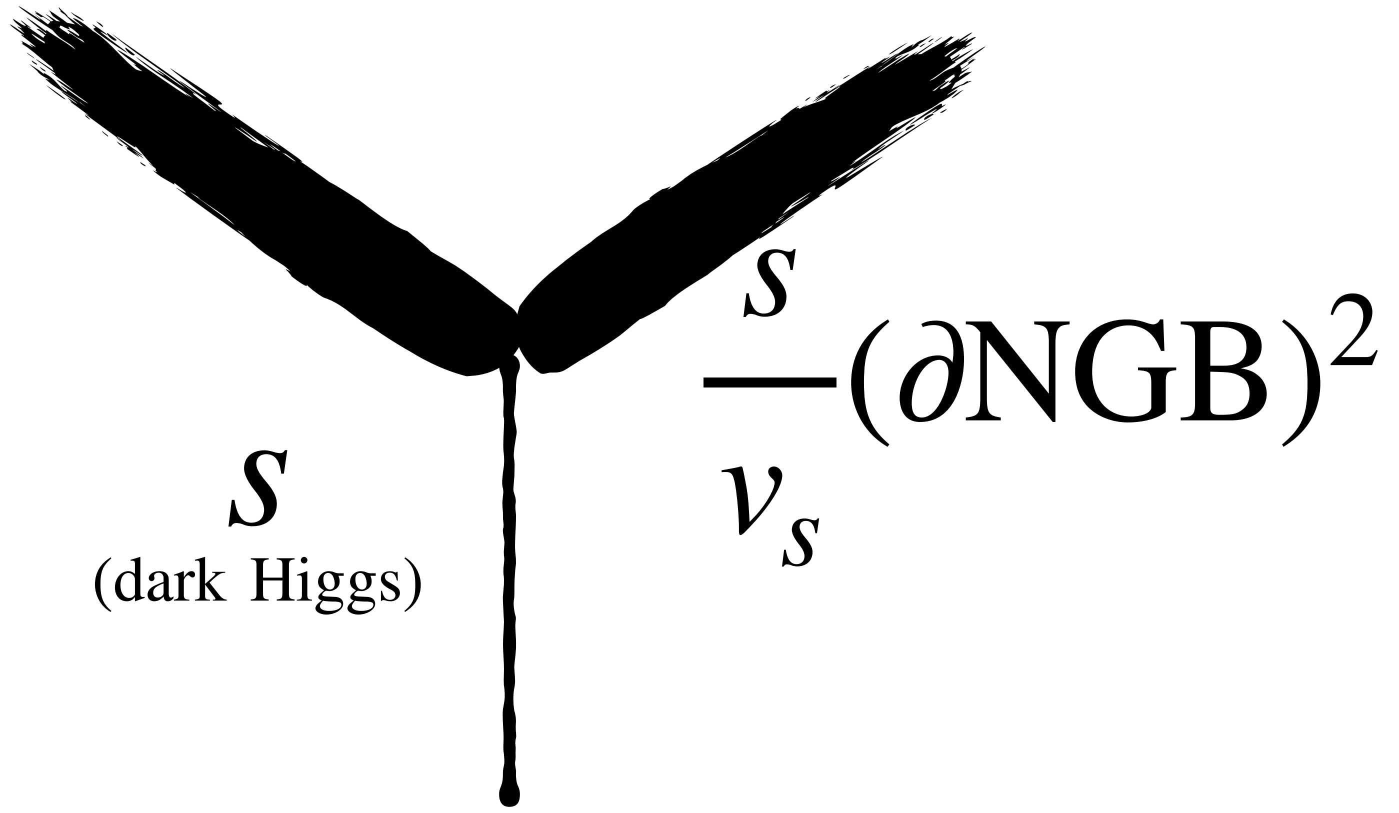
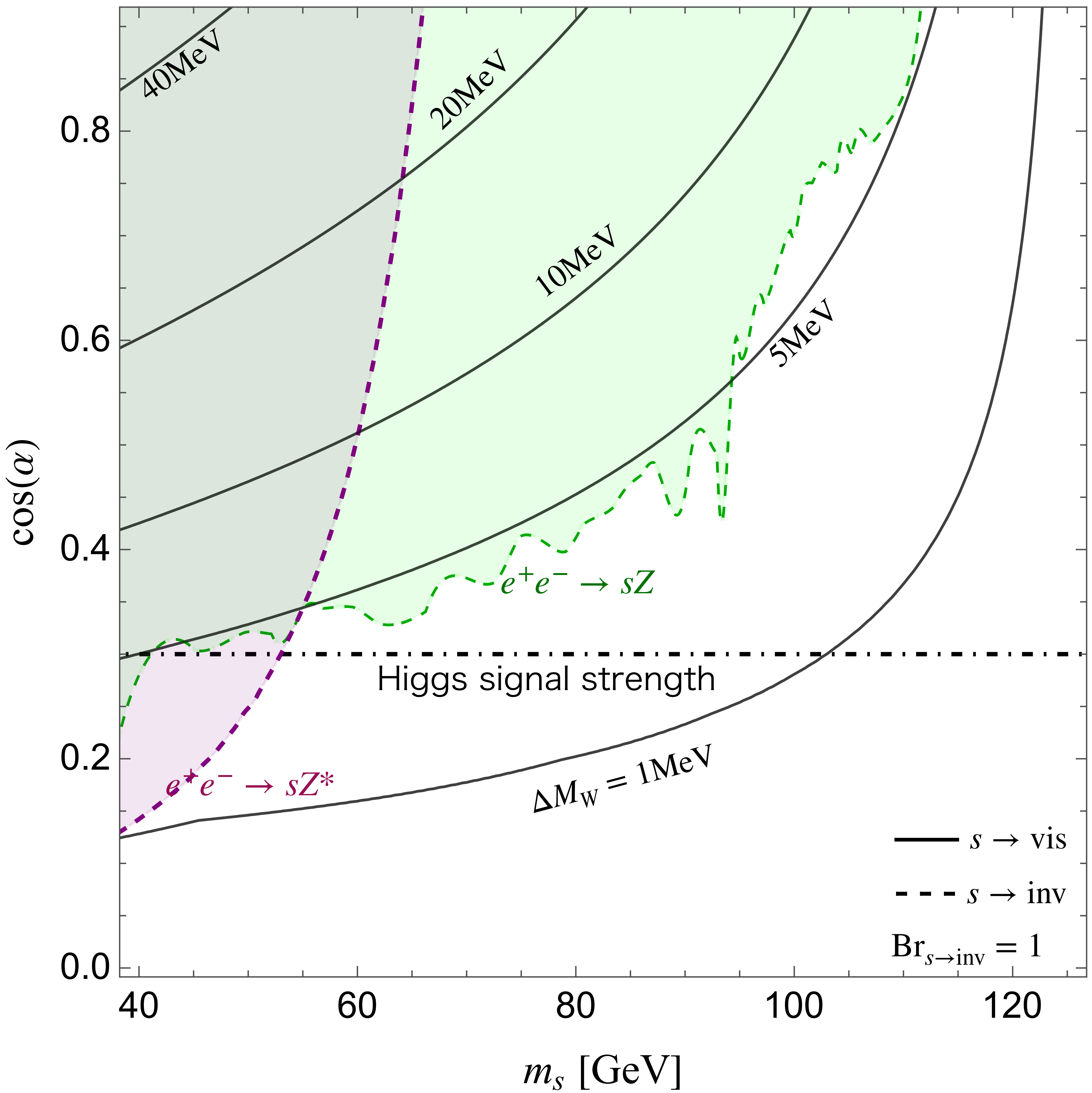
(would-be) NGB × 2

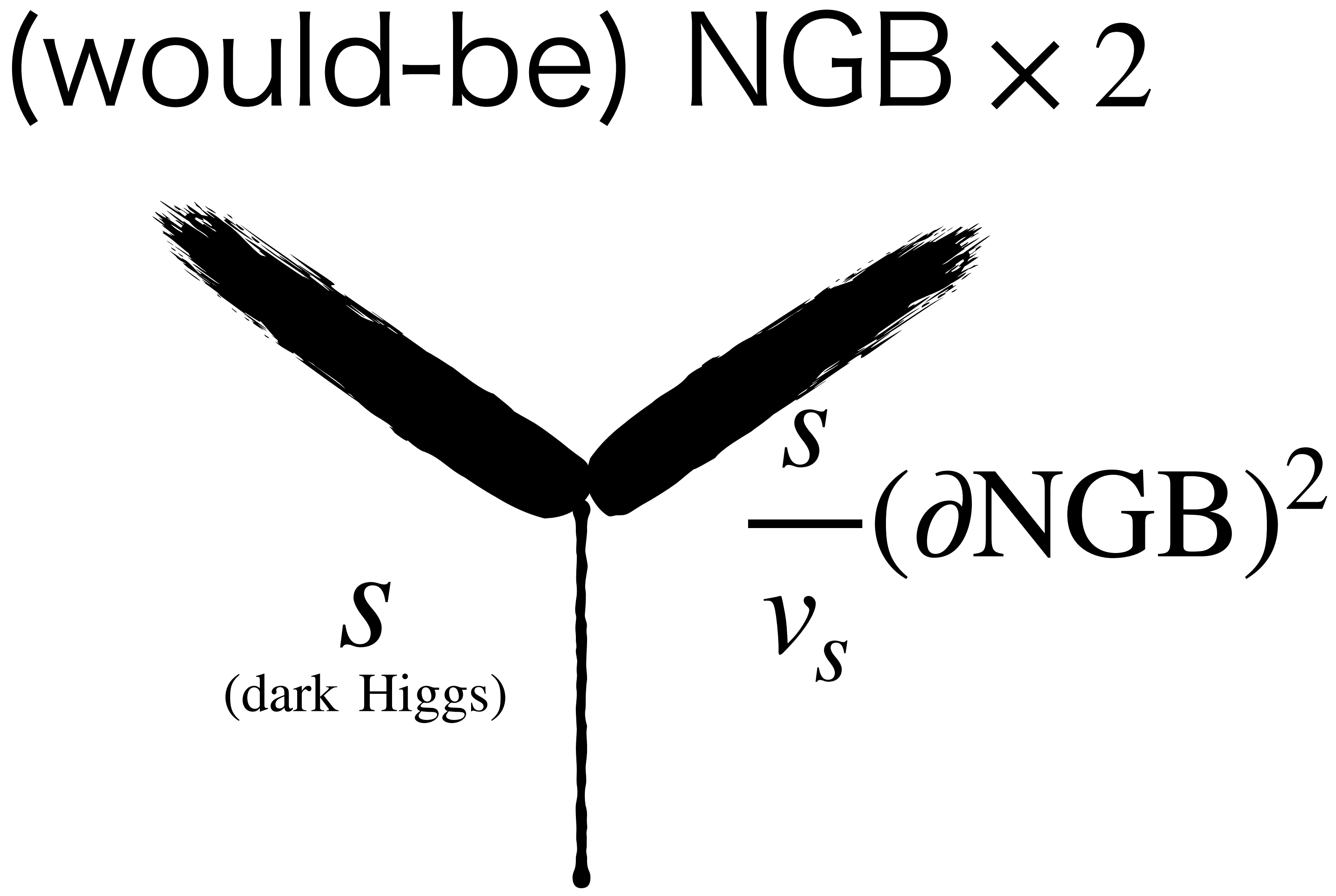


s (dark Higgs)

$\frac{s}{v_s}(\partial \mathrm{NGB})^2$

s may decay invisibly.





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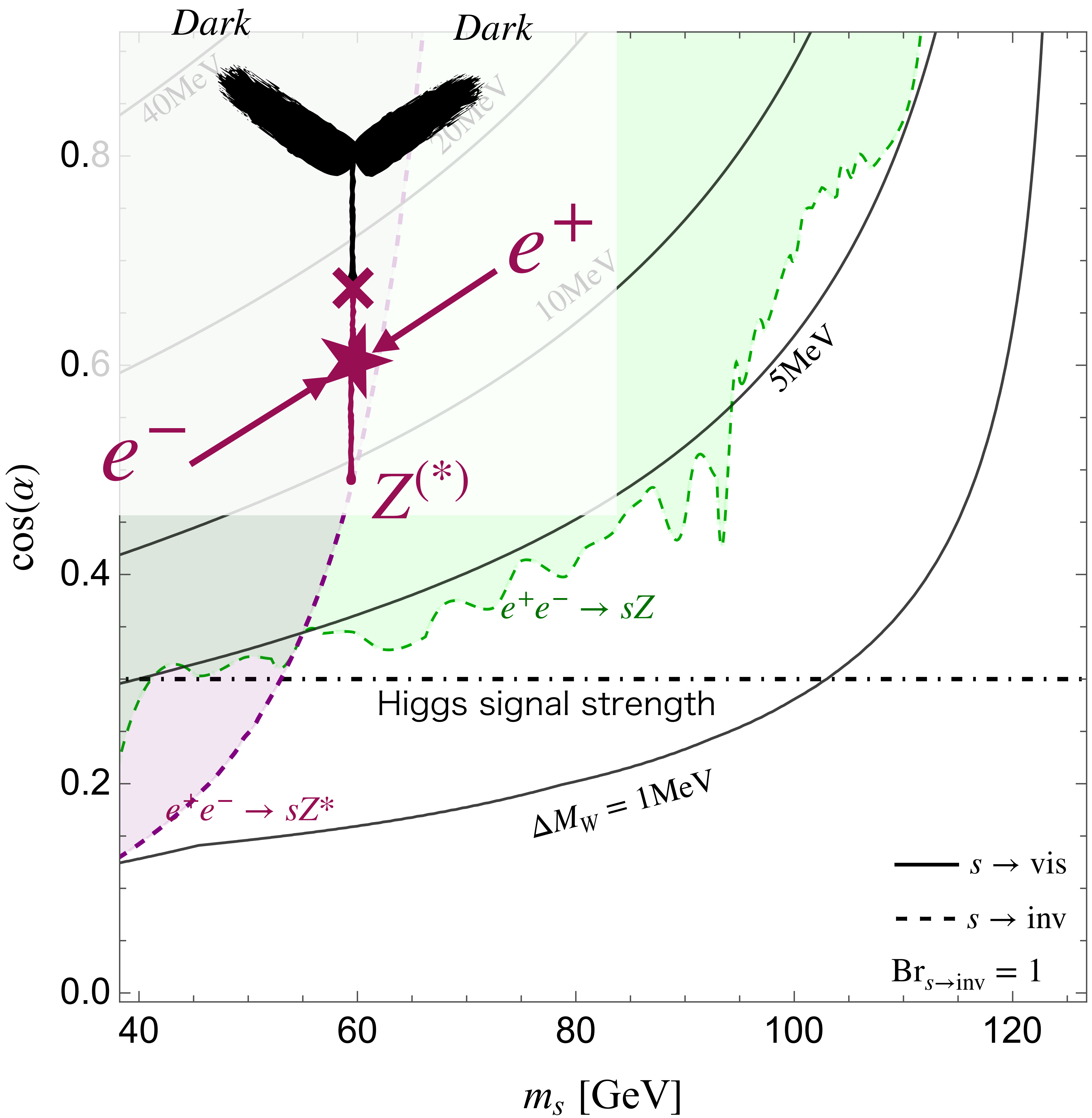

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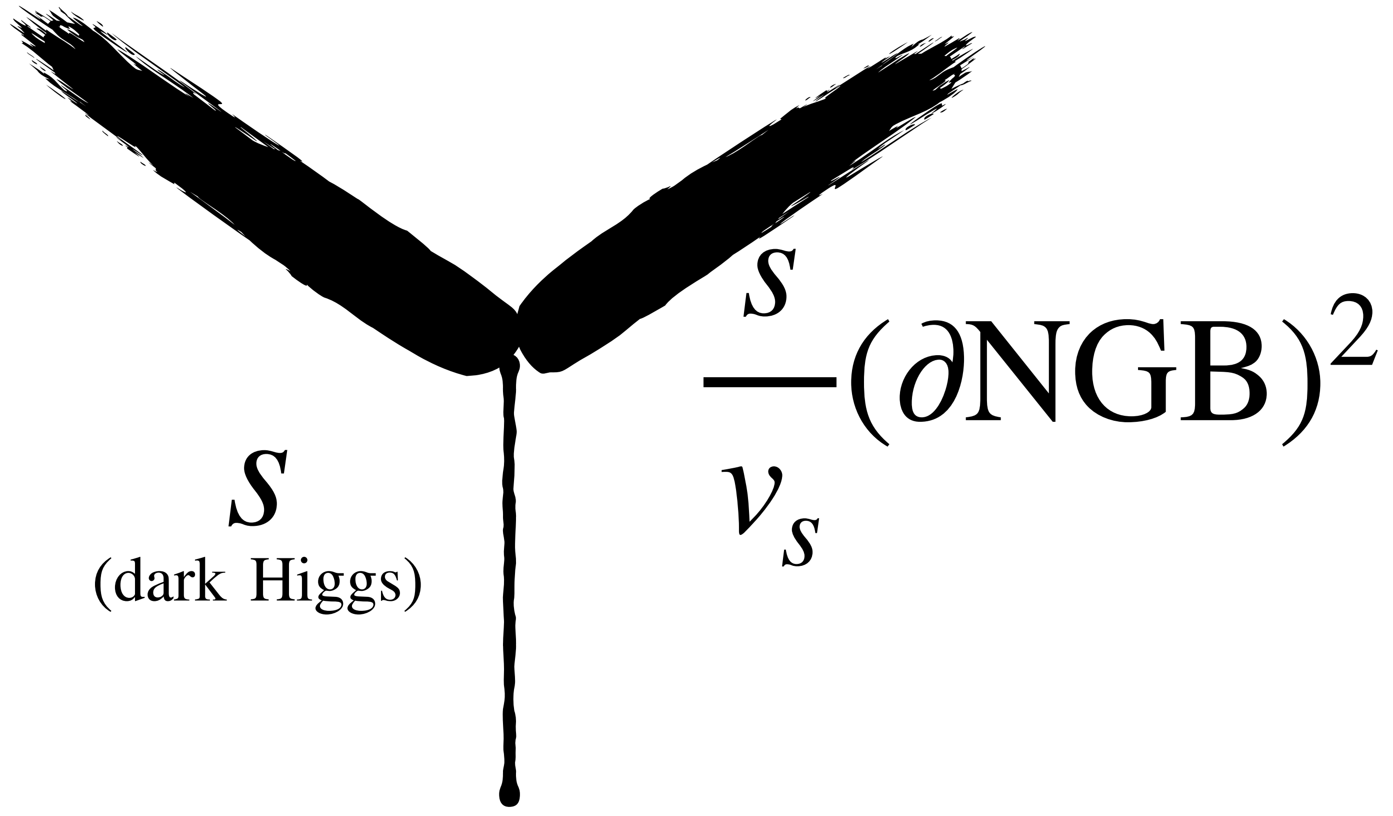
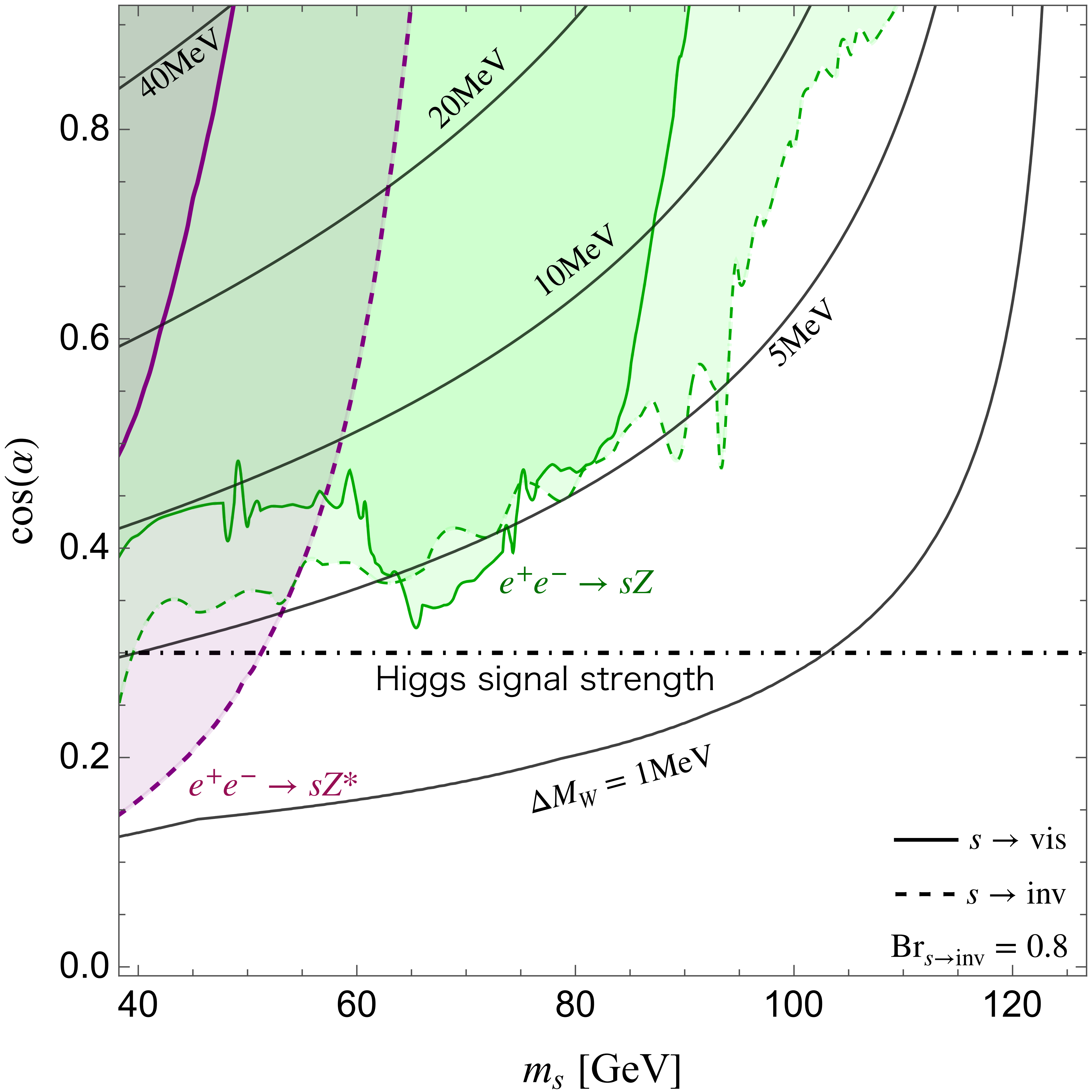
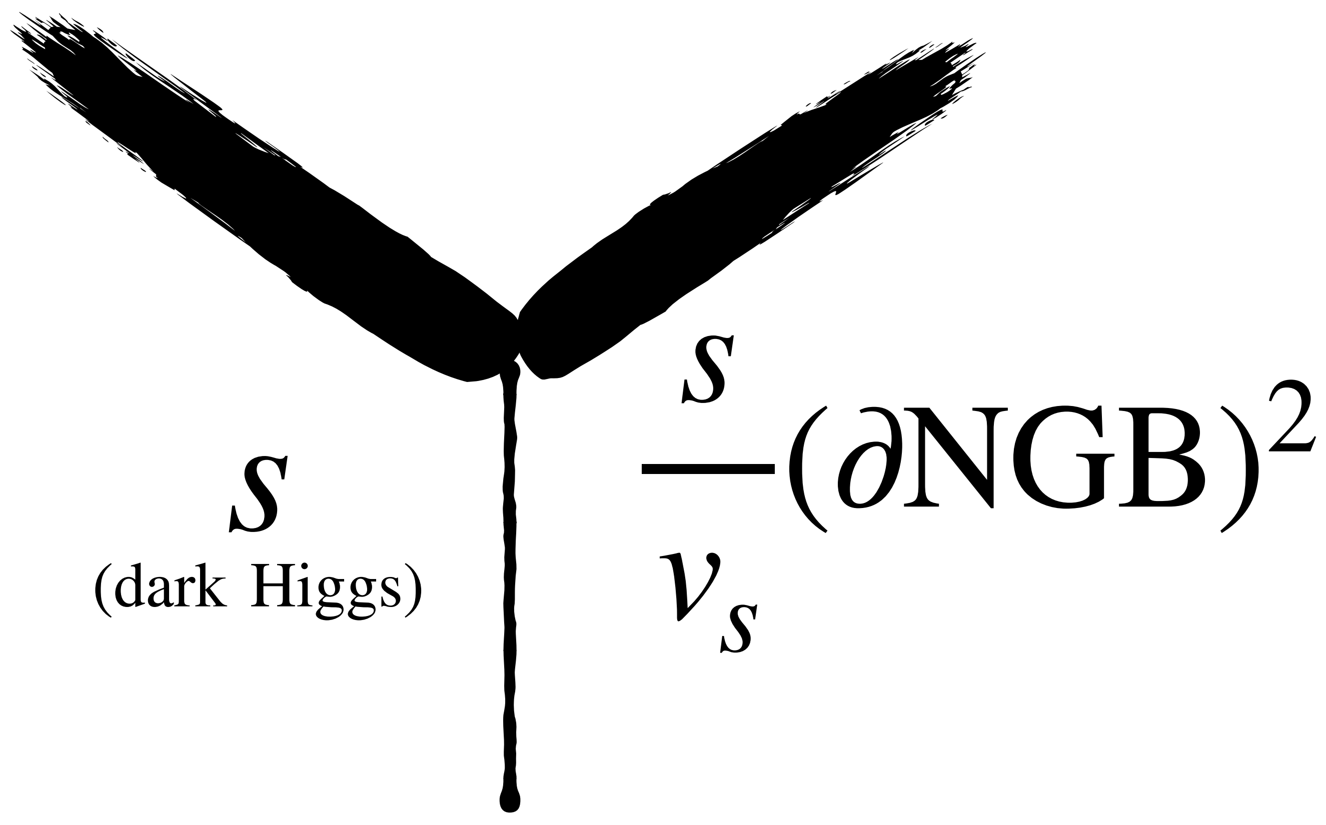


$$\frac{s}{v_s}(\partial \text{NGB})^2$$

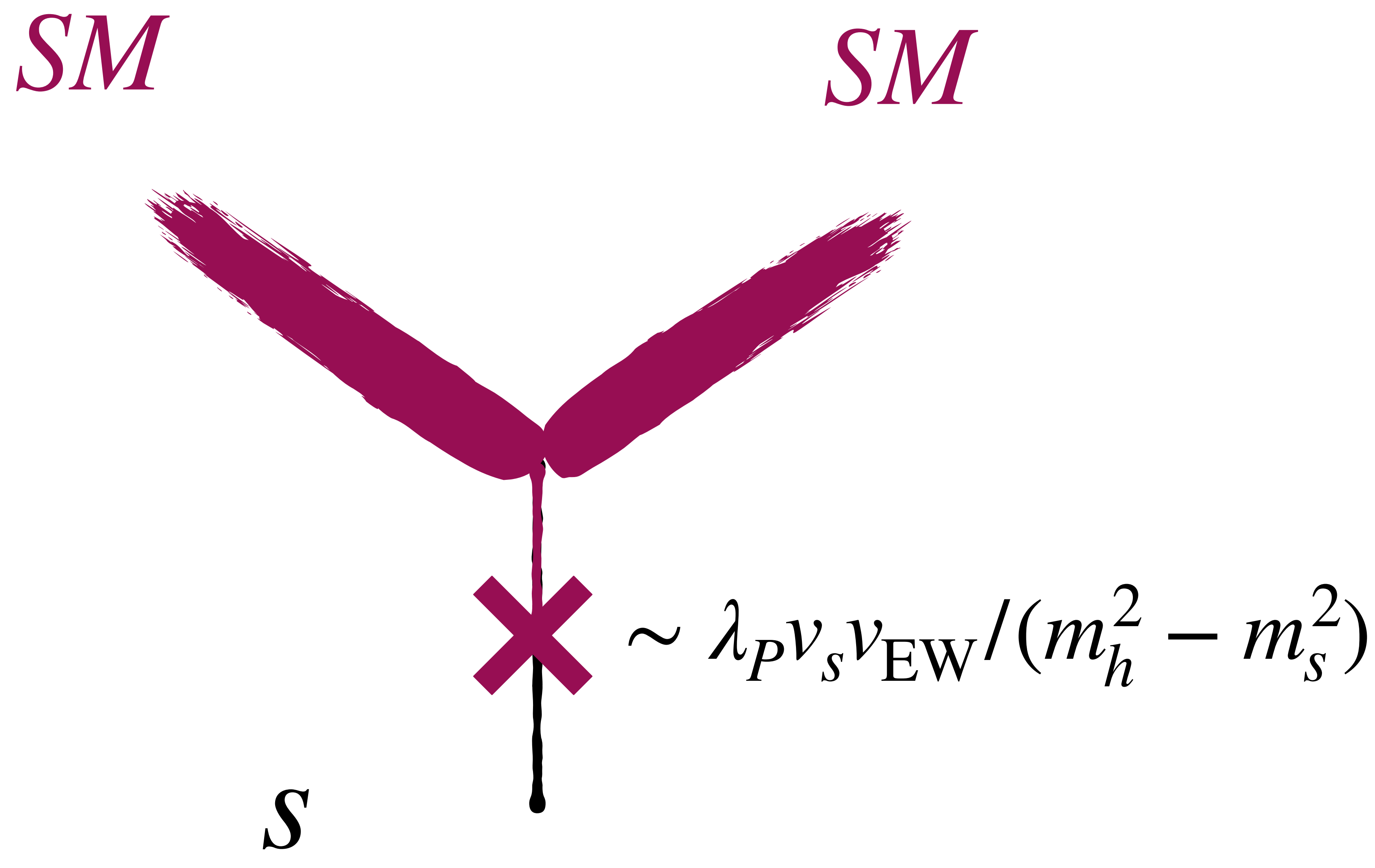
s may both decay visibly and invisibly.



(would-be) NGB × 2

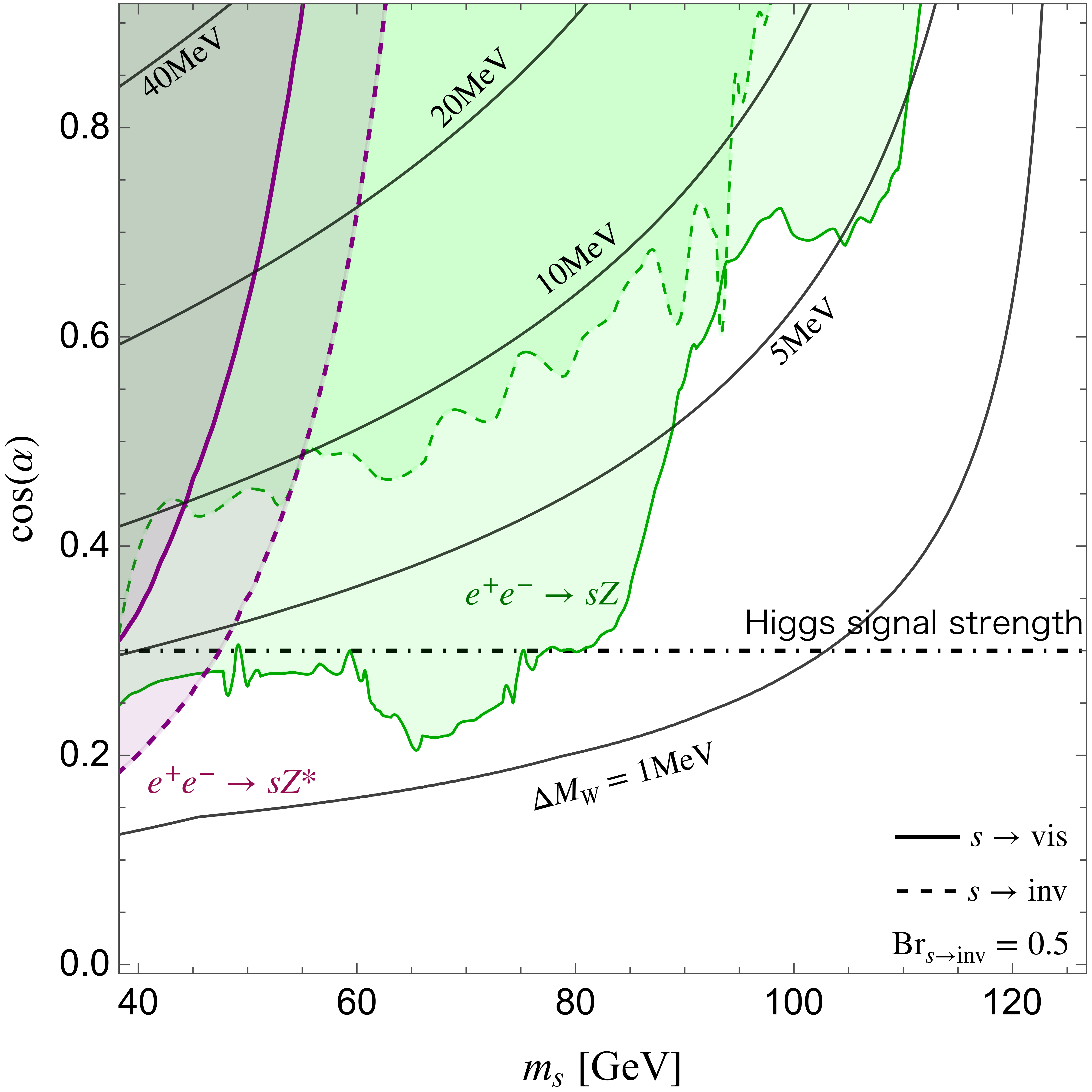


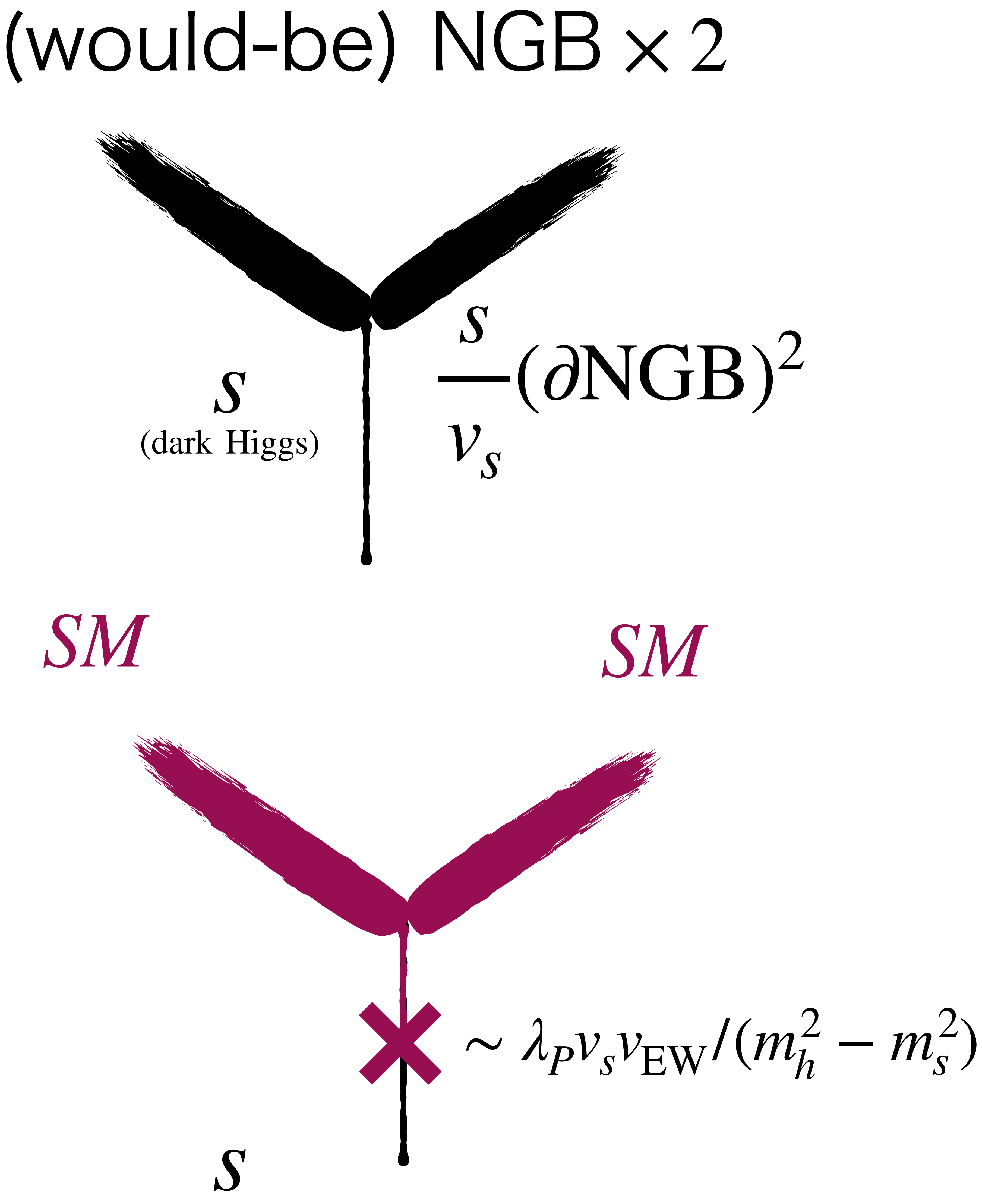
$\frac{s}{v_s}(\partial \text{NGB})^2$



$\sim \lambda_P v_s v_{\text{EW}}/(m_h^2 - m_s^2)$

s may both decay visibly and invisibly. m_W shift is at most 4-5 MeV.





3. Conclusions.

Sakurai, Takahashi, WY 2204.04770

- Singlet scalar extensionsでは余分な仮定なしに、フレーバー、CP的に安全でかつ、陽子崩壊は起こらない。標準模型の歴史的な成功例を犠牲にするが、暗黒物質と関連し、広く応用できる。
- Wボソン質量がどれほどズレるかははっきり指摘されてなかった。
- $\Delta M_w \lesssim 2$ MeV for s visible decay, and

  $\Delta M_w < 4-5$ MeV for s both visible and invisible decay

  を指摘した。
- Singlet scalar extension cannot explain the CDF-II result at all.

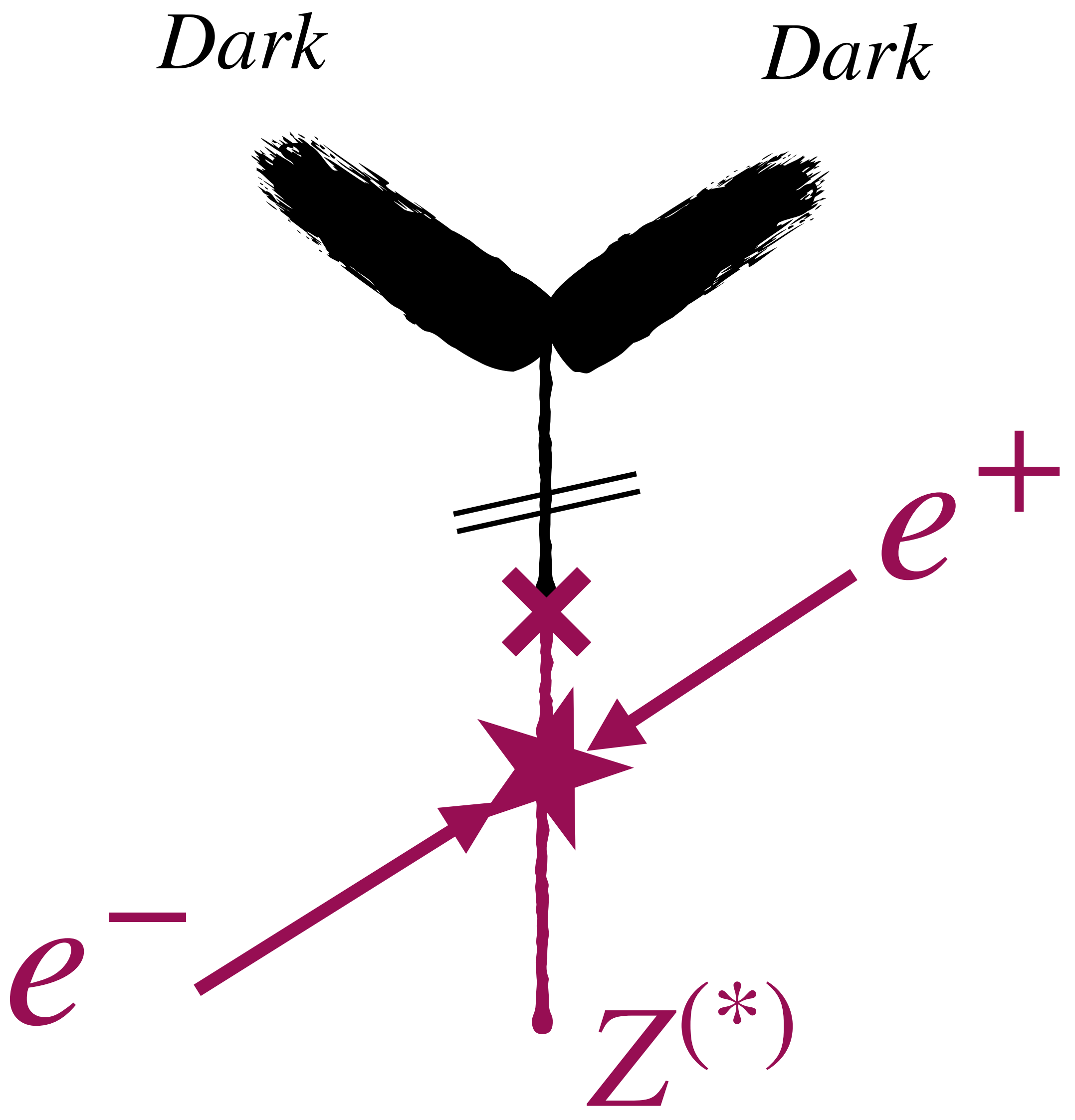
backup

3. Conclusions.

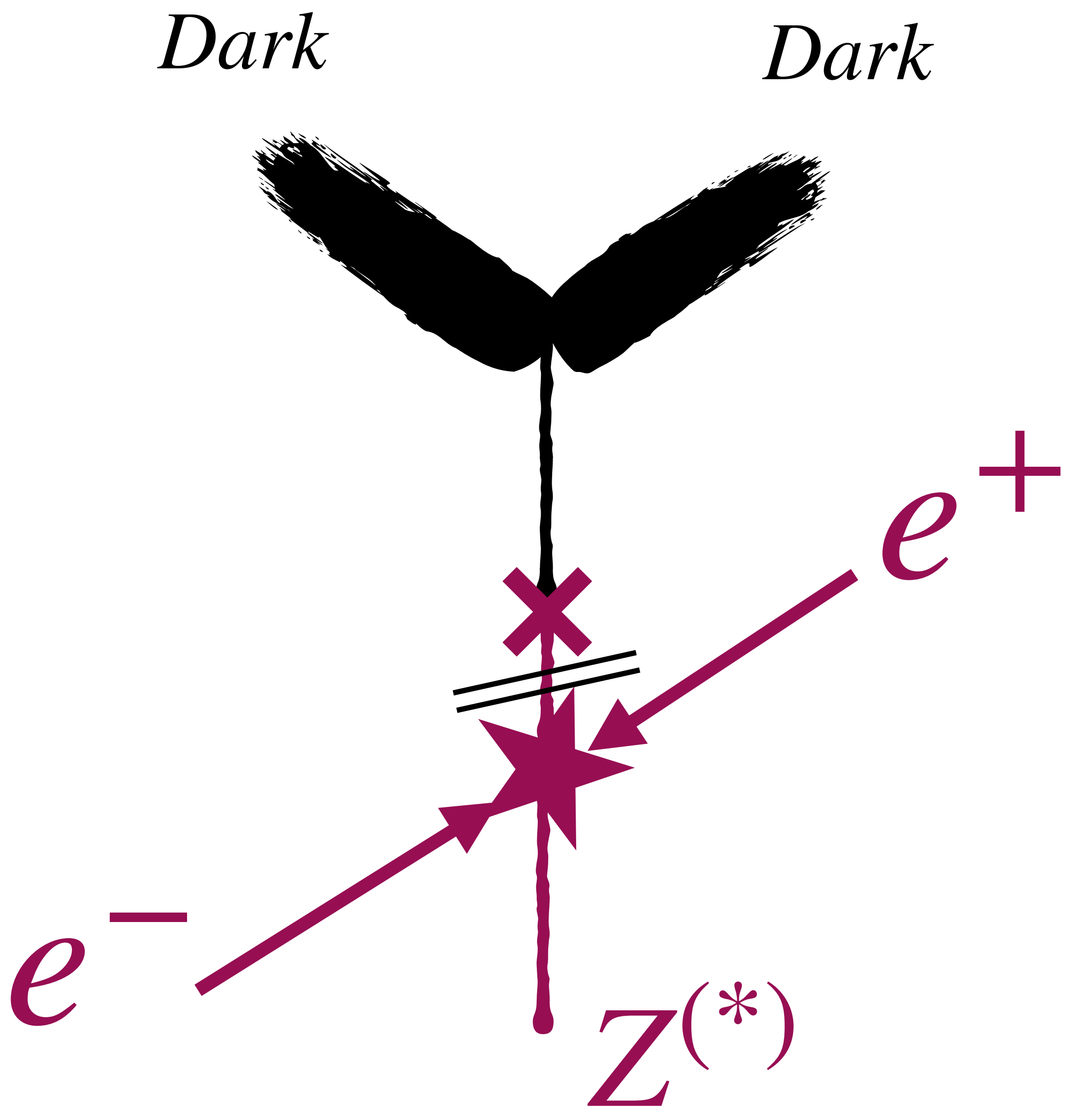
- Singlet scalar extension cannot explain the CDF-II result at all. $\Delta M_w < 2$ MeV for s visible decay.

  $\Delta M_w < 4-5$ MeV for s both visible and invisible decay.
- It may explain the slight preference without the CDF data.

ダークヒッグスインビジブル崩壊



125GeVヒッグスインビジブル崩壊



ヒッグスインビジブル崩壊が

$\Delta M_w > (1-2)$MeVならば

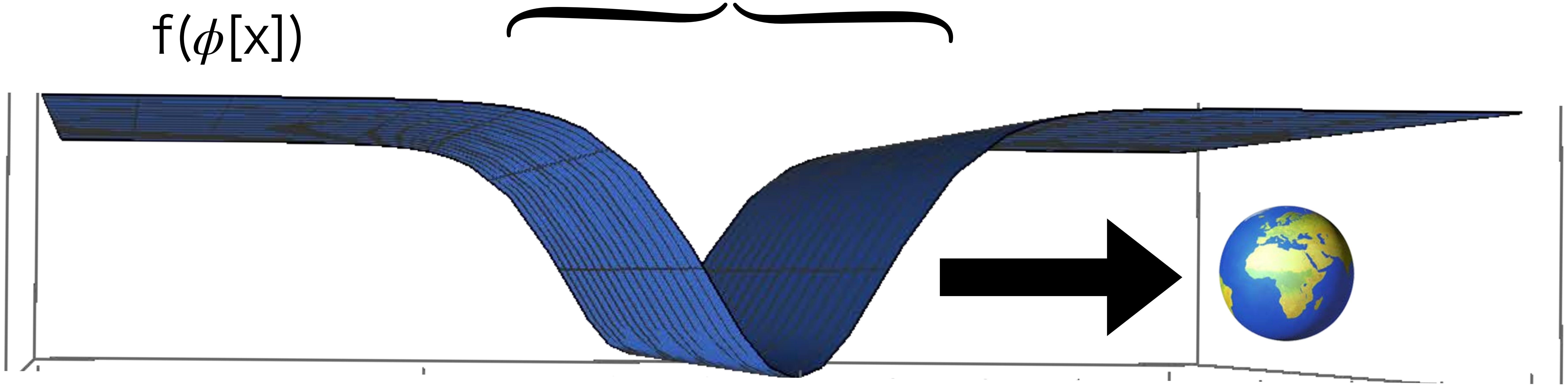
ILCで必ずチェックできる。

Crazy注意！

2002-2006年 or 2009-2011年にHiggs が軽くなった説

LEP 1989-2000 1997-2000 data taking
D0 1983–2011, 2006 to 2009 data taking.
CDF II 1983-2011. 2002 and 2011 data taking
Tevatron Higgs search 2001-2011 https://arxiv.org/pdf/1209.1586.pdf

$$V = f(\phi) V_{SM}[\,|H|^2]$$



CDF IIの*W*ボソン質量 M_Wの測定結果 (Kodai's slide)

[CDF Collaboration et al., Science 376, 170–176 (2022)]

Tevatronのdetector:

D0, CDF

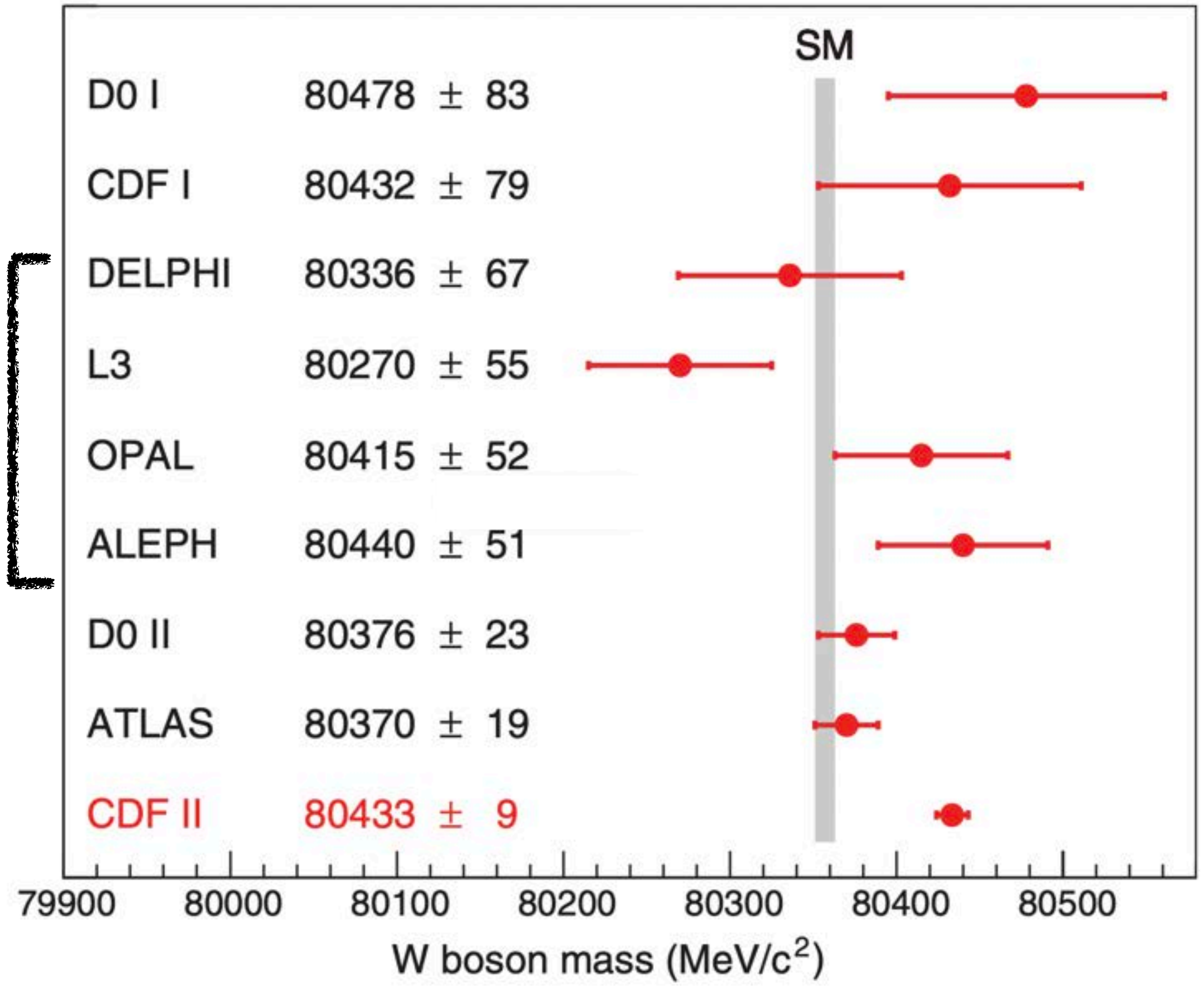
LEPのdetector:

DELPHI,L3, OPAL, ALEPH

LEP combined result

[Phys.Rept. 532 (2013) 119]

$80376 \pm 33 [\mathrm{MeV}]$



SMの理論予言： $80357 \pm 6 \; [\mathrm{MeV}]$ ← EW parameterの global fit により得られた値

[PDG2021]

[J. Erler, M. Sch

CDF IIの結果: 標準理論予言から7σ (~80 MeV) のずれ

Possible applications.

Degenerate scalar scenario

When dark higgs masses are similar, some parameter space
for WIMP and EWPT will open.

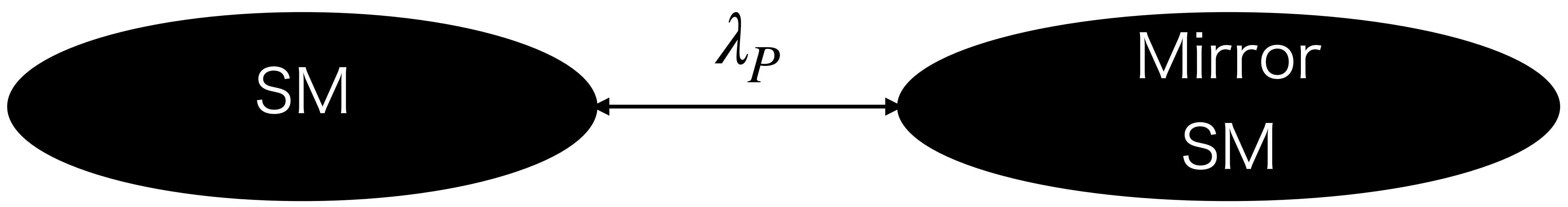
WIMP DM, Abe, Cho, Mawatari, 2101.04887
EWPT, Cho, Idegawa, Senaha 2105.11830

Degenerate scalars with $\Delta m \gtrsim 0.1\mathrm{GeV}$
can be distinguished at ILC Abe, Cho, Mawatari, 2101.04887

In the fuzzy Higgs region, the degenerate scalars cannot be distinguished. But it is probed by the Higgs invisible decay also at the ILC. Sakurai WY 2204.01739

Exact Z_2 mirror symmetry

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\mathrm{mirror\ SM}}$$
$$-\lambda_P |H|^2 |H_{\mathrm{mirror}}|^2$$



Relevant to fine-tuning problems or lighter QCD axion. Hook 1802.10093

$\Gamma_h = \Gamma_{mirrorh} \sim 4\mathrm{MeV},\ m_h \simeq m_{mirrorh} = 125.25GeV, \alpha = \pi/4.$

In this case, the Higgs coupling deviation of $\kappa_X = \cos(2\alpha_{\mathrm{eff}})$
can be also probed together with invisible decay.

Sakurai WY 2204.01739

Strongly coupled dark sector

Go beyond perturbative unitarity. If $\Gamma_{s\to dark}$ can be arbitrarily large,
fuzzy Higgs boson is realized with arbitrary $|m_1 - m_2|$
and thus generically realized.

Extention to dark scalar phenomena

Mixed axions with one component decay very fast has the other component stabilized.

3. CP-even ALP from generic CPV

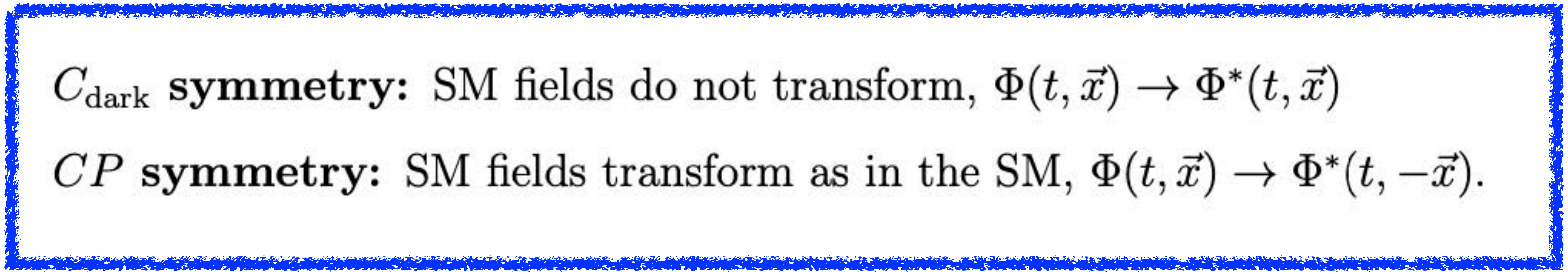
Kodai Sakurai, WY 2111.03653

In the following I take for simplicity $\theta_{\rm CP} = \theta_{CKM} = 0$, which does not change our conclusions.

If we do not impose CP symmetry in the dark sector,

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2\,.$$

Accidental discrete symmetry in dark global U(1) symmetric limit:



$C_{\rm dark}$ **symmetry:** SM fields do not transform, $\Phi(t,\vec{x}) \to \Phi^*(t,\vec{x})$

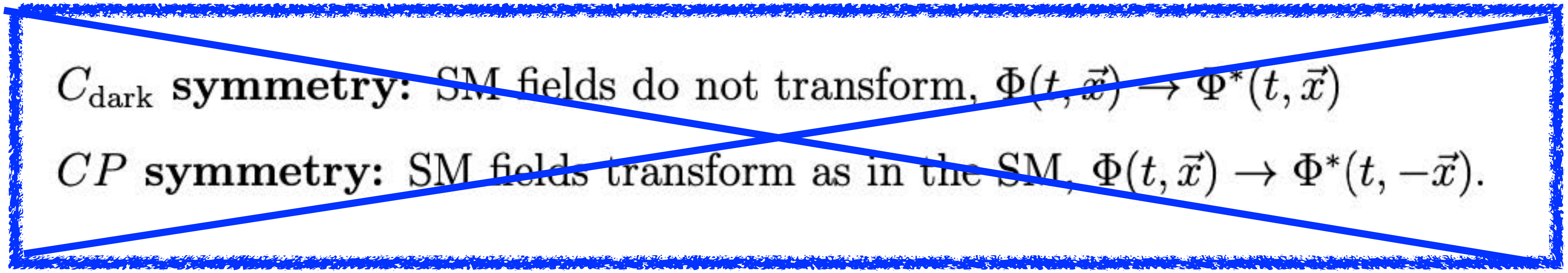
CP **symmetry:** SM fields transform as in the SM, $\Phi(t,\vec{x}) \to \Phi^*(t,-\vec{x})$.

If we do not impose CP symmetry in the dark sector,

Explicit breaking of dark $U(1)$ controlled by κ is

$$\delta V = \kappa \left(\sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} \left(\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j} \Phi^j |\Phi|^2 \right) \right) + \mathrm{h.c.}$$

$$\arg c, \tilde{c} \neq 0$$



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$$\arg c, \tilde{c} \neq 0$$

But $C_{\rm dark} \cdot CP$ remains: SM → CP SM,

$\Phi(t, \overrightarrow{x}) \to \Phi(t, -\overrightarrow{x})$ (a parity for dark Higgs).

If we do not impose CP symmetry in the dark sector,

Explicit breaking of dark $U(1)$ controlled by κ is

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$$\arg c, \tilde{c} \neq 0$$

$C_{\mathrm{dark}} \cdot CP$: SM → CP SM

$\Phi(t, \vec{x}) \to \Phi(t, -\vec{x})$, thus $a[t, \vec{x}](\equiv -i \arg \Phi) \to a[t, -\vec{x}]$

If we do not impose CP symmetry in the dark sector,

Explicit breaking of dark $U(1)$ controlled by κ is

$$\delta V = \kappa \left(\sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} (\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j} \Phi^j |\Phi|^2) \right) + \mathrm{h.c.}$$

$$\arg c, \tilde{c} \neq 0$$

$CP_{\mathrm{EFT}} \equiv C_{\mathrm{dark}} \cdot CP$: SM → CP SM, $a[t, \vec{x}] \to a[t, -\vec{x}]$

A simple UV completion of axion without imposing CP symmetry has accidental CP_{EFT} with **ALP being CP-even**.

Couplings of the CP-even ALP

$$V = -\,m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|H|^2|\Phi|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

- Induced from U(1) symmetric part, and thus $C_{\rm dark}\times CP$ symmetric.
- Non-renormalizable (dim 6 or 8).
  i.e. very weak at low energy.

$$\mathscr{L}_{\rm eff} \sim \frac{\mathcal{O}_{SM}}{m_\Phi^{d_{\mathcal{O}_{\rm SM}}}}(\partial a)^2$$

$$\delta V = \kappa\left(\sum_{j=1}^{4} c_j m_\Phi^{4-j}\Phi^j + \sum_{j=1}^{2}\left(\tilde{c}_j^H m_\Phi^{2-j}\Phi^j|H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j}\Phi^j|\Phi|^2\right)\right) + \mathrm{h.c.}$$

$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} ah,\ \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

- Induced from U(1) breaking part.
- At $\kappa \to 0$,(i.e. $m_a^2 \to 0$), it vanishes, i.e.
  amplitude $\propto m_a^2$
- Renormalizable, dominant at low energy.

3. Phenomenology of CP-even ALP

- Probing CP-even ALP in Higgs factory
- CP-even ALP DM

Kodai Sakurai, WY 2111.03653

CP-even ALP can be naturally produced via Higgs boson decay

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|\Phi|^2|H|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

Higgs portal coupling

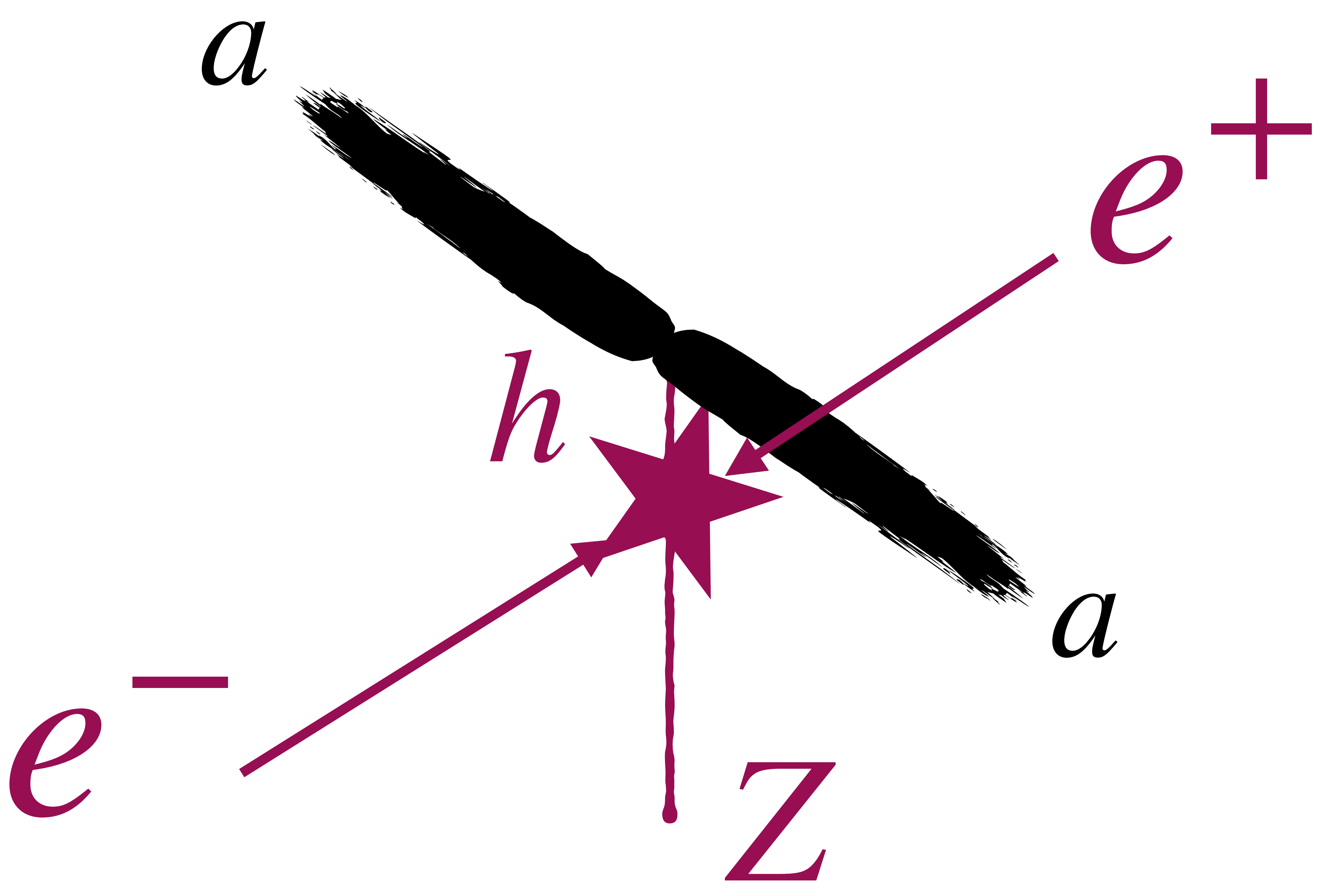
Φ: U(1) Higgs field

H :SM Higgs doublet

$$\mathscr{L}_{\text{eff}} \sim \frac{\sqrt{2}v}{\Lambda_H^2} h(\partial a)^2 \qquad \frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}.$$

$$\Gamma_{h\to aa} \simeq \frac{1}{16\pi}\frac{v^2 m_h^3}{\Lambda_H^4}.$$

$$\mathrm{Br}_{h\to aa} = 2\,\% \left(\frac{2\mathrm{TeV}}{\Lambda_H}\right)^4$$



Couplings of the CP-even ALP

$$V = -m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \lambda_P |H|^2 |\Phi|^2 + \lambda_H |H|^4 - \mu_H^2 |H|^2 .$$

$$\mathscr{L}_{\rm eff} \sim \frac{\sqrt{2}v}{\Lambda_H^2} h (\partial a)^2$$

$$\frac{1}{\Lambda_H^2} \equiv -\frac{\lambda_P}{m_s^2 - m_h^2}.$$

- Induced from U(1) symmetric part, and thus $C_{\rm dark} \times CP$ symmetric.
- Non-renormalizable (dim 6 or 8). i.e. very weak at low energy.

$$\delta V = \kappa \left(\sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} (\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \tilde{c}_j^\Phi m_\Phi^{2-j} \Phi^j |\Phi|^2) \right) + {\rm h.c.}$$

$$\mathscr{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} a h, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

- Induced from U(1) breaking part.
- At $\kappa \to 0$,(i.e. $m_a^2 \to 0$), it vanishes, i.e. amplitude $\propto m_a^2$
- Renormalizable, dominant at low energy.

CP-even ALP can be naturally produced via Higgs boson decay

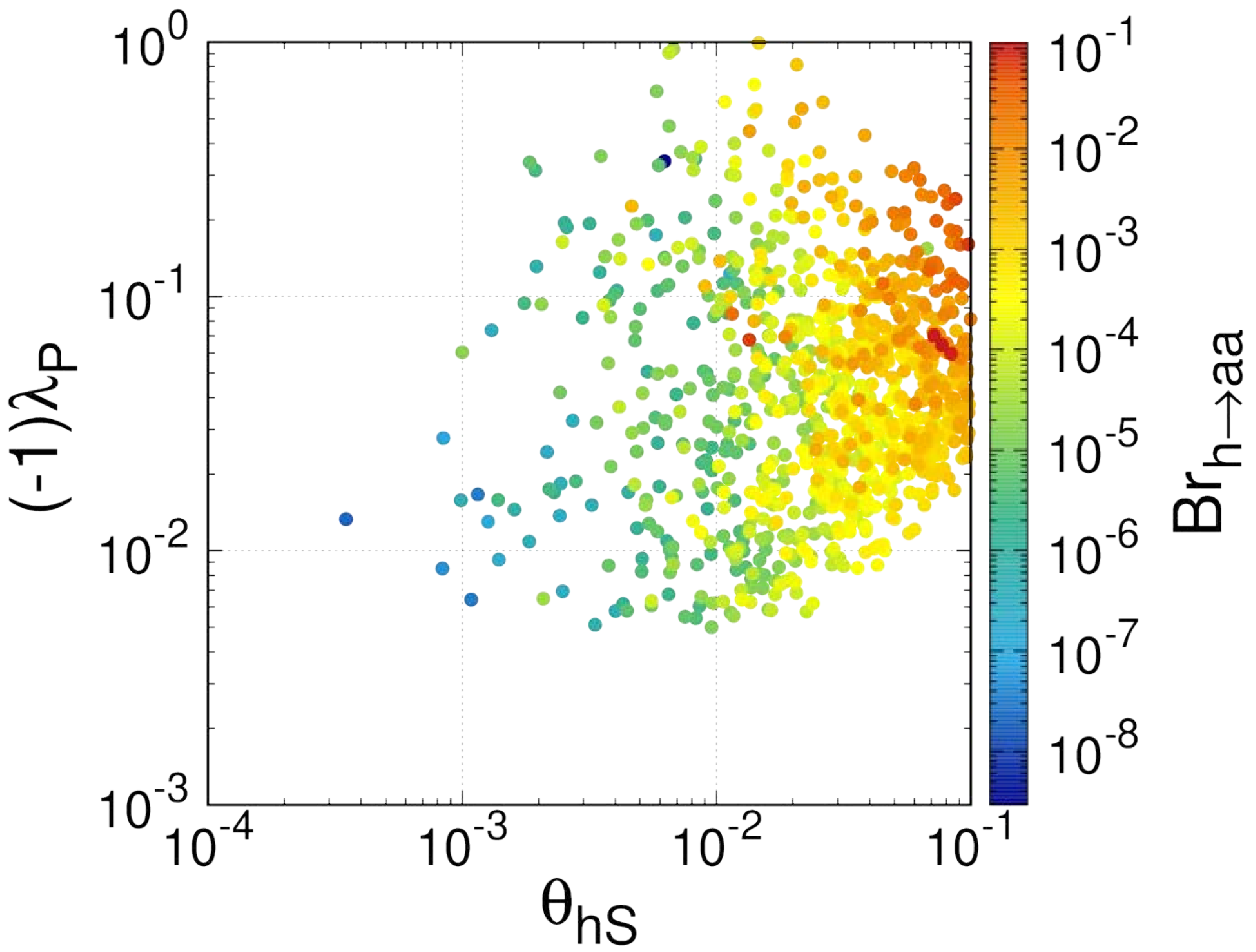
$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|\Phi|^2|H|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2.$$

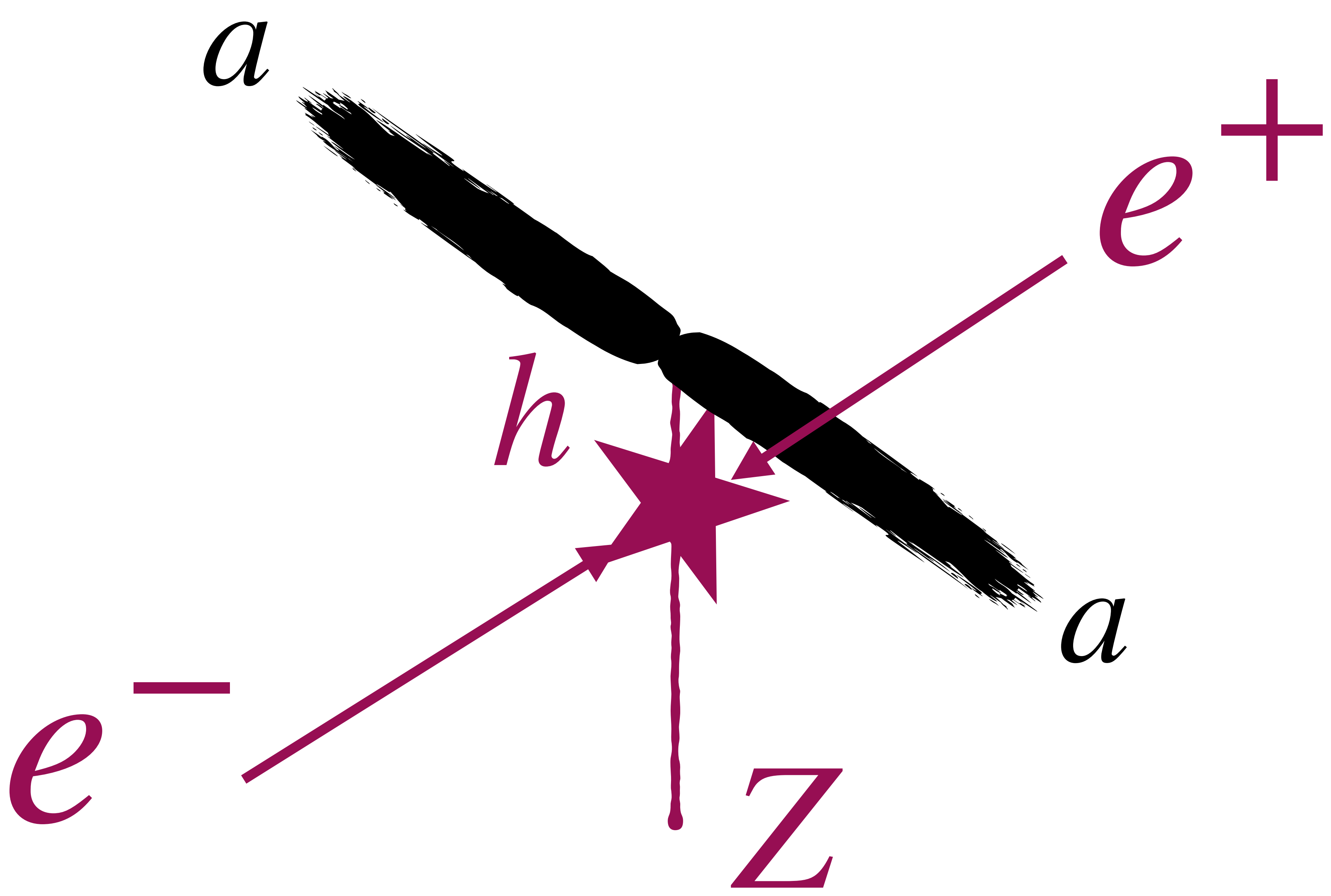
Higgs portal coupling

Φ: U(1) Higgs field

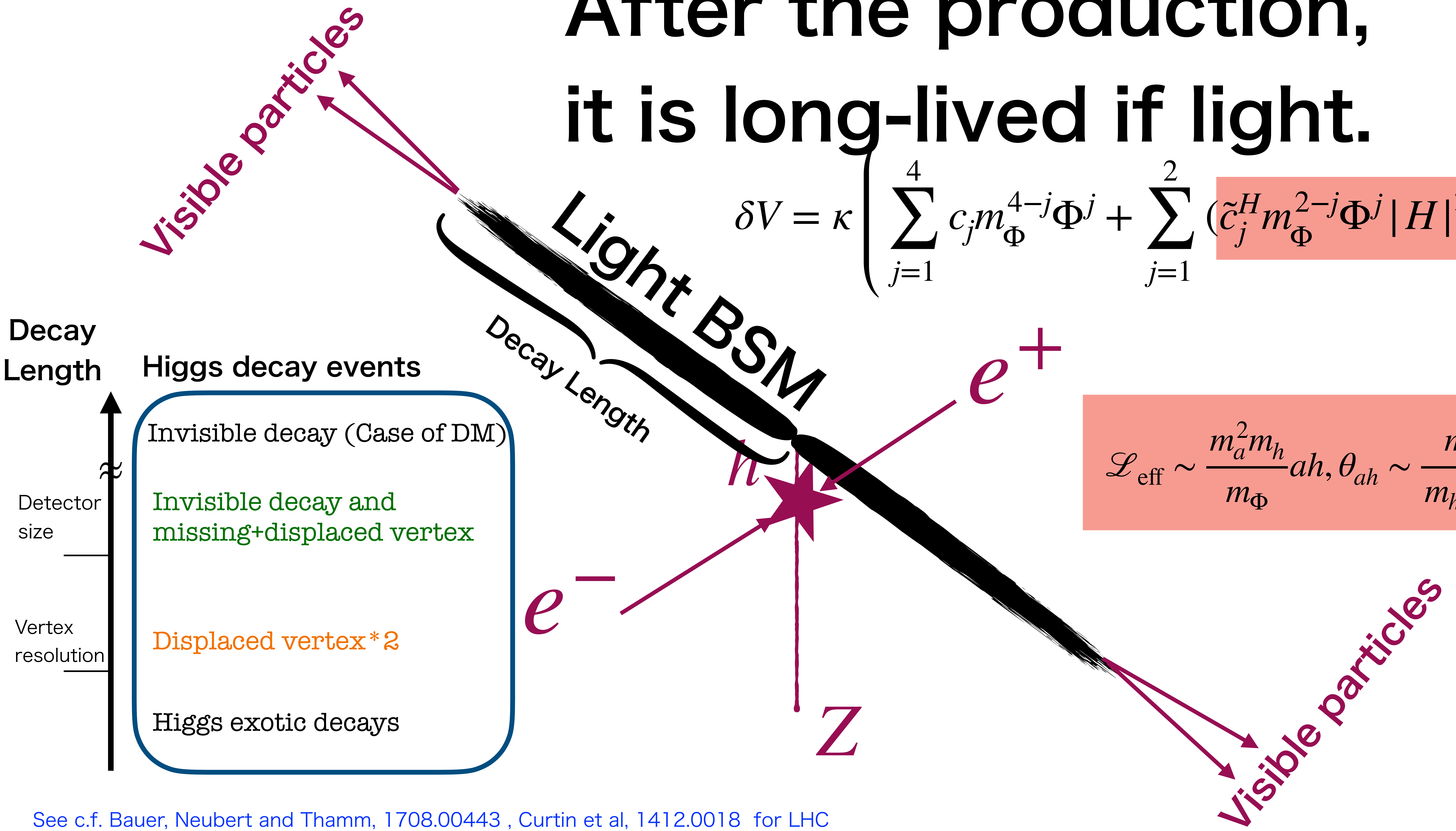
H :SM Higgs doublet

Production from Higgs decay





After the production, it is long-lived if light.



$$\delta V = \kappa \left\{ \sum_{j=1}^{4} c_j m_\Phi^{4-j} \Phi^j + \sum_{j=1}^{2} \left(\tilde{c}_j^H m_\Phi^{2-j} \Phi^j |H|^2 + \right. \right.$$

$$\mathcal{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} a h, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$

Decay Length

Higgs decay events

Invisible decay (Case of DM)

≈

Detector size

Invisible decay and missing+displaced vertex

Vertex resolution

Displaced vertex*2

Higgs exotic decays

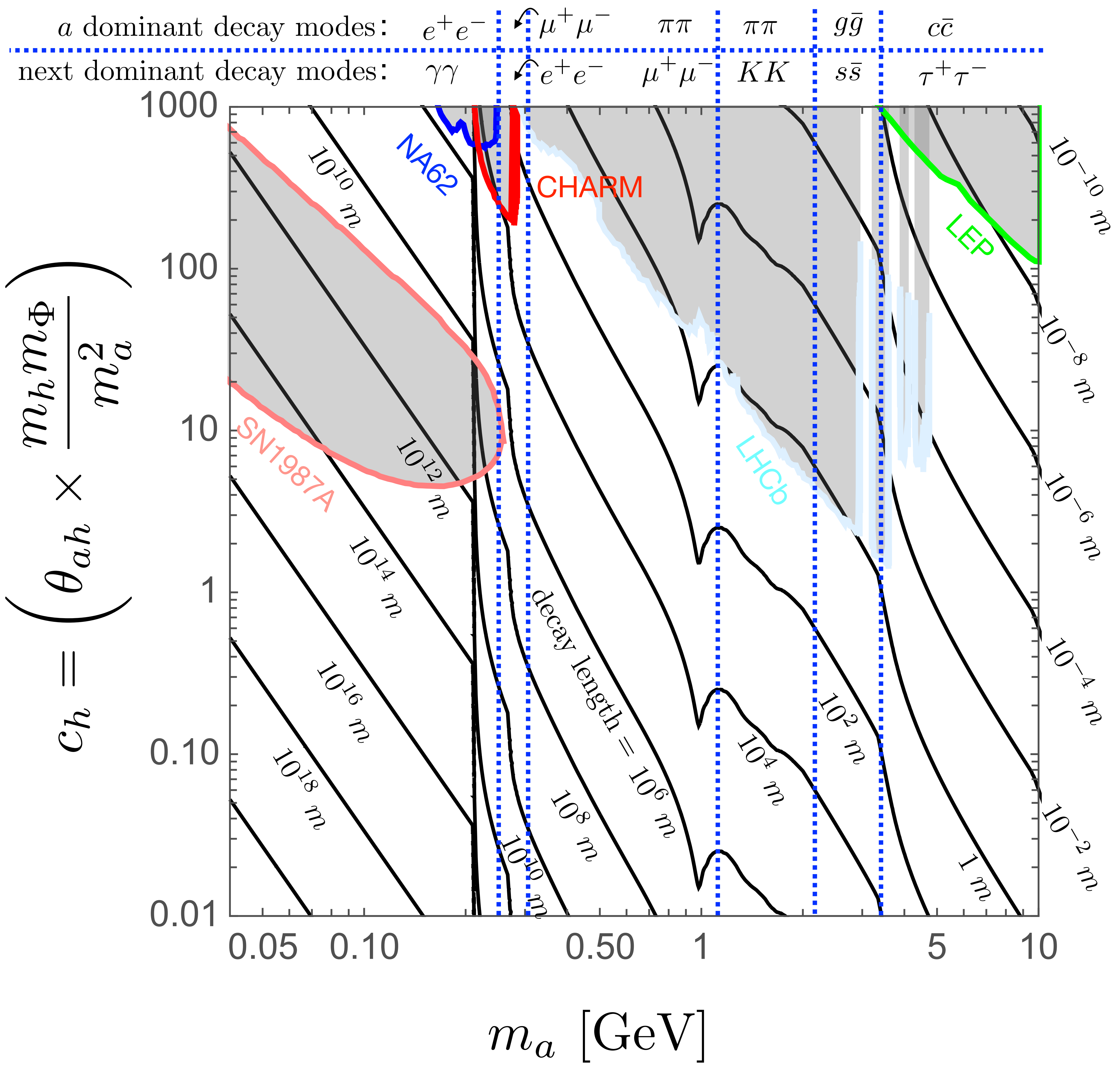
See c.f. Bauer, Neubert and Thamm, 1708.00443 , Curtin et al, 1412.0018 for LHC

Probing CP-even ALP at e.g. ILC 250GeV

Decay length and product of a from Higgs decay and signature at ILC

Kodai Sakurai, WY 2111.03653

$$\mathcal{L}_{\rm eff} \sim \frac{m_a^2 m_h}{m_\Phi} ah, \theta_{ah} \sim \frac{m_a^2}{m_h m_\Phi}$$



See also Bhattacherjee et al 2111.02437 for hadron collider reach of CP-even light mediator

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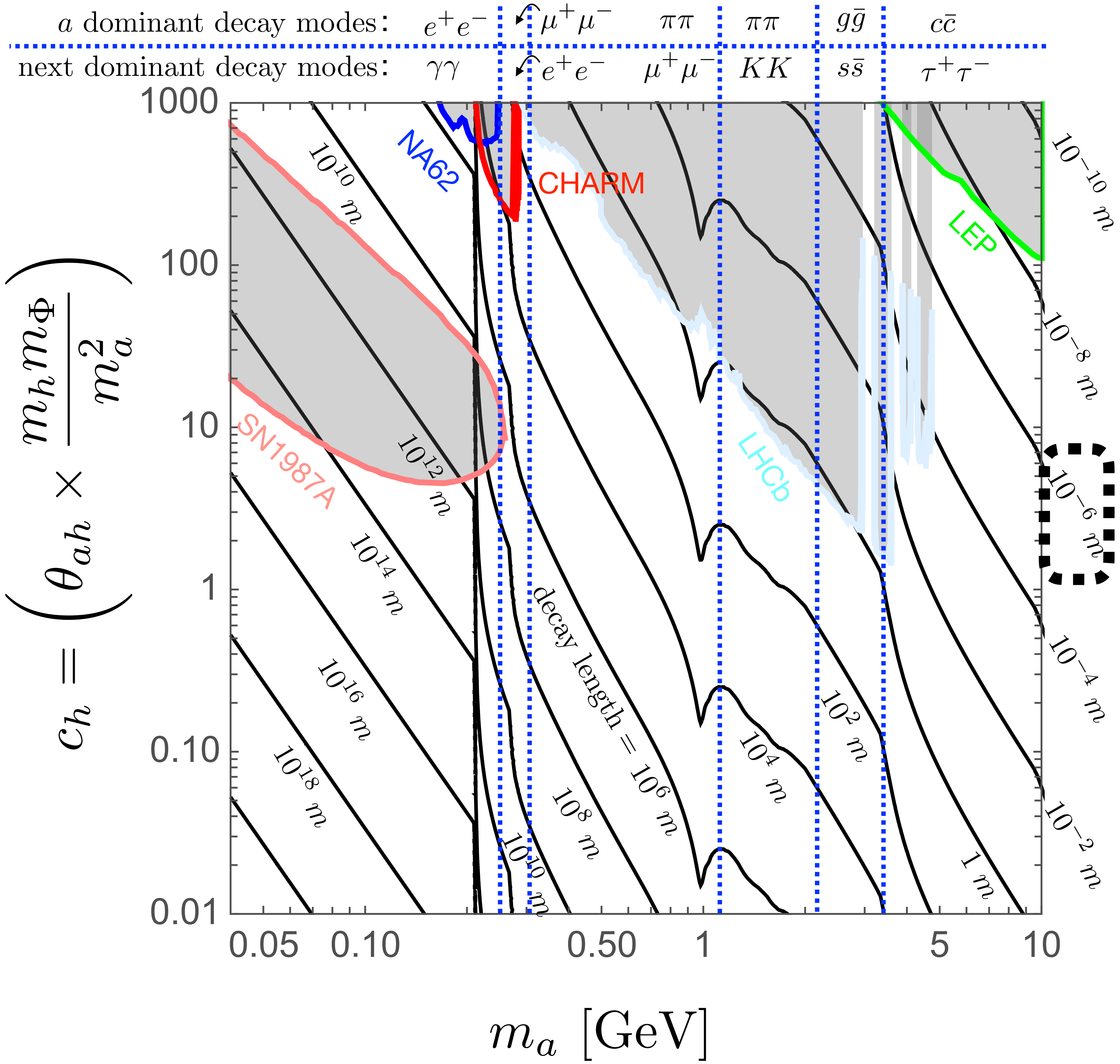

Vertex resolution

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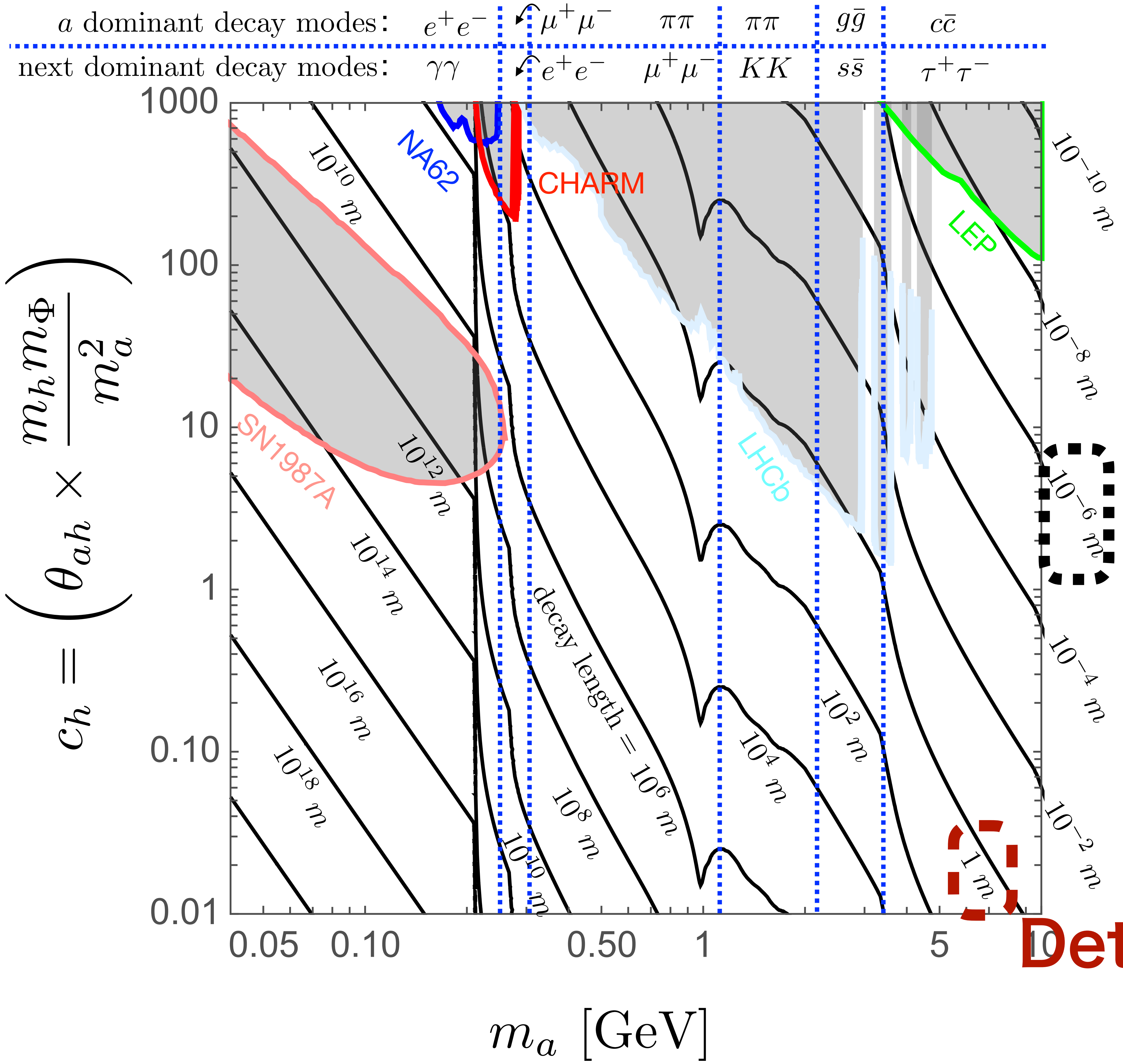

Vertex resolution

Detector size (TPC)

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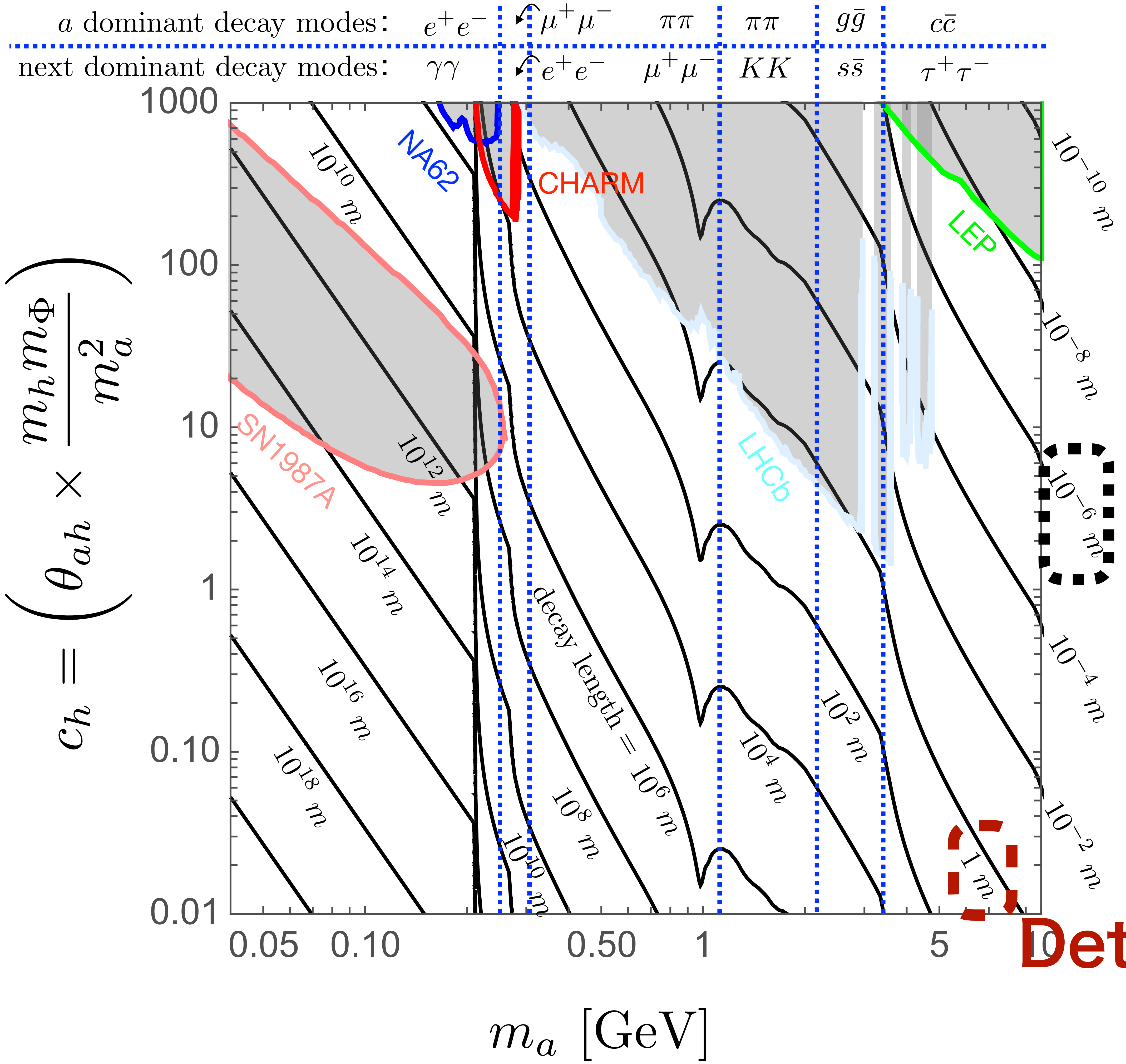

Higgs exotic decay

Vertex resolution

Detector size (TPC)

$$Br_{h\to aa(\to c\bar c c\bar c)} \gtrsim 10^{-3}\ (2\sigma\text{CL},2\ \text{ab}^{-1})$$

Liu et al, 1612.09284

See also Bhattacherjee et al 2111.02437 for hadron collider reach of CP-even light mediator

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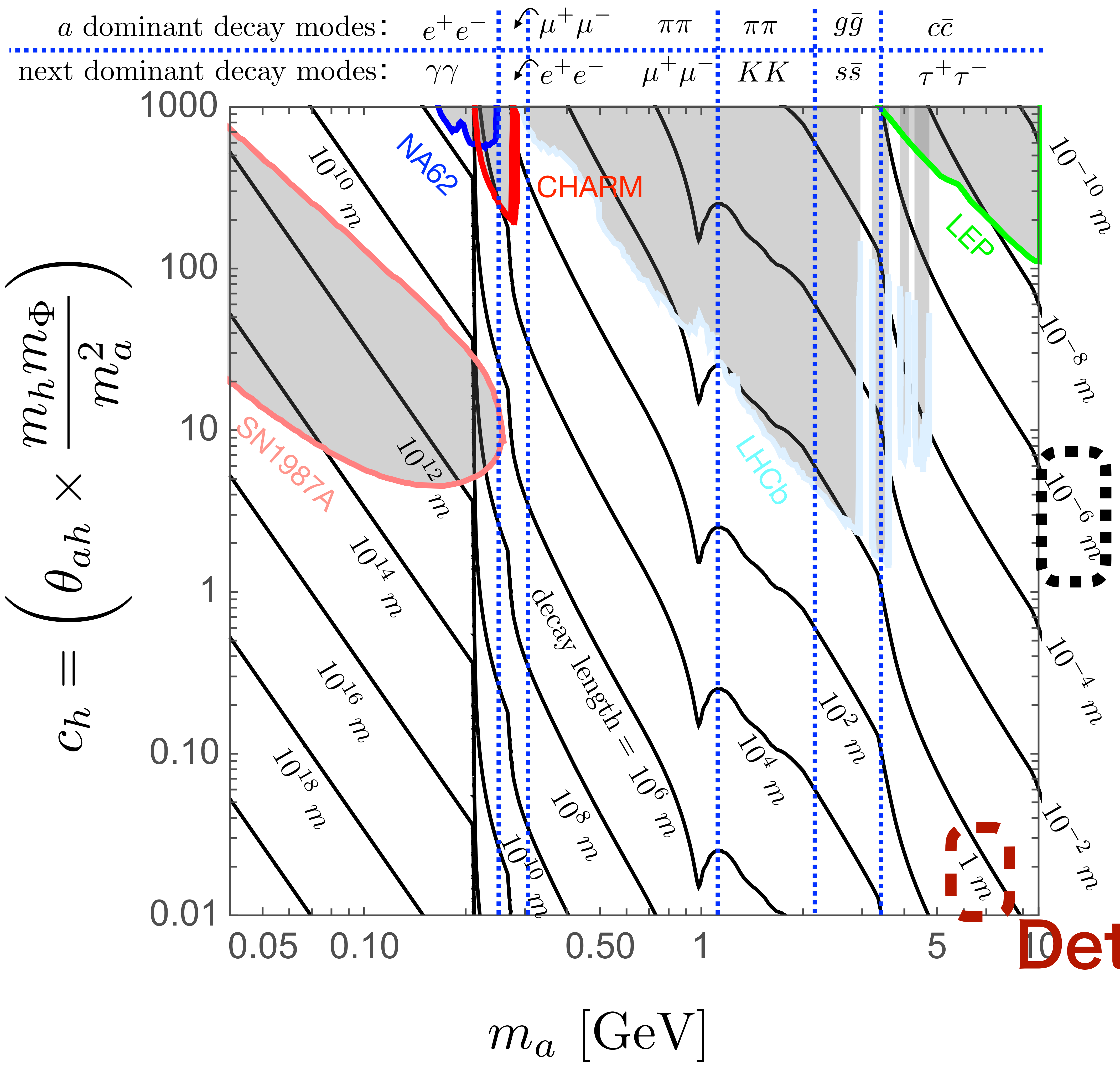

Vertex resolution

Detector size (TPC)

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Displaced vertex ×2

$$Br_{h\to aa} > 10^{-6},$$
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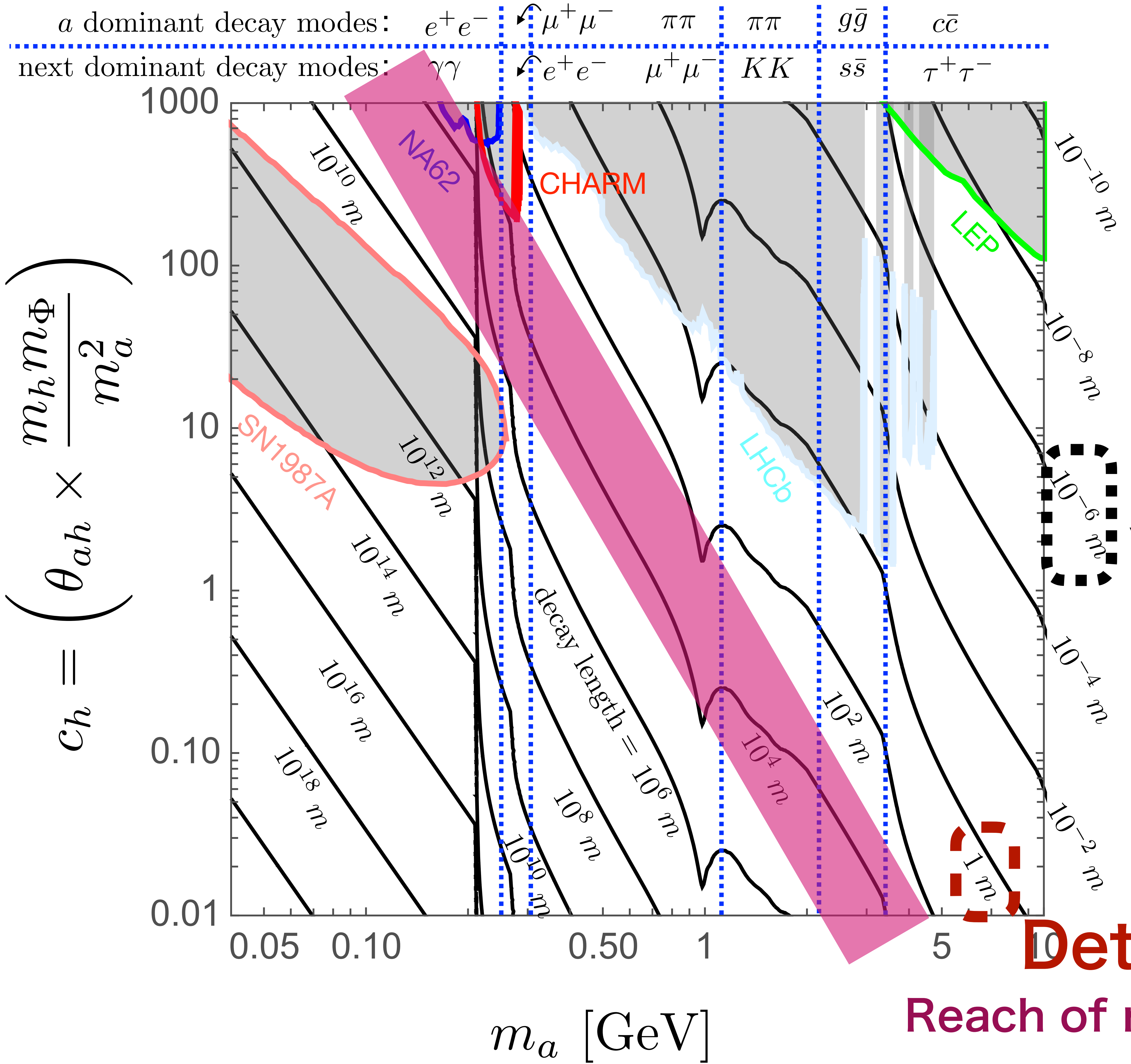

Higgs exotic decay

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Displaced vertex $\times 2$

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Detector size (TPC)

Reach of rare displaced vertex ($Br_{h\to aa} \sim 1\,\%$, 3ab^(-1))

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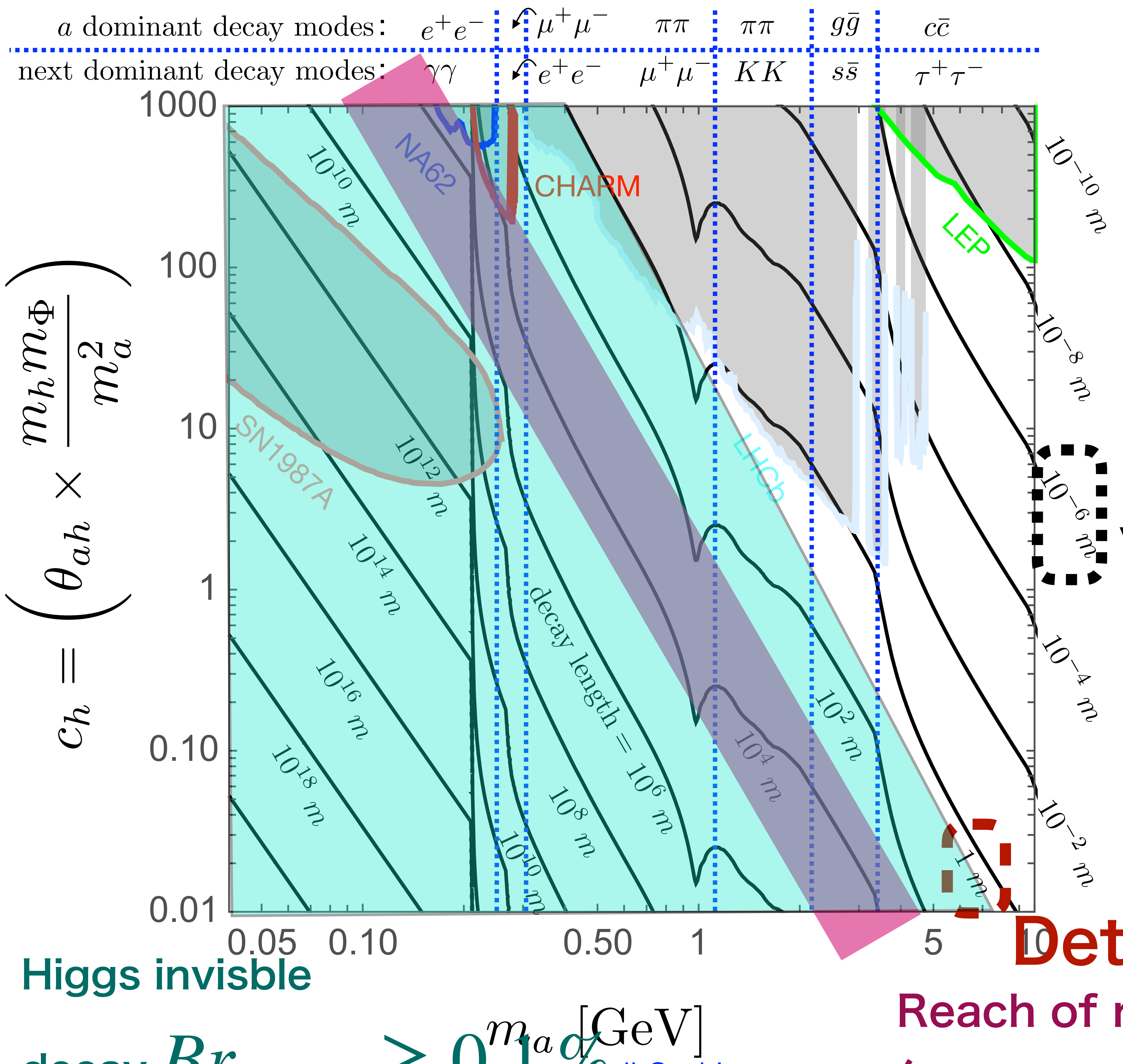

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Displaced vertex ×2

$$Br_{h\to aa} > 10^{-6},\ (2\sigma{\rm CL}, 3\ {\rm ab}^{-1})$$

See also Bhattacherjee et al 2111.02437 for hadron collider reach of CP-even light mediator

Higgs invisible decay $Br_{h\to aa} \gtrsim 0.1\,\%$ ILC whitepaper

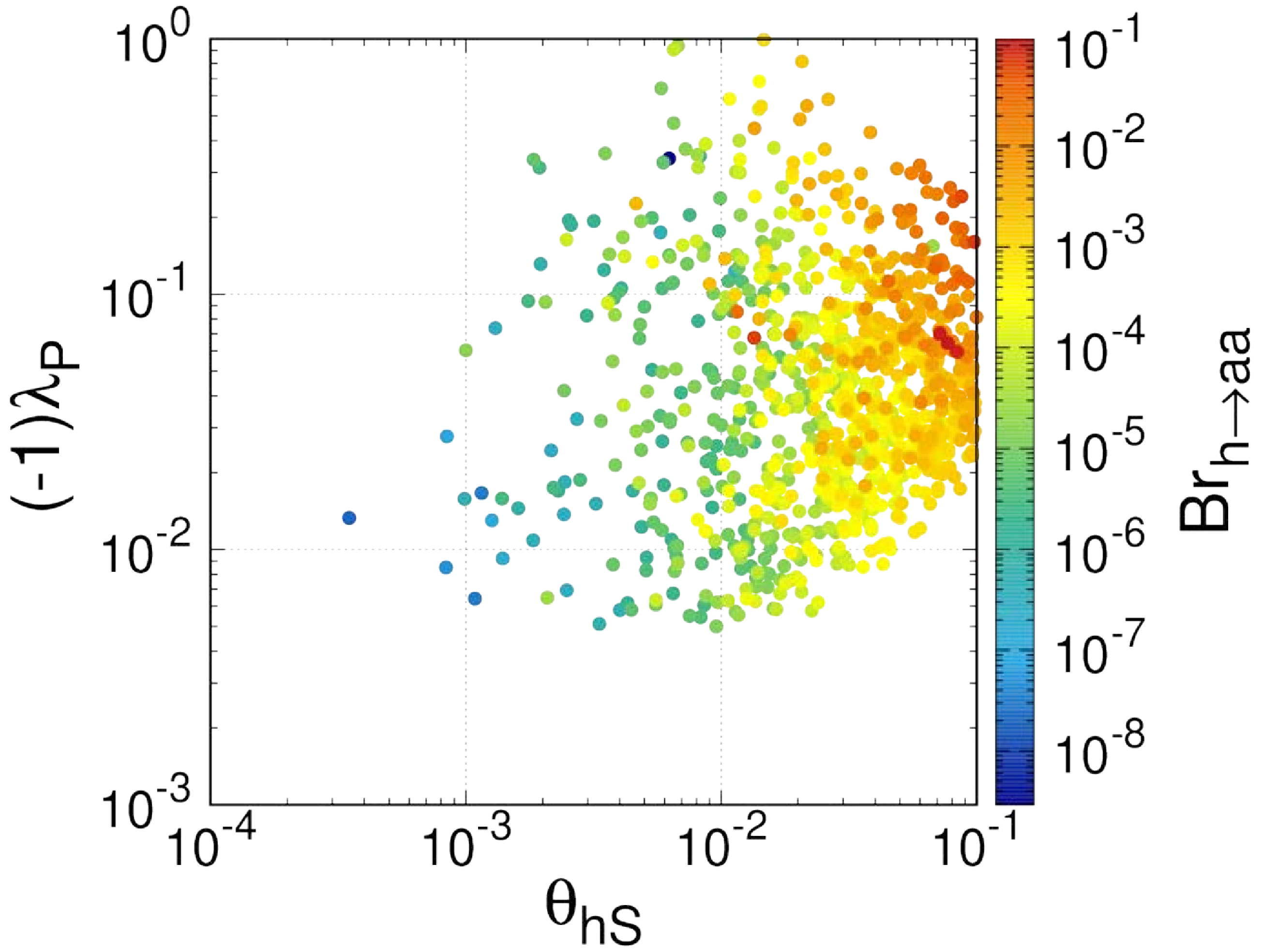
Detector size (TPC)

Reach of rare displaced vertex ($Br_{h\to aa} \sim 1\,\%$, 3ab^(-1))

Probing CP-even ALP at e.g. ILC 250GeV

Decay length and product of a from Higgs decay and signature at ILC

Kodai Sakurai, WY 2111.03653



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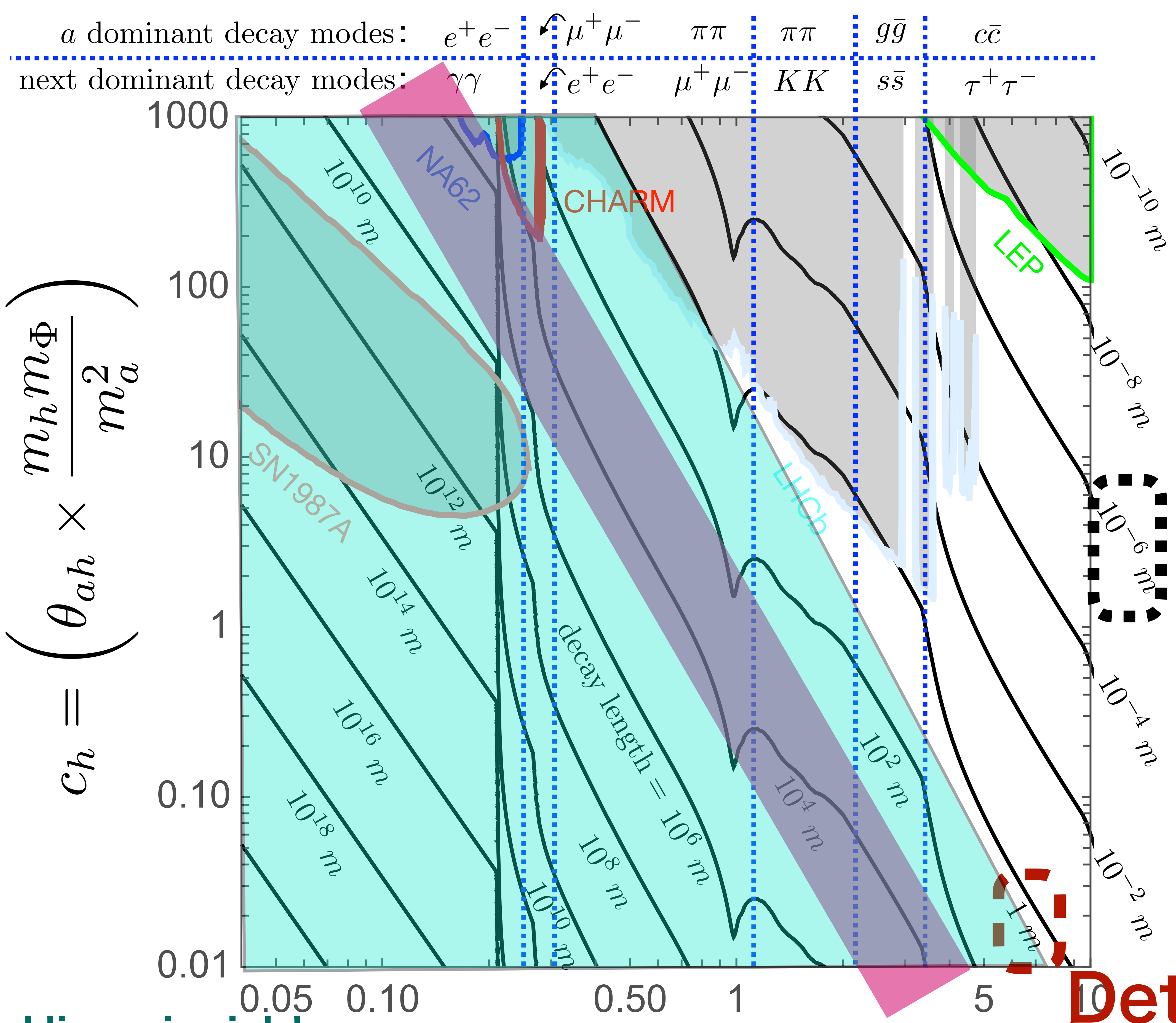

Higgs exotic decay

Vertex resolution

Displaced vertex $\times 2$

$$Br_{h\to aa} \gtrsim 10^{-6},$$
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Detector size (TPC)

Reach of rare displaced vertex

($Br_{h\to aa} \sim 1\,\%$, 3ab^(-1))

Higgs invisible decay $Br_{h\to aa} \gtrsim 0.1\,\%$ ILC whitepaper

What roles does CP-even ALP play in the early Universe?

- Light mediator to DM with $\mathscr{L} \supset \Phi \bar{\Psi}^c_{\mathrm{DM}} \Psi_{\mathrm{DM}}$.

ALP couples SM fermion weakly but strongly with DM, which is the desired property of a light mediator.

Please study it with WIMP, which should be an interesting topic!

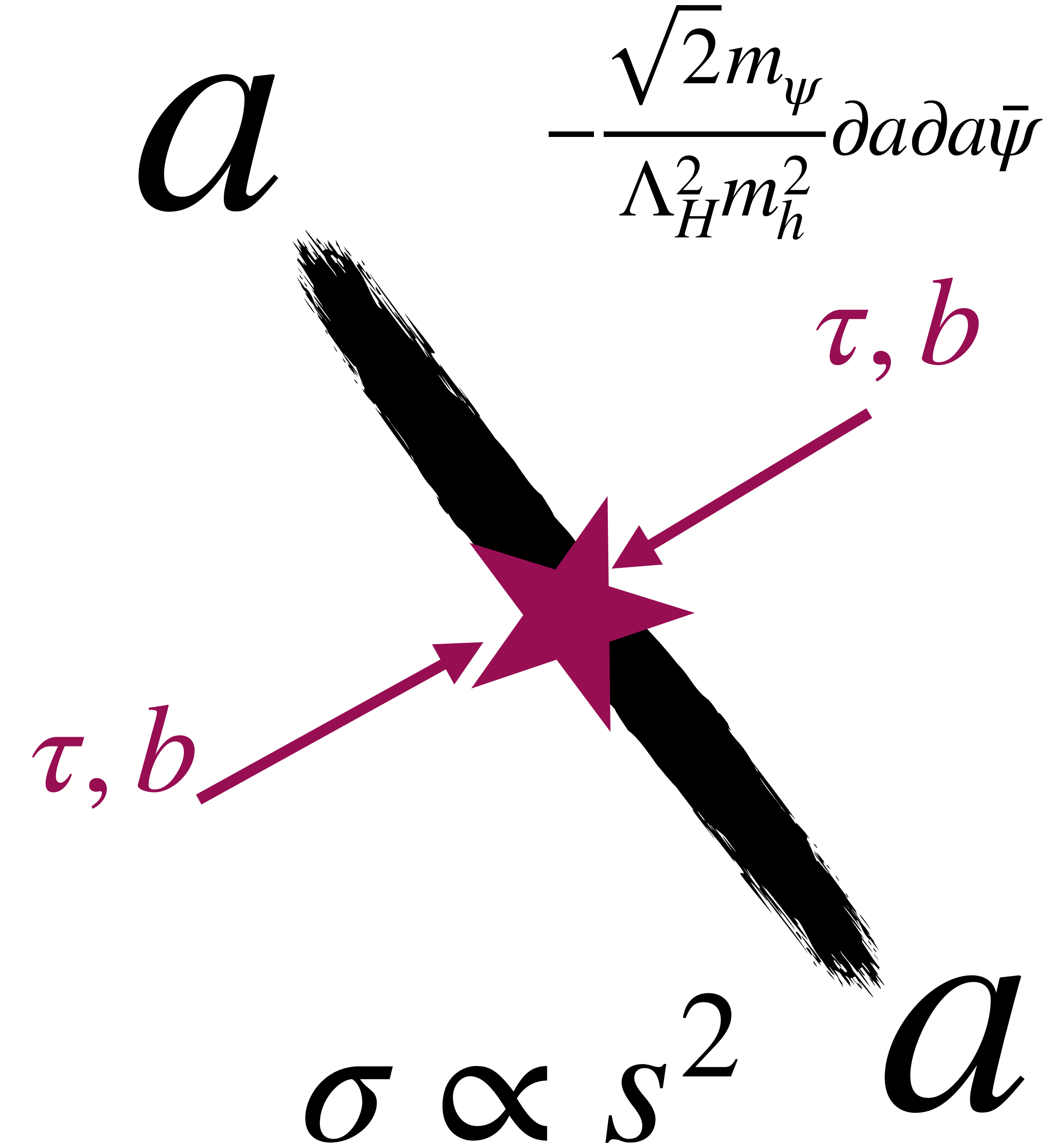
- **CP-even ALP DM.** This talk.

CP-even ALP is a good DM candidate if it is lighter than MeV.

$$\Gamma_{a\to\gamma\gamma} \sim 10^{-4} \frac{m_a^3 \theta_{ah}^2}{\pi^5 v^2} \propto \frac{m_a^7}{m_h^4 m_\Phi^2}$$

Thermally produced CP-even ALP DM

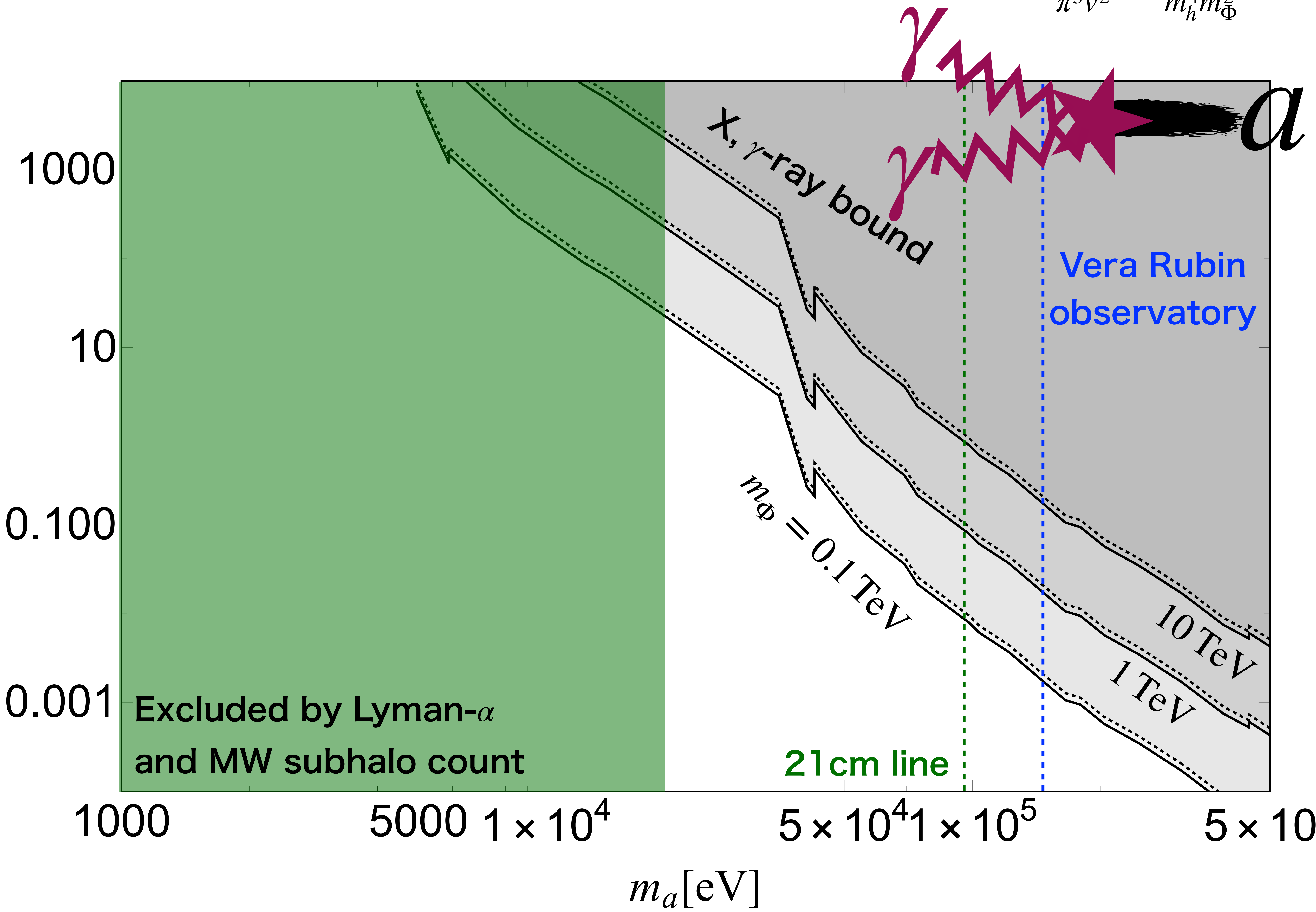
$$-\frac{\sqrt{2}m_\psi}{\Lambda_H^2 m_h^2}\partial a \partial a \bar{\psi}\psi .$$



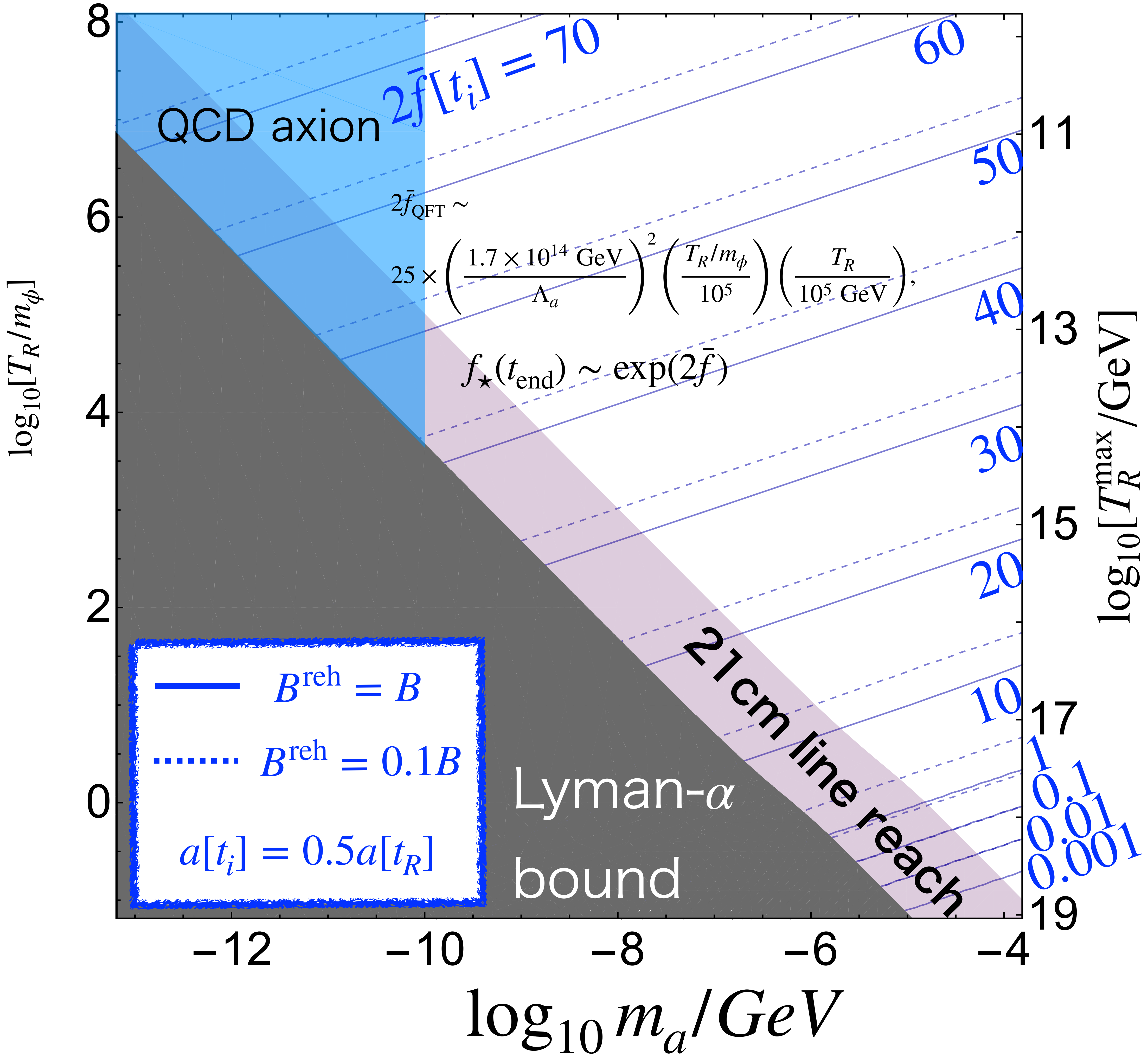
$$\sigma \propto s^2$$

$$\Omega_a \sim 0.35\frac{m_a}{20\mathrm{keV}}\left(\frac{m_\psi}{\mathrm{GeV}}\right)^2\left(\frac{T_R}{2\mathrm{GeV}}\right)^5\left(\frac{3\mathrm{TeV}}{\Lambda_H}\right)^4$$

$$\Gamma_{a\to\gamma\gamma} \sim 10^{-4}\frac{m_a^3\theta_{ah}^2}{\pi^5 v^2} \propto \frac{m_a^7}{m_h^4 m_\Phi^2}$$



Non-thermal production scenario: lighter mass range.



Light bosonic DM can be produced during reheating if $T_R > m_{inflaton}$ as laser.

Moroi, WY, 2011.09475, 2011.12285

$$\mathcal{L}_{\mathrm{int}} = \frac{\phi}{\Lambda_a}\partial_\mu a \partial^\mu a + \frac{\phi}{\Lambda_G} G^{(a)}_{\mu\nu} G^{(a)\mu\nu}$$

For CP-even ALP, we need $T_R \ll m_\Phi$ for the produced ALP not to be thermalized.

Probed by inflaton search, 21cm line.

There naturally exists the portal coupling between Φ and H.

$$V = -m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \lambda_P|\Phi|^2|H|^2 + \lambda_H|H|^4 - \mu_H^2|H|^2 .$$

Higgs portal coupling

Φ: U(1) Higgs field

H :SM Higgs doublet

$$\Gamma_{h\to aa} \simeq \frac{1}{16\pi}\frac{v^2 m_h^3}{\Lambda_H^4} .$$

$$\mathrm{Br}_{h\to aa} = 30\,\%\left(\frac{1\mathrm{TeV}}{\Lambda_H}\right)^4$$

$$\frac{1}{\Lambda_H^2} \equiv \frac{\lambda_P}{m_\Phi^2} .$$