Light mass window of inert doublet dark matter with lepton portal interaction

Yuji Omura (Kindai Univ.)

Based on
PRD109(2024)7,075007 (arXiv: 2310.13685)
with Ryo Higuchi (Kindai U.), Syuhei Iguro (KMI) and Shohei Okawa (KEK)

Reference
JHEP03(2023)010 (arXiv: 2208.05487) with Syuhei Iguro and Shohei Okawa (KEK);
JHEP02(2021)231 (arXiv: 2011.04788) with Shohei Okawa;
JHEP08(2020)042 (arXiv: 2002.12534) with Junichiro Kawamura (IBS) and Shohei Okawa

Introduction

Contents

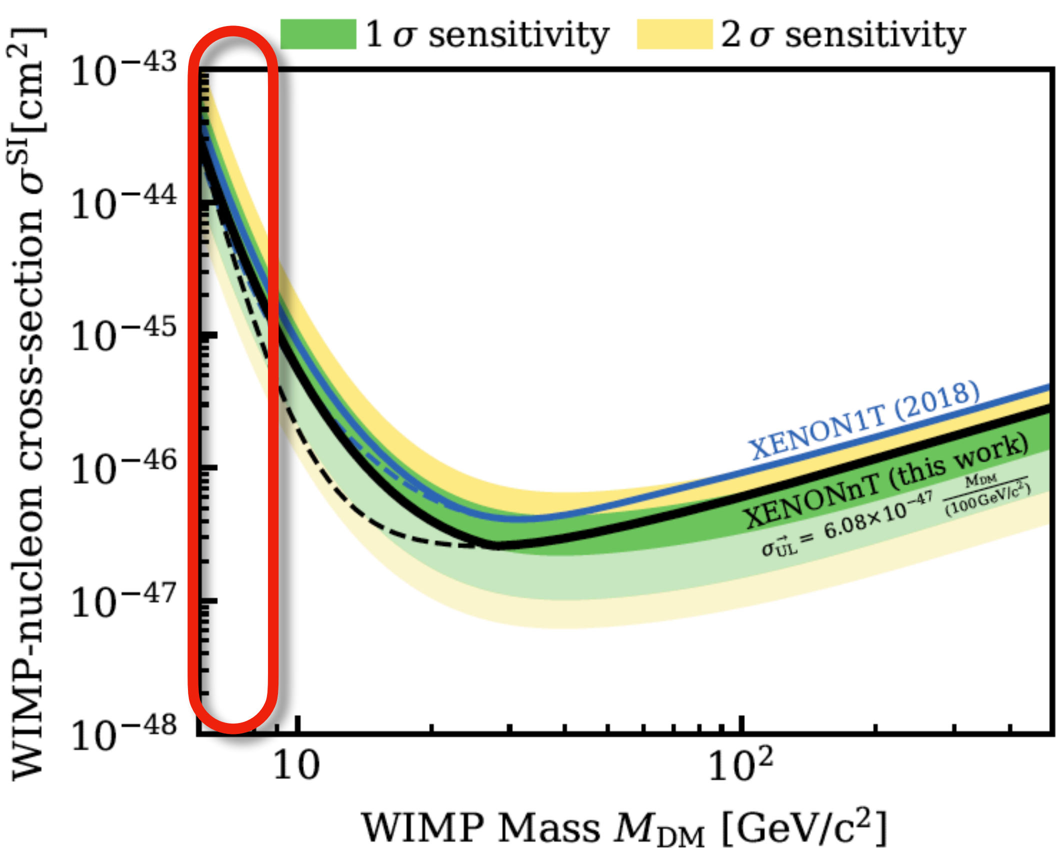
discuss <u>models with light thermal DM,</u>

Motivation

avoid the very strong constraints from the DM direct detection experiments.

$$m_{\rm DM} \lesssim 10{\rm GeV}$$

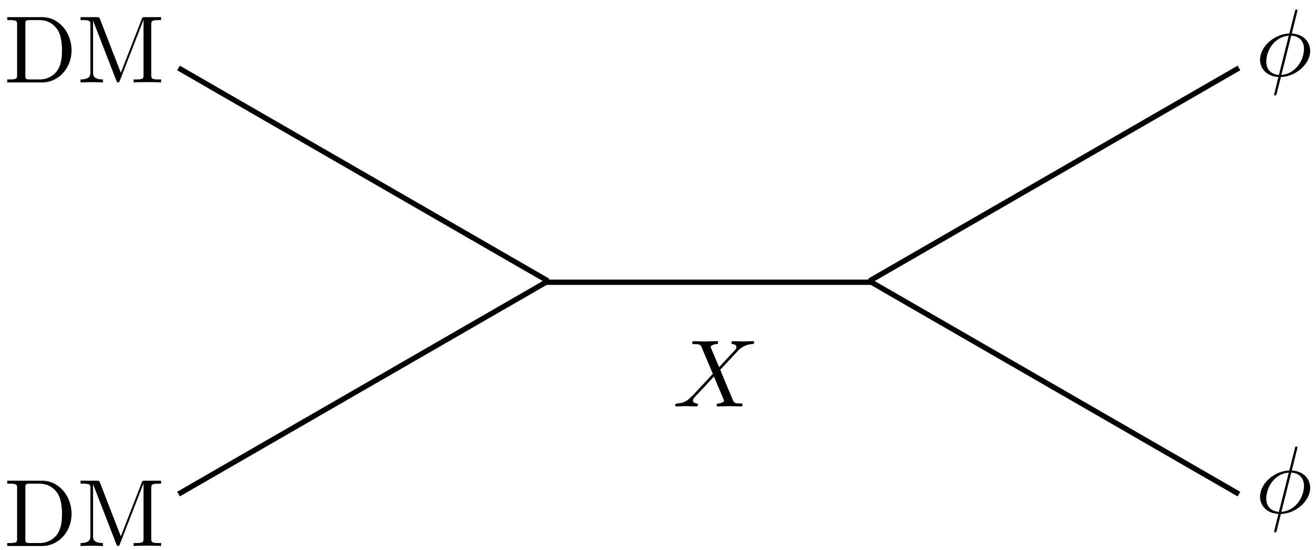
2303.14729, XENONnT

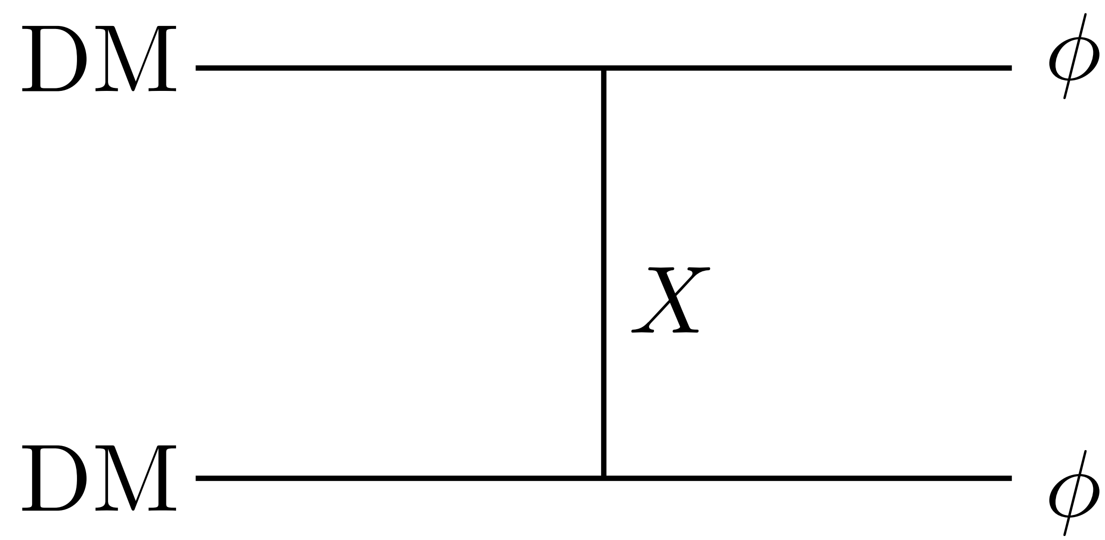


Comparison with previous research

Light thermal DM scenarios have been proposed in many papers.

YO, Gondolo, P.Ko, '12; Alvarado,et al.,'21; Herms,et al., '22; Asai,et al.,'21; Matsumoto,et al.,'19;Longas,et al.,'24; etc.





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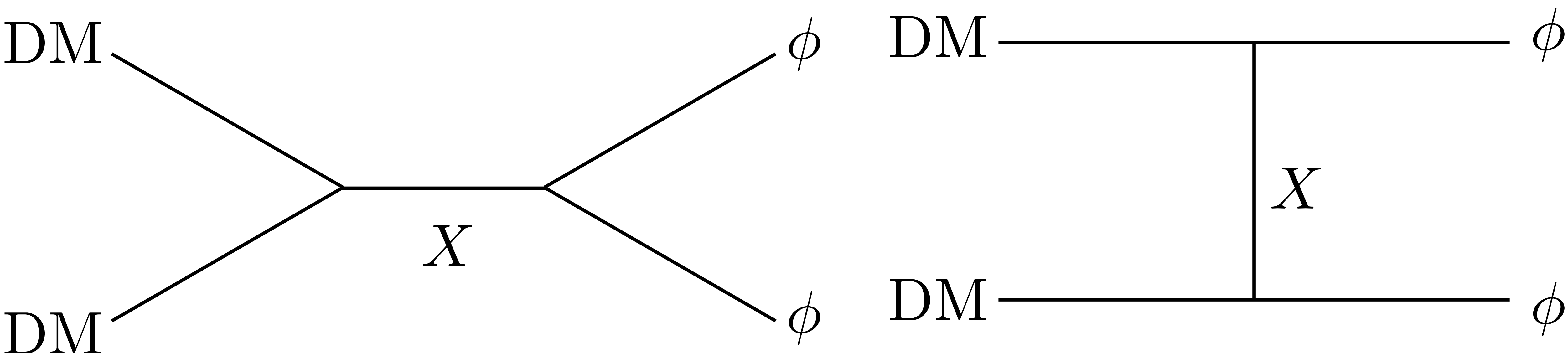

Light new particles, in addition to DM, are (usually) predicted, to realize the annihilation.

ϕ : light quarks, light leptons, **light new particles**

X : **light Z', light new scalar, light new fermion**

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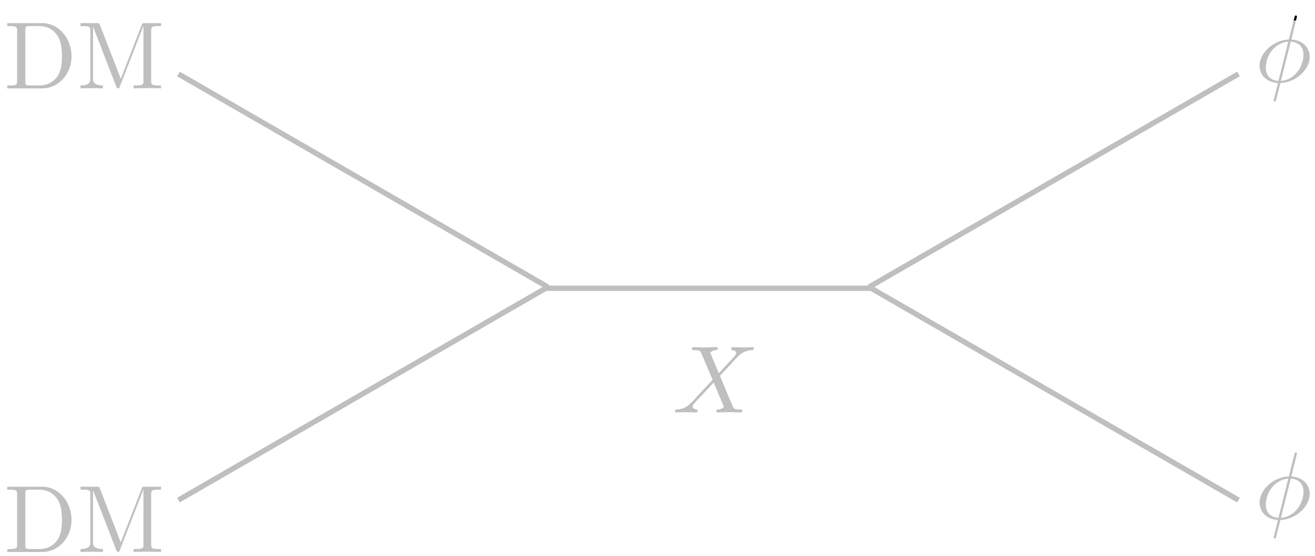

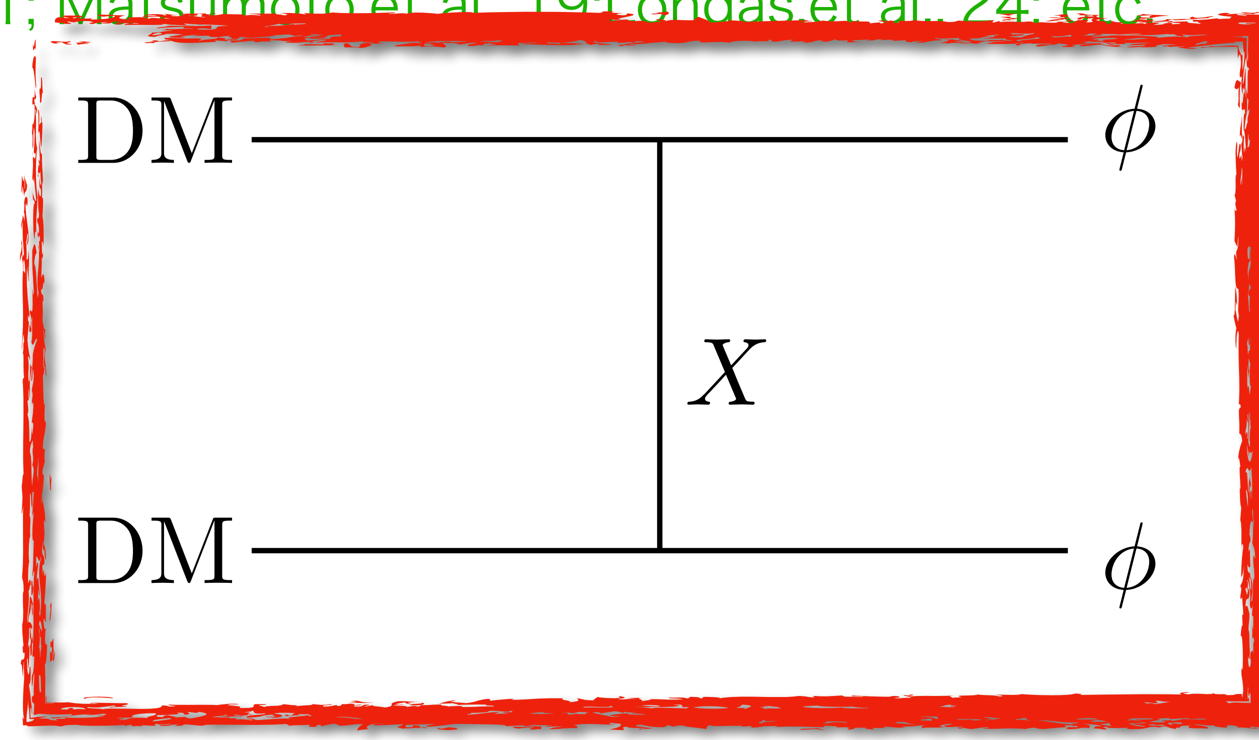

Light new particles, in addition to DM, are (usually) predicted, to realize the annihilation.

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X : **light Z', light new scalar, light new fermion**

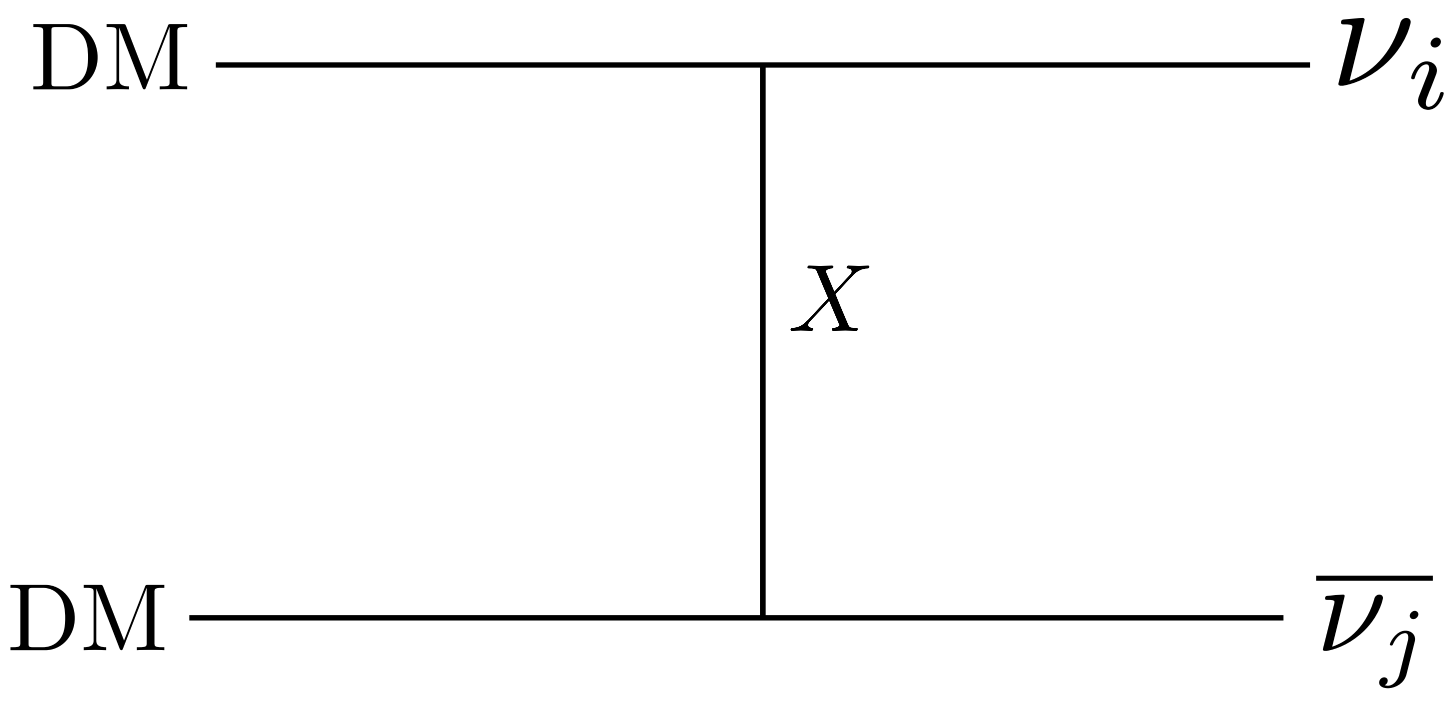
in this talk

Contents

- Setup of models with light scalar DM
- Phenomenology
    - DM physics
    - Signals at the LHC
    - Results
- Summary

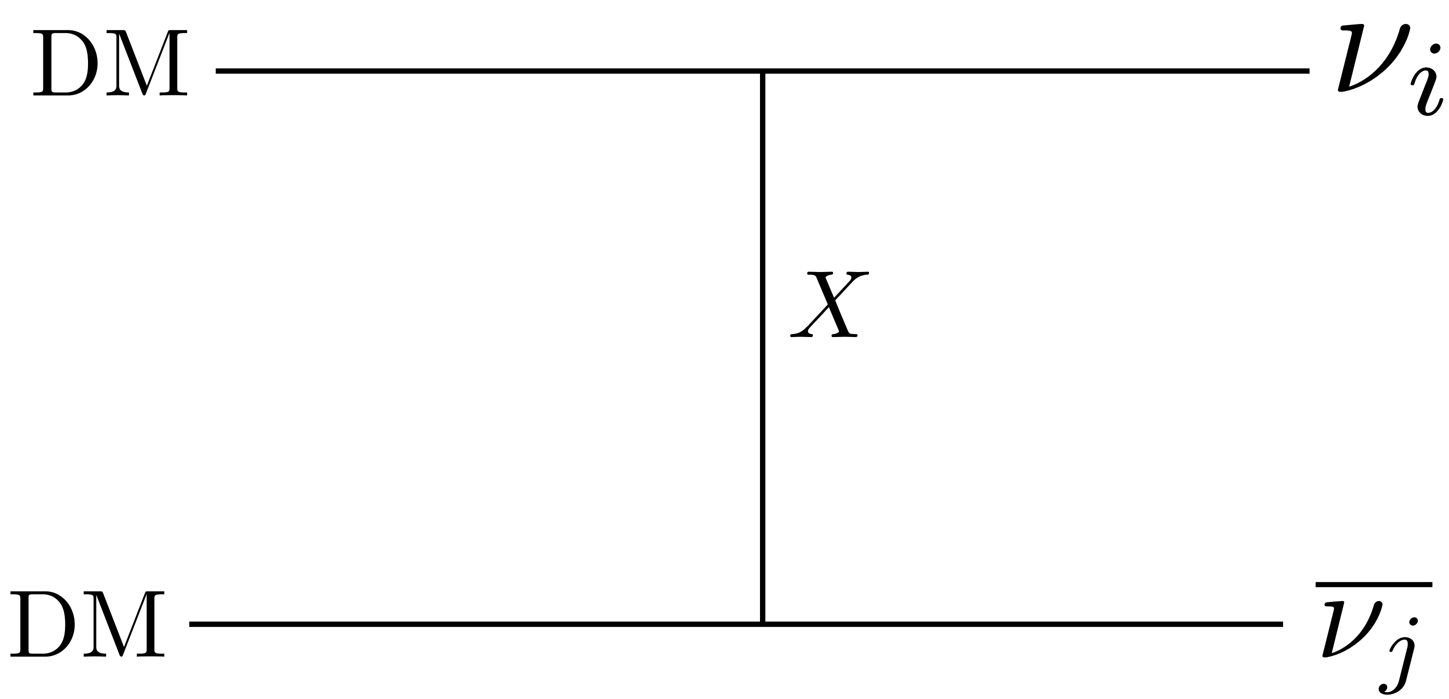
Setup
of
light thermal DM models

construct models where DM DM $\rightarrow \nu \;\; \nu$,



is enough large to thermally produce DM.

construct models where DM DM $\rightarrow \nu \ \nu$,



is enough large to thermally produce DM.

Required Yukawa couplings,

$$y_\nu^i \, \overline{\nu_i} X \chi_{\rm DM}$$

Matter content

	Fields	spin	$SU(3)$	$SU(2)_L$	$U(1)_Y$	Lepton num. $U(1)_L$	stabilize DM Z_2
	Q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0	$+$
	u_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	0	$+$
	d_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	0	$+$
	ℓ_L^i	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	1	$+$
	e_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	1	$+$
extra	ψ_L	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	1	$-$
extra	ψ_R	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	1	$-$
	Φ	1	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	$+$
extra	Φ_ν	1	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	$-$

ψ and neutral component of Φ_ν are good DM candidates.

to avoid too large neutrino masses radiatively induced.

The charge assignment allows this Yukawa couplings

$$-\mathcal{L}_\ell = y_\nu^i \, \overline{\ell_L^i} \, \widetilde{\Phi_\nu} \, \psi_R + h.c.$$

$\langle\Phi_\nu\rangle$ is vanishing, and decomposed as

$$\Phi_\nu = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

After EWSB ➡

$$-\mathcal{L}_\ell = y_\nu^i \left[\frac{1}{\sqrt{2}} \overline{\nu_L^i} (H - iA) \psi_R - \overline{e_L^i} H^- \psi_R \right] + h.c.$$

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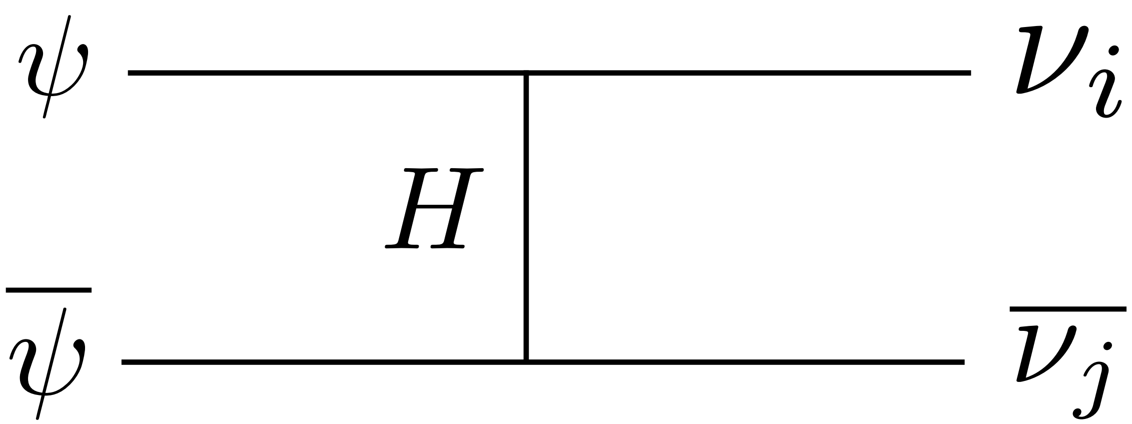
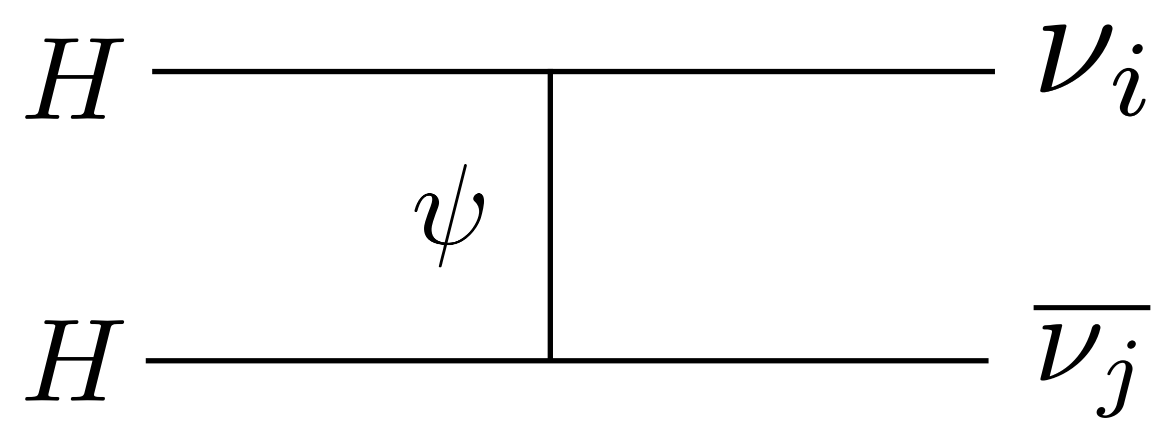
Then, we obtain the annihilation



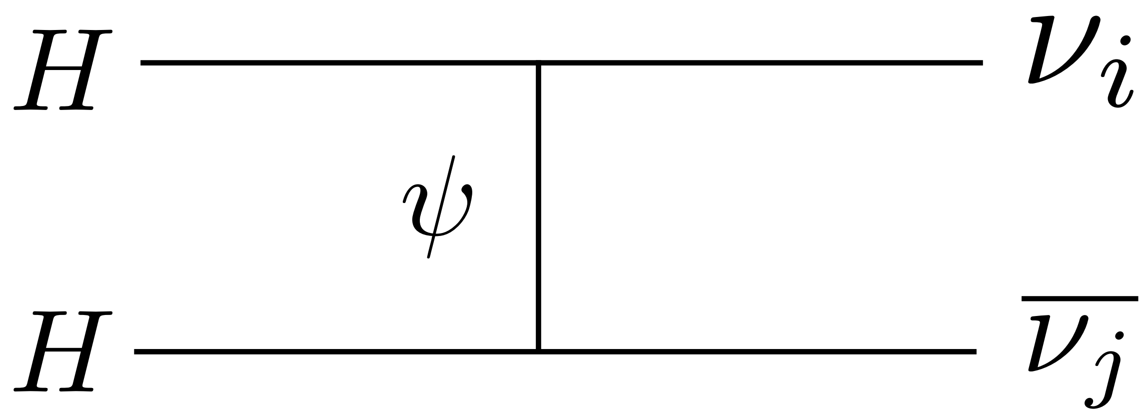


Phenomenology

DM candidate and the annihilation

I consider the case that H is DM. This is similar to Inert doublet DM.

The annihilation precess, in addition to the EW int., is



$$(\sigma v_{\rm rel})_{HH\to\nu_i\bar{\nu}_i} \simeq \frac{(y_\nu^i/\sqrt{2})^4 m_H^6}{60\pi(m_H^2+m_\psi^2)^4} v_{\rm rel}^4$$

masses <10GeV

To obtain the relic density,

- large Yukawa couplings are required (compared with ψ DM case.)

- $m_H \simeq m_\psi$ is also favored, making use of coannihilation processes.

Constraints on H couplings

- Large mass hierarchy is required to avoid the constraint of $H_\pm$

$$m_H \ll m_A \simeq m_{H^\pm} = \mathcal{O}(100)\,\mathrm{GeV}$$

➡ some couplings in Higgs potential should be large.

$$m_H^2 = m_{H^\pm}^2 + \frac{(\lambda_4+\lambda_5)v^2}{2}$$

should be large.

$$V = m_1^2(\Phi^\dagger\Phi) + m_2^2(\Phi_\nu^\dagger\Phi_\nu) + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2(\Phi_\nu^\dagger\Phi_\nu)^2$$
$$+ \lambda_3(\Phi^\dagger\Phi)(\Phi_\nu^\dagger\Phi_\nu) + \lambda_4(\Phi^\dagger\Phi_\nu)(\Phi_\nu^\dagger\Phi) + \frac{\lambda_5}{2}[(\Phi^\dagger\Phi_\nu)^2 + h.c.]$$

Constraints on H couplings

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$$V = m_1^2(\Phi^\dagger\Phi) + m_2^2(\Phi_\nu^\dagger\Phi_\nu) + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2(\Phi_\nu^\dagger\Phi_\nu)^2 + \lambda_3(\Phi^\dagger\Phi)(\Phi_\nu^\dagger\Phi_\nu) + \lambda_4(\Phi^\dagger\Phi_\nu)(\Phi_\nu^\dagger\Phi) + \frac{\lambda_5}{2}[(\Phi^\dagger\Phi_\nu)^2 + h.c.]$$

- Tuning parameters is needed because of constraints from invisible decay of **125 GeV Higgs** and **the EWPO**.

$$\frac{\lambda_{345}}{2}\, v\, h_{125} H^2$$

should be suppressed

$$(\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5)$$

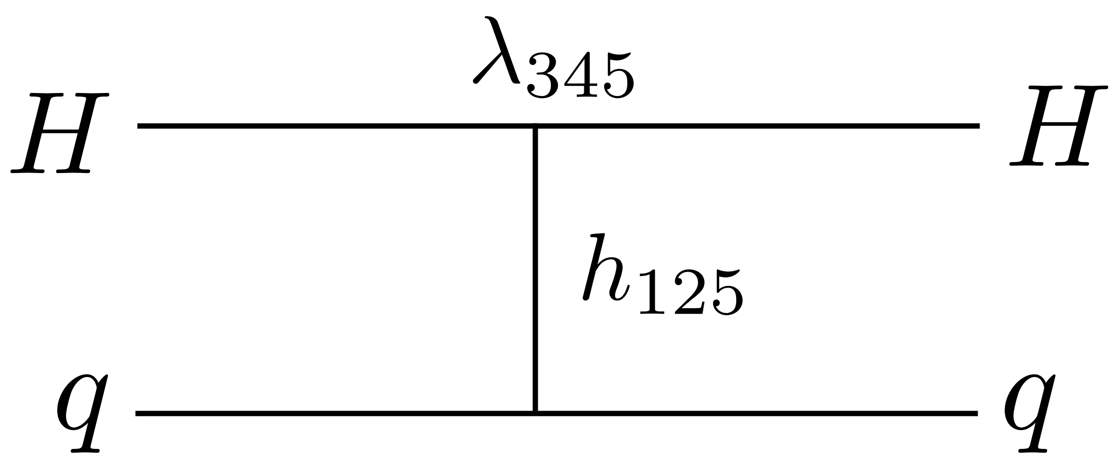
small large large

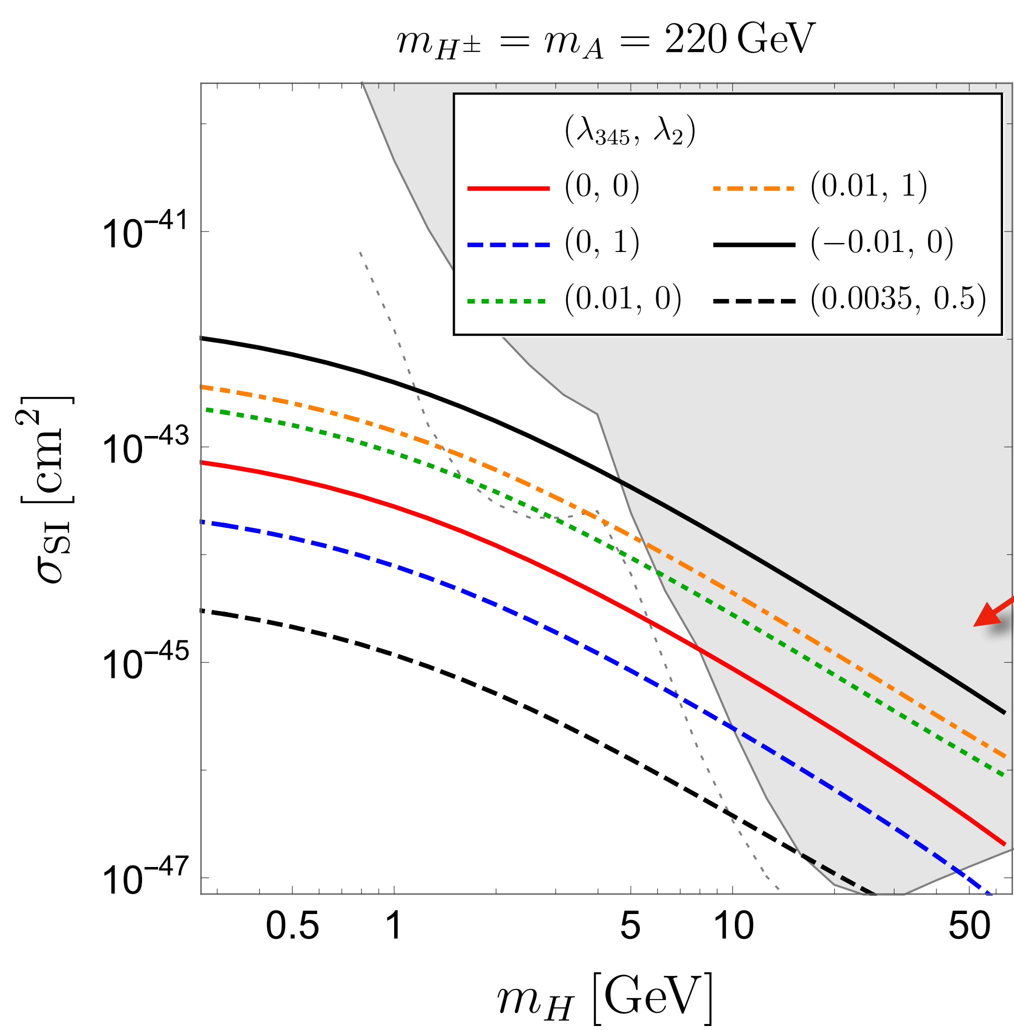
$$m_A^2 = m_{H^\pm}^2 + \frac{(\lambda_4-\lambda_5)v^2}{2}$$

should be suppressed for $m_A \simeq m_{H^\pm}$

Direct detection of H (DM)

The interaction of H with nuclei is given by 125 GeV Higgs exchange





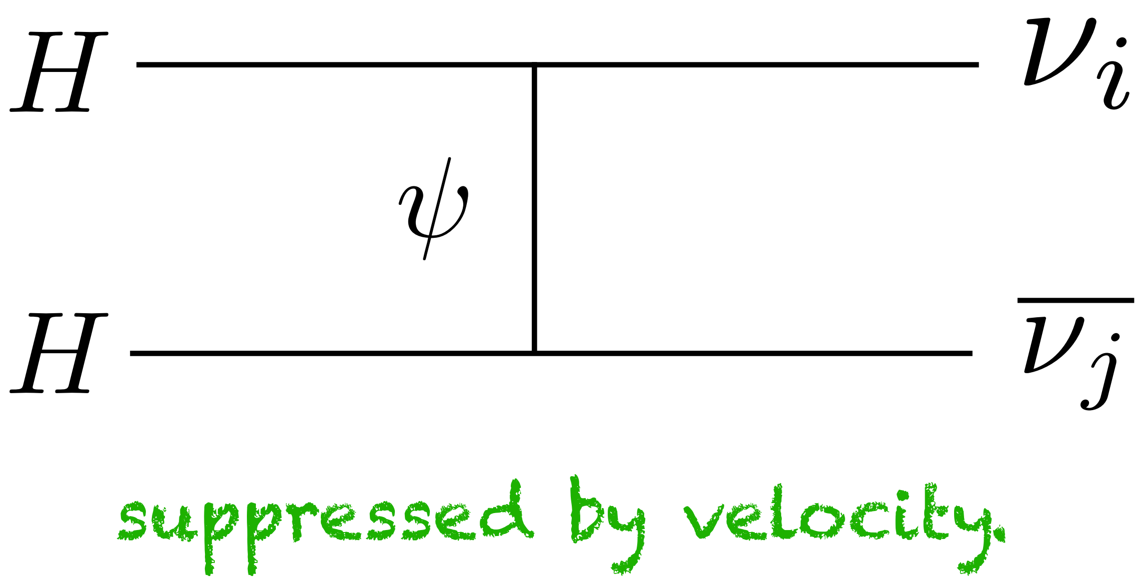
Our predictions including loop corrections. They are suppressed to be consistent with the bound from invisible Higgs decay.

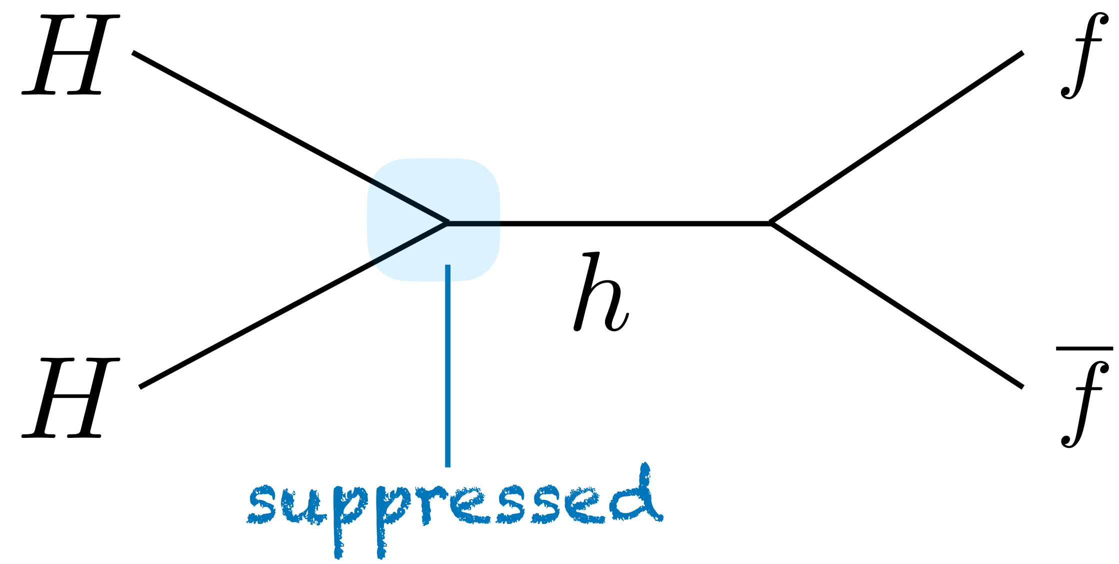
Abe,Sato,'15

R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

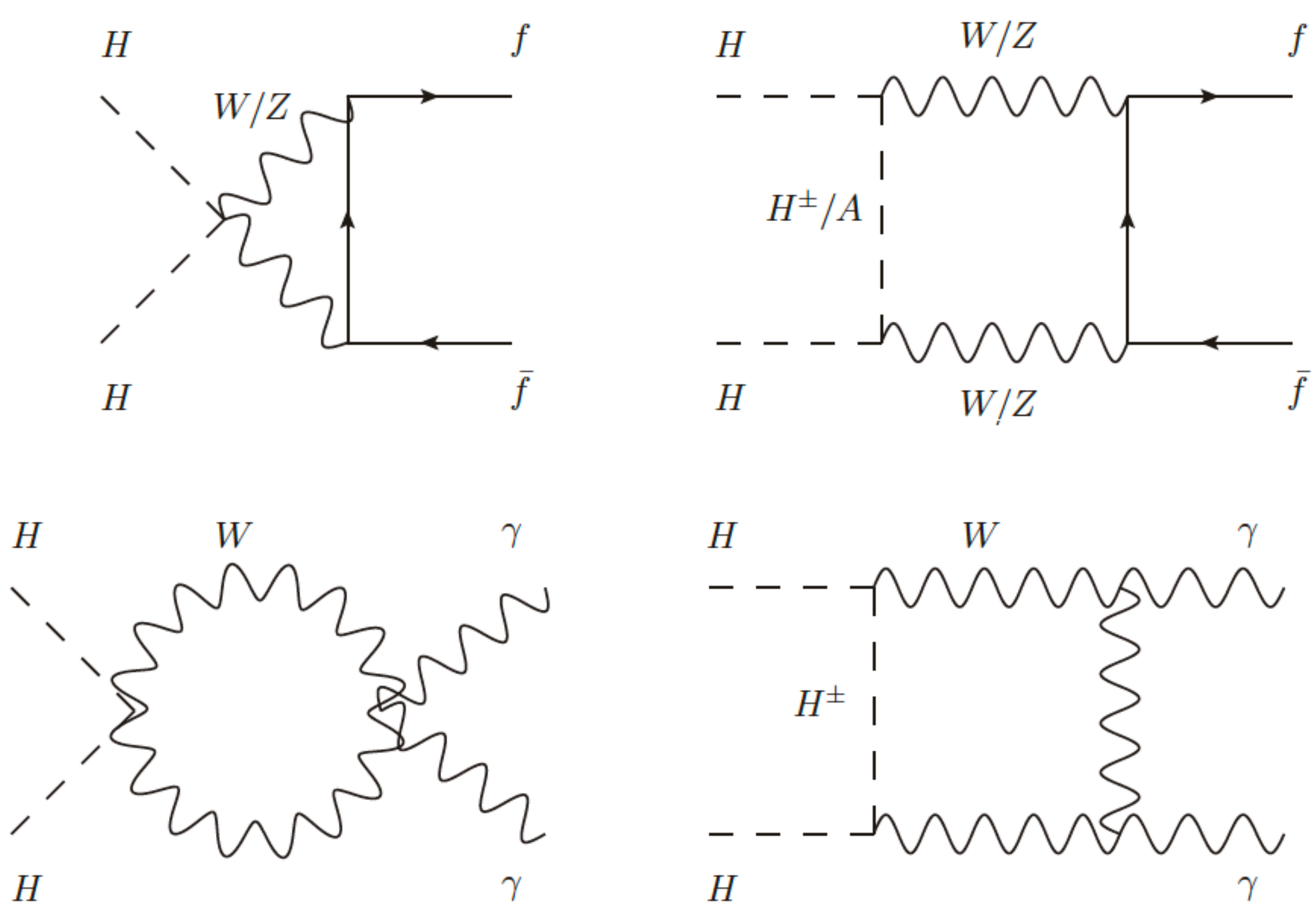
Indirect detection of H (DM)

DMs (H) annihilate to two fermions:





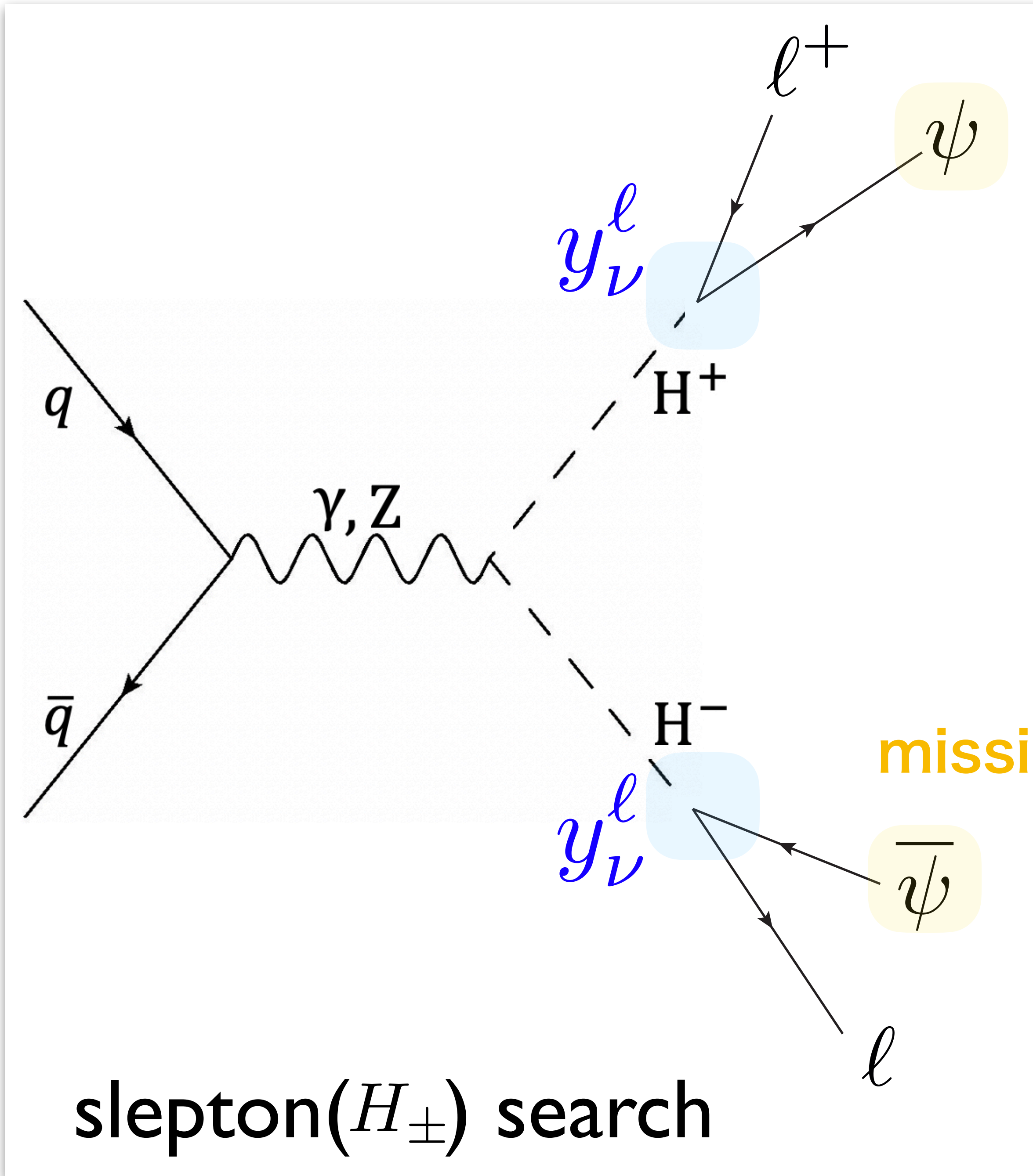
EW interaction gives some signals but small.

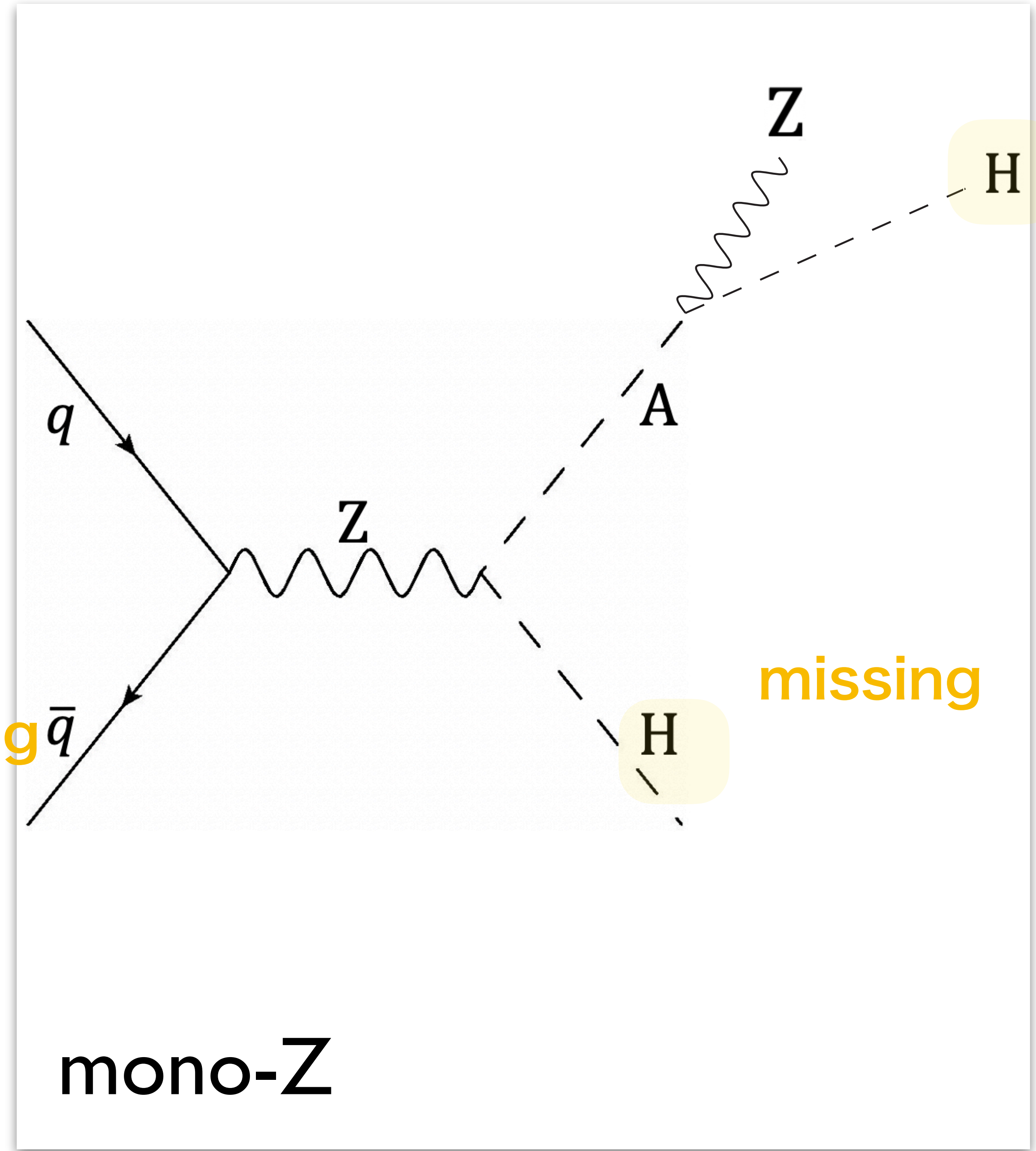


Signals at the LHC

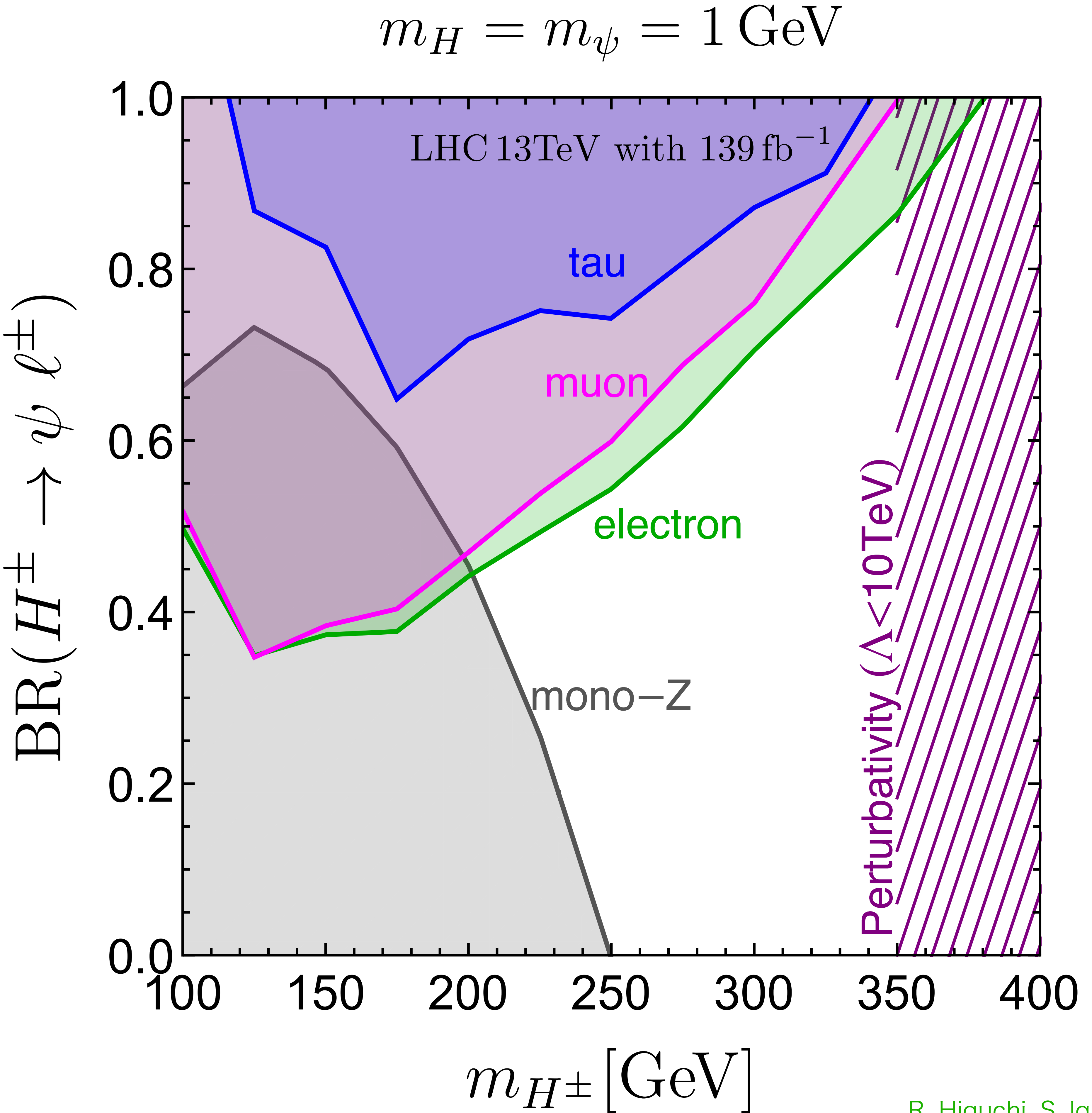
R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

H and ψ are produced via EW interaction.



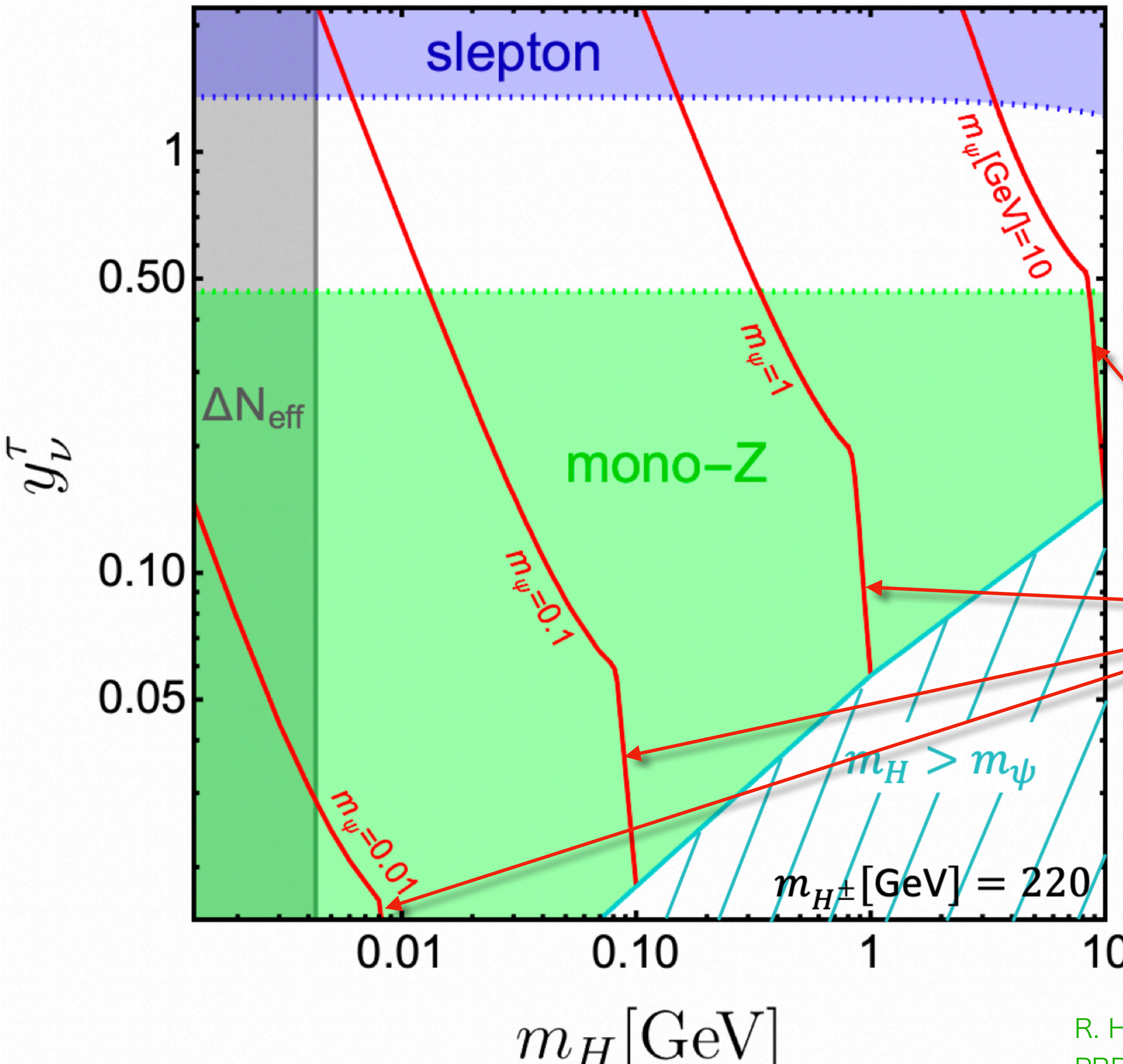


Mono-Z search is complementary to slepton search.



R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

Results assuming DM dominantly couples to τ and ν_τ .



DM annihilation to 2 leptons gives the correct relic density

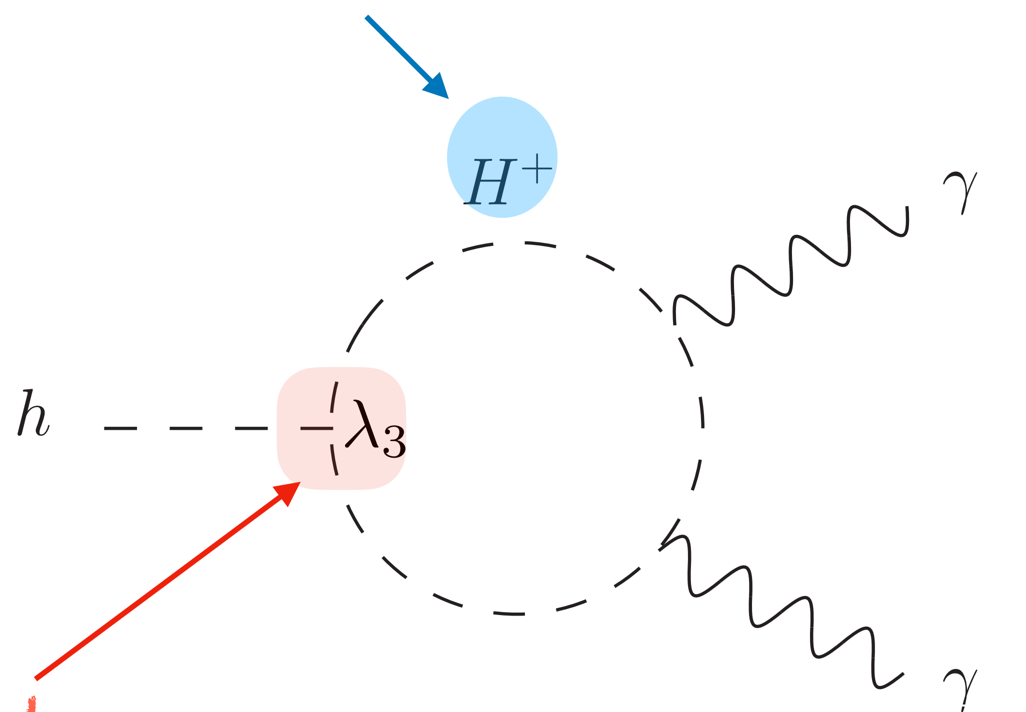
R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

Another way to test this model

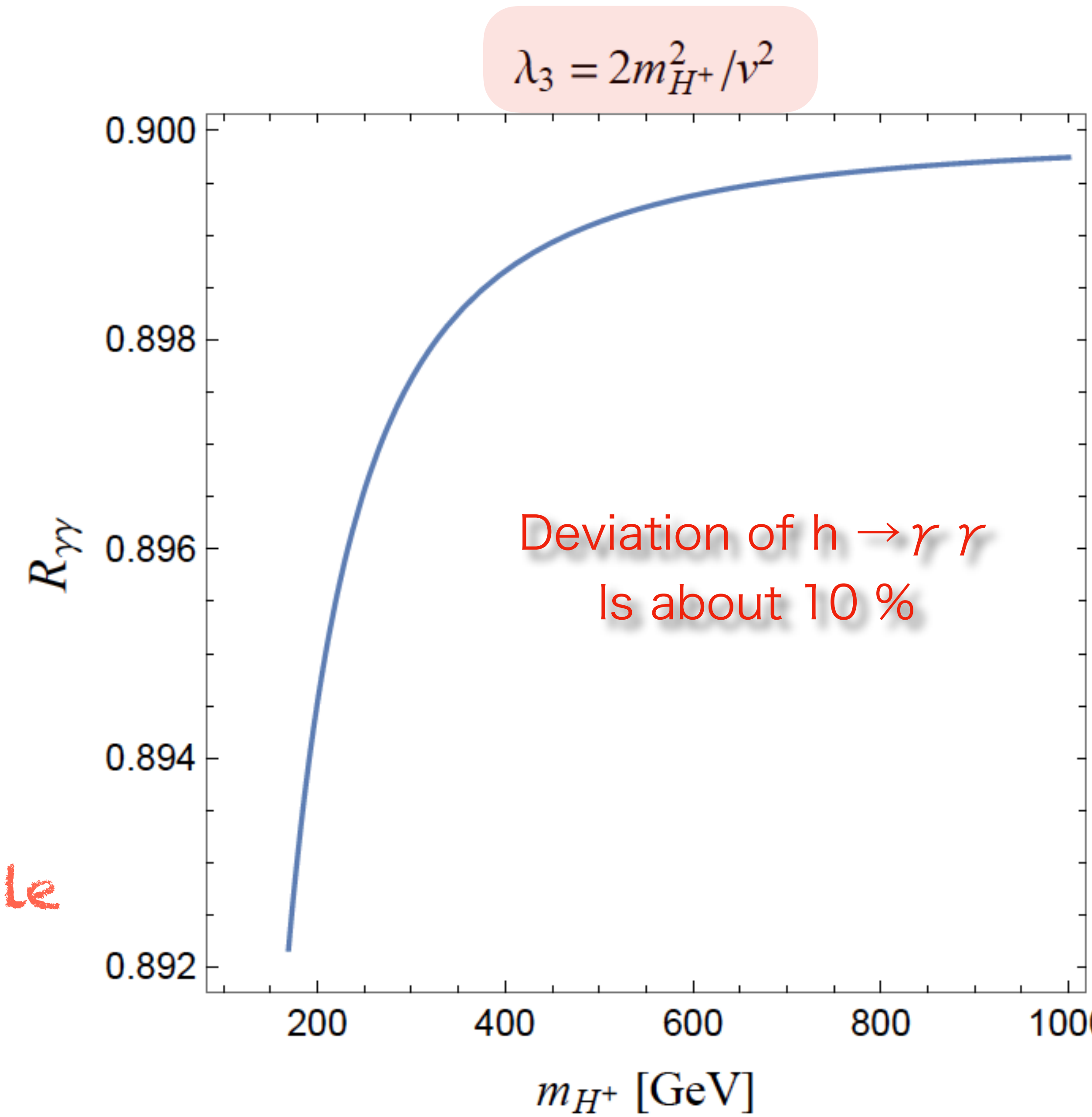
S. Okawa YO JHEP02(2021)231 (arXiv:2011.04788)

125 GeV Higgs signal is deviated from the SM prediction.

Heavier than ~250 GeV because of LHC



Very large
to make mass difference between
H and H+ large and suppress invisible
decay of h.



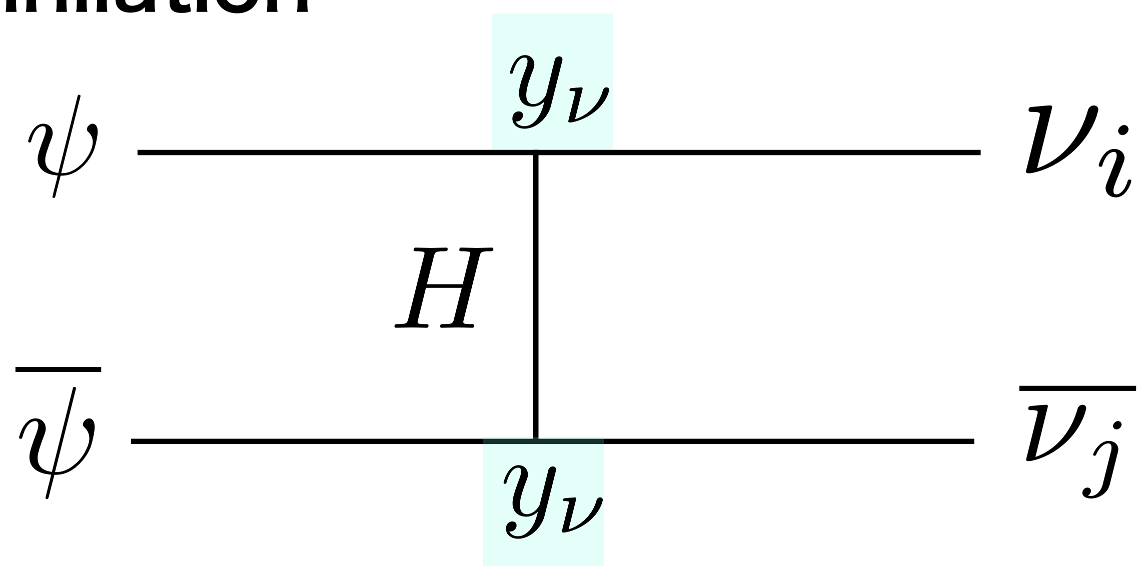
Fermionic DM case

S. Okawa YO JHEP02(2021)231 (arXiv:2011.04788)

S. Iguro, S. Okawa, YO JHEP03(2023)010
(arXiv: 2208.05487)

If extra fermion, ψ , is light than H , ψ is DM.

DM annihilation



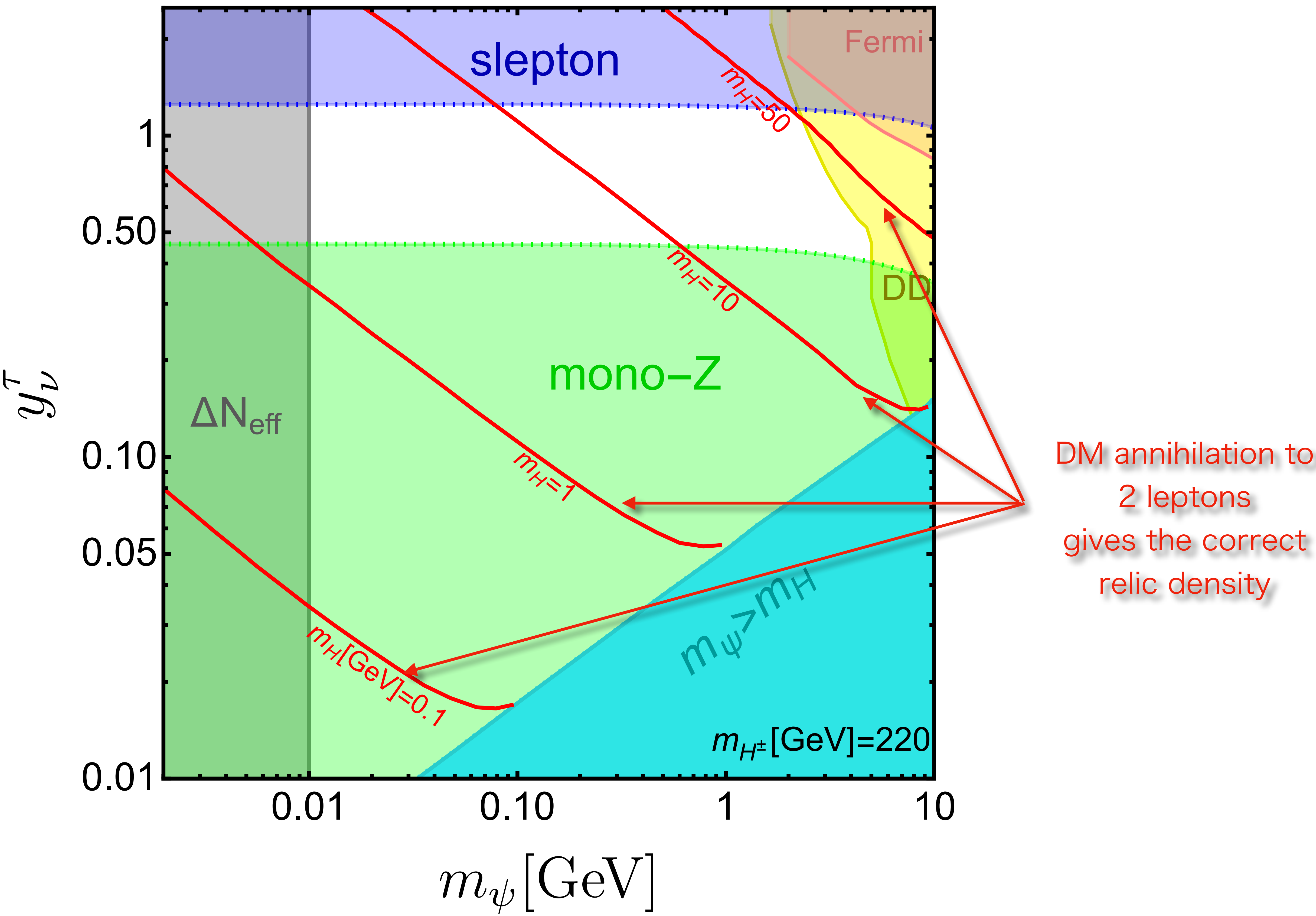
$$(\sigma v_{\rm rel})_{\psi\bar{\psi}\to\nu\bar{\nu}} \simeq \frac{y_\nu^4 m_\psi^2}{128\pi(m_\psi^2 + m_H^2 - m_\nu^2)^2}\sqrt{1-\frac{m_\nu^2}{m_\psi^2}}$$

Yukawa couplings can be relatively small.

Fermion DM case

S. Iguro, S. Okawa, YO JHEP03(2023)010
(arXiv: 2208.05487)

(DM dominantly couples to τ and ντ)



Summary

- I introduce a DM model where DM is scalar and the mass is lighter than 10 GeV. The setup is similar to Inert two Higgs doublet model, where the DM mass is around 60 GeV or heavy.
- Fermion, ψ , is also a good DM candidate. The Yukawa couplings are relatively small in the Fermion DM case. (arXiv: 2011.04788, 2208.05487, S. Iguro, S.Okawa and YO).
- Bounds from DM physics are not strong.
- We can search for the extra scalars and extra fermion at LHC. Mono-Z search is complementary to stau search.
- Making mass difference among scalars is one issue: large couplings required in the scalar potential. → A solution is to add one more scalar (See arXiv: 2011.04788, S.Okawa and YO).
- In Higgs physics, h $\rightarrow \gamma\gamma$ is largely deviated (about 10 %) and invisible decay is also large, because of the large couplings.

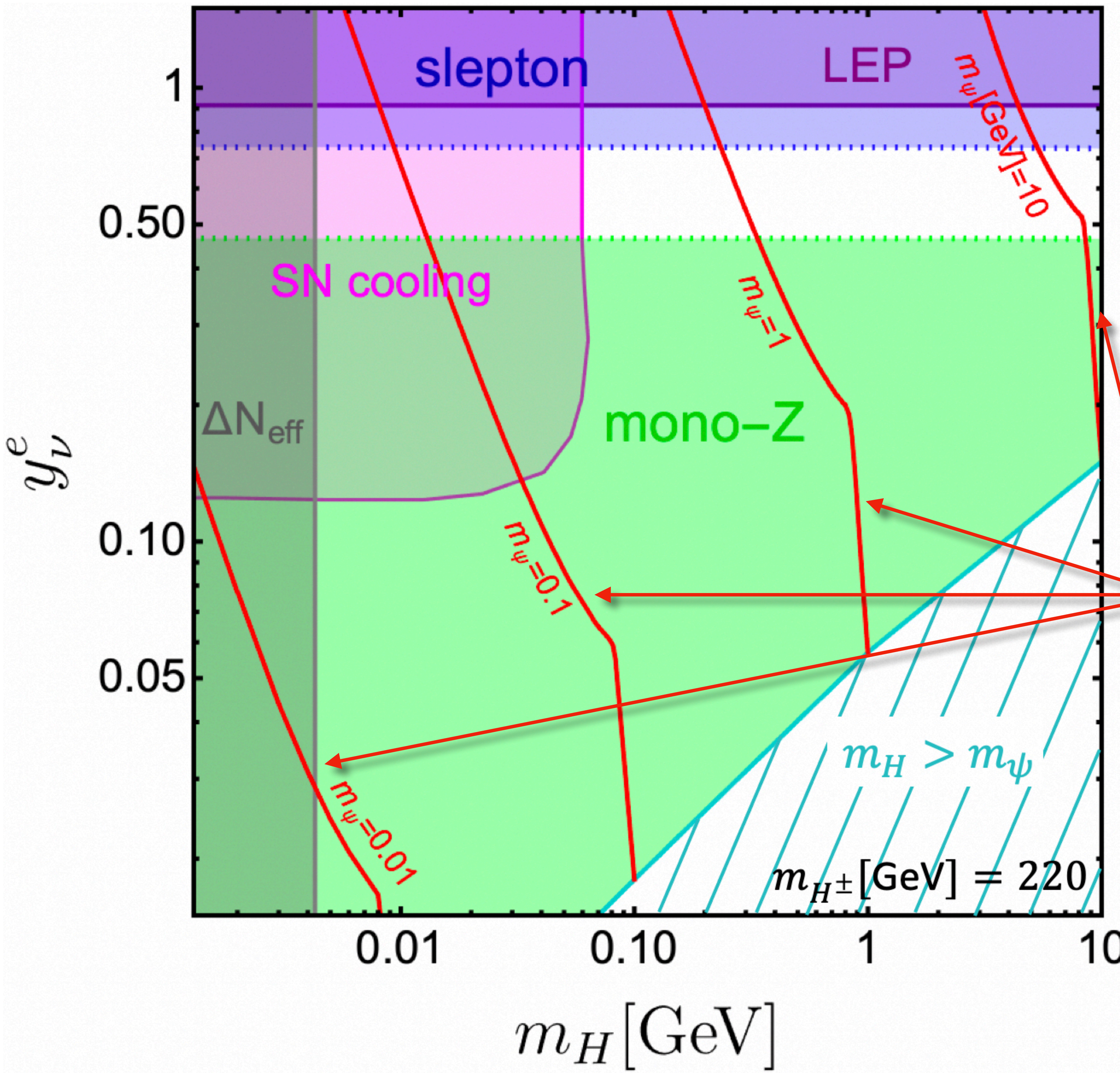
END

Backup

Scalar DM case

R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

(DM dominantly couples to e and ν_e)

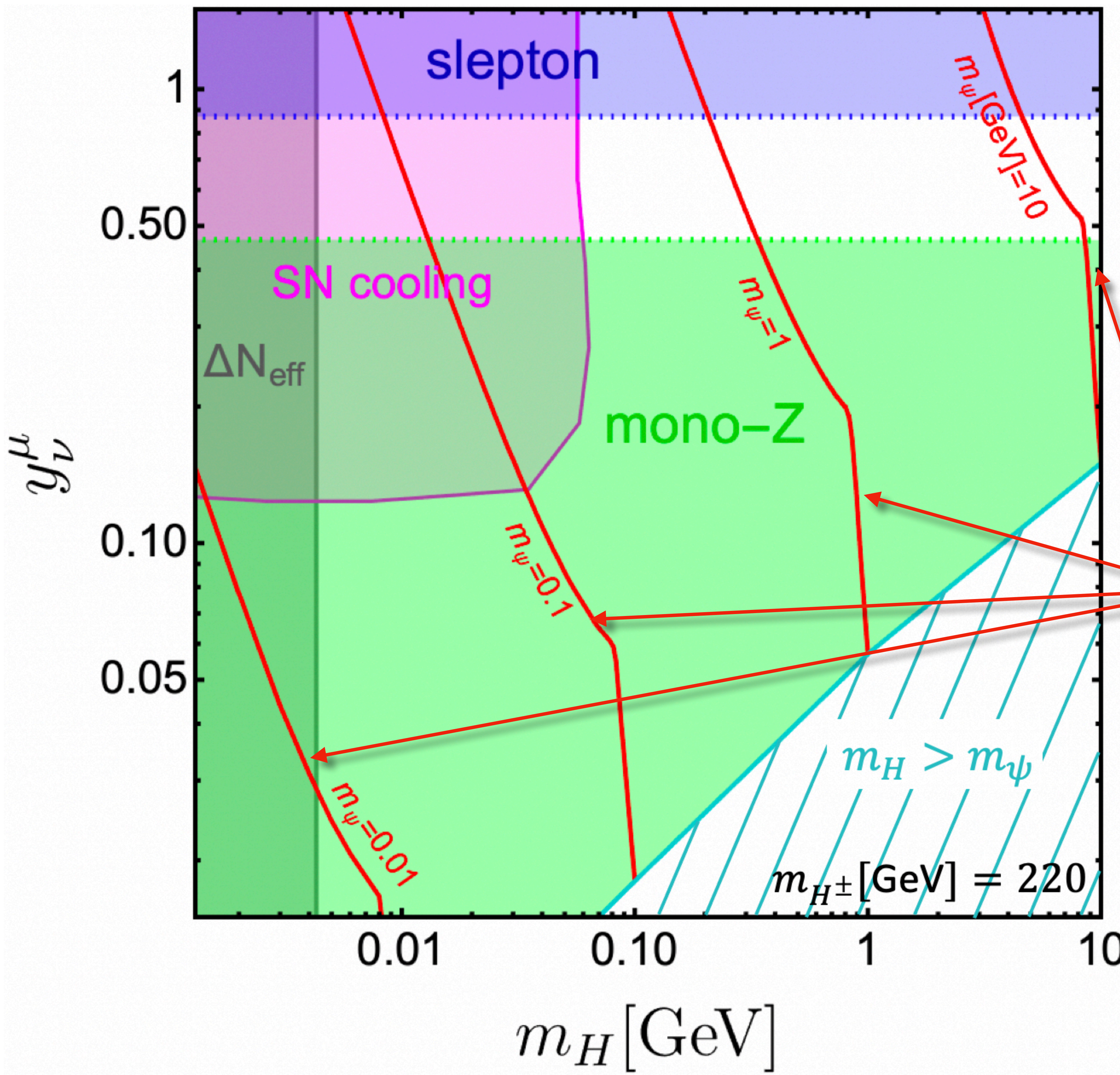


DM annihilation to 2 leptons gives the correct relic density

Scalar DM case

R. Higuchi, S. Iguro, S. Okawa, YO
PRD109(2024)7,075007 (arXiv: 2310.13685)

(DM dominantly couples to μ and νμ)



DM annihilation to 2 leptons gives the correct relic density

Extended model with a scalar

2011.04788 with Okawa

	Fields	spin	$SU(3)$	$SU(2)_L$	$U(1)_Y$	$U(1)_L$	Z_2
	Q_L^i	$1/2$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	0	$+$
	u_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$\frac{2}{3}$	0	$+$
	d_R^i	$1/2$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{2}{3}$	0	$+$
	ℓ_L^i	$1/2$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	1	$+$
	e_R^i	$1/2$	$\mathbf{1}$	$\mathbf{1}$	-1	1	$+$
	ψ_L	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	1	$-$
	ψ_R	$1/2$	$\mathbf{1}$	$\mathbf{1}$	0	1	$-$
	Φ	1	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	$+$
	Φ_ν	1	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0	$-$
extra	S	1	$\mathbf{1}$	$\mathbf{1}$	0	0	$-$

Additional coupling involving S

$$-\Delta\mathcal{L} = A_S\,\Phi^\dagger\Phi_\nu S + h.c.$$