

Non-abelian vector dark matter model with electroweak interactions

(10 min. talk w/ 10 pages)

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based on:

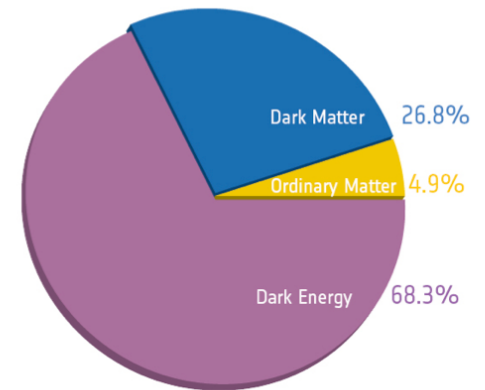
T. Abe, MF, J. Hisano, K. Matsushita, JHEP 07 (2020) 136 [[arXiv:2004.00884](https://arxiv.org/abs/2004.00884)]

Introduction: WIMP scenario Dark Matter

Dark Matter (DM) energy density

$$\Omega h^2 = 0.120 \pm 0.001$$

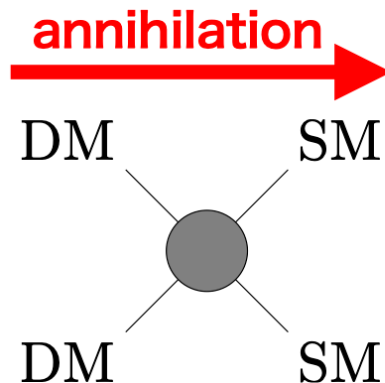
[Planck Collaboration arXiv:1807.06209]



<https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe>

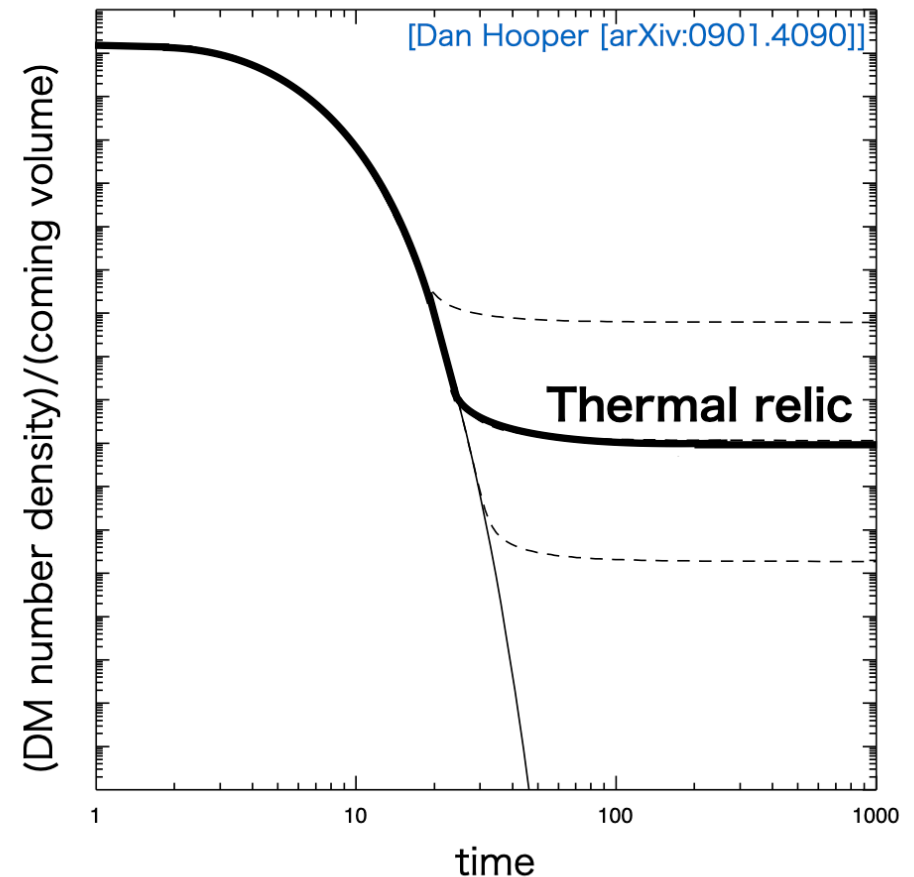
WIMP scenario

DM is assumed to have interactions w/ Standard Model (SM) particles



To achieve $\Omega h^2 = 0.12 \dots$

→ **Annihilation rate should be typical order of EW theory!**



Introduction: Electroweak Multiplet DM

Assumption

“DM is a $SU(2)_L$ multiplet”

[M. Farina, D. Pappadopulo, A. Strumia (2013)]

		Quantum numbers		DM could	DM mass	$m_{\text{DM}^\pm} - m_{\text{DM}}$	Finite naturalness	σ_{SI} in	
		$\text{SU}(2)_L$	$\text{U}(1)_Y$	Spin	decay into	in TeV	in MeV	bound in TeV	10^{-46} cm^2
Higgsino	→	2	1/2	0	EL	0.54	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6) 10^{-3}$
		2	1/2	1/2	EH	1.1	341	$1.9 \times \sqrt{\Delta}$	$(0.3 \pm 0.6) 10^{-3}$
Wino		3	0	0	HH^*	$2.0 \rightarrow 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
	→	3	0	1/2	LH	$2.4 \rightarrow 2.7$	166	$1.0 \times \sqrt{\Delta}$	0.12 ± 0.03
		3	1	0	HH, LL	$1.6 \rightarrow ?$	540	$0.22 \times \sqrt{\Delta}$	0.001 ± 0.001
		3	1	1/2	LH	$1.9 \rightarrow ?$	526	$1.0 \times \sqrt{\Delta}$	0.001 ± 0.001
		4	1/2	0	HHH^*	$2.4 \rightarrow ?$	353	$0.14 \times \sqrt{\Delta}$	0.27 ± 0.08
		4	1/2	1/2	(LHH^*)	$2.4 \rightarrow ?$	347	$0.6 \times \sqrt{\Delta}$	0.27 ± 0.08
		4	3/2	0	HHH	$2.9 \rightarrow ?$	729	$0.14 \times \sqrt{\Delta}$	0.15 ± 0.07
		4	3/2	1/2	(LHH)	$2.6 \rightarrow ?$	712	$0.6 \times \sqrt{\Delta}$	0.15 ± 0.07
		5	0	0	(HHH^*H^*)	$5.0 \rightarrow 9.4$	166	$0.10 \times \sqrt{\Delta}$	1.0 ± 0.2
		5	0	1/2	stable	$4.4 \rightarrow 10$	166	$0.4 \times \sqrt{\Delta}$	1.0 ± 0.2
	7	0	0	stable	$8 \rightarrow 25$	166	$0.06 \times \sqrt{\Delta}$	4 ± 1	

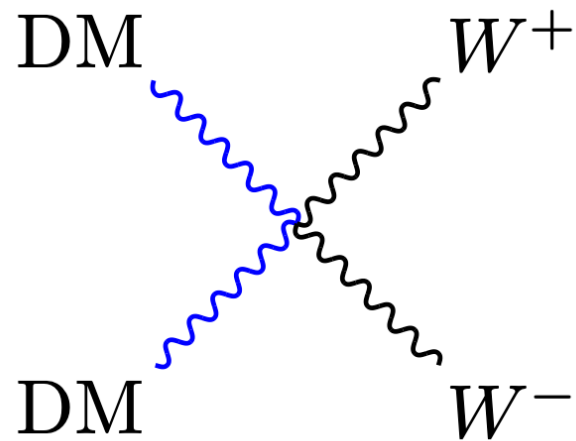
Feature

- $\Omega h^2 \sim 0.12 \rightarrow O(1) \text{ TeV DM}$
- mass splitting $\rightarrow O(100) \text{ MeV}$

How about Spin-1 DM?

Motivation

Spin-1 dark matter with **Electroweak interaction**



- How can we realize such kind of theory?
- How can we stabilize spin-1 DM?
- What kind of features does spin-1 DM have?

Our Model

Symmetry

$$SU(3)_c \otimes SU(2)_0 \otimes SU(2)_1 \otimes SU(2)_2 \otimes U(1)_Y$$

Exchange Symmetry

$$\Phi_1 \leftrightarrow \Phi_2, \quad W_{0\mu}^a \leftrightarrow W_{2\mu}^a$$

Matter Contents

field	spin	$SU(3)_c$	$SU(2)_0$	$SU(2)_1$	$SU(2)_2$	$U(1)_Y$
q_L	$\frac{1}{2}$	3	1	2	1	$\frac{1}{6}$
u_R	$\frac{1}{2}$	3	1	1	1	$\frac{2}{3}$
d_R	$\frac{1}{2}$	3	1	1	1	$-\frac{1}{3}$
ℓ_L	$\frac{1}{2}$	1	1	2	1	$-\frac{1}{2}$
e_R	$\frac{1}{2}$	1	1	1	1	-1
H	0	1	1	2	1	$\frac{1}{2}$
Φ_1	0	1	2	2	1	0
Φ_2	0	1	1	2	2	0

✱ gauge coupling: $g_0 = g_2$

Fermion sector

Each field corresponds to SM fermion

Scalar sector

Φ_1, Φ_2 : Bi-fundamental fields

$$W_{0\mu}^a \quad W_{1\mu}^a \quad W_{2\mu}^a$$

Z₂-Parity from Exchange Symmetry

Scalar field definition

$$H = \begin{pmatrix} i\pi_3^+ \\ \frac{v + \sigma_3 - i\pi_3^0}{\sqrt{2}} \end{pmatrix}, \quad \Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi_j^0}{\sqrt{2}} & i\pi_j^+ \\ i\pi_j^- & \frac{v_\Phi + \sigma_j - i\pi_j^0}{\sqrt{2}} \end{pmatrix}. \quad (j = 1, 2)$$

Exchange symmetry after SSB:

$$\sigma_1 \leftrightarrow \sigma_2, \quad W_{0\mu}^a \leftrightarrow W_{2\mu}^a$$

Z₂-odd states

$$h_D = \frac{\sigma_1 - \sigma_2}{\sqrt{2}}$$

DM

$$V^0 = \frac{W_{0\mu}^3 - W_{2\mu}^3}{\sqrt{2}}$$

$$V^\pm = \frac{W_{0\mu}^\pm - W_{2\mu}^\pm}{\sqrt{2}}$$

“V-particles”

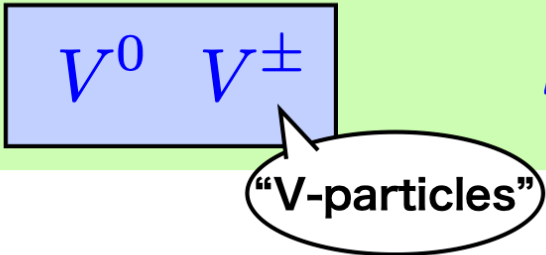
- U(1)_{em} charge eigenstates
- **Z₂-odd states** under exchange symmetry
- **Mass eigenstates**
($\because$ No off-diagonal elements in mass matrix)

Exchange symmetry $SU(2)_0 \leftrightarrow SU(2)_2$

$\Leftrightarrow$ **Z₂-Parity** for physical states

Spectrum after SSB

$$\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad \langle \Phi_1 \rangle = \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\Phi & 0 \\ 0 & v_\Phi \end{pmatrix} \quad (v \ll v_\Phi)$$

Energy	<u>Vector</u>	<u>Scalar</u>	<u>Z₂-Parity</u>	<u>Mass</u>
	$Z' \quad W'^{\pm}$	h'	even	$\sim v_\Phi \quad \mathcal{O}(1) \text{ TeV}$
	$V^0 \quad V^{\pm}$	h_D	odd	
				
	$Z \quad W^{\pm}$	h	even	$\sim v \quad \mathcal{O}(100) \text{ GeV}$
	γ		even	massless

★ SM limit: $v_\Phi \rightarrow \infty$ (All the BSM particles decouple from the SM sector)

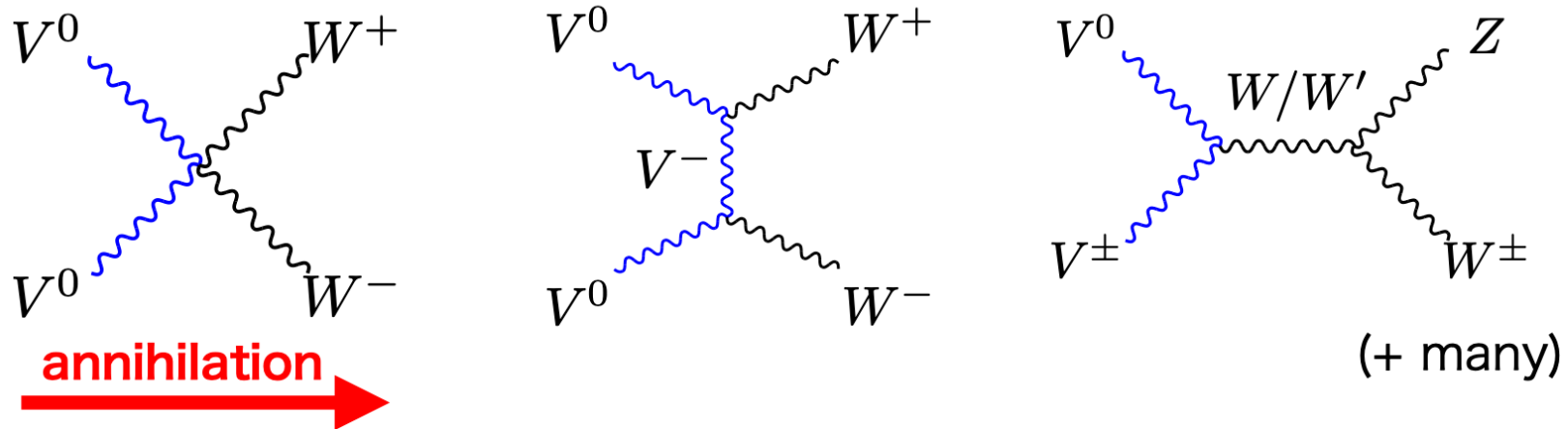
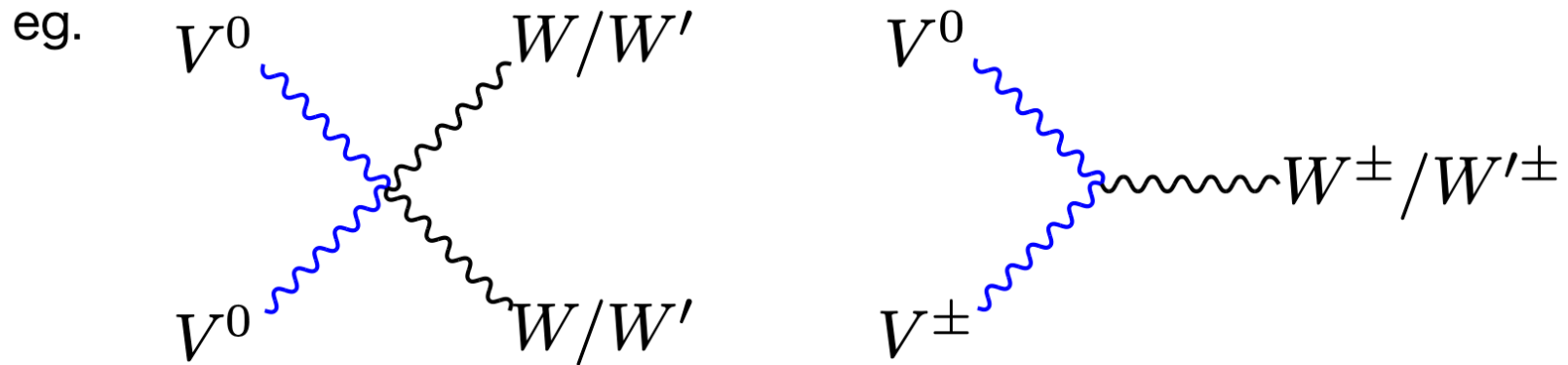
★ We need NO BSM fermions to realize the SM spectrum

$$\mathcal{L} \supset -y_u \bar{q}_L \tilde{H} u_R - y_d \bar{q}_L H d_R - y_e \bar{\ell}_L H e_R + h.c. \quad \left[\begin{array}{l} \tilde{H} = \epsilon H^* \\ \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \end{array} \right]_6$$

Annihilation: Non-Abelian couplings

Feature

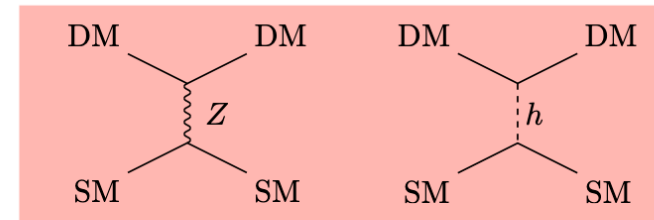
V-particles have non-Abelian vector couplings



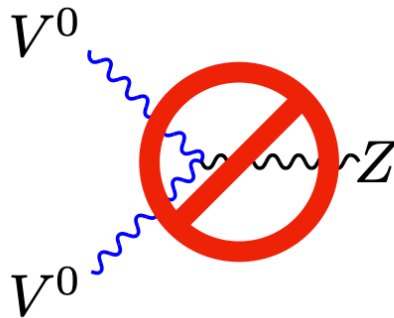
→ Rich annihilation channels between V-particles!

Annihilation vs Scattering

Z-exchange/Higgs-exchange process
is severely constrained in direct detection

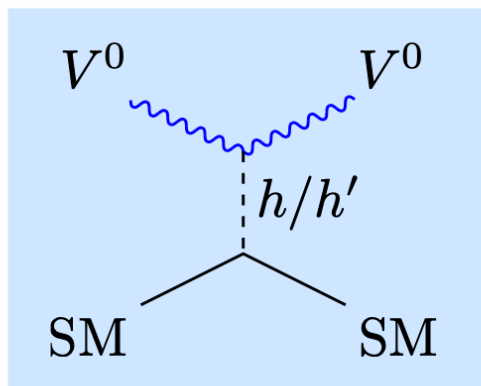


✓ Z-exchange process

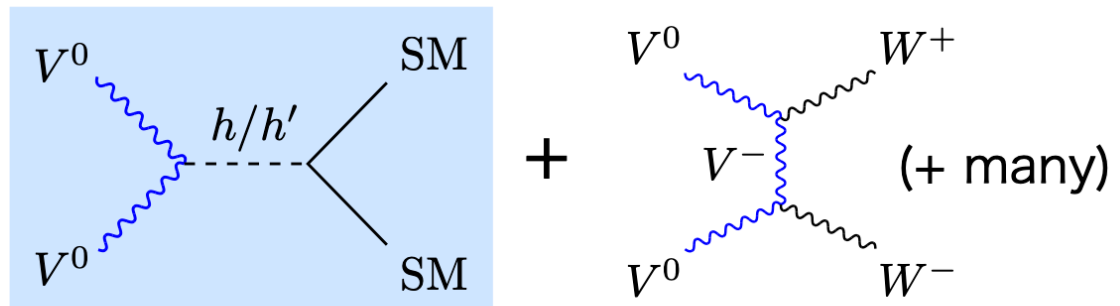


Neutral vector triple coupling is forbidden
in non-Abelian extension
→ No Z-exchange in scattering process!

✓ Higgs-exchange process

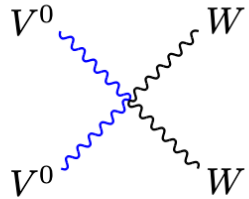


We do not rely on Higgs exchange process
in annihilation channel



We can break correlation between Annihilation and Scattering process!

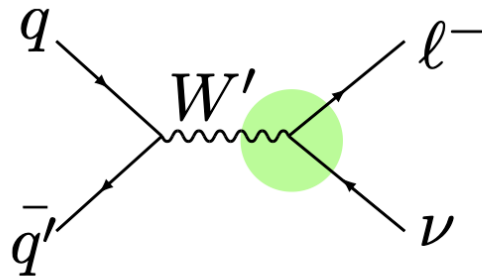
Result: Ωh^2 contours



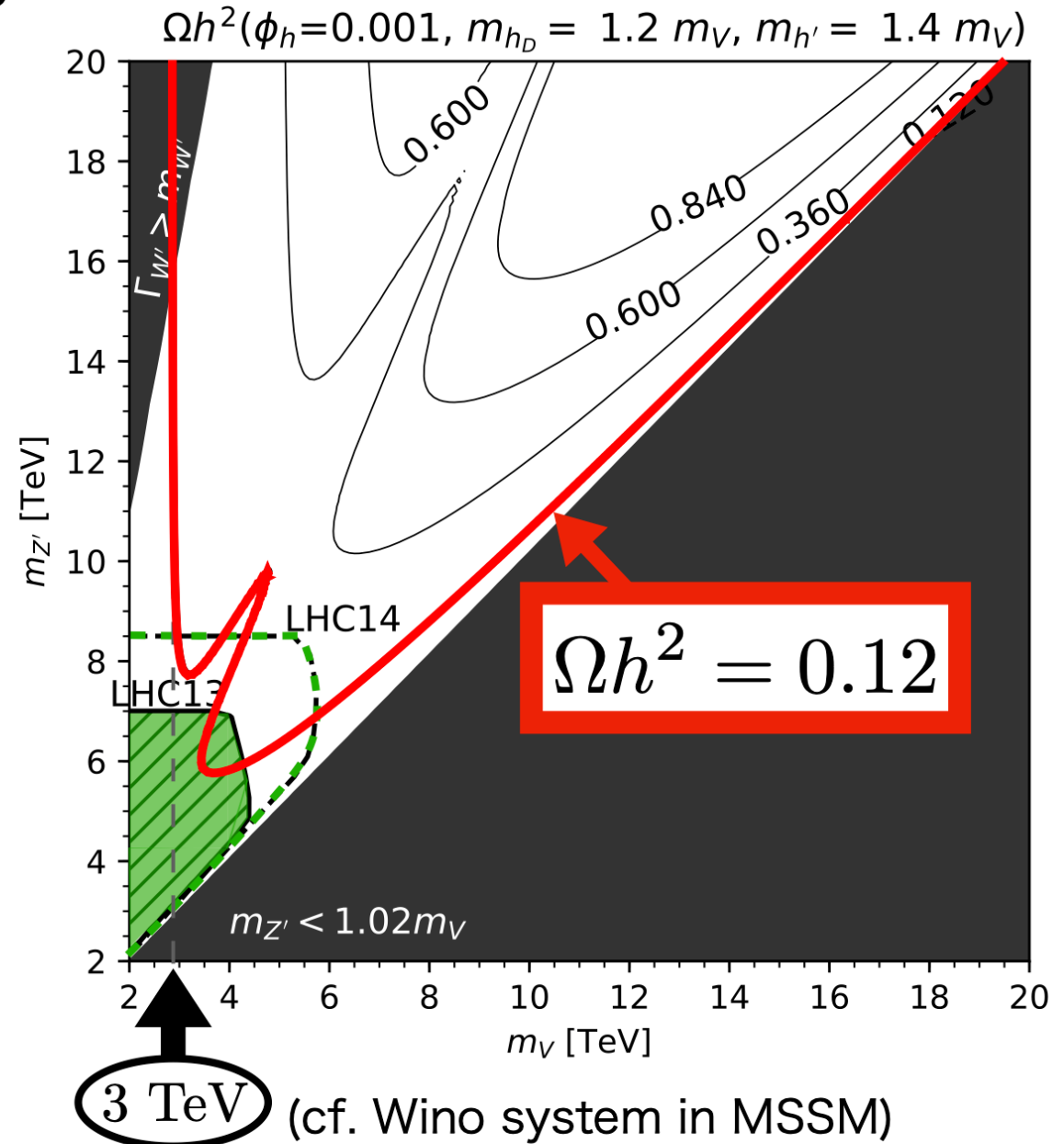
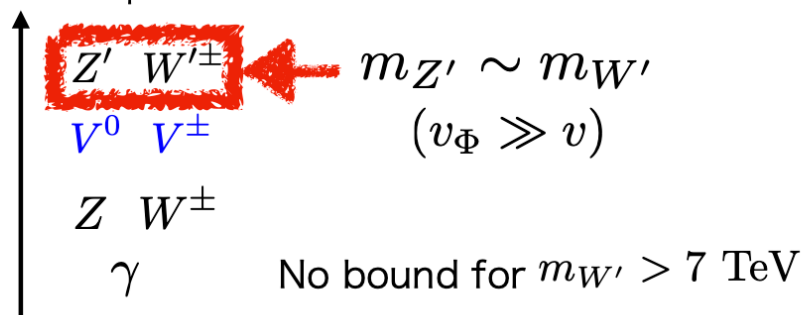
Thermal relic is determined by electroweak interaction

$\Omega h^2 = 0.12 \Rightarrow m_V \gtrsim 3 \text{ TeV}$

W' search @LHC [ATLAS Collaboration(2019)]



Vector Spectrum



ϕ_h : mixing angle of Z_2 -even scalars

Ωh^2 contours are degenerated for $\phi_h \lesssim 0.001$ 9

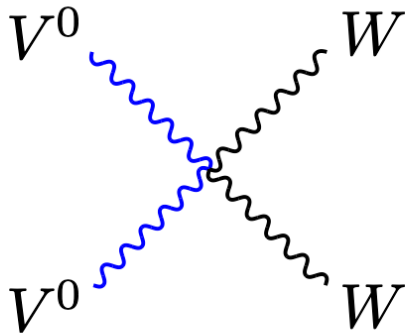
Summary

- Non-Abelian extension of EW symmetry
- Imposing exchange symmetry of SU(2)



• **Z₂-odd** vectors: $V^0, V^\pm$

• Non-Abelian EW couplings



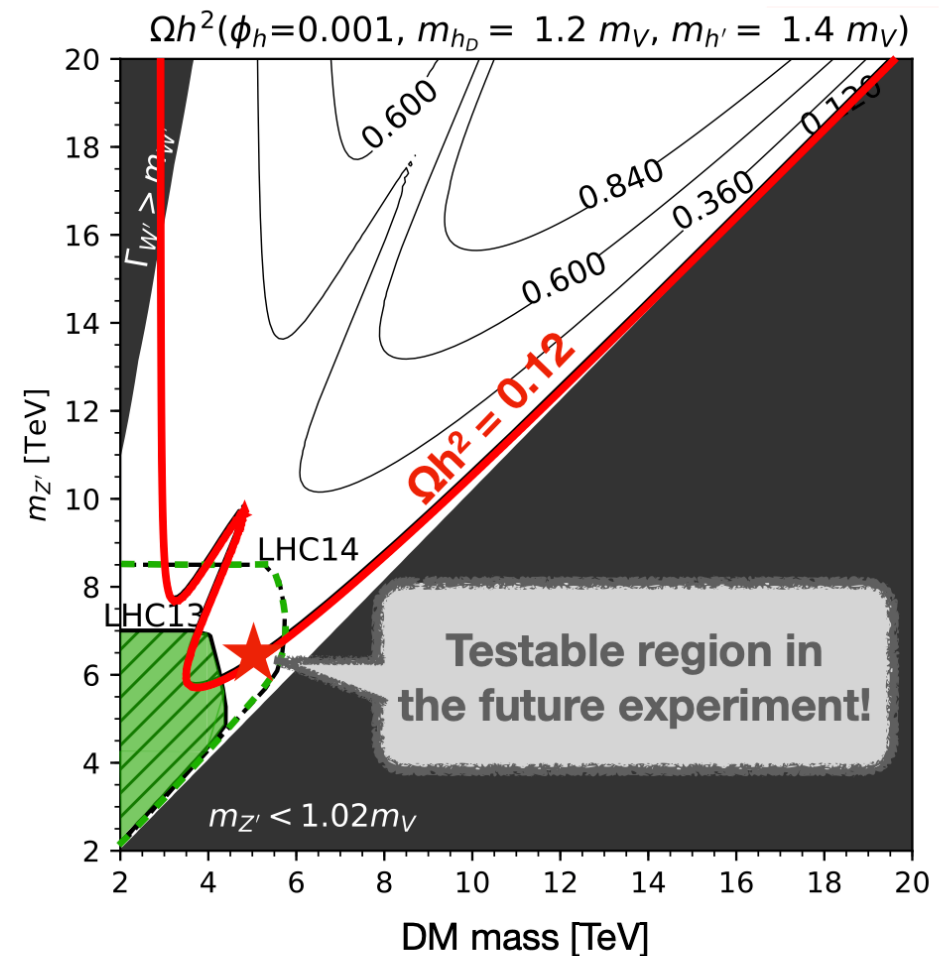
→ We can keep WIMP scenario while evading direct detection bounds!

Test of TeV scale WIMP scenario

→ W' search @LHC(14 TeV) is viable!

$$\text{SU}(2)_0 \otimes \text{SU}(2)_1 \otimes \text{SU}(2)_2$$

Exchange Symmetry



Future Work

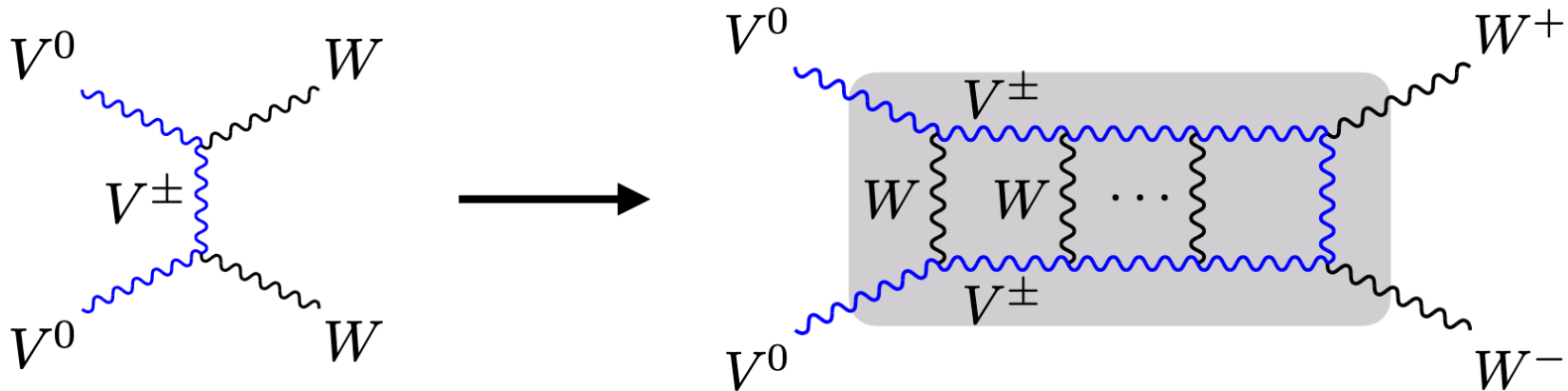
Result in this work

$$\Omega h^2 = 0.12 \text{ is obtained for } m_V \gg \mathcal{O}(100) \text{ GeV}$$



DM pair form the bound states in annihilation processes

(Sommerfeld enhancement) [J. Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]



※Schematically picture

Ωh^2 -contours may be affected by this bound states formation (future work)

Fin.

Thank you!

2020.11.16 Motoko FUJIWARA

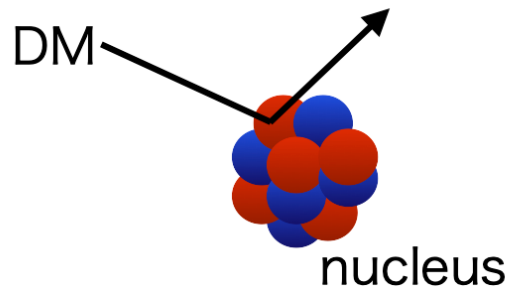
Backup

Spin-1 DM vs DM direct detection

For more details

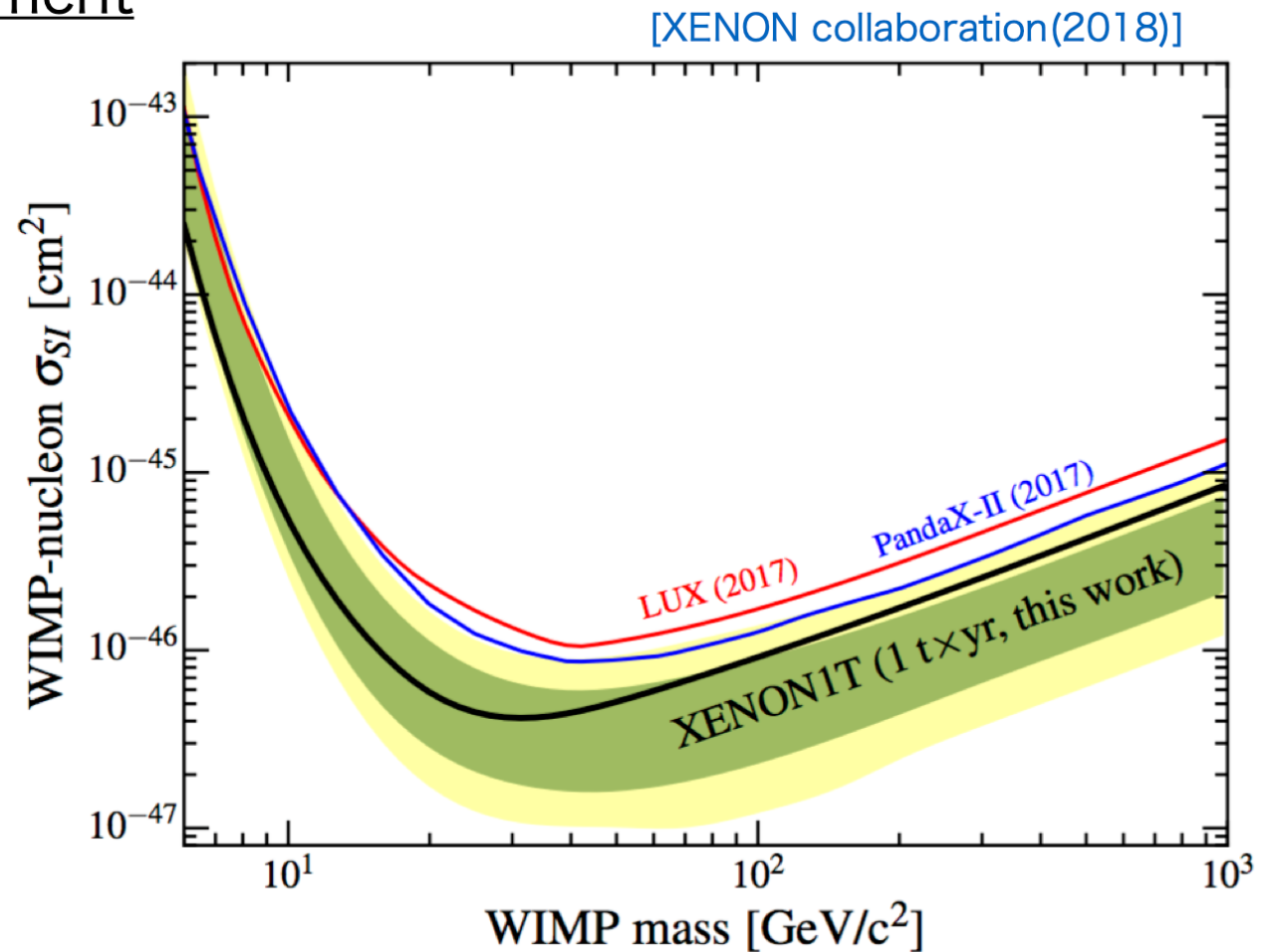
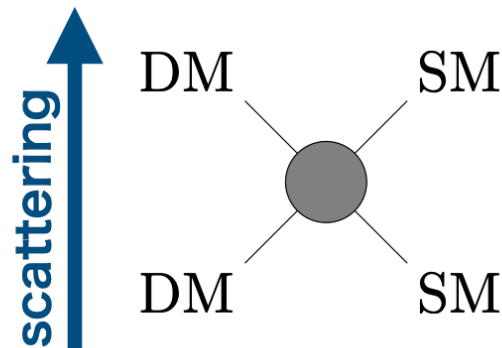
Introduction: Direct detection

DM direct detection experiment



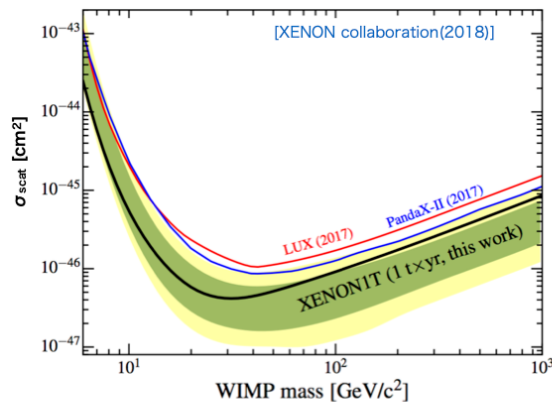
Null signal

→ Upper bound on scattering cross section (σ_{SI})

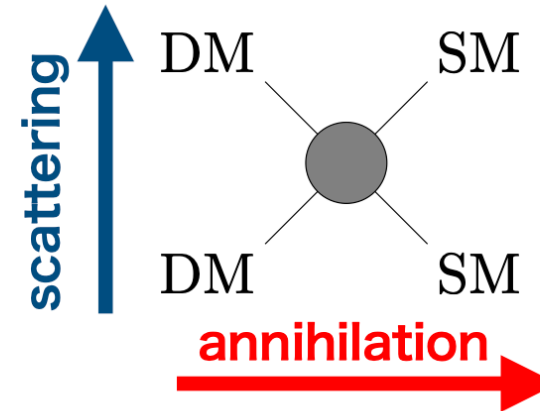


Strict bound on many WIMP DM models

Introduction: WIMP scenario vs Direct Detection

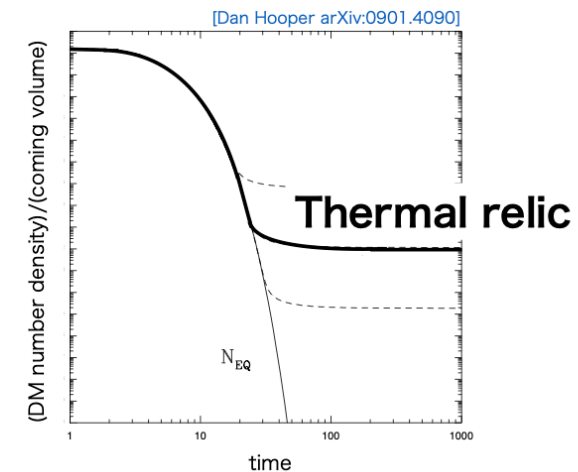


**Small σ_{scat} to explain
direct detection null signal**



**We must break the correlation
between Annihilation and Scattering**

→ We consider mechanism
in **spin-1 DM model**



Sufficient $\langle \sigma_{\text{anni}} v \rangle$ for WIMP scenario

Introduction: Annihilation vs Scattering

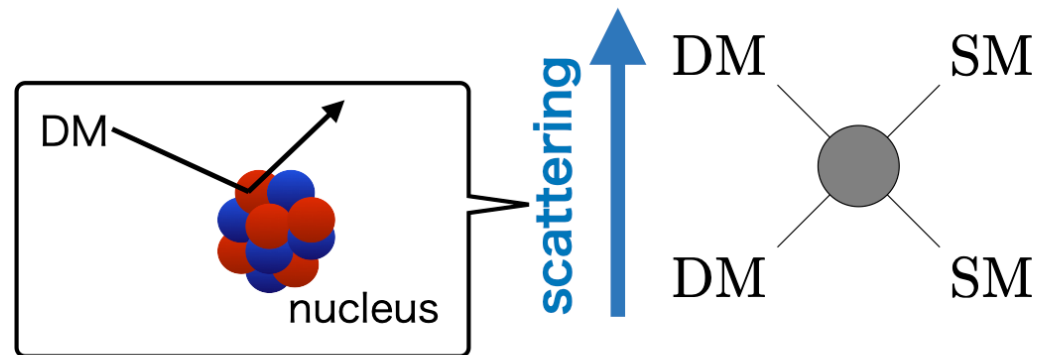
Existing Mechanisms

- spin-0 DM: Pseudo-Nambu-Goldstone boson DM model
[C.Gross, O. Lebedev, T. Toma(2017)]
- spin-1/2 DM: Pseudoscalar mediator DM model
[S. Ipek, D. McKeen, A. E. Nelson(2014)]

Suppression mechanism in DM scattering process

- spin-1 DM:

➔ **Today's talk!**



Existing spin-1 DM Models (review)

“Isolated” non-Abelian extension [T. Hambye (2009)]

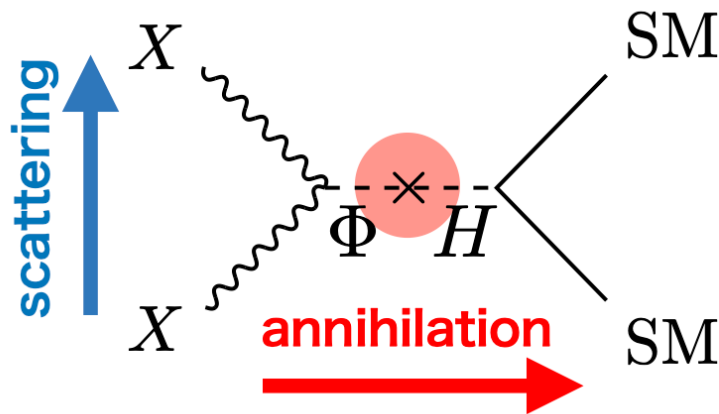
$$\text{SU}(3)_c \otimes \text{SU}(2)_L \otimes \text{SU}(2)_X \otimes \text{U}(1)_Y$$

$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu}^a X^{a\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

X_μ^a : $\text{SU}(2)_X$ gauge boson

$$V(\Phi, H) \supset \frac{\lambda_{\Phi H}}{4} (\Phi^\dagger \Phi)(H^\dagger H)$$

Φ : $\text{SU}(2)_X$ doublet scalar



DM Annihilation relies on Higgs exchange

We need other annihilation channels to break the correlation!

Trial:

$$\text{SU}(3)_c \otimes \text{SU}(2)_1 \otimes \text{SU}(2)_2 \otimes \text{U}(1)_Y$$

???

How can we realize

- variation in DM annihilation channels?
- stable spin-1 DM?
- realistic SM spectrum?

Our Model

[T. Abe, MF, J. Hisano, K. Matsushita [arXiv:2005.00884]]

For more details

Introduction: (De)construction technique

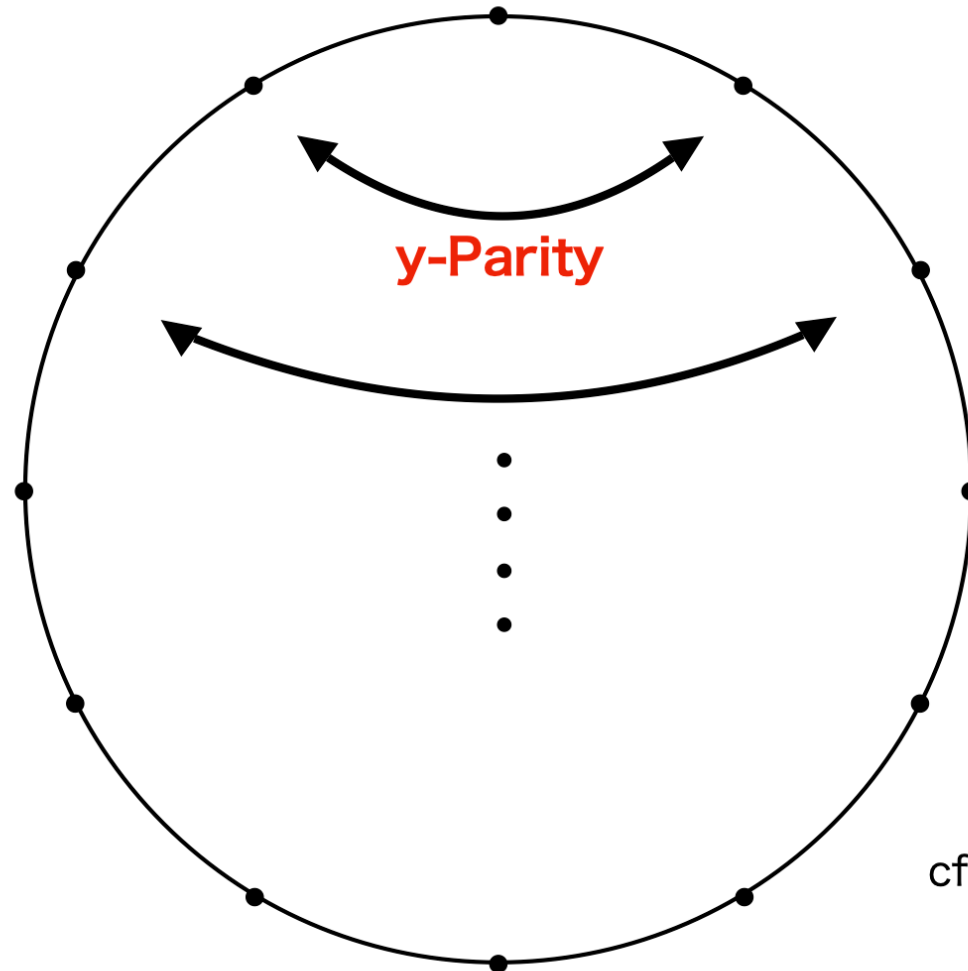
Discretized 5d coordinate

※Schematically picture

5d gauge theory

G : gauge group

$y = 0$ (Fixed point)



cf. Orbifold compactification
 S_1/Z_2

The spectrum of 5d theory is reproduced
in 4d theory with many direct products of gauge group

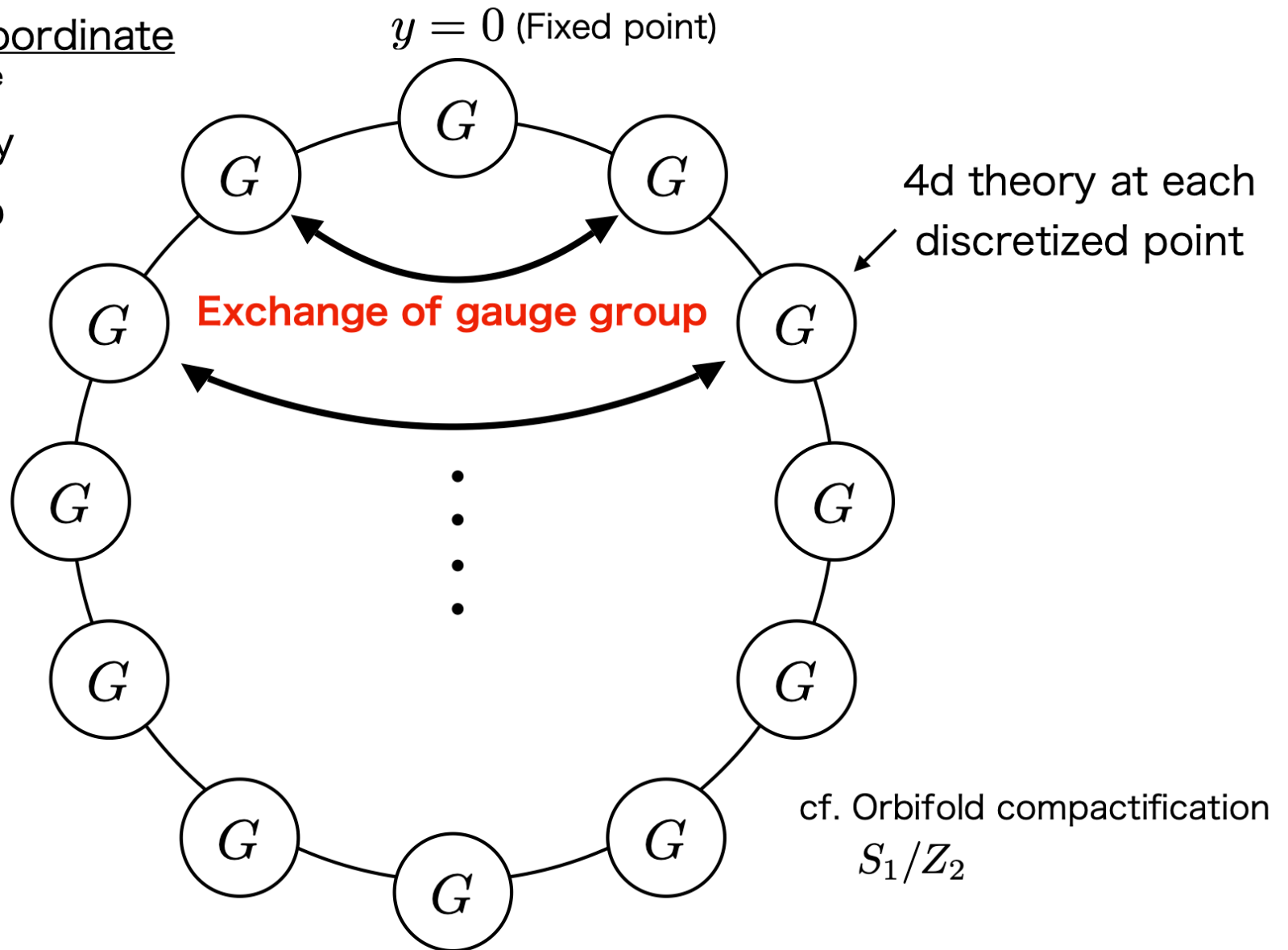
Introduction: (De)construction technique

Discretized 5d coordinate

※Schematically picture

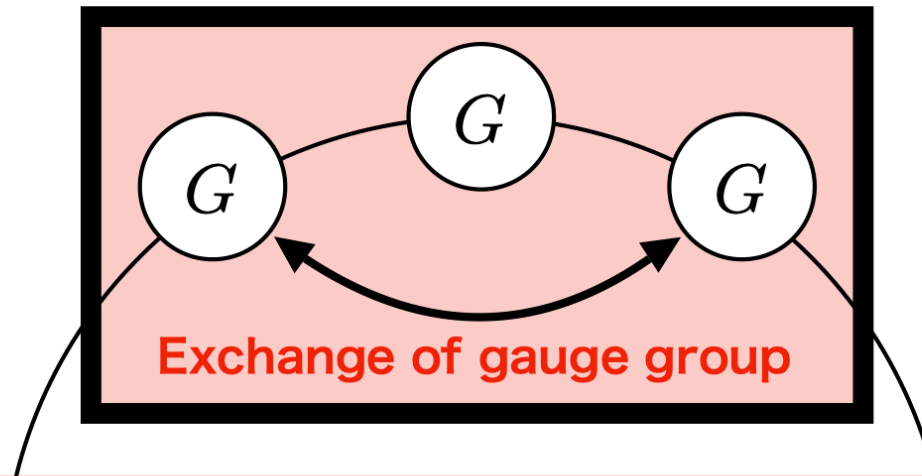
5d gauge theory

G : gauge group



The spectrum of 5d theory is reproduced
in 4d theory with many direct products of gauge group

Introduction: (De)construction technique



Our Work

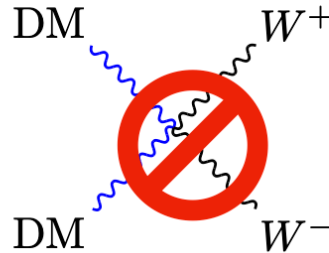
- **Non-Abelian extension** of electroweak symmetry
 - Imposing **Exchange Symmetry of gauge group**
- **Z_2 -odd spin-1 particles can be obtained while realizing SM spectrum!**

Abelian Extension with Exchange Symmetry(1/2)

We can also construct the Abelian extension spin-1 DM model with exchange symmetry

$$SU(2)_L \otimes \text{U}(1)_0 \otimes \text{U}(1)_1 \otimes \text{U}(1)_2$$

Exchange Symmetry



Stable neutral vector **CANNOT** have Non-Abelian EW couplings

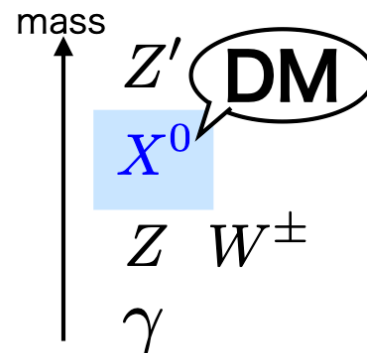
Model

$$\begin{aligned} \mathcal{L} \supset & -\frac{1}{4}(B^0)_{\mu\nu}(B^0)^{\mu\nu} - \frac{1}{4}(B^1)_{\mu\nu}(B^1)^{\mu\nu} - \frac{1}{4}(B^2)_{\mu\nu}(B^2)^{\mu\nu} \\ & + \frac{1}{2}\epsilon_{01} [(B^0)^{\mu\nu} + (B^2)^{\mu\nu}] (B^1)^{\mu\nu} + \frac{1}{2}\epsilon_{02}(B^0)_{\mu\nu}(B^2)^{\mu\nu} \\ & + (D_\mu \Phi_1)^\dagger (D^\mu \Phi_1) + (D_\mu \Phi_2)^\dagger (D^\mu \Phi_2) + (D_\mu H)^\dagger (D^\mu H) \\ & - (\text{Scalar Potential}) \end{aligned}$$

Spectrum

$$X^0 = \frac{B_\mu^0 - B_\mu^2}{\sqrt{2}}$$

(Z₂-odd neutral vector)



※ We have kinetic mixing terms(2nd line) in this Abelian extension model

field	spin	SU(3) _C	SU(2) _L	U(1) ₀	U(1) ₁	U(1) ₂
q_L	$\frac{1}{2}$	3	2	0	$\frac{1}{6}$	0
u_R	$\frac{1}{2}$	3	1	0	$\frac{2}{3}$	0
d_R	$\frac{1}{2}$	3	1	0	$-\frac{1}{3}$	0
ℓ_L	$\frac{1}{2}$	1	2	0	$-\frac{1}{2}$	0
e_R	$\frac{1}{2}$	1	1	0	-1	0
H	0	1	2	0	$\frac{1}{2}$	0
Φ_1	0	1	1	y_1^0	y_1^1	0
Φ_2	0	1	1	0	y_1^1	y_1^0

$W_\mu^a \quad B_\mu^0 \quad B_\mu^1 \quad B_\mu^2$

Abelian Extension with Exchange Symmetry(2/2)

NOTE: Exchange symmetry forbids X^0 to have EW interactions

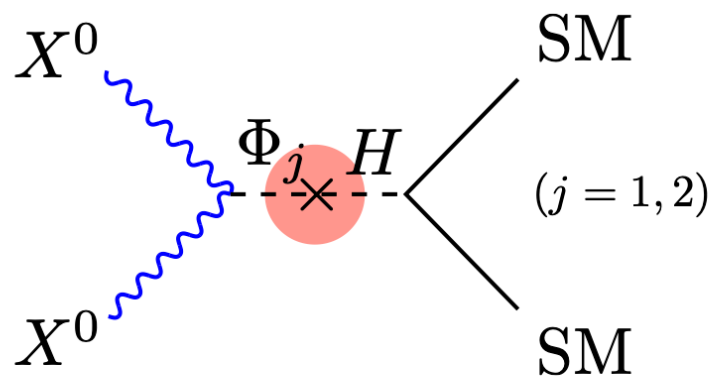
• X^0 do not appear in the $SU(2)_L$ neutral vector state

$$W_\mu^3 = \#A_\mu + \#Z_\mu + \#Z'_\mu \quad \leftarrow \text{No } X^0 \text{ states}$$

• X^0 do not mix with neutral vectors(Z_2 -even) even through the kinetic mixing terms

$$\mathcal{L}_{\text{kinetic}} = \frac{\epsilon_{02}}{4} X_{\mu\nu} X^{\mu\nu} + (\text{mixing btw } Z_2\text{-even vectors})$$

$$X_{\mu\nu} = \partial_\mu X_\nu^0 - \partial_\nu X_\mu^0$$



DM relies on the Higgs mixing in the annihilation process

→ **Strict bound from direct detection**

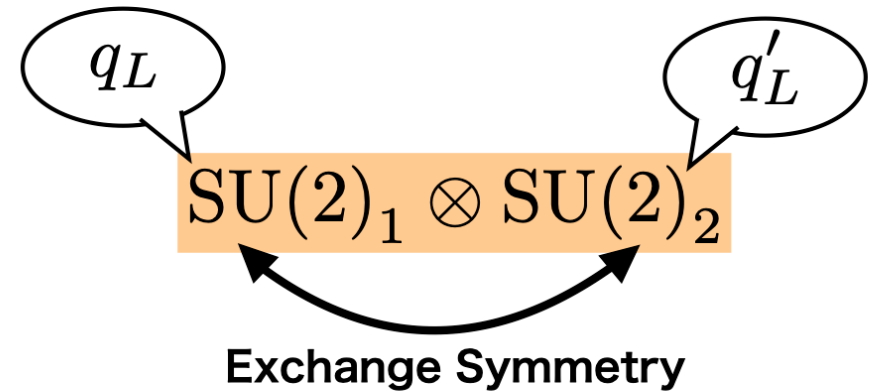
(That is why we choose the non-Abelian extension approach!)

FAQ: Why we need three SU(2) groups?

Answer: To obtain realistic SM fermion spectrum easily.

In two SU(2) case, we need fermion partners to realize exchange symmetry

→ It is hard to obtain realistic SM fermion spectrum



Yukawa sector in our model

$$\mathcal{L} \supset -y_u \bar{q}_L \tilde{H} u_R - y_d \bar{q}_L H d_R - y_e \bar{\ell}_L H e_R + h.c.$$

$$\left[\langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad \tilde{H} = \epsilon H^* \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \right]$$

Matter Contents

field	spin	SU(3) _c	SU(2) ₀	SU(2) ₁	SU(2) ₂	U(1) _Y
q_L	$\frac{1}{2}$	3	1	2	1	$\frac{1}{6}$
u_R	$\frac{1}{2}$	3	1	1	1	$\frac{2}{3}$
d_R	$\frac{1}{2}$	3	1	1	1	$-\frac{1}{3}$
ℓ_L	$\frac{1}{2}$	1	1	2	1	$-\frac{1}{2}$
e_R	$\frac{1}{2}$	1	1	1	1	-1
H	0	1	1	2	1	$\frac{1}{2}$
Φ_1	0	1	2	2	Fermion + H	
Φ_2	0	1	1	2	2	0

Higgs mechanism and Symmetry breaking

Gauge transformation

$$\Phi_1 \rightarrow U_0 \Phi_1 U_1^\dagger, \quad \Phi_2 \rightarrow U_2 \Phi_2 U_1^\dagger$$

$$U_0 = \exp [ig_0 \theta_0(x)]$$

$$U_1 = \exp [ig_1 \theta_1(x)]$$

$$U_2 = \exp [ig_2 \theta_2(x)]$$

Scalar field definition

$$H = \begin{pmatrix} i\pi_3^+ \\ \frac{v + \sigma_3 - i\pi_3^0}{\sqrt{2}} \end{pmatrix}, \quad \Phi_j = \begin{pmatrix} \frac{v_\Phi + \sigma_j + i\pi_j^0}{\sqrt{2}} & i\pi_j^+ \\ i\pi_j^- & \frac{v_\Phi + \sigma_j - i\pi_j^0}{\sqrt{2}} \end{pmatrix}. \quad (j = 1, 2)$$

$\langle \Phi_1 \rangle, \langle \Phi_2 \rangle$ remain unchanged under

• gauge trans. with $U_0 = U_1 = U_2 \leadsto$ **SU(2)_L gauge symmetry**

• exchange $\Phi_1 \leftrightarrow \Phi_2 \rightarrow$ **Exchange symmetry still alive!**

※We reduce degrees of freedom in Φ_j
by assuming the real conditions

$$\Phi_j = -\epsilon \Phi_j^* \epsilon, \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$

Mass Difference and Coannihilation

Loop induced mass difference

$$\text{@tree-level} \quad m_{V_0}^2 = m_{V^\pm}^2 = \frac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$$

$$\text{@loop-level} \quad \delta_{m_V} \equiv m_{V^\pm} - m_{V_0} \simeq 168 \text{ MeV} \ll m_V$$

The same property with the Wino system in MSSM

Coannihilation [\[Kim Griest, David Seckel \(1990\)\]](#)

Thanks to the small δ_{m_V} , all the V-particles exist in the thermal bath near the Freeze out temperature

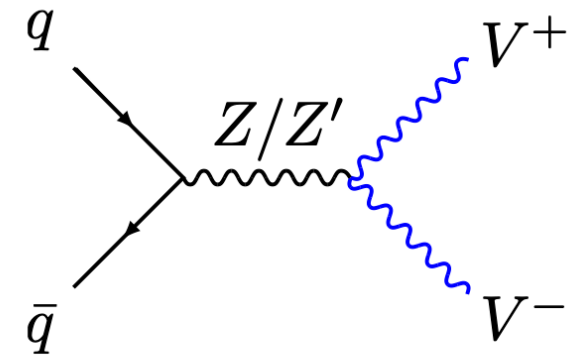
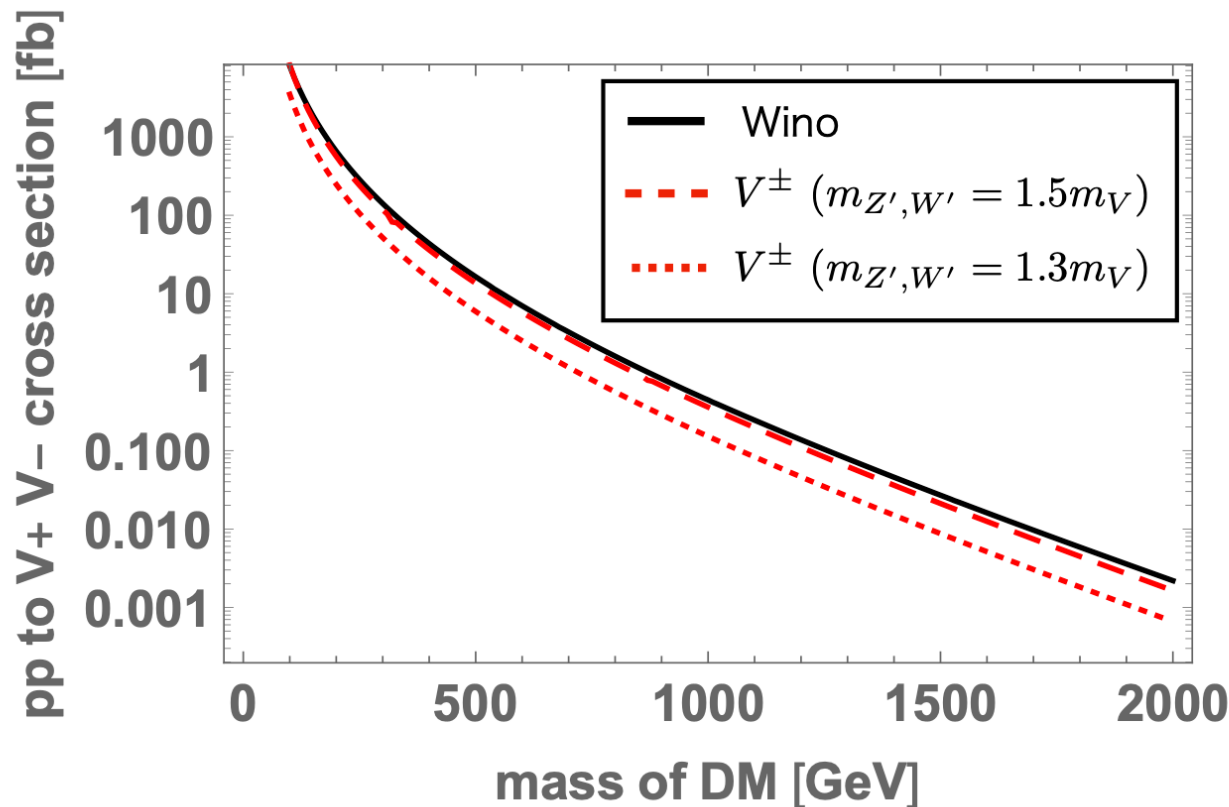
[	Number density in thermal equilibrium	
	$n_{\text{eq}} = g \left(\frac{mT}{2\pi} \right)^{\frac{3}{2}} \exp \left(-\frac{m}{T} \right)$	m : mass
		T : temperature
		g : degrees of freedom

→ All the V-particles contribute to the DM annihilation

Long-lived particle(LLP) search @LHC

$\{V^0, V^\pm\}$ has the similar features as the Wino system in MSSM:

- Decay rate of $V^\pm$ ✓ **Same**
- Mass difference δ_{m_V} ✓ **Same**
- Production rate from pp collision → less production rate than Wino case
due to the interference btw $W(Z)$ and $W'(Z')$



Wino case: $m_{\tilde{W}} \gtrsim 460 \text{ GeV}$

[M. Aaboud, et al [ATLAS Collaboration] (2018)]

LLP search is not relevant
for TeV scale V-particles

Lagrangian

BSM Lagrangian

$$\begin{aligned}\mathcal{L} \supset & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \sum_{j=0}^2 \sum_{a=1}^3 \frac{1}{4}W_{j\mu\nu}^a W_j^{a\mu\nu} \\ & + D_\mu H^\dagger D^\mu H + \frac{1}{2}\text{tr}D_\mu \Phi_1^\dagger D_\mu \Phi_1 + \frac{1}{2}\text{tr}D_\mu \Phi_2^\dagger D_\mu \Phi_2 \\ & - V_{\text{scalar}},\end{aligned}$$

Scalar potential

$$\begin{aligned}V_{\text{scalar}} = & m^2 H^\dagger H + m_\Phi^2 \text{tr} \left(\Phi_1^\dagger \Phi_1 \right) + m_\Phi^2 \text{tr} \left(\Phi_2^\dagger \Phi_2 \right) \\ & + \lambda (H^\dagger H)^2 + \lambda_\Phi \left(\text{tr} \left(\Phi_1^\dagger \Phi_1 \right) \right)^2 + \lambda_\Phi \left(\text{tr} \left(\Phi_2^\dagger \Phi_2 \right) \right)^2 \\ & + \lambda_{h\Phi} H^\dagger H \text{tr} \left(\Phi_1^\dagger \Phi_1 \right) + \lambda_{h\Phi} H^\dagger H \text{tr} \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_{12} \text{tr} \left(\Phi_1^\dagger \Phi_1 \right) \text{tr} \left(\Phi_2^\dagger \Phi_2 \right).\end{aligned}$$

Bounded from Below(BFB) conditions

BFB conditions in our model

$$\lambda > 0,$$

$$\lambda_{\Phi} > 0,$$

$$\lambda_{\Phi} + \frac{\lambda_{12}}{2} > 0,$$

$$\frac{\lambda_{h\Phi}}{2} + \sqrt{\lambda\lambda_{\Phi}} > 0,$$

$$\begin{cases} \lambda_{h\Phi} \geq 0, \\ \text{or} \\ \lambda_{h\Phi} < 0 \text{ and } \lambda \left(\lambda_{\Phi} + \frac{\lambda_{12}}{2} \right) - \frac{\lambda_{h\Phi}^2}{2} > 0. \end{cases}$$

✂ We find **all the BFB conditions are automatically satisfied** by using the the expressions of scalar quartic couplings

$$\begin{aligned} \lambda &= \frac{m_h^2 \cos^2 \phi_h + m_{h'}^2 \sin^2 \phi_h}{2v^2}, & \lambda_{\Phi} &= \frac{m_h^2 \sin^2 \phi_h + m_{h'}^2 \cos^2 \phi_h + m_{h_D}^2}{16v_{\Phi}^2}, \\ \lambda_{h\Phi} &= -\frac{\sin \phi_h \cos \phi_h}{2\sqrt{2}vv_{\Phi}}(m_{h'}^2 - m_h^2), & \lambda_{12} &= \frac{m_h^2 \sin^2 \phi_h + m_{h'}^2 \cos^2 \phi_h - m_{h_D}^2}{8v_{\Phi}^2}. \end{aligned}$$

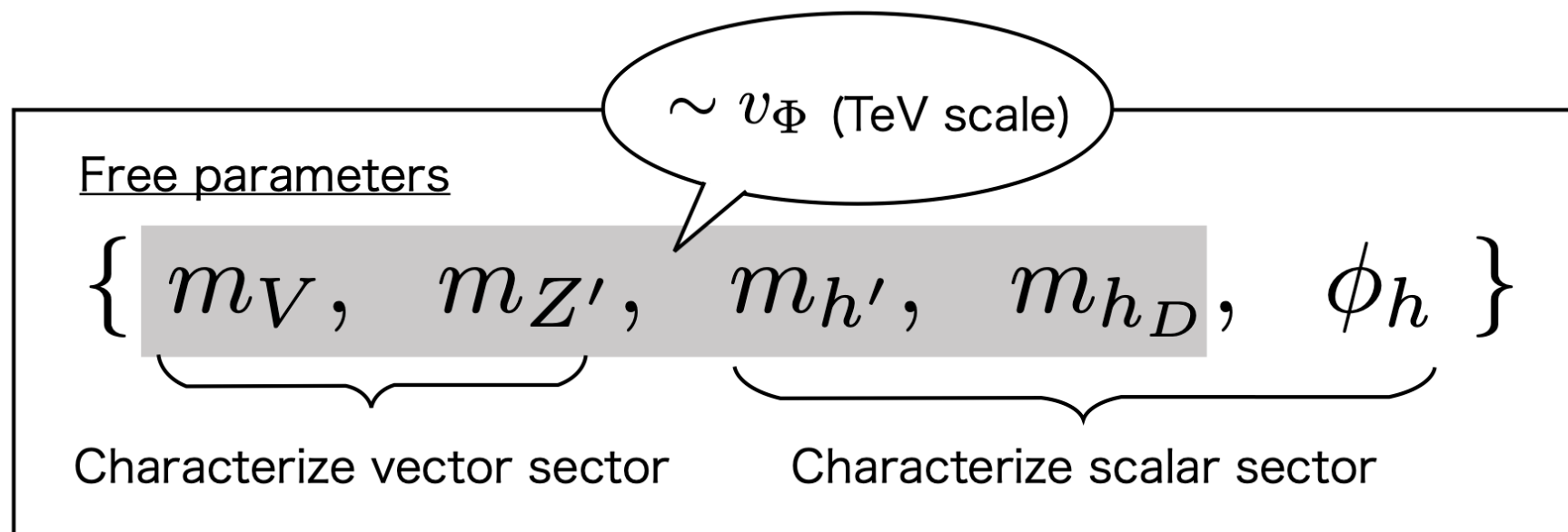
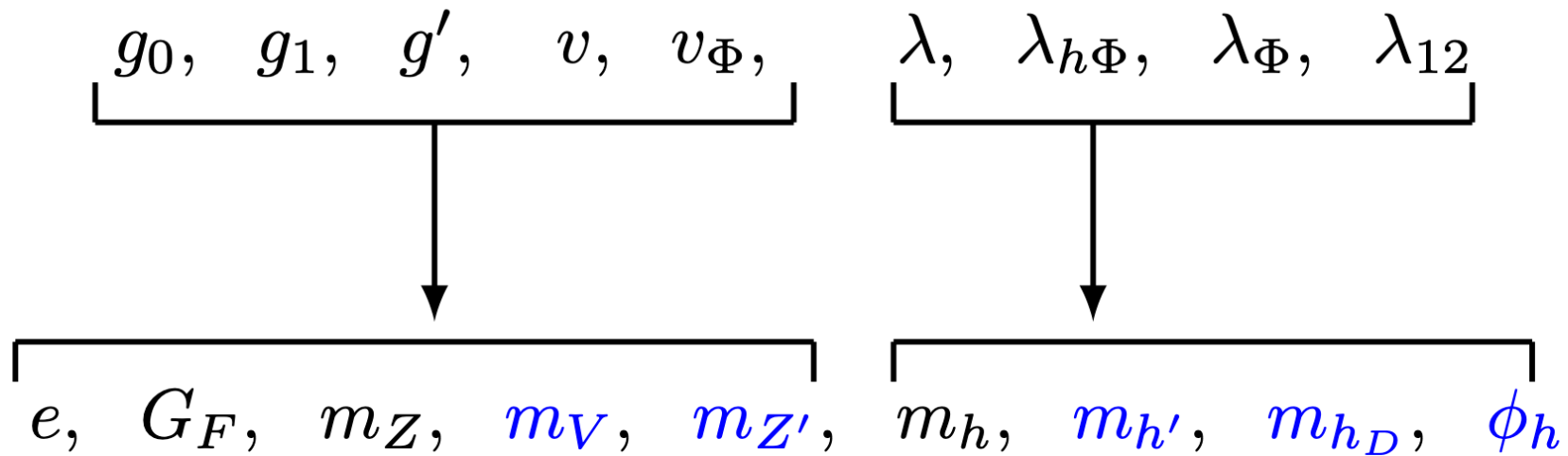
Results

[T. Abe, MF, J. Hisano, K. Matsushita [arXiv:2005.00884]]

For more details

Parameters in BSM sector

ϕ_h : mixing angle of
Z₂-even scalars

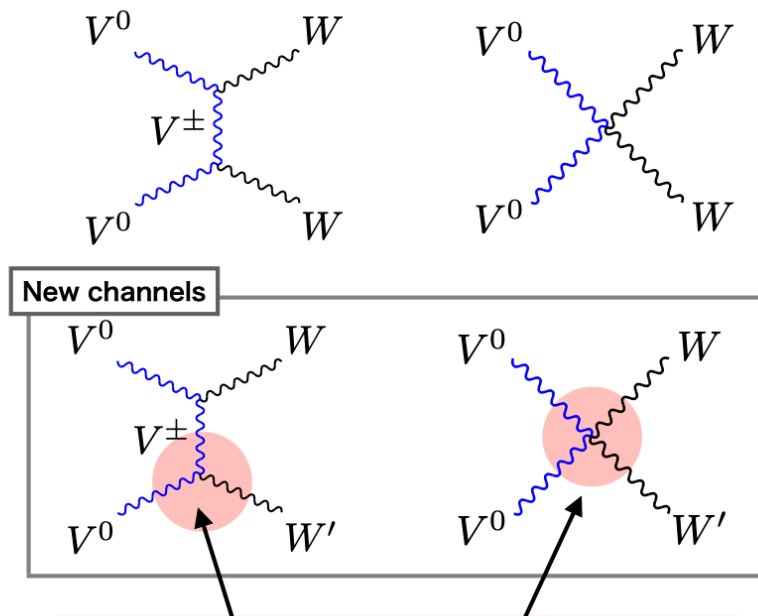


Ωh^2 contour: $m_{Z'} \gtrsim m_V$

DM pair can annihilate into the final states with W', Z'

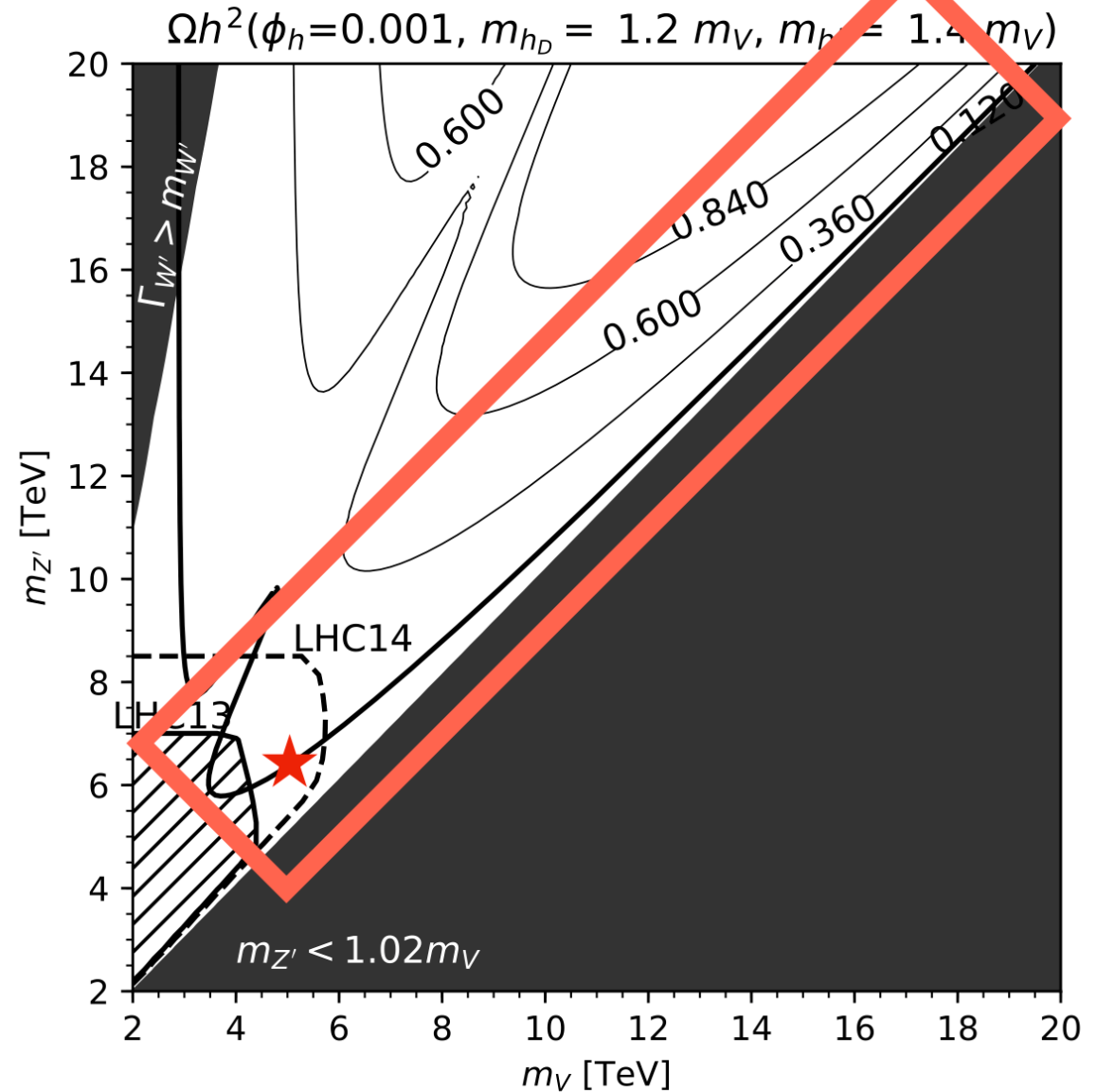
→ $\Omega h^2=0.12$ is achieved in heavier m_V region

Annihilation Channel



$$\frac{1}{\sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}} \quad \text{Enhancement factor in } m_{Z'}/m_V \sim 1$$

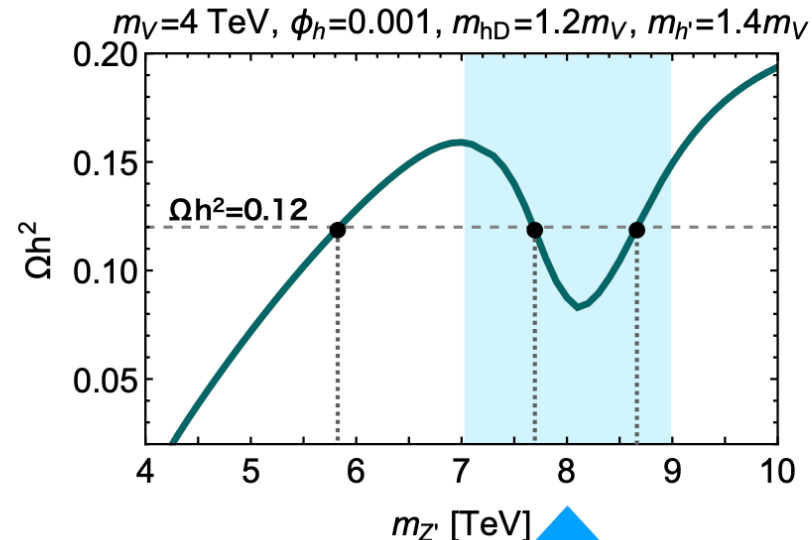
★: benchmark point
($m_V=5$ TeV, $m_{Z'}=6.5$ TeV)



※ Ωh^2 -contours are degenerated for $\phi_h \lesssim 0.001$

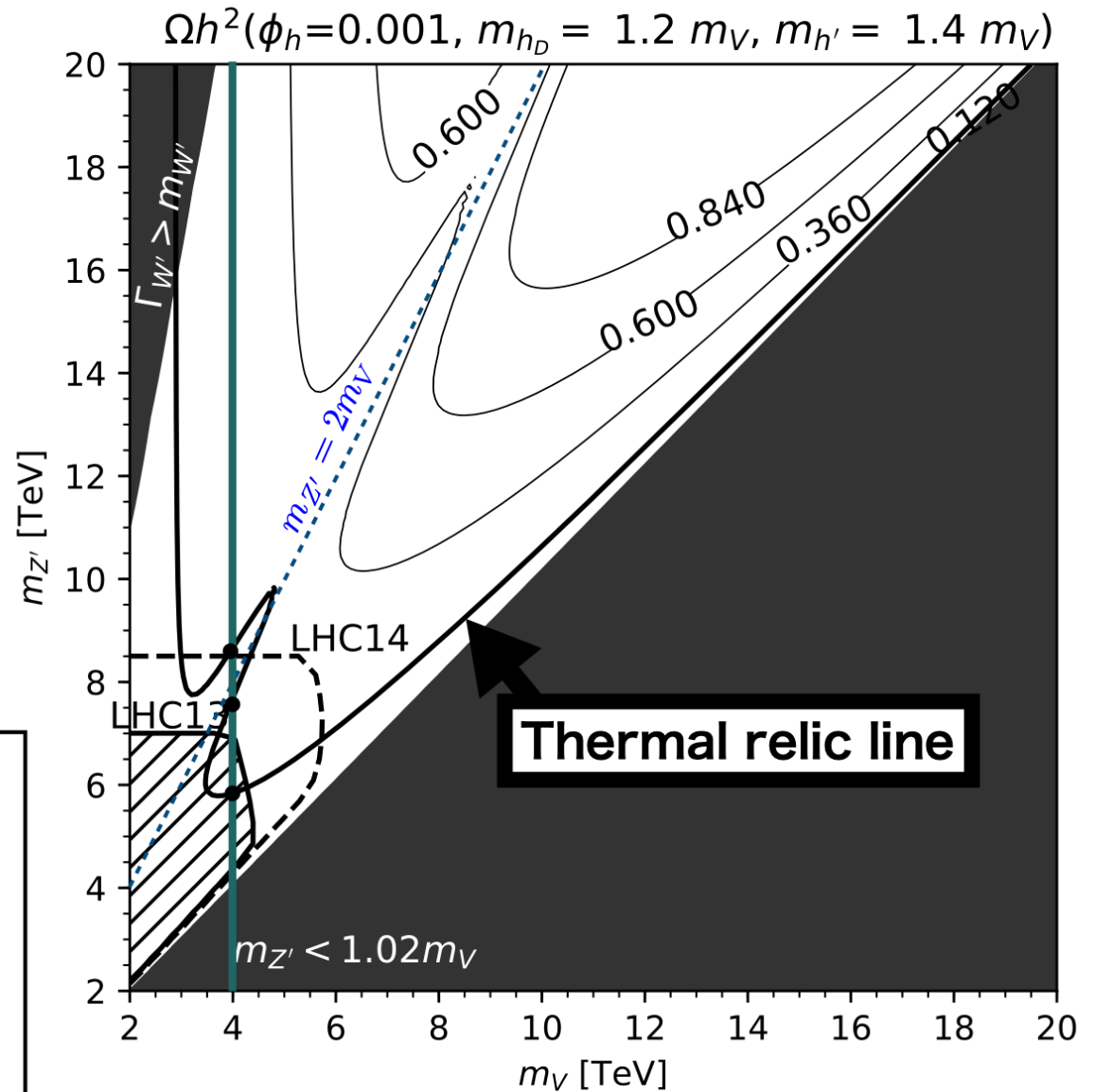
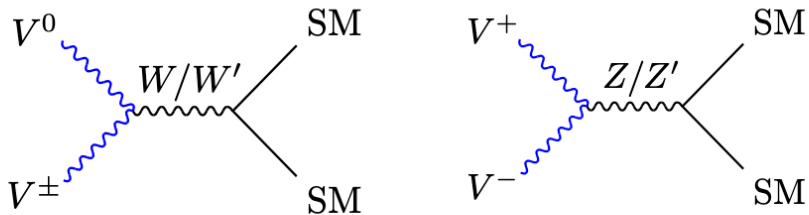
Resonance region in Ωh^2 contour

Contours of Ωh^2



$$m_{Z'} \sim 2m_V$$

resonance region of Z'/W' channel



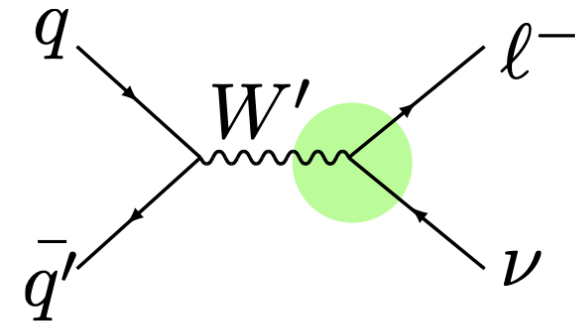
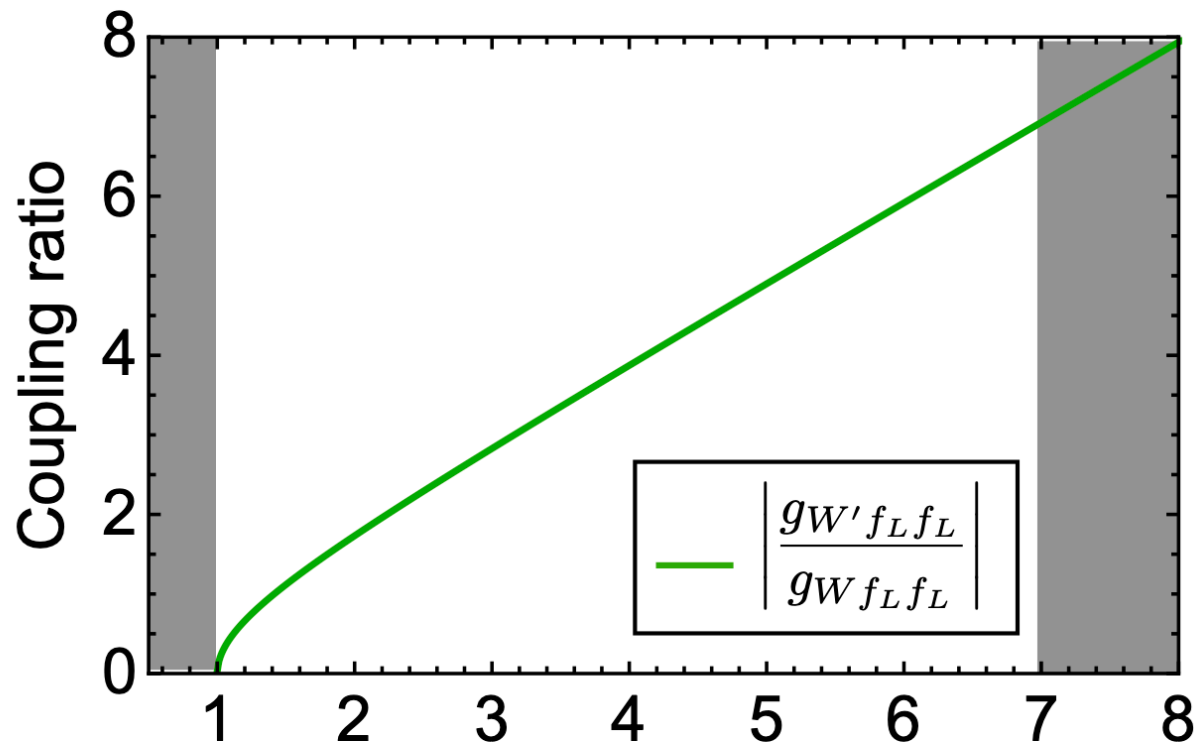
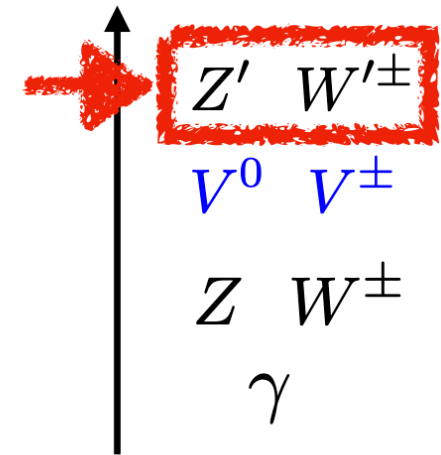
Viable Region: W' physics

W' -fermion coupling

$$\left| \frac{g_{W'} f_L f_L}{g_W f_L f_L} \right| \sim \sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}$$

$$m_{Z'} \sim m_{W'} \quad (v_\Phi \gg v)$$

cf. Vector Spectrum



→ TeV scale W' search may constrain the parameter region

※ Assuming $v_\Phi \gg v$ $m_{Z'}/m_V$

Why so large W'-f-f coupling?

Fermions have SU(2)₁ charge only

$$\begin{pmatrix} V^\pm \\ W^\pm \\ W'^\pm \end{pmatrix} = \begin{pmatrix} 1 & & \\ & \cos \phi_\pm & \sin \phi_\pm \\ & -\sin \phi_\pm & \cos \phi_\pm \end{pmatrix} \begin{pmatrix} \frac{1}{\sqrt{2}} & 0 & -\frac{1}{\sqrt{2}} \\ 0 & 1 & 0 \\ \frac{1}{\sqrt{2}} & 0 & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} (W^0)^\pm \\ (W^1)^\pm \\ (W^2)^\pm \end{pmatrix}$$

↑
mixing btw Z₂-even charged vectors

$$\mathcal{L} \supset \frac{g_1}{\sqrt{2}} (W_1^-)_\mu \bar{\ell} \gamma^\mu P_L \nu$$

$$\supset \frac{g_1 \cos \phi_\pm}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L \nu - \frac{g_1 \sin \phi_\pm}{\sqrt{2}} W'_\mu \bar{\ell} \gamma^\mu P_L \nu$$

$$= \frac{g_W f_L f_L}{\sqrt{2}} W_\mu \bar{\ell} \gamma^\mu P_L \nu + \frac{g_{W'} f_L f_L}{\sqrt{2}} W'_\mu \bar{\ell} \gamma^\mu P_L \nu$$

$m_{Z'}/m_V$	g_1	$ g_{W'} f_L f_L / g_W f_L f_L $
1.02	0.661	0.207
1.05	0.680	0.321
$\sqrt{2}$	0.916	1
4.63	3	4.52
5.45	3.53	5.36
6.97	4.53	6.90

$$\left| \frac{g_{W'} f_L f_L}{g_W f_L f_L} \right| = \frac{g_1 \sin \phi_\pm}{g_1 \cos \phi_\pm} \quad \Downarrow$$

↑
fixed as SM value

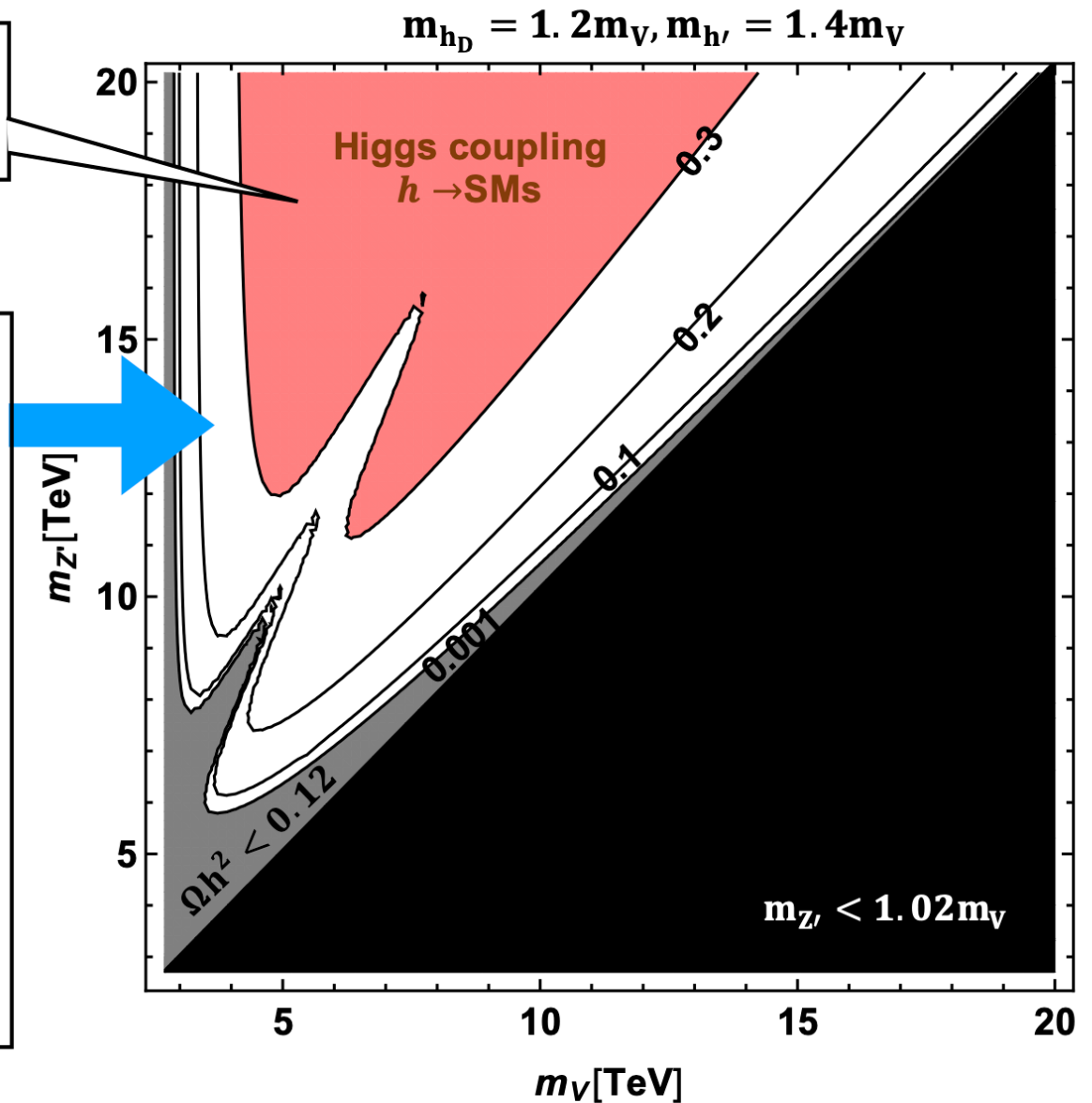
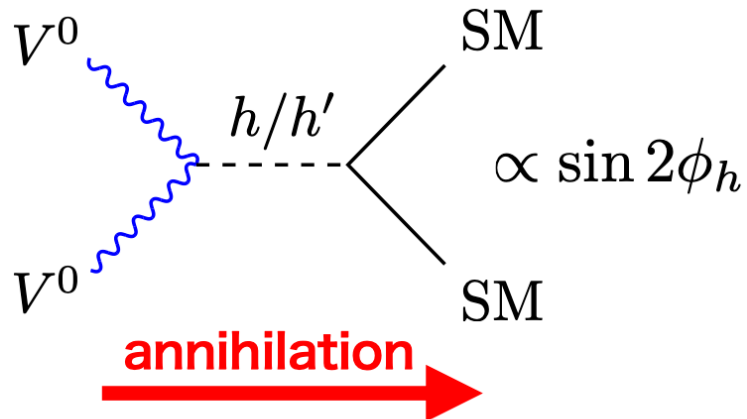
$(\text{large } g_1) \times (\text{large } \sin \phi_\pm) = (\text{large } g_{W'} f_L f_L)$

ϕ_h contours: (1/3)

We need $|\phi_h| > 0.3$
to obtain $\Omega h^2 \sim 0.12$

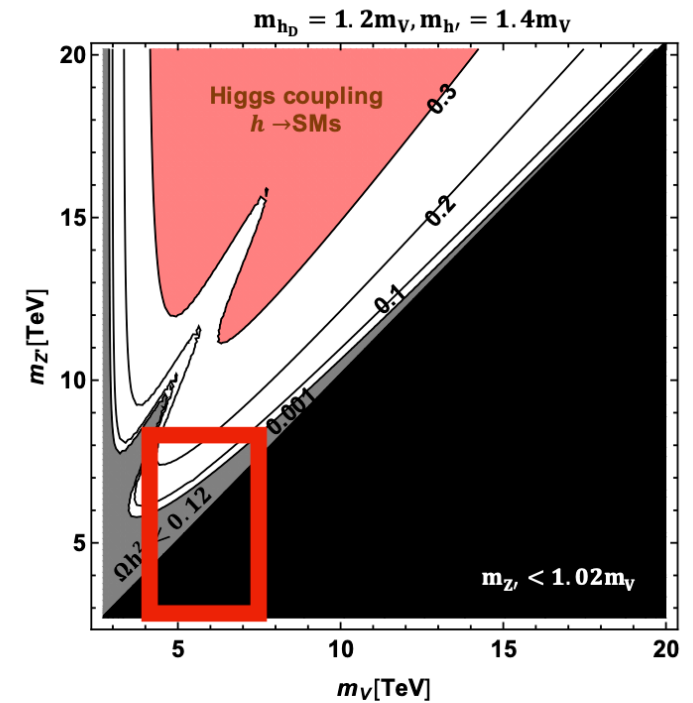
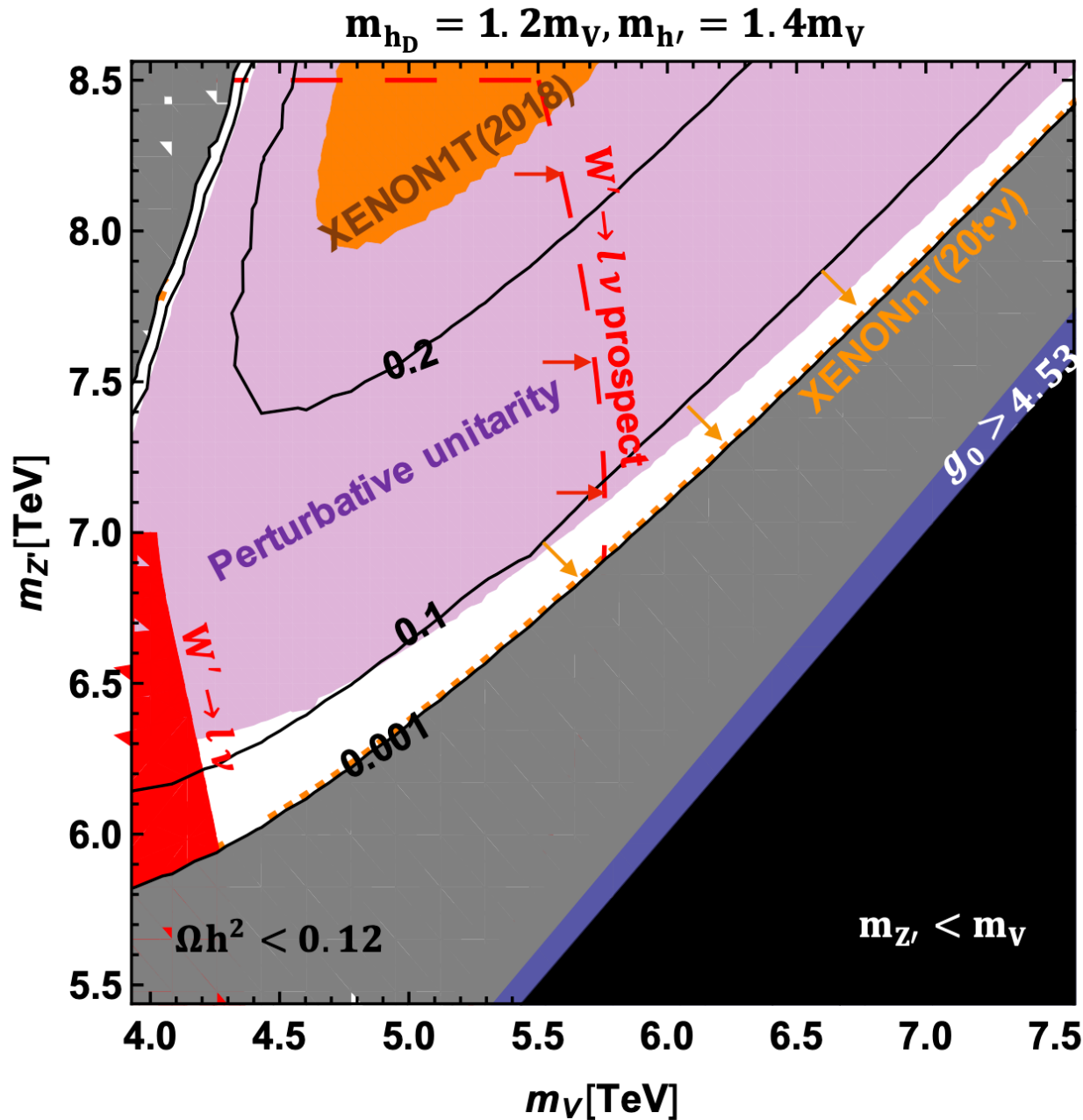
White region:

$\Omega h^2 \sim 0.12$ is achieved
by adjusting ϕ_h



→ Constraints on this plane? (Next page)

ϕ_h contours: (2/3)



Relatively large ϕ_h

→ Constrained from

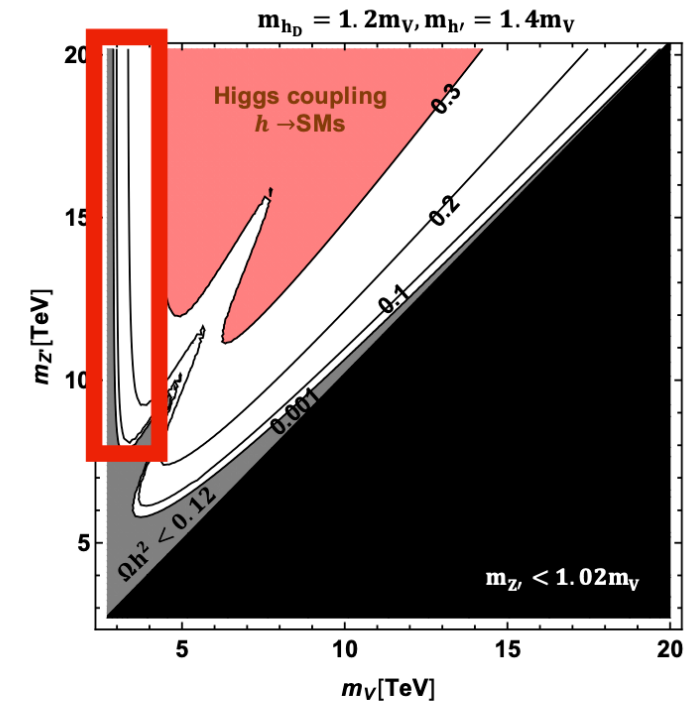
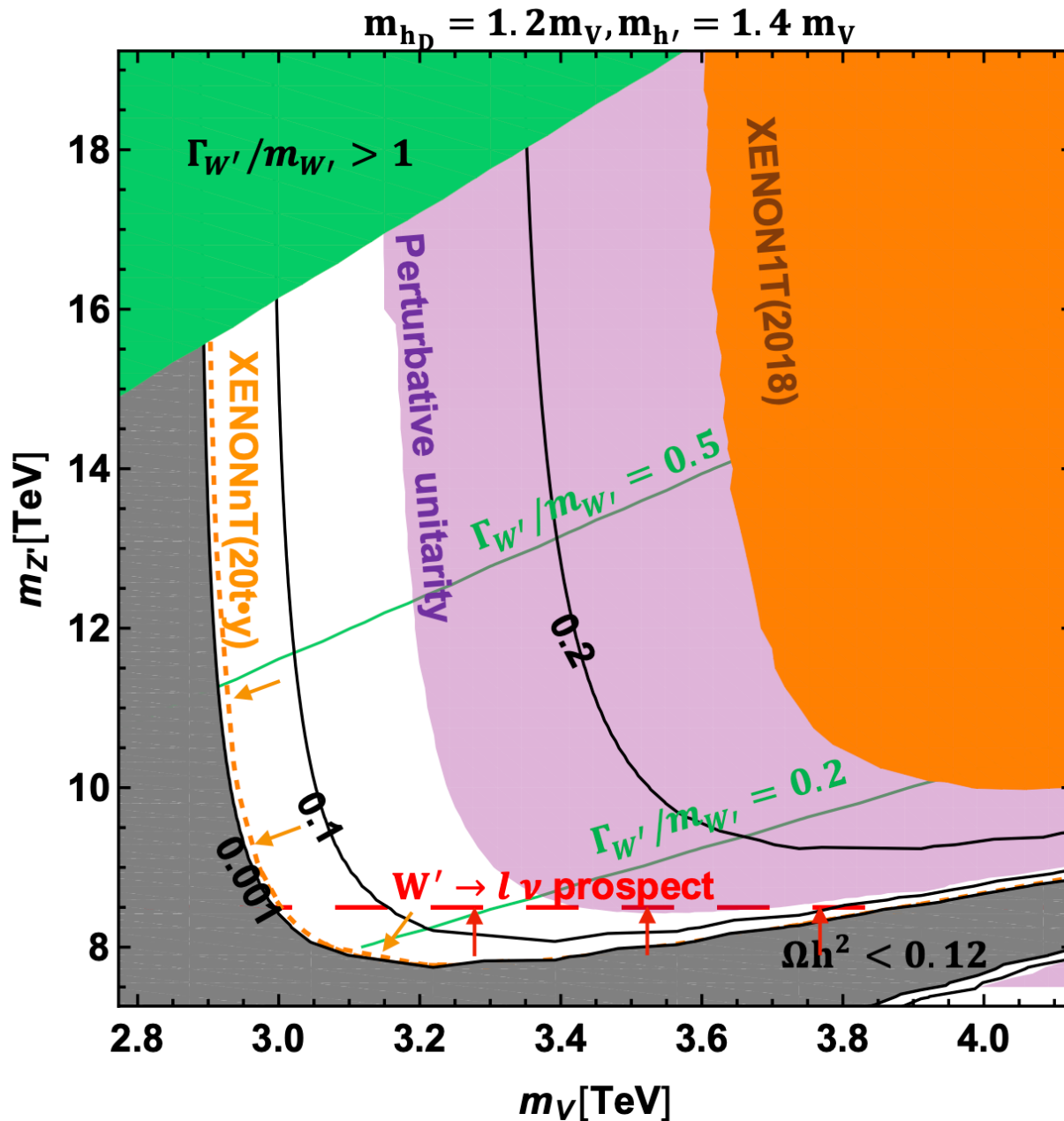
- XENON1T result
- Perturbative unitarity for scalar coupling

Very small ϕ_h

→ Proved by

- Future direct detection ($|\phi_h| < 0.001$)
- W' search by HL-LHC

ϕ_h contours: (3/3)



- Large ϕ_h region is already constrained from
 - perturbative unitarity
 - XENON1T result
- Future direct detection can cover large region $|\phi_h| \gtrsim 0.001$