電弱相互作用を行うベクトル暗黒物質理論の模型構築とその現象論

(A model of electroweakly interacting non-abelian vector dark matter)

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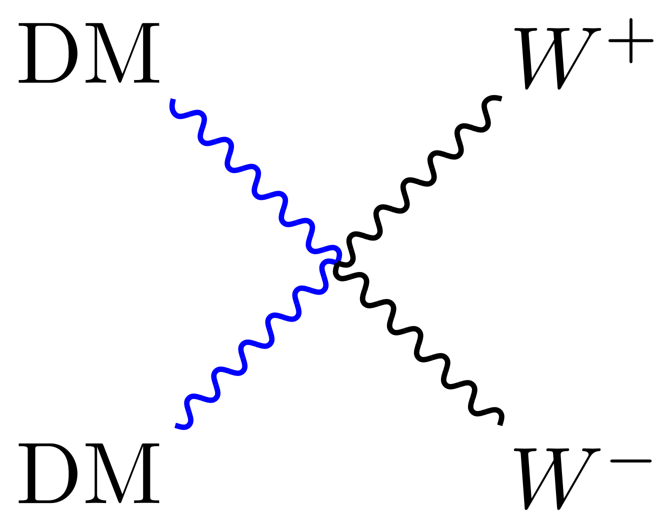
based on: T. Abe, MF, J. Hisano, K. Matsushita, [arXiv:2004.00884]

Presentation @新学術「地下宇宙」領域研究会(Zoom) June, 2nd, 2020

Overview

We propose a model of
electroweakly interacting spin-1 dark matter (DM)



Feature: Rich annihilation channels for DM

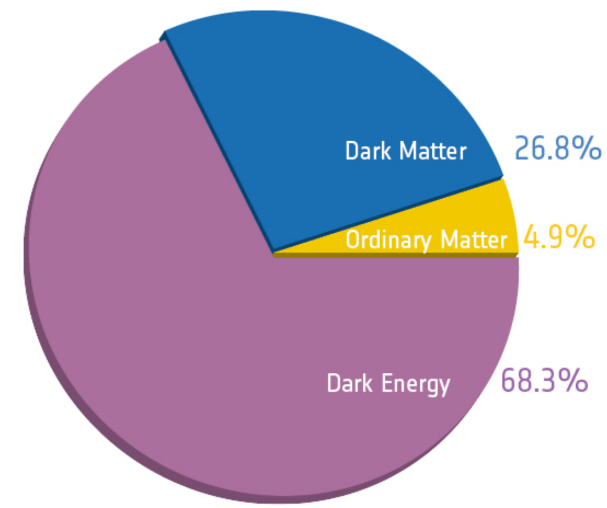
➡ **Correct DM energy density is explained while evading the current experimental bound**

Introduction: WIMP scenario Dark Matter

Dark Matter (DM) energy density

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

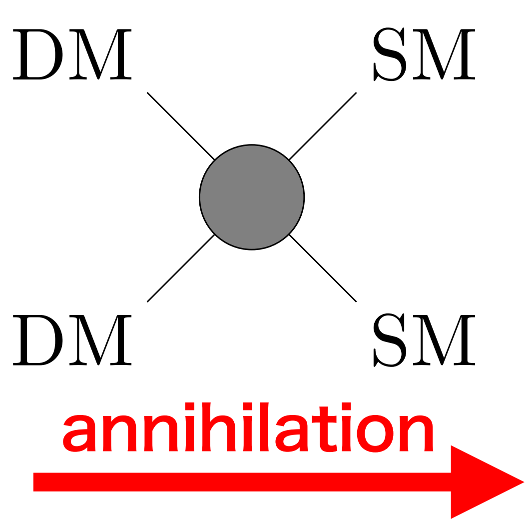
[Planck Collaboration arXiv:1807.06209]

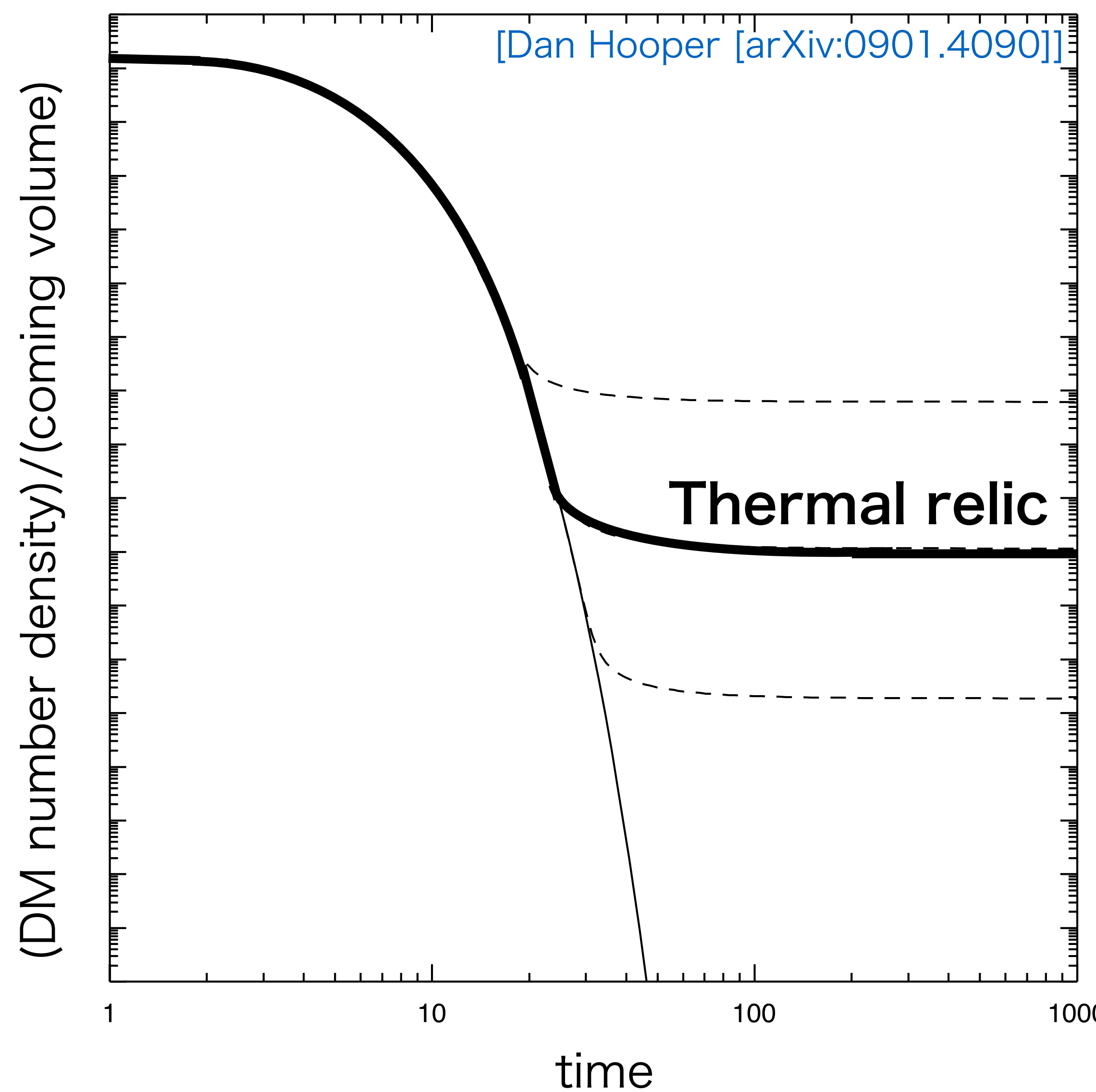


https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe

WIMP scenario

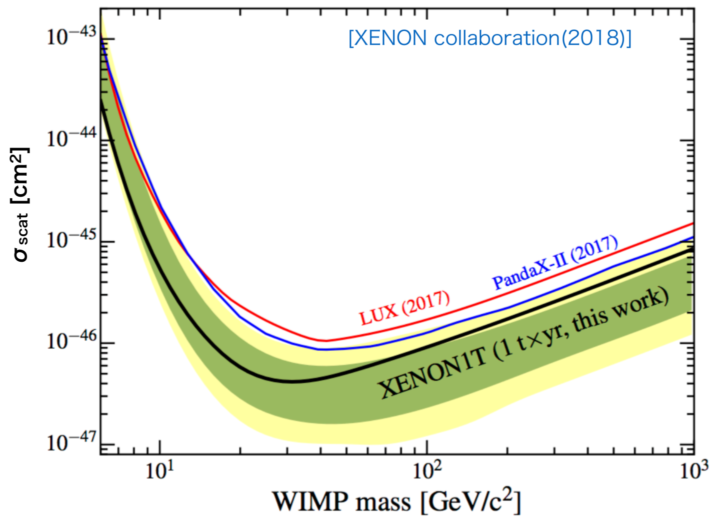
DM is assumed to have interactions w/ Standard Model (SM) particles



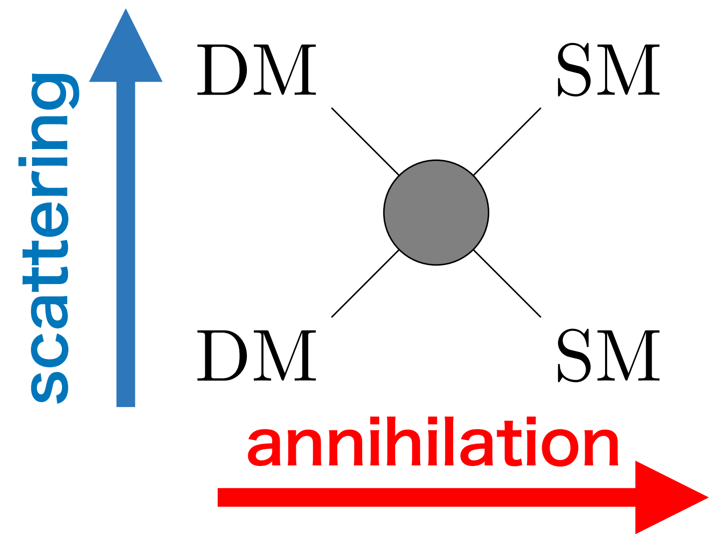


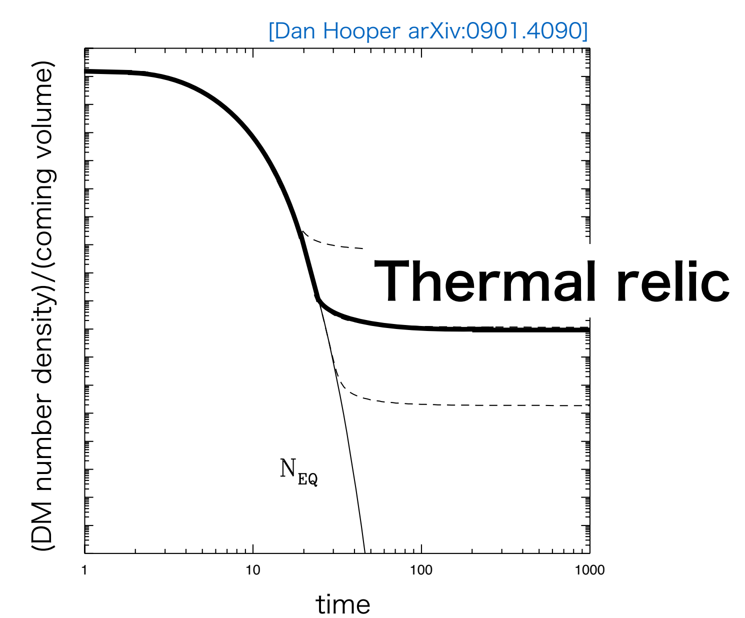
To obtain Ωh²=0.12, we need sufficient DM annihilation rate: $\langle \sigma_{\rm anni} v \rangle \simeq 3 \times 10^{-26}\ {\rm cm}^3/{\rm s}$

Introduction: WIMP scenario vs Direct Detection



Small σ_{scat} to explain direct detection null signal





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

<u>We must break the correlation between Annihilation and Scattering</u>

→ We consider mechanism in spin-1 DM model

Existing Models (review)

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

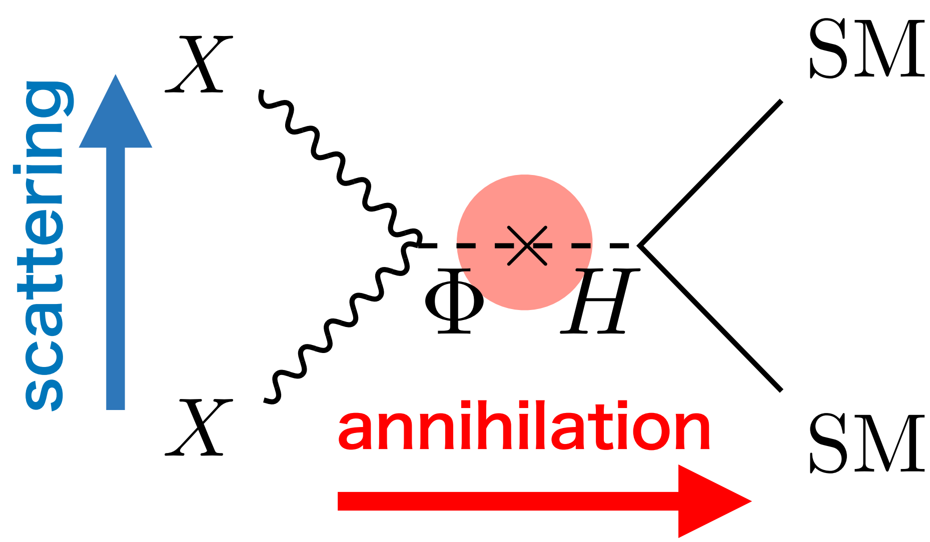
$$\boxed{\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_X \otimes \mathrm{U}(1)_Y}$$

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

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

X^a_μ : $\mathrm{SU}(2)_X$ gauge boson

Φ : $\mathrm{SU}(2)_X$ doublet scalar



DM Annihilation relies on Higgs exchange

We need other annihilation channels to break the correlation!

Trial:

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

???

How can we realize

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

Our Model

Symmetry

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

Exchange Symmetry

$$\boxed{\Phi_1 \leftrightarrow \Phi_2, \; W^a_{0\mu} \leftrightarrow W^a_{2\mu}}$$

※ gauge coupling: $g_0 = g_2$

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
			$W^a_{0\mu}$	$W^a_{1\mu}$	$W^a_{2\mu}$	

Fermion sector

Each field corresponds to SM fermion

Scalar sector

Φ_1, Φ_2 : Bi-fundamental fields

Z_2-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: $\boxed{\sigma_1 \leftrightarrow \sigma_2, \; W^a_{0\mu} \leftrightarrow W^a_{2\mu}}$

Z_2-odd states

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

DM

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

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

"V-particles"

- $U(1)_{em}$ charge eigenstates
- **Z_2-odd states** under exchange symmetry
- **Mass eigenstates**
  (∵ No off-diagonal elements in mass matrix)

Exchange symmetry $\mathrm{SU}(2)_0 \leftrightarrow \mathrm{SU}(2)_2$

$\Longleftrightarrow$ **Z_2-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

Vector	Scalar	Z_2-Parity	Mass	
Z' $W'^{\pm}$	h'	**even**	$\sim v_\Phi$	$\mathcal{O}(1)$ TeV
V^0 $V^{\pm}$	h_D	**odd**		
Z $W^{\pm}$	h	**even**	$\sim v$	$\mathcal{O}(100)$ GeV
γ		**even**		massless

"V-particles"

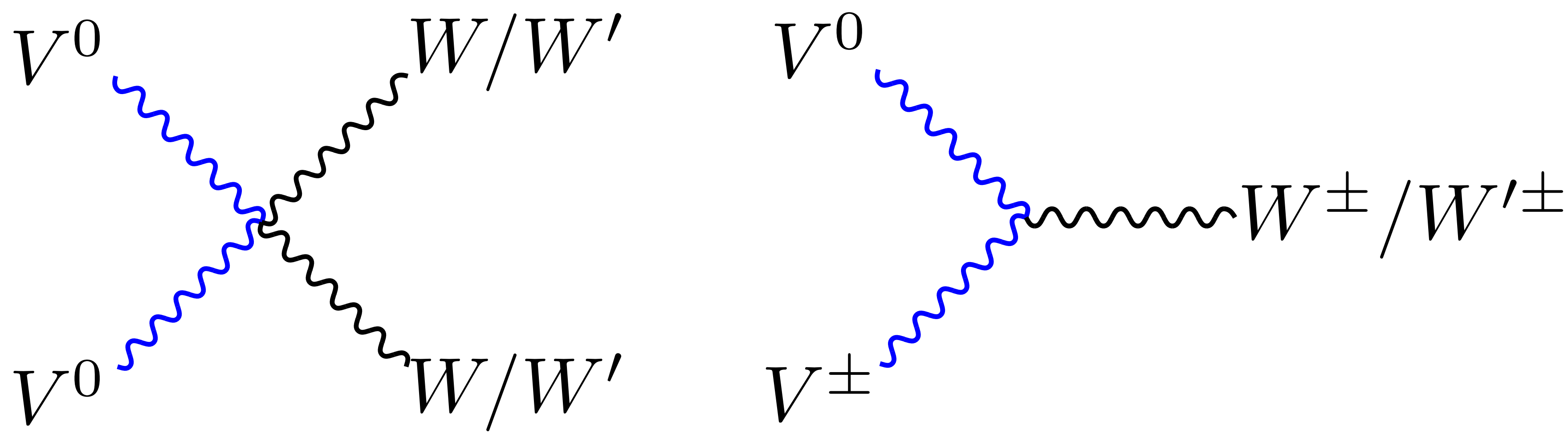
★SM limit: $v_\Phi \to \infty$ (All the BSM particles are decoupled from the SM sector)

★We need NO BSM fermions to realize the SM spectrum

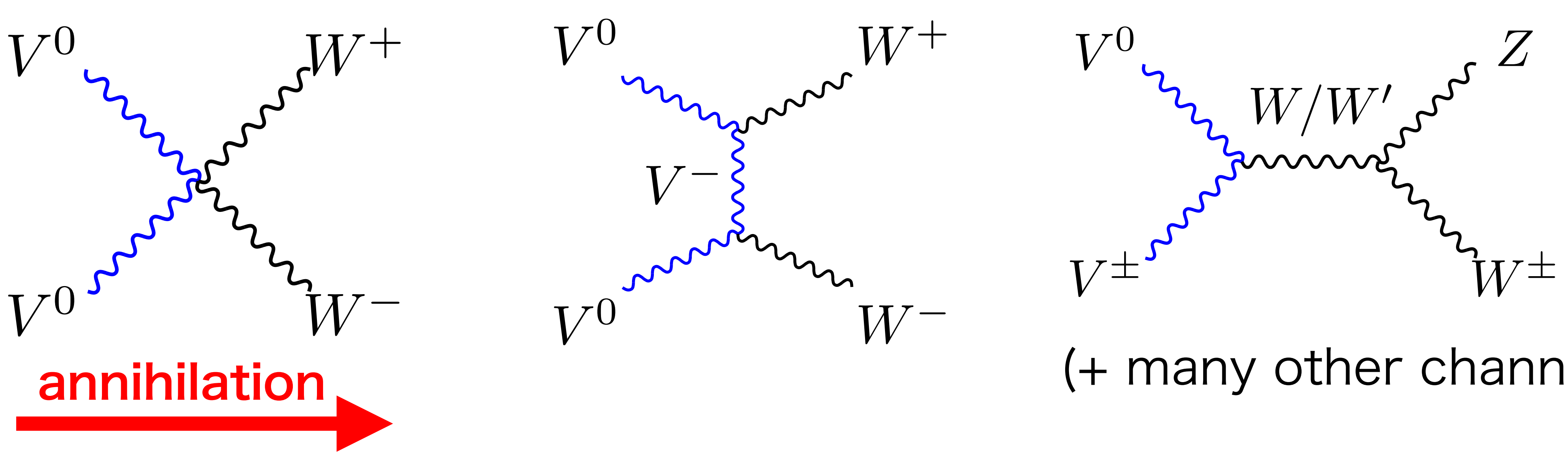
$$\mathcal{L} \supset -y_u \bar{q}_L \tilde{H} u_R - y_d \bar{q}_L H d_R - y_e \bar{\ell}_L H e_R + h.c. \qquad \left[\tilde{H} = \epsilon H^\star \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \right]$$

Annihilation through Non-Abelian couplings

Feature: V-particles have Non-Abelian vector couplings



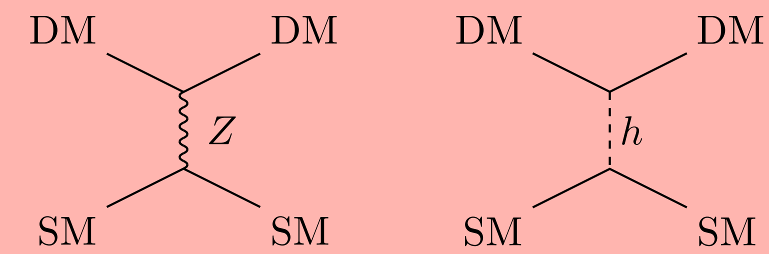
Spin-1 DM has various annihilation channels!



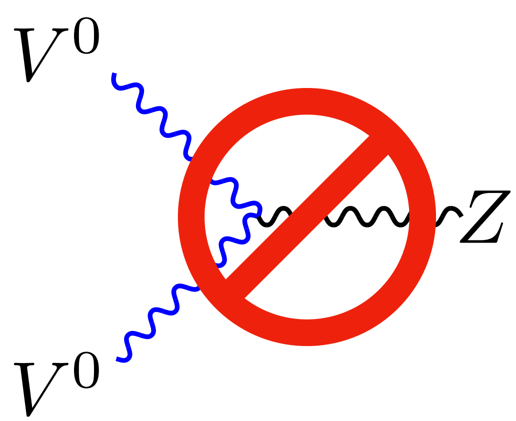
(+ many other channels)

Annihilation vs Scattering

Dangerous scattering channels



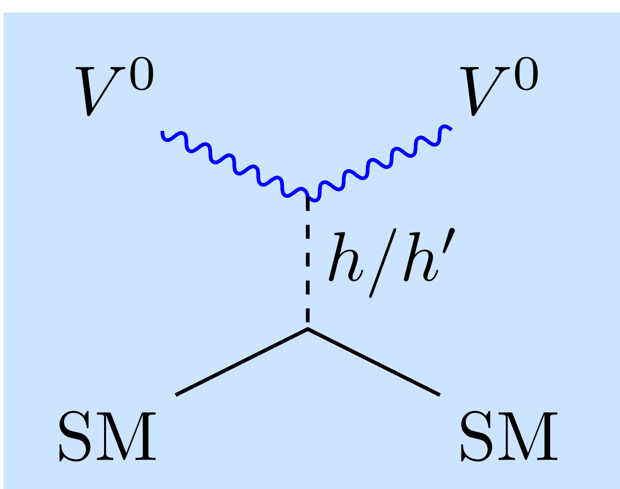
Z-exchange process

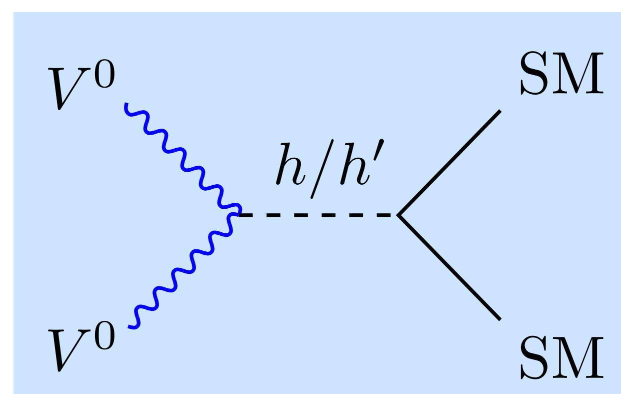


Neutral vector triple coupling is forbidden in non-Abelian extension

→ No Z-exchange in scattering process!

Higgs-exchange process





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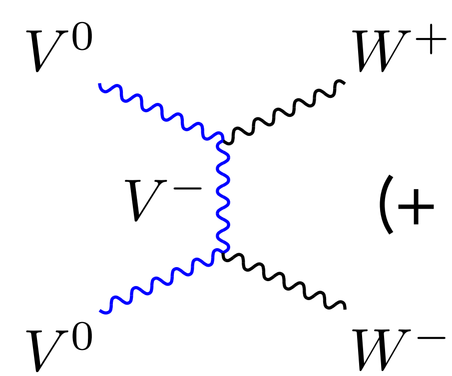


(+ many)

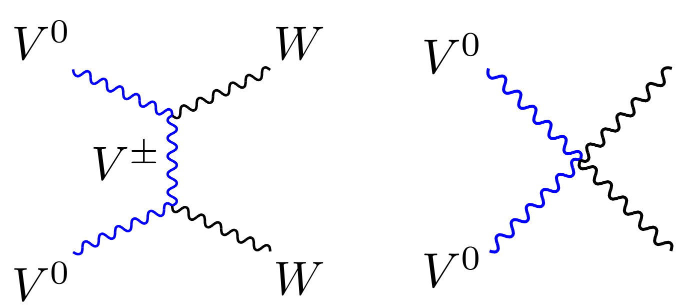
→ We do not need Higgs exchange process to obtain $\Omega h^2 \sim 0.12$

We can break correlation between Annihilation and Scattering process!

Ωh^2 contours

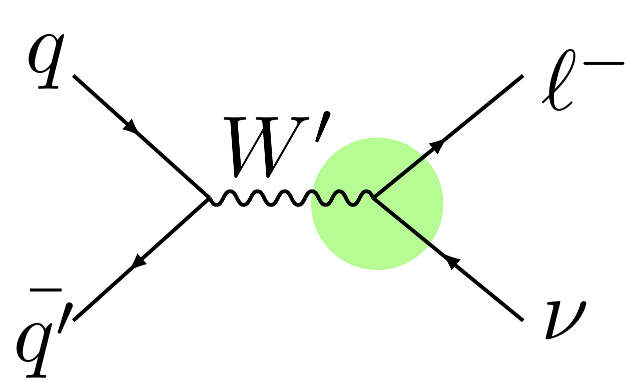
$\Omega h^2 = 0.12 \Rightarrow m_V \gtrsim 3\ \mathrm{TeV}$

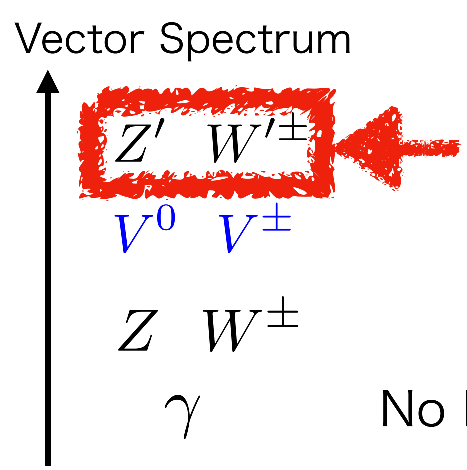
Annihilation channels



(+ many)

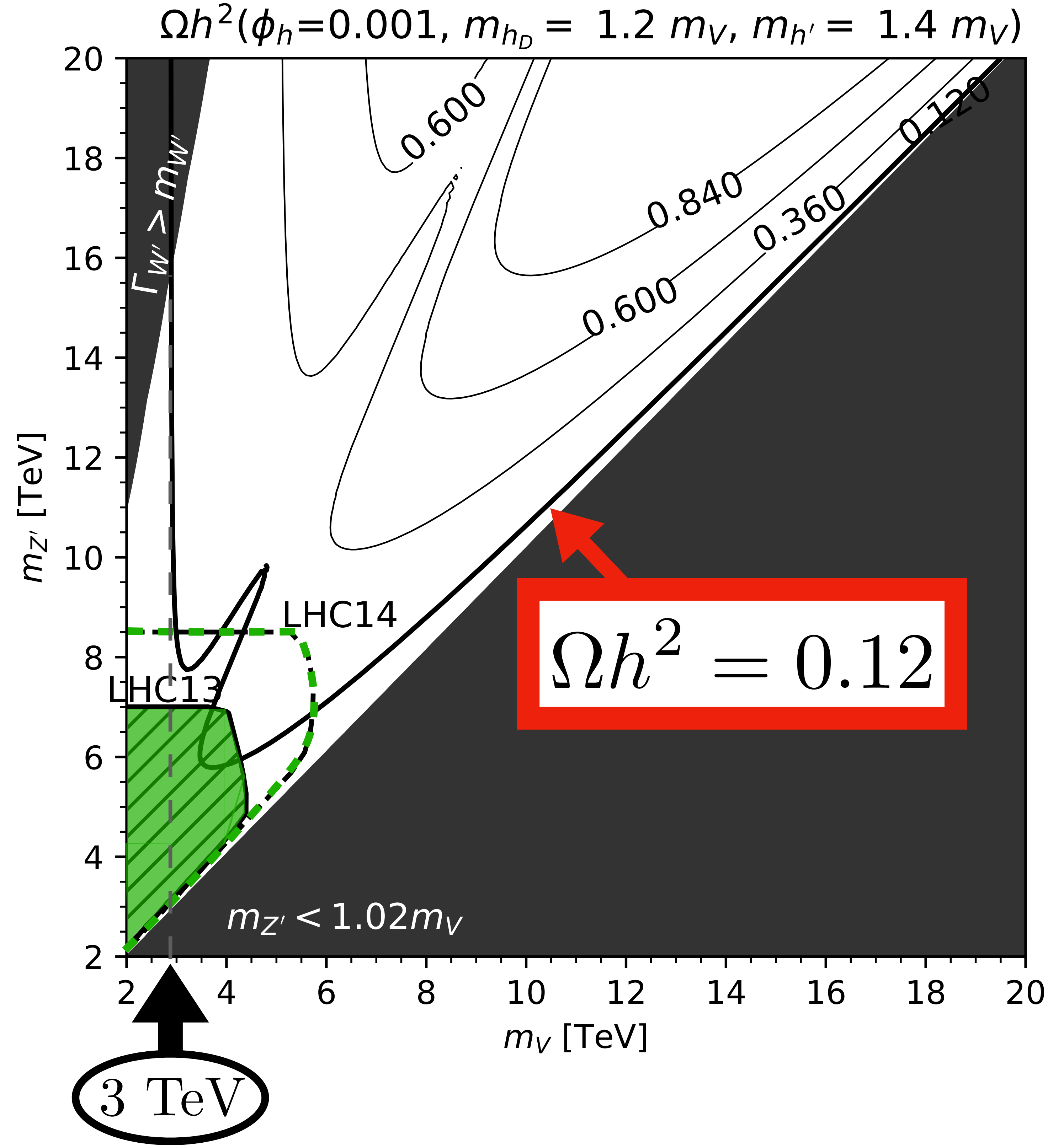
W' search @LHC [ATLAS Collabolation(2019)]





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

No bound for $m_{W'} > 7\ \mathrm{TeV}$



ϕ_h : mixing angle of Z2-even scalars

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

Summary

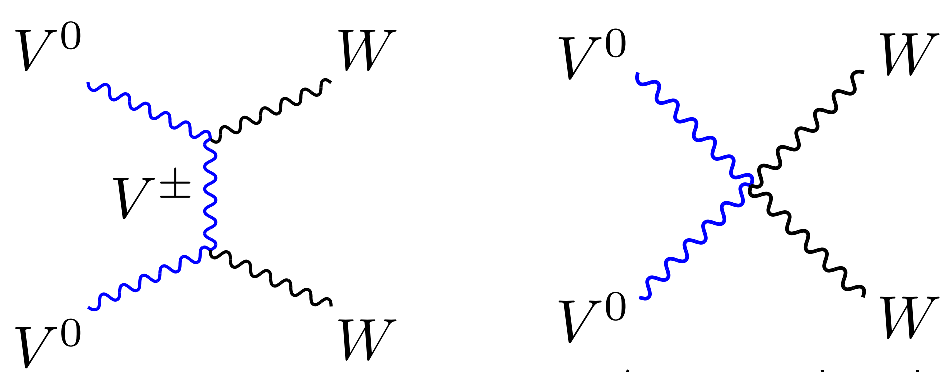
- ・Non-Abelian extension of EW symmetry
- ・Imposing exchange symmetry of SU(2)

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

Exchange Symmetry

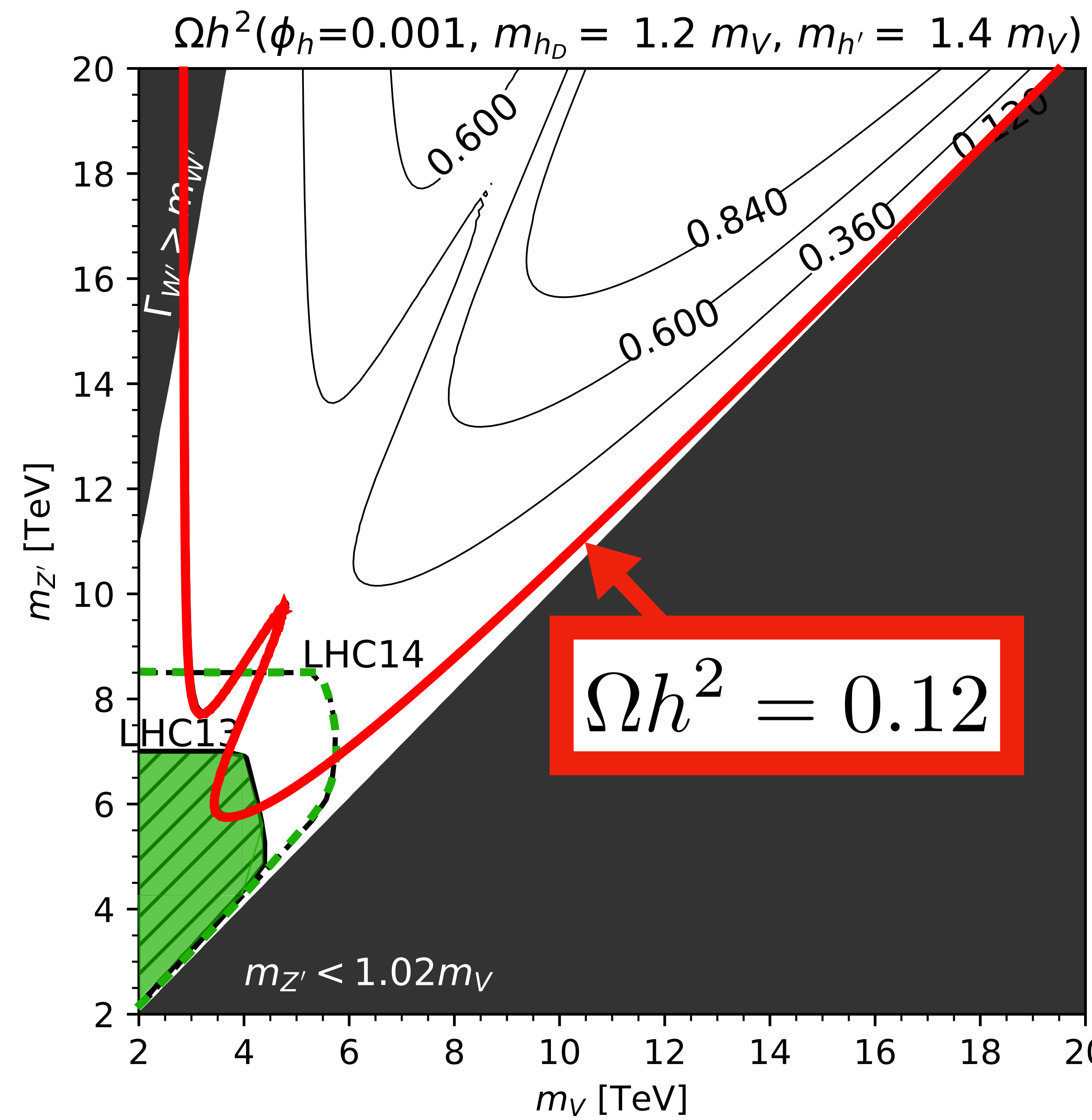
・**Z₂-odd vectors:** $V^0, V^\pm$

・**Non-Abelian EW couplings**



(+ many other channels)

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



<u>Test of TeV scale WIMP scenario</u>

→ W' search @LHC is viable!

Back Up

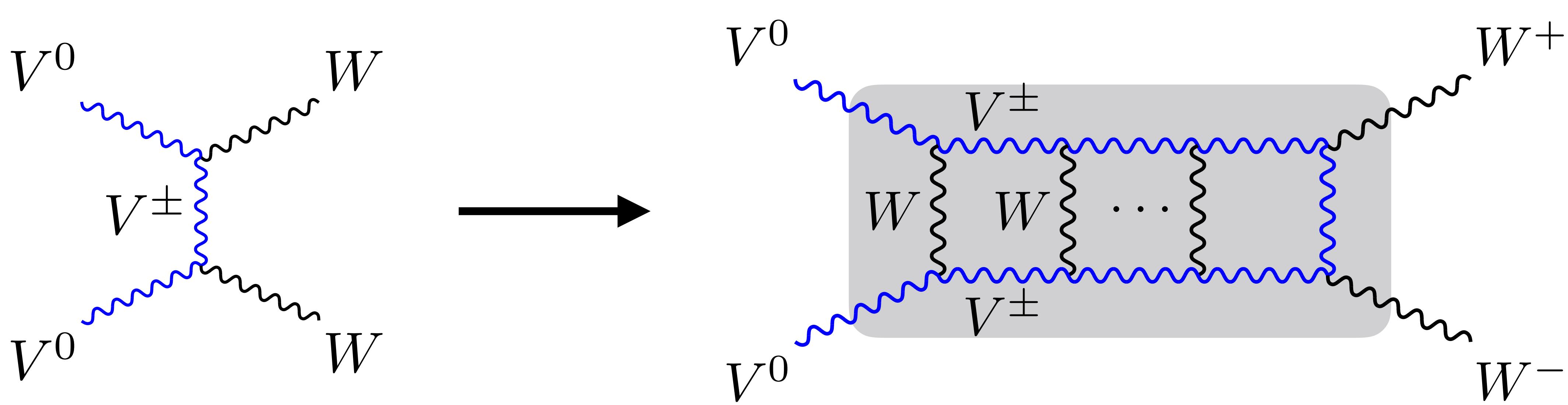
Future Work

Result in this work

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

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)

Our Model

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

For more details

[N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)]

Introduction: (De)construction technique

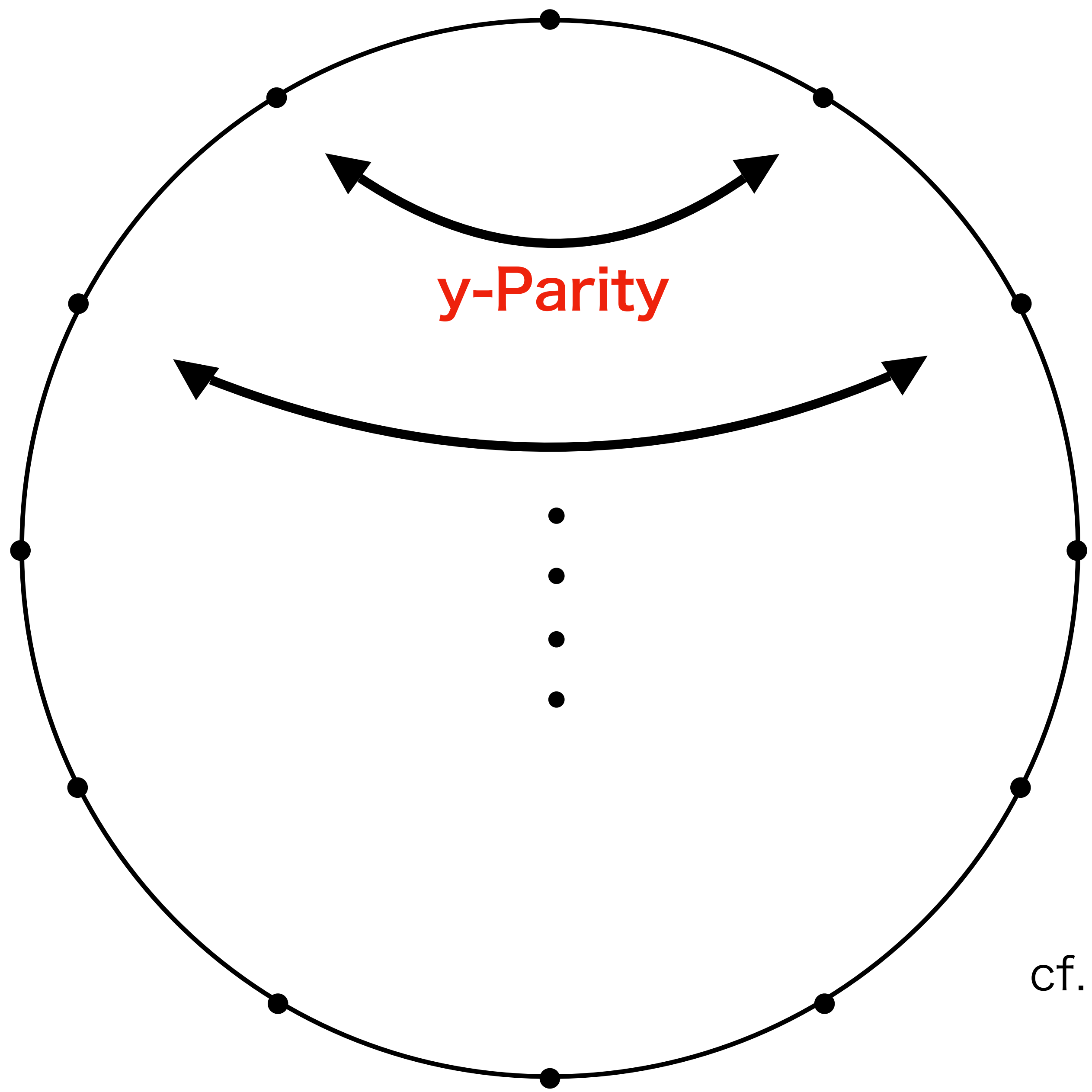
Discretized 5d coordinate

※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

[N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)]

Introduction: (De)construction technique

<u>Discretized 5d coordinate</u>

※Schematically picture

5d gauge theory

G : gauge group

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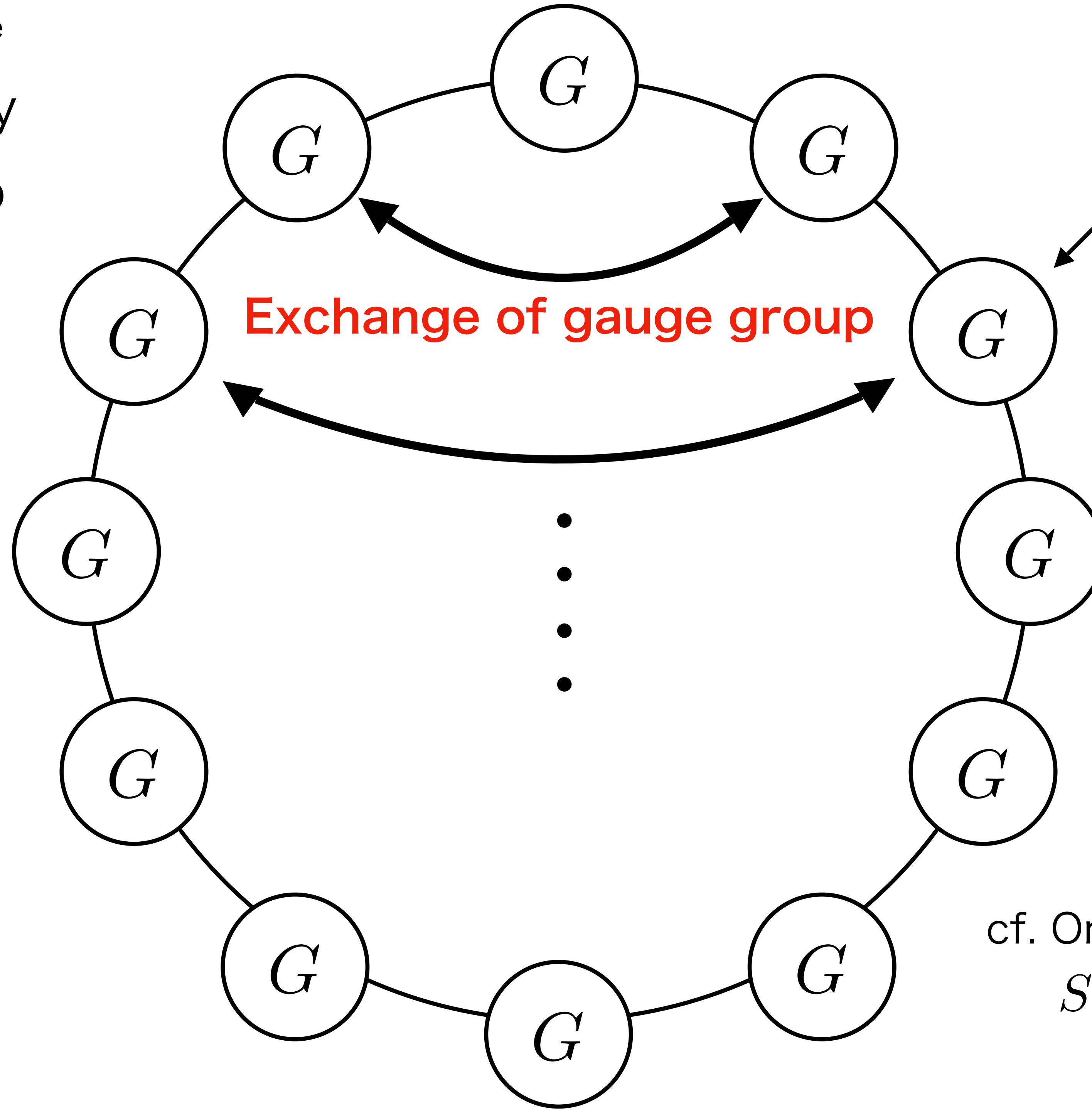


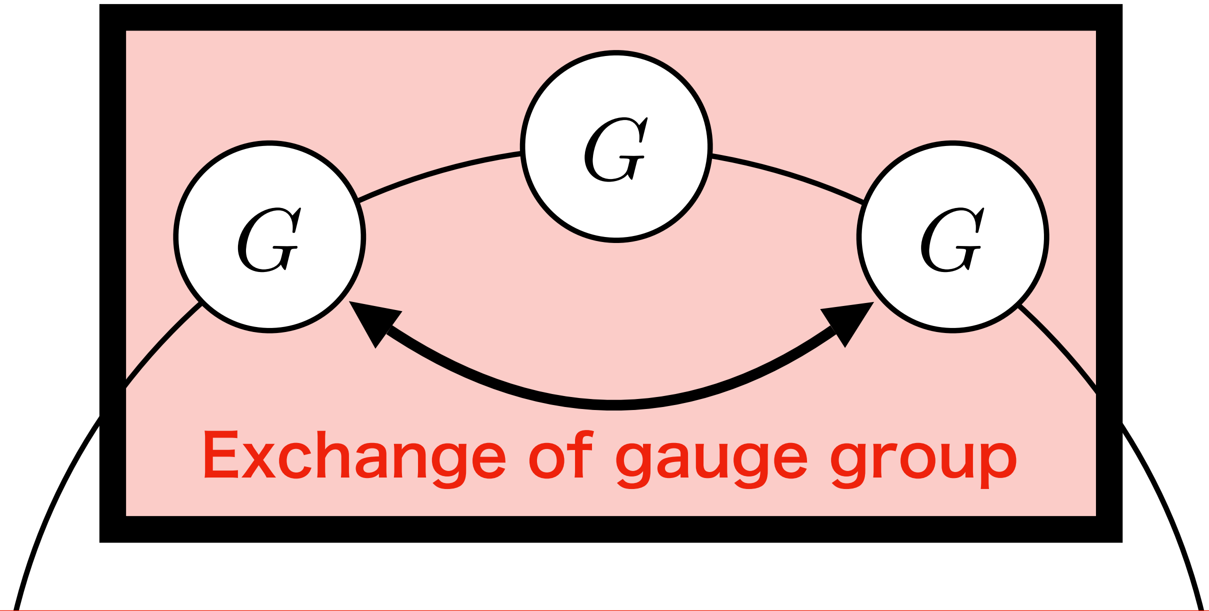
4d theory at each discretized point

cf. Orbifold compactification S_1/Z_2

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

[N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)]

Introduction: (De)construction technique



Our Work

- **Non-Abelian extension** of electroweak symmetry
- Imposing **Exchange Symmetry of gauge group**

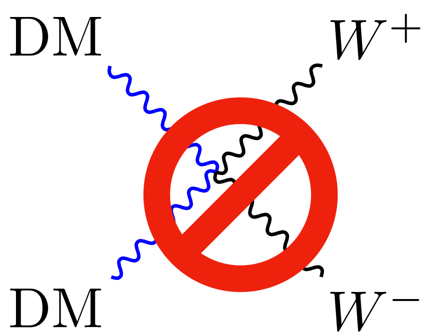
→ Z_2-odd spin-1 particles can be obtained while realizing SM spectrum!

Abelian Extension with Exchange Symmetry(1/2)

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

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

Exchange Symmetry



Stable neutral vector CANNOT have Non-Abelian EW couplings

Model

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

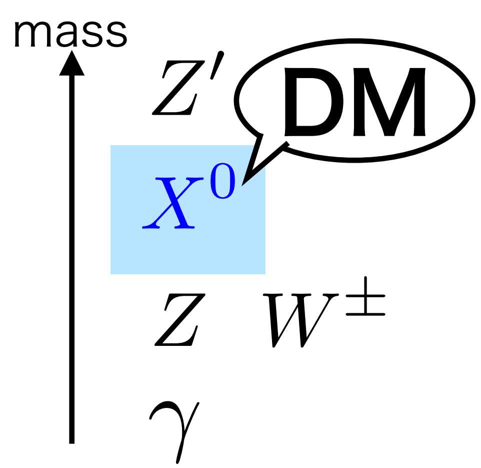
※ We have kinetic mixing terms(2nd line) in this Abelian extension model

field	spin	$\mathrm{SU}(3)_C$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_0$	$\mathrm{U}(1)_1$	$\mathrm{U}(1)_2$
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_μ^a	B_μ^0	B_μ^1	B_μ^2

Spectrum

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

(Z_2-odd neutral vector)



Abelian Extension with Exchange Symmetry(2/2)

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

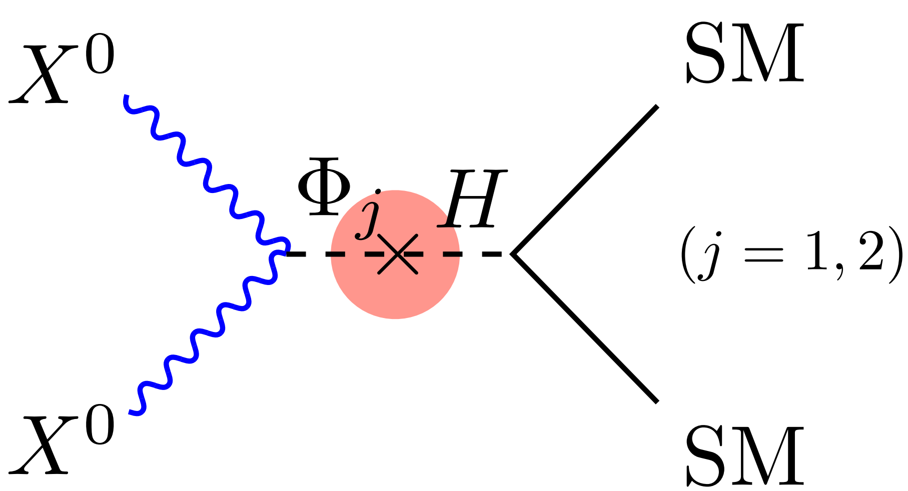
- X^0 do not appear in the $SU(2)_L$ neutral vector state

$$W^3_\mu = \#A_\mu + \#Z_\mu + \#Z'_\mu \longleftarrow \textbf{No } X^0 \textbf{ states}$$

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

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

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



DM relies on the Higgs mixing in the annihilation process

→ **Strict bound from direct detection**

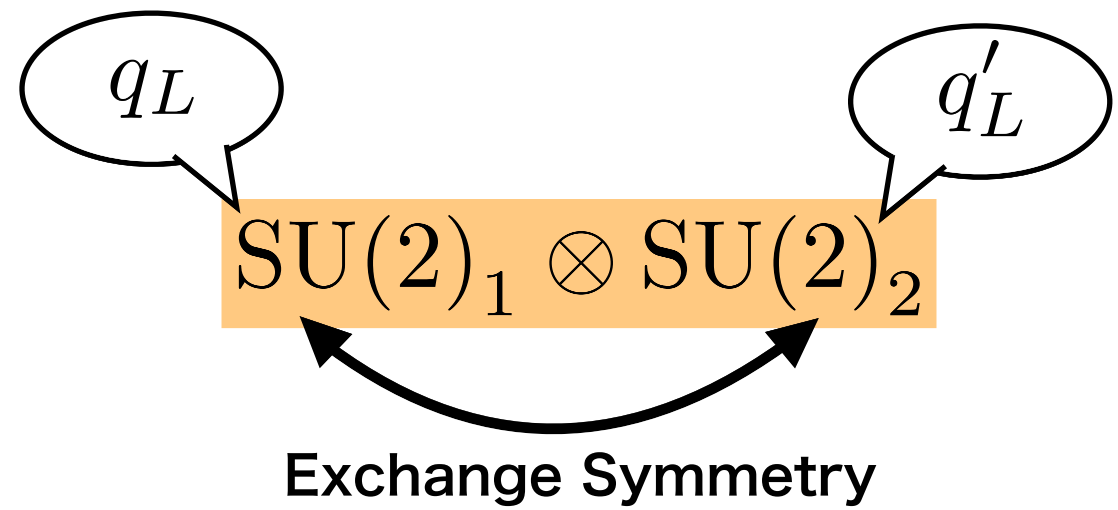
(That is why we choose the non-Abelian extension approach!)

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

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

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

Matter Contents

field	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_0$	$\mathrm{SU}(2)_1$	$\mathrm{SU}(2)_2$	$\mathrm{U}(1)_Y$
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		
Φ_2	0	1	1	2	2	0

Fermion + H

Higgs mechanism and Symmetry breaking

Gauge transformation

$$\Phi_1 \to U_0 \Phi_1 U_1^\dagger, \qquad \Phi_2 \to U_2 \Phi_2 U_1^\dagger$$

$U_0 = \exp\left[i g_0 \theta_0(x) \right]$
$U_1 = \exp\left[i g_1 \theta_1(x) \right]$
$U_2 = \exp\left[i g_0 \theta_2(x) \right]$

Scalar field definition

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

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

- gauge trans. with $U_0 = U_1 = U_2$ ⤳ **SU(2)$_L$ gauge symmetry**
- exchange $\Phi_1 \leftrightarrow \Phi_2$ → **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

@tree-level $$m_{V^0}^2 = m_{V^\pm}^2 = \frac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$$

@loop-level $$\delta_{m_V} \equiv m_{V^\pm} - m_{V^0} \simeq 168 \text{ MeV} \ll m_V$$

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 equivilium

$$n_{\rm eq} = g\left(\frac{mT}{2\pi}\right)^{\frac{3}{2}} \exp\left(-\frac{m}{T}\right)$$

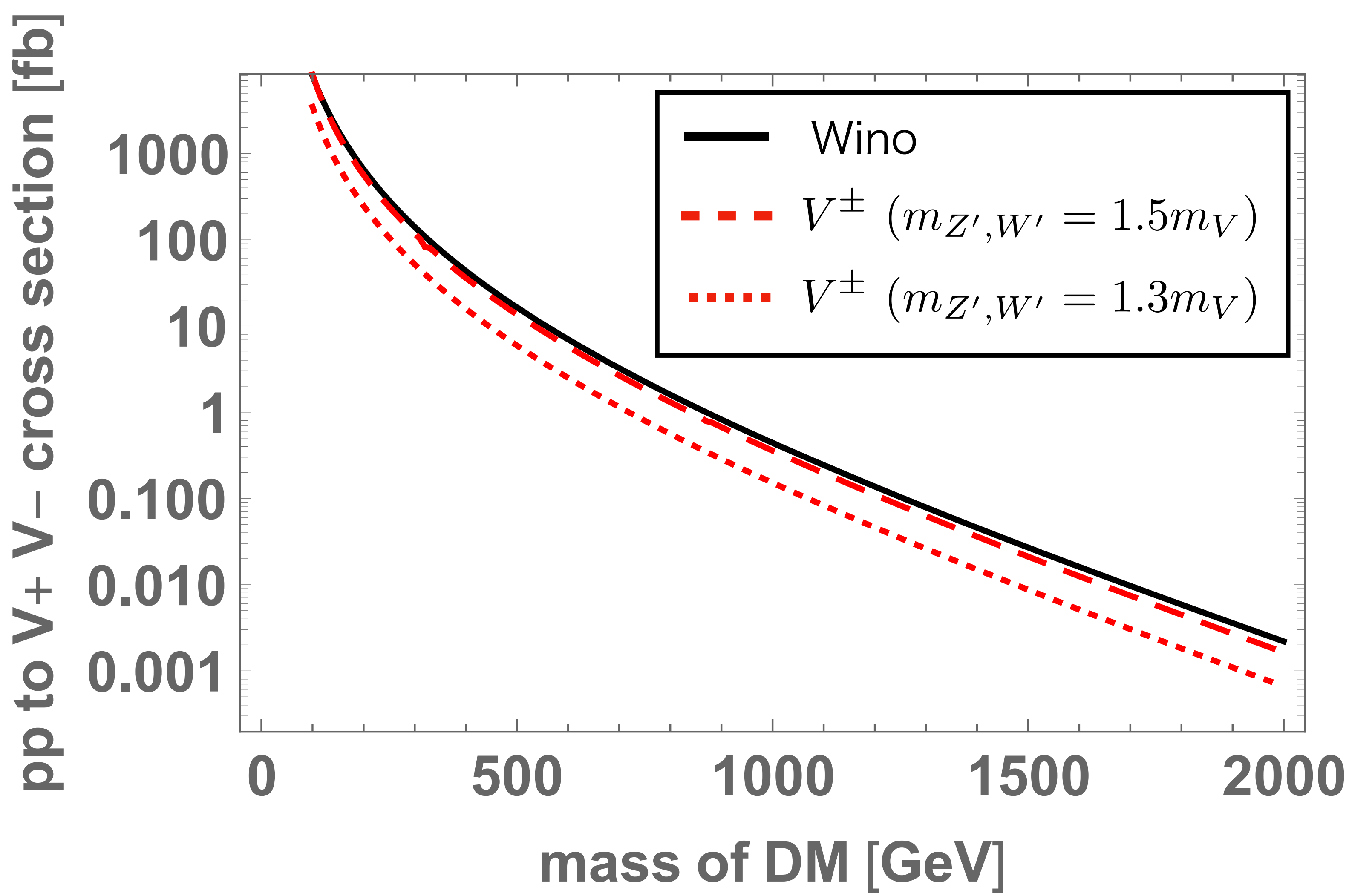
m : mass
T : temperature
g : degrees of freedom

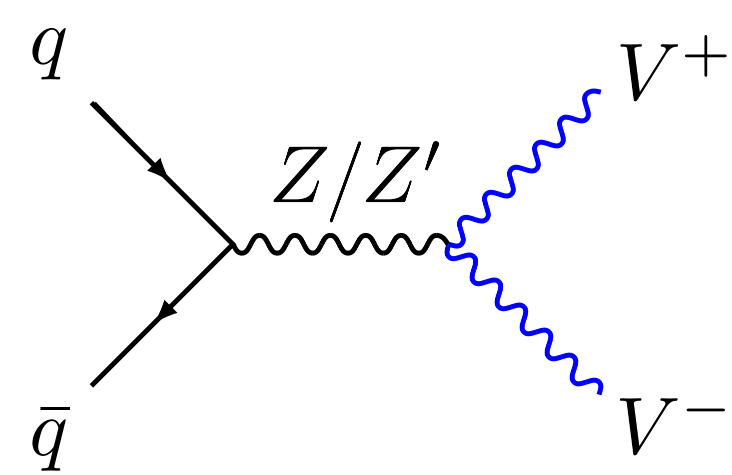
→ **All the V-particles contribute to the DM annihilation**

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: $m_{\tilde{W}} \gtrsim 460$ GeV

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

LLP search is not relevant for TeV scale V-particles

Lagrangian

BSM Lagrangian

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

Scalar potential

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

Bounded from Below(BFB) conditions

BFB conditions in our model

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

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

$$
\lambda = \frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2}, \qquad \lambda_\Phi = \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h + m_{h_D}^2}{16 v_\Phi^2},
$$

$$
\lambda_{h\Phi} = -\frac{\sin\phi_h \cos\phi_h}{2\sqrt{2} v v_\Phi}(m_{h'}^2 - m_h^2), \qquad \lambda_{12} = \frac{m_h^2 \sin^2\phi_h + m_{h'}^2 \cos^2\phi_h - m_{h_D}^2}{8 v_\Phi^2}.
$$

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

$$g_0,\quad g_1,\quad g',\quad v,\quad v_\Phi,\qquad \lambda,\quad \lambda_{h\Phi},\quad \lambda_\Phi,\quad \lambda_{12}$$

$$\downarrow$$

$$e,\quad G_F,\quad m_Z,\quad m_V,\quad m_{Z'},\quad m_h,\quad m_{h'},\quad m_{h_D},\quad \phi_h$$

$\sim v_\Phi$ (TeV scale)

<u>Free parameters</u>

$$\{\ \underbrace{m_V,\quad m_{Z'}}_{\text{Characterize vector sector}},\quad \underbrace{m_{h'},\quad m_{h_D},\quad \phi_h}_{\text{Characterize scalar sector}}\ \}$$

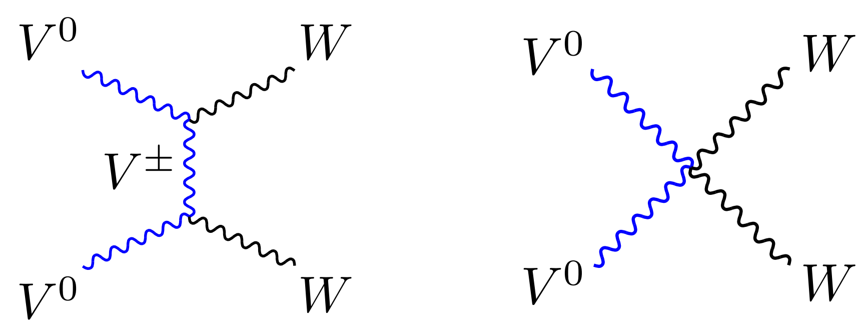
Ωh^2 contour: $m_{Z'} \gtrsim m_V$

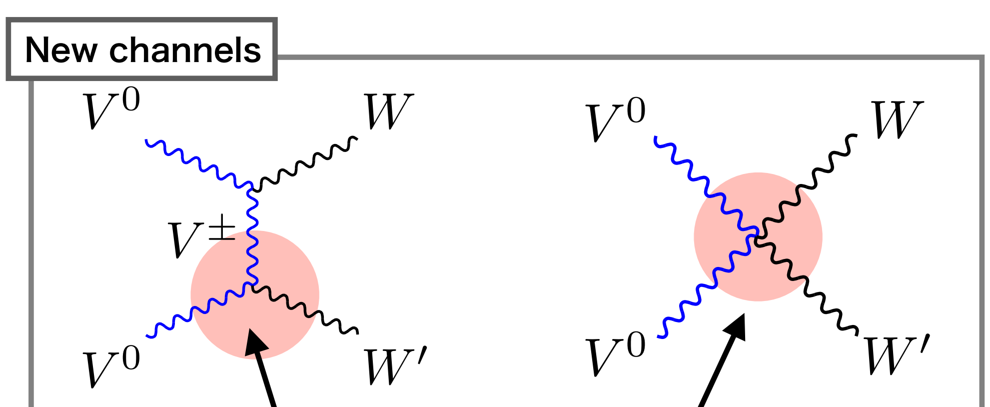
★ : benchmark point
(m_V=5 TeV, $m_{Z'}$=6.5 TeV)

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

→ Ωh^2=0.12 is achieved in heavier m_V region

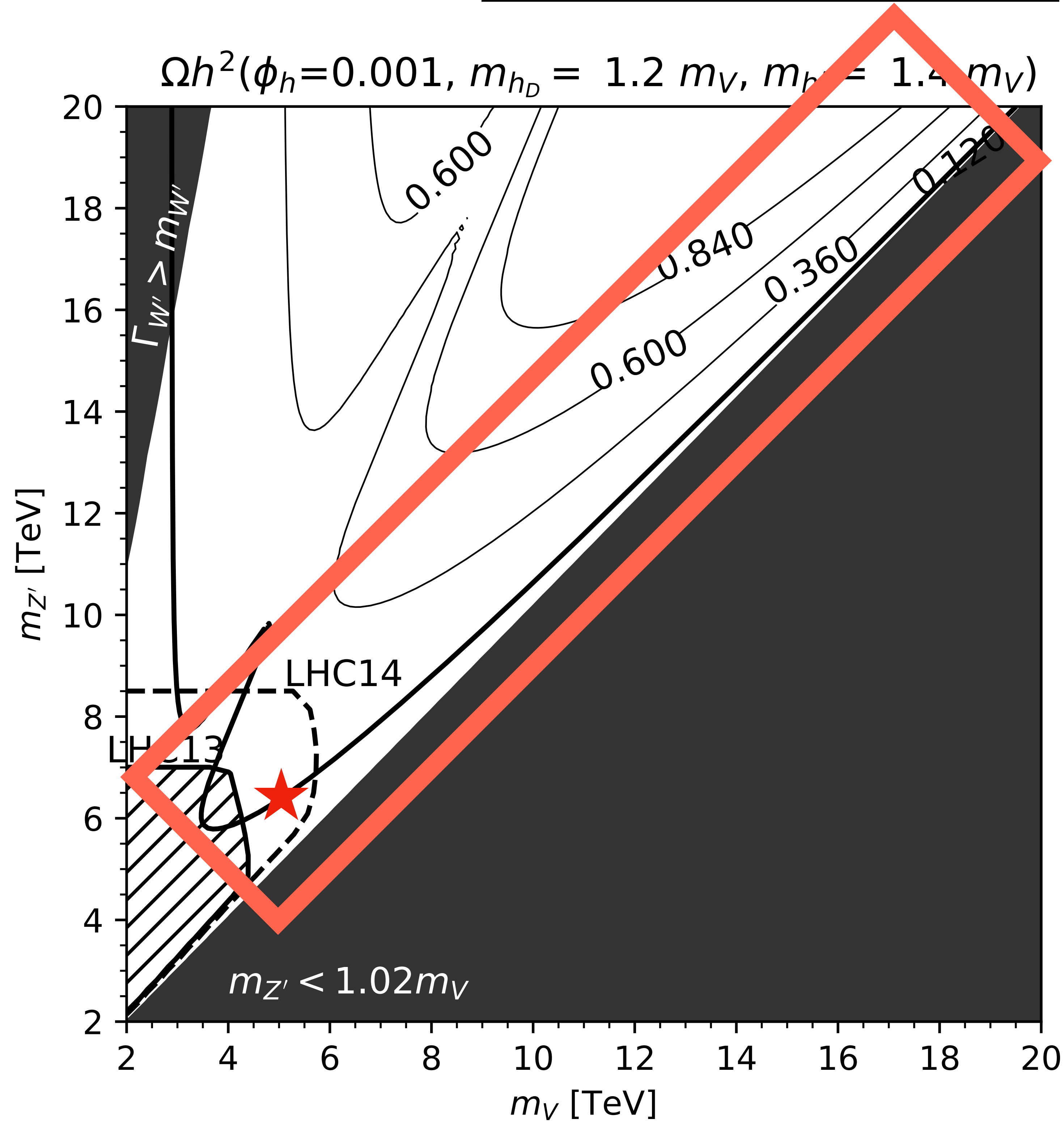
<u>Annihilation Channel</u>





$$\frac{1}{\sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}}$$

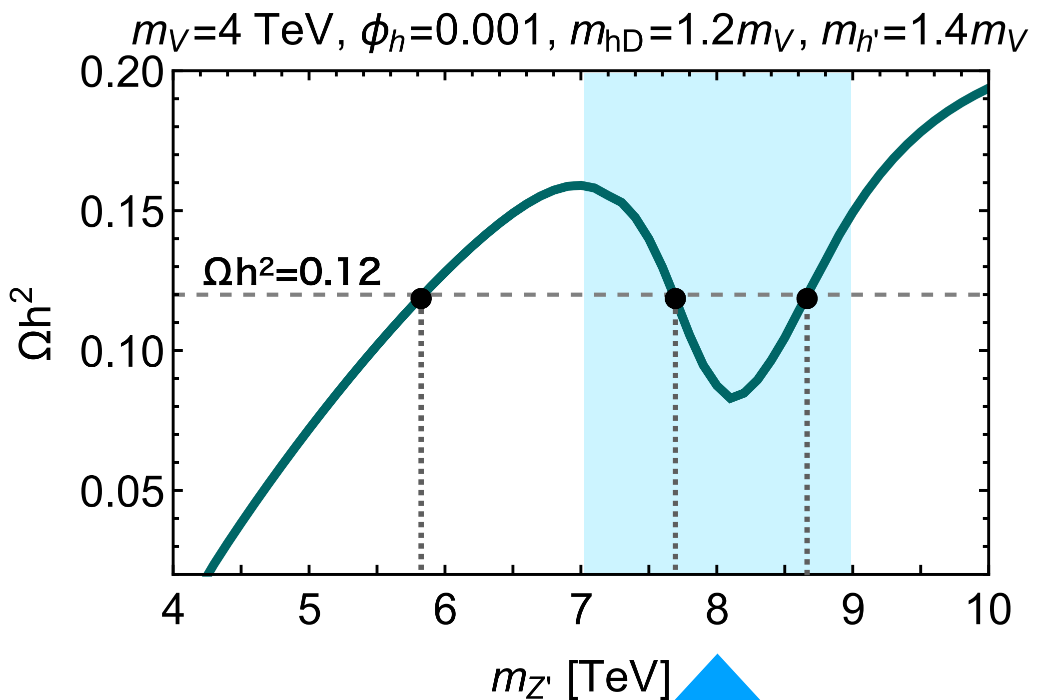
Enhancement factor in $m_{Z'}/m_V$ ~1



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

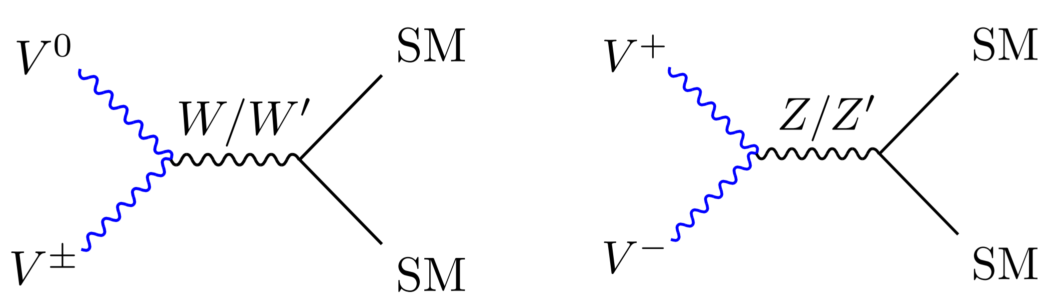
Resonance region in Ωh^2 contour

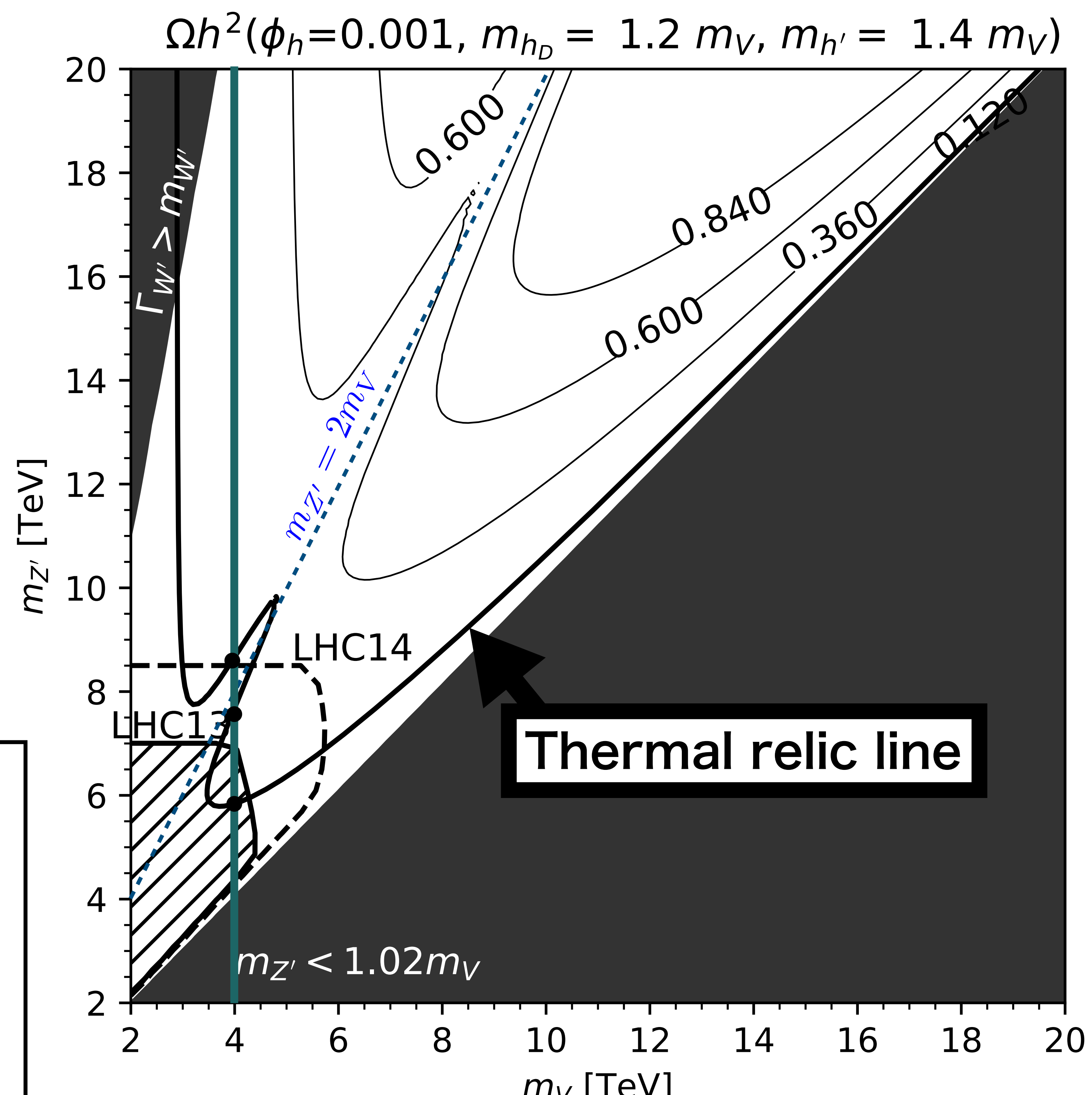
Contours of Ωh^2



$m_{Z'} \sim 2m_V$

resonance region of Z'/W' channel





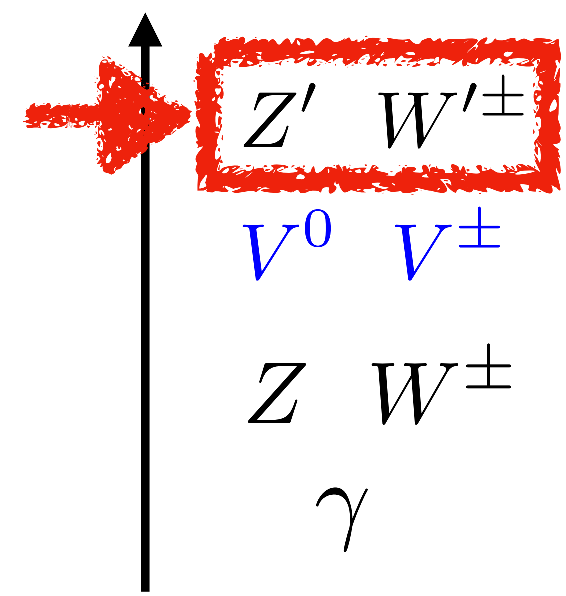
Viable Region: W' physics

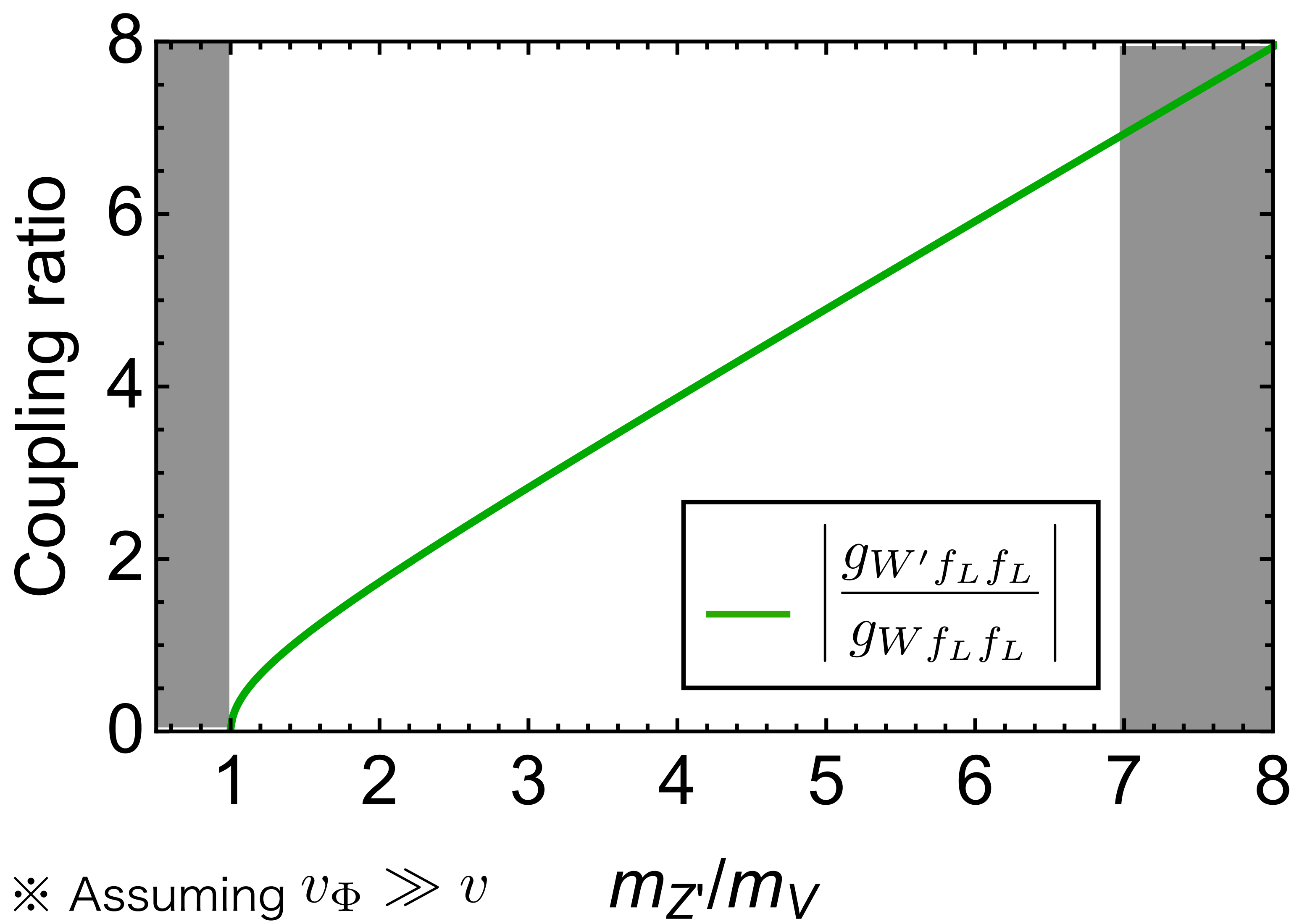
W'-fermion coupling

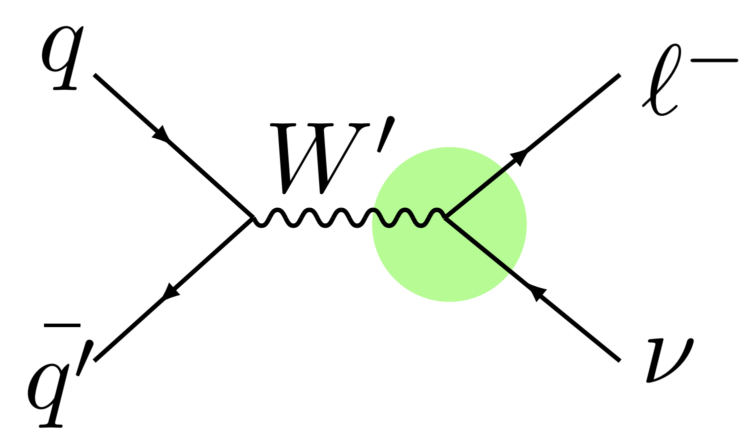
$$\left|\frac{g_{W' f_L f_L}}{g_{W f_L f_L}}\right| \sim \sqrt{\frac{m_{Z'}^2}{m_V^2} - 1}$$

cf. Vector Spectrum

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







→ TeV scale W' search may constrain the parameter region

※ Assuming $v_\Phi \gg v$

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 Z$_2$-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	$\lvert g_{W'f_Lf_L}/g_{Wf_Lf_L}\rvert$
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

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

fixed as SM value

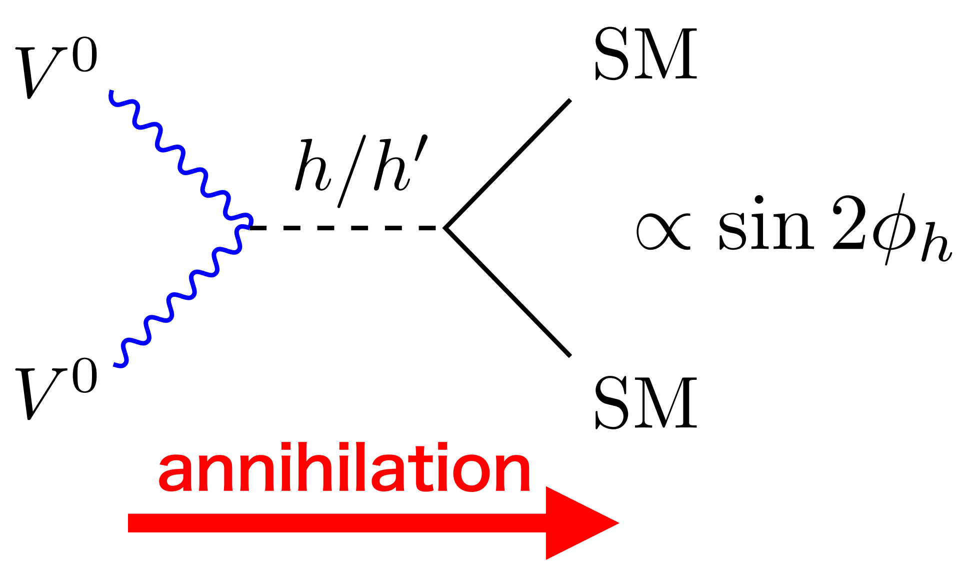
(large g$_1$) $\times$ (large $\sin\phi_\pm$) = (large $g_{W' f_L f_L}$)

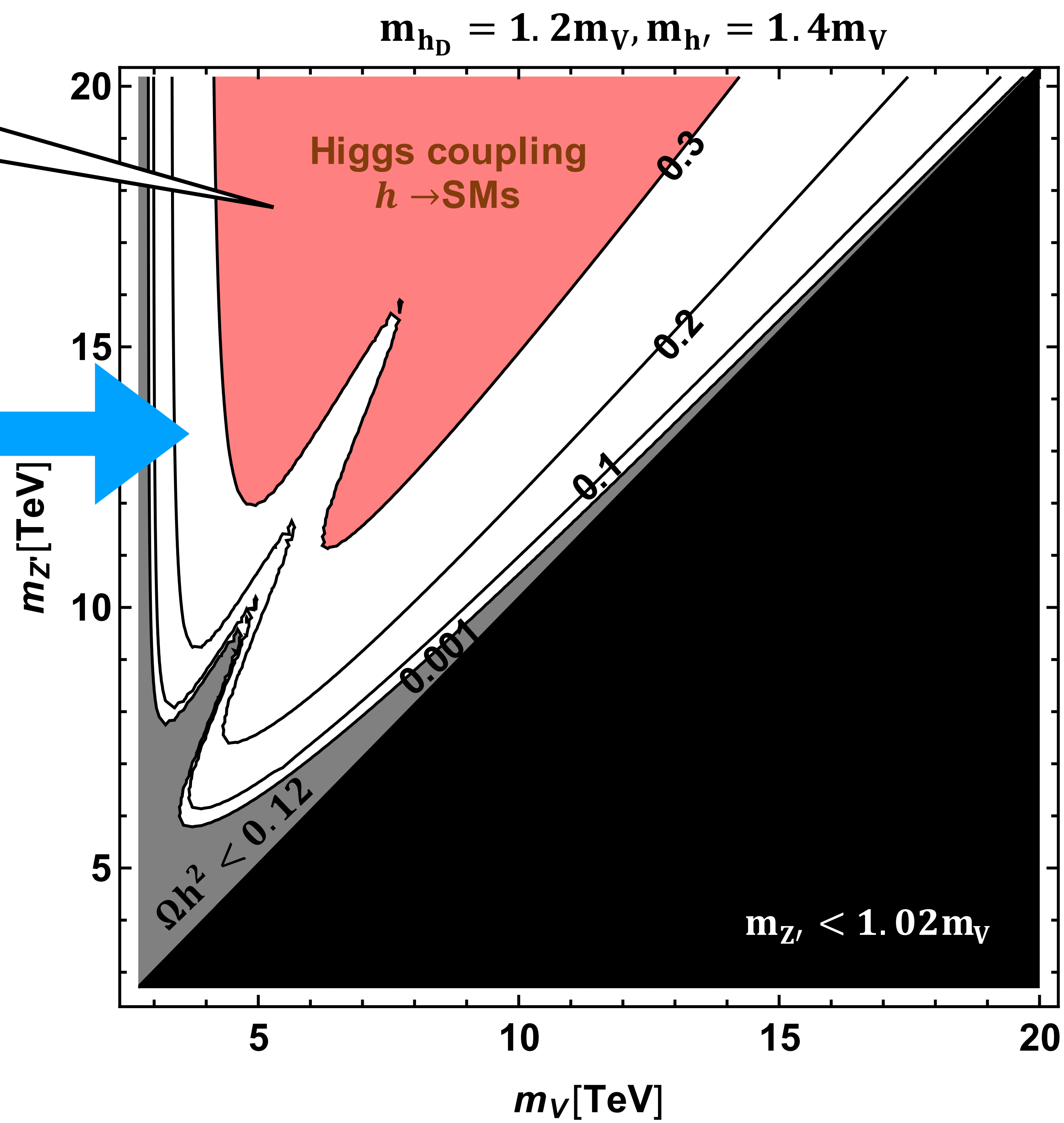
ϕ_h contours: (1/3)

We need $|\phi_h| > 0.3$
to obtain Ωh^2~0.12

White region:

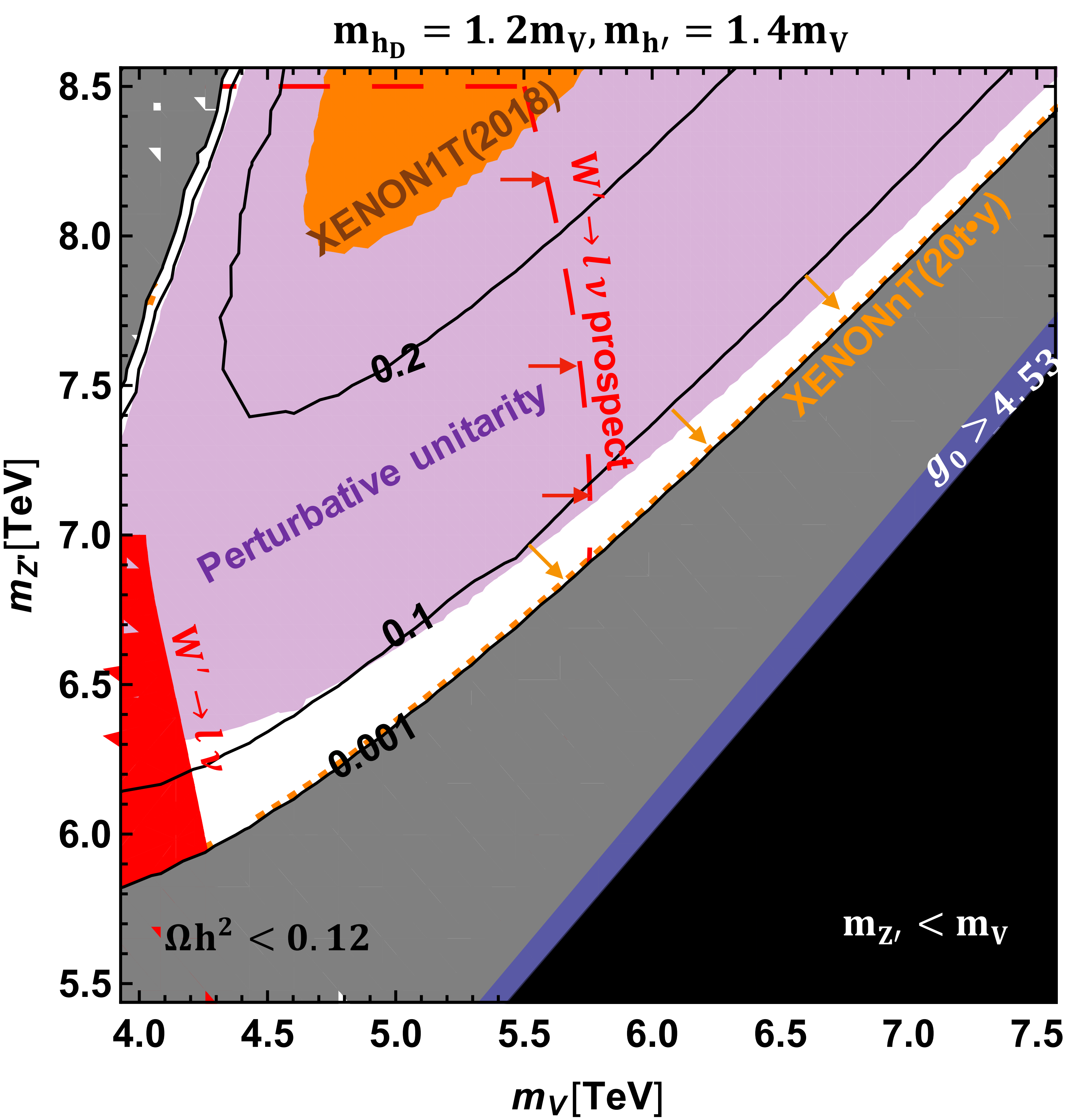
Ωh^2~0.12 is achieved
by adjusting ϕ_h

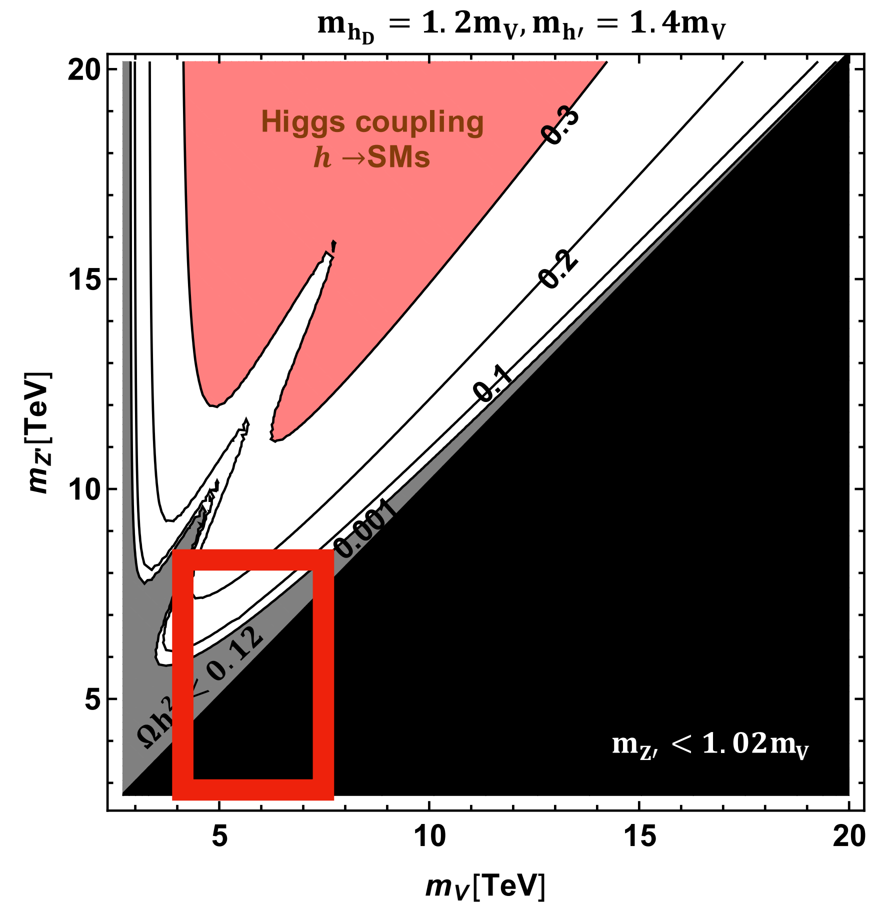




→ Constraints on this plane? (Next page)

ϕ_h contours: (2/3)





Relatively large ϕ_h

→ Constrained from

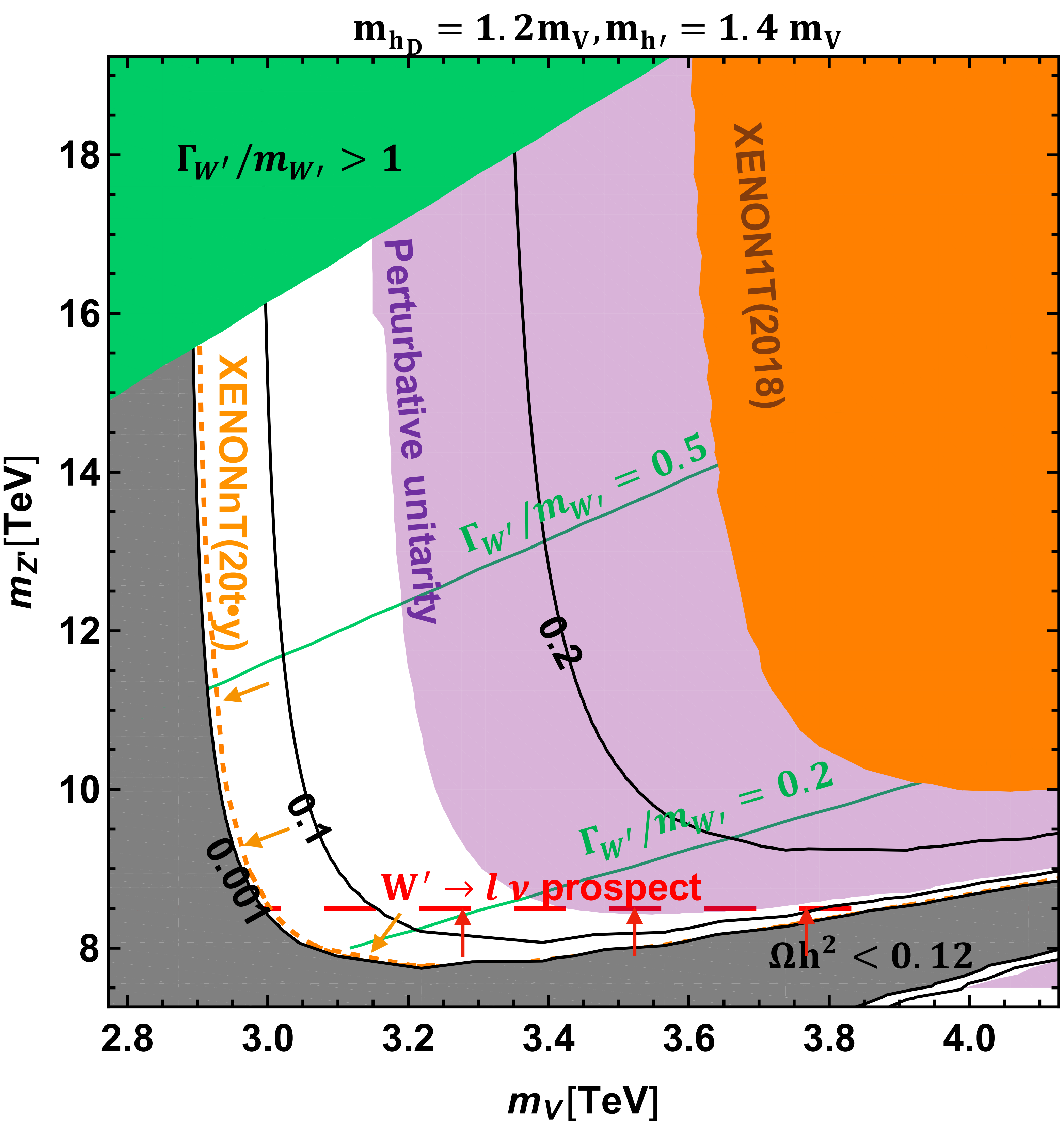
- XENON1T result
- Perturbative unitarity for scalar coupling

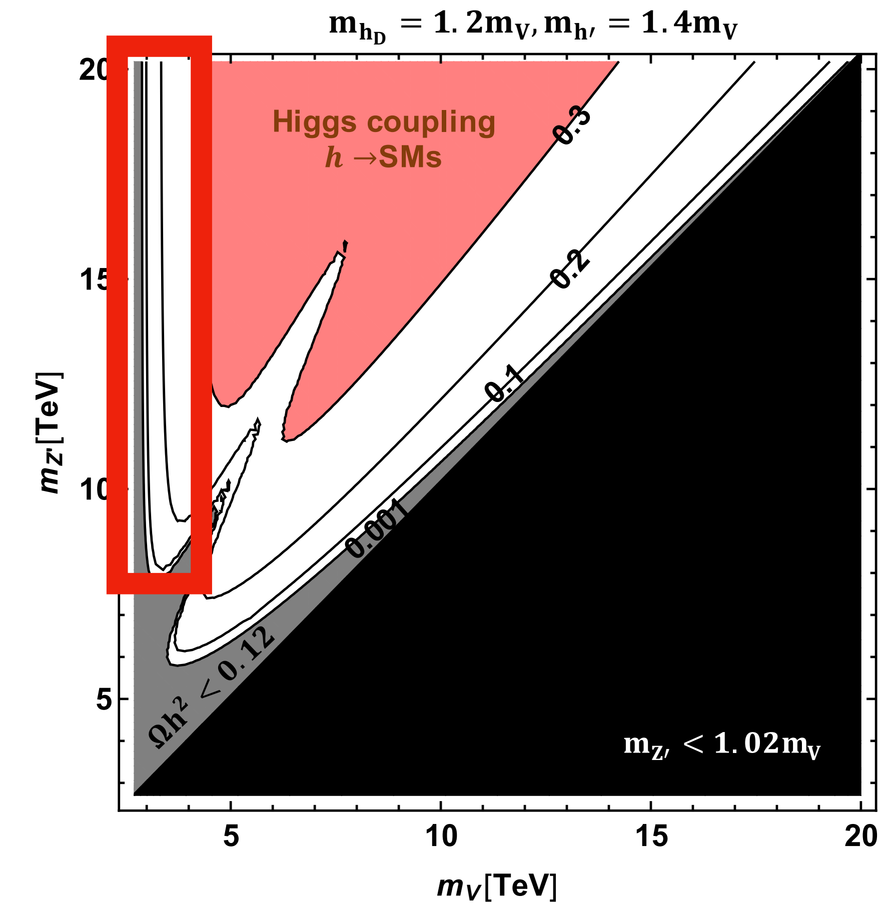
Very small ϕ_h

→ 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 $|\phi_h| \gtrsim 0.001$

Fin.

Thank you!

2020.06.02　Motoko FUJIWARA