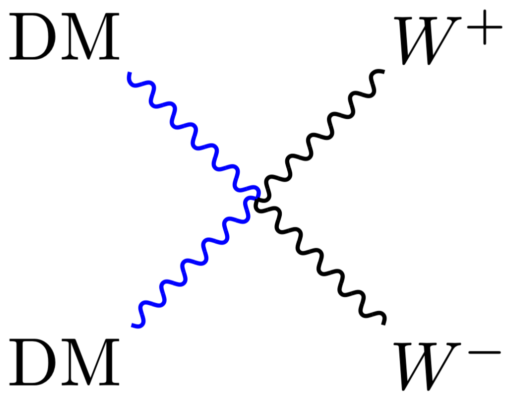
A Model of electroweakly interacting non-abelian vector dark matter



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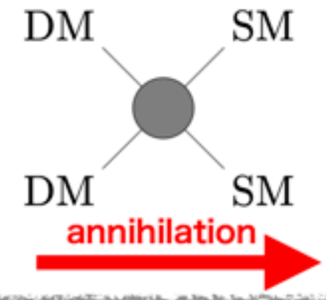
based on: T. Abe, MF, J. Hisano, K. Matsushita, JHEP 07 (2020) 136 [arXiv:2004.00884]

Introduction: Electroweakly interacting dark matter

Dark matter(DM) w/ electroweak int.

$$\boxed{\Omega h^2 = 0.120 \pm 0.001} \quad \langle \sigma_{\rm anni} v \rangle \simeq 3 \times 10^{-26}\ {\rm cm^3/s} \simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2}$$

N.Aghanim, et al. [Planck Collaboration] (2020)



Assumption: DM is a SU(2)L multiplet $\alpha_{\rm DM} \sim \alpha_{\rm EW}$

Table (Partially modified) from [M. Farina, D. Pappadopulo, A. Strumia (2013)]

Quantum numbers			DM mass	$m_\pm - m_{\rm DM}$
$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	Spin	[TeV]	[MeV]
2	1/2	0	0.54	350
2	1/2	1/2	1.1	341
3	0	0	2.5	166
3	0	1/2	2.7	166
	⋮		⋮	⋮

$m_{\rm DM}$: DM mass
$m_\pm$: mass of charged component

Feature

- Ωh^2~0.12 → O(1) TeV DM
- mass splitting → O(100) MeV

General for Electroweak Multiplet DM
(∵ Determined by EW interactions)

How about Spin-1 DM?

- Electroweakly interacting spin-1 DM theory?
- Phenomenology?
- Difference from spin-0, or 1/2 cases?

Introduction: Electroweakly interacting Spin-1 DM

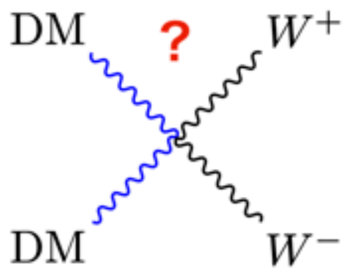
How to explore

1. DM candidate from Extra dimension [T. Flacke, A.Menon, D. J. Phalen (2009)] [T. Flacke, D. W. Kang, K. Kong, G. Mohlabeng, S. C. Park (2017)]
2. Introducing as the matter contents [A. Belyaev, G. Cacciapaglia, J. McKay, D. Marin, A. R. Zerwekh (2019)]
3. Extending the gauge symmetry

cf. $Z, W^{\pm}$ = gauge bosons from SM gauge symmetry

$\rightarrow$ Spin-1 **DM** $\stackrel{?}{=}$ gauge bosons from extended gauge symmetry

w/ **non-abelian electroweak int.**



Questions:

- **How can we realize electroweak int. for new spin-1 spectrum?**
- **How can we stabilize DM candidate?**
- **How can we obtain the SM spectrum?**

Our Idea: Exchange symmetry of gauge group

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

Our Idea

- **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!

※inspired from (De)construction method
[N. Arkani-Hamed, A. G. Cohen, H. Georgi (2001)]

Our model

Symmetry

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

Exchange Symmetry

Matter Contents

field	spin	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_0$ ($W^a_{0\mu}$)	$\mathrm{SU}(2)_1$ ($W^a_{1\mu}$)	$\mathrm{SU}(2)_2$ ($W^a_{2\mu}$)	$\mathrm{U}(1)_Y$
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
Φ_1	0	1	2	2	1	0
Φ_2	0	1	1	2	2	0
H	0	1	1	2	1	$\frac{1}{2}$

·Exchange trans.

$$\boxed{\begin{aligned} \Phi_1 &\mapsto \Phi_2, & W^a_{0\mu} &\mapsto W^a_{2\mu} \\ \Phi_2 &\mapsto \Phi_1, & W^a_{2\mu} &\mapsto W^a_{0\mu} \end{aligned}}$$

※ gauge coupling: $g_0 = g_2$

·Gauge trans.

$$\Phi_1 \mapsto U_0 \Phi_1 U_1^\dagger$$
$$\Phi_2 \mapsto U_2 \Phi_2 U_1^\dagger$$
$$H \mapsto U_1 H$$

$$U_n = \exp[i\theta_n(x)] \quad (n = 0, 1, 2)$$

Where is $\mathrm{SU(2)_L}$ and Z_2 parity? → **SSB structure is key to answer!**

Symmetry breaking

$\left[\begin{array}{l} \cdot\text{gauge trans.} \quad U_n = \exp[i\theta_n(x)] \quad (n=0,1,2) \\ \Phi_1 \mapsto U_0 \Phi_1 U_1^\dagger, \quad \Phi_2 \mapsto U_2 \Phi_2 U_1^\dagger, \quad H \mapsto U_1 H \end{array}\right]$

$$\boxed{\mathrm{SU}(2)_0 \otimes \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \xrightarrow{\langle \Phi_j \rangle \neq 0} \underset{\mathrm{SU(2)_L}}{\underset{\wr|}{\mathrm{SU}(2)}} \otimes \mathrm{U}(1)_Y \xrightarrow{\langle H \rangle \neq 0} \mathrm{U}(1)_{\mathrm{em}}}$$

Vacuum Expectation Value(VEV)

$$\langle \Phi_1 \rangle = \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_\Phi & 0 \\ 0 & v_\Phi \end{pmatrix}, \qquad \langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \qquad (\underset{\mathcal{O}(1)\ \mathrm{TeV}}{\underset{\uparrow}{v_\Phi}} \gg \underset{\mathcal{O}(100)\ \mathrm{GeV}}{\underset{\uparrow}{v}})$$

$\langle \Phi_1 \rangle$, $\langle \Phi_2 \rangle$ are invariant under

(1) Gauge trans. w/ $U_0 = U_1 = U_2$

$$U_0 \langle \Phi_1 \rangle U_1^\dagger = \langle \Phi_1 \rangle$$
$$U_2 \langle \Phi_2 \rangle U_1^\dagger = \langle \Phi_2 \rangle$$

(2) Exchange trans.

$$\langle \Phi_1 \rangle \leftrightarrow \langle \Phi_2 \rangle$$

Generators of SU(2)$_{0,1,2}$ are identified

$\rightsquigarrow$ **SU(2)$_L$ gauge symmetry**

(approximately)

Exchange symmetry still alive

$\Rightarrow$ **Z_2 parity structure**

(Next page)

Z_2-Parity from Exchange Symmetry

Scalar fields (after SSB)

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

Exchange symmetry trans. after SSB

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

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

$\Leftrightarrow$ **Z_2-Parity for physical states**

Neutral scalar: $\{\sigma_1, \sigma_2, \sigma_3\}$

Physical states

$$\frac{\sigma_1 - \sigma_2}{\sqrt{2}} \mapsto -\frac{\sigma_1 - \sigma_2}{\sqrt{2}} \quad Z_2\text{-odd} \quad \xrightarrow{\text{No mixing}} \quad h_D = \frac{\sigma_1 - \sigma_2}{\sqrt{2}}$$

$$\frac{\sigma_1 + \sigma_2}{\sqrt{2}} \mapsto +\frac{\sigma_1 + \sigma_2}{\sqrt{2}} \quad Z_2\text{-even}$$

$$\sigma_3 \mapsto +\sigma_3 \quad Z_2\text{-even}$$

mixing with ϕ_h $\rightarrow$ h (125 GeV Higgs), h'

States can be classified by **Z_2-parity**!

Z_2-odd vectors and DM candidate

$$W^{\pm}_{n\mu} = \frac{W^1_{n\mu} \mp i W^2_{n\mu}}{\sqrt{2}} \quad (n = 0, 2)$$

Z2-odd vector

DM

$$V^0 = \frac{W^3_{0\mu} - W^3_{2\mu}}{\sqrt{2}} \quad \text{(neutral)}$$

$$V^{\pm} = \frac{W^{\pm}_{0\mu} - W^{\pm}_{2\mu}}{\sqrt{2}} \quad \text{(charged)}$$

$SU(2)_L$ triplet-like features

tree-level: $m^2_{V^0} = m^2_{V^{\pm}} = \dfrac{g_0^2 v_\Phi^2}{4} \quad (\equiv m_V^2)$

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

(EW radiative corrections)

※ We assume $m_{V_0} < m_{h_D}$ to focus on spin-1 DM scenario

Energy

Collider search

Vector		Z2-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

SM limit: $v_\Phi \to \infty$

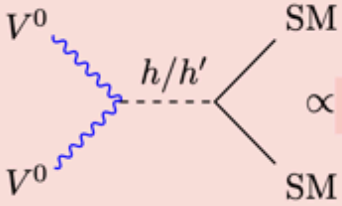
Thermal relic region in ϕ_h contour

ϕ_h : mixing angle btw h and h'

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

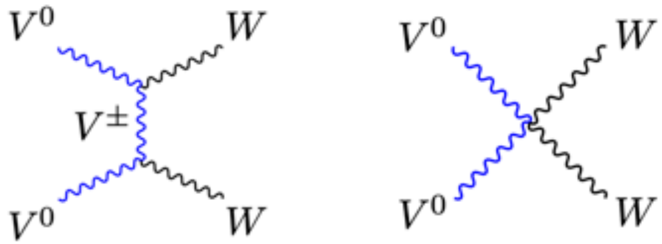
Annihilation Channel

・Higgs channels



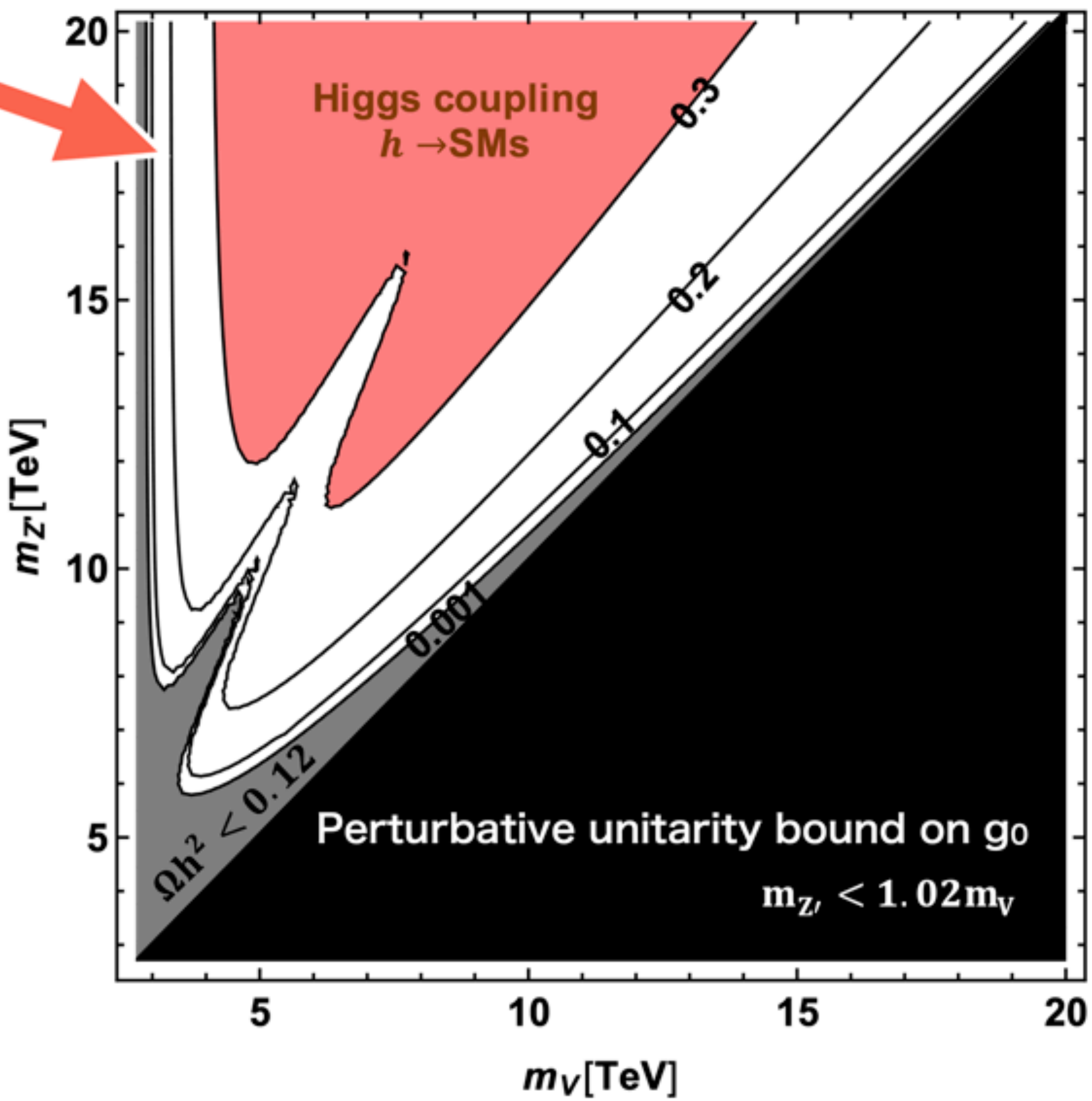
$\propto \sin 2\phi_h$

・EW channels



(+ many other channels…)

ϕ_h-contours $(m_{h_D} = 1.2\, m_V, m_{h'} = 1.4\, m_V)$



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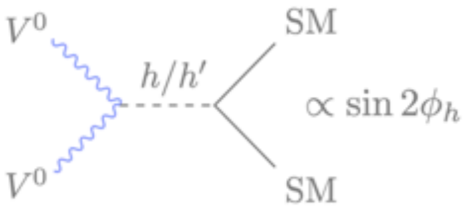
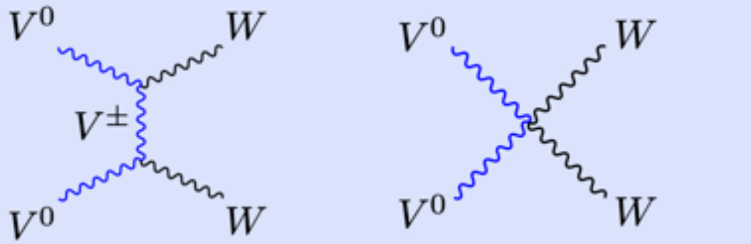
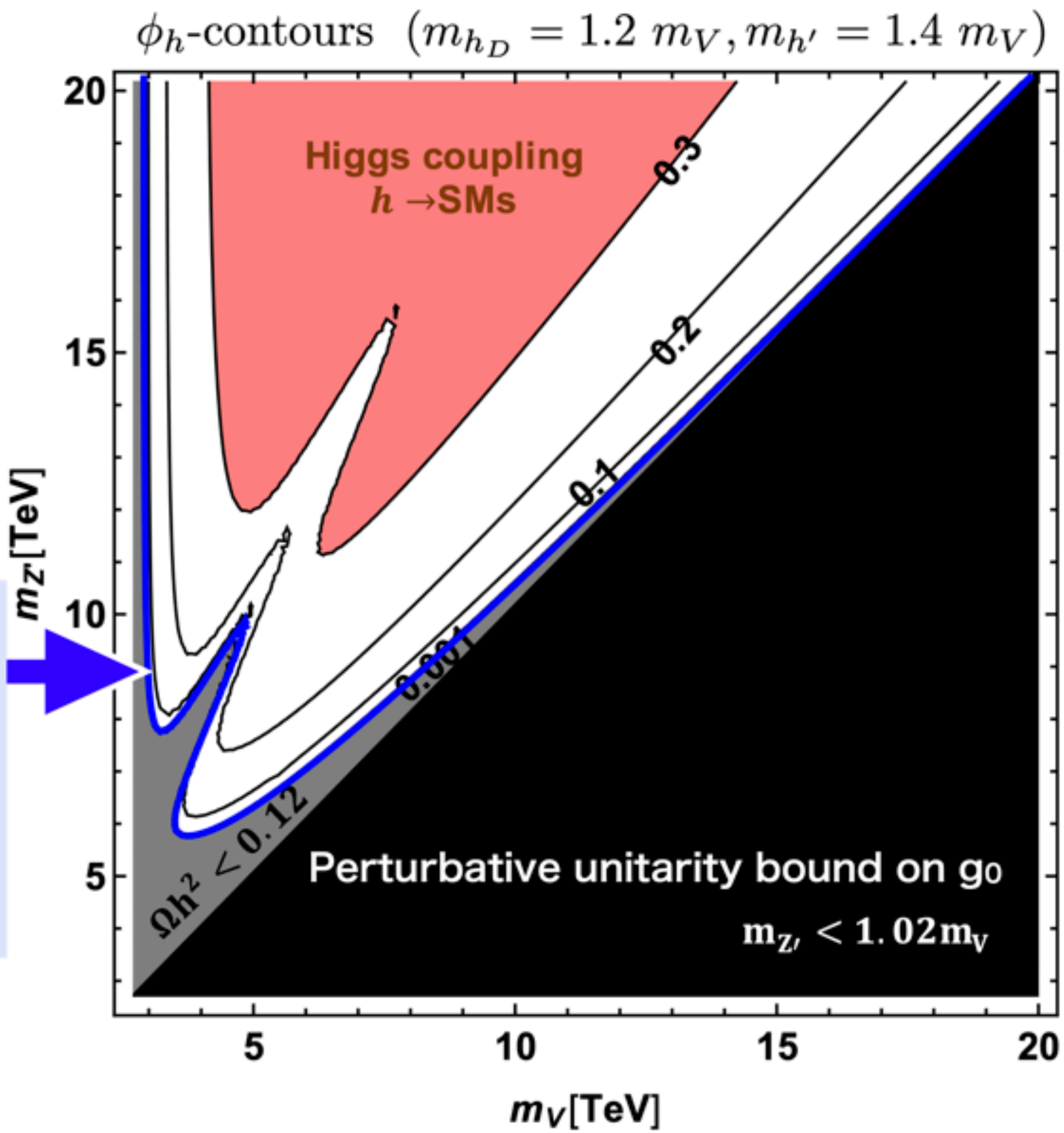


- EW channels

EW channel only



(+ many other channels…)

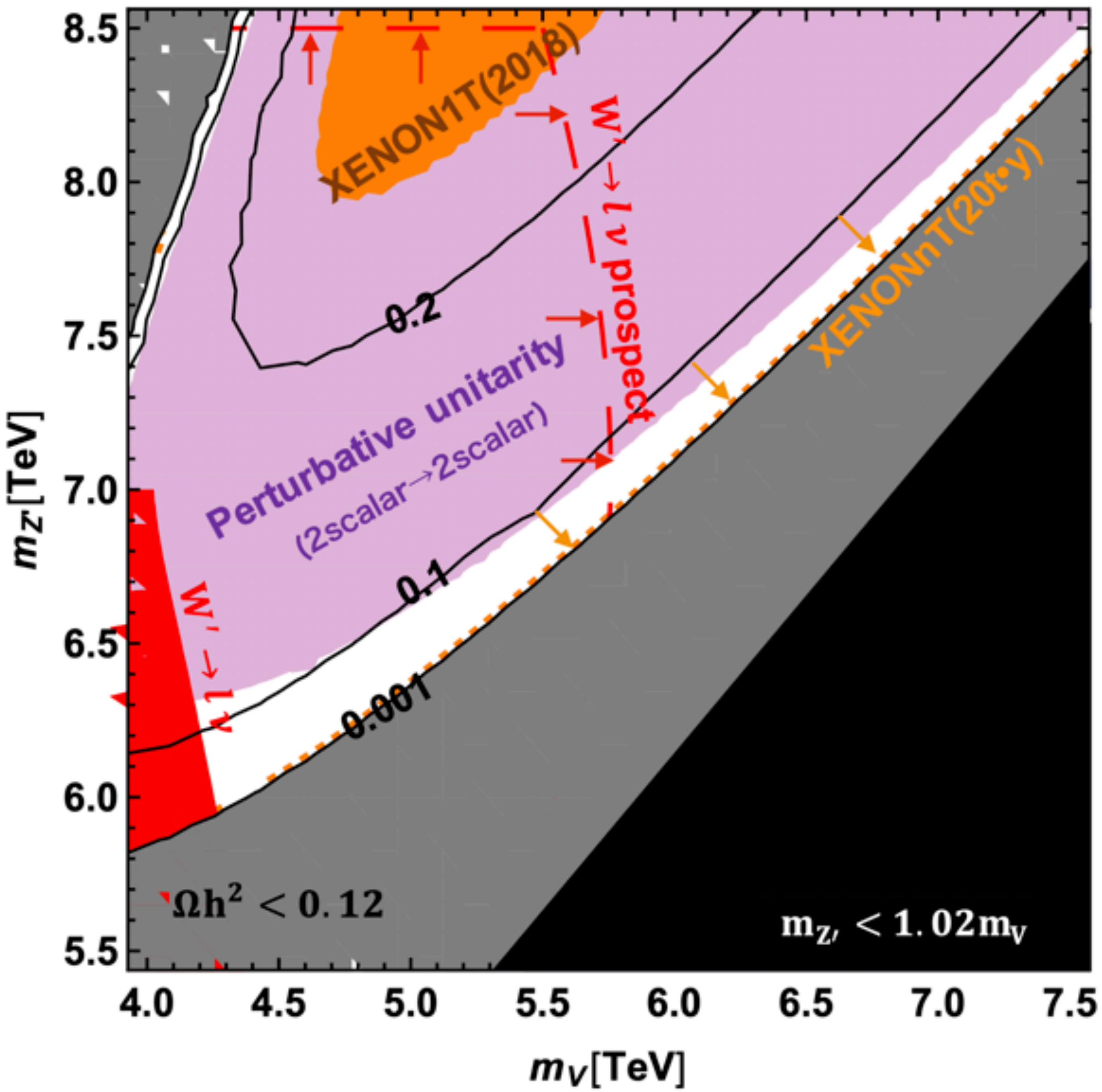


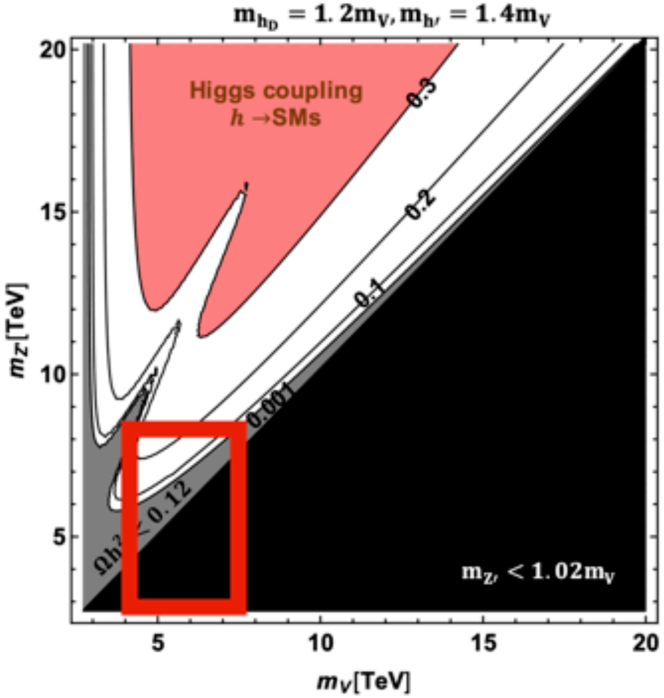
"Electroweakly interacting" spin-1 DM

→ Constraints on this plane? (Next page)

Constraints & Future detectability

ϕ_h-contours $(m_{h_D} = 1.2\, m_V, m_{h'} = 1.4\, m_V)$





- Perturbative unitarity bounds

(2scalar→2scalar scattering)

$\rightarrow \phi_h \lesssim 0.1$

LHC13TeV 139 fb[-1] [ATLAS Collabolation(2019)] (※ No bound for $m_{W'} > 7$ TeV)

HL-LHC14TeV 3000 fb[-1] [ATL-PHYS-PUB-2018-044(2018)]

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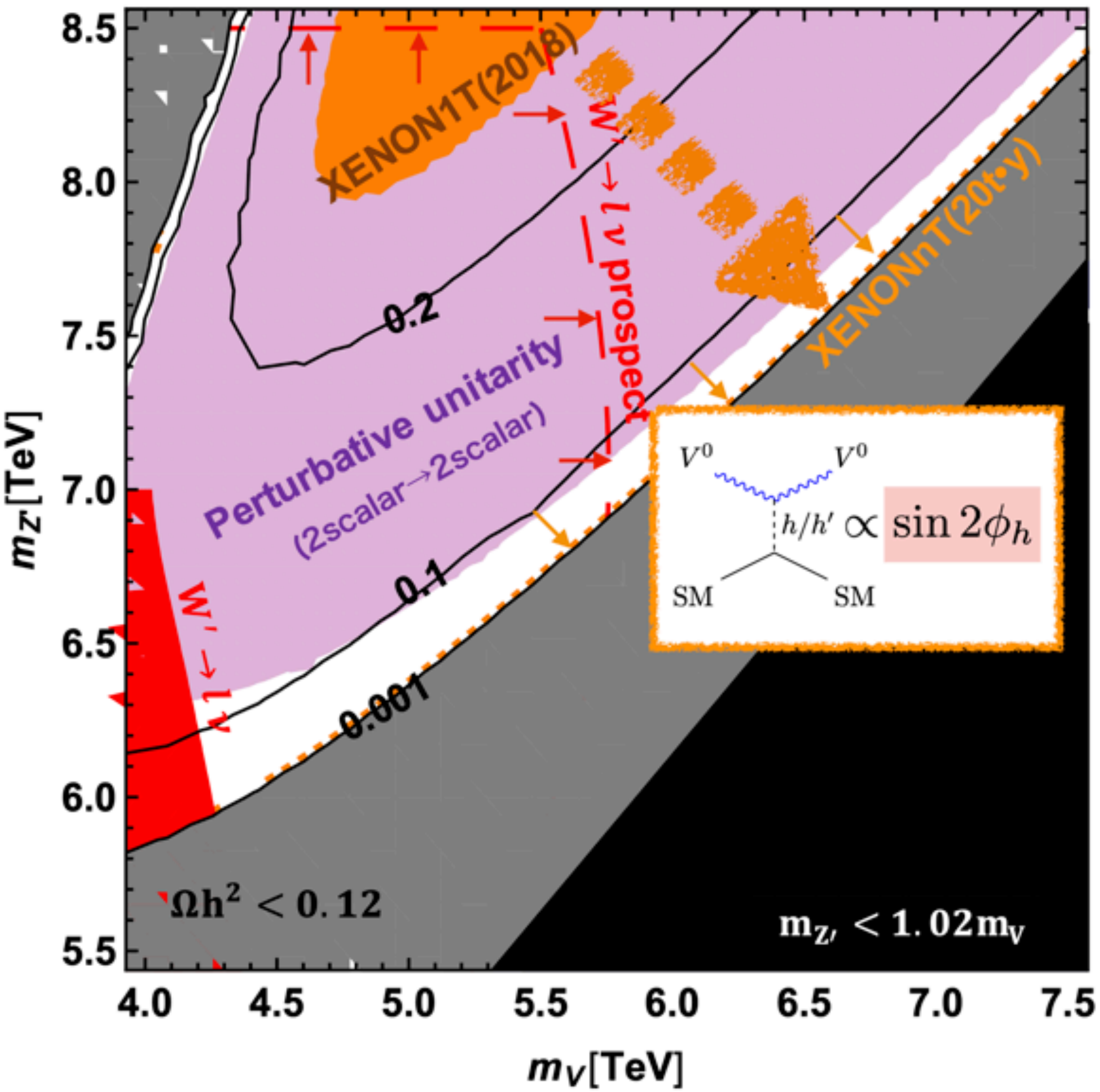

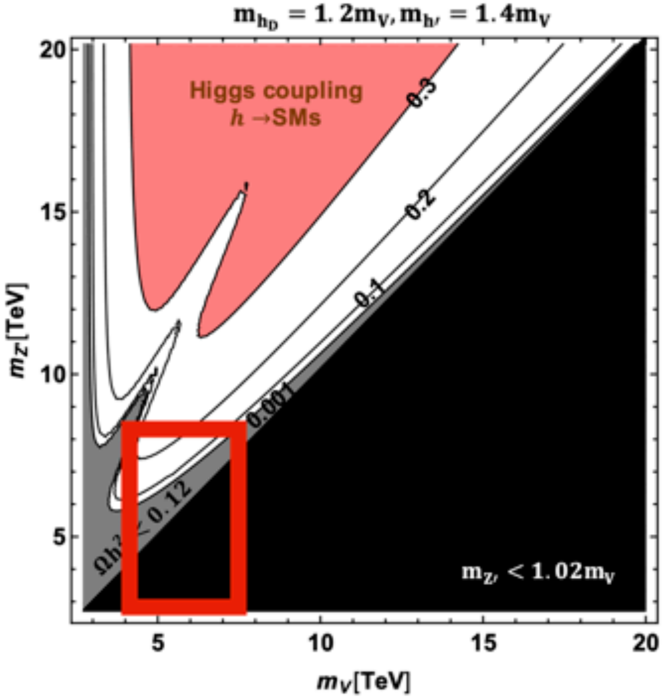

- Perturbative unitarity bounds
  (2scalar→2scalar scattering)
  $\rightarrow\ \phi_h \lesssim 0.1$

- Direct detection(XENON1T/nT)
  → probe Higgs contribution
  to DM annihilation process

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Constraints & Future detectability

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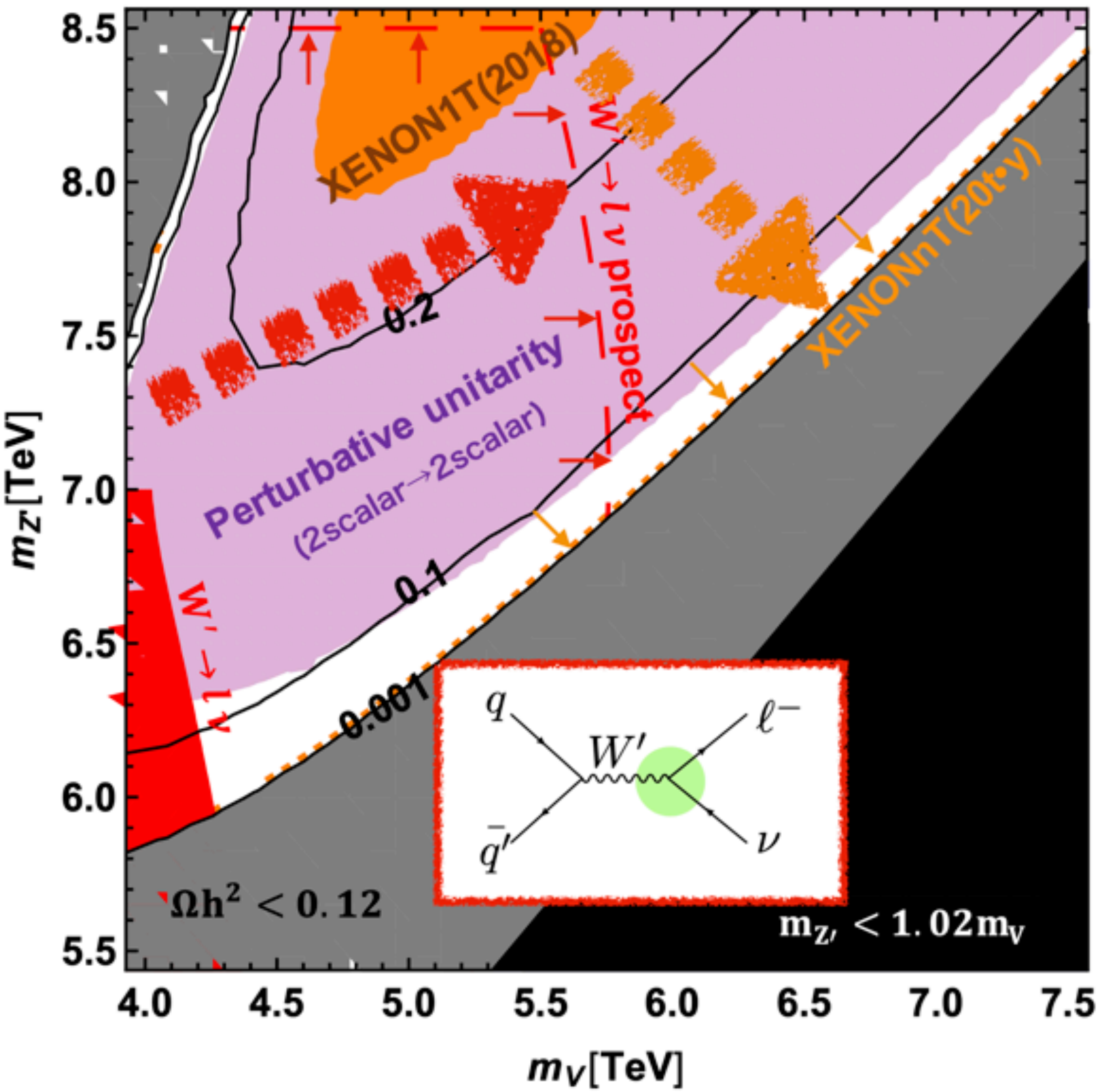
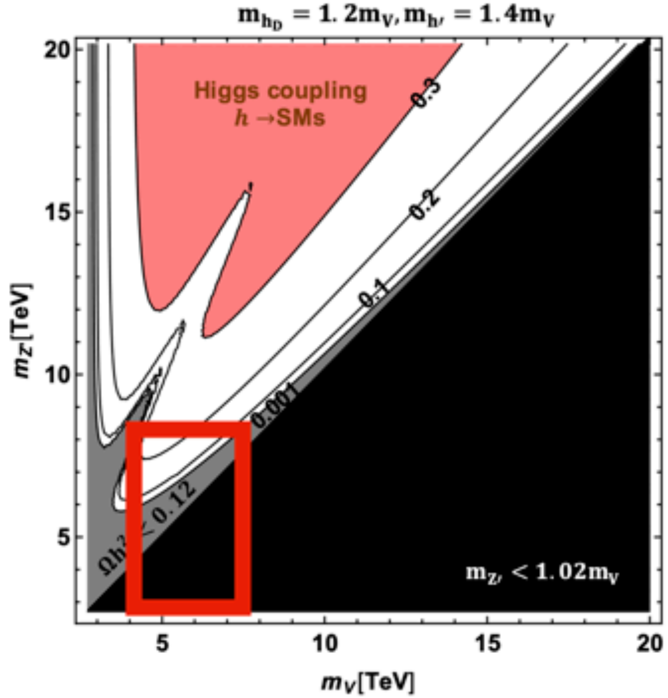




- Perturbative unitarity bounds
  (2scalar→2scalar scattering)
  → $\phi_h \lesssim 0.1$

- Direct detection(XENON1T/nT)
  → probe Higgs contribution to DM annihilation process

- W' search by LHC/HL-LHC
  → probe thermal relic scenario **even if** $\phi_h \simeq 0$

LHC13TeV 139 fb^{-1} [ATLAS Collabolation(2019)] (※ No bound for $m_{W'} > 7$ TeV)

HL-LHC14TeV 3000 fb^{-1} [ATL-PHYS-PUB-2018-044(2018)]

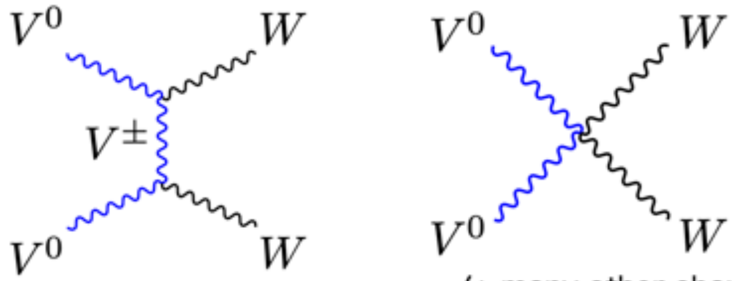
Summary

- 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

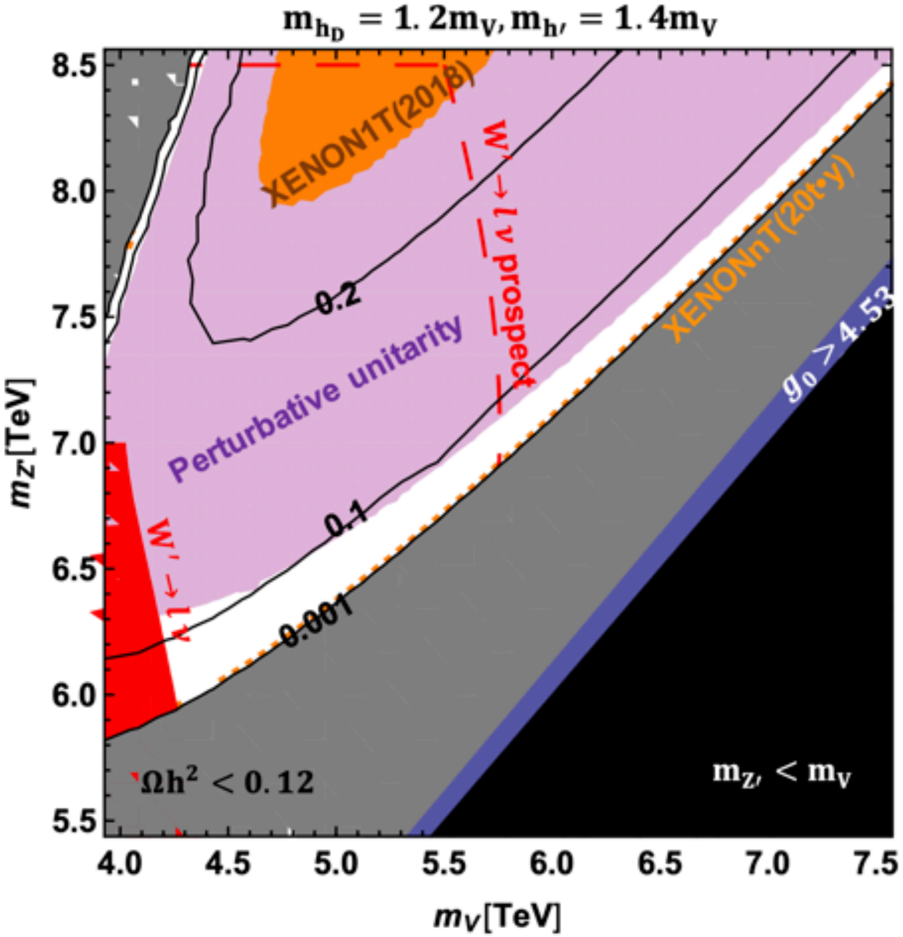
- Z_2-odd vectors: $V^0, V^\pm$
- Non-Abelian EW couplings



(+ many other channels…)

→ **EW int. can dominate DM annihilation**

Thermal relic region: $m_V \gtrsim \mathcal{O}(1)\mathrm{TeV}$



Test of TeV scale WIMP scenario

-Future direct detection experiments

-W' search @HL-LHC

Future Work

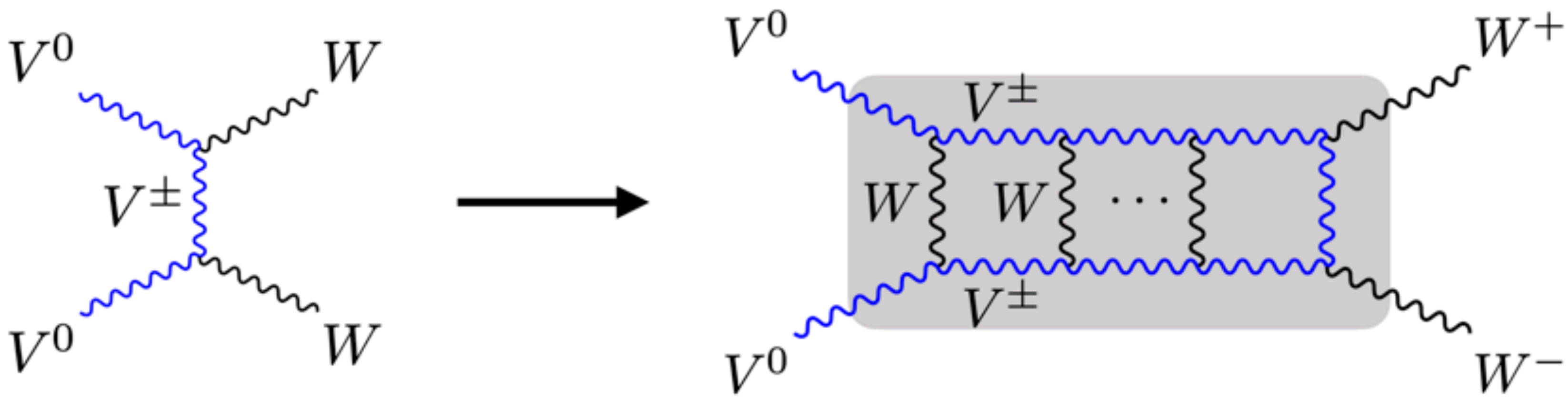
Difference from spin-0, spin-1/2 DM?

Result in this work

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

DM pair form the bound states in Annihilation processes

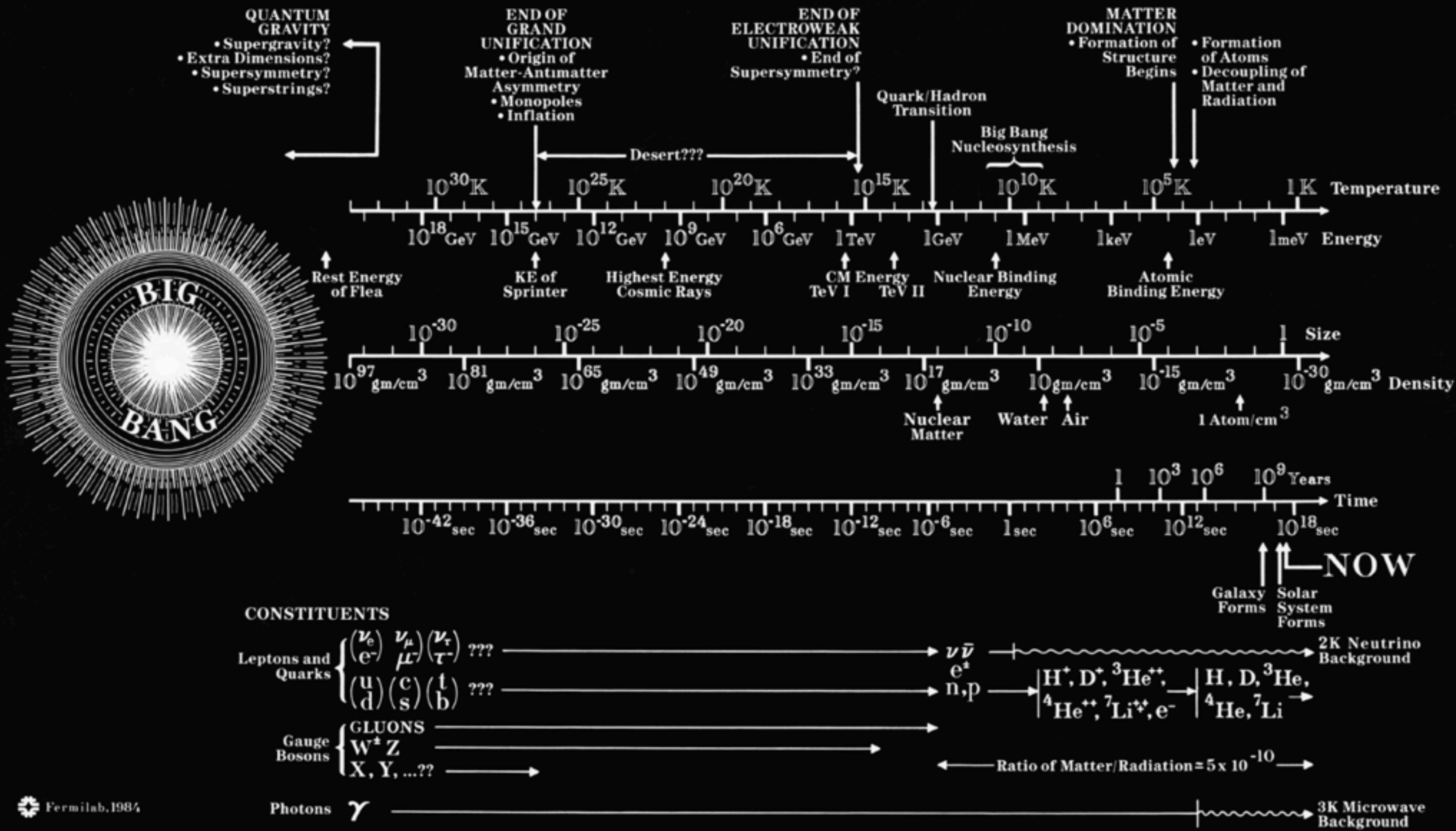
(Sommerfeld enhancement) [J. Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]



※Schematically picture

- Ωh^2-contours may be affected by this bound states formation
- Selection rules in annihilation process depend on DM spin

Backup



QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^{30}K 10^{25}K 10^{20}K 10^{15}K 10^{10}K 10^{5}K 1K Temperature
10^{18}GeV 10^{15}GeV 10^{12}GeV 10^{9}GeV 10^{6}GeV 1TeV 1GeV 1MeV 1keV 1eV 1meV Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10} 10^{-5} 1 Size
10^{97}gm/cm^3 10^{81}gm/cm^3 10^{65}gm/cm^3 10^{49}gm/cm^3 10^{33}gm/cm^3 10^{17}gm/cm^3 10gm/cm^3 10^{-15}gm/cm^3 10^{-30}gm/cm^3 Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1 10^3 10^6 10^9 Years
Time
10^{-42}sec 10^{-36}sec 10^{-30}sec 10^{-24}sec 10^{-18}sec 10^{-12}sec 10^{-6}sec 1sec 10^{6}sec 10^{12}sec 10^{18}sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
$\binom{\nu_e}{e^-}\binom{\nu_\mu}{\mu^-}\binom{\nu_\tau}{\tau^-}$???
$\binom{u}{d}\binom{c}{s}\binom{t}{b}$???
$\nu\bar{\nu}$
$e^\pm$
n,p
2K Neutrino Background
$H^+, D^+, {}^3He^{++}, {}^4He^{++}, {}^7Li^{+++}, e^-$
$H, D, {}^3He, {}^4He, {}^7Li$
Gauge Bosons
GLUONS
$W^\pm$ Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^{-10}
Photons γ
3K Microwave Background
Fermilab,1984

Our Model

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

For more details

Model

BSM Lagrangian

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

Scalar potential

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

Mass matrix: gauge sector

$$\mathcal{L} \supset \begin{pmatrix} W^+_{0\mu} & W^+_{1\mu} & W^+_{2\mu} \end{pmatrix} \mathcal{M}_C^2 \begin{pmatrix} W_0^{-\mu} \\ W_1^{-\mu} \\ W_2^{-\mu} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} W^3_{0\mu} & W^3_{1\mu} & W^3_{2\mu} & B_\mu \end{pmatrix} \mathcal{M}_N^2 \begin{pmatrix} W_0^{3\mu} \\ W_1^{3\mu} \\ W_2^{3\mu} \\ B^\mu \end{pmatrix}$$

<u>Charged vector</u>

$$\mathcal{M}_C^2 = \frac{1}{4} \begin{pmatrix} g_0^2 v_\Phi^2 & -g_0 g_1 v_\Phi^2 & 0 \\ -g_0 g_1 v_\Phi^2 & g_1^2(v^2 + 2v_\Phi^2) & -g_1 g_0 v_\Phi^2 \\ 0 & -g_1 g_0 v_\Phi^2 & g_0^2 v_\Phi^2 \end{pmatrix},$$

<u>Neutral vector</u>

$$\mathcal{M}_N^2 = \frac{1}{4} \begin{pmatrix} g_0^2 v_\Phi^2 & -g_0 g_1 v_\Phi^2 & 0 & 0 \\ -g_0 g_1 v_\Phi^2 & g_1^2(v^2 + 2v_\Phi^2) & -g_1 g_0 v_\Phi^2 & -g_1 g' v^2 \\ 0 & -g_1 g_0 v_\Phi^2 & g_0^2 v_\Phi^2 & 0 \\ 0 & -g_1 g' v^2 & 0 & g'^2 v^2 \end{pmatrix}.$$

Mass matrix: scalar sector

$$\mathcal{L} \supset \frac{1}{2}\begin{pmatrix}\sigma_3 & \sigma_1 & \sigma_2\end{pmatrix}\begin{pmatrix} 2\lambda v^2 & 2vv_\Phi\lambda_{h\Phi} & 2vv_\Phi\lambda_{h\Phi} \\ 2vv_\Phi\lambda_{h\Phi} & 8v_\Phi^2\lambda_\Phi & 4v_\Phi^2\lambda_{12} \\ 2vv_\Phi\lambda_{h\Phi} & 4v_\Phi^2\lambda_{12} & 8v_\Phi^2\lambda_\Phi \end{pmatrix}\begin{pmatrix}\sigma_3 \\ \sigma_1 \\ \sigma_2\end{pmatrix}.$$

<u>Quartic couplings</u>

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

Scalar sector

τ^a : Pauli matrices

$$\epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$

Scalar Field

$$\Phi_j = \mathbf{1}\sigma_j + \tau^a \pi^a_j \quad \text{(j=1, 2)} \qquad H = \frac{1}{\sqrt{2}} \begin{pmatrix} i\pi^1 - \pi^2 \\ \sigma - i\pi^3 \end{pmatrix}$$

(w/ real conditions $\Phi_j = -\epsilon \Phi^*_j \epsilon$)

Gauge transformation $U_n = \exp[i\theta_n(x)] \quad (n = 0, 1, 2)$

$$\Phi_1 \mapsto U_0 \Phi_1 U_1^\dagger \qquad \Phi_2 \mapsto U_2 \Phi_2 U_1^\dagger \qquad H \mapsto U_1 H$$

$$\boxed{\text{Symmetry:} \quad \mathrm{SU}(2)_0 \otimes \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \dashrightarrow \mathrm{U}(1)_{\mathrm{em}}}$$

Gauge sector: $W^a_0 \; W^a_1 \; W^a_2 \; B$

3 + 3 + 3 + 1 = 10

massive : massless

9 + 1

eaten

Scalar sector: $\Phi_1 \quad \Phi_2 \quad H$

4 + 4 + 4 = 12

NG boson : Physical scalar

9 + 3

Where is $SU(2)_L$ and Z_2 parity? → **SSB structure is key to answer!**

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**

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

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

Unitarity bound for scalar quartic couplings

Perturbative unitarity bounds

$$|\lambda| \leq 4\pi,$$

$$|\lambda_{h\Phi}| \leq 4\pi,$$

$$|\lambda_{\Phi}| \leq \pi,$$

$$|\lambda_{12}| \leq 2\pi,$$

$$|3\lambda_{\Phi} - \lambda_{12}| \leq \pi,$$

$$\left|3\lambda + 4(3\lambda_{\Phi} + \lambda_{12}) \pm \sqrt{(3\lambda - 4(3\lambda_{\Phi} + \lambda_{12}))^2 + 32\lambda_{h\Phi}^2}\right| \leq 8\pi.$$

$$|\lambda| = \left|\frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2}\right| \lesssim \frac{4}{3}\pi$$ in the limit of $\lambda \gg \lambda_{h\Phi}, \lambda_{\Phi}, \lambda_{12}$

For $m_{h'} \gg v$, we need small ϕ_h to realize $\lambda \simeq \mathcal{O}(1)$

→ **Perturbative unitarity bounds give a viable constraint on ϕ_h**

Backup: Fermion Sector

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

Yukawa interaction

We need NO BSM particles in fermion sector

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

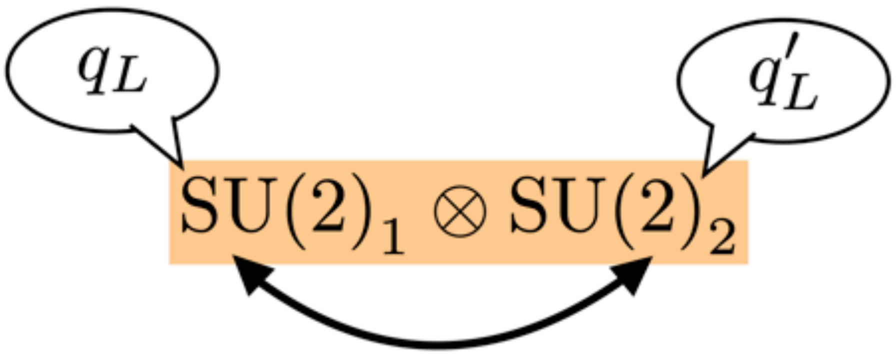
$$\left[\tilde{H} = \epsilon H^\star \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \right]$$

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	1	0
Φ_2	0	1	1	2	2	0

Fermion + H

Why we need three SU(2) groups?



Exchange Symmetry

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

→ difficulties to obtain realistic SM fermion spectrum

Parameters in BSM sector

[g_0 : gauge coupling for $SU(2)_0$ & $SU(2)_2$
g_1 : gauge coupling for $SU(2)_1$]

$$\underbrace{g_0,\quad g_1,\quad g',\quad v,\quad v_\Phi,}\qquad \underbrace{\text{(scalar quartic couplings)} \times 4}$$

$$\downarrow \qquad\qquad\qquad \downarrow$$

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

ϕ_h : mixing angle of
Z_2-even scalars

$\sim v_\Phi$ (TeV scale)

Free parameters

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

Constraint in vector sector: {m_V, $m_{Z'}$}

Mass ratio

$$\frac{m_{Z'}^2}{m_V^2} \simeq 1 + \frac{2g_1^2}{g_0^2} \quad (v_\Phi \gg v)$$

$m_{Z'}/m_V$ parametrizes the couplings in the limit of $v_\Phi \gg v$

$$\Rightarrow \begin{cases} \cdot\, m_{Z'} \simeq m_V & \rightarrow g_0 \gg 1 \\ \cdot\, m_{Z'} \gg m_V & \rightarrow g_1 \gg 1 \end{cases}$$

(1)Unitarity bound on g_0 & g_1

(2Gauge boson→2scalar scattering)

$$g_j < \sqrt{\frac{16\pi}{\sqrt{6}}} \simeq 4.53. \quad (j = 0, 1)$$

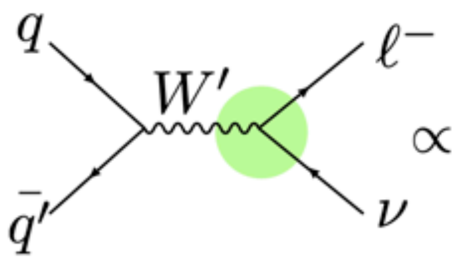
[K. Hally, H. E. Logan, T. Pilkington (2012)]

$$\boxed{1.02 \lesssim m_{Z'}/m_V \lesssim 6.97}$$

(2)Z', W' search @LHC

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

Z', W' strongly couples to SM fermion for $m_{Z'} \gg m_V$



$$\propto \frac{1}{m_{W'}^2}\left(\frac{m_{Z'}^2}{m_V^2} - 1\right)$$

Constraint in scalar sector: {m_h, m_{hD}, ϕ_h}

Higgs masses

We focus on the spin-1 DM scenario $\rightarrow$ $m_{h_D} > m_V$

$$\boxed{\text{Benchmark value:} \quad m_{h_D} = 1.2 m_V, \quad m_{h'} = 1.4 m_V}$$

Higgs mixing angle

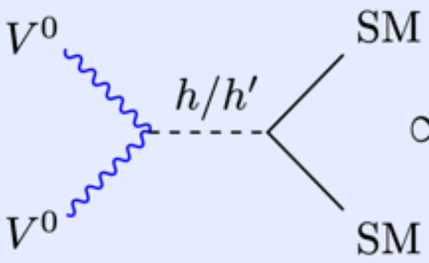
- Higgs coupling strength
  [ATLAS collaboration (2020)]

$$\begin{cases} \kappa_F = \cos\phi_h \\ \kappa_V \simeq \cos\phi_h \quad (v_\Phi \gg v) \end{cases} \Rightarrow \boxed{\phi_h < 0.3}$$

- Perturbative unitarity in 2scalar→2scalar scattering

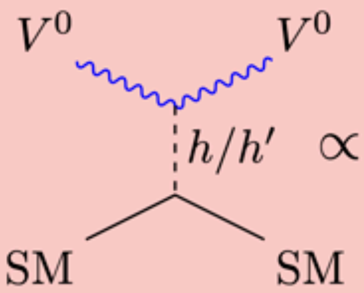
- ϕ_h tunes the annihilation & scattering process

Annihilation



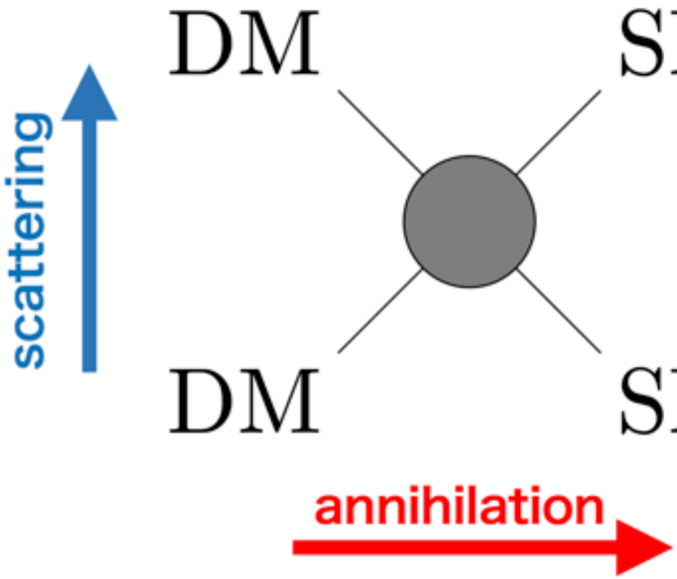
$\propto \sin 2\phi_h$

Scattering



$\propto \sin 2\phi_h$

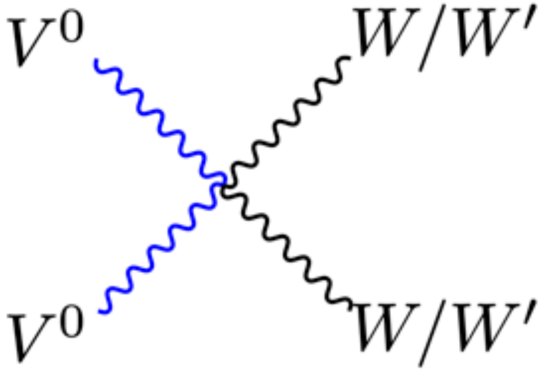
DM Phenomenology

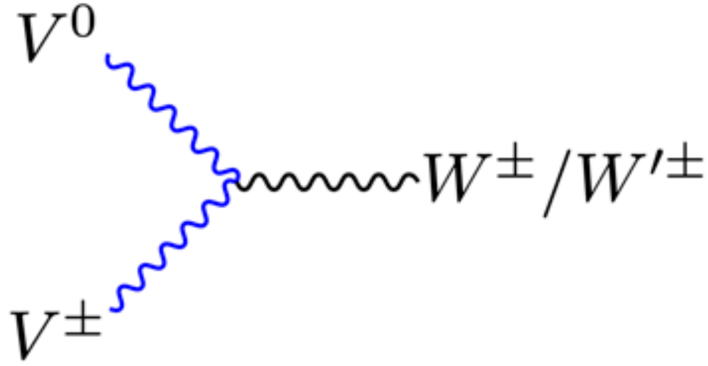


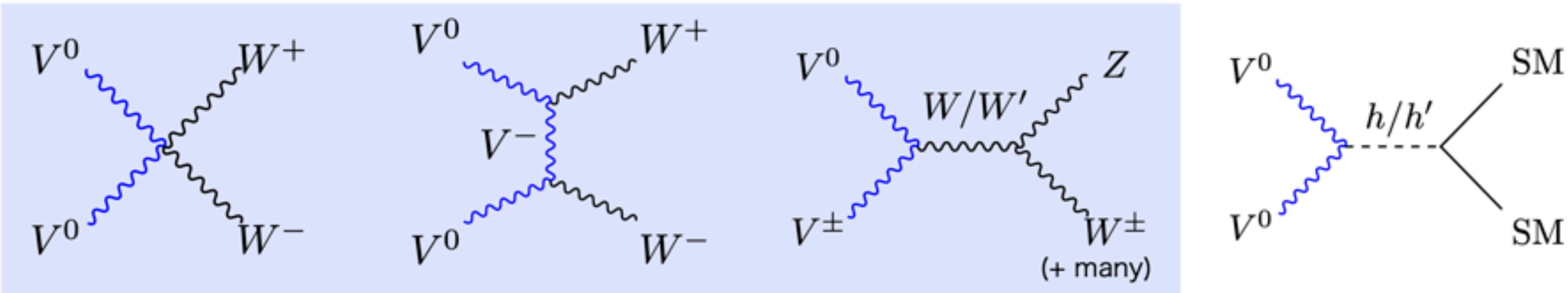
Annihilation process: DM thermal relic

Feature **V-particles have non-Abelian vector couplings**

eg.







annihilation $\longrightarrow$

EW annihilation channels between V-particles (not only Higgs-exchange)

$\rightarrow$ DM thermal relic is determined by EW interactions

☑ **"Electroweakly interacting" spin-1 DM**

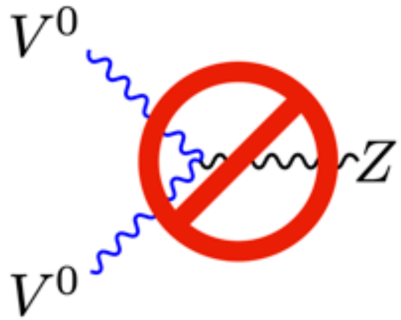
Scattering Process: DM direct detection

Direct detection

DM-nucleus scattering is searched, but no significant excess now

→ Severe constraint on DM-Z coupling & DM-Higgs coupling

Z-exchange process

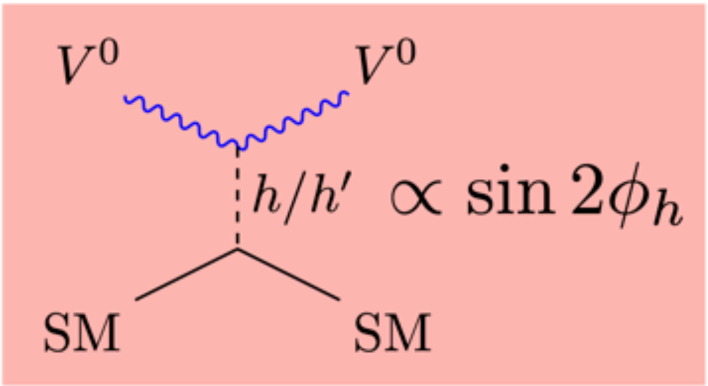


Neutral boson triple coupling is forbidden

(∵ non-Abelian extension)

→ No Z-exchange in scattering process!

Higgs-exchange process



Mixing angle ϕ_h tunes the scattering process

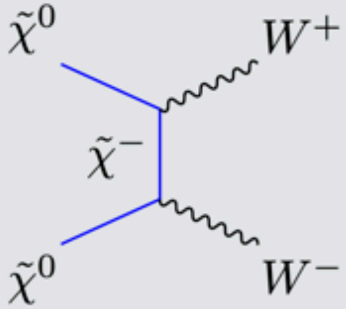
→ direct detection bounds give upper bound on ϕ_h

For sufficiently small ϕ_h,

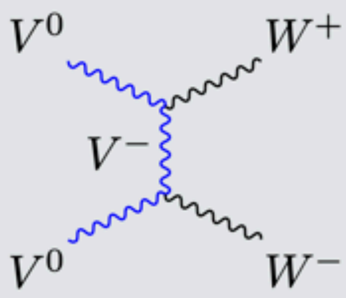
σ_{scat} is dominated by 1-loop EW processes

Features of EW spin-1 DM (Compared w/ Wino DM)

Wino vs V-particles



vs



	Wino	V-particles
Spin	1/2 (Majorana fermion) [SU(2)$_L$ triplet, Y=0]	1 (Vector)
Mass difference	~ 166 MeV	~ 168 MeV
Annihilation	EW	EW + Higgs exchange
Scattering	tree-level: No loop-level: EW	tree-level: Higgs exchange loop-level: EW
Z$_2$-even vectors	—	Z', W'

Features of EW spin-1 DM?

Coannihilation is relevant

Thermal relic region
$\rightarrow m_V \gtrsim \mathcal{O}(1)\mathrm{TeV}$

Direct detection

W' search @LHC

We can probe the thermal relic region by Direct detection & W' search!

Direct detection

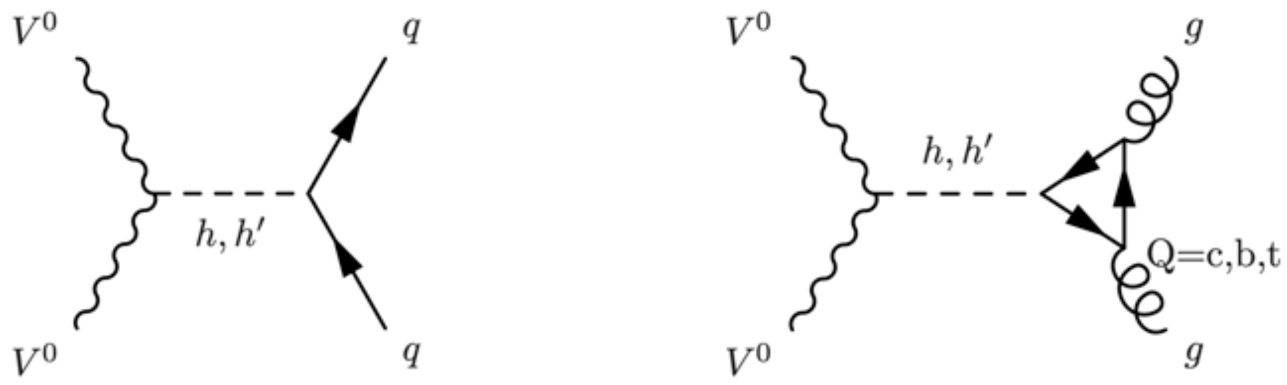
For more details

Viable Region: W' physics

Relevant couplings

$$\mathcal{L} \supset \frac{m_V^2}{\sqrt{2} v_\Phi} (\sin\phi_h h + \cos\phi_h h') V^0_\mu V^{0\mu} - \sum_q \frac{m_q}{v} (\cos\phi_h h - \sin\phi_h h') \bar{q} q.$$

Diagrams



Cross section

$$\sigma_{\rm SI} = \frac{\mu^2}{8\pi} \left(\frac{m_N m_V f^N \sin 2\phi_h}{v v_\Phi} \right)^2 \left(\frac{1}{m_h^2} - \frac{1}{m_{h'}^2} \right)^2 \simeq 10^{-44} \times g_0^2 (\sin 2\phi_h)^2 \ \ [\mathrm{cm}^2]$$

$$\left[\mu = \frac{m_V m_N}{m_V + m_N}, \quad f^N \equiv \frac{2}{9} + \frac{7}{9} \left(\sum_{q=u,d,s} f^N_{T_q} \right). \right]$$

W' physics

For more details

Constraint on $m_V/m_{Z'}$: Unitarity bound on g_0 & g_1

Mass ratio

$$\frac{m_{Z'}^2}{m_V^2} \simeq 1 + \frac{2g_1^2}{g_0^2} \quad (v_\Phi \gg v)$$

$m_{Z'}/m_V$ parametrizes the couplings in the limit of $v_\Phi \gg v$

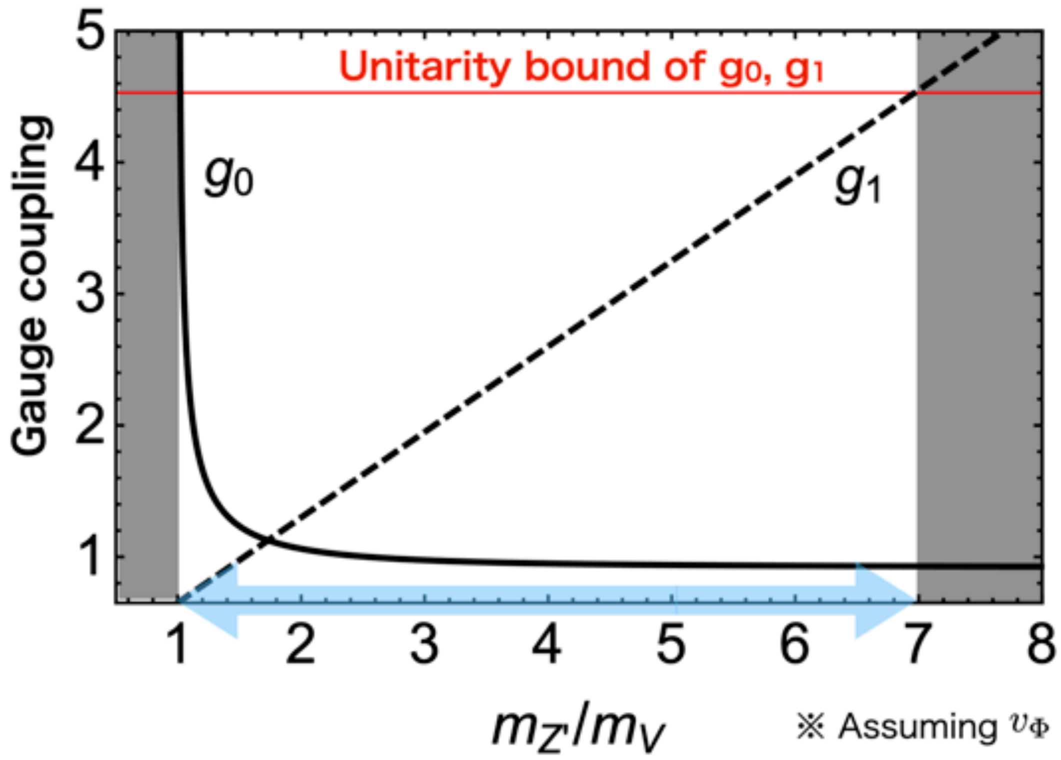
- $m_{Z'} \simeq m_V$ $\rightarrow$ $g_0 \gg 1$
- $m_{Z'} \gg m_V$ $\rightarrow$ $g_1 \gg 1$

(1)Unitarity bound on g_0 & g_1

$$g_j < \sqrt{\frac{16\pi}{\sqrt{6}}} \simeq 4.53. \quad (j = 0, 1)$$

[K. Hally, H. E. Logan, T. Pilkington (2012)]

$$\boxed{1.02 < m_{Z'}/m_V < 6.97}$$



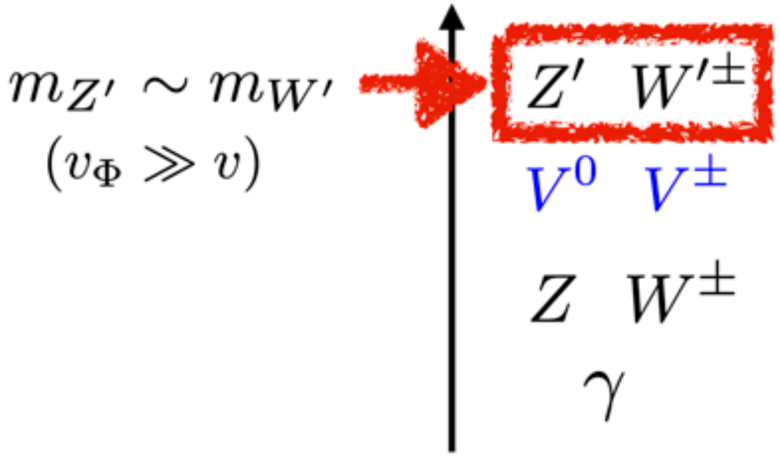
※ Assuming $v_\Phi \gg v$

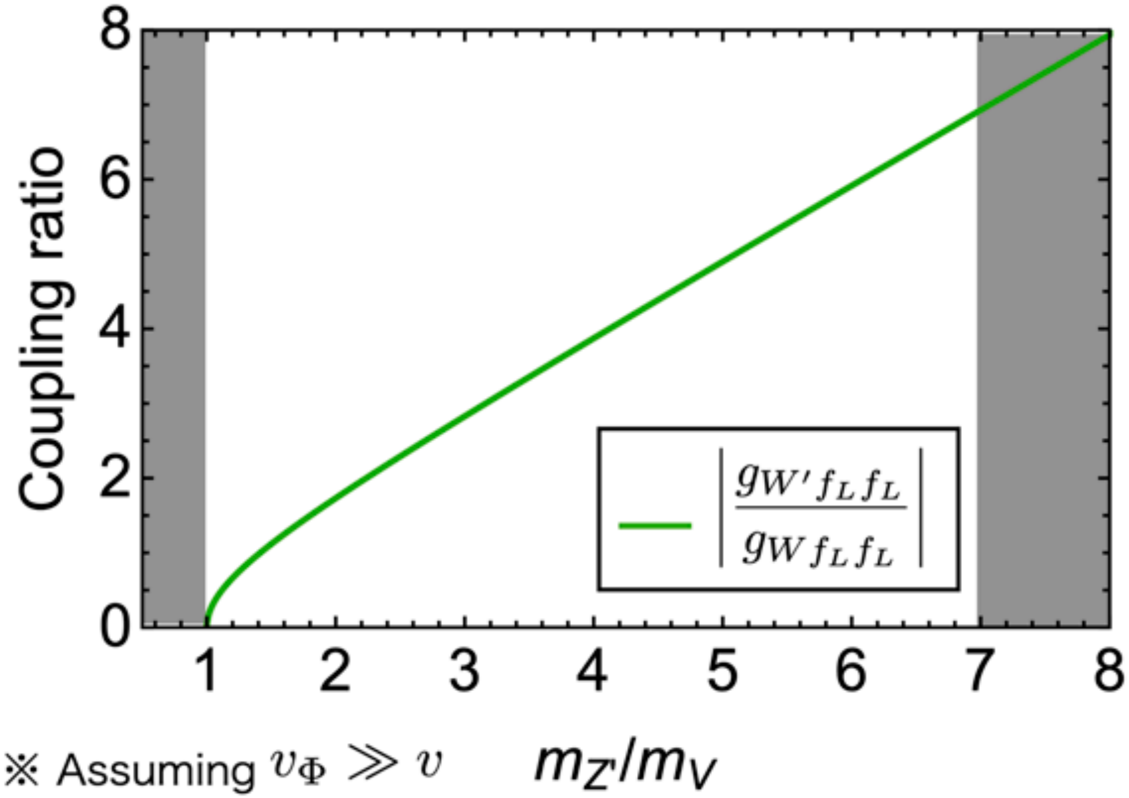
Constraint on $m_V/m_{Z'}$: W' search

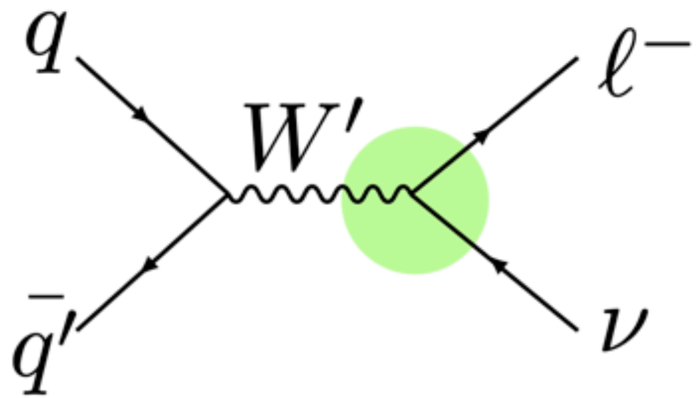
W'-fermion coupling

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

cf. Vector Spectrum







※ Assuming $v_\Phi \gg v$

→ TeV scale W' search may constrain the parameter region

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	$\lvert g_{W' f_L f_L}/g_{W f_L f_L} \rvert$
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

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

fixed as SM value

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

Coannihilation

Mass Difference and Coannihilation(1/2)

Loop induced mass difference

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

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

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

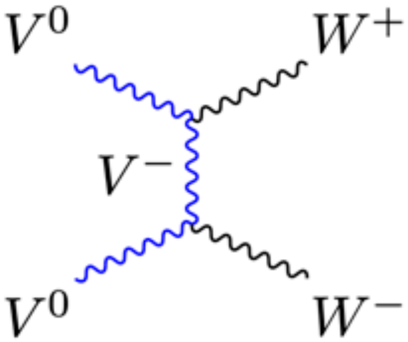
$$n_{\mathrm{eq}} = g \left(\frac{mT}{2\pi}\right)^{\frac{3}{2}} \exp\left(-\frac{m}{T}\right)$$

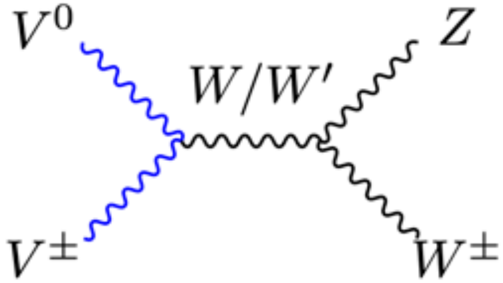
m : mass
T : temperature
g : degrees of freedom

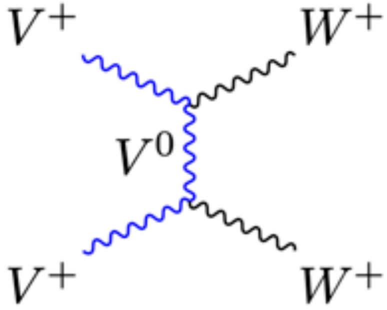
→ **All the V-particles contribute to the DM annihilation**

Mass Difference and Coannihilation(2/2)

<u>Involving diagrams(examples)</u>

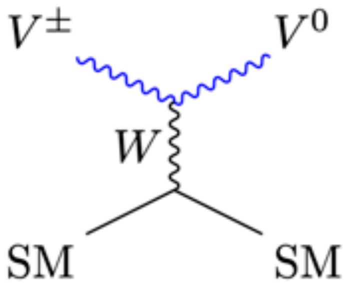


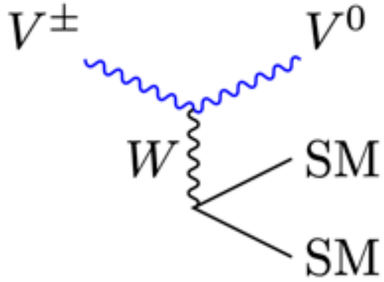




DM abundance can also be decreased by annihilation of $V^\pm$

※ All the $V^\pm$ decays into V^0

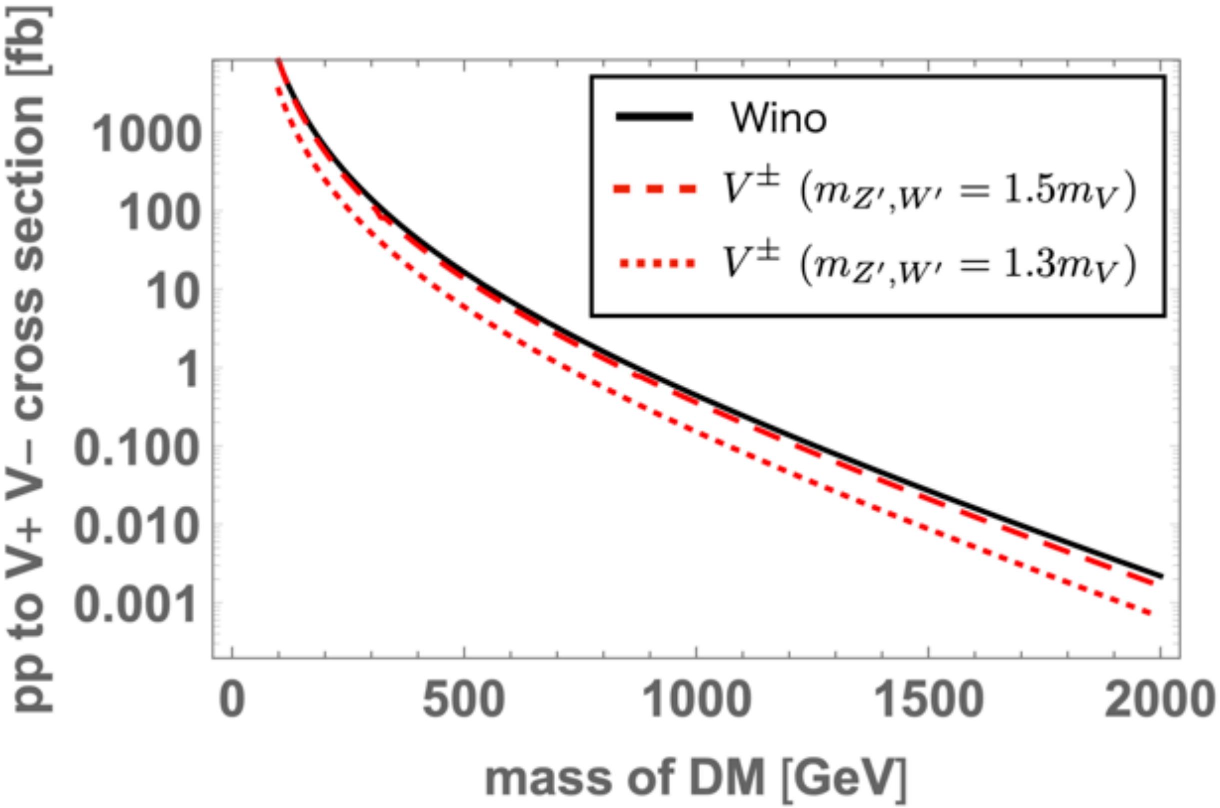


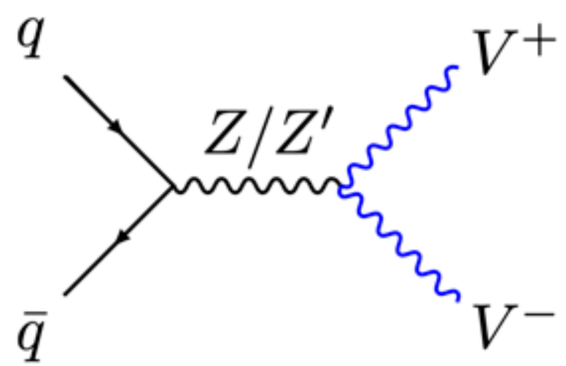


Long-lived particle search @LHC

$\{V^0, V^\pm\}$ 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 $\rightarrow$ less production rate than Wino case due to the interference btw W and W'





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

Ωh^2 contours

w/ Small Higgs mixing angle (ϕh << 1)

For more details

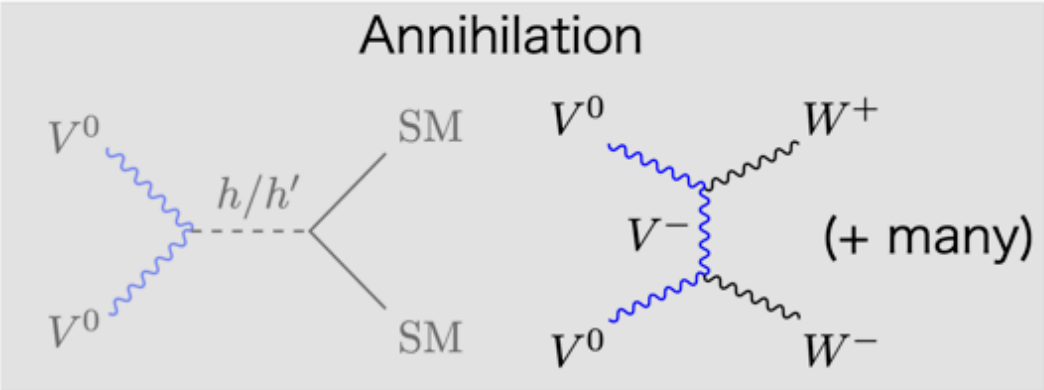
Small ϕ_h regime:

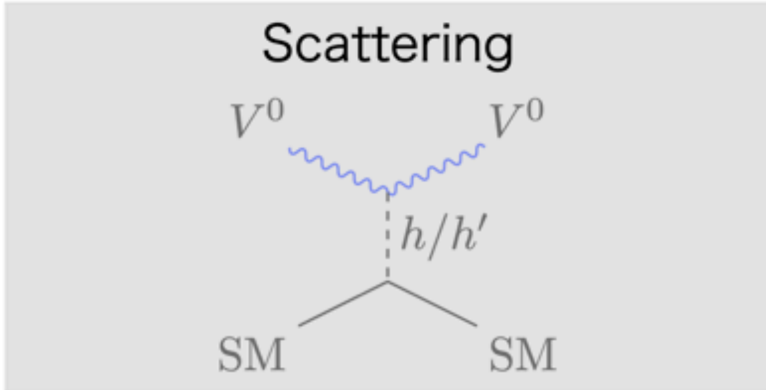
ϕ_h : mixing angle of Z_2-even scalars

Higgs mixing angle

Small ϕ_h regime: DM annihilation only occur through the EW interaction

No direct detection bounds (EW 1-loop diagram dominate $\sigma_{\rm Scat}$)





Higgs masses

We focus on the spin-1 DM scenario $\rightarrow$ $m_V < m_{h_D}$

Benchmark point (Scalar sector)

$$\phi_h = 0.001, \quad m_{h_D} = 1.2 m_V, \quad m_{h'} = 1.4 m_V$$

Ωh^2 contour(1/3)

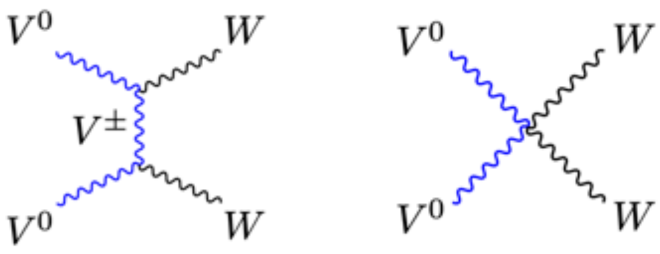
★ : benchmark point
(m_V=3 TeV, $m_{Z'}$=10 TeV)

(1) $m_{Z'} \gg m_V$

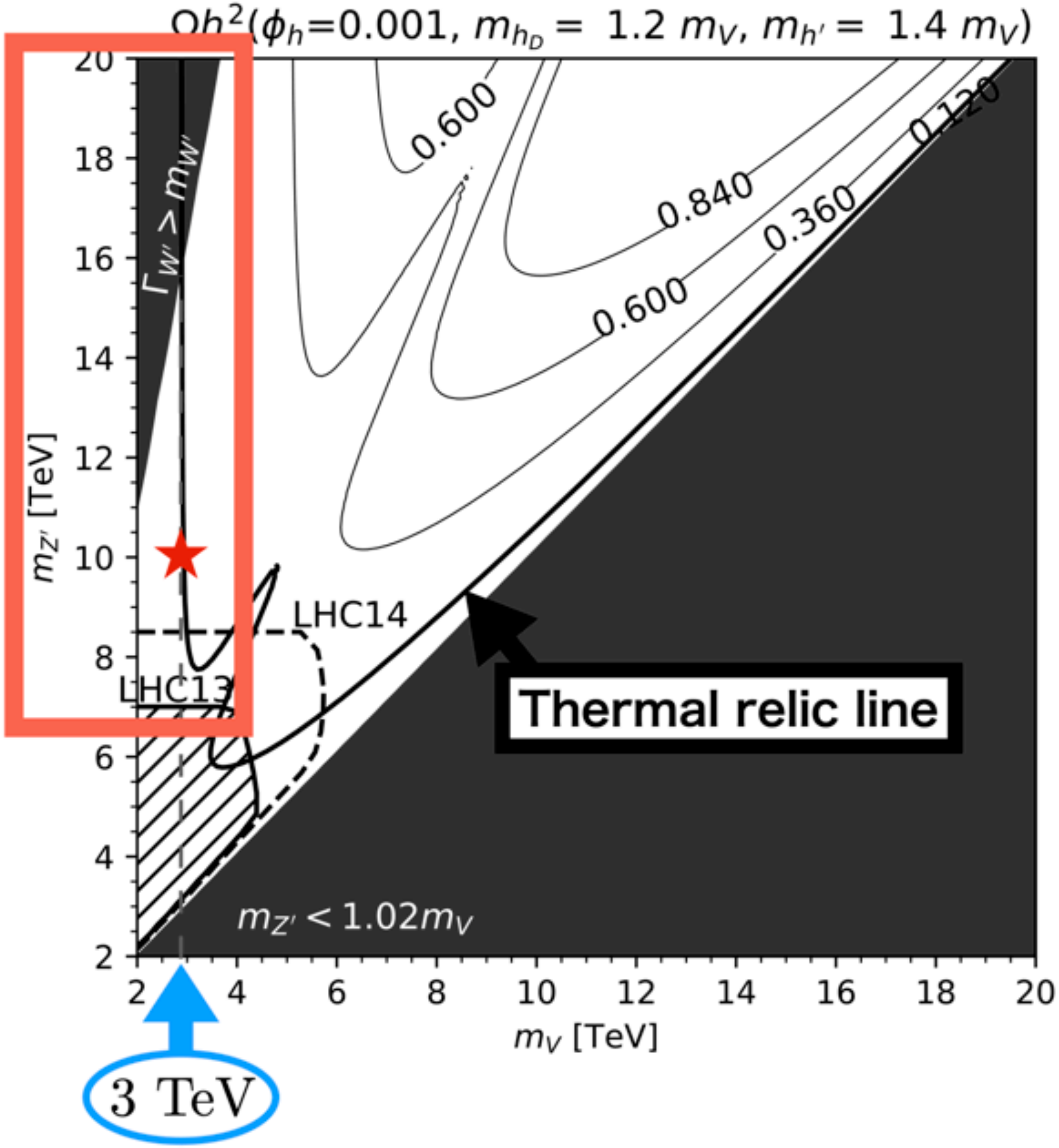
Ωh^2 is determined independently of $m_{Z'}$

Ωh^2=0.12 $\Leftrightarrow$ $m_V \sim 3\ \mathrm{TeV}$

Annihilation Channel



(+ many other channels…)



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

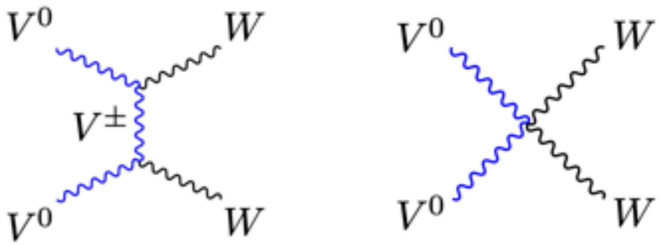
Ωh^2 contour(2/3)

(2) $m_{Z'} \gtrsim m_V$

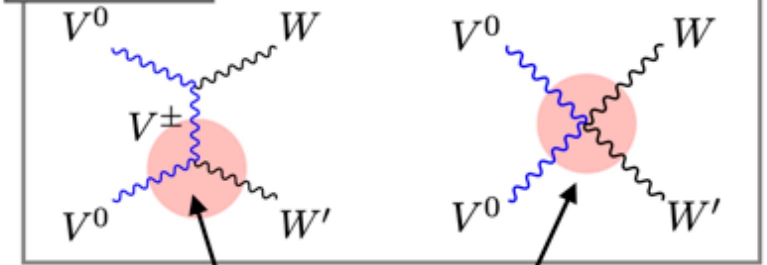
DM pair can annihilate into the final states with W', Z'

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

Annihilation Channel

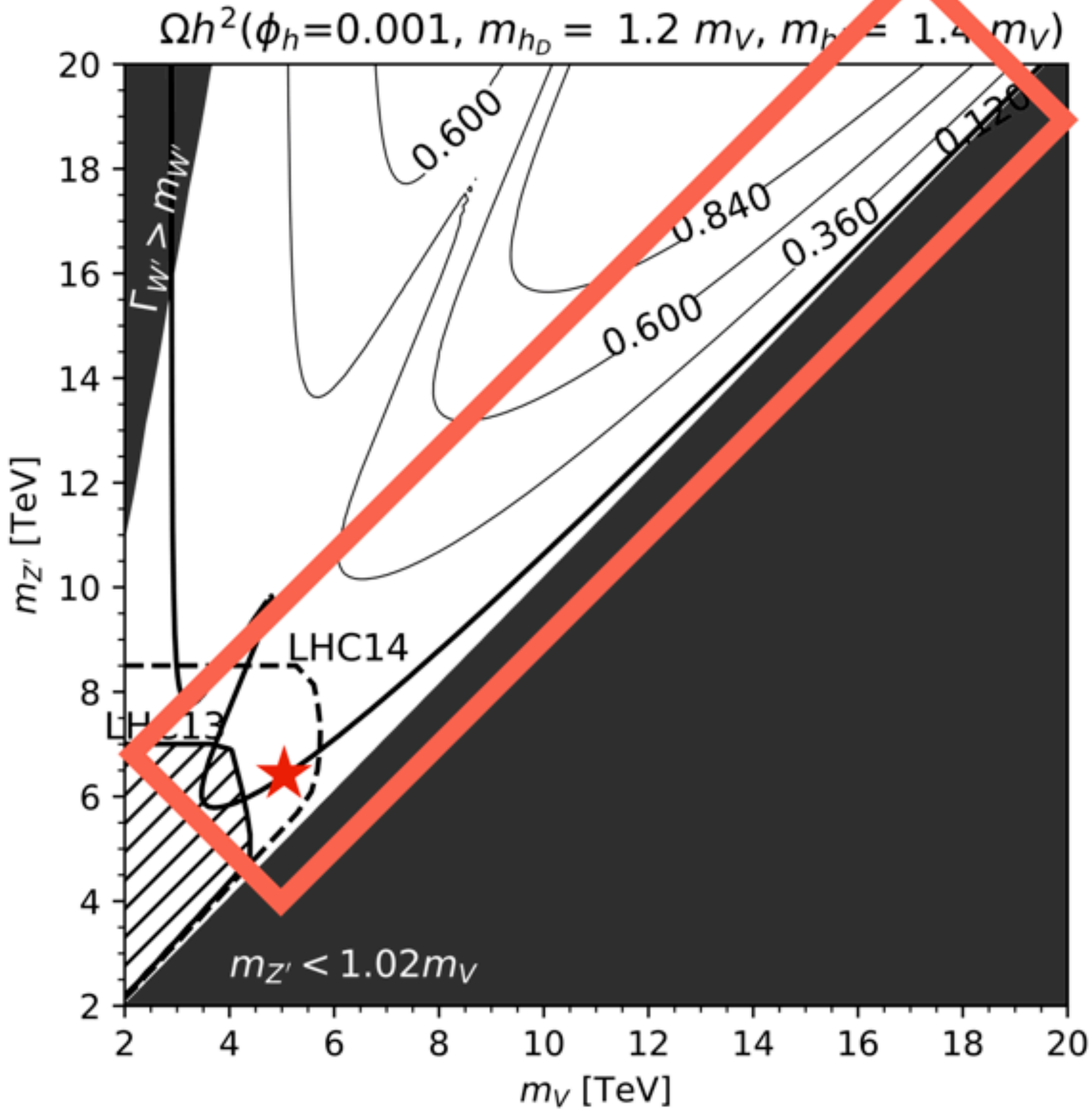


New channels



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

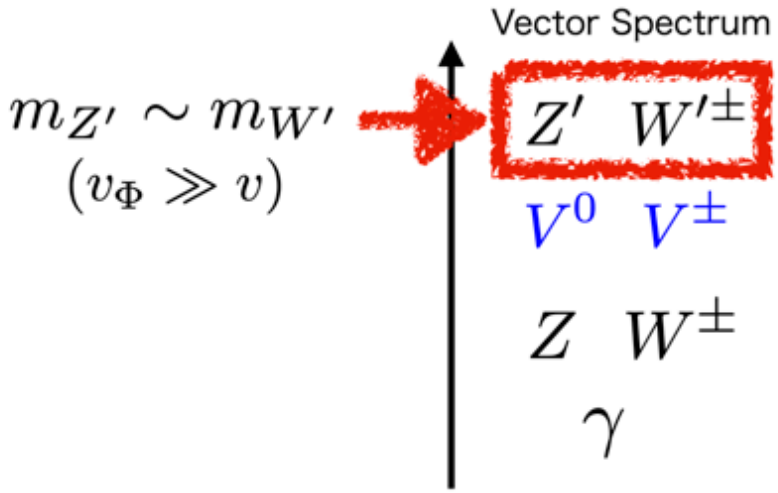
★ : benchmark point (m_V=5 TeV, $m_{Z'}$=6.5 TeV)

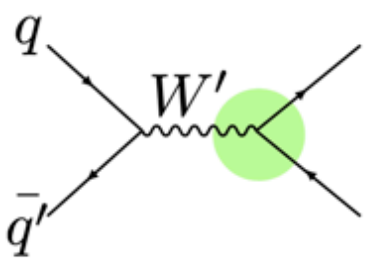


※ Ωh^2-contours are degenerated for $\phi_h \lesssim 0.001$

Ωh^2 contour(3/3)

<u>W' search in TeV scale</u>



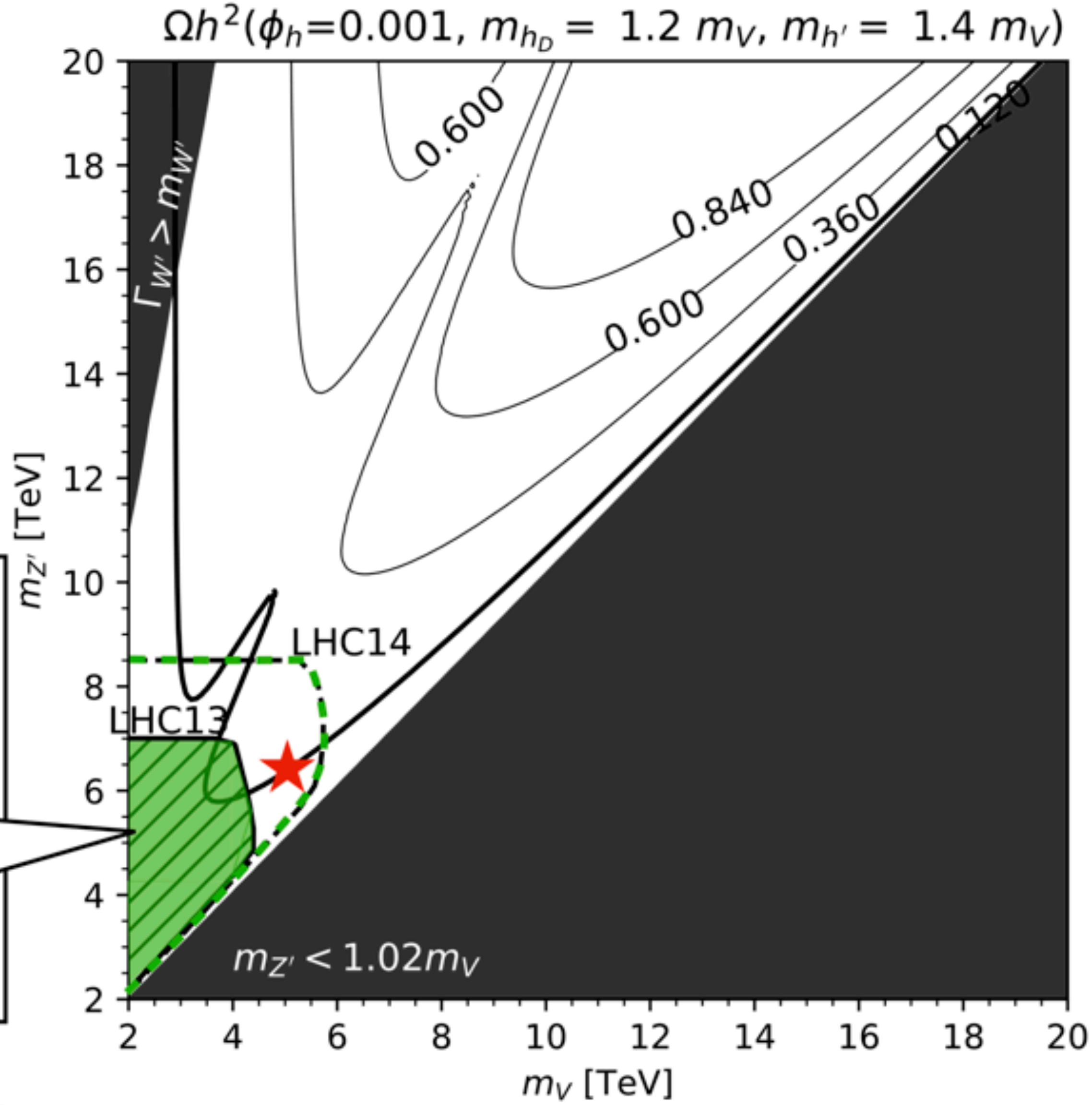


$$\propto \frac{1}{m_{W'}^2}\sqrt{\frac{m_{Z'}^2}{m_V^2}-1}$$

※ No bound for $m_{W'} > 7$ TeV

[ATLAS Collabolation(2019)]

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

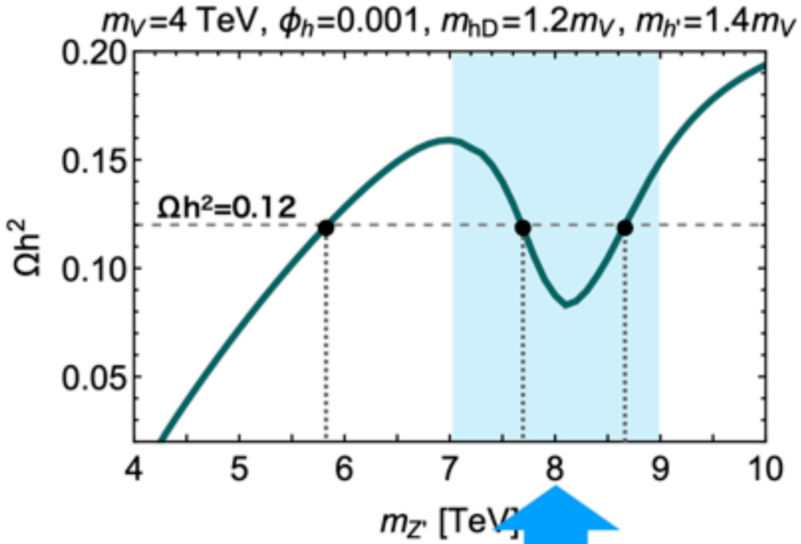


We can test thermal relic region in W' search @LHC(14 TeV)

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

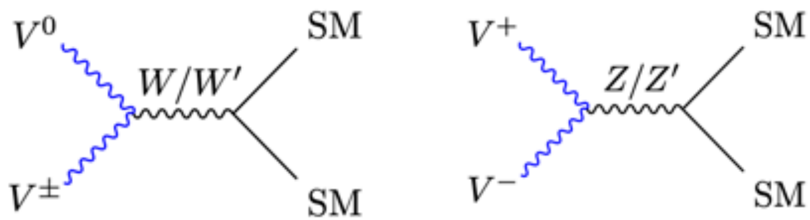
Resonance region in Ωh^2 contour

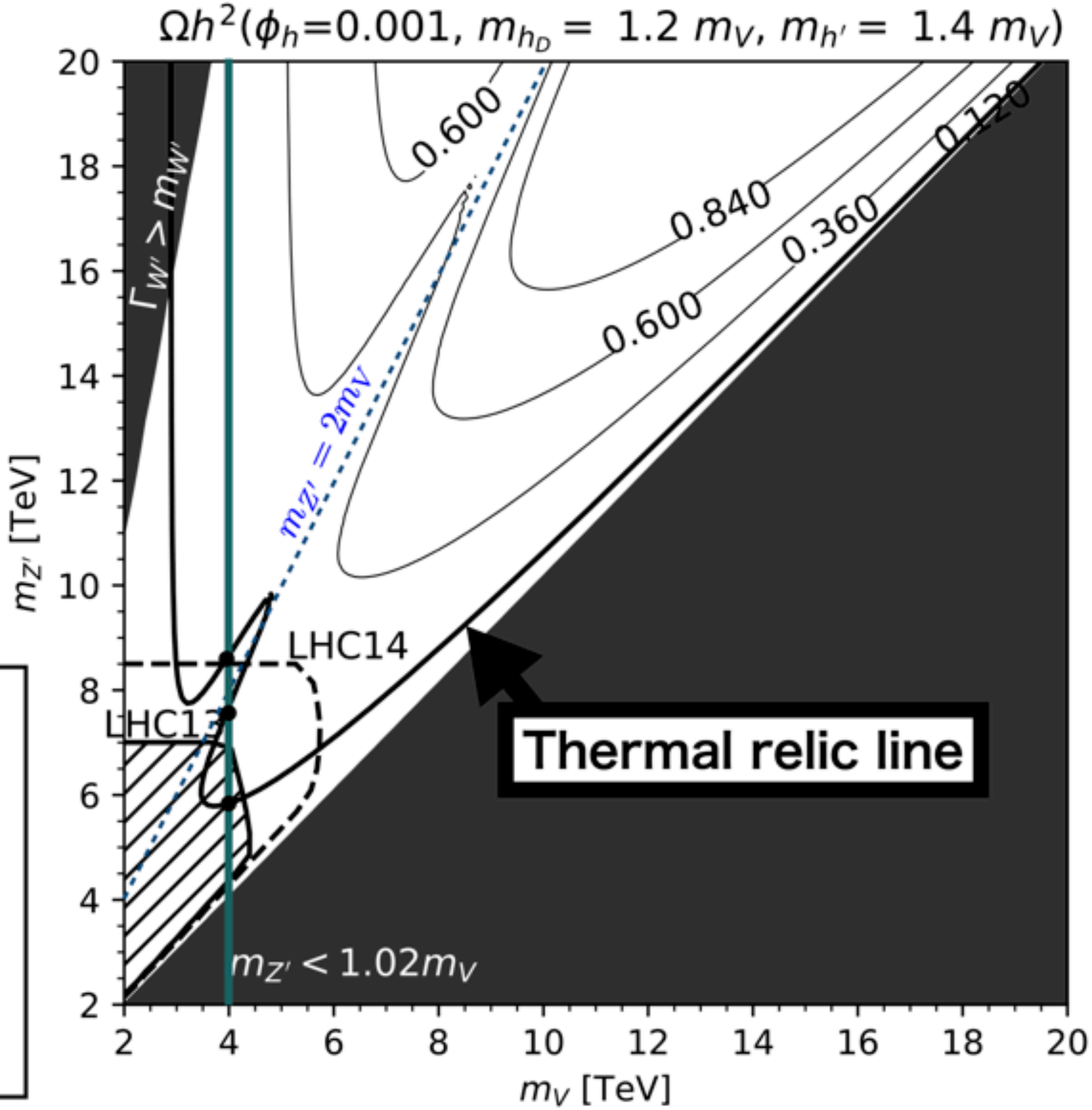
Contours of Ωh^2



$m_{Z'} \sim 2m_V$

resonance region of Z'/W' channel





Ωh^2 contours

w/ relatively large Higgs mixing angle

For more details

Viable Region: Higgs sector

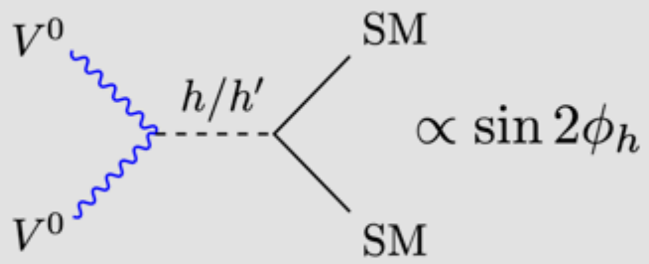
ϕ_h : mixing angle of
Z_2-even scalars

Higgs mixing angle

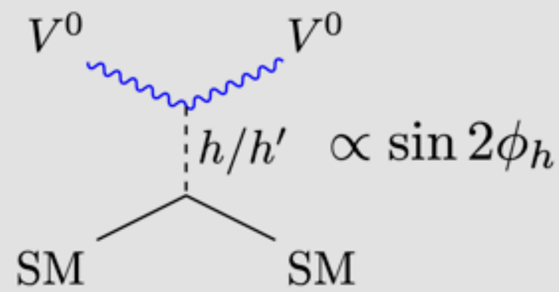
Small ϕ_h regime: DM annihilation only occur through the EW interaction
No direct detection bounds

Large ϕ_h regime: Higgs exchange process can contribute DM annihilation
Direct detection experiments may be the good probe

Annihilation



Scattering



Higgs masses

We focus on the spin-1 DM scenario $\rightarrow$ $m_V < m_{h_D}$

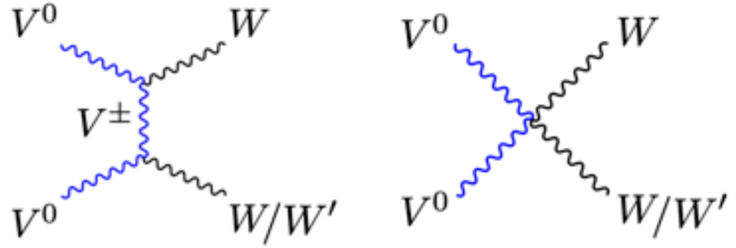
Benchmark value: $m_{h_D} = 1.2 m_V, \quad m_{h'} = 1.4 m_V$

Thermal relic region in ϕ_h contour

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

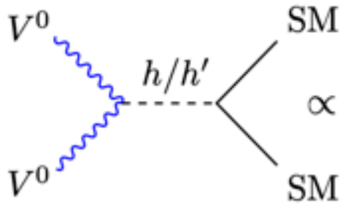
Annihilation Channel

·EW channels

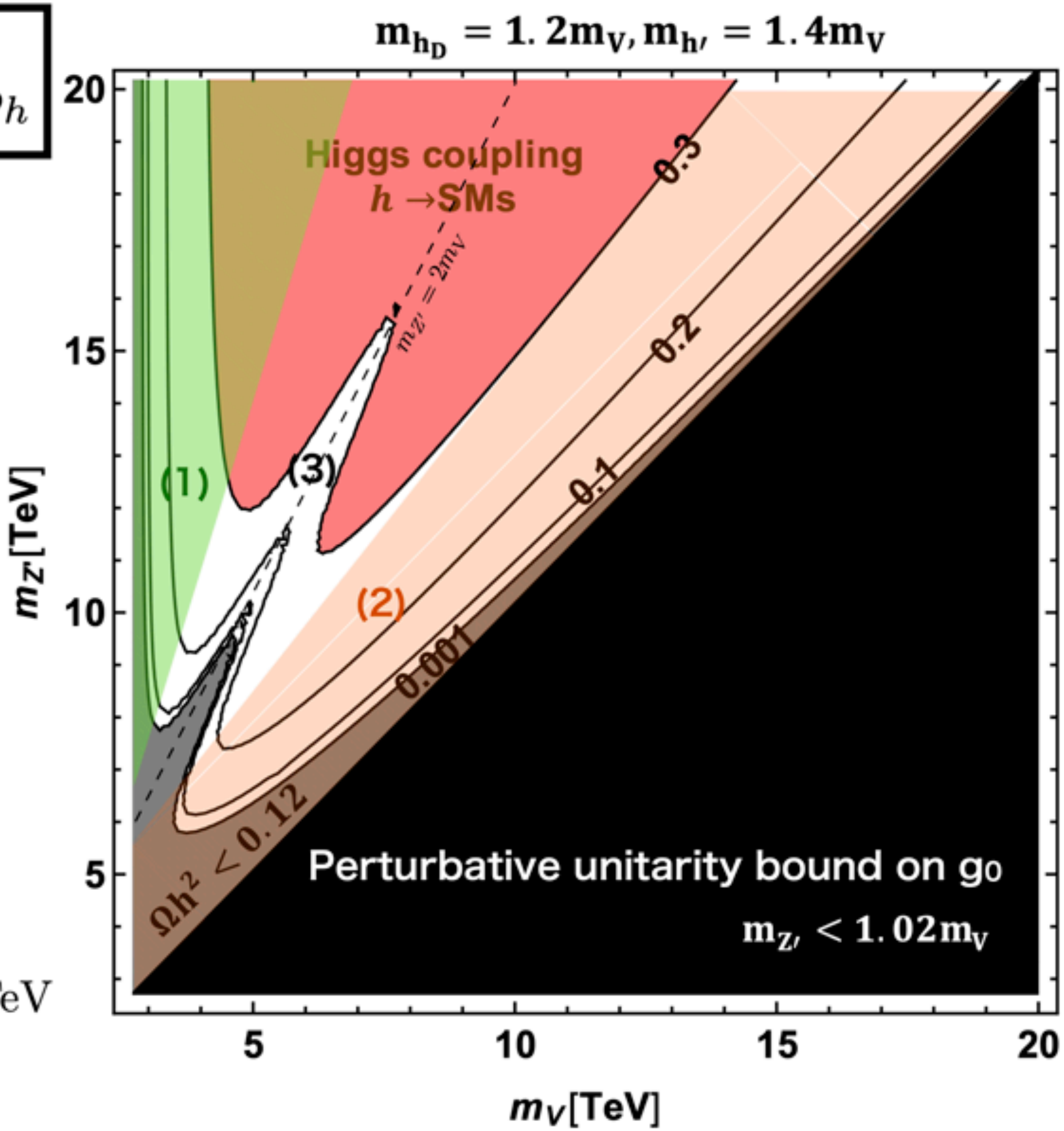


(+ many other channels…)

·Higgs channels



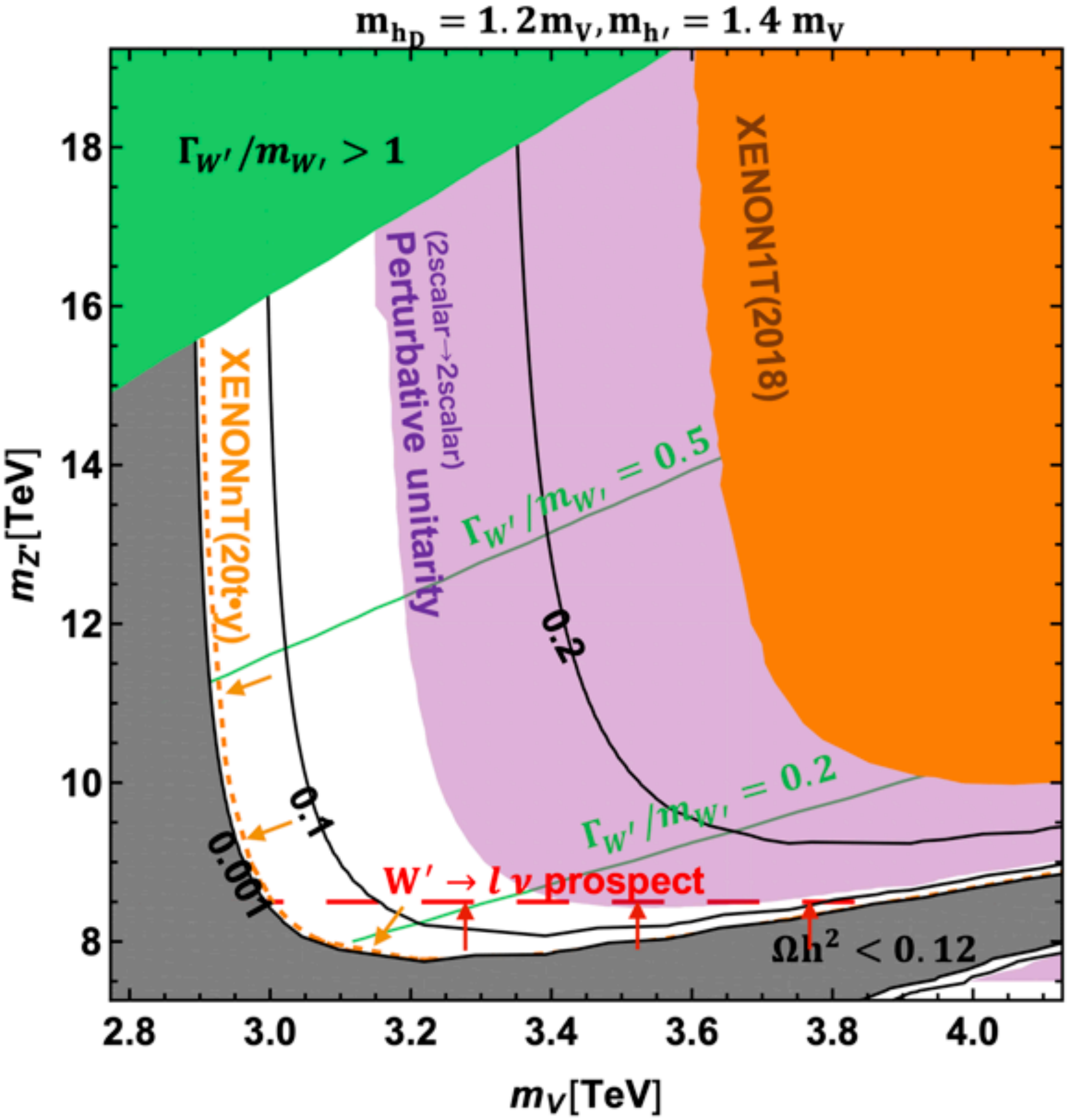
$\propto \sin 2\phi_h$

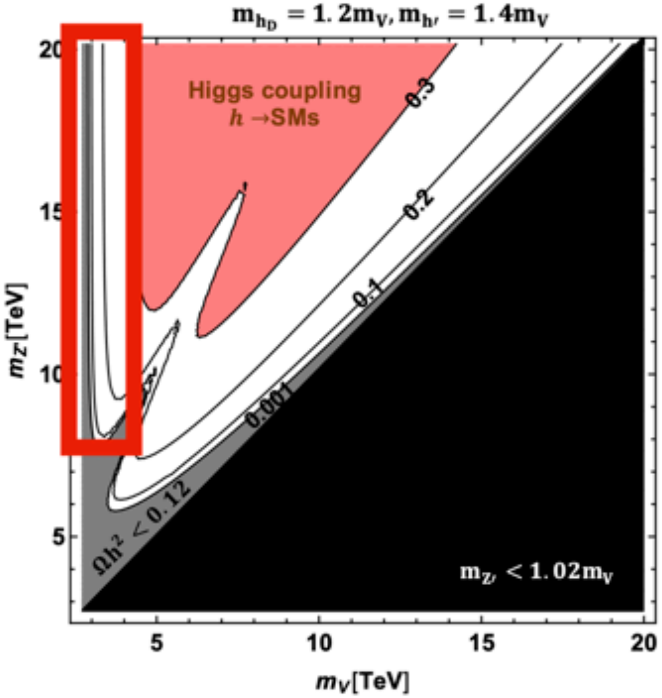


$$\begin{cases} (1) \quad m_{Z'} \gg m_V \quad 3\ \text{TeV} \lesssim m_V \lesssim 5\ \text{TeV} \\ (2) \quad m_{Z'} \gtrsim m_V \\ (3) \quad m_{Z'} \simeq 2m_V \quad \text{(Resonant region)} \end{cases}$$

→ Constraints on this plane? (Next page)

(1) ϕ_h contours: $m_{Z'} \gg m_V$





(1) $m_{Z'} \gg m_V$

Ωh^2 is determined independently of $m_{Z'}$

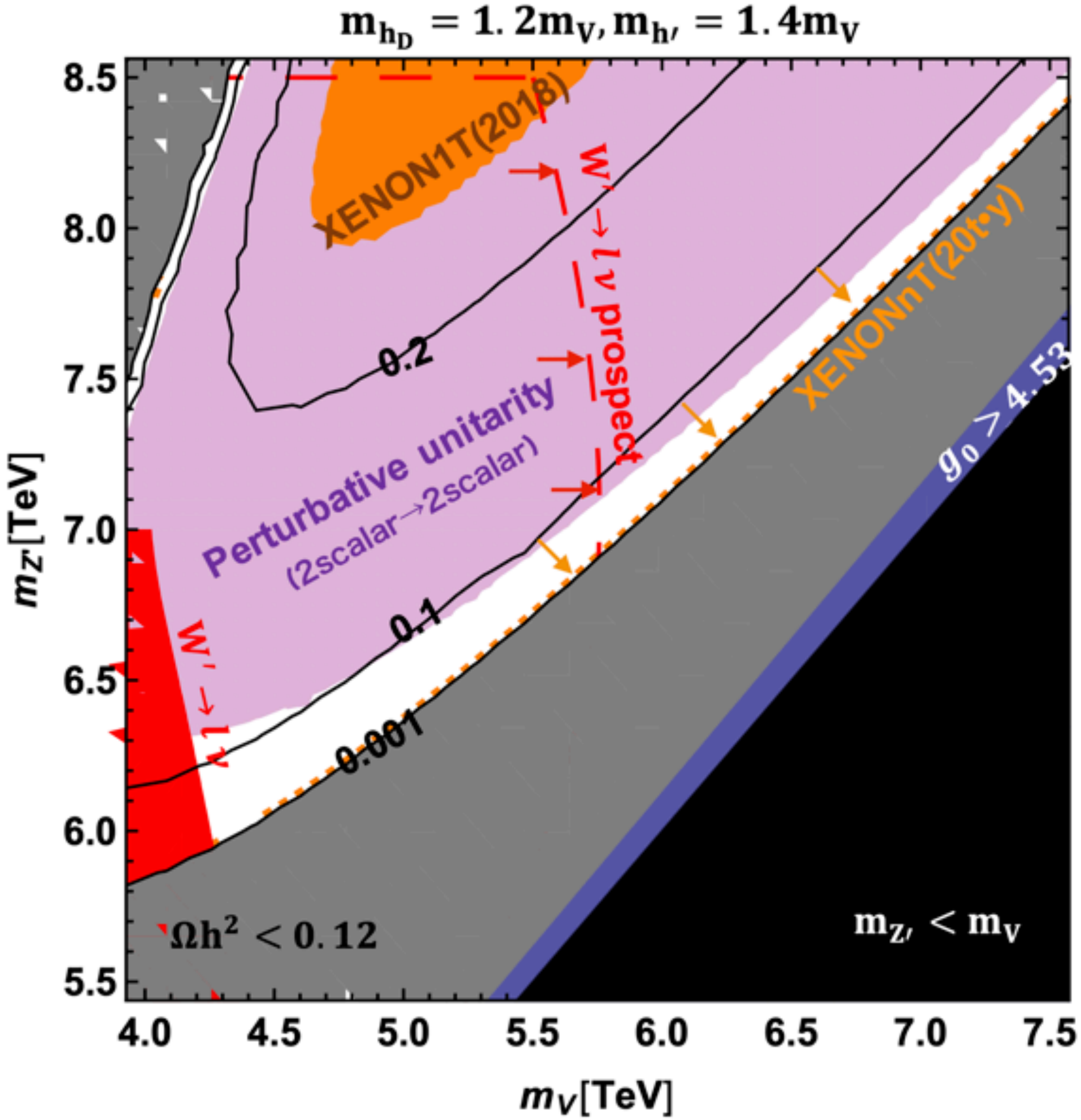
Ωh^2=0.12

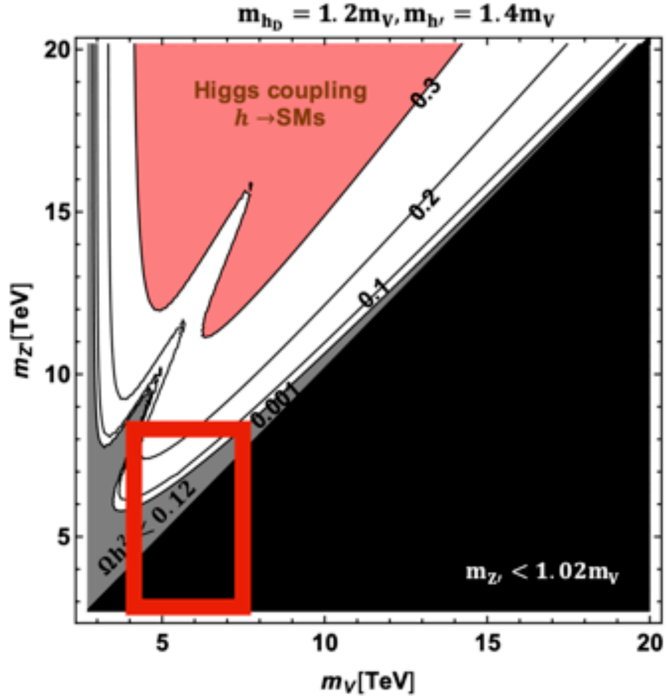
$\Leftrightarrow$ $\boxed{3\ \text{TeV} \lesssim m_V \lesssim 5\ \text{TeV}}$

·Future direct detection can cover large region

- - - HL-LHC14TeV 3000 fb^{-1} [ATL-PHYS-PUB-2018-044(2018)]

(2) ϕ_h contours: $m_{Z'} \gtrsim m_V$





LHC13TeV 139 fb^{-1} [ATLAS Collabolation(2019)] (※ No bound for $m_{W'} > 7$ TeV)

HL-LHC14TeV 3000 fb^{-1} [ATL-PHYS-PUB-2018-044(2018)]

(2) $m_{Z'} \gtrsim m_V$

Relatively large ϕ_h

→ Constrained from
- XENON1T result
- Perturbative unitarity

Very small ϕ_h

→ Probed by
- Future direct detection
- W' search by HL-LHC

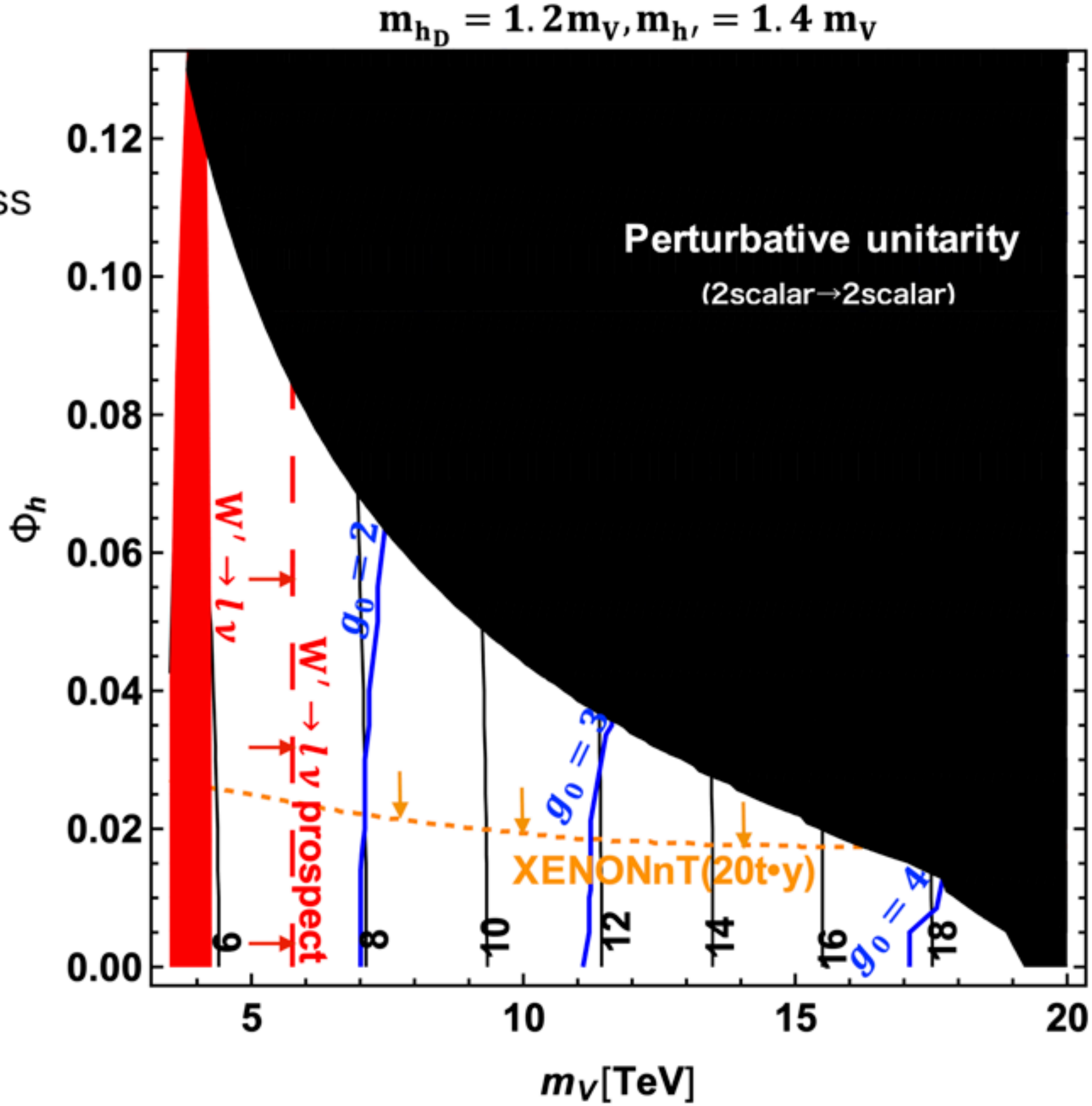
m_V-ϕ_h plot

- Perturbative unitarity gives the upper bound on DM mass

- Future direct detection give the upper bound on ϕ_h

$$\boxed{\phi_h \lesssim 0.02}$$

- Small ϕ_h region can be probed by W' search



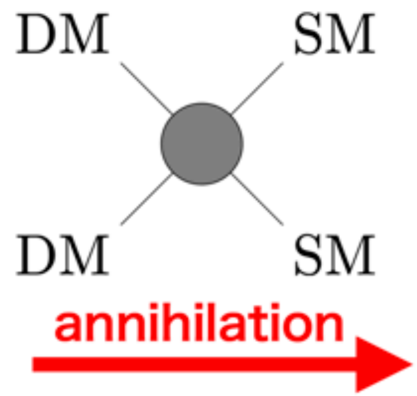
Electroweak Multiplet DM

For more details

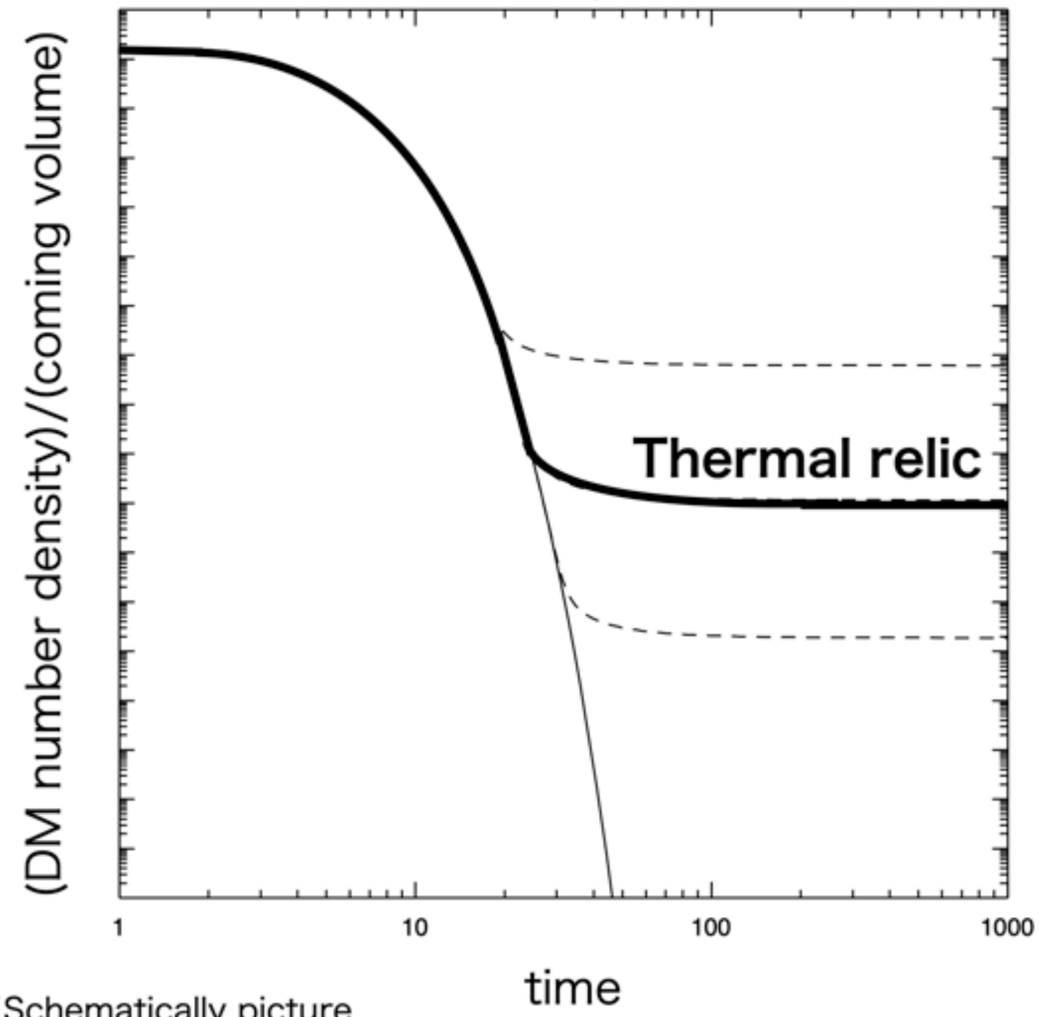
Introduction: WIMP scenario Dark Matter

WIMP scenario

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



[Dan Hooper [arXiv:0901.4090]]



※Schematically picture

Thermal relic is controlled by DM annihilation rate: $\langle \sigma_{\rm anni} v \rangle$

To obtain Ωh^2=0.12,

$$\langle \sigma_{\rm anni} v \rangle \simeq 10^{-9}\ {\rm GeV}^{-2}$$

$$\simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2} \quad \begin{cases} \alpha_{\rm DM} \sim \alpha_{\rm EW} \\ m_{\rm DM} \sim \mathcal{O}(100)\ {\rm GeV} \end{cases}$$

Typical scale of electroweak theory in SM!

Introduction: Electroweak Multiplet DM

→ : Including Sommerfeld effect
* : No significant Sommerfeld effect
※ Perturbativity of α_2 is required below M_{pl}

<u>Assumption</u>

“DM is a $SU(2)_L$ multiplet“

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

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

<u>Feature</u>

- $\Omega h^2 \sim 0.12$ → O(1) TeV DM
- mass splitting → O(100) MeV

Determined by EW interaction

How about Spin-1 DM?

- Electroweakly interacting spin-1 DM theory?
- Phenomenology?
- Difference from spin 0, or 1/2 cases?

Introduction: Electroweakly interacting Spin-1 DM

How to explore

1. DM candidate from Extra dimension [T. Flacke, A.Menon, D. J. Phalen (2009)] [T. Flacke, D. W. Kang, K. Kong, G. Mohlabeng, S. C. Park (2017)]

   e.g. non-minimal Universal Extra Dimension model

   → DM = Lightest Kaluza-Klein EW boson

2. Introducing as the matter contents [A. Belyaev, G. Cacciapaglia, J. McKay, D. Marin, A. R. Zerwekh (2019)]

   e.g. $SU(2)_L$ triplet, Y=0 spin-1 particle with Z_2 symmetry

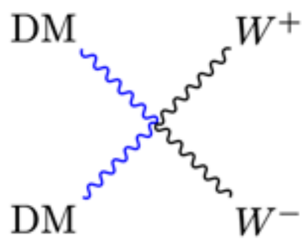
   → DM = Stable & Electrically neutral component

3. Extending the gauge symmetry

   → DM $\overset{?}{=}$ gauge bosons for extended gauge symmetry

   Questions

   - How can we realize EW interacting spin-1 particle?
   - How can we stabilize gauge boson?
   - How can we realize SM spectrum?



→ Today's talk!

Existing idea of Spin-1 DM
(review)

Naive construction of Spin-1DM model (1/2)

U(1)X extension Higgs portal DM model [S. Beak, P. Ko, W-I. Park, E. Senaha (2013)]

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

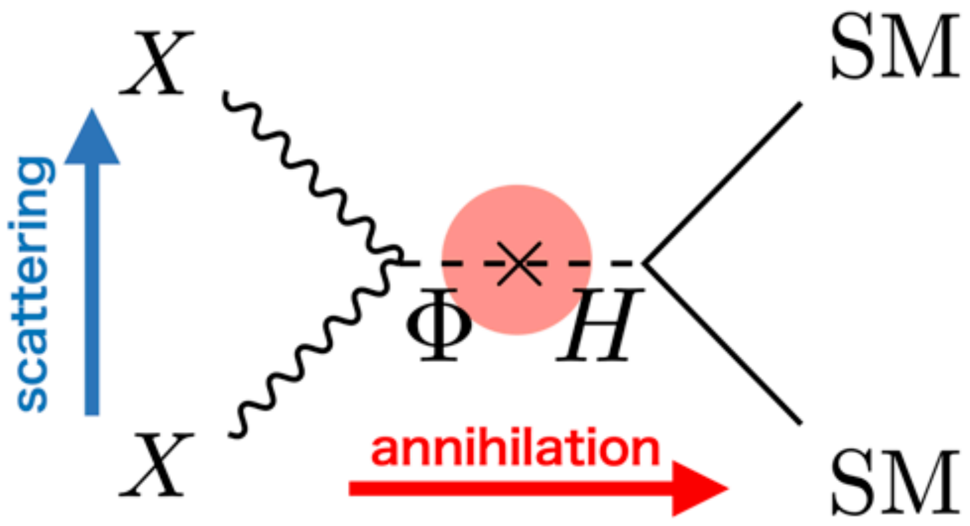
$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

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

X_μ : $\mathrm{U}(1)_X$ gauge boson

Φ : $\mathrm{U}(1)_X$ charged scalar

DM and SM particles interact only through Higgs exchange



What we found:

- No EW int. → Higgs portal only
- Tension from direct detection

"Isolated" gauge symmetry extension does not work

(※In this work, they did not include the kinetic mixing term: $\mathcal{L} \supset \frac{1}{2} \epsilon X_{\mu\nu} B^{\mu\nu}$)

Naive construction of Spin-1DM model (2/2)

SU(2)x extension Higgs portal DM model [T. Hambye (2009)]

"Isolated" Non-abelian extension does not work, too

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

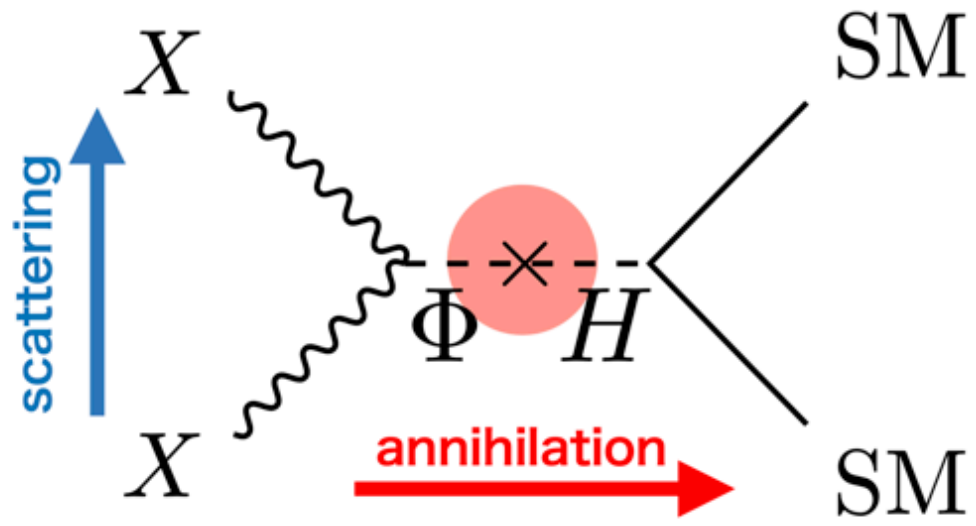
$$\mathcal{L} \supset -\frac{1}{4} X^a_{\mu\nu} X^{a\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

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

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

Φ : $\mathrm{SU}(2)_X$ doublet scalar

DM and SM particles interact only through Higgs exchange



What we found:

- No EW int. → Higgs portal only※
- Tension from direct detection

"Isolated" gauge symmetry extension does not work

※ For the realization of "kinetic mixing portal" (even in non-abelian model), see [I. Chaffey, P. Tanedo(2020)]

→ **We need another idea to construct a EW int. Spin-1 DM model**

(De)construction

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

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

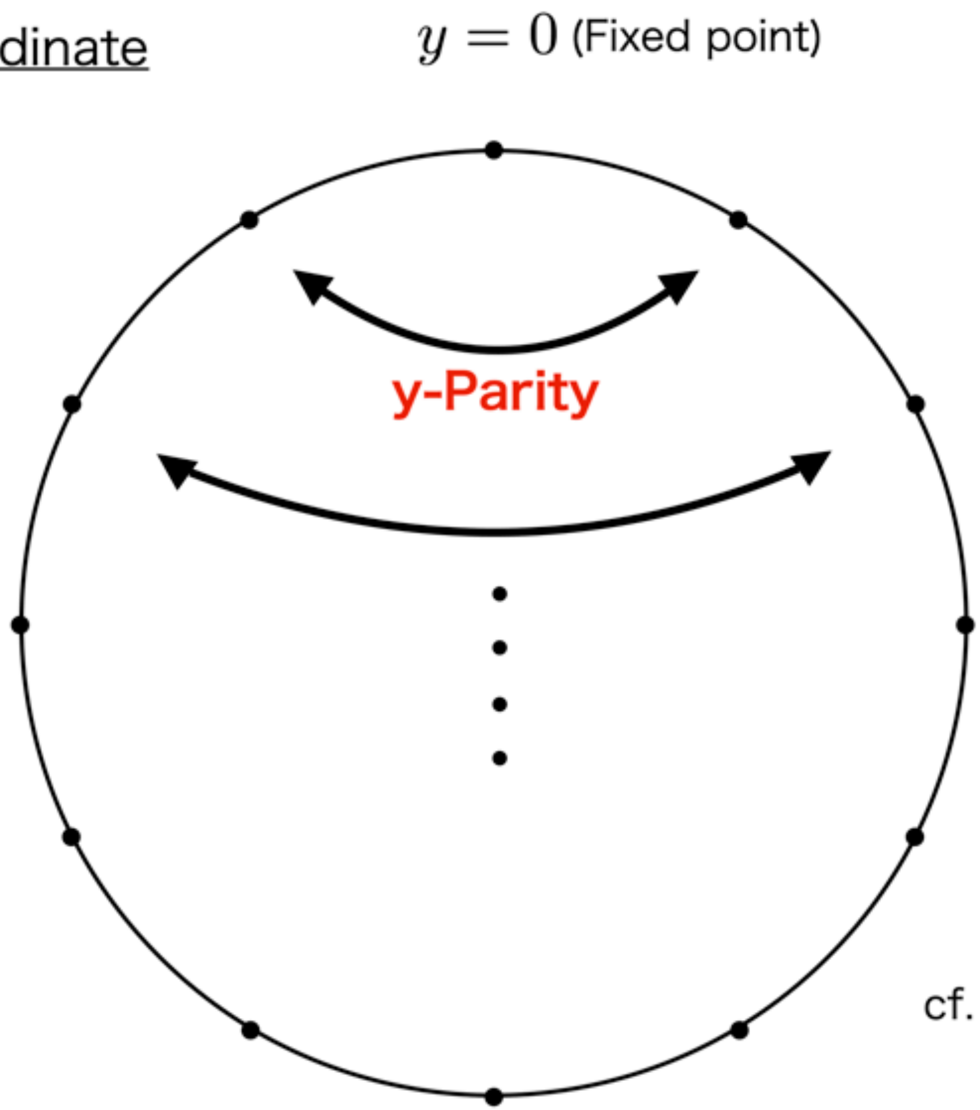
Introduction: (De)construction technique

Discretized 5d coordinate

※Schematically picture

5d gauge theory

G : gauge group



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)]

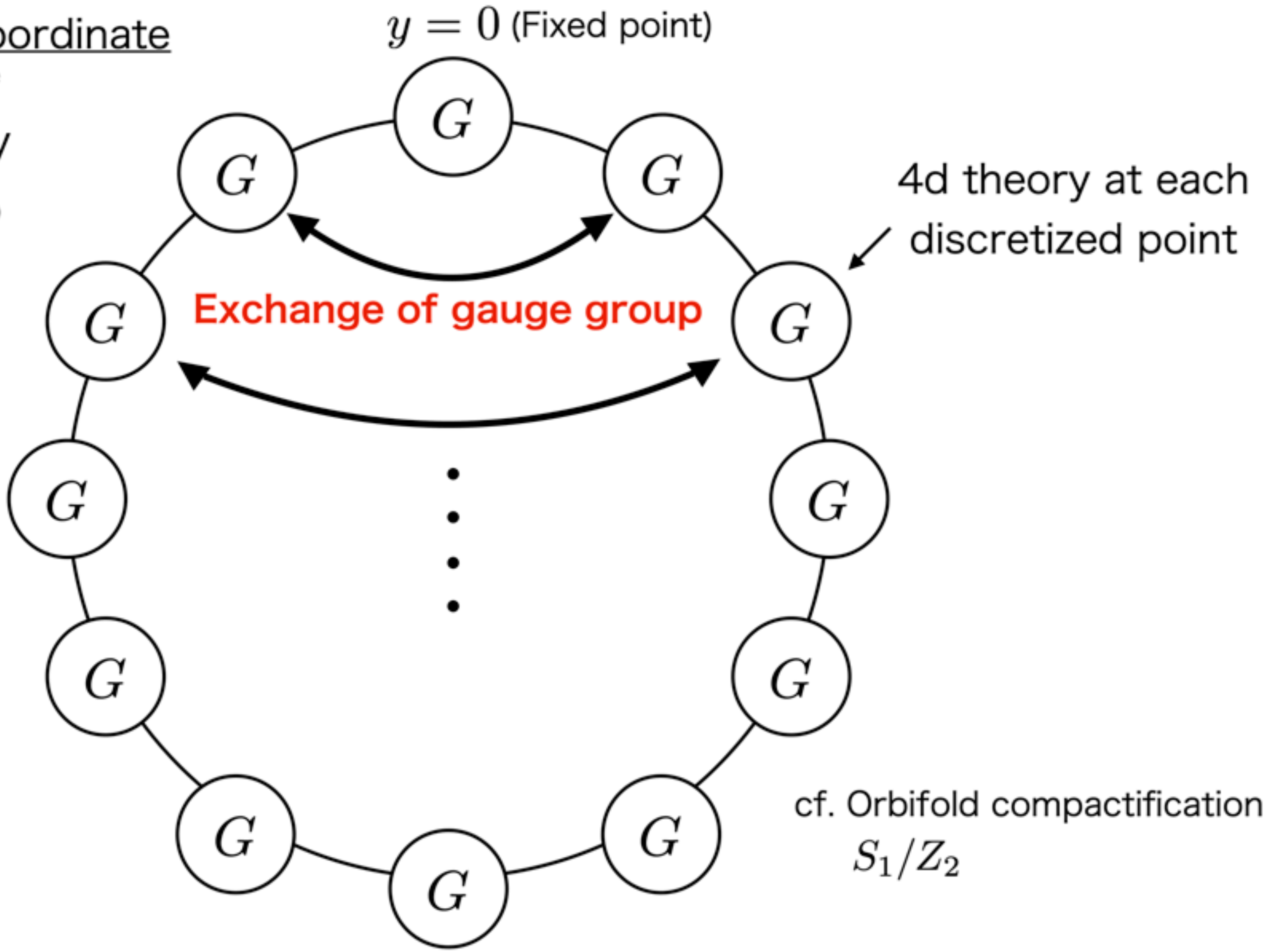
Introduction: (De)construction technique

Discretized 5d coordinate

※Schematically picture

5d gauge theory

G: gauge group



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

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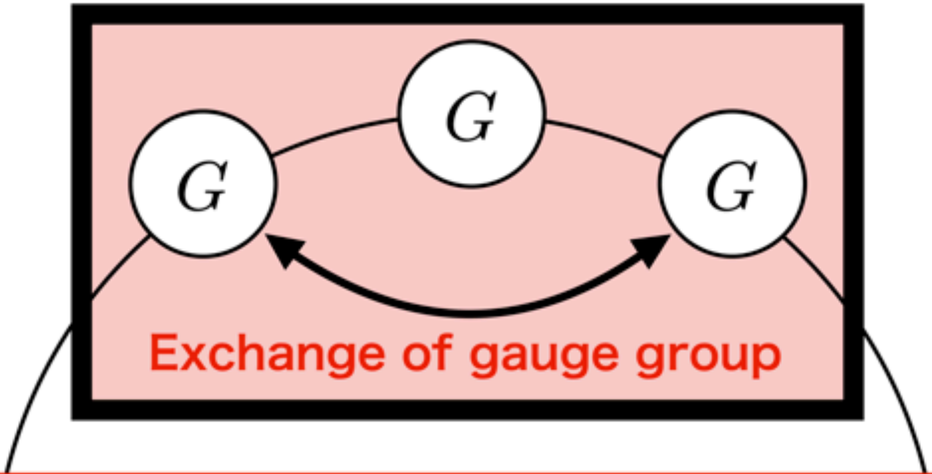
Introduction: (De)construction technique



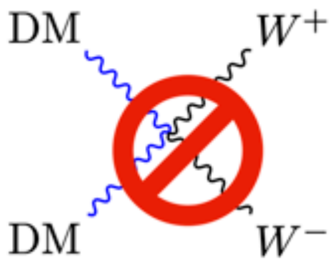
Our Work

- 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

CAUTION!



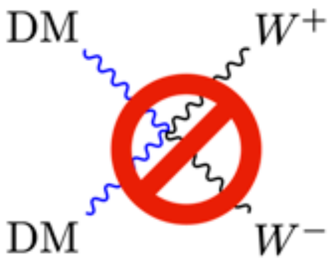
Stable neutral vector CANNOT have Non-Abelian EW couplings

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

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

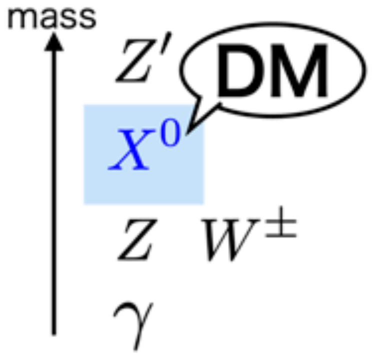
※ We have kinetic mixing terms(2nd line) in this Abelian extension model

field	spin	$\mathrm{SU}(3)_\mathrm{C}$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_0$	$\mathrm{U}(1)_1$	$\mathrm{U}(1)_2$
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

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

(Z_2-odd neutral vector)



Abelian Extension with Exchange Symmetry(2/2)

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

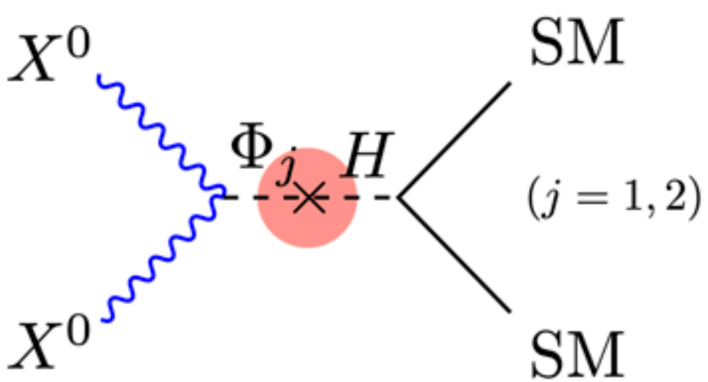
- X^0 do not appear in the $SU(2)_L$ neutral vector state

$$W_\mu^3 = \#A_\mu + \#Z_\mu + \#Z'_\mu$$ ← **No X^0 states**

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

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

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



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!)

Fin.

Thank you!
I’m looking forward to seeing you again
(maybe in person)!

2021.06.17　Motoko FUJIWARA