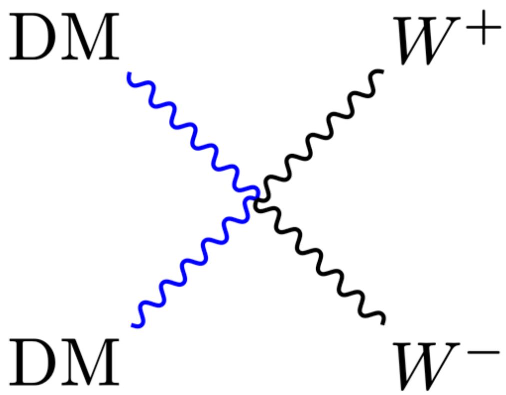
A Model of electroweakly interacting non-abelian vector dark matter



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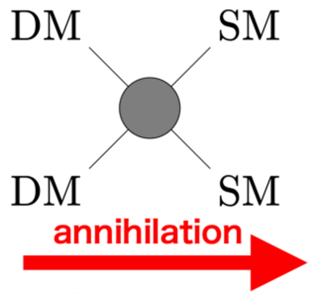
based on: T. Abe, MF, J. Hisano, K. Matsushita, JHEP 07 (2020) 136 [arXiv:2004.00884]

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

- $\Omega h^2 \sim 0.12$ → 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

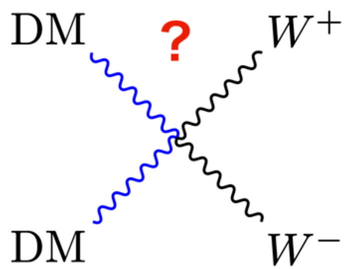
How to explore

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

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

Exchange Symmetry

Matter Contents

field	spin	$SU(3)_c$	$SU(2)_0$ ($W^a_{0\mu}$)	$SU(2)_1$ ($W^a_{1\mu}$)	$SU(2)_2$ ($W^a_{2\mu}$)	$U(1)_Y$
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.

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

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

Symmetry breaking

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

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

$$\mathrm{SU}(2)_0 \otimes \mathrm{SU}(2)_1 \otimes \mathrm{SU}(2)_2 \otimes \mathrm{U}(1)_Y \xrightarrow{\langle \Phi_j \rangle \neq 0} \underbrace{\mathrm{SU}(2)}_{\cong\,\mathrm{SU}(2)_L} \otimes \mathrm{U}(1)_Y \xrightarrow{\langle H \rangle \neq 0} \mathrm{U}(1)_{\mathrm{em}}$$

SU(2)L

Vacuum Expectation Value(VEV)

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

$$(v_\Phi \gg v)$$

v_Φ: $\mathcal{O}(1)$ TeV, v: $\mathcal{O}(100)$ GeV

$\langle \Phi_1 \rangle$, $\langle \Phi_2 \rangle$ 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

⟶ **SU(2)L gauge symmetry**

(approximately)

Exchange symmetry still alive

⟶ **Z2 parity structure**

(Next page)

Z_2-Parity from Exchange Symmetry

Scalar fields (after SSB)

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

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

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

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

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

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

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

Z_2-odd vectors and DM candidate

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

<u>Z_2-odd vector</u>

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

(EW radiative corrections)

※ We assume $m_{V^0} < m_{h_D}$ to focus on spin-1 DM scenario

Energy

Collider search

Vector		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

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

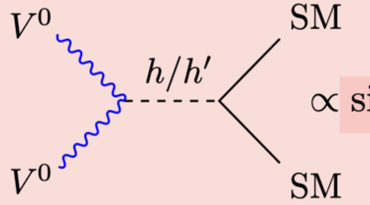
Thermal relic region in ϕ_h contour

ϕ_h : mixing angle btw h and h'

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

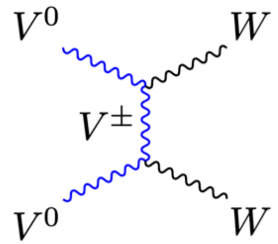
<u>Annihilation Channel</u>

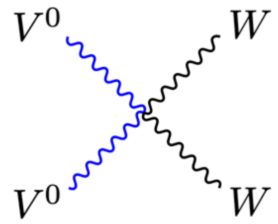
・Higgs channels



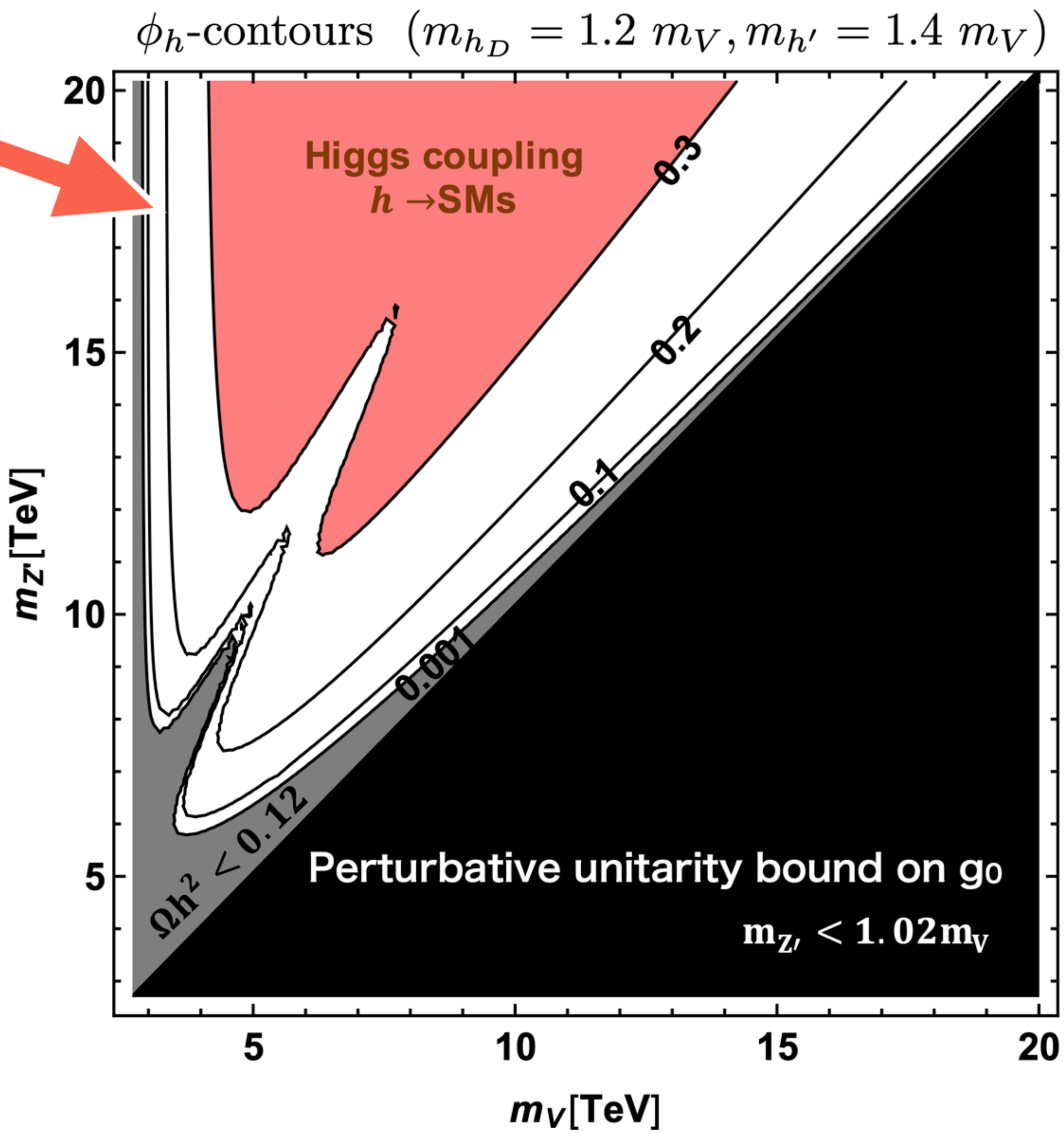
$\propto \sin 2\phi_h$

・EW channels





(+ many other channels…)



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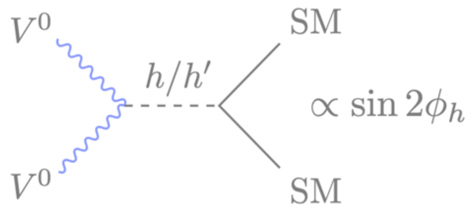
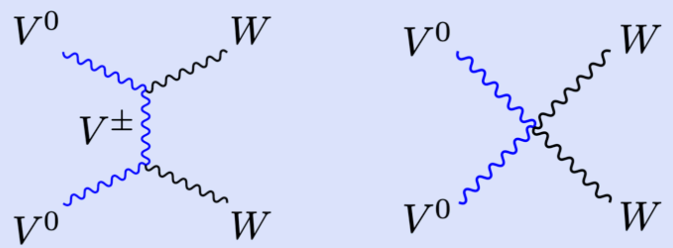


・EW channels

EW channel only



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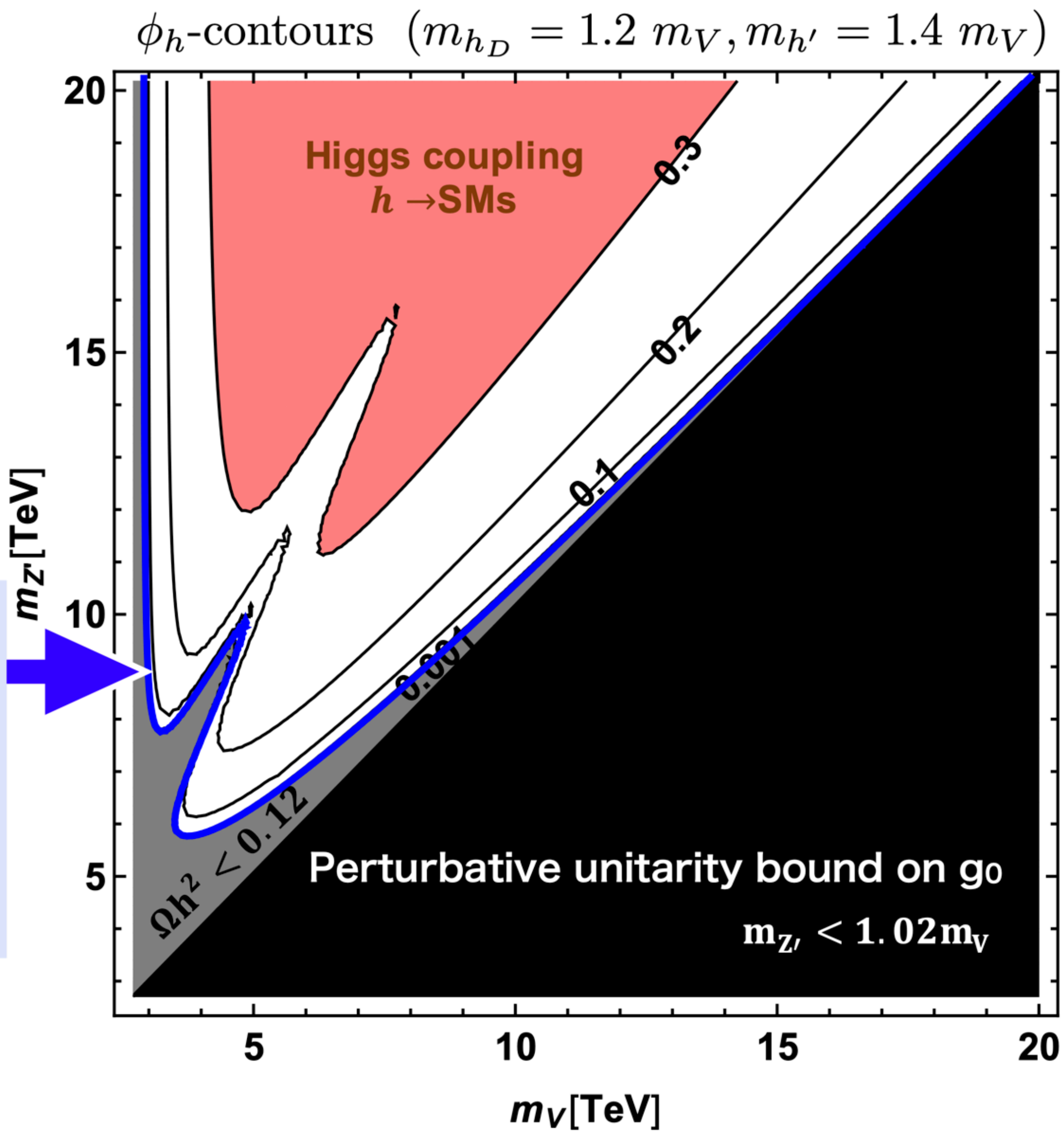
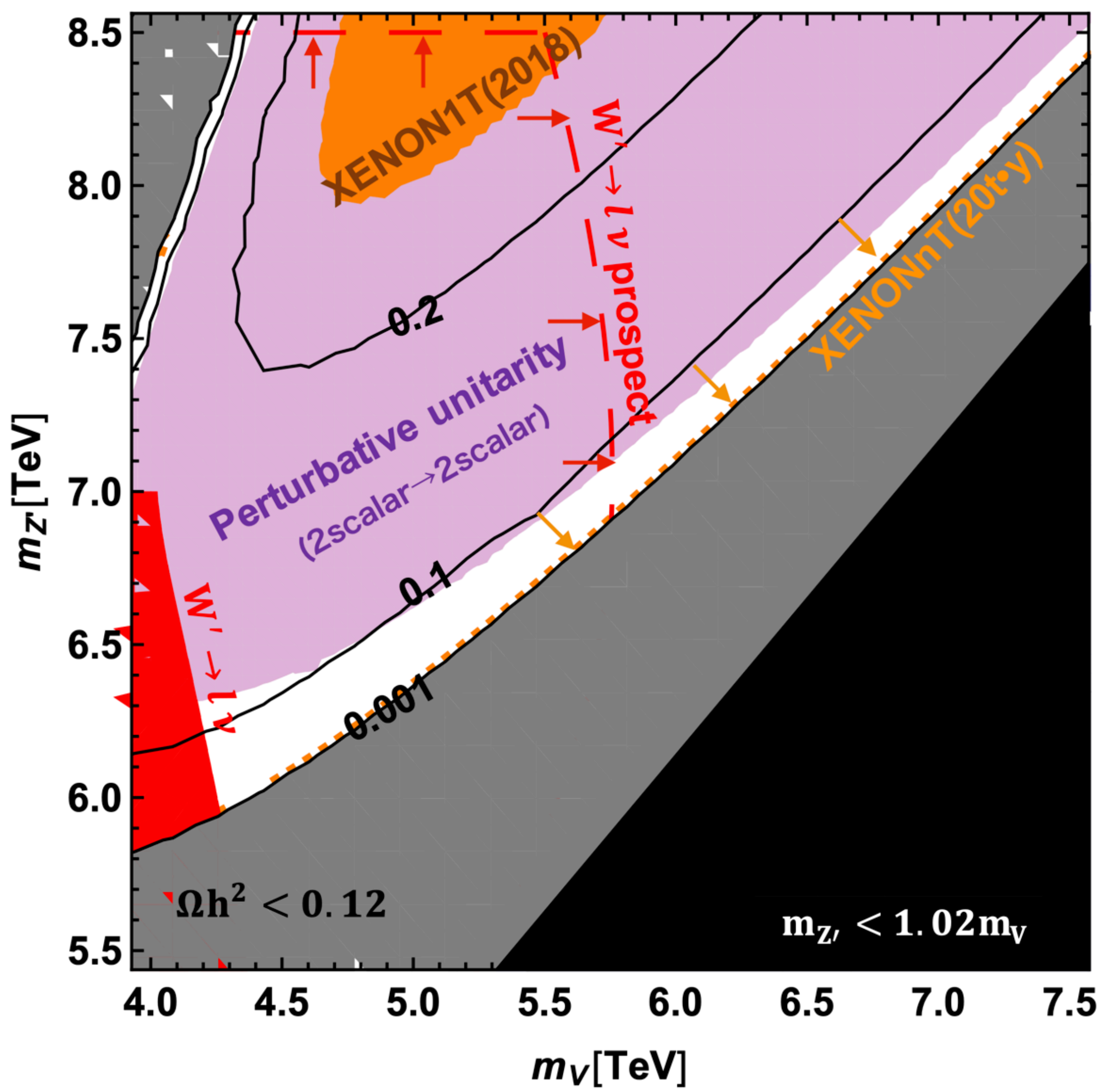


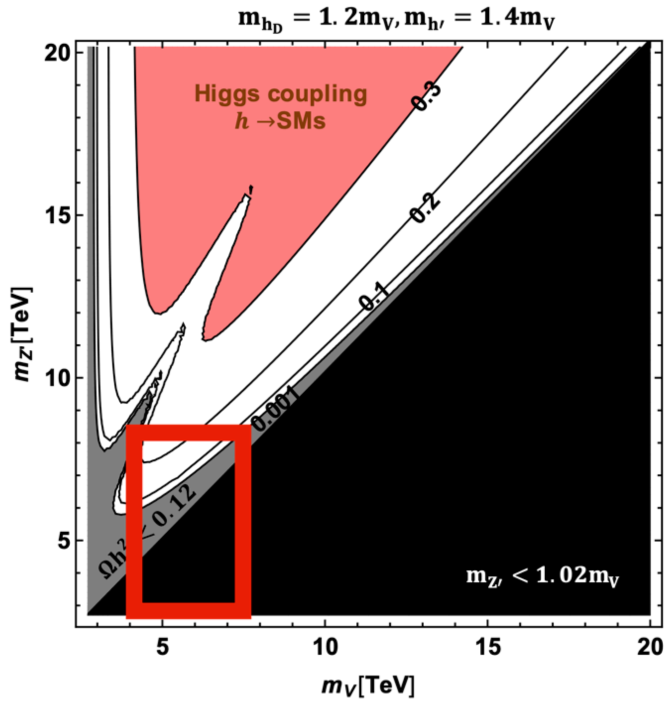
"Electroweakly interacting" spin-1 DM

→ **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

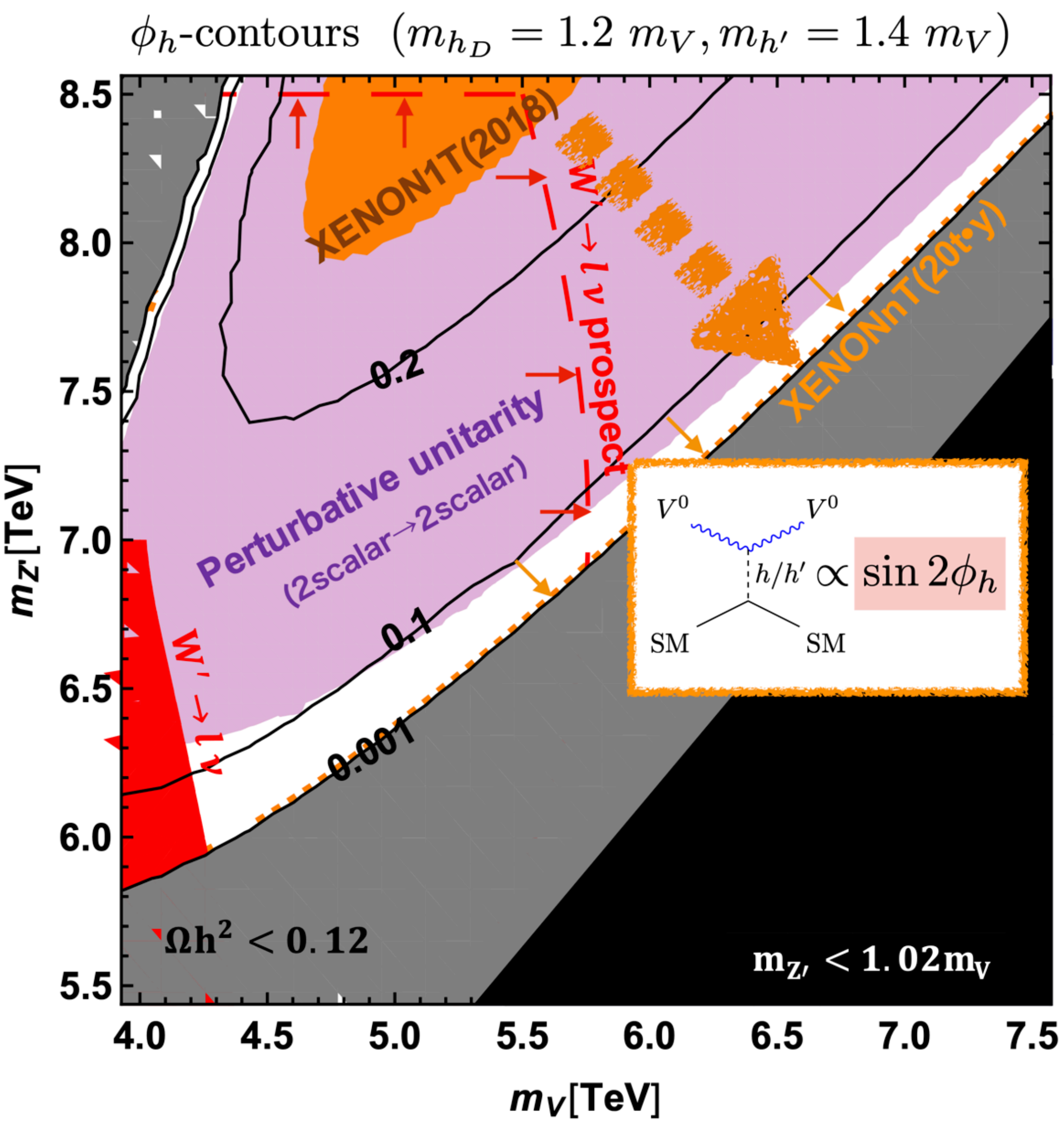
(2scalar→2scalar scattering)

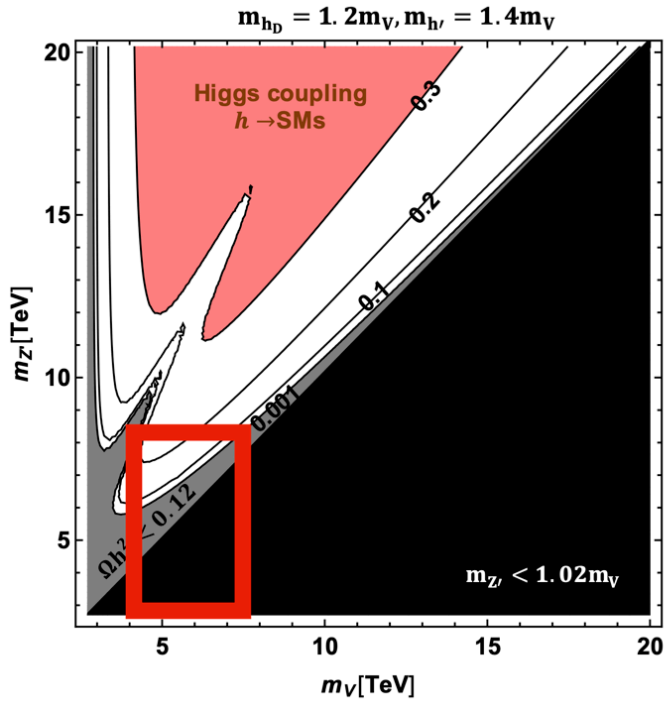
$\rightarrow \phi_h \lesssim 0.1$

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)]

Constraints & Future detectability





- Perturbative unitarity bounds
  (2scalar→2scalar scattering)
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- Direct detection(XENON1T/nT)
  → probe Higgs contribution
  to DM annihilation process

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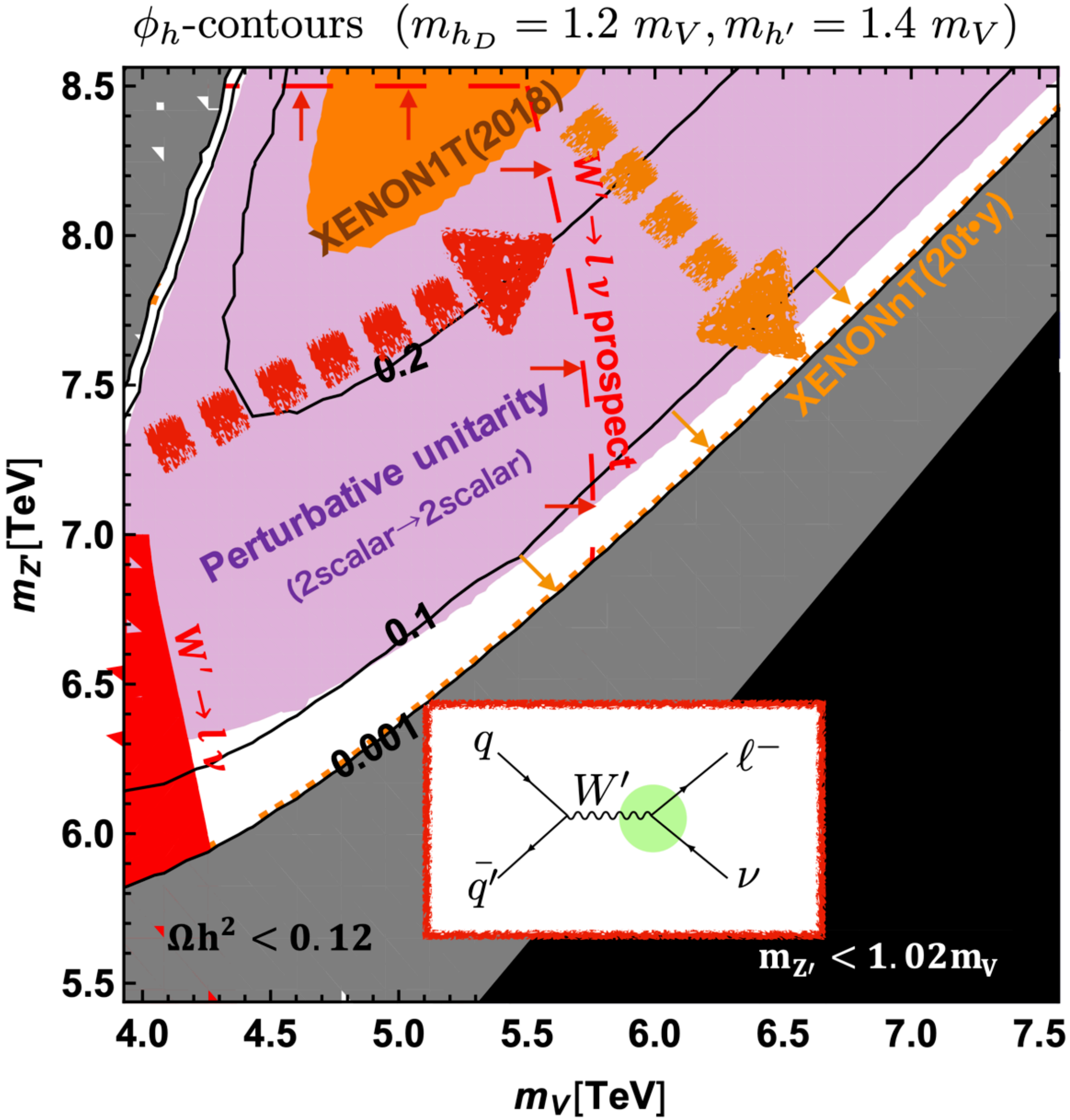
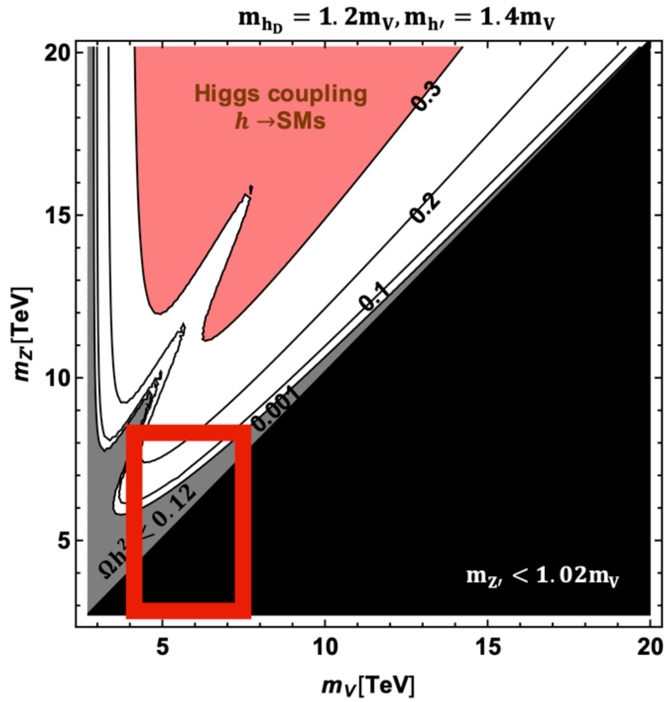
Constraints & Future detectability





- 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)]

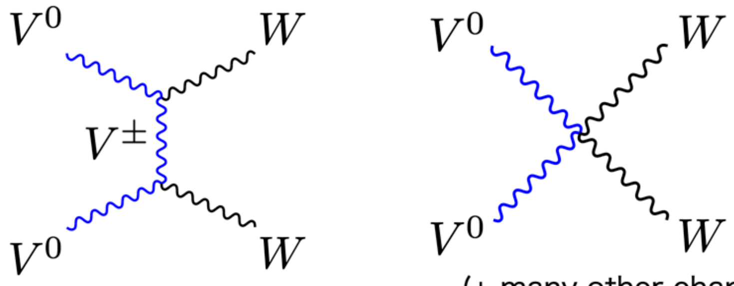
Summary

- 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

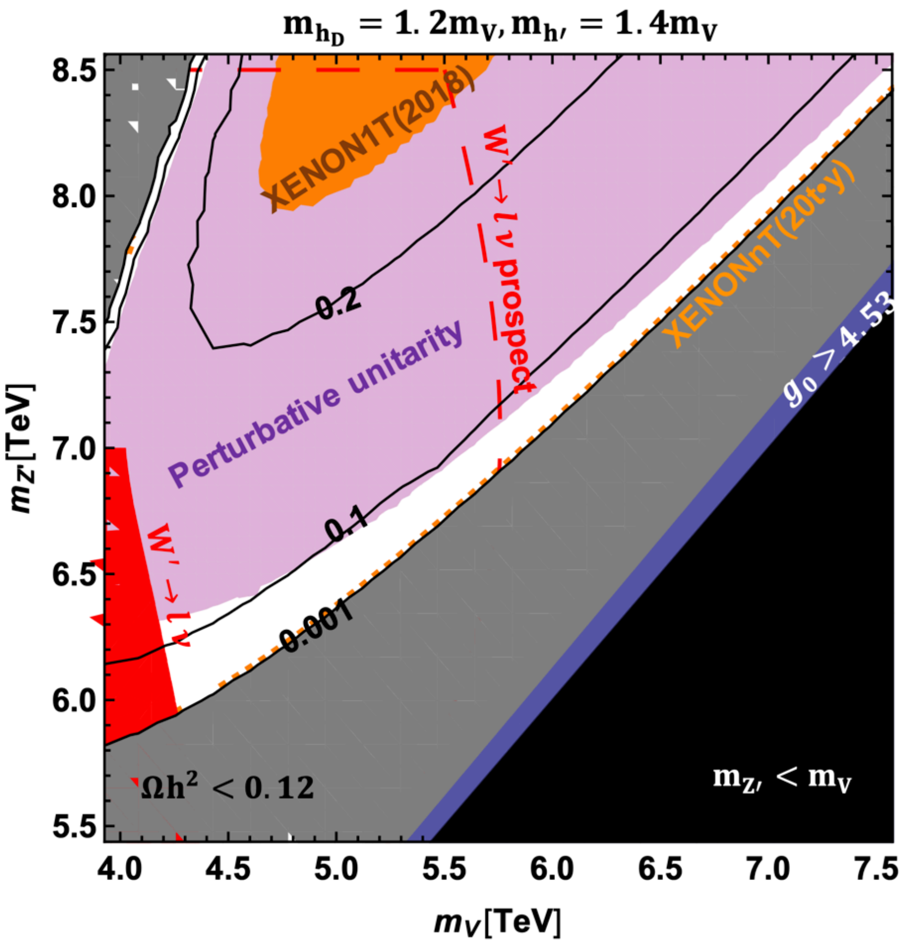
- **Z2-odd vectors:** $V^0, V^\pm$
- **Non-Abelian EW couplings**



(+ 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

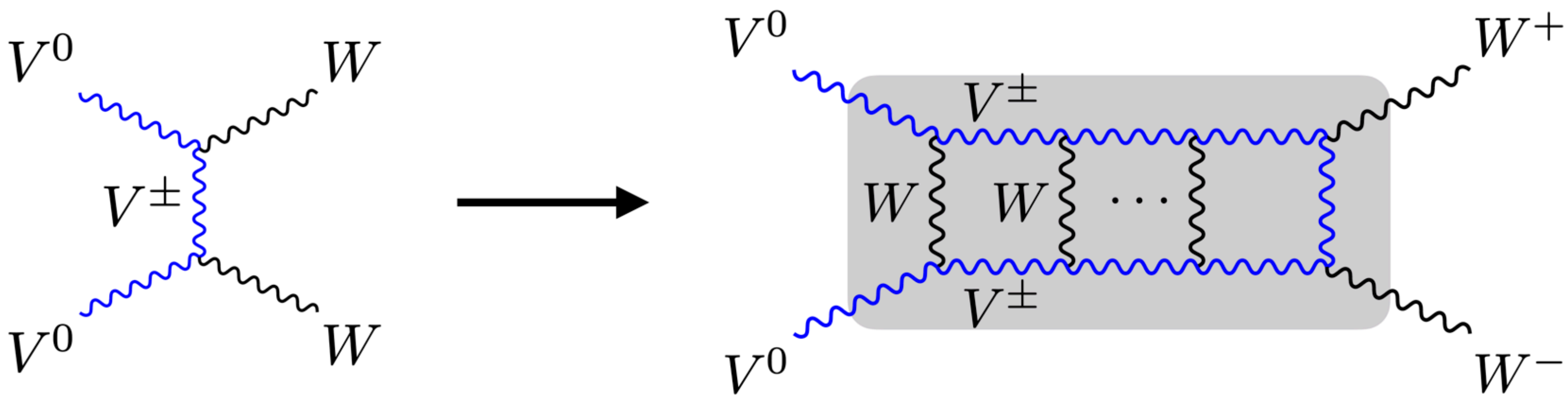
<u>Result in this work</u>

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

Ωh² = 0.12 is obtained with $m_V \gg \mathcal{O}(100)\ \mathrm{GeV}$

DM pair form the bound states in Annihilation processes

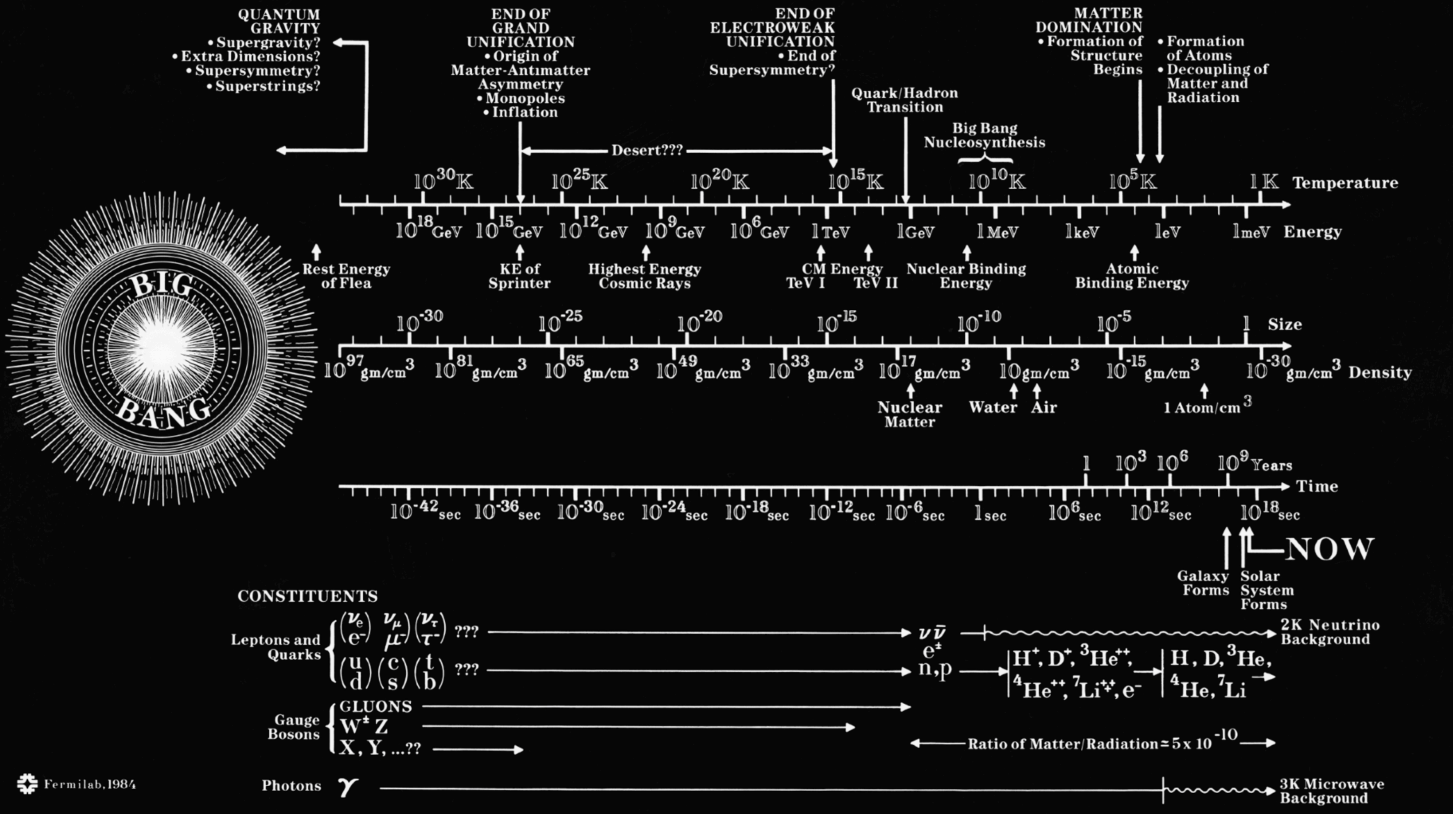
(Sommerfeld enhancement) [J. Hisano, S. Matsumoto, M. M. Nojiri, O. Saito (2005)]



※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
1 K
Temperature
10^18 GeV
10^15 GeV
10^12 GeV
10^9 GeV
10^6 GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
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
10 gm/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
1 sec
10^6 sec
10^12 sec
10^18 sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
(νe e-) (νμ μ-) (ντ τ-) ???
(u d) (c s) (t b) ???
ν ν̄
e±
n,p
2K Neutrino Background
H+, D+, 3He++, 4He++, 7Li+++, e-
H, D, 3He, 4He, 7Li
Gauge Bosons
GLUONS
W± 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

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

Scalar potential

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

Mass matrix: gauge sector

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

Charged vector

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

Neutral vector

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

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>

$$\lambda = \frac{m_h^2 \cos^2\phi_h + m_{h'}^2 \sin^2\phi_h}{2v^2},$$

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

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

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

Scalar sector

τ^a : Pauli matrices

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

Scalar Field

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

(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: $W_0^a \; W_1^a \; W_2^a \; B$

3 + 3 + 3 + 1 = 10

massive : massless

9 + 1

eaten

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

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

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

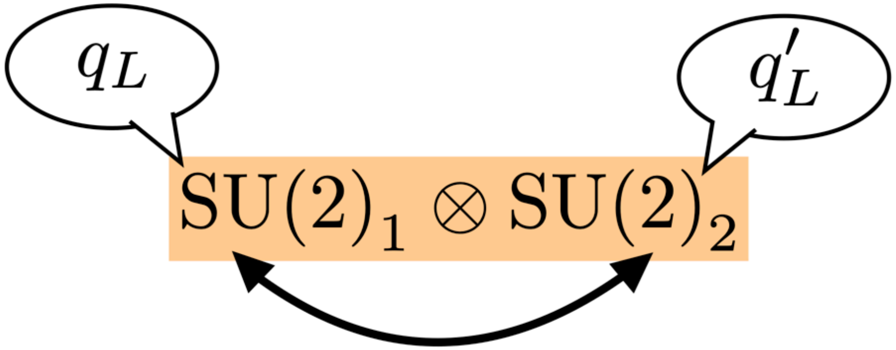
$$\left[\tilde{H} = \epsilon H^\star \qquad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}. \right]$$

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

$\left[\begin{array}{l} g_0 \text{ : gauge coupling for SU(2)}_0 \text{ \& SU(2)}_2 \\ g_1 \text{ : gauge coupling for SU(2)}_1 \end{array}\right]$

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

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

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

ϕ_h : mixing angle of
Z_2-even scalars

$\sim v_\Phi$ (TeV scale)

<u>Free parameters</u>

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

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

<u>Mass ratio</u>

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

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

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

(1)Unitarity bound on g_0 & g_1

(2Gauge boson→2scalar scattering)

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

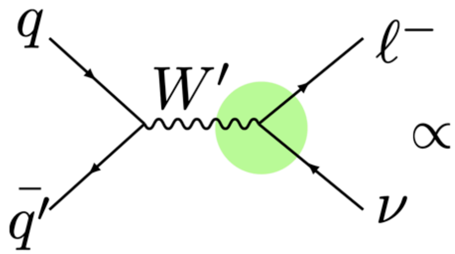
[K. Hally, H. E. Logan, T. Pilkington (2012)]

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

(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 $\rightarrow$ $m_{h_D} > m_V$

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

Higgs mixing angle

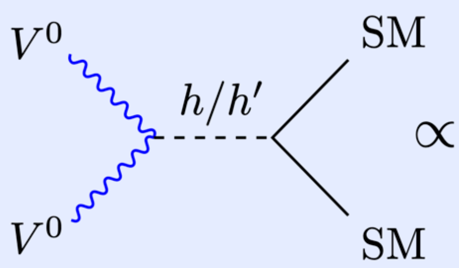
- Higgs coupling strength
  [ATLAS collaboration (2020)]

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

- Perturbative unitarity in 2scalar→2scalar scattering

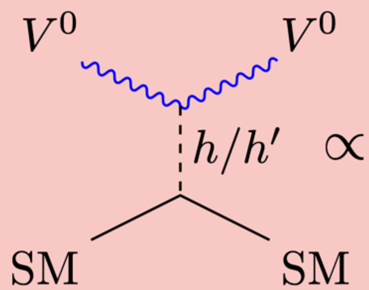
- ϕ_h tunes the annihilation & scattering process

Annihilation



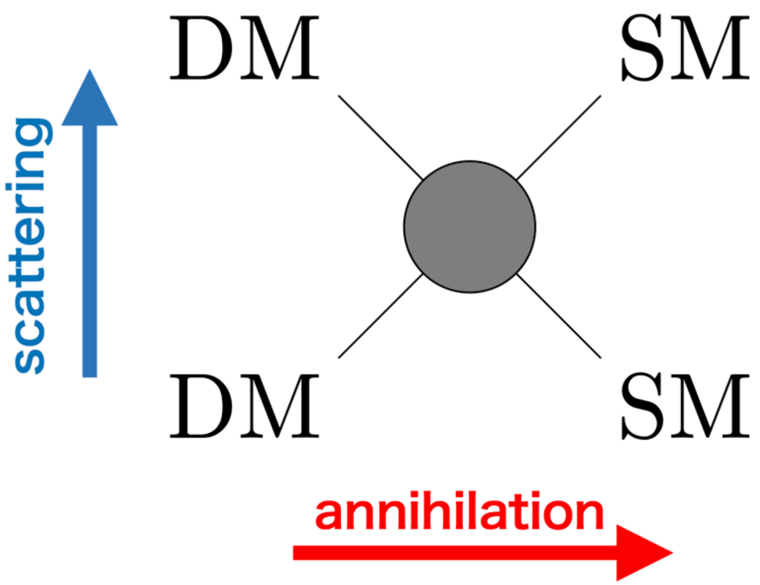
$\propto \sin 2\phi_h$

Scattering



$\propto \sin 2\phi_h$

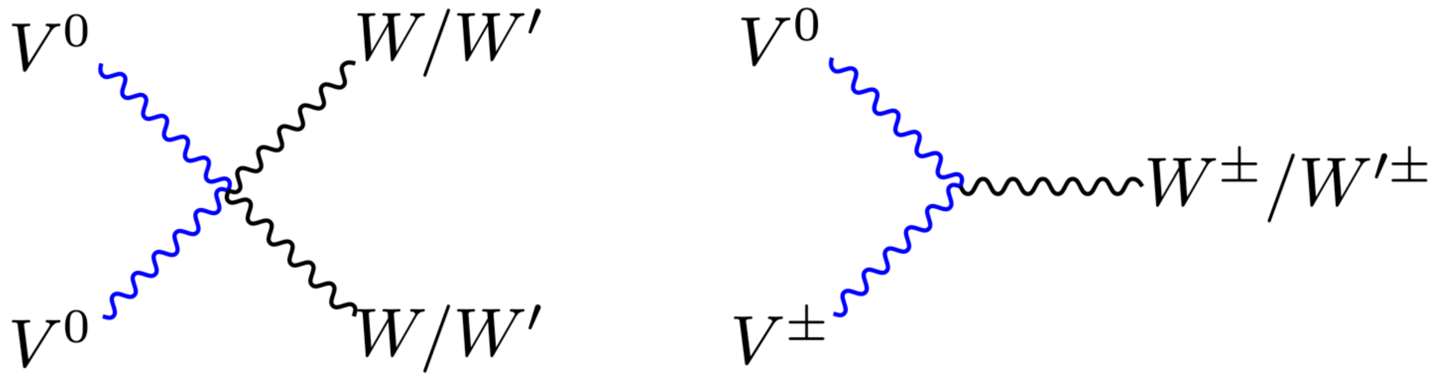
DM Phenomenology

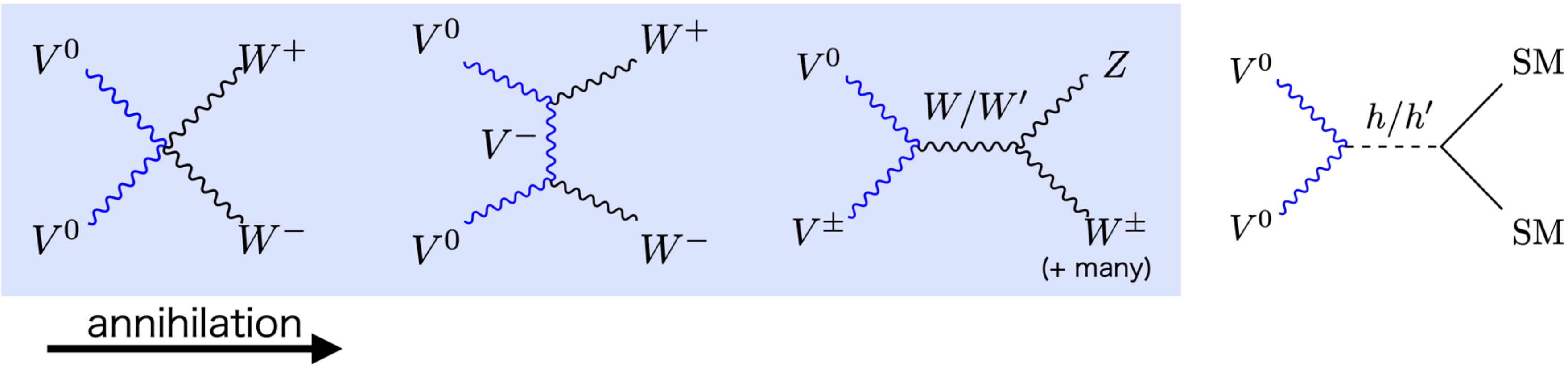


Annihilation process: DM thermal relic

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

eg.





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

→ DM thermal relic is determined by EW interactions

"Electroweakly interacting" spin-1 DM

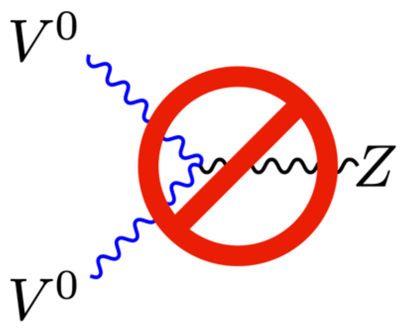
Scattering Process: DM direct detection

Direct detection

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

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

Z-exchange process

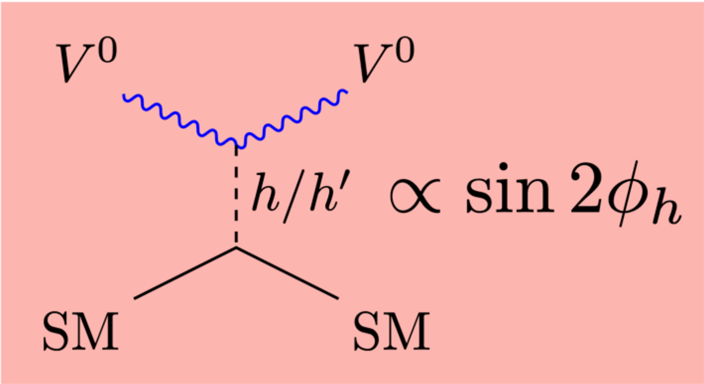


Neutral boson triple coupling is forbidden

(∵ non-Abelian extension)

→ No Z-exchange in scattering process!

Higgs-exchange process



Mixing angle ϕ_h tunes the scattering process

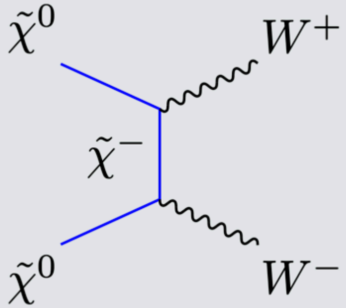
→ direct detection bounds give upper bound on ϕ_h

For sufficiently small ϕ_h,

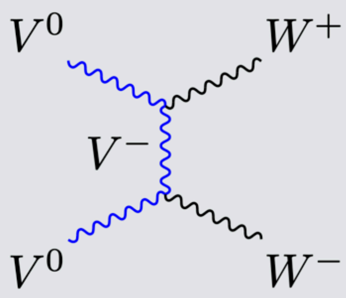
σ_{scat} is dominated by 1-loop EW processes

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

Wino vs V-particles



vs



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

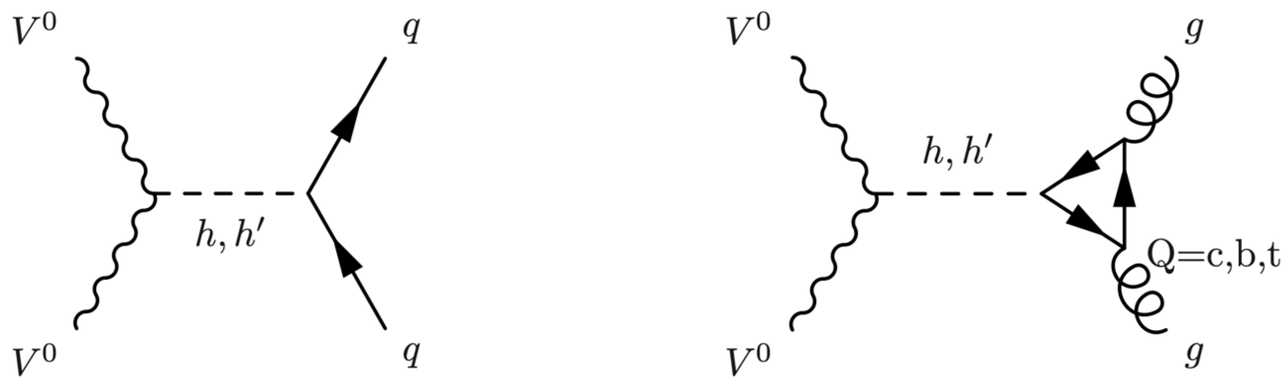
For more details

Viable Region: W' physics

Relevant couplings

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

Diagrams



Cross section

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

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

W’ physics

For more details

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

<u>Mass ratio</u>

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

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

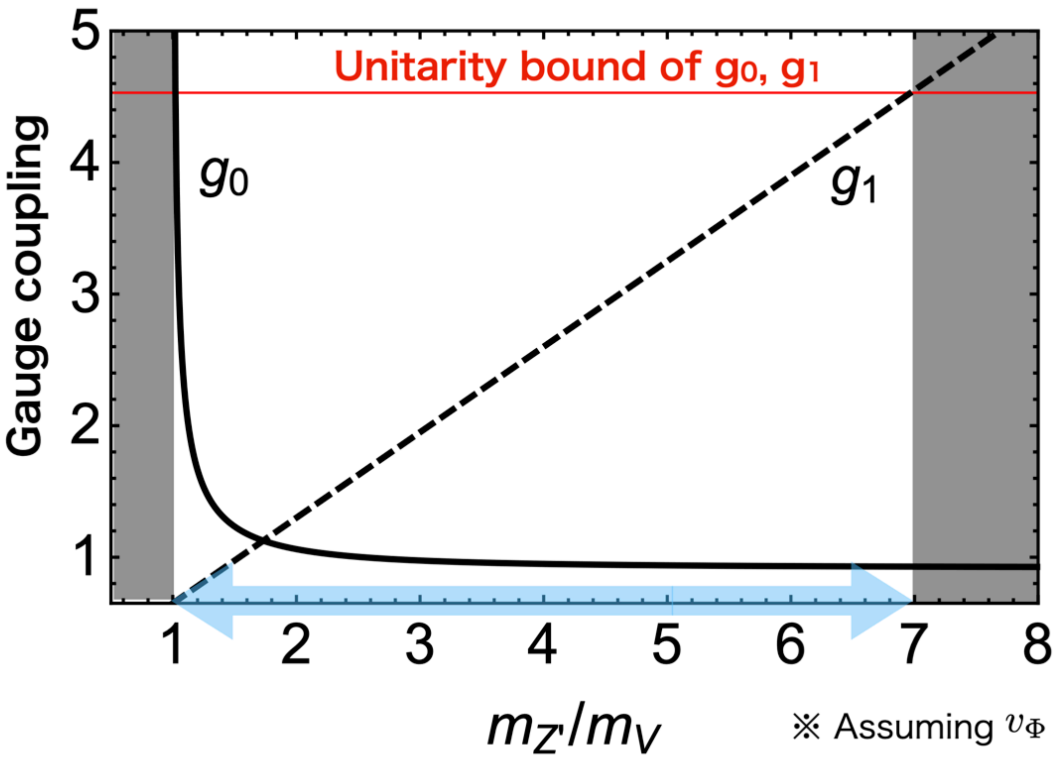
$$\Rightarrow \begin{cases} \cdot\, m_{Z'} \simeq m_V & \to g_0 \gg 1 \\ \cdot\, m_{Z'} \gg m_V & \to g_1 \gg 1 \end{cases}$$

(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)]

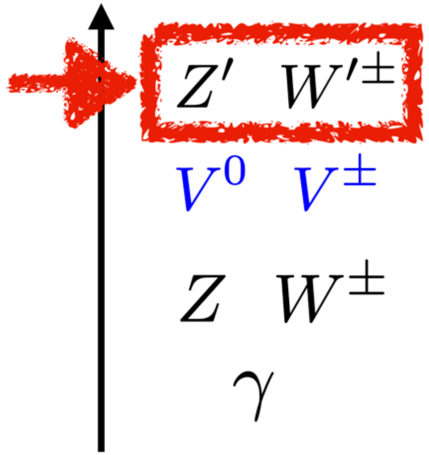
$$\boxed{1.02 < m_{Z'}/m_V < 6.97}$$



※ Assuming $v_\Phi \gg v$

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

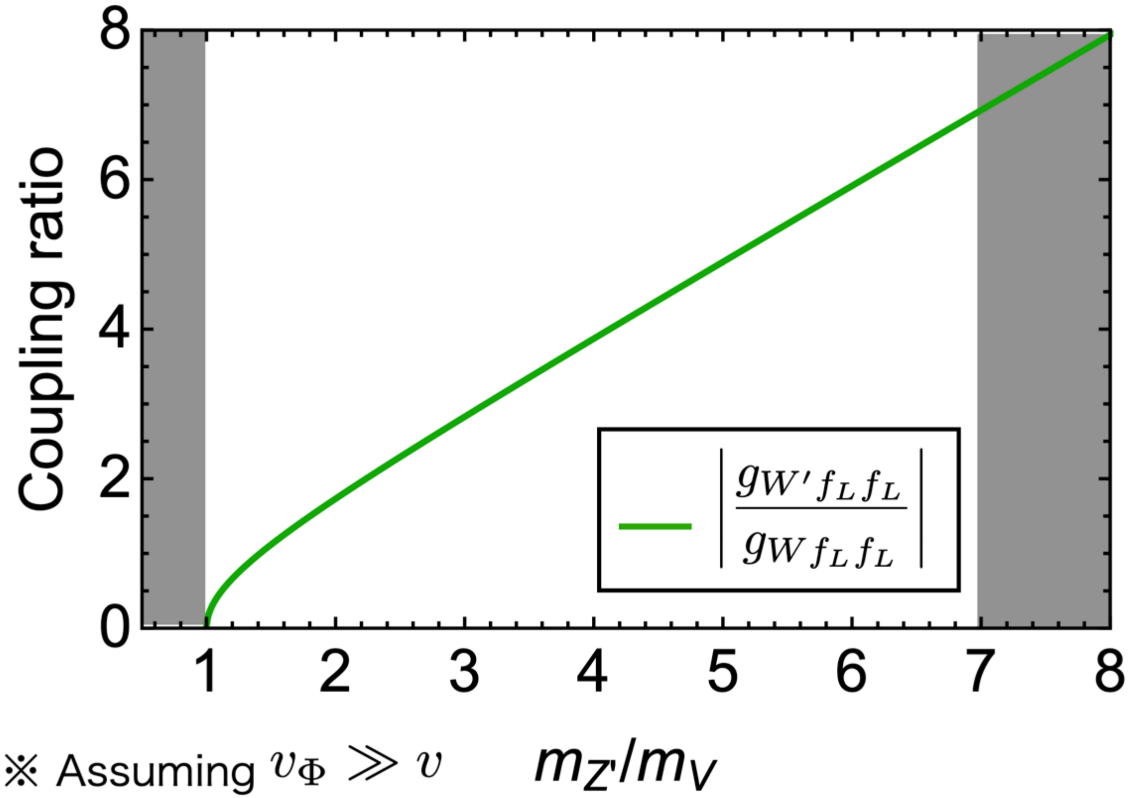
cf. Vector Spectrum



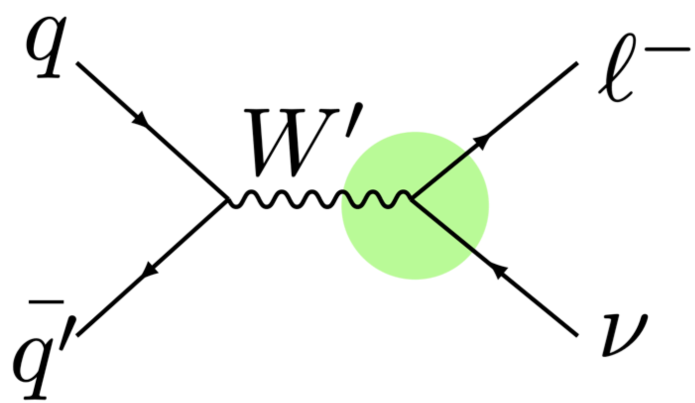
$m_{Z'} \sim m_{W'}$
$(v_\Phi \gg v)$

<u>W'-fermion coupling</u>

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



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

@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

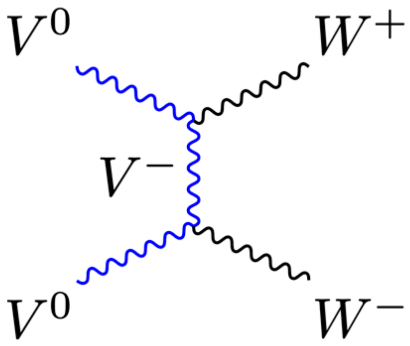
$$n_{\rm eq} = g \left(\frac{mT}{2\pi}\right)^{\frac{3}{2}} \exp\left(-\frac{m}{T}\right)$$

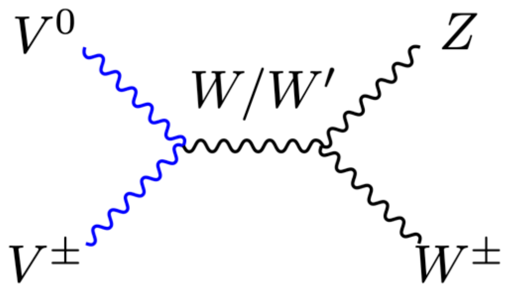
m : mass
T : temperature
g : degrees of freedom

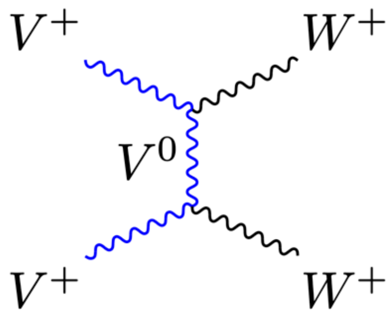
→ **All the V-particles contribute to the DM annihilation**

Mass Difference and Coannihilation(2/2)

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

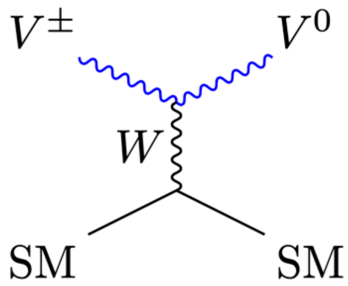


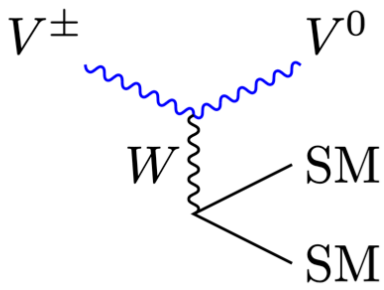




DM abundance can also be decreased by annihilation of $V^\pm$

※ All the $V^\pm$ decays into V^0

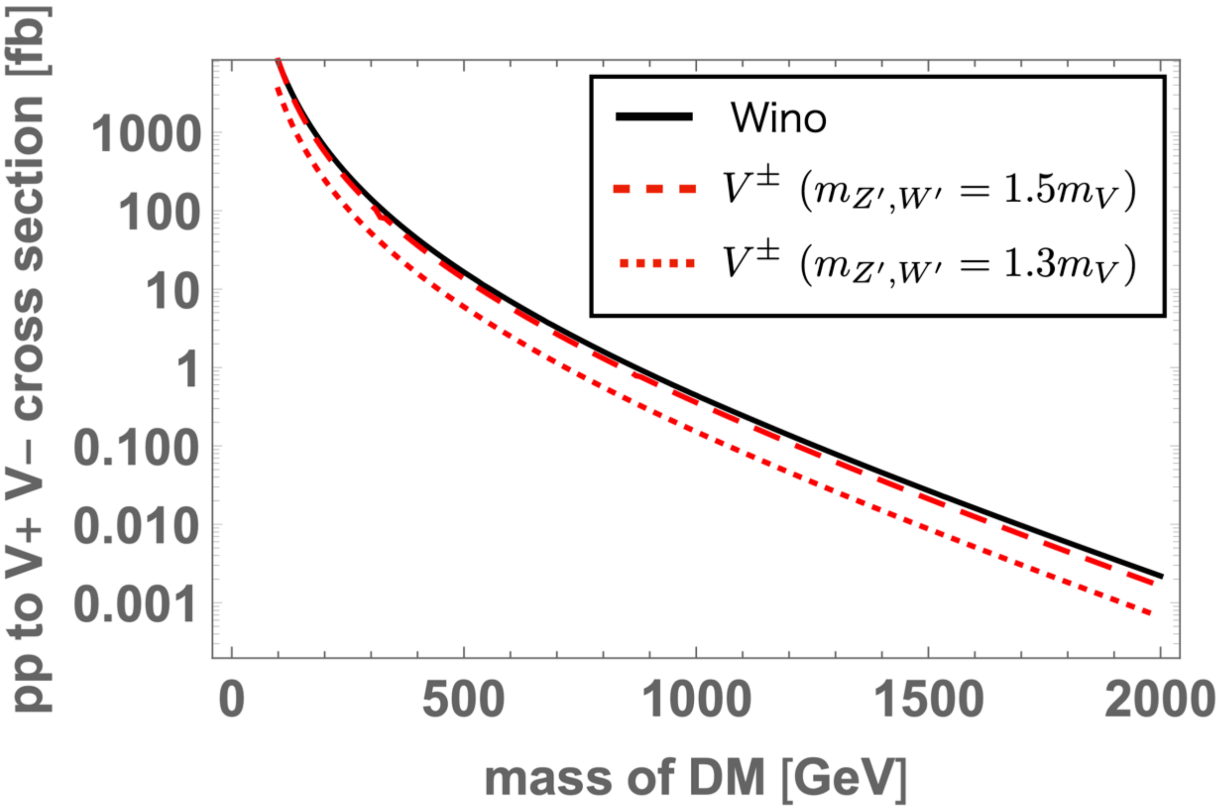


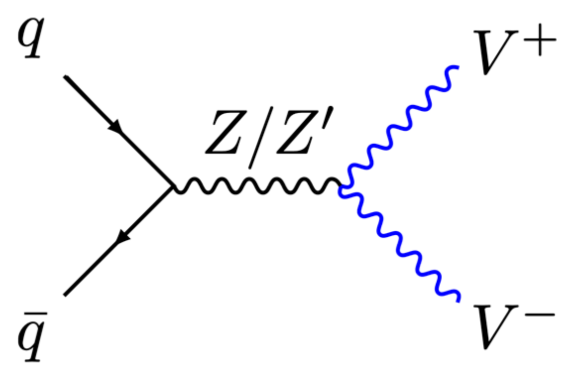


Long-lived particle search @LHC

$\{V^0, V^\pm\}$ 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: $m_{\tilde{W}} \gtrsim 460\ \mathrm{GeV}$

[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 ($\phi_h \ll 1$)

For more details

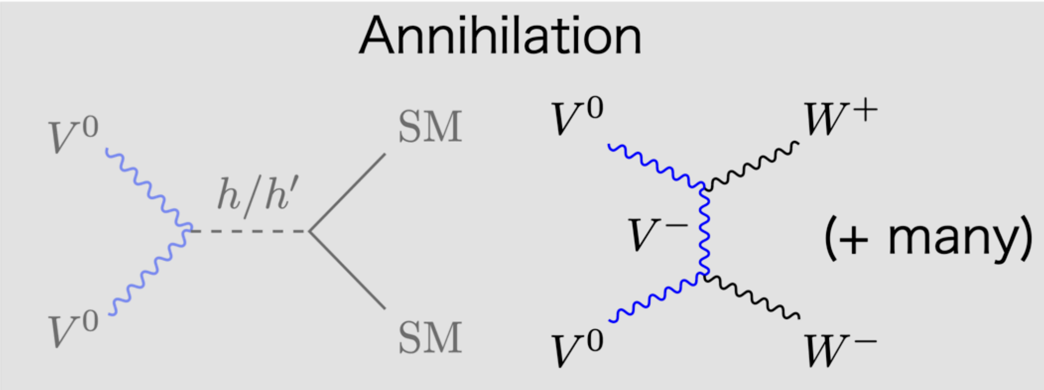
Small ϕ_h regime:

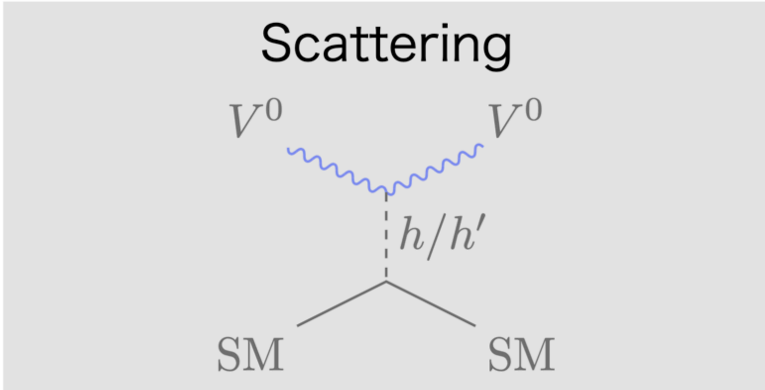
ϕ_h : mixing angle of Z_2-even scalars

Higgs mixing angle

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

No direct detection bounds (EW 1-loop diagram dominate σ_{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)

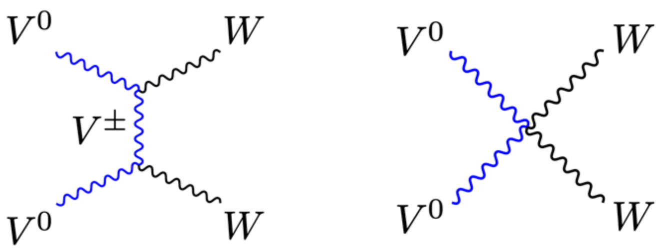
★ : benchmark point
(m_V=3 TeV, $m_{Z'}$=10 TeV)

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

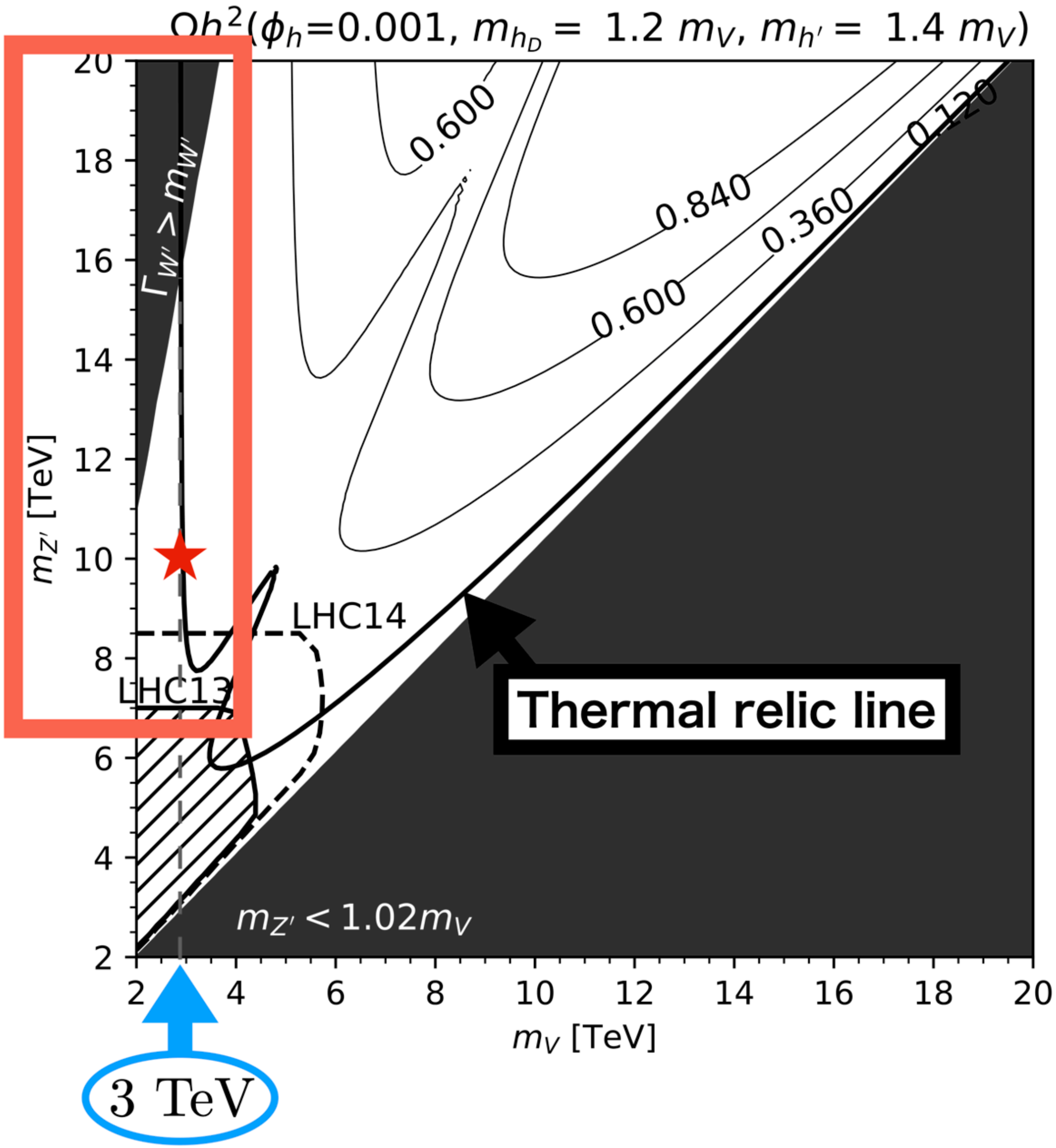
Ωh^2 is determined independently of $m_{Z'}$

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

Annihilation Channel



(+ many other channels…)



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

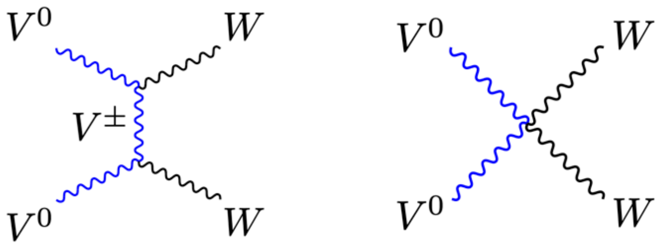
Ωh^2 contour(2/3)

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

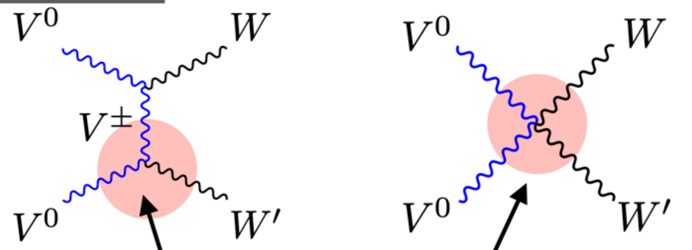
DM pair can annihilate into the final states with W', Z'

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

Annihilation Channel



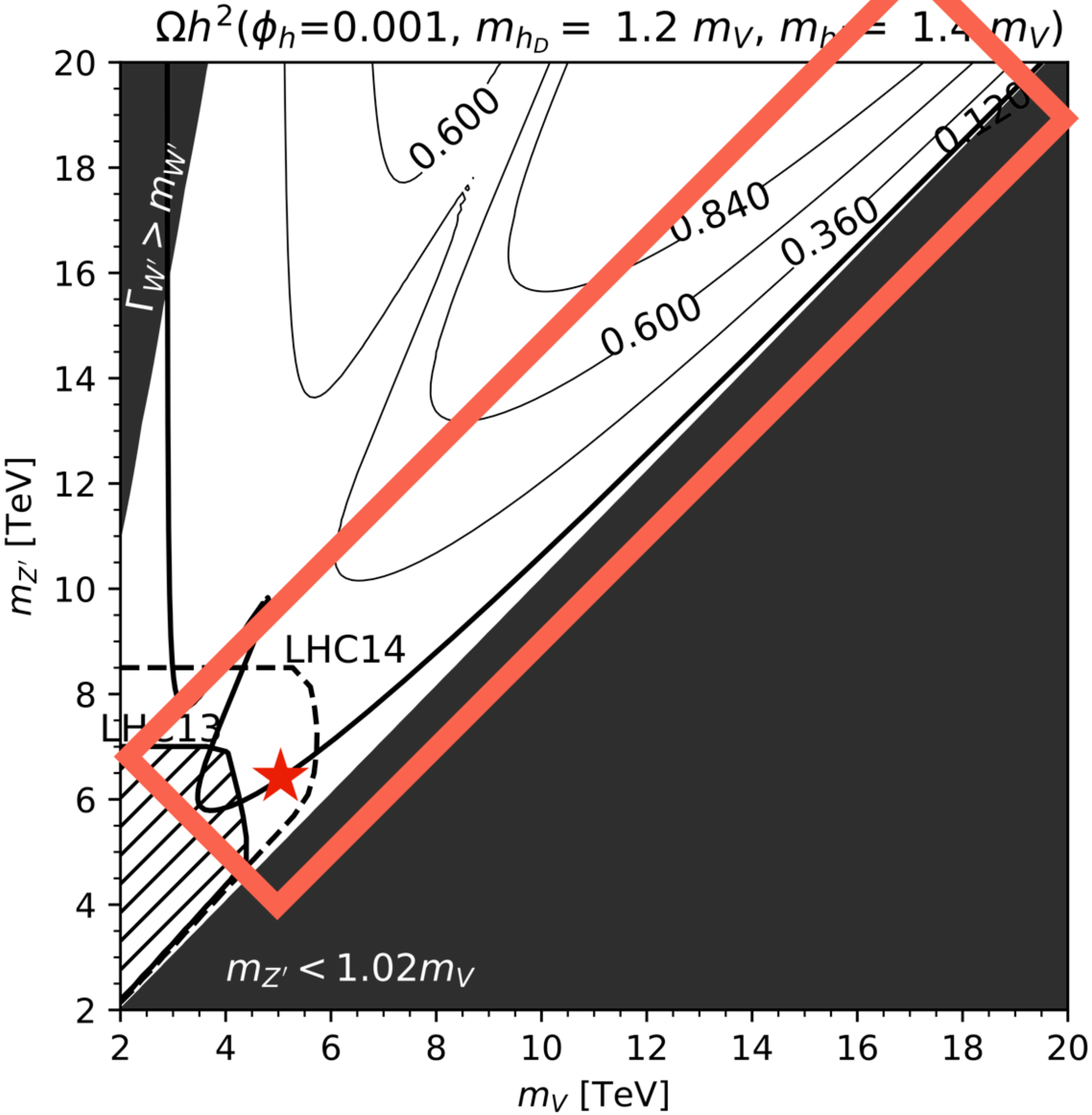
New channels



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

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

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

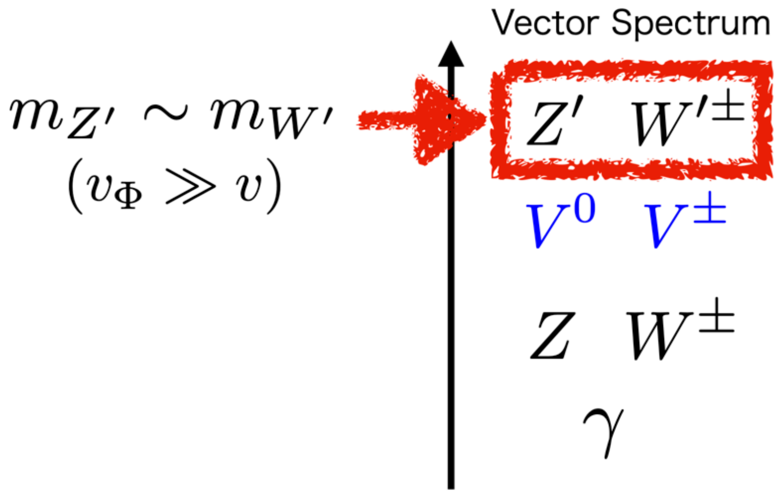


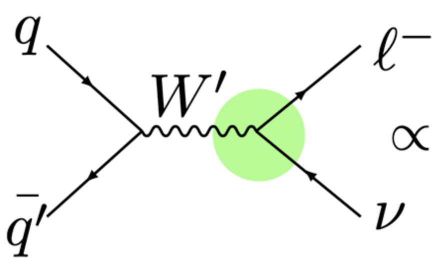
※ Ωh^2-contours are degenerated for $\phi_h \lesssim 0.001$

Ωh^2 contour(3/3)

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

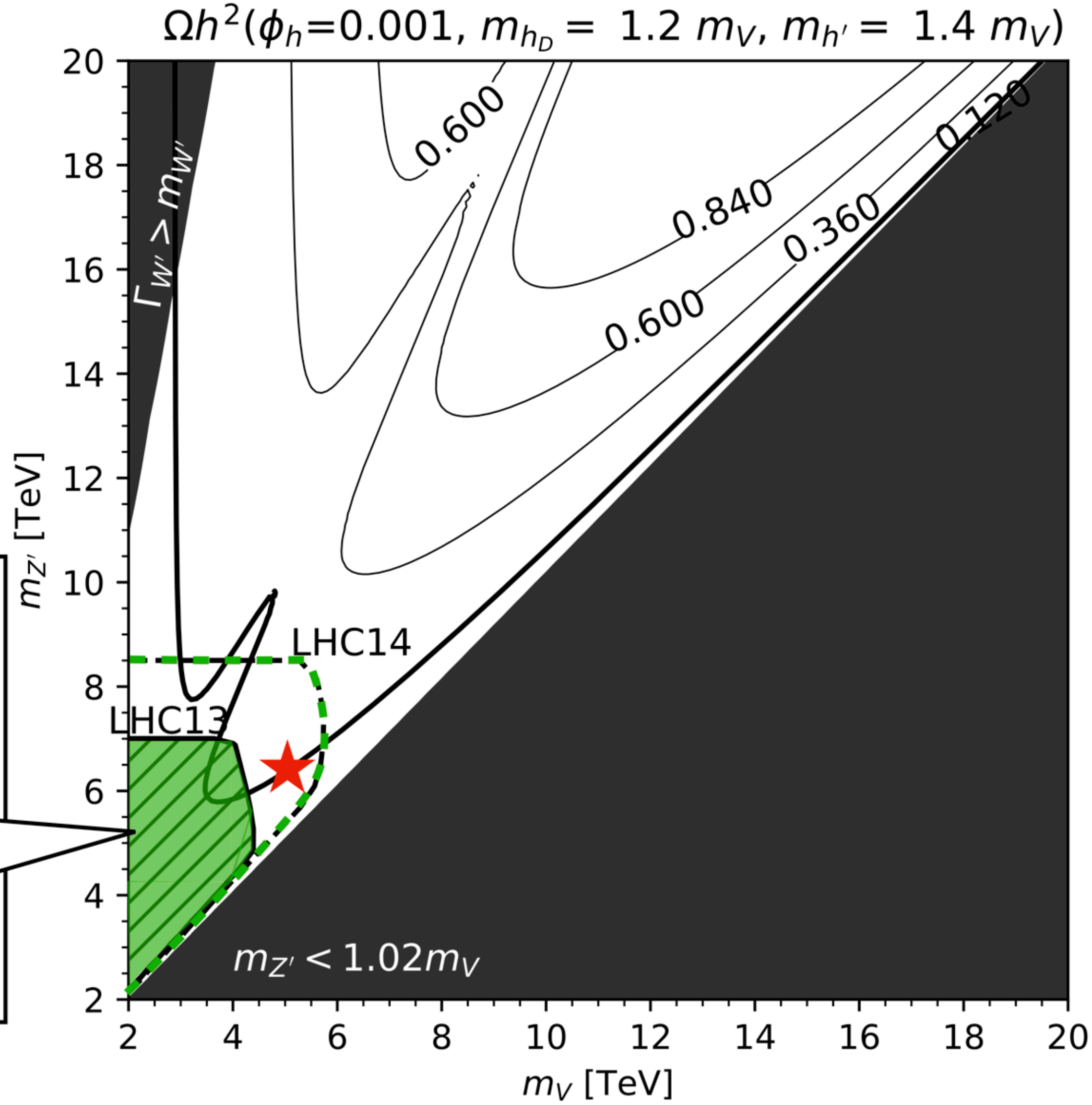
W' search in TeV scale





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

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

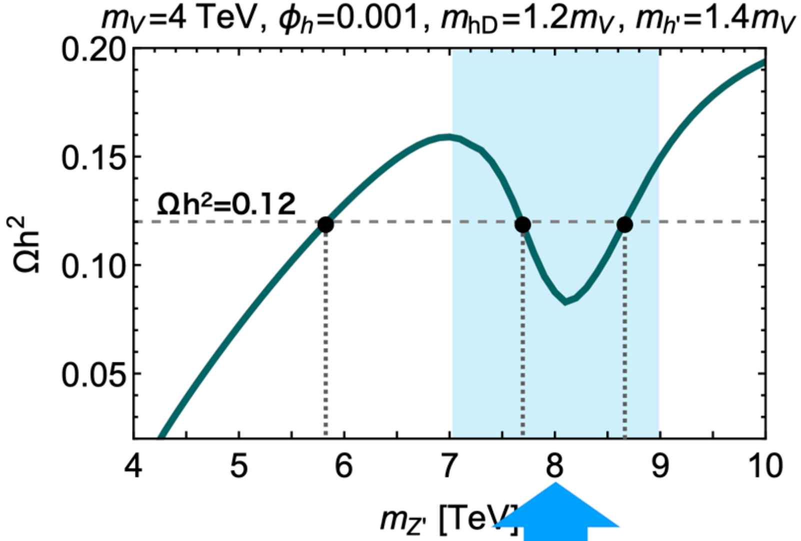


We can test thermal relic region in W' search @LHC(14 TeV)

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

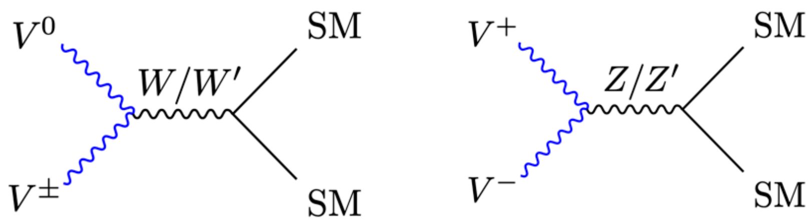
Resonance region in Ωh² contour

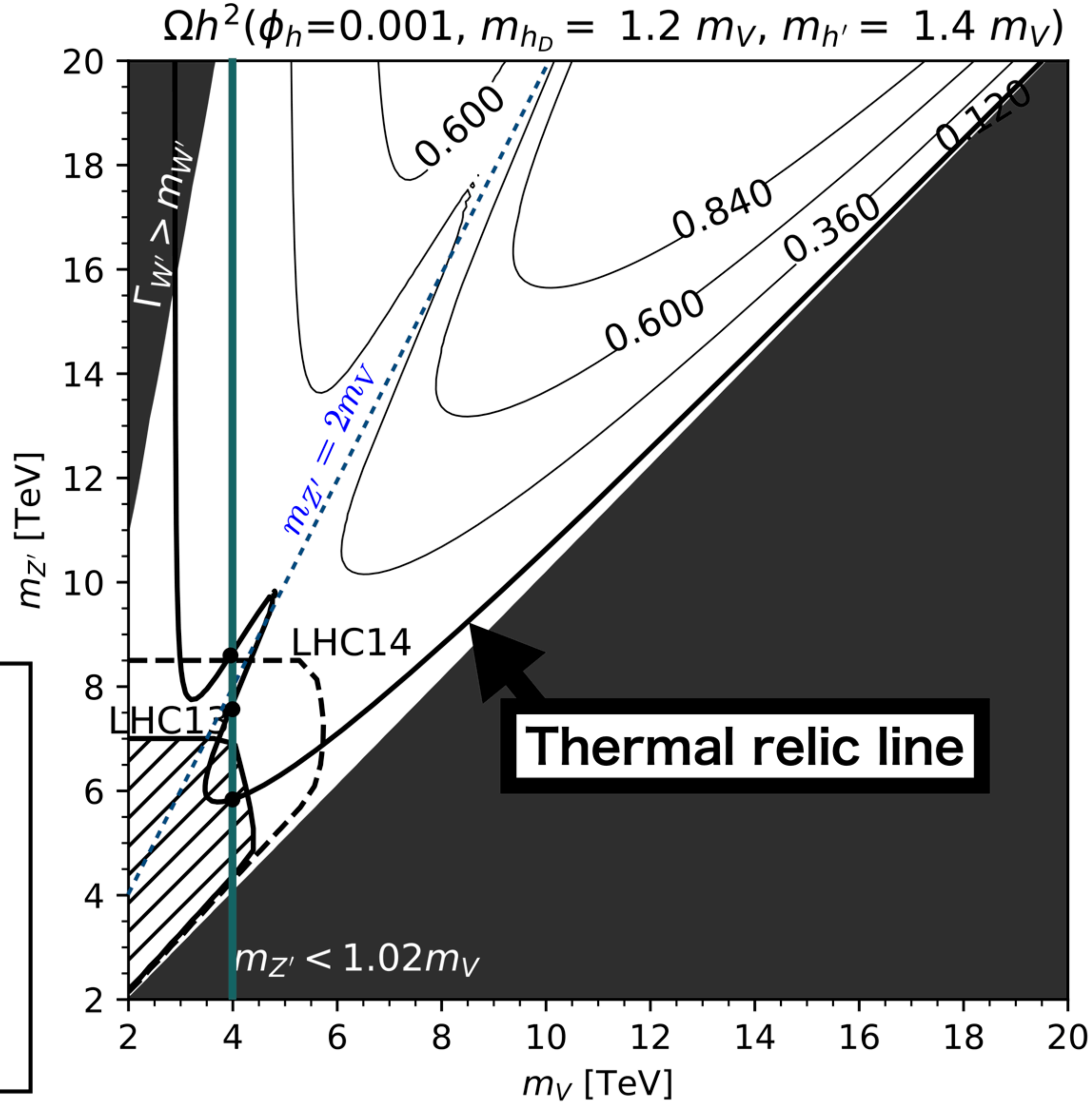
Contours of Ωh²



$m_{Z'} \sim 2m_V$

resonance region of Z'/W' channel





Thermal relic line

Ωh^2 contours

w/ relatively large Higgs mixing angle

For more details

Viable Region: Higgs sector

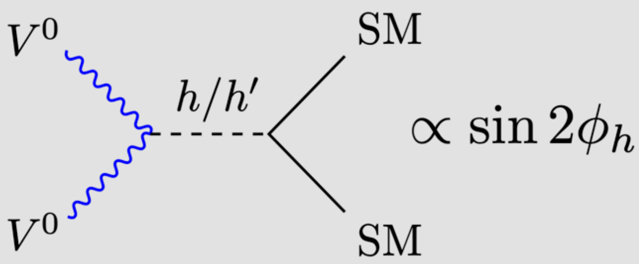
ϕ_h : mixing angle of Z_2-even scalars

<u>Higgs mixing angle</u>

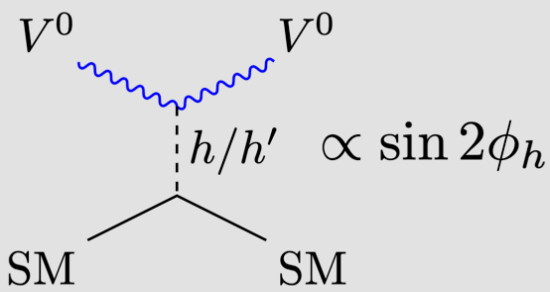
Small ϕ_h regime: DM annihilation only occur through the EW interaction
No direct detection bounds

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

Annihilation



Scattering



<u>Higgs masses</u>

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

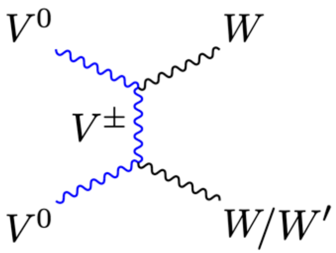
Benchmark value: $m_{h_D} = 1.2 m_V, \quad m_{h'} = 1.4 m_V$

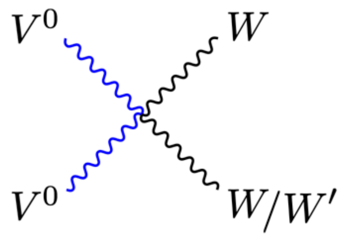
Thermal relic region in ϕ_h contour

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

<u>Annihilation Channel</u>

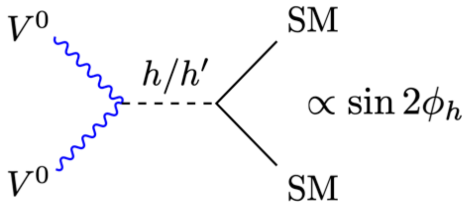
- EW channels



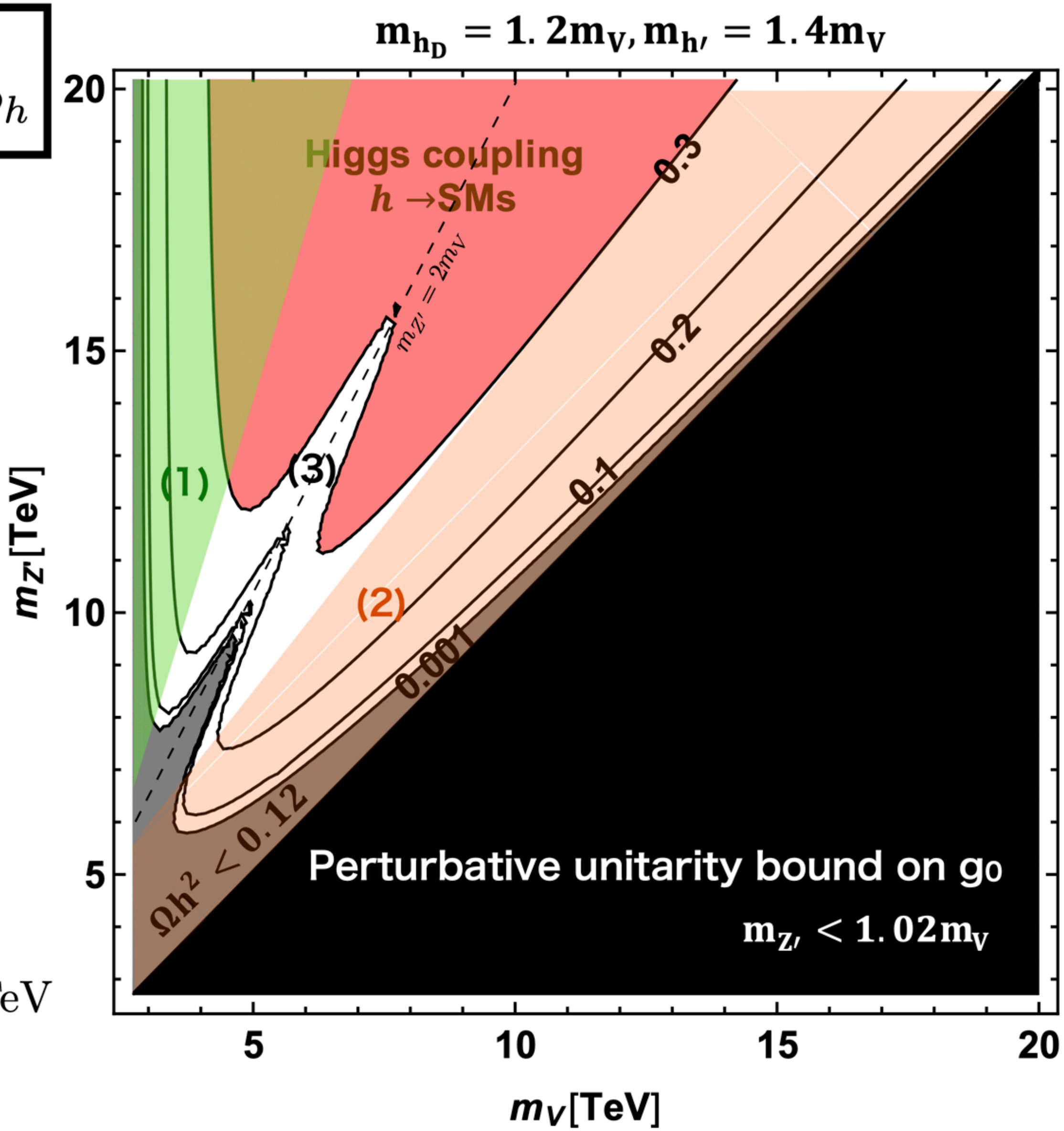


(+ many other channels…)

- Higgs channels

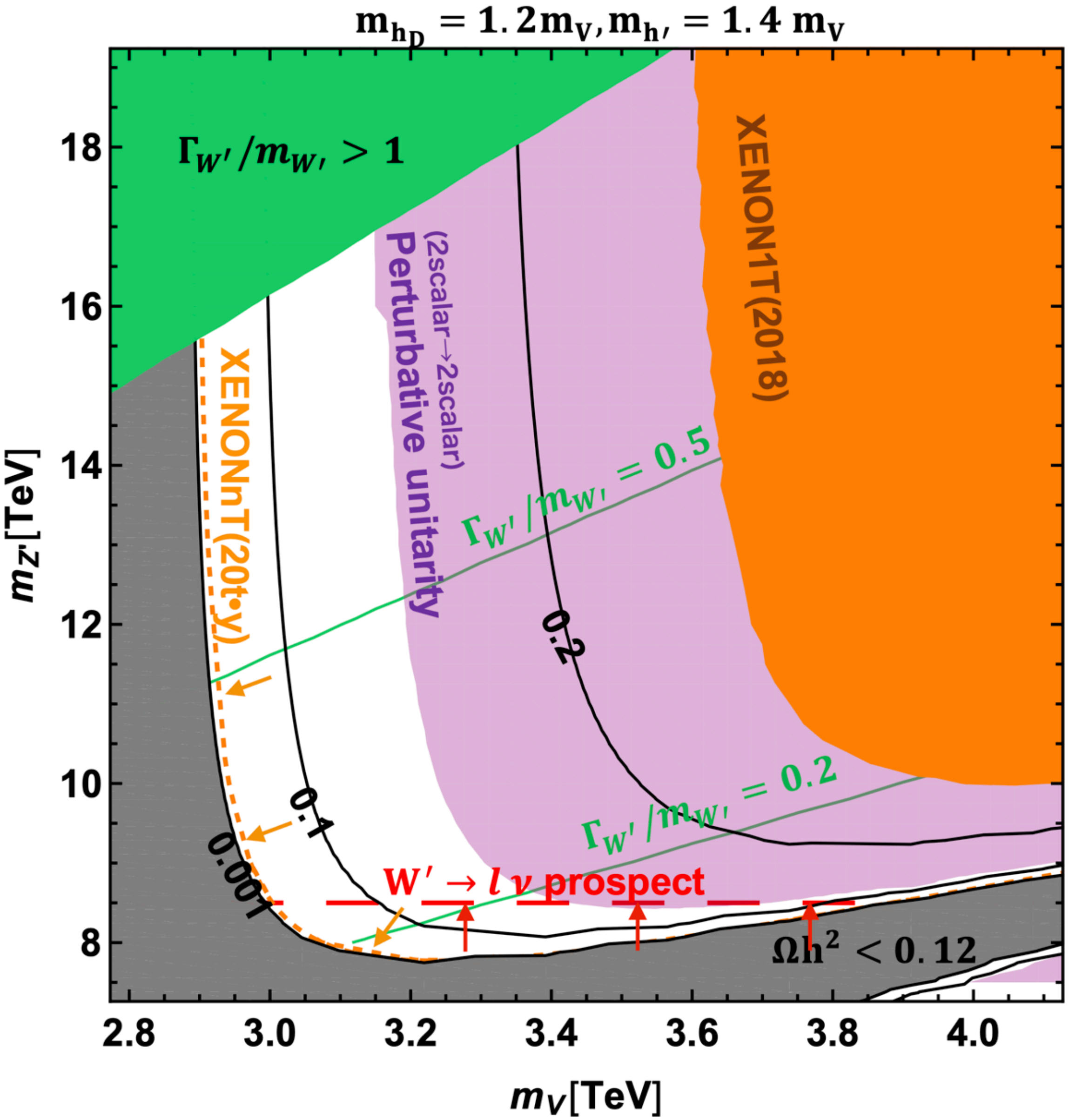


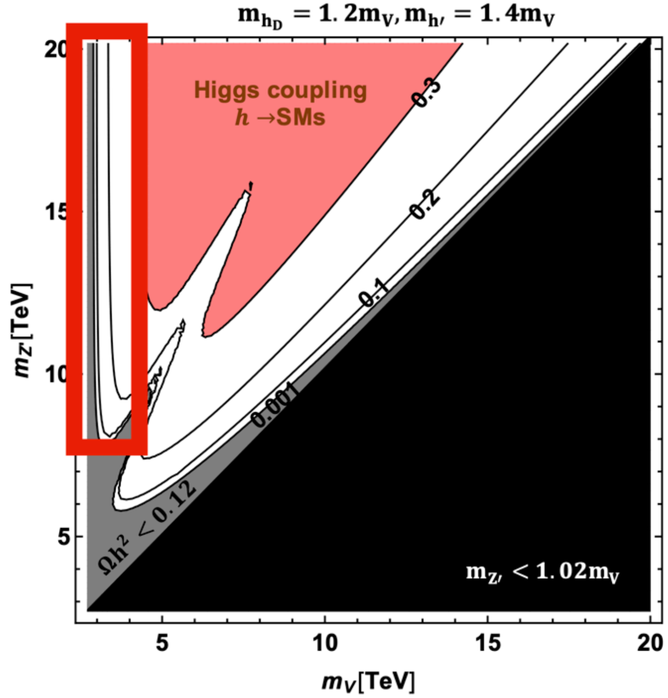
(1) $m_{Z'} \gg m_V$ $\quad 3\ \mathrm{TeV} \lesssim m_V \lesssim 5\ \mathrm{TeV}$
(2) $m_{Z'} \gtrsim m_V$
(3) $m_{Z'} \simeq 2m_V$ (Resonant region)



→ 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 $m_{Z'}$

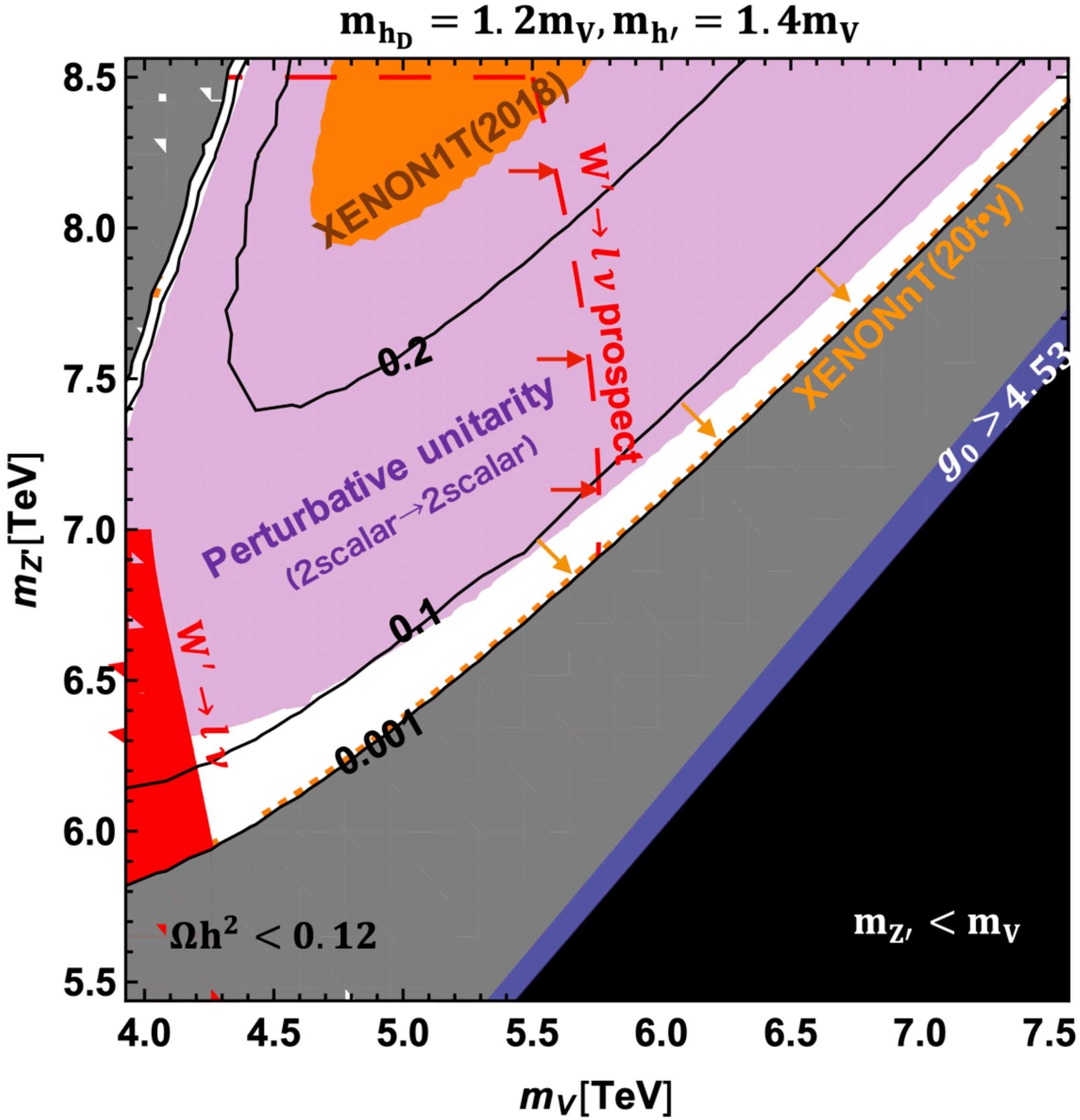
$\Omega h^2 = 0.12$

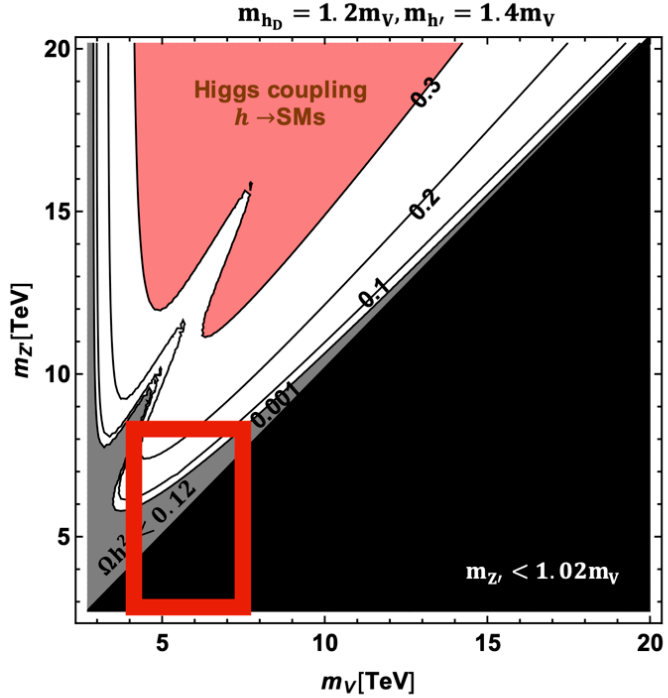
$\Leftrightarrow$ $\boxed{3 \text{ TeV} \lesssim m_V \lesssim 5 \text{ TeV}}$

- 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

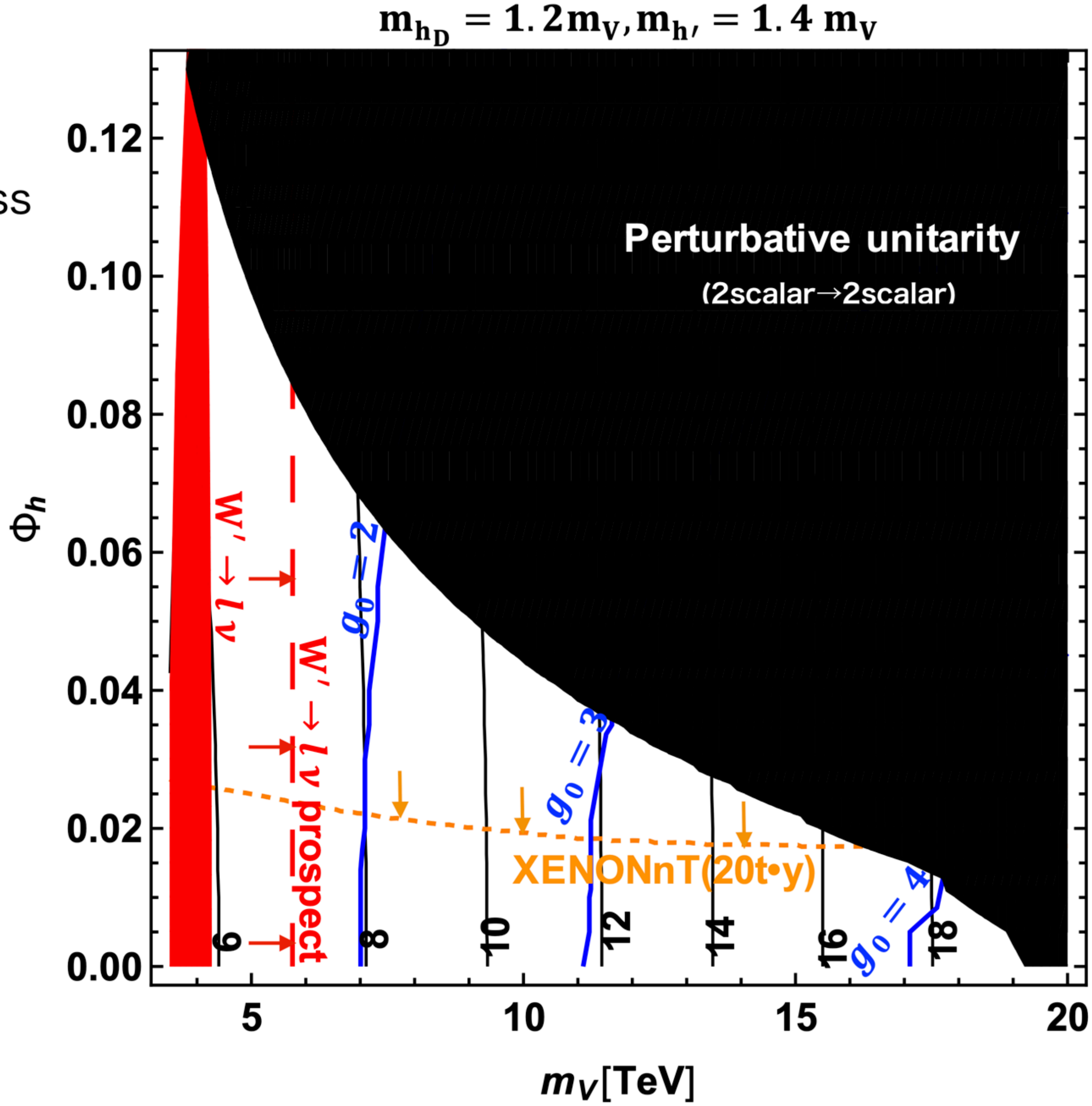
m_V-ϕ_h plot

- 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



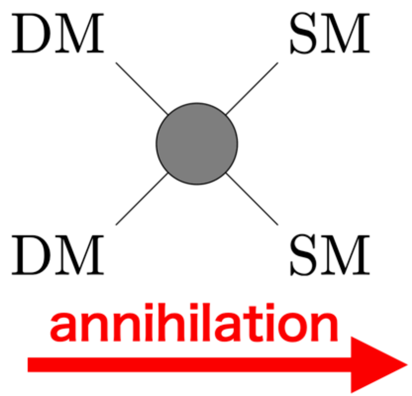
Electroweak Multiplet DM

For more details

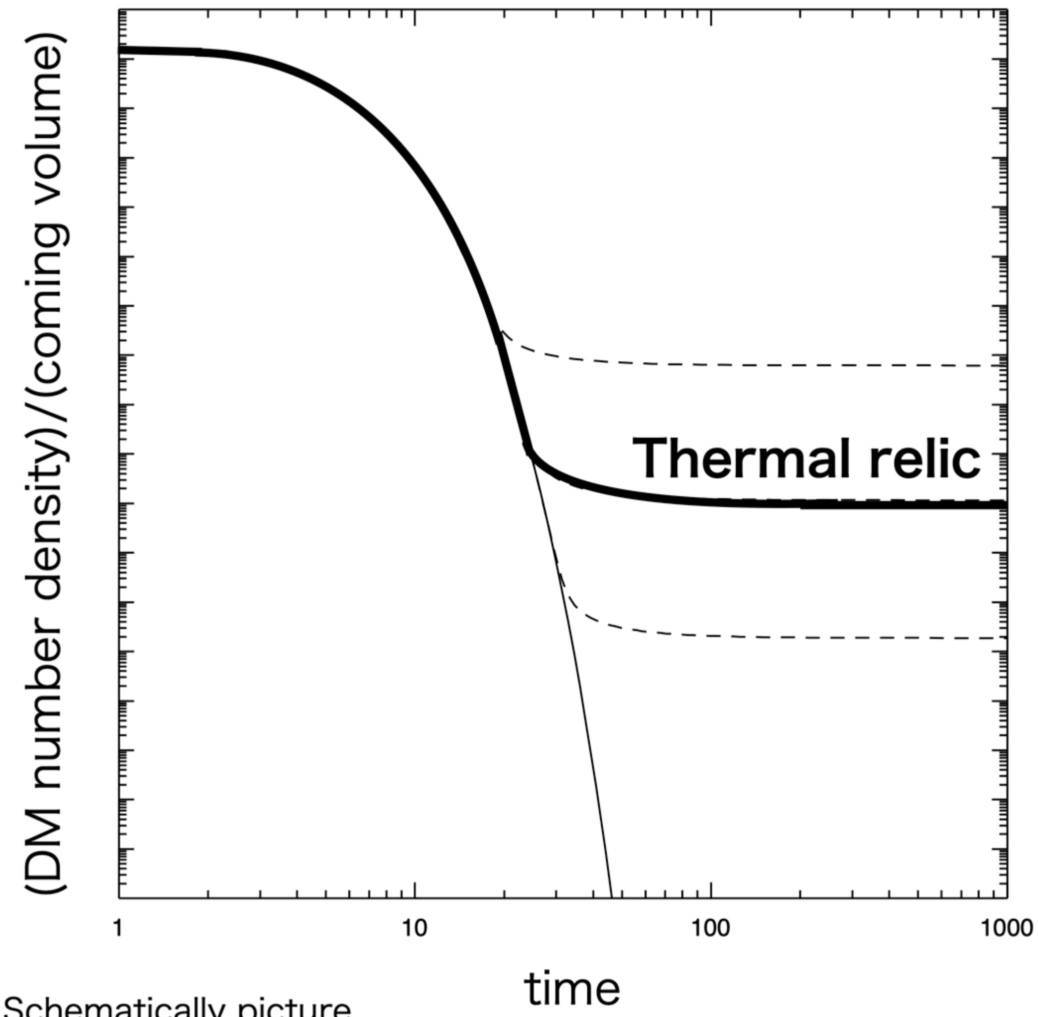
Introduction: WIMP scenario Dark Matter

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,

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

$$\simeq \frac{\alpha_{\rm DM}^2}{m_{\rm DM}^2} \quad \left\{ \begin{array}{l} \alpha_{\rm DM} \sim \alpha_{\rm EW} \\ m_{\rm DM} \sim \mathcal{O}(100)\ {\rm GeV} \end{array} \right.$$

Typical scale of electroweak theory in SM!

Introduction: Electroweak Multiplet DM

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

Assumption

"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 $10^{-46}\,\mathrm{cm}^2$
	2	1/2	0	EL	0.54^*	350	$0.4 \times \sqrt{\Delta}$	$(0.4 \pm 0.6)\,10^{-3}$
Higgsino $\rightarrow$	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^*	$2.0 \rightarrow 2.5$	166	$0.22 \times \sqrt{\Delta}$	0.12 ± 0.03
Wino $\rightarrow$	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) TeV DM
- mass splitting $\rightarrow$ 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

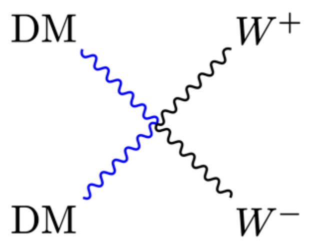
   → DM = Stable & Electrically neutral component

3. Extending the gauge symmetry

   → DM $\stackrel{?}{=}$ 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)]

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

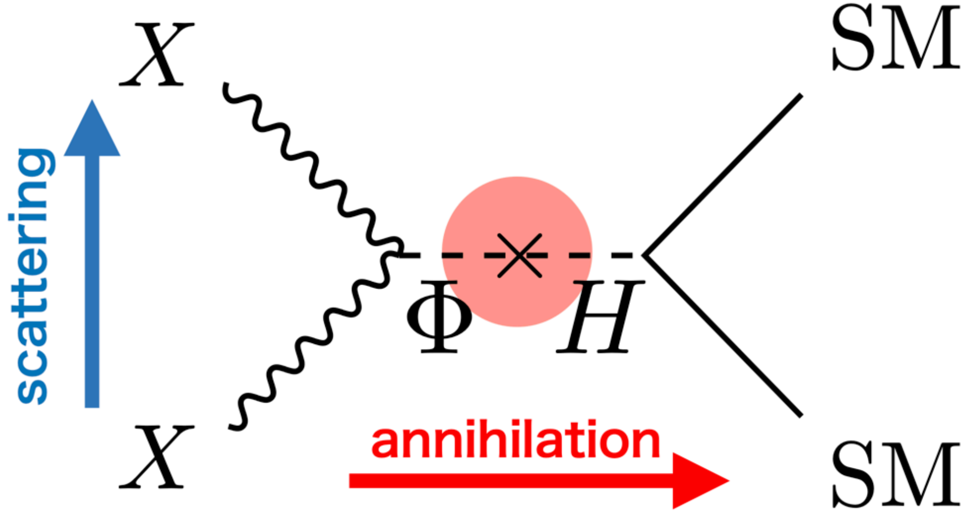
$$\mathcal{L} \supset -\frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

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

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

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

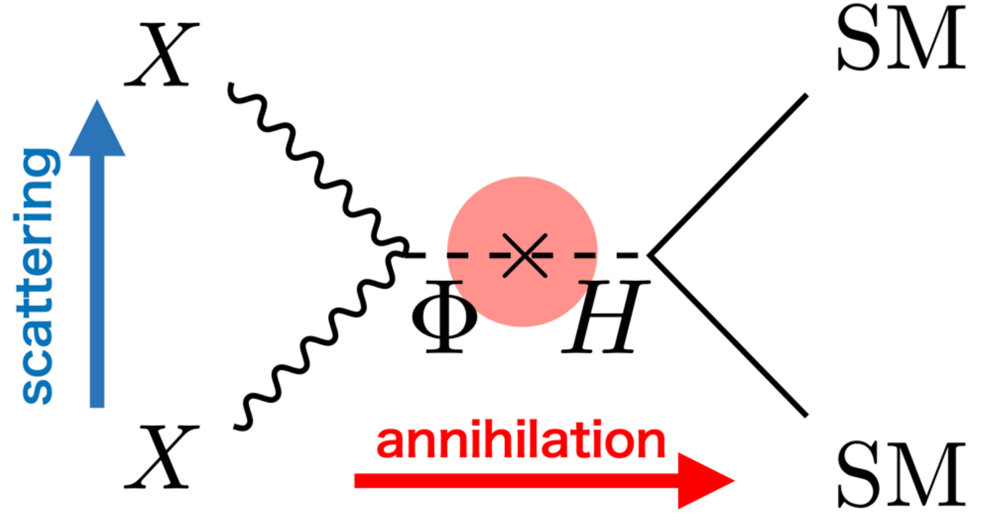
$$\mathcal{L} \supset -\frac{1}{4} X^a_{\mu\nu} X^{a\mu\nu} + (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi, H)$$

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

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)]

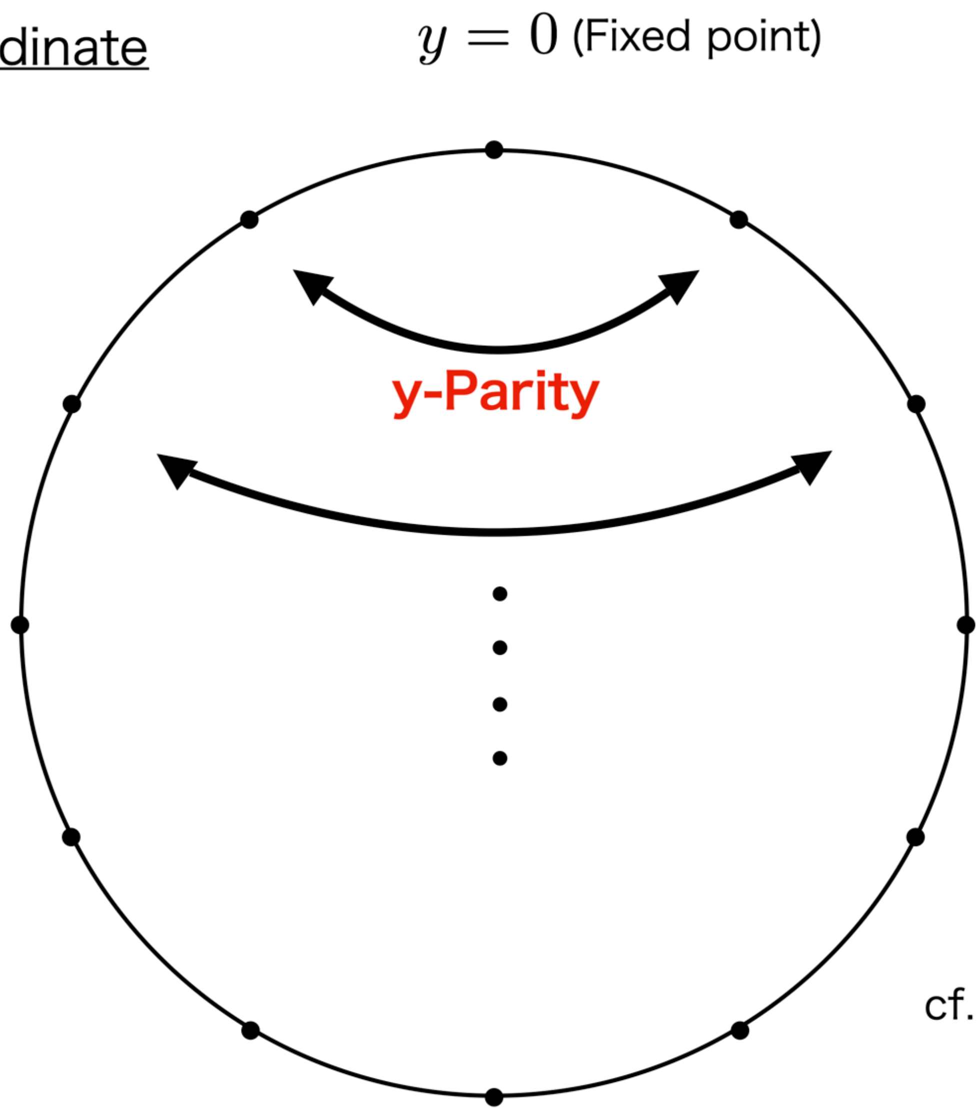
Introduction: (De)construction technique

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)]

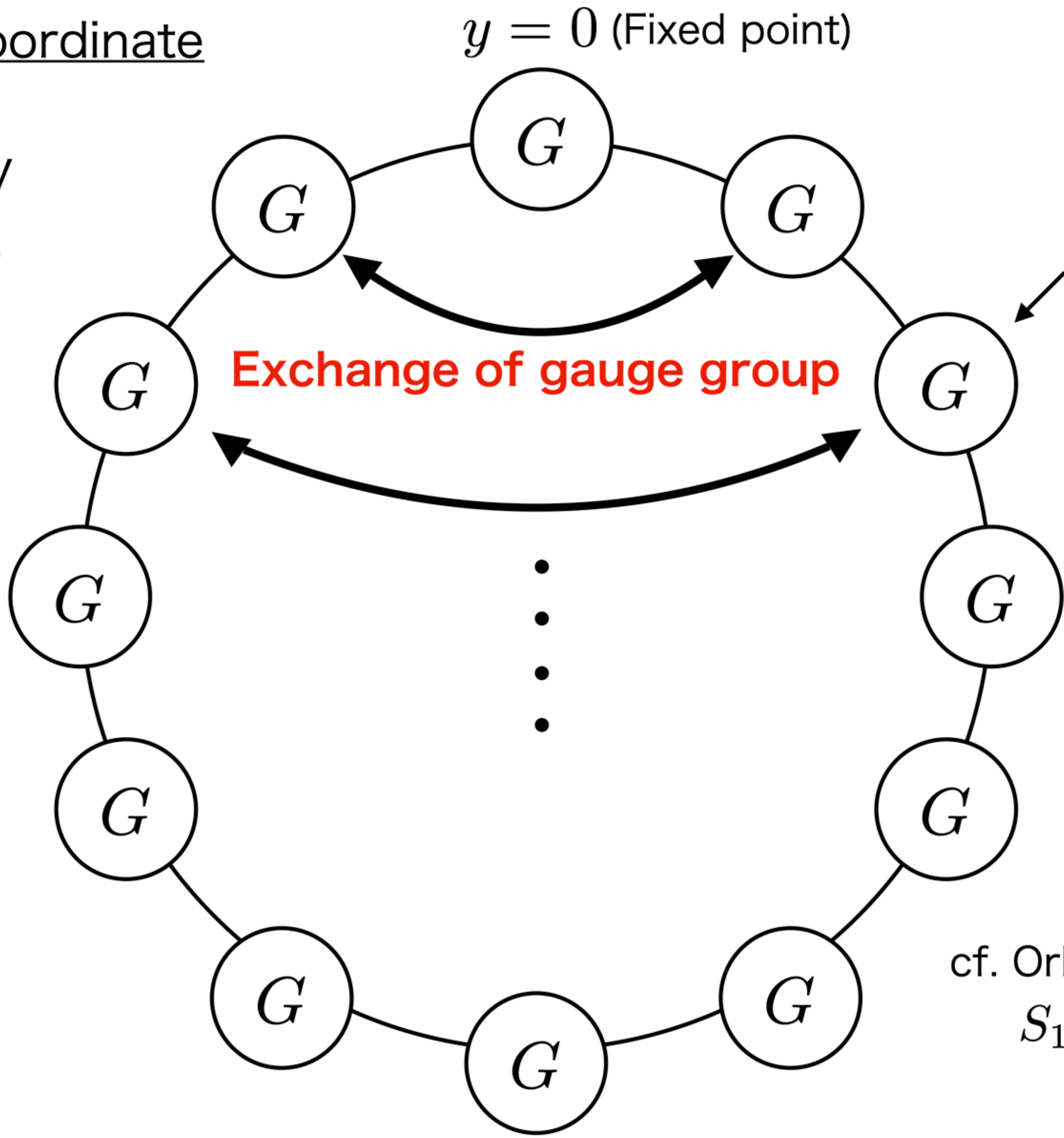
Introduction: (De)construction technique

Discretized 5d coordinate

※Schematically picture

5d gauge theory

G: gauge group



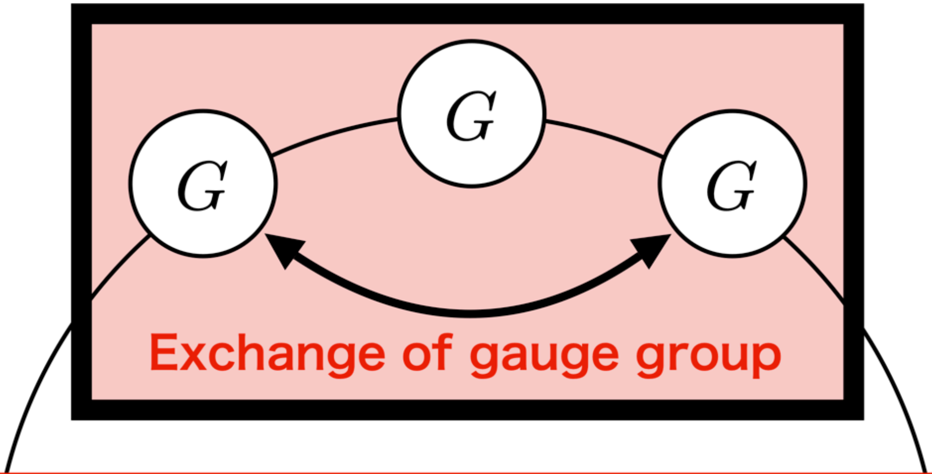
4d theory at each discretized point

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



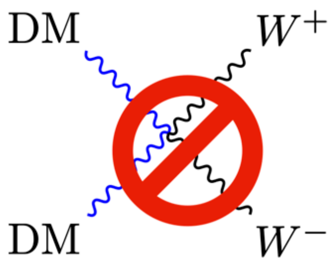
Our Work

- **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!



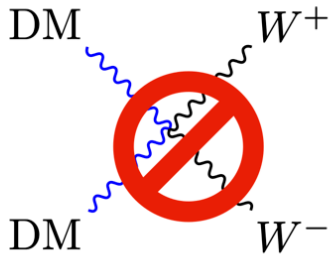
Stable neutral vector CANNOT have Non-Abelian EW couplings

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

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

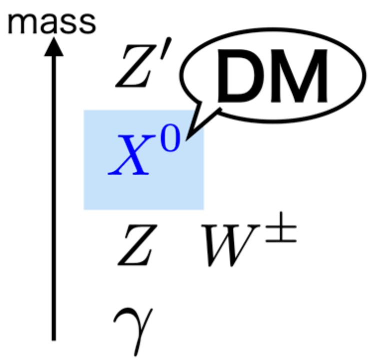
※ We have kinetic mixing terms(2nd line) in this Abelian extension model

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

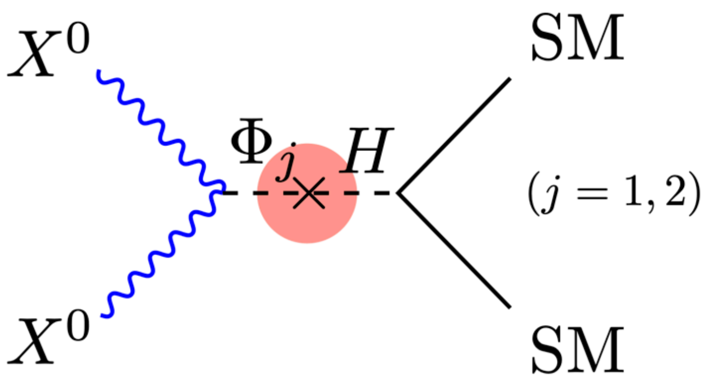
- X^0 do not appear in the $SU(2)_L$ neutral vector state

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

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

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

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



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)!

2021.05.25　Motoko FUJIWARA