A Classification of Simple W' Models

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based on **arXiv:1607.03706**

Life with Higgs

Higgs was discovered in 2012

- consistent with the SM prediction
- no significant deviations so far

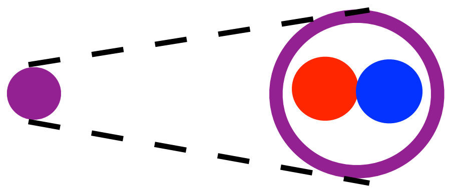
Higgs is still mysterious

- hierarchy problem? ($v_{EW} << m_{Planck}$?)
- Yukawa interaction? ($y_{up} << y_{top}$?)
- origin of the potential?
- elementary or composite?
- only one scalar?
- …

Spin-1 particle

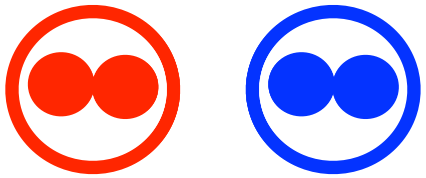
Composite Higgs

- a solution of the hierarchy problem
- many other composite particles



Spin-1 new particles (V′ = W′, Z′)

- composite particles
- easy to treat (extension of gauge symmetry)



V′ also appears in different context

- extension of EW gauge symmetry (Left-Right symmetric model, ⋯)
- some kind of GUT models
- Extra-dimension (KK modes)
- ⋯

too many V' models …

Q. What is an efficient way to treat many models?

A. Use effective theory **[Pappadopulo et.al (2014)]**

- three important parameters ($g_{V'ff}$, $g_{V'VV}$, $m_{V'}$)
- V' = $SU(2)_L$ triplet vector field

Q. If V' is discovered at the LHC, does effective theory satisfy us?

A. No, we need to find the model

Q. But too many models ⋯. Any efficient ways?

A. OK, classify V' setup.

What is the main decay mode of V'?

parametrize couplings

$$g_{V'ff} = -\xi_f g_{Vff},$$
$$g_{V'VV} = \xi_V \frac{m_V^2}{m_{V'}^2} g_{VVV}$$

ratio of Γ

$$\frac{\Gamma(V' \to f\bar{f})}{\Gamma(V' \to VV)} \simeq 4N_c \frac{\xi_f^2}{\xi_V^2}$$

main decay mode is determined by the relation between ξ_f and ξ_V

- For $\xi_f > \xi_V$ or $\xi_f \sim \xi_V$, V' mainly decay to fermions
- For $\xi_f < \xi_V$, V' mainly decay to bosons

perturbative unitarity helps us to find the relation between ξ_f and ξ_V without specifying any models

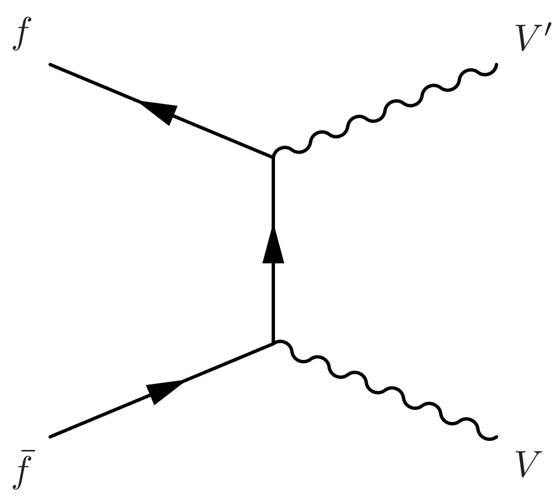
Perturbative unitarity

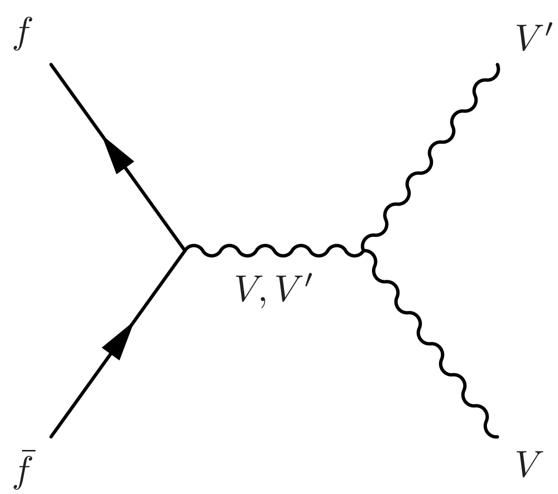
processes and amplitude

- ff → VV, ff → VV′ ff → V′V′ Amp ~ **a** E^2 + **b** E^1 + ⋯
- VV → VV, VV → VV′, ⋯ Amp ~ **c** E^4 + **d** E^2 + ⋯

impose : a = b = c = d = 0

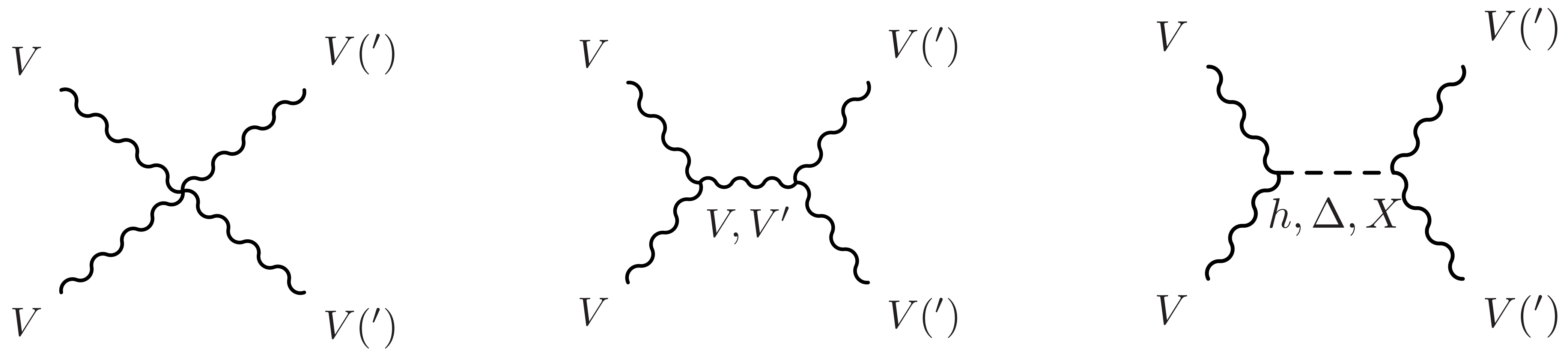
- example: a = 0 leads $g_{Vff}g_{V'ff} = g_{Vff}g_{V'VV} + g_{V'ff}g_{V'V'V}$,





Perturbative unitarity (cont’)

VV→ VV, VV → VV’, VV → V’V’ (Amp ~ **c** E^4 + **d** E^2 + ⋯)



h: SU(2) singlet, Δ: triplet, X: five-plet

example: d = 0 in VV → VV’ leads

$$(3m_V^2 + m_{V'}^2)g_{V'VVV} - 3\sum_k m_k^2 g_{V_kVV}g_{V'V_kV} = \sum_h g_{VVh}g_{VV'h} - \frac{5}{6}\sum_X g_{VVX}g_{VV'X},$$

Perturbative unitarity (cont')

we find various coupling relations

- quadratic equations for the couplings
- two solutions for the relation $\boldsymbol{\xi_f}$ and $\boldsymbol{\xi_V}$

$$g_{V'ff} = -\xi_f g_{Vff},$$
$$g_{V'VV} = \xi_V \frac{m_V^2}{m_{V'}^2} g_{VVV}$$

In all scalars are SU(2) singlet case

V' decay to fermion

"type-F"

$$\xi_V = \frac{\xi_f}{1 - \frac{m_W^2}{m_{W'}^2}(1-\xi_f^2)} \simeq \xi_f \qquad \frac{\Gamma(V' \to ff)}{\Gamma(V' \to VV)} \simeq 4N_c$$

$$\xi_V = -\frac{1}{\xi_f}\frac{1}{1 - \frac{m_W^2}{m_{W'}^2}(1-\xi_f^{-2})} \simeq -\frac{1}{\xi_f} \qquad \frac{\Gamma(V' \to ff)}{\Gamma(V' \to VV)} \simeq 4N_c\xi_f^4$$

"type-B"

V' decay to bosons

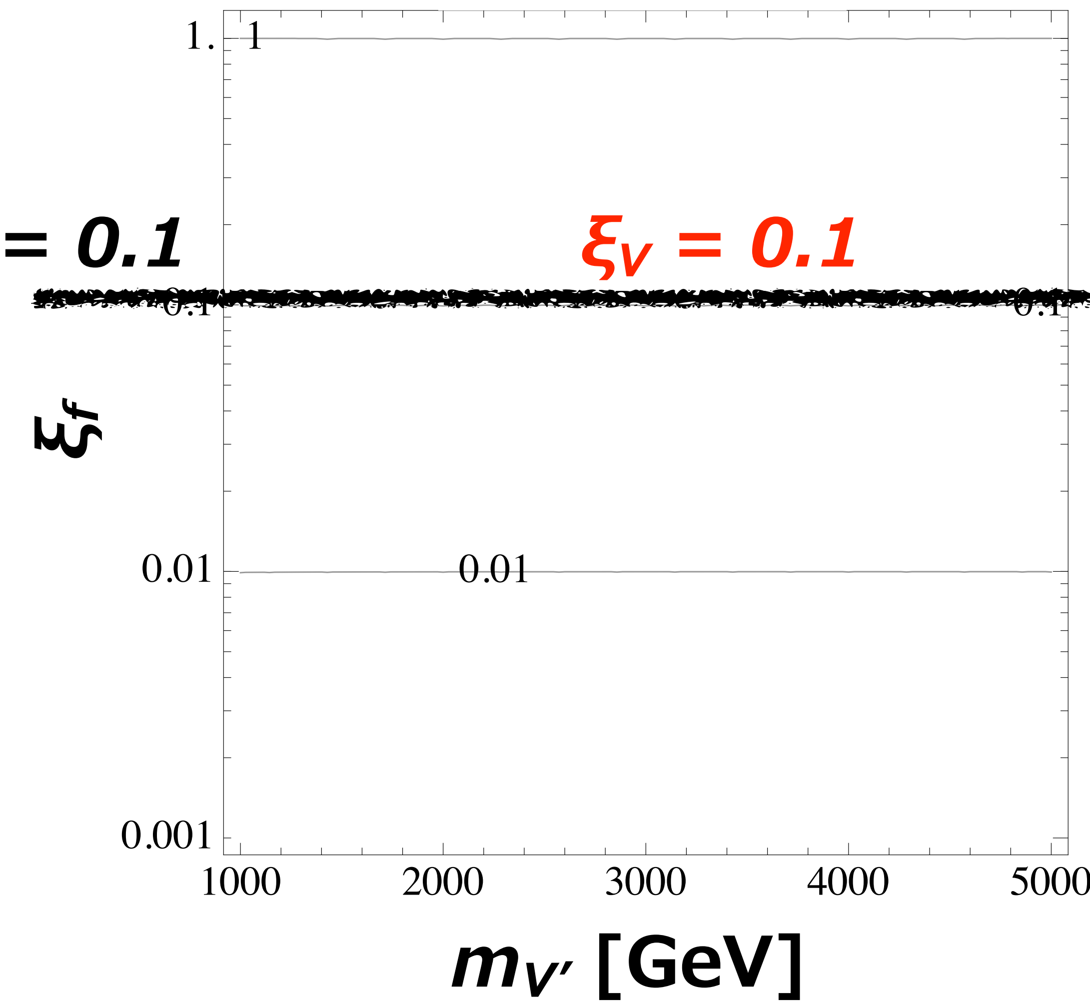
(if ξ_f < 1)

ξ_V vs ξ_f (all scalars are SU(2) singlet)

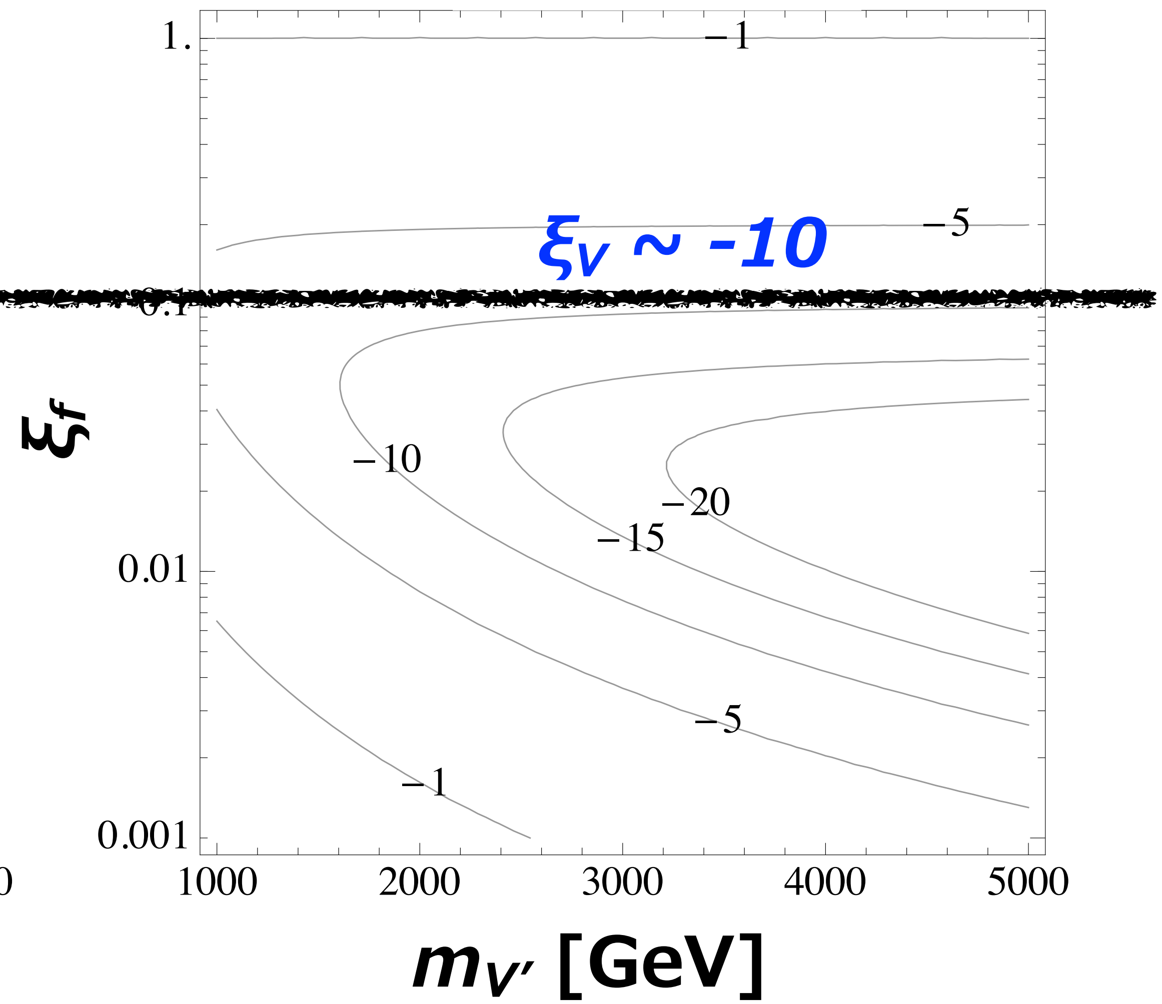
$$\xi_V = \frac{\xi_f}{1 - \frac{m_W^2}{m_{W'}^2}(1 - \xi_f^2)} \simeq \xi_f$$

$$\xi_V = -\frac{1}{\xi_f} \frac{1}{1 - \frac{m_W^2}{m_{W'}^2}(1 - \xi_f^{-2})} \simeq -\frac{1}{\xi_f}$$

$\xi_f = 0.1$



$\xi_V = 0.1$



$\xi_V \sim -10$

two classes of V' models

We found two classes of models

- **type-F: $\xi_V \sim \xi_f$, $\Gamma(V' \to ff)$ >> $\Gamma(V' \to VV)$**
- **type-B: $\xi_V \sim 1/\xi_f$, $\Gamma(V' \to ff)$ << $\Gamma(V' \to VV)$**

$$g_{V'ff} = -\xi_f g_{Vff},$$

$$g_{V'VV} = \xi_V \frac{m_V^2}{m_{V'}^2} g_{VVV}$$

This classification also valid in systems with triplet/five-plet scalars

This is model independent result, but

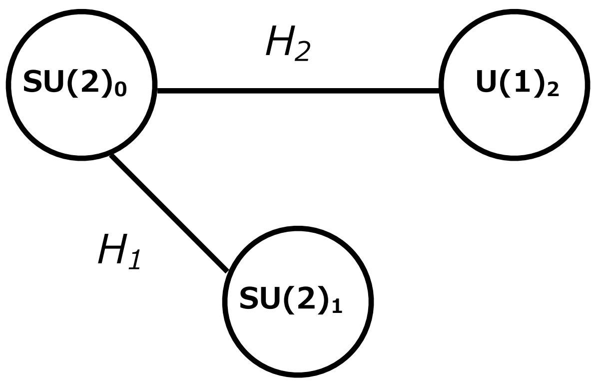
- specific models are suitable for the LHC pheno.
- next step is find benchmark models for each of types

type-F example : HVT model A

$SU(2)_0 \times SU(2)_1 \times U(1)_2 \to U(1)_{QED}$

Barger - Keung - Ma (1980)
Pappadopulo - Thamm - Torre - Wulzer (2014)

	SU(2)	SU(2)	U(1)
q	2	1	1/6
u	1	1	2/3
d	1	1	-1/3
ℓ	2	1	-1/2
e	1	1	-1
H	2	1	1/2
H	2	2	0

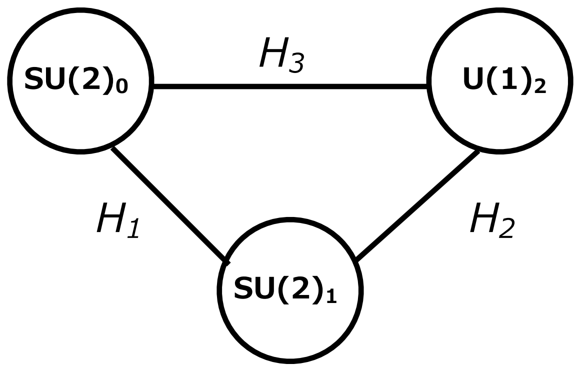


$$H_1 = \begin{pmatrix} v_1 + h_1 + i\pi_1^0 & i\sqrt{2}\pi_1^+ \\ i\sqrt{2}\pi_1^- & v_1 + h_1 - i\pi_1^0 \end{pmatrix} \qquad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} i\sqrt{2}\pi_2^+ \\ v_2 + h_2 - i\pi_2^0 \end{pmatrix}$$

type-B example

TA - Kitano (2013)

$SU(2)_0 \times SU(2)_1 \times U(1)_2 \to U(1)_{QED}$

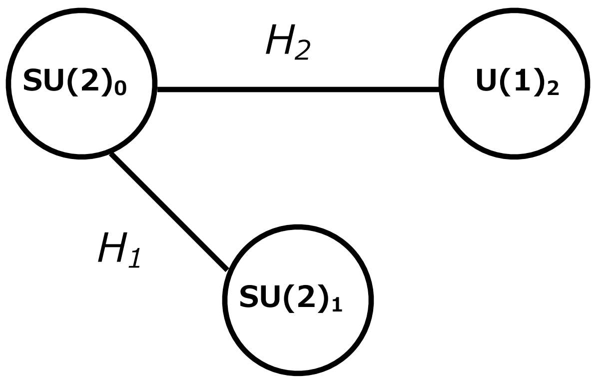


	SU(2)	SU(2)	U(1)
q	2	1	1/6
u	1	1	2/3
d	1	1	-1/3
ℓ	2	1	-1/2
e	1	1	-1
H	2	1	1/2
H	2	2	0
H	1	2	1/2

$$H_1 = \begin{pmatrix} v_1 + h_1 + i\pi_1^0 & i\sqrt{2}\pi_1^+ \\ i\sqrt{2}\pi_1^- & v_1 + h_1 - i\pi_1^0 \end{pmatrix} \qquad H_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} i\sqrt{2}\pi_2^+ \\ v_2 + h_2 - i\pi_2^0 \end{pmatrix} \qquad H_3 = \frac{1}{\sqrt{2}}\begin{pmatrix} i\sqrt{2}\pi_3^+ \\ v_3 + h_3 - i\pi_3^0 \end{pmatrix}$$

what makes difference?

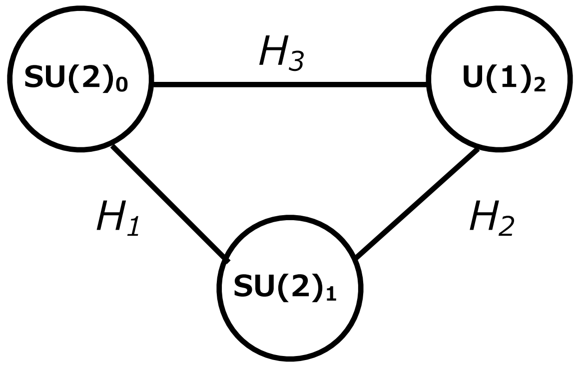
type-F



Note:

***V'VV* coupling ~ *V'*$\pi_V \pi_V$ coupling**

type-B

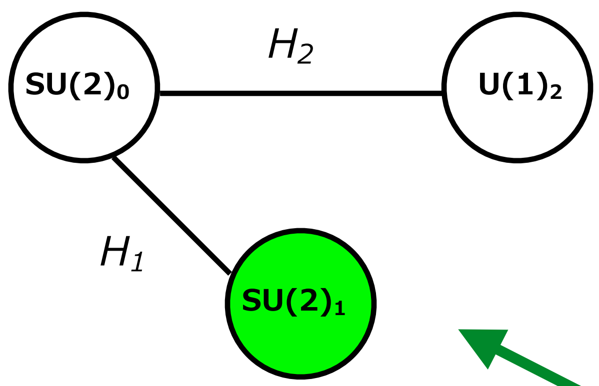


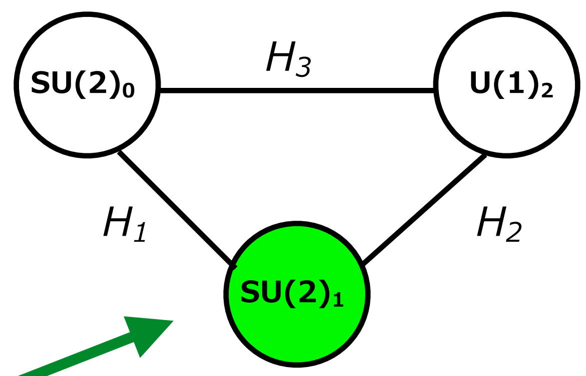
what makes difference?

type-F

type-B

Note:
$V'VV$ coupling ~ $V'\pi_V\pi_V$ coupling





assume V' ~ SU(2)$_1$
(this is true if g_1 >> 1)

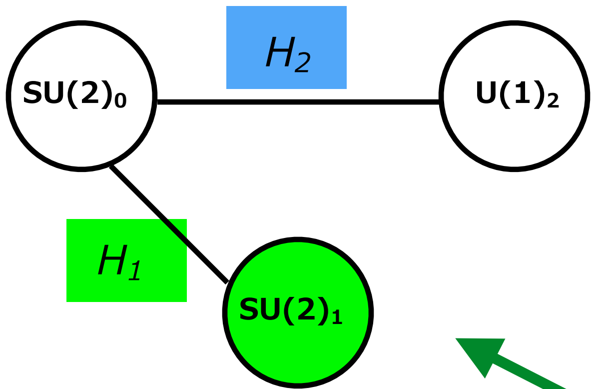
what makes difference?

type-F

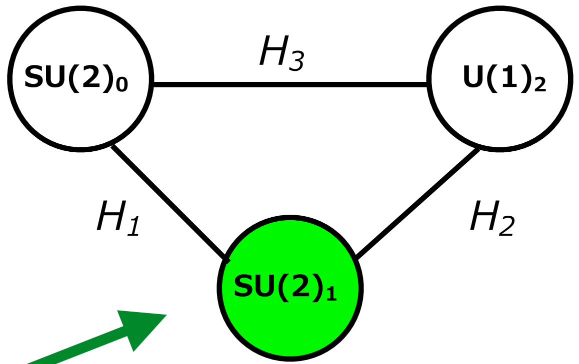
type-B

Note:
***V'VV* coupling ~ *V'$\pi_V\pi_V$* coupling**

πV should be here



πV' should be here



assume V' ~ SU(2)$_1$
(this is true if g_1 >> 1)

V' coupling to πV is suppressed

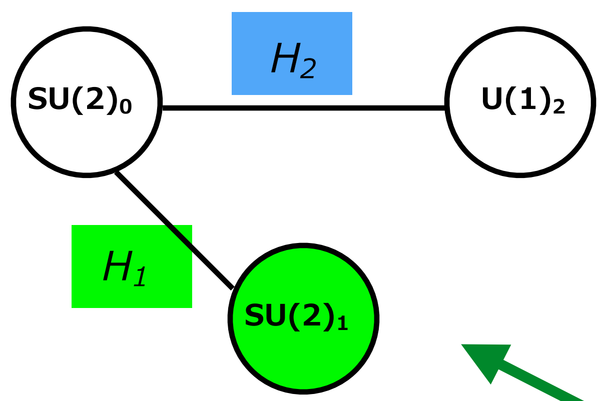
what makes difference?

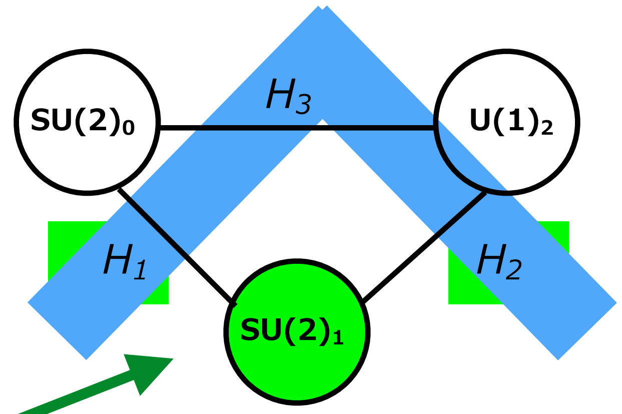
type-F

type-B

Note:
***V'VV* coupling ~ *V'*$\pi_V \pi_V$ coupling**

πv should be here





πv' should be here

assume V' ~ SU(2)$_1$
(this is true if $g_1 >> 1$)

πv' are mixture of H_1 and H_2

πv are mixture of H_1 H_2 and H_3

V' coupling to πv is suppressed

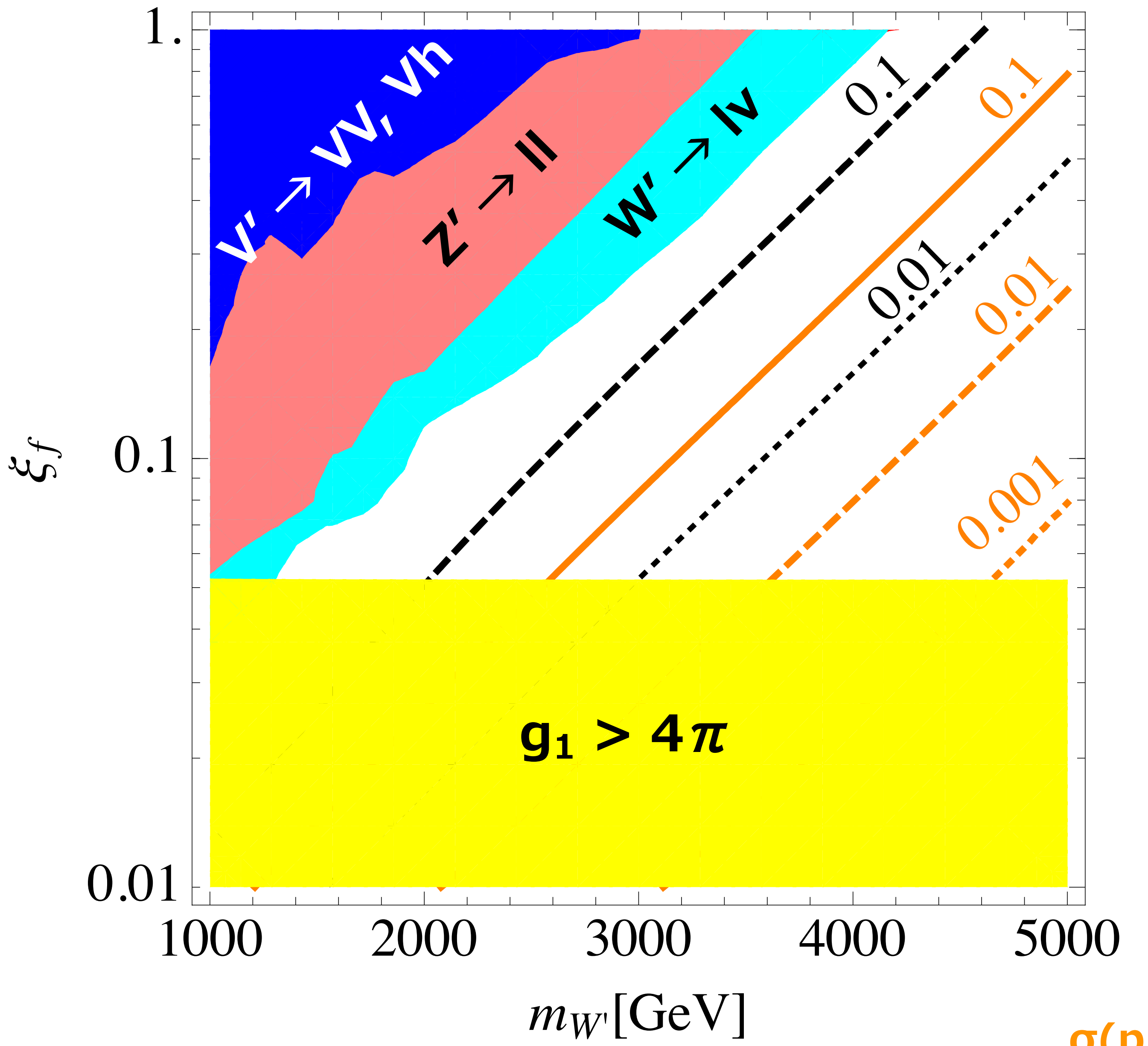
V' directly couple to πv

$$g_{V'VV} << g_{V'VV}$$

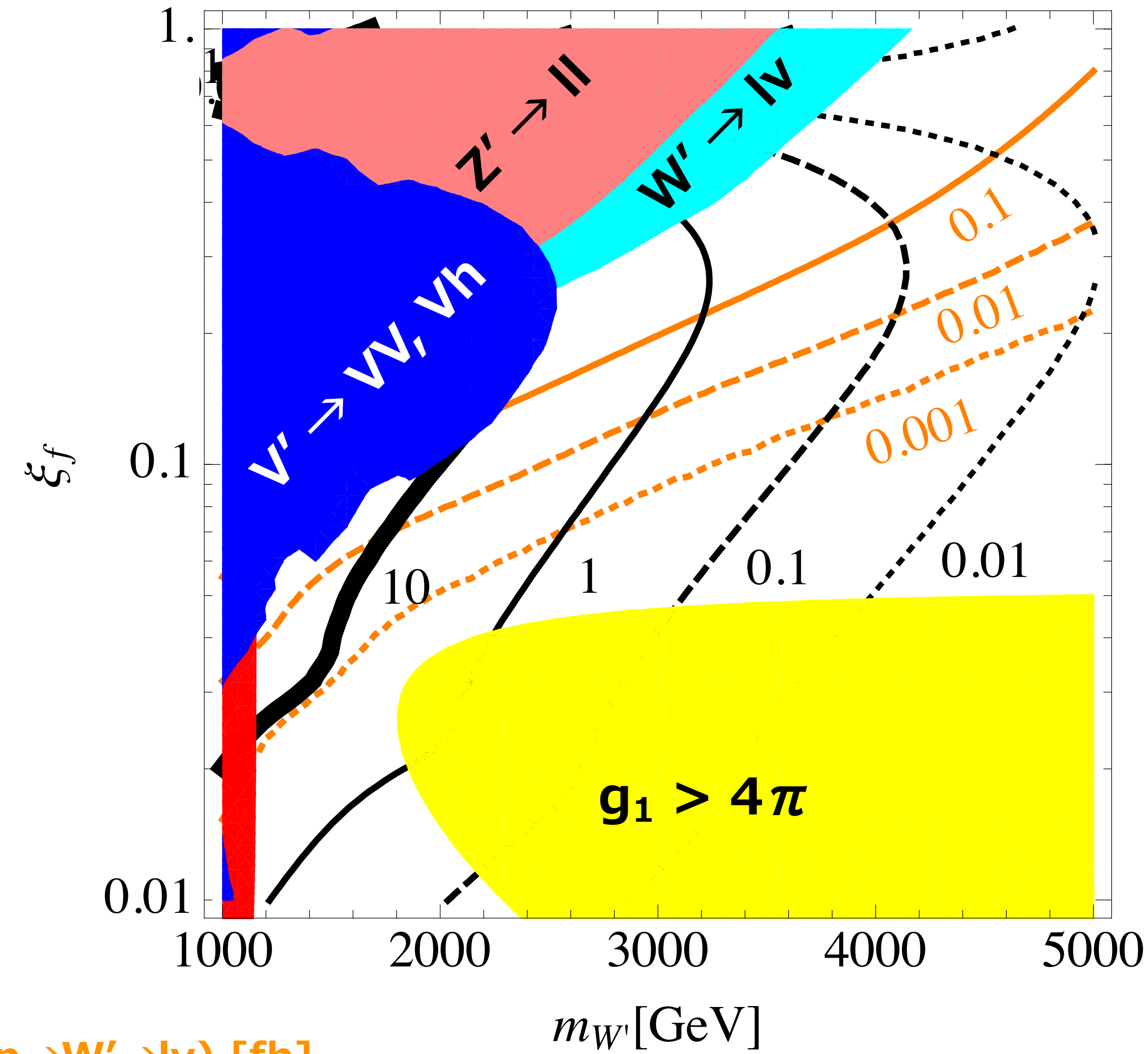
TA - Nagai (arXiv:1607.03706)

LHC bounds

type-F



type-B



σ(pp→W′→lν) [fb]

σ(pp→W′→WZ) [fb]

Summary

- **there are many models with spin-1 new particles (V')**
  - ⋆ composite Higgs models
  - ⋆ extra-dimension models
  - ⋆ GUT
  - ⋆ ⋯

- **two types of V'**
  - ⋆ **type-F:** V' → ff is main decay mode
  - ⋆ **type-B:** V' → VV is main decay mode

- **we showed the clear difference of the two types**

- **we showed benchmark models for each type**