Extra Higgs bosons
and
spin-1 heavy vector bosons

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based on

RN and T. Abe PRD 95 075022 [arXiv: 1607.03706]

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Extra spin-1 particles (V')

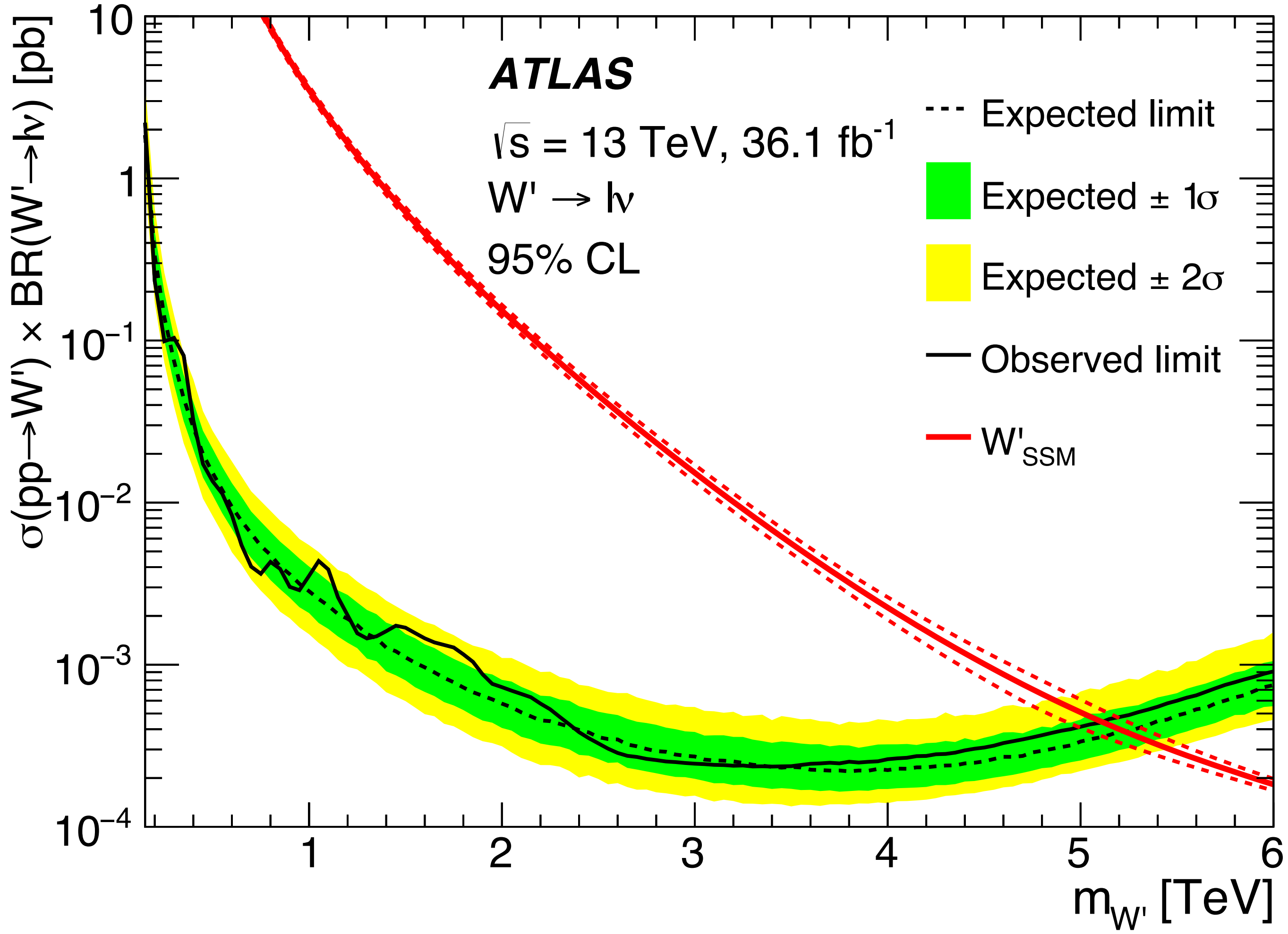
What is V' = W'/Z' ?

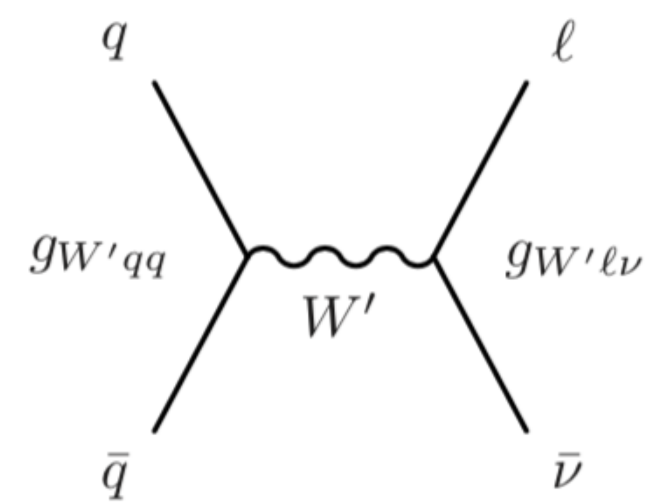
- Heavier version of W/Z boson.

Various BSMs predict them

- Extra dimension models (KK gauge boson)
- Unification models (W_R, ….)
- Dynamical EWSB scenarios (ρ' meson)
- …….

Current bound on V'





CERN-EP-2017-082

- $m_{W'}$ > 5TeV with the assumption, $g_{W'ff} = g_{Wff}$ (SM).
- This bound depends on W' couplings.

Question

Property of V' ??

Question

Property of V' ??

- Couplings to the SM particles

gV'ff = gVff (SM)   ??

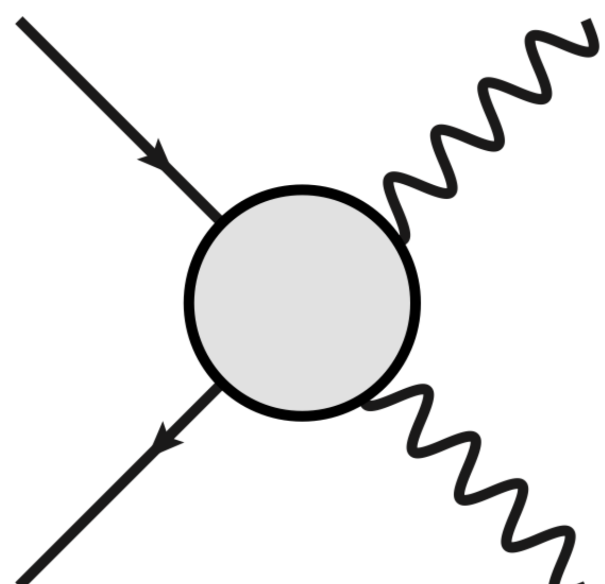
- Main decay mode of V'

V' $\rightarrow$ Fermions ??

or $\rightarrow$ Bosons ??

Strategy

Let us focus on V_L/V'_L scattering processes



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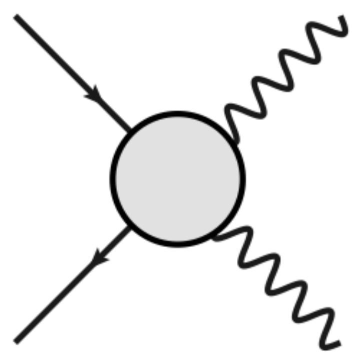
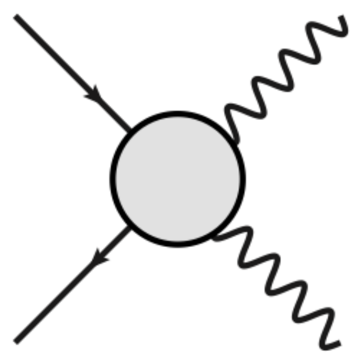


$$\simeq A\frac{E^2}{m^2} + B\frac{E}{m}$$

Strategy

Let us focus on V_L/V'_L scattering processes



$$\simeq A\frac{E^2}{m^2} + B\frac{E}{m}$$

- If the model keep unitarity in high-energy limit, A = B = 0.

"Unitarity sum rules"

Strategy

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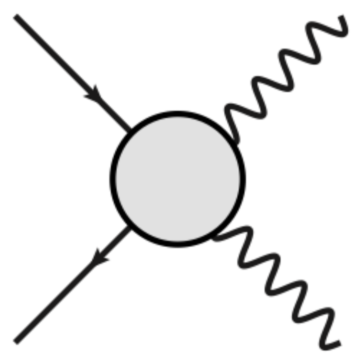


$$\simeq A\frac{E^2}{m^2} + B\frac{E}{m}$$

- If the model keep unitarity in high-energy limit, A = B = 0.
  "Unitarity sum rules"

- Unitarity sum rules tell us model-independent features of V'.

Setup

- Let us focus on the following simple class of models.

$$\mathbf{SM + V' + (\, h', h'', h''', \ldots \,)}$$

CP-even neutral Higgses

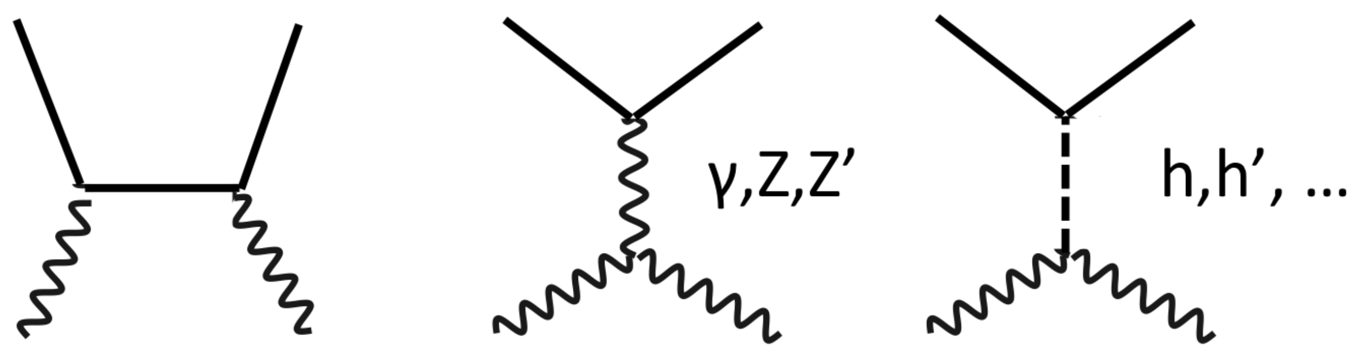
- For simplicity,
  - Right-handed fermions are singlet under SU(2).
  - Minimal flavour violation.
  - No CP-violation in Higgs sector

Perturbative Unitarity

<u>$f\bar{f} \to W_L W'_L$ scattering</u>

Perturbative Unitarity

ff $\rightarrow W_L W'_L$ scattering



$$\mathcal{M}_{-+} = s\,\mathcal{A}\sin\theta + \mathcal{O}(s^0)$$

(± : twice of helicity)

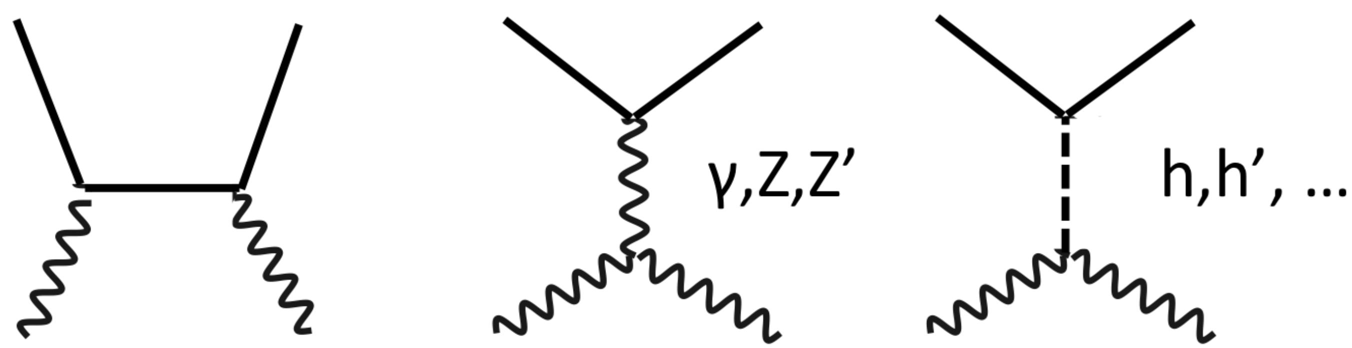
$$\mathcal{M}_{+-} = s\,\mathcal{B}\sin\theta + \mathcal{O}(s^0)$$

$$\mathcal{M}_{++} = \sqrt{s}\,(\mathcal{C}^{(0)} + \mathcal{C}^{(1)}\cos\theta) + \mathcal{O}(s^0)$$

$$\mathcal{M}_{++} = \sqrt{s}\,(\mathcal{D}^{(0)} + \mathcal{D}^{(1)}\cos\theta) + \mathcal{O}(s^0)$$

Perturbative Unitarity

$ff \rightarrow W_L W'_L$ scattering



Unitarity Sum Rules $A = B = C^{(0)} = C^{(1)} = D^{(0)} = D^{(1)} = 0$

$$g_{Wff}\, g_{W'ff} = \sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} \qquad (A - B = 0)$$

$$\sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} \frac{M_W^2 - M_{W'}^2}{M_V^2} = 0 \qquad (C^{(0)} - D^{(0)} = 0)$$

PU and W'couplings

- To ensure perturbative unitarity of ff $\rightarrow$ $W_L W'_L$ scattering,

$$g^2_{W'ff} = g^2_{WW'Z} \frac{m_Z^4}{m_{Z'}^4} \left(1 - \frac{m_Z^2}{m_{Z'}^2}\right)^2 \frac{g^2_{Zff}}{g^2_{Wff}}$$

W'ff coupling

W'WZ coupling

PU and W'couplings

- To ensure perturbative unitarity of ff $\to$ $W_L W'_L$ scattering,

$$g_{W'ff}^2 = g_{WW'Z}^2 \frac{m_Z^4}{m_{Z'}^4} \left(1 - \frac{m_Z^2}{m_{Z'}^2}\right)^2 \frac{g_{Zff}^2}{g_{Wff}^2}$$

W'ff coupling W'WZ coupling

- Let us focus on

$$R = \frac{\Gamma(W' \to WZ)}{\sum_f \Gamma(W' \to ff)} \simeq \frac{1}{48} \frac{m_{W'}^4}{m_W^2 m_Z^2} \frac{g_{WW'Z}^2}{g_{W'ff}^2}$$

PU and W'couplings

- To ensure perturbative unitarity of ff $\rightarrow$ $W_L W'_L$ scattering,

$$g^2_{W'ff} = g^2_{WW'Z} \frac{m_Z^4}{m_{Z'}^4} \left(1 - \frac{m_Z^2}{m_{Z'}^2}\right)^2 \frac{g^2_{Zff}}{g^2_{Wff}}$$

W'ff coupling W'WZ coupling

- Above relation leads to

$$R = \frac{\Gamma(W' \to WZ)}{\sum_f \Gamma(W' \to ff)} \simeq \frac{1}{48} \times \underbrace{\frac{m_{W'}^4}{m_{Z'}^4}}_{\sim 1} \times \underbrace{\frac{g^2_{Wff} m_Z^2}{g^2_{Zff} m_W^2}}_{\sim 1}$$

PU and W'couplings

- We find that perturbative unitarity of ff $\rightarrow$ WW' scattering in the model with W'/Z' and neutral scalars requires.

$$\mathrm{Br}(W' \to WZ) = \frac{\Gamma(W' \to WZ)}{\Gamma(W' \to WZ) + \sum_f \Gamma(W' \to ff) + \sum_X \Gamma(W' \to X)}$$

$$\leq \frac{\Gamma(W' \to WZ)}{\Gamma(W' \to WZ) + \sum_f \Gamma(W' \to ff)} \simeq 0.02$$

- If W' is discovered in WZ decay channel in future, it implies

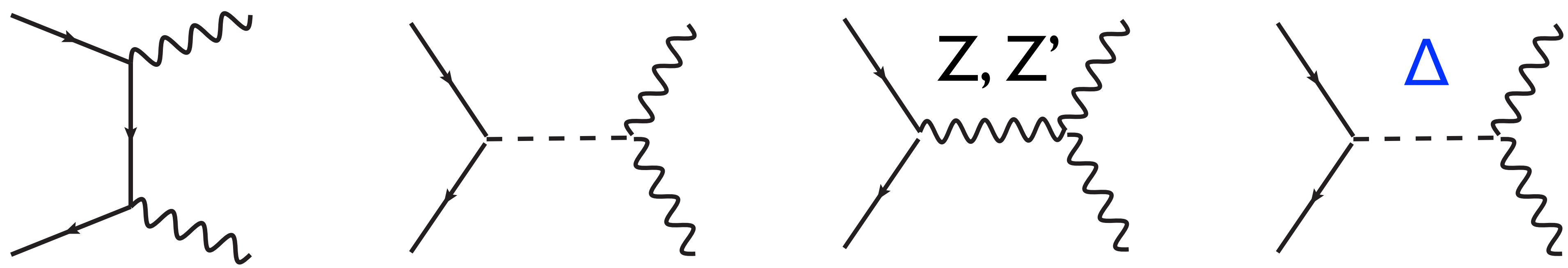
[1] The existence of other new particles

[2] Non-perturbative ff $\rightarrow$ WW' scattering

PU and W' couplings

- CP-odd scalar can make Br(W'→WZ) >> 2%.

ff → $W_L W'_L$ scattering



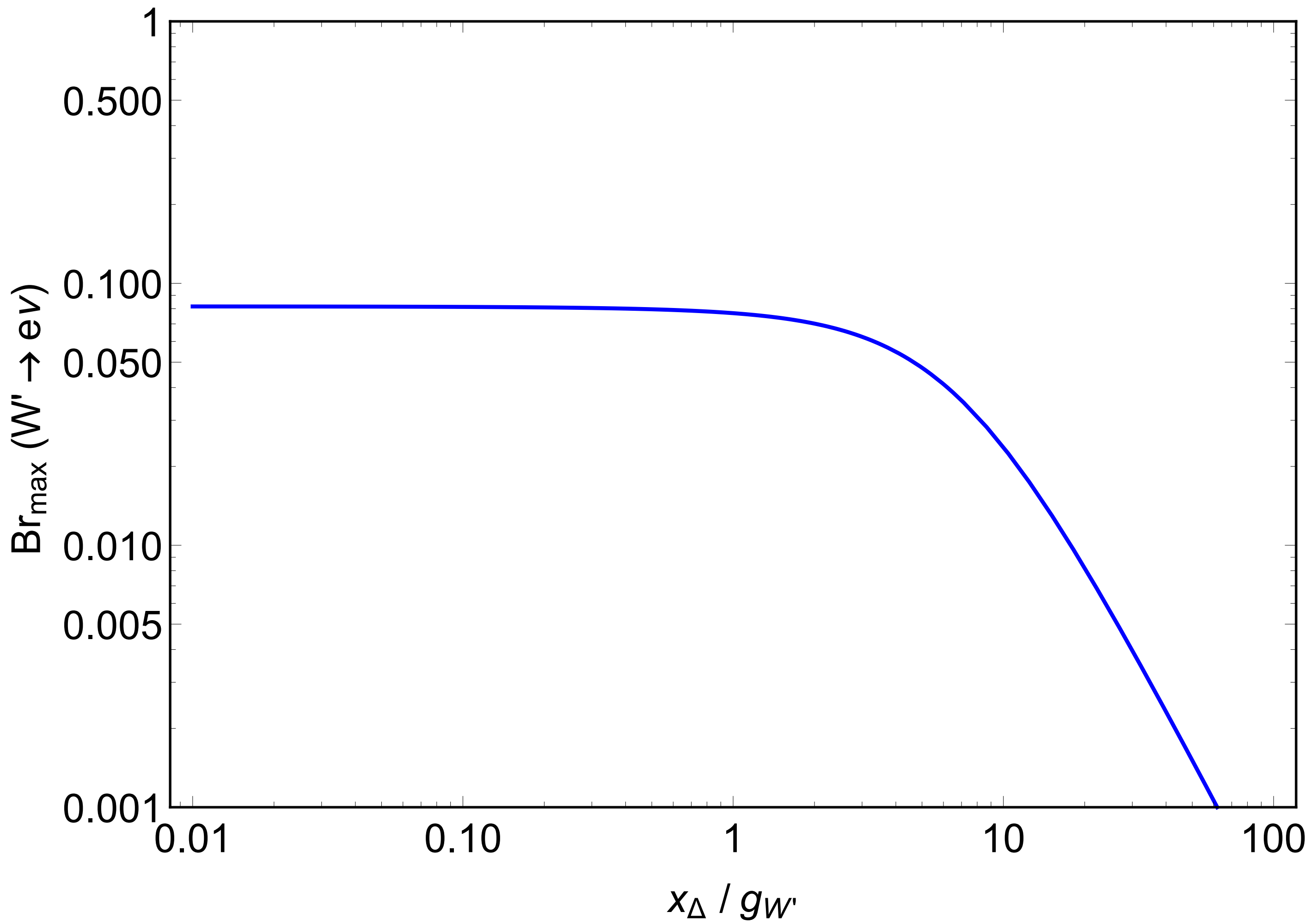
Unitarity sum rules

E²-term: $$\sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} = g_{Wff}\, g_{W'ff}$$

E-term: $$m_f \sum_{V=Z,Z'} g_{WW'V}\, g_{Vff} \frac{m_W^2 - m_{W'}^2}{m_V^2} = \frac{1}{2} \sum_{\Delta} g_{ff\Delta}\, g_{W'W\Delta}$$

PU and W'couplings

- CP-odd scalar can make Br(W'→WZ) >> 2%.



$$x_\Delta = \sum_\Delta \frac{g_{ff\Delta}}{m_f} \frac{g_{WW'\Delta}}{g_{Wff}}$$

- Concrete example: T. Abe and R. Kitano (2013)

Summary

- We discussed the property of V' by focusing the perturbative unitarity.

- We show that Br(W'→WZ) ~ 2% in the system that contains V' and CP-even scalars as well as the SM particles.

- CP-odd scalar helps to make Br(W'→WZ) >> 2%.

- The existence of the CP-odd scalar couplings is a useful guideline to construct models that predict Br(W'→WZ) >> 2%.

Back-up slides

Explicit examples

V' → Fermions

	$SU(2)_0$	$SU(2)_1$	$U(1)_2$
q_L	**1**	**2**	1/6
u_R	**1**	**1**	2/3
d_R	**1**	**1**	- 1/3
l_L	**1**	**2**	- 1/2
e_R	**1**	**1**	- 1
H_1	**2**	**2**	0
H_2	**1**	**2**	1/2

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

V' → Bosons

	$SU(2)_0$	$SU(2)_1$	$U(1)_2$
q_L	**2**	**1**	1/6
u_R	**1**	**1**	2/3
d_R	**1**	**1**	- 1/3
l_L	**2**	**1**	- 1/2
e_R	**1**	**1**	- 1
H_1	**2**	**2**	0
H_2	**1**	**2**	1/2
H_3	**2**	**1**	1/2

Abe-Kitano (2013)