Classification of Simple W' Models

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What is W' ?

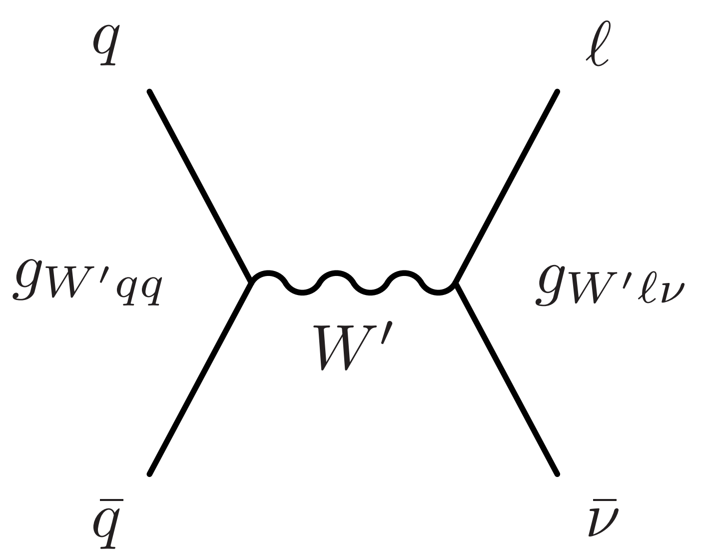
Hypothetical particle

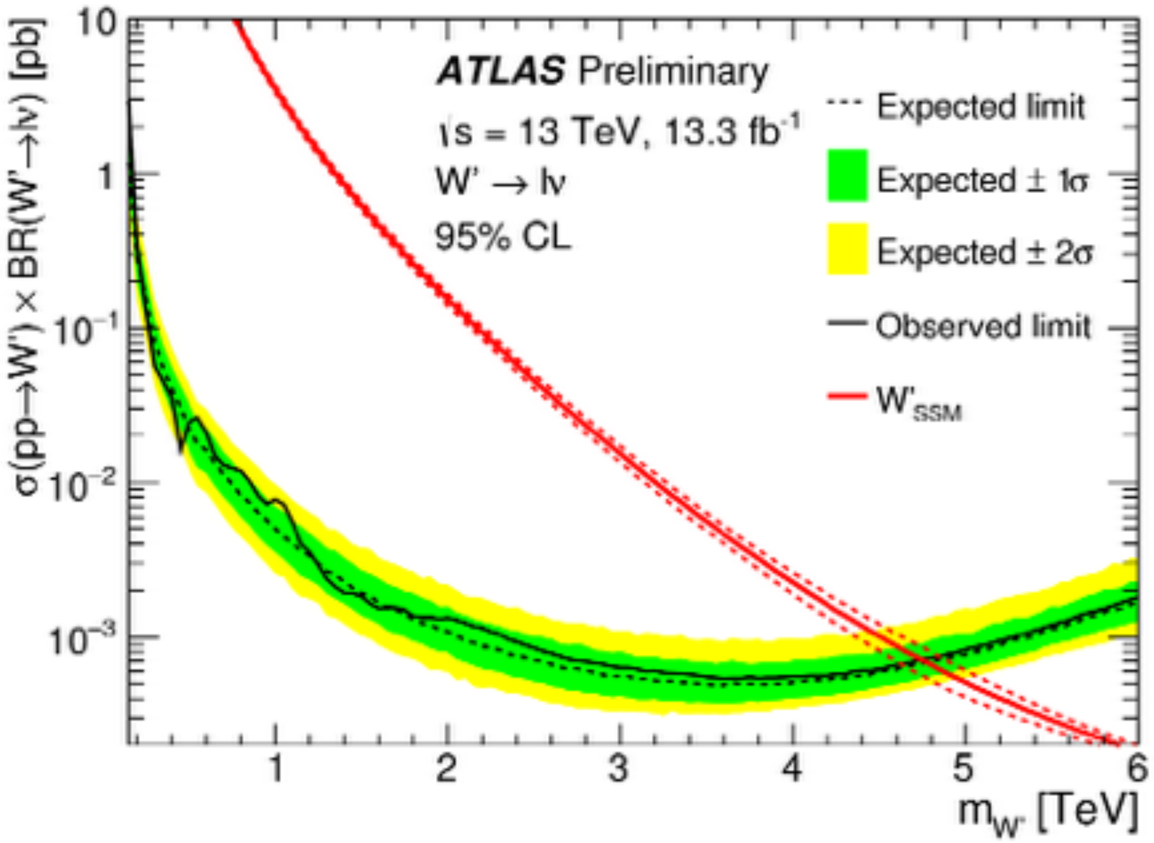
- spin 1
- heavier version of W boson

Motivated by various models beyond the standard model

- dynamical electroweak symmetry breaking
- Extra dimension models (KK gauge boson)
- Unification models (W_R, ⋯)
- ⋯

current bound W’



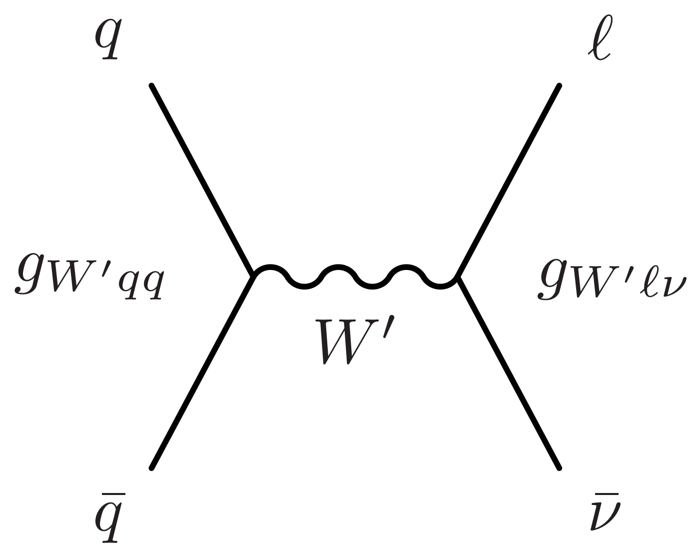


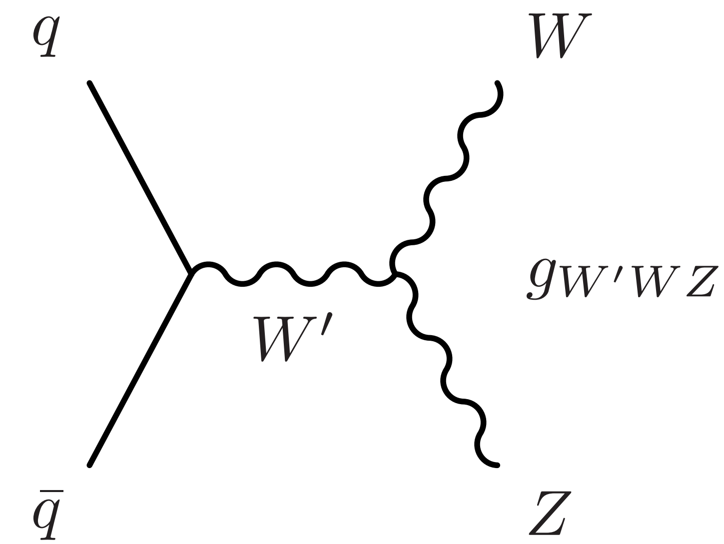
$m_{W'}$ > 4.7 TeV with **the assumiptions, $g_{W'ff} = g_{Wff}^{SM}$**

This bound depends on W’ couplings.

However, **couplings are unknown**

W' couplings are unknown parameters





Decay width are unknown

$$\Gamma(W' \to WZ) \simeq \frac{1}{192\pi}\frac{m_{W'}^5}{m_W^2 m_Z^2} g_{WW'Z}^2,$$

$$\Gamma(W' \to u_i d_j) \simeq \frac{1}{16\pi}|V_{CKM}^{ij}|^2 m_{W'} g_{W'}^2,$$

$$\Gamma(W' \to \ell\nu) \simeq \frac{1}{48\pi} m_{W'} g_{W'}^2,$$

However, the ratio could be predicted, if we know relations among couplings

$$\frac{\Gamma(W' \to WZ)}{\Gamma(W' \to \ell\nu)} \simeq \frac{m_{W'}^4}{4m_W^2 m_Z^2}\frac{g_{WW'Z}^2}{g_{W'}^2}$$

We can predict the main decay mode of W'

This work

Goal

- find the main decay mode of W′ in a model independent manner

Strategy

- perturbative unitarity
- find relations among various couplings
- compare widths $\Gamma(W' \to ff)$ and $\Gamma(W' \to WZ)$
- find the main decay mode of W′

I will discuss Two setups

(1) SM + W' + Z' + CP-even scalars

- minimal flavor violation is assumed
- arbitrary number of CP-even scalars

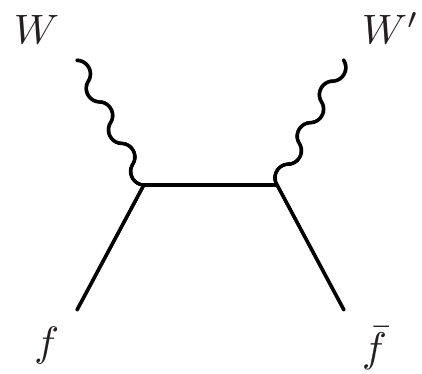
$$g^L_{\bar{u}_i d_j V^+} = V^{ij}_{CKM} g_V, \quad g^L_{\bar{\nu}_i \ell_j V^+} = \delta^{ij} g^\ell_V,$$

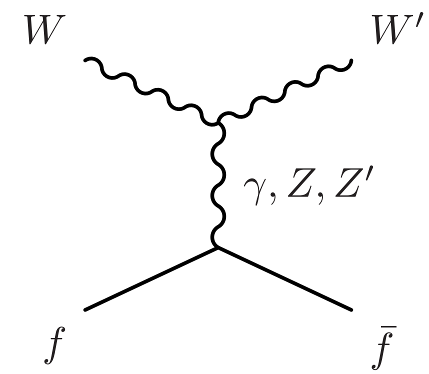
$$g^{L,R}_{\bar{u}_i u_j V^0} = \delta^{ij} g^{L,R}_{\bar{u}u V^0}, \quad g^{L,R}_{\bar{d}_i d_j V^0} = \delta^{ij} g^{L,R}_{\bar{d}d V^0}, \quad g^{L,R}_{\bar{\ell}_i \ell_j V^0} = \delta^{ij} g^{L,R}_{\bar{\ell}\ell V^0},$$

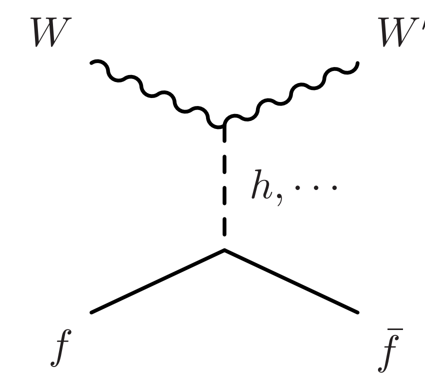
$$g_{\bar{u}_i u_j h} = \delta^{ij} g_{\bar{u}uh}, \quad g_{\bar{d}_i d_j h} = \delta^{ij} g_{\bar{d}dh}, \quad g_{\bar{\ell}_i \ell_j h} = \delta^{ij} g_{\bar{\ell}\ell h}.$$

(2) SM + W' + Z' + CP-even scalars + CP-odd scalars

two fermions → WW’







amplitude $\mathbf{M}_{\mathbf{ij}}$ at high energy limit (i, j are the twice of the helicity of f and f-bar)

$$\mathcal{M}_{-+} \simeq \frac{s}{2m_W m_{W'}} \mathcal{A} \sin\theta,$$
$$\mathcal{M}_{+-} \simeq \frac{s}{2m_W m_{W'}} \mathcal{B} \sin\theta,$$
$$\mathcal{M}_{++} \simeq \frac{\sqrt{s}}{2m_W m_{W'}} \left(\mathcal{C}^{(0)} + \mathcal{C}^{(1)} \cos\theta\right),$$
$$\mathcal{M}_{--} \simeq \frac{\sqrt{s}}{2m_W m_{W'}} \left(\mathcal{D}^{(0)} + \mathcal{D}^{(1)} \cos\theta\right),$$

where

$$\mathcal{A} = -\frac{1}{2} g_W g_{W'} + \sum_{V=Z,Z'} g_{WW'V} g^L_{\bar{u}uV},$$
$$\mathcal{B} = \sum_{V=Z,Z'} g_{WW'V} g^R_{\bar{u}uV},$$
$$\cdots$$

We impose A = 0, B = 0, $C^{(0)}$ = 0, $D^{(0)}$ = 0, $C^{(1)}$ = 0, $D^{(1)}$ = 0

two fermions → WW'

After taking linear combination, we find four independent relations

$$
\begin{aligned}
\frac{1}{2} g_W g_{W'} &= \sum_{V=Z,Z'} g_{WW'V}\, g^L_{\bar{u}uV}, \\
0 &= \sum_{V=Z,Z'} g_{WW'V}\, g^R_{\bar{u}uV}, \\
g_W g_{W'} &= 2 \sum_h g_{WW'h} \frac{g_{\bar{u}uh}}{m_u}, \\
0 &= \sum_{V=Z,Z'} \frac{m_W^2 - m_{W'}^2}{m_V^2} g_{WW'V} (g^L_{\bar{u}uV} - g^R_{\bar{u}uV})
\end{aligned}
$$

two fermions → WW’

By combining sum rules, we find

$$g_{WW'Z} \simeq -\frac{m_W m_Z}{m_{Z'}^2} g_{W'} \qquad (m_{W'} \simeq m_{Z'} \gg m_W, m_Z)$$

W’ decay width

$$\Gamma(W' \to WZ) \simeq \frac{1}{192\pi} \frac{m_{W'}^5}{m_W^2 m_Z^2} g_{WW'Z}^2,$$

$$\Gamma(W' \to u_i d_j) \simeq \frac{1}{16\pi} |V_{CKM}^{ij}|^2 m_{W'} g_{W'}^2,$$

$$\Gamma(W' \to \ell\nu) \simeq \frac{1}{48\pi} m_{W'} g_{W'}^2,$$

ratio

$$\frac{\Gamma(W' \to WZ)}{\Gamma(W' \to f_i f_j)} \simeq \frac{1}{4c_{ij}}$$

$$c_{ij} = \begin{cases} N_c |V_{CKM}^{ij}|^2 & \text{(for quarks)} \\ \delta^{ij} & \text{(for leptons)} \end{cases}$$

two fermions → WW'

We find

$$\frac{\Gamma(W' \to WZ)}{\sum_f \Gamma(W' \to f_i f_j)} \simeq \frac{1}{4 \times ((N_c + 1) \times 3)} = \frac{1}{48},$$

and thus

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

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

$$\simeq 2\%$$

$\Gamma(W' \to X)$ is the sum of the other partial decay widths of W' such as $\Gamma(W' \to Wh)$

short summary and next step

SM + W' + Z' + CP-even scalars

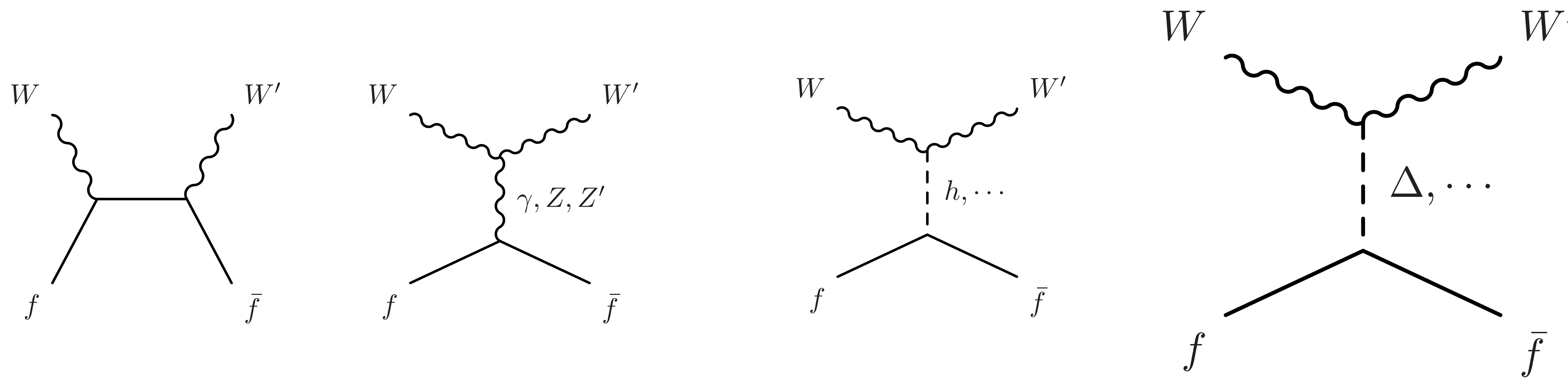
- unitarity analysis
- Br(W' → WZ) < 2%
- W' → fermions is the main decay mode
- independent of the number of CP-even scalars

If W' is discovered in future through W' → WZ,
then it implies Br(W' → WZ) >> 2%. Is it possible?

A possible way to make Br(W' → WZ) > 2%

- add other interactions and/or particles
- (or unitarity violation)

Adding CP-odd scalars Δ



coupling relations

$$\frac{1}{2} g_W g_{W'} = \sum_{V=Z,Z'} g_{WW'V}\, g^L_{\bar{u}uV},$$

$$0 = \sum_{V=Z,Z'} g_{WW'V}\, g^R_{\bar{u}uV},$$

$$g_W g_{W'} = 2 \sum_h g_{WW'h} \frac{g_{\bar{u}uh}}{m_u}$$

$$\sum_{\Delta^0} \frac{g_{\bar{u}u\Delta^0}}{m_u} g_{WW'\Delta} = \sum_{V=Z,Z'} 2 g_{WW'V} \frac{m_W^2 - m_{W'}^2}{m_V^2} (g^L_{\bar{u}uV} - g^R_{\bar{u}uV})$$

Adding CP-odd scalars Δ

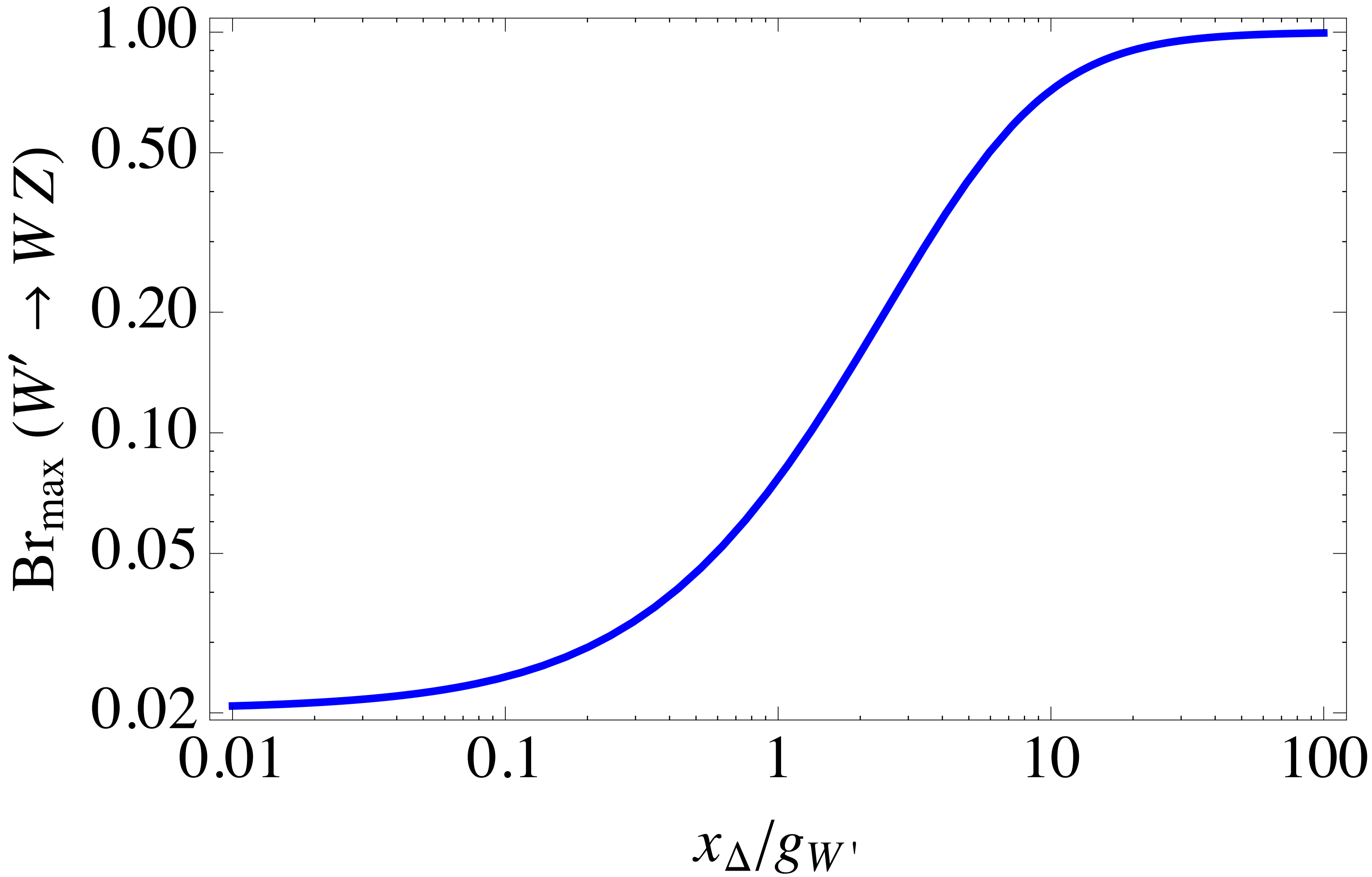
$$g_{WW'Z} \simeq -\frac{m_W m_Z}{m_{Z'}^2}\left(g_{W'} + x_\Delta\right)$$

$$x_\Delta = \sum_\Delta \frac{g_{\bar{u}u\Delta}}{m_u}\frac{g_{WW'\Delta}}{g_W}.$$

We can estimate the branching ratio

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

Br(W'→WZ)>2% thanks to CP-odd scalars



$$x_\Delta = \sum_\Delta \frac{g_{\bar{u}u\Delta}}{m_u} \frac{g_{WW'\Delta}}{g_W}.$$

Summary

W' is a popular particle in physics beyond the standard model

- dynamical electroweak symmetry breaking
- Extra dimension models (KK gauge boson)
- Unification models (W_R, $\cdots$)

We have studied W' in a model independent manner

⋆ perturbative unitarity

⋆ coupling relations

Setup 1: SM + W' + Z' + CP-even scalars

⋆ Br(W' $\rightarrow$ WZ) < 2%

Setup 2: SM + W' + Z' + CP-even scalars + CP-odd scalars

⋆ Br(W' $\rightarrow$ WZ) can be >> 2%