LHC constraints on W' mass: a theoretical point of view

Stefano Morisi

Based on *Top-flavor scheme in the context of W' searches at LHC*, **Phys. Rev.D** 104 -2021
& Calabrese's master thesis

In collaboration with

Miele *(head of Napoli AstroParticle Theory Group)*
Iorio *(CMS member)*
De Iorio *(CMS member)*
Calabrese *(PhD student)*
Fiorillo *(Former PhD student)*

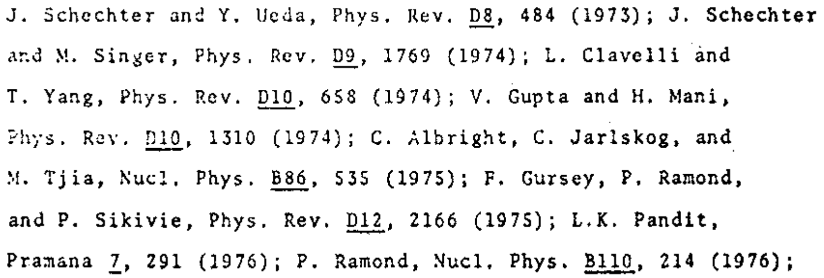
Extra charged gauge bosons $W'^{\pm}$ are predicted in many extensions of the standard model like,

$SU_L(2) \times SU_R(2)$

Pati-Salam PRD10 (1975)
Mohapatra, Senjanovic PRL44 (1980)
………..

$SU_L(3) \supset SU_L(2)$

Addazzi,Ricciardi,Scarlatella,Srivastava,Valle(2022)
Buras et al JHEP(2014)
Long PRD (1996)
Singer,Valle,Schechter PRD(1980)



J. Schechter and Y. Ueda, Phys. Rev. D8, 484 (1973); J. Schechter and M. Singer, Phys. Rev. D9, 1769 (1974); L. Clavelli and T. Yang, Phys. Rev. D10, 658 (1974); V. Gupta and H. Mani, Phys. Rev. D10, 1310 (1974); C. Albright, C. Jarlskog, and M. Tjia, Nucl. Phys. B86, 535 (1975); F. Gursey, P. Ramond, and P. Sikivie, Phys. Rev. D12, 2166 (1975); L.K. Pandit, Pramana 7, 291 (1976); P. Ramond, Nucl. Phys. B110, 214 (1976);

Extra-dimensions

Appelquist,Cheng,Dobrescu, PRD64(2001)
Cheng, Hill, Pokorski, Wang, PRD64(2001)
Burdman, Dobrescu,Ponton, PRD74(2006)

Grand unified theories…

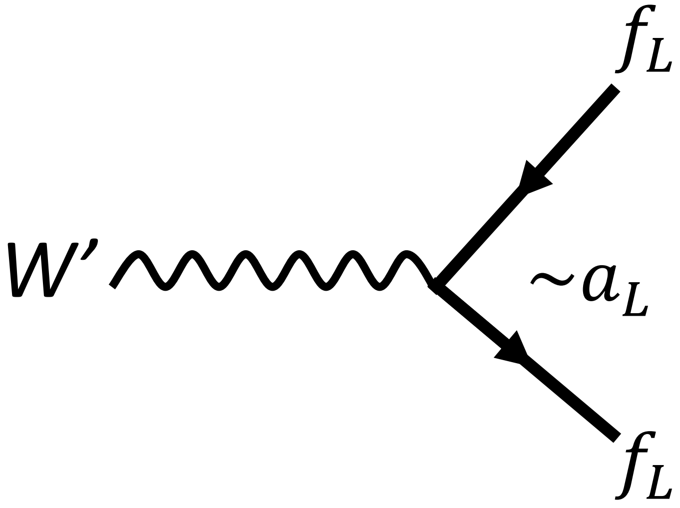
Modelling W’ coupling

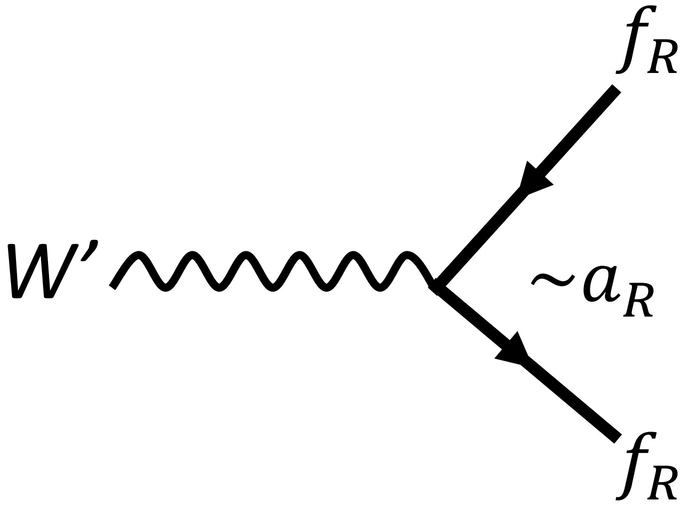
$g_w = e/\sin\theta_W$

$$\mathcal{L}^{\text{eff}} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu [\alpha_R^{f_i f_j}(1+\gamma^5) + \alpha_L^{f_i f_j}(1-\gamma^5)] W'^\mu f_j + \text{H.c.}$$

In general 18 free parameters !

flavor blind → $\alpha_R^{f_i f_j} = a_R \delta_{ij}$ $\alpha_L^{f_i f_j} = a_L \delta_{ij}$ → typically only 2 free parameters





Two benchmark cases @ LHC

W'_L : $a_L = 1; a_R = 0$

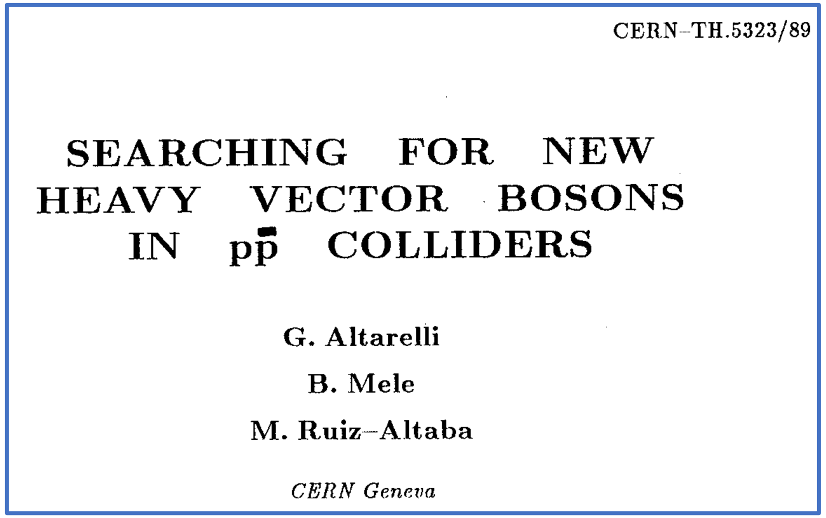
W'_R : $a_L = 0; a_R = 1$

(The sequential standard model)

W'_R : $a_L = 0; a_R = 1$ → particular case of left-right

$SU_L(2)\times SU_R(2)$

W'_L : $a_L = 1; a_R = 0$ →



CERN–TH.5323/89

SEARCHING FOR NEW HEAVY VECTOR BOSONS IN p$\bar{p}$ COLLIDERS

G. Altarelli

B. Mele

M. Ruiz–Altaba

CERN Geneva

Discovery W boson

UA1 Collaboration 83’

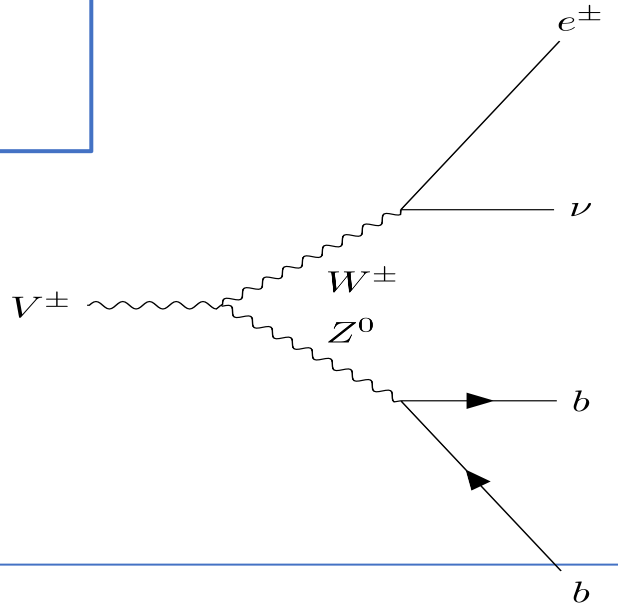
$W^{\pm} \longrightarrow e^{\pm}\nu$

$W'^{\pm} \longrightarrow e^{\pm}\nu$

$W'^{\pm} \longrightarrow e^{\pm}\nu jj$

from

$W'^{\pm} \longrightarrow W^{\pm}Z$



The sequential model (as proposed by Altarelli et al.)
can not derive from any extended gauge model

The paper aim was
mostly explorative

While the couplings to fermions are the same of Standard Model

$W'^{\pm} \rightarrow W^{\pm}Z$ *is suppressed if* W' *and* W *arise from different gauge groups*

i.e. $W \in SU(2)\ X\ U(1)$, $W' \in SU'(2)$

$W'^{\pm} \rightarrow W^{\pm}Z$ comes from mixing after symmetry breaking $O(\frac{M_W^2}{M_{W'}^2})$

ATLAS & CMS

$W' \rightarrow tb$ $\qquad$ $W' \rightarrow \ell v$ $\qquad$ $W' \rightarrow WZ$

W' detection: @LHC the most promising channel is $W' \to tb$ (single top)

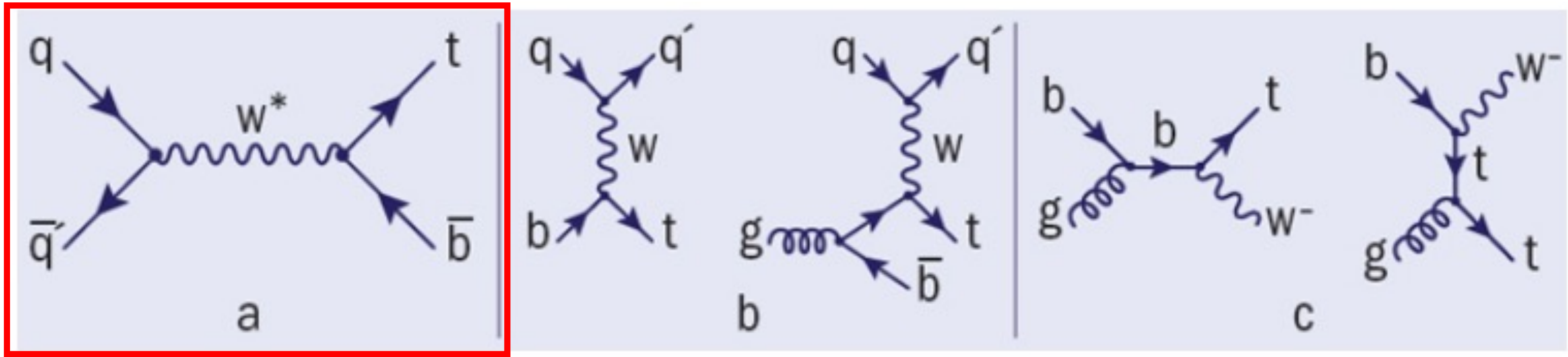
- *small QCD background comparing to light-jets*
- *less model dependent:*

$$W'_{L,R} \to \ell\, \upsilon_{L,R}$$

Kinematically suppressed if

$$M_{\upsilon R} > M_{WR}$$

Standard Model single top production

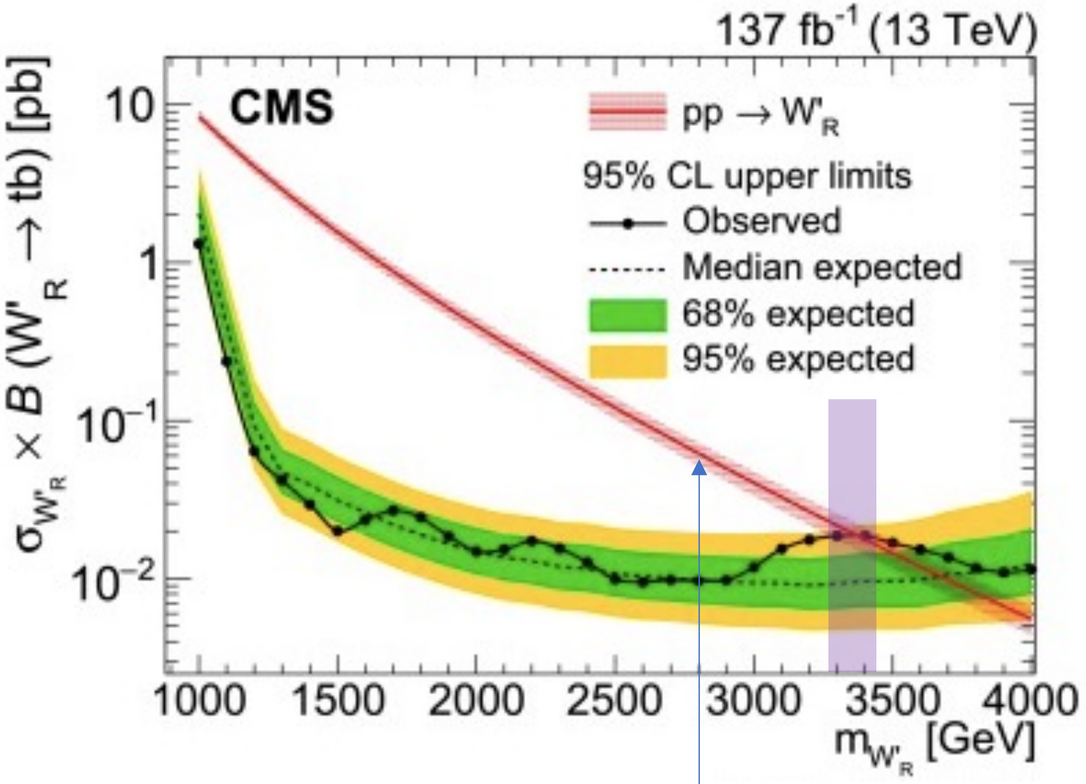


Three different production channels for single top quarks can be distinguished: the s-channel (a), the t-channel (b) and the W-associated channel (c)

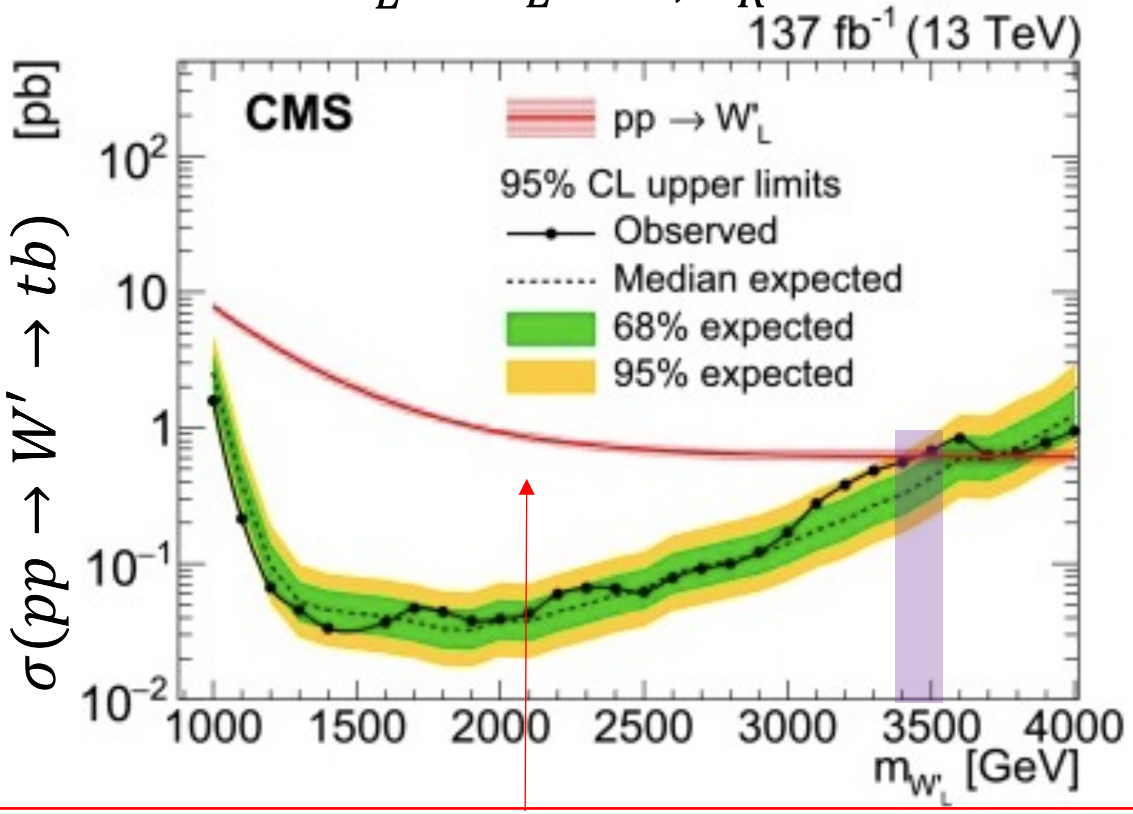
Dominant for $M_W \ll M_{W'}$

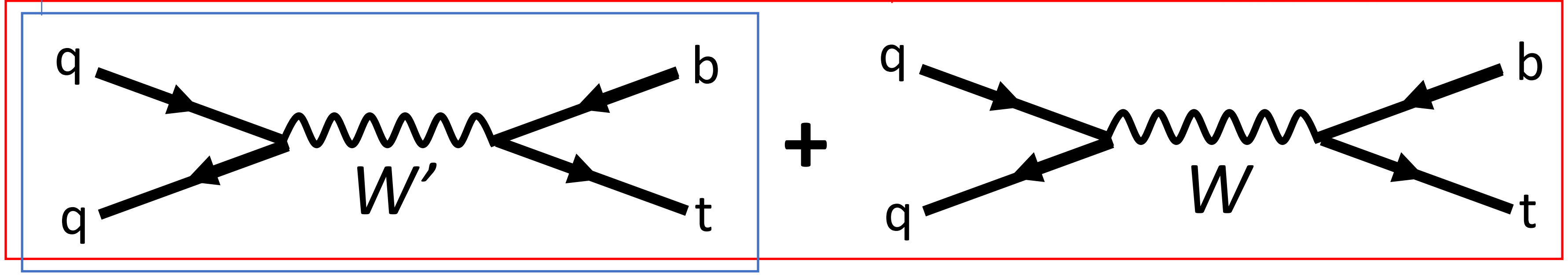
Remarks on experimental searches

$W'_R: \quad a_L = 0; a_R = 1$



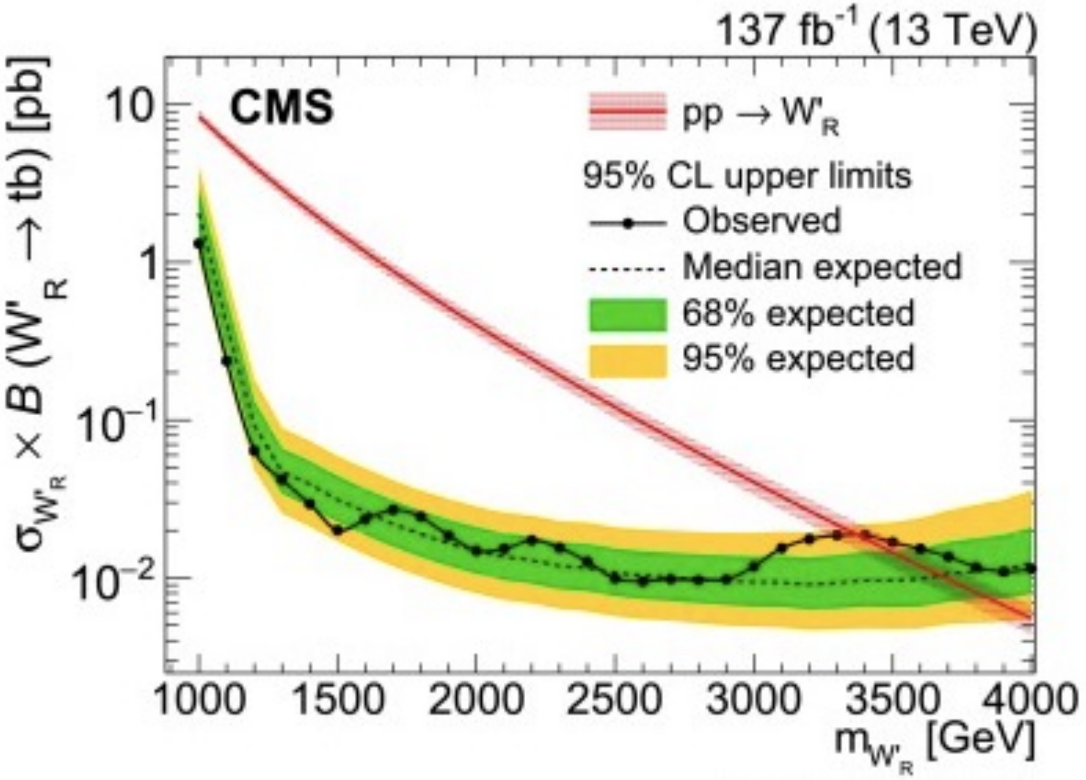
$W'_L: \quad a_L = 1; a_R = 0$

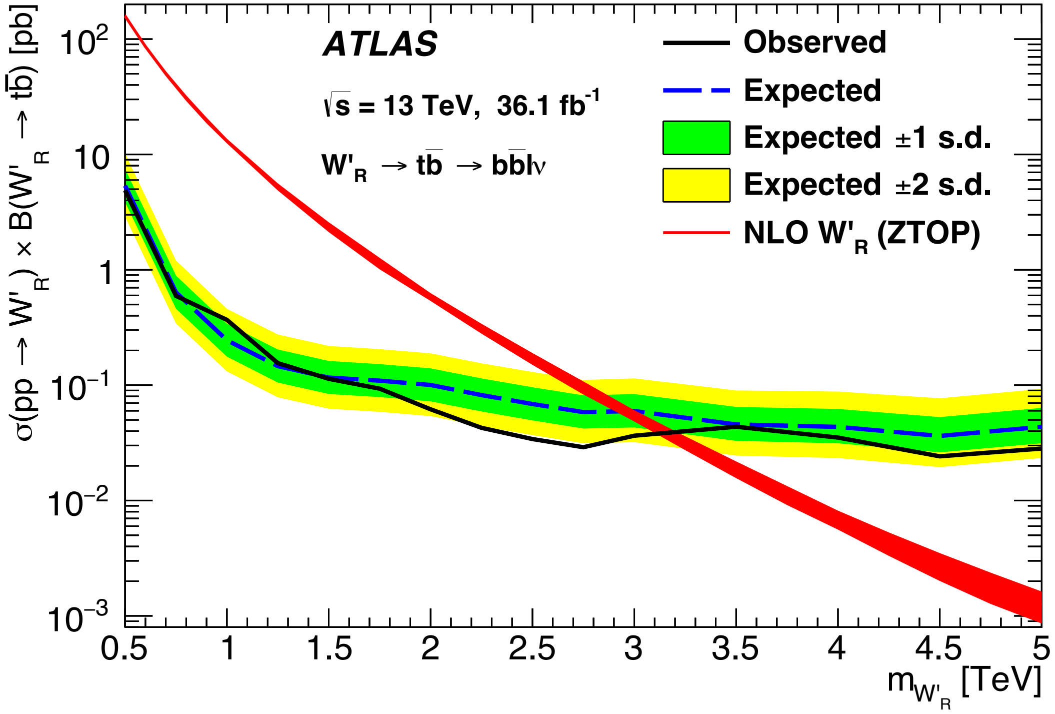




Boos,Bunichev,Dudko,Perfilov, PLB655(2007)
Interference between W’ and W in single-top quark production processes,

CMS vs ATLAS





Is this the end of the story?

What if we consider a flavor unblind bechmark case?

top-flavor model: an unblind example

$$SU(3)_C \times SU(2)_1 \times SU(2)_2 \times SU(2)_3 \times U(1)_Y$$

Li, Ma PRL 47 (81)

$$SU(3)_C \times SU(2)_{12} \times SU(2)_3 \times U(1)_Y$$ →

Li, Ma JPG 19 (1993)
Muller, Nandi PLB 383 (96)
Muller, Nandi PLBPS52 (97)

	$SU(2)_{12}$	$SU(2)_3$	$U(1)_Y$
L^3	1	2	$-1/2$
$L^{1,2}$	2	1	$-1/2$
Q^3	1	2	$1/6$
$Q^{1,2}$	2	1	$1/6$
$u_R^{1,2,3}$	1	1	$2/3$
$d_R^{1,2,3}$	1	1	$-1/3$
$\ell_R^{1,2,3}$	1	1	-1
Σ	2	2	0
Φ	1	2	$1/2$

$$\langle\Sigma\rangle = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} \qquad SU(2)_{12} \times SU(2)_3 \xrightarrow{\Sigma} SU(2)_L$$

$$\langle\Phi\rangle = \begin{pmatrix} 0 \\ v \end{pmatrix} \qquad SU(2)_L \times U(1)_Y \xrightarrow{\Phi} U(1)_{\rm EM}$$

Yukawa interactions

$$\overline{L^3}\ell_R^i\Phi$$

$$\frac{1}{\Lambda}\overline{L^{1,2}}\ell_R^i\Phi\Sigma$$

$SU(2)_{12} \times SU(2)_3 \times U(1)_Y$

g_{12}	g_3	g_0
$W_{12}^{\pm}, W_{12}^{0}$	$W_3^{\pm}, W_3^{0}$	B

$$\mathcal{L}^{\rm eff} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu [\alpha_R^{f_i f_j}(1+\gamma^5) + \alpha_L^{f_i f_j}(1-\gamma^5)] W'^{\mu} f_j + \text{H.c.}$$

$$\alpha_L^{f_i f_j} \propto g_{12} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} + g_3 \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \alpha_R^{f_i f_j} = 0$$

Flavor dependent: lepton universality broken

$$i\bar{L}_L^j \gamma_\mu \left(\partial^\mu + i\frac{g_{12}}{2}\sigma^i W_{12}^{i\mu} - i\frac{g_0}{2}B^\mu\right) L_L^j + i\bar{Q}_L^j \gamma_\mu \left(\partial^\mu + i\frac{g_{12}}{2}\sigma^i W_{12}^{i\mu} + i\frac{g_0}{6}B^\mu\right) Q_L^j \quad j=1,2$$

$$+ i\bar{L}_L^3 \gamma_\mu \left(\partial^\mu + i\frac{g_3}{2}\sigma^i W_3^{i\mu} - i\frac{g_0}{2}B^\mu\right) L_L^3 + i\bar{Q}_L^3 \gamma_\mu \left(\partial^\mu + i\frac{g_3}{2}\sigma^i W_3^{i\mu} + \frac{g_0}{6}B^\mu\right) Q_L^3 +$$

$SU(2)_{12} \times SU(2)_3 \times U(1)_Y$

g_{12}	g_3	g_0
$W_{12}^{\pm}, W_{12}^0$	$W_3^{\pm}, W_3^0$	B

+

u	v

$u \gg v$

$$\mathcal{M}_2 = \begin{array}{c} \begin{array}{ccc} B & W_{12}^0 & W_3^0 \end{array} \\ \begin{pmatrix} \frac{g_0^2 v^2}{4} & -\frac{g_{12} g_0 v^2}{4} & 0 \\ -\frac{g_{12} g_0 v^2}{4} & \frac{g_{12}^2 (v^2+u^2)}{4} & -\frac{g_{12} g_3 u^2}{4} \\ 0 & -\frac{g_{12} g_3 u^2}{4} & \frac{g_3^2 u^2}{4} \end{pmatrix} \end{array}$$

$\theta \sim \theta_W$

$\phi \sim \theta'$

γ, Z, Z'

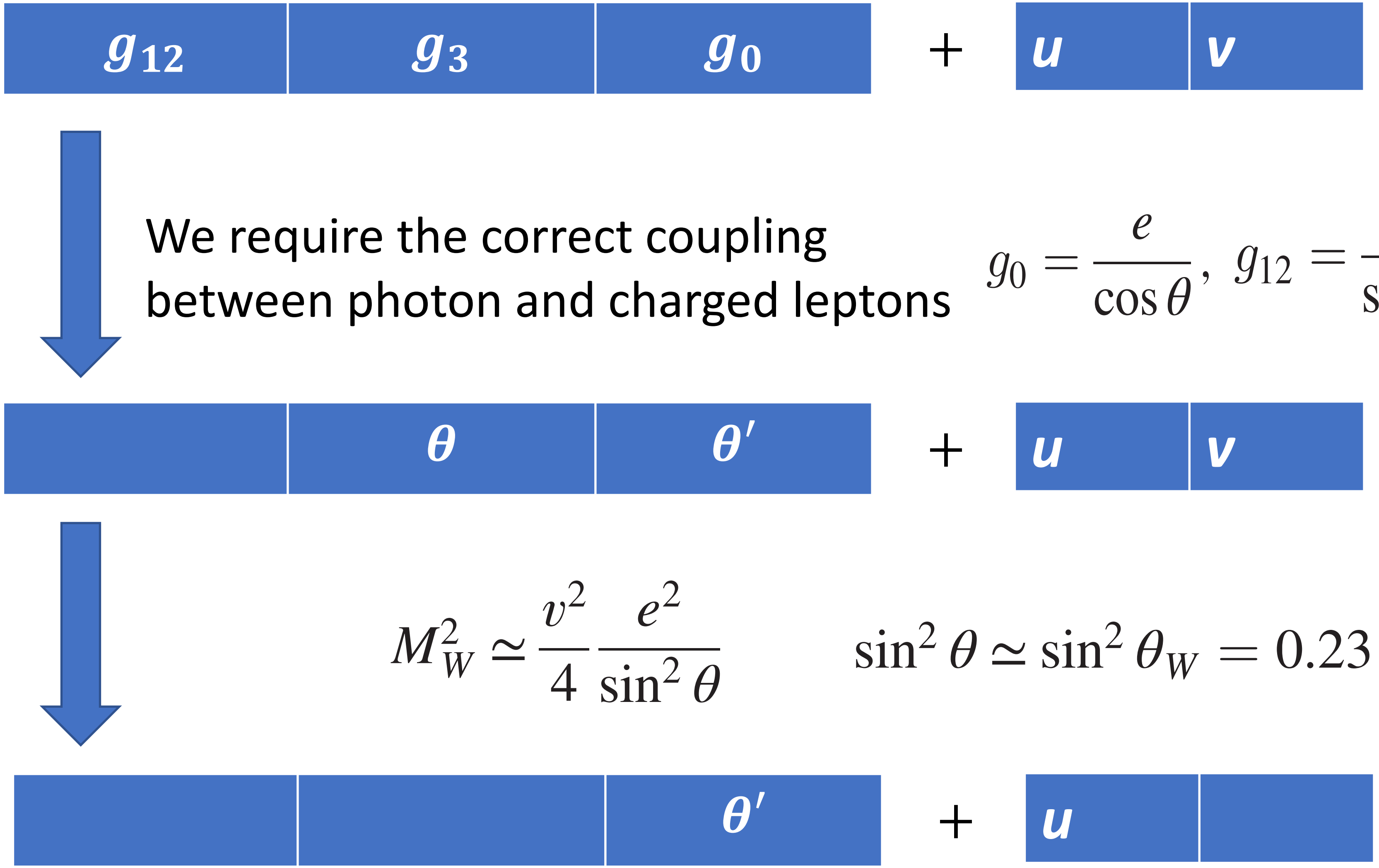
$$\mathcal{M}_1 = \begin{array}{c} \begin{array}{cc} W_{12}^{\pm} & W_3^{\pm} \end{array} \\ \begin{pmatrix} \frac{g_{12}^2 (u^2+v^2)}{4} & -\frac{g_{12} g_3 u^2}{4} \\ -\frac{g_{12} g_3 u^2}{4} & \frac{g_3^2 u^2}{4} \end{pmatrix} \end{array}$$

θ'

W, W'

Note that we restore SM when $g_{12} = g_3 \rightarrow \theta' = \pi/4$

$SU(2)_{12} \times SU(2)_3 \times U(1)_Y$



g_{12}	g_3	g_0	+	u	v

$$u \gg v$$

We require the correct coupling between photon and charged leptons

$$g_0 = \frac{e}{\cos\theta},\ g_{12} = \frac{e}{\sin\theta\cos\theta'},\ g_3 = \frac{e}{\sin\theta\sin\theta'}$$

	θ	θ'	+	u	v

$$M_W^2 \simeq \frac{v^2}{4}\frac{e^2}{\sin^2\theta}$$

$$\sin^2\theta \simeq \sin^2\theta_W = 0.23$$

$$v \simeq v_{\mathrm{SM}} \simeq 246\ \mathrm{GeV}$$

		θ'	+	u	

Remaining free parameters

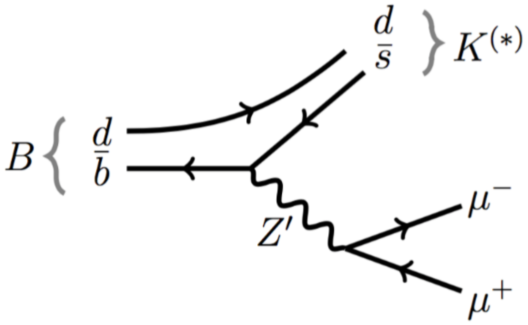
lepton universality is broken

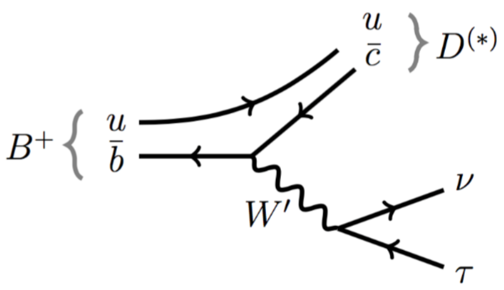
He, Valencia: B decays with tau leptons in nonuniversal left-right models,'' PRD87 (2013)

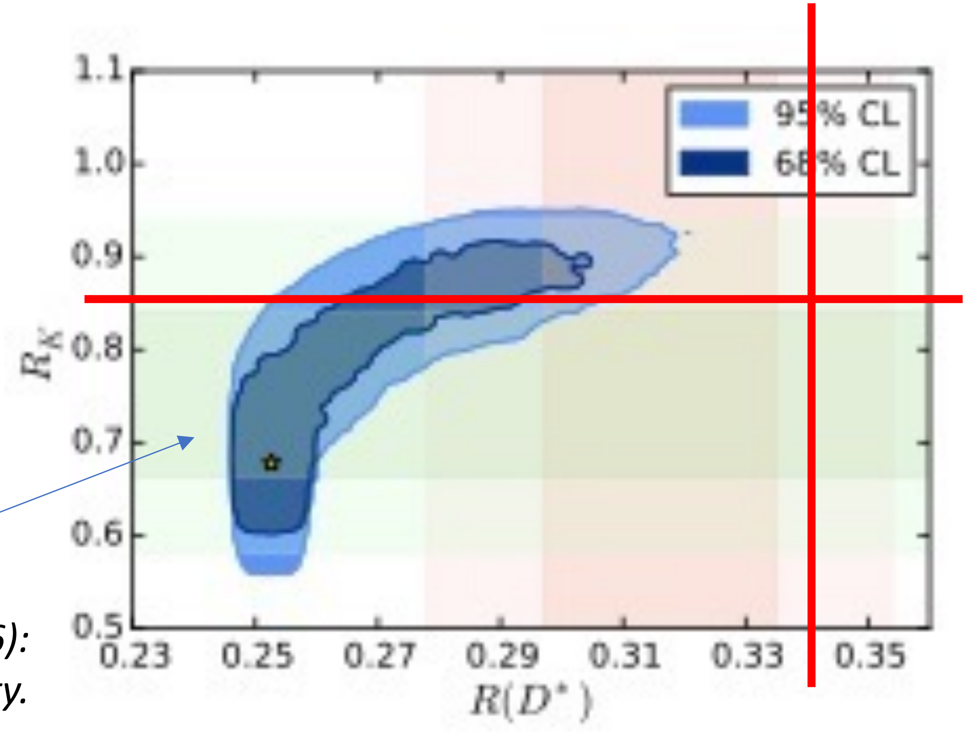
$$g_{SM}\,(\overline{e}_L\,\nu_{eL}+\overline{\mu}_L\,\nu_{\mu L}+\overline{\tau}_L\,\nu_{\tau L})\,W$$

$$g_{SM}\ \tan\theta'\,(\overline{e}_L\,\nu_{eL}+\overline{\mu}_L\,\nu_{\mu L})\,W'+g_{SM}\ \cot\theta'\,\overline{\tau}_L\,\nu_{\tau L}\,W'$$

W’ couplings is flavor dependend







Boucenna, Celis,Fuentes-Martin, Vicente, Virto, JHEP12(2016): Phenomenology of an SU(2)XSU(2)XU(1) model with lepton-flavour non-universality.

Branching ratio: some remarks

Note that $\theta' = \pi/4 \rightarrow V'_{CKM} = V_{CKM}$

$$V'_{\rm CKM} = V_{\rm CKM} \cdot G + \cot^2\theta' \; V_{\rm CKM} \cdot R$$

$$R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad G = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\Gamma(W' \rightarrow tq) = \frac{h'^2_{I,II}}{16\pi} |V'_{tq}|^2 \frac{\beta^2}{M_{W'}} \left(M^2_{W'} + \frac{m^2_t}{2} \right),$$

$$\Gamma(W' \rightarrow qq') = \frac{h'^2_{I,II}}{16\pi} |V'_{qq'}|^2 M_{W'},$$

$$\Gamma(W' \rightarrow e\nu_e) = \frac{h'^2_{I,II}}{16\pi} \frac{M_{W'}}{3},$$

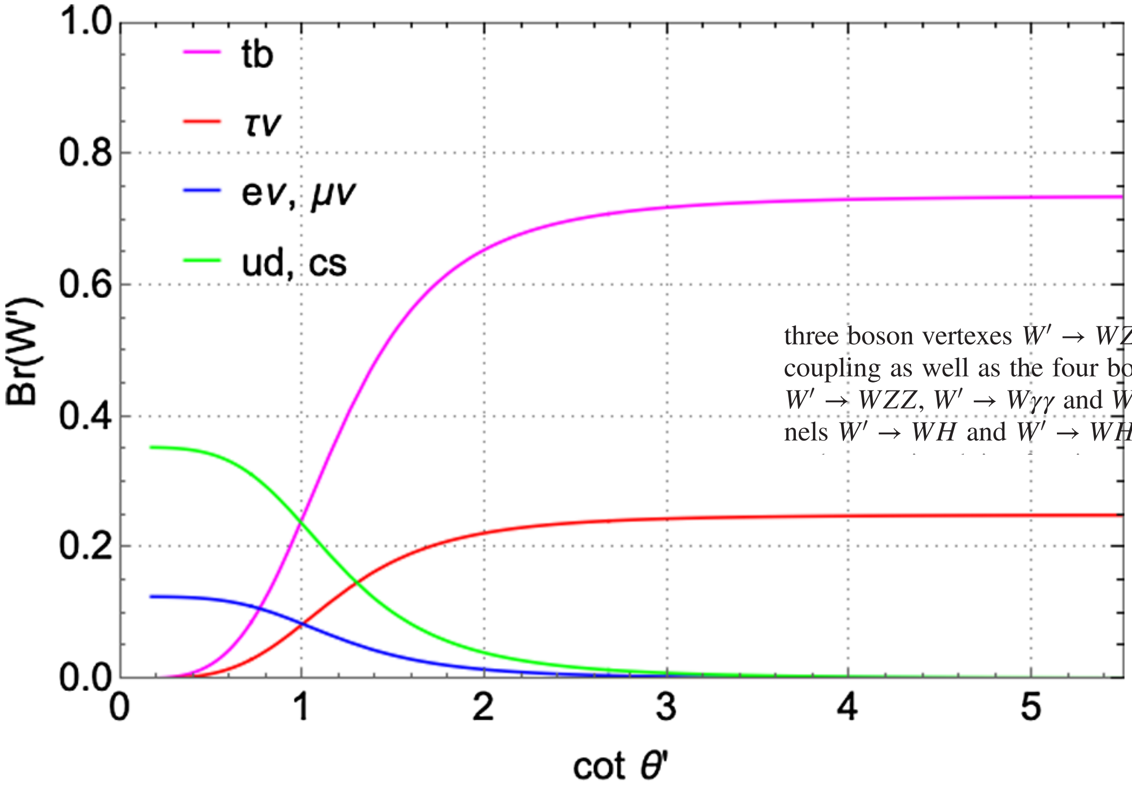
$$\Gamma(W' \rightarrow \mu\nu_\mu) = \Gamma(W' \rightarrow e\nu_e),$$

$$\Gamma(W' \rightarrow \tau\nu_\tau) = \frac{h'^2_{III}}{16\pi} \frac{M_{W'}}{3},$$

$$h_{I,II} = g_{12} \cos\theta', \; h_{III} = g_3 \sin\theta',$$

$$\beta^2 = 1 - \frac{m_t^2}{M_{W'}^2}$$

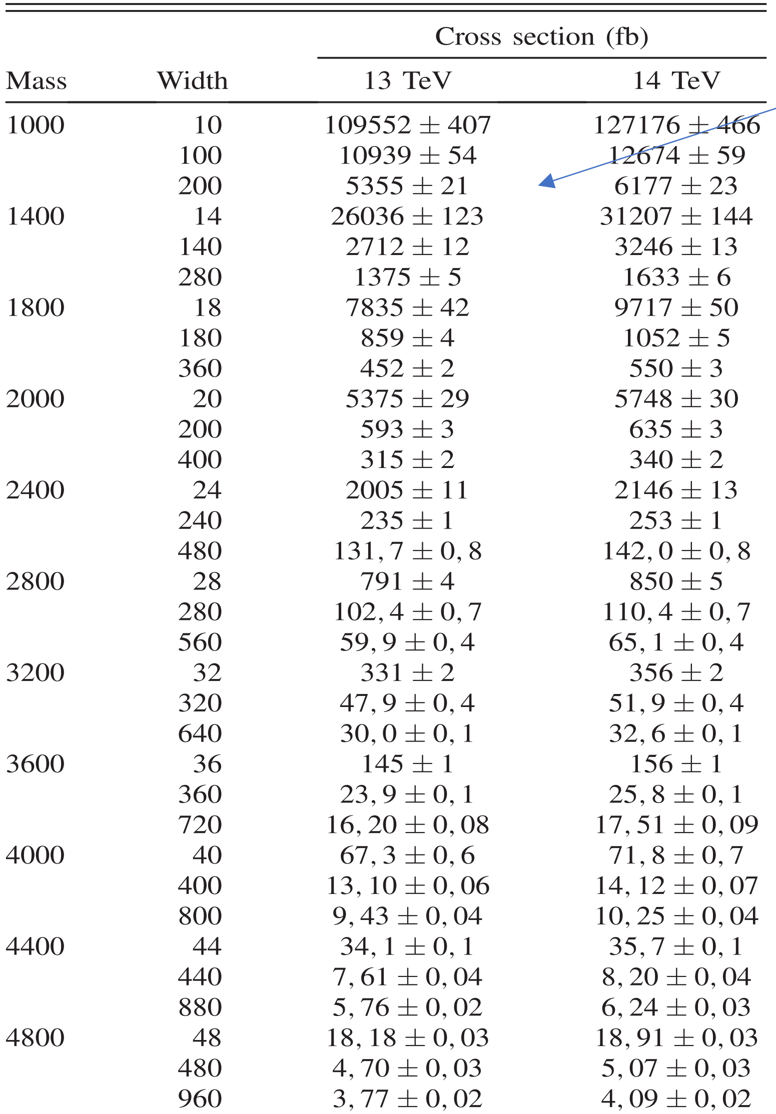
$$h'_{I,II} = g_{12} \sin\theta' \quad h'_{III} = g_3 \cos\theta'$$



three boson vertexes $W' \rightarrow WZ$ and $W' \rightarrow W\gamma$ have a null coupling as well as the four boson vertexes $W' \rightarrow WWW$, $W' \rightarrow WZZ$, $W' \rightarrow W\gamma\gamma$ and $W' \rightarrow WZ\gamma$. The decay channels $W' \rightarrow WH$ and $W' \rightarrow WHH$ are negligible compared

See also Kim and Lee, Direct search for heavy gauge bosons at the LHC in the nonuniversal SU(2) model,' PRD90 (2014)

W’ cross section @ LHC



Mass	Width	Cross section (fb)	
		13 TeV	14 TeV
1000	10	109552 ± 407	127176 ± 466
	100	10939 ± 54	12674 ± 59
	200	5355 ± 21	6177 ± 23
1400	14	26036 ± 123	31207 ± 144
	140	2712 ± 12	3246 ± 13
	280	1375 ± 5	1633 ± 6
1800	18	7835 ± 42	9717 ± 50
	180	859 ± 4	1052 ± 5
	360	452 ± 2	550 ± 3
2000	20	5375 ± 29	5748 ± 30
	200	593 ± 3	635 ± 3
	400	315 ± 2	340 ± 2
2400	24	2005 ± 11	2146 ± 13
	240	235 ± 1	253 ± 1
	480	$131,7 \pm 0,8$	$142,0 \pm 0,8$
2800	28	791 ± 4	850 ± 5
	280	$102,4 \pm 0,7$	$110,4 \pm 0,7$
	560	$59,9 \pm 0,4$	$65,1 \pm 0,4$
3200	32	331 ± 2	356 ± 2
	320	$47,9 \pm 0,4$	$51,9 \pm 0,4$
	640	$30,0 \pm 0,1$	$32,6 \pm 0,1$
3600	36	145 ± 1	156 ± 1
	360	$23,9 \pm 0,1$	$25,8 \pm 0,1$
	720	$16,20 \pm 0,08$	$17,51 \pm 0,09$
4000	40	$67,3 \pm 0,6$	$71,8 \pm 0,7$
	400	$13,10 \pm 0,06$	$14,12 \pm 0,07$
	800	$9,43 \pm 0,04$	$10,25 \pm 0,04$
4400	44	$34,1 \pm 0,1$	$35,7 \pm 0,1$
	440	$7,61 \pm 0,04$	$8,20 \pm 0,04$
	880	$5,76 \pm 0,02$	$6,24 \pm 0,03$
4800	48	$18,18 \pm 0,03$	$18,91 \pm 0,03$
	480	$4,70 \pm 0,03$	$5,07 \pm 0,03$
	960	$3,77 \pm 0,02$	$4,09 \pm 0,02$

$\sigma_{SSM}(pp \to W')$ for Sequential Standard Model from $MadGraph5_{MC}@NLO\ tool$

$$\sigma_{TF}(pp \to W') \approx \sigma_{SSM}(pp \to W') \times \tan^2\theta'$$

$$\begin{array}{cc} & \begin{array}{cc} W_{12}^{\pm} & W_3^{\pm} \end{array} \\ \mathcal{M}_1 = & \begin{pmatrix} \frac{g_{12}^2(u^2+v^2)}{4} & -\frac{g_{12}g_3u^2}{4} \\ -\frac{g_{12}g_3u^2}{4} & \frac{g_3^2u^2}{4} \end{pmatrix} \end{array}$$

θ'

W' width

1%, 10%, 20%

Mass	Width	Cross section (fb) 13 TeV	14 TeV
1000	10	109552 ± 407	127176 ± 466
	100	10939 ± 54	12674 ± 59
	200	5355 ± 21	6177 ± 23
1400	14	26036 ± 123	31207 ± 144
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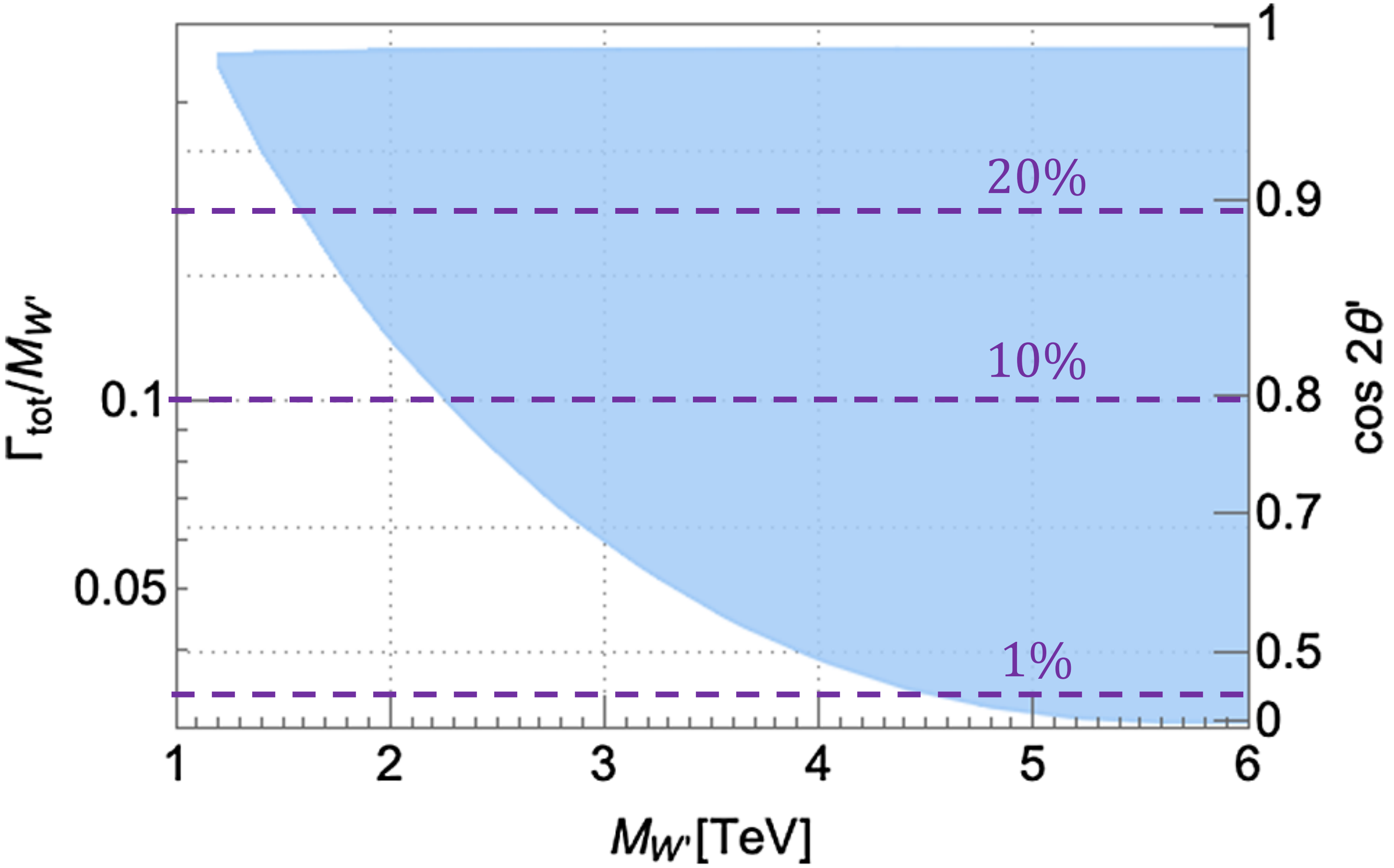
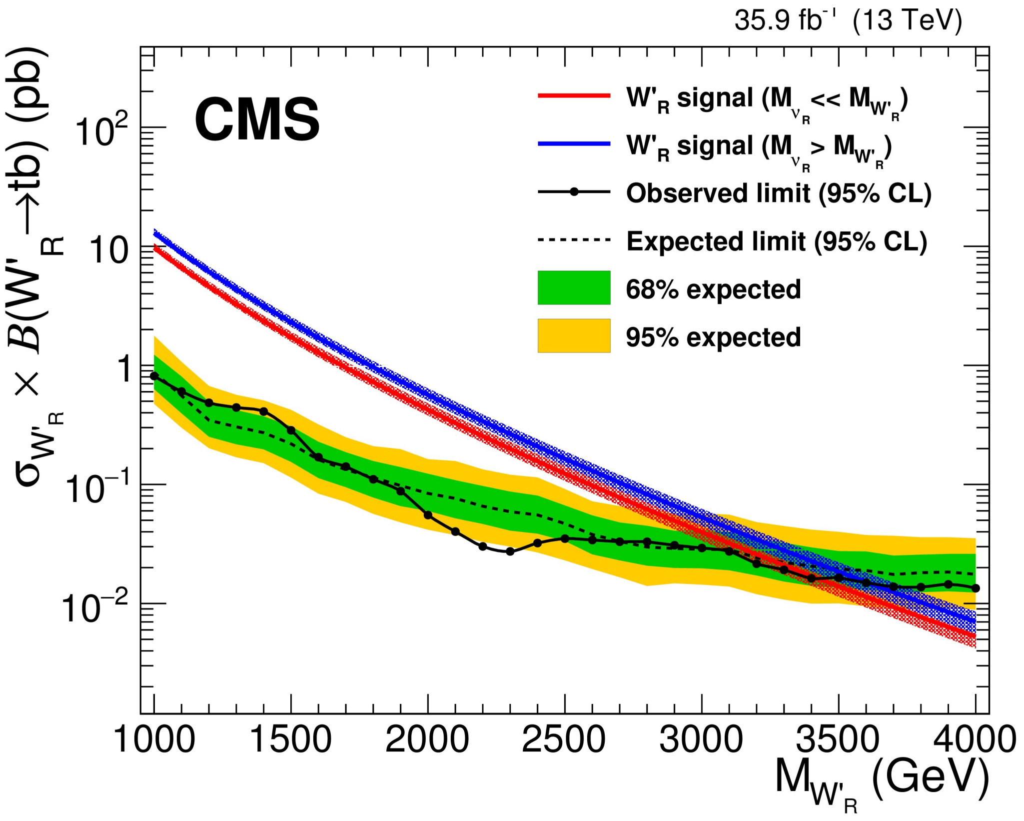
	200	593 ± 3	635 ± 3
	400	315 ± 2	340 ± 2
2400	24	2005 ± 11	2146 ± 13
	240	235 ± 1	253 ± 1
	480	131, 7 ± 0, 8	142, 0 ± 0, 8
2800	28	791 ± 4	850 ± 5
	280	102, 4 ± 0, 7	110, 4 ± 0, 7
	560	59, 9 ± 0, 4	65, 1 ± 0, 4
3200	32	331 ± 2	356 ± 2
	320	47, 9 ± 0, 4	51, 9 ± 0, 4
	640	30, 0 ± 0, 1	32, 6 ± 0, 1
3600	36	145 ± 1	156 ± 1
	360	23, 9 ± 0, 1	25, 8 ± 0, 1
	720	16, 20 ± 0, 08	17, 51 ± 0, 09
4000	40	67, 3 ± 0, 6	71, 8 ± 0, 7
	400	13, 10 ± 0, 06	14, 12 ± 0, 07
	800	9, 43 ± 0, 04	10, 25 ± 0, 04
4400	44	34, 1 ± 0, 1	35, 7 ± 0, 1
	440	7, 61 ± 0, 04	8, 20 ± 0, 04
	880	5, 76 ± 0, 02	6, 24 ± 0, 03
4800	48	18, 18 ± 0, 03	18, 91 ± 0, 03
	480	4, 70 ± 0, 03	5, 07 ± 0, 03
	960	3, 77 ± 0, 02	4, 09 ± 0, 02

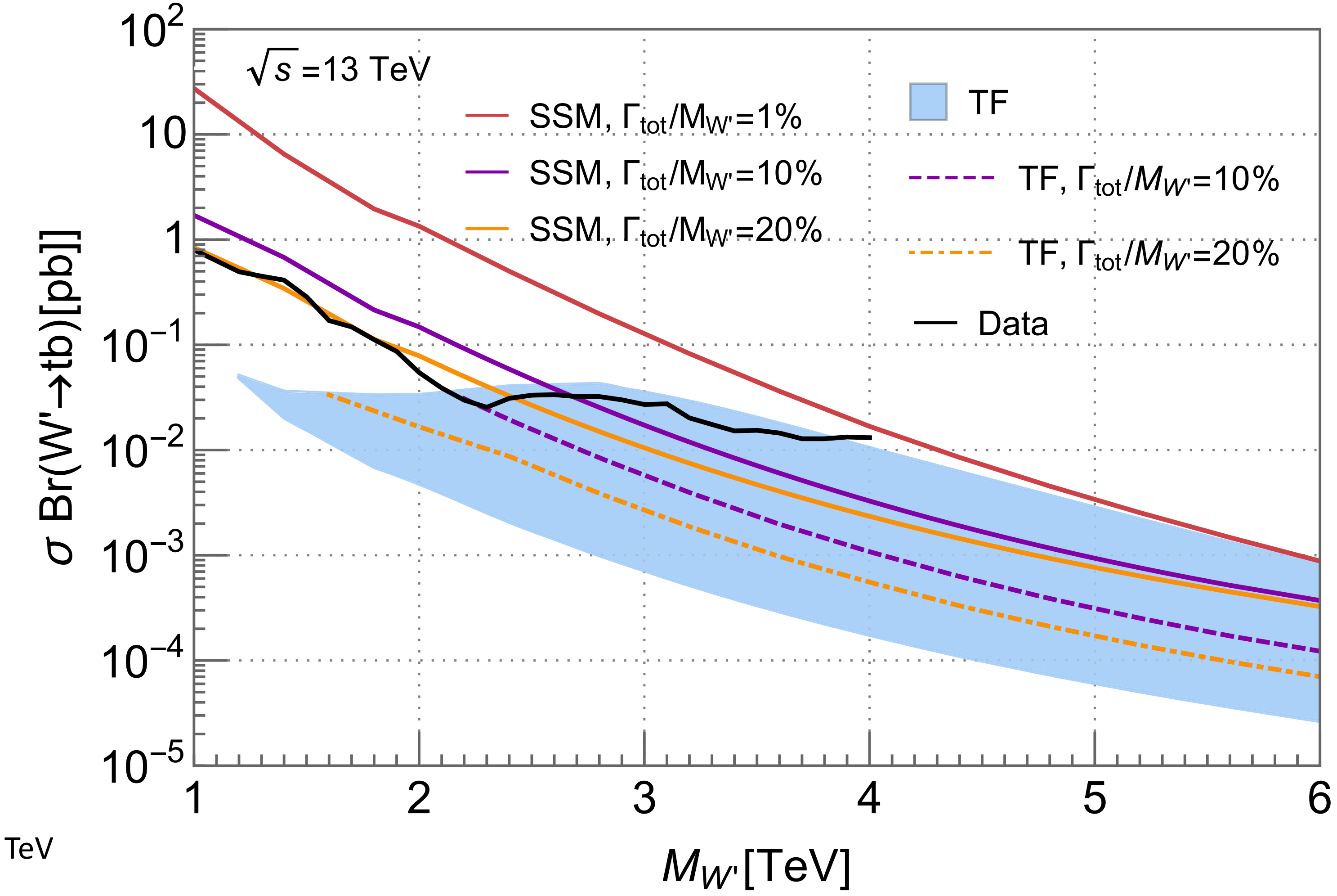
- Typically in the analysis the total width is fixed
- In top-flavor model is a function of the mass



$$\boxed{\sigma(pp \to W')\mathrm{Br}(W' \to tb),}$$



Sirunyan et al, PLB(2018)
Search for heavy resonances decaying to a top quark and a bottom quark in the lepton+jets final state in p-p collisions at 13 TeV



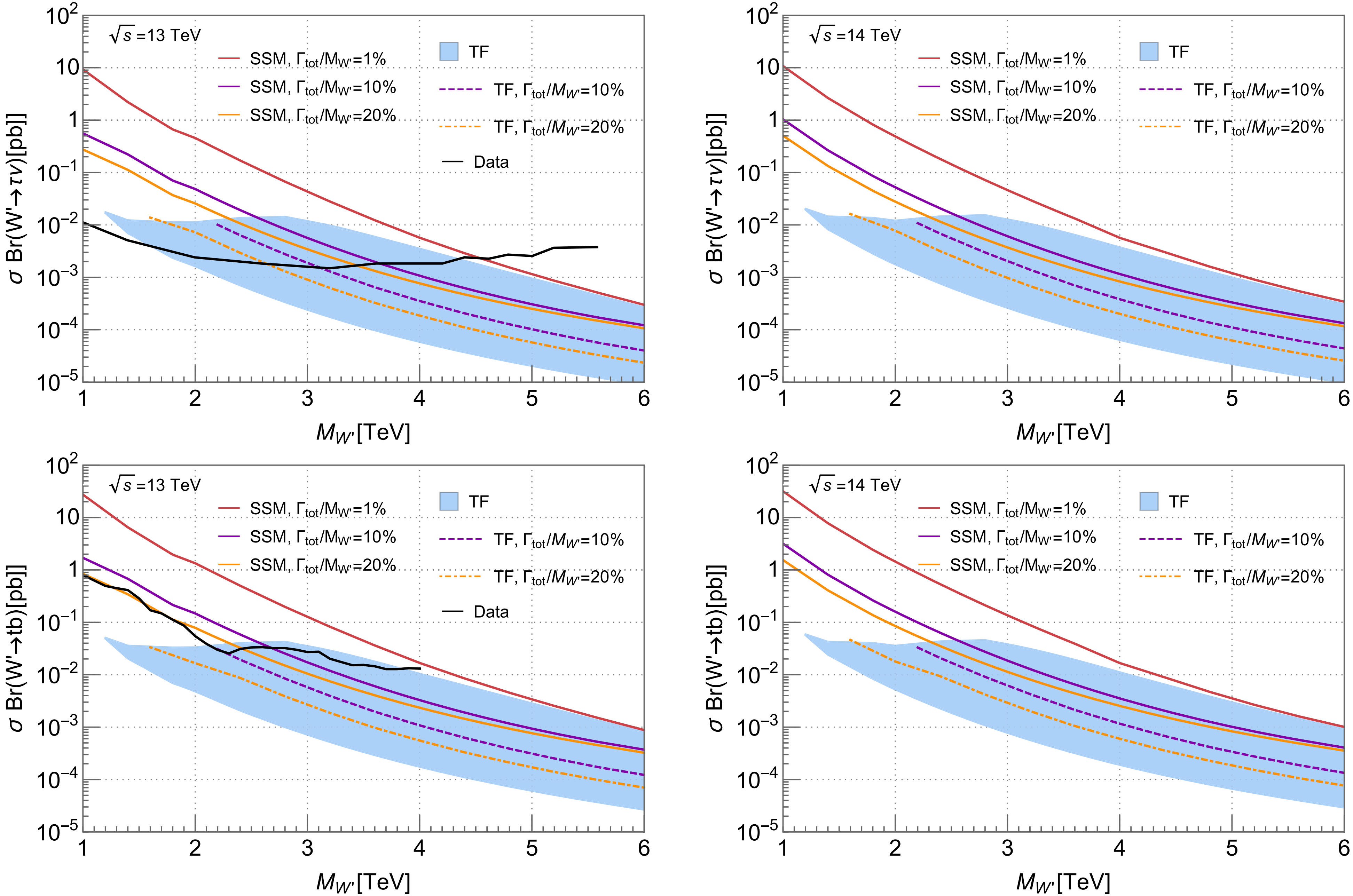
Conclusions

- LHC searches for W’ extra charged gauge boson often use *sequantial model* as benchmark

- Even if sequential model incorporates a wide variety of models, *search results are not so general*

- We consider *top-flavor* as an example showing that a very different conclusion can be obtained from current data

- The main motivation probably is due to *blind vs unblind* flavor model


$\sqrt{s}$ =13 TeV
SSM, $\Gamma_{tot}/M_{W'}$=1%
SSM, $\Gamma_{tot}/M_{W'}$=10%
SSM, $\Gamma_{tot}/M_{W'}$=20%
TF
TF, $\Gamma_{tot}/M_{W'}$=10%
TF, $\Gamma_{tot}/M_{W'}$=20%
Data
σ Br(W'→$\tau\nu$)[pb]
$M_{W'}$[TeV]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
1
2
3
4
5
6
$\sqrt{s}$ =14 TeV
SSM, $\Gamma_{tot}/M_{W'}$=1%
SSM, $\Gamma_{tot}/M_{W'}$=10%
SSM, $\Gamma_{tot}/M_{W'}$=20%
TF
TF, $\Gamma_{tot}/M_{W'}$=10%
TF, $\Gamma_{tot}/M_{W'}$=20%
σ Br(W'→$\tau\nu$)[pb]
$M_{W'}$[TeV]
$\sqrt{s}$ =13 TeV
SSM, $\Gamma_{tot}/M_{W'}$=1%
SSM, $\Gamma_{tot}/M_{W'}$=10%
SSM, $\Gamma_{tot}/M_{W'}$=20%
TF
TF, $\Gamma_{tot}/M_{W'}$=10%
TF, $\Gamma_{tot}/M_{W'}$=20%
Data
σ Br(W'→tb)[pb]
$M_{W'}$[TeV]
$\sqrt{s}$ =14 TeV
SSM, $\Gamma_{tot}/M_{W'}$=1%
SSM, $\Gamma_{tot}/M_{W'}$=10%
SSM, $\Gamma_{tot}/M_{W'}$=20%
TF
TF, $\Gamma_{tot}/M_{W'}$=10%
TF, $\Gamma_{tot}/M_{W'}$=20%
σ Br(W'→tb)[pb]
$M_{W'}$[TeV]