The 10th TeV Physics Workshop @ UCAS, 2015

Simple Non-Abelian Extensions and Diboson Excesses at the LHC

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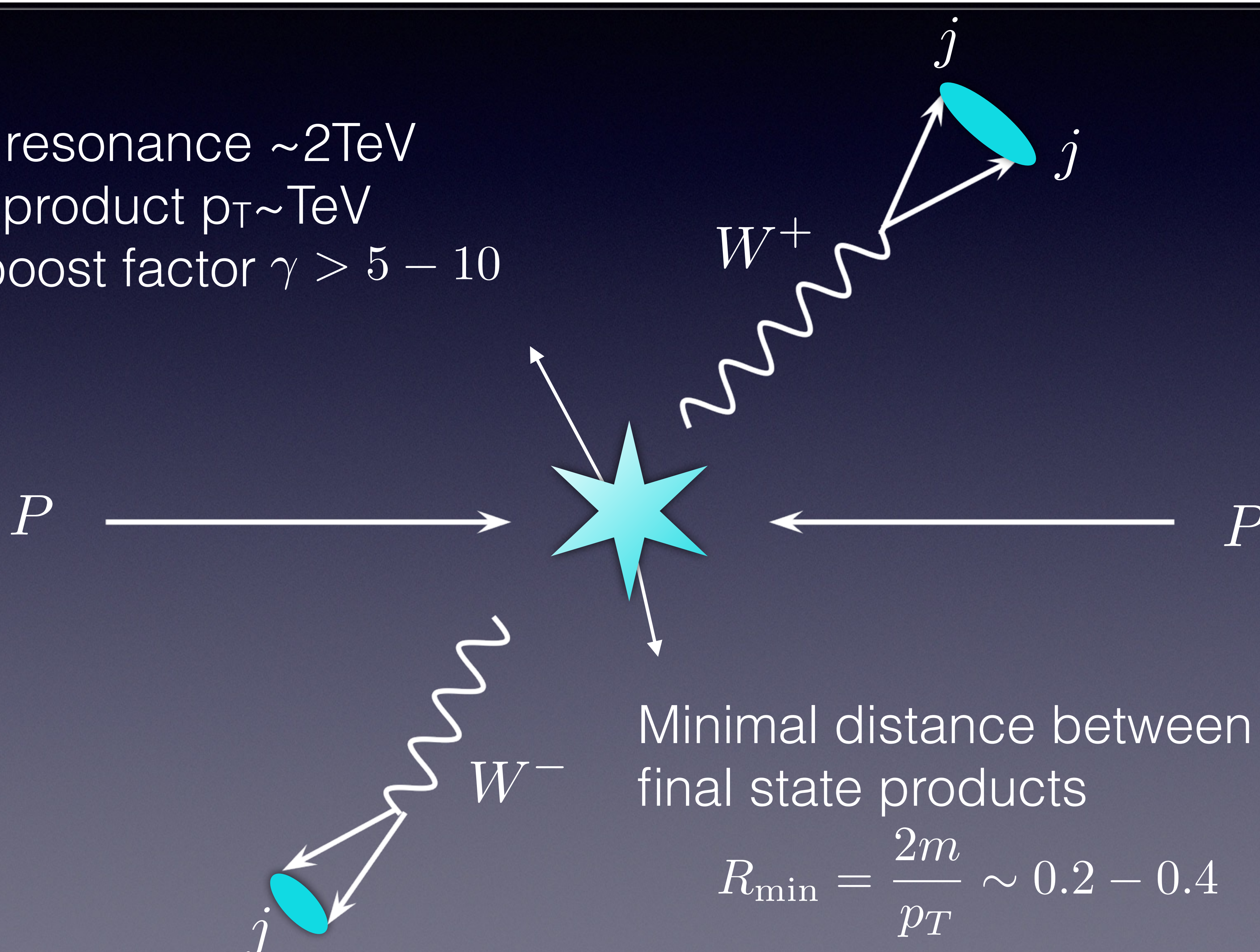
QHC, Bin Yan, Dong-Ming Zhang, 1507.00268

ATLAS Diboson Excesses

1506.00962

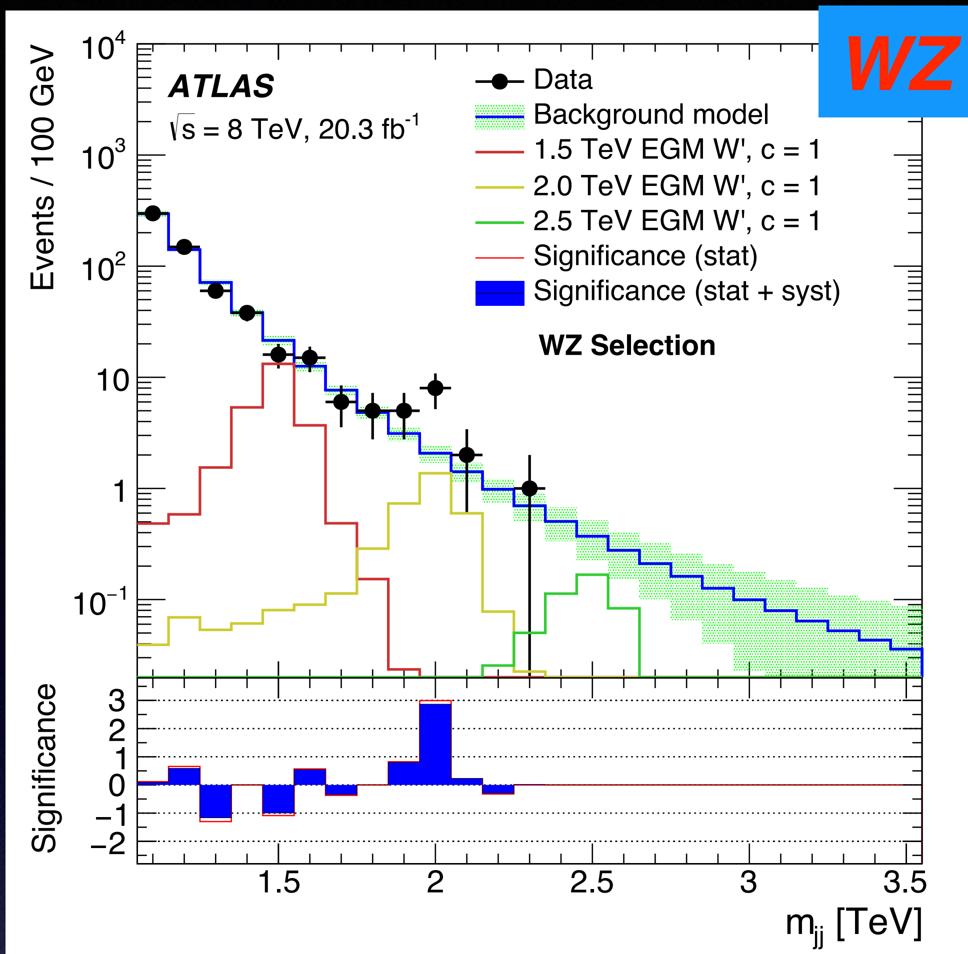
Search for high-mass diboson resonances with boson-tagged jets in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

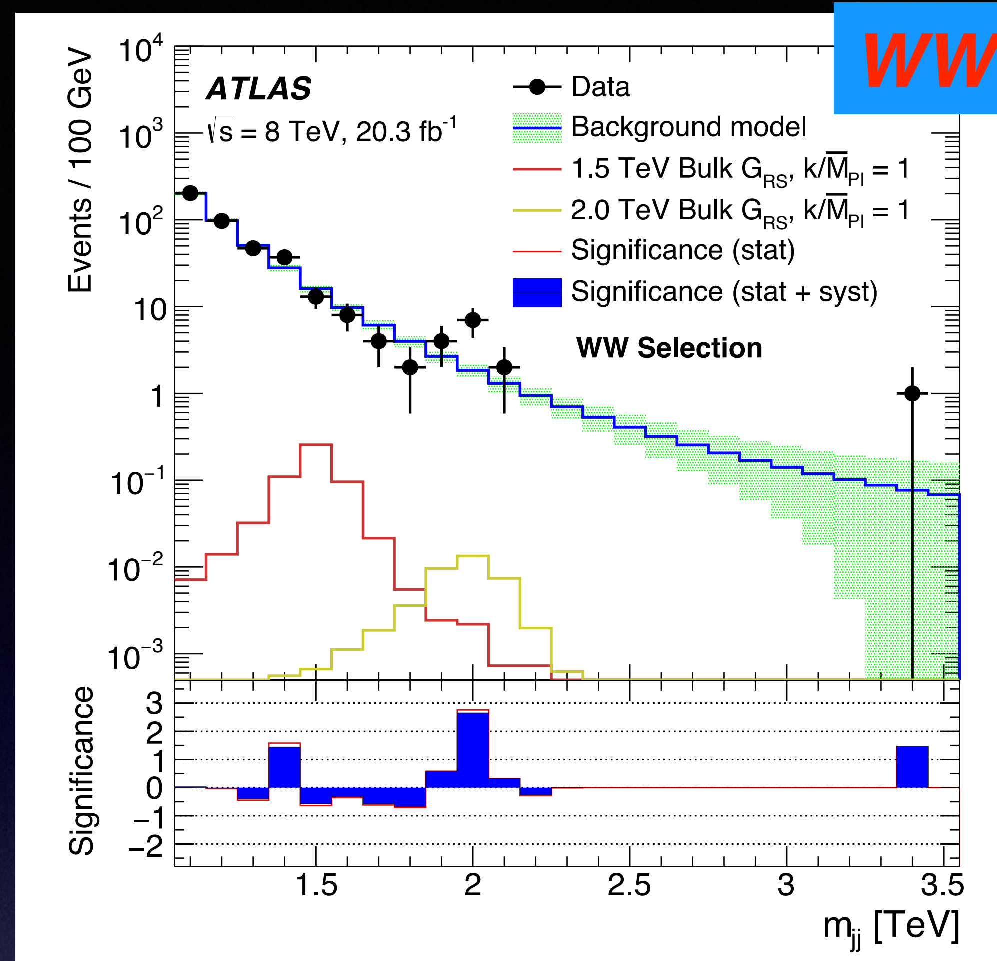
Heavy resonance ~2TeV
decay product p_T~TeV
large boost factor $\gamma > 5 - 10$



Minimal distance between final state products

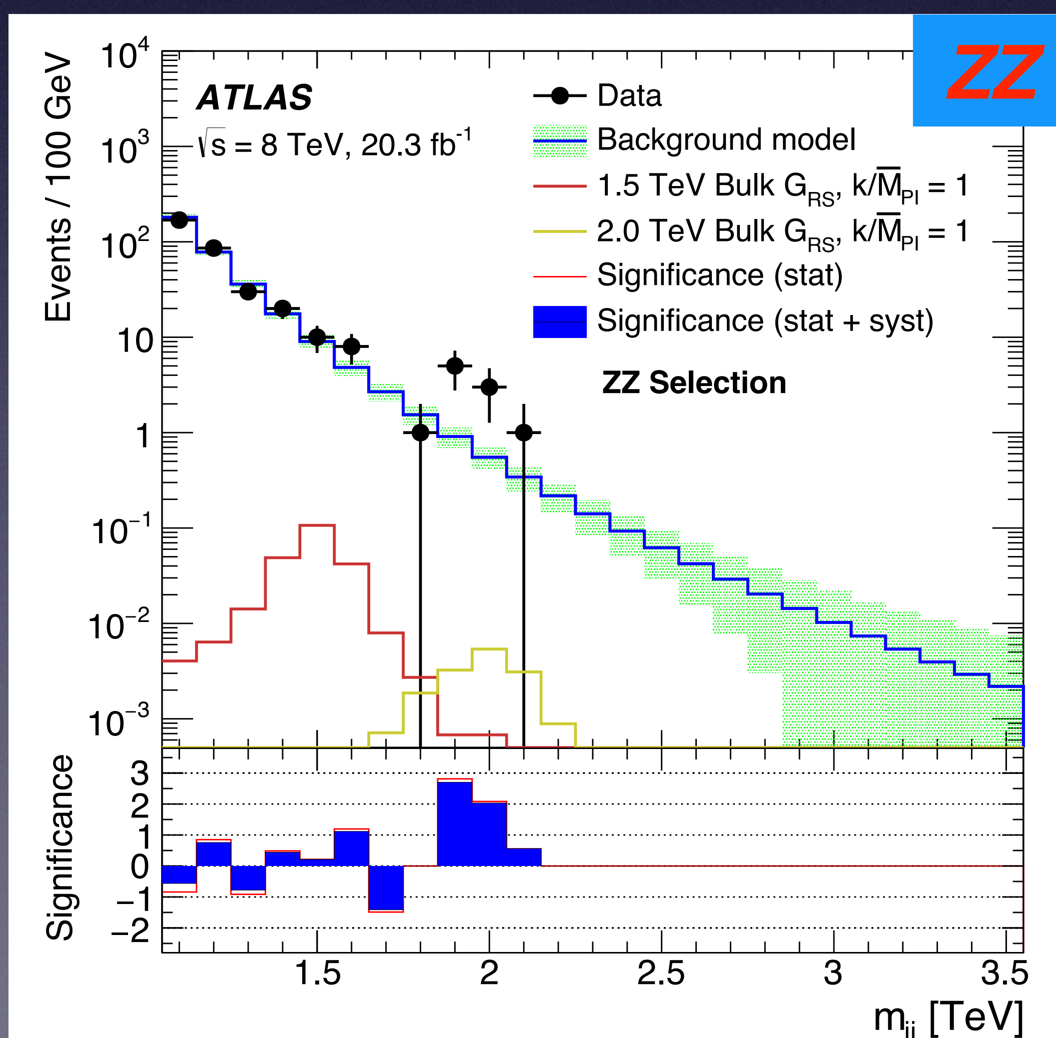
$$R_{\min} = \frac{2m}{p_T} \sim 0.2 - 0.4$$





ATLAS
1506.00962

see Qiang Li's talk for CMS results



If the excesses were induced by NP, then

$$\sigma(WZ) \sim 4 - 8 \text{ fb}$$

$$\sigma(WW) \sim 3 - 7 \text{ fb}$$

$$\sigma(ZZ) \sim 3 - 9 \text{ fb}$$

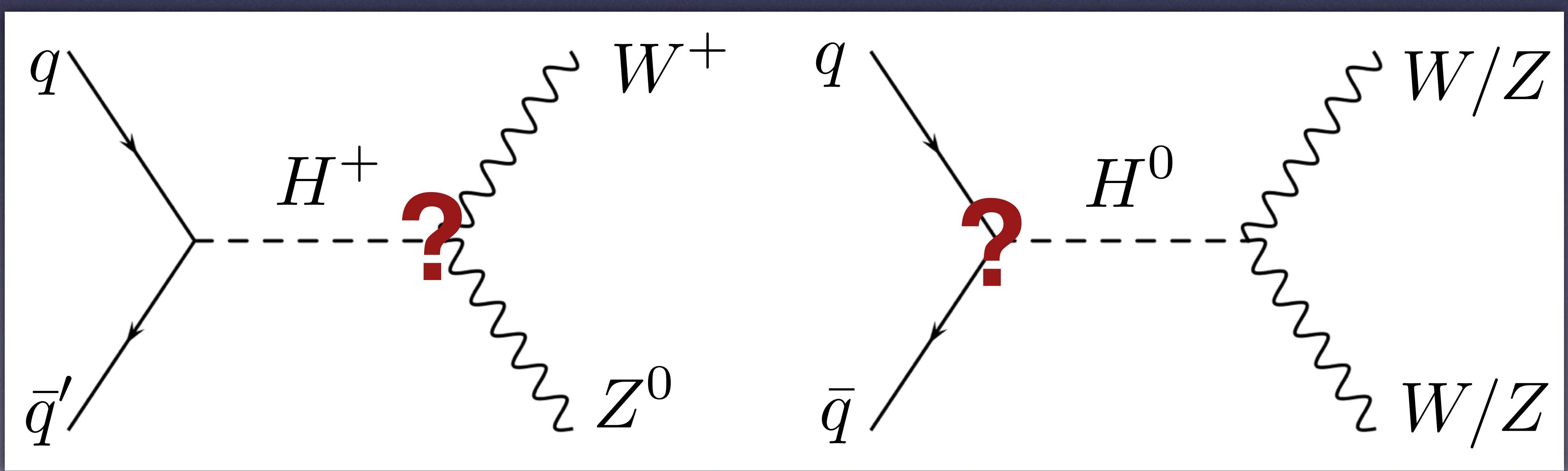
for ~2TeV resonances

New Physics Explanations?

$$\sigma(WZ) \sim 4 - 8 \text{ fb} \qquad \sigma(WW) \sim 3 - 7 \text{ fb}$$
$$\sigma(ZZ) \sim 3 - 9 \text{ fb}$$

Spin-0

H^+ $\qquad$ H^0

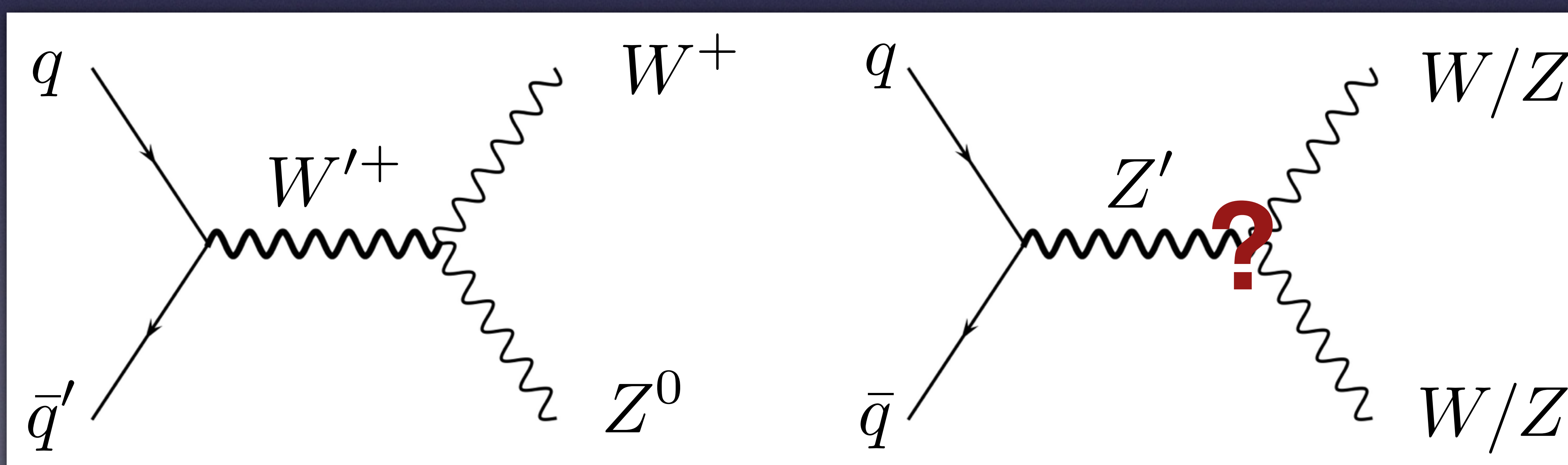


New Physics Explanations?

$$\sigma(WZ) \sim 4 - 8 \text{ fb} \qquad \sigma(WW) \sim 3 - 7 \text{ fb}$$
$$\sigma(ZZ) \sim 3 - 9 \text{ fb}$$

Spin-1

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



$Z' - Z - Z$ coupling highly suppressed

Other constraints for a 2TeV W'/Z' boson

$$\sigma(pp \to Z'/W' \to jj) \leq 102 \text{ fb}$$

ATLAS, 1407.1376
CMS, 1501.04198

$$\sigma(pp \to Z' \to t\bar{t}) \leq 11 \text{ fb}$$

ATLAS, 1410.4103

$$\sigma(pp \to W'_R \to t\bar{b}) \leq 124 \text{ fb}$$

$$\sigma(pp \to W'_L \to t\bar{b}) \leq 162 \text{ fb}$$

CMS, 1506.03062

$$\sigma(pp \to Z' \to e^+e^-/\mu^+\mu^-) \leq 0.2 \text{ fb}$$

ATLAS, 1405.4123
CMS, 1412.6302

$$\sigma(pp \to W' \to e\nu/\mu\nu) \leq 0.7 \text{ fb}$$

ATLAS, 1407.7494
CMS, 1408.2745

$$\sigma(pp \to W' \to WH) \leq 7.1 \text{ fb}$$

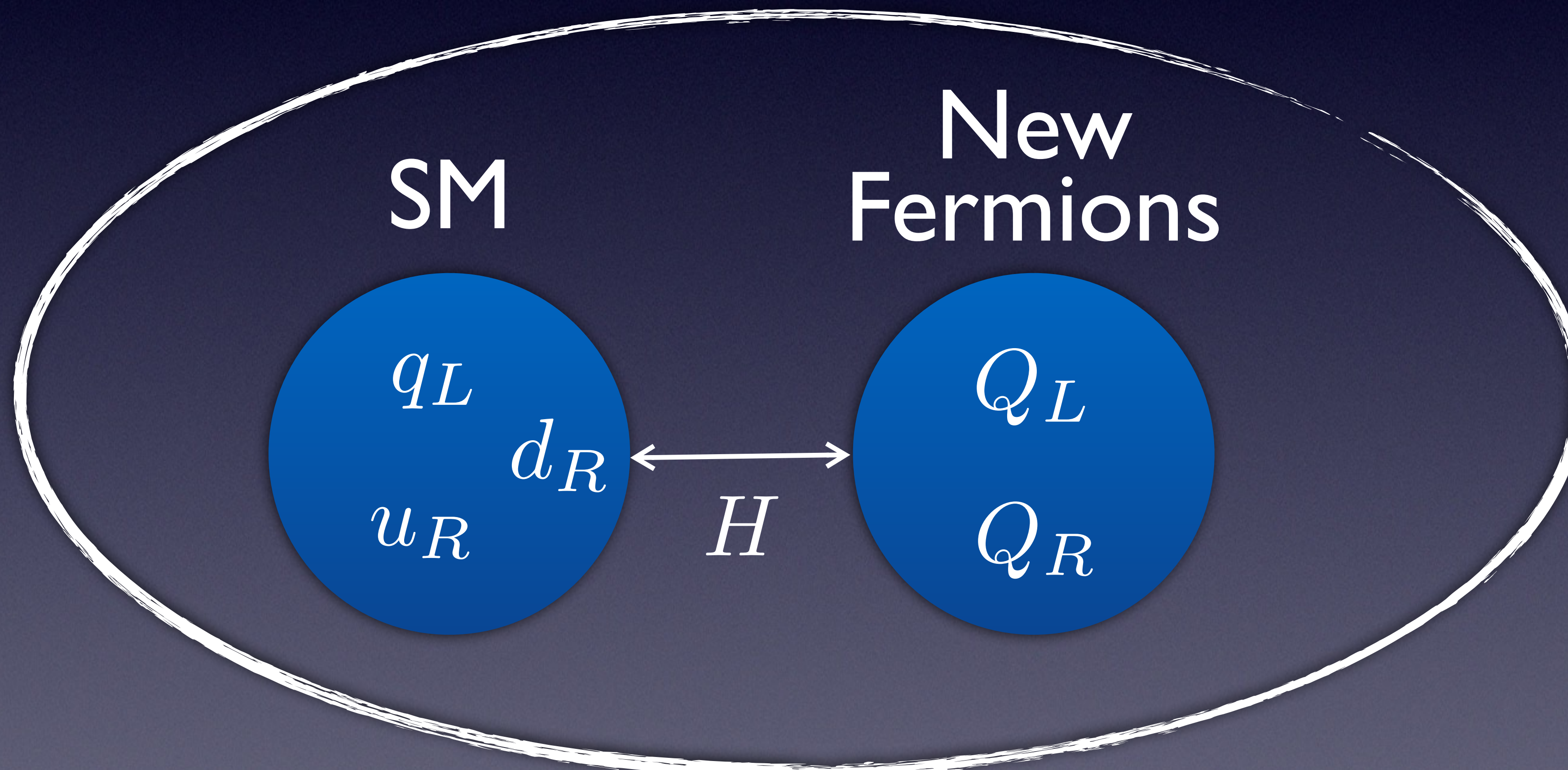
$$\sigma(pp \to W' \to ZH) \leq 6.8 \text{ fb}$$

CMS, 1506.01143

Simple Non-Abelian Extensions

G(221) Model

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



$$SU(3)_C \times SU(2)_L$$
$$\times U(1)_L \times U(1)_X$$

U(1) Extension

Z-prime

not considered in this work

G(331) Model

$$SU(3)_C \times SU(3)_W \times U(1)_X$$

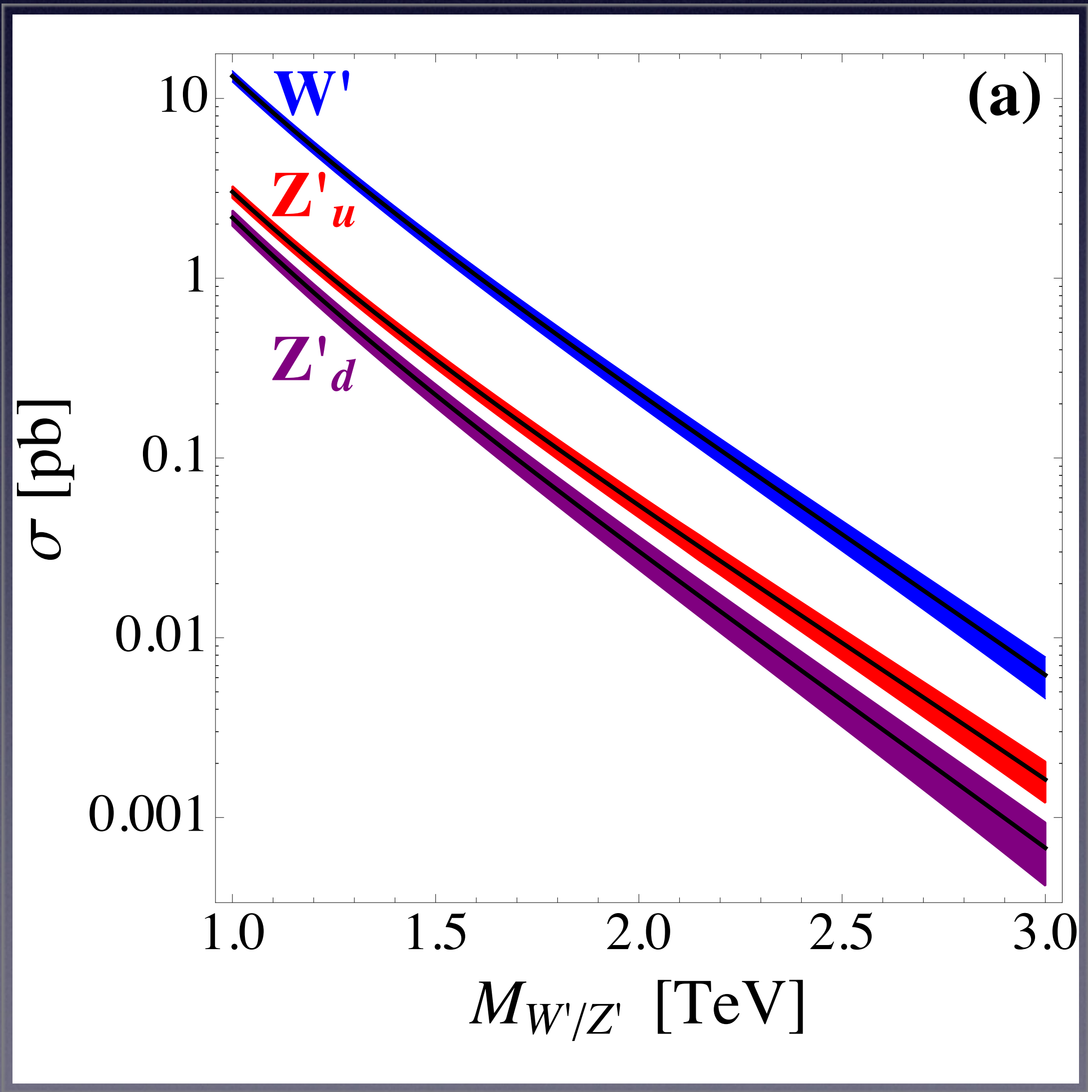
G(221) Models

Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $Y_{\rm SM}$ for leptons.
Hadro-phobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$Y_{\rm SM}$ for quarks, $-\frac{1}{2}$ for leptons.
Fermio-phobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\rm SM}$ for all fermions.
Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$Y_{\rm SM}$ for all fermions.
Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\rm st},2^{\rm nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\rm rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\rm rd}}$	$Y_{\rm SM}$ for all fermions.

Production Rate of Sequential W'/Z'

$$\sigma(pp \to V' \to XY) \simeq \sigma(pp \to V') \otimes \mathrm{BR}(V' \to XY) \equiv \sigma(V') \times \mathrm{BR}(V' \to XY)$$

$$\log\left[\frac{\sigma(M_{V'})}{\mathrm{pb}}\right] = A\left(\frac{M_{V'}}{\mathrm{TeV}}\right)^{-1} + B + C\left(\frac{M_{V'}}{\mathrm{TeV}}\right),$$

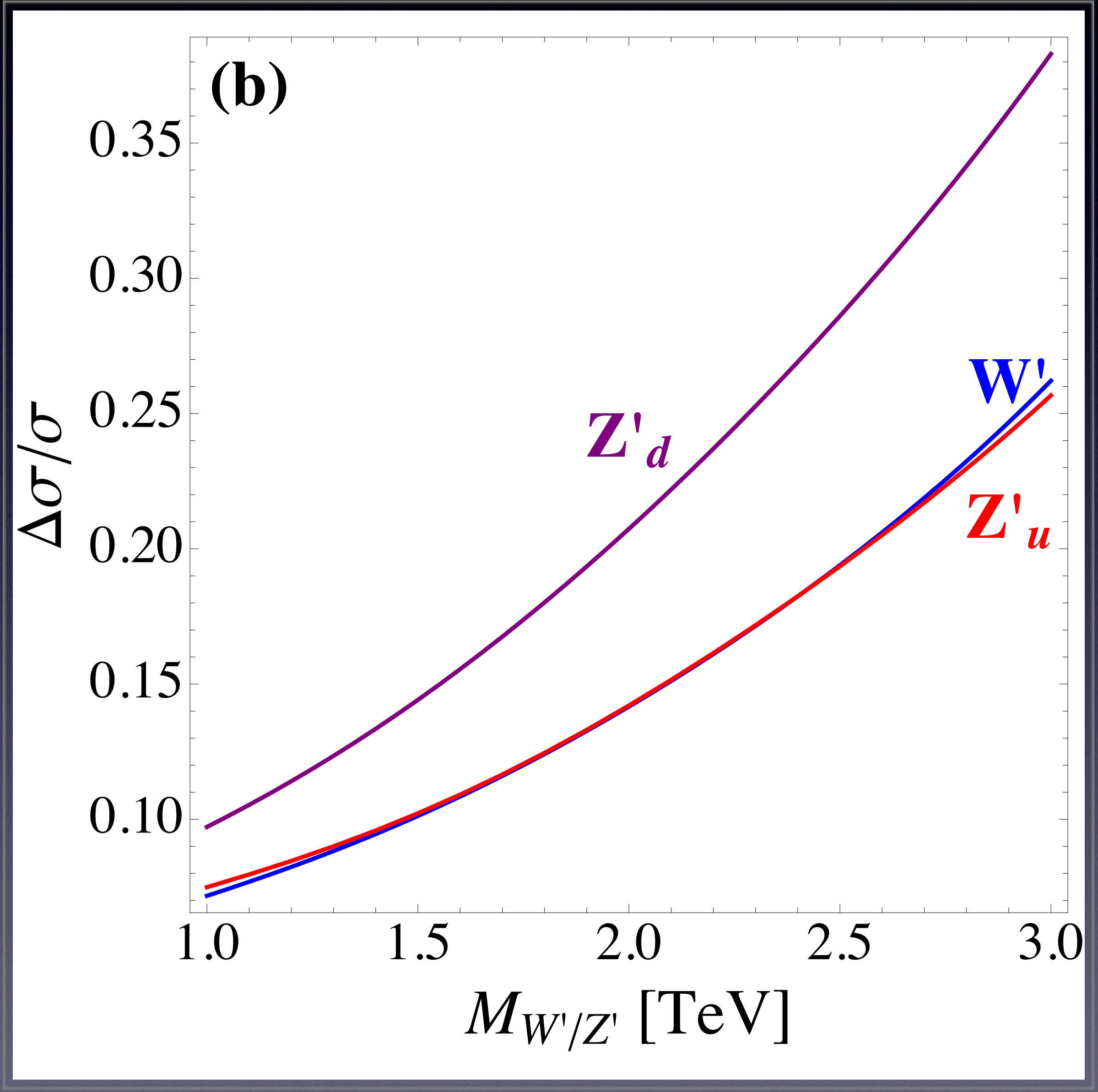


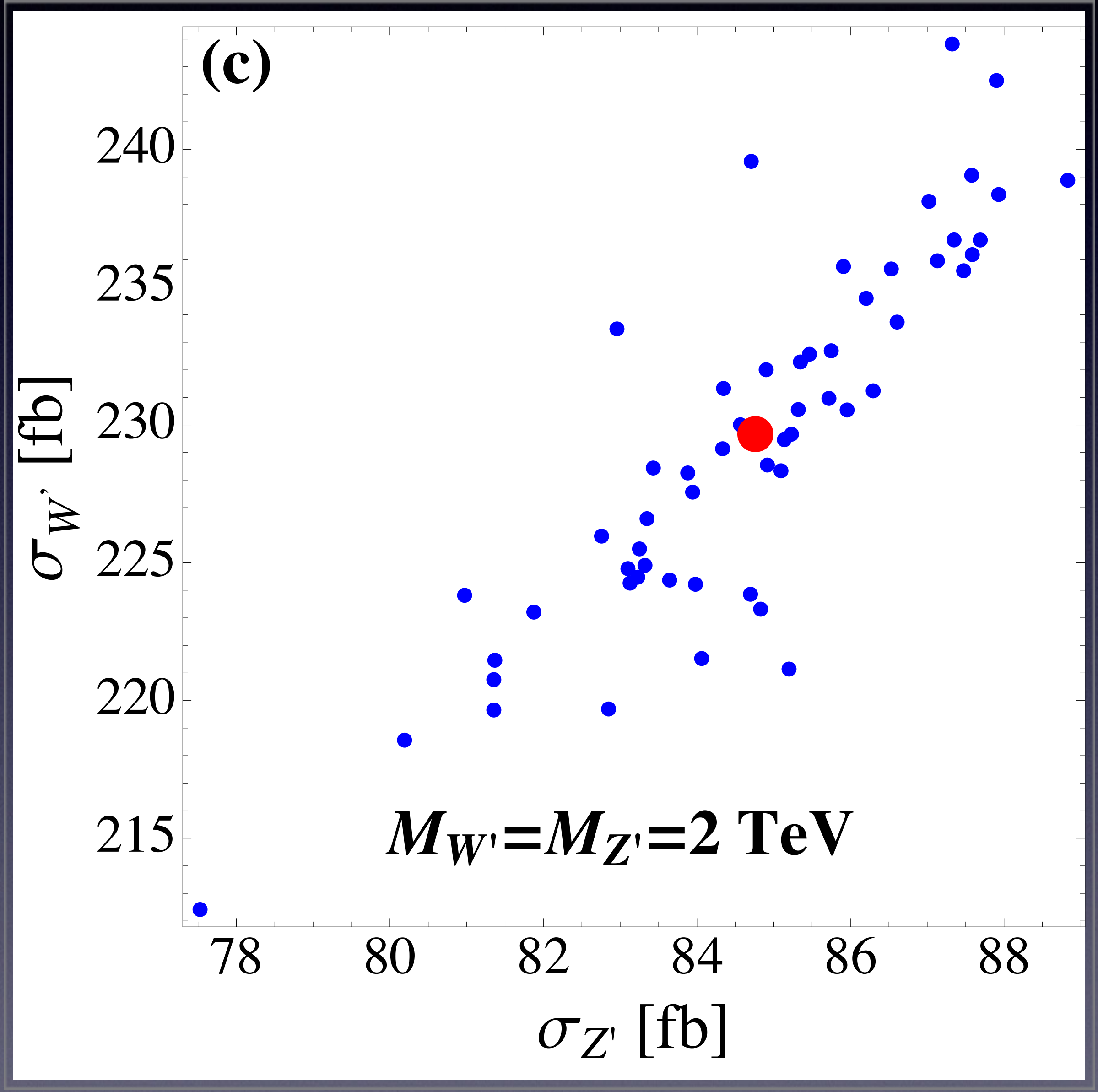
$\sigma(pp \to V')$

W'	:	$4.59925 + 1.34518x^{-1} - 3.37137x$
Z'_u	:	$2.82225 + 1.51681x^{-1} - 3.24437x$
Z'_d	:	$2.88763 + 1.42266x^{-1} - 3.54818x,$

PDF and Scale Uncertainties

CT14 NNLO PDFs (56 sets)





The PDF uncertainty is ~15-20%
The scale uncertainty is ~5%

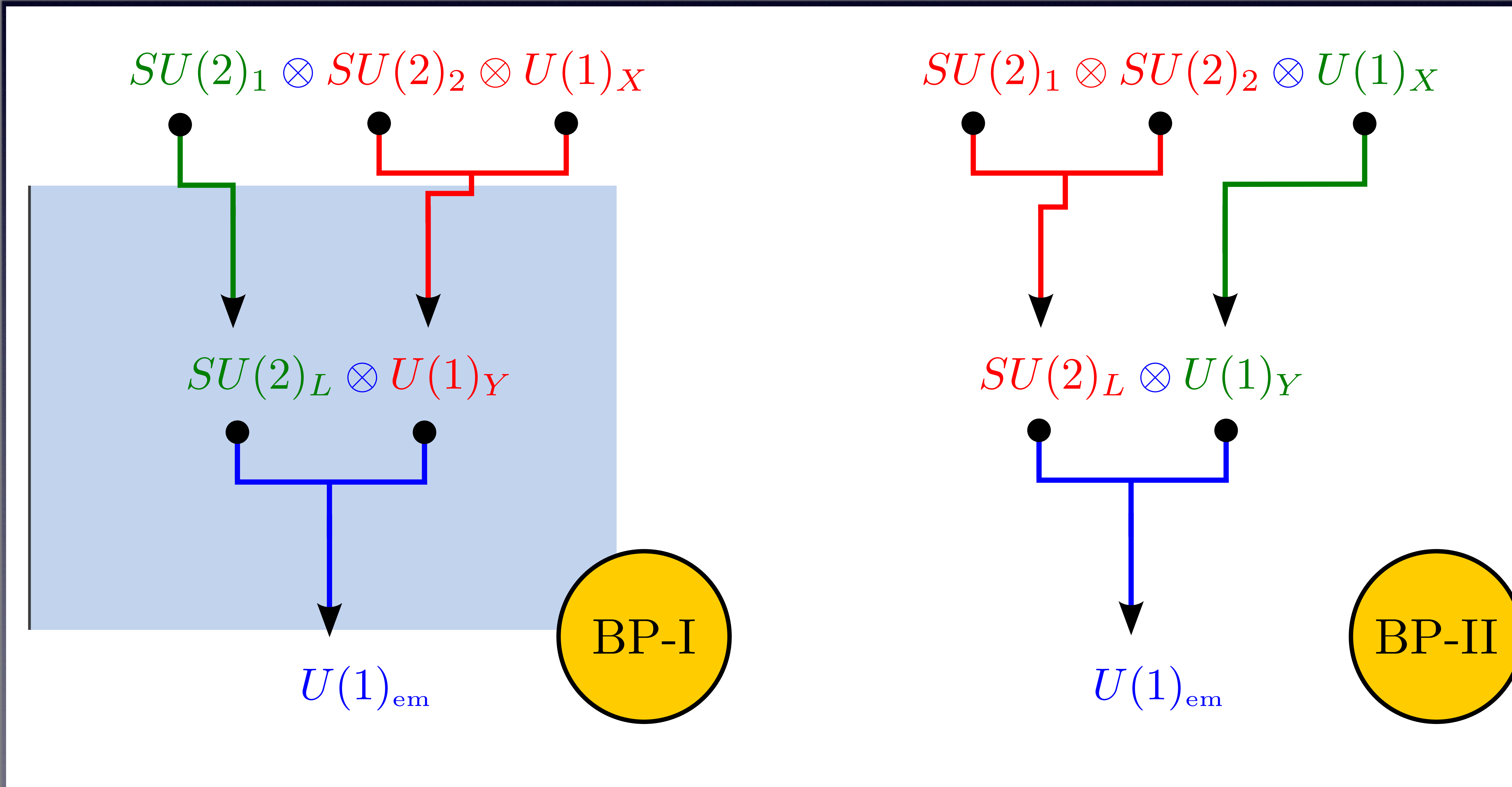
for a 2TeV W'/Z'

G(221) Models: Symmetry Breaking

Two patterns of spontaneously symmetry breaking

1st stage: $\Phi \to \langle \Phi \rangle \sim u \geq 1\ \text{TeV}$

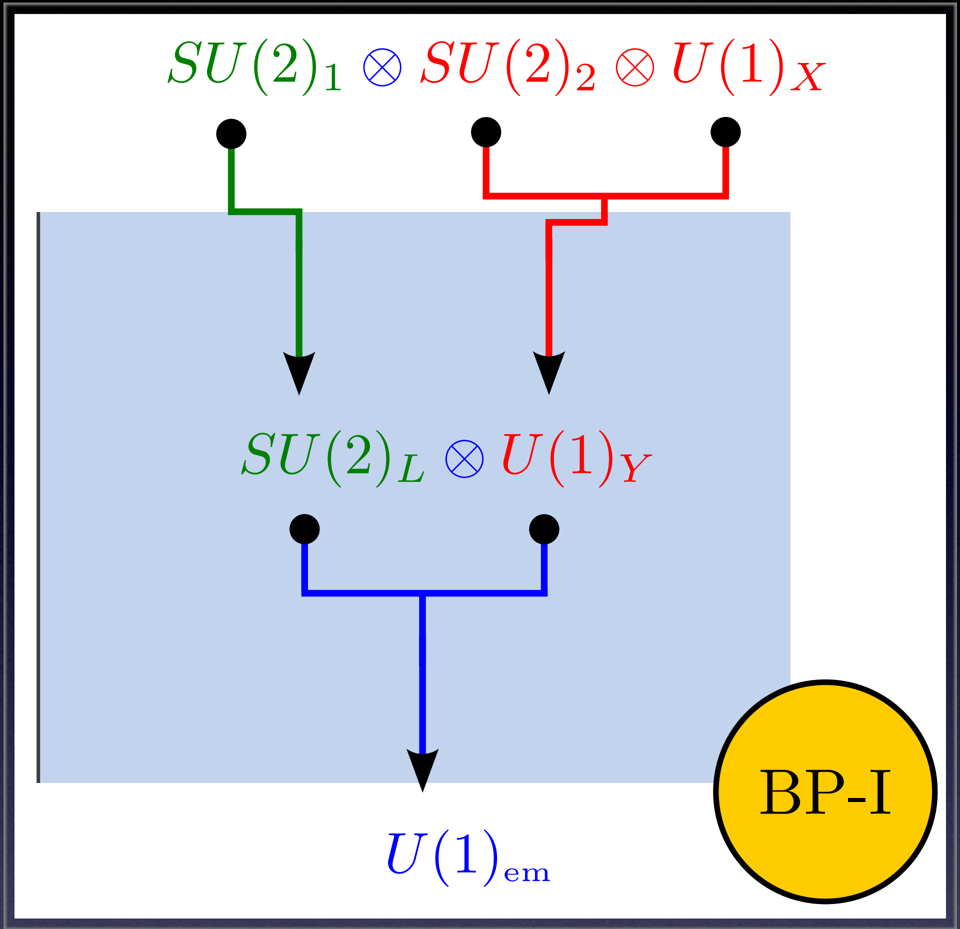
2nd stage: $H \to \langle H \rangle \sim v \geq 250\ \text{GeV}$



G(221) Models: Breaking Pattern 1

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u \end{pmatrix}$$



$$\Sigma = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi^+ & \sqrt{2}\phi^{++} \\ \sqrt{2}\phi^0 & -\phi^+ \end{pmatrix}$$

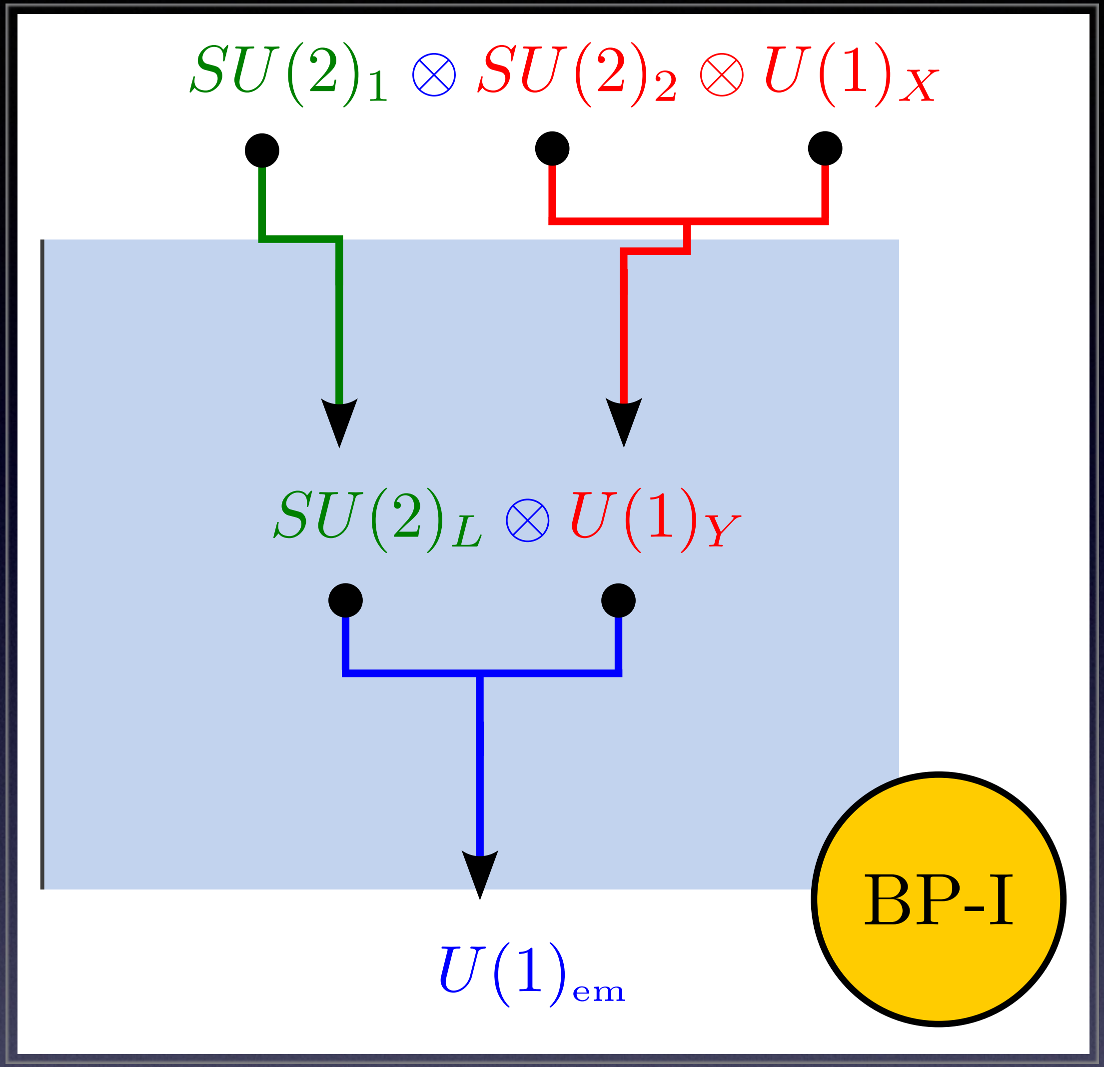
$$\langle \Sigma \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ u & 0 \end{pmatrix}$$

$$H = \begin{pmatrix} h_1^0 & h_1^+ \\ h_2^- & h_2^0 \end{pmatrix} \qquad \langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix}$$

$$x \equiv u^2/v^2 \qquad \tan\beta = v_1/v_2$$

$$g_1 = \frac{e}{s_W}, \quad g_2 = \frac{e}{c_W s_\phi}, \quad g_X = \frac{e}{c_W c_\phi},$$

$M_{W'}/M_{Z'}$ in G(221): BP-1



$$g_1 = \frac{e}{s_W}$$

$$g_2 = \frac{e}{c_W s_\phi} \qquad g_X = \frac{e}{c_W c_\phi}$$

$$x = u^2/v^2$$

$$\tan\beta = v_1/v_2$$

Doublet: $M^2_{W'^\pm} = \frac{e^2 v^2}{4 c_W^2 s_\phi^2}(x+1)\,,\, M^2_{Z'} = \frac{e^2 v^2}{4 c_W^2 s_\phi^2 c_\phi^2}(x + c_\phi^4)$

Triplet: $M^2_{W'^\pm} = \frac{e^2 v^2}{4 c_W^2 s_\phi^2}(2x+1)\,,\, M^2_{Z'} = \frac{e^2 v^2}{4 c_W^2 s_\phi^2 c_\phi^2}(4x + c_\phi^4)$

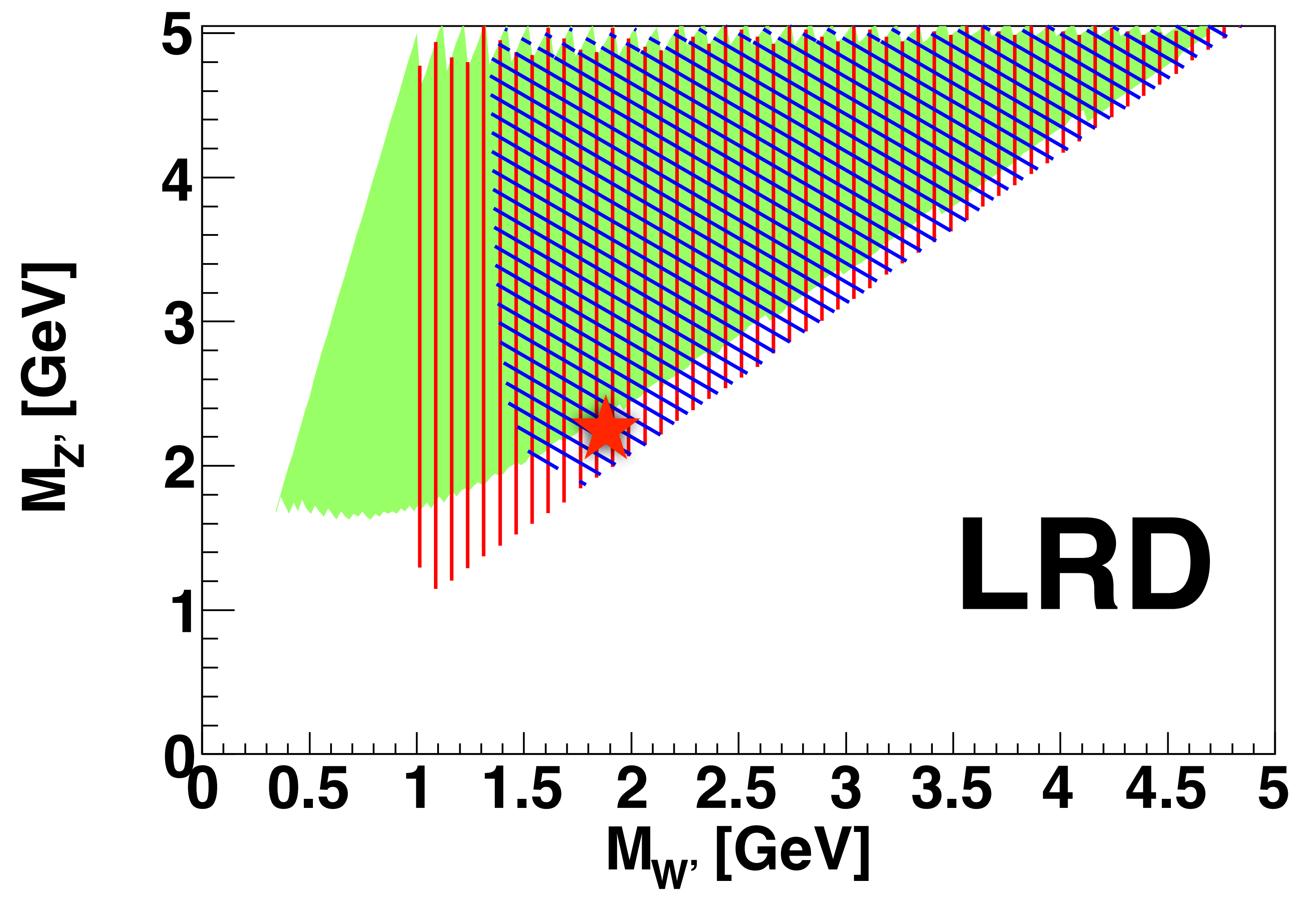
G(221) BP-1: Left-Right Doublet Model

Low energy precision test and Direct search bounds

37 observables

- Z pole data (21): Total width Γ_Z, cross section $\sigma_{\text{had.}}$, ratios $R(f)$, LR, FB, and charge asymmetries $A_{LR}(f)$, $A_{FB}(f)$, and Q_{FB};
- $W^{\pm}$ and top data (3): Mass M_W and total width Γ_W, m_t pole mass;
- νN-scattering (5): NC couplings $\left(g_L^{\nu N}\right)^2$ and $\left(g_R^{\nu N}\right)^2$, NC-CC ratios R_ν and $R_{\bar{\nu}}$;
- νe^--scattering (2): NC couplings $g_V^{\nu e}$ and $g_A^{\nu e}$;
- PV interactions (5): $Q_W\left({}^{133}\text{Cs}\right)$ $Q_W\left({}^{205}\text{Tl}\right)$, $Q_W(e)$, NC couplings $\mathcal{C}_1, \mathcal{C}_2$;
- τ lifetime (1).

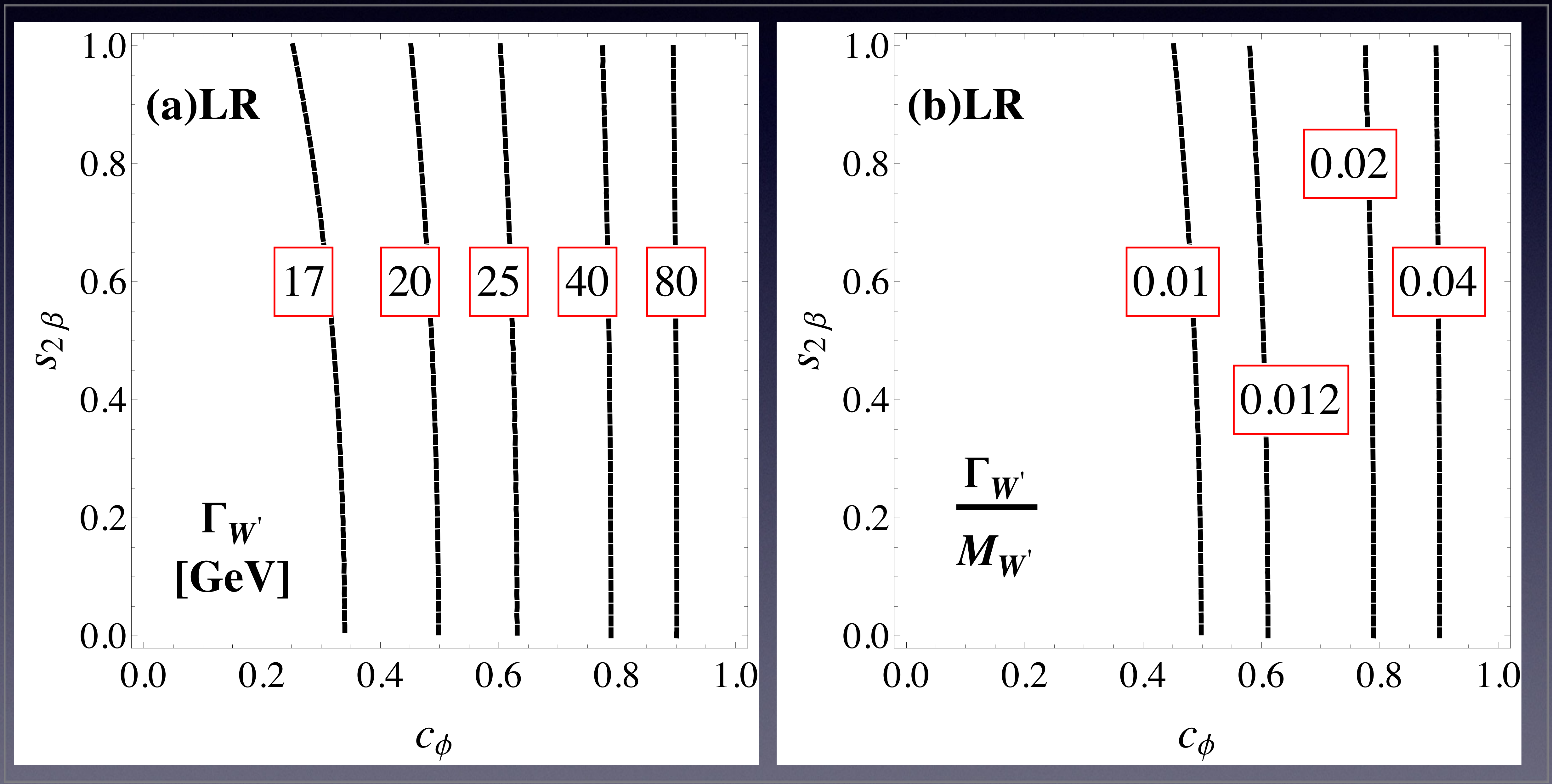
$$\chi^2 \equiv \sum_i \mathcal{P}_i^2 \equiv \sum_i \frac{1}{\sigma_i^2}\left(\bar{\mathcal{O}}_i^{\text{exp.}} - \mathcal{O}_i^{\text{theo.}}\right)^2 \; ; \; \chi^2_{\text{min.}} = 43.22$$



Green: EWPT
Red: Tevatron Direct Searches
Blue: LHC Direct Searches

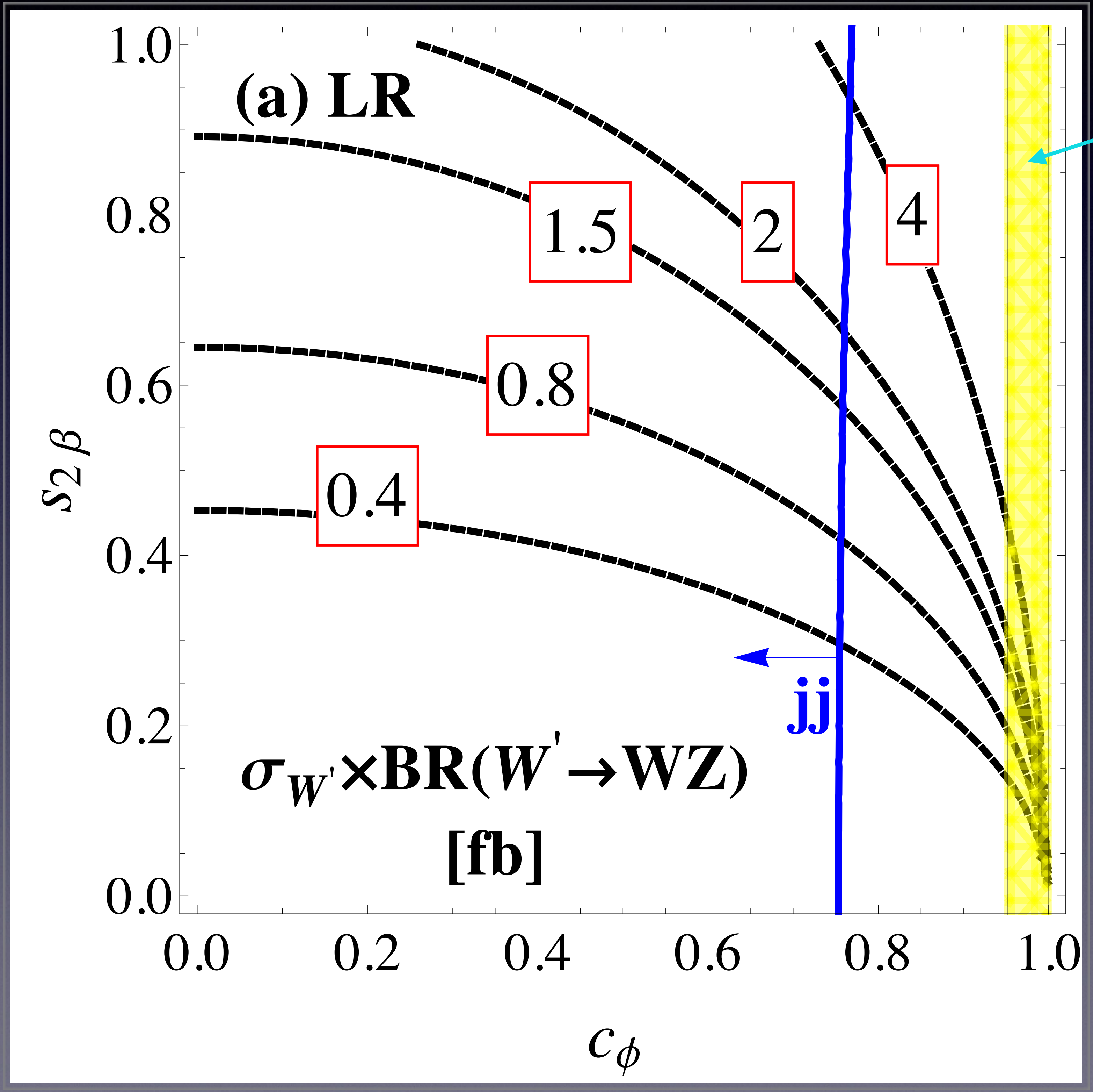
Left-Right Doublet: a 2TeV W-prime

Narrow width approximation works well



Left-Right Doublet: a 2TeV W-prime

cross section contour



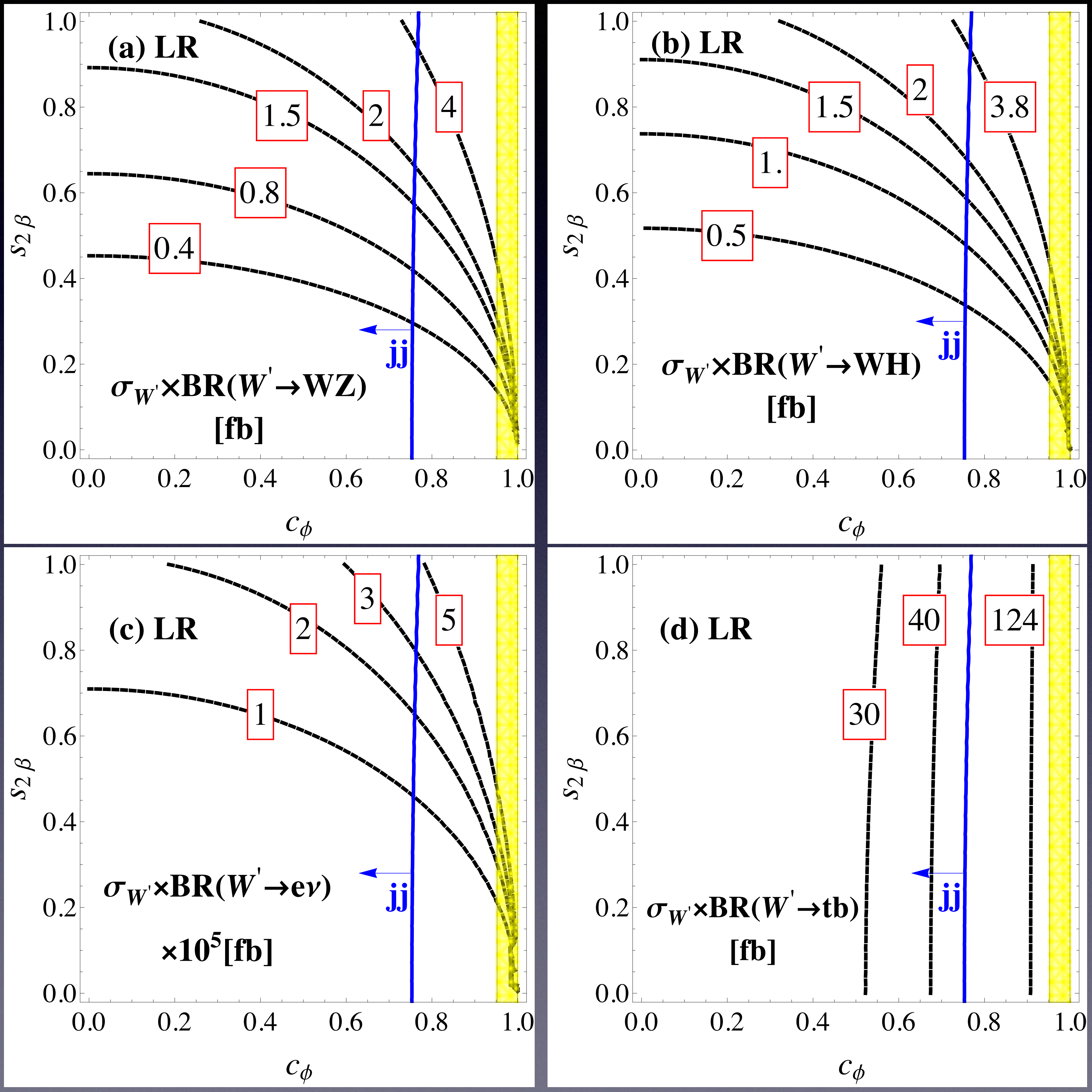
$M_{W'} \simeq M_{Z'}$

$c_\phi \sim 1$

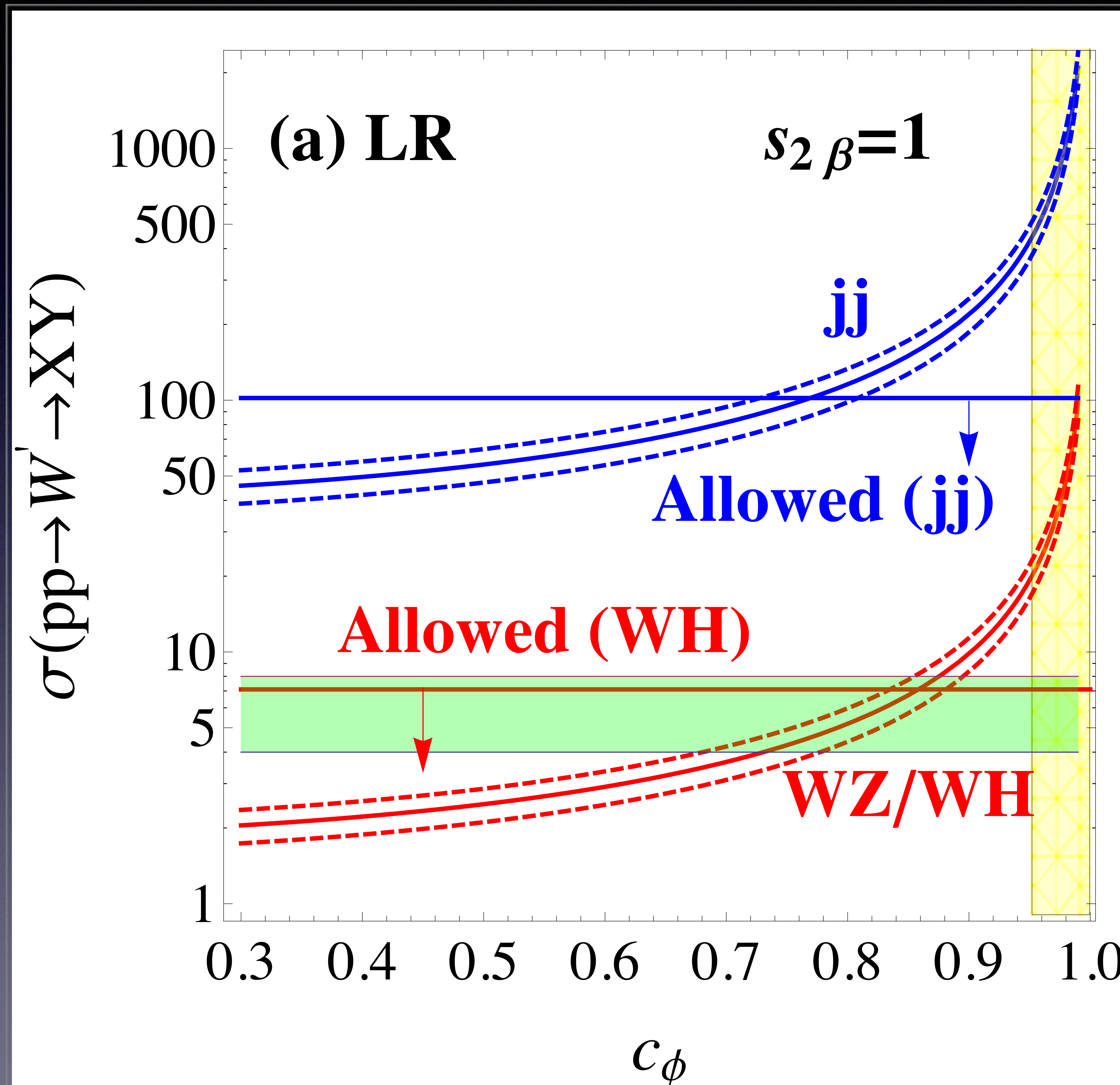
the dijet bound requires

$c_\phi < 0.75$

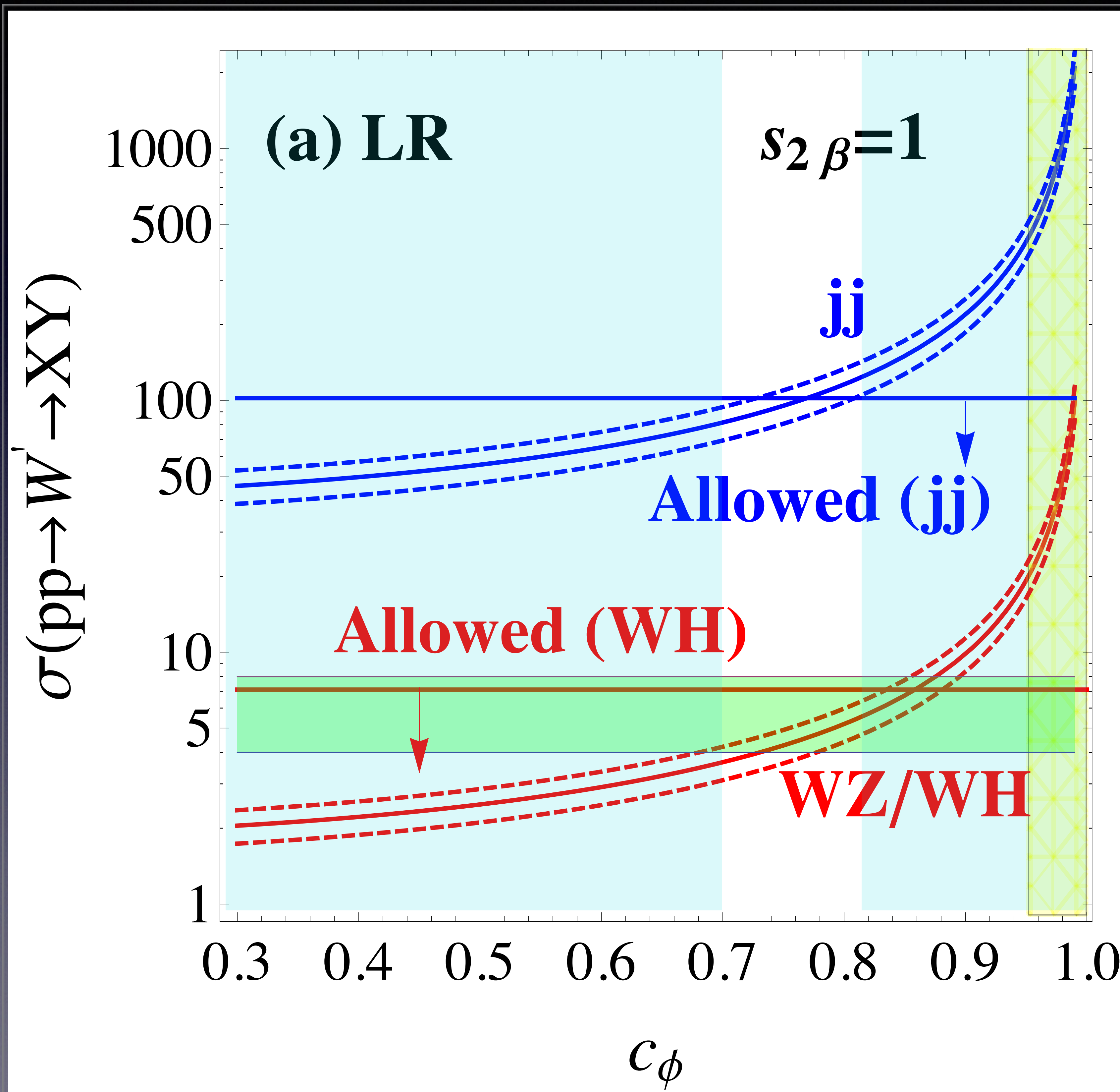
Left-Right Doublet: a 2TeV W-prime



Left-Right Doublet: a 2TeV W-prime



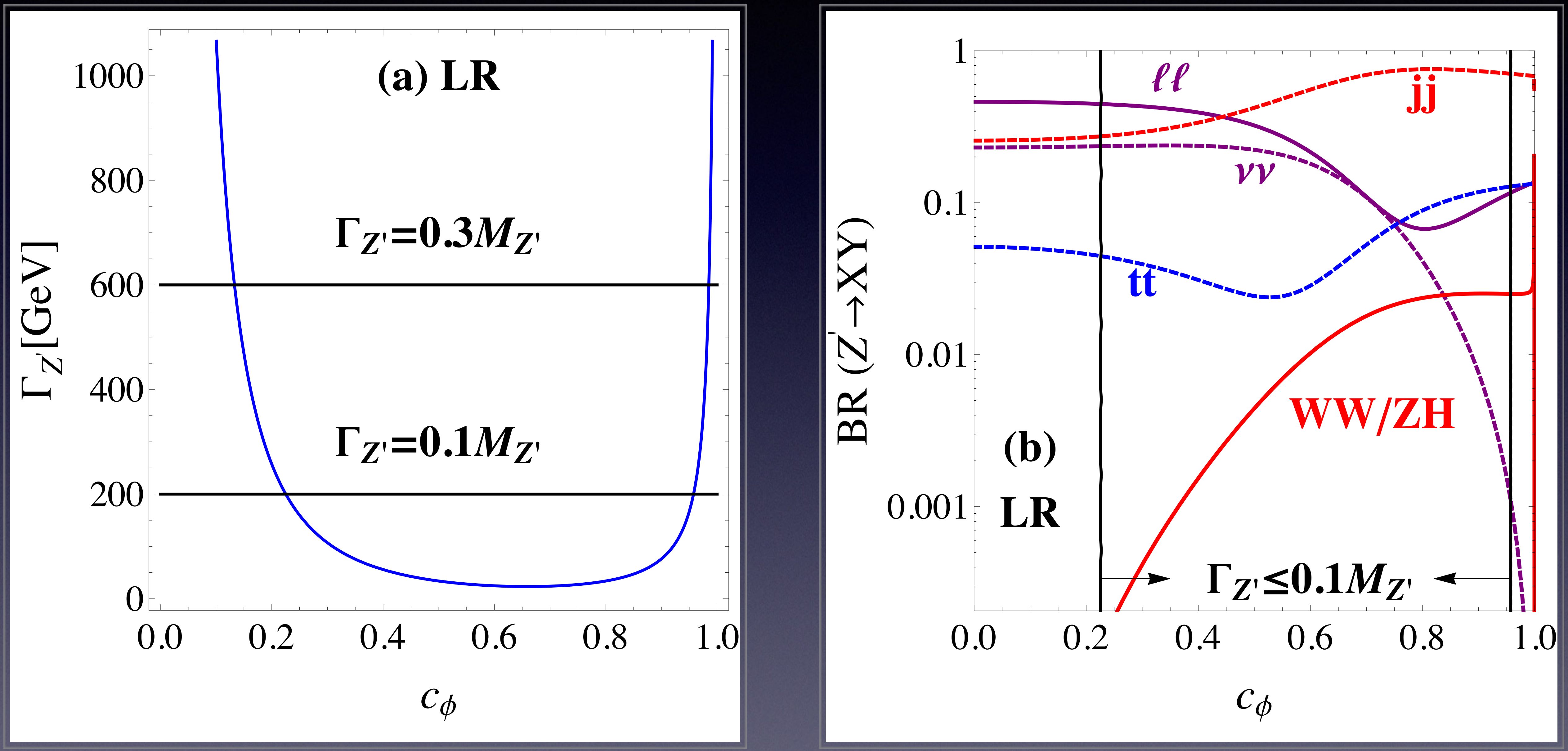
Left-Right Doublet: a 2TeV W-prime



W-prime can explain the WZ excess in the region of $c_\phi \sim 0.7 - 0.82$

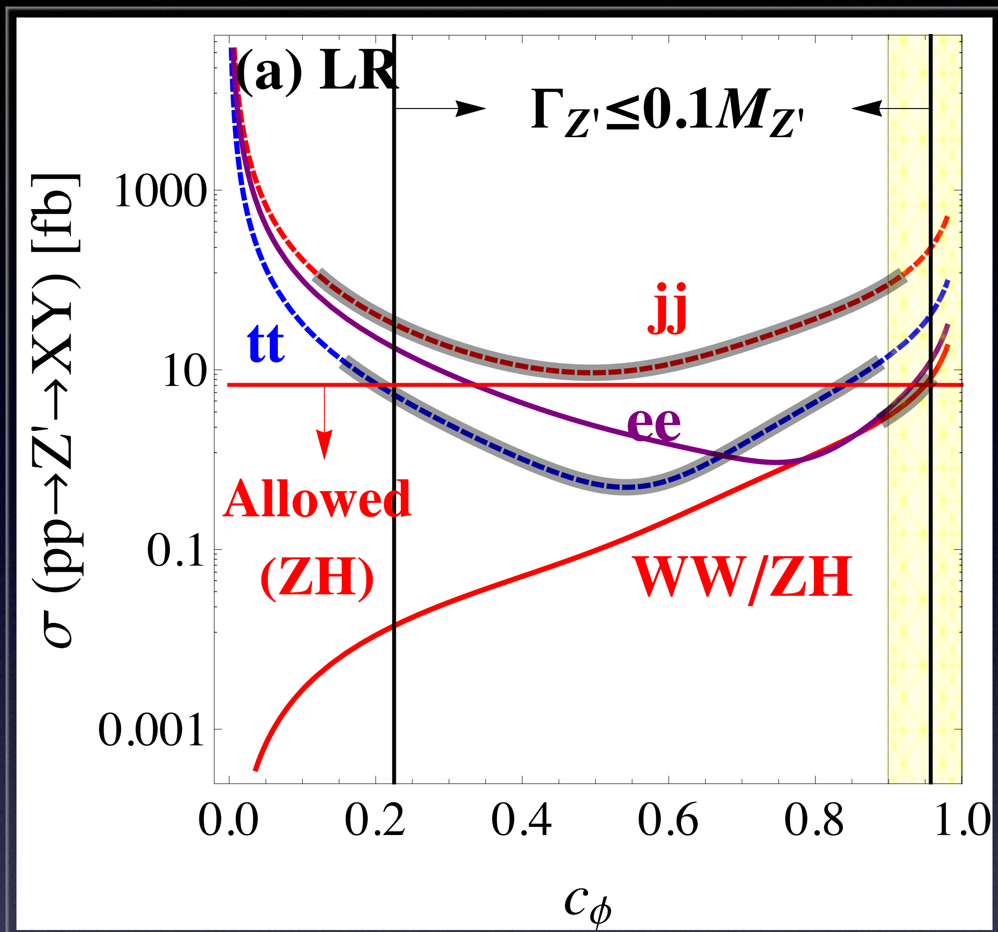
but it requires $M_{Z'} \sim 2.5 - 2.8$ TeV

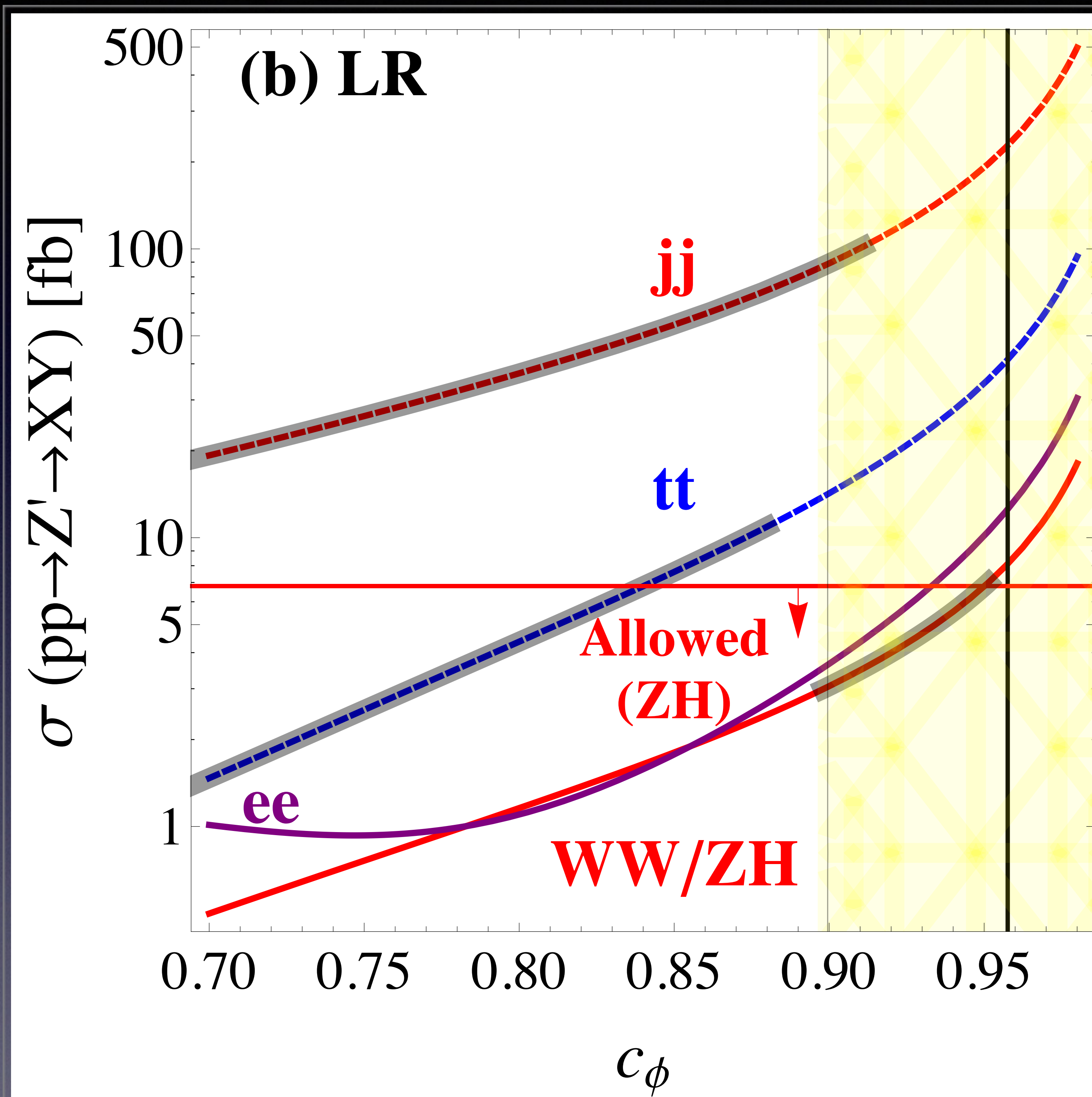
Left-Right Doublet: a 2TeV Z-prime



$$g_1 = \frac{e}{s_W} \qquad g_2 = \frac{e}{c_W s_\phi} \qquad g_X = \frac{e}{c_W c_\phi}$$

Left-Right Doublet: a 2TeV Z-prime

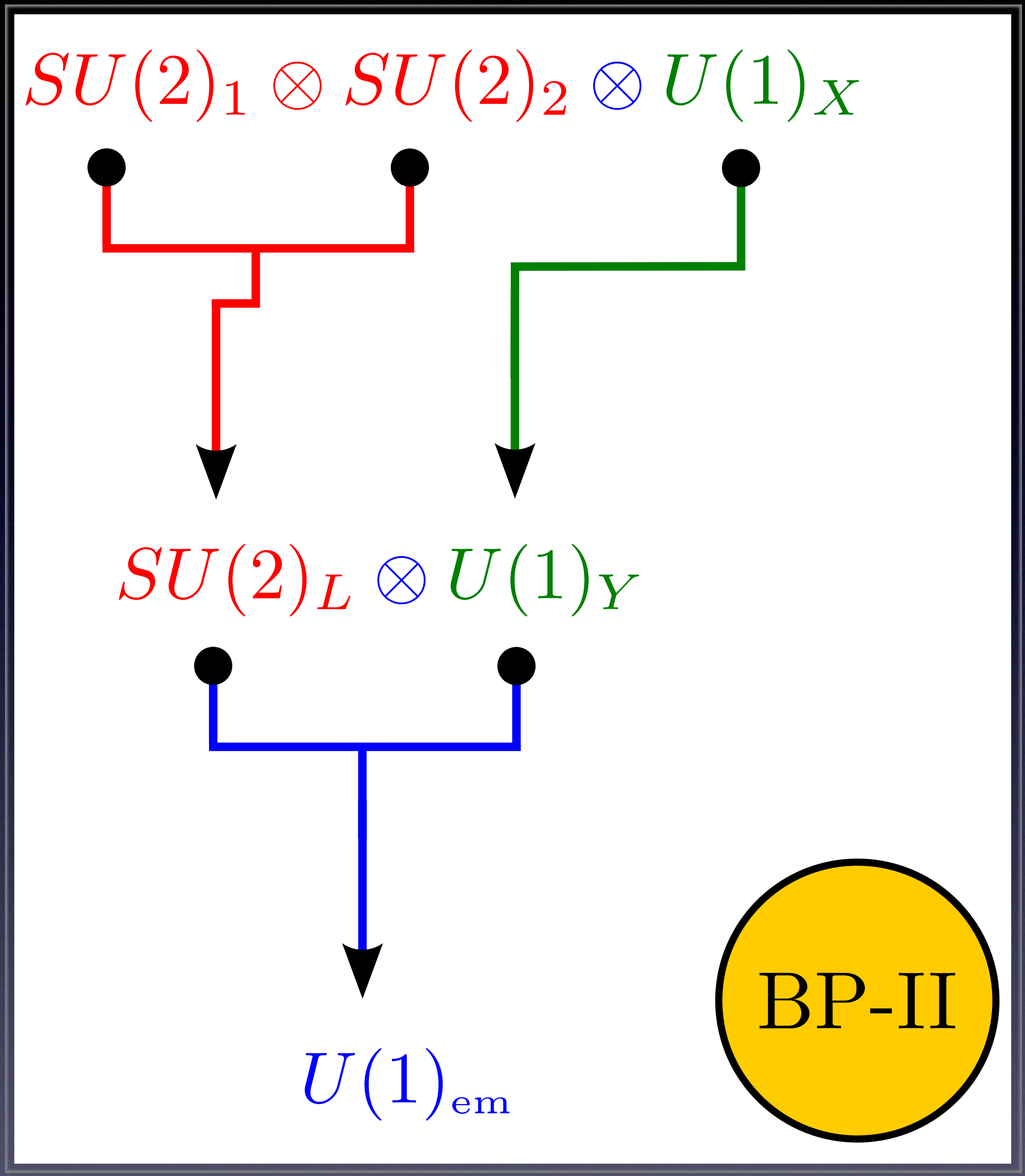




$$\sigma(pp \to Z' \to e^+e^-/\mu^+\mu^-) \leq 0.2 \text{ fb}$$

For a 2TeV Z-prime to explain the *WW* excess, it requires $c_\phi \sim 0.9 - 0.94$, but it violates $e^+e^-/\mu^+\mu^-$ bounds

G(221) Models: Breaking Pattern 2



$$\Phi = \begin{pmatrix} \phi^0 & \sqrt{2}\phi^+ \\ \sqrt{2}\phi^- & \phi^0 \end{pmatrix}$$

$$\langle \Phi \rangle = \frac{1}{2}\begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$$

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix}$$

$$\langle H \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}$$

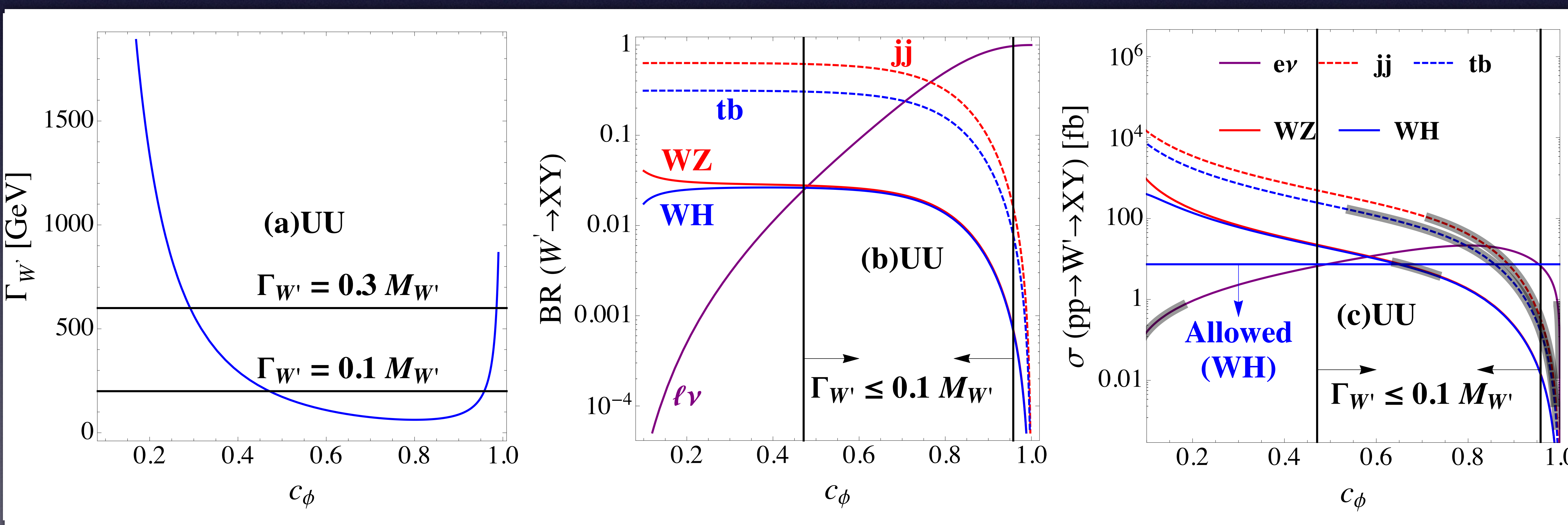
$$g_1 = \frac{e}{s_W c_\phi} \quad g_2 = \frac{e}{s_W s_\phi} \quad g_X = \frac{e}{c_W}$$

$$M_{W'}^2 = M_{Z'}^2 = \frac{e^2 v^2}{4 s_W^2 s_\phi^2 c_\phi^2}(x + s_\phi^4)$$

G(221) BPII: Un-unified Models

$SU(2)_1$	$SU(2)_2$	$U(1)_X$	
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	Y_{SM}	for all the SM fermions

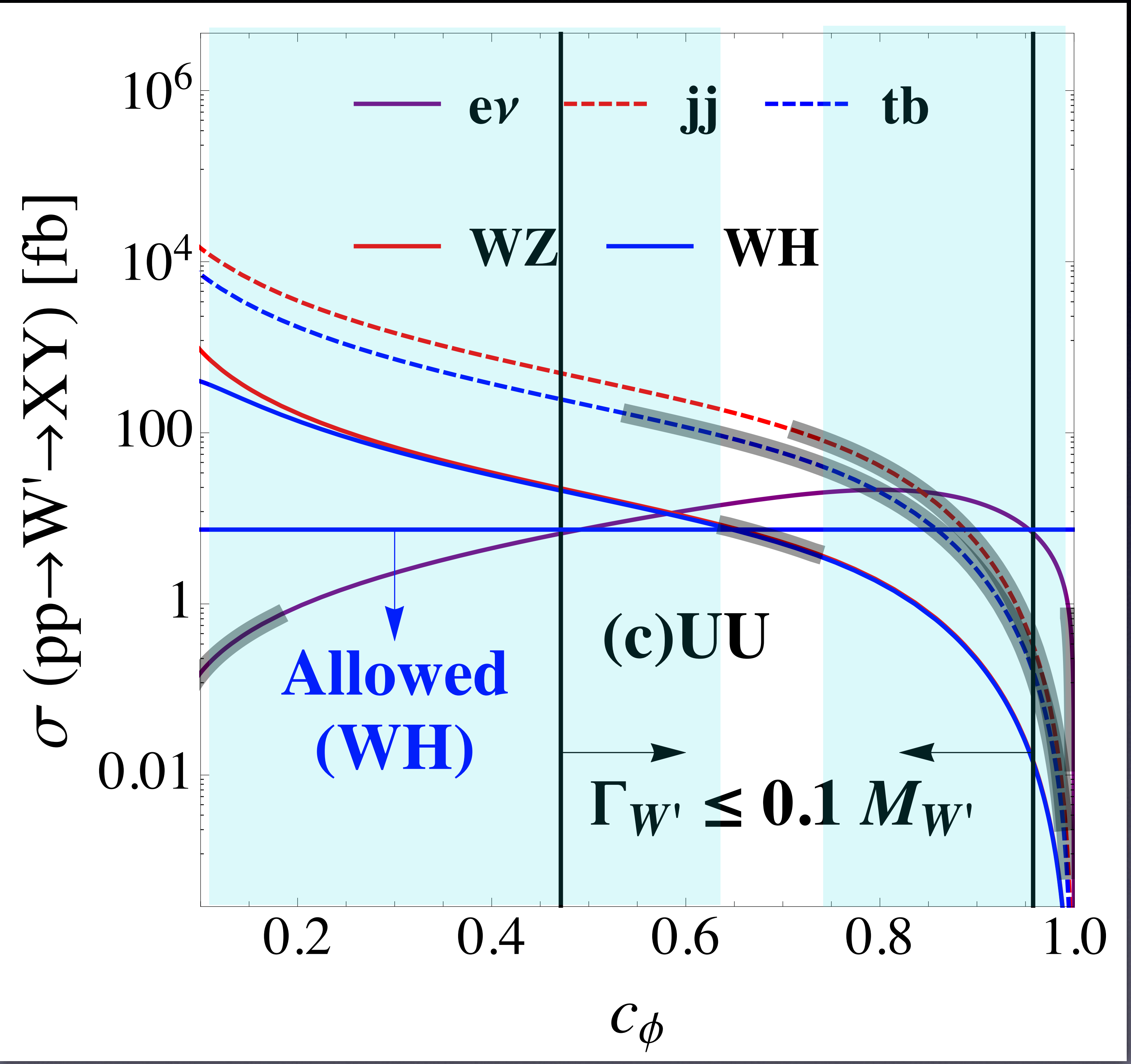
$M_{W'} = 2\ \mathrm{TeV}$



It satisfies $WZ/WH/tb/jj$ at 2σ CL but violates $e^+\nu$

G(221) BPII: Un-unified Models

$M_{W'} = 2$ TeV

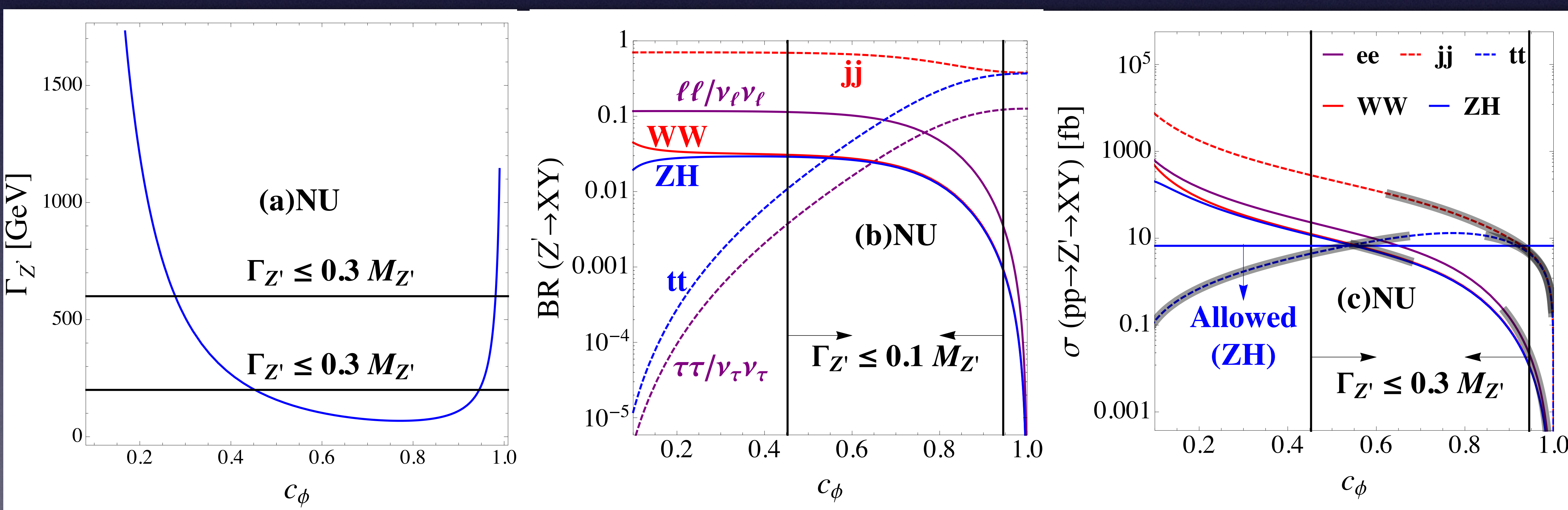


It satisfies $WZ/WH/tb/jj$ at 2σ CL but violates $e^+\nu$

G(221) BPII: Un-unified Models

$SU(2)_1$	$SU(2)_2$	$U(1)_X$	
$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	Y_{SM}	for all the SM fermions

$M_{Z'} = 2$ TeV



It satisfies $WW/ZH/tt/jj$ at 2σ CL but violates e^+e^-

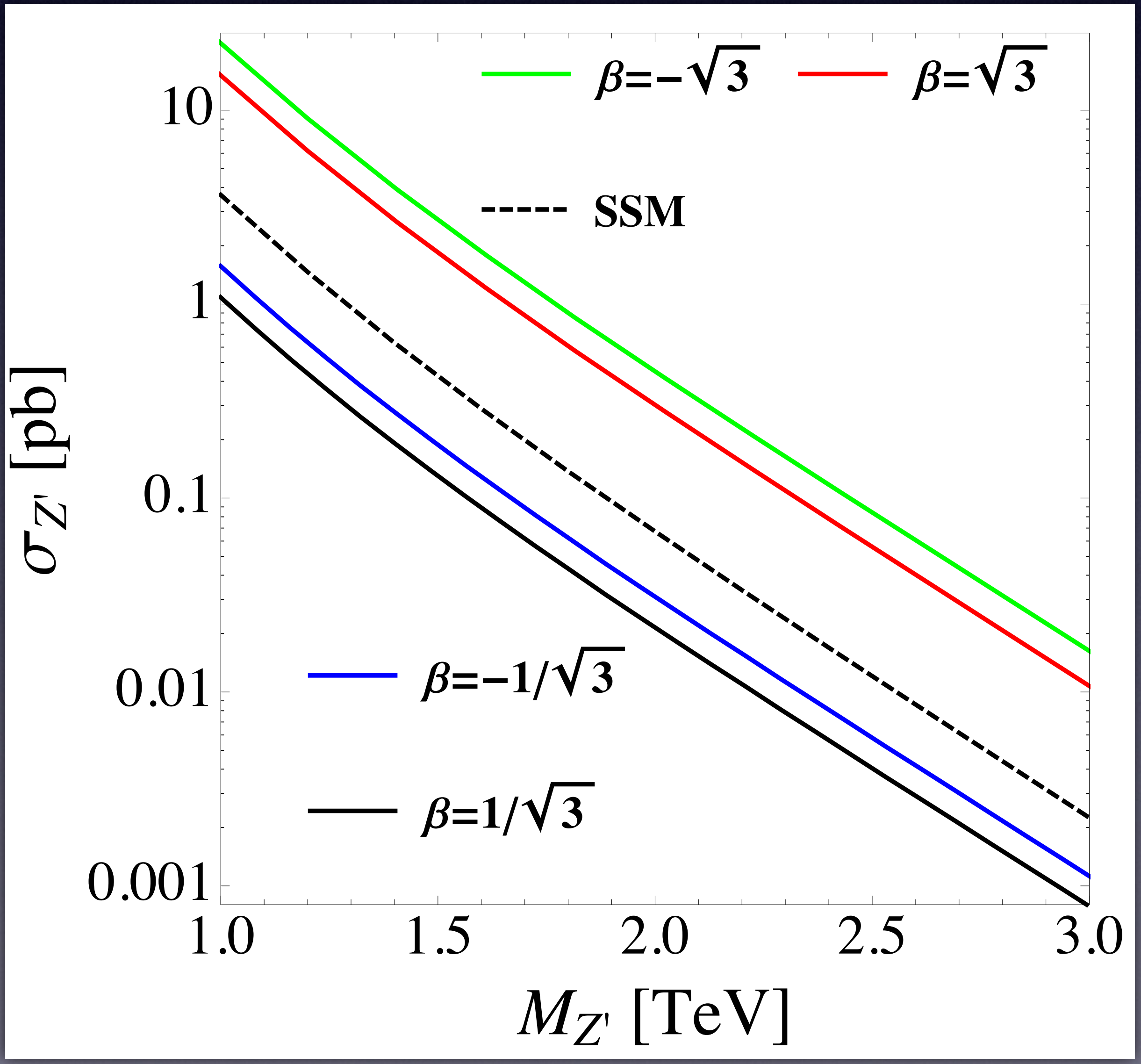
G(331) Models

$$SU(3)_L \times U(1)_X \to SU(2)_L \times U(1)_Y \to U(1)_{\text{em}}$$

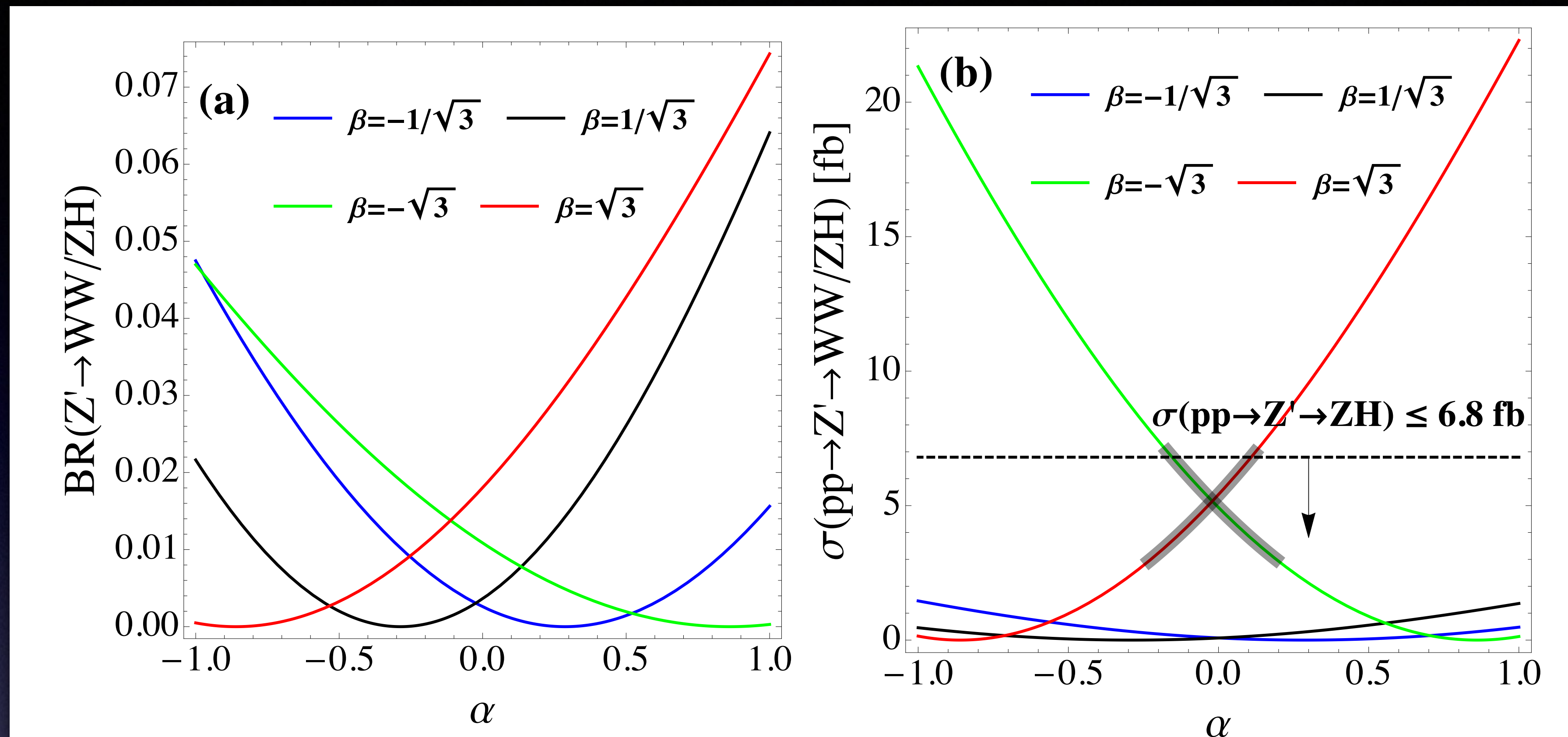
$$\langle\rho\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_\rho \\ 0 \end{pmatrix} \quad \langle\eta\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} v_\eta \\ 0 \\ 0 \end{pmatrix} \quad \langle\chi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ 0 \\ v_\chi \end{pmatrix}$$

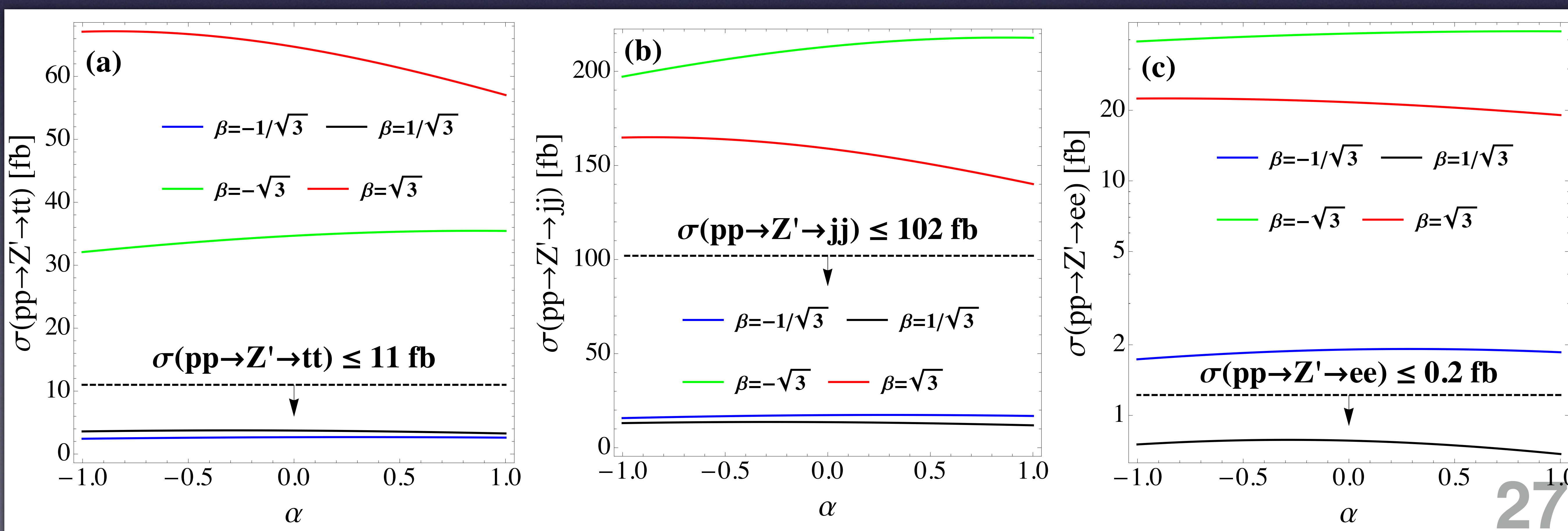
$W'WZ$ coupling forbidden

$Z'WW$ coupling induced by $Z'-Z$ mixing



G(331) Models: WW production





Summary

1) We consider simple non-Abelian extensions to explain the WZ / WW / ~~ZZ~~ excesses observed by ATLAS collaboration.

2) We found that tensions exist among the diboson excesses and leptonic decay modes.

3) Luckily for us, it will be clear when LHC Run-2 data comes.

Thank you!

Backup Slides

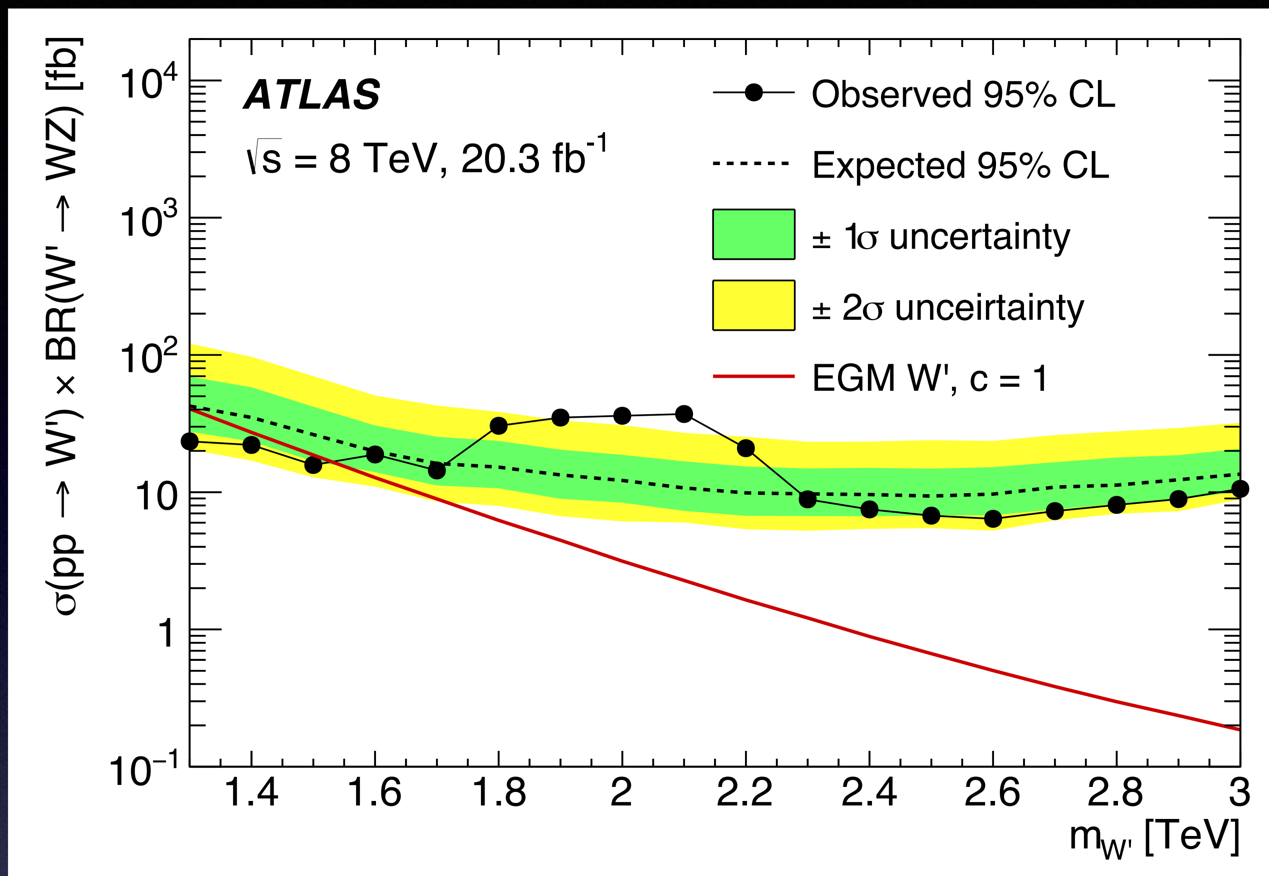
W'/Z' Coupling to SM Fermions

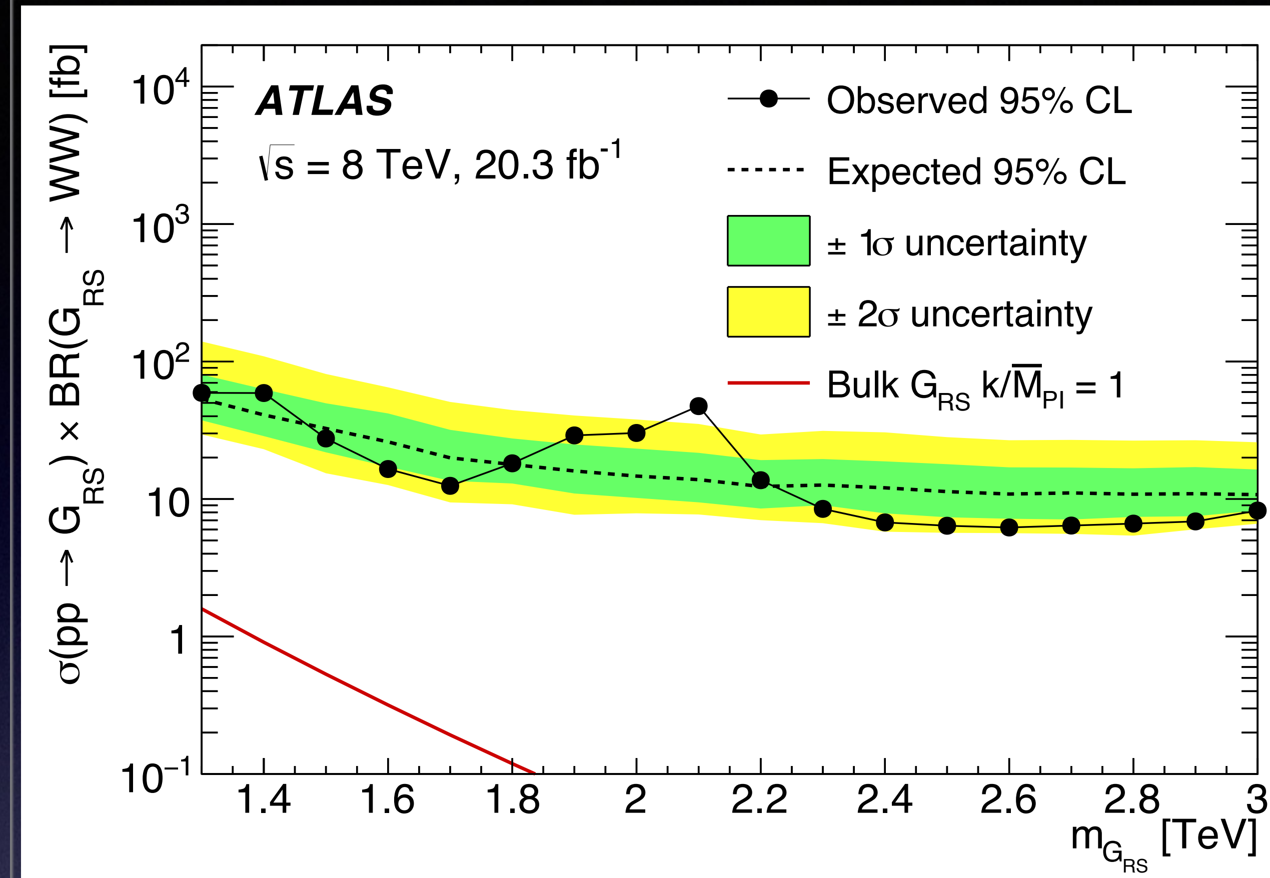
Couplings	g_L	g_R
$W'^{+\mu}\bar{f}f'$ (BP-I)	$-\frac{e_m}{\sqrt{2}s_W^2}\gamma_\rho T_L^+ \frac{c_W s_{2\beta} s_\phi}{x}$	$\frac{e_m}{\sqrt{2}c_W s_\phi}\gamma_\rho T_R^+$
$Z'\bar{f}f$ (BP-I)	$\frac{e_m}{c_W c_\phi s_\phi}\gamma_\rho\left[(T_{3L}-Q)\,s_\phi^2 - \frac{c_\phi^4 s_\phi^2\,(T_{3L}-Qs_W^2)}{x s_W^2}\right]$	$\frac{e_m}{c_W c_\phi s_\phi}\gamma_\rho\left[(T_{3R}-Qs_\phi^2)+Q\frac{c_\phi^4 s_\phi^2}{x}\right]$
$W'^{\pm\mu}\bar{f}f'$ (BP-II)	$-\frac{e_m s_\phi}{\sqrt{2}s_W c_\phi}\gamma^\mu T_l^\pm\left(1+\frac{s_\phi^2 c_\phi^2}{x}\right)$	0
$W'^{\pm\mu}\bar{F}F'$ (BP-II)	$\frac{e_m c_\phi}{\sqrt{2}s_W s_\phi}\gamma^\mu T_h^\pm\left(1-\frac{s_\phi^4}{x}\right)$	0
$Z'\bar{f}f$ (BP-II)	$-\frac{e_m}{s_W}\gamma^\mu\left[\frac{s_\phi}{c_\phi}T_{3l}\left(1+\frac{s_\phi^2 c_\phi^2}{x c_W^2}\right)-\frac{s_\phi}{c_\phi}\frac{s_\phi^2 c_\phi^2}{x c_W^2}s_W^2 Q\right]$	$\frac{e_m}{s_W}\gamma^\mu\left(\frac{s_\phi}{c_\phi}\frac{s_\phi^2 c_\phi^2}{x c_W^2}s_W^2 Q\right)$
$Z'\bar{F}F$ (BP-II)	$\frac{e_m}{s_W}\gamma^\mu\left[\frac{c_\phi}{s_\phi}T_{3h}\left(1-\frac{s_\phi^4}{x c_W^2}\right)+\frac{c_\phi}{s_\phi}\frac{s_\phi^4}{x c_W^2}s_W^2 Q\right]$	$\frac{e_m}{s_W}\gamma^\mu\left(\frac{c_\phi}{s_\phi}\frac{s_\phi^4}{x c_W^2}s_W^2 Q\right)$

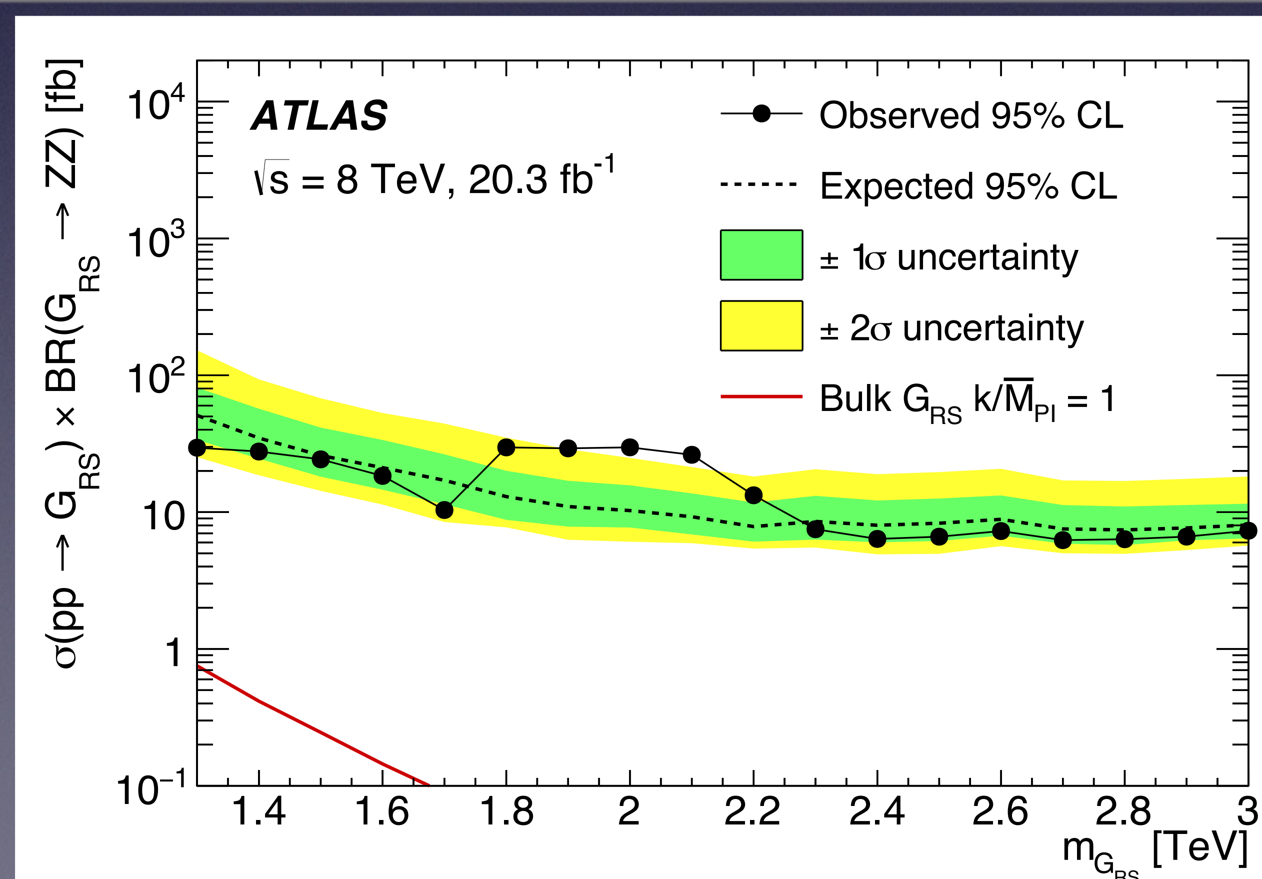
W'/Z' Non-Abelian Coupling

Couplings	BP-I	BP-II
$H\ W_\nu\ W'_\rho$	$-\frac{i}{2}\frac{e_m^2 s_{2\beta}}{c_W s_W s_\phi} v g_{\nu\rho}\left[1+\frac{\left(c_W^2 s_\phi^2 - s_W^2\right)}{x s_W^2}\right]$	$-\frac{i}{2}\frac{e_m^2 s_\phi}{s_W^2 c_\phi} v g_{\nu\rho}\left[1+\frac{s_\phi^2\left(c_\phi^2 - s_\phi^2\right)}{x}\right]$
$H\ Z_\nu\ Z'_\rho$	$-\frac{i}{2}\frac{e_m^2 c_\phi}{c_W^2 s_W s_\phi} v g_{\nu\rho}\left[1-\frac{c_\phi^2\left(c_\phi^2 s_W^2 - s_\phi^2\right)}{x s_W^2}\right]$	$-\frac{i}{2}\frac{e_m^2 s_\phi}{c_W s_W^2 c_\phi} v g_{\nu\rho}\left[1-\frac{s_\phi^2\left(s_\phi^2 c_W^2 - c_\phi^2\right)}{x c_W^2}\right]$
$W_\mu^+\ W_\nu'^-\ Z_\rho$	$i\frac{e_m s_{2\beta} s_\phi}{x s_W^2}$	$i\frac{e_m c_\phi s_\phi^3}{x s_W c_W}$
$W_\mu^+\ W_\nu^-\ Z'_\rho$	$i\frac{e_m s_\phi c_W c_\phi^3}{x s_W^2}$	$i\frac{e_m c_\phi s_\phi^3}{x s_W}$

ATLAS results (1506.00962)

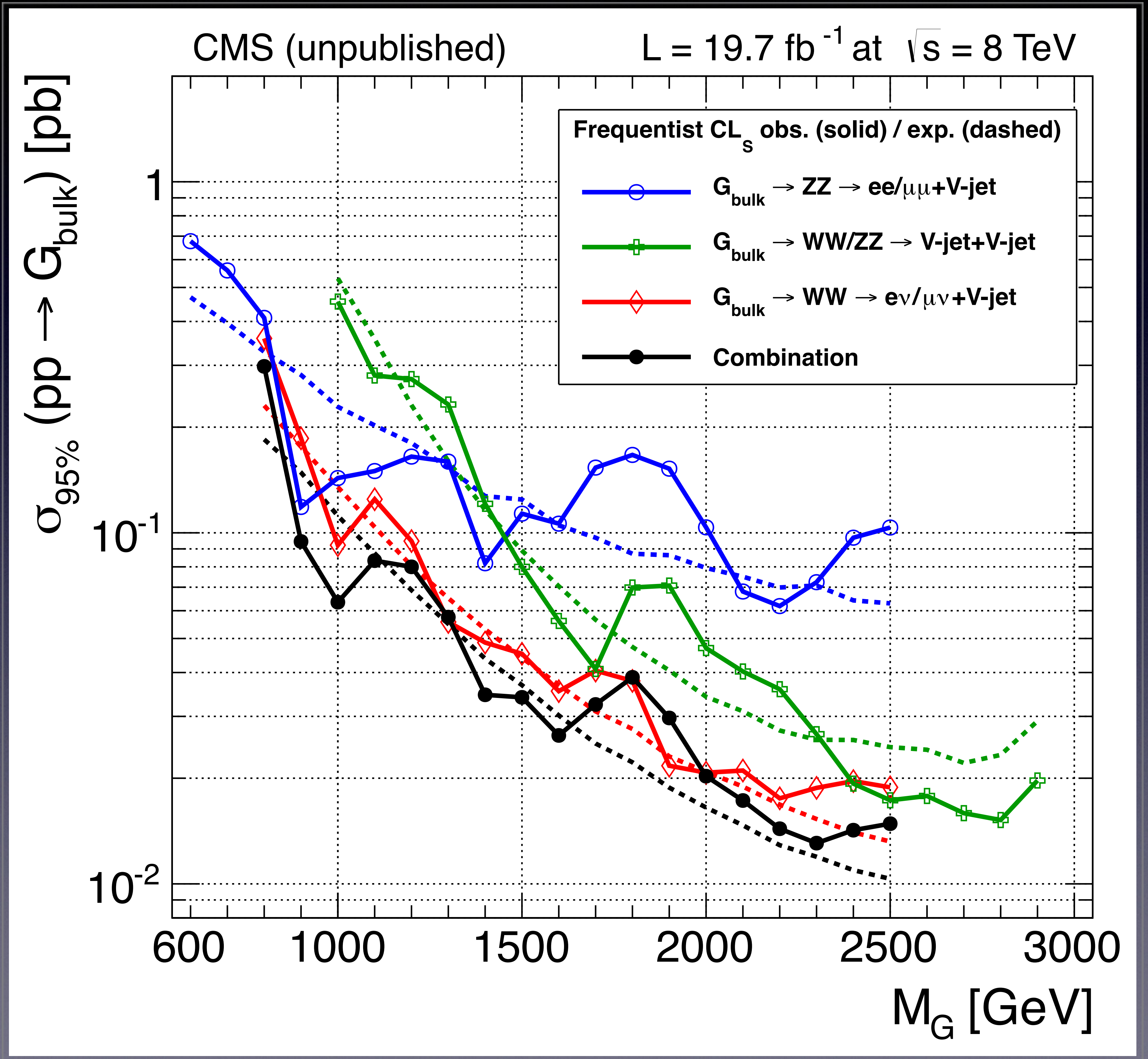




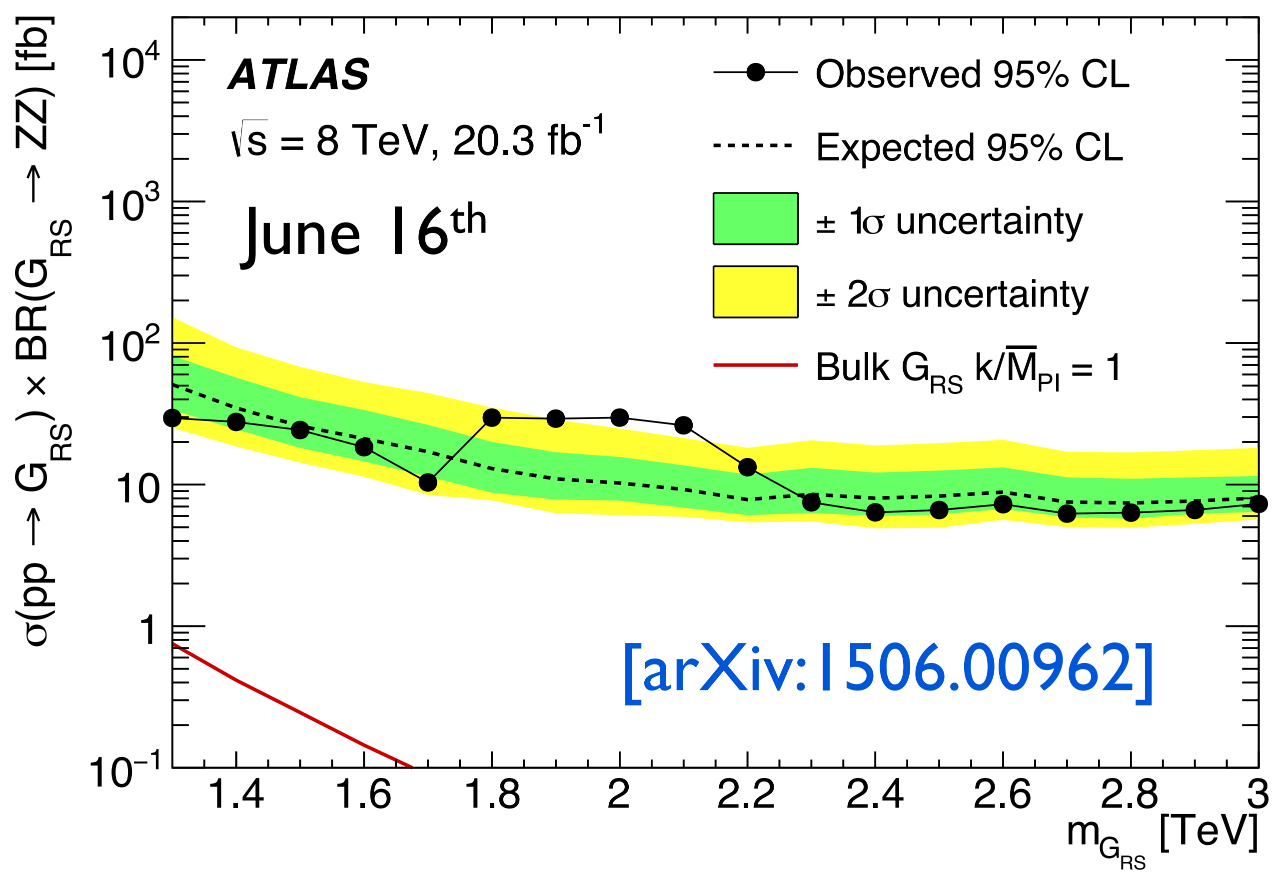


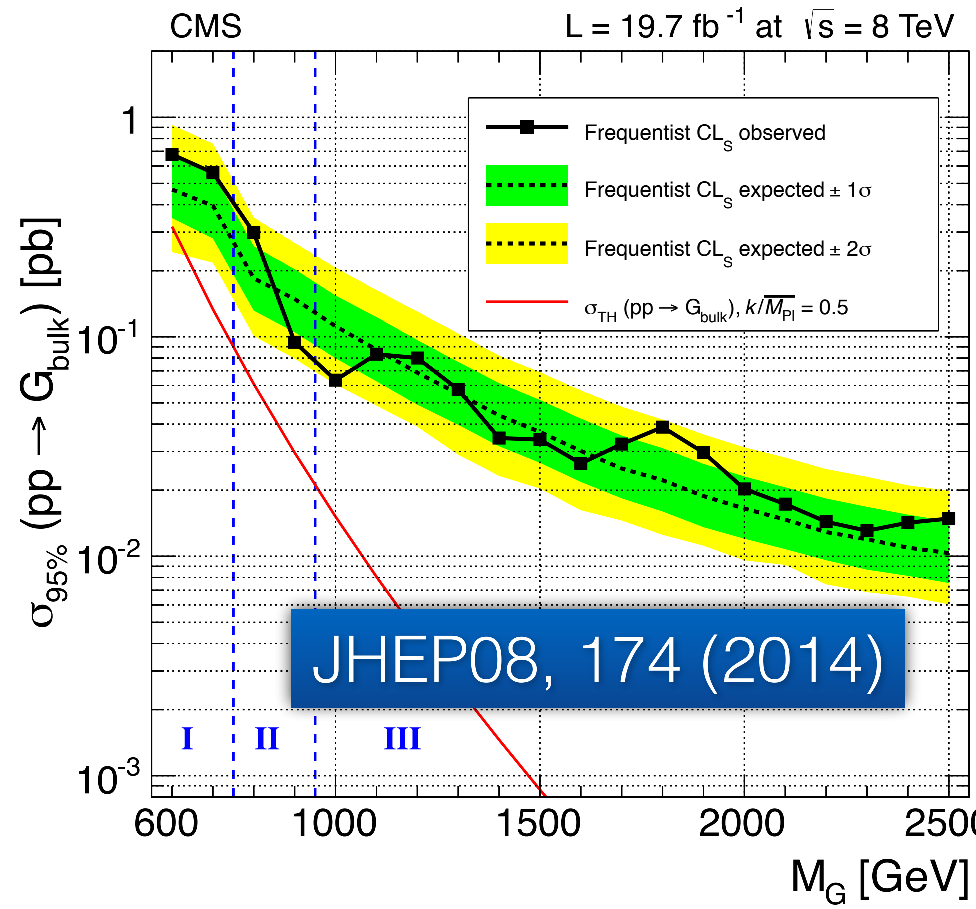
CMS: Diboson Bounds

See Qiang Li's talk



ATLAS versus CMS





Comparable sensitivity on $\sigma_{95\%}$(pp→G) x BR(G→ZZ)

Deviations from expected limit at 1.8 - 2.0 TeV (if larger than 1σ):

local p-values

	CMS	**ATLAS**
V_{jet} V_{jet}	1.3σ	3.4σ (2.5σ global)
ℓℓ V_{jet}	2σ	-
ℓν V_{jet}	1.2σ	-