RS Z'/W' at a Muon Collider

GuiYu Huang

University of California, Davis

MUON COLLIDER WORKSHOP, FERMILAB

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Kaustubh Agashe, Hooman Davoudiasl, Shrihari Gopalakrishna
Tao Han, Gilad Perez, Zong-Guo Si, Amarjit Soni

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Warped Extra Dimension

RS in the bulk

- Also explains flavor hierarchy with field profile (or wavefunction) in extra dimension
- Mass and couplings explained by overlappings of profiles

$$C^{FFG}_{mnq} = \int \frac{d\phi}{\sqrt{k}} \frac{e^{t\sigma}\ \chi_F^{(m)} \chi_F^{(n)} \chi_G^{(q)}}{\sqrt{R}} .$$

Gauge Symmetry

Bulk Gauge Group

Neglecting $SU(3)_C$,

$$SU(2)_L \times SU(2)_R \times U(1)_X$$
$$\Rightarrow \text{(BoundaryCondition)}\ SU(2)_L \times U(1)_Y$$
$$\Rightarrow \text{(HiggsMechanism)}\ U(1)_Q$$

$$Y = T_{3R} + X,\ Q = T_{3L} + Y/2.$$

Gauge Bosons

- Charged: $W_L^{\pm}, W_R^{\pm}$
- Neutral:

$$W_L^3, W_R^3, X$$
$$\Rightarrow W_L^3, B, Z_X$$
$$\Rightarrow A, Z, Z_X$$

Only A, Z, W_L have zero-mode, W_R, Z_x don't. (-+) BC

Representations

- Higgs $\Sigma = (2,2)$

Fermions

- $Q_L = (2,2) = \begin{pmatrix} t_L & \chi_L \\ b_L & T_L \end{pmatrix}$
- $t_R = (1,1)\ or\ (1,3) \in (1,3) \oplus (3,1) = \begin{pmatrix} \chi''_R \\ t_R \\ B''_R \end{pmatrix} \oplus \begin{pmatrix} \chi'''_R \\ T'''_R \\ B'''_R \end{pmatrix}$
- Case (i): $t_R \to (1,1)$, $c_{Q_L^3} = 0$, $c_{t_R} = 0.4$.
- Case (ii): $t_R \to (1,3)$, $c_{Q_L^3} = 0.4$, $c_{t_R} = 0$.

- $Zb\bar{b}$: protected
- Precision EW constraints

Mass Spectrum

Mass term for zero mode and 1st excitations:

$$\begin{pmatrix} Z^{(0)} & Z^{(1)} & Z'^{(1)} \end{pmatrix} \mathcal{M}_Z^2 \begin{pmatrix} Z^{(0)} \\ Z^{(1)} \\ Z'^{(1)} \end{pmatrix}$$

$$\mathcal{M}_Z^2 =$$

$$\begin{pmatrix} m_Z^2 & m_Z^2\sqrt{2k\pi R} & -m_Z^2\sqrt{2k\pi R}\frac{g_{Z'}}{g_Z}c_W'^2 \\ m_Z^2\sqrt{2k\pi R} & m_{KK}^2 + m_Z^2 2k\pi R & -m_Z^2\ 2k\pi R\frac{g_{Z'}}{g_Z}c_W'^2 \\ -m_Z^2\sqrt{2k\pi R}\frac{g_{Z'}}{g_Z}c_W'^2 & -m_Z^2\ 2k\pi R\frac{g_{Z'}}{g_Z}c_W'^2 & 0.963\ m_{KK}^2 + m_Z^2 2k\pi R\left(\frac{g_{Z'}}{g_Z}c_W'^2\right)^2 \end{pmatrix}$$

$$m_{Z_1} \sim m_{KK}\,, \quad m_{Z_{1x}} \sim 0.981 m_{KK}$$

$$m_{A_1} = m_{KK}$$

Mass Spectrum

Mass term for zero mode and 1st excitations:

$$\begin{pmatrix} W_L^{+\,(0)} & W_{L_1}^{+} & W_{R_1}^{+} \end{pmatrix} \mathcal{M}_W^2 \begin{pmatrix} W_L^{-\,(0)} \\ W_{L_1}^{-} \\ W_{R_1}^{-} \end{pmatrix}$$

$$\mathcal{M}_W^2 =$$

$$\begin{pmatrix} m_W^2 & m_W^2\sqrt{k\pi R} & -m_W^2\sqrt{k\pi R}\,\frac{g_R}{g} \\ m_W^2\sqrt{k\pi R} & m_{KK}^2 + m_W^2 k\pi R & -m_W^2 k\pi R\,\frac{g_R}{g} \\ -m_W^2\sqrt{k\pi R}\,\frac{g_R}{g_L} & -m_W^2 k\pi R\,\frac{g_R}{g} & 0.963\, m_{KK}^2 + m_W^2 k\pi R\left(\frac{g_R}{g}\right)^2 \end{pmatrix}$$

$$m_{W_{1L}} \sim m_{KK}\,, \quad m_{W_{1R}} \sim 0.981 m_{KK}$$

Mixings

$$
\begin{aligned}
g' &= \frac{g_X g_R}{\sqrt{g_R^2 + g_X^2}} \ , \ s' = \frac{g_X}{\sqrt{g_R^2 + g_X^2}} \ , \ c' = \sqrt{1 - s'^2} \ , \\
e &= \frac{g_L g'}{\sqrt{g'^2 + g_L^2}} \ , \ s_W = \frac{g'}{\sqrt{g'^2 + g_L^2}} \ , \ c_W = \sqrt{1 - s_W^2} \ , \\
g_Z &= g_L / c_W \ , \ g_{Z'} = g_R / c' \ .
\end{aligned}
$$

For $g_R = g_L$, $s' = 0.55$, $c' = 0.84$.

$$
\sin\theta_{01} \approx \left(\frac{M_Z}{M_{Z_1}}\right)^2 \sqrt{k\pi R} \ ,
$$

$$
\sin\theta_{01X} \approx -\left(\frac{M_Z}{M_{Z_{X1}}}\right)^2 \left(\frac{g_{Z'}}{g_Z}\right) c'^2 \sqrt{k\pi R} \ .
$$

$$
\sin\theta_{0L} \approx \left(\frac{M_W}{M_{W_{L_1}}}\right)^2 \sqrt{k\pi r_c} \ ,
$$

$$
\sin\theta_{0R} \approx -\left(\frac{M_W}{M_{W_{R_1}}}\right)^2 \left(\frac{g_R}{g_L}\right) \sqrt{k\pi r_c} \ .
$$

Mixings

$$\tan 2\theta_1 = \frac{-2M_Z^2 (g_{Z'}/g_Z) c'^2 k\pi R}{(M_{Z_{X\,1}}^2 - M_{Z_1}^2) + M_Z^2 \left((g_{Z'}/g_Z)^2 c'^4 - 1\right) k\pi R} \ .$$

$$\tan 2\theta_1^c = \frac{-2M_W^2 (g_R/g_L) k\pi R}{(M_{W_{R_1}}^2 - M_{W_{L_1}}^2) + M_W^2 \left((g_R/g_L)^2 - 1\right) k\pi R} \ .$$

For $m_{KK} = 2000$ GeV

$s_1 = 0.48$, $c_1 = 0.88$; $\quad s_1^c = 0.6$, $c_1^c = 0.8$.

Couplings

$$\frac{g_{\rm RS}^{q\bar{q},l\bar{l}A^{(1)}}}{g_{\rm SM}} \simeq -\xi^{-1} \approx -\frac{1}{5}$$

$$\frac{g_{\rm RS}^{Q^3\bar{Q}^3A^{(1)}}}{g_{\rm SM}}, \frac{g_{\rm RS}^{t_R\bar{t}_RA^{(1)}}}{g_{\rm SM}} \simeq 1 \text{ to } \xi \ (\approx 5)$$

$$\frac{g_{\rm RS}^{HHA^{(1)}}}{g_{\rm SM}} \simeq \xi \approx 5 \quad (H = h, W_L, Z_L)$$

$$\frac{g_{\rm RS}^{A^{(0)}A^{(0)}A^{(1)}}}{g_{\rm SM}} \sim 0$$

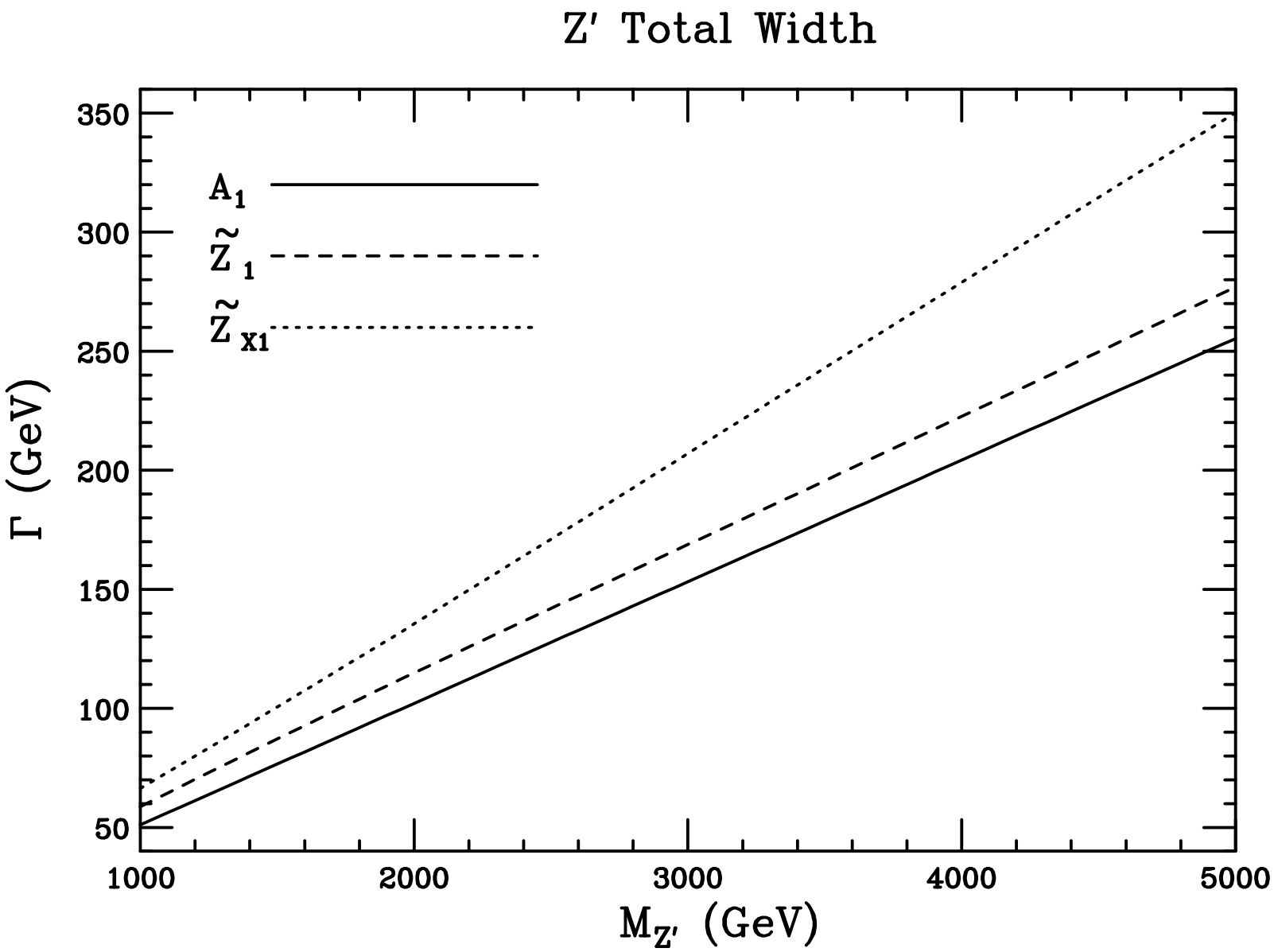
$$\xi \equiv \sqrt{k\pi R}$$

$c_{Q_L^3} = 0, c_{t_R} = 0.4$	Q_L^3	t_R	other fermions
$\mathcal{I}^{++}_{++,++}$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} \approx -0.2$
$\mathcal{I}^{++}_{-+,-+}$	ξ	ξ	$-$
$\mathcal{I}^{-+}_{++,-+}$	$0.8\xi \approx 4.6$	$0.4\xi \approx 2.3$	≈ 0

$c_{Q_L^3} = 0.4, c_{t_R} = 0$	Q_L^3	t_R	other fermions
$\mathcal{I}^{++}_{++,++}$	$-\frac{1.13}{\xi} + 0.2\xi \approx 1$	$-\frac{1.13}{\xi} + 0.7\xi \approx 3.9$	$-\frac{1.13}{\xi} \approx -0.2$
$\mathcal{I}^{++}_{-+,-+}$	ξ	ξ	$-$
$\mathcal{I}^{-+}_{++,-+}$	$0.4\xi \approx 2.3$	$0.8\xi \approx 4.6$	≈ 0

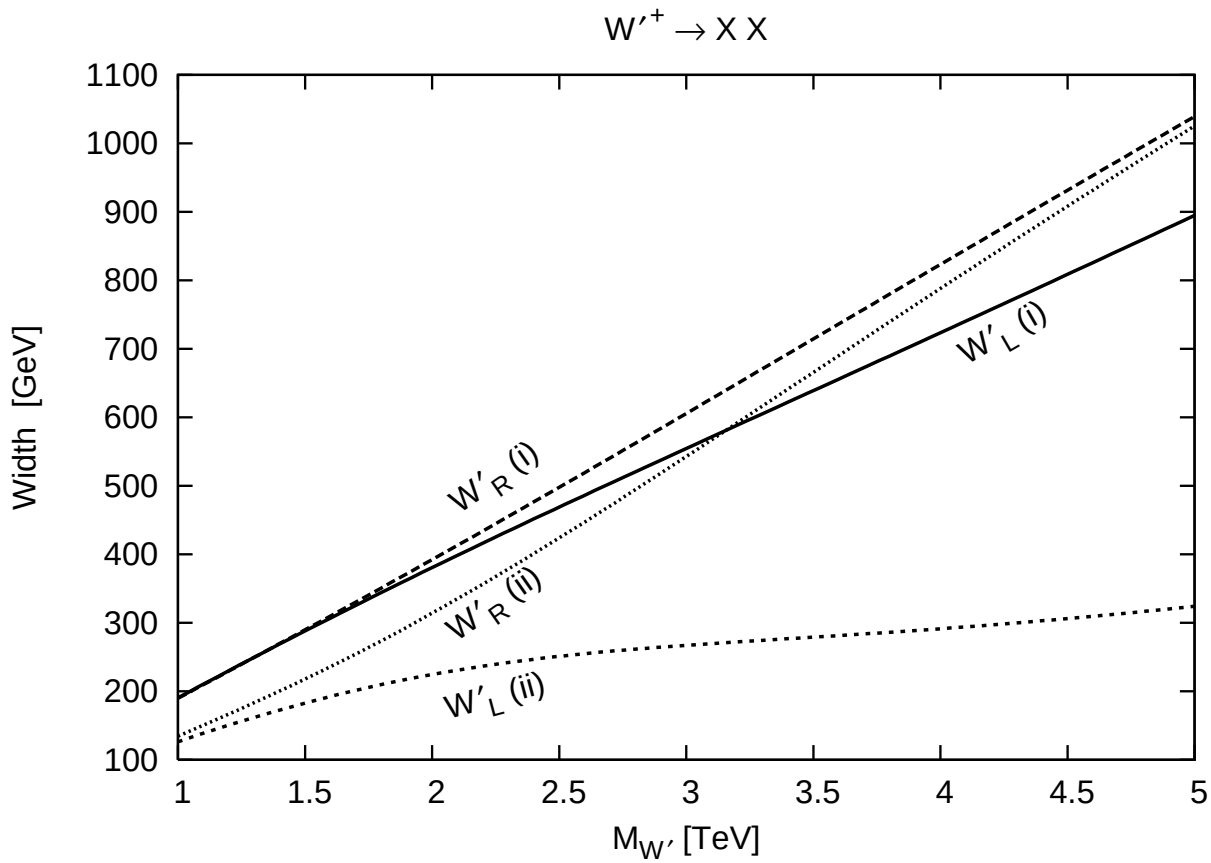
Table: Values of $\psi\psi W'^{\pm}$ overlap integrals. $\xi = \sqrt{k\pi r_c} = 5.83$. All SM fermions have (++) BC, ”exotic” BSM fermions have $(-+)$, W_{L_1} has (++), and, W_{R_1} has $(-+)$ BC.

Z' Widths



Not very narrow resonances. Scanning might not help a lot.

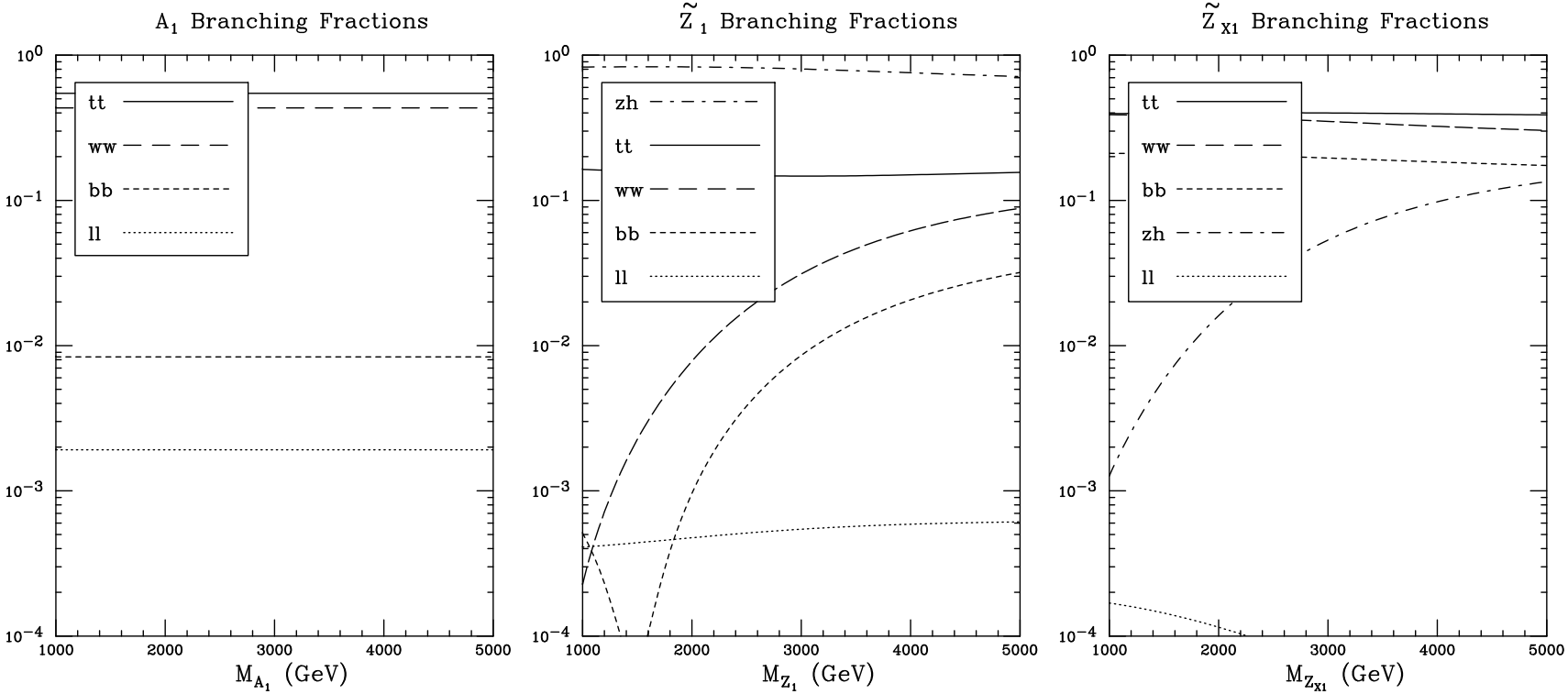
W' Widths



Case (i): $t_R \to (1,1)$, $c_{Q_L^3} = 0$ and $c_{t_R} = 0.4$. All the other c's > 0.5

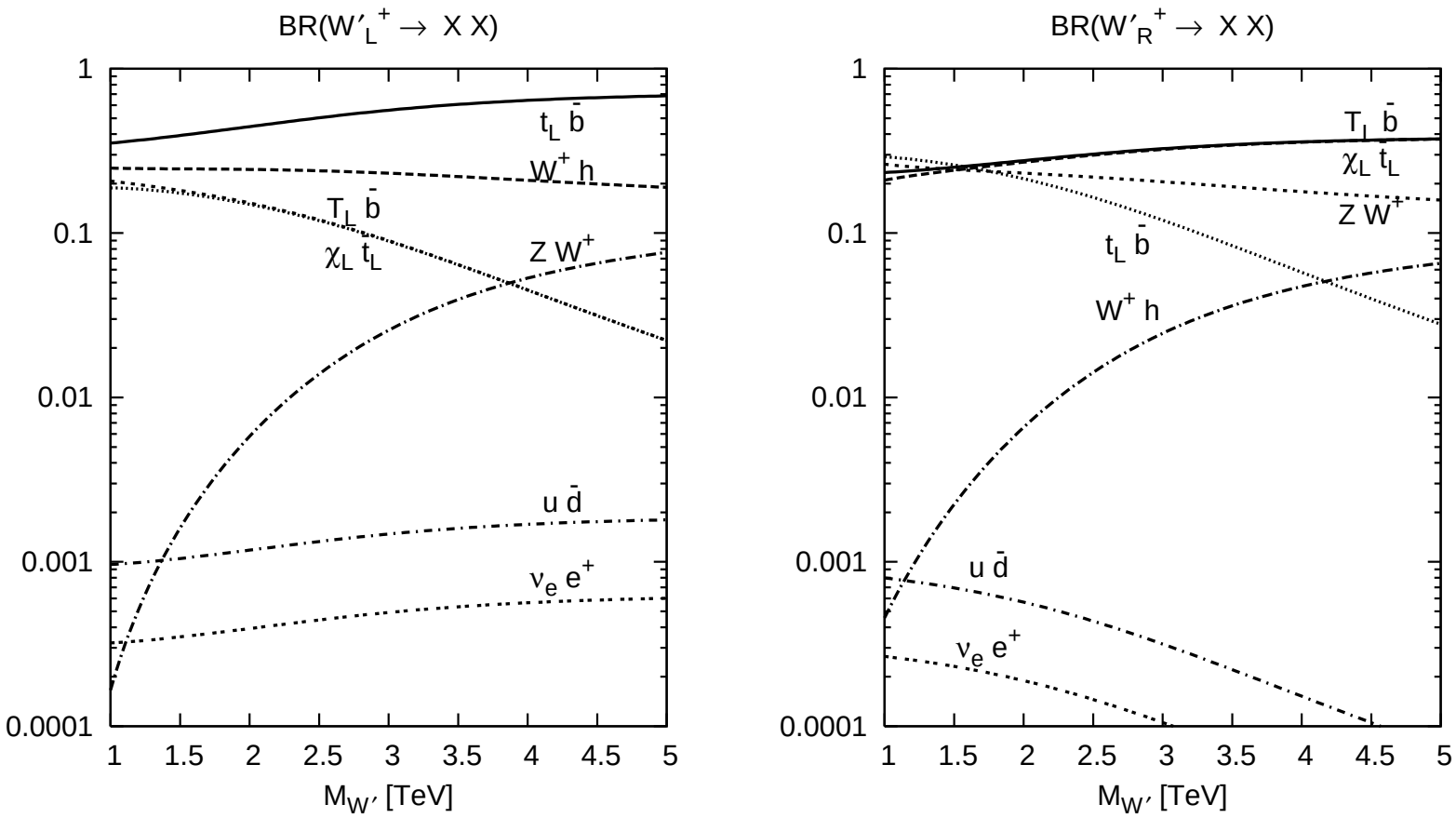
Case (ii): $t_R \to (1,3)$, $c_{Q_L^3} = 0.4$ and $c_{t_R} = 0$. All the other c's > 0.5

Z' Branchings



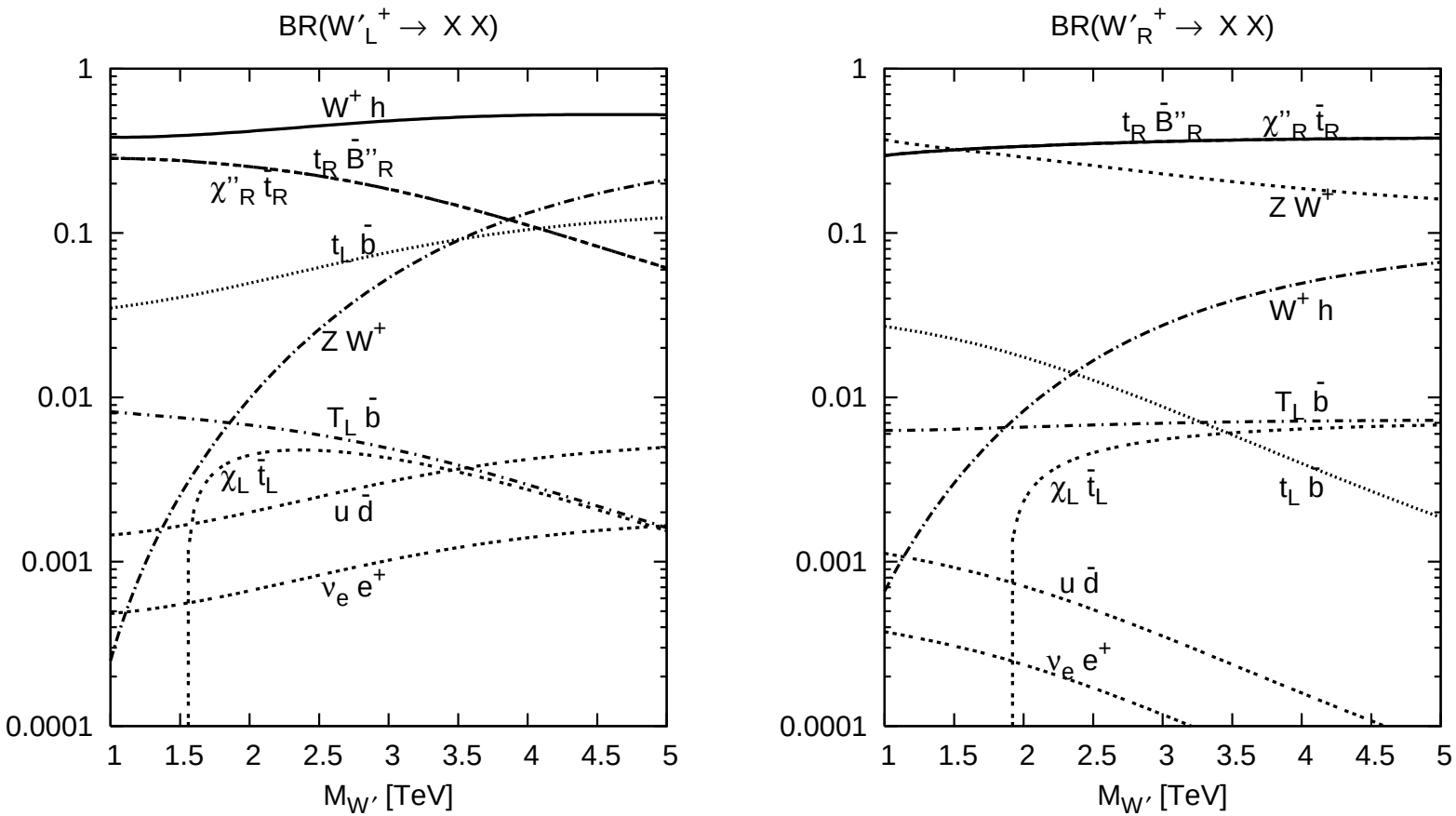
▶

W' Branchings



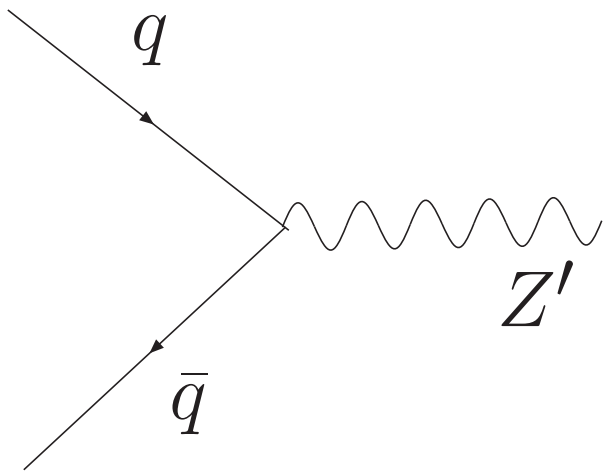
Case (i)

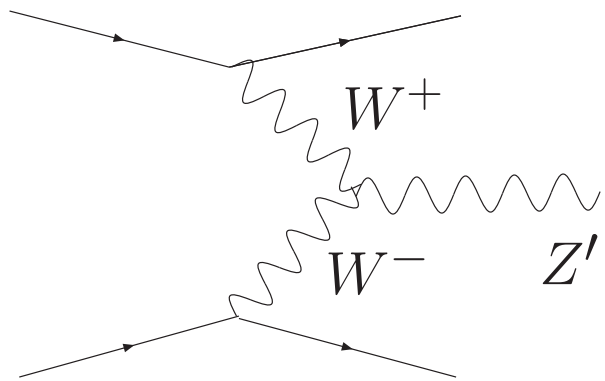
W' Branchings



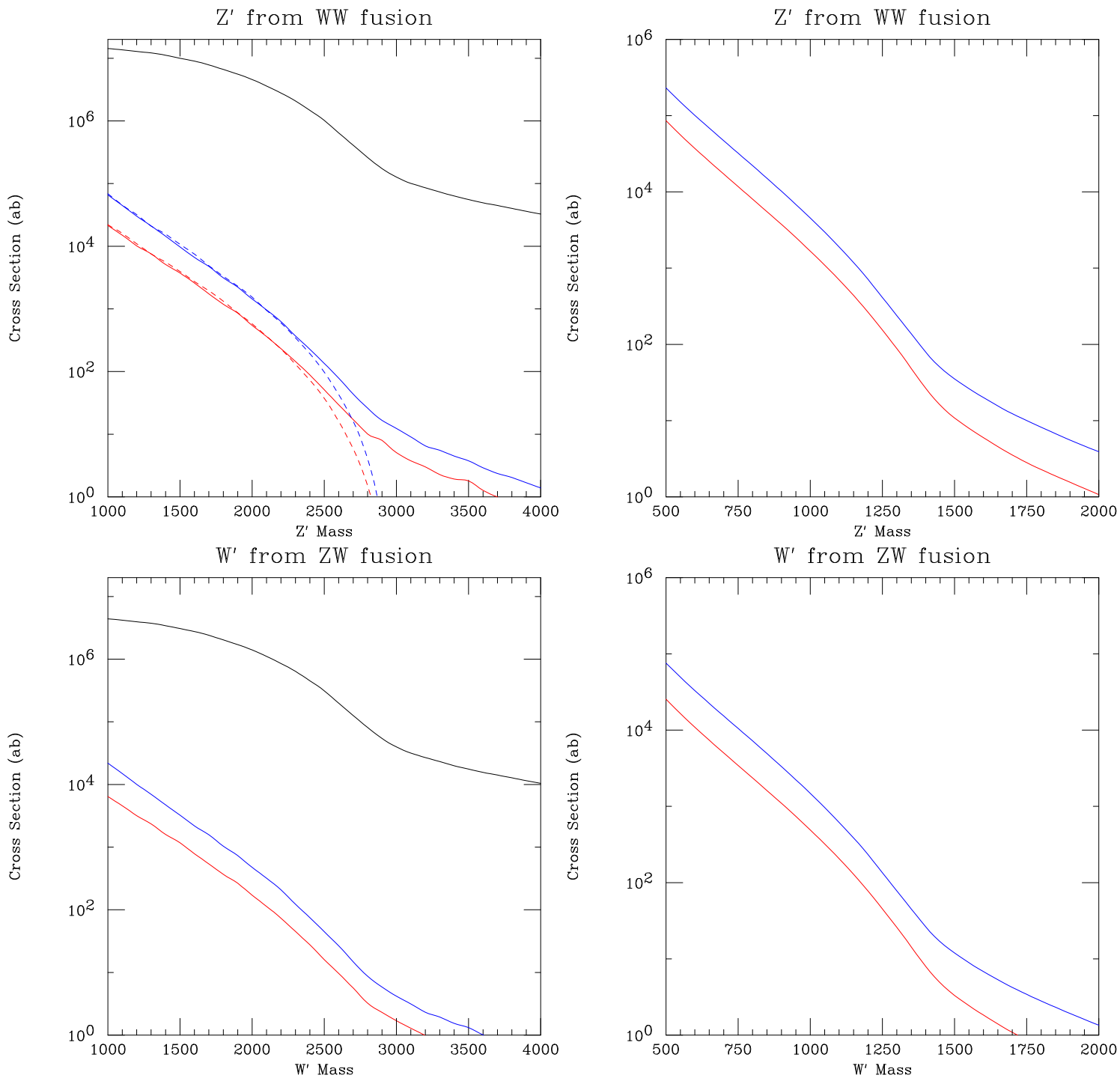
Case (ii)

Productions





- Drell-Yan $\mu\mu \to Z'$
- W Associated Production $\mu\mu \to Z/Z' \to WW'$
- Weak Boson Fusion

No Direct Production of W'

Weak Boson Fusion