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EWKKDM

Seong Chan Park (Yonsei Univ.)

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with T. Flacke(IBS, CTPU), D.W. Kang(Yonsei),
KC Kong (Kansas), G. Mohlabeng (BNL)

motivation

- unless primordial black holes dominate the whole DM amount, we need something additional…
- among O(100) theoretical ideas, KK DM is still an attractive one
- and its full phenomenology is still to be clarified (interestingly!)

Kaluza-Klein Dark Matter

- **Any Symmetric extra dimension** (flat or warped)
- If LKP is a neutral EW particle, it is a good DM candidate because of KK-parity
- **KK-B_1** (=KK photon) has been studied extensively as **RGEs say so within mUED** framework.

EW KK gauge boson

- **In general**, however, the LKP is a mixture of KK excitation modes of neutral EW gauge bosons:

$$\chi = aB_1 + bW_1^3$$

s=1

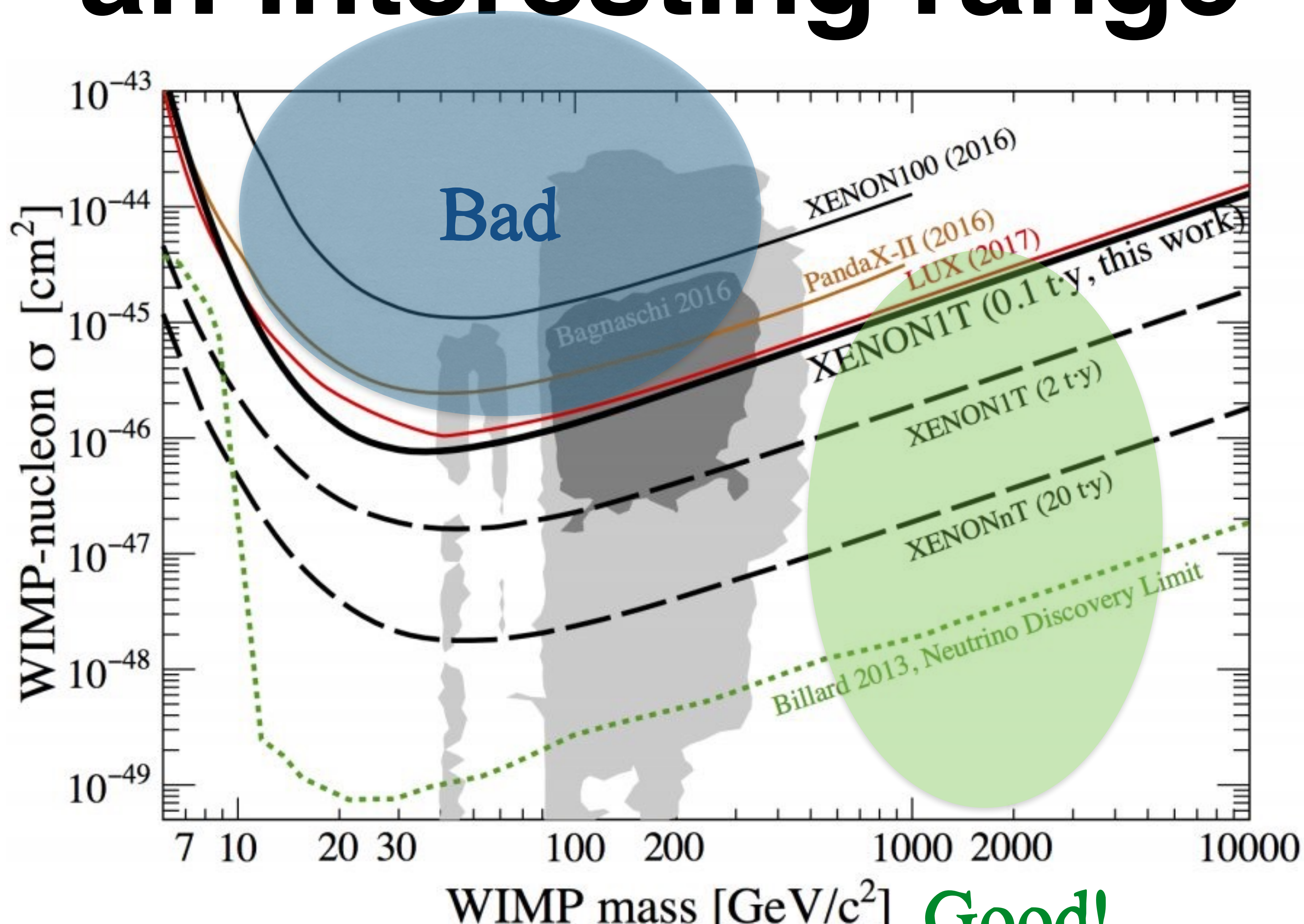
- Just like neutralino

$$\tilde{\chi} = a\tilde{B} + b\tilde{W}^3 + c\tilde{h}_1 + d\tilde{h}_2$$

s=1/2

- **Phenomenology heavily depends on "a" and "b"** and these are controlled by "**BLKT's**" => we study this carefully.

We found: KK DM locates in an interesting range



Good!
KKDM is here

MODEL: general UED

a review: Flacke, Kong and SCP arXiv:1408.4024

- 5D bulk: S_1/Z_2 ~ [-L, L] (but ANY symmetric space is fine)
- Same gauge symmetries with the SM
- 5D Fermions ~Dirac fields (**with bulk masses**, in general) chiral zero modes =SM fermions
- 5D Gauge bosons (**with boundary localized kinetic terms**, in general) zero modes = SM gauge bosons
- KK particles = heavy modes with definite KK-parity
- **LKP** = the lightest KK neutral gauge boson (B & W) = DM

Bulk Lagrangian

$$S_5 = \int d^4x \int_{-L}^{L} dy \, [\mathcal{L}_V + \mathcal{L}_\Psi + \mathcal{L}_H + \mathcal{L}_{\rm Yuk}]$$

$$\begin{aligned}
\mathcal{L}_V &= \sum_{\mathcal{A}}^{G,W,B} -\frac{1}{4}\mathcal{A}^{MN}\cdot\mathcal{A}_{MN}\,, \\
\mathcal{L}_\Psi &= \sum_{\Psi}^{Q,U,D,L,E} i\overline{\Psi} D_M \Gamma^M \Psi\,, \\
\mathcal{L}_H &= (D_\mu H)^\dagger D^\mu H + \mu_5^2 |H|^2 - \lambda_5 |H|^4\,, \\
\mathcal{L}_{\rm Yuk} &= \lambda_5^E \overline{L} H E + \lambda_5^D \overline{Q} H D + \lambda_5^U \overline{Q}\tilde{H} D + \text{h.c.}
\end{aligned}$$

$$[\mathcal{A}_M] = [H] = \text{Mass}^{3/2}$$

$$[\hat{g}_i] = \text{Mass}^{-1/2}$$

$$[\Psi] = \text{Mass}^2$$

$$[\mu_5] = \text{Mass}$$

$$[\lambda_5^\Psi] = \text{Mass}^{-1/2}$$

$$D_M = \partial_M + i\hat{g}_3 \lambda\cdot G_M + i\hat{g}_2 \tau\cdot W_M + i\hat{g}_1 Y B_M$$

Boundary Lagrangian

@ boundaries, 4D Lorentz symmetry respected

$$S_{bdy} = \int d^4x \int_{-L}^{L} dy \left(-\frac{r_W}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{r_B}{4} B_{\mu\nu} B^{\mu\nu},\right) [\delta(y-L) + \delta(y+L)]$$

$$[r_W] = [r_B] = \mathrm{Mass}^{-1}$$

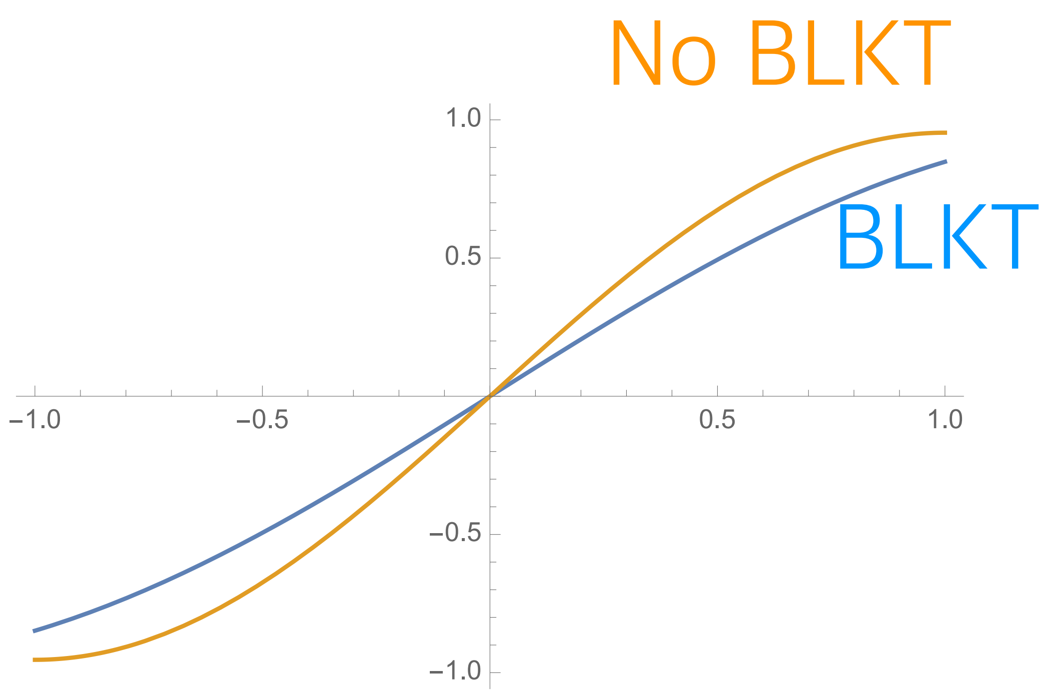
Symmetric

(cf) In 'minimal' UED model, $r_W(\Lambda) = 0 = r_B(\Lambda)$

then induced at low scale via RGE $r_W(\mu) \neq 0 \neq r_B(\mu)$

effects of BLKT

Large r => more expels from the boundary
=> flatten wave function => lighter KK mass



wave function of 1st KK mode

Wave functions w/o BLTs

$$f^e(y) = \begin{cases} f_0^e & = & \sqrt{\frac{1}{2L}}\,, \\ f_{2n}^e & = & \sqrt{\frac{1}{L}}\cos\frac{2ny}{R}\,, \\ f_{2n+1}^e & = & \sqrt{\frac{1}{L}}\sin\frac{(2n+1)y}{R} \end{cases}\,,$$

$$f^o(y) = \begin{cases} f_{2n+1}^o & = & \sqrt{\frac{1}{L}}\cos\frac{(2n+1)y}{R}\,, \\ f_{2n}^o & = & \sqrt{\frac{1}{L}}\sin\frac{2ny}{R}\,, \end{cases}$$

$$\Psi(x,y) = \sum_n \psi_L^n(x) f_L^n(y) + \psi_R^n(x) f_R^n(y)$$

$$[f^{e/o}] = \mathrm{Mass}^{1/2} = \mathrm{Length}^{-1/2}$$

orthogonality $$\int_{-L}^{L} dy f_n^* f_m = \delta_{mn}$$

KK spectra $$m^2_{\Phi^{(n)}} = (n/R)^2 + m^2_{\Phi^{(0)}}$$

Wave functions with BLKTs

$$f_n^{W/B}(y) = \begin{cases} \mathcal{N}_0^{W/B} & \text{if } n = 0, \\ \mathcal{N}_n^{W/B} \sin(k_n^{W/B} y) & \text{if } n = odd, \\ \mathcal{N}_n^{W/B} \cos(k_n^{W/B} y) & \text{if } n = even, \end{cases}$$

$$W_\mu(x,y) = \sum_{n=0}^{\infty} W_\mu^{(n)}(x) f_n^W(y)\,,$$

$$B_\mu(x,y) = \sum_{n=0}^{\infty} B_\mu^{(n)}(x) f_n^B(y)\,,$$

$$\mathcal{N}_n^{W/B} = \begin{cases} \frac{1}{\sqrt{2L(1+\frac{r_{W/B}}{L})}} & \text{if } n = 0, \\ \frac{1}{\sqrt{L+r_{W/B}\sin^2(k_n^{W/B}L)}} & \text{if } n = odd, \\ \frac{1}{\sqrt{L+r_{W/B}\cos^2(k_n^{W/B}L)}} & \text{if } n = even. \end{cases}$$

$$\int_{-L}^{L} dy\, f_m^{W/B} f_n^{W/B} \left[1 + r_{W/B} \left(\delta(y+L) + \delta(y-L)\right)\right] = \delta_{mn}$$

orthogonality

$$\begin{aligned} \cot(k_n^{W/B}L) &= r_{W/B} k_n^{W/B} & \text{if } n = odd, \\ \tan(k_n^{W/B}L) &= -r_{W/B} k_n^{W/B} & \text{if } n = even\,. \end{aligned}$$

→ KK spectrum

4D effective action

$$S_{4D} \ni \int d^4x \; \Bigg\{ \sum_n \Bigg[-\frac{1}{4} \sum_n B^{(n)\mu\nu} B^{(n)}_{\mu\nu} - \frac{\left(k_n^B\right)^2}{2} B^{(n)\mu} B^{(n)}_{\mu} - \frac{1}{4} \sum_n W^{(n)a\mu\nu} \cdot W^{(n)a}_{\mu\nu} - \frac{\left(k_n^W\right)^2}{2} W^{(n)a\mu} W^{(n)a}_{\mu} \Bigg] + \sum_{m,n} \Bigg[-\frac{\hat{g}_1^2 v^2}{8} \mathcal{F}^{BB}_{mn} B^{(m)\mu} B^{(n)}_{\mu} - \frac{\hat{g}_1 \hat{g}_2 v^2}{8} \mathcal{F}^{WB}_{mn} B^{(m)\mu} W^{(n)3}_{\mu} - \frac{\hat{g}_2^2 v^2}{8} \mathcal{F}^{WW}_{mn} W^{(m)a\mu} W^{(n)a}_{\mu} \Bigg] \Bigg\} ,$$

Wave function overlaps:

$$\mathcal{F}^{BB}_{mn} = \int_{-L}^{L} \frac{dy}{2L} \, f^B_m(y) f^B_n(y) \, ,$$

$$\mathcal{F}^{BW}_{mn} = \int_{-L}^{L} \frac{dy}{2L} \, f^B_m(y) f^W_n(y) \, ,$$

$$\mathcal{F}^{WW}_{mn} = \int_{-L}^{L} \frac{dy}{2L} \, f^W_m(y) f^W_n(y) \, ,$$

Masses of odd modes

$$M^2_{n,odd} = \begin{pmatrix} \left(k_1^B\right)^2 + \frac{\hat{g}_1{}^2\hat{v}^2}{4}\mathcal{F}_{11}^{BB} & \frac{\hat{g}_1\hat{g}_2\hat{v}^2}{4}\mathcal{F}_{11}^{BW} & \cdots \\ \frac{\hat{g}_1\hat{g}_2\hat{v}^2}{4}\mathcal{F}_{11}^{BW} & \left(k_1^W\right)^2 + \frac{\hat{g}_2{}^2\hat{v}^2}{4}\mathcal{F}_{11}^{WW} & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

Mass eigenstates

$$A_{1,2} = a_{1,2}B_1 + b_{1,2}W_1^3$$

the lighter one is LKP = DM

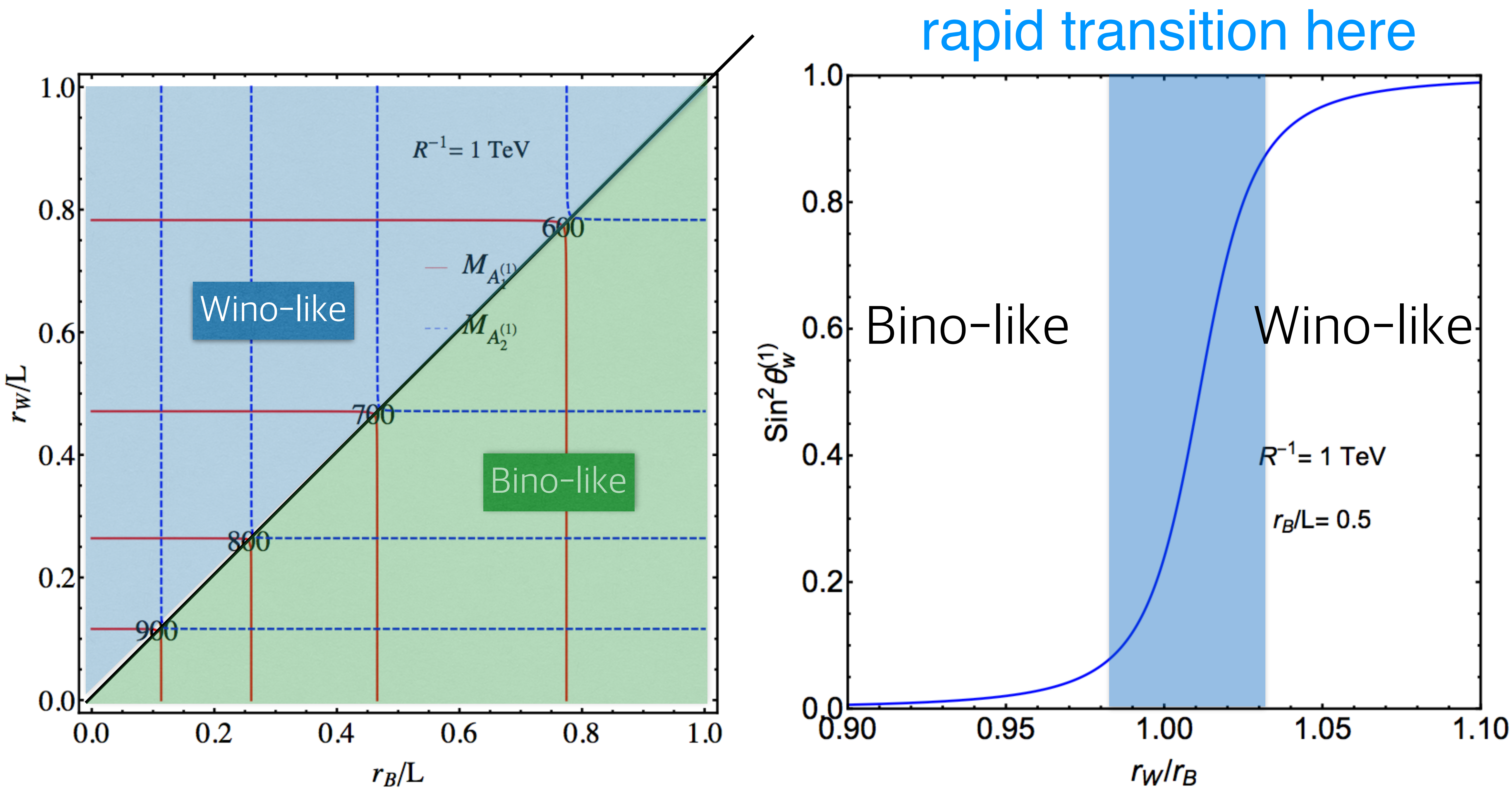


Figure 1: Left: Contours of constant mass for the level 1 electroweak KK bosons $A_1^{(1)}$ and $A_2^{(1)}$. The contours were made assuming $R^{-1} = 1$ TeV, and they show the mass dependence on the boundary terms r_B and r_W. Right: The level 1 KK Weinberg angle $\sin^2\theta_W^{(1)}$ for $R^{-1} = 1$ TeV and $r_B/L = 0.5$.

Mass matrix for neutral gauge bosons (even modes)

basis: $B^{(2n)} - W^{3(2n)}$

$$M_{n,e}^2 = \begin{pmatrix} \frac{\hat{g}_1{}^2 v^2}{4}\mathcal{F}_{00}^{BB} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{00}^{BW} & \frac{\hat{g}_1{}^2 v^2}{4}\mathcal{F}_{02}^{BB} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{02}^{BW} & \cdots \\ \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{00}^{BW} & \frac{\hat{g}_2{}^2 v^2}{4}\mathcal{F}_{00}^{WW} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{02}^{BW} & \frac{\hat{g}_2{}^2 v^2}{4}\mathcal{F}_{02}^{WW} & \cdots \\ \frac{\hat{g}_1{}^2 v^2}{4}\mathcal{F}_{20}^{BB} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{20}^{BW} & \left(k_2^B\right)^2 + \frac{\hat{g}_1{}^2 v^2}{4}\mathcal{F}_{22}^{BB} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{22}^{BW} & \cdots \\ \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{20}^{BW} & \frac{\hat{g}_2{}^2 v^2}{4}\mathcal{F}_{20}^{WW} & \frac{\hat{g}_1\hat{g}_2 v^2}{4}\mathcal{F}_{22}^{BW} & \left(k_2^W\right)^2 + \frac{\hat{g}_2{}^2 v^2}{4}\mathcal{F}_{22}^{WW} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathcal{F}_{mn}^{BB} = \int_{-L}^{L} \frac{dy}{2L}\, f_m^B(y) f_n^B(y)\,,$$

$$\mathcal{F}_{mn}^{BW} = \int_{-L}^{L} \frac{dy}{2L}\, f_m^B(y) f_n^W(y)\,,$$

$$\mathcal{F}_{mn}^{WW} = \int_{-L}^{L} \frac{dy}{2L}\, f_m^W(y) f_n^W(y)\,,$$

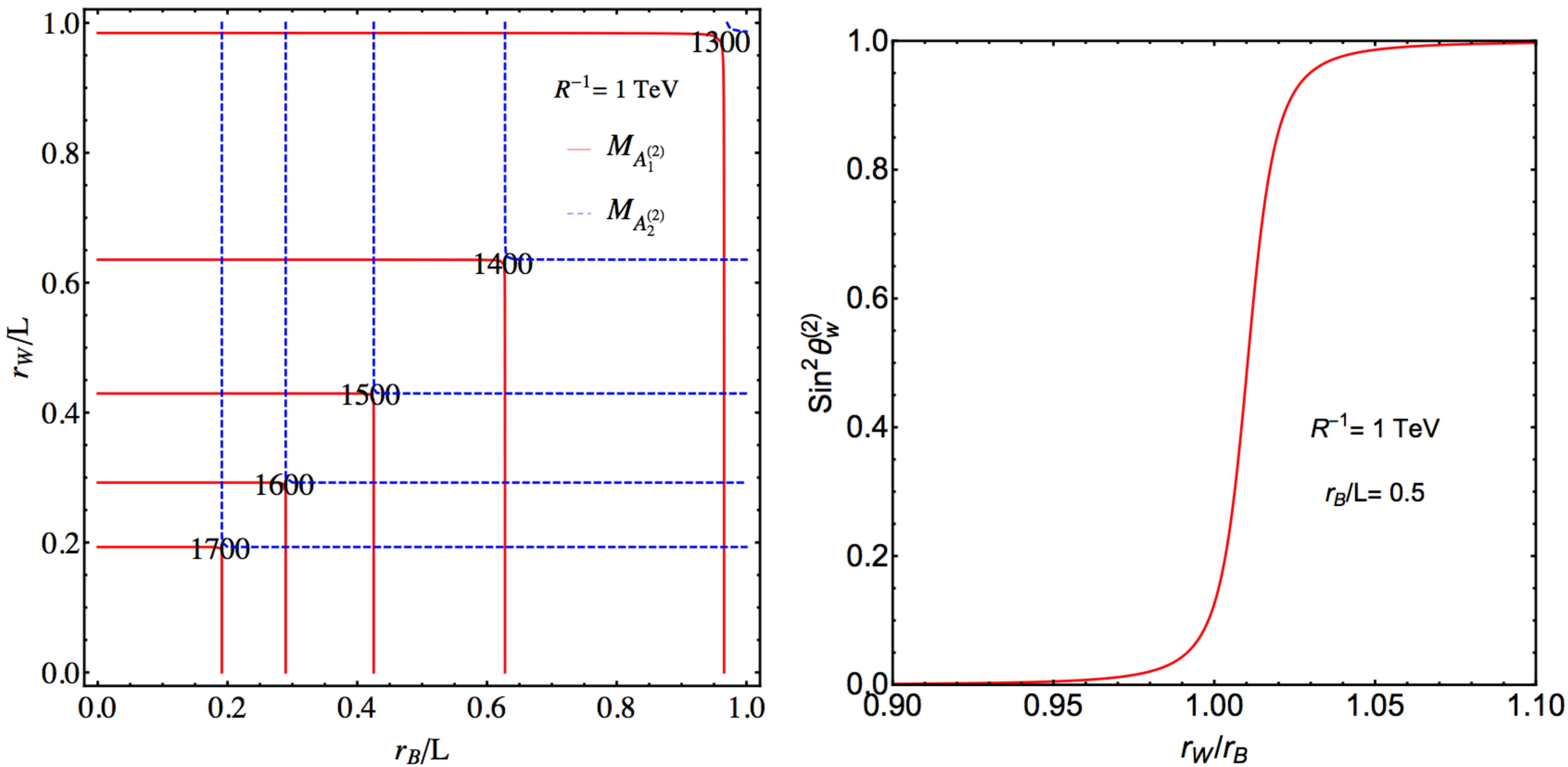
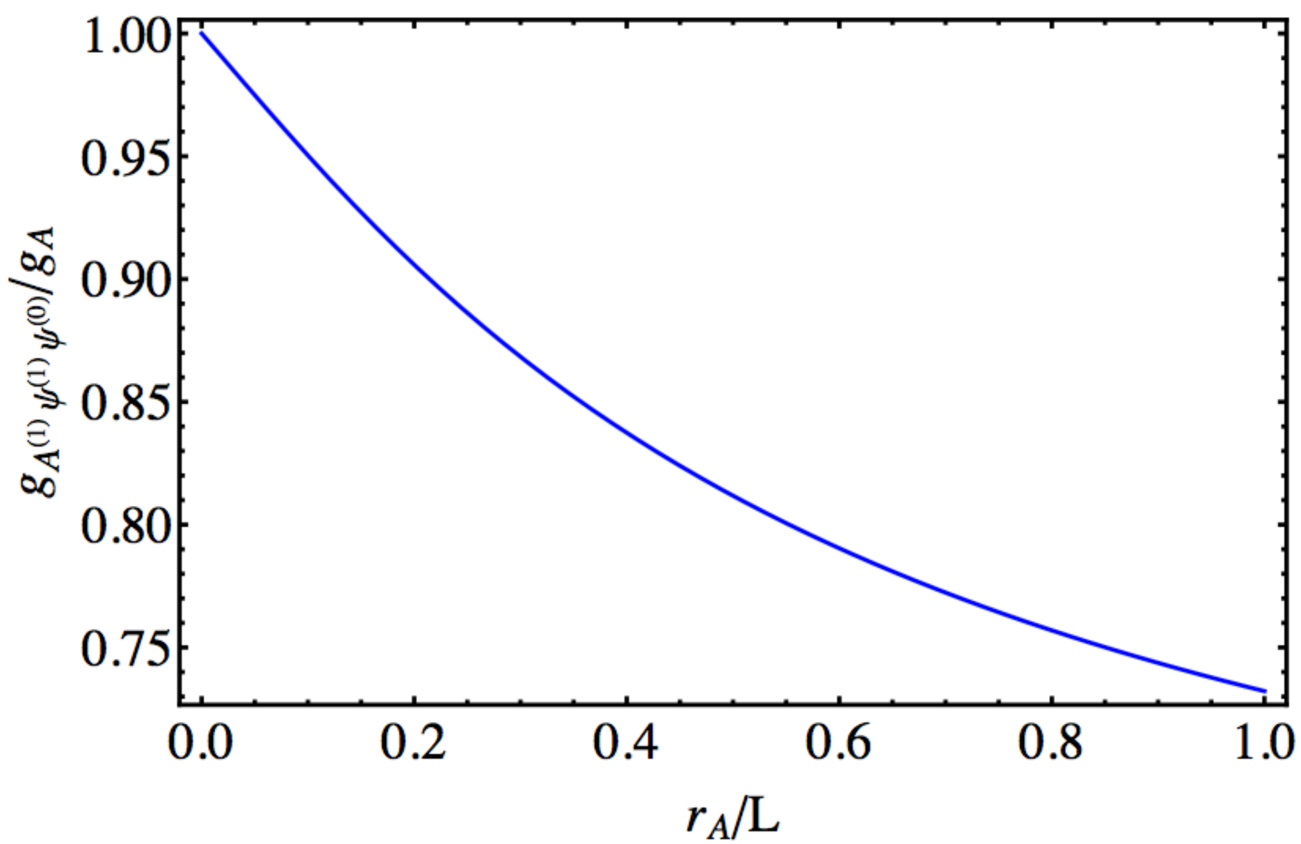


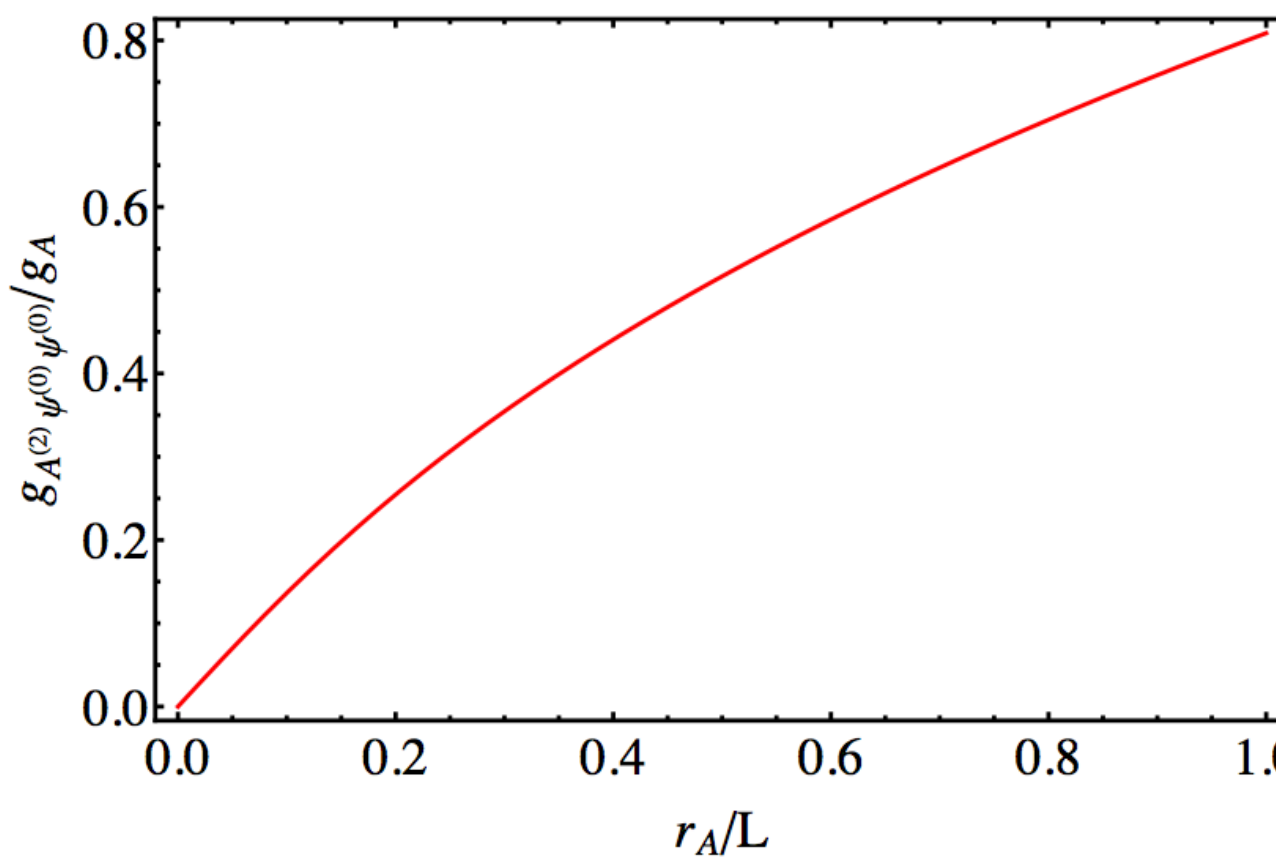
Figure 2: Left: Contours of constant level 2 gauge boson masses for $R^{-1} = 1$ TeV. The red contours show the mass of the lighter eigenstate $A_1^{(2)}$ and the blue contour represents mass of heavier eigenstate $A_2^{(2)}$. Right: The level 2 KK Weinberg angle $\sin^2\theta_W^{(2)}$ for $R^{-1} = 1$ TeV and $r_B/L = 0.5$.

Effective couplings: A-f-f

$$g_{\mathcal{A}^{(\ell)}\psi^{(m)}\psi^{(n)}} = g_{\mathcal{A}}\tilde{\mathcal{F}}^{\mathcal{A}}_{\ell mn}$$

$$\tilde{\mathcal{F}}^{\mathcal{A}}_{\ell mn} \equiv \frac{1}{\mathcal{N}^{\mathcal{A}}_0}\int_{-L}^{L} dy\, f^{\mathcal{A}}_{\ell}(y) f^{\psi}_{m}(y) f^{\psi}_{n}(y),$$

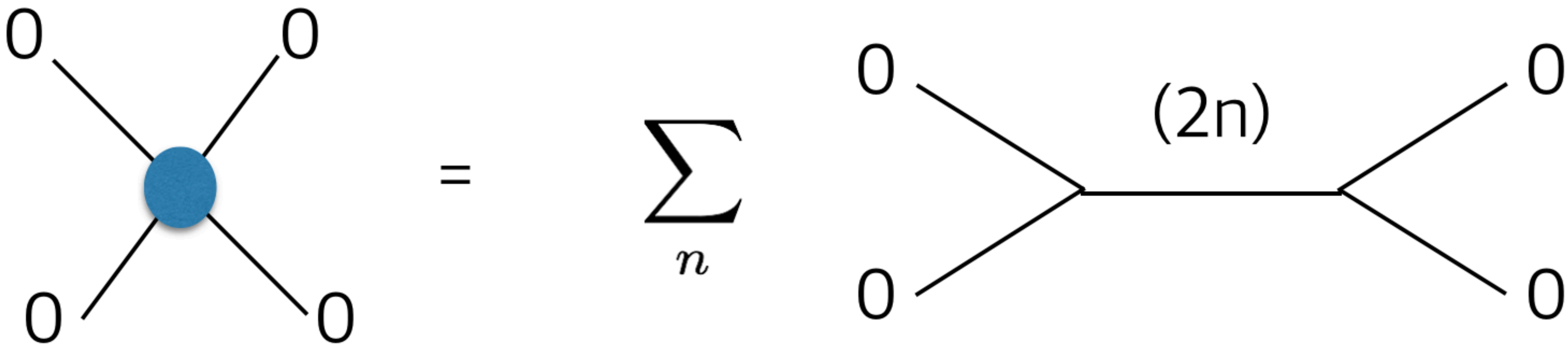




N.B. KK-parity is conserved but KK number is not.

Experimental constraints

Bounds: 4-fermi interactions

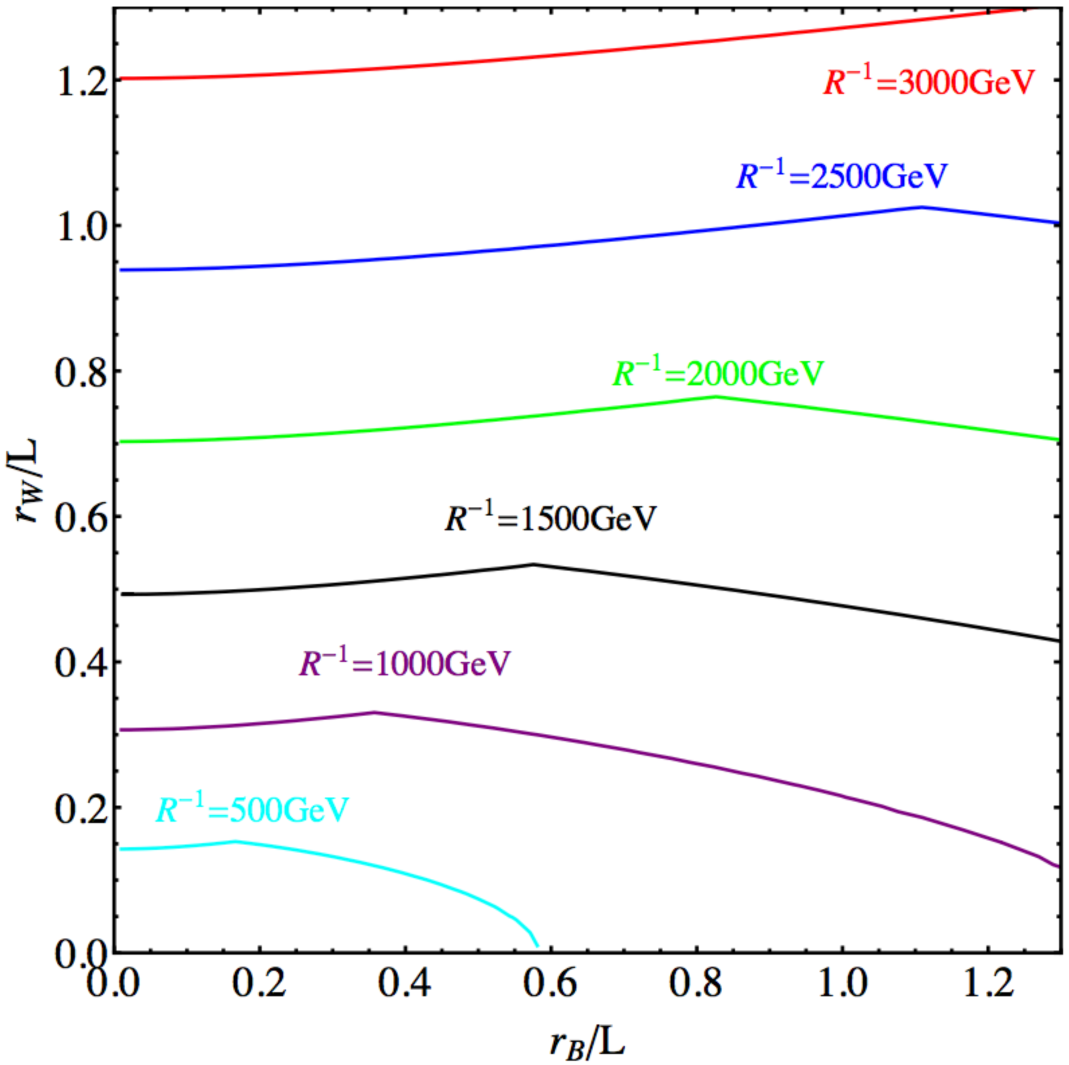


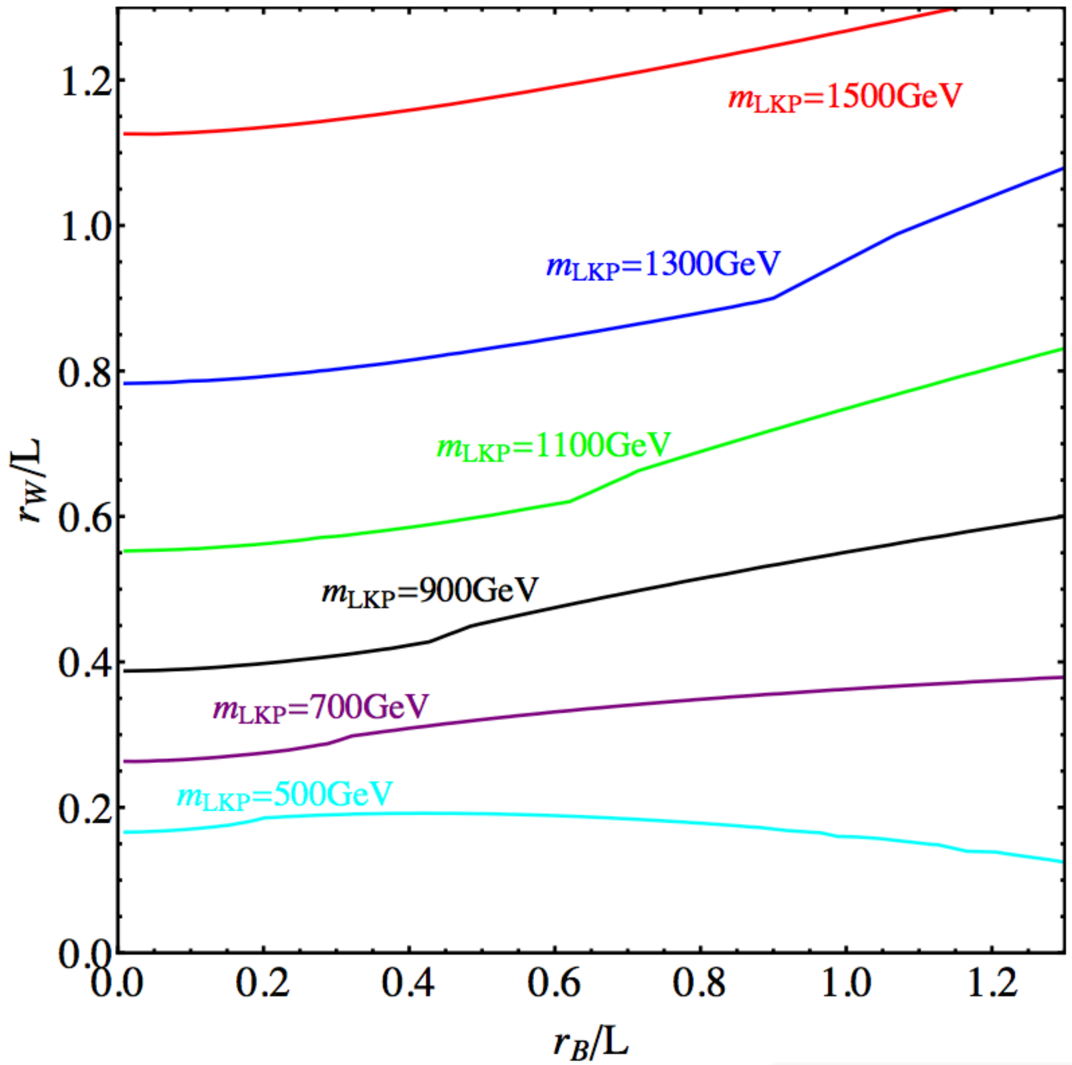
$$\mathcal{L}_{eff} \supset \sum_{f1,f2}\sum_{A,B=L,R} \eta^{s}_{f_1 f_2,AB}\frac{4\pi}{(\Lambda^{s}_{f1f2,AB})^2}\overline{f}_{1,A}\gamma^{\mu} f_{1,A}\overline{f}_{2,B}\gamma_{\mu} f_{2,B},$$

$$\begin{aligned}\frac{4\pi}{\Lambda^2_{eq,AB}}\eta_{eq,AB} &= 4\pi N_c\left[\sum_{n=1}^{\infty}(\tilde{\mathcal{F}}^{B}_{2n00})^2\frac{3}{5}\frac{\alpha_1 Y_{eA}Y_{qB}}{Q^2-M^2_{B^{(2n)}}}+\sum_{n=1}^{\infty}(\tilde{\mathcal{F}}^{W}_{2n00})^2\frac{\alpha_2 T^3_{eA}T^3_{qB}}{Q^2-M^2_{W_3^{(2n)}}}\right]\\ &\approx -12\pi\left[\sum_{n=1}^{\infty}(\tilde{\mathcal{F}}^{B}_{2n00})^2\frac{3}{5}\frac{\alpha_1 Y_{eA}Y_{qB}}{M^2_{B^{(2n)}}}+\sum_{n=1}^{\infty}(\tilde{\mathcal{F}}^{W}_{2n00})^2\frac{\alpha_2 T^3_{eA}T^3_{qB}}{M^2_{W_3^{(2n)}}}\right].\end{aligned}$$

4-fermi constraints

minimum allowed values



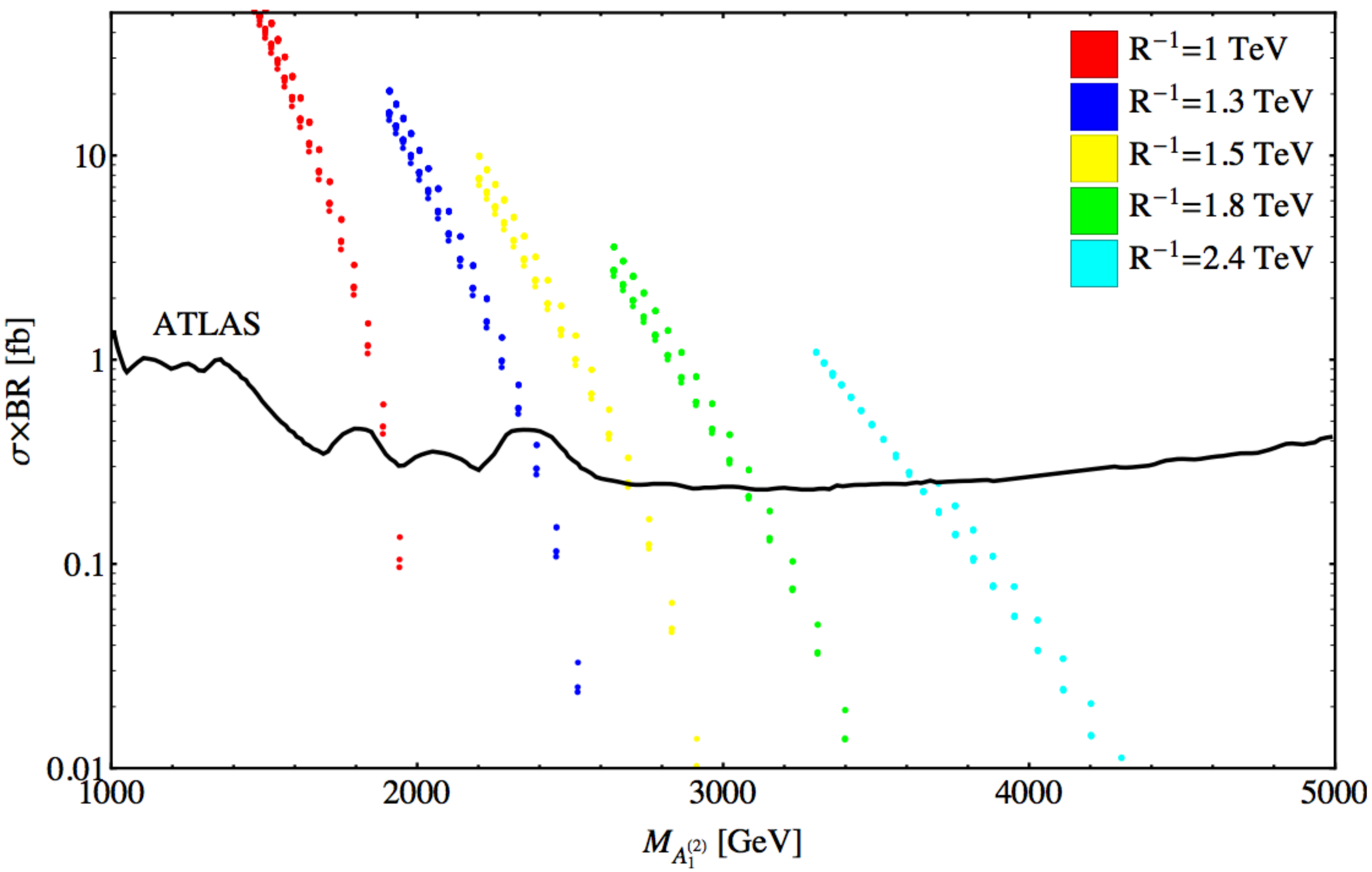


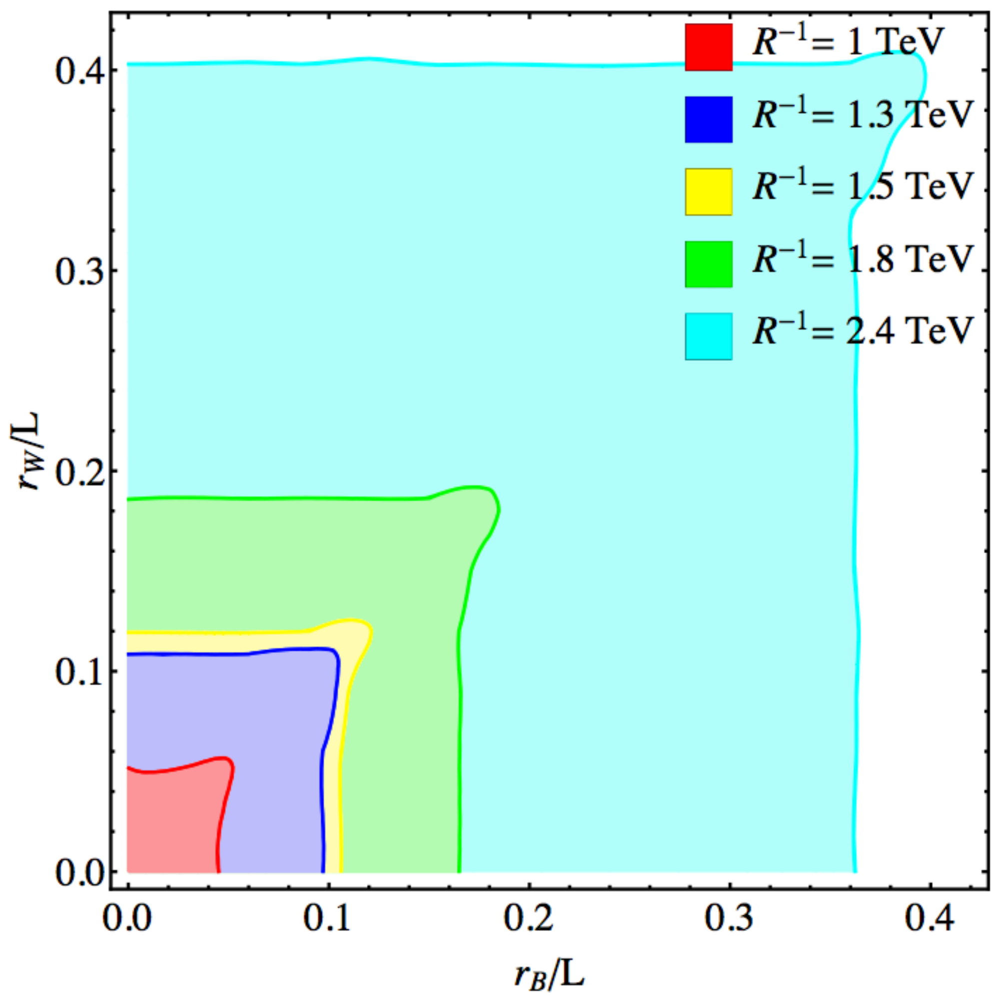
LHC Run2 results

TeV	$eeee$	$ee\mu\mu$	$ee\tau\tau$	$\ell\ell\ell\ell$	$qqqq$	$eeuu$	$eedd$
Λ_{LL}^{+}	> 8.3	> 8.5	> 7.9	> 9.1	> 9.0	> 23.3	> 11.1
Λ_{LL}^{-}	> 10.3	> 9.5	> 7.2	> 10.3	> 12.0	> 12.5	> 26.4

Dilepton resonance search at the LHC

13 TeV with 13.3 /fb (ATLAS), 13.0/fb (CMS)

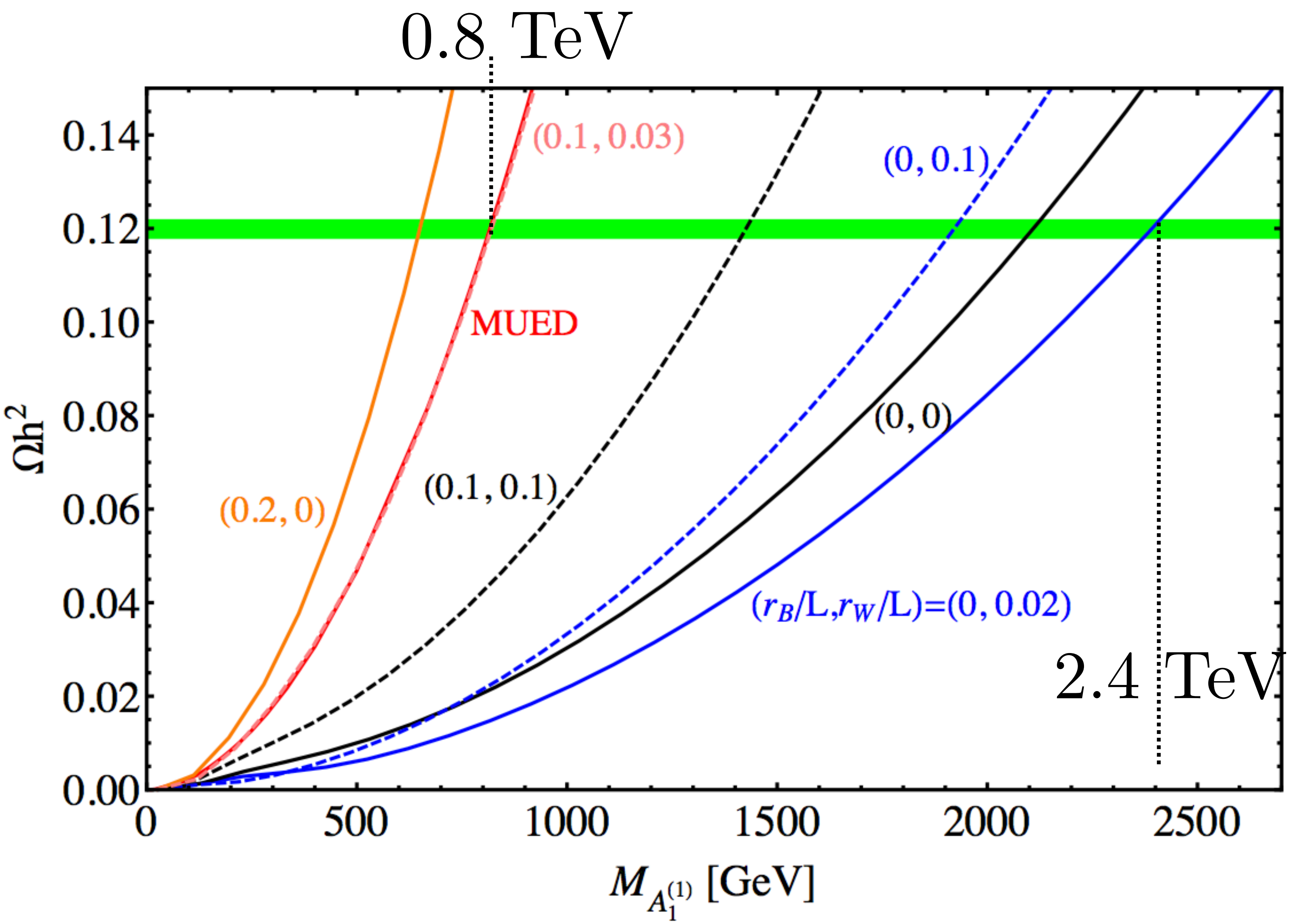




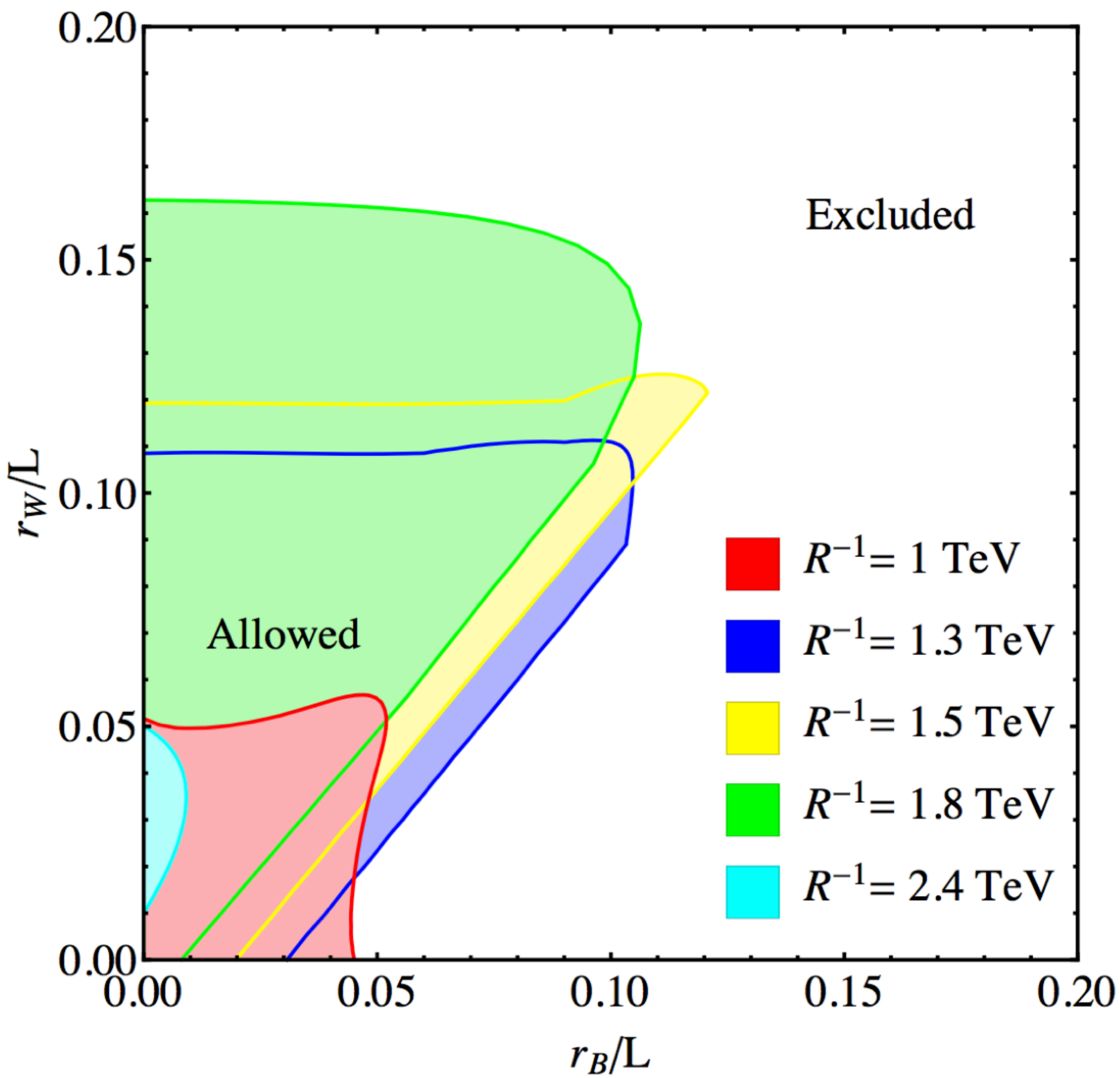
$$g_{W^{(2)}\psi^{(0)}\psi^{(0)}} = g_2 \int_{-L}^{L} \frac{dy}{2L} \frac{f_2^W(y)}{N_0^W} = g_2 \sqrt{\frac{2(1+r_W/L)}{1+\frac{r_W}{L}\cos^2(k_2^W L)}} \frac{\sin(k_2^W L)}{k_2^W L}$$

$$g_{B^{(2)}\psi^{(0)}\psi^{(0)}} = g_1 \int_{-L}^{L} \frac{dy}{2L} \frac{f_2^B(y)}{N_0^B} = g_1 \sqrt{\frac{2(1+r_B/L)}{1+\frac{r_B}{L}\cos^2(k_2^B L)}} \frac{\sin(k_2^B L)}{k_2^B L}.$$

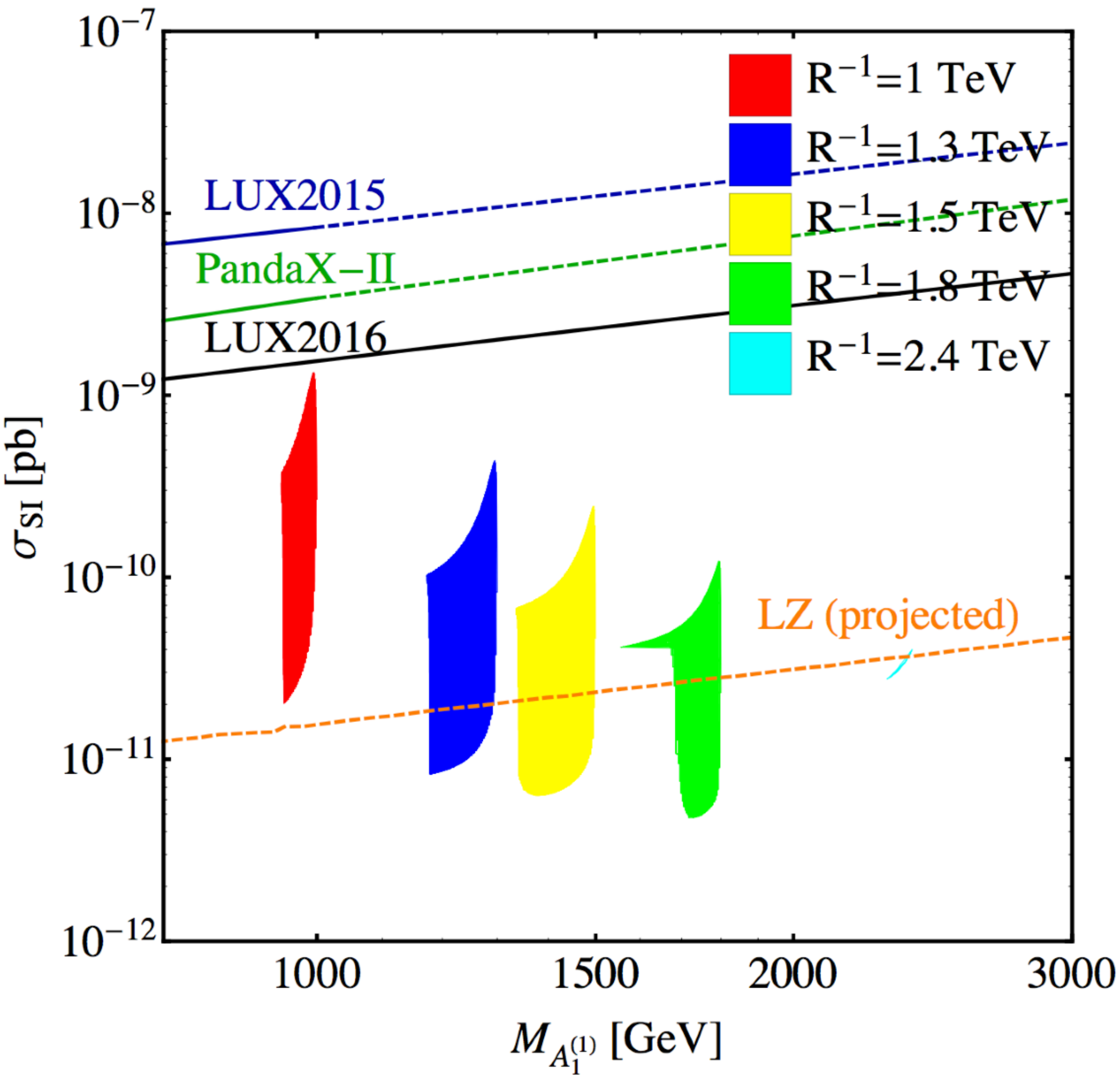
Relic abundance



LHC + relic abundance



Direct section of KK DM



Conclusion

- **EWKKDM** = LKP of the neutral gauge boson (mixture of the KK states of B and W_3)
- Depending on BLKT, the LKP can be either B-like or W-like or in between.
- Phenomenology is rich. LKP can be as heavy as 2.4 TeV (without BLKT, KK-photon DM $<$ 800 GeV (1.3 TeV with resonance effect))
- Future DD experiments will cover more. We will see!