The physics of a new gauge boson in a Stueckelberg extension of the two-Higgs-doublet model

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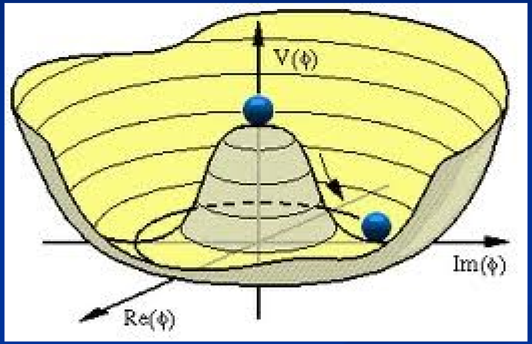
Outline

- Motivation
- The model
- Analysis/Results
- Conclusions

Higgs mechanism: The SM missing part

- Introduce a spin-0 boson with a potential $V(\phi)$



- Generates mass for gauge bosons and fermions

  Gauge bosons: Covariant derivative

  Fermions: Yukawa couplings

Another option: Stueckelberg mechanism

- Abelian vector boson and an axionic scalar field

$$\mathcal{L}_{St} = \frac{1}{2}(MA_\mu + \partial_\mu a)^2$$

- Gauge transformations

$$A'_\mu = A_\mu + \partial_\mu \epsilon$$

$$a' = a - M\epsilon$$

2 Higgs doublets

Minimize potential

$$\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

Fermion mass matrix

$$M_{ij} = y^1_{ij} \frac{v_1}{\sqrt{2}} + y^2_{ij} \frac{v_2}{\sqrt{2}}$$

Yukawa couplings

$$\mathcal{L}_Y = y^1_{ij} \bar{\psi}_i \psi_j \Phi_1 + y^2_{ij} \bar{\psi}_i \psi_j \Phi_2$$

Yukawas are not simultaneously diagonalizable

! Higgs mediate FCNC

unless Z_2 parity: $\Phi_1 \rightarrow \Phi_1, \ \Phi_2 \rightarrow -\Phi_2$ (Inert model)

Extra U(1)s

- BSM: Supersymmetry

- Particle physics models

$$G = G_{SM} \times U(1)_X$$

Anomaly cancellation

coupling constant g_X

gauge boson C_μ

- New mixing for neutral gauge bosons:

$$A_\mu = W^{3\mu} \sin\theta_w + B^\mu \cos\theta_w$$

$$Z_\mu = W^{3\mu} \cos\theta_w - B^\mu \sin\theta_w + \epsilon C^\mu$$

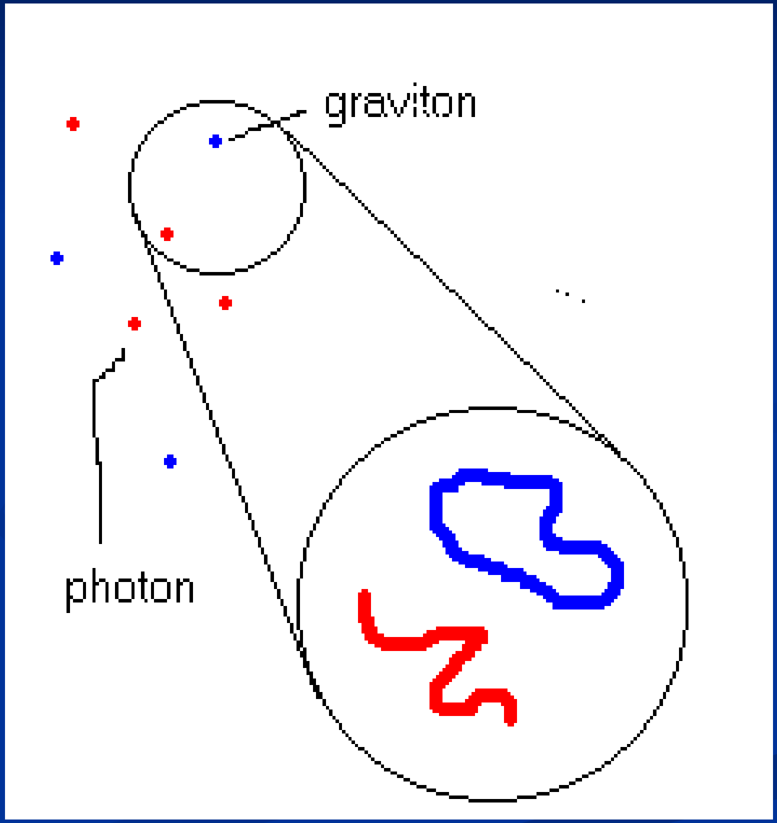
$$Z'_\mu = C^\mu - \epsilon \left(W^{3\mu} \cos\theta_w - B^\mu \sin\theta_w \right)$$

Small mixing

$$|\epsilon| \leq 10^{-3}$$

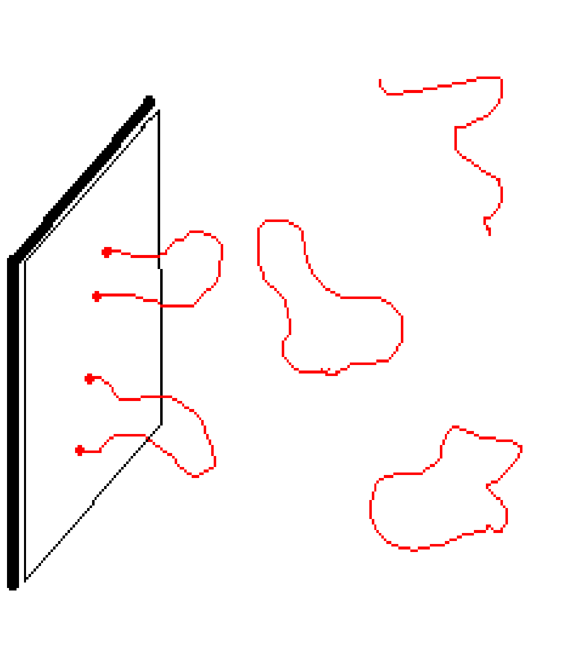
Superstring theory: basic idea

- Really fundamental objects are one-dimensional (strings)
- In low energies string looks like a point-like particle
- All known particles are different oscillatory modes of the string



Extended objects: Branes

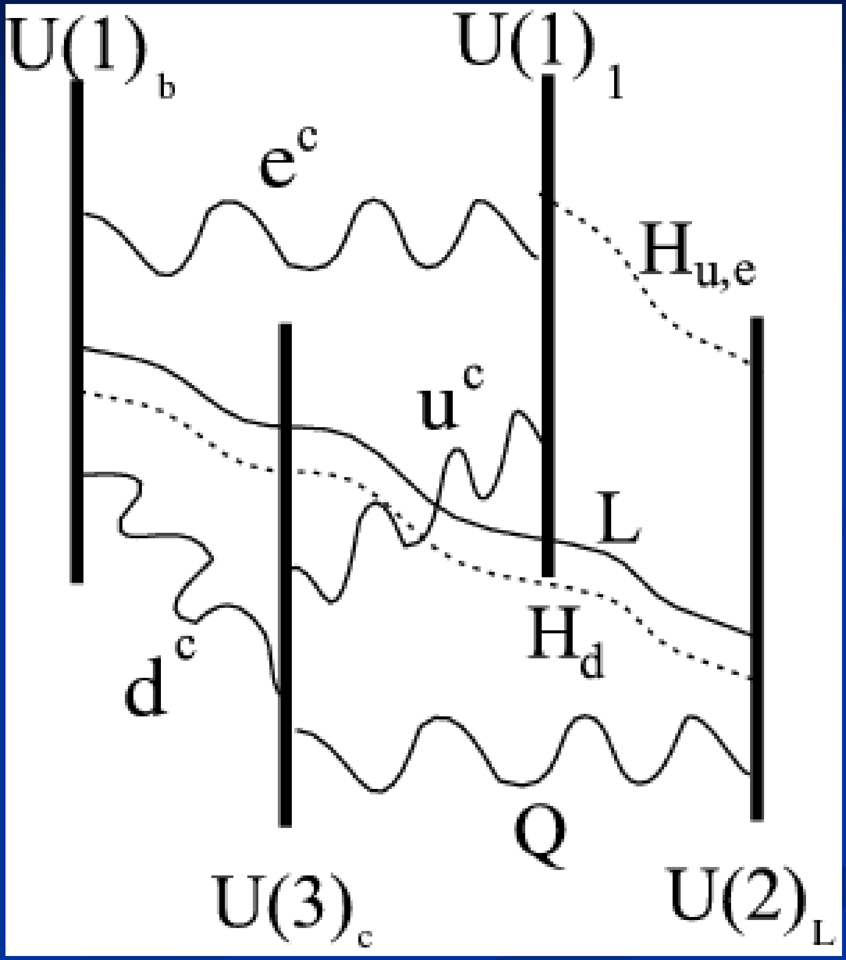
- String theory does not contain strings only
- Normally, open strings satisfy Neumann boundary conditions
- End points move at speed of light
- Dirichlet boundary conditions also make sense



- End points are stuck on a hypersurface
- This hyperurface is interpreted as a heavy solitonic object, a D-brane
- Brane-world idea : We are confined on such an object

SM embedding in string theory

- Several stucks of D-branes, extra U(1)s
- Gauge bosons: Same stuck
- Fermions: Different stucks
- Two Higgs doublets (at least)



Model in our work

- $SU(3) \times S(2) \times U(1)_Y \times U(1)_X$ H_1 H_2
- $$\mathcal{L}_{\mathrm{St}} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1 C_\mu + M_2 B_\mu)^2$$
- Fermions and H_1 neutral under $U(1)_X$

  H_2 charged ($Y_X = \pm 1$) under $U(1)_X$

- Symmetry breaking: V=O E

  V=(W3,B,C) & E=(Z´,Z, A)

$$\tan\theta = \frac{g_Y}{g_2}\cos\phi \qquad \tan\phi = \frac{M_2}{M_1}$$

$$\tan\psi = \frac{\tan\theta\tan\phi M_{\mathrm{W}}^2}{\cos\theta(M_{\mathrm{Z}'}^2 - (1+\tan^2\theta)M_{\mathrm{W}}^2)}$$

Higgs potential & EWSB

$$V = \mu_1^2 H_1^\dagger H_1 + \mu_2^2 H_2^\dagger H_2 + \frac{1}{2}\lambda_1 (H_1^\dagger H_1)^2 + \frac{1}{2}\lambda_2 (H_2^\dagger H_2)^2$$

$$+\lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$

Yukawa couplings as in SM

$$H_1 = \left[\begin{array}{c} 0 \\ \frac{1}{\sqrt{2}}(v+h) \end{array} \right] \qquad H_2 = \left[\begin{array}{c} H^+ \\ \frac{1}{\sqrt{2}}(H+iA) \end{array} \right]$$

$$M_h^2 = \lambda_1 v^2$$

$$M_H^2 = \mu_2^2 + \frac{1}{2}(\lambda_3 + \lambda_4) v^2$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2$$

$$M_A^2 = M_H^2$$

Higgs self-interactions

$$V_{int} = \frac{1}{2}\lambda_2 \left[H^+H^- + \frac{1}{2}H^2 + \frac{1}{2}A^2\right]^2$$

$$+\lambda_3 \left(vh + \frac{1}{2}h^2\right) \left[H^+H^- + \frac{1}{2}H^2 + \frac{1}{2}A^2\right]$$

$$+\frac{1}{2}\lambda_4 \left(vh + \frac{1}{2}h^2\right) H^2 + \frac{1}{2}\lambda_4 \left(vh + \frac{1}{2}h^2\right) A^2$$

mass matrix for neutral gauge bosons

$$M_{ab}^2 = \begin{bmatrix} M_1^2 & M_1 M_2 & 0 \\ M_1 M_2 & M_2^2 + \frac{1}{4}g_Y^2 v^2 & -\frac{1}{4}g_Y g_2 v^2 \\ 0 & -\frac{1}{4}g_Y g_2 v^2 & \frac{1}{4}g_2^2 v^2 \end{bmatrix}$$

2 body decays (for Z′)

$M \longrightarrow m_1 \; m_2$ $\qquad$ $M > m_1 + m_2$

$$\Gamma(M \longrightarrow m_1 \; m_2) = \frac{\lambda^{1/2}(M^2, m_1^2, m_2^2)}{16\pi M^3} |\mathcal{M}_{fi}|^2$$

$$\lambda(a, b, c) \equiv a^2 + b^2 + c^2 - 2ab - 2ac - 2bc$$

Comment: $H^\pm \rightarrow W^\pm H$ $\qquad$ $H^\pm \rightarrow W^\pm A$

$$BR_1 = 0.5 = BR_2$$

Z´ boson searches

$$Z' \longrightarrow f\bar{f}$$

$$g_{Z'H^+H^-} = \frac{1}{2}(g_2 O_{31} + g_Y Y O_{21} + g_X Y_X O_{11})$$

$$Z' \longrightarrow W^+W^-$$

$$g_{Z'HA} = \frac{1}{2}(-g_2 O_{31} + g_Y Y O_{21} + g_X Y_X O_{11})$$

$$Z' \longrightarrow H^+H^-$$

$$Q = T_3 + \frac{Y}{2} - \frac{g_X Y_X M_2}{2 g_Y M_1}$$

$$Z' \longrightarrow H\,A$$

$$Y = 1 \pm \frac{g_X}{g_Y}\,\frac{M_2}{M_1}$$

$$Z' \longrightarrow h\ Z$$

Z´ into fermions

$$L_{Vff} = -g_{Vff}\bar{f}\gamma^{\mu}(c_V + c_A\gamma^5)fV_{\mu}$$

$$\Gamma(V \to f\bar{f}) = N_c \frac{g_{Vff}^2 M_V}{12\pi}\left[c_V^2 + c_A^2 + 2(c_V^2 - 2c_A^2)\frac{m_f^2}{M_V^2}\right]\sqrt{1 - 4\frac{m_f^2}{M_V^2}}$$

$$\Gamma(V \to f\bar{f}) = N_c \frac{g_{Vff}^2(c_V^2 + c_A^2)M_V}{12\pi}$$

$$M_V \gg m_f$$

$$c_V = 2T_3\cos(\theta_w)O_{31} + (Y_L + Y_R)\sin(\theta_w)O_{21}$$

$$c_A = -2T_3\cos(\theta_w)O_{31} - (Y_L - Y_R)\sin(\theta_w)O_{21}$$

$$g_{Z'ff} = \frac{g_2}{4\cos(\theta_w)}$$

Z′ into inert Higgs bosons

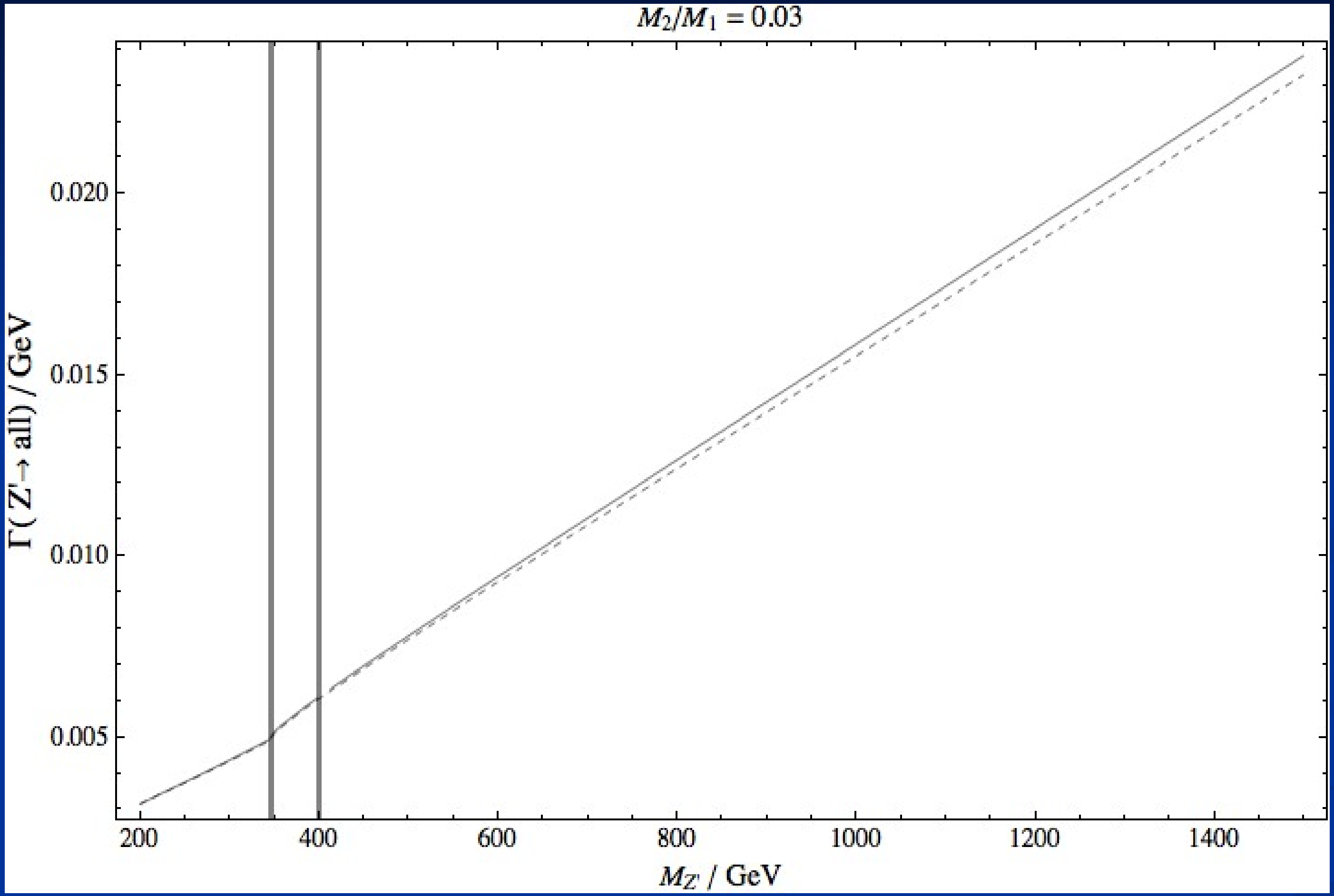
$$|\mathcal{M}_{Z'\to H^+H^-}|^2 = \frac{1}{3} g_{Z'H^+H^-}^2 \ M_{Z'}^2 \left(1 - \frac{4M_{H^\pm}^2}{M_{Z'}^2}\right)$$

$$|\mathcal{M}_{Z'\to HA}|^2 = \frac{1}{3} g_{Z'HA}^2 \left[\frac{(M_H^2 - M_A^2)^2}{M_{Z'}^2} + M_{Z'}^2 \left(1 - \frac{2(M_H^2 + M_A^2)}{M_{Z'}^2}\right)\right]$$

$$g_{Z'H^+H^-} = \frac{1}{2}(g_2 O_{31} + g_Y Y O_{21} + g_X Y_X O_{11})$$

$$g_{Z'HA} = \frac{1}{2}(-g_2 O_{31} + g_Y Y O_{21} + g_X Y_X O_{11})$$

Numerical results I



$g_X = 0.001$

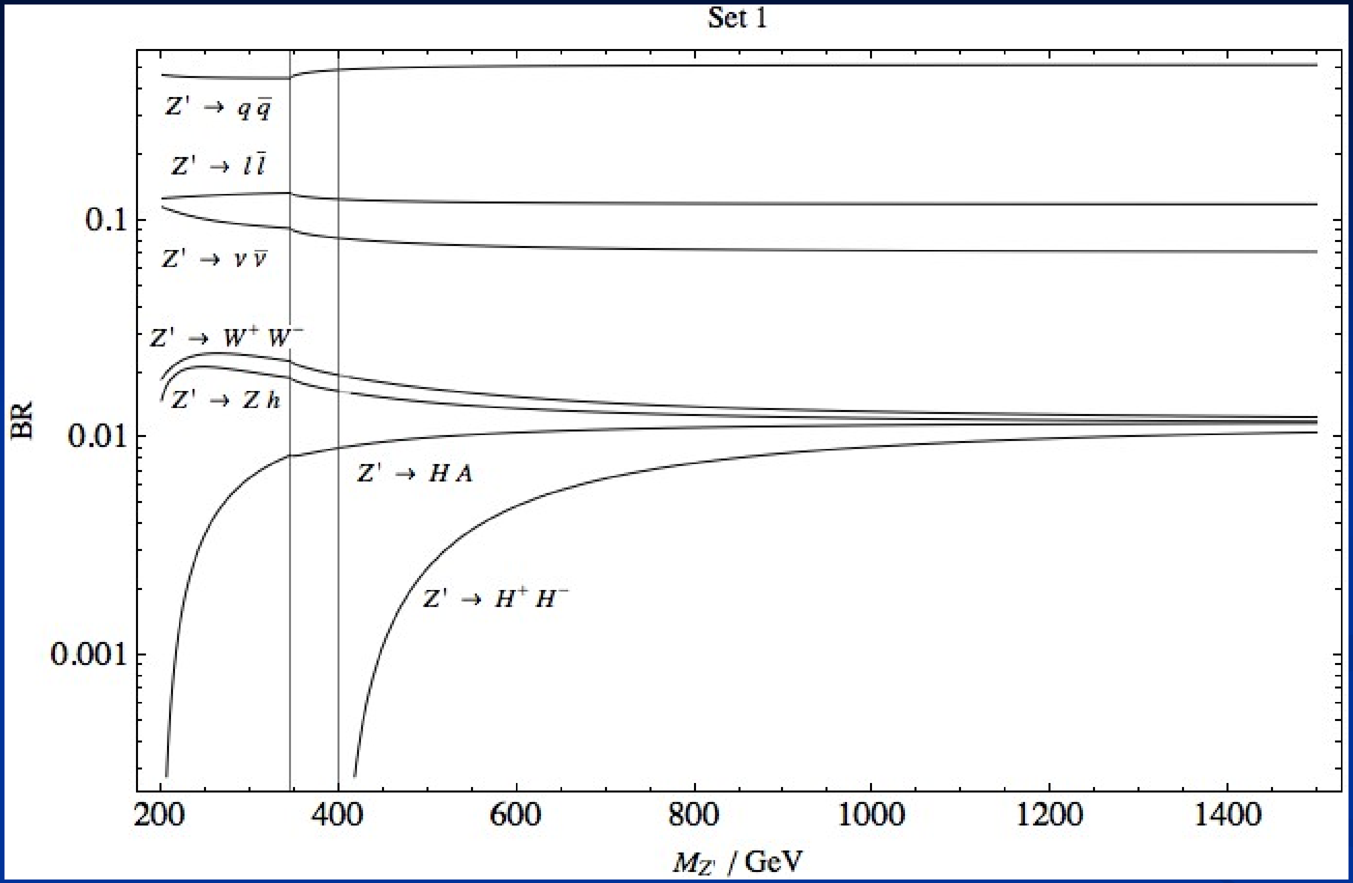
$M_h = 100GeV$

$M_A = 100GeV$

$M_{H^\pm} = 200GeV$

Z' can be seen as a sharp resonance

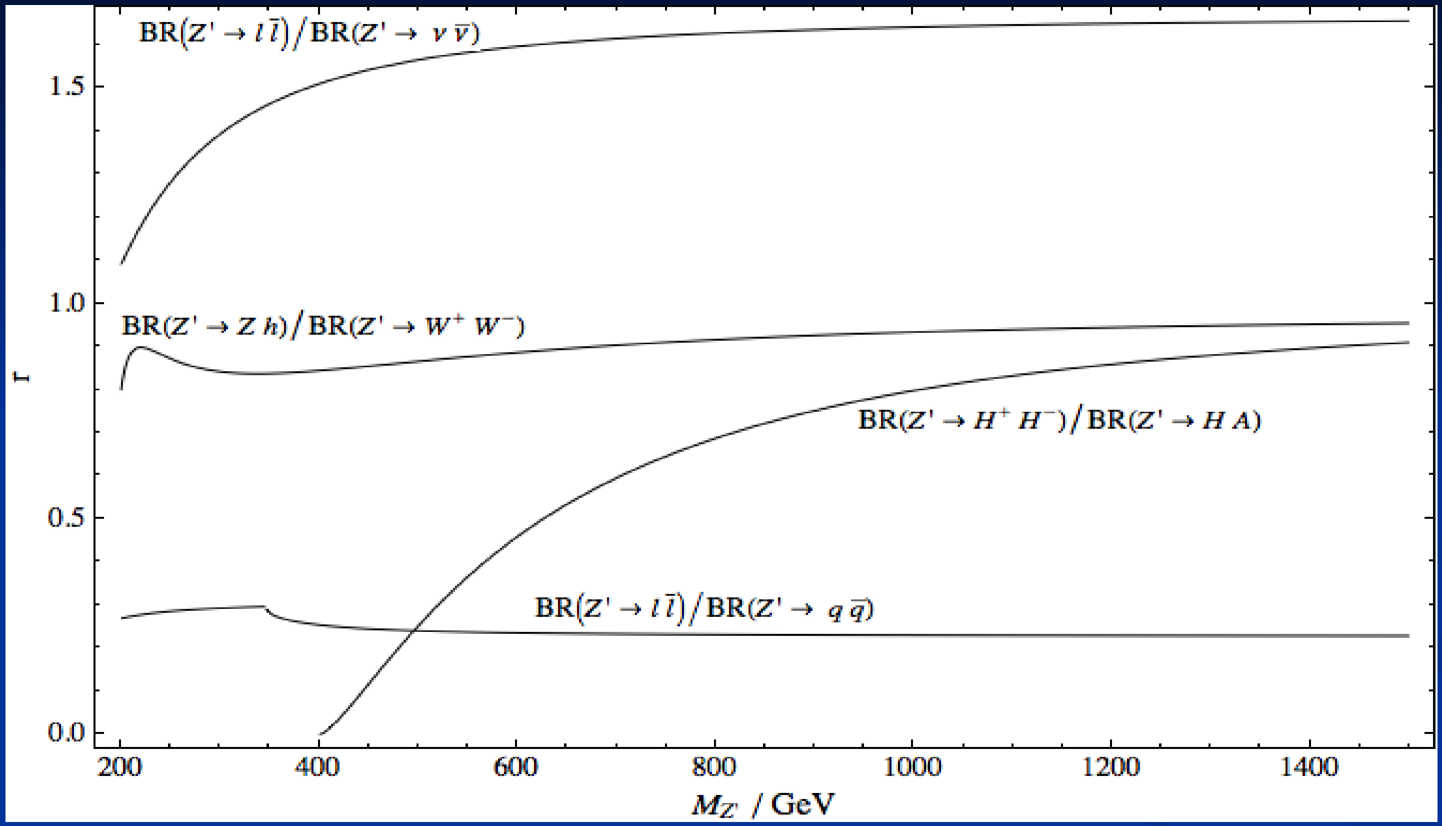
Numerical results II



in SM (for Z boson)

$BR(leptons) = 0.034$ $BR(neutrinos) = 0.2$ $BR(quarks) = 0.7$

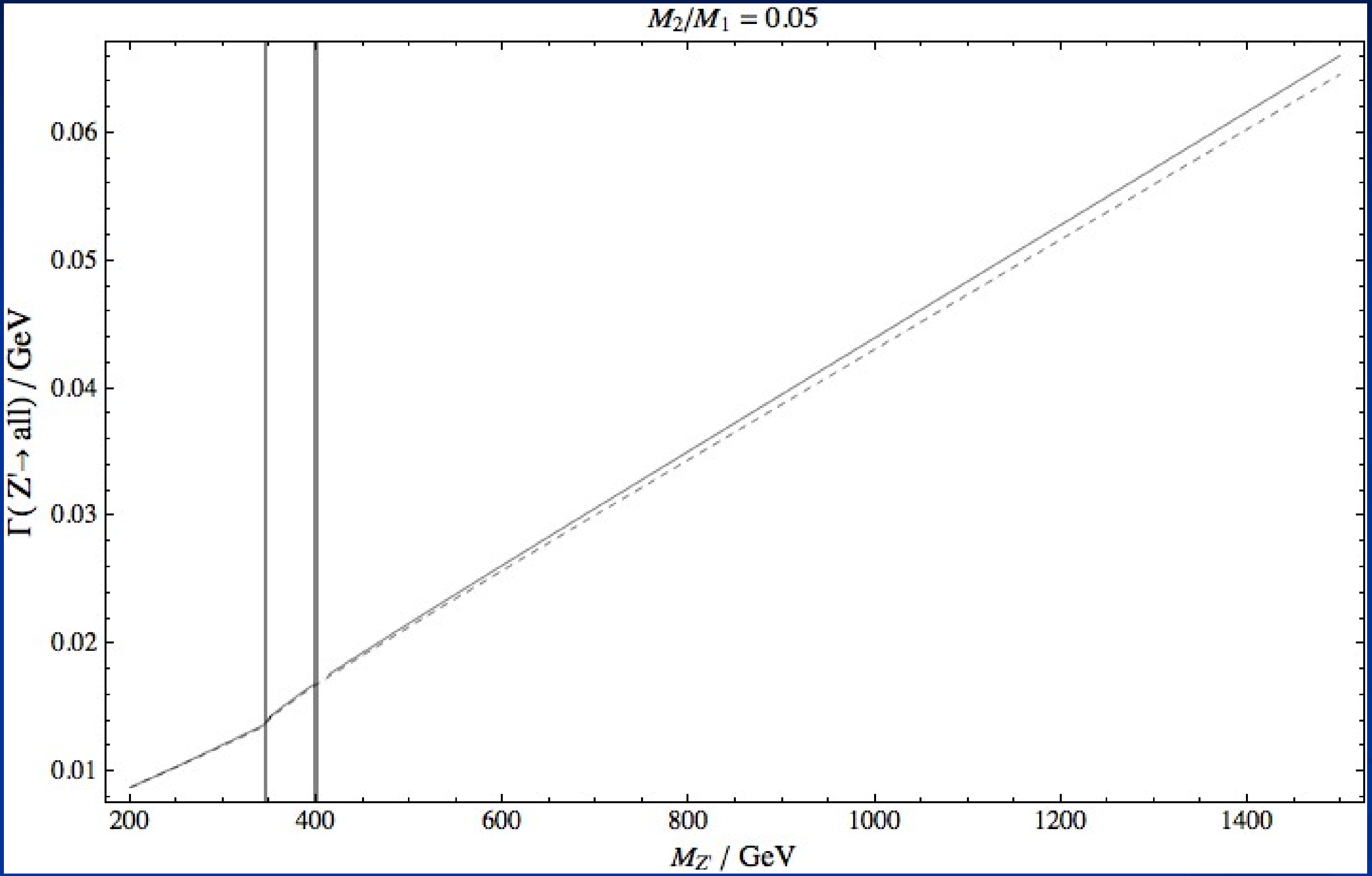
Numerical results III



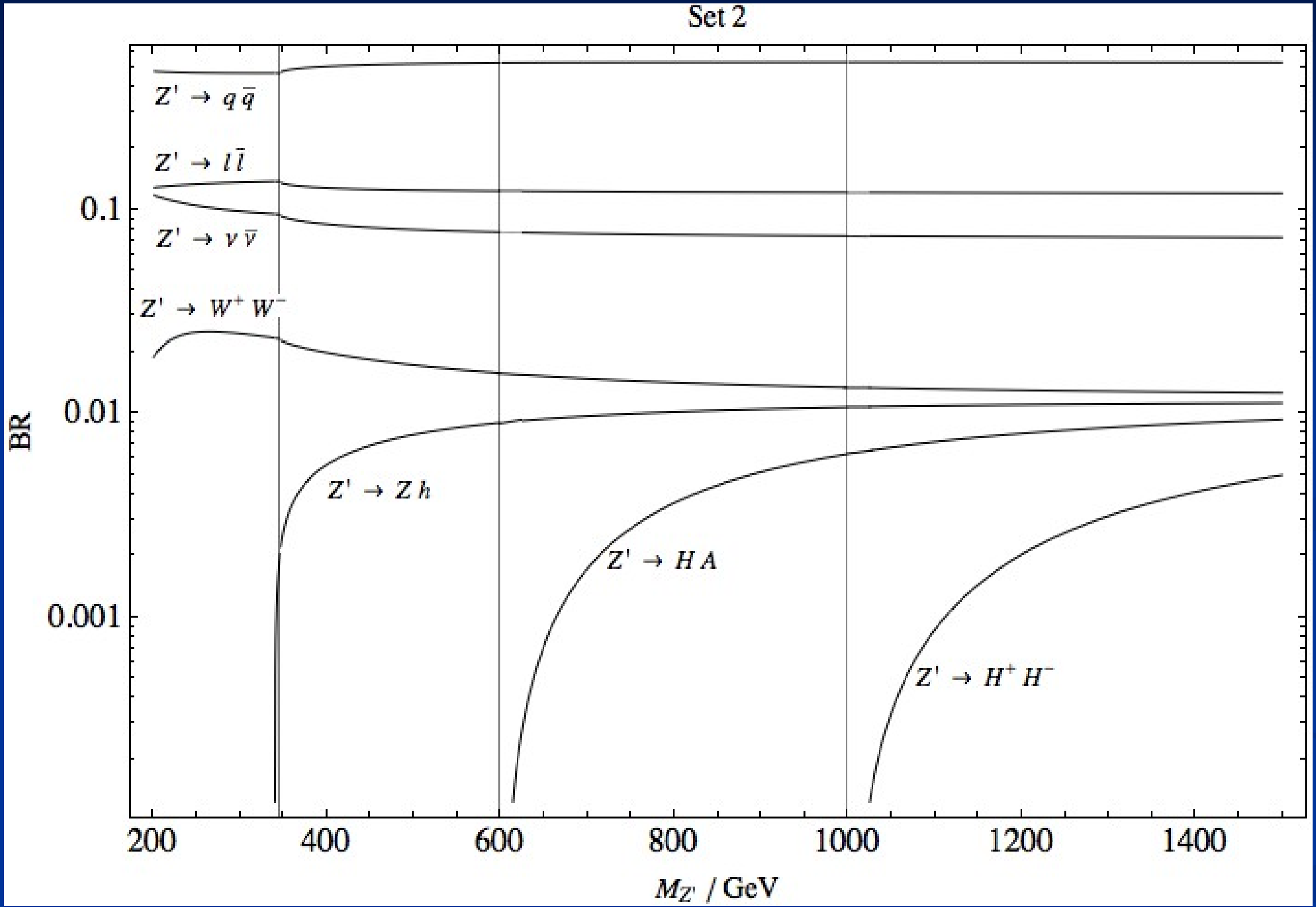
in SM (for Z boson)

$$\text{leptons}/\text{neutrinos} = 0.17 \qquad \text{leptons}/\text{quarks} = 0.05$$

Numerical results IV



Numerical results V

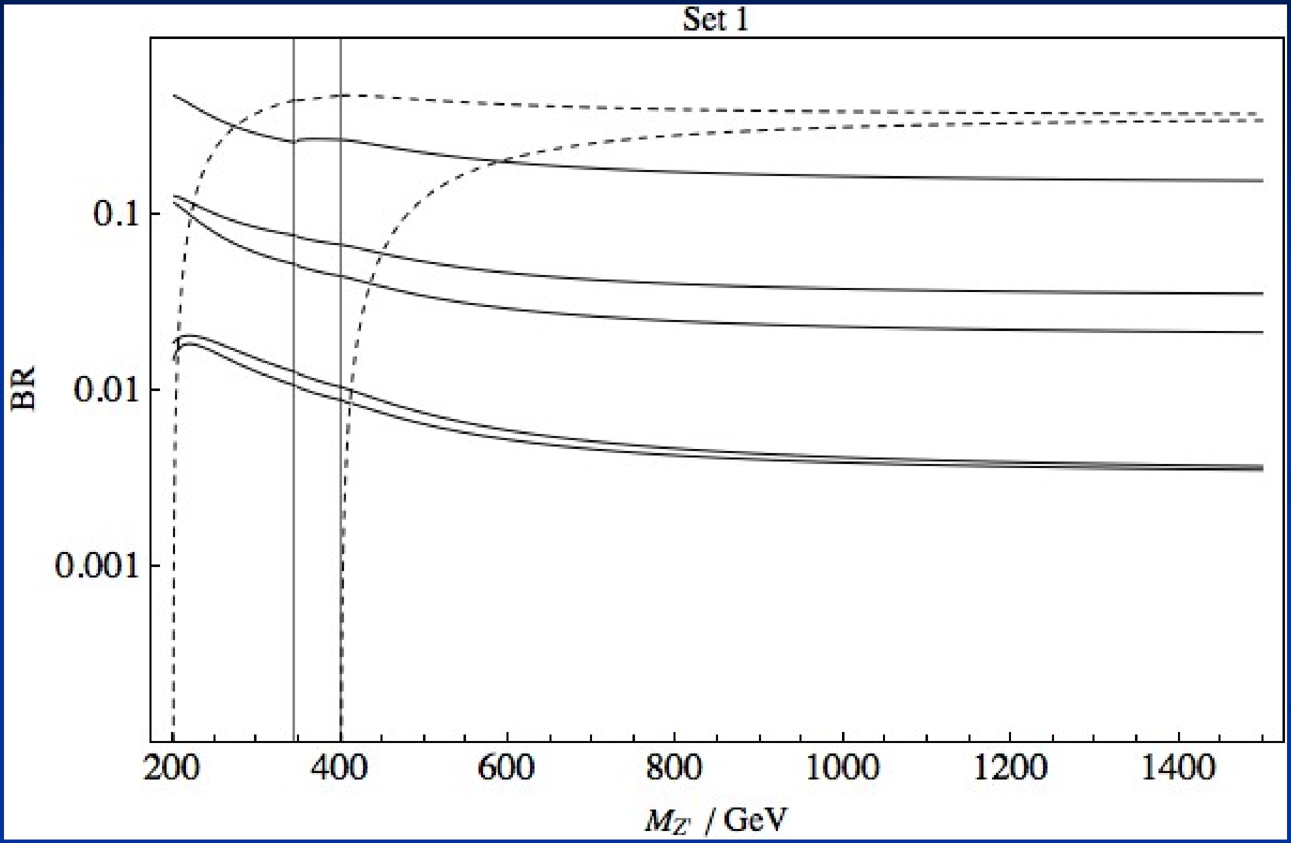


$$M_h = 250GeV$$

$$M_A = 300GeV$$

$$M_{H^\pm} = 500GeV$$

Numerical results VI



$g_X = 0.1$

Conclusions

- Extra U(1)s, extended Higgs sector and Stueckelberg mechanism: physics BSM
- Brane intersection in string theory: Contain all the ingredients
- Model discussed here: Z' boson light as a sharp resonance
- BR ratios and ratios of partial Γ_i different compared to other models
- Charged Higgs with 2 decay channels (BR=0.5)
- Further work: Phenomenology of the Higgs sector