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

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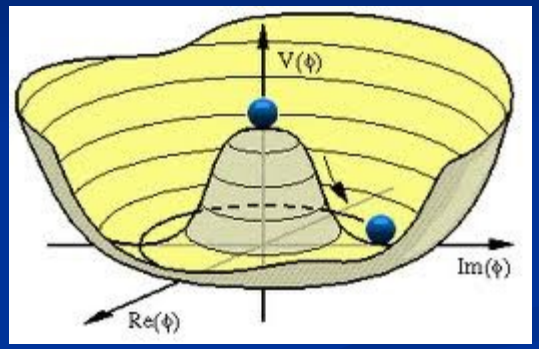
Outline

- 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: $\Phi_1 \to \Phi_1, \ \Phi_2 \to -\Phi_2$ (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:

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

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

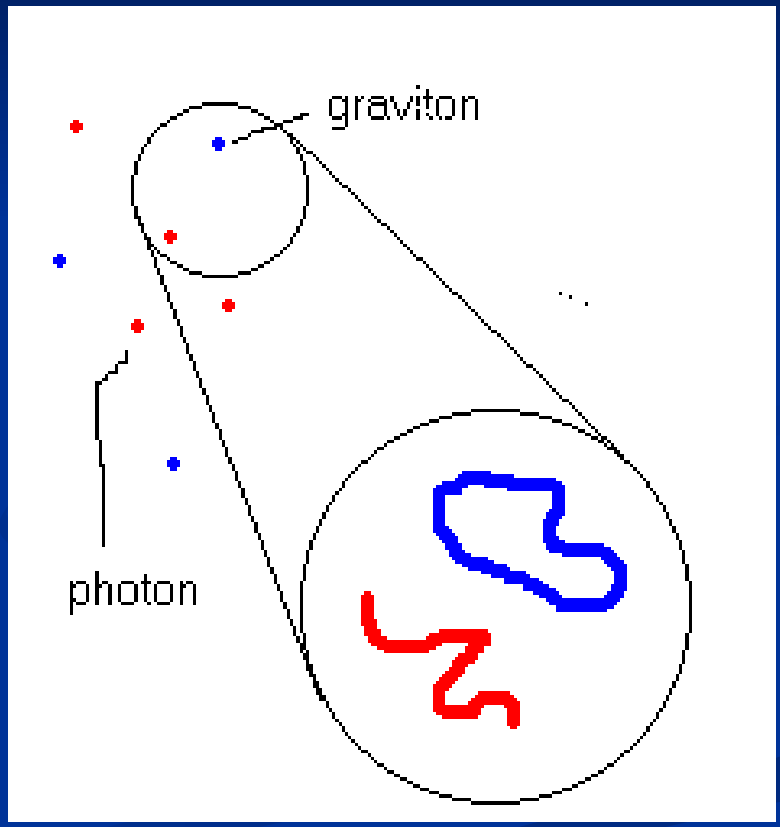
$$Z'_\mu = C^\mu - \epsilon \left(W^{3\mu} \cos\theta_w - B^\mu \sin\theta_w \right)$$

Small mixing

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

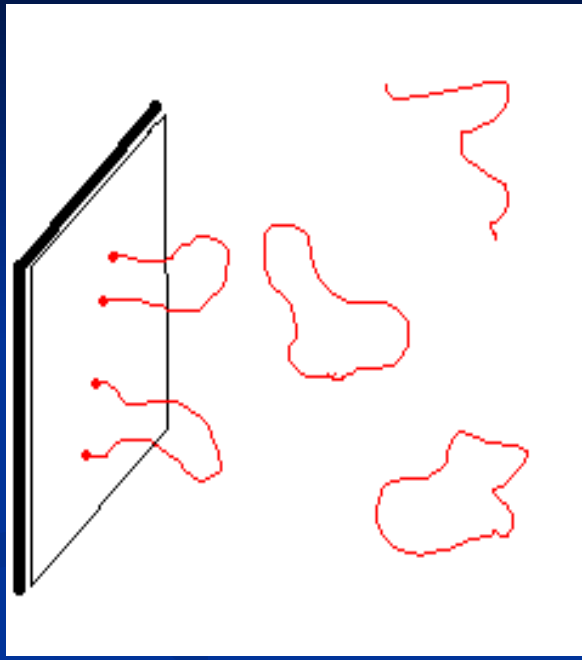
Superstring theory: basic idea

- 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

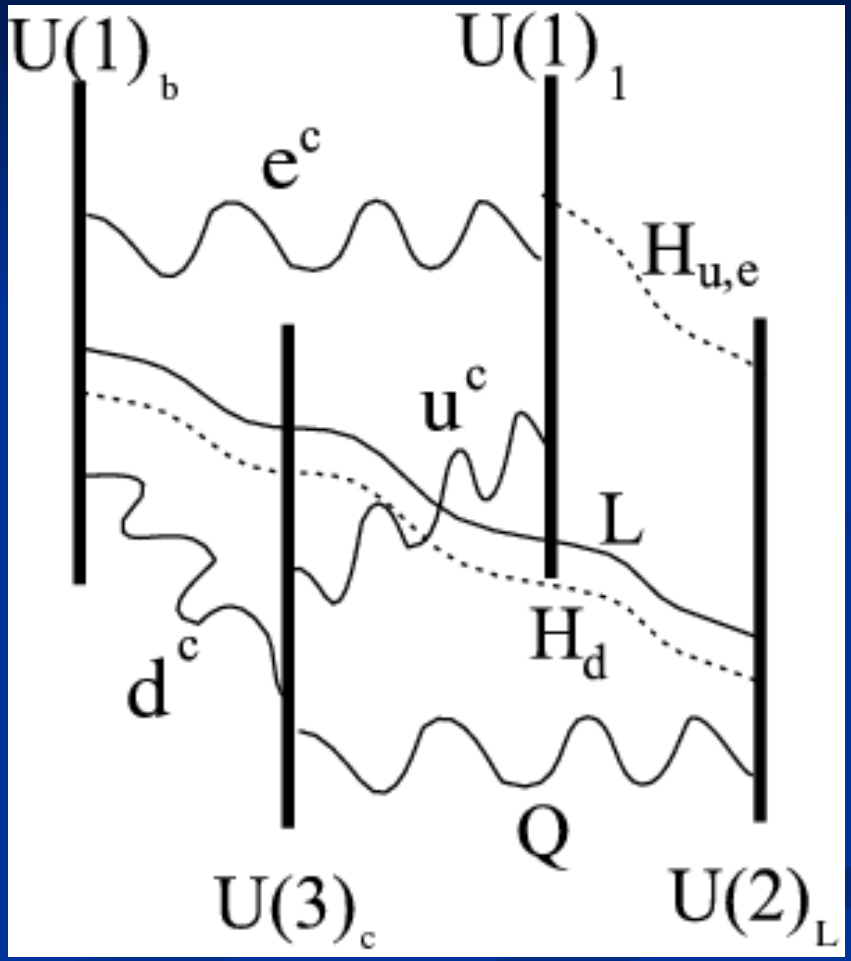
- String theory does not contain strings only
- Normally, open strings satisfy Neumann boundary conditions
- End points move at speed of light
- Dirichlet boundary conditions also make sense



- 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



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)

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

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

2 body decays (for Z´)

$$M \to m_1\ m_2 \qquad M > m_1 + m_2$$

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

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

Comment: $H^\pm \to W^\pm H$ $H^\pm \to W^\pm A$

$$BR_1 = 0.5 = BR_2$$

Z´ boson searches

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

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

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

$Z' \to HA$

$Z' \to h\,Z$

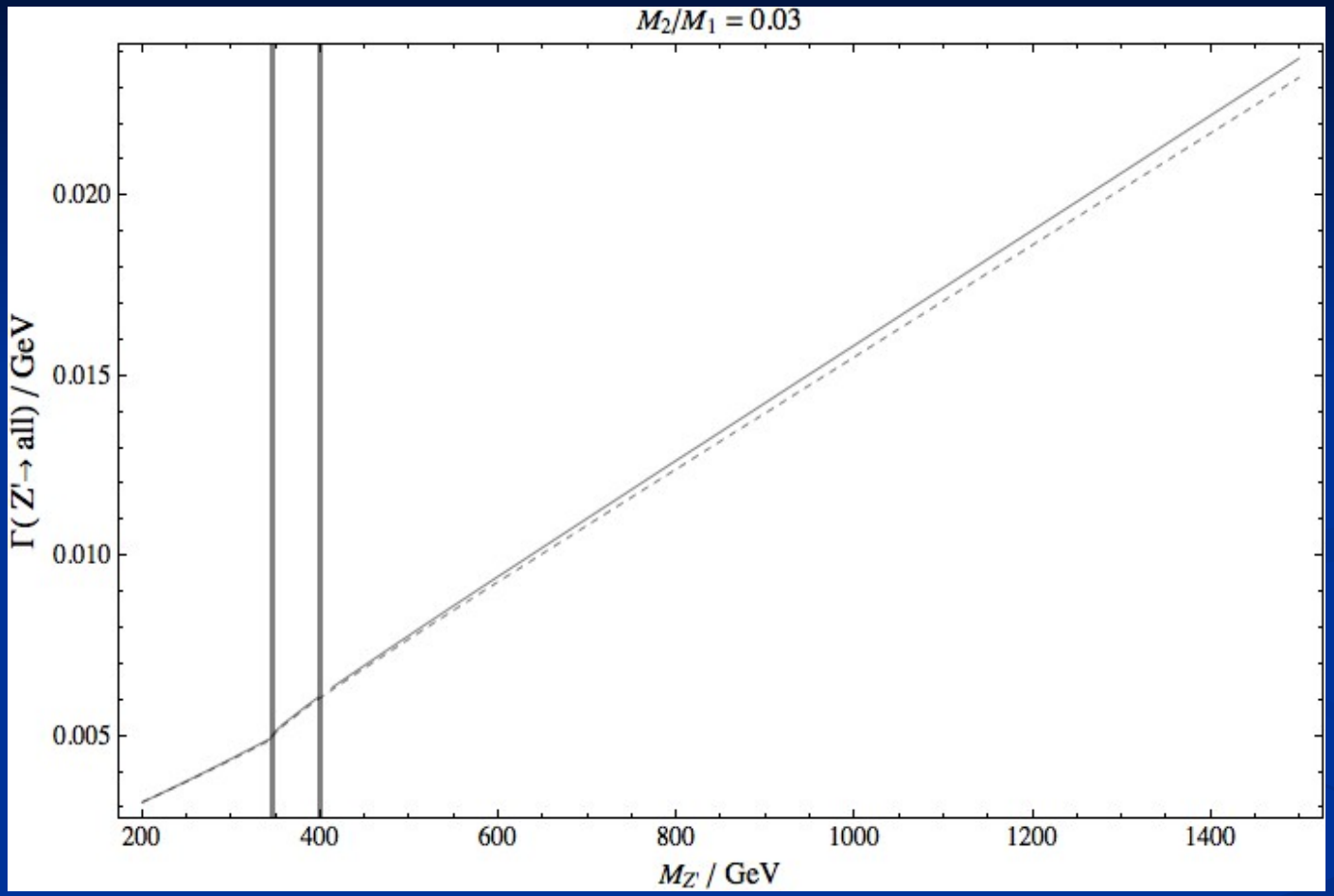
$$g_{Z'H^+H^-} = \frac{1}{2}(g_2 O_{31} + g_Y Y O_{21} + g_X Y_X O_{11})$$

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

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

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

Numerical results I



$$g_X = 0.001$$

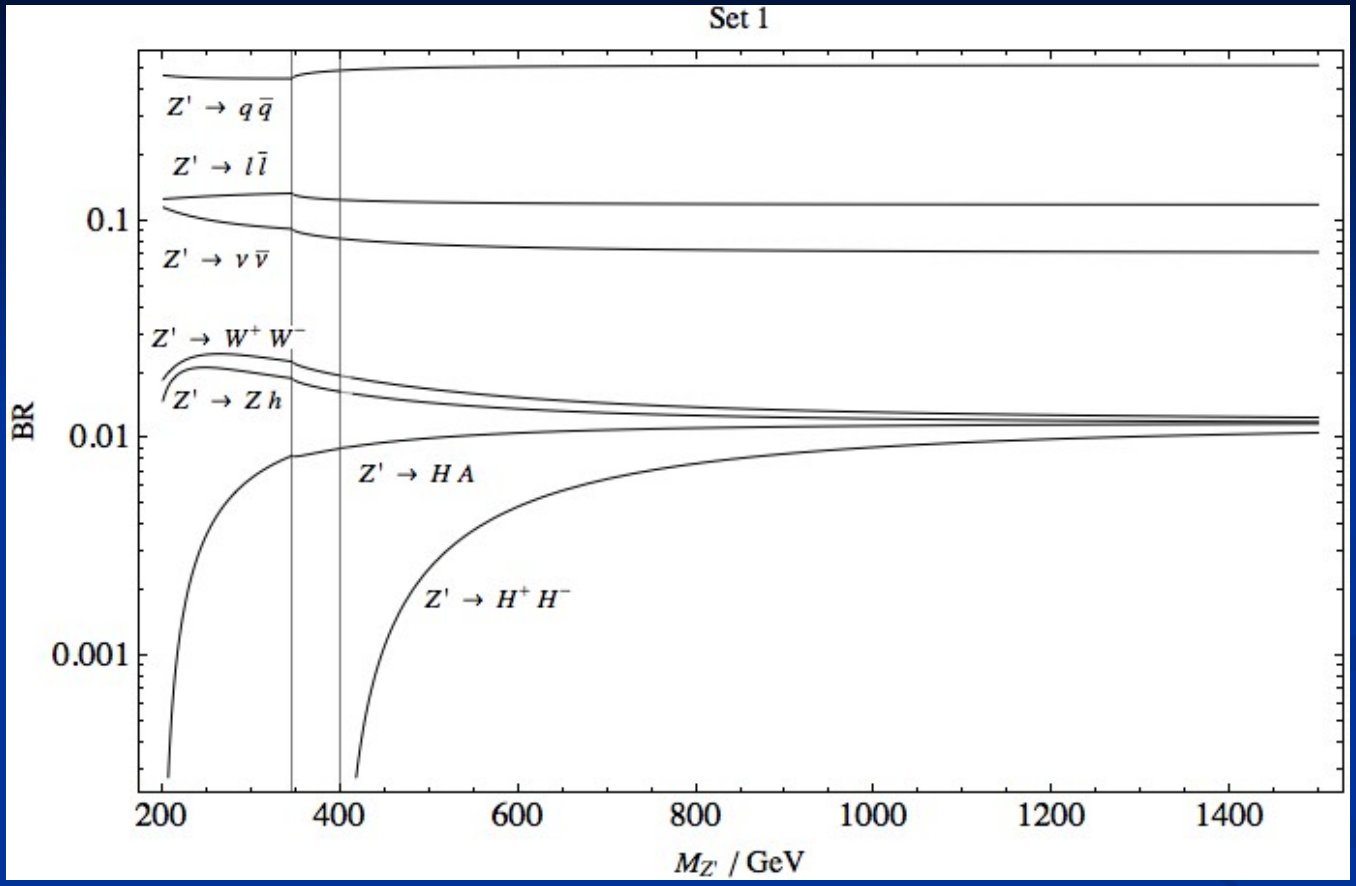
$$M_h = 100GeV$$

$$M_A = 100GeV$$

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

Z' can be seen as a sharp resonance

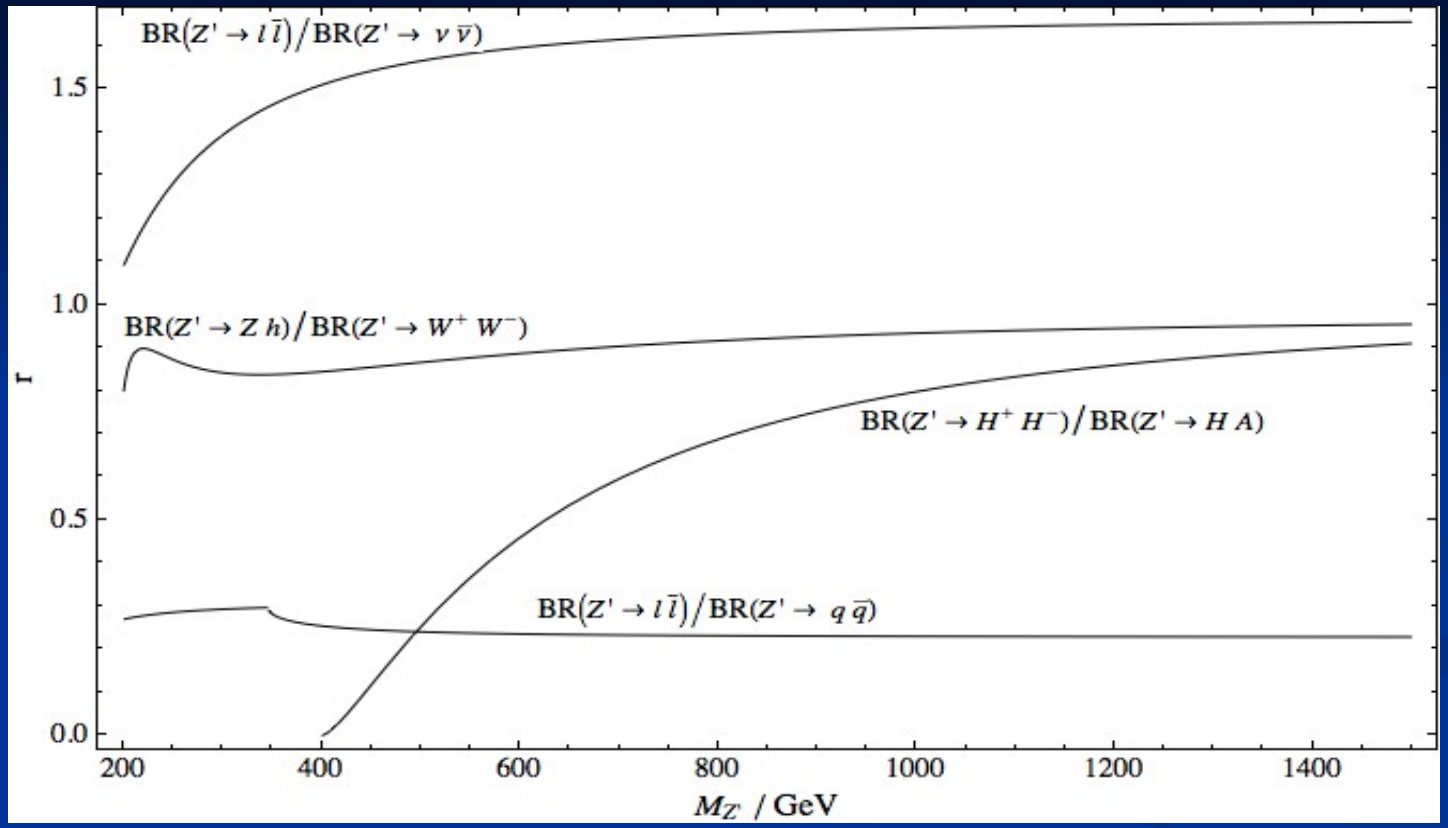
Numerical results II



in SM (for Z boson)

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

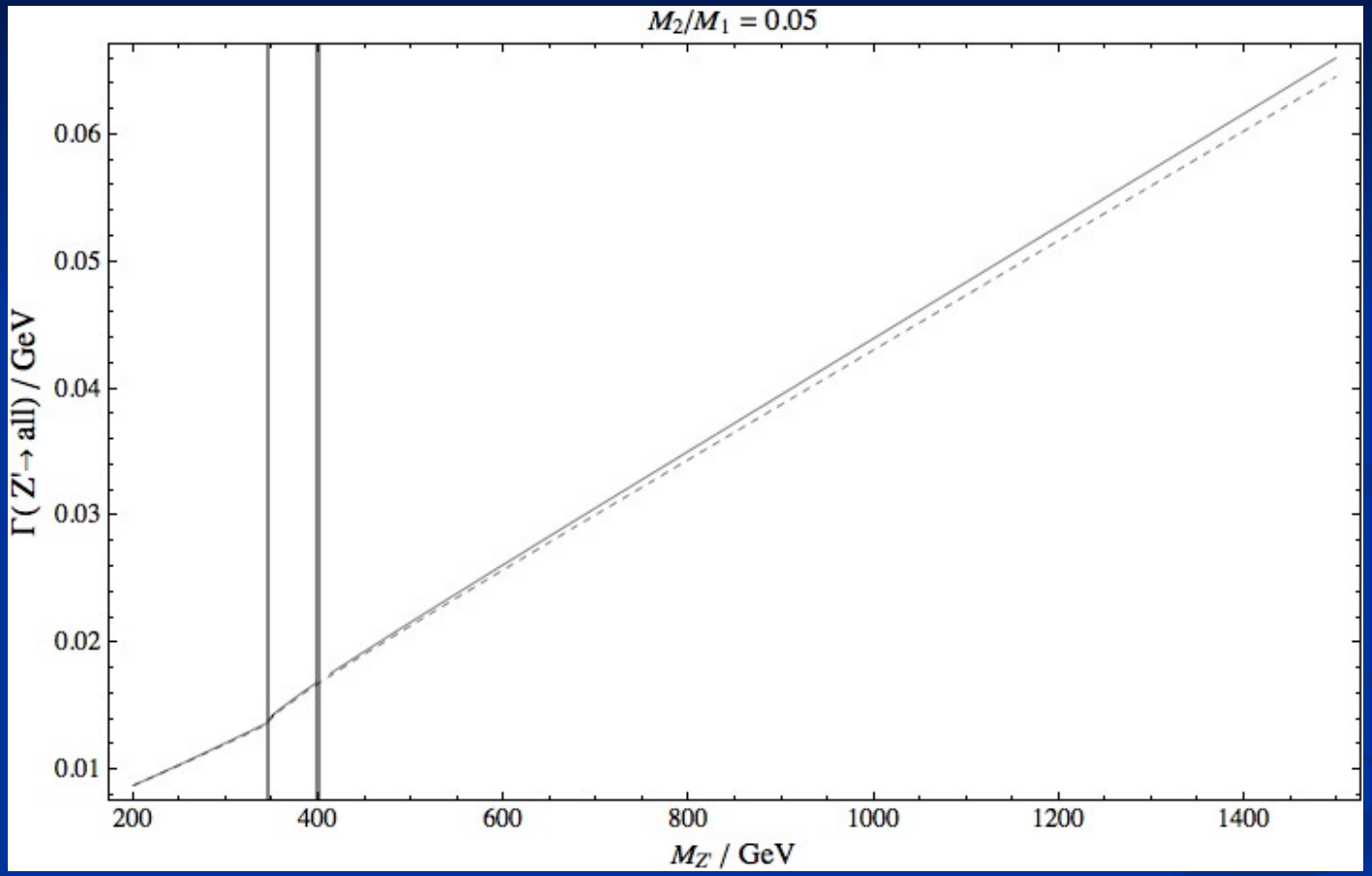
Numerical results III



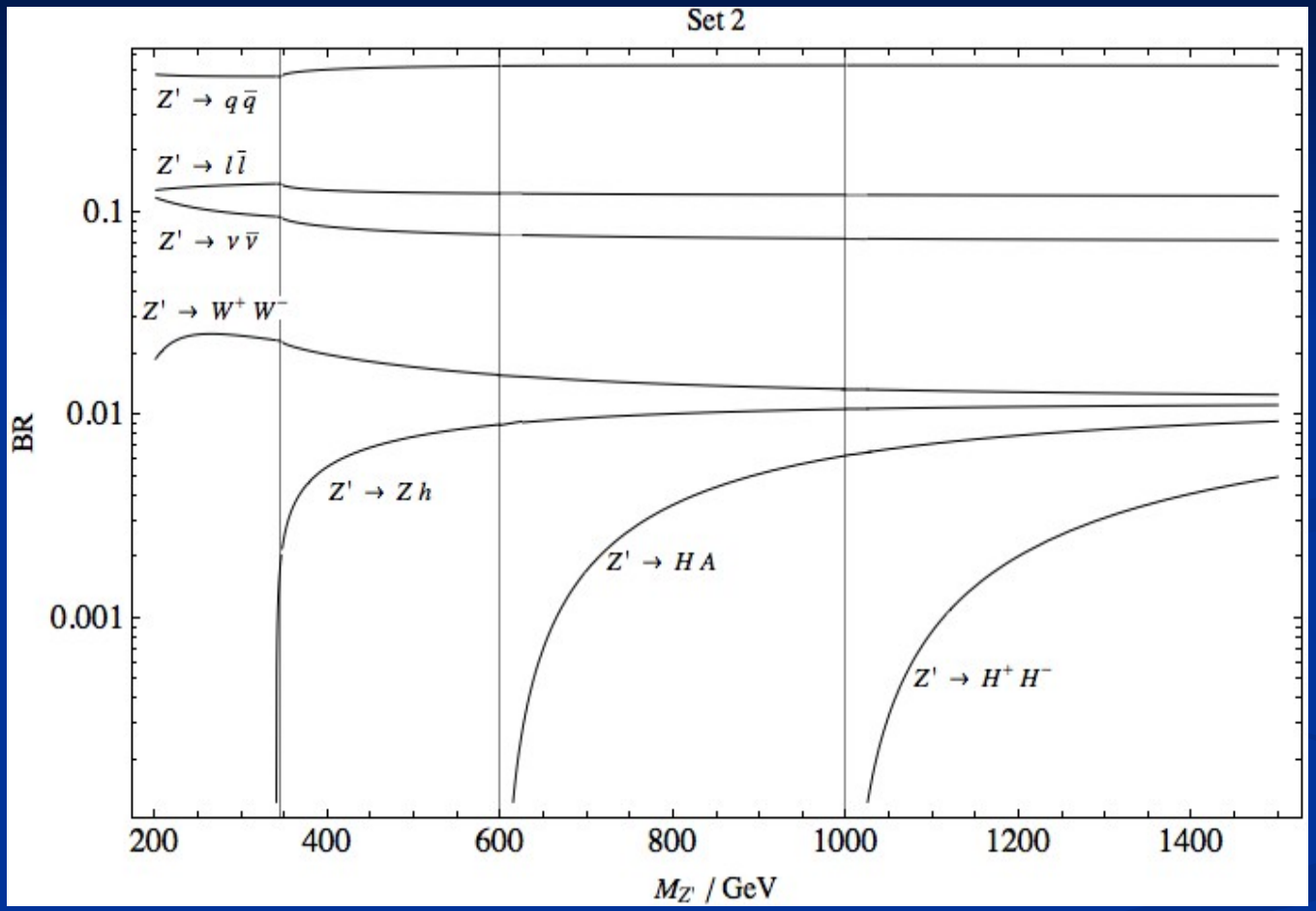
in SM (for Z boson)

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

Numerical results IV



Numerical results V

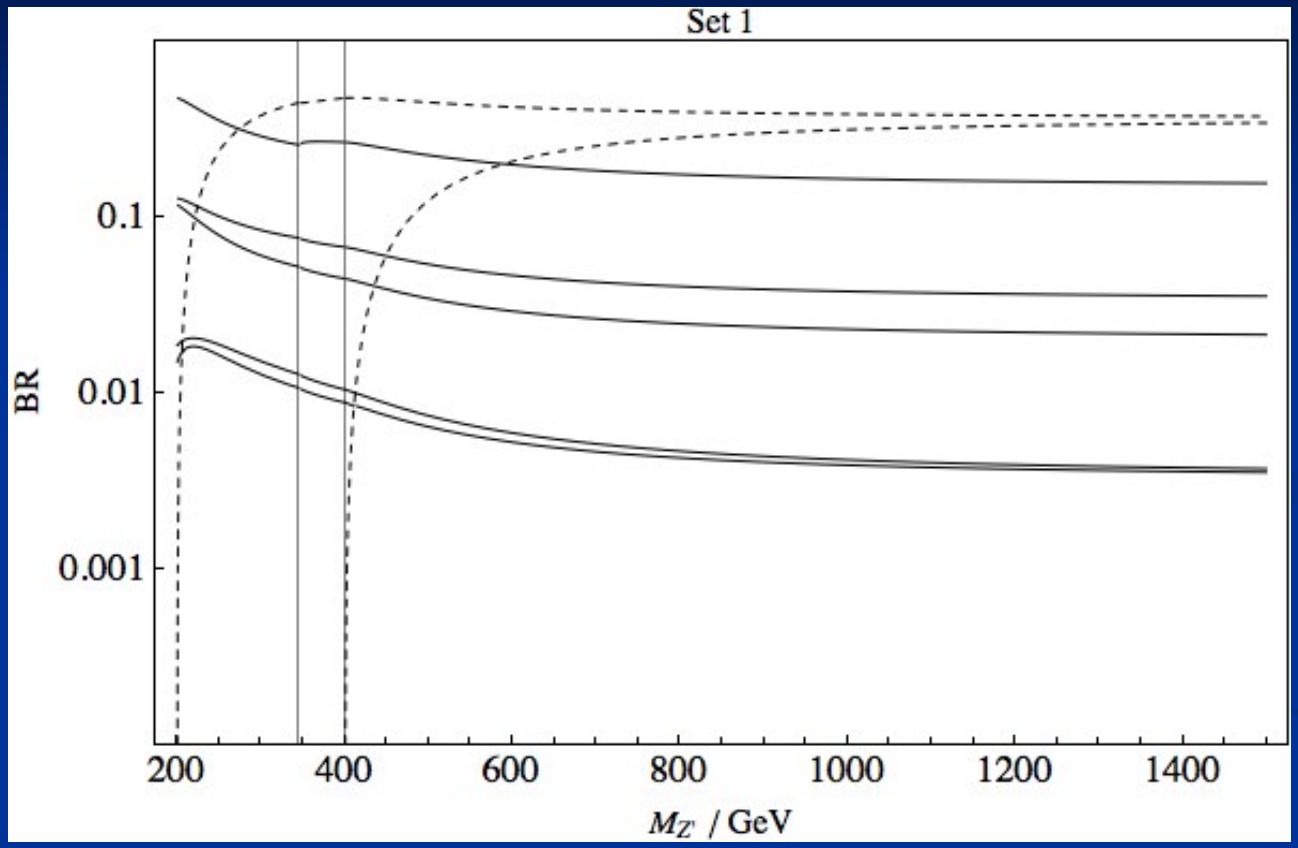


$$M_h = 250GeV$$

$$M_A = 300GeV$$

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

Numerical results VI



$$g_X = 0.1$$

Conclusions

- Extra U(1)s, extended Higgs sector and Stueckelberg mechanism: physics BSM
- Brane constructions 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)