GDR Neutrinos
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a warped A_4 neutrino mass model

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based on **arXiv:*0806.0356*** with C.Csaki, C.Grojean & Y.Grossman (*JHEP2008*)

Outline

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- **Review of A_4 models in 4d**
- **Introducing fermions in AdS_5**

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- **Stability of the 5d model predictions**
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masses : $\Delta m^2_{sol} \simeq 8 \times 10^{-5}\mathrm{eV}^2, \Delta m^2_{atm} \simeq 2 \times 10^{-3}\mathrm{eV}^2 \longrightarrow \Delta m^2_{atm} \simeq 25 \Delta m^2_{sol}$

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$$\frac{g}{\sqrt{2}} \bar{l}^i \gamma^\mu U_{i\alpha} \nu^\alpha W^-_\mu + h.c. \qquad \alpha = \{1,2,3\}$$

Harrison et al. '02

$$U \simeq U_{HPS} = \begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & 0 \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

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- **yet to be known :** - ***normal*** **or** ***inverted*** **hierarchy ?**
  - ***absolute*** **mass scale ?**

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Tri-bimaximal mixings from A_4 in 4d

A_4 = discrete subgroup of SO(3) *subgroups : Z_2 and Z_3*

12 elements in 4 classes $\longrightarrow$ *4 irr. rep. :* $1, 1', 1''$ *and* $\mathbf{3}$ *(with* $1'' = \bar{1}'$*)*

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our warped 5d setup will eliminate these drawbacks

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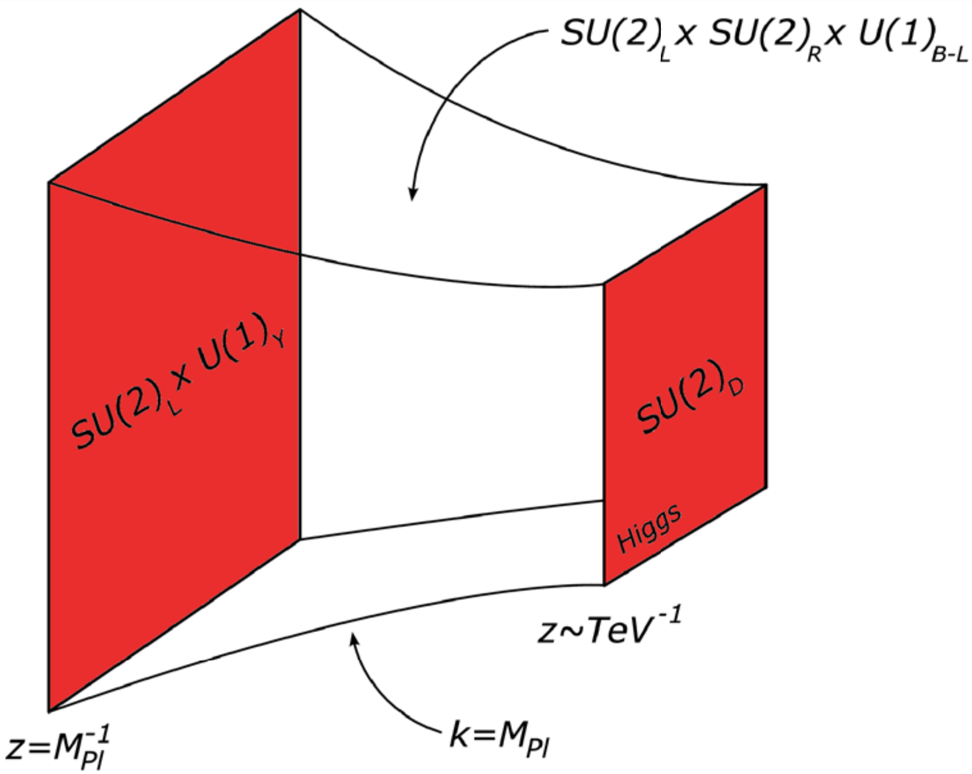
Electroweak breaking in AdS5

Csaki et al. '04

$$ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu - dz^2)$$



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breaking by BC's at $z_{UV} = R = M_{Pl}^{-1}$

$$\partial_z A^a_{L,\mu} = 0, \;\; A^{\pm}_{R,\mu} = 0$$
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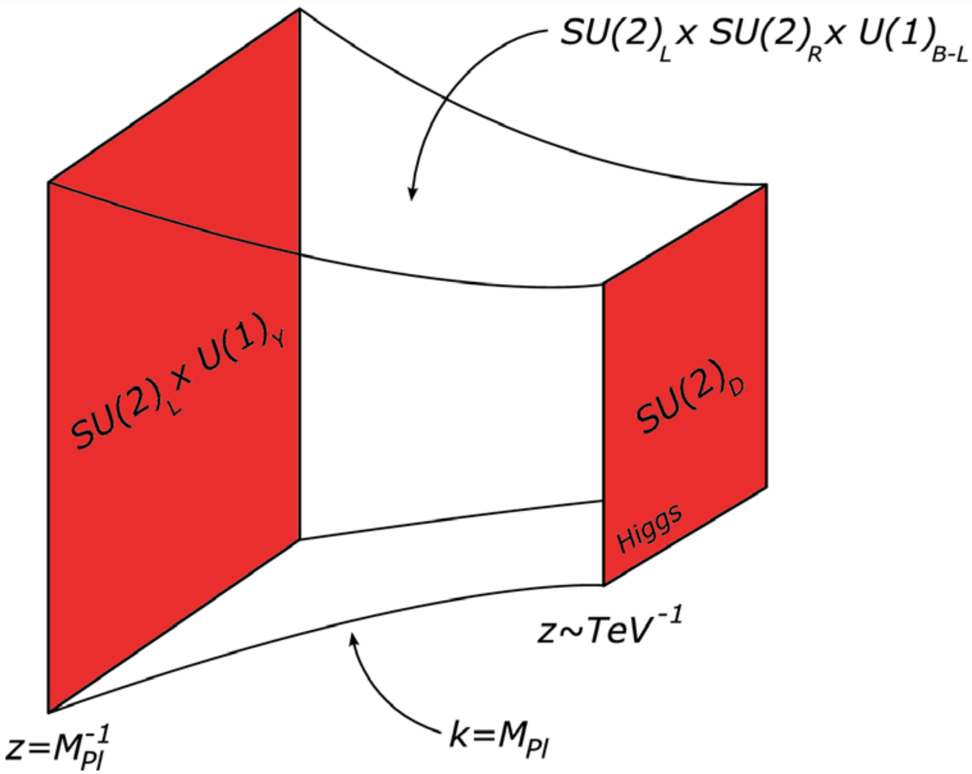

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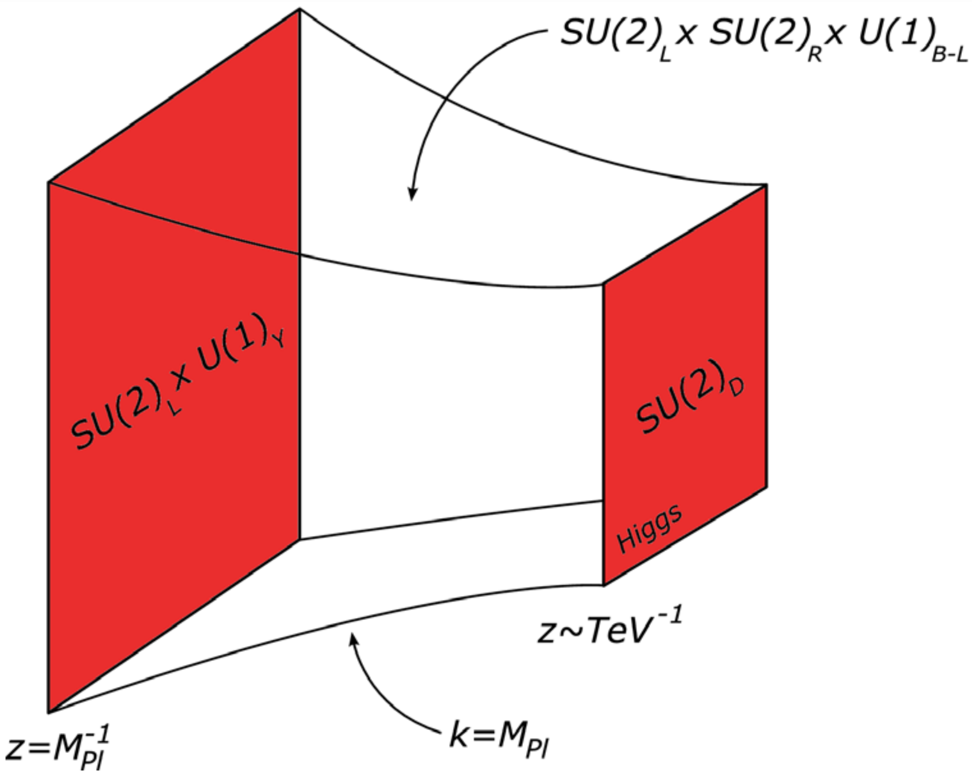

EWSB with a boundary Higgs
at $z_{IR} = R' \sim \mathrm{TeV}^{-1}$

$$\mathcal{H} \sim (\mathbf{2}_L, \mathbf{2}_R)_0$$

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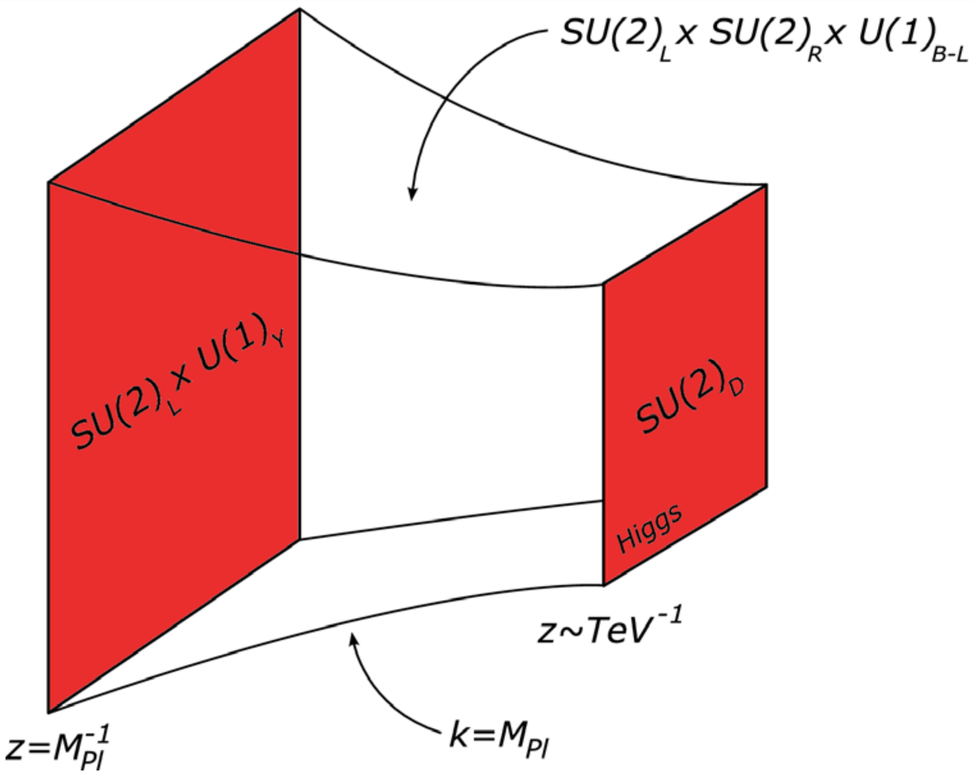

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so that in 4d : *1 massless mode :* γ_μ

W_μ, Z_μ = *Kaluza-Klein modes*

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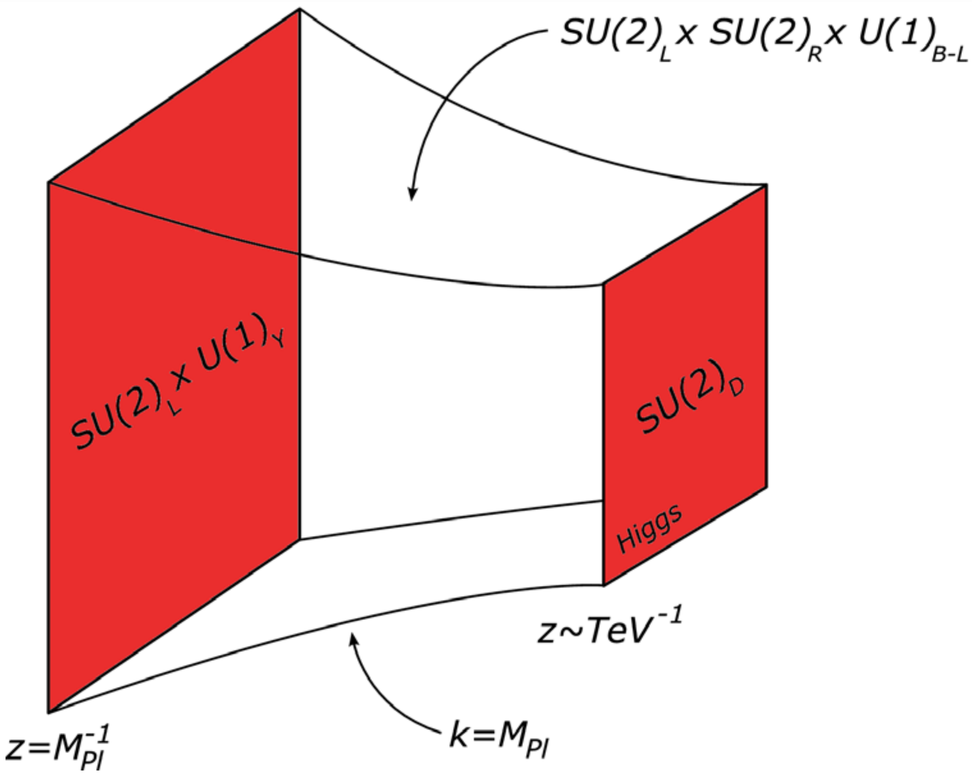
custodial $SU(2)_D \longrightarrow \ \rho \simeq 1$



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- **5d fermions of Dirac-type $\longrightarrow$ chirality in 4d via BC's**

ex : $\Psi = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix} \begin{matrix} [++] \\ [--] \end{matrix} \leftrightarrow \bar{\psi}|_{R,R'} = 0$ *:* χ *only has a massless mode*

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natural fermion mass hierarchy

$$|c| \gtrsim 1/2 \rightarrow m_f \ll m_W$$

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SM fermion masses from AdS_5

Dirac mass from IR brane Yukawa couplings

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ν_R Majorana mass from UV brane

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seesaw mechanism

after integrating ψ_{ν_R} out :

$$\boxed{m_{\nu_L} = \frac{y^2 v_H^2}{2M}\frac{f_L^2 f_{-R}^2}{F^2_{-R}}} \qquad \boxed{m_e = y\frac{v_H}{\sqrt{2}} f_L f_{-R}}$$

$$\Lambda' \sim R'^{-1}, \; \Lambda \sim R^{-1}$$

A warped 5d model

Embedding A_4 in AdS_5

Bulk leptons

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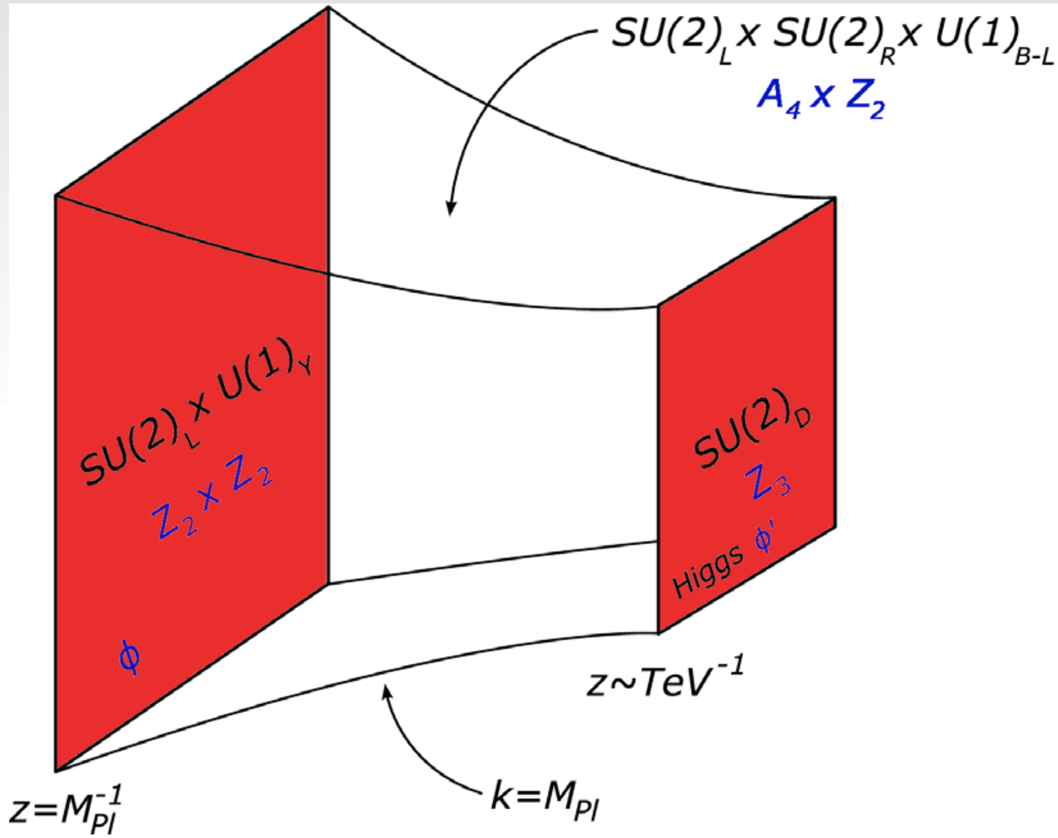

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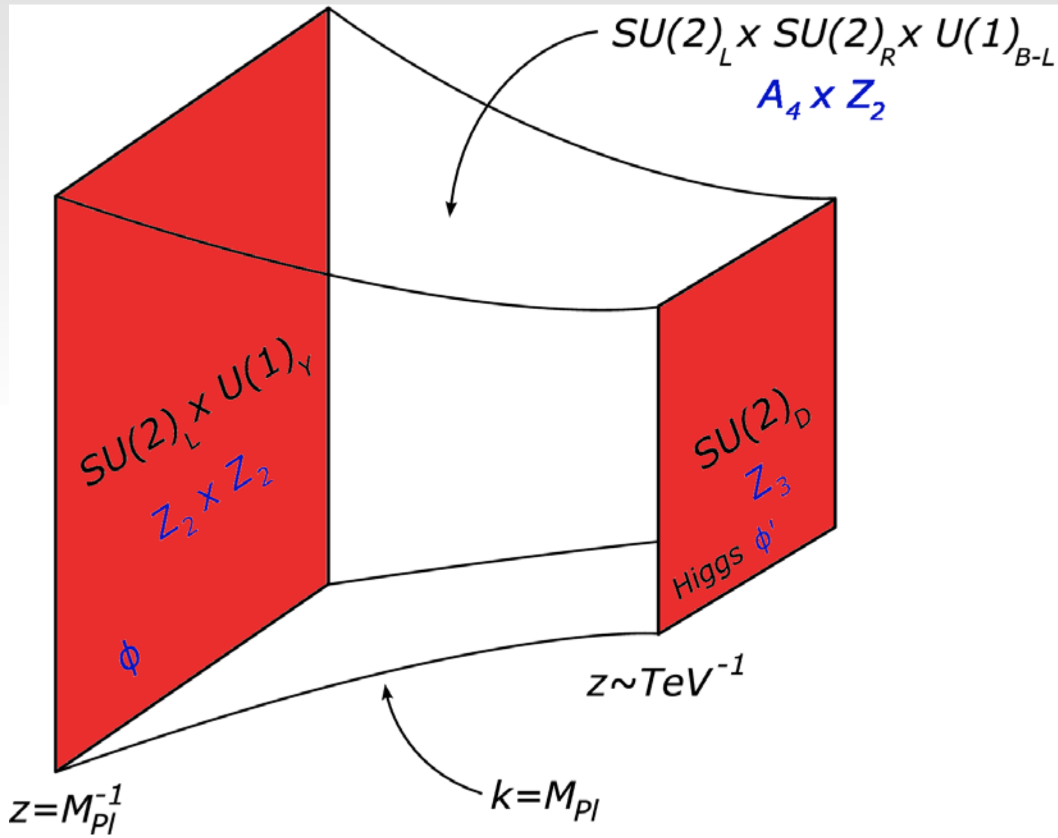
A_4 breaking scalar VEVs

$\phi \sim 3_+ \sim (v, 0, 0)$ **at** $z = R$

$\phi' \sim 3_- \sim (v', v', v')$ **at** $z = R'$



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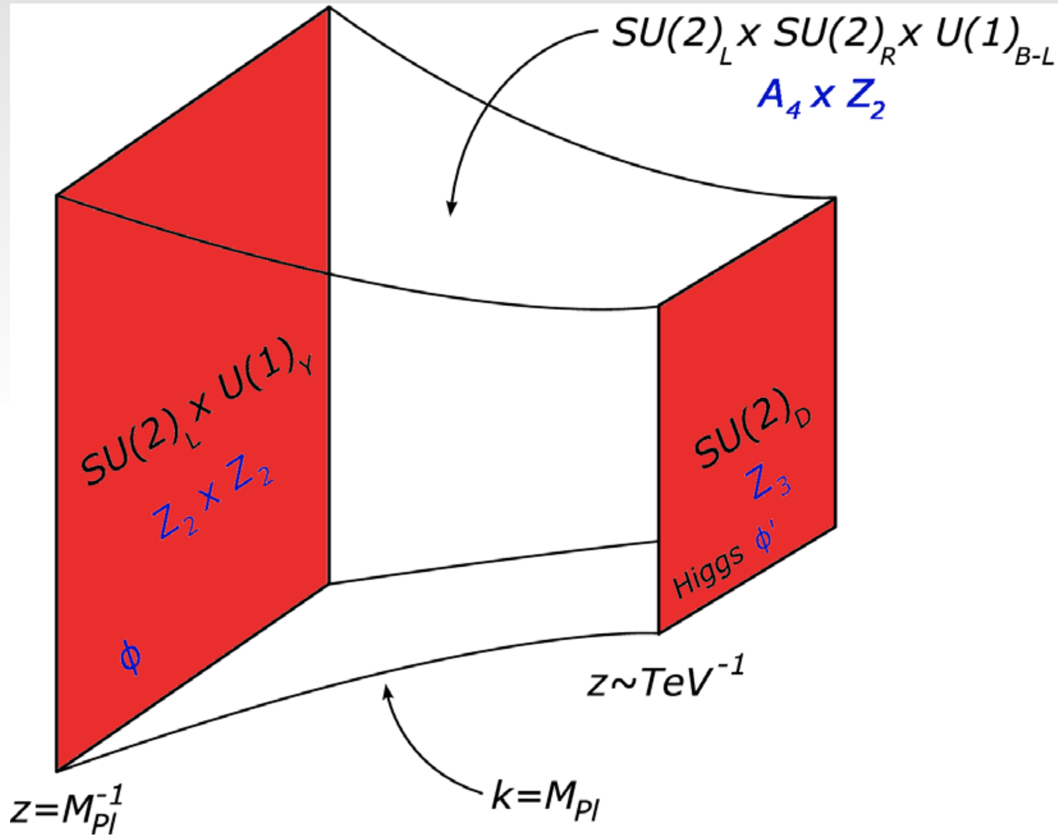
$$\Psi_{e,\mu,\tau} = \begin{pmatrix} \tilde{\nu}_R\ [+-] \\ l_R\ [--] \end{pmatrix} \sim (1, 1', 1'')_+$$

$$\Psi_\nu = \begin{pmatrix} \nu_R\ [--] \\ \tilde{l}_R\ [+-] \end{pmatrix} \sim 3_-$$

A_4 breaking scalar VEVs

$\phi \sim 3_+ \sim (v, 0, 0)$ **at** $z = R$

$\phi' \sim 3_- \sim (v', v', v')$ **at** $z = R'$



Boundary lagrangians

$$-\mathcal{L}_Y^{IR} = \frac{y_e}{\Lambda'^2}(\bar{\Psi}_L \phi')\mathcal{H}\Psi_e + \frac{y_\mu}{\Lambda'^2}(\bar{\Psi}_L \phi')''\mathcal{H}\Psi_\mu + \frac{y_\tau}{\Lambda'^2}(\bar{\Psi}_L \phi')'\mathcal{H}\Psi_\tau + \frac{y_\nu}{\Lambda'}(\bar{\Psi}_L \mathcal{H}\Psi_\nu) + h.c.$$

$$-\mathcal{L}_Y^{UV} = \frac{M}{2\Lambda}(\nu_R \nu_R) + \frac{x_\nu}{2\Lambda}(\phi \nu_R \nu_R) + h.c.$$

A warped 5d model

Predictions of the model

HPS type mixing matrix

$$M_l = V D_l 1_R \qquad M_d^\nu = D_d^\nu \qquad M_{\nu_R} = V^\dagger U_{HPS} D_{\nu_R} U_{HPS}^T V^\dagger$$

after seesaw : $M_{\nu_L} = -M_d^\nu M_{\nu_R}^{-1} (M_d^\nu)^T = V^\dagger U_{HPS} D_{\nu_L} U_{HPS}^T V^\dagger$

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$$\boxed{m_l = y_l f_L f_{-l} \sqrt{3/2} \frac{v' v_H}{\Lambda'}}$$

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ex: $x_\nu = 1, y_\nu = 1, c_\nu = -0,37$

heaviest $m_{\nu_L} \simeq 50\mathrm{meV}$

A warped 5d model

Effective corrections

IR brane $\phi' = (v', v', v')$ $A_4 \times Z_2 \longrightarrow Z_3$ $\phi'^2 \sim 1 + \phi'$

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no corrections to charged lepton mass matrix at all order $M_l = V D_l 1_R$

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all Yukawa couplings are taken to saturate their perturbative bounds (NDA)

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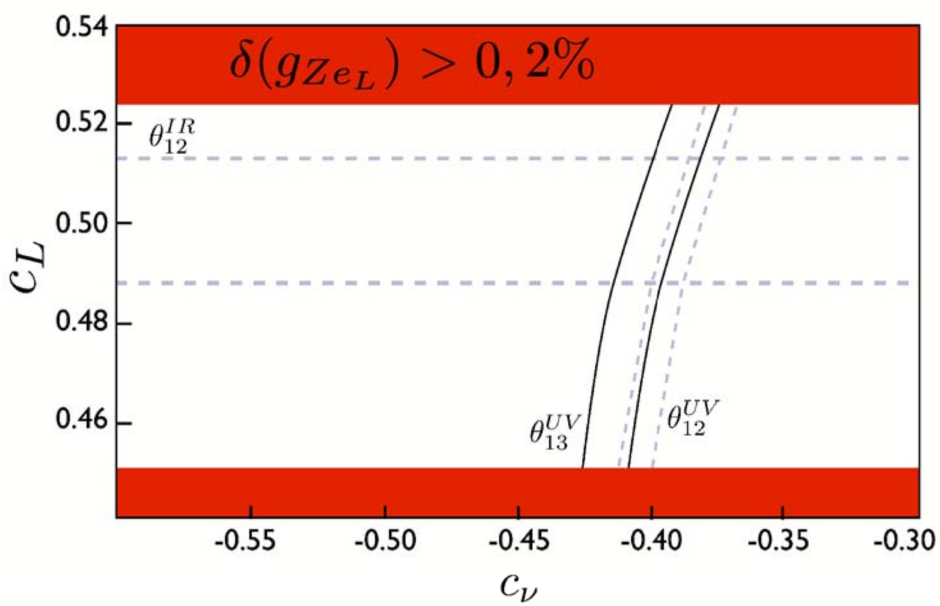

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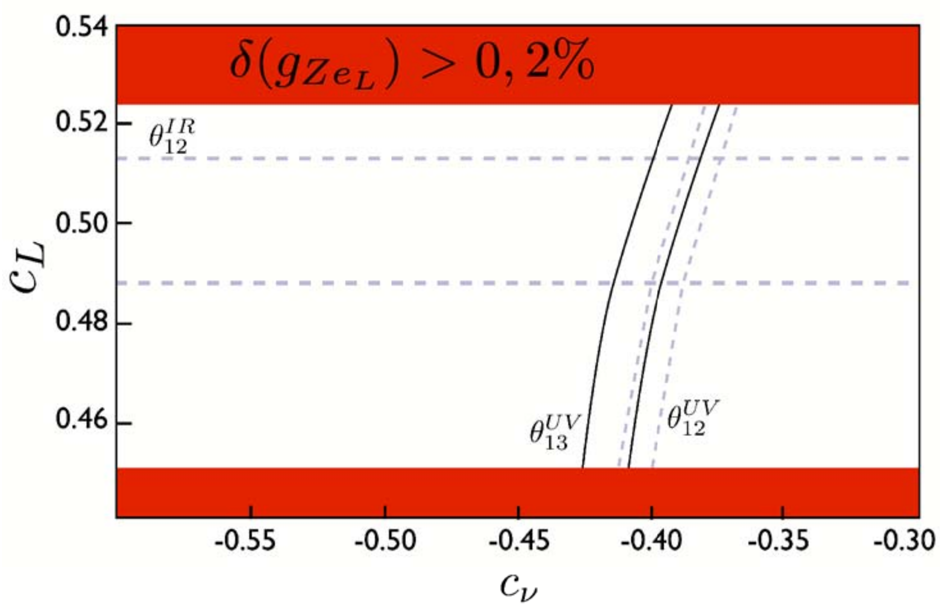

HPS pattern is stable under any corrections!

A warped 5d model

LFV constraints

Neutral current exchanged at tree-level (Z, Z_{KK})

A warped 5d model

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interaction basis : $g_k^L(c_L)\bar{l}_L^i\bar{\sigma}_\mu l_L^i Z_k^\mu + g_k^R(c_i) l_R^i \sigma_\mu \bar{l}_R^i Z_k^\mu$

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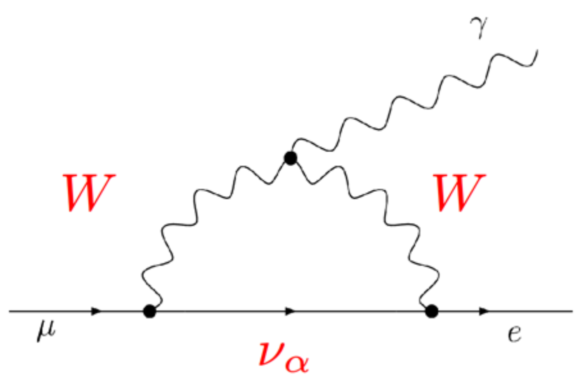
BSM loop-level contributions to $\mu \to e\gamma$

$B_{exp} < 1,2 \times 10^{-11}$



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Cheng et al. '77

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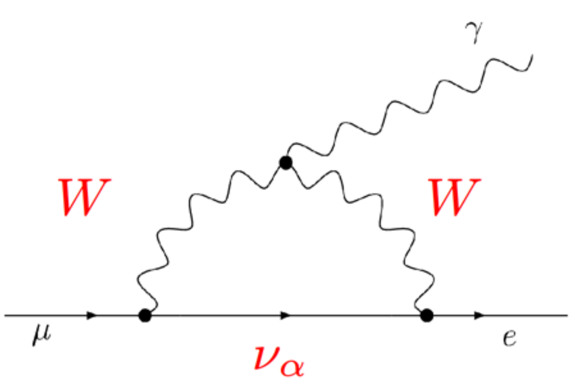

$$B(\mu \to e\gamma) = \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{8\pi} \left| \sum_\alpha U_{\mu\alpha}^* U_{e\alpha} F\left(\frac{m_{\nu_\alpha}^2}{m_W^2}\right) \right|^2$$

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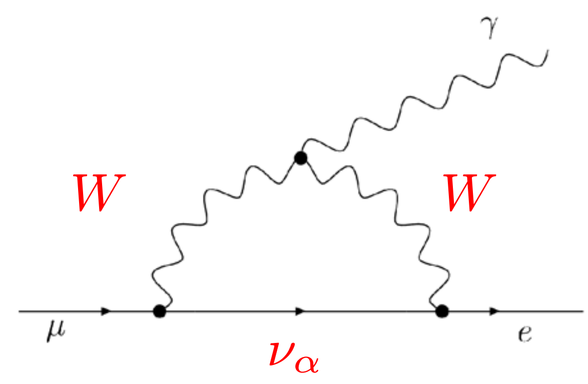

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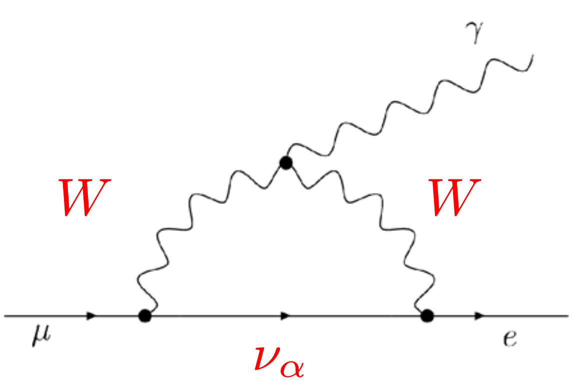

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Other benefits of this model :

θ_{13} **is naturally small, KK-gauge boson and KK-neutrino @LHC**