Non-custodial warped extra dimensions at the LHC?

arXiv:1410.7345 [hep-ph] (with Stephan Huber)

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Overview

- What is a warped extra dimension and why are we interested?
- Scalar fields in a warped ED
- Gauge and fermion fields in a warped ED
- Electroweak precision observables
  $\rightarrow$ large incalculable contribution from HDOs?
  $\rightarrow$ KK resonances at 5 TeV?
- Corrections to Higgs couplings
  $\rightarrow$ to gauge bosons
  $\rightarrow$ to fermions

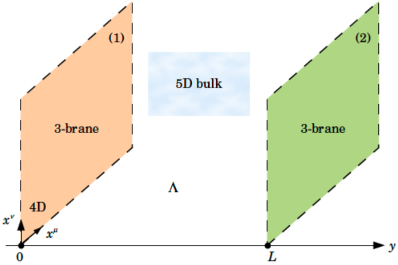
  Experimental Constraints?
  HL-LHC should measure $\lambda_t \lesssim 10\%$
  Other couplings could be measured $\lesssim 1\%$ at ILC or TLEP.

Warped extra dimensions

Randall & Sundrum '99

1 extra dimension bounded by UV and IR 3-branes → compactification

Metric: $g_{MN} = (-e^{-2k|y|}, e^{-2k|y|}, e^{-2k|y|}, e^{-2k|y|}, 1)$



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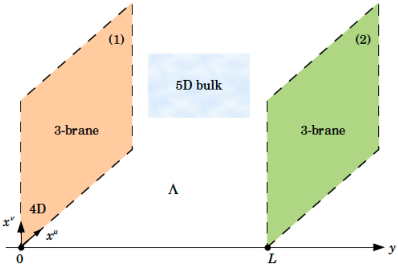

Mass scales can get suppressed by $\sim e^{-2kL}$, $kL \sim 35 \Rightarrow$ Planck scale masses can get shifted to TeV scale!

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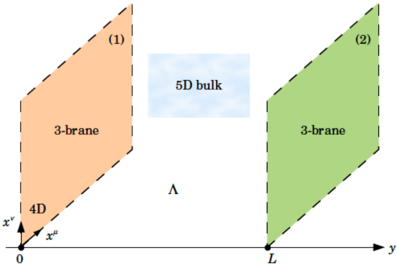

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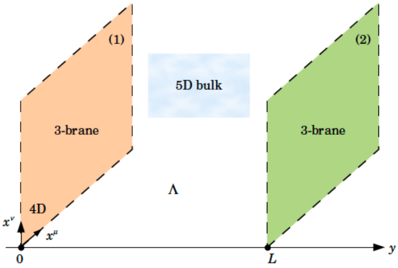

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A field in the bulk has a tower of modes $\Rightarrow$ TeV scale resonances.

Different fermion localisations $\Rightarrow$ naturally generated fermion mass hierarchy with $\mathcal{O}(1)$ Yukawas.

Scalar fields in a warped extra dimension

$$S_\Phi = \int d^4x \int_0^L dy\ \frac{1}{2}\sqrt{|g|}\left((\partial_M \Phi)^2 - m_\Phi^2 \Phi^2\right),$$

where $M = \mu, y$ and $\sqrt{|g|} = e^{-4ky}$. The 5D mass term consists of both bulk and brane terms such that

$$m_\Phi^2 = (b^2 + \delta b^2)k^2 - \delta(y)a^2 k + \delta(y-L)(a^2 + \delta a^2)k.$$

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$$b^2 = a^2(a^2 + 4).$$

Zero mode profile:

$$f_0(y) = \sqrt{\frac{2(1+a^2)kL}{1 - e^{-2(1+a^2)kL}}}\, e^{-a^2 ky}.$$

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+ tower of IR localised Kaluza-Klein resonances with $m_n \simeq \left(n + \frac{\alpha}{2} - \frac{3}{4}\right)\pi k e^{-kL}$

Scalar fields in a warped extra dimension

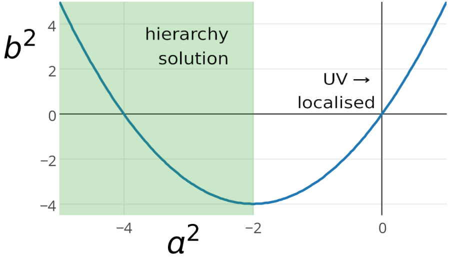

Figure : The solid line shows the relationship between the bulk and brane mass terms required to have a massless scalar mode of eq. (1). The shaded region shows the parameter space for which the Higgs profile is sufficiently IR localised such that the hierarchy problem is resolved.

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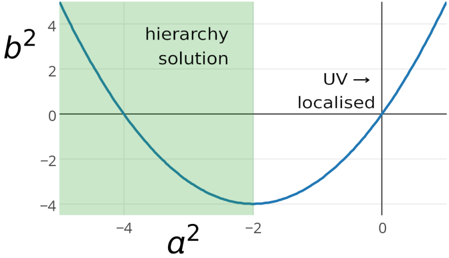

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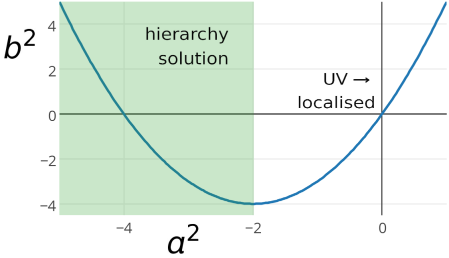

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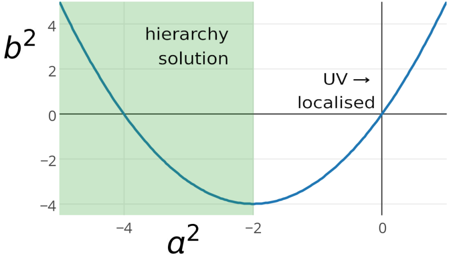

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and for $(a^2+2) \gtrsim 1/(kL)$

$$\delta m^2_{00} \simeq 2(a^2+1)\left(\frac{\delta b^2}{a^2+2} - \delta a^2\right) k^2 e^{-2kL}.$$

Higgs potential in Randall Sundrum

Complex SU(2) Higgs doublet in a slice of AdS:

$$S = \int d^4x \int_0^L dy \; e^{-4ky} \left((D^M\Phi)^\dagger (D_M \Phi) - m_\Phi^2 \Phi^\dagger \Phi - \lambda_5 (\Phi^\dagger \Phi)^2 \right)$$

BRANE and BULK quartics:

$$\lambda_5 = \lambda_B + \frac{1}{k}\lambda_{IR}\delta(y-L) + \frac{1}{k}\lambda_{UV}\delta(y).$$

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	λ_{0000}	λ_{1000}	λ_{1100}	λ_{1110}	λ_{1111}
Brane Quartic	1.00	-1.00	1.00	-1.00	1.00
Bulk Quartic	1.00	-0.54	0.66	-0.34	0.70

Table : This shows the values of the quartic couplings for brane and bulk EWSB with $a^2 = -2$ and $\lambda_B = 1$ or $\lambda_{IR} = 1/4$.

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Multiple Higgs doublet models

If the 5D Higgs acquires a v.e.v., the zero mode and higher KK modes in the effective theory acquire a v.e.v. also, with

$$v_n \simeq -\frac{\lambda_{n000}}{\lambda_{0000}}\frac{m_H^2}{m_n^2}v_0.$$

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Observables:

$\tan(\beta) = v_1/v_0$

$\cos(\beta - \alpha) = g_{HVV}^{2HDM}/g_{HVV}^{SM}$

We find both $\sim v^2/M_{KK}^2$, per-mille corrections $\Rightarrow$ well within experimental constraints

Tension with expt constraints would require $M_{KK} \sim 1$ TeV

Gauge and fermion fields in a warped extra dimension

$$S_{A,\Psi} = \int d^4x \int_0^L dy\ \sqrt{|g|} \left(-\frac{1}{4} F_{MN} F^{MN} + \frac{1}{2} \left(\bar{\Psi} \gamma^M D_M \Psi - D_M \bar{\Psi} \gamma^M \Psi \right) - c_\Psi k \bar{\Psi} \Psi \right).$$

where $E_a^M \gamma^a = \gamma^M$, $\gamma^a = (\gamma^\mu, i\gamma^5)$, using a KK decomposition:

$A(x,y) = \frac{1}{\sqrt{L}} \sum_n A_n(x) w_n(y) \rightarrow w_0 = 1$

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$\rightarrow$ Varying 5D fermion localisation in bulk allows us to vary the fermion-Higgs coupling without changing the 5D Yukawa coupling

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Both fields give rise to towers of KK resonances in the effective theory

Gauge KK masses: $m_n \simeq \left(n - \frac{1}{4}\right)\pi k e^{-kL}$

Fermion KK masses: $m_n \simeq \left(n + \frac{|\alpha|}{2} - \frac{1}{4}\right)\pi k e^{-kL}$

The electroweak sector & precision observables

Electroweak observables $\rightarrow$ α, G_F, M_Z, M_W, Γ_{l+l-}, and $\sin(\theta_W)^2$

The effective Lagrangian for the zero modes = SM + shifts in masses and couplings

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$$-e(1+\delta a^\psi)\sum_i \bar{\psi}_i\gamma^\mu Q_i\psi_i A_\mu - \frac{e}{s_W\sqrt{2}}(1+\delta w^\psi)\sum_{ij}(V_{ij}\bar{\psi}_i\gamma^\mu P_L\psi_j W_\mu^+ + c.c.)$$
$$-\frac{e}{s_W c_W}(1+\delta z^\psi)\sum_i \bar{\psi}_i\gamma^\mu\left[T_{3i}P_L - Q_i s_W^2 + Q_i s_W c_W \lambda_{ZA}\right]\psi_i Z_\mu,$$

This Lagrangian can be used to calculate the above observables.
The measured values of the observables and their uncertainties can then be used to put bounds on the sizes of the mass and coupling shifts.

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We do not need to constrain all 6 parameter shifts individually. The corrections can all be re-expressed in terms of 3 parameters - S, T and U.

$$\alpha S = 4s_W^2 c_W^2(-2\delta a^\psi + 2\delta z^\psi)$$
$$\alpha T = (\delta w - \delta z) - 2(\delta w^\psi - \delta z^\psi)$$
$$\alpha U = 8s_W^2(-\delta a^\psi s_W^2 + \delta w^\psi - c_W^2\delta z^\psi).$$

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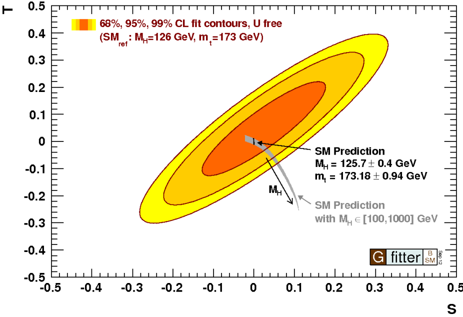

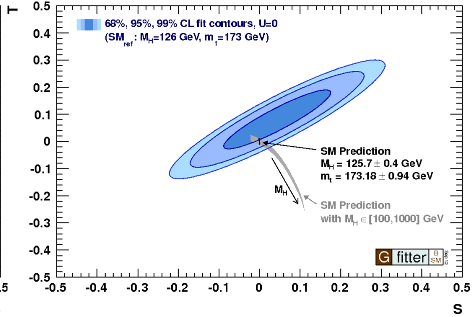

Constraints from the U parameter are usually negligible in phenomenology of extra dimensions.

$\rightarrow$ It is important that we know the correlation between our S and T parameters!

Corrections in the EW sector

Gauge boson masses

Mass matrices for gauge zero mode and KK modes in effective theory:

$$M_W^2 = \frac{g^2}{4}\begin{pmatrix} M_{00}^2 & M_{01}^2 & \cdots \\ M_{01}^2 & \frac{4}{g^2}m_1^2 + M_{11}^2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \qquad M_\gamma^2 = \begin{pmatrix} 0 & 0 & \cdots \\ 0 & m_1^2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

$$M_Z^2 = \frac{g^2+g'^2}{4}\begin{pmatrix} M_{00}^2 & M_{01}^2 & \cdots \\ M_{01}^2 & \frac{4}{g^2+g'^2}m_1^2 + M_{11}^2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

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Diagonalising these, assuming that $M_{00}^2, M_{0n}^2 << m_n^2$, we find

$$(M_W^2)_0 \simeq \frac{g^2 v_0^2}{4}\left(1 - \frac{g^2 v_0^2}{4}\sum_n \frac{R_n^2}{m_n^2}\right)$$

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where $M_{mn}^2 = \frac{v_0^2}{L}\int_0^L dy\ e^{-2ky} w_m w_n f_0^2$

and $R_n = M_{0n}^2/v_0^2$

Corrections in the EW sector

Fermion gauge couplings

We write the unshifted vertex term between a fermion and the W boson as

$$\sum_n \frac{g_{0n}}{\sqrt{2}s_W} \sum_i (V_{i0}\bar{\psi}_{i0}\gamma^\mu P_L \psi_{j0} W^+_{\mu n} + c.c.),$$

where g_{mn} is the effective coupling,

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Rotating the gauge fields to the mass eigenbasis $\Rightarrow$ a shift in the effective coupling for the zero mode:

$$\frac{g_{00}}{\sqrt{2}s_W}\left(1 - \frac{g^2}{4}\sum_n \frac{M^2_{0n}}{m^2_n}\frac{g_{0n}}{g_{00}}\right)\sum_i (V_{ij}\bar{\psi}_{i0}\gamma^\mu P_L \psi_{j0} W^+_{\mu 0} + c.c.).$$

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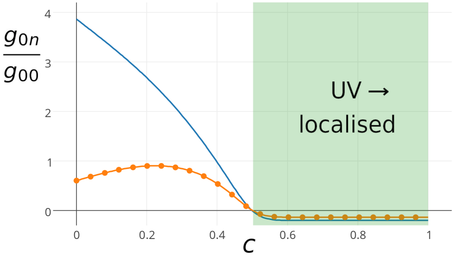
Rotating the gauge fields to the mass eigenbasis $\Rightarrow$ a shift in the effective coupling for the zero mode:

$$\frac{g_{00}}{\sqrt{2}s_W} \left(1 - \frac{g^2}{4} \sum_n \frac{M^2_{0n}}{m^2_n} \frac{g_{0n}}{g_{00}}\right) \sum_i (V_{ij}\bar{\psi}_{i0}\gamma^\mu P_L \psi_{j0} W^+_{\mu 0} + c.c.).$$



Electroweak precision observables

Constraints on the KK scale

$$S \simeq \left(\frac{-9\pi}{2} \sum_n \frac{R_n}{(n-\frac{1}{4})^2} \frac{g_{0n}}{g_{00}} \right) \frac{v_0^2}{M_{KK}^2}, \quad U \sim (g^2 - (g^2 + g'^2) c_W^2) = 0$$

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We can quantify the correlation between S and T as

$$T \simeq \frac{1}{8 c_W^2} \left(2 - \frac{g_{00}}{g_{01}} R_1 \right) S.$$

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	R_1	R_2	R_3	R_4
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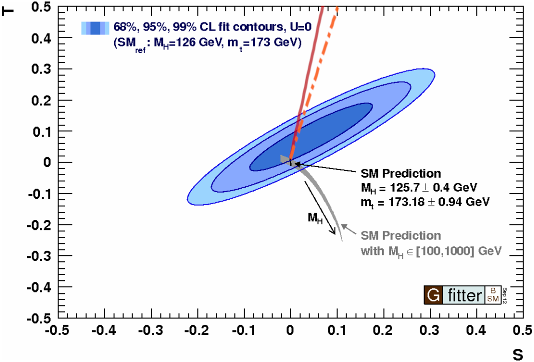

Figure : Here we have overlaid the GFITTER bounds with the S and T correlations for brane (solid) and bulk (dashed) Higgs cases.

Can we reduce these constraints?

Yes..

T corrections $(\delta w - \delta z)$ arise from mixing of hypercharge resonances with neutral W_L^3 zero mode, and are enhanced by large couplings of the Higgs to the KK gauge modes. Solutions??

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  Bulk gauge symmetry: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

  Break on UV brane to $SU(2)_L \times U(1)_Y$, Dirichlet BCs $\Rightarrow$ no W_R zero modes.

  RESULT: mixing in neutral and charged sectors, $\delta w - \delta z \simeq 0$
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- Reduce coupling between Higgs and KK gauge bosons

  1 - A(lmost)AdS backgrounds, soft wall backgrounds...

  2 - Bulk & IR-brane kinetic terms for gauge bosons
  Flat zero modes, IR localised KK modes $\Rightarrow$ KK modes get larger contributions from the IR term than the zero modes.
  Normalisation of the kinetic term $\Rightarrow$ couplings to KK gauge bosons get a larger re-scaling then the zero modes $\rightarrow$ reduced coupling to Higgs
  IR kinetic operators typically require large coefficients, $\sim kL \sim 35$, unnatural?

Incalculable HDO contributions to EWPOs

UV physics unknown, parameterise possible effects in HDOs. Relevant operators:

S: $\frac{\rho}{M_5^3}(\Phi^\dagger T^a \Phi) W^a_{MN} B_{MN}$

T: $\frac{\lambda}{M_5^3}|\Phi^\dagger D^M \Phi|^2$

U: $\frac{\theta}{M_5^6}|\Phi^\dagger W^{MN} \Phi|^2$

where $\kappa = k/M_5$ $(0.01 \le \kappa \le 1)$ and the operators are present on brane and in bulk, i.e. $\rho = \rho_B + \rho_{IR} M_5^{-1} \delta(y - \pi R)$.

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We find that S, T are $\sim v_0^2/M_{KK}^2$ and $U \sim v_0^4/M_{KK}^4 \rightarrow U$ corrections are irrelevant. Also, S and U receive additional volume suppression. $\sim (kL)^{-1} \sim (35)^{-1} \rightarrow$ only T gets sizeable corrections.

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We find that:

$$T_6 \simeq T\,(1 + \delta_6)\,,$$

where

$$\delta_6 = \left(\frac{1}{\pi c_W^2} \sum_n \frac{R_n^2}{(n - 0.25)^2} \right)^{-1} \left(\frac{2}{3} \frac{\kappa^3}{\alpha} \lambda_B + 4 \frac{\kappa^4}{\alpha} \lambda_{IR} \right).$$

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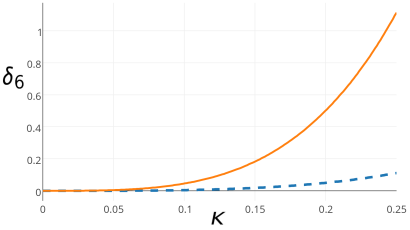

Figure : Here we show how δ_6 varies with κ for $\lambda_B = \lambda_{IR} = 1$ (dashed) and $\lambda_B = \lambda_{IR} = 10$ (solid).

$\rightarrow$ For reasonable values of κ and $\lambda_{B,IR}$ we can get sizeable corrections to the T parameter.

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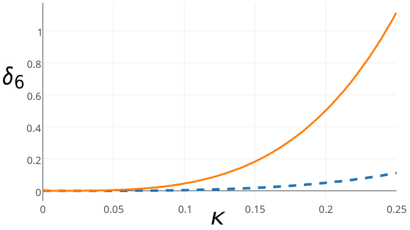

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This also modifies the correlation between S and T!

$$T_6 \simeq \frac{1}{8c_W^2}\left(2 - \frac{g_{00}}{g_{01}} R_1\right)(1+\delta_6)\, S.$$

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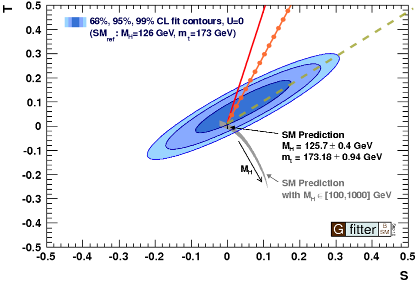

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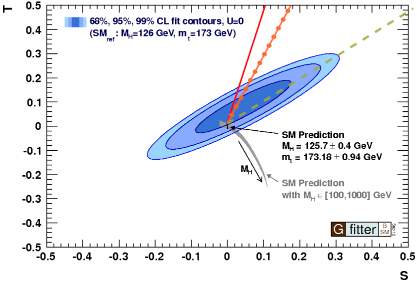

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$$\delta_6 = -0.4 \Rightarrow M_{KK} \geq 6 \text{ TeV}$$

$$\delta_6 = -0.8 \Rightarrow M_{KK} \geq 2.7 \text{ TeV}$$

Possibility of KK resonances at LHC!

Misalignment in gauge couplings to the Higgs

Before diagonalising the fields, the mass term for the W fields is of the form

$$\sim \begin{pmatrix} W_0^+ & W_1^+ & \dots \end{pmatrix} \begin{pmatrix} M_{00}^2 & M_{01}^2 & \cdots \\ M_{01}^2 & \frac{4}{g^2} m_1^2 + M_{11}^2 & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix} \begin{pmatrix} W_0^- \\ W_1^- \\ \vdots \end{pmatrix}$$

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$\Rightarrow$ when rotated to the mass eigenbasis there will be a misalignment in the gauge masses and their coupling to the Higgs!

misalignment $\sim R_1^2 m_W^2 / M_{KK}^2$

$\rightarrow$ with $M_{KK} \sim 8$ TeV the misalignment in the HZZ and HWW couplings are 0.4% and 0.3% respectively.

Observable at ILC and TLEP?

Misalignment in Yukawa couplings

Consider an SU(2) singlet fermion t and doublet $Q = (T, B)$ in the 5D theory. The action for such a system, omitting terms in B, can be written as

$$S = \int d^4x \int_0^L dy \ \sqrt{|g|} \left(\frac{1}{2} \left(\bar{t}\gamma^M D_M t - D_M \bar{t}\gamma^M t \right) - m_t \bar{t} t \right.$$
$$\left. + \frac{1}{2} \left(\bar{T}\gamma^M D_M T - D_M \bar{T}\gamma^M T \right) - m_T \bar{T} T + \lambda_t^{(5)} \sqrt{L} \phi^0 \bar{T} t + \text{h.c.} \right)$$

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where $E_a^M \gamma^a = \gamma^M$, $\gamma^a = (\gamma^\mu, i\gamma^5)$. The fermion mass matrix can be written as,

$$\begin{pmatrix} \bar{T}_L^0 & \bar{T}_L^1 & \bar{t}_L^1 & \bar{T}_L^2 & \bar{t}_L^2 & \cdots \end{pmatrix} \begin{pmatrix} m_{t,0}^{T,0} & 0 & m_{t,1}^{T,0} & 0 & m_{t,2}^{T,0} & \cdots \\ m_{t,0}^{T,1} & M_{T,1} & m_{t,1}^{T,1} & 0 & m_{t,2}^{T,1} & \cdots \\ 0 & m_{T,1}^{t,1} & M_{t,1} & m_{T,2}^{t,1} & 0 & \cdots \\ m_{t,0}^{T,2} & 0 & m_{t,1}^{T,2} & M_{T,2} & m_{t,2}^{T,2} & \\ 0 & m_{T,1}^{t,2} & 0 & m_{T,2}^{t,2} & M_{t,2} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots & \end{pmatrix} \begin{pmatrix} t_R^0 \\ T_R^1 \\ t_R^1 \\ T_R^2 \\ t_R^2 \\ \vdots \end{pmatrix},$$

where $m_{\phi,n}^{\psi,m} = \frac{1}{\sqrt{2}} \lambda_{\phi,n}^{\psi,m} v_0 = \frac{\lambda_t^{(5)} v_0}{\sqrt{2L}} \int_0^L dy \, \sqrt{|g|} f_{\psi L}^m f_{\phi R}^n f_0$.

Misalignment in Yukawa couplings

The mass matrix can be partially diagonalized using orthogonal transformations of the left and right handed KK modes, i.e. $O_L^T M O_R$

$$\begin{pmatrix} 1-\frac{\theta_{L2}^2}{2} & \theta_{L1} & \theta_{L2} \\ -\theta_{L1} & 1 & 0 \\ -\theta_{L2} & 0 & 1-\frac{\theta_{L2}^2}{2} \end{pmatrix} \begin{pmatrix} m_{t,0}^{T,0} & 0 & m_{t,1}^{T,0} \\ m_{t,0}^{T,1} & M_{T,1} & m_{t,1}^{T,1} \\ 0 & m_{T,1}^{t,1} & M_{t,1} \end{pmatrix} \begin{pmatrix} 1-\frac{\theta_{R1}^2}{2} & -\theta_{R1} & -\theta_{R2} \\ \theta_{R1} & 1-\frac{\theta_{R1}^2}{2} & 0 \\ \theta_{R2} & 0 & 1 \end{pmatrix}$$

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The couplings to the Higgs are slightly different. Again there are no large contributions from KK masses,

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$\Rightarrow$ In the mass eigenbasis the fermion mass and Higgs coupling will be misaligned:

$$r_t^{(4)} = \frac{\sqrt{2}\, m_t^{(4)}}{\lambda_t^{(4)} v} - 1 = \frac{(\lambda_{t,0}^{T,1} v_0)^2}{M_{T,1}^2} + \frac{(\lambda_{t,1}^{T,0} v_0)^2}{M_{t,1}^2} - 2\left(\frac{\lambda_{T,1}^{t,1}}{\lambda_{t,0}^{T,0}}\right)\frac{\lambda_{t,1}^{T,0}\lambda_{t,0}^{T,1} v_0^2}{M_{T,1} M_{t,1}} + \frac{\delta w}{2} + \mathcal{O}\left(\frac{\lambda^3 v_0^3}{M_{KK}^3}\right).$$

$\rightarrow$ HL-LHC should measure $r_t^{(4)} \lesssim 10\%$

Misalignment in Yukawa couplings

$m_t^{(4)}$ [GeV]	$\lambda_t^{(5)}$	c_L	c_R	M_{T1} [TeV]	M_{t1} [TeV]	(a) [%]	(b) [%]	(c) [%]	Total [%]
173.48	4	0.550	-0.26	6.52	7.12	12.97	0.05	19.72	32.7
173.73	2	0.530	-0.07	6.05	7.64	5.93	0.01	3.35	9.29
173.07	1	0.488	-0.20	5.98	7.12	1.29	0.03	1.31	2.62
4.17	4	0.526	-0.6320	6.04	6.46	$\sim 10^{-3}$	0.02	6.76	6.78
4.17	2	0.510	-0.6190	5.97	6.41	$\sim 10^{-3}$	0.02	2.48	2.50
4.17	1	0.500	-0.6004	5.93	6.33	$\sim 10^{-3}$	0.02	0.98	1.00
1.79	4	0.542	-0.650	6.10	6.53	$\sim 10^{-3}$	$\sim 10^{-3}$	3.86	3.87
1.79	2	0.508	0.650	5.97	6.53	$\sim 10^{-4}$	$\sim 10^{-3}$	1.07	1.08
1.79	1	0.516	-0.621	6.00	6.41	$\sim 10^{-4}$	$\sim 10^{-3}$	0.58	0.58

Table : Relative shifts in the 4D Yukawa coupling, $r_t^{(4)}$, from eq. (67). The columns denoted by (a), (b), (c) and Total give the first, second, third contribution and the total result in percent. M_{KK} is taken to be 5.9 TeV.

$\rightarrow$ $r_t^{(4)}$ scales with the 5D Yukawa couplings as $(\lambda_t^{(5)})^2$ and with the KK scale as $1/M_{KK}^2$

$\rightarrow$ term (c), not present in the brane Higgs case, dominates for small fermion masses

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  $\rightarrow$ Higgs mediated flavour violation?
  $\rightarrow$ top misalignment observable at HL-LHC
  $\rightarrow$ bottom and tau misalignment visible at ILC and TLEP?