The role of Flavour in model building

a report on behalf of CERN-TH BSM 'think tank'
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EWSB & Flavour Interplay

The physics needed to stabilize the weak scale
might potentially lead to dangerous effects in the flavour sector

Cancellation of the infamous Λ^2 divergences

$$m_H^2 \sim m_0^2 - (115\ \mathrm{GeV})^2 \left(\frac{\Lambda}{400\ \mathrm{GeV}}\right)^2$$

need new degrees of freedom around the TeV scale to avoid fine-tuning

Flavour changing operators generated by these new degrees of freedom?

$$\frac{\mathcal{O}(1)}{\Lambda^2}\left((\bar{Q}_L^i\gamma^\mu Q_L^j)^2 + (\bar{D}_R^i\gamma^\mu D_R^j)^2 + (\bar{Q}_L^i\gamma^\mu Q_L^j)(\bar{D}_R^i\gamma_\mu D_R^j) + (\bar{D}_R^i\gamma^\mu Q_L^j)(\bar{Q}_L^i\gamma_\mu D_R^j)\right)$$

K and B physics ($\Delta M_B, \varepsilon_K$ ...) set strong bounds on Λ: $\Lambda > 10^5\ \mathrm{TeV}$

(only a factor 3 improvement if 1-loop suppression)

Not only these bounds increase fine-tuning
but they also make discoveries at the LHC unlikely

Flavour Issues in Model Building

- Is there a flavour structure built-in in the new models of EWSB?
- Is an additional flavour structure needed?

They are clearly model-dependent questions
Nonetheless generic features emerge

Weakly coupled models

prototype: Susy
susy partners ~ 100 GeV

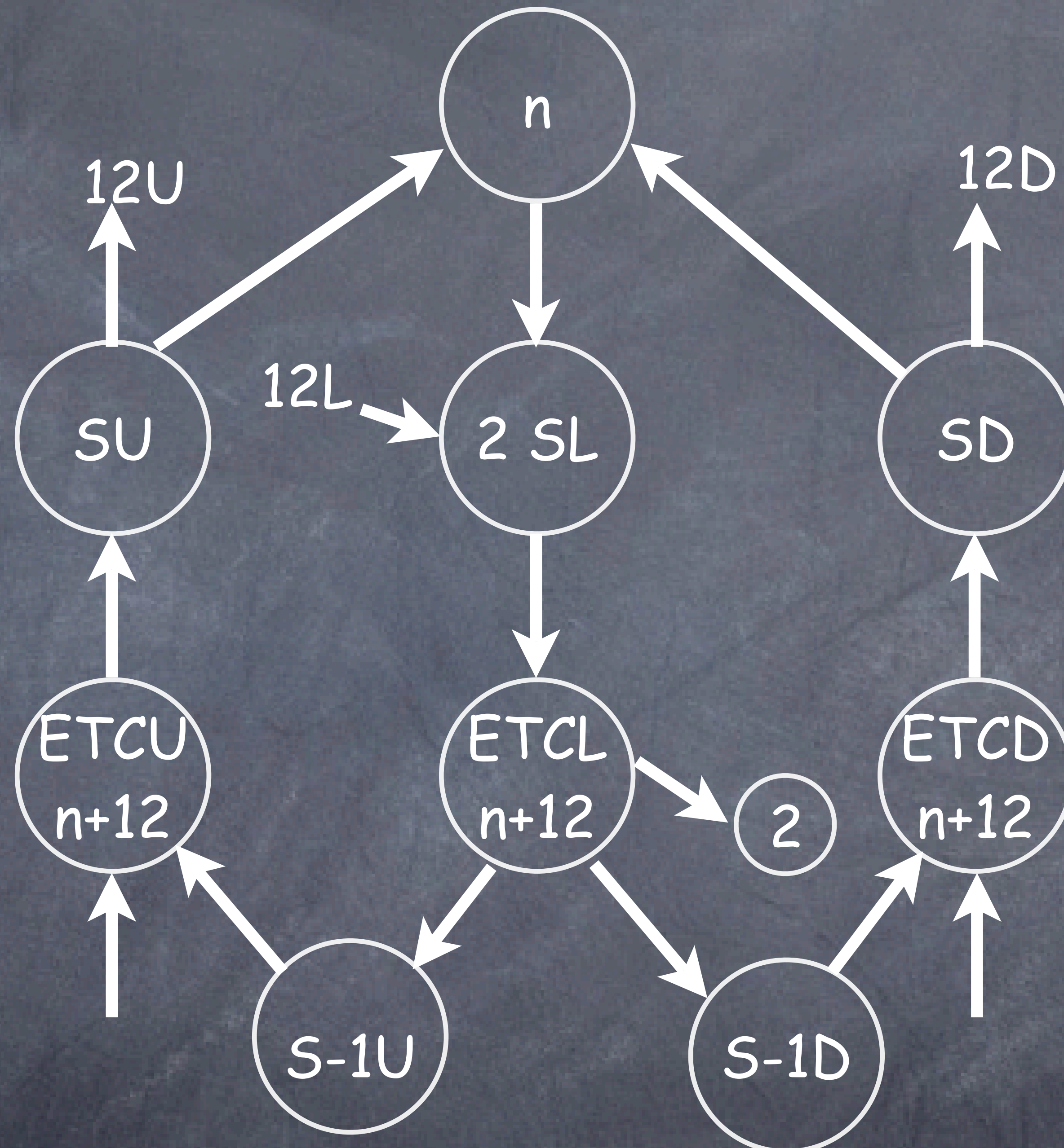
Already well covered in this workshop

Strongly coupled models

prototype: Technicolor
rho meson ~ 1 TeV

Notoriously difficult for old TC models:
1/ to generate flavour hierarchy
2/ to implement flavour symmetry to suppress FCNC
New twist thanks to 5D holographic approach

Example of Flavour Structure in Old TC...



Randall, NPB '93

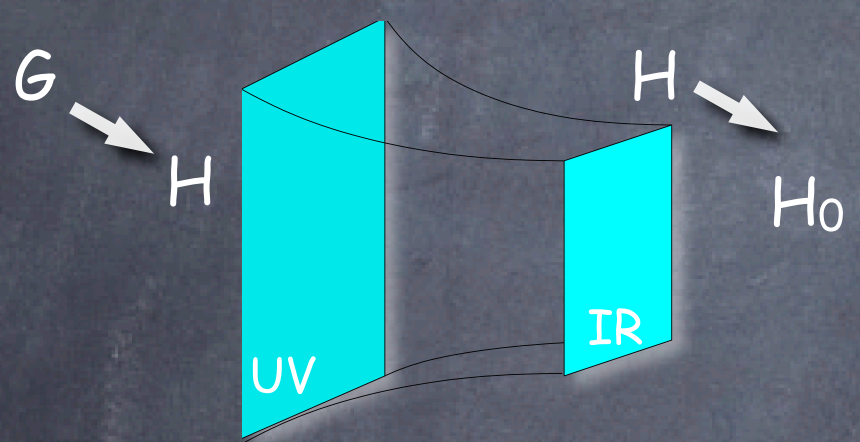
... Back then I would have had a hard time talking about flavour in model-building!

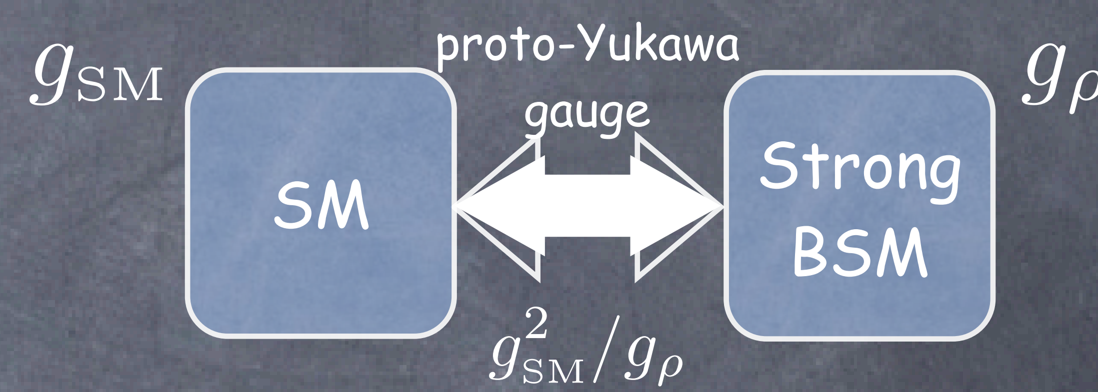
Holographic Approach to Strong Sector

"AdS/CFT" correspondence for model-builder

Warped gravity with fermions and gauge field in the bulk and Higgs on the brane

Strongly coupled theory with slowly-running couplings in 4D

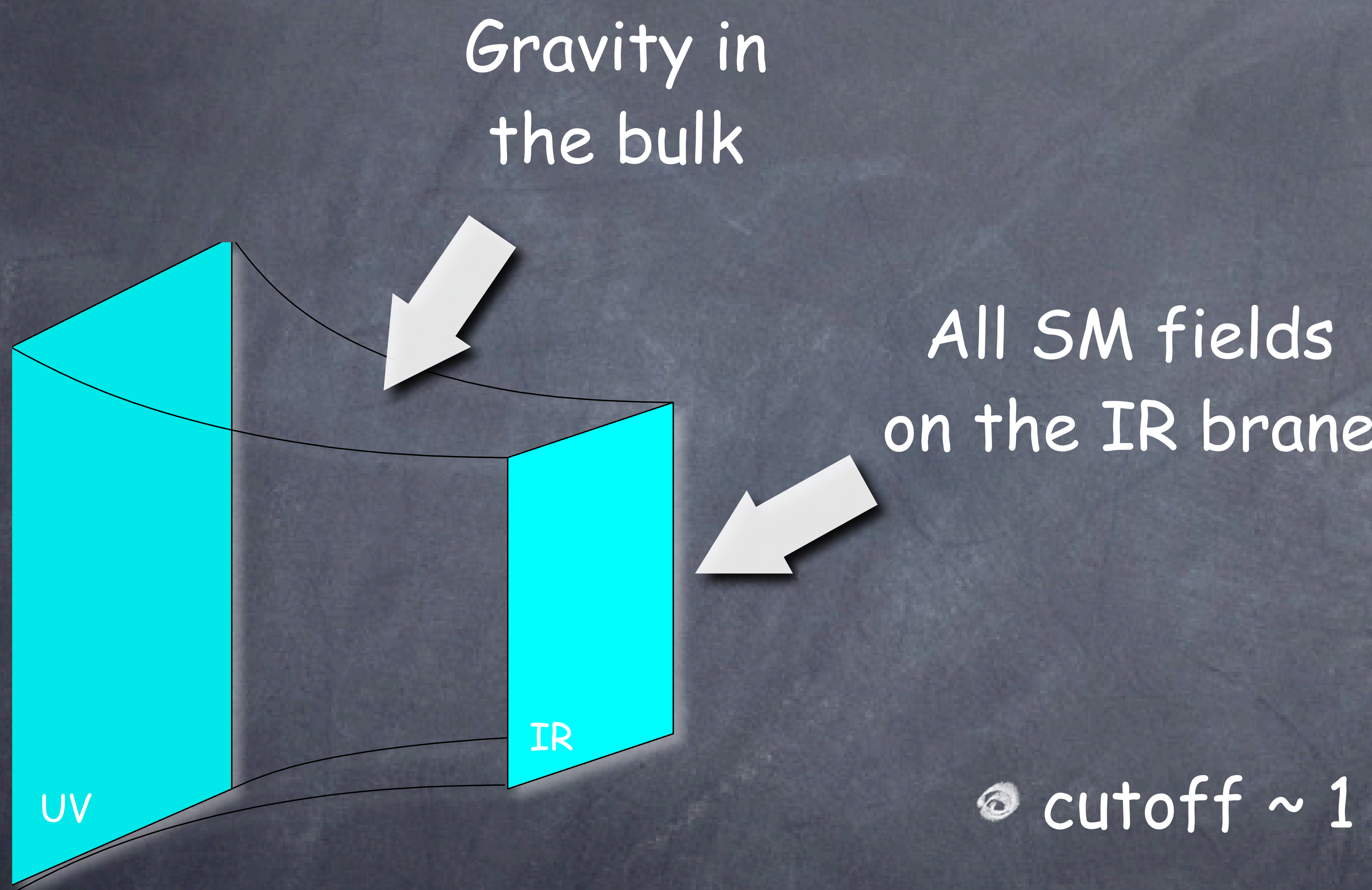




5D	4D
KK modes	vector resonances (ρ mesons in QCD)
motion along 5th dim	RG flow
UV brane	UV cutoff
IR brane	break. of conformal inv.
bulk local sym.	global sym.

Holographic Models of EWSB

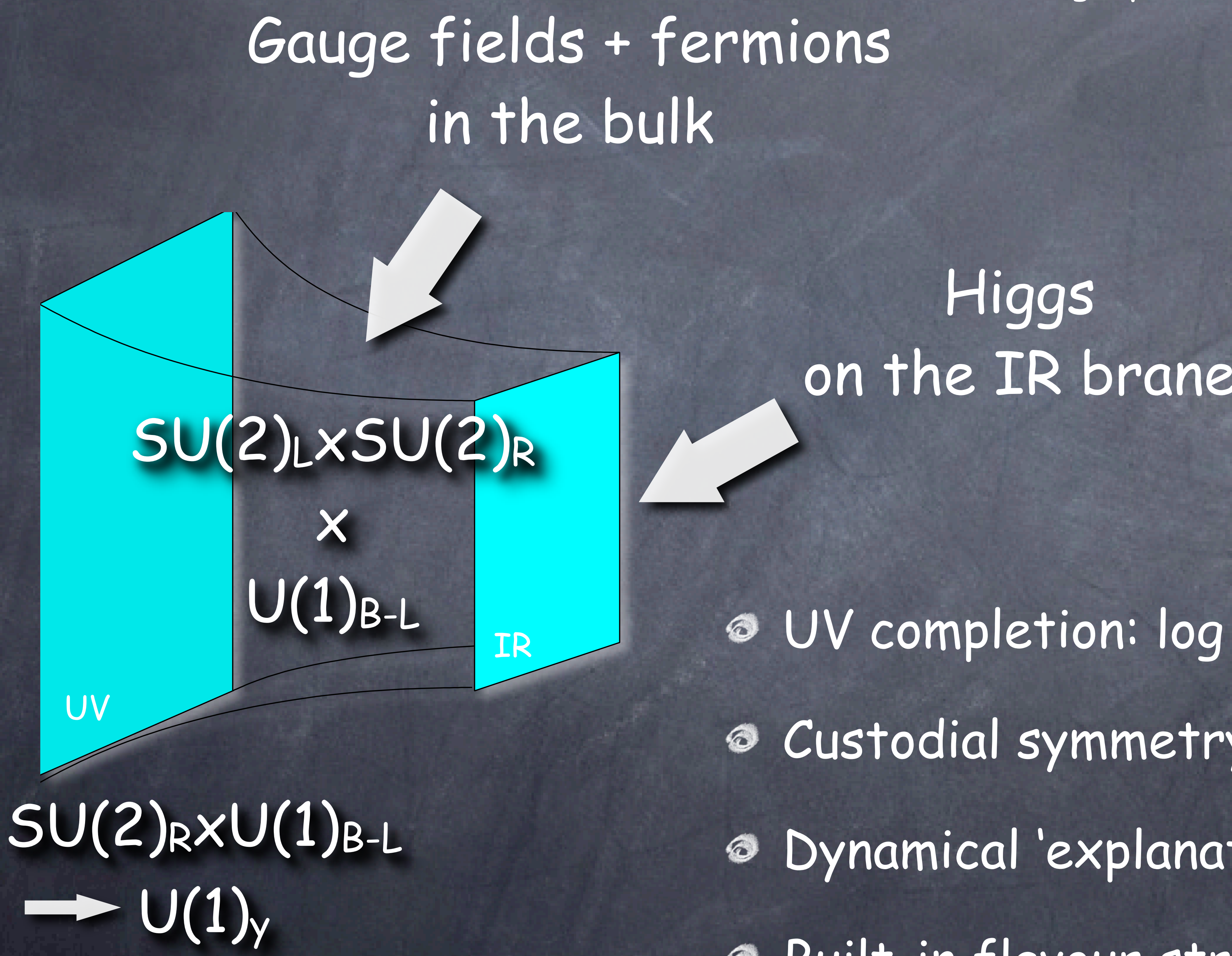
Original Randall-Sundrum proposal: '99



- cutoff ~ 1 TeV
- conflict with EW precision data
- problems with flavour

Holographic Models of EWSB

Bulk gauge fields: Pomarol, '00
Holographic technicolor=Higgsless: Csaki et al., '03
Holographic composite Higgs: Agashe et al., '04



- UV completion: log running of gauge couplings
- Custodial symmetry from bulk SU(2)R
- Dynamical 'explanation' of fermion masses
- Built-in flavour structure

Fermions in AdS: Partial Compositeness

Grossman and Neubert, '00
Gherghetta and Pomarol, '00

5D fermion = no chirality

$$\Psi = \begin{pmatrix} \chi_\alpha \\ \bar{\psi}^{\dot{\alpha}} \end{pmatrix}$$

4D LH chirality

4D RH chirality

Chirality in 4D KK theory

thanks to
orbifold projection/
boundary condition

ψ Dirichlet bc on IR and UV branes
⊃ zero mode for χ

AdS wavefunction

$$\mathcal{S} = \int d^5x \frac{R^4}{z^4} \left(-i\bar{\chi}\bar{\sigma}^\mu \partial_\mu \chi - i\psi\sigma^\mu\partial_\mu\bar{\psi} + \tfrac{1}{2}\left(\psi \overleftrightarrow{\partial_5} \chi - \bar{\chi}\overleftrightarrow{\partial_5}\bar{\psi}\right) + \boxed{\frac{c}{z}(\psi\chi + \bar{\chi}\bar{\psi})} \right)$$

5D mass term in AdS unit: c ~ O(1)

fermion zero mode:

$$\chi = a_0 \left(\frac{z}{z_{UV}}\right)^{2-c} \tilde{\chi}_{4D} \quad \text{with} \quad \int_{z_{IR}}^{z_{UV}} dz\, a_0^2 \left(\frac{z}{z_{UV}}\right)^{2-c} = 1$$

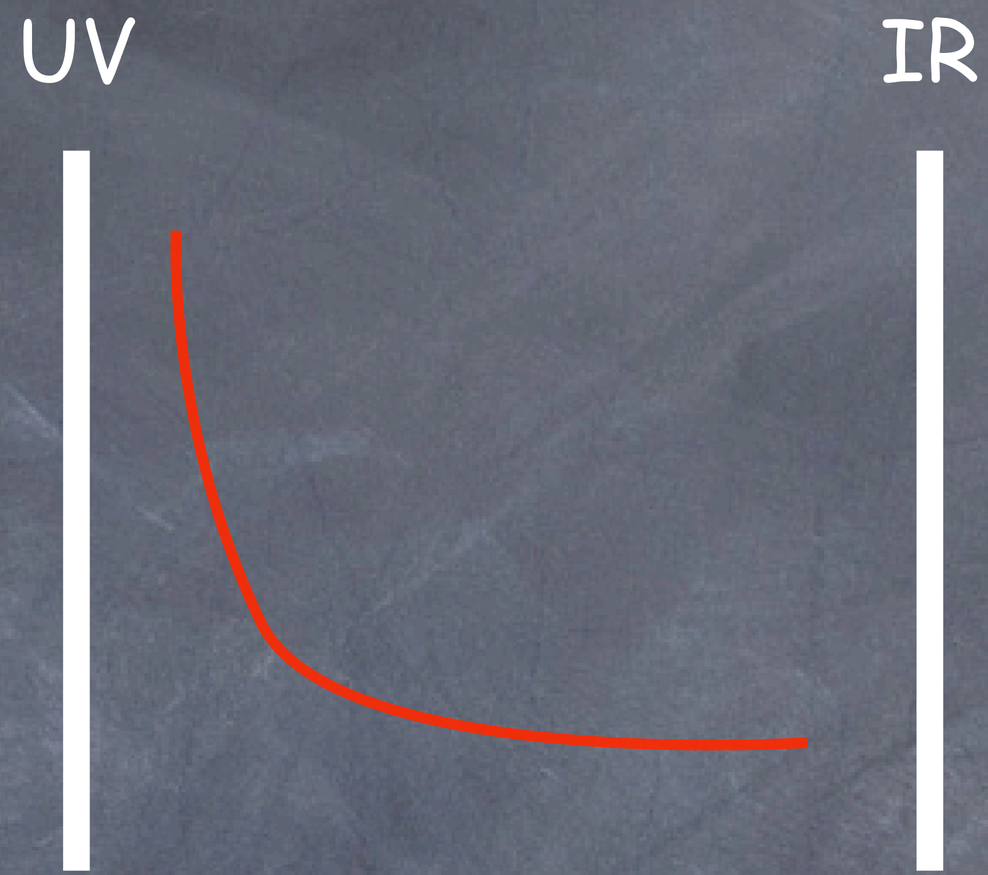
c > 1/2: the zero is normalizable when z^{IR} is sent to infinity (no IR brane): UV localized

c < 1/2: the zero is normalizable when z^{UV} is sent to 0 (no UV brane): IR localized

Elementary fermion

Composite fermion

Masses from IR overlaps



light fermion exponentially localized on the UV brane
⊃ overlap with Higgs vev on the IR tiny
⊃ exponentially small 4D mass

Partial Compositeness: Dual Picture

SM sector

strong sector
EWSB

linear mixing

$\Delta\,\bar{\chi}_L \psi_R$

elementary fermions: χ

$\bar{\chi}_L \not{\partial} \chi_L$

Higgs
heavy fermions: ψ
vector resonances: ρ

$\bar{\psi}_{L,R}(\not{\partial} + g_* \not{\rho}\,)\psi_{L,R} - M_\psi \bar{\psi}_L \psi_R$

mass eigenstate is a mixture of elementary and composite

- massless

$|light\rangle_L = \cos\varphi|\chi_L\rangle + \sin\varphi|\psi_L\rangle$

amount of compositeness in the light dof

- massive

$|heavy\rangle_L = -\sin\varphi|\chi_L\rangle + \cos\varphi|\psi_L\rangle$

$|heavy\rangle_R = |\psi_R\rangle$

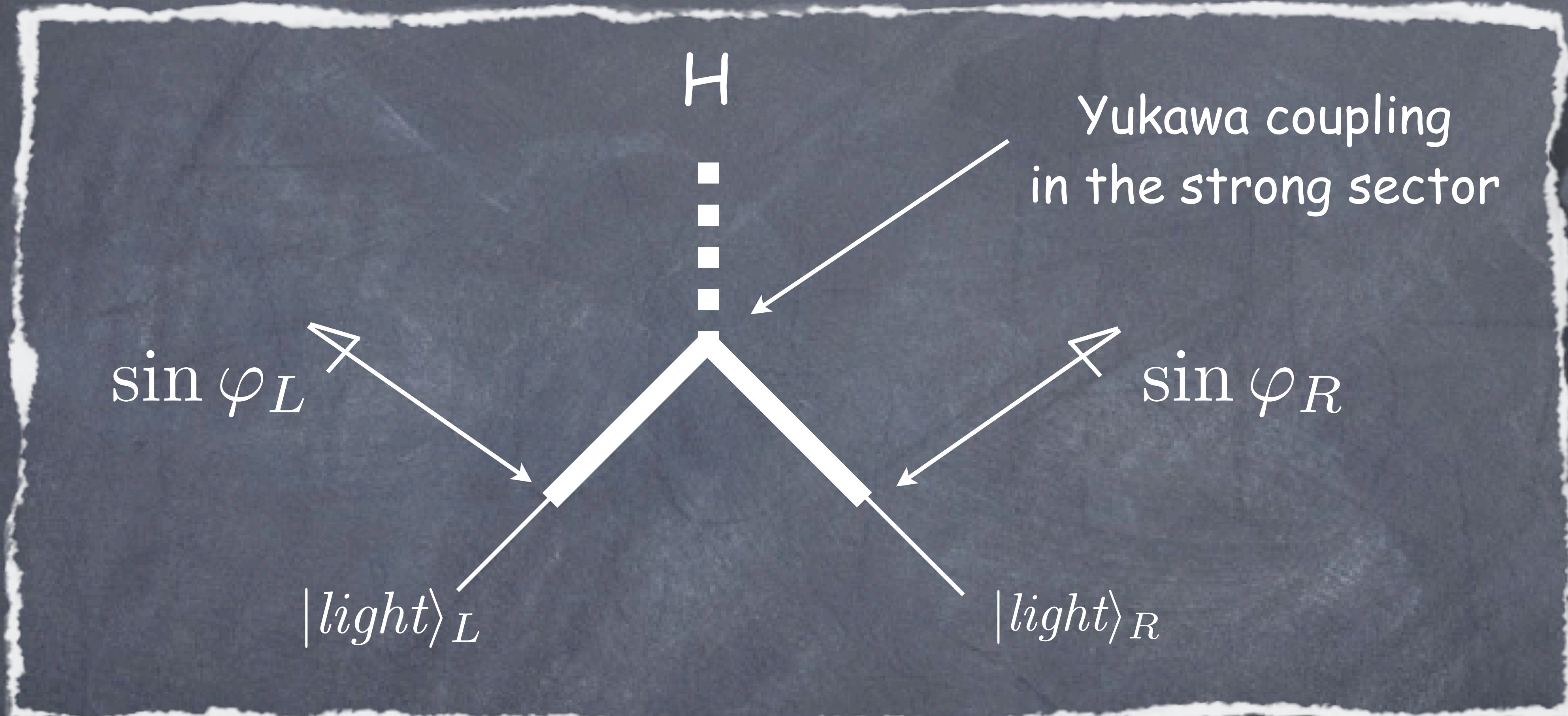
$\tan\varphi = \dfrac{\Delta}{M_*}$

the smaller is the angle, the more elementary is the light fermion

the 5D picture gives a rationale for hierarchical angles

Partial Compositeness: Yukawa Couplings

Higgs part of the strong sector: it couples only to composite fermions



when the Higgs gets a vev, the light dof will acquire a mass prop. to

$$y = y_* \sin\varphi_L \sin\varphi_R$$

Yukawa hierarchy comes from the hierarchy of compositeness

Partial Compositeness with 3 Families

Neglecting brane kinetic terms, we can diagonalize simultaneously the mixing and the composite masses

$\sin\varphi_L^{d,s,b}$ & $\sin\varphi_R^{d,s,b}$ are diagonal matrices

flavour mixings arise through
non-diagonal (anarchic) Yukawa in the strong sector

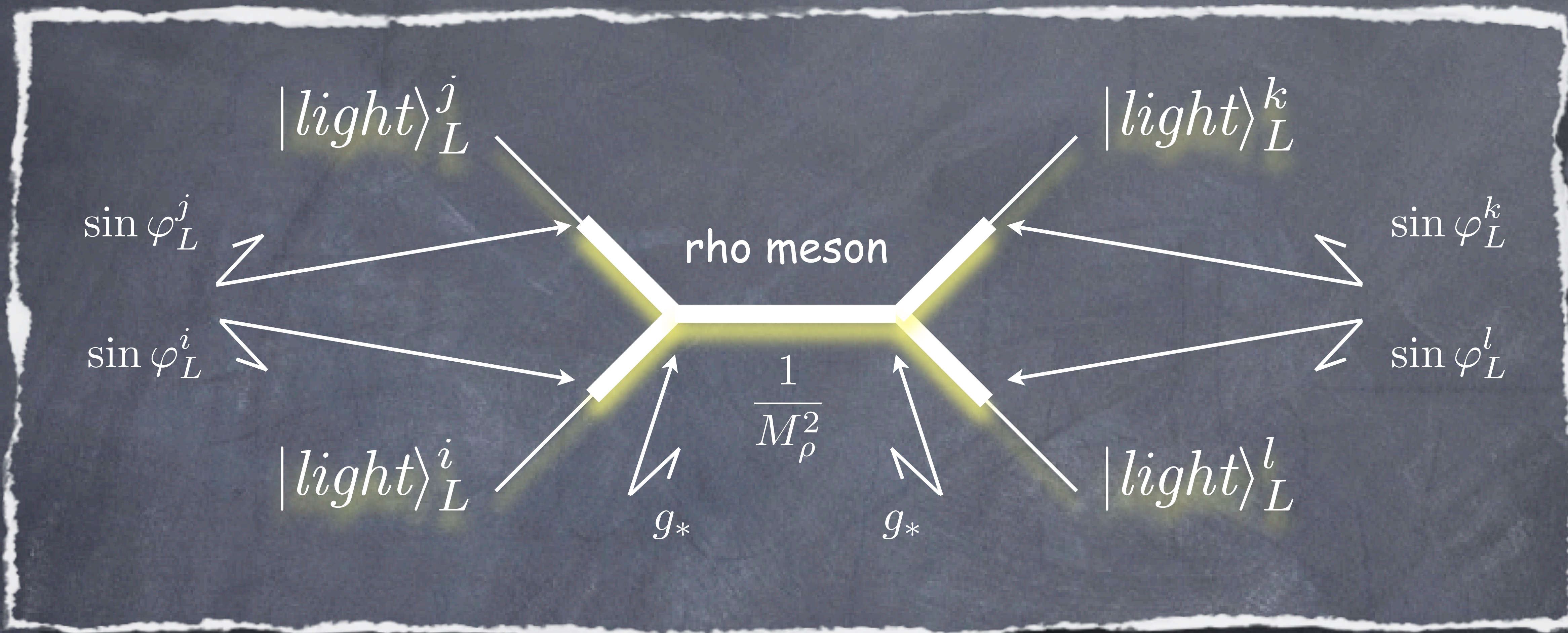
$$y^{ij} = y_*^{ij} \sin\varphi_L^i \sin\varphi_R^j$$

For hierarchical angles, we can easily diagonalize the mass matrices

$$(V_{CKM})_{ij} = \frac{\sin\varphi_L^i}{\sin\varphi_L^j}$$

FCNC from KK gluons/rho meson

Agashe, Perez, Soni '04
Contino, Kramer, Son, Sundrum '06



$$\mathcal{A}^{ijkl}_{LL} \propto \frac{g_*^2}{M_\rho^2} \sin\varphi^i_L \sin\varphi^j_L \sin\varphi^k_L \sin\varphi^l_L$$

Built-in GIM supression

the smaller the mass ⊃ the smaller the angle ⊃ the smaller coefficient

Structure of ΔF=2 operators

$$y_{d^i} = y_* \sin\varphi_L^i \sin\varphi_R^i \qquad\qquad \sin\varphi_L^i = \sin\varphi_L^3 V_{ti}$$

- L^iL^j $\quad \mathcal{A}_{LL}^{ij} \propto \frac{g_*^2}{M_\rho^2}\sin^2\varphi_L^i \sin^2\varphi_L^j \sim \frac{g_*^2 \sin^4\varphi_L^3}{M_\rho^2}|V_{ti}|^2|V_{tj}|^2$
- R^iR^j $\quad \mathcal{A}_{RR}^{ij} \propto \frac{g_*^2}{M_\rho^2}\sin^2\varphi_R^i \sin^2\varphi_R^j \sim \frac{g_*^2}{y_*^4\sin^4\varphi_L^3 M_\rho^2}\frac{y_{d^i}^2 y_{d^j}^2}{|V_{ti}|^2|V_{tj}|^2}$
- L^iR^j $\quad \mathcal{A}_{LR}^{ij} \propto \frac{g_*^2}{M_\rho^2}\sin\varphi_L^i \sin\varphi_L^j \sin\varphi_R^i \sin\varphi_R^j \sim \frac{g_*^2}{y_*^2 M_\rho^2} y_{d^i} y_{d^j}$

structure similar to the general set-up recently proposed by Davidson et al.

"Solving the flavour problem with hierarchical fermion wave functions", hep-th/0711.3376

Estimates

Agashe et al '07
UTfit '07

- B system

LL and LR operators give similar constraints

$$\mathcal{A}_{LL}^{31} \sim \mathcal{A}_{SM} \left(1 + .3 \left(\frac{4\,\mathrm{TeV}}{M_{KK}} \right)^2 \right).$$

- K system

more stringent constraint from LR operator (ε_K)

$$\mathcal{A}_{LR}^{21} \sim \mathcal{A}_{SM} \left(1 + .5 \left(\frac{8\,\mathrm{TeV}}{M_{KK}} \right)^2 \right).$$

The bounds on M_{KK} are slightly stronger than those obtained from EW precision data

They can be relaxed by O(1) parameters (y_*) or additional flavour structures

5D Minimal Flavour Violation

Fitzpatrick, Perez, Randall '07

MFV in 5D: bulk masses related to IR Yukawas

$$C_{u,d} = y_{u,d}^\dagger y_{u,d} \qquad C_Q = r y_u y_u^\dagger + y_d y_d^\dagger$$

When r=0, no flavour violation

It is possible to fit SM data with r ~ .25

Reduce FCNC amplitudes by r^2

Lower the bounds on M_{KK} by a factor 4

Dynamical models that implement 5D MFV are still under construction

Csaki, Grossman, Perez, Surujon, Weiler, to appear

Implementing a Flavour Symmetry

Cacciapaglia, Csaki, Galloway, Marandella, Terning, Weiler '07

universal bulk masses

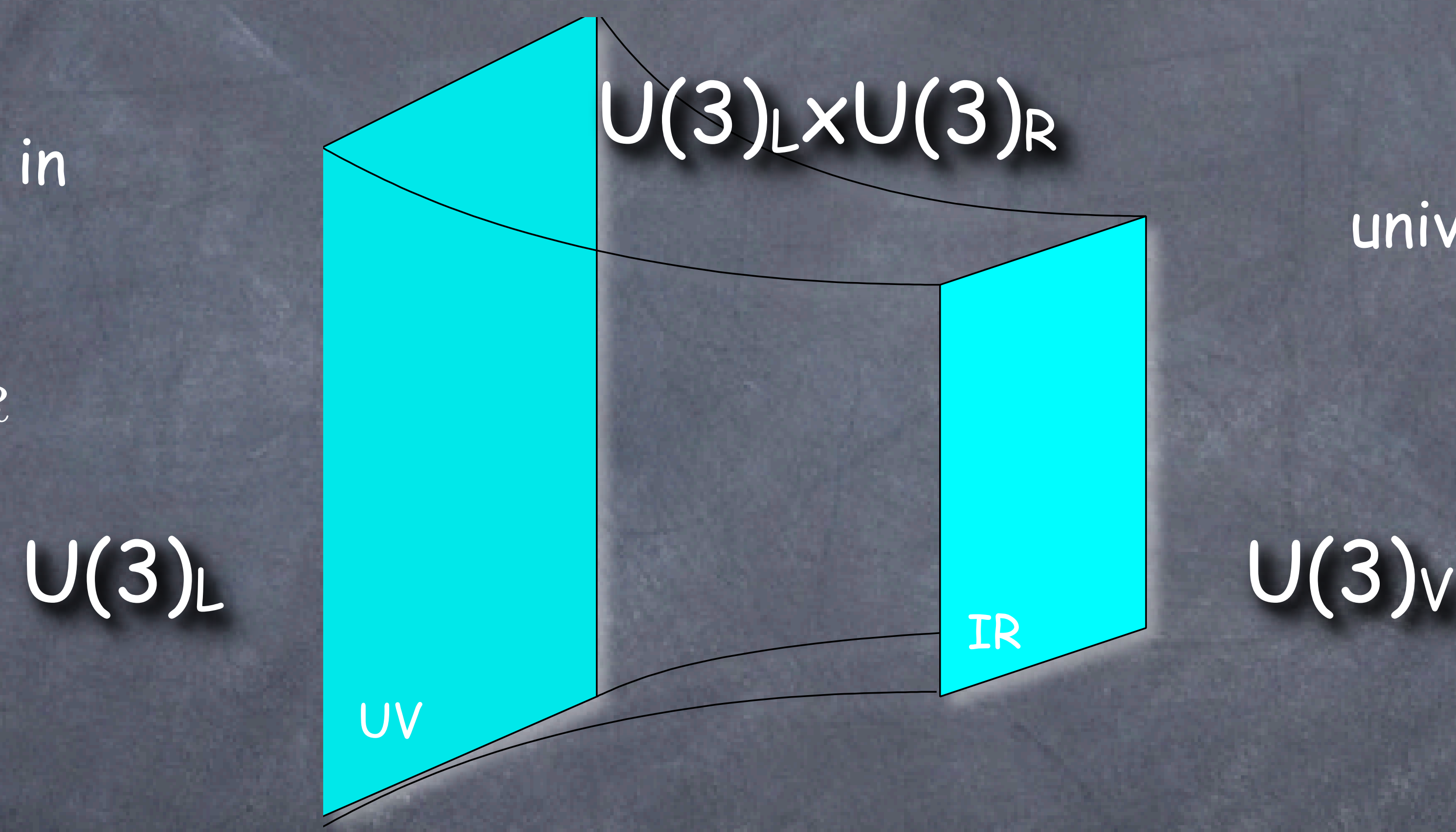
$C_u \& C_d \propto \mathbf{1}$

UV kinetic mixing in the RH sector

$\mathcal{K}_{ij}\bar{\chi}^i_R \not{\partial} \chi^j_R$

universal Yukawas

$y_u \,\&\, y_d \propto \mathbf{1}$



exact GIM structure

but no more explanation of the mass hierarchy

Flavour Non-Universality

The couplings of gauge bosons to fermions receive corrections
the more composite, the bigger the correction
expect O(10%) deviation in Zb_Lb_L, beyond exp. bound

As noticed recently, custodial symmetry might be helpful to protect $Z_{b_L\bar{b}_L}$

Agashe, Contino, Da Rold, Pomarol '06

usual $SU(2)_L \times SU(2)_R \times U(1)_X$ embedding

$$Q_L = \begin{pmatrix} t_L \\ b_L \end{pmatrix} \equiv (2,1)_{1/6}$$

$$Q_R = \begin{pmatrix} t_R \\ b_R \end{pmatrix} \equiv (1,\bar{2})_{-1/6}$$

other embedding

$$Q_L = \begin{pmatrix} t_L^{2/3} & t_L^{5/3} \\ b_L^{-1/3} & b_L^{2/3} \end{pmatrix} \equiv (2,\bar{2})_{2/3}$$

$$t_R \equiv (1,1)_{-2/3}$$

$$b_R \equiv (1,1)_{-2/3}$$

then b_L is an eigenstate of L ⇔ R and this ensures that $\delta Z_{b_L\bar{b}_L} = 0$

but we expect deviations in $Zt_L\bar{t}_L$ $Wt_L\bar{b}_L$ $Zb_R\bar{b}_R$

\+ exotic LH quarks

Conclusions

5D Holography gives us powerful tools to study strongly coupled models

Models of EWSB (composite Higgs, Higgsless) can (almost) satisfy flavour constraints thanks to a built-in GIM mechanism that suppress FCNCs

There is room to implement additional flavour structure