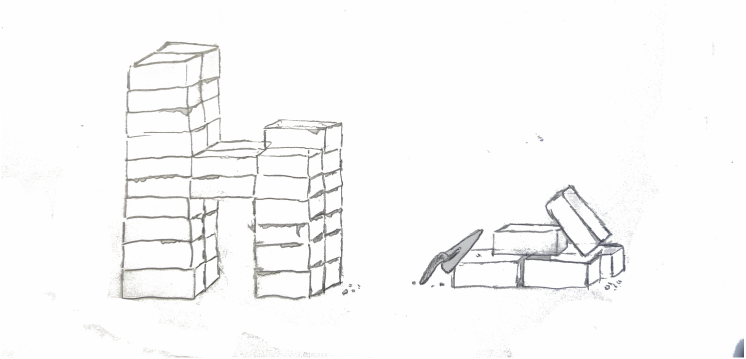
Unterstützt von / Supported by

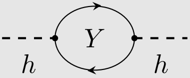


Composite Higgs Working Group: Benchmarks & Flavor

Martin Bauer

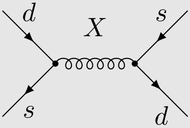
THE SM AS AN EFFECTIVE THEORY

$$\mathcal{L}_{\text{eff}} = \Lambda_{\text{UV}}^2 H^\dagger H - \lambda (H^\dagger H)^2 + \mathcal{L}^{(4)}_{\text{Gauge}} + \mathcal{L}^{(4)}_{\text{Yukawa}} + \frac{\mathcal{L}^{(5)}}{\Lambda_{\text{UV}}} + \frac{\mathcal{L}^{(6)}}{\Lambda_{\text{UV}}^2} + \dots$$



$$\sim \frac{g_Y^2}{16\pi^2}\Lambda_{\text{UV}}^2$$

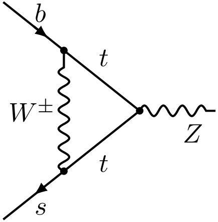
$\Lambda_{\text{UV}} \lesssim 1$ TeV

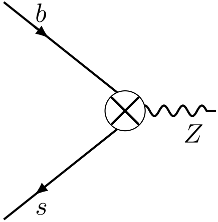


$$\sim \frac{g_X^2}{\Lambda_{\text{UV}}^2}$$

$\Lambda_{\text{UV}} \gtrsim 10^3$ TeV

GIM Mechanism(s)

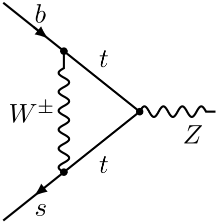


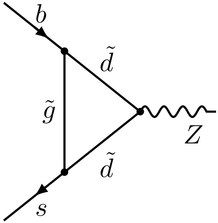


$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{\delta g_{Zbs}}{M_{\rm NP}^2}$$

- FCNCs need to be suppressed *beyond* loop level in order to be compatible with a TeVish New physics scale

GIM Mechanism(s) - MSSM

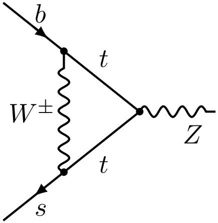


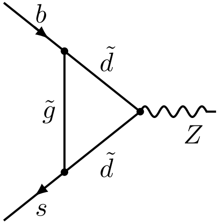


$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{16\pi^2} \times \frac{1}{\Lambda^2_{\cancel{\text{SUSY}}}} \times \delta_{ij}$$

$$\frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{\Lambda^2_{\cancel{\text{SUSY}}}} \times \delta_{ij}$$

GIM Mechanism(s) - MSSM



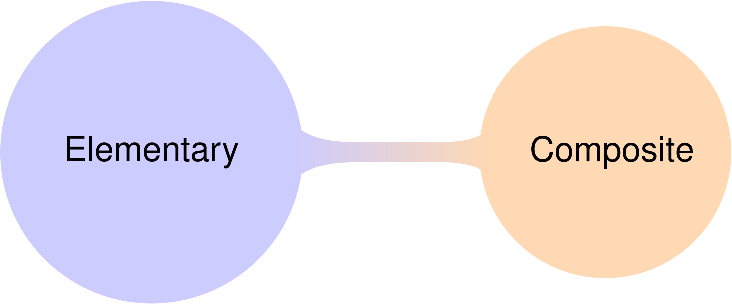


$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{16\pi^2} \times \frac{1}{\Lambda^2_{\cancel{\text{SUSY}}}} \times \delta_{ij}$$

$$\frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{\Lambda^2_{\cancel{\text{SUSY}}}} \times \delta_{ij}$$

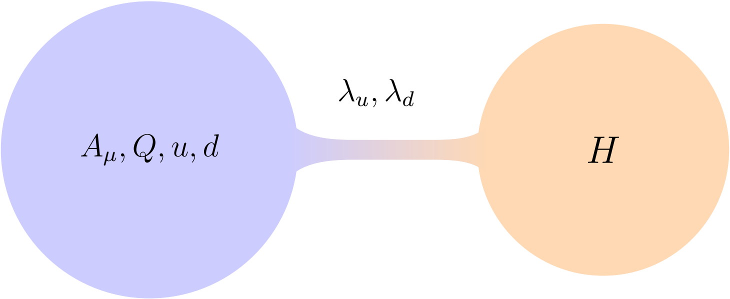
- additional structure in δ_{ij}
- $\Lambda_{\cancel{\text{SUSY}}}$ is pushed way above the TeV scale

Composite Higgs Models



Composite Higgs Models

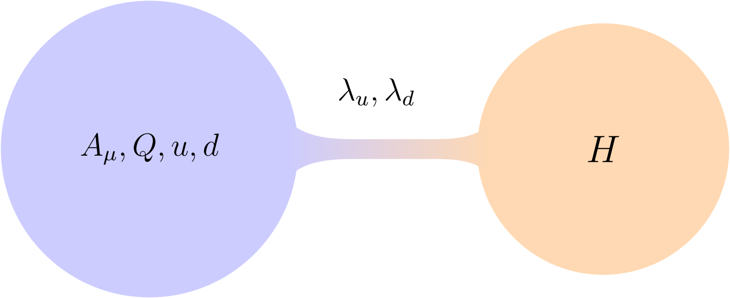
Technicolor, ETC, CTC: [. . . Holdom '80s, Luty, Okui '06]



$$\mathcal{L} = \mathcal{L}_{\rm el} + \lambda_u \bar{Q} H u + \lambda_d \bar{Q} H^* d - V(H)$$

Composite Higgs Models

Technicolor, ETC, CTC: [. . . Holdom ’80s, Luty, Okui ’06]



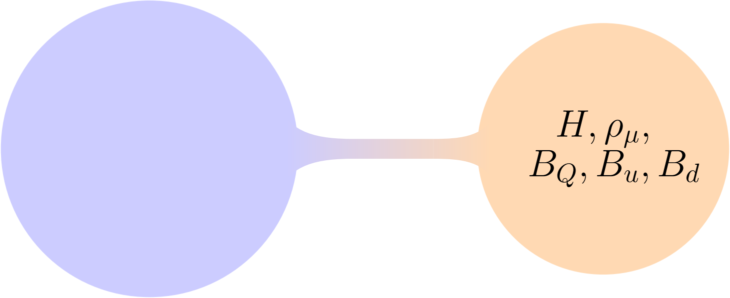
$$\mathcal{L} = \mathcal{L}_{\rm el} + \lambda_u \bar{Q} H u + \lambda_d \bar{Q} H^* d - V(H)$$

Top Yukawa coupling: $\frac{\lambda_u}{\Lambda^2_{\rm comp}} Q_L < \bar{\psi}\psi > t_R$

Composite Higgs Models

Total Compositeness (RS1)

[Randall, Sundrum '98]

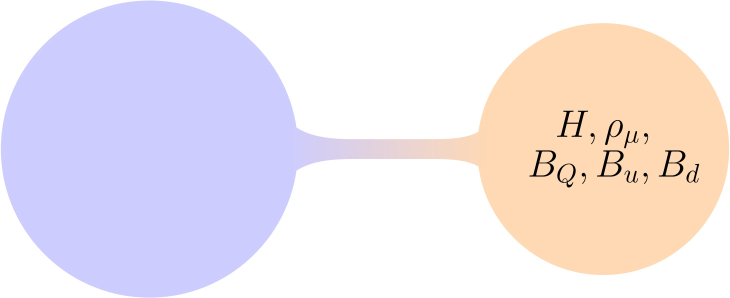


$$\mathcal{L} = \mathcal{L}_{\rm comp}$$

Composite Higgs Models

Total Compositeness (RS1)

[Randall, Sundrum '98]



$$\mathcal{L} = \mathcal{L}_{\text{comp}}$$

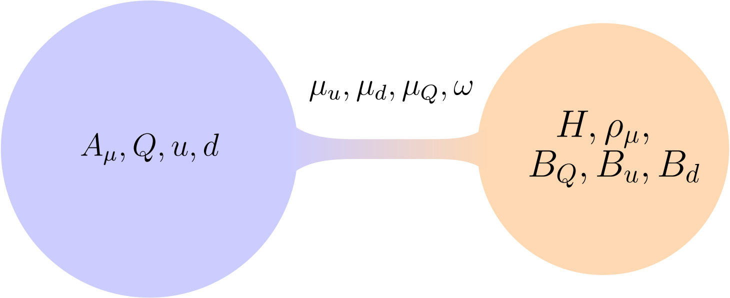
Dijet Searches: $\Lambda_{\text{comp}} > 7 - 8$ TeV

[ATLAS '12]

Composite Higgs Models

Partial Compositeness (RS1)

[Kaplan '91]



$$\mathcal{L} \ni \mathcal{L}_{\rm el} + \omega\, A_\mu \rho^\mu + \mu_u\, \overline{u} B_u + \mu_d\, \overline{d} B_d + \mu_Q\, \overline{Q} B_Q + \mathcal{L}_{\rm comp}.$$

Composite Higgs Models

Partial Compositeness: Mass generation

$$\mathcal{L} \ni \mathcal{L}_{\rm el} + \mu_q \, \overline{q}_L B_R - \Lambda_{\rm comp} \overline{B} B + \overline{B}_L \left(\lambda H B_R^c\right) \, .$$

Rotating to the mass eigenbasis

$$\begin{pmatrix} q_L \\ B_L \end{pmatrix} = \begin{pmatrix} \cos\varphi_L & -\sin\varphi_L \\ \sin\varphi_L & \cos\varphi_L \end{pmatrix} \begin{pmatrix} \psi_L \\ \chi_L \end{pmatrix} , \qquad \tan\varphi_L = \frac{\mu_q}{\Lambda_{\rm comp}}$$

leads to

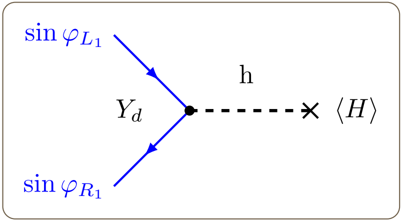
$$\mathcal{L} \ni -m_\chi \overline{\chi}\chi + \left(\overline{\psi}_L \sin\varphi_L + \overline{\chi}_L \cos\varphi_L\right) \lambda H \left(\psi_R \sin\varphi_R + \chi_R^c \cos\varphi_R\right) \, .$$

Couplings to vector mesons read

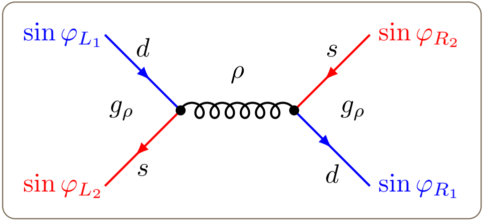
$$\mathcal{L} \ni g_\rho \bar{B} \not{\rho} B \quad \longrightarrow \quad g_\rho \sin\varphi_L^2 \; \overline{\psi}_L \not{\rho} \, \psi_L + g_\rho \, \sin\varphi_R^2 \, \overline{\psi}_R \, \not{\rho} \, \psi_R \, ,$$

Composite Higgs Models

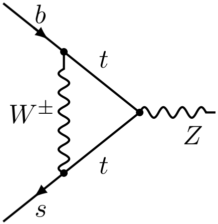
$$m_d \sim \frac{v}{\sqrt{2}} \sin\varphi_{L_1} \lambda \sin\varphi_{R_1}$$
$$\sim \frac{v}{\sqrt{2}} Y_d^{\text{eff}}$$

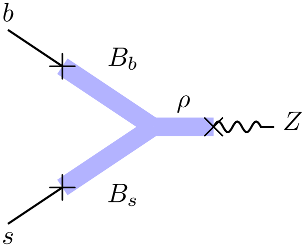


$$\frac{g_\rho^2}{M_{\text{KK}}^2} \sin\varphi_{L_1} \sin\varphi_{R_1} \sin\varphi_{L_2} \sin\varphi_{R_2}$$
$$\sim \frac{g_\rho^2}{M_{\text{KK}}^2} \frac{2 m_d m_s}{(v\lambda)^2}$$



GIM Mechanism(s)

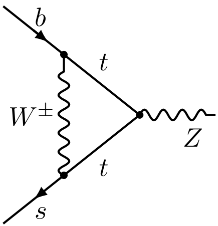


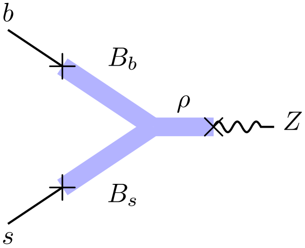


$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{\Lambda_{\rm comp}^2} \times \sin\varphi_b \sin\varphi_s$$

$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \approx \frac{1}{\Lambda_{\rm comp}^2}$$

GIM Mechanism(s)





$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \times \sum_i V_{ib}^* V_{is} f(m_i^2) \approx \frac{1}{\Lambda_{\rm comp}^2} \times \sin\varphi_b \sin\varphi_s$$

$$\frac{1}{16\pi^2} \times \frac{1}{M_W^2} \approx \frac{1}{\Lambda_{\rm comp}^2}$$

$$\Rightarrow \Lambda_{\rm comp} \sim 4\pi M_W \approx 1\text{TeV}$$

Benchmarks

What parameters describe (the flavor sector of) a composite Higgs model?

Parameters

- Compositeness scale $\Lambda_{\rm comp}$
- 9 Quark mixing angles
  $\varphi_{Q_1}, \varphi_{Q_2}, \varphi_{Q_3}, \varphi_d, \varphi_s, \varphi_b, \varphi_u, \varphi_c, \varphi_t$
- 2 Yukawa matrices Y_u, Y_d

BENCHMARKS

What parameters describe (the flavor sector of) a composite Higgs model?

Parameters

- Compositeness scale $\Lambda_{\rm comp}$
- 9 Quark mixing angles
  $\varphi_{Q_1}, \varphi_{Q_2}, \varphi_{Q_3}, \varphi_d, \varphi_s, \varphi_b, \varphi_u, \varphi_c, \varphi_t$ ← 8 are fixed by the six quark masses and two of the Wolfenstein parameters
- 2 Yukawa matrices Y_u, Y_d ← No Flavor structure in the Yukawas!

BENCHMARKS

What parameters describe (the flavor sector of) a composite Higgs model?

Parameters

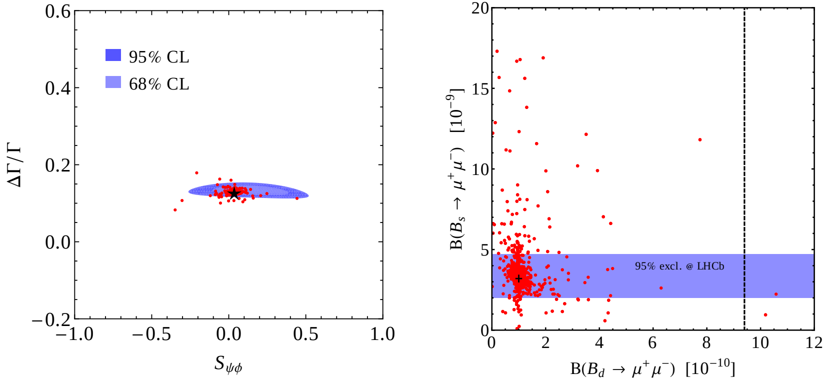
- Compositeness scale $\mathbf{\Lambda}_{\rm comp}$
- 9 Quark mixing angles
  $\varphi_{Q_1}, \varphi_{Q_2}, \varphi_{Q_3}, \varphi_d, \varphi_s, \varphi_b, \varphi_u, \varphi_c, \varphi_{\mathbf{t}}$
- 2 Yukawa matrices Y_u, Y_d

← 8 are fixed by the six quark masses and two of the Wolfenstein parameters

← No Flavor structure in the Yukawas!

Flavor Physics in the RS Model

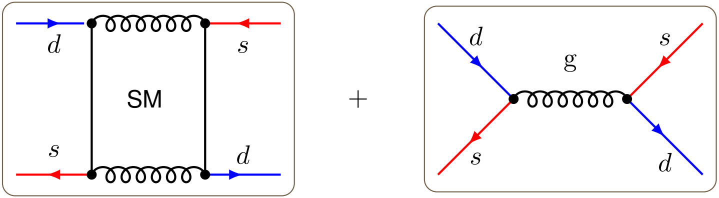
Large mixing angles suggest large effects in observables which are sensitive to couplings of third generation quarks.



Flavor Physics in the RS Model

The RS-GIM mechanism is extremely effective, apart from one observable,

$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\mathrm{exp}}} \,\mathrm{Im}\,\langle K^0|\mathcal{H}_{eff}^{\Delta S=2}|\bar{K}^0\rangle \,,$$



Flavor Physics in the RS Model

The RS-GIM mechanism is extremely effective, apart from one observable,

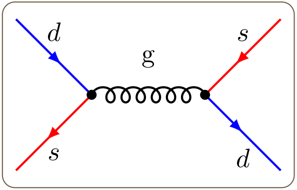
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\text{exp}}} \text{Im} \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle \,,$$

$$Q_1^{sd} = (\bar{d}_L \gamma^\mu s_L)\,(\bar{d}_L \gamma_\mu s_L)$$

$$\widetilde{Q}_1^{sd} = (\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_R \gamma_\mu s_R)$$

$$Q_4^{sd} = -\tfrac{1}{2}(\bar{d}_R^\alpha \gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

$$Q_5^{sd} = -\tfrac{1}{2}(\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_L \gamma_\mu s_L)$$



Flavor Physics in the RS Model

The RS-GIM mechanism is extremely effective, apart from one observable,

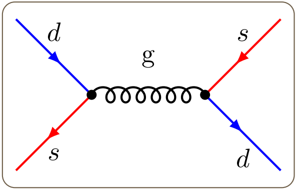
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\rm exp}} \, {\rm Im} \, \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle \,,$$

$$Q_1^{sd} = (\bar{d}_L \gamma^\mu s_L)\,(\bar{d}_L \gamma_\mu s_L)$$

$$\widetilde{Q}_1^{sd} = (\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_R \gamma_\mu s_R)$$

$$Q_4^{sd} = -\tfrac{1}{2}(\bar{d}_R^\alpha \gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

$$Q_5^{sd} = -\tfrac{1}{2}(\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_L \gamma_\mu s_L)$$



$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

Large chiral enhancement $\sim \left(\frac{m_K}{m_s+m_d}\right)^2$

RGE running
$3\,{\rm TeV} \to 2\,{\rm GeV}$

FLAVOR PHYSICS IN THE RS MODEL

The RS-GIM mechanism is extremely effective, apart from one observable,

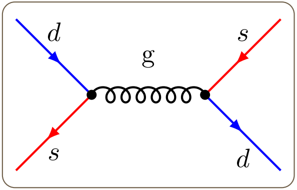
$$\epsilon_K = \frac{\kappa_\epsilon e^{i\phi_\epsilon}}{\sqrt{2}(\Delta m_K)_{\rm exp}} \, {\rm Im} \, \langle K^0 | \mathcal{H}_{eff}^{\Delta S=2} | \bar{K}^0 \rangle \, ,$$

$$Q_1^{sd} = (\bar{d}_L \gamma^\mu s_L)\,(\bar{d}_L \gamma_\mu s_L)$$

$$\widetilde{Q}_1^{sd} = (\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_R \gamma_\mu s_R)$$

$$Q_4^{sd} = -\tfrac{1}{2} (\bar{d}_R^\alpha \gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

$$Q_5^{sd} = -\tfrac{1}{2} (\bar{d}_R \gamma^\mu s_R)\,(\bar{d}_L \gamma_\mu s_L)$$

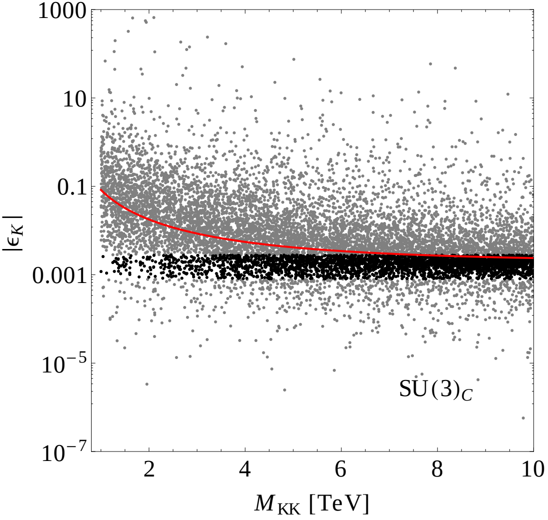


$$\langle K^0 | \mathcal{H}_{\rm RS}^{\Delta S=2} | \bar{K}^0 \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 100 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle B | \mathcal{H}_{\rm RS}^{\Delta B=2} | \bar{B} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 7 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

$$\langle D | \mathcal{H}_{\rm RS}^{\Delta C=2} | \bar{D} \rangle \propto C_1^{\rm SM+RS} + \widetilde{C}_1^{\rm RS} + 13 \left(C_4^{\rm RS} + \tfrac{1}{N_C} C_5^{\rm RS} \right)$$

FLAVOR PHYSICS IN THE RS MODEL



BENCHMARKS–QUARK SECTOR

- **Anarchy**: Mixing angles reproduce flavor hierarchies,

$$\begin{matrix} \sin\varphi_{ij}^{Q} = \sin\varphi_{ii}^{Q} \\ \sin\varphi_{ij}^{u,d} = \sin\varphi_{ii}^{u,d} \end{matrix}, \quad Y_{u,d} \approx \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}, \qquad \Lambda_{\rm comp} > 8\,\text{TeV}$$

- **Right-handed Compositeness**: $U(3)^3$ symmetry in the composite sector,

$$\sin\varphi_{ij}^{Q_u} \sim Y_u^{\rm SM}, \quad \sin\varphi_{ij}^{u} \sim \mathbb{1}, \qquad Y_u \sim \mathbb{1}, \qquad \Lambda_{\rm comp} \sim 1\,\text{TeV}$$
$$\sin\varphi_{ij}^{Q_d} \sim Y_d^{\rm SM}, \quad \sin\varphi_{ij}^{d} \sim \mathbb{1}, \qquad Y_d \sim \mathbb{1}$$

- $\mathbf{U(2)^3}$ symmetry in the composite sector,

$$\sin\varphi_{ij}^{Q} \sim \text{diag}(a,a,b), \qquad Y_{u,d} \sim \text{diag}(a,a,b)\,, \qquad \Lambda_{\rm comp} \sim 1\,\text{TeV}$$
$$\sin\varphi_{ij}^{u,d} \sim \begin{pmatrix} \Delta Y_{u,d}^{\rm SM} & 0 \\ 0 & 1 \end{pmatrix}$$

Flavor Physics in the RS Model

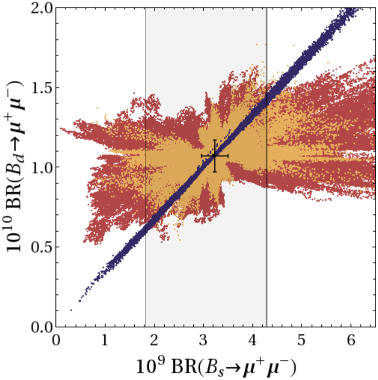
Expected Correlations

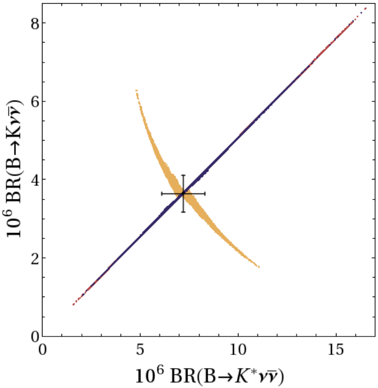
$U(2)^3$

Anarchic Model (triplet)

Anarchic Model (bidoublet)

	g_{Zd_L}	g_{Zd_R}	g_{Zu_L}	g_{Zu_R}
triplet	0	✓	✓	0
bidoublet	✓	0	✓	0





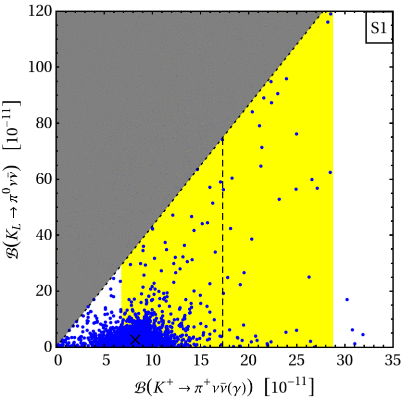
[Straub '13]

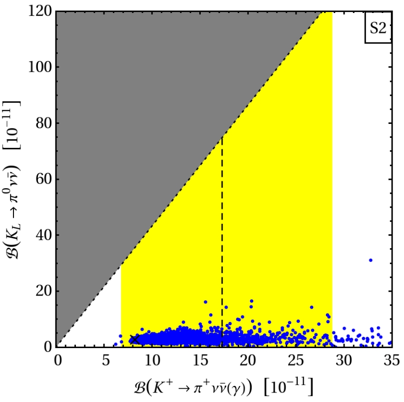
Flavor Physics in the RS Model

Unexpected Correlations

S1: Anarchic Models

S2: Aligned down quark mixing angles





BENCHMARKS–LEPTON SECTOR

Additional Question: How to get anarchical PMNS matrix?

- **Anarchy**: Mixing angles reproduce charged lepton masses,

$$\sin\varphi^L_{ij} = \sin\varphi^L_{ii} \qquad \sin\varphi^E_{ij} = \sin\varphi^E_{ii}, \qquad Y_E \approx \mathcal{O}(1)$$

Majorana: $\frac{Y_\nu}{\Lambda_{\rm UV}} LLHH$ [Vecchi '12 , Randall, Gilad '09]

Dirac: $Y_\nu\, LH\nu_R$ [Sundrum, Agashe '08]

- **Global Flavor Symmetries**:

$$\sin\varphi^L_{ij} = \mathbb{1} + f(Y_\nu Y_\nu^\dagger,\, Y_E Y_E^\dagger)\,, \quad \sin\varphi^{E,\nu}_{ij} = \mathbb{1} + f(Y^\dagger_{E,\nu} Y_{E,\nu})$$

$Y_E \approx \mathcal{O}(1), \quad Y_\nu$ very small

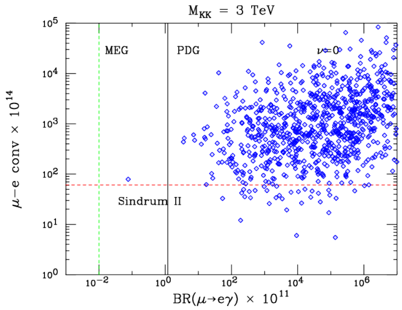
- **A4 symmetric models**:

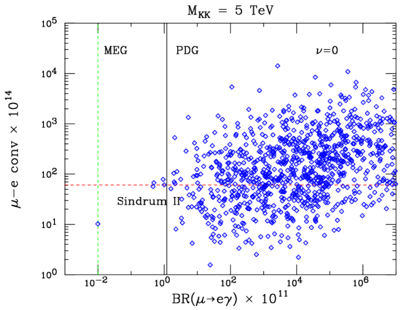
$$\sin\varphi^L_{ij} = \mathbb{1}\,, \quad \sin\varphi^\nu_{ij} = \mathbb{1}$$

$$Y_E \approx Y_\nu \approx \mathcal{O}(1)$$

A4: No tree-lvl FCNCs! [Csaki et al. '08]

FLAVOR PHYSICS IN THE RS MODEL



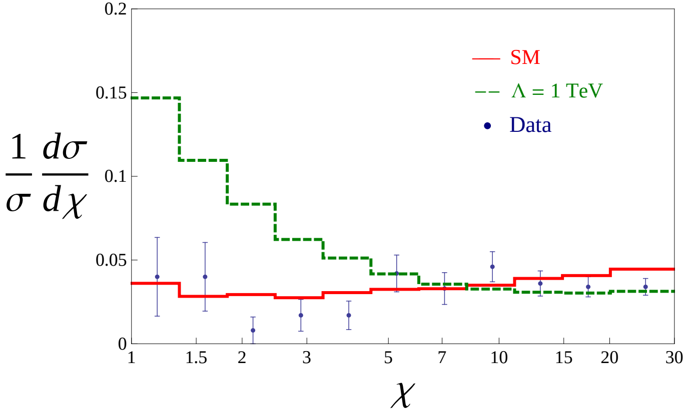


[Agashe et al. '06]

CONCLUSION

- RS/Composite Higgs is a model of flavor physics
- It cuts of the Higgs quadratic divergencies in the Higgs sector at some scale
- The intensity frontier has the capability to find out whether it also “solves” the hierarchy problem

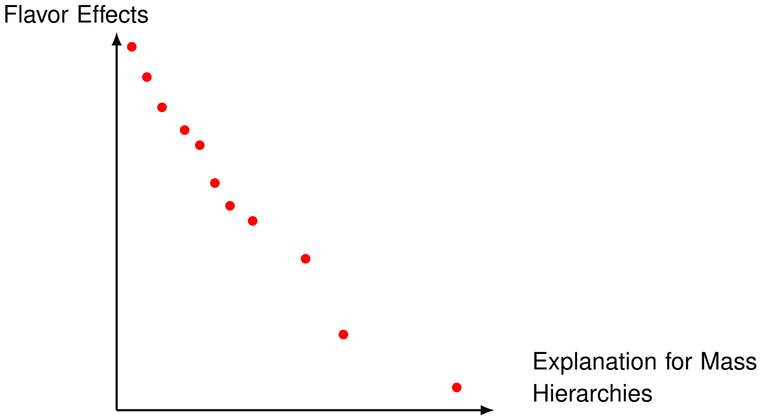
BACKUP



[Pomarol '12]

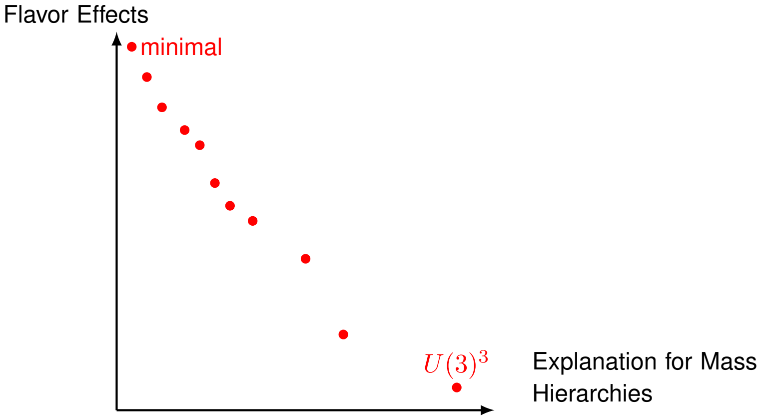
Backup

$$Q_4^{sd} = -\frac{1}{2}(\bar{d}_R^\alpha \gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$

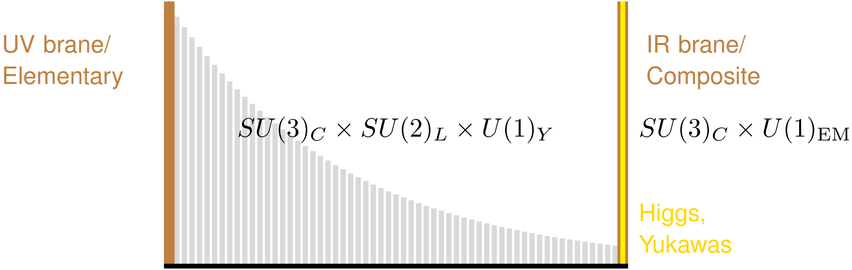


Backup

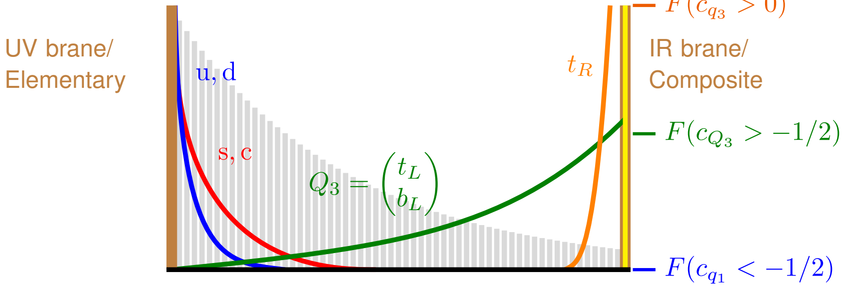
$$Q_4^{sd} = -\frac{1}{2}(\bar{d}_R^\alpha \gamma^\mu s_R^\beta)\,(\bar{d}_L^\beta \gamma_\mu s_L^\alpha)$$



RS Models

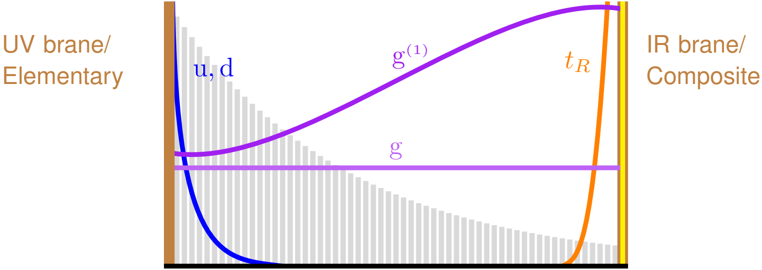

UV brane/
Elementary
IR brane/
Composite
$SU(3)_C \times SU(2)_L \times U(1)_Y$
$SU(3)_C \times U(1)_{\mathrm{EM}}$
Higgs,
Yukawas

RS MODELS



$$F(c) \approx \begin{cases} \left(\frac{TeV}{M_{\rm Pl}}\right)^{-\left(\frac{1}{2}+c\right)}, & c < -\frac{1}{2} \\ \sqrt{1+2c}, & c > -\frac{1}{2} \end{cases}$$

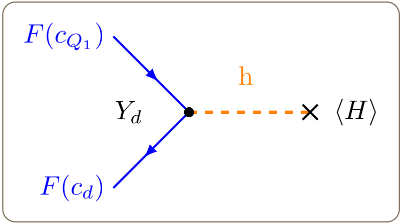
RS Models



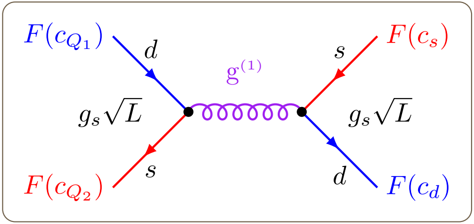
RS MODELS

The same parameters, which generate the masses of the light quarks suppress contributions to FCNCs: RS-GIM.

$$m_d \sim \frac{v}{\sqrt{2}} F(c_{Q_1}) Y_d^{(5D)} F(c_d)$$
$$\sim \frac{v}{\sqrt{2}} Y_d^{\text{eff}}$$



$$\frac{g_s^2 L}{M_{\text{KK}}^2} F(c_{Q_1}) F(c_d) F(c_{Q_2}) F(c_s)$$
$$\sim \frac{g_s^2}{M_{\text{KK}}^2} L \frac{2 m_d m_s}{\left(v Y_d^{(5D)}\right)^2}$$

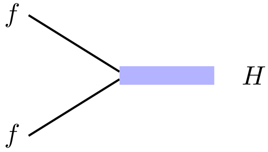


RS MODELS

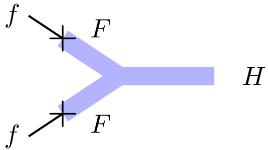
Composite Higgs		Warped Geometry (RS)
(Large N) CFT with a confining phase below Λ	$\leftrightarrow$	Anti de Sitter space with an IR brane at $1/\Lambda$
Amount of Compositeness: $\sin\varphi_q$	$\leftrightarrow$	Localization in the ED: $F(c_q)$
Global symmetry in the strongly coupled sector	$\leftrightarrow$	Gauge symmetry in the bulk
Composite vector mesons (baryons)	$\leftrightarrow$	Gauge boson (quark) KK Modes

RS Models

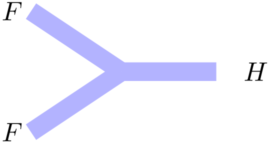
There are different composite Higgs models:



Models in which only the Higgs is a composite.



Models in which the Higgs is a composite and the fermions are *partially* composite.



Models in which the Higgs and the fermions are completely composite.