The flavor of the holographic pGB

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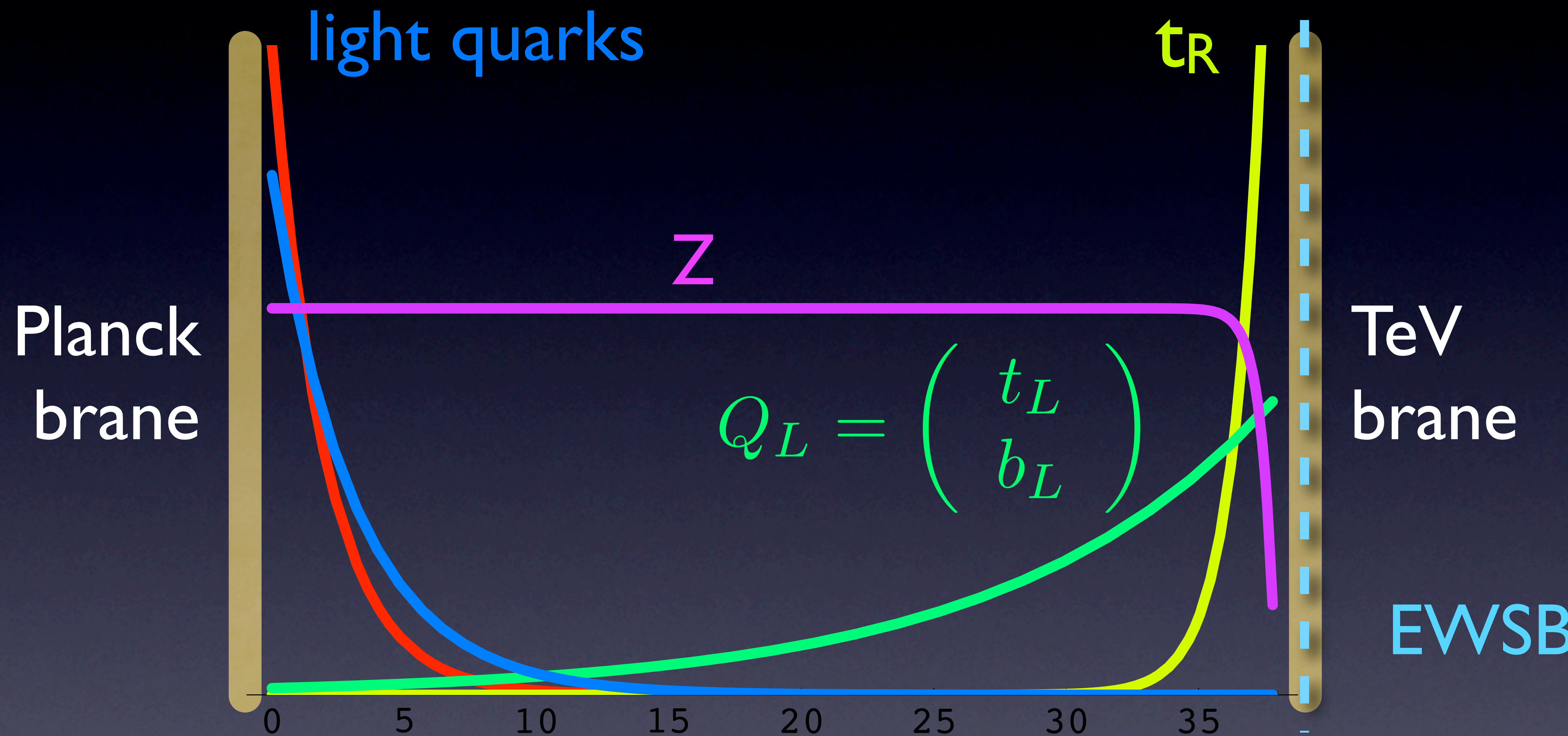
based on papers with:

C. Csaki and A. Falkowski (pGB flavor, U(1)’s);
C. Csaki, Y. Grossman, G. Perez, and Z. Surujon

Hierarchies without symmetries

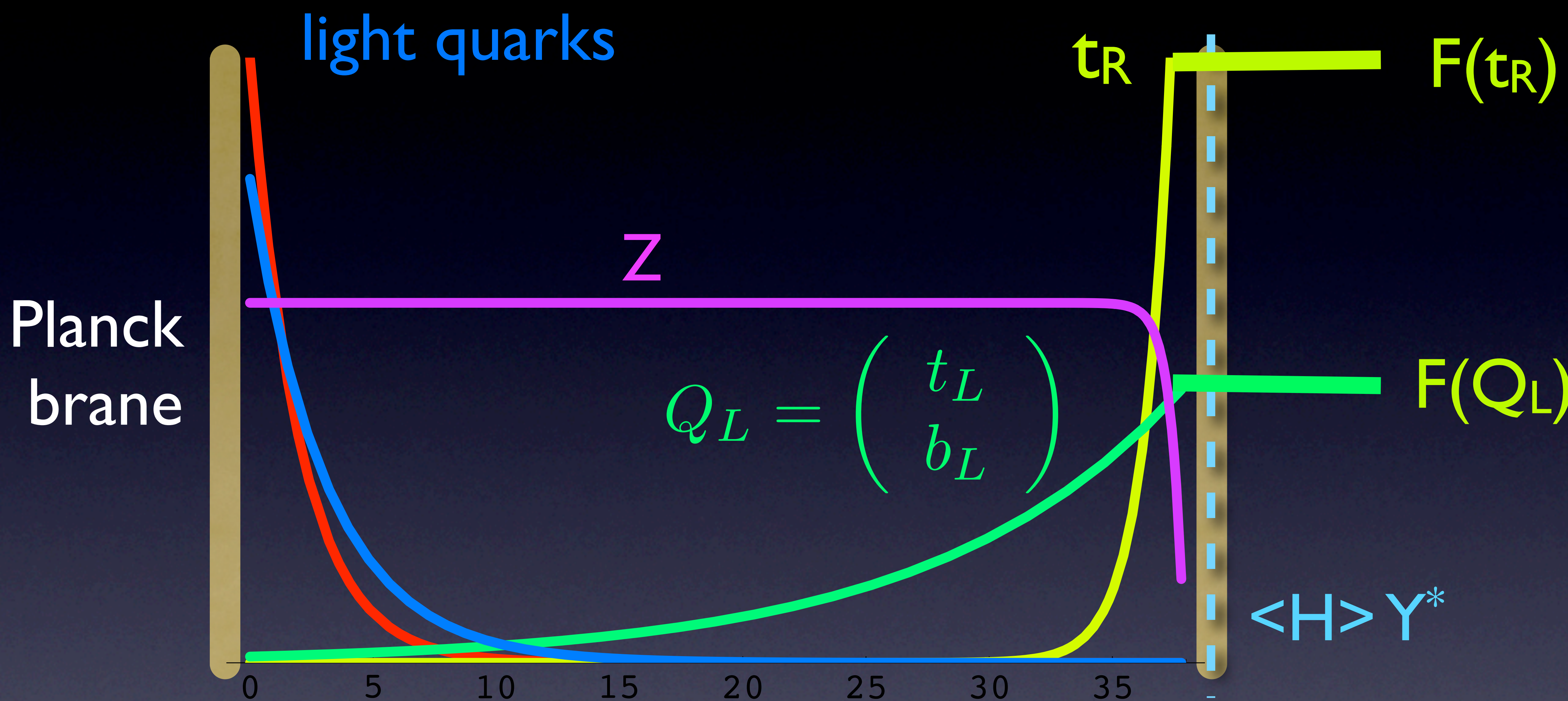
Arkani-Hamed, Schmaltz; Grossman, Neubert;
Gherghetta, Pomarol



warped extra dimensions as a theory of flavor

Gherghetta, Pomarol; Huber; Agashe, Perez, Soni

Wavefunction overlap generates hierarchies



F = wave function @ IR brane :

F ~ $(\text{TeV/Planck})^{2c-1}$ c > 1/2, c = bulk mass

F ~ $\sqrt{(1-2c)}$ c < 1/2

Csaki, Falkowski, AW

RS has a flavor problem

LR chiral contributions to CPV in K-K mixing generically require m_{KK} > 11 TeV +

But there is also fine-tuning in EWSB…

+ terms and conditions apply

(scalar bulk Higgs with less perturbative control m > 5 TeV possible)

RS and little hierarchy problem

Precision electroweak data suggests

- o light Higgs ($m_H < 200$ GeV)
- o (S,T,U,…) new contributions $\Lambda > 5$ TeV

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Large UV sensitive contribution to Higgs mass.
Top loops e.g. induce

$$m_H^2 \sim -3\,\lambda_t^2\,\frac{1}{8\pi^2}\,\Lambda^2$$

Significant fine-tuning if not taken care of:
RS with Higgs on the brane or scalar bulk Higgs suffers from little hierarchy problem!

Solution: pGB Higgs models

Agashe, Contino, Pomarol 05

Simple model with

- o custodial symmetry
- o A_5 zero mode $\in SO(5)/SO(4)$ = Higgs
- o small corrections to S, T, U, $Zb\bar{b}$

$y = R_{uv}$

$y = R_{ir}$

Planck brane

AdS_5

$SO(5)xU(1)_x$

TeV brane

$SU(2)xU(1)_Y$

$SO(4)xU(1)_x$

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- o custodial symmetry
- o A_5 zero mode $\in SO(5)/SO(4)$ = Higgs
- o sr

Dual to pGB composite Higgs (Georgi, Kaplan '83)

R_{ir}

Planck brane

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TeV brane

$SU(2)xU(1)_Y$

$SO(4)xU(1)_x$

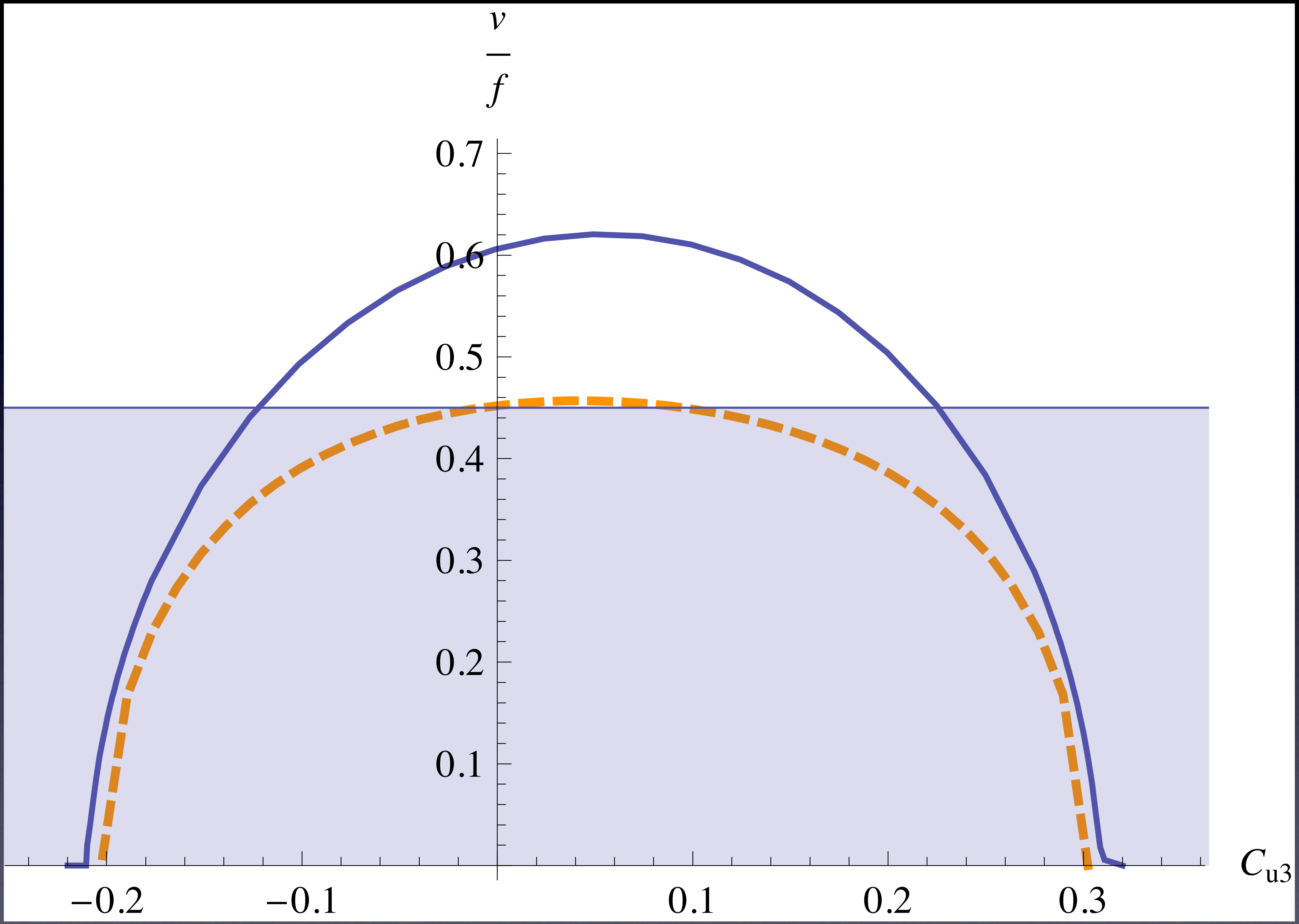
Calculable radiative EWSB

A_5 = Higgs : Non-local Coleman-Weinberg induces potential and $\langle A_5 \rangle \neq 0$

$$V(v) = \frac{3}{32\pi^2} \int_0^\infty dt t \left[-4 \log \rho_t(-t) + 2 \log \rho_W(-t) + \log \rho_Z(-t) \right]$$

UV finite, depends on 5D fermion mass sector

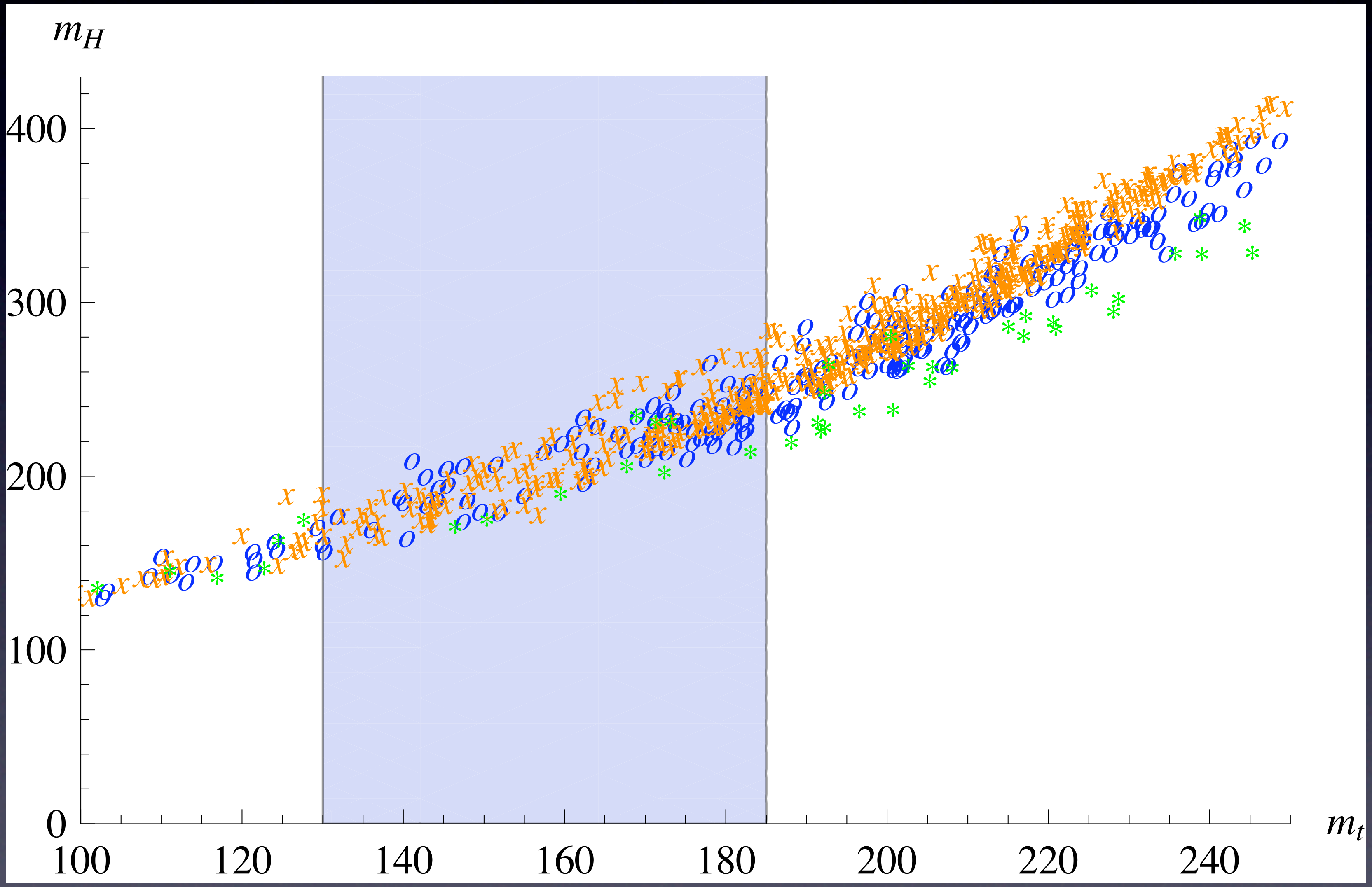
<H> / (new physics scale)



c_{u3} : bulk mass of top

Realistic EWSB only for correlated parameter set

m_H



m_t

Fermion Masses in Gauge-Higgs models

A_5 = Higgs being a gauge field couples only to fields in the same multiplet.

Add boundary mixing terms:
Zero modes lives in multiple representations
→ kinetic mixing.

Yukawa = bulk gauge coupling g_*

Mass terms from gauge interactions

Csaki, Falkowski, AW

Some freedom to embed fermion content
Example here: **4** (spinor) of SO(5)

$$\Psi_q = \begin{pmatrix} \boxed{q_q[+,+]} \\ u^c_q[-,+] \\ d^c_q[-,+] \end{pmatrix} \qquad \Psi_u = \begin{pmatrix} q_u[+,-] \\ \boxed{u^c_u[-,-]} \\ d^c_u[+,-] \end{pmatrix} \qquad \Psi_d = \begin{pmatrix} q_d[+,-] \\ u^c_d[+,-] \\ \boxed{d^c_d[-,-]} \end{pmatrix}$$

1) $\boxed{}$ = chiral zero modes

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1) [red box] = chiral zero modes

2) <A5> marries fields in same multiplet

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$\tilde{M}_u$

1) = chiral zero modes

2) $<A_5>$ marries fields in same multiplet

3) SO(4) invariant brane mixings mix multiplets

$$\mathcal{L}_{IR} = -\left(\frac{R}{R'}\right)^4 \left[\tilde{m}_u \chi_{q_q}\psi_{q_u} + \tilde{m}_d \chi_{q_q}\psi_{q_d} + \tilde{M}_u(\chi_{u_q^c}\psi_{u_u^c} + \chi_{d_q^c}\psi_{d_u^c}) + \tilde{M}_d(\chi_{u_q^c}\psi_{u_d^c} + \chi_{d_q^c}\psi_{d_d^c})\right]$$

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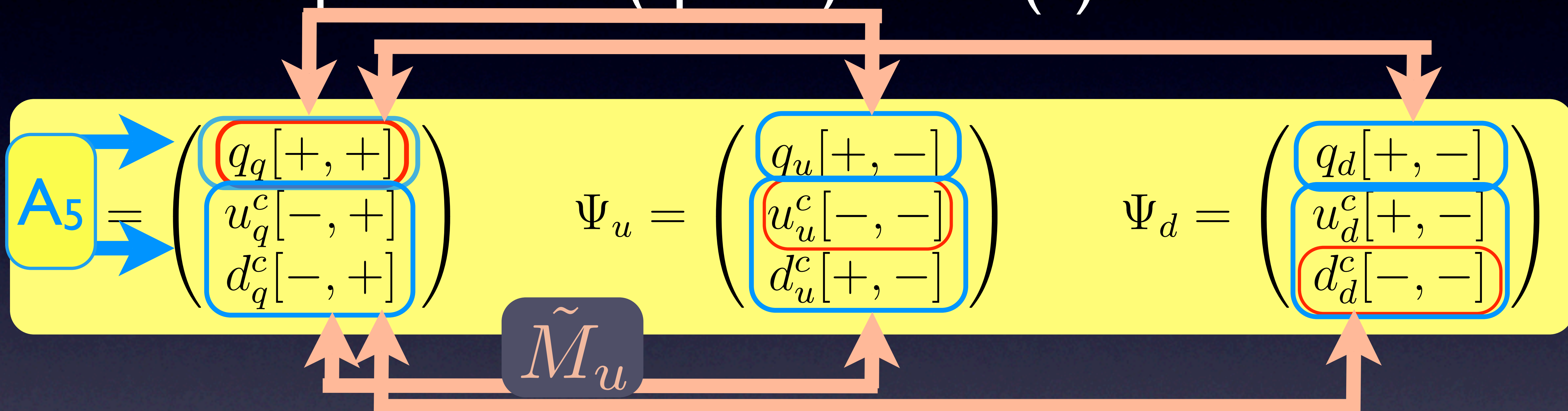

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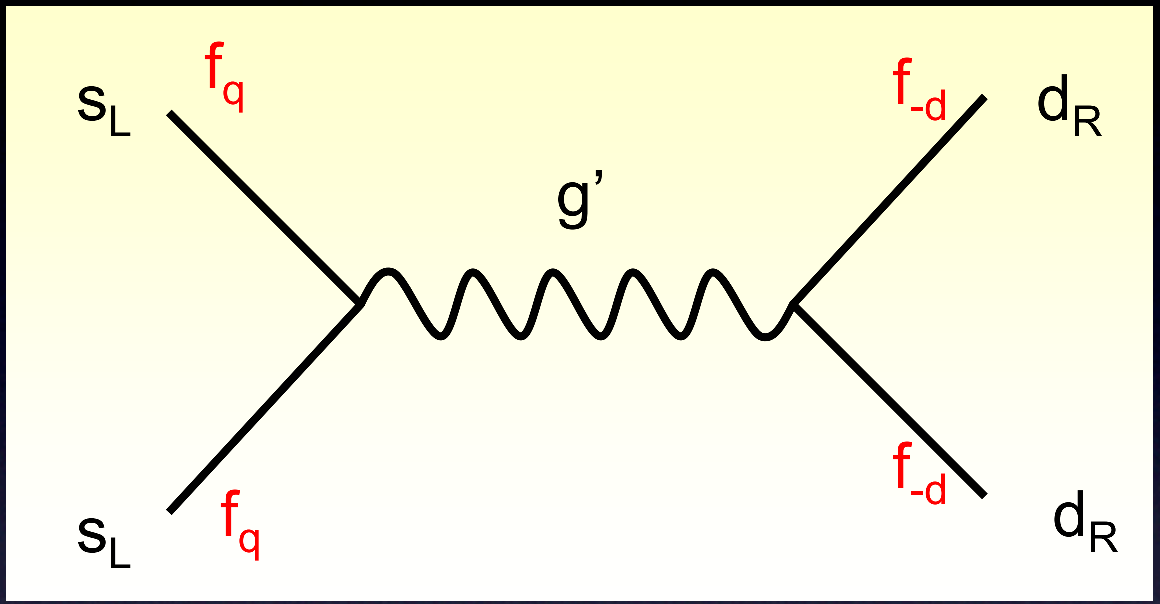
Effective mass terms pGB model

$$
\begin{aligned}
m_u^{SM} &= \frac{g_* v}{2\sqrt{2}} H_q f_q (\tilde{m}_u - \tilde{M}_u) f_{-u} H_u \\
m_d^{SM} &= \frac{g_* v}{2\sqrt{2}} H_q f_q (\tilde{m}_d - \tilde{M}_d) f_{-d} H_d
\end{aligned}
$$

Effective 4 fermi operators

Csaki, Falkowski, AW

Integrating out the KK gluon



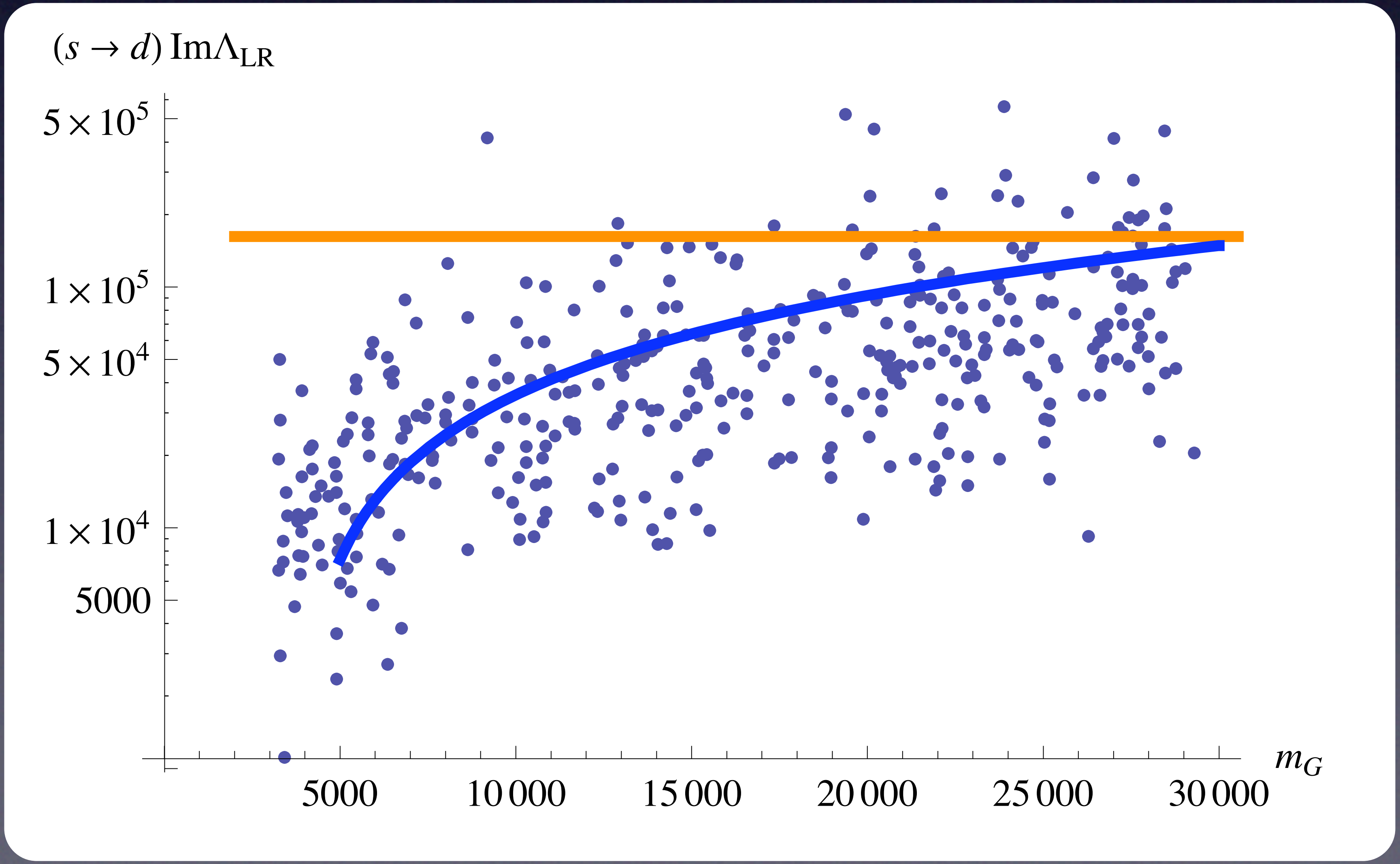
$$\begin{aligned}
\mathcal{H} &= \frac{1}{M_G^2}\left[\frac{1}{6} g_L^{ij} g_L^{kl} (\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) - g_R^{ij} g_L^{kl}\left((\bar{q}_R^{i\alpha} q_{L\alpha}^k)\,(\bar{q}_L^{l\beta} q_{R\beta}^j) - \frac{1}{3}(\bar{q}_R^{i\alpha} q_{L\beta}^l)\,(\bar{q}_L^{k\beta} q_{R\alpha}^j)\right)\right] \\
&= C^1(M_G)(\bar{q}_L^{i\alpha}\gamma_\mu q_{L\alpha}^j)\,(\bar{q}_L^{k\beta}\gamma^\mu q_{L\beta}^l) + C^4(M_G)(\bar{q}_R^{i\alpha} q_{L\alpha}^k)\,(\bar{q}_L^{l\beta} q_{R\beta}^j) + C^5(M_G)(\bar{q}_R^{i\alpha} q_{L\beta}^l)\,(\bar{q}_L^{k\beta} q_{R\alpha}^j)
\end{aligned}$$

$$C_{4K}^{RS} \sim \frac{g_{s*}^2}{M_G^2} f_{q_1} f_{q_2} f_{-d_1} f_{-d_2} \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{Y_*^2}\frac{2 m_d m_s}{v^2}$$

Four fermi operators

$$C_K^4 \sim \frac{1}{M_G^2}\frac{g_{s*}^2}{g_*^2}\frac{8m_d m_s}{v^2}\frac{1+m^2}{\tilde{m}_d^2}$$

pGB worse than RS: $Y^* \leftrightarrow g_* / 2$, $M_{KK} > 30$ TeV



Low KK scale w/o adding flavor structure

+ live with fine-tuned Yukawas (large radiative corrections)

Blanke, Buras, Dulling, Gori, AW; Casagrande, Goertz, Haisch, Neubert, Pfoh

or

Agashe, Azatov, Zhu

+ bulk Higgs model (not applicable to pGB), push Yukawa to perturbative limit $Y^* > 6$ and g_{s*} as small as possible (1-loop matching)

$$M_{KK} > \frac{g_{s*}}{Y^*} \frac{\sqrt{2 m_d m_s}}{v} \Lambda_4$$

With some tuning $M_{KK} \sim 5$ TeV possible

Testable at LHC? Little hierarchy?

Low KK scale by adding flavor structure

Csaki, Falkowski, AW

+ Propose $U(1)_d \times U(1)_q$ for quark representation with custodial protection of $Z\underline{b}b$ of pGB
  Key ingredient: two rep.'s for (q_u, q_d) for Q_L

Low KK scale by adding flavor structure

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BC on UV:

$$\theta q_u - q_d = 0$$

Forces θ to be diagonal

	$U(1)_d$ $(-,+)$	$U(1)_q$ $(+,-)$
q_u	0	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
u	0	0
q_d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$
d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	0

Low KK scale by adding flavor structure II

Csaki, Falkowski, AW

\+ Propose $U(1)_d \times U(1)_q$ for quark representation with custodial protection of $Z b\bar{b}$ of pGB

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d	$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix}$	0

IR masses:

$$\boxed{\frac{v}{\sqrt{2}} f_{q_u} Y_u f_{-u}}$$

$$\boxed{\frac{v}{\sqrt{2}} f_{q_d} Y_d f_{-d}}$$

Y_d diagonal

Low KK scale by adding flavor structure II

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Key ingredient: two rep.'s for (q_u, q_d) for Q_L

All flavor violation in up-sector, constraint from D-$\underline{D}$ bar mixing: $M_{KK} > 1$ TeV

$U(1)_d \times U(1)_q$ gauge bosons give additional contributions, need them to be almost global $g_5^D < 1/50\, g_{QCD}$.

Conclusions

- RS GIM suppresses most of the dangerous FCNCs
- Contributions to ε_K with LR chirality typically too large
- Bulk Higgs $m_{KK} > 5$ TeV (best cases)
  Brane Higgs $m_{KK} > 11$ TeV
  pGB Higgs $m_{KK} > 15$ TeV
- Additional mechanisms needed, e.g. horizontal U(1)'s to allow $m_{KK} \sim$ 1-2 TeV

Low KK scale by adding flavor structure

Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW

+ exact GIM structure
  flavor symmetry in bulk and IR brane, UV kinetic terms generate flavor, no explanation for fermion masses (likely the only way for Higgsless)

Santiago

+ Minimal flavor protection bulk U(3) flavor symmetry in d_R sector (radiatively unstable)

Fitzpatrick, Randall, Perez

+ 5D MFV only two flavor spurions (Y_U, Y_D)
  Need to align bulk and brane matrices by hand. Can we really avoid tuning?