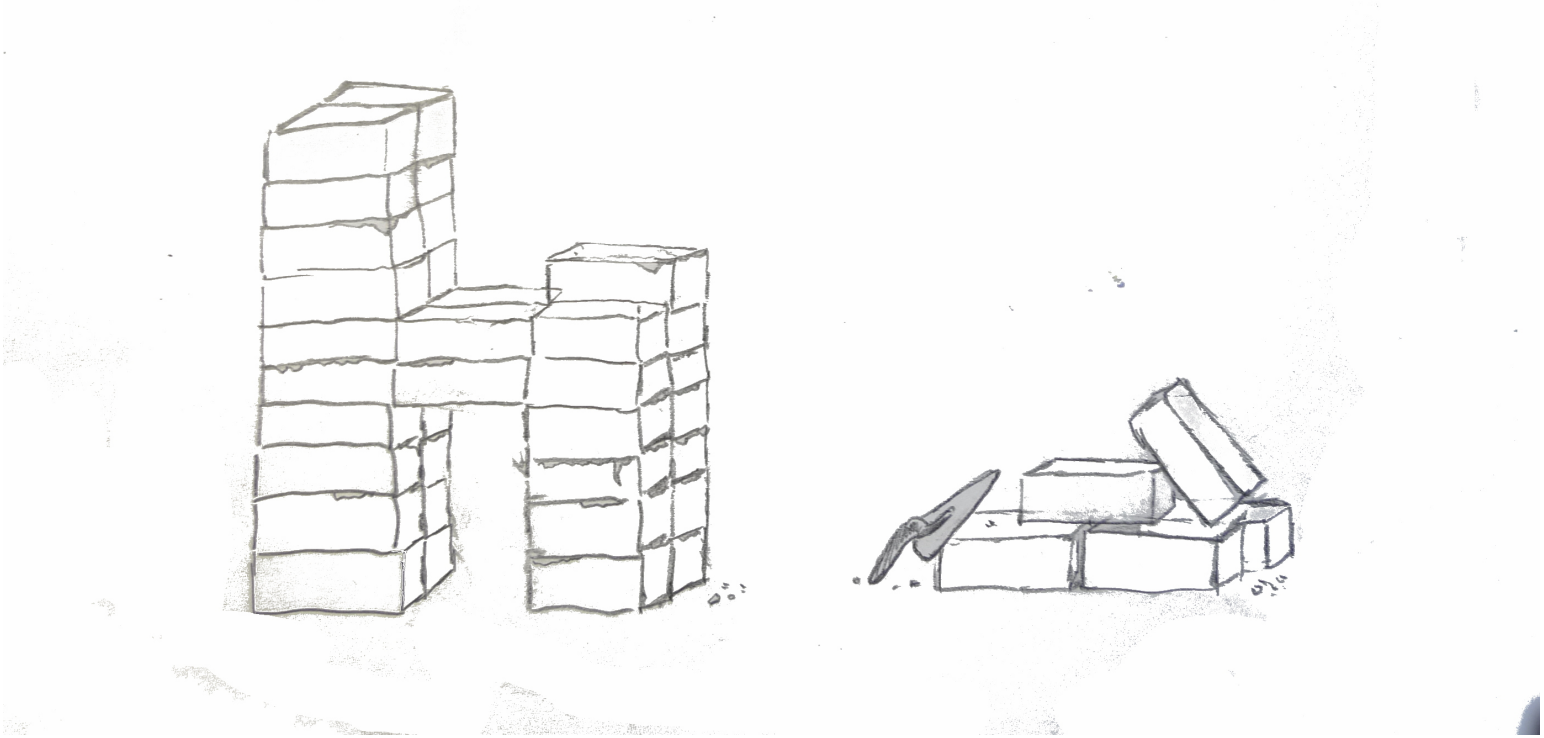
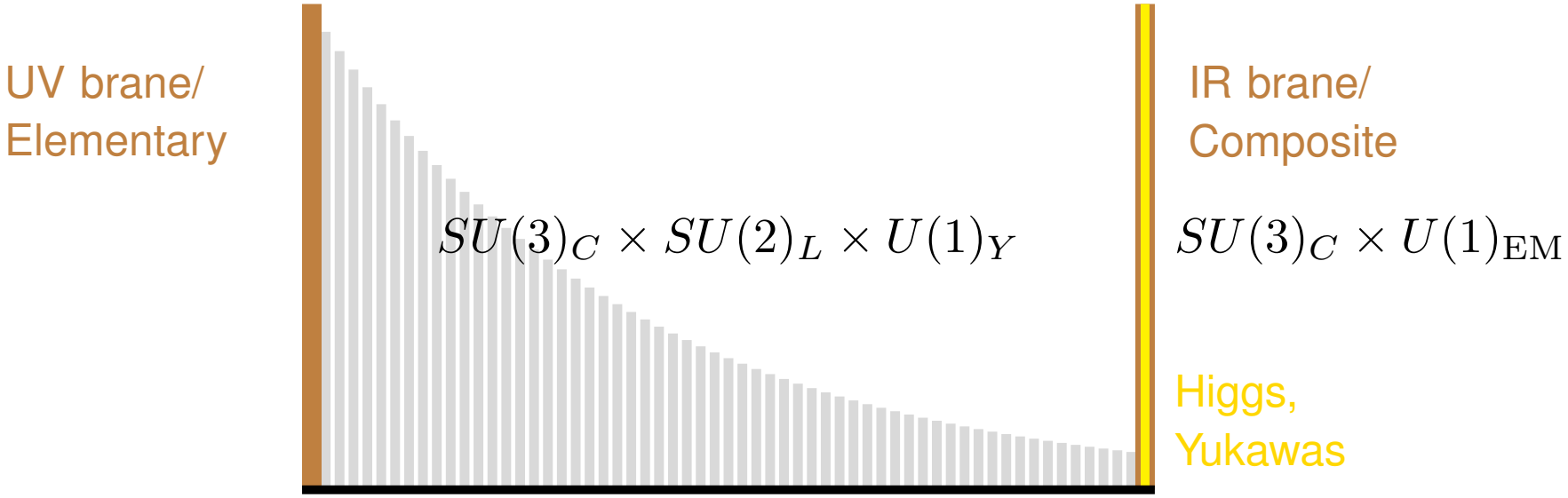
THE UNIVERSITY OF CHICAGO



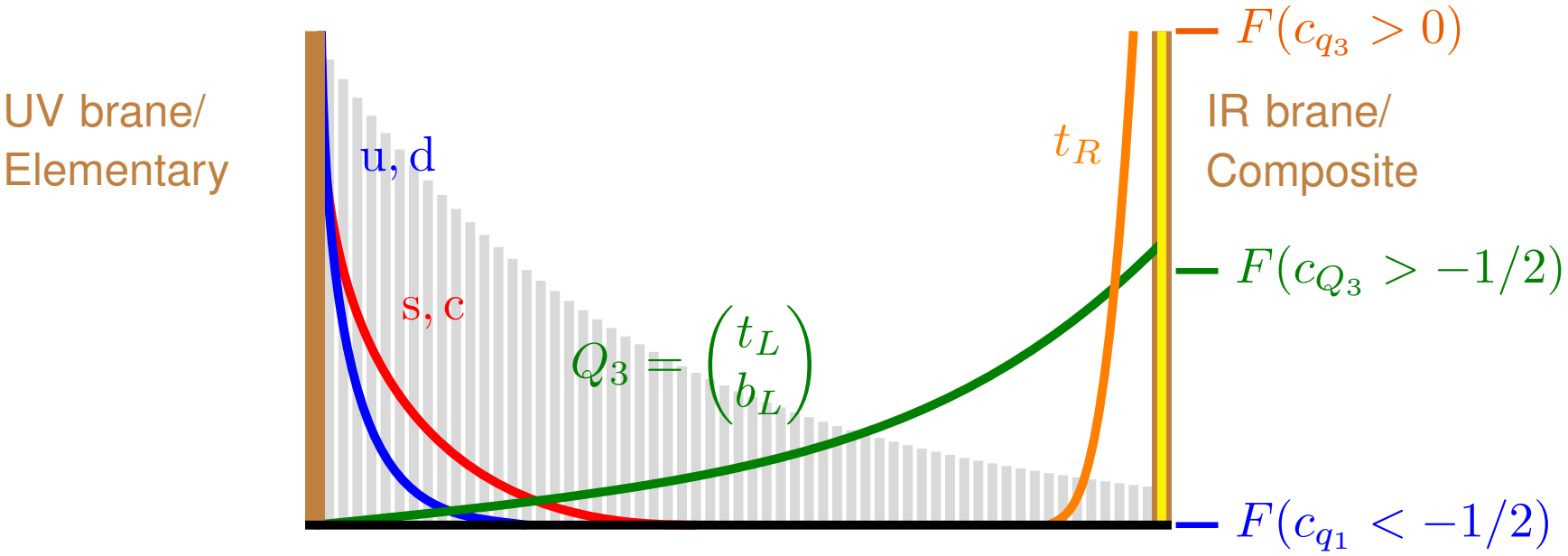
Warped/Composite Higgs and Flavor

Kaustubh Agashe, Martin Bauer, Florian Goertz, Luca Vecchi, LianTao Wang

RS Models


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

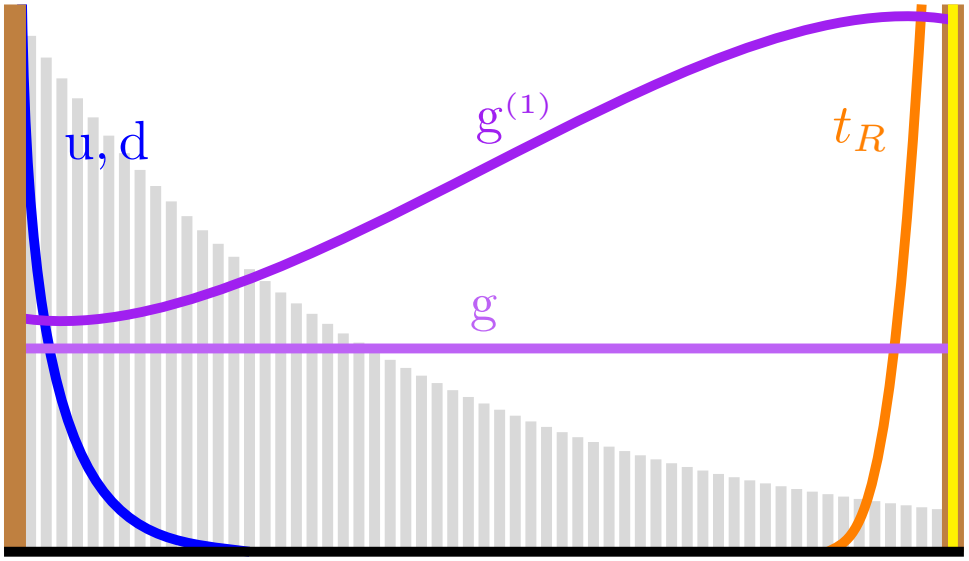
RS Models



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

RS Models

UV brane/
Elementary

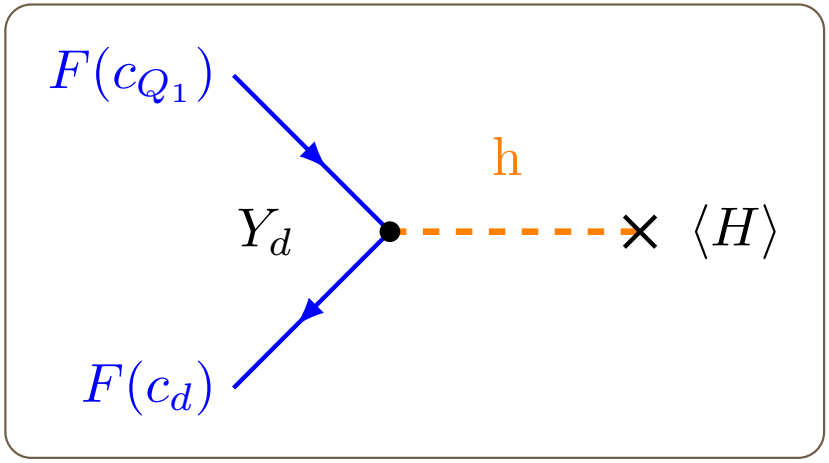


IR brane/
Composite

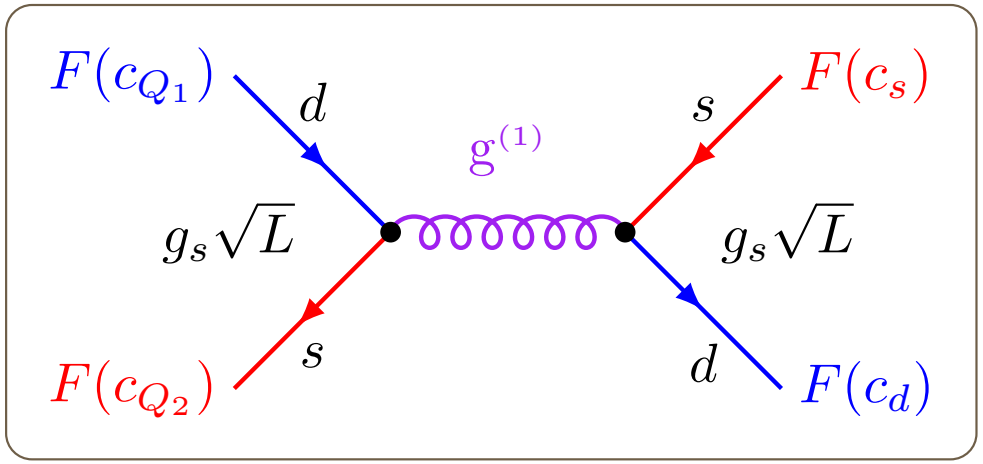
Warped Space Froggatt Nielsen

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

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



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



Warped Space Froggatt Nielsen

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

Parameters

- KK scale M_{KK}
- 9 Quark localizations
  $c_{Q_1}, c_{Q_2}, c_{Q_3}, c_d, c_s, c_b, c_u, c_c, c_t$
- 2 Yukawa matrices Y_u, Y_d

Warped Space Froggatt Nielsen

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Warped Space Froggatt Nielsen

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Warped Space Froggatt Nielsen

Quark Masses and mixing angles relate the quark profiles:

$$m_u \sim Y_* \, |F(c_{Q_1})| \, |F(c_u)| \qquad m_d \sim Y_* \, |F(c_{Q_1})| \, |F(c_d)|$$
$$m_c \sim Y_* \, |F(c_{Q_2})| \, |F(c_c)| \qquad m_s \sim Y_* \, |F(c_{Q_2})| \, |F(c_s)|$$
$$m_t \sim Y_* \, |F(c_{Q_3})| \, |F(c_t)| \qquad m_b \sim Y_* \, |F(c_{Q_3})| \, |F(c_b)|$$

$$\lambda \sim Y_* \, \frac{|F(c_{Q_1})|}{|F(c_{Q_2})|} \qquad A \sim Y_* \, \frac{1}{\lambda^2} \, \frac{|F(c_{Q_2})|}{|F(c_{Q_3})|}$$

Moving the right handed top towards the IR will push the localization of the left-handed 3rd generation profile into the UV.
The Wolfenstein Parameters force 1st and 2nd generation left-handed profiles to shift towards the UV as well.
All right-handed profiles shift towards the IR due to the mass relations.

Warped Space Froggatt Nielsen

The localization of the right-handed top quark controls whether FCNCs are dominated by right-handed or left-handed currents.

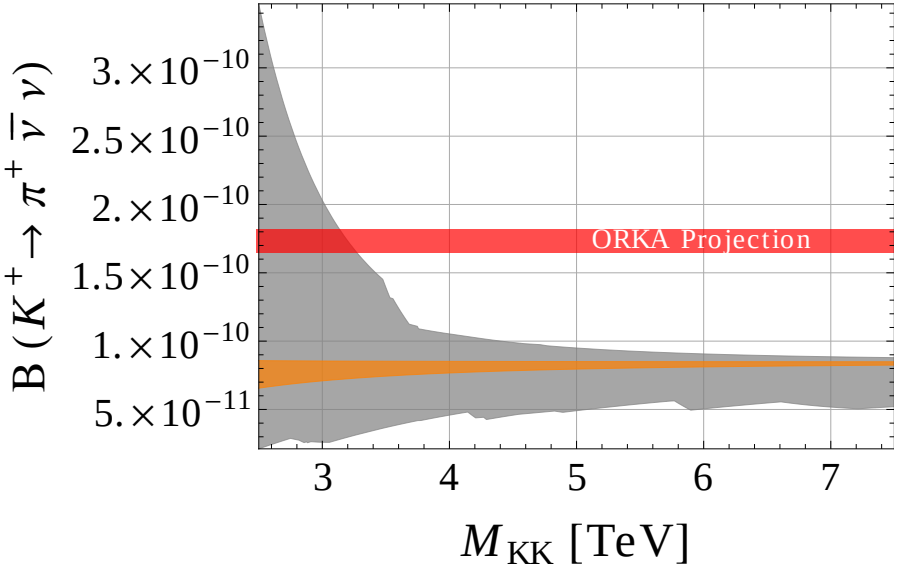
$c_t \to IR \Rightarrow$ large contributions to right-handed currents

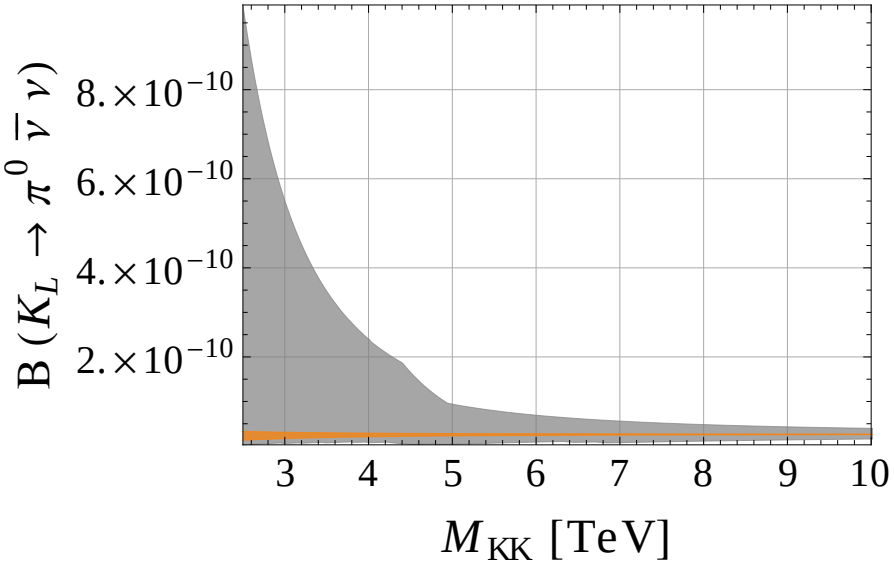
$c_t \to UV \Rightarrow$ large contributions to left-handed currents

A custodial symmetry protects electroweak precision observables and the Zb_Lb_L vertex from sizable corrections.
Left-handed currents involving down quarks are therefore small due to a protection from the gauge sector.

Flavor experiments will have good sensitivity for “IR top models”

OBSERVABLES





Current Bounds:

$B(K^+ \to \pi^+ \bar{\nu}\nu) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ $\qquad$ $B(K^0 \to \pi^0 \bar{\nu}\nu) < 3.8 \times 10^{-10}$

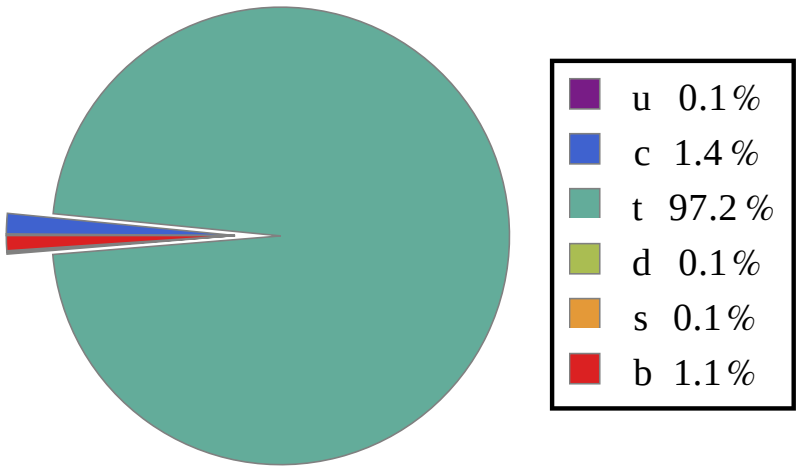
Gray area : 90% of the models with $F(c_t) > 2.2$

Orange area: 90% of the models with $F(c_t) < 0.5$

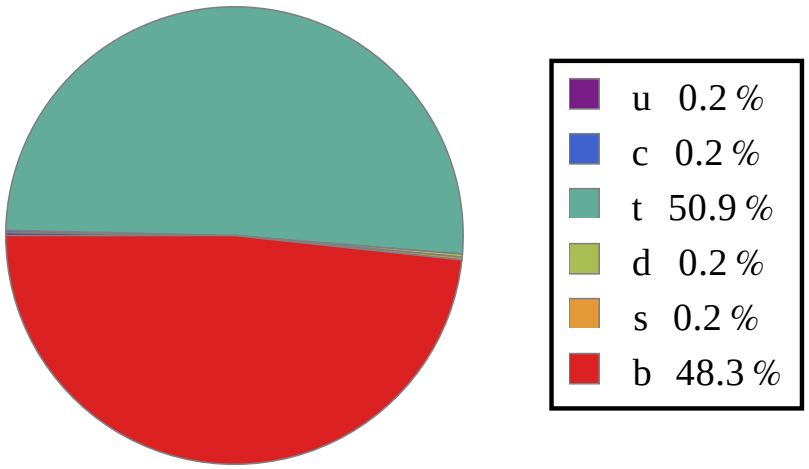
OBSERVABLES

Dijet searches have complementary sensitivity, because the top localization controls the branching fraction of the new resonance into light flavors.

$F(c_t) > 2.2$



$F(c_t) < 0.5$



- This complementarity is expected to be even more pronounced in models with flavor symmetries.
- The flavor off-diagonal decay $g_{KK} \to tc$ can distinguish between flavor symmetric and anarchic model and will be part of the collider study for Snowmass

LEPTONS

- The strongest bound is from $\mu \to e\gamma$. In models of partial compositeness the relevant operator scales as:

$$c_{L,R} \frac{Y^2}{16\pi^2} \frac{\sqrt{m_\mu m_e}}{m_\rho^2} \overline{\mu} \sigma^{\mu\nu} e_{L,R}\, eF_{\mu\nu}$$

with $c_{L,R} = O(1)$ (here $Y =$ 5D Yukawa, $m_\rho =$ KK mass).
The current 90% CL bound is $\mathcal{B}(\mu \to e\gamma) \leq 5.7 \times 10^{-13}$ (MEG), and reads

$$\frac{m_\rho}{Y} \gtrsim 18 \sqrt{|c_L|^2 + |c_R|^2}\ \mathrm{TeV}.$$

Bound on the NP scale gets <u>weaker</u> for smaller Y

LEPTONS

- $\mu \to e$ conversion is dominantly mediated by:

$$\frac{c}{Y f^2} \frac{\sqrt{m_\mu m_e}}{v} \, \overline{e} \gamma^\mu \mu \, H^\dagger i \overleftrightarrow{D}_\mu H,$$

with $c = O(1)$ and $f = m_\rho / g_\rho$, $g_\rho =$ KK coupling.
Most stringent bound from conversion in gold nuclei $R_{\mu e}^{\mathrm{Au}} \leq 7 \times 10^{-13}$ (SINDRUM II)

$$f \sqrt{Y} \gtrsim 2.0 \sqrt{|c|} \, \mathrm{TeV}.$$

Bound on the NP scale gets <u>stronger</u> for smaller Y

LEPTONS

- electron EDM:

$$\frac{d_e}{e} = \mathrm{Im}(c_e)\frac{Y^2}{16\pi^2}\frac{m_e}{m_\rho^2}$$

with $c_e = O(1)$.
Current bound [1] $d_e \leq (6.9 \pm 7.4) \times 10^{-28} e$ cm gives

$$\frac{m_\rho}{Y} \gtrsim (7-36)\sqrt{|\mathrm{Im}(c_e)|}\ \mathrm{TeV}.$$

Probe of CPV even in models where FV is suppressed

[1] Regan et al. (2002)

SUMMARY OF THE MAIN CONSTRAINTS ON ANARCHIC SCENARIOS

Keren-Zur et al.

Operator	$\lvert\mathrm{Re}(c)\rvert$	$\lvert\mathrm{Im}(c)\rvert$	Observable
$c\frac{Y^2}{16\pi^2}\frac{m_e}{m_\rho^2}\,\bar{e}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	—	$1.1\left(\frac{m_\rho/Y}{10\ \mathrm{TeV}}\right)^2$	electron EDM
$c\frac{Y^2}{16\pi^2}\frac{\sqrt{m_e m_\mu}}{m_\rho^2}\,\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	$0.31\left(\frac{m_\rho/Y}{10\ \mathrm{TeV}}\right)^2$		$\mu\to e\gamma$
”	$3.7\left(\frac{m_\rho/Y}{10\ \mathrm{TeV}}\right)^2$		$\mu\to ee^+e^-$
$\frac{c}{Yf^2}\frac{\sqrt{m_e m_\mu}}{v}\,\bar{e}\gamma^\mu\mu_{L,R}H^\dagger i\overleftrightarrow{D}_\mu H$	$0.25\left(\frac{\sqrt{Y}f}{1\ \mathrm{TeV}}\right)^2$		$\mu(Au)\to e(Au)$
”	$0.38\left(\frac{\sqrt{Y}f}{1\ \mathrm{TeV}}\right)^2$		$\mu\to ee^+e^-$

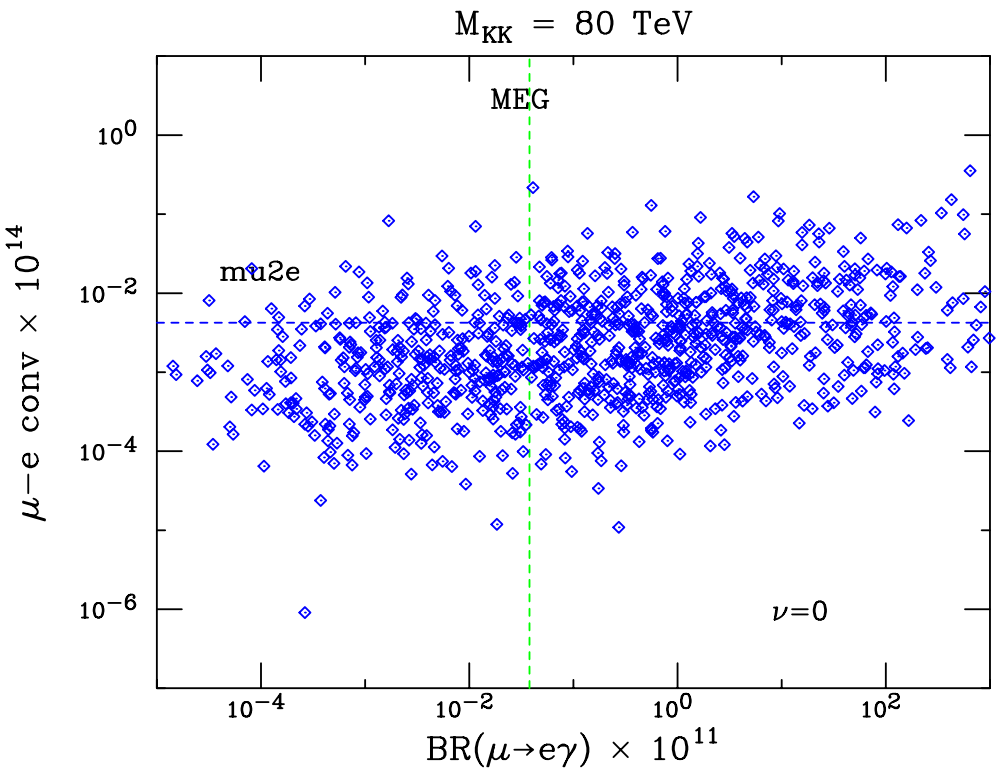
complementarity of the bounds:

– $\mu\to e$ with different dependence on Y

– d_e probes CPV rather than $\ell_i\to\ell_j$

Analysis of Anarchic RS Model

(Agashe et al.)



$\nu = 0$ for maximally spread Higgs profile (best case scenario)

$M_{KK} = m_\rho = 20$ TeV, $g_\rho \sim 4$, $Y \in [0.5, 4]$, all points reproduce $m_{e,\mu,\tau}$

- **non-hierarchical neutrino masses** can be obtained by cutoff-suppressed operators (i.e., operators on the UV brane) either as Dirac or Majorana. The UV cutoff must be $\lesssim O(\Lambda_{\mathrm{see-saw}})$.
- **hierarchical masses for the charged leptons** can be obtained as in the quark sector by partial compositeness (i.e., wave function localization in 5D): the Majorana/Dirac nature of neutrinos does not impact the physics of charged leptons.

Anarchic Lepton Scenarios at the Intensity Frontier

- $\mu \to e$ transitions:
  $\mu \to e\gamma$, $\mu(Au) \to e(Au)$, and $\mu \to e\bar{e}e$
  currently require $m_\rho \gtrsim O(20)$ TeV
  $\mathcal{B}(\mu \to \mu\gamma) \lesssim 10^{-14}$ (expected) gives $m_\rho \gtrsim O(50)$ TeV;
- electron EDM d_e:
  relevant even in models with flavor symmetries;
- $\tau \to \mu$ transitions ($\tau \to e$ suppressed by m_e/m_μ)
  — $\mathcal{B}(\tau \to \mu\gamma) \lesssim 10^{-12}$ is not observable
  — $\mathcal{B}(\tau \to \mu\bar{\mu}\mu, \mu\bar{e}e, \mu\eta) \sim (10^{-10} - 10^{-9})$
  currently allowed, but probed in the future

SUMMARY

- IF observables are sensitive to the localization of fermions.
- IF and EF experiments are sensitive to different localization schemes and are therefore complementary tools for excluding/discovering RS models.
- Experiments measuring flavor diagonal (EDM) and off-diagonal ($\mu \to e\gamma$, $\tau \to \mu$ conversion) observables in the lepton sector will also constrain models with and without flavor symmetries in a complementary way.
- A comprehensive analysis of these observables is in preparation.