4G and 125 H

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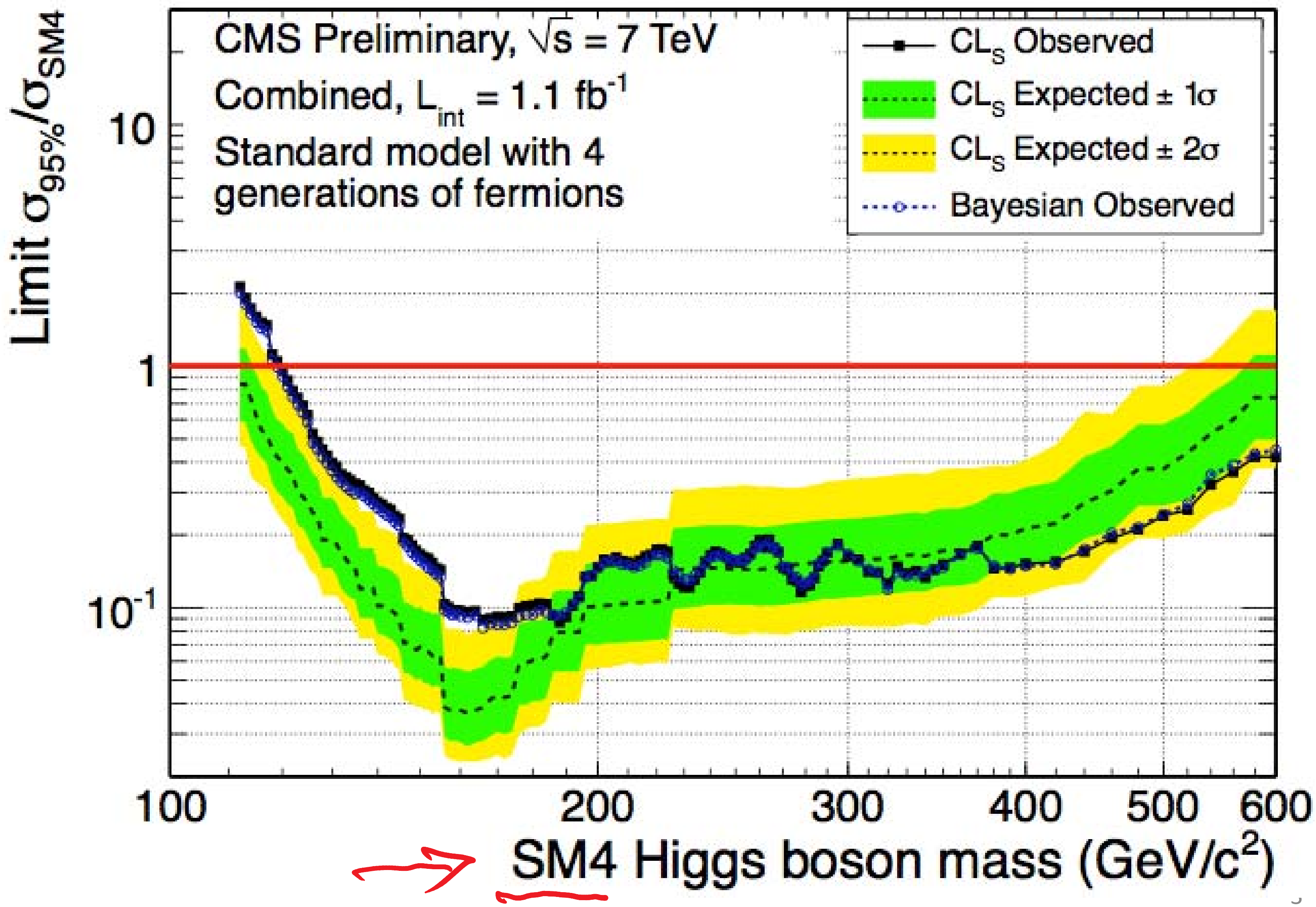
outline

- **Motivation**
- **Model**
- **Implications**
- **In progress**
- **Summary**

Based primarily on recent works with

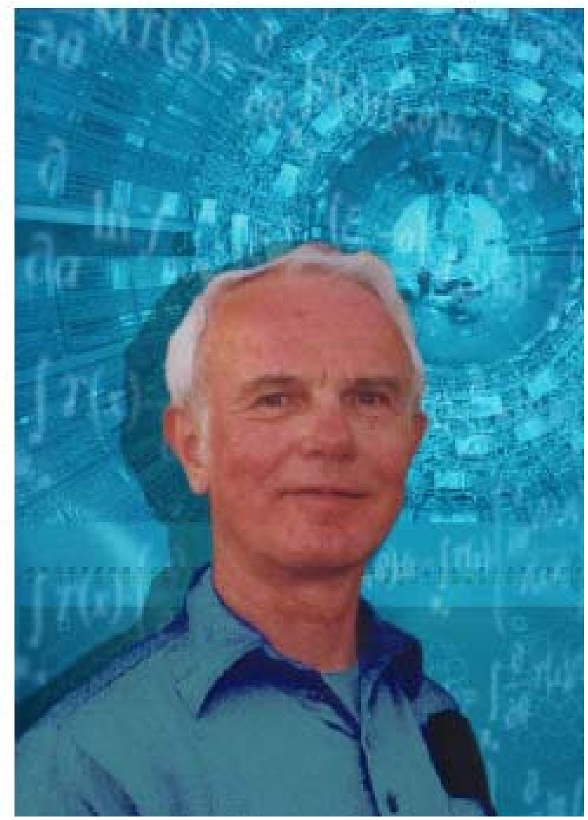
Shaouly Bar-shalom; **Michael Geller**; Soumitra Nandi: arXiv:1105.3490; 1209.4081; in prog.

The Higgs: 4th Generation?



4^{th} Generation

- My main interest was due DEWSB (possible indoctrination from Cornwall + Norton,PRD'73?)

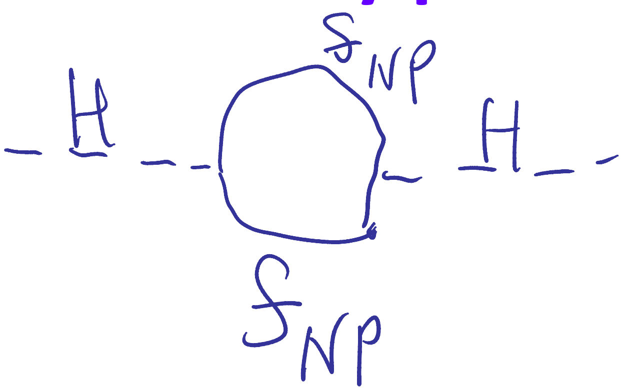


4G : a revisit

- **Inspired by classic works on “SSB w/o fundamental scalars” by Cornwall and Norton [‘73], studied with Norton and students Carpenter & Siegemund-Broka, role of heavy quarks in DEWSB in [87-90]**
- **potential of B-physics forSM4 studied extensively with George Hou~86-88**

Outstanding Th.puzzles of our times

- **Hierarchy puzzle**

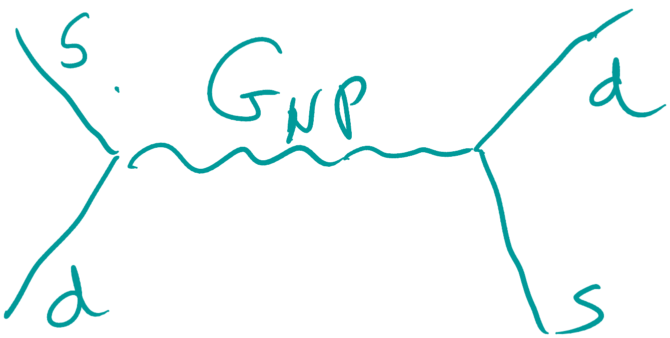


$$\sim \frac{g^2_{NP}}{16\pi^2}\Lambda^2_{NP} \Rightarrow \Lambda_{NP} \lesssim \text{TeV}$$

to avoid fine tuning m_H

- **Flavor puzzle**

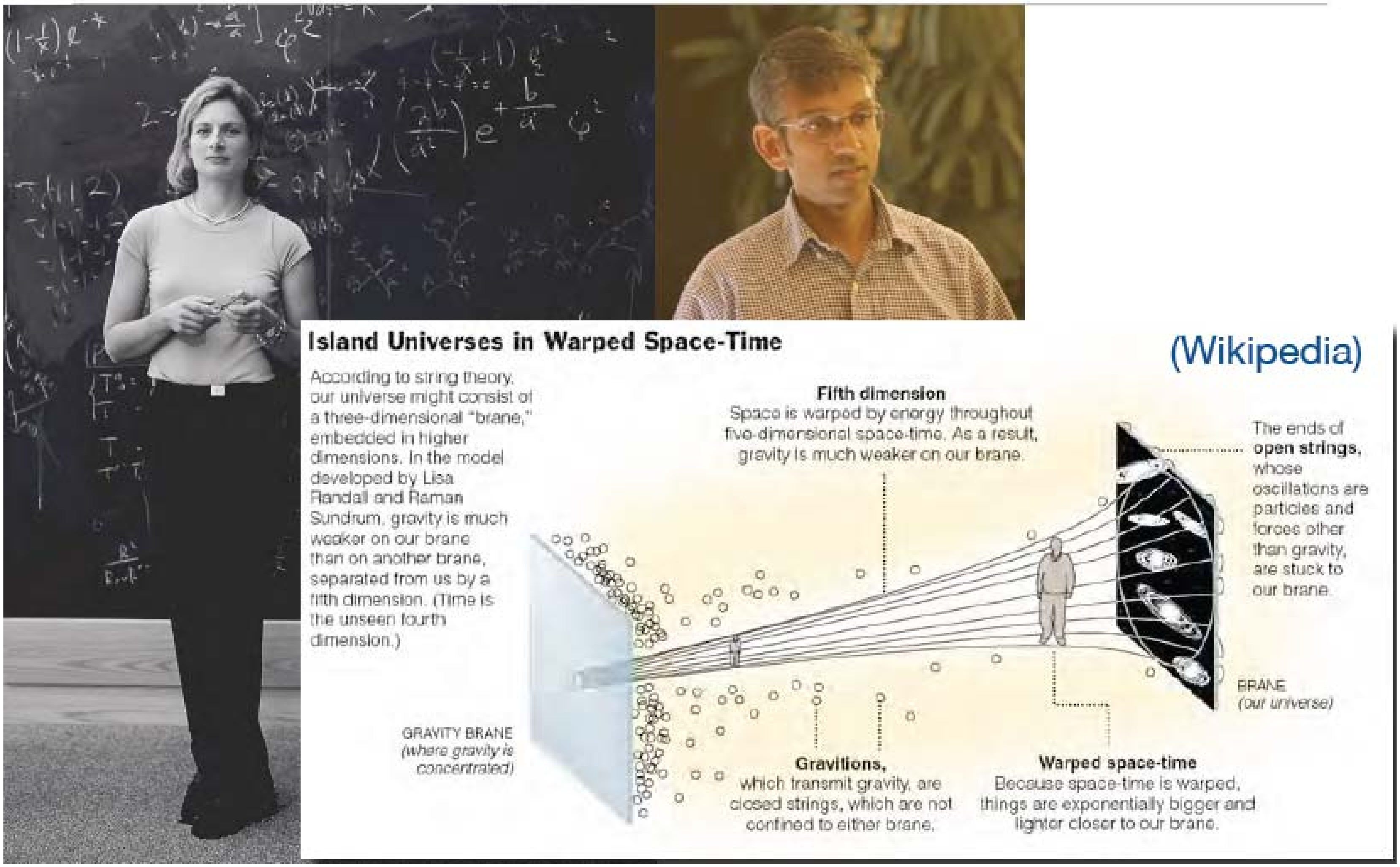
Δ flava = 2 e.g.



$$\sim \frac{g^2_{NP}}{\Lambda^2_{NP}} \Rightarrow \Lambda_{NP} \gtrsim 10^3 \text{ TeV}$$

to avoid constraint from Δm_K

The Randall-Sundrum (RS) idea



[Stolen from Neubert]

RANDALL+SUNDRUM '99

[Stolen from H DAVOUDIASL]

Points along 5th dim correspond to diff. eff. 4d scale!

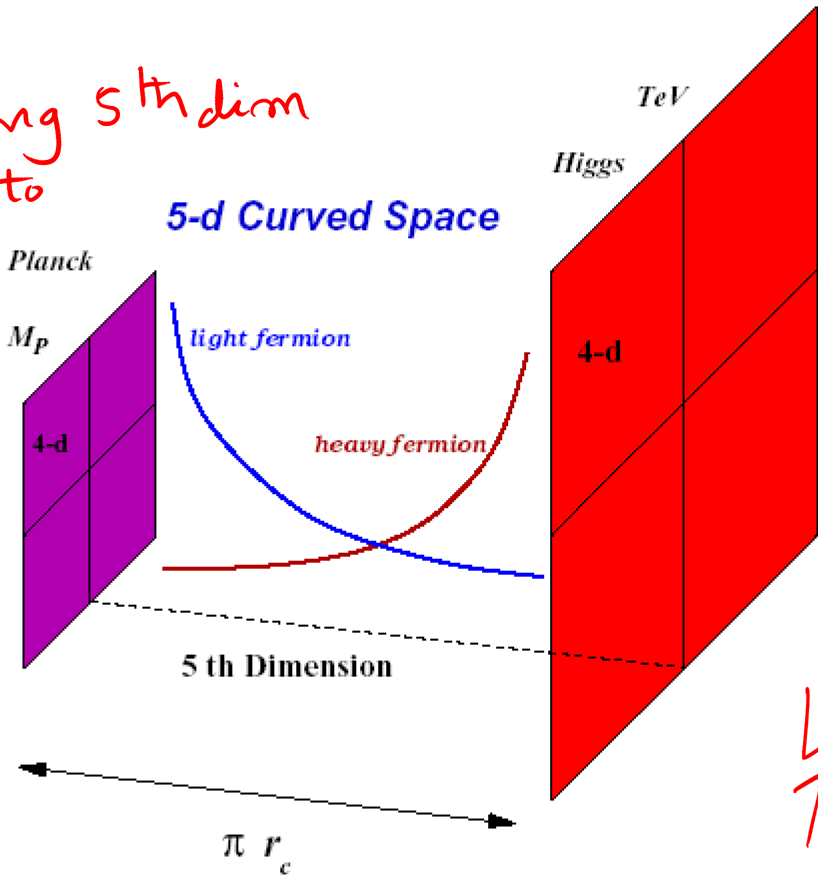


Figure 1: Warped geometry with flavor from fermion localization. The Higgs field resides on the TeV-brane. The size of the extra dimension is $\pi r_c \sim M_P^{-1}$.

$$ds^2 = e^{-2\sigma}\eta_{\mu\nu}\, dx^\mu dx^\nu - r_c^2\, d\phi^2$$

$$\langle H_4 \rangle = e^{-\sigma} \langle H_5 \rangle$$

TeV ← → M_P

$$\sigma = k r_c \pi$$

$k r_c \sim 12$

Simultaneous resolution to hierarchy and flavor puzzles

Fermion "geography" (localization) naturally explains:

Grossman&Neubert; Gherghetta&Pomarol; Davoudiasl, Hewett & Rizzo

- **Why they are light (or heavy); 5 D localizarions all O(1) despite huge hierachy in 4D masses →**
- **FCNC for light quarks are severely suppressed**
- **RS-GIM MECHANISM (Agashe, Perez,AS'04) flavor changing transitions though at the *tree level* (resulting from rotation from interaction to mass basis)are suppressed roughly to the same level as the loop in SM Kaon mixing constraints now O(10 TeV) with some tuning to O(1 TeV)**
- **Most flavor violations are driven by the top**

EXTENSIVE RECENT STUDIES by BURAS et al and NEUBERT et al; Weiler

Localization parameters

Quarks	c^D	c^S	m_q(SM) (GeV)	m_q^{KK}/m_g^{KK}
$\begin{pmatrix} u \\ d \end{pmatrix}$	0.5	$\begin{pmatrix} -1.4 \\ -0.7 \end{pmatrix}$	$\begin{pmatrix} 3.5 \times 10^{-14} \\ 4.8 \times 10^{-3} \end{pmatrix}$	$1.0, \begin{pmatrix} 1.5 \\ 1.1 \end{pmatrix}$
$\begin{pmatrix} c \\ s \end{pmatrix}$	0.5	$\begin{pmatrix} -0.53 \\ -0.61 \end{pmatrix}$	$\begin{pmatrix} 1.2 \\ 0.11 \end{pmatrix}$	$1.0, \begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$
$\begin{pmatrix} t \\ b \end{pmatrix}$	0.4	$\begin{pmatrix} \cdots \\ -0.52 \end{pmatrix}$	$\begin{pmatrix} 170.6 \\ 4.1 \end{pmatrix}$	$1.0, \begin{pmatrix} \cdots \\ 1.0 \end{pmatrix}$

Davoudiasl & A.S. PRD '07

These theories are supposed to be dual to strong dynamics …The prospects for that get enhanced due heavy quarks via large yukawas

Maldacena

- So heavy quarks may trigger condensation -> STRONG DYNAMICS/ DEWSB,no need 4 fundamental Higgs,SUSY
- 1,2,3, why not 4?
- 4G has significant advantage for baryogenesis over SM3 [Jarlskog & Stora('88); Branco et al('98); Hou('08)]
- Also offers new avenue for DMC

BTW

- **Also Accounts also for AFB(tt)**
  [Davoudiasl,McElmurry & A S]

Baryogenesis

- For SM3, there is unique CP invariance [Jarlskog '87]

$$J = \mathrm{Im}\det[M_u M_u^\dagger M_d M_d^\dagger]$$

$$= 2(m_t^2 - m_u^2)(m_t^2 - m_c^2)(m_c^2 - m_u^2)$$

$$(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2)A$$

→ Area of UT

⇒ exceedingly small CP ∵ of small masses

$J/v^{12} \sim 10^{-20}$!

4G facilitates baryogenesis significantly

KM Theorem: 3 Families 1 CP-odd phase

Family #s 2,3,4 ⇒ J_{234}/J_{123} :

$$(m_t^2/m_c^2)(m_t'^4/m_t^4)(m_b^2/m_s^2)(m_b'^4/m_b^4) \approx 10^{16}$$!!!

W. S. Hou, arXiv:0803.1234 DIG THIS!!!

DIVINE intervention

See also, F. del Aguila, J. A. Aguilar-Saavedra and G. C. Branco, Nucl. Phys. B **510**, 39 (1998); hep-ph/9703410.

C. Jarlskog and R. Stora, Phys. Lett. B208, 288 (1988)

Cannot be simple SM4

- Even if a 4th generation exists it is unlikely to be a simple replica of SM3: Highly implausible that heavy quarks will not be used for DEWSB
- Neutrino mass provides a strong clue
- DM possibility and baryogenesis both strongly suggest 4G not in SM4…Baryogenesis also needs 2HDM as single Higgs doublet phase transition not strong enough [see e.g. Dine & Kusenko]
- [not surprising] Simple SM4 light higgs now strongly disfavored by data

• Recall current direct limits:

Current limits on the masses of a 4th generation heavy quarks
(though "naive" - based on SM4 decay topology):

$m_{b'}$, $m_{t'}$ 550 GeV $\gtrsim$

[17] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1203.5410 [hep-ex].
[18] G. Aad *et al.* [Atlas Collaboration], arXiv:1202.6540 [hep-ex].
[19] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1204.1088 [hep-ex].
[20] See g.g., M.S. Chanowitz, M.A. Furman and I. Hinchliffe, Phys. Lett. **B78**, 285 (1978); *ibid.*, Nucl. Phys. **B153**, 402 (1979); W.J. Marciano, G. Valencia and S. Willenbrock, Phys. Rev. **D 40**, 1725 (1989).

Implications of such a heavy 4th generation spectrum are far reaching …

• What to expect?

Large Yukawa's "run" into a Landau pole
Theory is cutoff @ a near by scale !

a simplified argument:

RGE for y_4
(4G, neglect gauge couplings & top Yukawa + assume all 4th gen Yukawa's are the same)

$$(16\pi^2)\mu\frac{\partial}{\partial\mu}y_4 \cong 8y_4^3.$$

Landau pole: $1/y_4^2(\mu = \Lambda_y) = 0 \Rightarrow \Lambda_y = m_4 e^{\frac{v^2\pi^2}{2m_4^2}}$

$$\Lambda_y = 8\,(10)\ \mathrm{TeV},\ 3\,(3)\ \mathrm{TeV},\ 2\,(2)\ \mathrm{TeV}.$$

FOR:

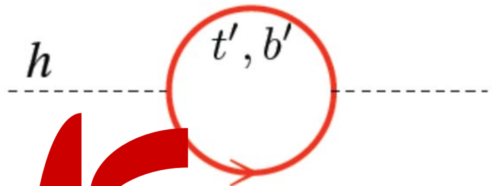
$$m_4 = 300\ \mathrm{GeV},\ 400\ \mathrm{GeV},\ 500\ \mathrm{GeV}\,.$$

- **further rationale**

that SM4 not compatible and that a 4th family might be tied up with new strong dynamics …

- **Higgs mass corrections are pushed to the cutoff scale**
- **Higgs quartic coupling also run into a similar Landau pole**
- **RGE (SM4)**

- **Heavy 4th Q' loops:**
  direct contribution to Higgs mass



assume cutoff $\Lambda > m_{q'}$ $\longrightarrow$

$$\delta m^2 \sim \left(\frac{m_{q'}}{400\,GeV} \right)^2 \cdot \Lambda^2$$

- A heavy 4th family fermion cannot co-exist with a single light Higgs

In the absence of fine-tuning the Higgs mass is pushed up to the cutoff scale where the new physics enter

$\Rightarrow$ Higgs description meaningless

need a "regulator"/NP …

TeV-scale compositeness ?

spectrum ?

Expect multi-"Higgs"/composite states:

Higgs particles are viewed as composites primarily of the 4th gen fermions, with condensates: $<Q'_L\, t'_R> \neq 0$, $<Q'_L\, b'_R> \neq 0$

(**and possibly also $<L'_L\, \nu'_R> \neq 0$, $<L'_L\, \tau'_R> \neq 0$**)

Which induces EWSB and generates a dynamical mass for the condensing fermions …

Luty (already 20 years ago: M.A. Luty, Phys. Rev. **D41**, 2893 (1990).):
EWSB by 4th gen condensation naturally leads to an effective 2HDM at low-energies

And more recently:

Heavy 4th generation fermions can feel a strong attractive force from Higgs exchanges that may give rise to multiple <q'q'> bound states

Ishiwata & Wise, PRD83, 074015, 2011

Hung & Xiong, arXiv:0911.3890; PLB694, 430, 2011; arXiv:1012.4479

Holdom et al, arXiv:0904.4698

Holdom, PLB686,146,2010

Our goal

[BAR-SHALOM, NANDI + AS, arXiv 1105.3490]

construct a class of 2HDMs with a 4th gen. of fermions that can: effectively address the low-energy phenomenology of a TeV-scale dynamical EWSB scenario

(i.e., possibly triggered by the condensates of the 4th gen. fermions)

↓

a 2HDM "for the 4th generation" (4G2HDM)

(giving a special status to the 4th gen. fermions)

The 4G2HDMs

- Basic idea:

  ϕ_h ("heavier" field) couples only to the heavy fermions

  ϕ_l ("lighter" field) couples to all other (light) fermions

→ FCNC

$t' \leftrightarrow t$

$b' \leftrightarrow b$

$$\mathcal{L}_Y = -\bar{Q}_L \left(\Phi_\ell F \cdot \left(I - \mathcal{I}_d^{\alpha_d \beta_d}\right) + \Phi_h F \cdot \mathcal{I}_d^{\alpha_d \beta_d}\right) d_R$$

$$- \bar{Q}_L \left(\tilde{\Phi}_\ell G \cdot \left(I - \mathcal{I}_u^{\alpha_u \beta_u}\right) + \Phi_h G \cdot \mathcal{I}_u^{\alpha_u \beta_u}\right) u_R + h.c.$$

With: $\mathcal{I}_q^{\alpha_q \beta_q} \equiv \mathrm{diag}\left(0, 0, \alpha_q, \beta_q\right)$

* INSPIRED BY a warped theory of flavor

Type I 4G2HDM:

$$(\alpha_d, \beta_d, \alpha_u, \beta_u) = (0,1,0,1) \Rightarrow I_d = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix}, I_u = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix}$$

$$\mathbf{L}_{\mathbf{Y}}^{\mathbf{quark}} = -\overline{Q}_L^i \phi_l F_{i,j\neq 4} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} - \overline{Q}_L^i \tilde{\phi}_l G_{i,j\neq 4} \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} - F_{i4} \overline{Q}_L^i \phi_h b'_R - G_{i4} \overline{Q}_L^i \tilde{\phi}_h t'_R$$

- **expect** $\tan\beta \equiv \frac{v_h}{v_l} \approx \frac{m_{q'}}{m_t} \sim O(1)$

Phenomenology of type-I 4G2HDM

- **FCNC effects only in t' → t & b' → b transitions**

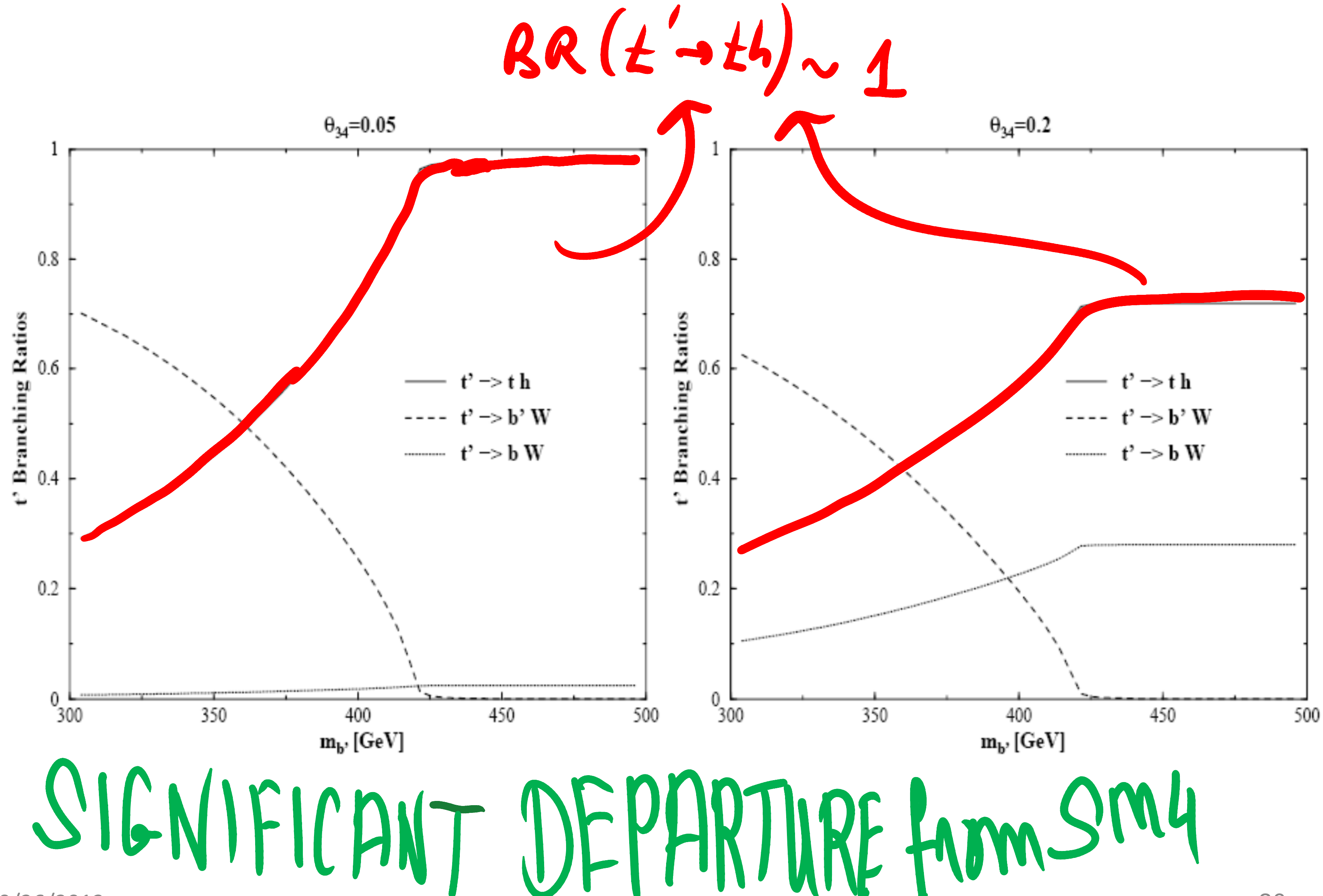
e.g., $$\mathcal{L}(ht't) = -\frac{g}{2}\frac{m_{t'}}{m_W}\epsilon_t\sqrt{1+t_\beta^2}\,\bar{t}'\left(R+\frac{m_t}{m_{t'}}L\right)th\ ,$$

- **Enhanced htt Yukawa interaction while suppressed ht't' one:**

$$\mathcal{L}(htt) \approx \frac{g}{2}\frac{m_t}{m_W}\sqrt{1+t_\beta^2}\left(1-|\epsilon_t|^2\right)\ \bar{t}th \stackrel{|\epsilon_t|^2\ll 1}{\longrightarrow} \frac{g}{2}\frac{m_t}{m_W}\sqrt{1+t_\beta^2}\ \bar{t}th$$

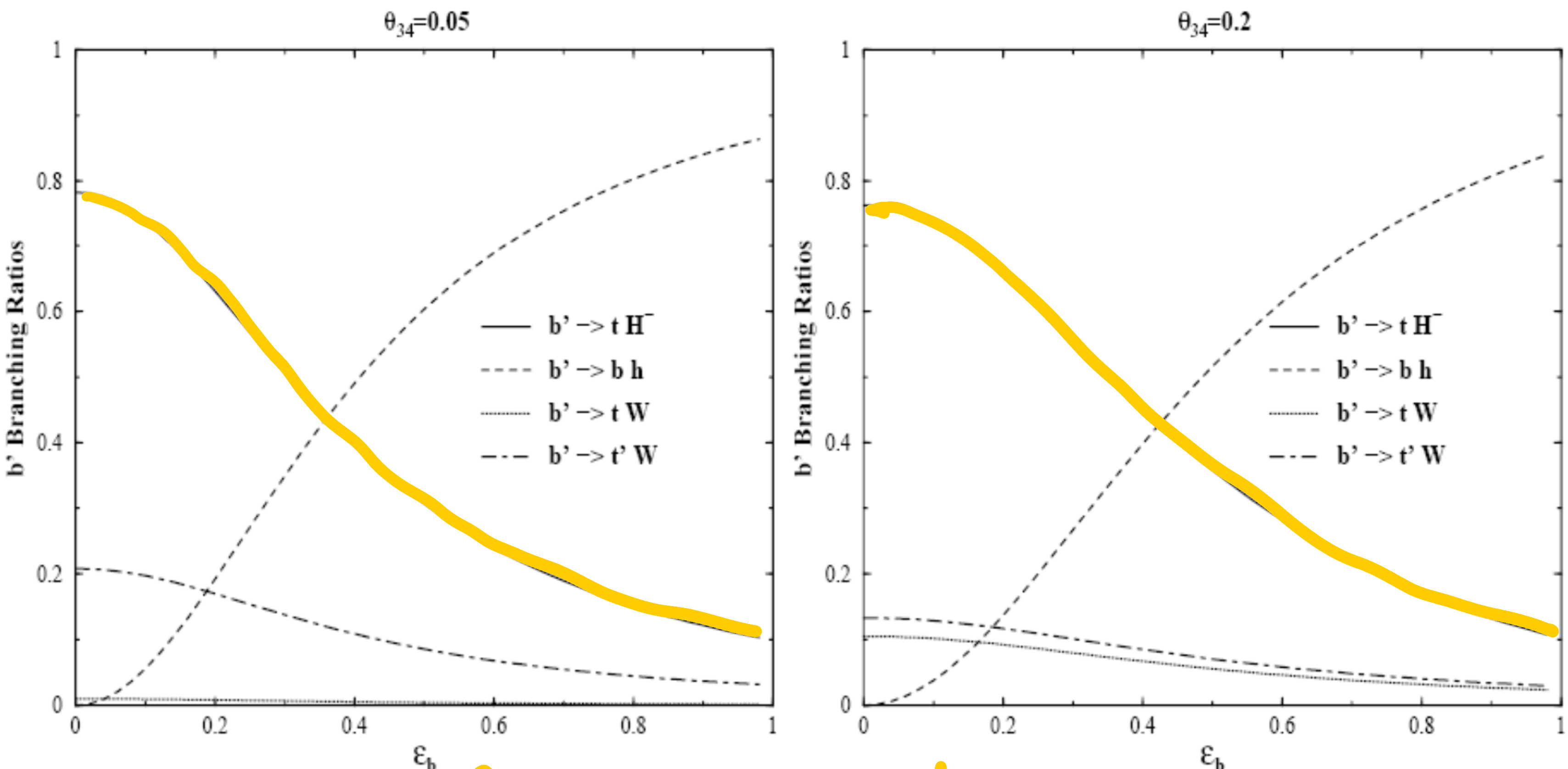
$$\mathcal{L}(ht't') \approx \frac{g}{4}\frac{m_{t'}}{m_W}\sqrt{1+t_\beta^2}|\epsilon_t|^2\ \bar{t}'t'h$$

t' decays


BR(t'→th) ~ 1
θ34=0.05
θ34=0.2
t' Branching Ratios
t' -> t h
t' -> b' W
t' -> b W
mb' [GeV]
0
0.2
0.4
0.6
0.8
1
300
350
400
450
500
SIGNIFICANT DEPARTURE from SM4

b' decays

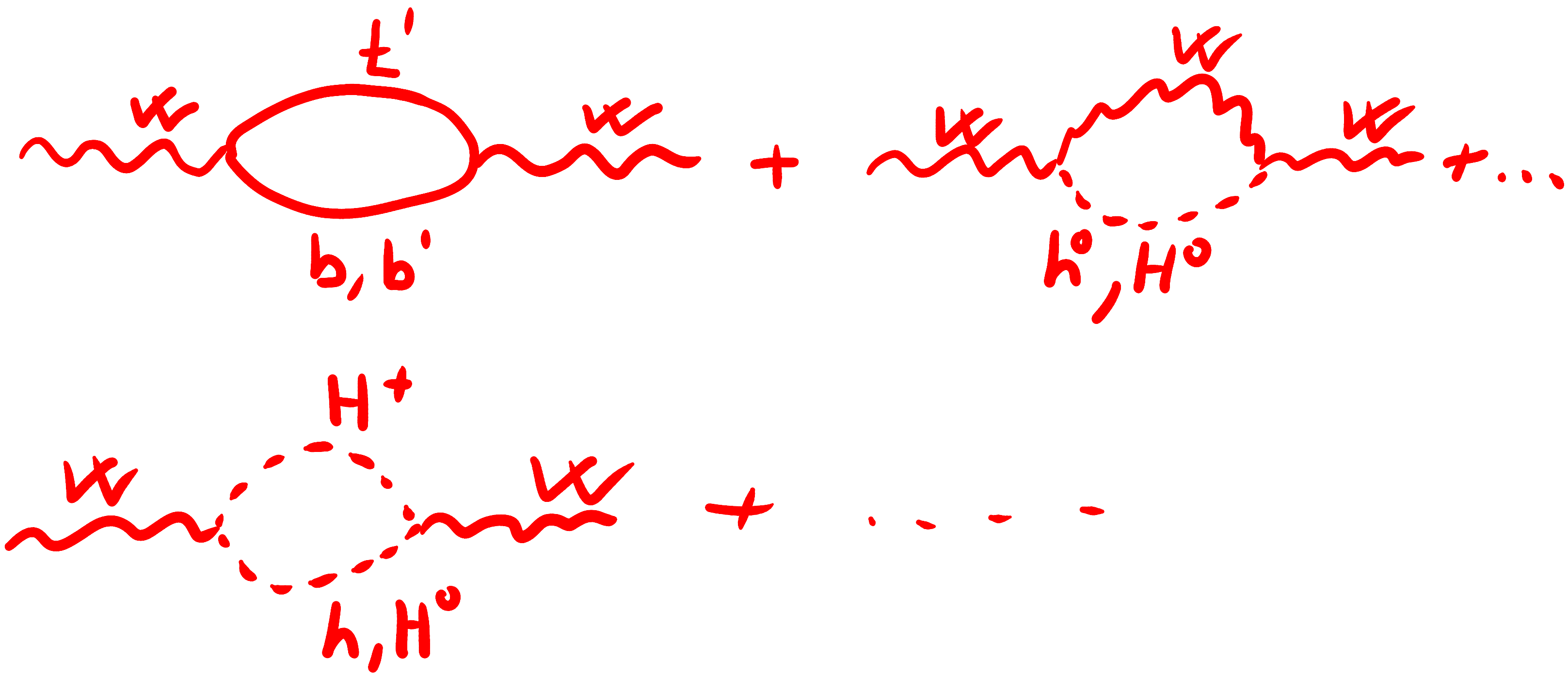
$BR(b' \to t H^+) \sim \mathcal{O}(1)$



recall: $\varepsilon_b \ll 1$ ....

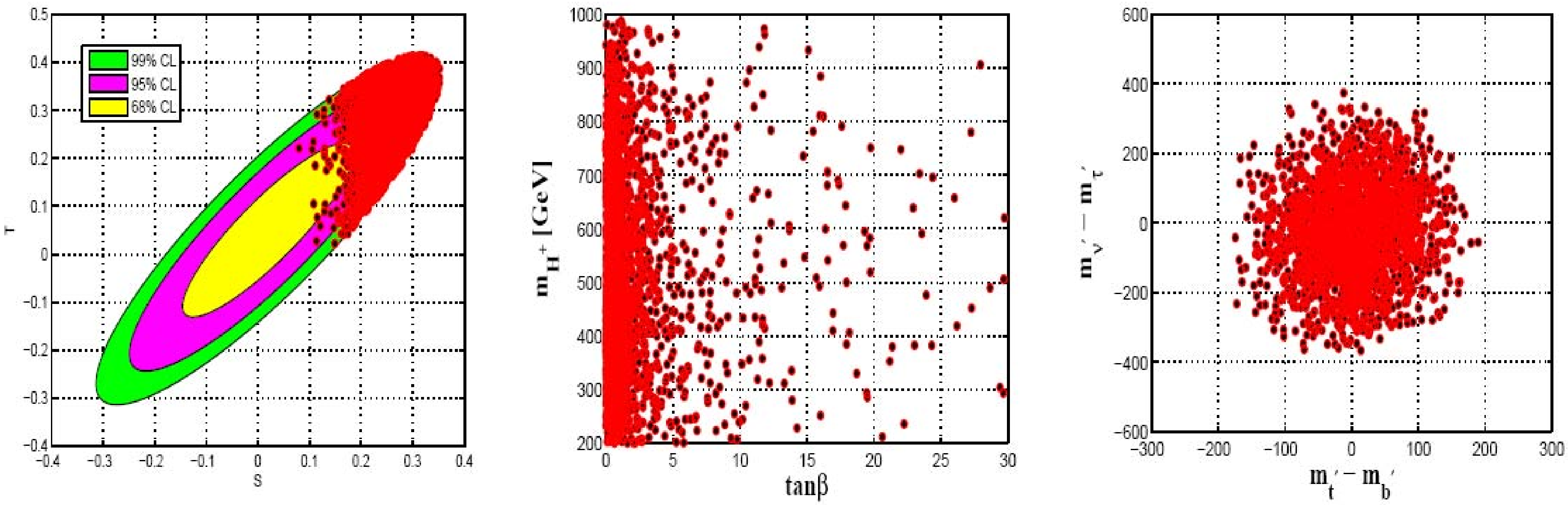
Oblique corrections to gauge-bosons 2-point functions:

e.g.,



Contributions to S & T from Higgs exchanges are identical to generic 2HDMs

m_h = 125 GeV &
random scans (100000 models) of other parameters:



parameters in the ranges: $\tan\beta \leq 30$, $\theta_{34} \leq 0.3$, $150~\text{GeV} \leq m_H \leq 1~\text{TeV}$, $150~\text{GeV} \leq m_A \leq 1~\text{TeV}$, $200~\text{GeV} \leq m_{H^+} \leq 1~\text{TeV}$, $400~\text{GeV} \leq m_{t'}, m_{b'} \leq 600~\text{GeV}$, $100~\text{GeV} \leq m_{\nu'}, m_{\tau'} \leq 1.2~\text{TeV}$ *and the CP-even neutral Higgs mixing angle in the range* $0 \lesssim \alpha \lesssim 2\pi$.

- **Consistent with EWPD within 68%CL**
- **Small tanβ favoured**
- **Allows $m_{t'} - m_{b'} > m_W$**
- **Allows solutions with both degenerate 4th gen doublets**

Higgs searches:

125 GeV Higgs and the 4G2HDMI

Use: $$R_{XX}^{Model/Observed} = \frac{\sigma\left(pp/p\bar{p} \to h \to XX\right)_{Model/Observed}}{\sigma\left(pp/p\bar{p} \to h \to XX\right)_{SM}}$$

with: $R_{XX}^{Observed}$ **=**

- $VV \to h \to \gamma\gamma$: 2.2 ± 1.4 (taken from $\gamma\gamma + 2j$)
- $gg \to h \to \gamma\gamma$: 1.68 ± 0.42
- $gg \to h \to WW^*$: 0.78 ± 0.3
- $gg \to h \to ZZ^*$: 0.83 ± 0.3
- $gg \to h \to \tau\tau$: 0.2 ± 0.85
- $pp/p\bar{p} \to hW \to b\bar{b}W$: 1.8 ± 1.5

(ICHEP2012)

Fit model using:

$$\chi^2 = \sum_X \frac{\left(R_{XX}^{Model} - R_{XX}^{Observed}\right)^2}{\sigma_{XX}^2}$$

with: $$R_{XX}^{Model} = \frac{\Gamma\left(h \to YY\right)_{Model}}{\Gamma\left(h \to YY\right)_{SM}} \cdot \frac{Br\left(h \to XX\right)_{Model}}{Br\left(h \to XX\right)_{SM}}$$

$$\left(\frac{\sigma(YY \to h)_{Model}}{\sigma(YY \to h)_{SM}} = \frac{\Gamma(h \to YY)_{Model}}{\Gamma(h \to YY)_{SM}}\right)$$

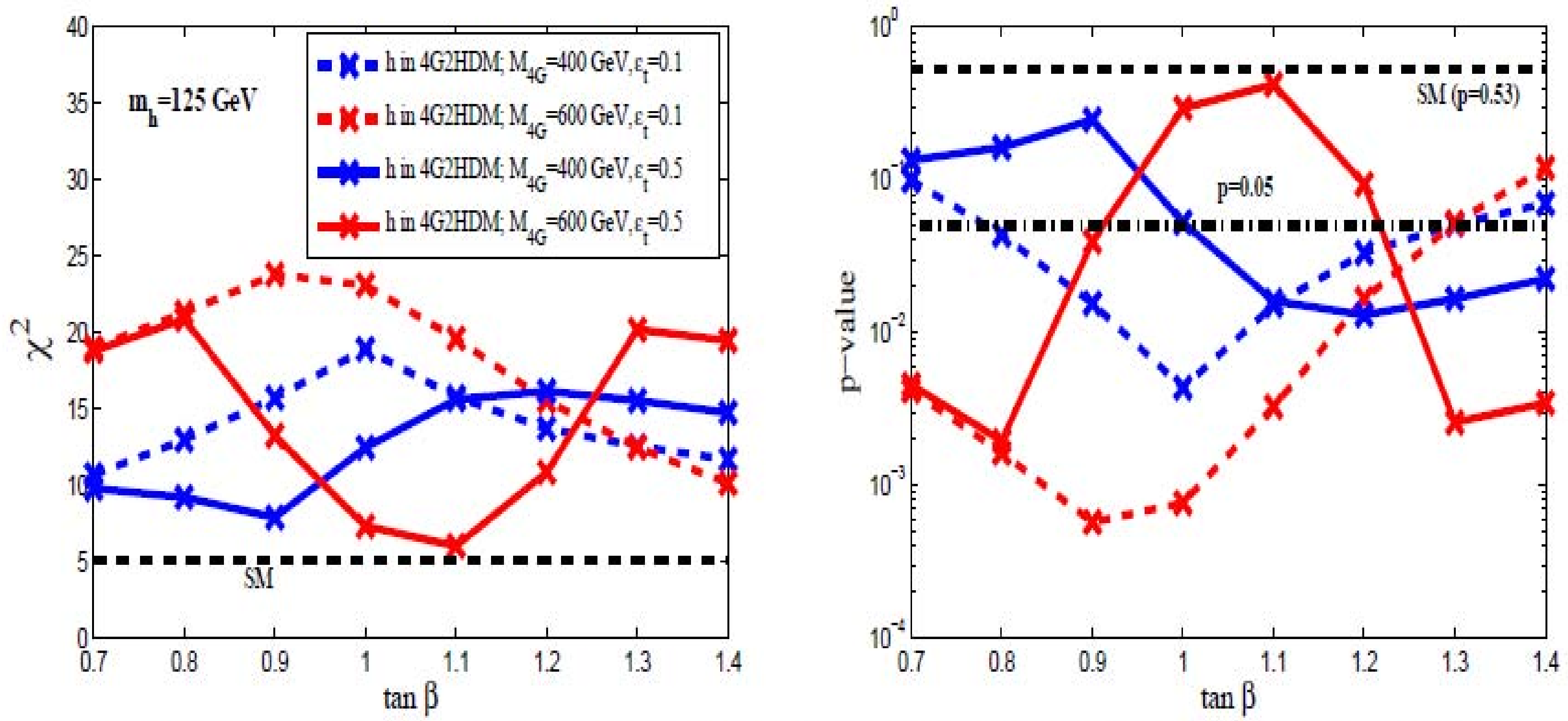


FIG. 3: χ^2 *(left plot) and p-values (right plot), as a function of* $\tan\beta$, *for the lightest 4G2HDM CP-even scalar h, with* $m_h = 125$ *GeV,* $\epsilon_t = 0.1$ *and* 0.5 *and* $M_{4G} \equiv m_{t'} = m_{b'} = m_{l_4} = m_{\nu_4} = 400$ *and* 600 *GeV. The value of the Higgs mixing angle* α *is the one which minimizes* χ^2 *for each value of* $\tan\beta$. *The SM best fit is shown by the horizontal dashed-line and the dash-doted line in the right plot corresponds to* $p = 0.05$ *and serves as a reference line.*

⇒ 4G2HDM with large-ish $t' \leftrightarrow t$ FCNC, $m_{t'}$ 400-600 GeV, $\tan\beta \lesssim 1$, fits as well as SM

Top pair FB asymmetry from strongly coupled 4G quarks

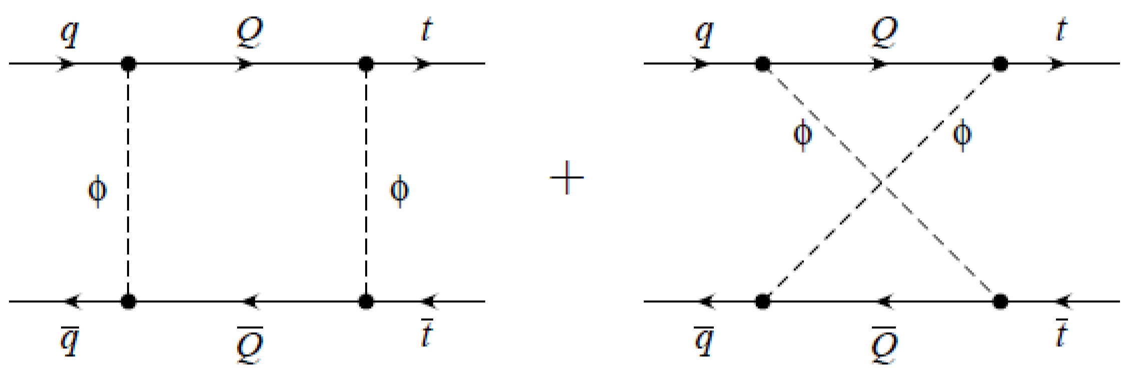
- [Davoudiasl, McElmurry and AS arXiv:1108.1173]
- CDF has been reporting ~2 sigma deviation from SM in the integrated asymm. And in the high invariant top pair mass about 3.5 sigma deviation from SM:
- 0.158 +- 0.075 vs 0.058+-0.009
- For high (>450 GeV), 0.475+-0.114 vs 0.088+-0.013
- NEW (EPS'11) D0 finds similar integrated asymmetery (a bit more significant than CDF); in the high mass region they see some increase but not so pronounced

We consider a simple toy 4G model with [FC] scalars

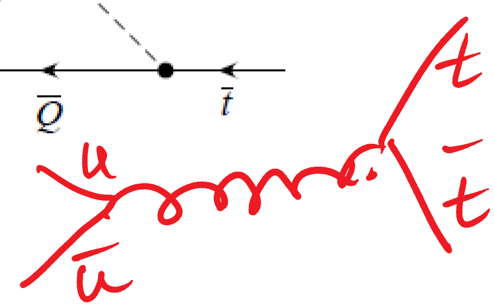
$$\mathcal{L} \supset \lambda_{ut'}\phi^0\bar{u}t' + \lambda_{ub'}\phi^+\bar{u}b' + \lambda_{dt'}\phi^-\bar{d}t'$$

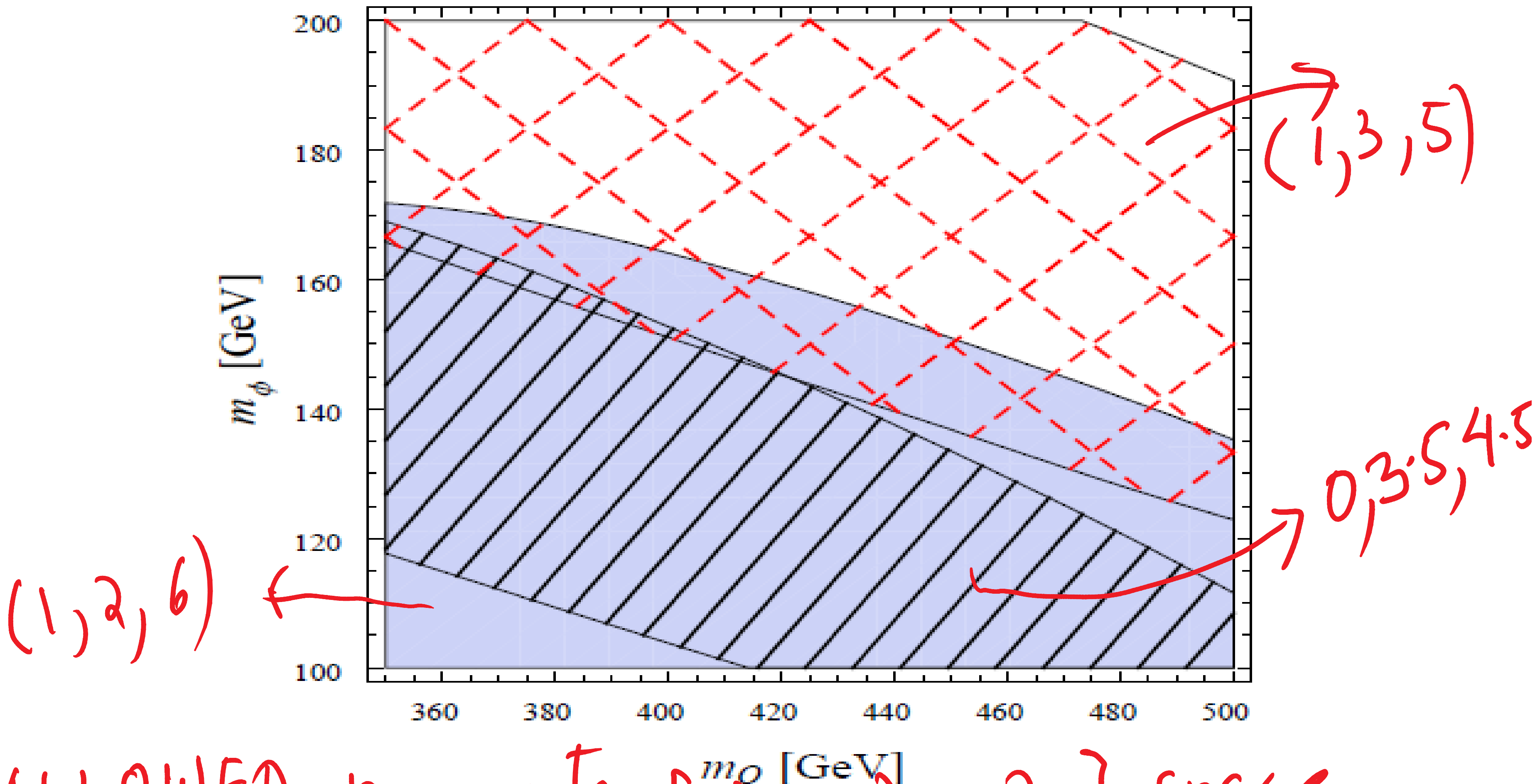
$$+\lambda_{db'}\phi^0\bar{d}b' + \lambda_{tt'}\phi^0\bar{t}t' + \lambda_{tb'}\phi^+\bar{t}b' + \mathrm{H.C.},$$

NOTE $t' \to t\,\phi$ DOMINANT Not $t' \to bW$



ASYMMETRY from inteference with





ALLOWED parameter [λ_u, λ_d, λ_t] space

FIG. 3: Regions of parameter space that yield 2σ agreement with the CDF results [1], as well as agreement with the $t\bar{t}$ total cross section within 30%, for $(\lambda_u, \lambda_d, \lambda_t) = (1, 2, 6)$ (shaded), for $(\lambda_u, \lambda_d, \lambda_t) = (0, 3.5, 4.5)$ (hatched) and for $(\lambda_u, \lambda_d, \lambda_t) = (1, 3, 5)$ (cross-hatched).

Summary & outlook

- ***Inspired by warped (geometric) theory of flavor, it is speculated that the dual 4D theory with strong dynamics needs 4G heavy quarks embedded in 4G2HDM***
- ***toy construction compatible with EWPT as well as recent Higgs data; requires 4G quarks above 400 GeV, smallish tan beta, largish t'<->t, b'<->b FCNC; t' => t h …dominates***
- ***Lattice studies would be useful but appear difficult (under consideration)***

EXTRAS

DM possibilities in 4G models

- **Lee,Liu, AS arXiv: 1105.3490 [c also Volovik hep-ph/0310006]**
- **Link heaviness of $\nu 4$ with new abelian gauge interaction: B – 4 L4 distinguishing it from SM3 neutrinos**
- **Just a heavy $\nu 4$ in SM4 is NOT a viable DMcandidate …conflicts with direct detection bounds[CDMS & XENON} both for Dirac (spin independent) or Majorana (spin dependent) cases [XENON 10]**

The 4G2HDMs

- Yukawa textures can be realized in terms of a Z_2-symmetry:

$$\Phi_\ell \to -\Phi_\ell,\ \Phi_h \to +\Phi_h,\ Q_L \to +Q_L,$$
$$d_R \to -d_R\ (d = d, s),\ u_R \to -u_R\ (u = u, c),$$
$$b_R \to (-1)^{1+\alpha_d} b_R,\ b'_R \to (-1)^{1+\beta_d} b'_R,$$
$$t_R \to (-1)^{1+\alpha_u} t_R,\ t'_R \to (-1)^{1+\beta_u} t'_R.$$

⇒ **Thus, construct several models that have a non-trivial Yukawa structure, possibly associated with the compositeness scenario …**

Heavy Higgs:
quartic coupling also "run" into a similar Landau pole

RGE for λ :

(neglect gauge couplings & top Yukawa + assume all 4th generation Yukawa's are the same)

$$(16\pi^2)\mu\frac{\partial}{\partial\mu}\lambda \cong 24\lambda^2 + \left(32y_4^2\lambda - 16y_4^4\right)\theta(\mu - m_4)$$

Landau pole: $\lambda(\mu = \Lambda_\lambda) = \infty$

$$\Lambda_\lambda = m_{\phi^0}\exp\left[t_{\phi^0}\left\{1 - (1-\zeta_\lambda)^{\frac{1}{\sqrt{7}}}\right\}\right]$$

$$t_{\phi^0} \equiv \ln\frac{\Lambda_y}{m_{\phi^0}} = \ln\frac{m_4}{m_{\phi^0}} + \frac{v^2\pi^2}{2m_4^2},$$

$$\zeta_\lambda \equiv \frac{2\sqrt{7}}{\frac{3m_{\phi^0}^2 t_{\phi^0}}{2\pi^2 v^2} + \sqrt{7} + 1},$$

$$\Lambda_\lambda = 4.3\,(3.7)\ \text{TeV},\ 2.5\,(2.4)\ \text{TeV},\ 2.1\,(2.1)\ \text{TeV}$$

FOR

$$m_{\phi^0} = 500\ \text{GeV},\ 600\ \text{GeV},\ 700\ \text{GeV},$$

New Tev-scale physics: Light Higgs not consistent with SM4

Type II 4G2HDM:

$$(\alpha_d, \beta_d, \alpha_u, \beta_u) = (1,1,1,1) \Rightarrow I_d = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}, I_u = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}$$

$$\mathrm{L}_{\mathrm{Y}}^{\mathrm{quark}} = -\overline{Q}_L^i \phi_l F_{i,j\neq 3,4} \begin{pmatrix} d_R \\ s_R \end{pmatrix} - \overline{Q}_L^i \tilde{\phi}_l G_{i,j\neq 3,4} \begin{pmatrix} u_R \\ c_R \end{pmatrix} - F_{i,j=3,4} \overline{Q}_L^i \phi_h \begin{pmatrix} b_R \\ b'_R \end{pmatrix} - G_{i,j=3,4} \overline{Q}_L^i \tilde{\phi}_h \begin{pmatrix} t_R \\ t'_R \end{pmatrix}$$

Type III 4G2HDM:

$$(\alpha_d, \beta_d, \alpha_u, \beta_u) = (0,1,1,1) \Rightarrow I_d = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 0 & \\ & & & 1 \end{pmatrix}, I_u = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}$$

$$\mathrm{L}_{\mathrm{Y}}^{\mathrm{quark}} = -\overline{Q}_L^i \phi_l F_{i,j\neq 4} \begin{pmatrix} d_R \\ s_R \\ b_R \end{pmatrix} - \overline{Q}_L^i \tilde{\phi}_l G_{i,j\neq 3,4} \begin{pmatrix} u_R \\ c_R \end{pmatrix} - F_{i,4} \overline{Q}_L^i \phi_h b'_R - G_{i,j=3,4} \overline{Q}_L^i \tilde{\phi}_h \begin{pmatrix} t_R \\ t'_R \end{pmatrix}$$

- **expect** $\tan\beta >> 1$

The new Yukawa interactions:

$$\mathcal{L}(hq_iq_j) = \frac{g}{2m_W}\bar{q}_i\left\{m_{q_i}\frac{s_\alpha}{c_\beta}\delta_{ij} - \left(\frac{c_\alpha}{s_\beta}+\frac{s_\alpha}{c_\beta}\right)\cdot\left[m_{q_i}\Sigma^q_{ij}R + m_{q_j}\Sigma^{q\star}_{ji}L\right]\right\}q_jh\ ,$$

$$\mathcal{L}(Hq_iq_j) = \frac{g}{2m_W}\bar{q}_i\left\{-m_{q_i}\frac{c_\alpha}{c_\beta}\delta_{ij} + \left(\frac{c_\alpha}{c_\beta}-\frac{s_\alpha}{s_\beta}\right)\cdot\left[m_{q_i}\Sigma^q_{ij}R + m_{q_j}\Sigma^{q\star}_{ji}L\right]\right\}q_jH\ ,$$

$$\mathcal{L}(Aq_iq_j) = -iI_q\frac{g}{m_W}\bar{q}_i\left\{m_{q_i}\tan\beta\gamma_5\delta_{ij} - (\tan\beta+\cot\beta)\cdot\left[m_{q_i}\Sigma^q_{ij}R - m_{q_j}\Sigma^{q\star}_{ji}L\right]\right\}q_jA\ ,$$

$$\mathcal{L}(H^+u_id_j) = \frac{g}{\sqrt{2}m_W}\bar{u}_i\left\{\left[m_{d_j}\tan\beta\cdot V_{u_id_j} - m_{d_k}(\tan\beta+\cot\beta)\cdot V_{ik}\Sigma^d_{kj}\right]R\right.$$
$$\left.+\left[-m_{u_i}\tan\beta\cdot V_{u_id_j} + m_{u_k}(\tan\beta+\cot\beta)\cdot\Sigma^{u\star}_{ki}V_{kj}\right]L\right\}d_jH^+\ ,$$

Model types I,II,III & FCNC's are encoded in the new Σ mixing matrices, obtained after diagonalizing the quark matrices

The new mixing matrices: Σ^d, Σ^u

$$\Sigma^d_{ij} = \Sigma^d_{ij}(\alpha_d, \beta_d, D_R) = \alpha_d D^\star_{R,3i} D_{R,3j} + \beta_d D^\star_{R,4i} D_{R,4j} \ ,$$
$$\Sigma^u_{ij} = \Sigma^u_{ij}(\alpha_u, \beta_u, U_R) = \alpha_u U^\star_{R,3i} U_{R,3j} + \beta_u U^\star_{R,4i} U_{R,4j} \ ,$$

- **U_R, D_R : rotation (unitary) matrices of right-handed up, down - quarks**
- **physics depends only on 3rd & 4th rows of U_R & D_R**
  (recall, in SM/SM4 and/or “standard” 2HDM setups U_R & D_R are rotated away …)

Construction of Σ - an Anzats:

Inspired by the working assumption of our 4G2HDMs & by the observed flavor pattern in the up and down – quark sectors:

$$D_R = \begin{pmatrix} \cos\theta_{ds} & -\sin\theta_{ds} & \sin\theta_{ds}\cos\theta_{bb'}\epsilon_s^\star & -\cos\theta_{ds}\cos\theta_{bb'}\epsilon_s^\star \\ \sin\theta_{ds} & \cos\theta_{ds} & -\sin\theta_{ds}\sin\theta_{bb'}\epsilon_s^\star e^{-i\delta_b} & \cos\theta_{ds}\sin\theta_{bb'}\epsilon_s^\star e^{-i\delta_b} \\ 0 & \epsilon_s & \cos\theta_{bb'} & -\sin\theta_{bb'}e^{-i\delta_b} \\ 0 & 0 & \sin\theta_{bb'}e^{i\delta_b} & \cos\theta_{bb'} \end{pmatrix}$$

$$U_R = \begin{pmatrix} \cos\theta_{uc} & -\sin\theta_{uc} & \sin\theta_{uc}\cos\theta_{tt'}\epsilon_c^\star & -\cos\theta_{uc}\cos\theta_{tt'}\epsilon_c^\star \\ \sin\theta_{uc} & \cos\theta_{uc} & -\sin\theta_{uc}\sin\theta_{tt'}\epsilon_c^\star e^{-i\delta_t} & \cos\theta_{uc}\sin\theta_{tt'}\epsilon_c^\star e^{-i\delta_t} \\ 0 & \epsilon_c & \cos\theta_{tt'} & -\sin\theta_{tt'}e^{-i\delta_t} \\ 0 & 0 & \sin\theta_{tt'}e^{i\delta_t} & \cos\theta_{tt'} \end{pmatrix}$$

And take: $\epsilon_s = \frac{m_s}{m_b}e^{i\delta_s}$ and $\epsilon_c = \frac{m_c}{m_t}e^{i\delta_c}$, $\epsilon_b = \sin\theta_{bb'}e^{i\delta_b}$, $\epsilon_t = \sin\theta_{tt'}e^{i\delta_t}$

$\sin\theta_{uc} \sim m_u/m_c << 1$ and $\sin\theta_{ds} \sim m_d/m_s << 1$

Similar textures can be found in RS warped models of flavor
Agashe,Perez,Soni PRD71,016002 (2005); Casagrande et al, JHEP0810, 094 (2008); Blanke et al, JHEP0903, 001 (2009)

Construction of Σ - an Anzats (cont.):

$$D_R = \begin{pmatrix} 1 & 0 & 0 & -\epsilon_s^\star\left(1-\frac{|\epsilon_b|^2}{2}\right) \\ 0 & 1 & 0 & \epsilon_s^\star\epsilon_b^\star \\ 0 & \epsilon_s & \left(1-\frac{|\epsilon_b|^2}{2}\right) & -\epsilon_b^\star \\ 0 & 0 & \epsilon_b & \left(1-\frac{|\epsilon_b|^2}{2}\right) \end{pmatrix}, \quad U_R = \begin{pmatrix} 1 & 0 & 0 & -\epsilon_c^\star\left(1-\frac{|\epsilon_t|^2}{2}\right) \\ 0 & 1 & 0 & \epsilon_c^\star\epsilon_t^\star \\ 0 & \epsilon_c & \left(1-\frac{|\epsilon_t|^2}{2}\right) & -\epsilon_t^\star \\ 0 & 0 & \epsilon_t & \left(1-\frac{|\epsilon_t|^2}{2}\right) \end{pmatrix}$$

$$\Sigma^d = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \alpha_d|\epsilon_s|^2 & \alpha_d\epsilon_s^\star\left(1-\frac{|\epsilon_b|^2}{2}\right) & -\alpha_d\epsilon_s^\star\epsilon_b^\star \\ 0 & \alpha_d\epsilon_s\left(1-\frac{|\epsilon_b|^2}{2}\right) & \alpha_d\left(1-\frac{|\epsilon_b|^2}{2}\right)+\beta_d|\epsilon_b|^2 & (\beta_d-\alpha_d)\epsilon_b^\star\left(1-\frac{|\epsilon_b|^2}{2}\right) \\ 0 & -\alpha_d\epsilon_s\epsilon_b & (\beta_d-\alpha_d)\epsilon_b\left(1-\frac{|\epsilon_b|^2}{2}\right) & \alpha_d|\epsilon_b|^2+\beta_d\left(1-\frac{|\epsilon_b|^2}{2}\right) \end{pmatrix}$$

and similarly for Σ^u by replacing $\alpha_d, \beta_d \to \alpha_u, \beta_u$ and $\epsilon_s, \epsilon_b \to \epsilon_c, \epsilon_t$

ε_t & ε_b free parameters with a natural choice:

$$|\epsilon_t| = \sin\theta_{tt'} \sim m_t/m_{t'}$$
$$|\epsilon_b| = \sin\theta_{bb'} \sim m_b/m_{b'}$$

e.g., Σ in the 4G2HDM of type I:

$$\Sigma^d \simeq \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & |\epsilon_b|^2 & \epsilon_b^\star \\ 0 & 0 & \epsilon_b & \left(1 - \frac{|\epsilon_b|^2}{2}\right) \end{pmatrix} \; , \; \Sigma^u \simeq \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & |\epsilon_t|^2 & \epsilon_t^\star \\ 0 & 0 & \epsilon_t & \left(1 - \frac{|\epsilon_t|^2}{2}\right) \end{pmatrix}$$

Leads to interesting patterns (in flavor space) of the Higgs-quarks Yukawa's: potentially large tree-level t' → t and b' → b FCNC transitions, with no other tree-level FCNC

– "safe" from dangerous FCNC effects in light-meson systems ...