On Partial Compositeness and the CP asymmetry in D-meson decays

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FERMILAB

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Outline

- Introduction
- Partial Compositeness (PC)
- PC in Composite Higgs Models
  - Lepton Sector?
- PC in the MSSM
  - Flavorful SUSY
  - R-Parity Violation
- Conclusions

Introduction

...so far...

- **A “SM-Higgs” at ~125 GeV!**

- **No Evidence of New Physics**
  “Big Questions” left unanswered
  (e.g. What about *Naturalness*?! What about *Flavor*? …)

Yet…. LHCb and CDF found a tantalizing result...:

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}.$$

$$\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-} = (-0.67 \pm 0.16)\%.$$

This result is larger than the naïve SM expectation by ~5-10 Grossman, Kagan, Nir (2006)

Now, two obvious possibilities:

Naïve SM expectation is wrong

Golden, Grinstein (1989)
Brod, Kagan, Zupan (2011)
Brod, Grossman, Kagan, Zupan (2011)
....

New Physics is present (if so, what kind?)

Grossman, Kagan, Nir (2006)
Isidori, Kamenik, Ligeti (2011)
Altmannshofer, Primulando, Yu, Yu (2012)
....

Needless to say...

I will be optimistic!!!

- **Perhaps this is a first sign of New Physics?!**

  (if the NP is “unnatural”, then it may first appear in flavor observables)

- **Perhaps this can teach us something about Flavor?!**

  (the mechanism controlling flavor violation within the SM might be the same as the one within the NP)

Plan:

Let’s focus on a very promising model of Flavor:

Partial Compositeness:

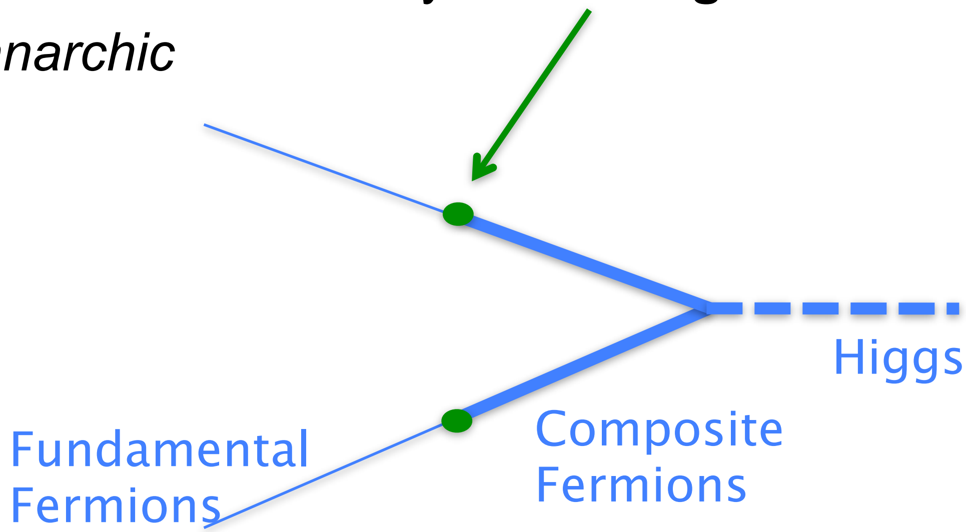
1) Can it be responsible for the D-meson CP Asymmetry?
2) What are the phenomenological signatures?

D. B. Kaplan (1991)

Partial Compositeness

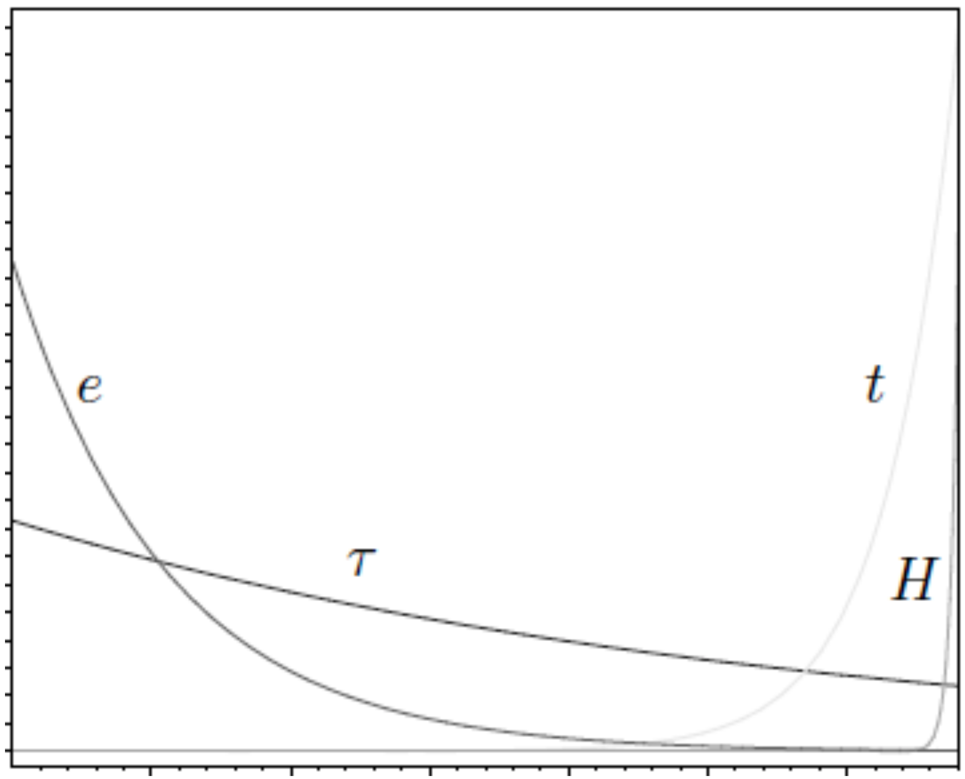
The SM fermions **mix with composite operators of a Flavor Sector** that directly couples to the Higgs Sector (and thus emerge as partially composite states)

The SM masses are controlled by the **mixing** while the Flavor Sector can be flavor *anarchic*



Wave-function localization in a Randall-Sundrum background is the 5D picture of Partial Compositeness:

UV–brane



IR–brane

(technical 4D view)

Assume the dominant interactions (flavor-violating) between the SM fermions and the Flavor Sector arise at some high energy scale Λ^{cutoff} from

Composites of the Flavor Sector

$$\mathcal{L}_{\Lambda^{\text{cutoff}}} = \lambda_L f_L \mathcal{O}_R + \lambda_R f_R \mathcal{O}_L + \text{h.c.}$$

Mixing

(technical 4D view)

- ✓ at the scale $m_\rho << \Lambda^{\text{cutoff}}$ where the Flavor Sector confines the mixing parameters can naturally be hierarchical because of RG flow effects

$$\lambda(\mu) \sim \lambda(\Lambda) \left(\frac{\mu}{\Lambda^{\text{cutoff}}}\right)^{\Delta - 5/2}$$

Scaling dimension of $\mathcal{O}$

Strong Dynamics =>
Natural Hierarchy

- ✓ the Yukawa coupling will also be hierarchical, and scale as (see RS)

$$Y \propto \lambda_L(\mu)\lambda_R(\mu)$$

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Minimal Realizations

("**Randall-Sundrum**")
The Higgs is a Composite of the Flavor Sector and
m_ρ = few TeV

SUSY

$m_\rho >> \text{TeV}$

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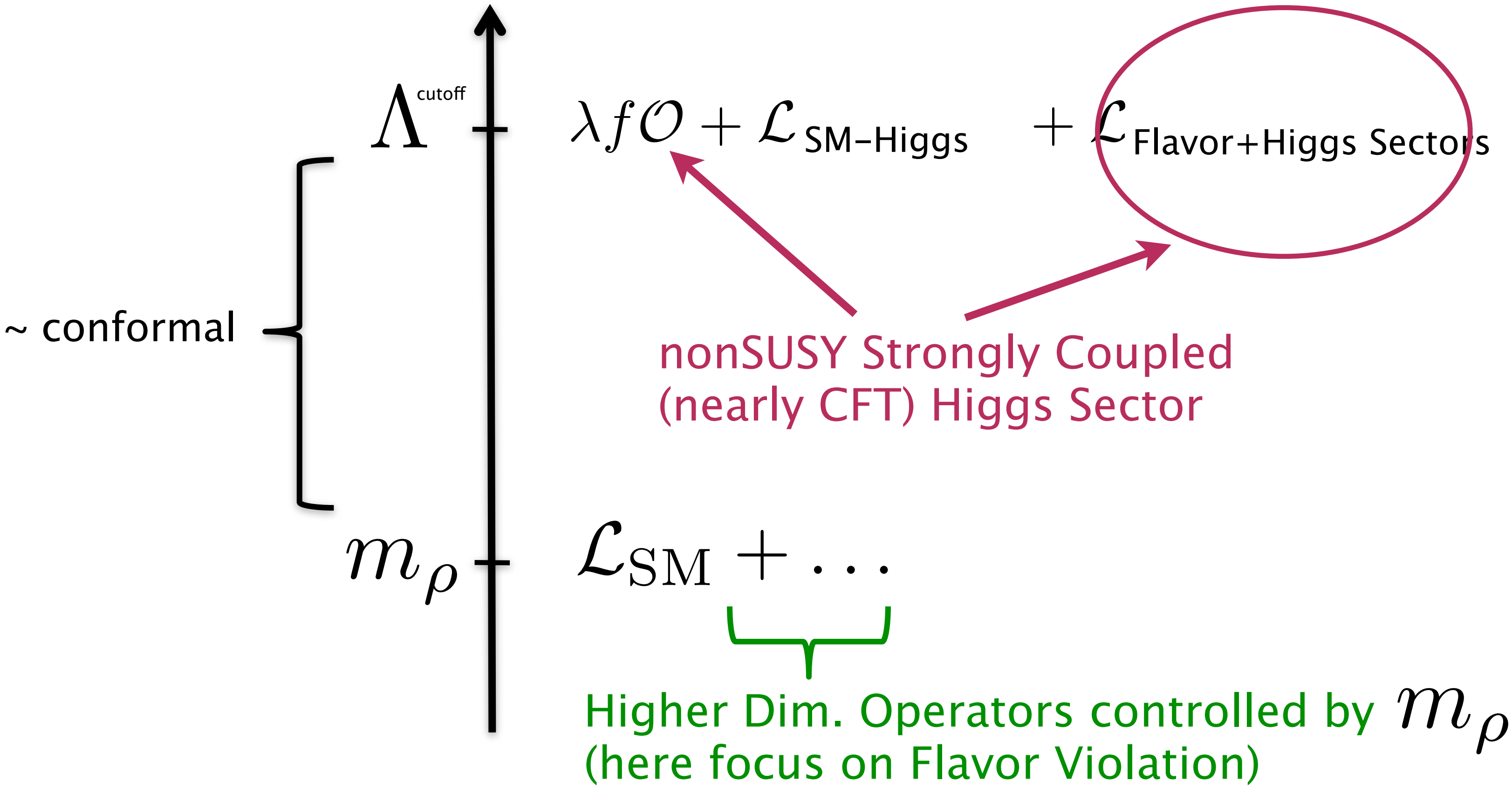
Composite Higgs Models (nonSUSY)



Use Naïve Dimensional Analysis to estimate the Wilson Coefficients (could focus on RS, but that would be a particular limit) :

- 1 coupling $g_\rho \lesssim 4\pi$
- 1 mass m_ρ

$$\mathcal{L}_{\rm NDA} = \frac{m_\rho^4}{g_\rho^2}\left[\mathcal{L}^{(0)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \frac{g_\rho^2}{16\pi^2}\mathcal{L}^{(1)}\left(\frac{g_\rho \epsilon_i^a f_i^a}{m_\rho^{3/2}}, \frac{D_\mu}{m_\rho}, \frac{g_\rho H}{m_\rho}\right) + \dots\right]$$

For convenience I introduced a measure of the compositeness of the SM fields $\epsilon = \frac{\lambda(m_\rho)}{g_\rho}$

$\epsilon = 1$ If the fermion is part of the Flavor Dynamics

($\epsilon_H = 1$ as anticipated above)

Yukawa

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u, \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d.$$

Natural Explanation of the SM masses! $m_i^{u,d} \sim g_\rho \epsilon_i^q \epsilon_i^{u,d} v$

Natural Explanation of the CKM matrix! 2 free parameters (e.g. g_ρ and ϵ_3^u)

Result a la Froggatt-Nielsen

$$(L_u)_{ij} \sim (L_d)_{ij} \sim \min\left(\frac{\epsilon_i^q}{\epsilon_j^q}, \frac{\epsilon_j^q}{\epsilon_i^q}\right)$$

$$(R_{u,d})_{ij} \sim \min\left(\frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}}, \frac{\epsilon_j^{u,d}}{\epsilon_i^{u,d}}\right)$$

$$V_{CKM} = L_d^\dagger L_u \sim L_{u,d}$$

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \qquad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \qquad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3$$

Flavor Violation

$\epsilon_i^a \epsilon_j^b g_\rho$ is fixed...

$$\mathcal{L}_{\Delta F=1} \sim \epsilon_i^a \epsilon_j^b g_\rho \frac{v}{m_\rho^2} \frac{g_\rho^2}{(4\pi)^2} \overline{f}_i^a \sigma_{\mu\nu} g_{\rm SM} F_{\rm SM}^{\mu\nu} f_j^b$$

$$+ \epsilon_i^a \epsilon_j^b \frac{g_\rho^2}{m_\rho^2} \overline{f}_i^a \gamma^\mu f_j^b i H^\dagger \overleftrightarrow{D}_\mu H$$

$$\mathcal{L}_{\Delta F=2} \sim \epsilon_i^a \epsilon_j^b \epsilon_k^c \epsilon_l^d \frac{g_\rho^2}{m_\rho^2} \overline{f}_i^a \gamma^\mu f_j^b \overline{f}_k^c \gamma_\mu f_l^d$$

$\overline{f}_i^a \gamma_\mu f_j^b D_\nu F_{\rm SM}^{\mu\nu}$ **Suppressed!**

$\overline{f}_i^a H f_j^b H^\dagger H$ **Dangerous!** (usually ignored in RS...)

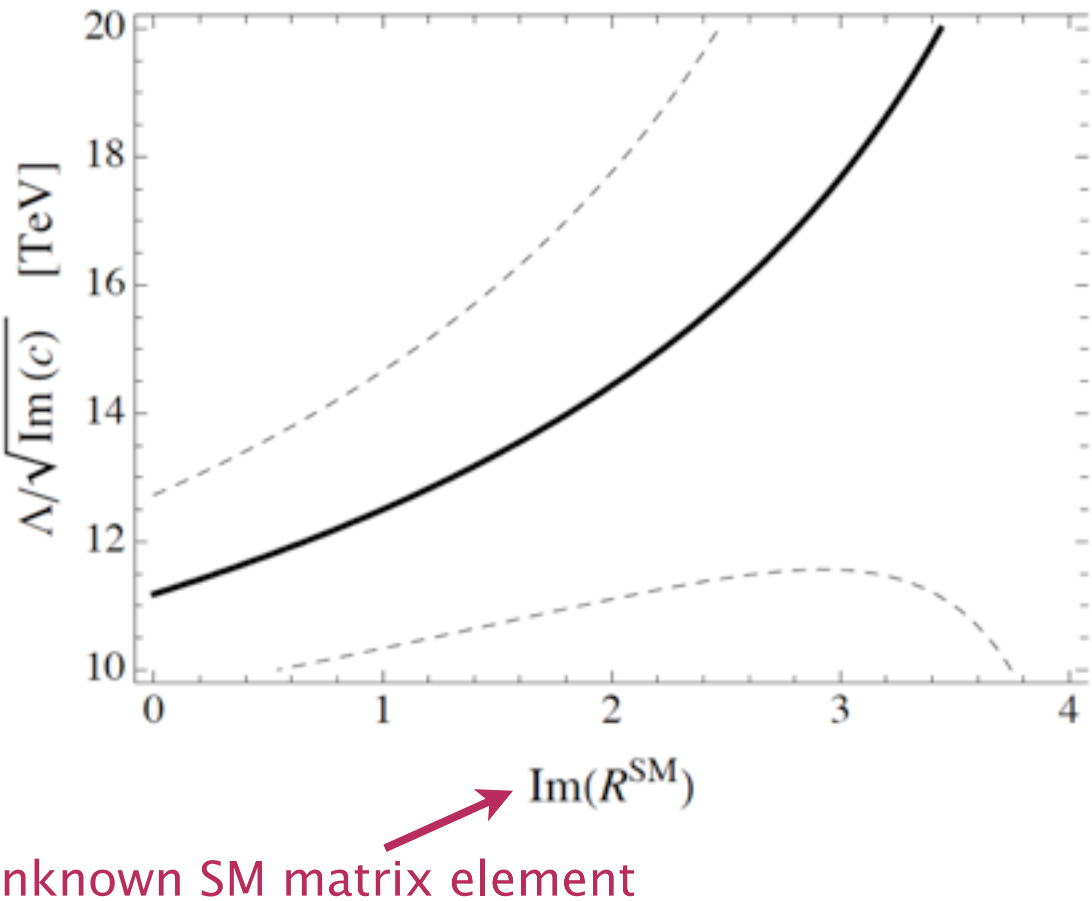
can avoid new sources of FV if the Higgs is a PNGB

Agashe, Contino (2009)

CP Asymmetry

Dominant contribution from the **chromo-electric** dipole operators

$$\Lambda = \frac{4\pi}{g_\rho} m_\rho .$$



Operator $\Delta F = 2$	$\mathrm{Re}(c) \times (4\pi/g_\rho)^2$	$\mathrm{Im}(c) \times (4\pi/g_\rho)^2$	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	$6 \times 10^2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	$2 \left(\frac{\epsilon_3^u}{\epsilon_3^q}\right)^2$	Δm_K; ϵ_K [44] [45]
$(\bar{s}_R d_L)^2$	500	2	"
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	2×10^2	0.6	"
Operator $\Delta F = 1$	**$\mathrm{Re}(c)$**	**$\mathrm{Im}(c)$**	**Observables**
$\overline{s_R} \sigma^{\mu\nu} e F_{\mu\nu} b_L$	1		$B \to X_s$ [46]
$\overline{s_L} \sigma^{\mu\nu} e F_{\mu\nu} b_R$	2	9	"
$\overline{s_R} \sigma^{\mu\nu} g_s G_{\mu\nu} d_L$	-	0.4	$K \to 2\pi$; ϵ'/ϵ [47]
$\overline{s_L} \sigma^{\mu\nu} g_s G_{\mu\nu} d_R$	-	0.4	"
$\bar{s}_L \gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$30 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$		$B_s \to \mu^+ \mu^-$ [48]
$\bar{s}_L \gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$6 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$10 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$	$B \to X_s \ell^+ \ell^-$ [46]
Operator $\Delta F = 0$	**$\mathrm{Re}(c)$**	**$\mathrm{Im}(c)$**	**Observables**
$\bar{d} \sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$	-	3×10^{-2}	neutron EDM [49] [50]
$\bar{u} \sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$	-	0.3	
$\bar{d} \sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$	-	4×10^{-2}	
$\bar{u} \sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$	-	0.2	
$\bar{b}_L \gamma^\mu b_L\, H^\dagger i \overleftrightarrow{D}_\mu H$	$5 \left(\frac{g_\rho}{4\pi}\right)^2 (\epsilon_3^u)^2$		$Z \to b\bar{b}$ [51]

not excluded,
given the uncertainties

C~1 by NDA m_ρ ~ 10 TeV g_ρ ~ 4π

LEPTON SECTOR !!!!

Leptonic Operator	Re(c)	Im(c)	Observables
$\bar{e}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	-	8×10^{-3}	electron EDM [52]
$\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}e_{L,R}$	4×10^{-3}		$\mu \to e\gamma$ [53]
$\bar{e}\gamma^{\mu}\mu_{L,R}H^{\dagger}i\overleftrightarrow{D}_{\mu}H$	$1.5\left(\frac{g_\rho}{4\pi}\right)\frac{\epsilon_3^e}{\epsilon_3^\ell}$		$\mu(Au) \to e(Au)$ [54]

If this was the case then the model would be clearly ruled out (no hadronic uncertainties to blame!)

This problem is easily solved by relaxing an unnecessary assumption....

LV (2012)

(Parenthesis...)

Minimal Realizations

(NonSUSY)

~~The Higgs is a Composite of the Flavor Sector and~~

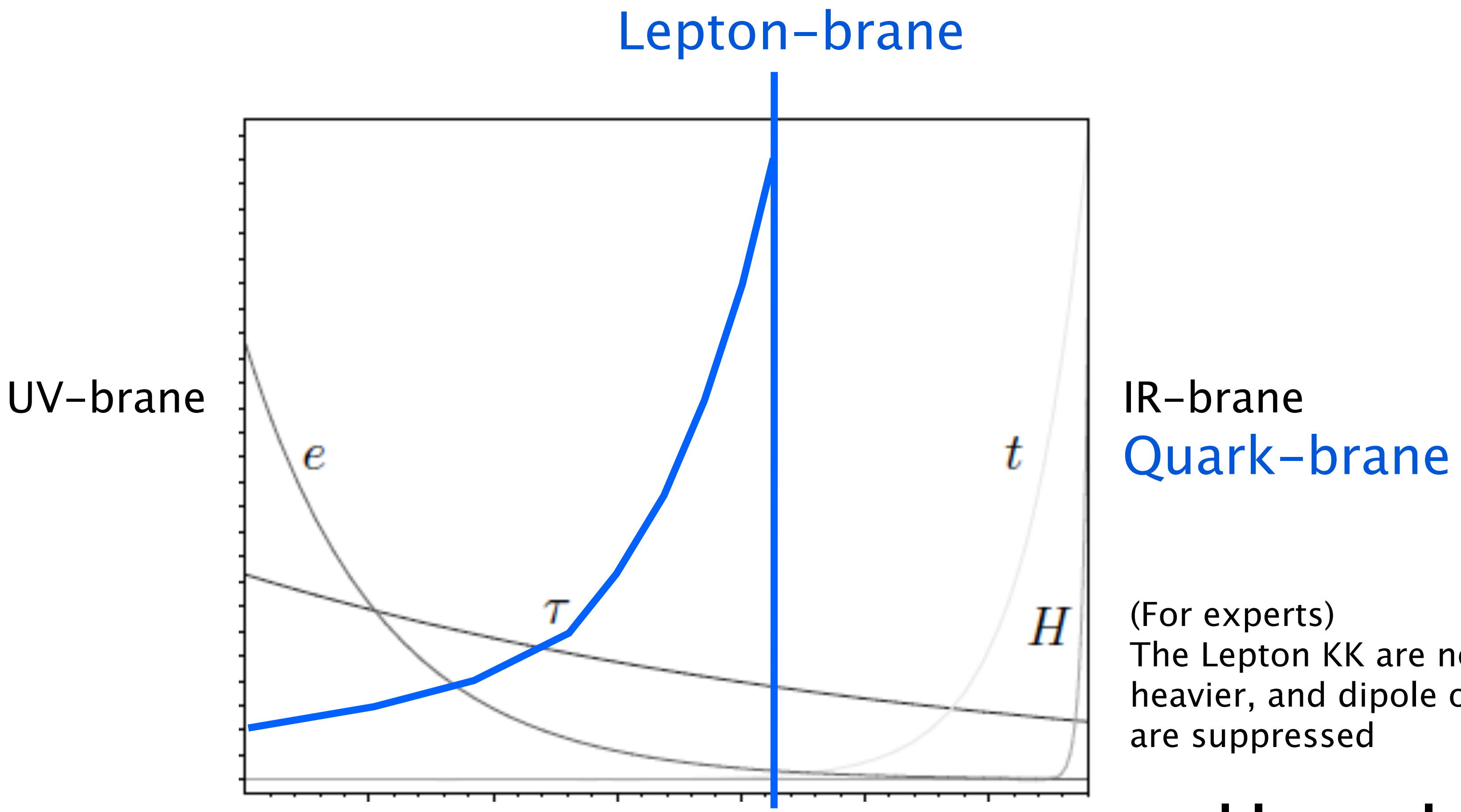
$m_\rho =$ few TeV

SUSY

$m_\rho >>$ TeV

The Higgs and Flavor sectors need not be the same!

(...Parenthesis) If we allow the Higgs and Flavor sectors to be 2 distinct dynamics, we basically end up with the following 5D picture



(For experts)
The Lepton KK are now heavier, and dipole operators are suppressed

problem solved
no new symmetries invoked!

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In Conclusion (Composite Higgs)

1) **The NP scale required to saturate the CPV in D decay is too large for direct production...**

   tuning of O(0.1%-1%): why not?

2) **The model is marginally consistent with all bounds. The neutron EDM provides the most robust constraint (signature?!)** ϵ_K, ϵ'/ϵ as well as $B \to X_s\gamma$,

3) Bounds from the Lepton sector can be avoided

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Minimal Realizations

("**Randall-Sundrum**")
The Higgs is a Composite of the Flavor Sector and
$m_\rho =$ few TeV

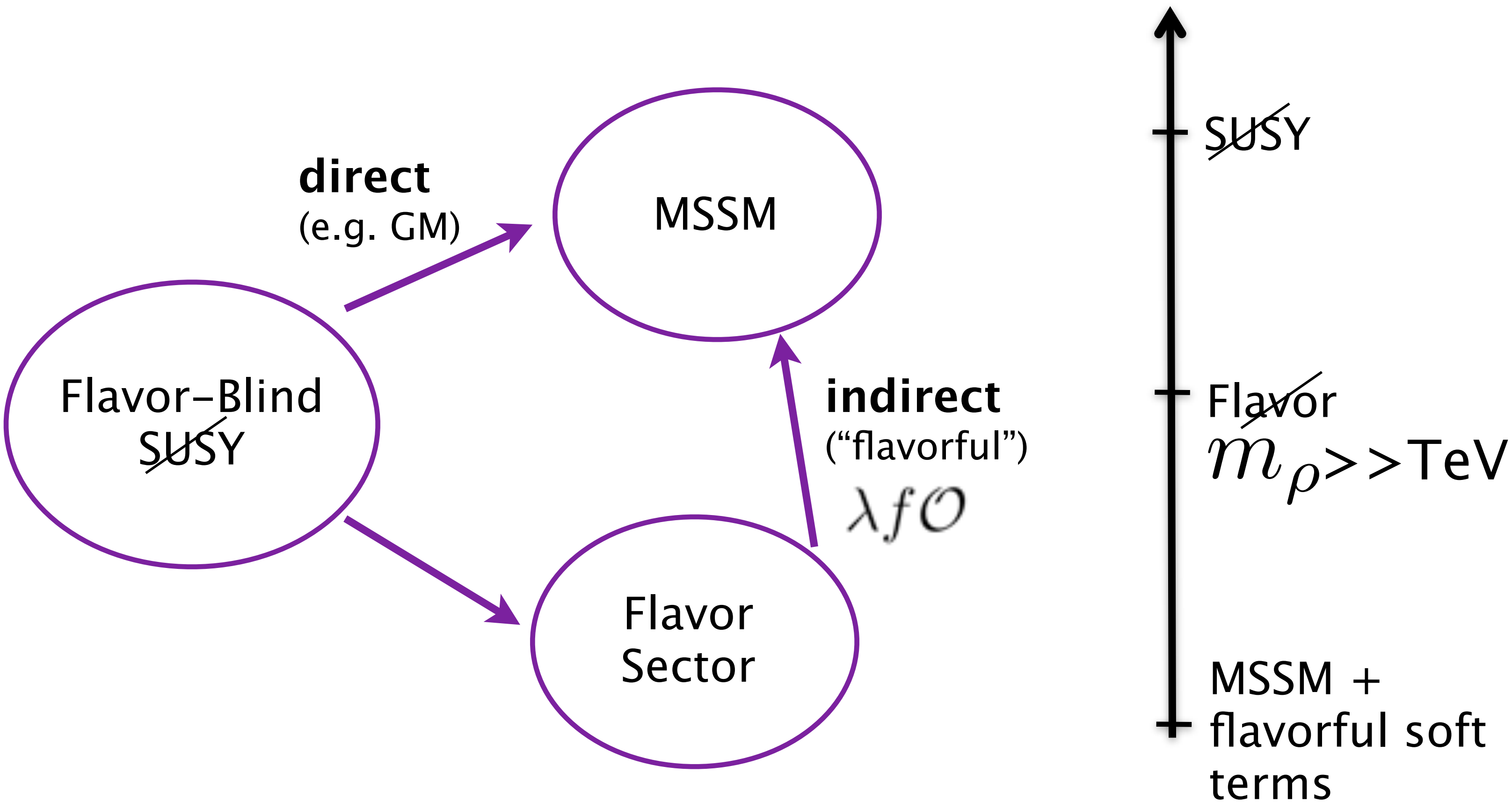
SUSY

$m_\rho >>$ TeV

Partial Compositeness in SUSY

leads to natural flavor hierarchy
plus flavor-violating soft terms

see also Nomura, Papucci, Stolarski (2008)
(flavorful SUSY)



Yukawa (as before)

$$(Y_u)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^u, \qquad (Y_d)_{ij} \sim g_\rho \epsilon_i^q \epsilon_j^d.$$

Soft Terms (realize the “disoriented A-term scenario” of Giudice, Isidori, Paradisi)

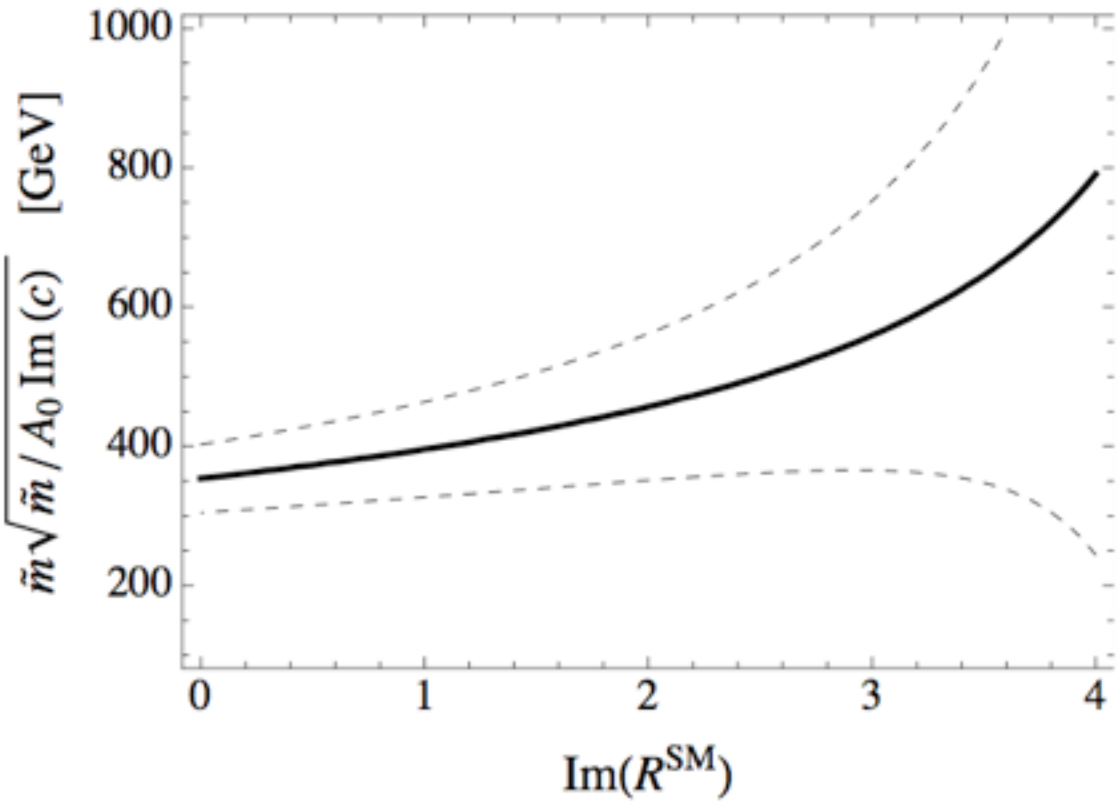
universal (GM)

$$\begin{aligned} (m_a^2)_{ij} &\sim \tilde{m}_a^2 \delta_{ij} + \epsilon_i^a \epsilon_j^a c_{ij}^a \tilde{m}_0^2, \quad a = q, u, d, \\ A_{ij}^{u,d} &\sim g_\rho \epsilon_i^q \epsilon_j^{u,d} d_{ij}^{u,d} A_0, \quad (A_0 \propto \tilde{m}_0) \end{aligned}$$

O(1) numbers

CP Asymmetry

Dominant contribution from the **chromo-electric** dipole operators



CP Asymmetry

degenerate spectrum...

$$\mathrm{Im}(c^u_{12})_{LR} \times \frac{A_0}{\tilde{m}} \times \left(\frac{1\ \mathrm{TeV}}{\tilde{m}}\right)^2 \sim 8$$

1) Take $\tilde{m}$ = 1 TeV and either large A-term (color breaking) or an accidentally large $\mathrm{Im}(c^u_{12})_{LR}$

2) Take $A_0/\tilde{m} < 3$ and $\tilde{m}$ < 600 GeV (RPV?)

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In Conclusion (SUSY)

1) **Large A-terms required to saturate CPV in D decay** (125 GeV Higgs?!) **and new physics around the corner** (as opposed to CH models)

2) **The model is marginally consistent with all bounds. The neutron EDM provides the most robust constraint (signature?!)** (basically as in CH models)

3) (New effects in electron EDM and $\mu \to e\gamma$ unless sleptons are much heavier than the squarks)

Partial Compositeness as a nice organizing principle for

R-Parity Violation

$$W_{\not{B}} = \frac{1}{2}\lambda''_{ijk} u_i d_j d_k,$$
$$W_{\not{L}} = \frac{1}{2}\lambda_{ijk} L_i L_j e_k + \lambda'_{ijk} L_i Q_j d_k + \mu_i L_i H_u$$

The same rules used above give

$$\lambda''_{ijk} \sim 2 g_{\not{B}} \epsilon^u_i \epsilon^d_j \epsilon^d_k \qquad \lambda_{ijk} \sim 2 g_{\not{L}} \epsilon^\ell_i \epsilon^\ell_j \epsilon^e_k \qquad \lambda'_{ijk} \sim g_{\not{L}} \epsilon^\ell_i \epsilon^q_j \epsilon^d_k \qquad \mu_i \sim \frac{g_{\not{L}}}{g_\rho} \epsilon^\ell_i \mu,$$

We introduced separate L and R couplings

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- Proton decay requires $g_{\not L}\, g_{\not B} \ll g_\rho^2.$

- Neutrino/Neutralino mixing requires $g_{\not L} \ll g_\rho.$

- **B-violation** **(mainly dinucleon decay and neutron-antineutron oscillation) allow**

$$g_{\not B} \sim g_\rho$$

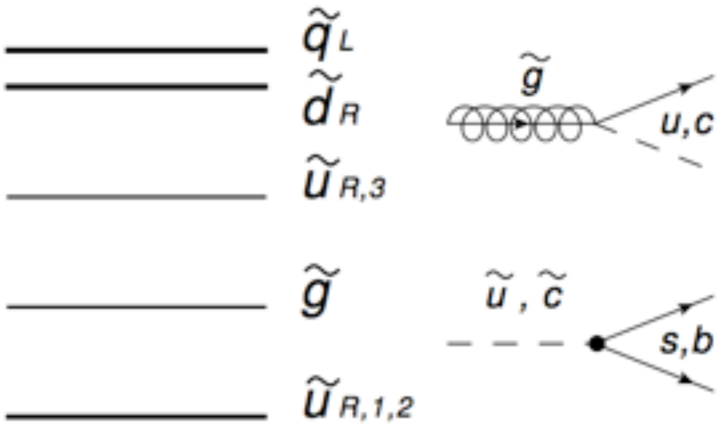
$$\lambda''_{ijk} \sim \left(\frac{g_{\not B}}{4\pi}\right)\left(\frac{\tan\beta}{3}\right)^2\left(\frac{\epsilon_3^u}{0.5}\right)^3 (\equiv \lambda_0) \times \begin{cases} 2.7\times 10^{-3} & (tbs) \\ 0.6\times 10^{-3} & (tbd) \\ 1.7\times 10^{-4} & (cbs) \\ 0.5\times 10^{-4} & (cbd) \\ 1.7\times 10^{-6} & (ubs) \\ 0.4\times 10^{-6} & (ubd) \end{cases}$$

prompt decay

Phenomenology

Example of an "unusual" signature (no MET, no isolated leptons, no displaced vertices)

B-violating RPV and RH up or charm squarks LSP:



(roughly)
>500 GeV from 3j resonances
>400 GeV from 4j events

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Conclusions

- Partial Compositeness provides a natural explanation of the SM Flavor hierarchy (in SUSY and nonSUSY models)

- PC can saturate the large CPV in D decay. It predicts:
  - **NP effects in neutron EDM**
  - **large NP scale** for Composite Higgs models
    (tuning 1% or less in minimal models and no direct production on NP)
  - **low NP scale and large A-terms** for SUSY
    (rich phenomenology)

- PC can be an efficient organizing principle for Baryonic RPV

THANK YOU!