Flavor physics hints for a natural Higgs

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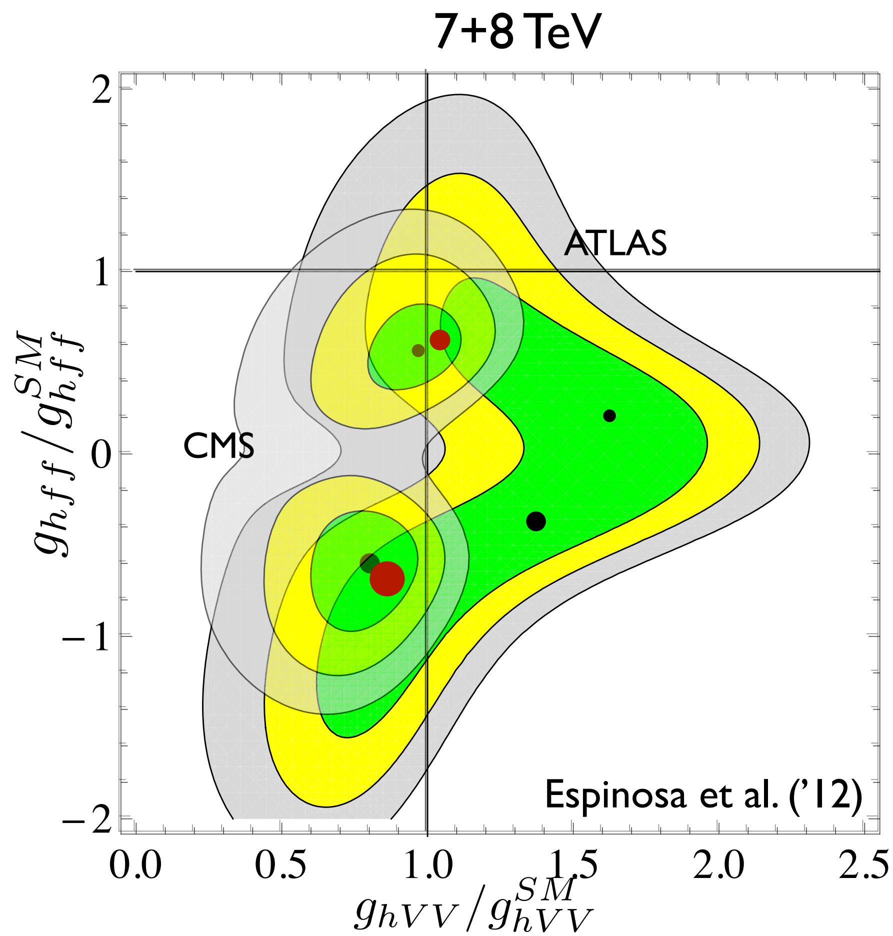
Duccio Pappadopulo

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

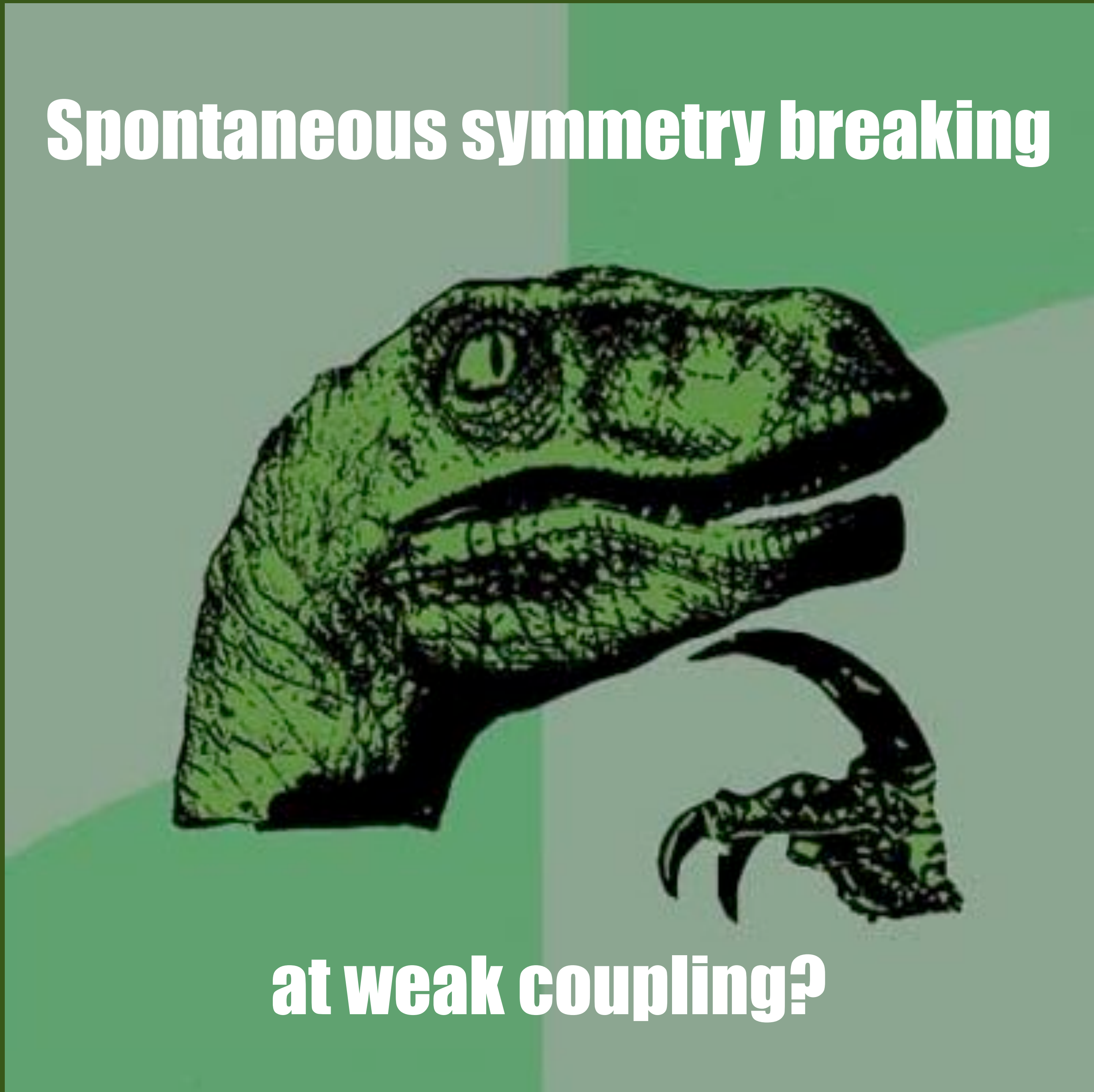
A Higgs boson has been discovered,



CMS: m_h=125 GeV

ATLAS: m_h=126.5 GeV

and it is weirdly SM like. Too early to be excited.


Spontaneous symmetry breaking
at weak coupling?

Two (non anthropic) solution:

Compositness

Supersymmetry

In both cases the point $m_h = 0$ is made special by symmetries and the weak scale is generated dynamically.

Both examples predict new states around the weak scale and they have to face the extraordinary agreement of the SM with low energy experiments.

Flavor problem

Any hint?

Direct CP asymmetry measurement in D decays:

$$\text{LHCb: } \Delta A_{CP}^{\text{dir}} = -(0.82 \pm 0.21 \pm 0.11)\%$$

$$\text{CDF: } \Delta A_{CP}^{\text{dir}} = -(0.62 \pm 0.21 \pm 0.10)\%$$

$$\text{Avg.: } \Delta A_{CP}^{\text{dir}} = -(0.64 \pm 0.218)\%$$

Naive expectation (SU(3) symmetry): $\Delta A_{CP}^{\text{dir}} \approx 4 \frac{V_{cb} V_{ub}}{V_{cs} V_{us}} \frac{P}{T} \approx 4\lambda^4 \frac{\alpha_s(m_c)}{\pi} \approx 0.1\%$

A SM explanation cannot be excluded (non-nominal SU(3) breaking, large penguins...)

If new physics, it can be explained by

$$O(1) \times \frac{\lambda m_c}{(10\text{TeV})^2} \bar{u}_L \sigma^{\mu\nu} \cdot g_s G_{\mu\nu} c_R$$

consistently with $\Delta S = 1$ e $\Delta C = 2$ in the low energy theory. (Isidori et al. ('11))

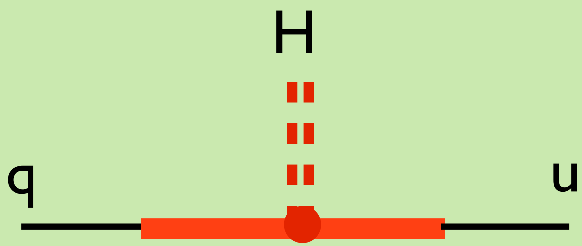
Watch out, as usual non trivial flavor structure is required for $\Delta S = 2$

Partial compositness Kaplan ('91)

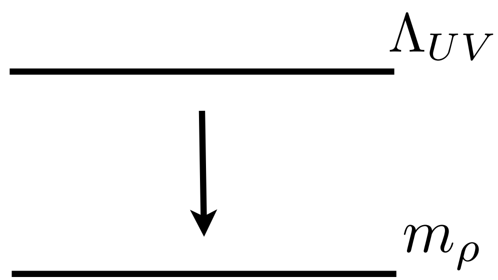
Partial compositness is introduced in composite Higgs models to generate fermion masses and decouple the technicolor flavor problem without reintroducing a hierarchy. Elementary fermions couple to the strong sector via bilinears.

$$\mathcal{L}_{PC} = \lambda_q \bar{q}_L O_{qR} + \lambda_u \bar{u}_R O_{uL} + \lambda_d \bar{d}_R O_{dL} + \text{h.c.}$$

3x3 matrices



Yukawas: $y = \dfrac{\lambda_L \lambda_R}{g_\rho} \equiv g_\rho \epsilon_L \epsilon_R$



Quark sector : CKM + quark masses leave 2 free parameters (+O(1))

$$\frac{\epsilon_1^q}{\epsilon_2^q} \sim \lambda \quad \frac{\epsilon_2^q}{\epsilon_3^q} \sim \lambda^2 \quad \frac{\epsilon_1^q}{\epsilon_3^q} \sim \lambda^3 \qquad \frac{\epsilon_i^{u,d}}{\epsilon_j^{u,d}} = \frac{y_i^{u,d}}{y_j^{u,d}} \frac{\epsilon_j^q}{\epsilon_i^q}.$$

$$g_\rho, \quad \epsilon_3^{q,u}$$
$$\epsilon_3^q, \quad \epsilon_3^u$$

Lepton sector : more freedom due to anarchic PMNS + small neutrino masses

In general one would expect $V_{ij}^{PMNS} \sim \min\left(\frac{\epsilon_i^\ell}{\epsilon_j^\ell}, \frac{\epsilon_j^\ell}{\epsilon_i^\ell}\right) \Rightarrow \epsilon_i^\ell \approx 1, \quad \frac{\epsilon_i^e}{\epsilon_j^e} \sim \frac{m_i^e}{m_j^e}$

It may be that the ϵs which are necessary for neutrino masses are too small (eg. large operator dimension) so that the dominant operators are

$$O(1)_{ij}\ell_i\ell_j\mathcal{O}_{HH} \qquad O(1)_{ij}\ell_i\nu_j\mathcal{O}_H \qquad \Lambda_{UV}$$

Majorana | Dirac

These generate anarchic neutrino masses and an anarchic rotation to the neutrino mass basis which is enough to obtain an anarchic PMNS matrix. Charged leptons still described by partial compositness

Taking: $\frac{\epsilon_i^\ell}{\epsilon_j^\ell} \sim \frac{\epsilon_i^e}{\epsilon_j^e} \sim \sqrt{\frac{m_i^e}{m_j^e}}$ minimizes the constraint from LFV

Effective lagrangian at m_ρ

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

We expect the chromomagnetic operator to come from here

$$\mathcal{L}_{\Delta F=1} \sim \epsilon_i^a \epsilon_j^b g_\rho \frac{v}{m_\rho^2} \frac{g_\rho^2}{(4\pi)^2} \bar{f}_i^a \sigma_{\mu\nu} g_{\rm SM} F_{\rm SM}^{\mu\nu} f_j^b \qquad \Lambda \equiv \frac{4\pi m_\rho}{g_\rho} \approx 10 \text{TeV} \, (\text{LHCb})$$

Large g_ρ suppresses four fermion operators

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

Chromomagnetic ops. can be controlled by a chiral symmetry ('Higgs' coupling to fermion) while four fermion ops. are typically generated by tree lever vector exchange. Taking $g_\psi < g_\rho$ flavor worsen, **Higgs mass gets better (smaller)**.

Tuning Higgs VEV: $\boxed{\frac{v^2}{f^2} \approx 10\%}$ + quartic coupling tuning!

Analysis of flavor bounds

$g_\rho \approx 4\pi \; m_\rho = 10\,\mathrm{TeV}$

Operators $\Delta F = 2$	Re c	Im c	Observables
$(\bar{s}_R d_L)^2$	500	2	$\Delta m_K, \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	200	0.6	"
$(\bar{c}_L u_R)^2$	30	6	Δm_D, $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	$5\ (\epsilon_3^u/\epsilon_3^q)^2$	$2\ (\epsilon_3^u/\epsilon_3^q)^2$	Δm_{B_d}, $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	$6\ (\epsilon_3^u/\epsilon_3^q)^2$		Δm_{B_s}
Operators $\Delta F = 1$	**Re c**	**Im c**	**Observables**
$\overline{s_R}\sigma^{\mu\nu} e F_{\mu\nu} b_L$	1		$B \to X_s$
$\overline{s_L}\sigma^{\mu\nu} e F_{\mu\nu} b_R$	2	9	"
$\overline{s_R}\sigma^{\mu\nu} g_s G_{\mu\nu} d_L$	-	0.4	$K \to 2\pi$; ϵ'/ϵ
$\overline{s_L}\sigma^{\mu\nu} g_s G_{\mu\nu} d_R$	-	0.4	"
Operators $\Delta F = 0$	**Re c**	**Im c**	**Observables**
$\bar{d}\sigma^{\mu\nu} e F_{\mu\nu} d_{L,R}$	-	0.03	neutron EDM
$\bar{u}\sigma^{\mu\nu} e F_{\mu\nu} u_{L,R}$	-	0.3	"
$\bar{d}\sigma^{\mu\nu} g_s G_{\mu\nu} d_{L,R}$	-	0.04	"
$\bar{u}\sigma^{\mu\nu} g_s G_{\mu\nu} u_{L,R}$	-	0.2	"
Leptonic Operators	**Re c**	**Im c**	**Observables**
$\bar{e}\sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$	-	0.05	electron EDM
$\bar{\mu}\sigma^{\mu\nu} e F_{\mu\nu} e_{L,R}$	4×10^{-3}		$\mu \to e\gamma$
$\bar{e}\gamma^\mu \mu_{L,R}\, H^\dagger i \overleftrightarrow{D}_\mu H$	$1.5(\epsilon_3^e/\epsilon_3^\ell)$		$\mu(Au) \to e(Au)$

Observable effects $K^+ \to \pi^+ \nu\bar{\nu}$

Also $B_s \to \mu^+\mu^-$, $B \to X_s \ell^+\ell^-$

Up chromoelectric dipole is expected to be quite solid. Mild tension, O(1) uncertainty on matrix elements.

Very bad

$\mu \to e\gamma \Rightarrow m_\rho \sim 150\,\mathrm{TeV}$

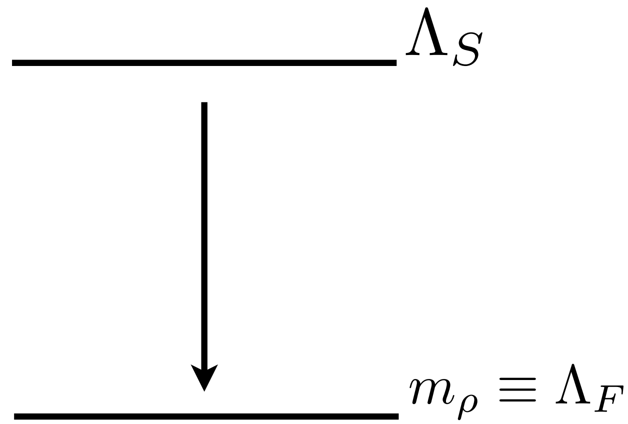
Separation between m_ρ and the flavor scale? Vecchi ('12)

Partial compositness + Supersymmetry

At Λ_S soft terms for the SM fields (universal) and for the heavy sector.

Anarchic interactions among the heavy fields generate O(1) non universality among their soft terms at Λ_F

Non-universality transmitted to SM fields.



see also Nomura et al. ('08)

$$(\delta^{u,d}_{ij})_{LL} = (c^{u,d}_{ij})_{LL} \times \frac{\tilde{m}_0^2}{\tilde{m}^2}\, \epsilon^q_i \epsilon^q_j \ldots \qquad (\delta^{u,d}_{ij})_{RL} = (c^{u,d}_{ij})_{RL} \times g_\rho\, \epsilon^{u,d}_i \epsilon^q_j \frac{v_{u,d}\, A_0}{\tilde{m}^2} \ldots$$

Realizes 'disoriented A-terms' of Giudice et al ('12)

Coefficient	Upper bound	Observables
$(c^u_{11})_{LR}$	0.4	EDMs
$(c^d_{11})_{LR}$	0.09	EDMs
$(c^e_{12})_{LR,RL}$	0.6	$\mu \to e\gamma$
$(c^e_{11})_{LR}$	0.5	electron EDM

$$(c^u_{12})_{LR} = 4, \quad \frac{A_0}{\tilde{m}} = 2,$$
$$\tilde{m} = \tilde{m}_0 = 2\mu = 1\,\mathrm{TeV}$$

Negative collider searches generate some tension with LHCb result

Partial compositness + Supersymmetry + **RPV**

Partial compositness provides an organizing principle to introduce RPV in the MSSM. Proton decay prohibits lepton **and** baryon number violation with high accuracy. Small neutrino masses disfavors RPV+lepton number violation.

$$UDD \quad LLE \quad QLD \quad LH_u$$

All flavor bounds are easily escaped provided $m_{\tilde{G}} > m_p - m_K$ to avoid $p \to K^+ \tilde{G}$ $(*)$

Collider bounds are relaxed due to reduced MET. Phenomenology varies according to the nature of the LSP. Generically one expects final states containing top quarks.

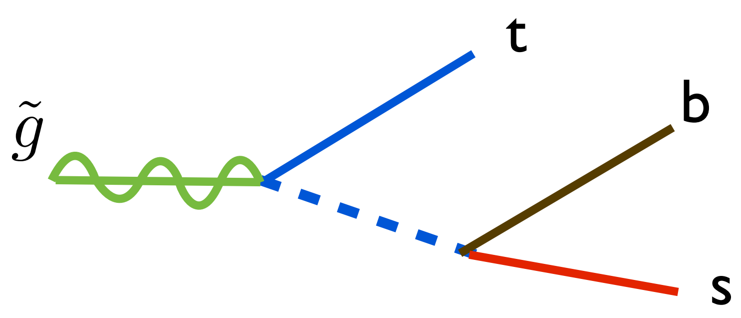
$$\lambda^{RPV}_{ijk} \sim \left(\frac{g_{\not{B}}}{4\pi}\right)\left(\frac{\tan\beta}{3}\right)^2\left(\frac{\epsilon^u_3}{0.5}\right)^3 \times \begin{cases} 2.7\times 10^{-3} & (tbs) \\ 0.6\times 10^{-3} & (tbd) \\ 1.7\times 10^{-4} & (cbs) \\ 0.5\times 10^{-4} & (cbd) \\ 1.7\times 10^{-6} & (ubs) \\ 0.4\times 10^{-6} & (ubd) \end{cases}$$

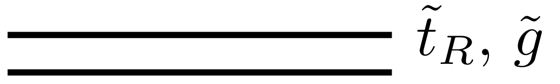
A good fit to the LHCb result with superpartners around 500-600 GeV is possible.

Need some help for the Higgs boson mass (NMSSM?)

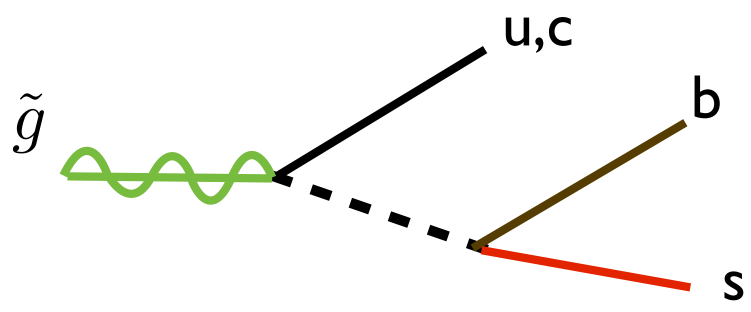
$(*)$ ~ high scale mediation

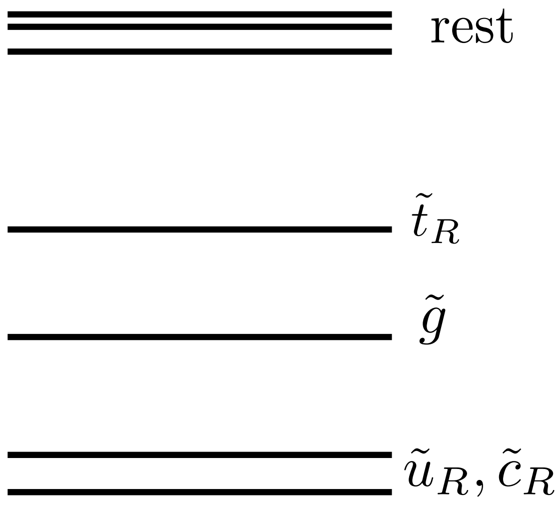
Constraints from SS dileptons from top decays (Allanach et al. ('12)): gluino ~ 600 GeV





Poorly constrained spectrum (realizable in PC+SUSY for grho~1)



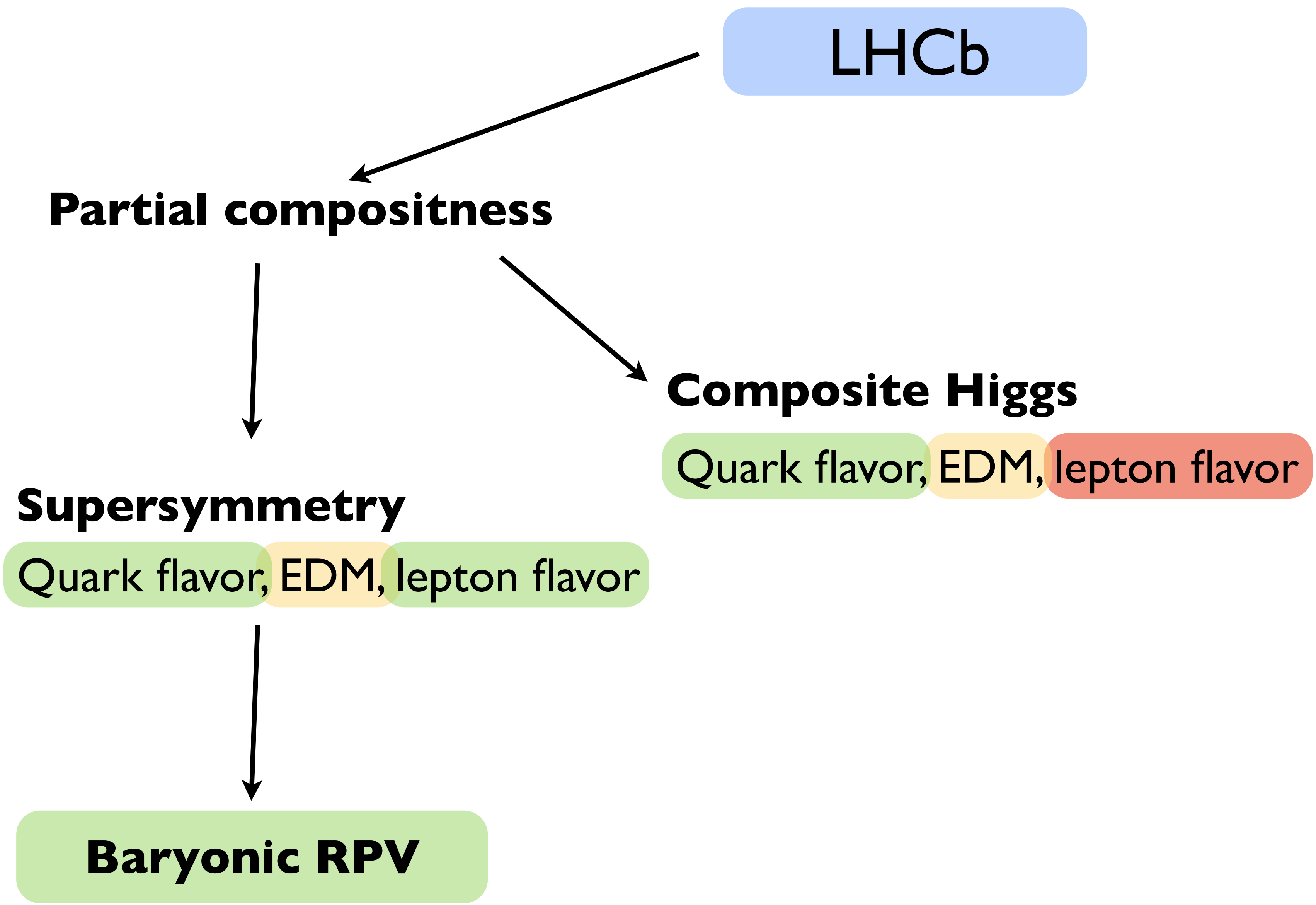


Bounds gluino ~ 460 GeV from gluino pair production and $\tilde{g} \to 3j$

Stronger bound if u squark light. (CMS EXO-11-060)

350-400 GeV bound on u, c squark mass from squark pair production and dijet searches

Conclusions



BACKUP

Partial Compositness vs MFV

A full comparison between the two approaches requires the specification of a **coupling** and a **mass scale** to completely define the structure of flavor-violating higher dimensional operators.

Eg: in SUSY with gauge mediation universal soft masses are generated at Mmess, non-universality generated through running respect MFV. Four-fermions operator at superpartner scale have the form

$$\frac{g_s^2}{16\pi^2}\frac{g_s^2}{\tilde{m}^2}\left(\bar{q}_L\frac{Y_U Y_U^\dagger}{16\pi^2}q_L\right)^2$$

$$\tilde{m}^2 = m_0^2 \qquad M_{\rm mess}$$

$$\tilde{m}^2 = m_0^2\left(1 + c\frac{Y_U Y_U^\dagger}{(4\pi)^2} + ...\right) \qquad \tilde{m}$$

d-d structures

Structure	MFV	PC
$\bar{d}_{iL}d_{jL}$	$V_{3i}^* V_{3j}$	$V_{3i}^* V_{3j}$
$\bar{d}_{iR}d_{jR}$	$y_i^d y_j^d V_{3i}^* V_{3j}$	$\frac{y_i^d y_j^d}{V_{3i}^* V_{3j}}$
$\bar{d}_{iL}d_{jR}$	$y_j^d V_{3i}^* V_{3j}$	$y_j^d \frac{V_{3i}}{V_{3j}}$

Shows only the structure in flavor space other coupling constants have been suppressed