The Abdus Salam International Centre for Theoretical Physics

2400-16

Workshop on Strongly Coupled Physics Beyond the Standard Model

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MFV composite Higgs at the LHC

Andreas Weiler
DESY

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

The MFV composite Higgs at the LHC

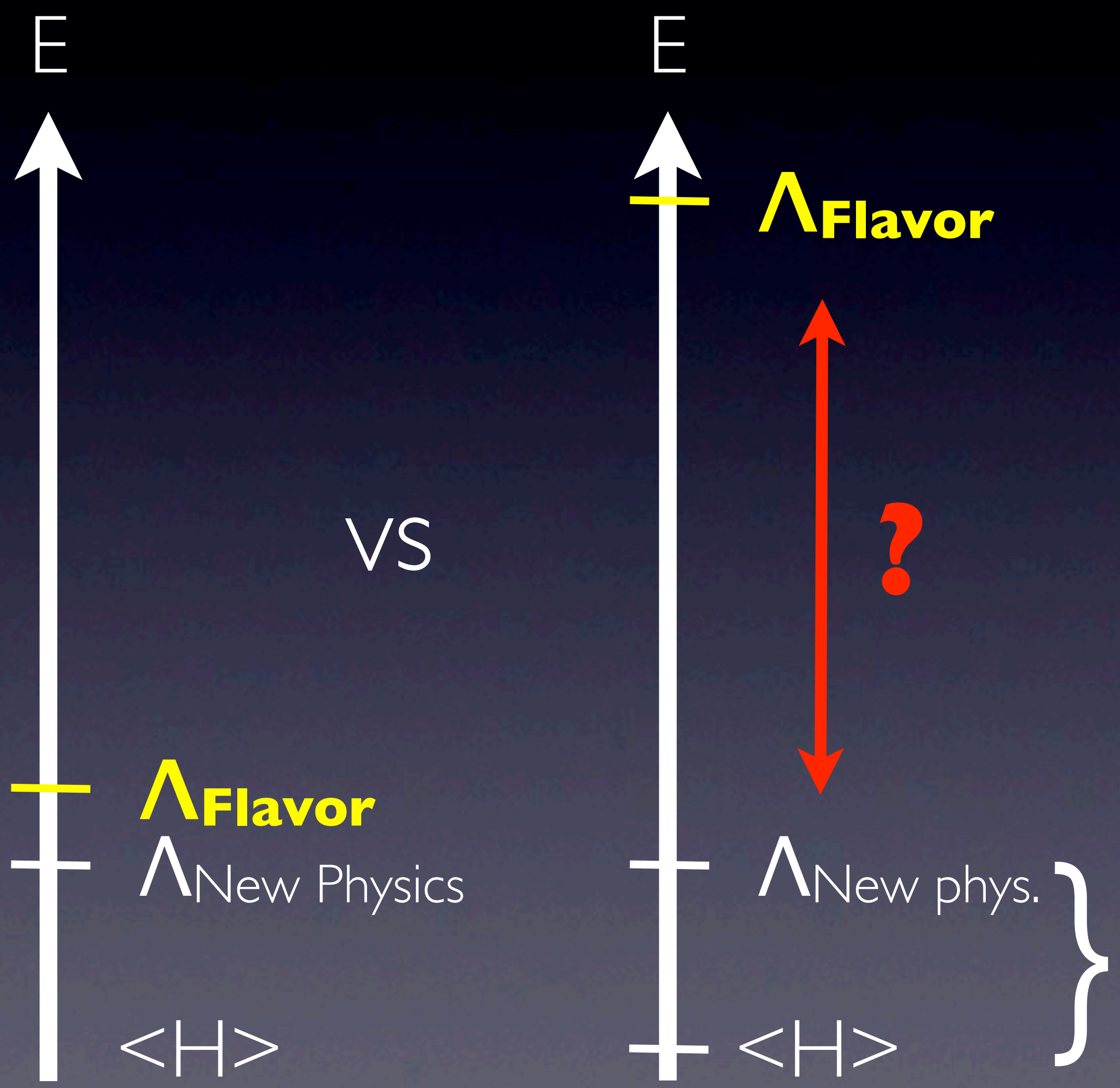
Andreas Weiler
(DESY)

ICTP
27/1/12

w/ Michele Redi

arxiv:1106.6357[hep-ph]

Flavor genesis scale



$$\frac{1}{\Lambda^2_{\rm Flavor}}(\bar{\psi}\psi)(\bar{\psi}\psi)$$

$$y_{ij}\,\bar{\psi}_i\mathcal{H}\psi_j$$

naturalness

Flavor problem of naive techni-color

If e.g. EWSB through condensate $D_{\mathcal{H}=\langle\bar{\psi}\psi\rangle} \approx 3$

$$\frac{1}{\Lambda^{D_{\mathcal{H}}-1}} y_{ij}\,\bar{\psi}_i \mathcal{H} \psi_j + \frac{1}{\Lambda^2} c_{ijkl}\,\bar{\psi}_i \psi_j \bar{\psi}_k \psi_l$$

Λ cannot be too large, because top mass is large

Λ must be very large because this leads to FCNCs

$K^0 - \bar{K}^0$

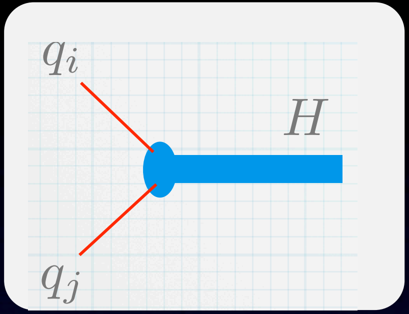
$$\Lambda = \mathcal{O}(\mathrm{TeV})$$

$$\Lambda > 10^5\ \mathrm{TeV}$$

✗

Two ways of giving mass to fermions

Bi-linear (like SM):



$$\mathcal{L} = y f_L \mathcal{O}_H f_R, \quad \mathcal{O}_H \sim (1,2)_{\frac{1}{2}}$$

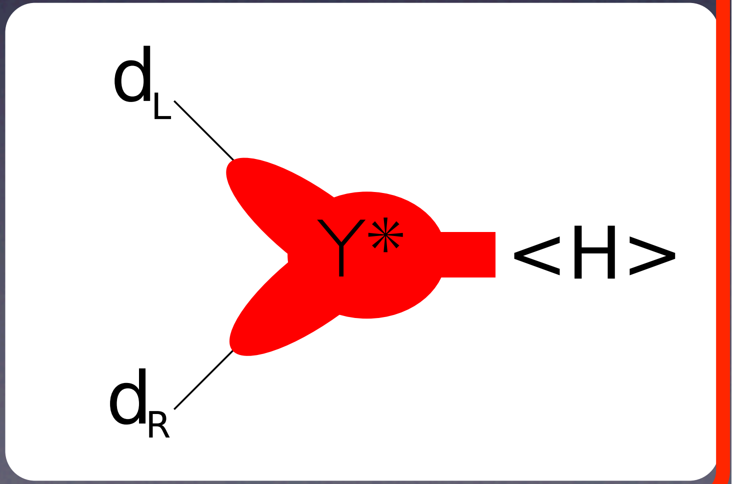
Linear:

D.B. Kaplan '91

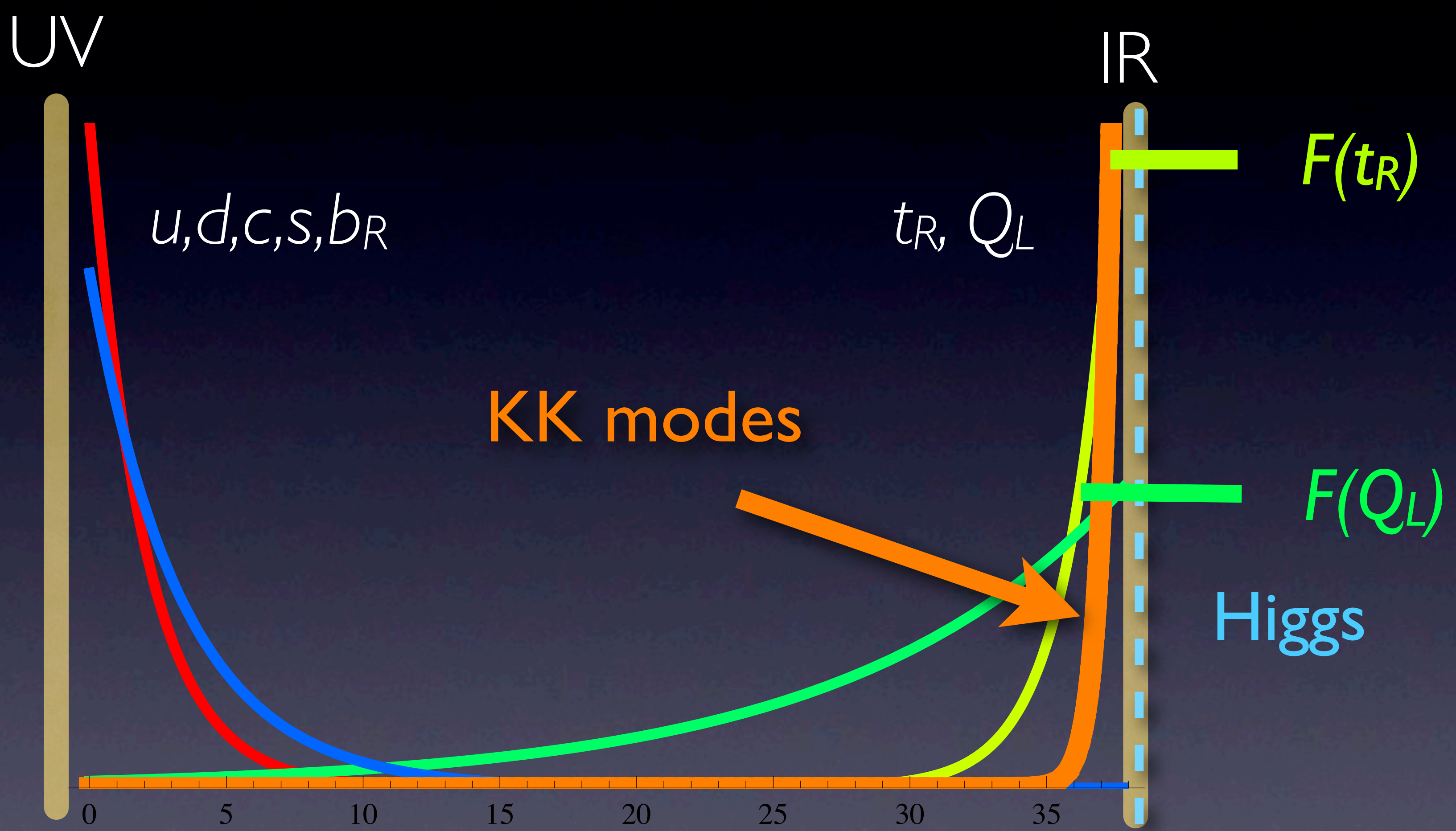
$$\mathcal{L} = y f_L \mathcal{O}_R + y_R f_R \mathcal{O}_L + m \mathcal{O}_L \mathcal{O}_R, \quad \mathcal{O}_R \sim (3,2)_{\frac{1}{6}}$$

Quarks & Leptons mix with strong sector

mass $\propto$ compositeness



Degree of compositeness: $\sin\phi = F(c) \sim \left(\frac{\mathrm{TeV}}{\mathrm{M_{pl}}}\right)^{c-\frac{1}{2}}$



Randall/Sundrum
Gherghetta/Pomarol,
…

RGE of the mixing UV ➡ IR

We can capture the relevant physics without using 5D constructions.

Simplified approach: 2 site picture.

→ talks by Michele Redi, Andrea Wulzer

Contino, Kramer, Son, Sundrum '06

Simplified 2 site picture:
Each SM chirality has a Dirac fermionic partner

$$\mathcal{L}_{\rm composite} = \bar{Q}^i (i\not{D} - m_Q^i) Q^i + \bar{U}^i (i\not{D} - m_U^i) U^i + Y_{ij}^U \bar{Q}_L^i \tilde{H} U_R^j$$

$$\mathcal{L}_{mixing} = m_\rho \left[\lambda_q^{ij} \bar{q}_{Li} Q_{Rj} + \lambda_u^{ij} u_{Ri} \bar{U}_{Lj} + h.c. \right]$$

Mass basis:

$$\begin{pmatrix} q_L \\ Q_L \end{pmatrix} = \begin{pmatrix} \cos\varphi_{q_L} & -\sin\varphi_{q_L} \\ \sin\varphi_{q_L} & \cos\varphi_{q_L} \end{pmatrix} \begin{pmatrix} q_L^{el} \\ Q_L^{co} \end{pmatrix}$$

Gauge fields:

$$\begin{pmatrix} A_\mu \\ \rho_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} A_\mu^{el} \\ \rho_\mu^{co} \end{pmatrix}$$

Composite sector has $SU(2)_L \otimes SU(2)_R \otimes U(1)_X$ symmetry $(Y = T_{3R} + U(1)_X)$

$$q_L \longrightarrow (2,2)_{\frac{2}{3}} \qquad L_U = \begin{pmatrix} T & T_{\frac{5}{3}} \\ B & T_{\frac{2}{3}} \end{pmatrix}$$

$$u_R \longrightarrow (1,1)_{\frac{2}{3}} \qquad U$$

To generate Yukawa for the down sector

$$q_L \longrightarrow (2,2)_{-\frac{1}{3}} \qquad L_D = \begin{pmatrix} B_{-\frac{1}{3}} & T' \\ B_{-\frac{4}{3}} & B' \end{pmatrix}$$

$$d_R \longrightarrow (1,1)_{-\frac{1}{3}} \qquad D$$

Corrections to SM couplings of down quarks are small and zero for right quarks.

Agashe , Contino, da Rold, Pomarol, '04

Yukawa couplings

$$(y^U)_{SM} = \lambda_q \cdot Y^U \cdot \lambda_u$$

Even with proto-Yukawa Y^U of strong sector anarchic, can generate masses and CKM by hierarchical mixings.

Requirement to reproduce CKM fixes LH mixing

$$F_{Q_1}/F_{Q_3} \sim \theta_{13} \sim \lambda^3$$
$$F_{Q_2}/F_{Q_3} \sim \theta_{23} \sim \lambda^2$$

predict cabbibo angle

$$\theta_{12} \sim F_{Q_1}/F_{Q_2} \sim F_{Q_1}/F_{Q_3} \cdot F_{Q_3}/F_{Q_2} \sim \lambda \qquad ✔$$

- Light generations mostly elementary

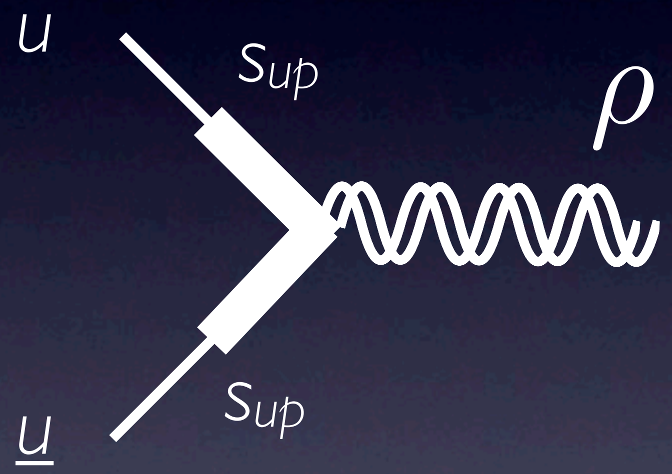
- Top strongly composite

Flavor hierarchies can be dynamically generated if the composite sector is conformal.

Signatures

Signatures

Resonance production (option 1)

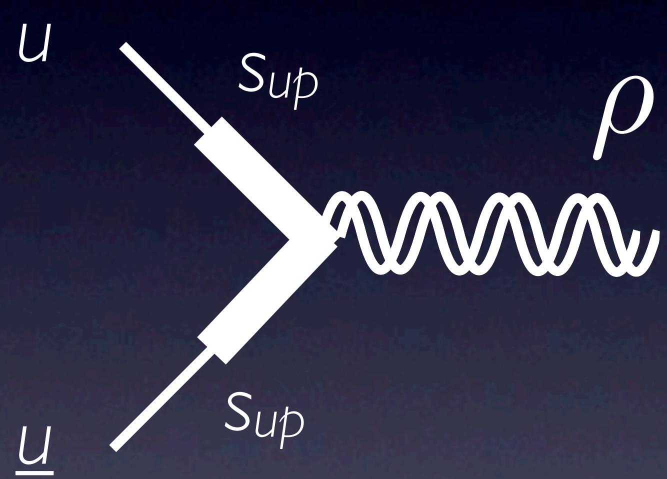


$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

Signatures

Resonance production (option 1)



$$\sim g_*^2 \sin^2 \theta_{u_R}$$

strongly suppressed for light quarks!

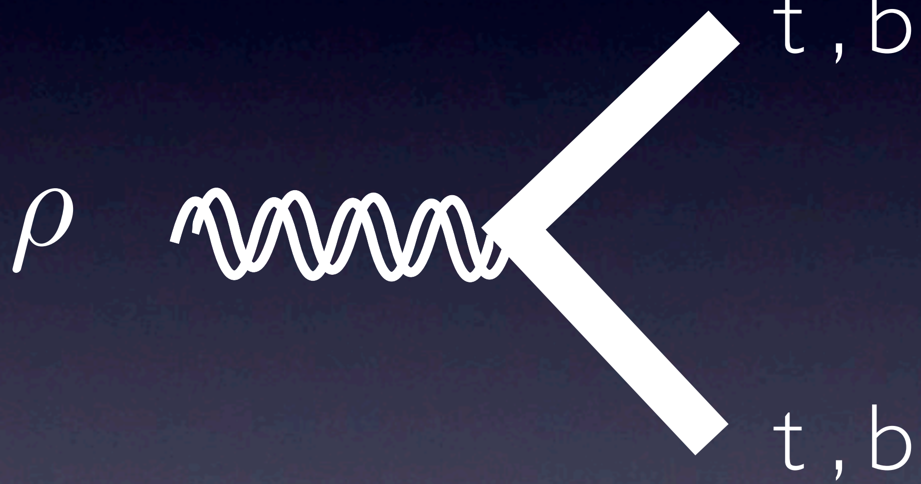
Resonance production (option 2)

$$\sim \frac{g_s}{g*}$$

similar to $\gamma - \rho$ mixing

NB, gluon-rho-rho = 0

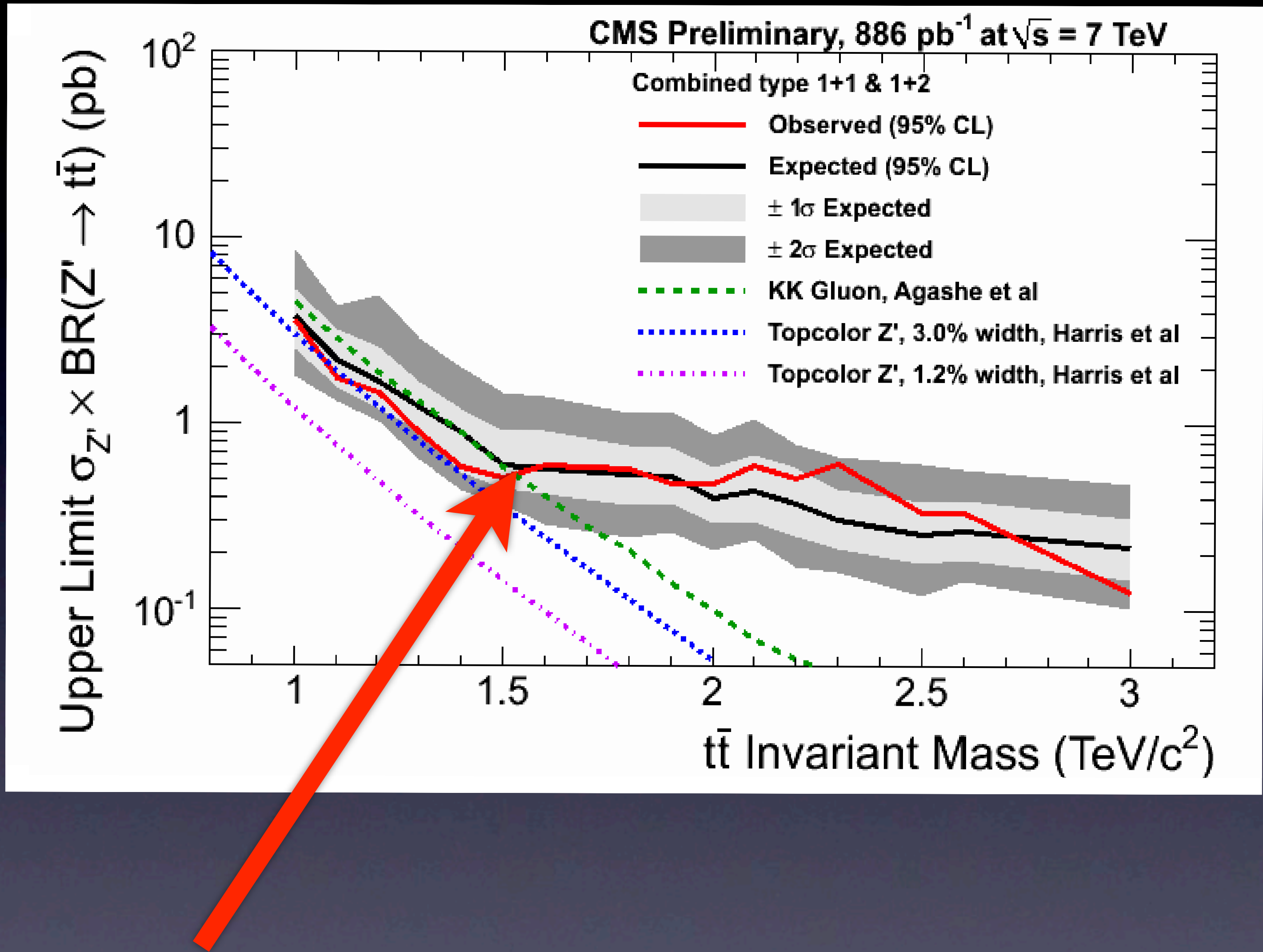
Resonance decay



decays dominantly into 3rd generation (tt, bt, bb, TT, Tt) & Higgs

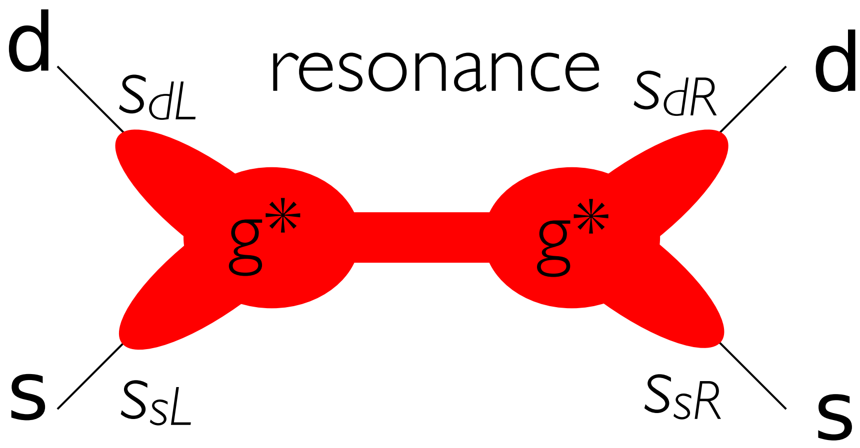
Agashe et al, Lillie et al, Bini, et al; Barcelo et al; Contino, Servant; Mrazek, Wulzer;

CMS-pas-exo-11-006 866/pb



M > 1.5 TeV @ 95CL

FCNCs



Csaki, Falkowski, AW

$$\sim \frac{g_\rho^2}{m_\rho^2} s_{d_L} s_{d_R} s_{s_L} s_{s_R}$$

with $m_d \sim v s_{d_L} Y s_{d_R}$

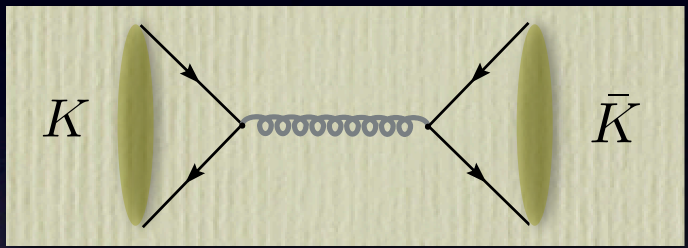
$$\sim \frac{g_\rho^2}{m_\rho^2} \frac{m_d m_s}{v^2 Y^2}$$

good, but not perfect...

CP problem

Csaki, Falkowski, AW; Buras et al; Casagrande et al

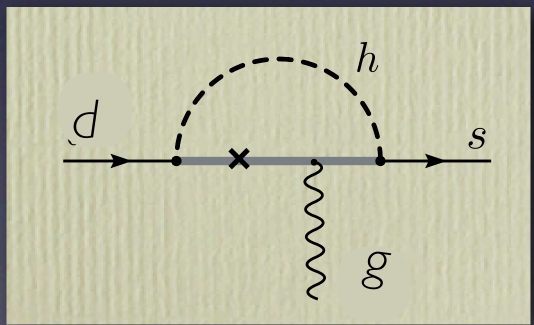
$\Delta F = 2$ (strongest from ϵ_K)



$$M_* \gtrsim 10 \left(\frac{g_*}{Y_*}\right) \text{TeV}$$

$\Delta F = 1$ (constraint from ϵ'/ϵ)

Gedalia et. al



$$M_* \gtrsim 1.3\, Y_* \,\text{TeV}$$

Even if one resolves the most severe FCNC constraint (ϵ_K), EDMs are still a problem:

$\Delta F = 0$ neutron EDM

$$M_* \geq 2.5\, Y_*\ \mathrm{TeV}$$

Agashe et. al, Delaunay et. al, Redi, AW

Combined Limit >= 10 TeV

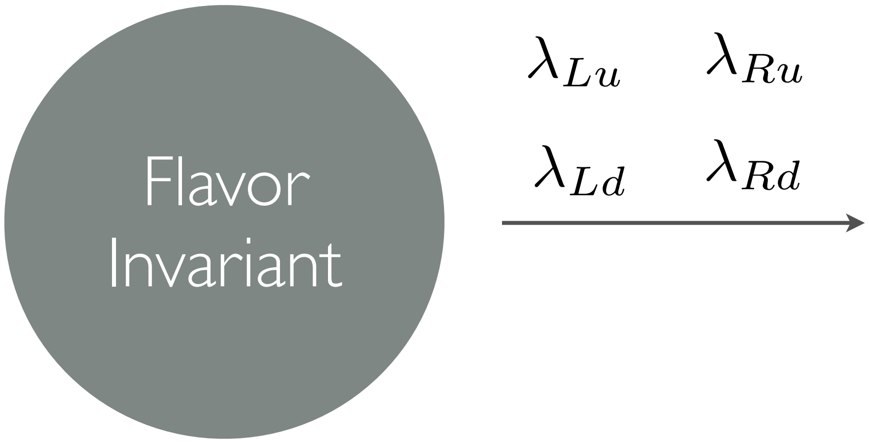
Flavor transparent strong sector

w/ Michele Redi

arxiv:1106.6357[hep-ph]

See also:
Rattazzi-Zaffaroni '01
Cacciapaglia, Csaki, Galloway, Marandella, Terning, AW. '07
Barbieri, Isidori, Pappadopulo '08
Delaunay, Gedalia, Lee, Perez, Ponton '11

Composite sector is trivial w.r.t flavor



All flavor violation comes from the external mixings.

$$y_u \propto \lambda_{Lu}\lambda_{Ru}$$

$$y_d \propto \lambda_{Ld}\lambda_{Rd}$$

Simple realization of Minimal Flavor Violation:

mixings ~ SM Yukawas

- Left-handed compositeness:

$$\lambda_{Lu} \propto Id\,, \qquad \lambda_{Ld} \propto Id$$
$$\lambda_{Ru} \propto y_u\,, \qquad \lambda_{Rd} \propto y_d$$

$$+ \qquad \begin{array}{c} SU(3)_F \\ L_U\,, L_D\,, U\,, D \in 3_F \end{array}$$

- Right-handed compositeness:

$$\lambda_{Lu} \propto y_u\,, \qquad \lambda_{Ld} \propto y_d$$
$$\lambda_{Ru} \propto Id\,, \qquad \lambda_{Rd} \propto Id$$

$$+ \qquad \begin{array}{c} SU(3)_U \otimes SU(3)_D \\ L_U\,, U \in (3,1) \quad L_D\,, D \in (1,3) \end{array}$$

MFV $\longrightarrow$ Mixing of one chirality of light quarks is large.

Flavor bounds are automatically satisfied.
No EDMs are generated to leading order.

LEP bounds,

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to q\bar{q})} = .21629 \pm .00066$$

$$R_h = \frac{\Gamma(Z \to q\bar{q})}{\Gamma(Z \to \mu\bar{\mu})} = 20.767 \pm .025$$

Modified couplings strongly constrained

$$\frac{\delta R_h}{R_h} \approx .57\frac{\delta g_{Lu}}{g_{Lu}} + .11\frac{\delta g_{Ru}}{g_{Ru}} + 1.28\frac{\delta g_{Ld}}{g_{Ld}} + .04\frac{\delta g_{Rd}}{g_{Rd}}$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \qquad \frac{\delta g_{Ru}}{g_{Ru}} < .01 \qquad \frac{\delta g_{Ld}}{g_{Ld}} < .001 \qquad \frac{\delta g_{Rd}}{g_{Rd}} < .02$$

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$\frac{\delta g_{Lu}}{g_{Lu}} < .002$ ~~$\frac{\delta g_{Ru}}{g_{Ru}} < .01$~~ ~~$\frac{\delta g_{Ld}}{g_{Ld}} < .001$~~ ~~$\frac{\delta g_{Rd}}{g_{Rd}} < .02$~~

protected reps

Similar bound is found from unitarity of CKM

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \approx 1 - .7\,\frac{\delta g_{Lu}}{g_{Lu}}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = .9999 \pm .0012$$

LH COMPOSITENESS:

$$\delta g \sim \frac{Y^2 v^2}{2\, m_\rho^2} \sin \varphi_q^2$$

$$\frac{\delta g_{Lu}}{g_{Lu}} < .002 \quad \xrightarrow{m_t} \quad \sin \varphi_{t_R} \geq 35 \frac{m_t}{m_\rho}$$

Strongly constrained and only possible if tR is composite.

RH COMPOSITENESS:

No bounds from LEP!

Main constraint from recent di-jet searches,

$$\mathcal{L}_{4-Fermi} = \frac{2\pi}{\Lambda^2} (\bar{q}_L \gamma^\mu q_L)^2$$

LHC: $\Lambda > 6\,\text{TeV}$

$$\frac{g_\rho^2}{4\,m_\rho^2} \sin^4 \varphi_{q_R} \left(\bar{q}^i_{R\alpha} \gamma^\mu q^i_{R\beta} \bar{q}^j_{R\beta} \gamma_\mu q^j_{R\alpha} \right) \xrightarrow{\text{COMPOSITENESS}} \sin^2 \varphi_{q_R} \leq \frac{2}{g_\rho} \left(\frac{m_\rho}{3\,\text{TeV}} \right)$$

Large or full compositeness is still allowed with $m_\rho = 3$ TeV

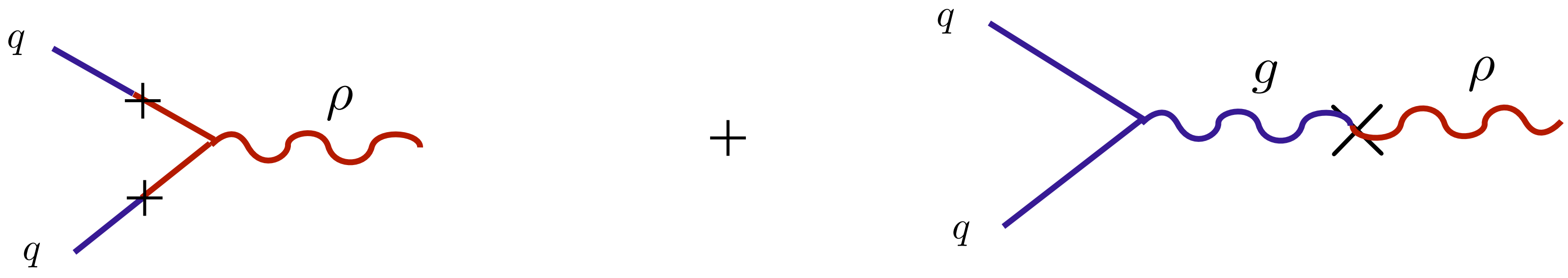
If RH quarks are fully composite: MFV follows automatically from the flavor symmetry.

(Only two possible mixings with strong sector).

LHC phenomenology

1) Proton is 1/2 composite!
2) Decay patter˙n change

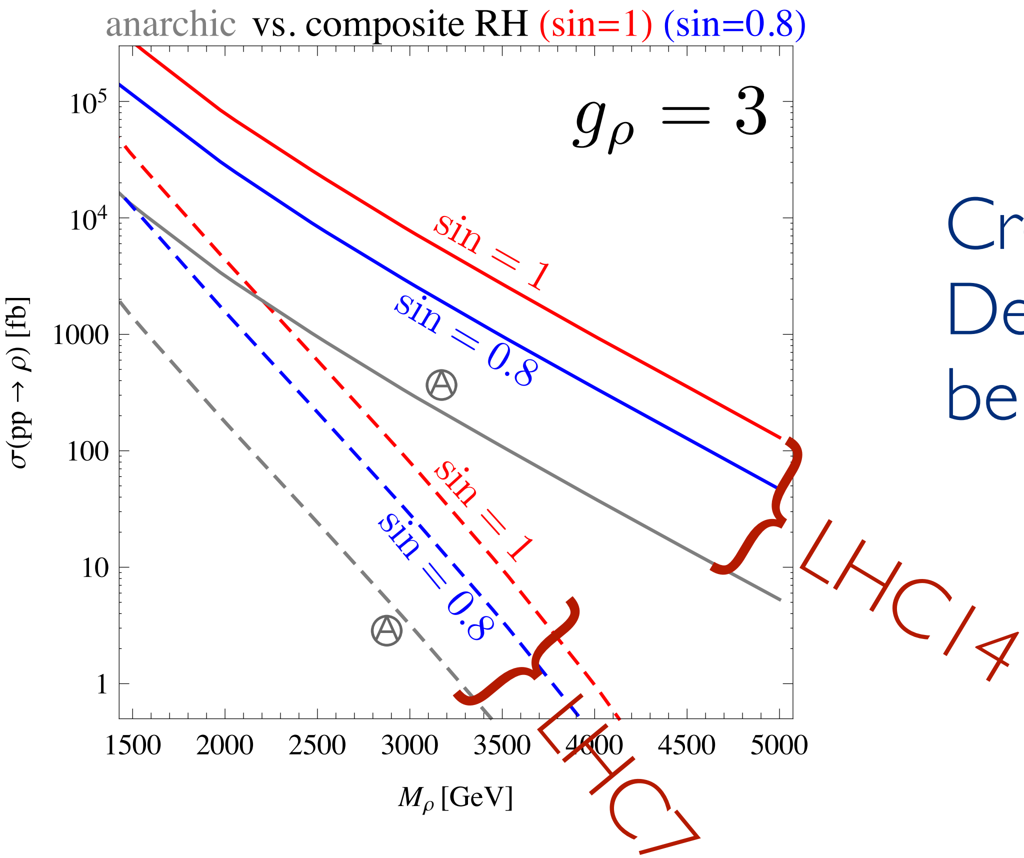
Spin-1: gluon, electro-weak, flavor resonances



$$g_{\rho\bar{q}q} = g(\sin^2\varphi\cot\theta - \cos^2\varphi\tan\theta)$$

First term easily dominates for RH compositeness.

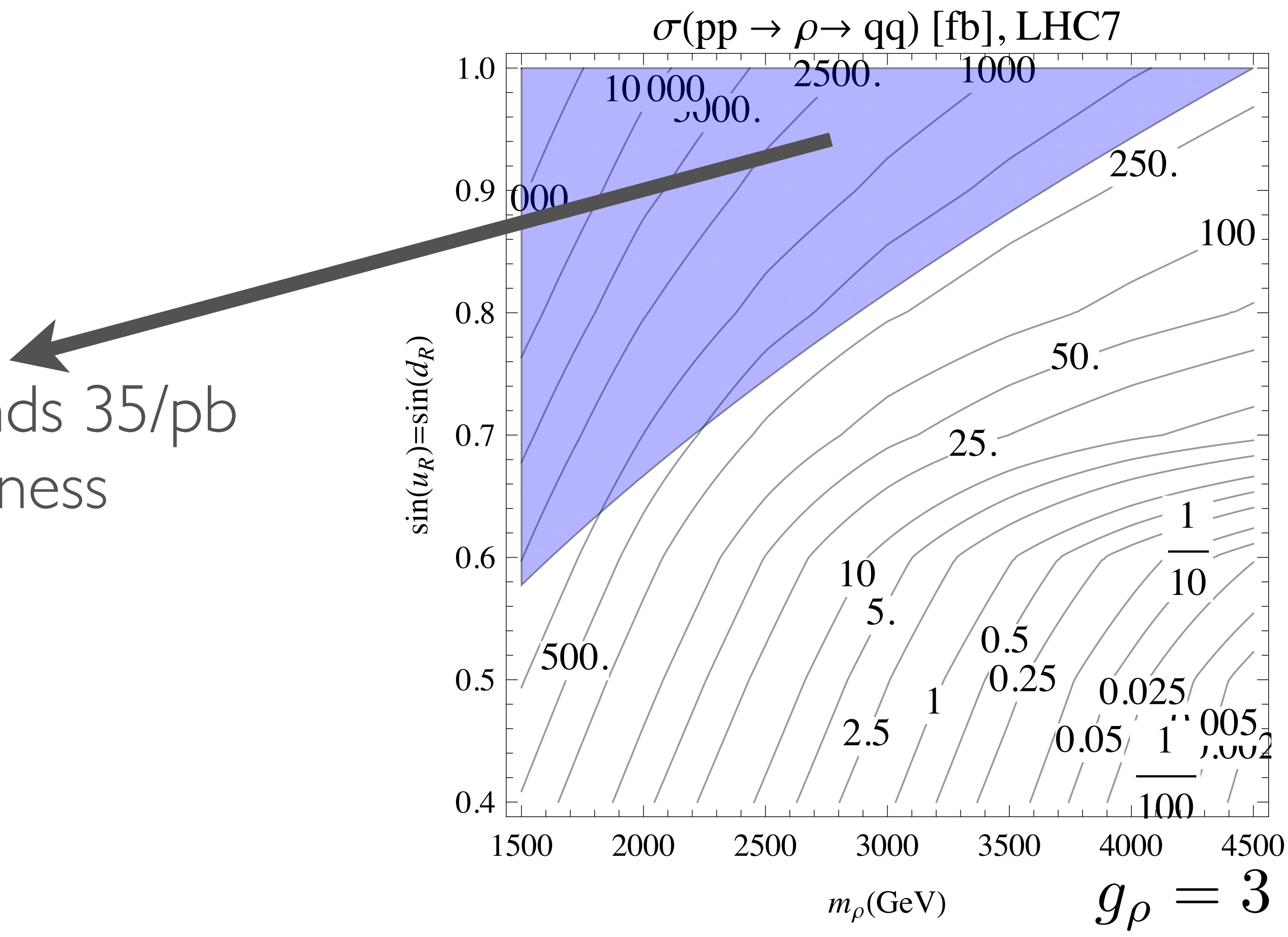
Gluon resonances:



Cross-sections > O(10) larger.
Decay into light generation can be important.

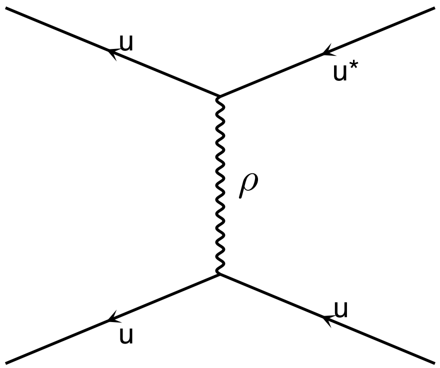
LHC7 bounds already relevant:

Di-jet bounds 35/pb
Compositeness



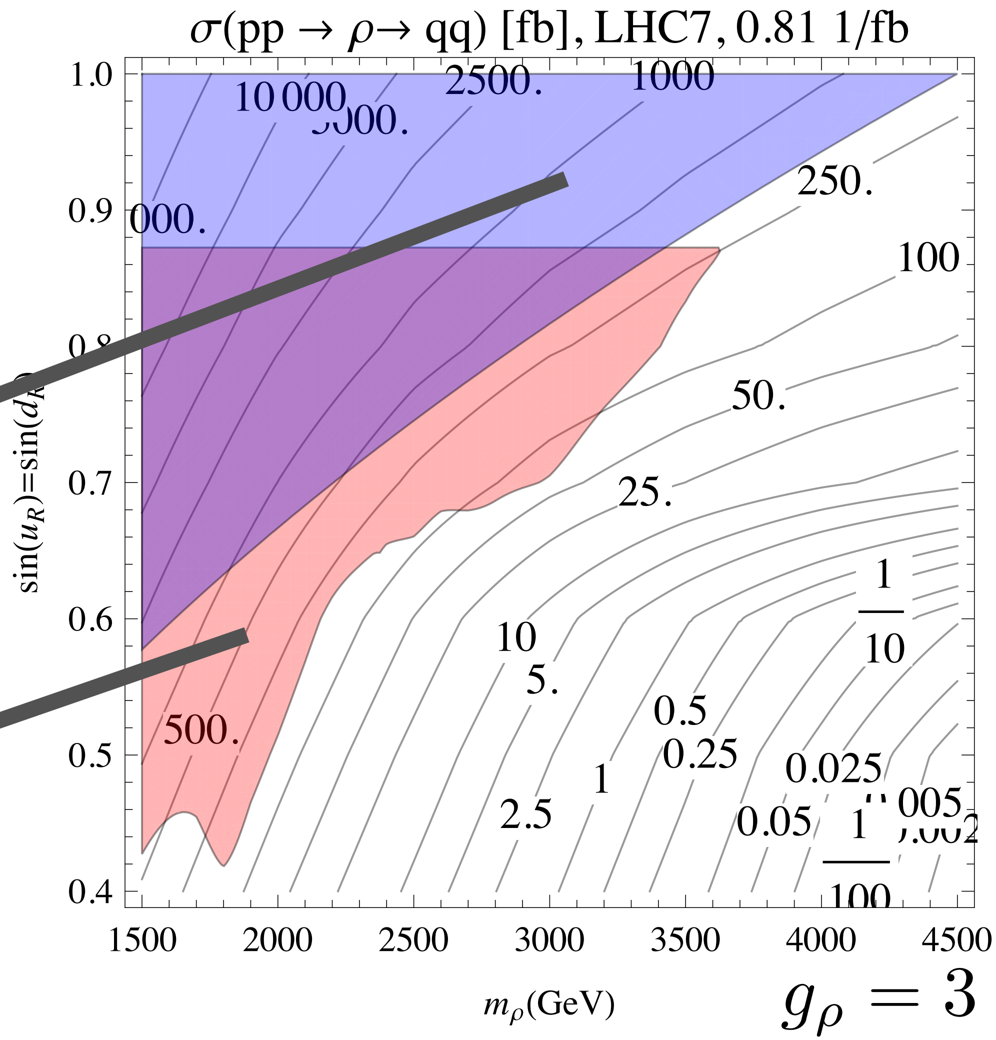
$g_\rho = 3$

LHC7 bounds already relevant:



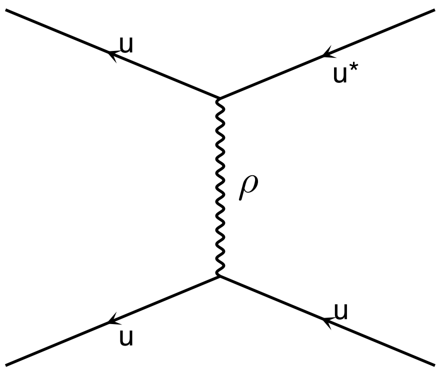
Di-jet bounds 35/pb
compositeness

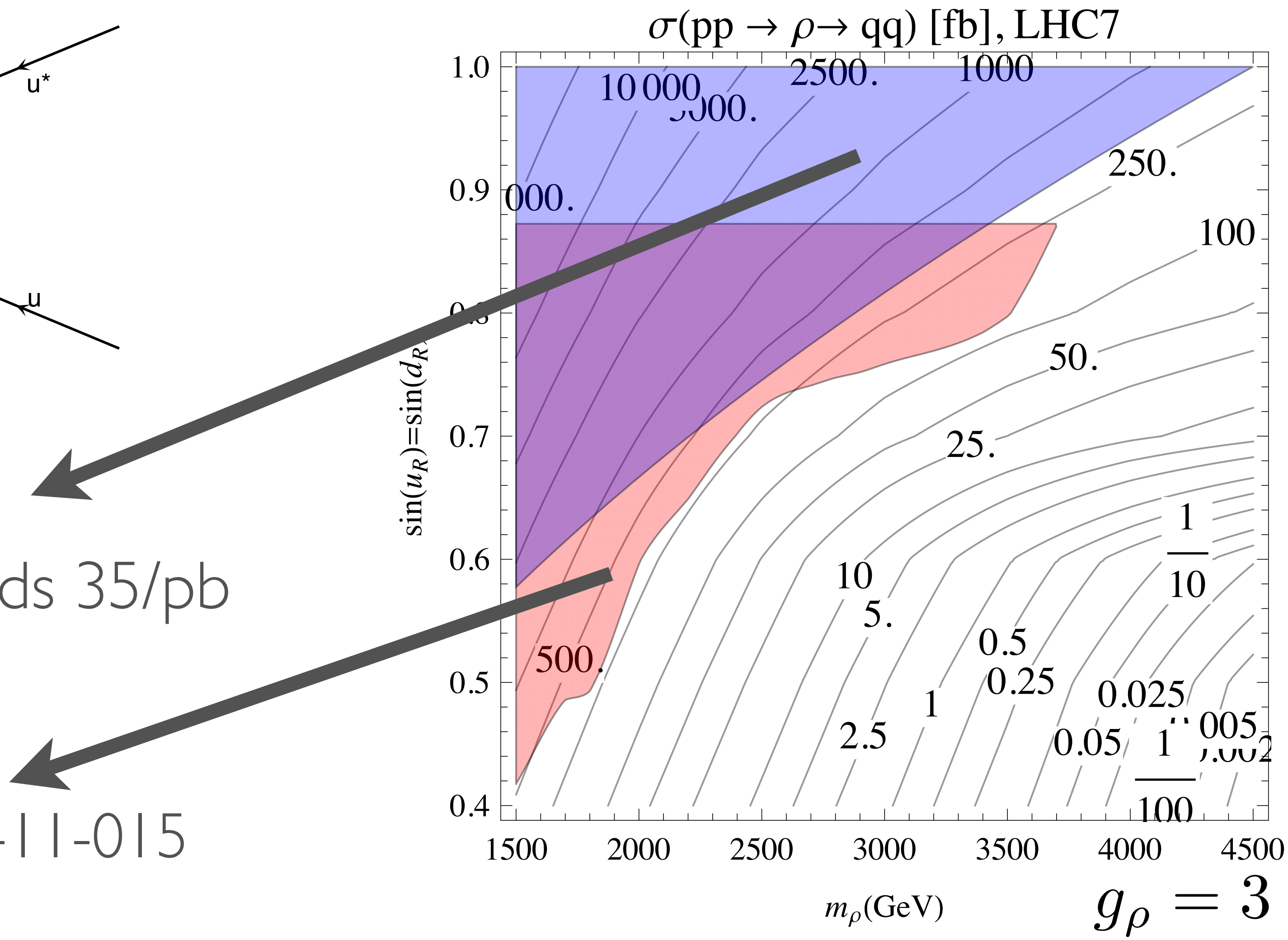
Atlas-Conf-2011-081
Bump search 810/pb



Expected signals in di-jet.

LHC7 bounds already relevant:

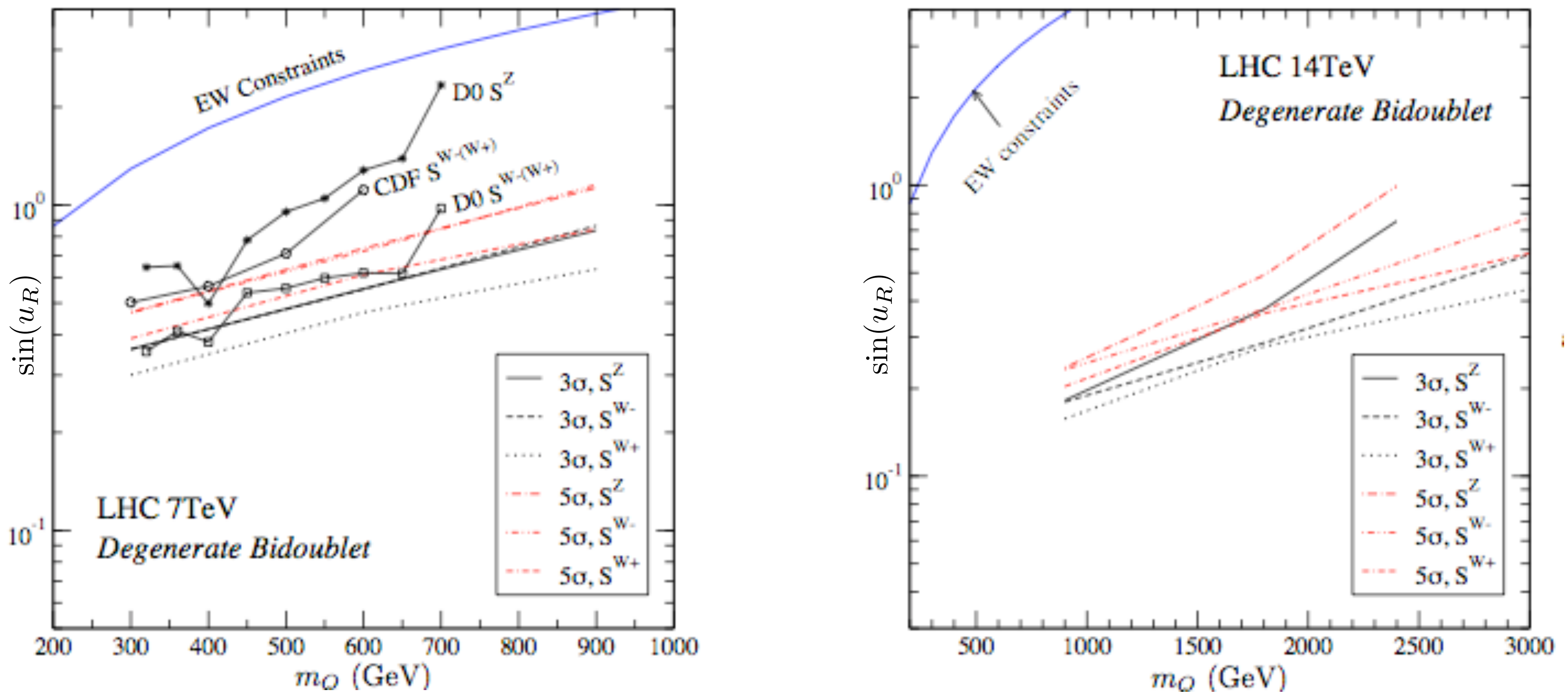




Di-jet bounds 35/pb

CMS-EXO-11-015
1/fb

Expected signals in di-jet.

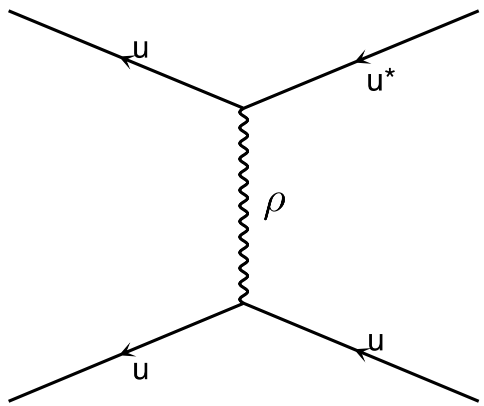


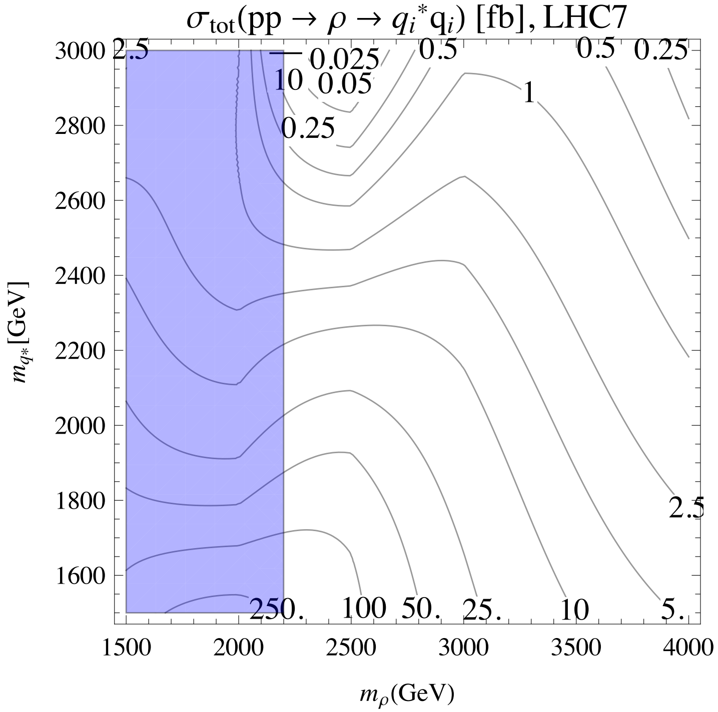
Atre, Azuelos, Carena, Han,
Ozcan, Santiago, Unel '11

LHC searches could probe fermions up to 1 TeV.

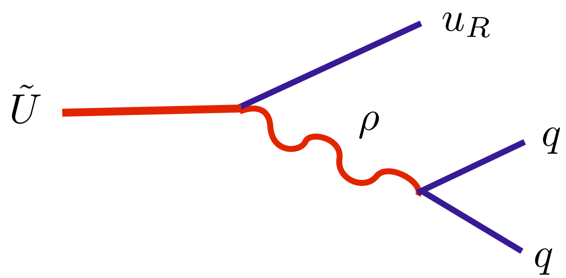
LHC14 will either discover or exclude the model.

Right quark partners produced by resonance exchange.





$$g_\rho = 3\,, \sin\varphi_{u_R} = .7\,, \sin\varphi_{d_R} = 1/6$$



MR, Sanz, Weiler, in progress

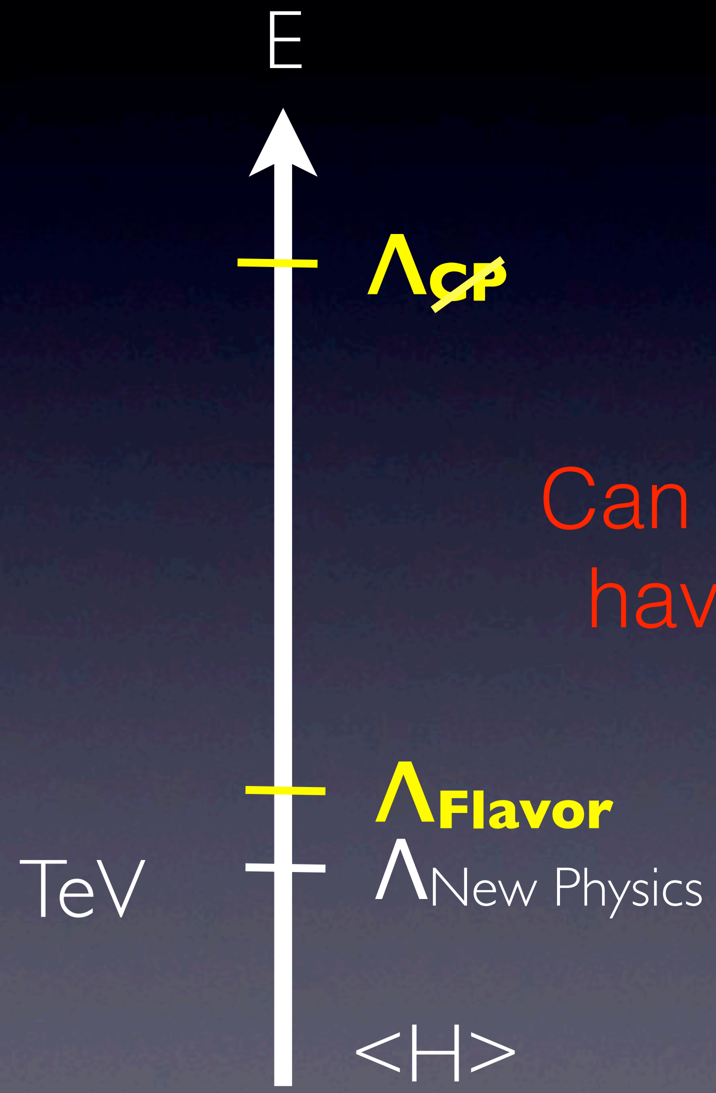
3-4 jet final states.

Can we keep the explanation of flavor while evading the CP bounds?

Minimal CP Violation

w/ Michele Redi
arxiv:1106.6357[hep-ph]

Sequestering CP & Flavor



Can Flavor and CPV
have separate origins?

CP and Flavor linked in SM

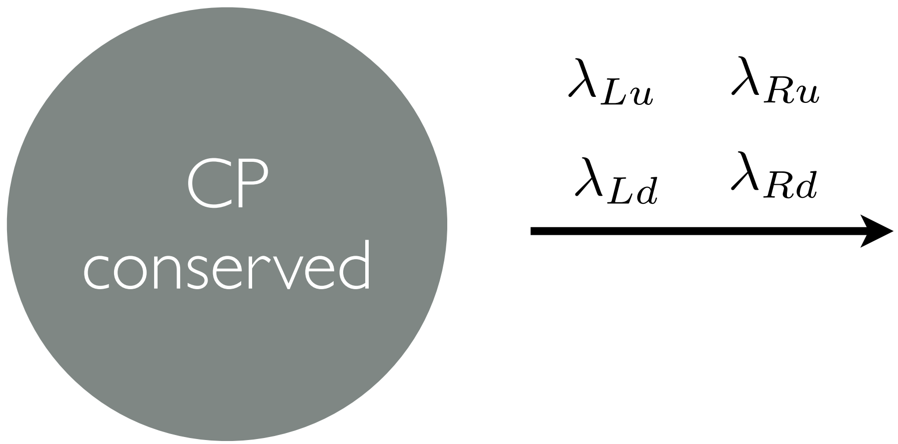
Jarlskog determinant measure of CPV

$$\det\left(\left[M_u M_u^\dagger, M_d M_d^\dagger\right]\right) =$$

$$-2i(m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)\times$$
$$(m_b^2 - m_d^2)(m_b^2 - m_s^2)(m_s^2 - m_d^2) s_1 s_2 s_3 c_1 c_2^2 c_3 \sin\delta$$

O(1) CP phase : $\sin\delta \sim 1$

Composite sector CP invariant



CP violated by mixings.

Composite Yukawas anarchic real matrices:
compatible with anarchic generation of flavor.

CP violation can be induced by left mixings

$$
\begin{aligned}
y_u &= e^{i\vec{\alpha}}.\lambda_{Lu}.Y^U.\lambda_{Ru} \\
y_d &= \lambda_{Ld}.Y^D.\lambda_{Rd}
\end{aligned}
$$

[everything real]

$$\vec{\alpha} = (\alpha_1, \alpha_2, \alpha_3)$$

CPV spurion

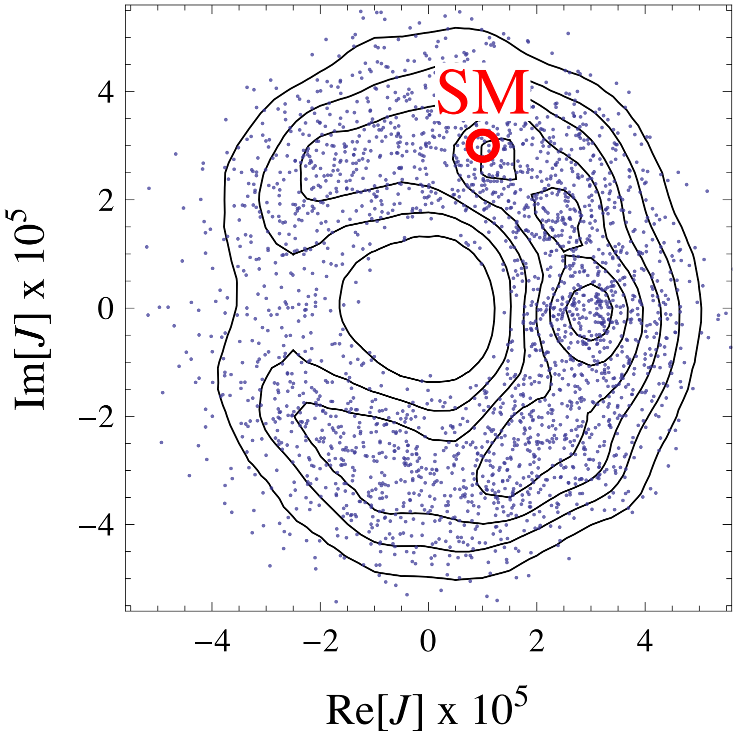
Diagonalization matrices:

$$
\begin{aligned}
U_L &= e^{i\vec{\alpha}}.V_{Lu} \\
D_L &= V_{Ld}
\end{aligned}
$$

$\longrightarrow$

$$V^{CKM} = V_{Lu}^T.e^{-i\vec{\alpha}}.V_{Ld}$$

O(1) CKM phase generated

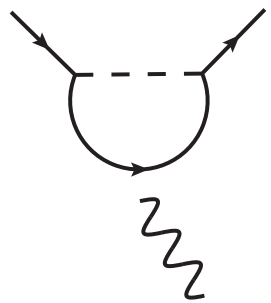


$$J = V_{12}^{CKM}\, V_{23}^{CKM}\, (V_{13}^{CKM})^*\, (V_{22}^{CKM})^*$$

average Jarlskog

$$\langle J \rangle = 2 \times 10^{-5} \qquad (J_{SM} = 3 \times 10^{-5})$$

No EDMs at leading order:



$$d_d \sim \frac{1}{32\pi^2} \frac{v}{\sqrt{2} m_\rho^2} \, \mathrm{Im} \left[D_L^\dagger \cdot f_{Ld} \cdot Y^D \cdot Y^{D\dagger} \cdot Y^D \cdot f_{Rd}^\dagger \cdot D_R \right]_{11}$$

Rotate into basis with phases in $\tilde{Y}$.

$\tilde{Y}$ do not contribute to EDM.

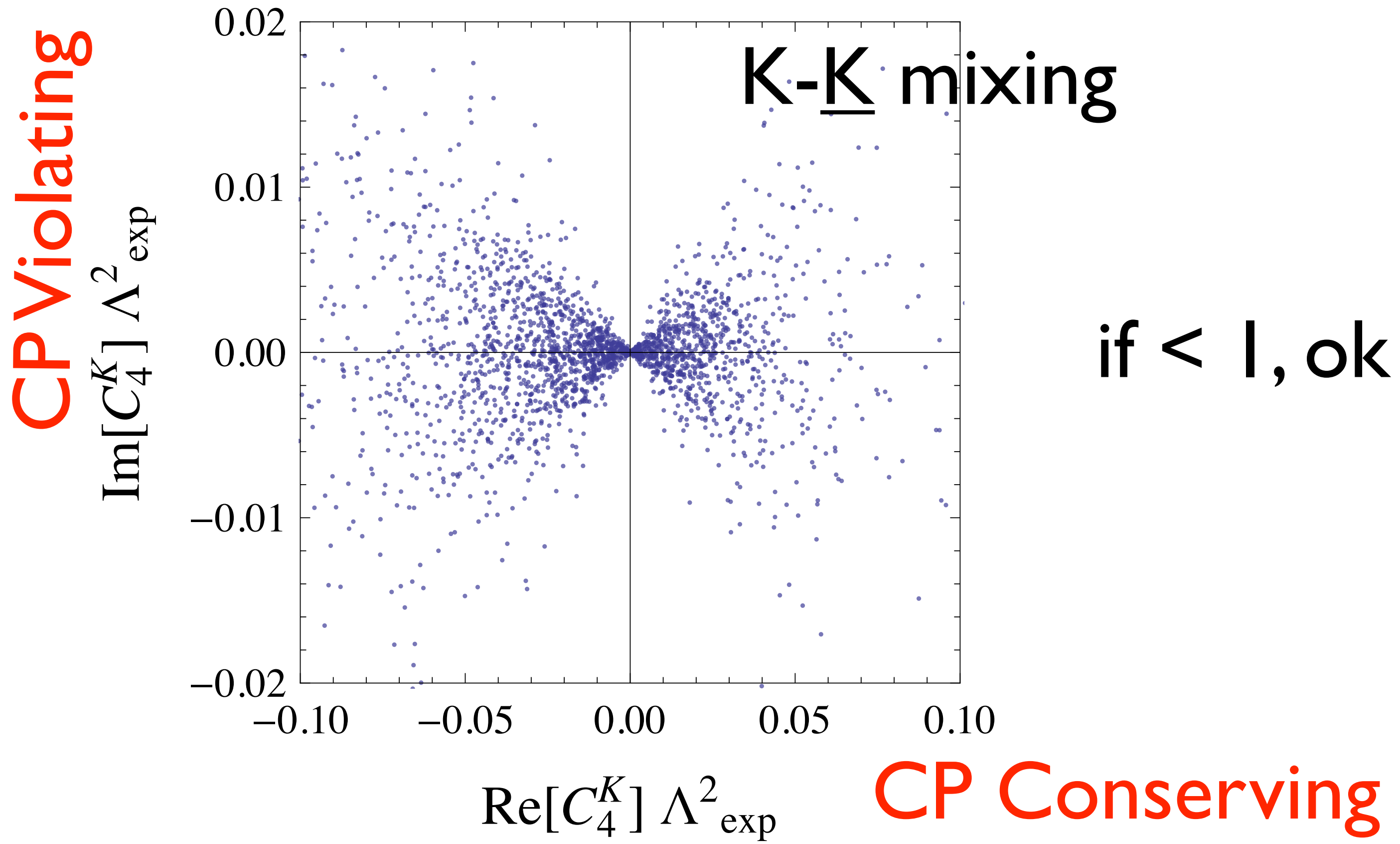
FCNC model dependent.
Severely suppressed CP violation in light generations if the CP phase induced through top mixing

$$\vec{\alpha} \sim (0, 0, 1)$$

Flavor bounds easily satisfied.

Numerical Example

m_ρ (GeV)	g_ρ	Y^U	Y^D	$\sin\varphi_{t_L}$	$\sin\varphi_{t_R}$	$\sin\varphi_{b_L}$	$\sin\varphi_{b_R}$
3000	3	3.1	3.2	0.5	0.75	0.125	0.035



All points allowed (vs. almost none in the anarchic case.)

CONCLUSIONS

- Flavor problems in composite Higgs models can be solved if the composite sector is flavor (or CP) invariant.

- MFV requires some light quarks to be composite. RH compositeness is weakly constrained, allowing large compositeness of light quarks.

- RH compositeness is extra-visible at LHC and signals could be seen at LHC7.