Title: MFV field content and phenomenology for LHC

Date: Dec 07, 2010 01:25 PM

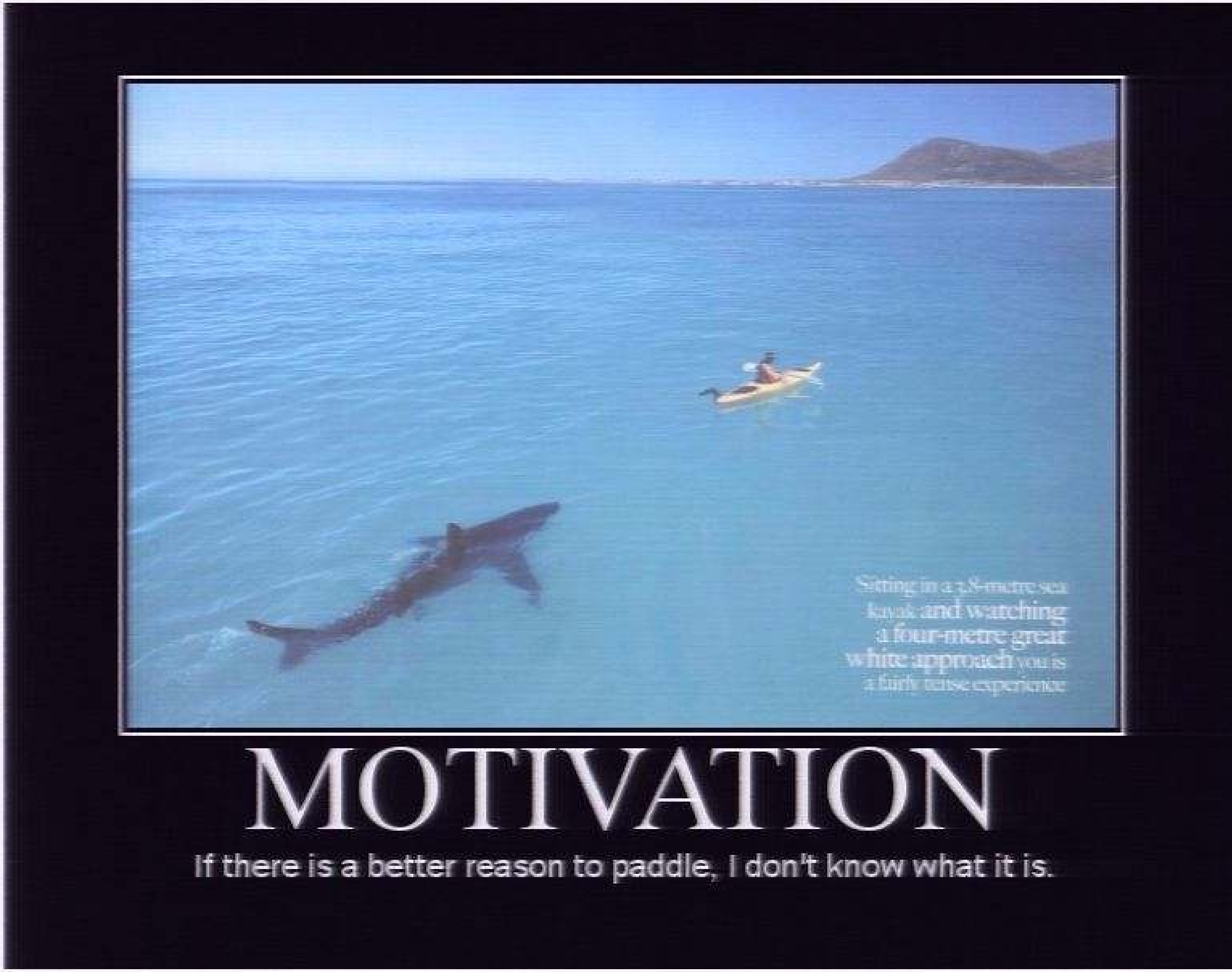
URL: http://pirsa.org/10120028

Abstract: TBA

MFV Field Content and Pheno for LHC.

Michael Trott, PI

arXiv:0907.2696 with C.P Burgess and S. Zuberi
arXiv: 0911.2225 with Arnold, Pospelov and M.Wise
arXiv: 1001.4287 with Fornal
arXiv: 1005.2185 with Arnold and Fornal
arXiv: 1009.2813 with M.Wise


Sitting in a 3.8-metre sea
kayak and watching
a four-metre great
white approach you is
a fairly tense experience
MOTIVATION
If there is a better reason to paddle, I don't know what it is.

What is your BSM motivation?

$$\mathcal{L}_{higgs} = (D_\mu H)^\dagger (D^\mu H) - \frac{\lambda}{4}(H^\dagger H - v^2/2)^2 + g_u^{ij} \bar{u}_R^i H^T \epsilon Q_L^j - g_d^{ij} \bar{d}_R^i H^\dagger Q_L^j + h.c.$$

$$+X$$

(good for LHC) TeV scale X stuff in your paper should:

a) Solve the Hierarchy Problem. Or solve a problem in someone else's solution to the HP.

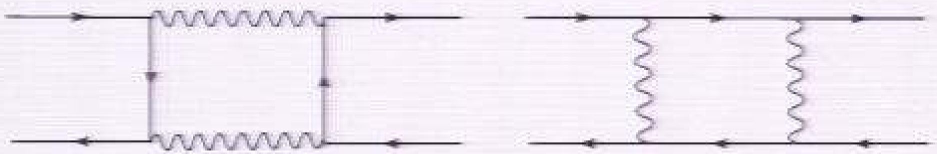
b) Solve another compelling problem - some observed anomaly.

c) Not already be ruled out by precision tests or simply carefully thinking.

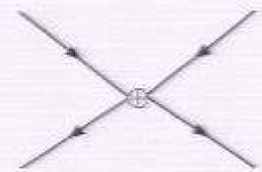
d) Not be too massive or weakly coupled to find at LHC.

e) Be reality.

What we already know about TeV Physics.



VS



Recall SM contribution to meson mixing:

$$\mathcal{A}_{SM} \sim \frac{m_t^2}{16\pi^2 v^4}(V_{3i}^{\star} V_{3j})^2 \langle \bar{M} | (\bar{d}_L^i \gamma^\mu d_L^j)^2 | M \rangle$$

Integrate out your desired NP states/sector

$$O_{ij} = \frac{c_{ij}}{\Lambda^2}(\bar{Q}_L^i \gamma^\mu Q_L^j)^2$$

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
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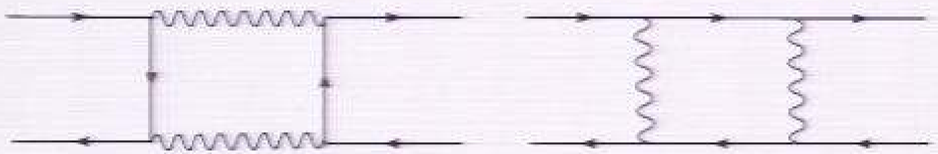
$(\bar{t}_L \gamma^\mu u_L)^2$	12		7.1×10^{-3}		$pp \to tt$

from 1005.3106 Gedalia,Perez

What we already know about TeV Physics.



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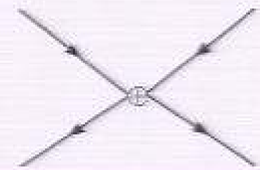

Considering LHC's discovery reach, ***anything*** we find will be consistent with these strong flavour constraints i.e. have a ***NON GENERIC*** symmetry structure.

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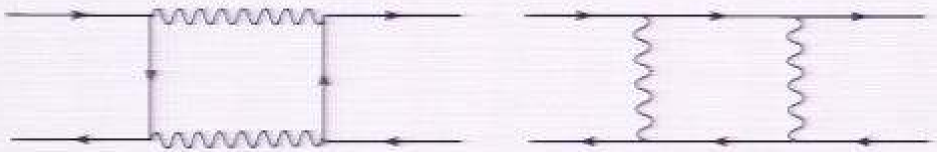

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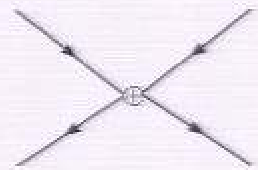

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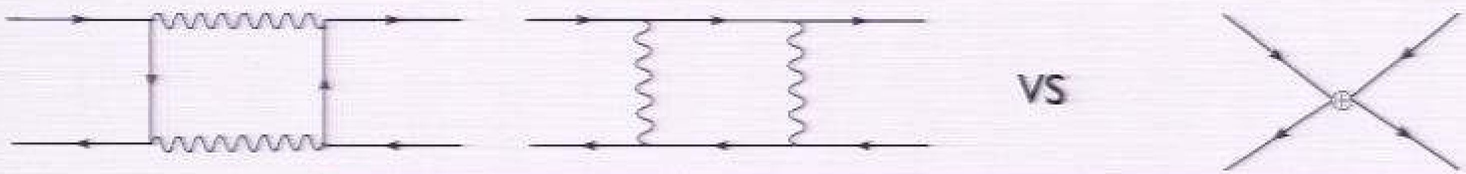

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A Symmetry Explanation.

Minimal Flavour Violation in an EFT formulation (0207036 D'Ambrosio, Giudice, Isidori, Strumia)

Restore the SM flavour symmetry: $\mathrm{G_F} = \mathrm{U(3)}^5 = \mathrm{S_Q} \otimes \mathrm{S_L} \otimes \mathrm{U(1)}^5$

where $S_Q = \mathrm{SU(3)_{Q_L}} \otimes \mathrm{SU(3)_{U_R}} \otimes \mathrm{SU(3)_{D_R}}$ $\quad S_L = \mathrm{SU(3)_{L_L}} \otimes \mathrm{SU(3)_{E_R}}$

By promoting the Yukawas to spurions: $Y_u \sim (3, \bar{3}, 1)$ $\quad Y_u \sim (3, 1, \bar{3})$

MFV means construct SM + NP theories that are invariant under $U(3)^5$

<u>So new physics will have the same symmetry breaking pattern in the flavour sector as the SM.</u>

→ Trivial implementation : No flavour structure in NP.

→ Non-Trivial implementation : Explore allowed TeV scale flavour reps.

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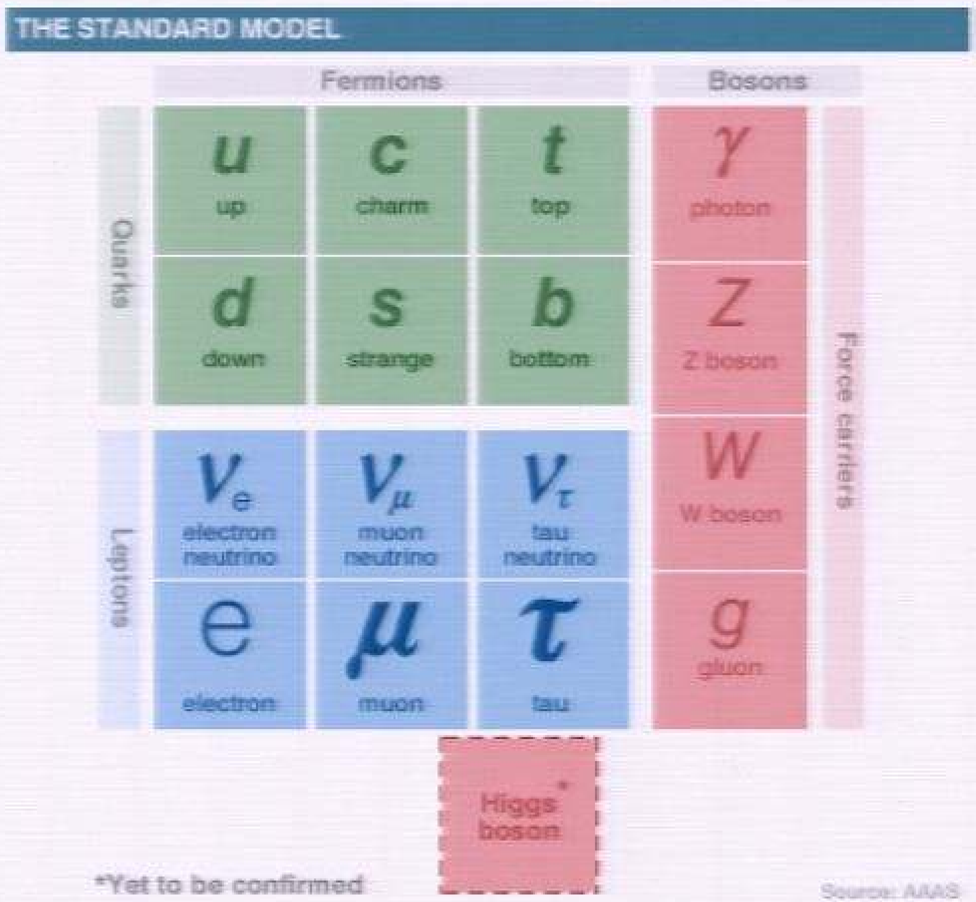
MFV field content

Historical Examples of Physics that DOES NOT solve the Hierarchy Problem.



$+GR$

There may be more....

Spin 0 - Reminder

Flavour Singlet case: Higgs: $(1,2)_{1/2}$

Octet Higgs: $(8,2)_{1/2}$ **hep-ph/0606172** Manohar and Wise

arXiv: **0911.2225** with Arnold, Pospelov and M.Wise

Case	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$	Couples to
I	1	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R\ Q_L$
II	8	2	1/2	$(3,1,\bar{3})$	$\bar{u}_R\ Q_L$
III	1	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R\ Q_L$
IV	8	2	-1/2	$(1,3,\bar{3})$	$\bar{d}_R\ Q_L$
V	3	1	-4/3	$(3,1,1)$	$u_R\ u_R$
VI	$\bar{6}$	1	-4/3	$(\bar{6},1,1)$	$u_R\ u_R$
VII	3	1	2/3	$(1,3,1)$	$d_R\ d_R$
VIII	$\bar{6}$	1	2/3	$(1,\bar{6},1)$	$d_R\ d_R$
IX	3	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$
X	$\bar{6}$	1	-1/3	$(\bar{3},\bar{3},1)$	$d_R\ u_R$
XI	3	1	-1/3	$(1,1,6)$	$Q_L\ Q_L$
XII	$\bar{6}$	1	-1/3	$(1,1,3)$	$Q_L\ Q_L$
XIII	3	3	-1/3	$(1,1,3)$	$Q_L\ Q_L$
XIV	$\bar{6}$	3	-1/3	$(1,1,\bar{6})$	$Q_L\ Q_L$

Cases I–IV: Baryon number conservation from gauge symmetry. Baryon number 0.

Cases V–XIV: Baryon number -2/3.

Gauge symmetries protect proton decay alone.

Need lepton MFV to protect the proton.

Spin 0 - Update

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Early Results using Dijet bounds of CMS/ATLAS

arXiv: **1010.4309** T. Han, I. Lewis and Z. Liu

~ Mass bound ~ 2.1 TeV

~ Mass bound ~ 0.5 TeV

~ Mass bound ~ 1.9 TeV

STILL NEEDS A DEDICATED EXPERIMENTAL STUDY!

Spin 1/2 - Vector Quarks

arXiv: 1005.2185 with Arnold and Fornal
see also arXiv:0706.1845 Grossman,Nir,Thaler,Volansky,Zupan

Consider flavour triplet (SU(2) singlet) Vector quarks that mix with the SM quarks:

$$\begin{aligned}\mathcal{L}^d &= \bar{Q}_L i D Q_L + \bar{d}_R i D d_R + \bar{V}_L^d i D V_L^d + \bar{V}_R^d i D V_R^d \\ &+ \left[\kappa_1^d m_1^d \bar{V}_L^d d_R + \kappa_2^d m_2^d \bar{V}_L^d V_R^d + \kappa_3^d \left(\frac{\sqrt{2} m_3^d}{v}\right) \bar{Q}_L H V_R^d + g_d \bar{Q}_L H d_R + \text{h.c.}\right] .\end{aligned}$$

Field content and couplings that satisfy MFV: (very similar story for up vector quarks)

	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$				
case	κ_1^d	κ_2^d	κ_3^d	V_L^d	V_R^d
I	0	(1,1,1)	(1,$\bar{3}$,3)	(1,3,1)	(1,3,1)
II	(1,$\bar{3}$,3)	(1,1,1)	(1,1,1)	(1,1,3)	(1,1,3)
III	0	(1,$\bar{3}$,3)	(1,$\bar{3}$,3)	(1,1,3)	(1,3,1)
IV	(1,1,1)*	(1,3,$\bar{3}$)	(1,1,1)	(1,3,1)	(1,1,3)
V	(1,$\bar{3}$,3)	($\bar{3}$,1,3)	($\bar{3}$,1,3)	(1,1,3)	(3,1,1)

← Only this one is Glashow-Weinberg "FLAVOUR NATURAL".

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V	$(1,\bar{3},3)$	$(\bar{3},1,3)$	$(\bar{3},1,3)$	(1,1,3)	(3,1,1)

Only this one is Glashow-Weinberg "FLAVOUR NATURAL".

Non Hierarchical SM quark masses due to mixing for ex..

MFV is Predictive!

It allows you to explicitly solve for the mass spectrum and mixing in these models.

Introduce Rotations:

$$d_R = \mathcal{U}(d,R)\, d'_R, \qquad d_L = \mathcal{U}(d,L)\, d'_L,$$
$$u_R = \mathcal{U}(u,R)\, u'_R, \qquad u_L = \mathcal{U}(u,L)\, d'_L,$$
$$V_R^d = \mathcal{U}(V,R)\, V_R^{d\prime}, \qquad V_L^d = \mathcal{U}(V,L)\, V_L^{d\prime}.$$

Where $\mathcal{U}(d,L)^\dagger\, g_d\, \mathcal{U}(d,R) = \frac{\sqrt{2}\mathcal{M}_d^0}{v}, \quad \mathcal{U}(u,L)^\dagger\, g_u\, \mathcal{U}(u,R) = \frac{\sqrt{2}\mathcal{M}_u^0}{v}.$

$$\mathcal{L}_m = \begin{pmatrix} \bar{d}'_L \\ \bar{V}_L^{d\prime} \end{pmatrix}^T M_d \begin{pmatrix} d'_R \\ V_R^{d\prime} \end{pmatrix} \qquad M_d = \begin{pmatrix} \mathcal{M}_d^0 & m_3^d\, \mathcal{U}^\dagger(d,L)\, \kappa_3^d\, \mathcal{U}(V,R) \\ m_1^d\, \mathcal{U}^\dagger(V,L)\, \kappa_1^d\, \mathcal{U}(d,R) & m_2^d\, \mathcal{U}^\dagger(V,L)\, \kappa_2^d\, \mathcal{U}(V,R) \end{pmatrix}$$

Can choose vector quark rotations as this ' basis is not an eigenstate basis of an interaction for the vector quark:

$$\begin{pmatrix} d''_L \\ V_L^{d\prime\prime} \end{pmatrix} = \begin{pmatrix} 1-\frac{\epsilon_i^2}{2} & -\epsilon_i \\ \epsilon_i & 1-\frac{\epsilon_i^2}{2} \end{pmatrix} \begin{pmatrix} d'_L \\ V_L^{d\prime} \end{pmatrix} \quad \text{where} \quad \epsilon_i = \sqrt{2}\,\frac{m_3}{m_2}\,\frac{(\mathcal{M}_d^0)_i}{v}$$

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$$\mathcal{L}^d = \bar{Q}_L i \not{D} Q_L + \bar{d}_R i \not{D} d_R + \bar{V}^d_L i \not{D} V^d_L + \bar{V}^d_R i \not{D} V^d_R + \left[\kappa^d_1 m^d_1 \bar{V}^d_L d_R + \kappa^d_2 m^d_2 \bar{V}^d_L V^d_R + \kappa^d_3 \left(\frac{\sqrt{2} m^d_3}{v}\right) \bar{Q}_L H V^d_R + g_d \bar{Q}_L H d_R + \text{h.c.}\right] .$$

Field content and couplings that satisfy MFV: (very similar story for up vector quarks)

	$SU(3)_{U_R} \times SU(3)_{D_R} \times SU(3)_{Q_L}$				
case	κ^d_1	κ^d_2	κ^d_3	V^d_L	V^d_R
I	0	(1,1,1)	$(1,\bar{3},3)$	(1,3,1)	(1,3,1)
II	$(1,\bar{3},3)$	(1,1,1)	(1,1,1)	(1,1,3)	(1,1,3)
III	0	$(1,\bar{3},3)$	$(1,\bar{3},3)$	(1,1,3)	(1,3,1)
IV	(1,1,1)*	$(1,3,\bar{3})$	(1,1,1)	(1,3,1)	(1,1,3)
V	$(1,\bar{3},3)$	$(\bar{3},1,3)$	$(\bar{3},1,3)$	(1,1,3)	(3,1,1)

Only this one is Glashow-Weinberg "FLAVOUR NATURAL".

Non Hierarchical SM quark masses due to mixing for ex..

MFV is Predictive!

It allows you to explicitly solve for the mass spectrum and mixing in these models.

Introduce Rotations:

$$d_R = \mathcal{U}(d,R)\, d'_R, \qquad d_L = \mathcal{U}(d,L)\, d'_L,$$
$$u_R = \mathcal{U}(u,R)\, u'_R, \qquad u_L = \mathcal{U}(u,L)\, d'_L,$$
$$V^d_R = \mathcal{U}(V,R)\, V^{d\prime}_R, \qquad V^d_L = \mathcal{U}(V,L)\, V^{d\prime}_L.$$

Where $\mathcal{U}(d,L)^\dagger\, g_d\, \mathcal{U}(d,R) = \frac{\sqrt{2}\mathcal{M}^0_d}{v}, \quad \mathcal{U}(u,L)^\dagger\, g_u\, \mathcal{U}(u,R) = \frac{\sqrt{2}\mathcal{M}^0_u}{v}.$

$$\mathcal{L}_m = \begin{pmatrix} \bar{d}'_L \\ \bar{V}^{d\prime}_L \end{pmatrix}^T M_d \begin{pmatrix} d'_R \\ V^{d\prime}_R \end{pmatrix} \qquad M_d = \begin{pmatrix} \mathcal{M}^0_d & m^d_3\, \mathcal{U}^\dagger(d,L)\, \kappa^d_3\, \mathcal{U}(V,R) \\ m^d_1\, \mathcal{U}^\dagger(V,L)\, \kappa^d_1\, \mathcal{U}(d,R) & m^d_2\, \mathcal{U}^\dagger(V,L)\, \kappa^d_2\, \mathcal{U}(V,R) \end{pmatrix}$$

Can choose vector quark rotations as this ' basis is not an eigenstate basis of an interaction for the vector quark:

$$\begin{pmatrix} d''_L \\ V^{d\prime\prime}_L \end{pmatrix} = \begin{pmatrix} 1-\frac{\epsilon_i^2}{2} & -\epsilon_i \\ \epsilon_i & 1-\frac{\epsilon_i^2}{2} \end{pmatrix} \begin{pmatrix} d'_L \\ V^{d\prime}_L \end{pmatrix} \quad \text{where} \quad \epsilon_i = \sqrt{2}\,\frac{m_3}{m_2}\frac{(\mathcal{M}^0_d)_i}{v}$$

Fun with MFV Vector Quarks

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- small diagonal mixing correction of the SM quarks couplings to W,Z

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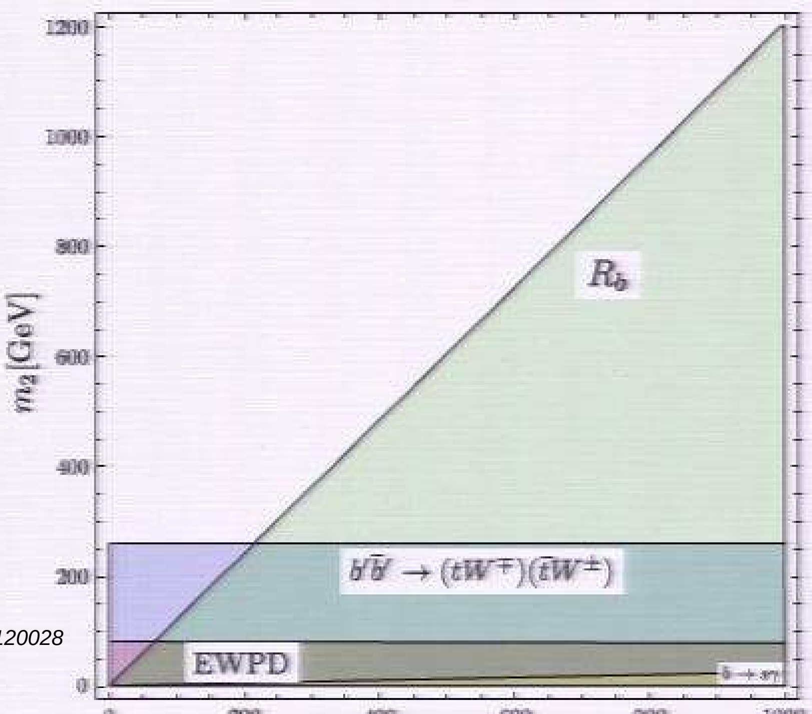
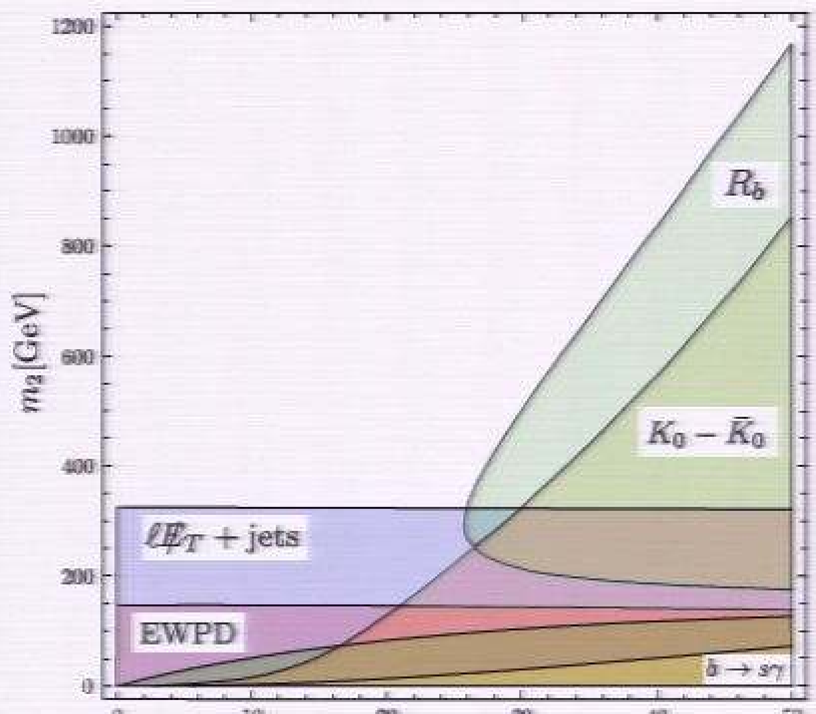
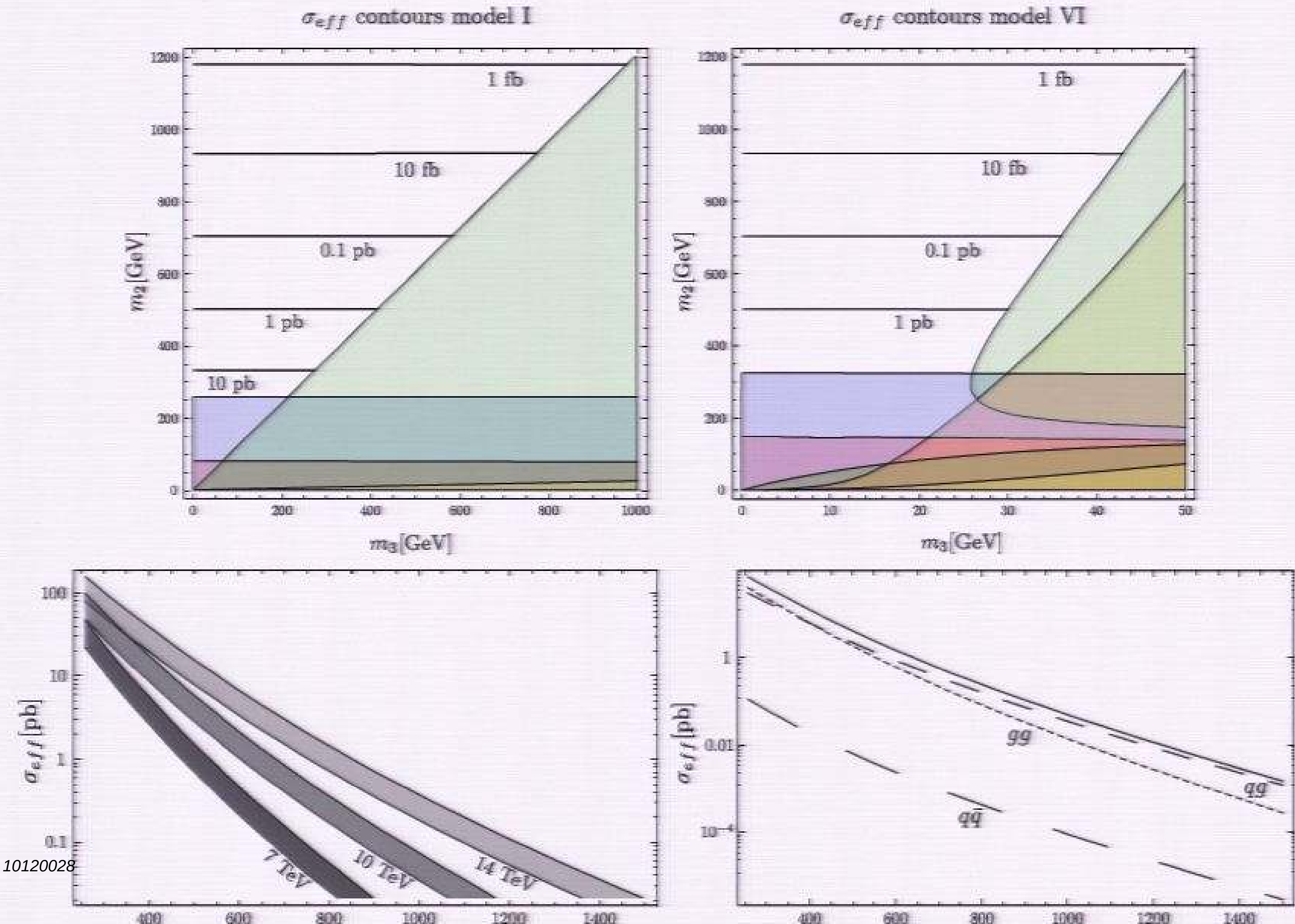


Constraints on model VI



Prospects for Discovery



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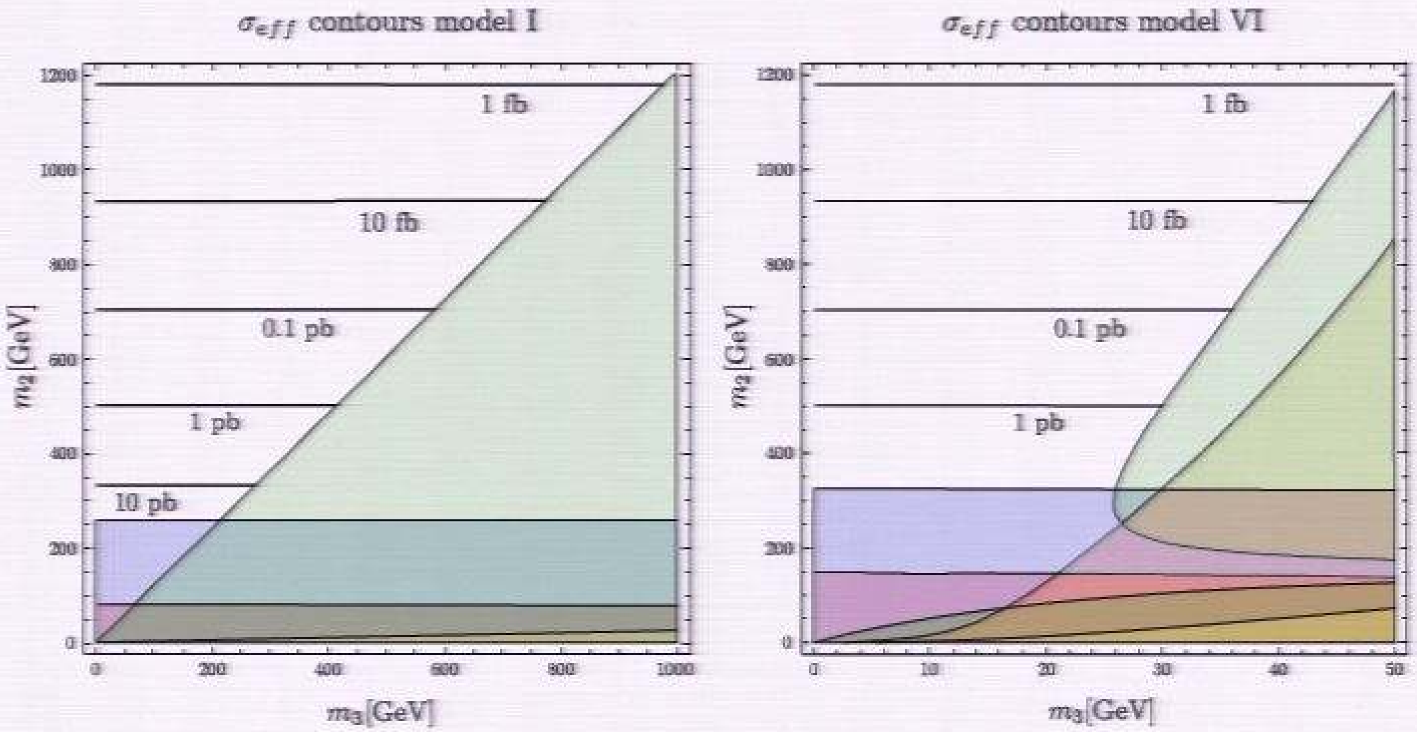

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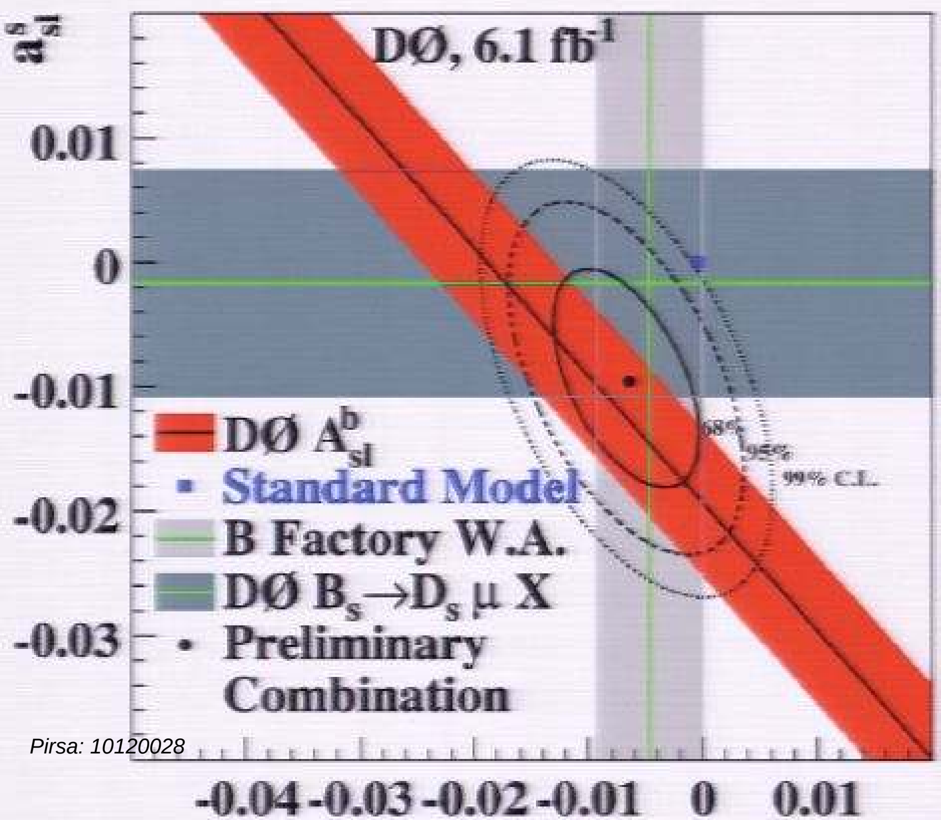

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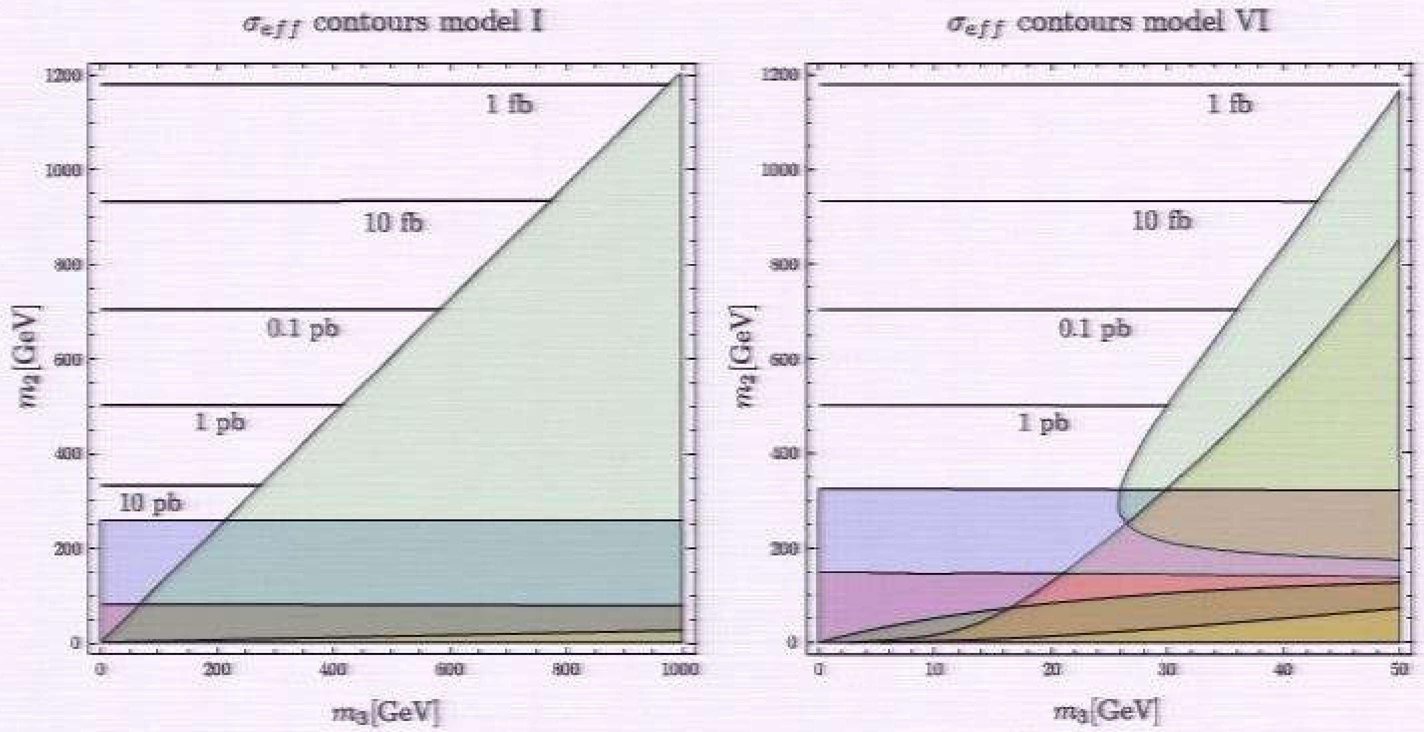

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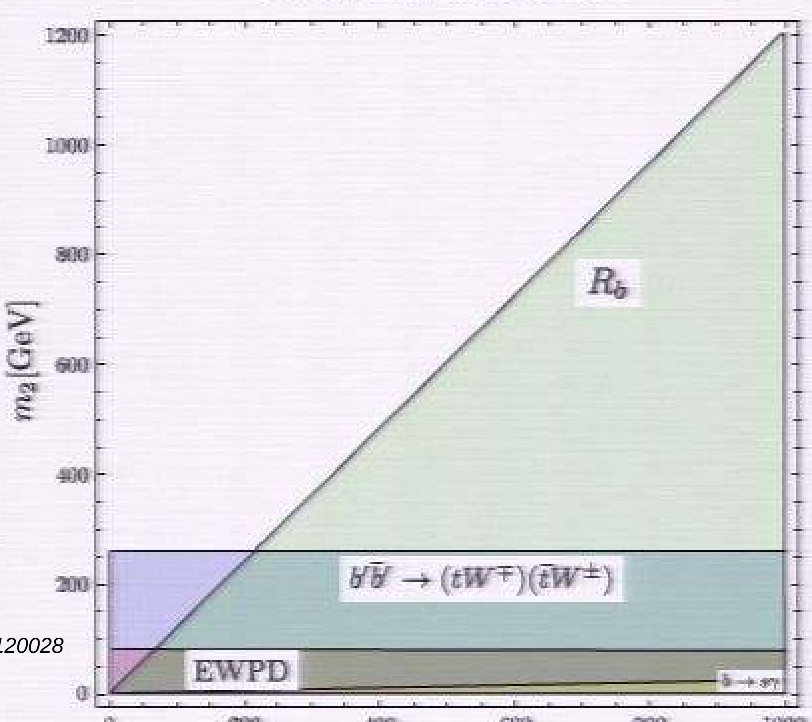

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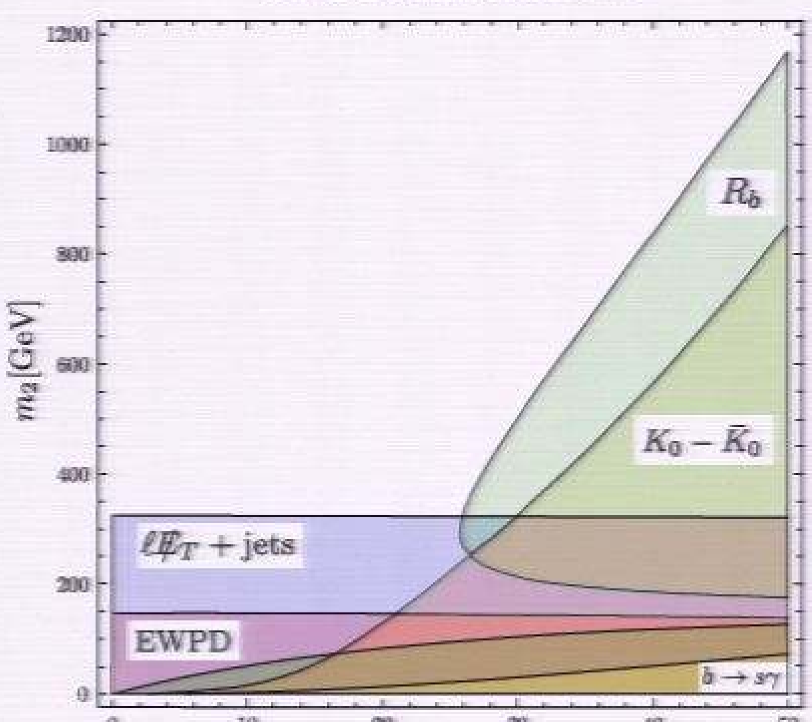

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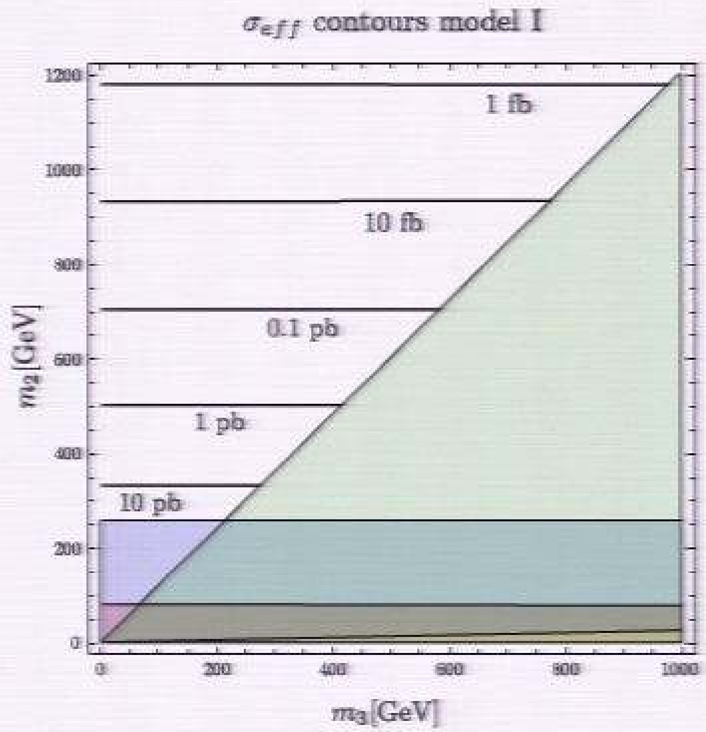

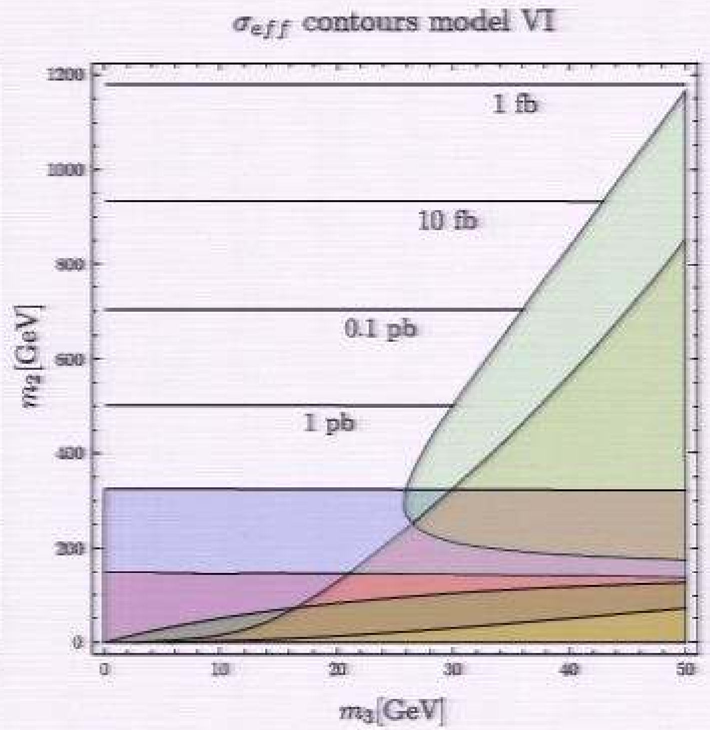

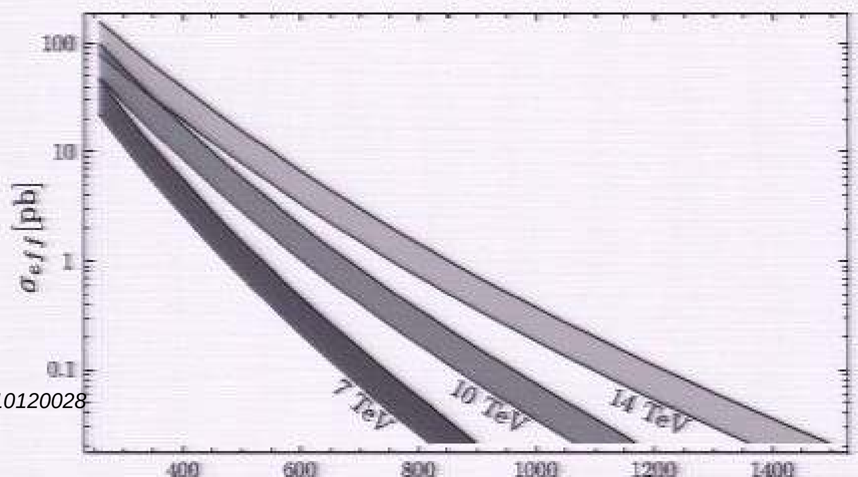

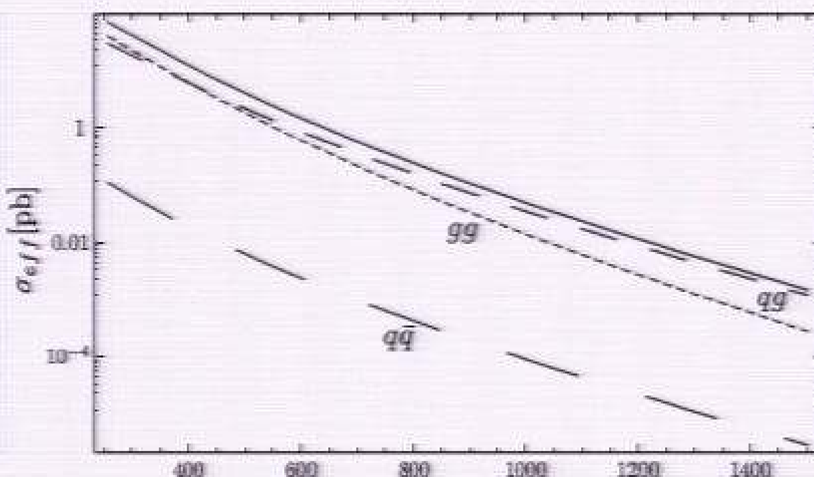

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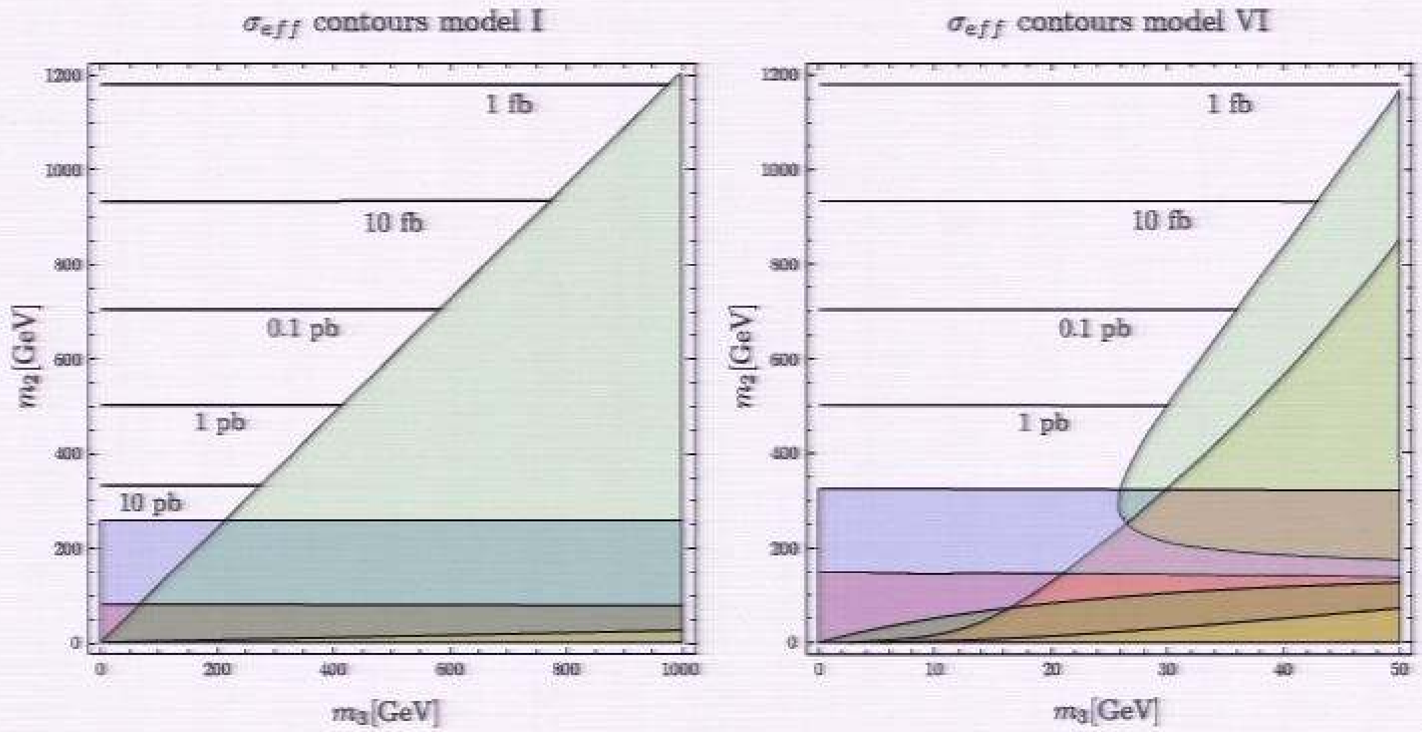

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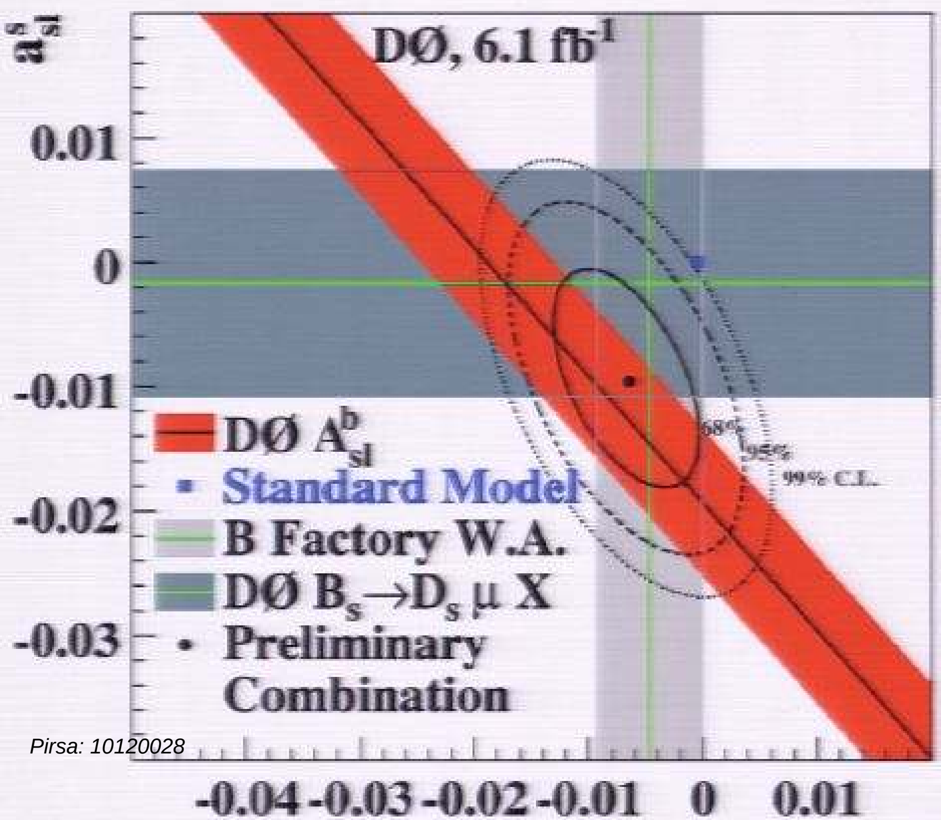

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Lunghi & Soni 0803.4340

Can MFV field content explain this?

The global fitting team CKMfitter (arXiv:1008.1593) argues there is a global $\sim 3\sigma$ anomaly.

For it to be consistent with the pattern of deviations it should be a correction of the form:

$$M_{12}^q = (M_{12}^q)^{SM}(1 + h_q e^{2i\sigma_q})$$

$$h_q = 0.255 \qquad 2\sigma_q = 180 + 63.4$$

arXiv:1008.1593

Considering spin, scalar exchange operators a good bet:

$$\mathcal{H}_q = (V_{tq}^\star V_{tb})^2 C^{SM} (\bar{b}_L^\alpha \gamma^\mu q_L^\alpha \bar{b}_L^\beta \gamma_\mu q_L^\beta) + (V_{tq}^\star V_{tb})^2 \frac{C^{NP}}{\Lambda^2} (\bar{b}_R^\alpha q_L^\alpha \bar{b}_R^\beta q_L^\beta)$$

Then $h_q e^{2i\sigma_q} \simeq -\frac{5}{8\Lambda^2}\left(\frac{C^{\rm NP}(m_t)}{C^{\rm SM}(m_t)}\right)\frac{\eta'}{\eta}.$

In terms of mass scale, fits say $\Lambda \sim 13\, y_b \sqrt{0.2/h_b}\,\mathrm{TeV}$ within MFV framework.

arXiv:1006.0432 Ligeti, Papucci, Perez, Zupan

What is a simple MFV way this could come about?

MFV Two Scalar doublet model

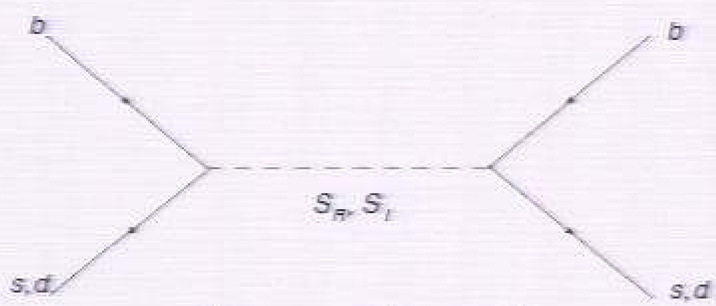
arXiv: 1009.2813 with M.Wise
see also arXiv:1007.5291 Buras,Isidori,Paradisi

$$\mathcal{L}_Y = \bar{u}^i_R \, {g_U}^j_{\ i} Q_{Lj} H + \bar{d}^i_R \, {g_D}^j_{\ i} Q_{Lj} H^\dagger + \bar{u}^i_R \, {Y_U}^j_{\ i} Q_{Lj} S + \bar{d}^i_R \, {Y_D}^j_{\ i} Q_{Lj} S^\dagger + \text{h.c.}$$

Second Scalar doublet S $\quad S = \begin{pmatrix} S^+ \\ (S^0_R + i S^0_I)/\sqrt{2} \end{pmatrix}.$

Here:
$$\begin{aligned} {Y_U}^j_{\ i} &= \eta_U \, {g_U}^j_{\ i} + \eta'_U \, {g_U}^j_{\ k} [(g^\dagger_U)^k_{\ l} \, (g_U)^l_{\ i}] + \cdots , \\ {Y_D}^j_{\ i} &= \eta_D \, {g_D}^j_{\ i} + \eta'_D \, {g_D}^j_{\ k} [(g^\dagger_U)^k_{\ l} \, (g_U)^l_{\ i}] + \cdots . \end{aligned}$$

Recall Yukawas are spurions in MFV: $\quad g_U \to V_U \, g_U \, V_Q^\dagger, \qquad g_D \to V_D \, g_D \, V_Q^\dagger$



Then: $\quad C^{\rm NP}(m_t) = (\eta'_D)^2 \left(\frac{\sqrt{2} m_t}{v} \right)^4 \left(\frac{\lambda_3 \, m_b^2}{m_S^4 - \lambda_3^2 v^4} \right).$

$$\begin{aligned} S_R^2 &= m_s^2 + \lambda_3 v^2, \\ S_I^2 &= m_s^2 - \lambda_3 v^2. \end{aligned}$$

Pheno Issues

Avoid a light neutral state:

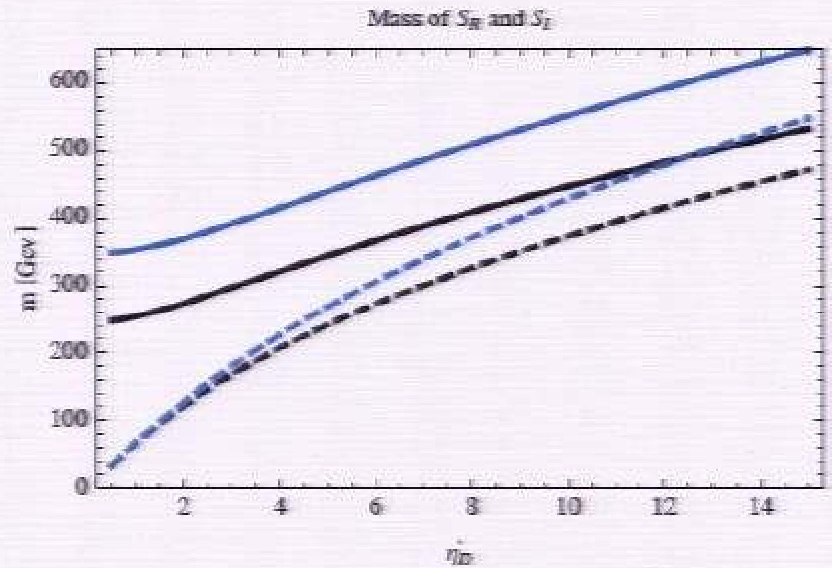


FIG. 1: Mass of S_R (solid) and S_I (dashed) as a function of η'_D for fixed λ_3. The upper (blue curves) are for $\lambda_3 = 1$ the lower (black) curves are for $\lambda_3 = 0.5$.

Enhanced couplings to b quarks preferred.

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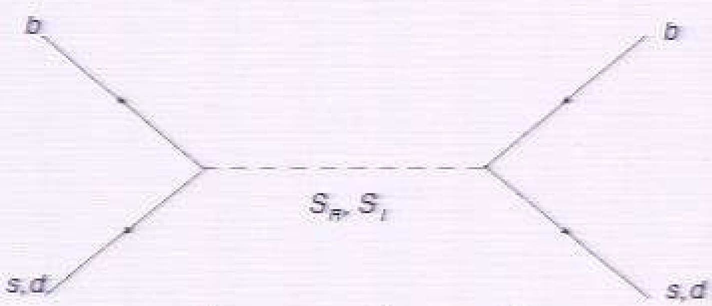

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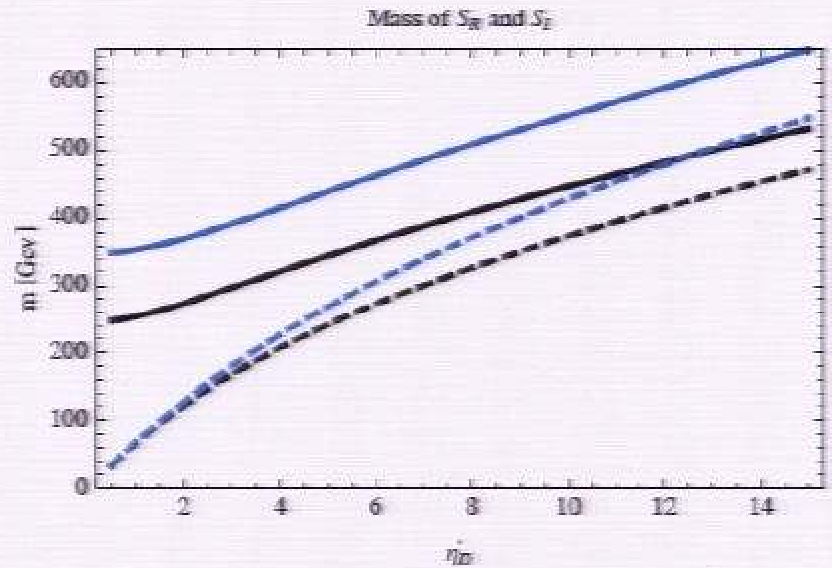

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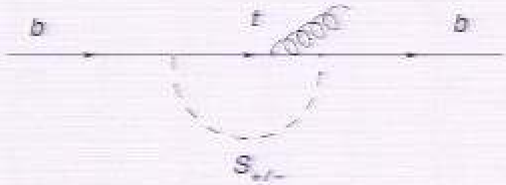

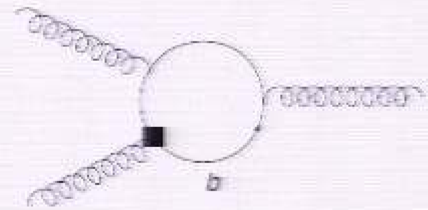

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$$O_G = g_3^3 \, f_{\alpha\beta\gamma} \, \epsilon^{\mu\nu\lambda\sigma} \, G_{\alpha\mu\rho} \, G^{\rho}_{\beta\nu} \, G_{\gamma\lambda\sigma},$$

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Using NDA this gives for the Neutron EDM:

$$d_n \sim 2\mathrm{Im}[\eta_U^\star \eta_D^\star + \eta_U'^\star \eta_D^\star + \eta_U^\star \eta_D'^\star + \eta_U'^\star \eta_D'^\star + \cdots] f(m_t^2/m_{s_\pm}^2) \left(\frac{1\,\mathrm{TeV}}{m_{s_\pm}}\right)^2 10^{-26}$$

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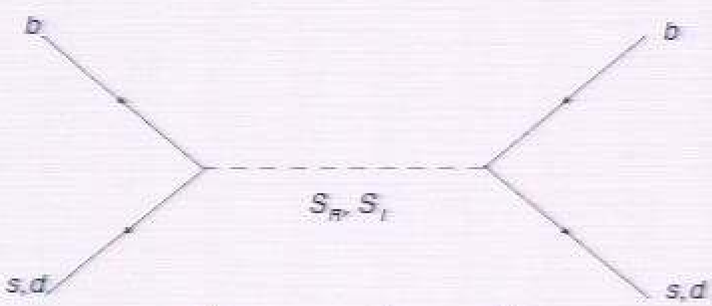

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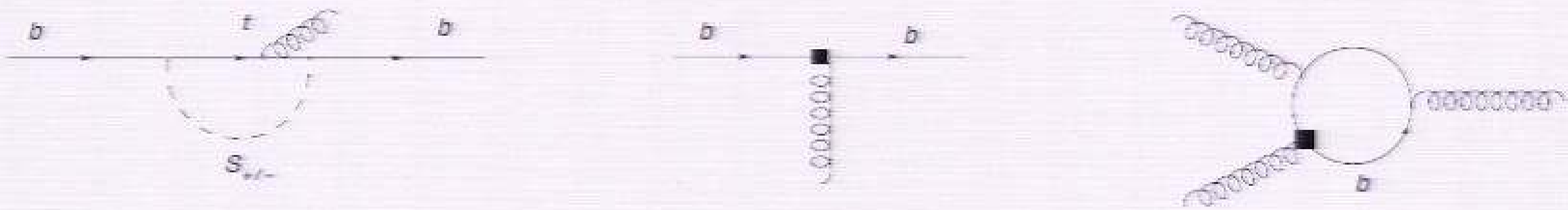

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Can MFV also do this with symmetry and avoid this parameter tuning? YES.

MFV to the Rescue,Again.

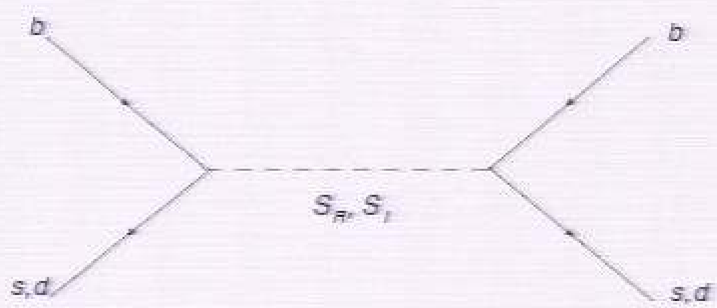
If the Second Scalar doublet S transforms as $(1, 8, 1)$ then

$$\mathcal{L}_Y = \bar{u}^i_R \hat{Y}_U{}^l{}_i (g^\dagger_D)^o{}_l (T^a)^n{}_o (g_D)^j{}_n Q_{Lj} S^a_8 + \bar{d}^n_R (T^a)^m_i (\hat{Y}_D)^j{}_m Q_{Lj} S^{\dagger a}_8 + \text{h.c.}$$

all the effective up quark couplings are suppressed by $y_b^2 \sim 10^{-3}$

Basic Pheo goes though the same and the pheno bounds are dealt with by MFV symmetry!

Wilson Coefficient in this case:



$$C^{\text{NP}}(m_t) = \frac{(\hat{\eta}'_D)^2 \left(\sqrt{2}\, m_t/v\right)^4 \hat{\lambda}_3\, m_b^2/6}{\hat{m}_S^4 - \hat{\lambda}_3^2 v^4/4}.$$

Summary

- Considering LHC's discovery reach, ***anything*** found will be consistent with flavour constraints.
- The NP flavour problem can be dealt with a simple symmetry, MFV, so that NP flavour violation follows the same pattern as the SM flavour violation
- Field content of this form is being classified and studied to explore a possible TeV scale MFV sector. Spin 0, Spin 1/2...
- MFV does allow flavour universal NP CP violating phases.
- MFV directly leads to simple models that can explain anomalies like the D0 dimuon asymmetry anomaly, if it is confirmed.
- You might find some of this stuff. Good to know what it is and how to look for it/confirm it.