

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?

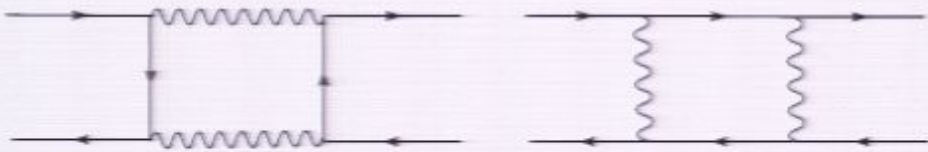
$$\mathcal{L}_{higgs} = (D_\mu H)^\dagger (D^\mu H) - \frac{\lambda}{4} (H^\dagger H - v^2/2)^2 + g_u^{ij} \bar{u}_R^i H^T \epsilon Q_L^j - g_d^{ij} \bar{d}_R^i H^\dagger Q_L^j + h.c. \\ + X$$

(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:

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

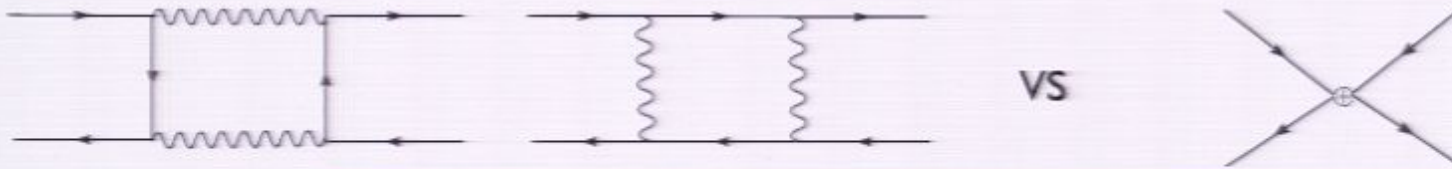
Integrate out your desired NP states/sector

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

Operator	Bounds on $\Lambda$ in TeV ( $c_{ij} = 1$ )		Bounds on $c_{ij}$ ( $\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	$9.8 \times 10^2$	$1.6 \times 10^4$	$9.0 \times 10^{-7}$	$3.4 \times 10^{-9}$	$\Delta m_K; \epsilon_K$
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from 1005.3106 Gedalia,Perez

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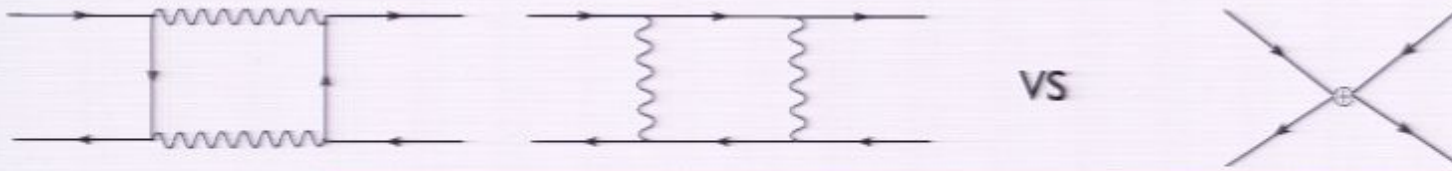
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# A Symmetry Explanation.

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


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


where  $S_Q = SU(3)_{QL} \otimes SU(3)_{UR} \otimes SU(3)_{DR}$      $S_L = SU(3)_{LL} \otimes SU(3)_{ER}$

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

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

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

 Trivial implementation : No flavour structure in NP.

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

## What is your BSM motivation?

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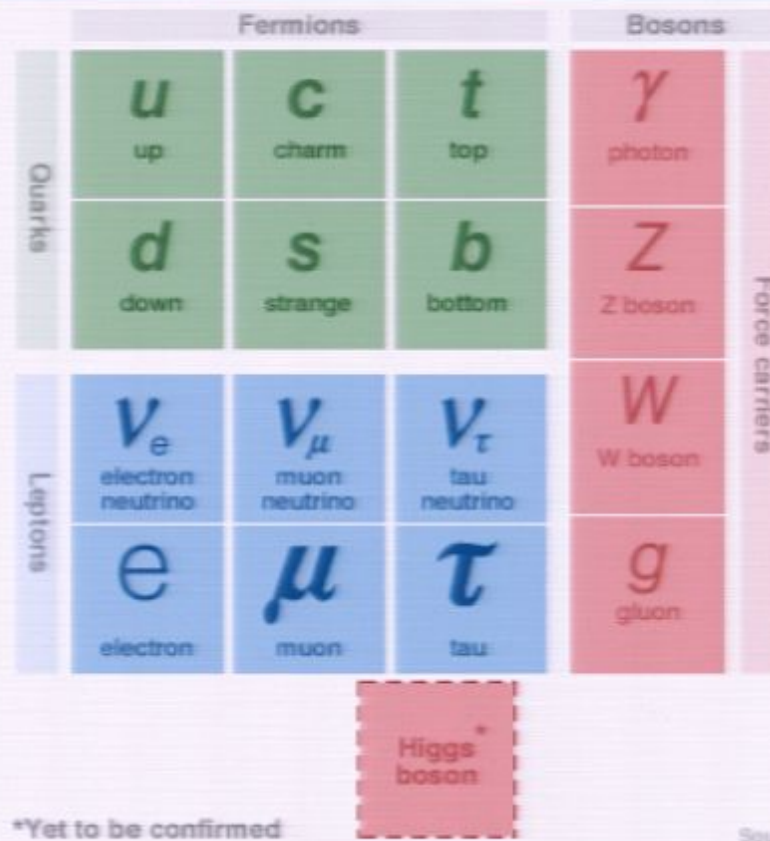
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MFV field  
content

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

## THE STANDARD MODEL



$+GR$

\*Yet to be confirmed

Source: AAAS



# Spin 0 - Reminder

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

Octet Higgs:  $(8, 2)_{1/2}$

hep-ph/0606172 Manohar and 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	$(1, 1, \bar{6})$	$Q_L Q_L$
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	$(1, 1, \bar{6})$	$Q_L Q_L$

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



Baryon number conservation from gauge symmetry. Baryon number 0.



✓  
✓  
✓  
✓  
✓  
✓  
✓  
✓  
✓  
✓

Baryon number -2/3.

Gauge symmetries protect proton decay alone.

Need lepton MFV to protect the proton.

## Spin 0 - Update

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

Octet Higgs:  $(8, 2)_{1/2}$

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
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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	$(1, 3, 1)$	$d_R d_R$
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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:

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

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	$\kappa_1^d$	$\kappa_2^d$	$\kappa_3^d$	$V_L^d$	$V_R^d$
I	0	(1,1,1)	(1,3,3)	(1,3,1)	(1,3,1)
II	(1,3,3)	(1,1,1)	(1,1,1)	(1,1,3)	(1,1,3)
III	0	(1,3,3)	(1,3,3)	(1,1,3)	(1,3,1)
IV	(1,1,1)*	(1,3,3)	(1,1,1)	(1,3,1)	(1,1,3)
V	(1,3,3)	(3,1,3)	(3,1,3)	(1,1,3)	(3,1,1)

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



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← 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:

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

Where

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

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

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

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



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## MFV is Predictive!

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

Introduce Rotations:

$$d_R = \mathcal{U}(d, R) d'_R, \quad d_L = \mathcal{U}(d, L) d'_L,$$

$$u_R = \mathcal{U}(u, R) u'_R, \quad u_L = \mathcal{U}(u, L) u'_L,$$

$$V_R^d = \mathcal{U}(V, R) V_R^{d'}, \quad V_L^d = \mathcal{U}(V, L) V_L^{d'}.$$

Where

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

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

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

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

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Solving in this way all models, we found one is FLAVOUR NATURAL in each case:

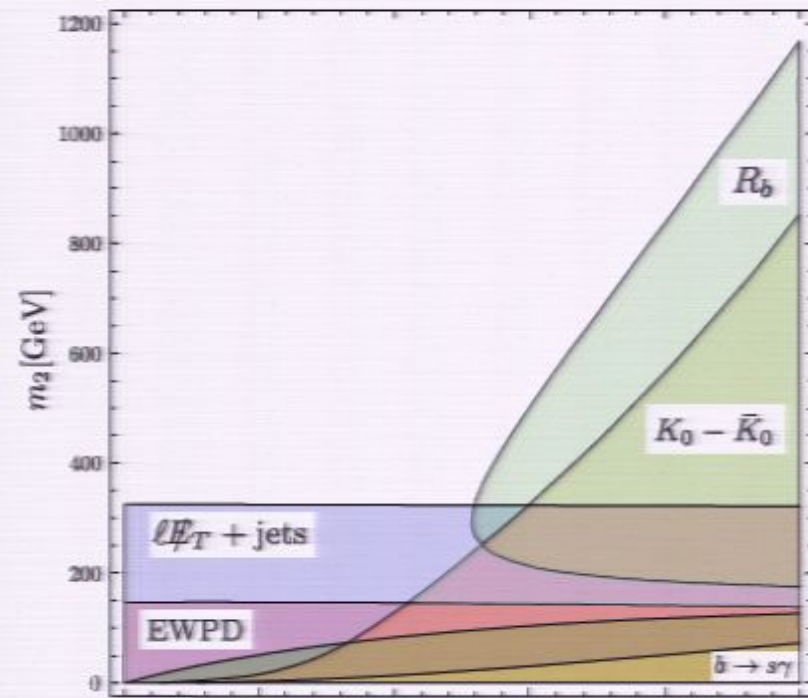
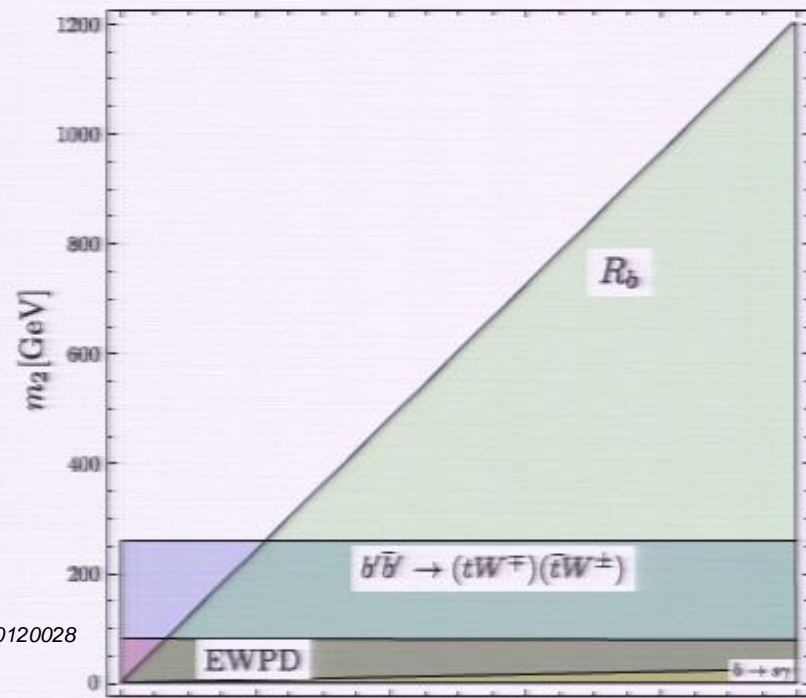
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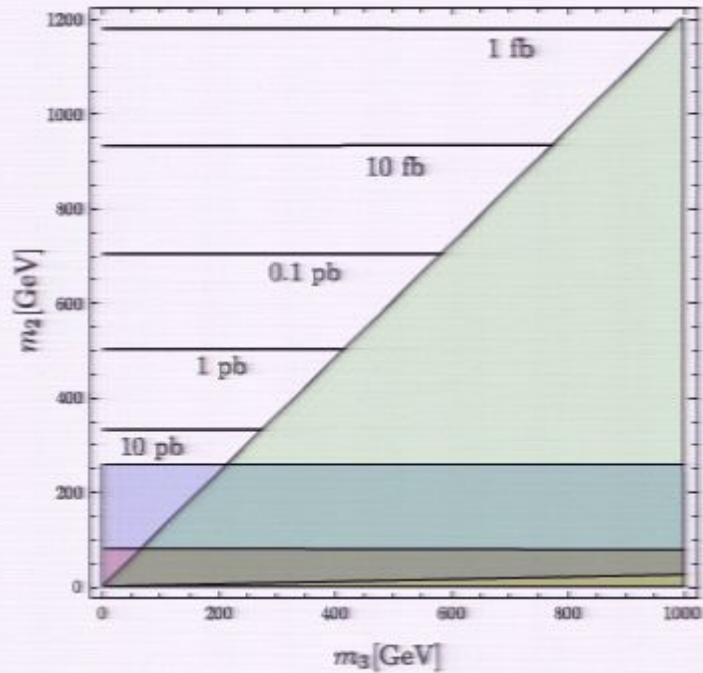
Constraints on model I

Constraints on model VI

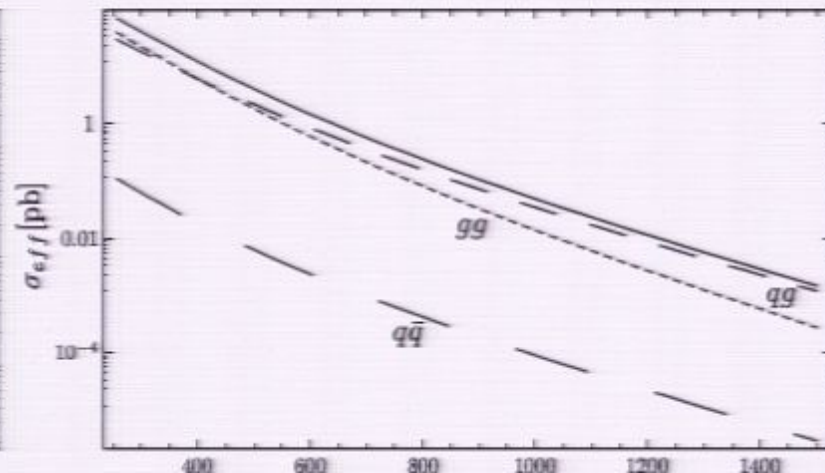
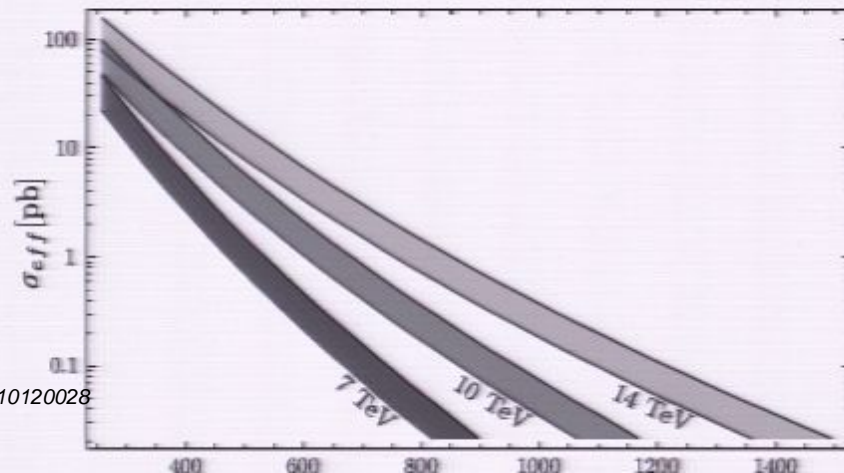
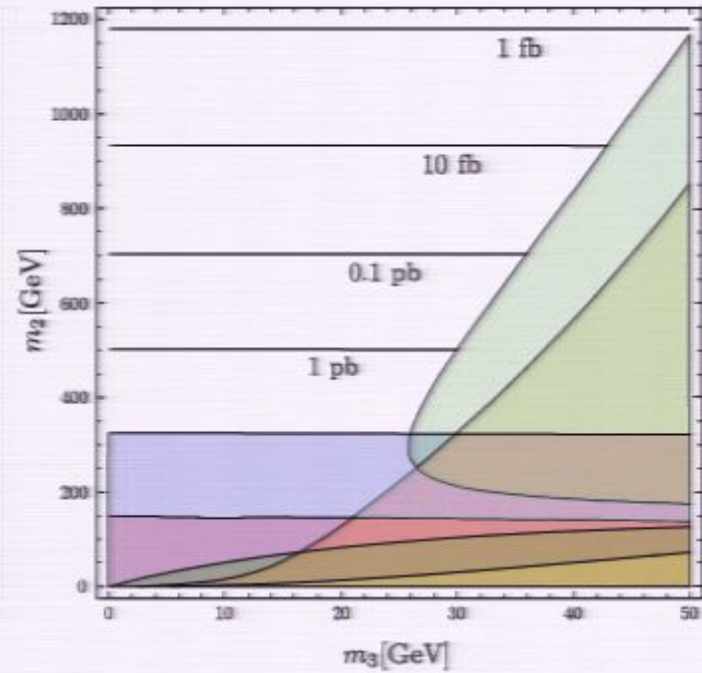


# Prospects for Discovery

$\sigma_{eff}$  contours model I



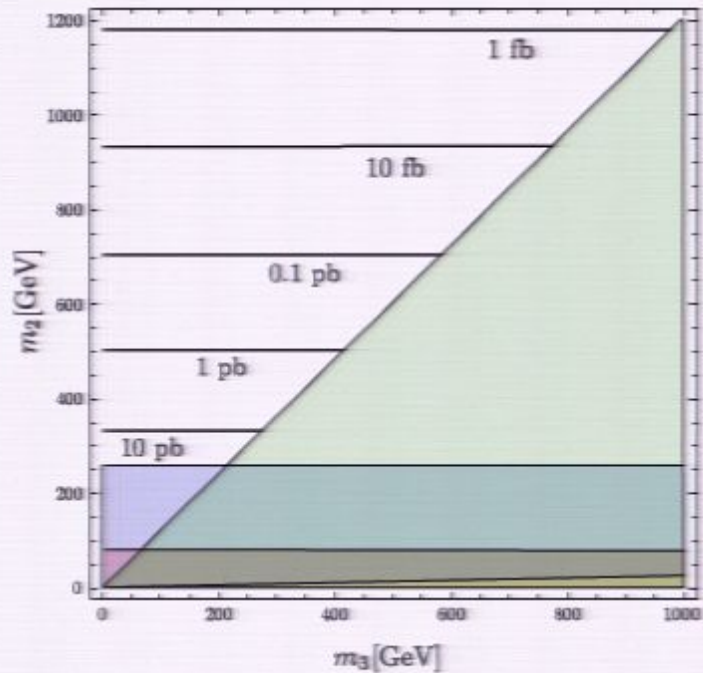
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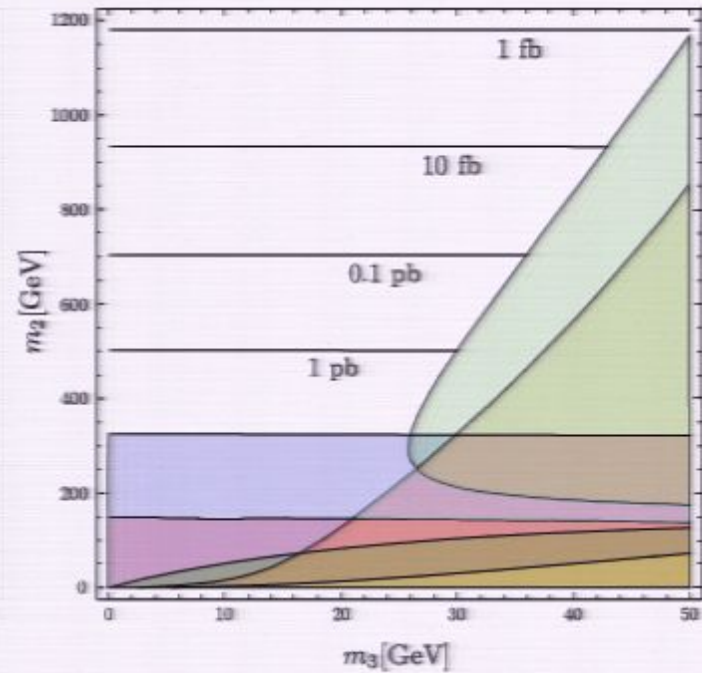


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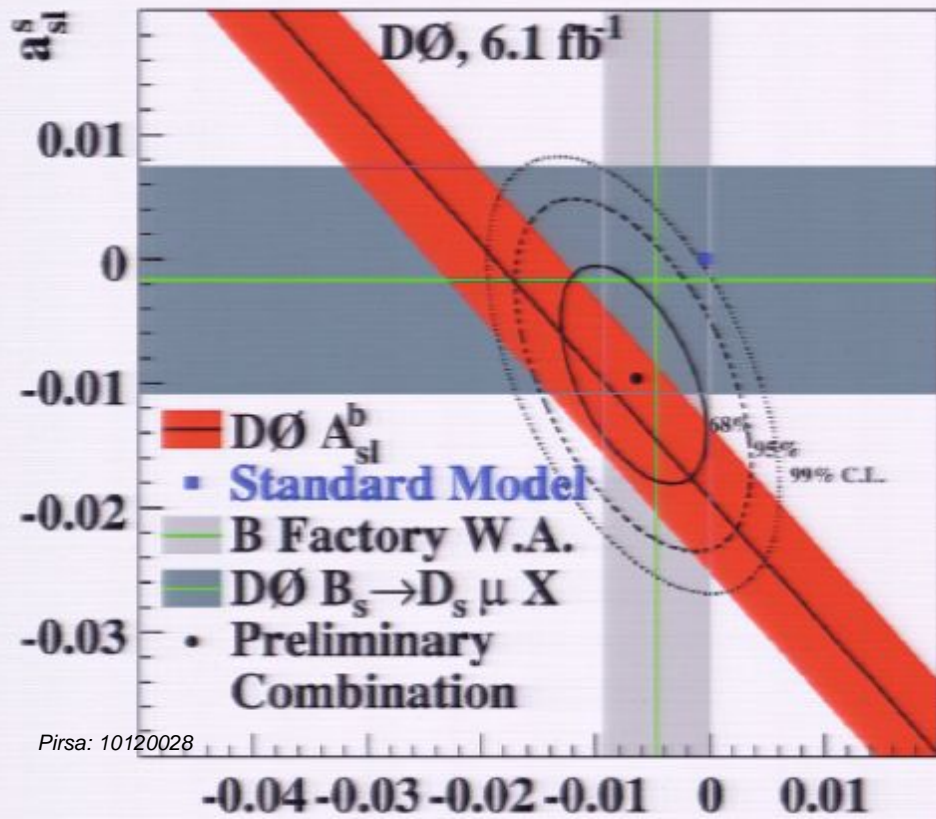


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Evidence for an anomalous like-sign dimuon charge asymmetry, DØ 1005.2757



Hint of a new CP violating phase?

$$\begin{aligned}
 a_{SL}^b &= \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}, \\
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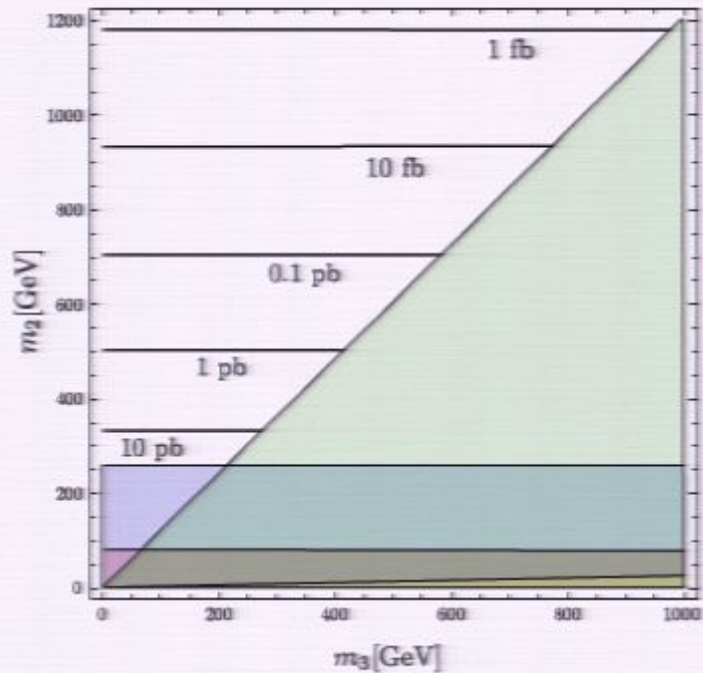
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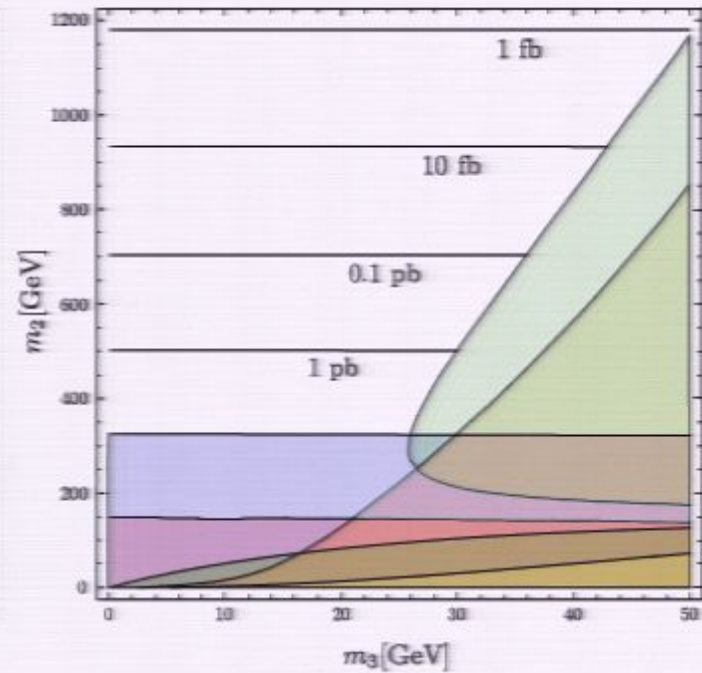


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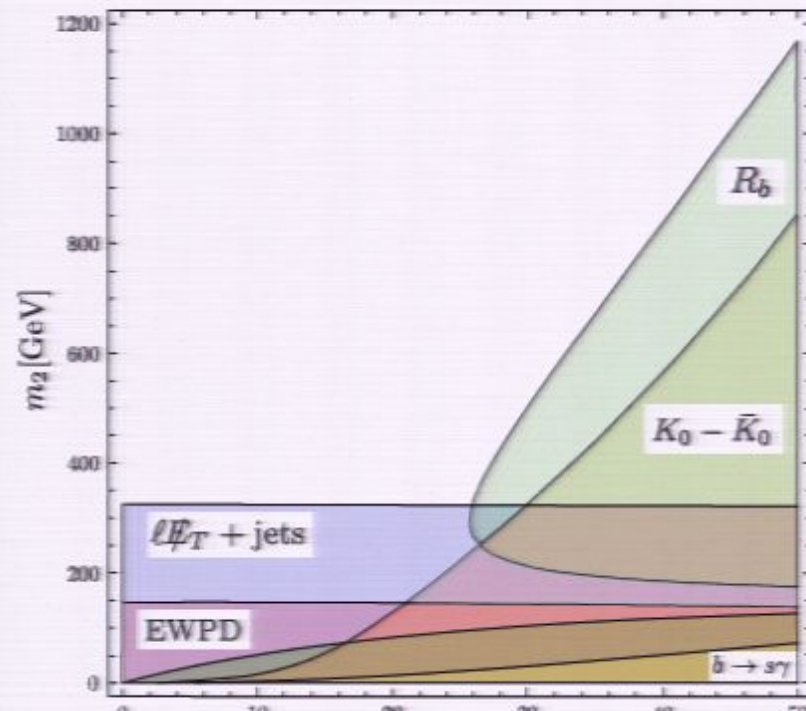
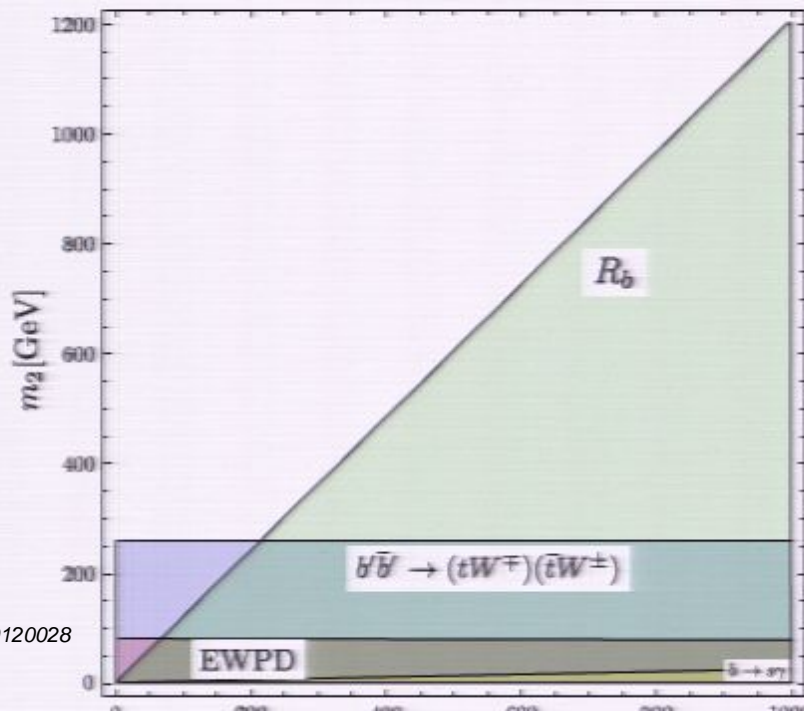
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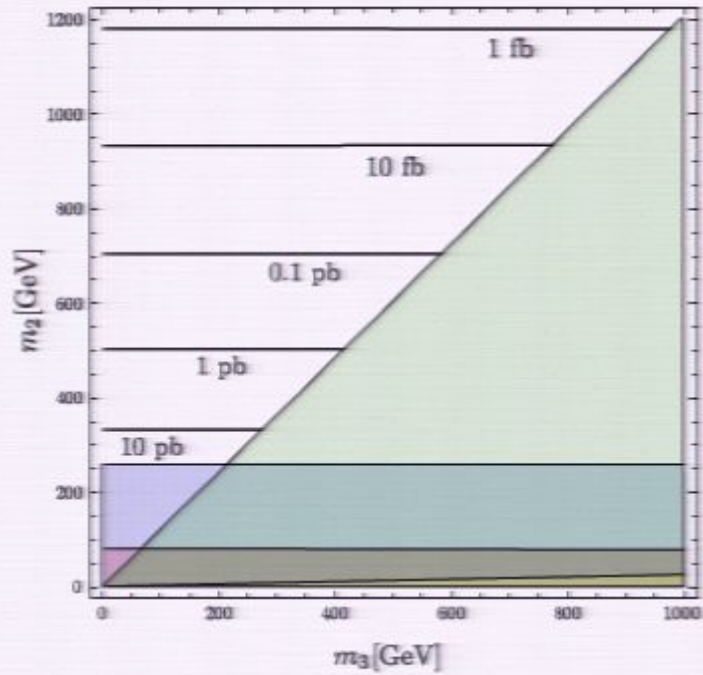
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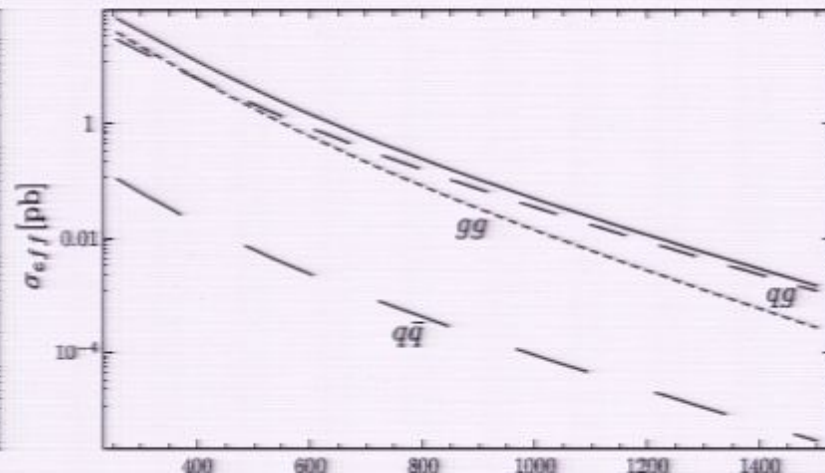
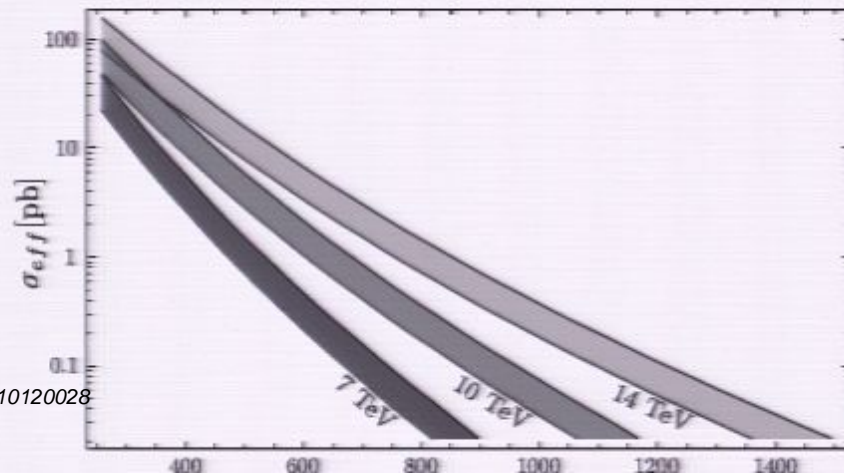
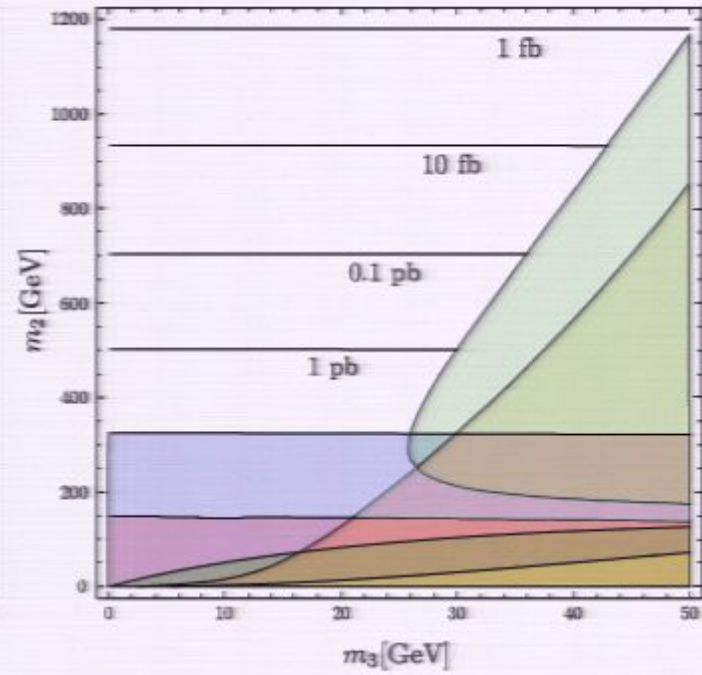


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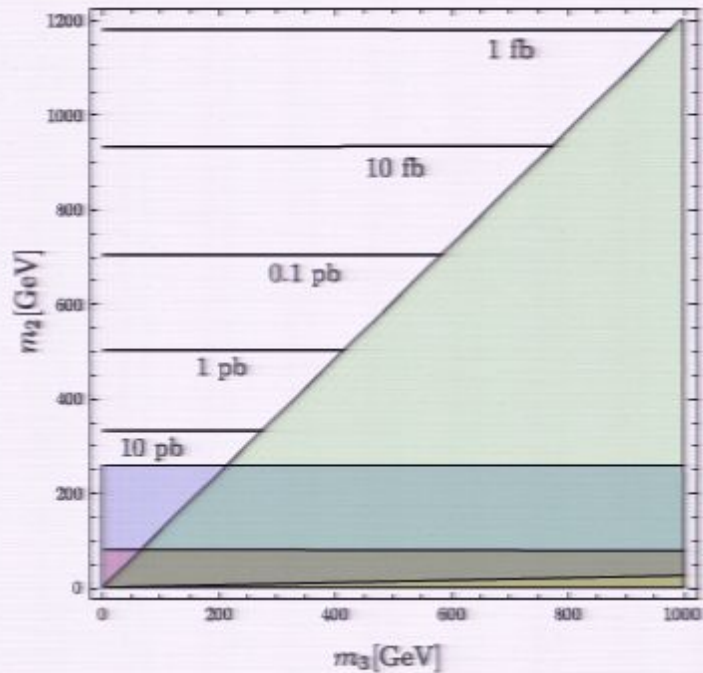


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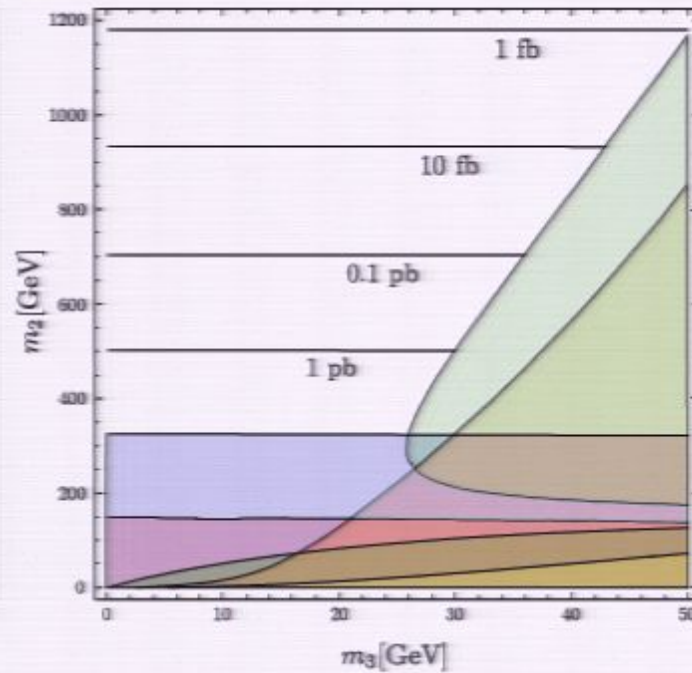


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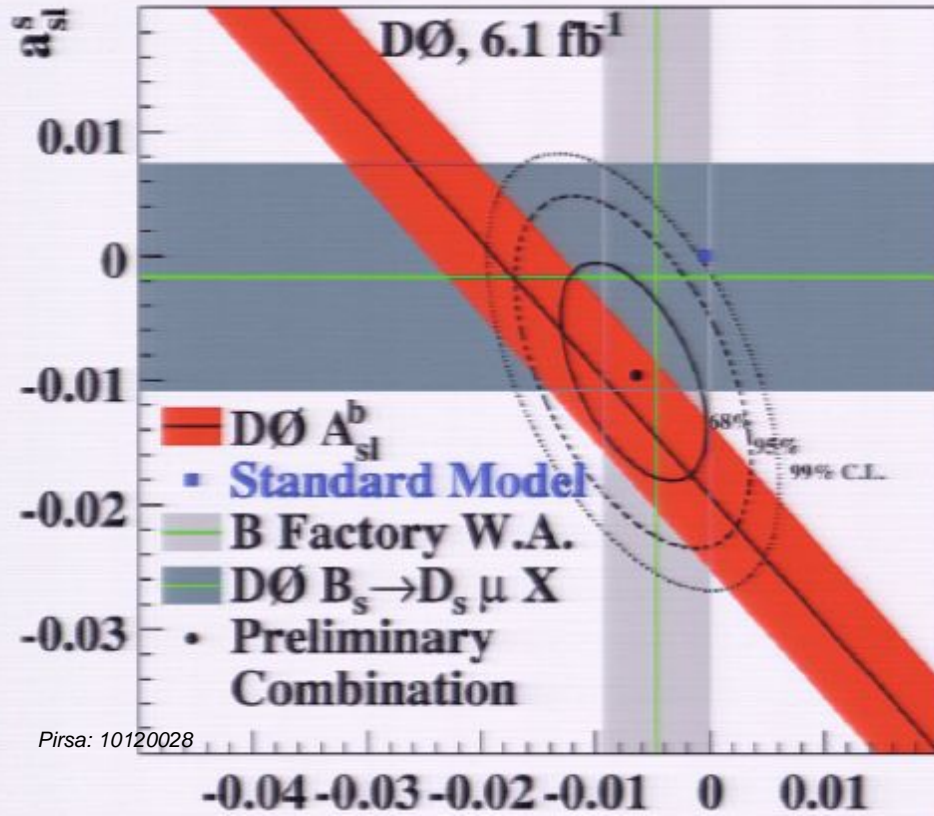
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## Can MFV field content explain this?

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:

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

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

arXiv:1008.1593

Considering spin, scalar exchange operators a good bet:

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

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

In terms of mass scale, fits say  $\Lambda \sim 13 y_b \sqrt{0.2/h_b}$  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

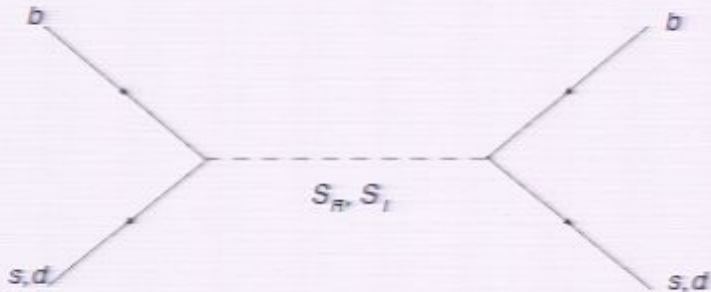
$$\mathcal{L}_Y = \bar{u}_R^i g_U^j Q_{Lj} H + \bar{d}_R^i g_D^j Q_{Lj} H^\dagger + \bar{u}_R^i Y_U^j Q_{Lj} S + \bar{d}_R^i Y_D^j Q_{Lj} S^\dagger + \text{h.c.}$$

Second Scalar doublet S 
$$S = \begin{pmatrix} S^+ \\ (S_R^0 + iS_I^0)/\sqrt{2} \end{pmatrix}.$$

Here: 
$$Y_U^j = \eta_U g_U^j + \eta'_U g_U^j [(g_U^\dagger)^k_l (g_U)^l_i] + \dots,$$
  

$$Y_D^j = \eta_D g_D^j + \eta'_D g_D^j [(g_U^\dagger)^k_l (g_U)^l_i] + \dots.$$

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



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

$$S_R^2 = m_s^2 + \lambda_3 v^2,$$

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# Pheno Issues

Avoid a light neutral state:

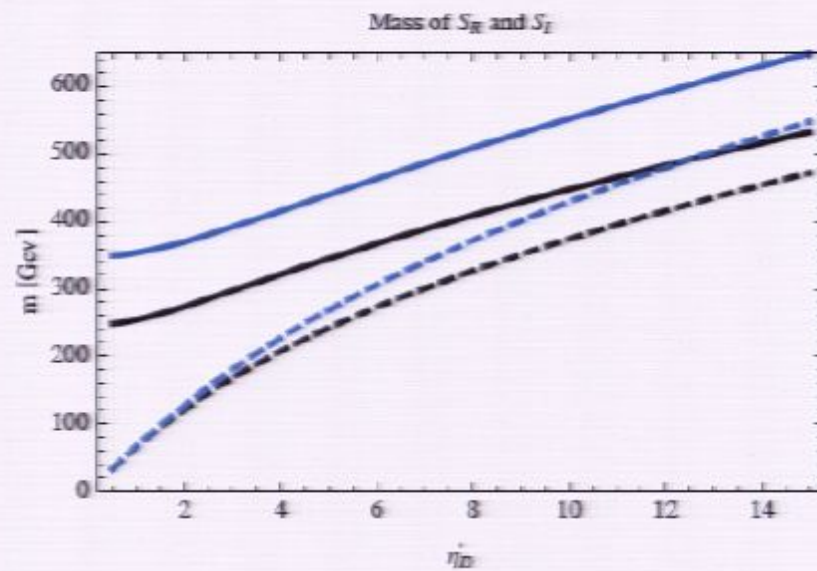


FIG. 1: Mass of  $S_R$  (solid) and  $S_I$  (dashed) as a function of  $\eta_D$  for fixed  $\lambda_3$ . The upper (blue curves) are for  $\lambda_3 = 1$  the lower (black) curves are for  $\lambda_3 = 0.5$ .

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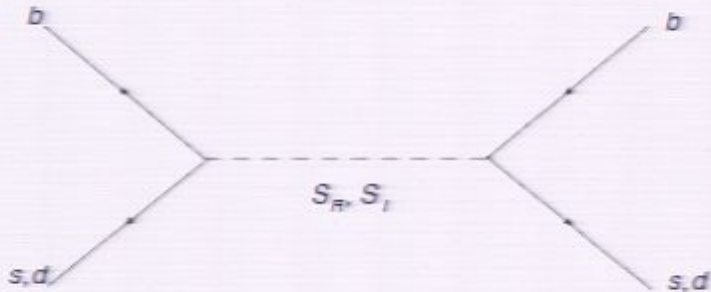
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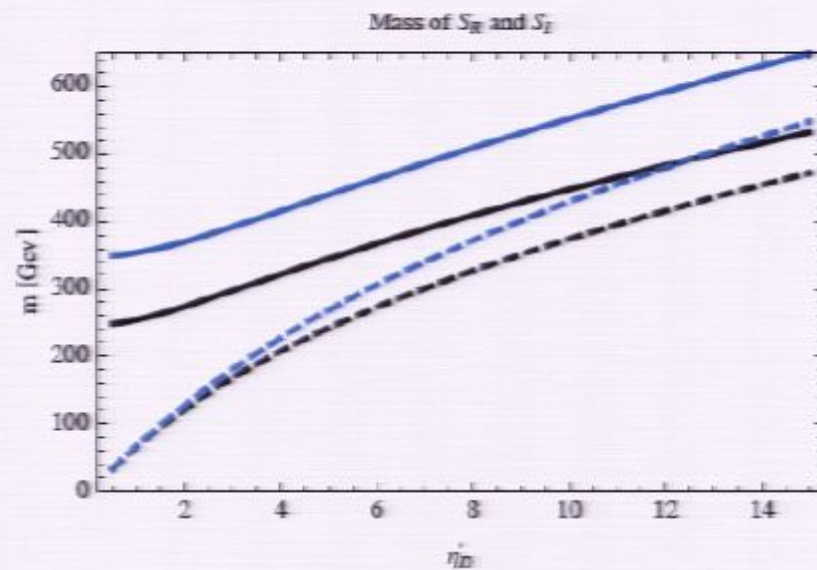
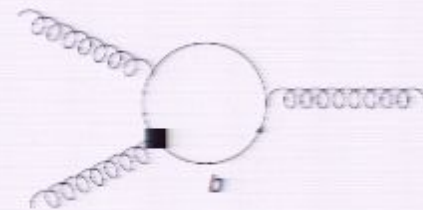
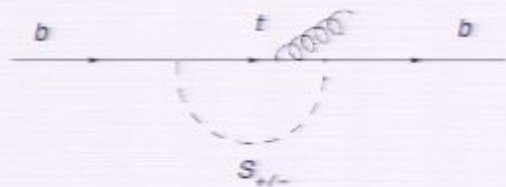


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$$O_G = g_3^3 f_{\alpha\beta\gamma} \epsilon^{\mu\nu\lambda\sigma} G_{\alpha\mu\rho} G_{\beta\nu}^{\rho} G_{\gamma\lambda\sigma},$$

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Using NDA this gives for the Neutron EDM:

$$d_n \sim 2\text{Im}[\eta_U^* \eta_D^* + \eta_U^* \eta_D^* + \eta_U^* \eta_D^* + \eta_U^* \eta_D^* + \dots] f(m_t^2/m_{S\pm}^2) \left( \frac{1 \text{ TeV}}{m_{S\pm}} \right)^2 10^{-26}$$

Quite a bit bigger than the experimental bound of  $d_n < 2.9 \times 10^{-26}$

Especially if the b Yukawa couplings are enhanced  $\eta_D' \sim 5, \eta_U, \eta_U' \dots < 10^{-2}$

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

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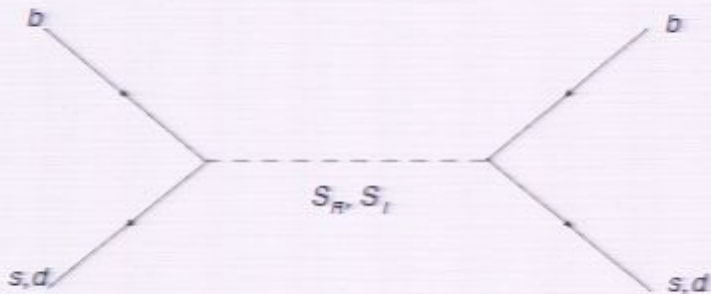
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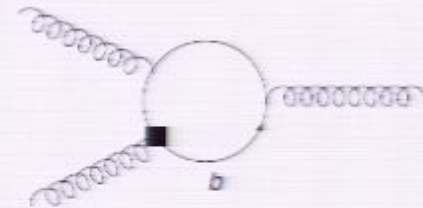
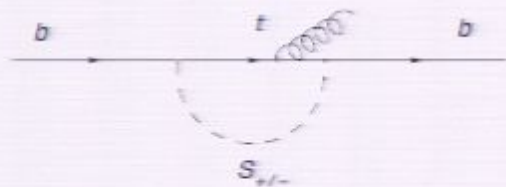


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## MFV to the Rescue, Again.

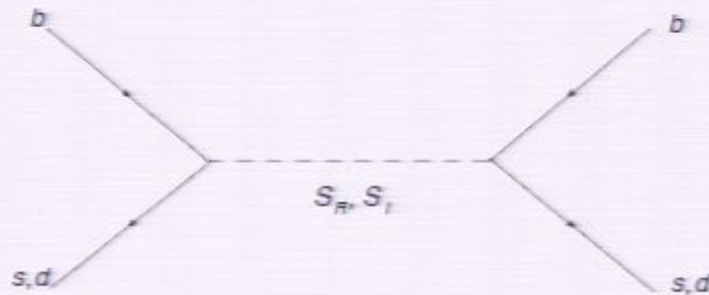
If the Second Scalar doublet  $S$  transforms as  $(1, 8, 1)$  then

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

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

Wilson Coefficient in this case:



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

## 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  $D_0$  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.