The Potential of Minimal Flavour Violation

Belén Gavela
Universidad Autónoma de Madrid (UAM) and IFT

with R. Alonso, L. Merlo, S. Rigolin

Beyond Standard Model because

1) **Experimental evidence** for new **particle** physics:

*** **Neutrino masses**

*** **Dark matter**

** **Matter-antimatter asymmetry**

2) **Uneasiness with SM fine-tunings**

SM

$\boxed{\text{SU(3) x SU(2) x U(1) x classical gravity}}$

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

SM $\boxed{\text{SU(3) x SU(2) x U(1) x classical gravity}}$

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

- The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^4$

SM $\boxed{\text{SU(3) x SU(2) x U(1) x classical gravity}}$

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

•The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^{4}$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} \leq 10^{-10}$

SM $\boxed{SU(3) \times SU(2) \times U(1) \times \text{classical gravity}}$

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

•The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^4$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} \leq 10^{-10}$

* The **electroweak** vacuum: Higgs-field, v.e.v.~O (100) GeV

SM $\boxed{SU(3) \times SU(2) \times U(1) \times \text{classical gravity}}$

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

•The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^{4}$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} \leq 10^{-10}$

* The **electroweak** vacuum: Higgs-field, v.e.v.~O (100) GeV

The (Tevatron->) LHC allow us to explore it

The happiness

in the air

of the LHC era

… as we are almost “touching” the Higgs

SM

SU(3) x SU(2) x U(1) x classical gravity

We ~understand ordinary particles= excitations over the vacuum

We DO NOT understand the vacuum = state of lowest energy:

- The **gravity** vacuum: cosmological cte. Λ , $\Lambda \sim 10^{-123}\, M_{Planck}^{4}$

* The **QCD** vacuum : Strong CP problem, $\theta_{QCD} \leq 10^{-10}$

* The **electroweak** vacuum: Higgs-field, v.e.v.~O (100) GeV

The Higgs excitation has the quantum numbers of the EW vacuum

BSM because

1) **Experimental evidence** for new **particle** physics:

*** **Neutrino masses**

*** **Dark matter**

** **Matter-antimatter asymmetry**

2) **Uneasiness with SM fine-tunings,** i.e. electroweak:

*** **Hierarchy problem**

*** **Flavour puzzle**

BSM electroweak

* **HIERARCHY PROBLEM**

Fine-tuning issue: if BSM physics, why Higgs so light

Interesting mechanisms to solve it from SUSY;
strong-int. Higgs, extra-dim….

In practice, none without further fine-tunings

* **FLAVOUR PUZZLE**

* All quark flavour data are ~consistent with SM

Kaon sector, B-factories, accelerators....

There are some ~2-3 sigma anomalies around, though:

-- sin 2β in CKM fit (Lunghi, Soni, Buras, Guadagnoli, UTfit, CKMfitter)

-- anomalous like-sign dimuon charge asymmetry in B_S decays (D0)

-- $B \longrightarrow \tau\nu$ (UTfit)

yet....we do NOT understand flavour

The Flavour Puzzle

u	ν_e	c	ν_μ	t	ν_τ
d	e	s	μ	b	τ

Why 2 replicas of the first family?

when we only need one to account for the visible universe

The Flavour Puzzle

u	ν_e	c	ν_μ	t	ν_τ
d	e	s	μ	b	τ

Why so diferent masses and mixing angles?

The Flavour Puzzle

u	ν_e	c	ν_μ	t	ν_τ
d	e	s	μ	b	τ

Why has nature chosen the number and properties of families so as to allow for CP violation... and explain nothing? (i.e. not enough for matter-antimatter asymmetry)

BSM electroweak

* **HIERARCHY PROBLEM**

Fine-tuning issue: if BSM physics, why Higgs so light

Interesting mechanisms to solve it from SUSY;
strong-int. Higgs, extra-dim….

In practice, none without further fine-tunings

$\longrightarrow \Lambda_{electroweak} \sim \mathbf{1\ TeV}$?

* **FLAVOUR PUZZLE**: no progress

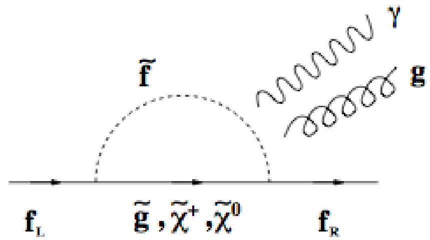
Understanding stalled since 30 years.

Only new B physics data AND neutrino masses and mixings $\longrightarrow \Lambda_f \sim \mathbf{100\text{'s}\ TeV}$???

BSMs tend to worsen the flavour puzzle

The FLAVOUR WALL for BSM

i) Typically, BSMs have **electric dipole moments** at one loop
i.e susy MSSM:

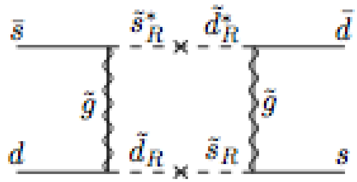


< 1 loop in SM ---> **Best (precision) window of new physics**

ii) **FCNC**

i.e susy MSSM:

$K^0 - \overline{K}^0$ mixing



$\mu \to e\gamma$

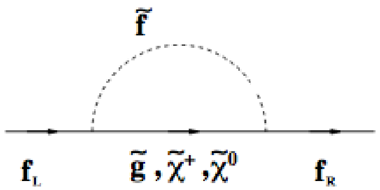
competing with SM at one-loop

The FLAVOUR WALL for BSM

* The **QCD** vaccuum : Strong CP problem, $\theta_{QCD} < 10^{-10}$

BSM in general induce $\theta_{QCD} > 10^{-10}$

i.e.



at one-loop (vs multiloop in SM)

* The **matter-antimatter asymmetry** : CP-violation from quarks in SM fails by ~10 orders of magnitude (+ too heavy Higgs)

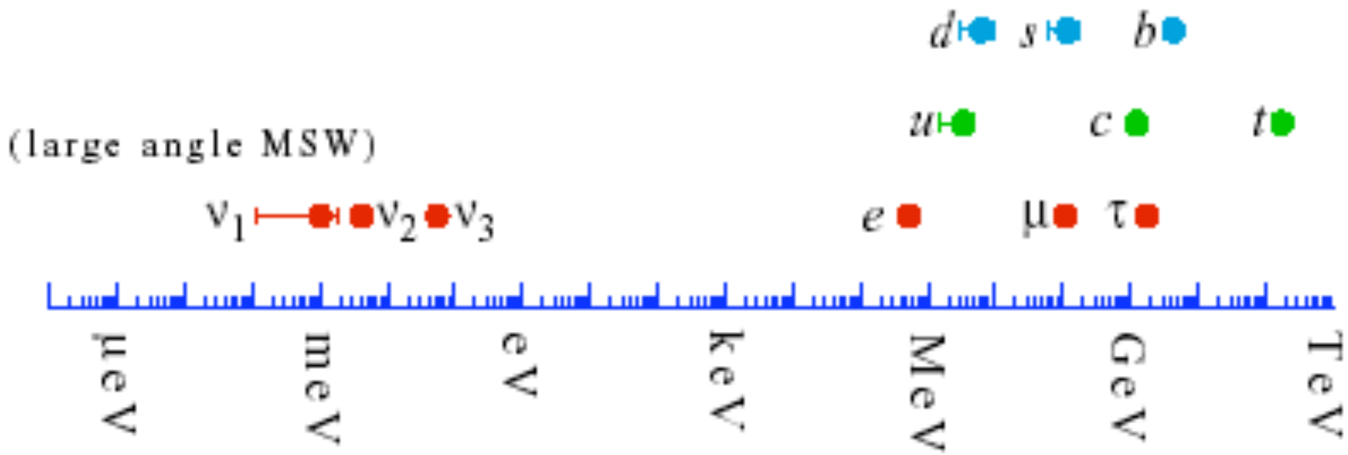
Neutrino light on flavour ?

* Neutrino masses indicate BSM.... yet consistent with 3 standard families

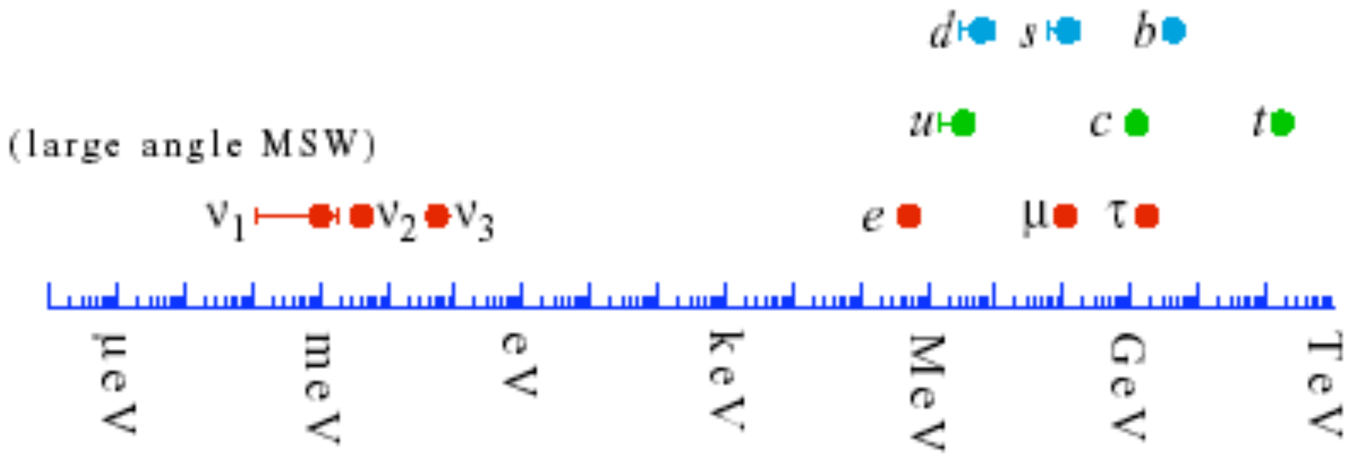
-- in spite of some 2-3 sigma anomalies:

* Minos, 2 sigma, neutrinos differ from antineutrinos
* Hints of steriles: LSND and MiniBoone in antineutrinos, new deficit in Double-Chooz nu_efluxes, Gallex deficit in antinu_e, cosmological-radiation, solar...

The Higgs mechanism can accomodate masses in SM... but neutrinos (?)



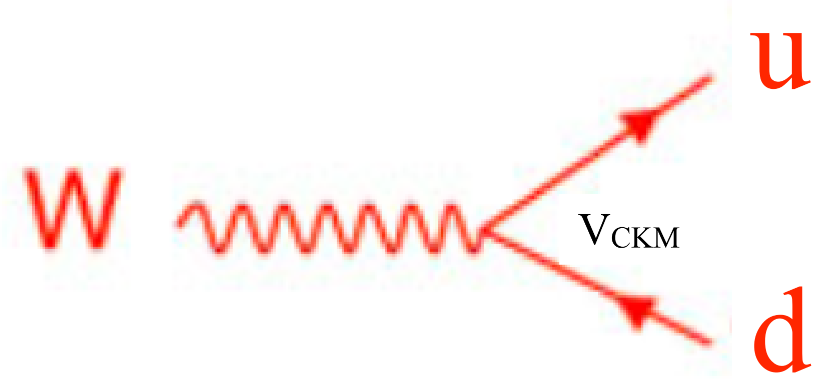
The Higgs mechanism can accomodate masses in SM... but neutrinos (?)



Neutrinos lighter because Majorana?

Lepton mixing in charged currents

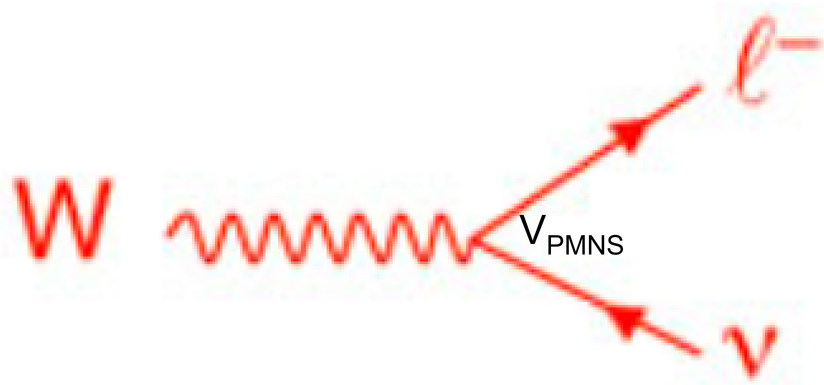
Quarks



$$V_{CKM} = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12}e^{-i\delta} & c_{12}c_{23} - s_{23}s_{13}s_{12}e^{-i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{-i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{-i\delta} & c_{23}c_{13} \end{pmatrix}$$

Lepton mixing in charged currents

Leptons



$$V_{PMNS} = \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13}e^{i\delta} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12}e^{-i\delta} & c_{12}c_{23} - s_{23}s_{13}s_{12}e^{-i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{-i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{-i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha} & & \\ & e^{i\beta} & \\ & & 1 \end{pmatrix}$$

More wood for the Flavour Puzzle

Leptons

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & ?(<10^{o}) \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & +0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

Why so different?

More wood for the Flavour Puzzle

Leptons

$$V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & ?(<10^o) \\ -0.4 & 0.5 & -0.7 \\ -0.4 & 0.5 & +0.7 \end{pmatrix}$$

Quarks

$$V_{CKM} = \begin{pmatrix} \sim 1 & \lambda & \lambda^3 \\ \lambda & \sim 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & \sim 1 \end{pmatrix} \quad \lambda \sim 0.2$$

Maybe because of Majorana neutrinos?

Dirac o Majorana ?

- **The only thing we have really understood in particle physics is the gauge principle**

- **SU(3)xSU(2)xU(1) allow Majorana masses....**

Lepton number was only an accidental symmetry of the SM

Anyway, it is for experiment to decide

How to advance in a model-independent way?

- In quark flavour puzzle
- In lepton flavour puzzle

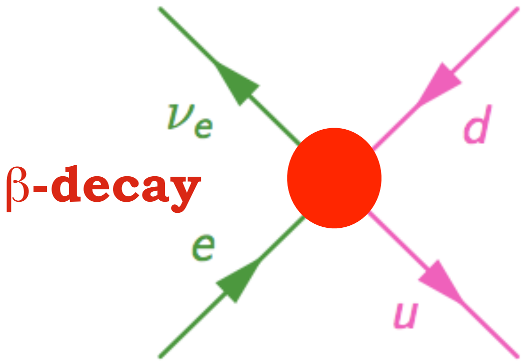
How to go about it model-independent ?....

Effective field theory

Mimic travel from Fermi's beta decay to SM

$$\mathcal{L}^{\text{Fermi}} = \mathcal{L}_{U(1)em} + \frac{O^{\text{Fermi}}}{M^2} + \ldots\ldots$$

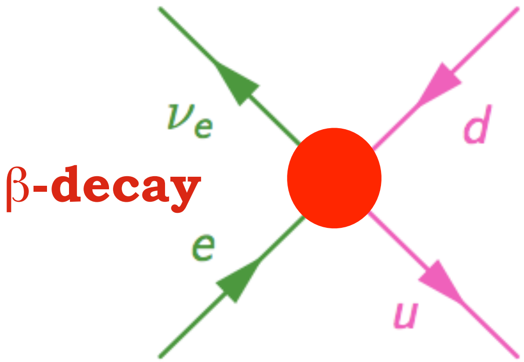
From the Fermi theory to SM



$G_F \ (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$

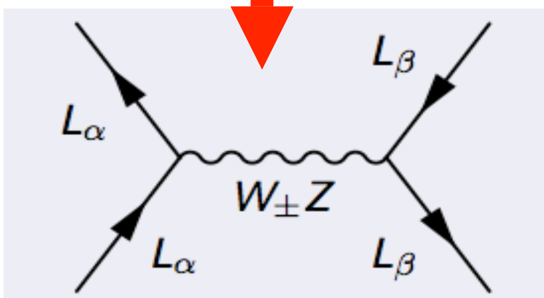
$U(1)_{em}$ invariant

<u>From the Fermi theory to SM</u>



$$G_F \; (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$$

$U(1)_{em}$ invariant



$$\frac{g^2}{M_W^2} \; (L_\alpha \gamma_\mu L_\alpha) \; (Q_{L\beta} \gamma_\mu Q_\beta)$$

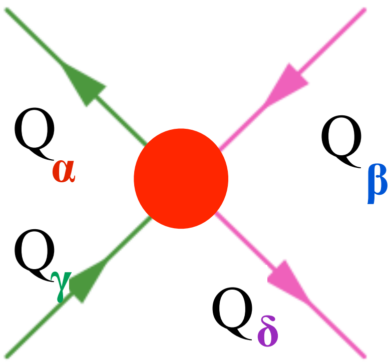
$SU(2)\, x U(1)_{em}$ gauge invariant

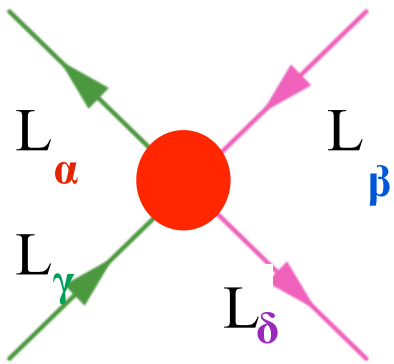
If new physics scale M > v

$$\mathcal{L} = \mathcal{L}_{SU(3)xSU(2)xU(1)} + \frac{O^{d=5}}{M} + \frac{O^{d=6}}{M^2} + \ldots\ldots$$

$$\mathcal{L} = \mathcal{L}_{SU(3)xSU(2)xU(1)} + \frac{O^{d=5}}{M} + \frac{O^{d=6}}{M^2} + \ldots\ldots$$

$O^{d=6}$ **: conserve B, L... and lead to new flavour effects for quarks and leptons**





$SU(2)\ xU(1)_{em}$ gauge invariant

A humble ansatz:

- Minimal Flavour Violation

(Chivukula. Georgi)
(D´Ambrosio, Giudice, Isidori, Strumia) (Buras)

A humble ansatz:

- Minimal Flavour Violation

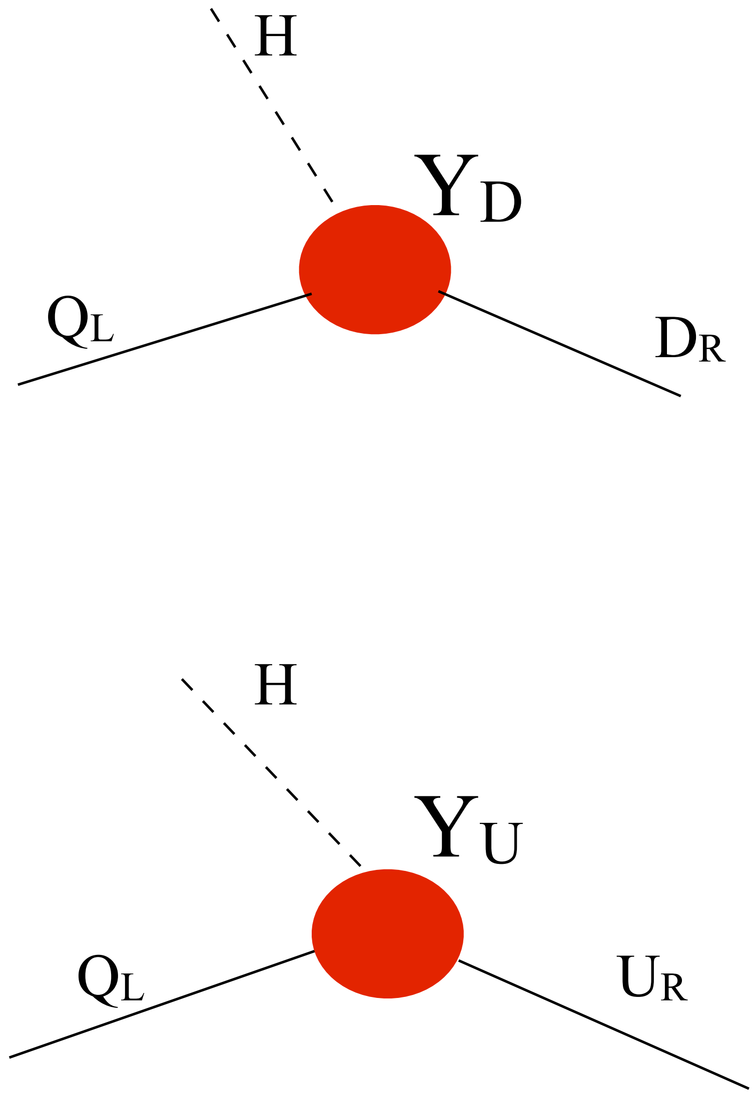
....taking laboratory data at face value

(Chivukula. Georgi)
(D´Ambrosio, Giudice, Isidori, Strumia) (Buras)

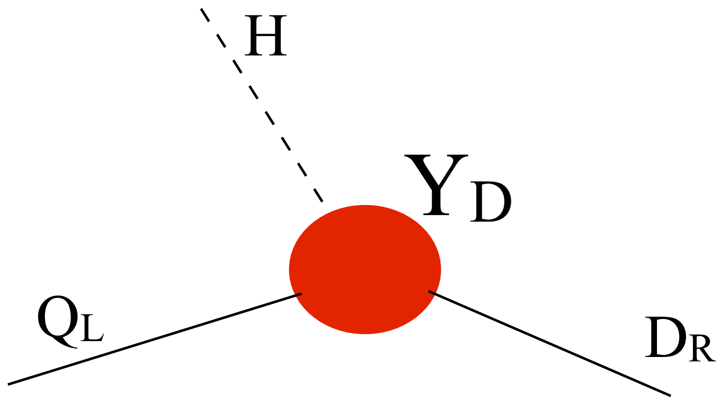
* All quark flavour data are consistent with SM

= consistent with CKM

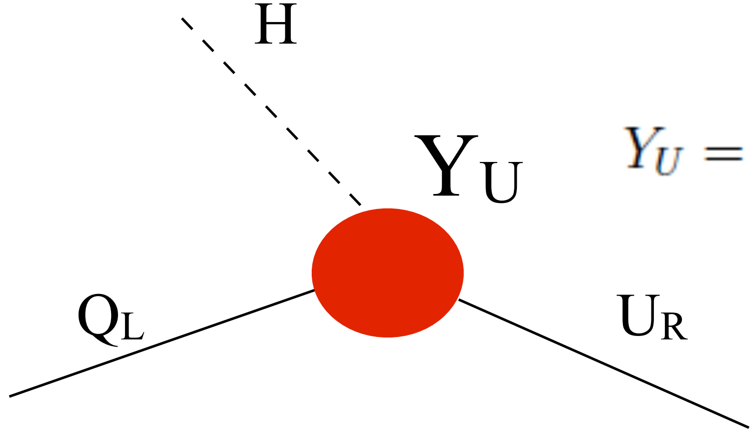
= consistent with all flavour effects due to Yukawas



H
Y D
QL
DR
H
Y U
QL
UR



$$Y_D = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$



$$Y_U = \mathcal{V}^{\dagger}_{CKM} \begin{pmatrix} y_u & 0 & 0 \\ 0 & y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}$$

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawas

MFV Hypothesis ≡ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B **188**, 99 (1987).

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis $\equiv$ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B 188, 99 (1987).

The global Flavour symmetry of the SM with massless fermions:

$$G_f = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$$Q_L \to \Omega_L \, Q_L \qquad D_R \to \Omega_d \, D_R \quad \ldots$$

$$D_R = (d_R, s_R, b_R) \sim (1, 1, 3)$$

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis $\equiv$ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B 188, 99 (1987).

The global Flavour symmetry of the SM with massless fermions:

$$G_f = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$$Q_L \rightarrow \Omega_L\, Q_L \qquad D_R \rightarrow \Omega_d\, D_R \quad \ldots$$

$$D_R = (d_R, s_R, b_R) \sim (\ 1,\ 1,\ 3)$$

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis ≡ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B 188, 99 (1987).

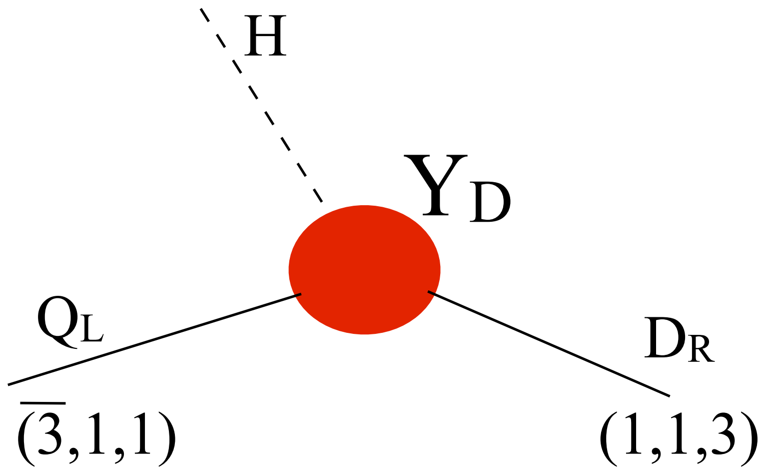
The global Flavour symmetry of the SM: Yukawas break it

$$G_f = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

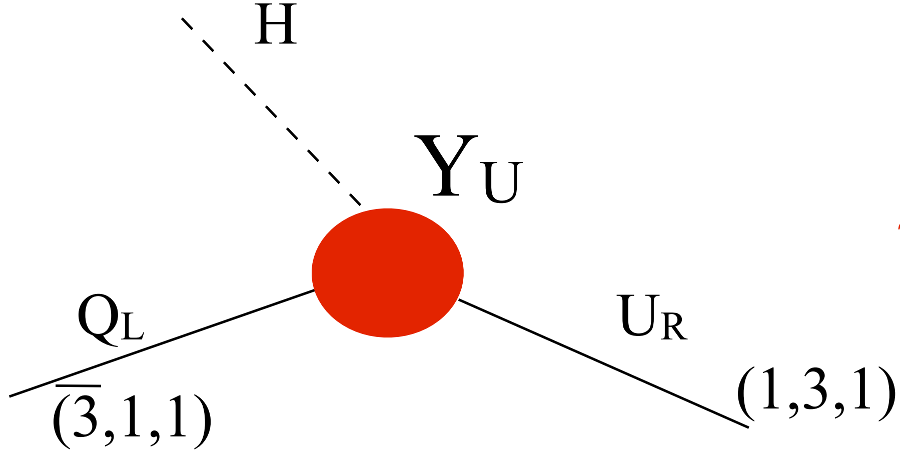
$Q_L \rightarrow \Omega_L\, Q_L \quad D_R \rightarrow \Omega_d\, D_R \quad ..$

$D_R = (d_R, s_R, b_R) \sim (\ 1,\ 1,\ 3)$

$$G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$



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



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

Minimal Flavour violation (MFV)

•Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis ≡ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

R. S. Chivukula and H. Georgi, Phys. Lett. B 188, 99 (1987).

The global Flavour symmetry of the SM: Yukawas break it unless

$$G_f = SU(3)_{Q_L} \times SU(3)_u \times SU(3)_d \times SU(3)_L \times SU(3)_e$$

$Q_L \to \Omega_L\, Q_L \qquad D_R \to \Omega_d\, D_R \quad \ldots \boxed{Y_d \to \Omega_L\, Y_u\, \Omega_d^+} \ldots$

$D_R = (d_R, s_R, b_R) \sim (\ 1,\ 1,\ 3)$

$\overline{Q}_L Y_D D_R H \qquad\qquad Y_D \sim (3, 1, \overline{3})$

Minimal Flavour violation (MFV)

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

MFV Hypothesis $\equiv$ The Yukawas are the only sources (*irreducible*) of flavour violation. in the SM and BSM

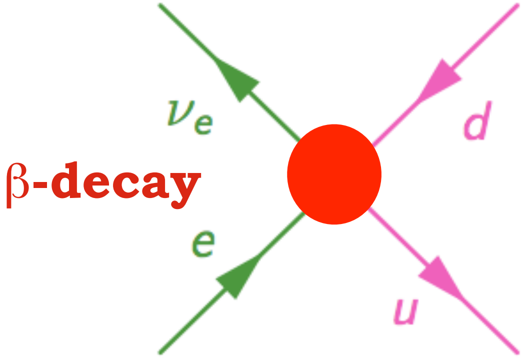
R. S. Chivukula and H. Georgi, Phys. Lett. B 188, 99 (1987).

It is very predictive for quarks: $O^{d=6} \sim \overline{Q}_\alpha Q_\beta \overline{Q}_\gamma Q_\delta$

$$\mathcal{L} = \mathcal{L}_{SM} + c^{d=6}\, O^{d=6} + \ldots\ldots$$

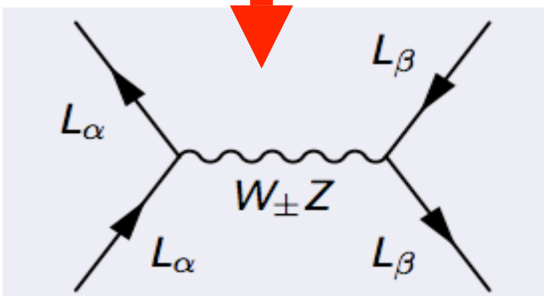
i.e. $c^{d=6} \sim \dfrac{Y^{+}_{\alpha\beta}\, Y_{\gamma\delta}}{\Lambda^2_{\text{flavour}}}$ $\quad O^{d=6} \sim \overline{Q}_\alpha Q_\beta \overline{Q}_\gamma Q_\delta$

From the Fermi theory to SM



$G_F \; (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$

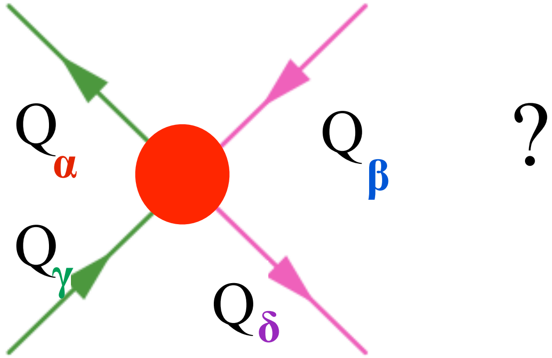
$U(1)_{em}$ invariant



$$\frac{g^2}{M_W^2} \; (L_\alpha \gamma_\mu L_\alpha) \; (Q_{L\beta} \gamma_\mu Q_\beta)$$

$SU(2)$ x$U(1)_{em}$ gauge invariant

From the SM to the theory of flavour



$SU(2)$ x$U(1)_{em}$ gauge invariant

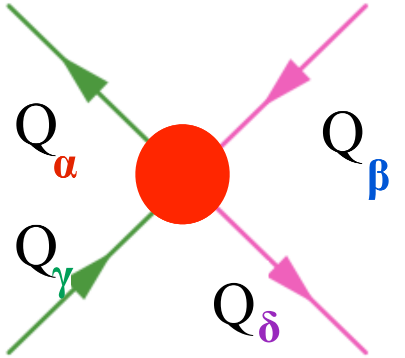
?

The Theory of Flavour

MFV IS NOT A MODEL OF FLAVOUR

IT REMAINS AT THIS LEVEL

From the SM to the theory of flavour



?

$SU(2)\ xU(1)_{em}$ gauge invariant

?

The Theory of Flavour

* MFV can reconcile Λ_f and $\Lambda_{electroweak}$:

$$\Lambda_f \sim \Lambda_{electroweak} \sim \mathrm{TeV}$$

... and induce observable flavour changing effects

WHY MFV?

FOR QUARKS

- Hierarchy Problem points to $\Lambda \sim$ TeV

$c_{d=6} \equiv c_{d=6}(Y_u, Y_d)$

$\mathcal{O}^i_{d=6}$	Λ_f	$c_{d=6} = 1$
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2	

$\mathcal{O}^i_{d=6}$	Λ_f
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right)(eF_{\mu\nu})$	6.1 TeV
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV
$H_D^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right)(g_s G^a_{\mu\nu})$	3.4 TeV
$(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)(\overline{E}_R \gamma_\mu E_R)$	2.7 TeV
$i\,(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L) H_U^\dagger D_\mu H_U$	2.3 TeV
$(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)(\overline{L}_L \gamma_\mu L_L)$	1.7 TeV
$(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)(eD_\mu F_{\mu\nu})$	1.5 TeV

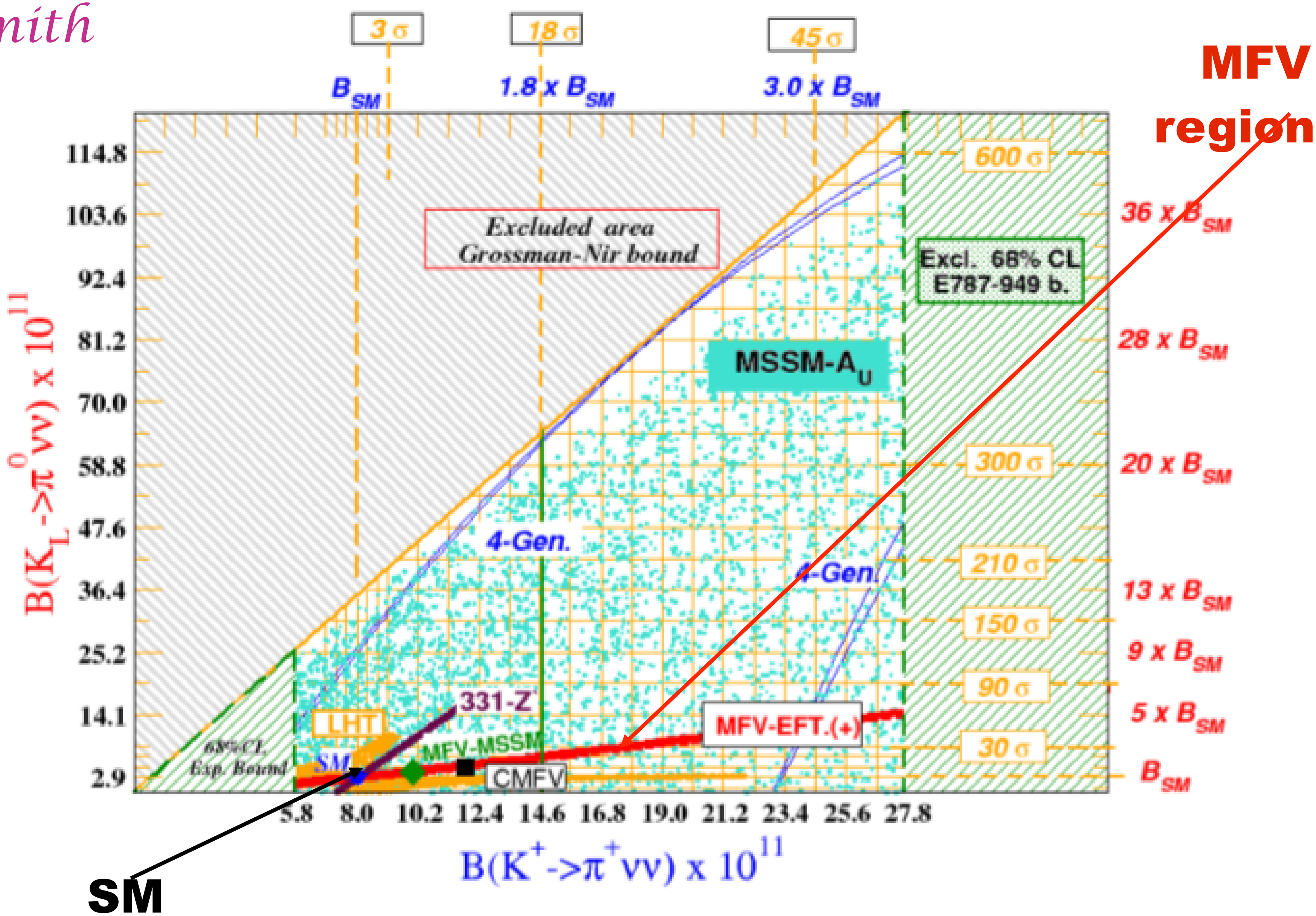
WITHOUT MFV: $\Lambda_f \gtrsim 10^2$ TeV

WITH MFV: $\Lambda_f \gtrsim$ TeV

G. Isidori, Y. Nir, G. Perez, 1002.09

I. *NA62 main targets are the rare K decays* ($Br \lesssim 10^{-11}$), *e.g.* $K^+ \to \pi^+ \nu\bar{\nu}$ S

Smith



In fact, MFV **assumes** more, e.g. **top dominance**:

$$\boxed{\left[Y^u (Y^u)^\dagger\right]^n_{i\neq j} \approx y_t^{2n} V_{ti}^* V_{tj}}$$

(Isidori)

O(1)

$$\longrightarrow \quad \mathcal{A}(d^i \to d^j)_{\rm MFV} = (V_{ti}^* V_{tj})\ \mathcal{A}_{\rm SM}^{(\Delta F=1)} \left[1 + a_1 \frac{16\pi^2 M_W^2}{\Lambda^2}\right]$$

$\longrightarrow$ d-d ~ s-d ~ b-s transitions of ~ equal strength

while it may not be so...

for instance for SM+ 2 Higgses (automatic Z_3) light quarks may dominate

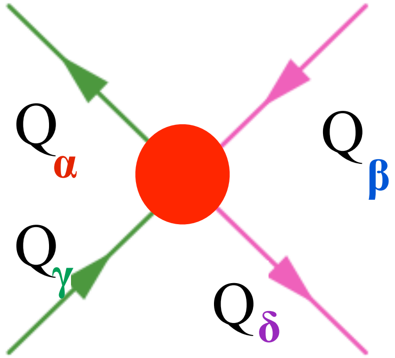
(Branco, Grimus, Lavoura)

MFV IS NOT A MODEL OF FLAVOUR

IT REMAINS AT THIS LEVEL

$$C^{d=6} \sim \frac{Y^{+}_{\alpha\beta}\, Y_{\gamma\delta}}{\Lambda^{2}_{\text{flavour}}}$$

From the SM to the theory of flavour



?

$SU(2)\, x U(1)_{em}$ gauge invariant

?

The Theory of Flavour

The Dynamics Behind MFV

MFV suggests that Y_U & Y_D have a dynamical origin at high energies ....

$$Y \sim \langle \varphi \rangle \quad \text{or} \quad \langle \varphi\, \chi \rangle \quad \text{or} \quad \langle (\quad)^n \rangle \ldots$$

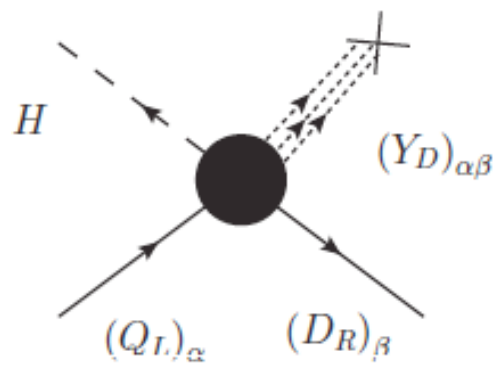
Spontaneous breaking of flavour symmetry dangerous

--> i.e. gauge it (Grinstein, Redi, Villadoro, 2010)
(Feldman, 2010)
(Guadagnoli, Mohapatra, Sung, 2010)

The Dynamics Behind MFV

MFV suggests that Y_U & Y_D have a dynamical origin at high energies ....

$$Y \sim <\varphi> \quad \text{or} \quad <\varphi\,\chi> \quad \text{or} \quad <(\quad)^n> \ldots$$

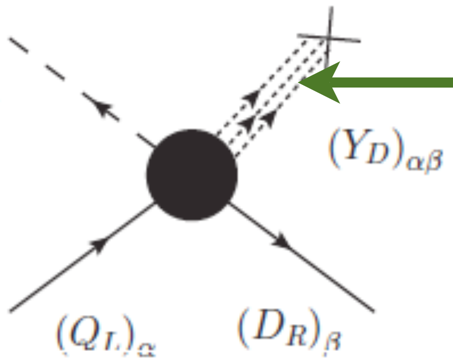


(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

The Dynamics Behind MFV

MFV suggests that Y_U & Y_D have a dynamical origin at high energies ....

$$Y \sim <\varphi> \quad \text{or} \quad <\varphi\,\chi> \quad \text{or} \quad <(\quad)^n> \ldots$$



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

That scalar field or aggregate of fields may have a potential

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

The Dynamics Behind MFV

MFV suggests that Y_U & Y_D have a dynamical origin at high energies ....

$$Y \sim \langle \varphi \rangle \quad \text{or} \quad \langle \varphi\, \chi \rangle \quad \text{or} \quad \langle (\quad)^n \rangle \ldots$$

What is the potential of Minimal Flavour Violation ?

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

The Dynamics Behind MFV

MFV suggests that Y_U & Y_D have a dynamical origin at high energies ....

$$Y \sim <\varphi> \quad \text{or} \quad <\varphi\,\chi> \quad \text{or} \quad <(\quad)^n> \ldots$$

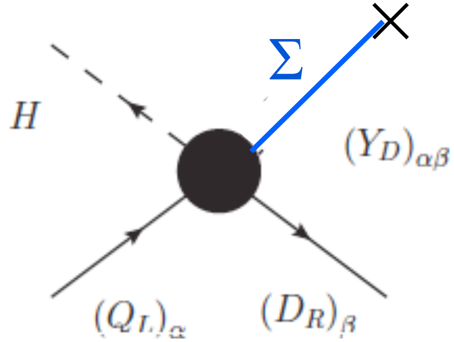
What is the potential of Minimal Flavour Violation ?

Can its minimum correspond to the observed masses and mixings?

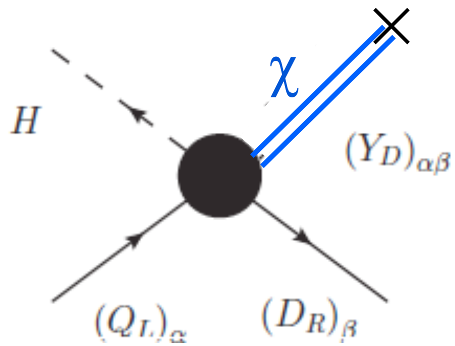
(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

We constructed the scalar potential for both 2 and 3 families, for scalar fields:

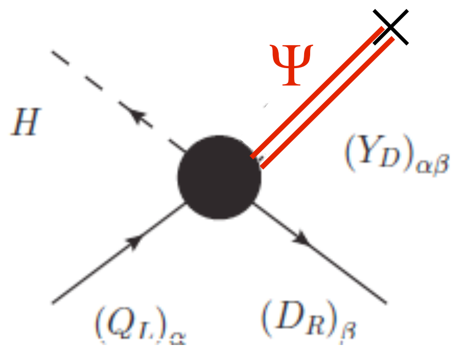
1) Y -- > one single scalar $\Sigma \sim (3, 1, \overline{3})$



2) Y -- > two scalars $\chi\,\chi^+ \sim (3, 1, \overline{3})$



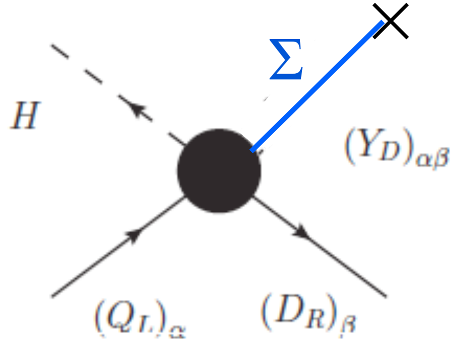
3) Y -- > two fermions $\overline{\Psi}\Psi \sim (3, 1, 3)$



We constructed the scalar potential for both 2 and 3 families, for scalar fields:

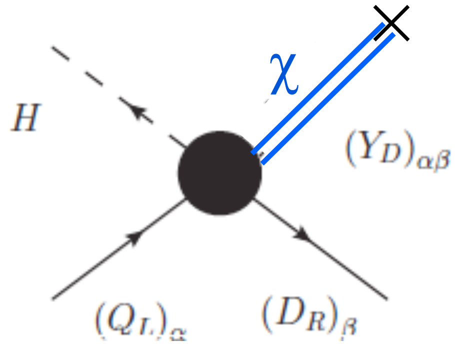
1) Y -- > one single scalar $\Sigma \sim (3, 1, \overline{3})$

d=5 operator



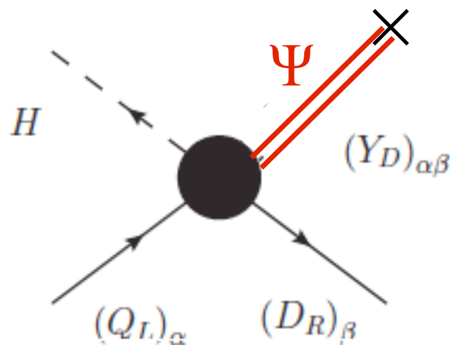
2) Y -- > two scalars $\chi\,\chi^{+} \sim (3, 1, \overline{3})$

d=6 operator



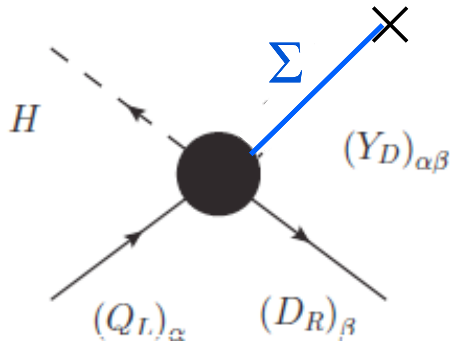
3) Y -- > two fermions $\overline{\Psi}\Psi \sim (3, 1, 3)$

d=7 operator



1) Y --> one single field Σ

$$Y \sim \frac{<\Sigma>}{\Lambda_f}$$



$Y \dashrightarrow$ one single field Σ

What is the potential for scalars fields Σ in the bifundamental of G_f ?

$$V(\Sigma, H)$$

invariant under SU(3)xSU(2)xU(1) and G_f

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

Y --> one single field Σ

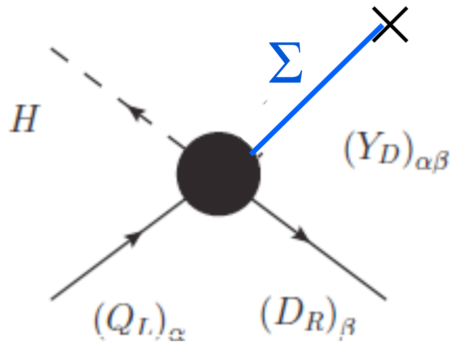
Dimension 5 Yukawa operator

Σ are bifundamentals of G_f :

$$\overline{Q}_L \frac{\Sigma_u}{\Lambda} U_R H \qquad \Sigma_u \sim (3, \overline{3}, 1)$$

$\uparrow$

Y_u



$$\overline{Q}_L \frac{\Sigma_d}{\Lambda} D_R H \qquad \Sigma_d \sim (3, 1, \overline{3})$$

$\uparrow$

Y_d

¿ $V(\Sigma_u \Sigma_u H)$?

$$Y_d \longleftrightarrow \langle \Sigma_d \rangle \; ; \quad Y_d \longleftrightarrow \langle \Sigma_d \rangle$$

Construction of the Potential

* two families: 5 invariants at renormalizable level:
  (Feldman, Jung, Mannel)

$$\mathrm{Tr}\,(\,\Sigma_u\,\Sigma_u^+\,) \qquad \det\,(\,\Sigma_u\,)$$

$$\mathrm{Tr}\,(\,\Sigma_d\,\Sigma_d^+\,) \qquad \det\,(\,\Sigma_d\,)$$

$$\mathrm{Tr}\,(\,\Sigma_u\,\Sigma_u^+\,\Sigma_d\,\Sigma_d^+\,)$$

Y --> one single field Σ

We constructed the most general potential :

$$V(\Sigma_u, \Sigma_d) = \Sigma_i \left[-\mu_i^2 \, \mathrm{Tr}(\Sigma_i \Sigma_i^+) - \tilde{\mu}_i^2 \det(\Sigma_i) \right]$$

$$+ \Sigma_{i,j} \left[\lambda_{ij} \, \mathrm{Tr}(\Sigma_i \Sigma_i^+) \, \mathrm{Tr}(\Sigma_j \Sigma_j^+) + \tilde{\lambda}_{ij} \det(\Sigma_i) \det(\Sigma_j) \right] + \ldots$$

it only relies on G_f symmetry

and analyzed its minima

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

Can its minimum correspond *naturally* to the observed masses and mixings?

i.e. with all dimensionless λ's ~ 1

and dimensionful μ's $\leqq \Lambda_f$

Y --> one single field Σ

The invariants can be written in terms of masses and mixing

* two families:

$$< \Sigma_d > = \Lambda_f \,.\, \mathrm{diag}\,(y_d)\,; \qquad < \Sigma_u > = \Lambda_f \,.\, V_{Cabibbo}\, \mathrm{diag}(y_u)$$

$$Y_D = \begin{pmatrix} y_d & 0 \\ 0 & y_s \end{pmatrix}, \qquad Y_U = \mathcal{V}_C^\dagger \begin{pmatrix} y_u & 0 \\ 0 & y_c \end{pmatrix} \qquad V_{Cabibbo} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

$$<\mathrm{Tr}\,(\Sigma_u \Sigma_u^+)> = \Lambda_f^2\,(y_u^2 + y_c^2)\,; \quad <\det(\Sigma_u)> = \Lambda_f^2\, y_u y_c$$

$$<\mathrm{Tr}\,(\Sigma_u \Sigma_u^+ \Sigma_d \Sigma_d^+)> = \Lambda_f^4\,[(y_c^2 - y_u^2)(y_s^2 - y_d^2)\cos 2\theta + \ldots]/2$$

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

Y --> one single field Σ

Minimum of the Potential

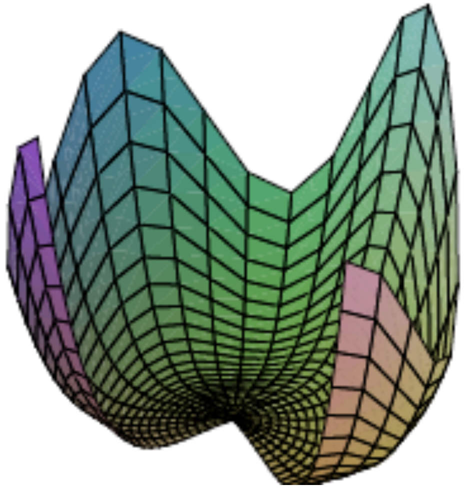
Dimension 5 Yukawa Operator

The minimum of the Potential is given by:

$$\frac{\partial V}{\partial y_i} = 0 \qquad \frac{\partial V}{\partial \theta_i} = 0$$

Take the angle for example:

$$\frac{\partial V}{\partial \theta_c} \propto (y_c^2 - y_u^2)\,(y_s^2 - y_d^2)\,\sin 2\theta_c = 0$$



Non-degenerate masses $\longrightarrow \sin 2\theta_c = 0$ No mixing !

Notice also that $$\frac{\partial V^{(4)}}{\partial \theta} \sim \sqrt{J}$$ (Jarlskog determinant)

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

Y --> one single field Σ

Minimum of the Potential

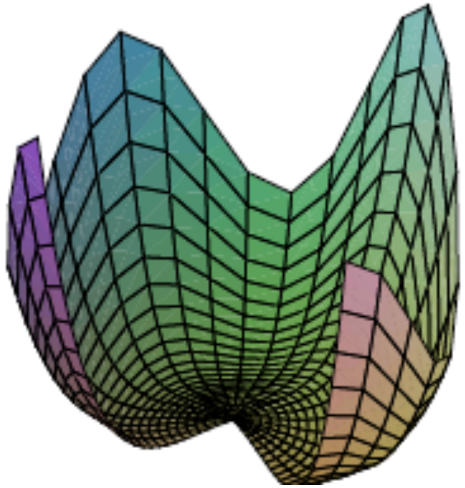
Dimension 5 Yukawa Operator

The minimum of the Potential is given by:

$$\frac{\partial V}{\partial y_i} = 0 \qquad \frac{\partial V}{\partial \theta_i} = 0$$

Take the angle for example:

$$\frac{\partial V}{\partial \theta_c} \propto \left(y_c^2 - y_u^2\right)\left(y_s^2 - y_d^2\right) \sin 2\theta_c = 0$$



Non-degenerate masses $\longrightarrow$ $\sin 2\theta_c = 0$ No mixing !

Can the actual masses and mixings fit naturally in the minimum of the Potential? e.g. adding non-renormalizable terms... **NO**

(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

Y --> one single field Σ

Minimum of the Potential

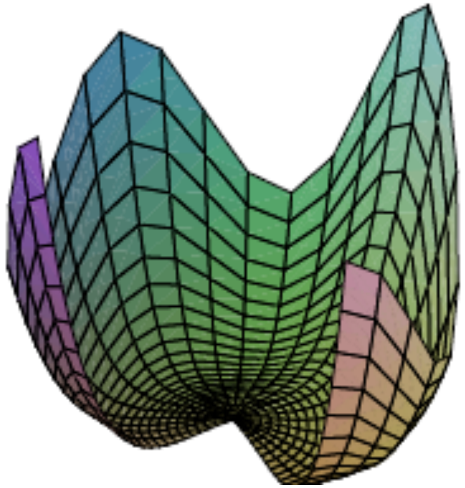
Dimension 5 Yukawa Operator

The minimum of the Potential is given by:

$$\frac{\partial V}{\partial y_i} = 0 \qquad \frac{\partial V}{\partial \theta_i} = 0$$

Take the angle for example:

$$\frac{\partial V}{\partial \theta_c} \propto (y_c^2 - y_u^2)\,(y_s^2 - y_d^2)\,\sin 2\theta_c = 0$$



Non-degenerate masses $\sin 2\theta_c = 0$ No mixing !

Can the actual masses and mixings fit naturally in the minimum of the Potential? e.g. adding non-renormalizable terms...

NO

* Without fine-tuning, for two families the spectrum is degenerate
* To accomodate realistic mixing one must introduce wild fine tunnings of $O(10^{-10})$ and nonrenormalizable terms of dimension 8

(Alonso, Gavela, Merlo, Rigolin)

Y --> one single field Σ

three families

* at renormalizable level: 7 invariants instead of the 5 for two families

$$\mathrm{Tr}\left(\Sigma_u\Sigma_u^\dagger\right) \overset{vev}{=} \Lambda_f^2\left(y_t^2+y_c^2+y_u^2\right)\,,\qquad Det\left(\Sigma_u\right) \overset{vev}{=} \Lambda_f^3 y_u y_c y_t\,,$$

$$\mathrm{Tr}\left(\Sigma_d\Sigma_d^\dagger\right) \overset{vev}{=} \Lambda_f^2\left(y_b^2+y_s^2+y_d^2\right)\,,\qquad Det\left(\Sigma_d\right)\Big| \overset{vev}{=} \Lambda_f^3 y_d y_s y_b\,,$$

$$\mathrm{Tr}\left(\Sigma_u\Sigma_u^\dagger\Sigma_u\Sigma_u^\dagger\right) \overset{vev}{=} \Lambda_f^4\left(y_t^4+y_c^4+y_u^4\right)\,,$$

$$\mathrm{Tr}\left(\Sigma_d\Sigma_d^\dagger\Sigma_d\Sigma_d^\dagger\right) \overset{vev}{=} \Lambda_f^4\left(y_b^4+y_s^4+y_d^4\right)\,,$$

$$\mathrm{Tr}\left(\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right) \overset{vev}{=} \Lambda_f^4\left(P_0+P_{int}\right)\,,$$

Interesting angular dependence:

$$P_0 \equiv -\sum_{i<j}\left(y_{u_i}^2-y_{u_j}^2\right)\left(y_{d_i}^2-y_{d_j}^2\right)\sin^2\theta_{ij}\,,$$

$$\begin{aligned}P_{int} \equiv &\sum_{i<j,k}\left(y_{d_i}^2-y_{d_k}^2\right)\left(y_{u_j}^2-y_{u_k}^2\right)\sin^2\theta_{ik}\sin^2\theta_{jk}+\\ &-\left(y_d^2-y_s^2\right)\left(y_c^2-y_t^2\right)\sin^2\theta_{12}\sin^2\theta_{13}\sin^2\theta_{23}+\\ &+\frac{1}{2}\left(y_d^2-y_s^2\right)\left(y_c^2-y_t^2\right)\cos\delta\,\sin 2\theta_{12}\sin 2\theta_{23}\sin\theta_{13}\,,\end{aligned}$$

Sad conclusions as for 2 families:

needs non-renormalizable + super fine-tuning

Y --> one single field Σ

Spectrum for flavons Σ in the bifundamental:

* **3 generations: for the largest fraction of the parameter space, the stable solution is a degenerate spectrum**

$$\begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \sim \begin{pmatrix} y & & \\ & y & \\ & & y \end{pmatrix}$$

instead of the observed hierarchical spectrum, i.e.

$$\begin{pmatrix} y_u & & \\ & y_c & \\ & & y_t \end{pmatrix} \sim \begin{pmatrix} 0 & & \\ & 0 & \\ & & y \end{pmatrix}$$

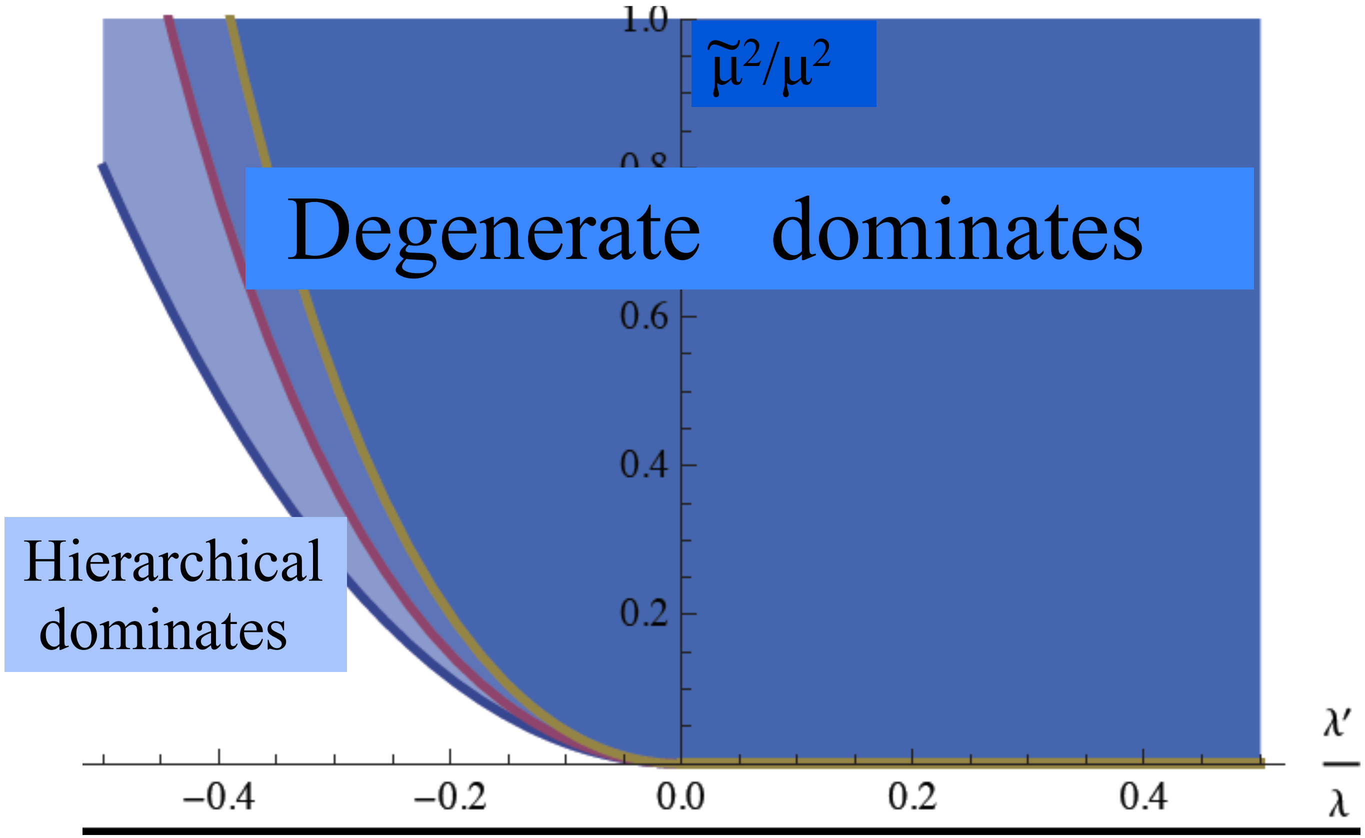
(at leading order)

Spectrum: the hierarchical solution is unstable in most of the parameter space.

Stability: $\boxed{\dfrac{\tilde{\mu}^2}{\mu^2} < \dfrac{2\lambda'^2}{\lambda}}$

$$V^{(4)} = \sum_{i=u,d} \left(-\mu_i^2 A_i + \tilde{\mu}_i B_i + \lambda_i A_i^2 + \lambda_i' A_{ii}\right) + g_{ud} A_u A_d + \lambda_{ud} A_{ud} \,.$$

ie, the u-part: $V^{(4)} = -\mu_u^2 A_u + \tilde{\mu}_u B_u + \lambda_u A_u^2 + \lambda_u' A_{uu}$



The real, unavoidable, problem is again mixing:

* Just one source:

$$\mathrm{Tr}\,(\Sigma_u \Sigma_u^+ \Sigma_d \Sigma_d^+) = \Lambda_f^4 (P_0 + P_{int})$$

P_0 and P_{int} encode the angular dependence,

$$P_0 \equiv -\sum_{i<j} \left(y_{u_i}^2 - y_{u_j}^2\right)\left(y_{d_i}^2 - y_{d_j}^2\right) \sin^2\theta_{ij}\,,$$

$$\begin{aligned} P_{int} \equiv &\sum_{i<j,k} \left(y_{d_i}^2 - y_{d_k}^2\right)\left(y_{u_j}^2 - y_{u_k}^2\right) \sin^2\theta_{ik} \sin^2\theta_{jk} + \\ &- \left(y_d^2 - y_s^2\right)\left(y_c^2 - y_t^2\right) \sin^2\theta_{12} \sin^2\theta_{13} \sin^2\theta_{23} + \\ &+ \frac{1}{2}\left(y_d^2 - y_s^2\right)\left(y_c^2 - y_t^2\right) \cos\delta\, \sin 2\theta_{12} \sin 2\theta_{23} \sin\theta_{13} \end{aligned}$$

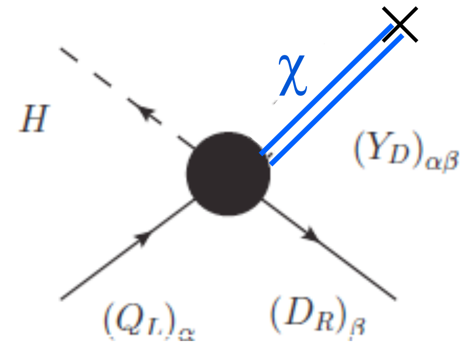
whose derivative -----> all sin θ = 0 at the renormalizable level

Summary

--> **Dynamical** MFV spurions in the bifundamental do not provide realistic masses and mixings (at least in the minimal realization)

2) Y --> quadratic in fields χ

$$Y \sim \frac{\langle \chi \chi^\dagger \rangle}{\Lambda_f^2}$$



→ **Automatic strong mass hierarchy and one mixing angle !**
already at the renormalizable level

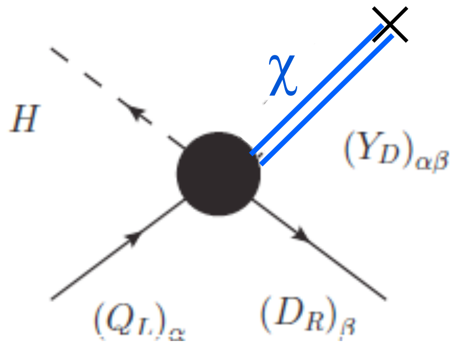
Holds for 2 and 3 families !

Y --> quadratic in fields χ

Dimension 6 Yukawa operator

χ are fundamentals of G_f : vectors, similar to quarks and leptons

$$\mathscr{L}_Y = \overline{Q}_L \frac{\chi_d^L \chi_d^{R\dagger}}{\Lambda_f^2} D_R H + \overline{Q}_L \frac{\chi_u^L \chi_u^{R\dagger}}{\Lambda_f^2} U_R \tilde{H} + \text{h.c.}\,,$$



i.e. $$Y_D \sim \frac{\chi^L{}_d\, (\chi^R{}_d)^+}{\Lambda_f^2} \sim (3,1,1)\,(1,1,\overline{3}) \sim (3,1,\overline{3})$$

$\chi^L{}_u, \chi^L{}_d \sim (3,1,1)$; $\chi^R{}_u \sim (1,3,1)$; $\chi^R{}_d \sim (1,1,3)$

$\boxed{\text{Y --> quadratic in fields } \chi}$

It is very simple:

- a square matrix built out of 2 vectors

$$\begin{pmatrix} d \\ e \\ f \\ \vdots \end{pmatrix} (\, a \,, b \,, c \, \ldots\ldots)$$

has only one non-vanishing eigenvalue

→ strong mass hierarchy at leading order:

-- only 1 heavy "up" quark

-- only 1 heavy "down" quark

only $|\chi|$´s relevant for scale

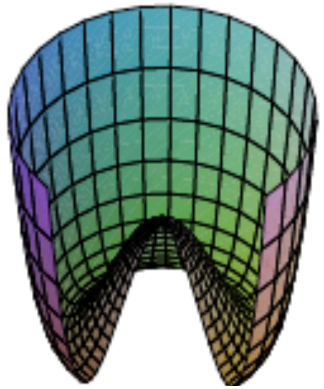
Y --> quadratic in fields χ

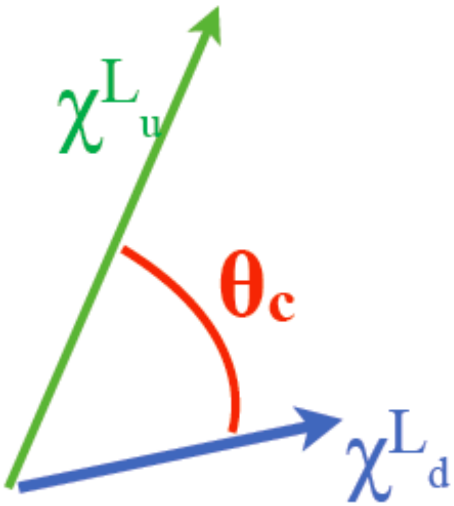
Minimum of the Potential

Dimension 6 Yukawa Operator

The invariants are:

$$\chi_u^{L\dagger}\chi_u^L\,,\qquad \chi_u^{R\dagger}\chi_u^R\,,\qquad \chi_d^{L\dagger}\chi_d^L\,,$$
$$\chi_d^{R\dagger}\chi_d^R\,,\qquad \chi_u^{L\dagger}\chi_d^L = \left|\chi_u^L\right|\left|\chi_d^L\right|\cos\theta_c\,.$$





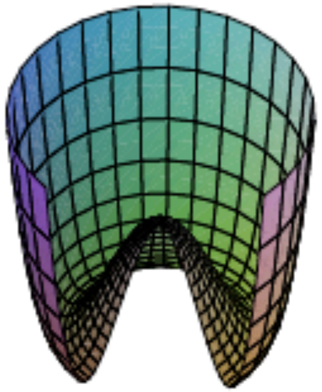
θ_c is the angle between up and down L vectors

Y --> quadratic in fields χ

Minimum of the Potential

Dimension 6 Yukawa Operator

The invariants are:



$$\chi_u^{L\dagger}\chi_u^L, \qquad \chi_u^{R\dagger}\chi_u^R, \qquad \chi_d^{L\dagger}\chi_d^L,$$
$$\chi_d^{R\dagger}\chi_d^R, \qquad \chi_u^{L\dagger}\chi_d^L = \left|\chi_u^L\right|\left|\chi_d^L\right|\cos\theta_c\,.$$

We can fit the angle and the masses in the Potential; as an example:

$$V' = \lambda_u\left(\chi_u^{L\dagger}\chi_u^L - \frac{\mu_u^2}{2\lambda_u}\right)^2 + \lambda_d\left(\chi_d^{L\dagger}\chi_d^L - \frac{\mu_d^2}{2\lambda_d}\right)^2$$
$$+\lambda_{ud}\left(\chi_u^{L\dagger}\chi_d^L - \frac{\mu_{ud}^2}{2\lambda_{ud}}\right)^2 + \cdots$$

Whose minimum sets (2 generations):

$$y_c^2 = \frac{\mu_u^2}{2\lambda_u\Lambda_f^2} \quad y_s^2 = \frac{\mu_d^2}{2\lambda_d\Lambda_f^2} \quad \cos\theta = \frac{\mu_{ud}^2\sqrt{\lambda_u\lambda_d}}{\mu_u\mu_d\lambda_{ud}}$$

Y --> quadratic in fields χ

Towards a realistic 3 family spectrum

e.g. replicas of χ^{L} , χ^{R}_{u} , χ^{R}_{d}

???

$Y \dashrightarrow$ quadratic in fields χ

Towards a realistic 3 family spectrum

e.g. replicas of χ^L , χ_u^R , χ_d^R

???

Suggests sequential breaking:

$$SU(3)^3 \xrightarrow[\text{mt, mb}]{} SU(2)^3 \xrightarrow[\text{mc, ms, } \theta_C]{} \cdots\cdots\cdots$$

$$Y_u \equiv \frac{\langle \chi^L \rangle \langle \chi_u^{R\dagger} \rangle}{\Lambda_f^2} + \frac{\langle \chi_u'^L \rangle \langle \chi_u'^{R\dagger} \rangle}{\Lambda_f^2} = \begin{pmatrix} 0 & \sin\theta\, y_c & 0 \\ 0 & \cos\theta\, y_c & 0 \\ 0 & 0 & y_t \end{pmatrix}$$

$$Y_d \equiv \frac{\langle \chi^L \rangle \langle \chi_d^{R\dagger} \rangle}{\Lambda_f^2} + \frac{\langle \chi_d'^L \rangle \langle \chi_d'^{R\dagger} \rangle}{\Lambda_f^2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} .$$

Y --> linear + quadratic in fields

Towards a realistic 3 family spectrum

Combining fundamentals and bi-fundamentals

i.e. combining d=5 and d =6 Yukawa operators

$$\Sigma_u \sim (3,\overline{3},1)\ , \qquad \Sigma_d \sim (3,1,\overline{3})\ , \qquad \Sigma_R \sim (1,3,\overline{3})\ ,$$

$$\chi_u^L \in (3,1,1)\ , \qquad \chi_u^R \in (1,3,1)\ , \qquad \chi_d^L \in (3,1,1)\ , \qquad \chi_d^R \in (1,1,3)\ .$$

The Yukawa Lagrangian up to the second order in $1/\Lambda_f$ is given by:

$$\mathscr{L}_Y = \overline{Q}_L \left[\frac{\Sigma_d}{\Lambda_f} + \frac{\chi_d^L \chi_d^{R\dagger}}{\Lambda_f^2}\right] D_R H + \overline{Q}_L \left[\frac{\Sigma_u}{\Lambda_f} + \frac{\chi_u^L \chi_u^{R\dagger}}{\Lambda_f^2}\right] U_R \tilde{H} + \text{h.c.}\ ,$$

* From bifundamentals: $\langle\Sigma_u\rangle = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_t \end{pmatrix}$

$$\langle\Sigma_d\rangle = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_b \end{pmatrix}$$

* From fundamentals χ : y_c, y_s and θ_C

*** At leading (renormalizable) order:**

$$Y_u \equiv \frac{\langle \Sigma_u \rangle}{\Lambda_f} + \frac{\langle \chi_u^L \rangle \langle \chi_u^{R\dagger} \rangle}{\Lambda_f^2} = \begin{pmatrix} 0 & \sin\theta_c\, y_c & 0 \\ 0 & \cos\theta_c\, y_c & 0 \\ 0 & 0 & y_t \end{pmatrix},$$

$$Y_d \equiv \frac{\langle \Sigma_d \rangle}{\Lambda_f} + \frac{\langle \chi_d^L \rangle \langle \chi_d^{R\dagger} \rangle}{\Lambda_f^2} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}.$$

without unnatural fine-tunings

*** The masses of the first family and the other angles from non-renormalizable terms or other corrections or replicas ?**

Are these constructions non-minimal MFV? NMFV

* When the Yukawa is a combination, the interpretation of the minima of the potential is not straightforward

*** Fundamentals χ lead to different hierarchy of FCNC operators than bifundamentals Σ:**

$$\overline{D}_R \, \Sigma_d^\dagger \, \Sigma_u \, \Sigma_u^\dagger \, Q_L \sim [\text{mass}]^6 \qquad \longleftrightarrow \qquad \overline{D}_R \, \chi_d^R \, \chi_u^{L\dagger} \, Q_L \sim [\text{mass}]^5$$

- possible different phenomenology than for minimal MFV

What is the scalar potential of MFV including Majorana νs?

- Work ongoing right now

- It should allow to answer the question - within MFV - of whether leptonic mixing differs from quark mixing because of the different nature of mass

Conclusions

We constructed the general Scalar Potential for MFV and explored its minima

* **The flavor symmetry imposes strong restrictions: just a few invariants allowed at the renormalizable and non-renormalizable level.** **Quark masses and mixings difficult to accomodate**

* **Flavons in the bifundamental alone ($Y \sim \langle\Sigma\rangle/\Lambda_f$) do NOT lead naturally to realistic mixing**

* **Flavons in the fundamental are tantalizing ($Y \sim \langle\chi^2\rangle/\Lambda^2$), inducing naturally:**

- **strong mass hierarchy**
- **non-trivial mixing !!**

-- We are exploring the leptonic MFV scalar potential

Back-up slides

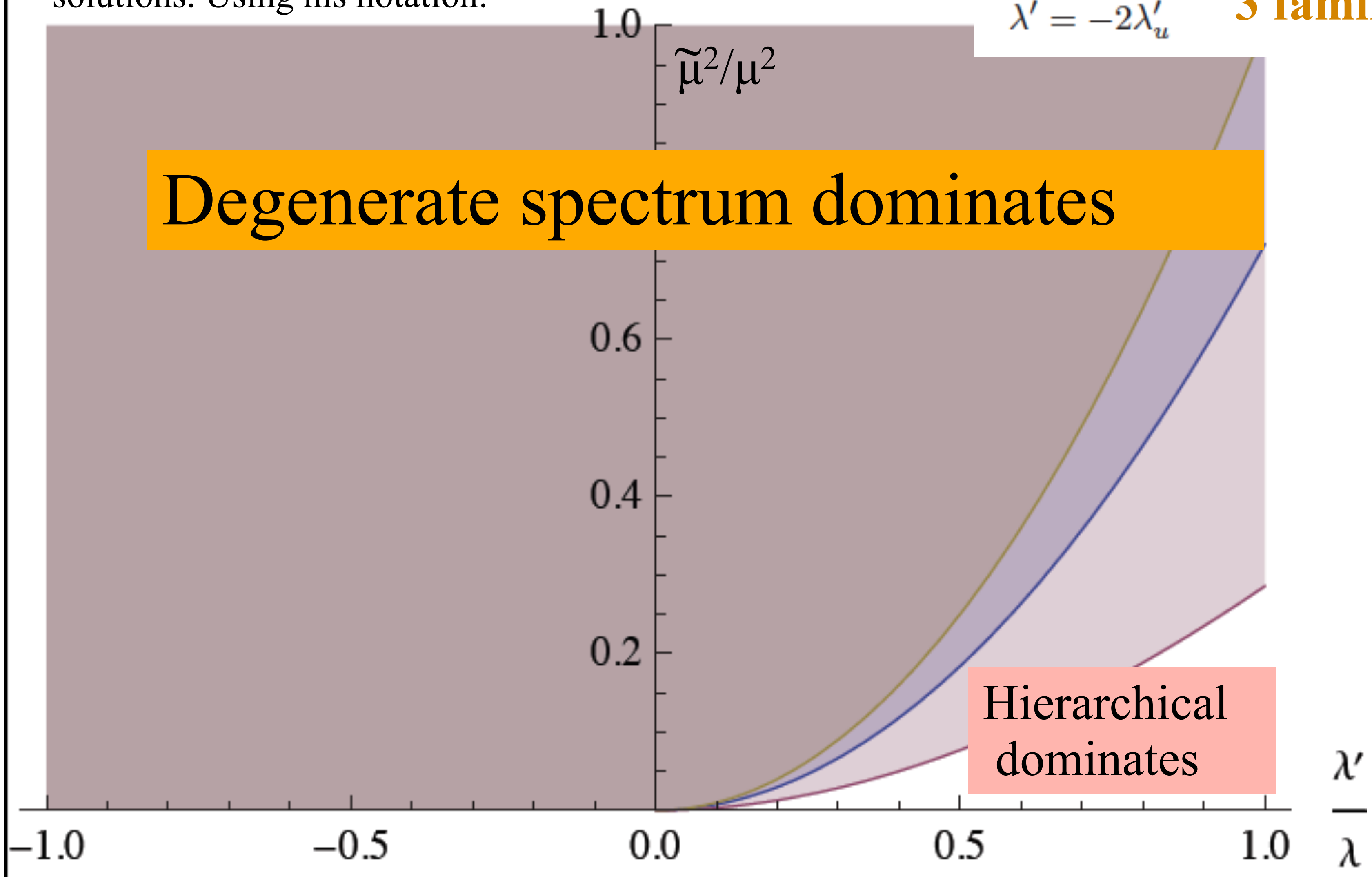
Three weeks ago, Nardi redid our analysis for flavons in the bifundamental, changing slightly the notation... and focusing on hierarchical sols.
But the stability conditions constraint the hierarchical solutions. Using his notation:

χ <---> Σ

Nardi *Alonso et al.*

$$\mu = \mu_u$$
$$\tilde{\mu} = \tilde{\mu}_u$$
$$\lambda = \lambda_u + \lambda'_u$$
$$\lambda' = -2\lambda'_u$$

3 families



Y --> quadratic in fields χ

Fundamental Fields

Dimension 6 Yukawa Operator

It holds also for 3 families: one heavy "up", one heavy "down", one angle

$$Y_D = \frac{\langle \chi_d^L \chi_d^{R\dagger} \rangle}{\Lambda_f^2} \qquad Y_U = \frac{\langle \chi_u^L \chi_u^{R\dagger} \rangle}{\Lambda_f^2}$$

The Yukawas are composed of two 'vectors'. Such a structure has only one eigenvalue, one mass . This fact becomes evident when rotating the v.e.v.s of the fields to the form:

$$V_L^\dagger Y_D V_{D_R} = \frac{|\chi_d^L|\,|\chi_d^R|}{\Lambda^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$V_L^\dagger Y_U V_{U_R} = \frac{|\chi_u^L|\,|\chi_u^R|}{\Lambda_f^2} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

This means a hierarchy among the masses and an angle only by construction! already at renormalizable level

A rationale for the MFV ansatz?

- Flavour data (i.e. B physics) consistent with all flavour physics coming from Yukawa

- Inspired in "condensate" flavour physics a la Froggat-Nielsen (Yukawas ~ $<\Psi\bar{\Psi}>^n/\Lambda_f^n$, rather than in susy-like options

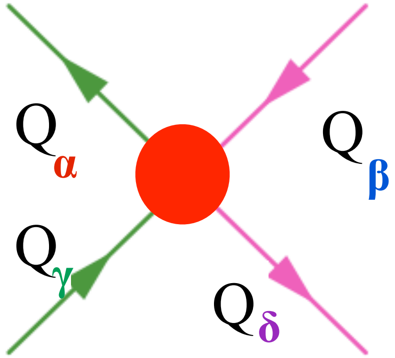
- It makes you think on the relation between scales:
  electroweak vs. flavour vs lepton number scales

MFV IS NOT A MODEL OF FLAVOUR

IT REMAINS AT THIS LEVEL

$$C^{d=6} \sim \frac{Y^{+}_{\alpha\beta}\, Y_{\gamma\delta}}{\Lambda^{2}_{\mathrm{flavour}}}$$

From the SM to the theory of flavour



?

$SU(2)\, x U(1)_{em}$ gauge invariant

?

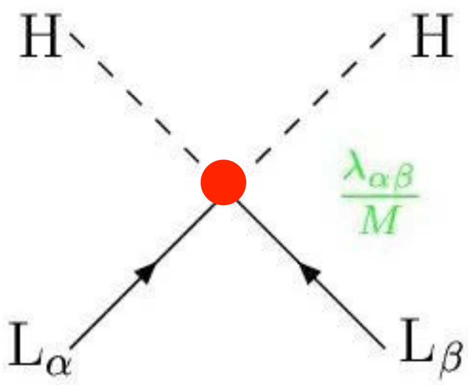
The Theory of Flavour

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

$$\lambda/M\ \underbrace{(L\ L\ H\ H)}_{O^{d=5}} \rightarrow \lambda v^2/M\ (\nu\nu)$$



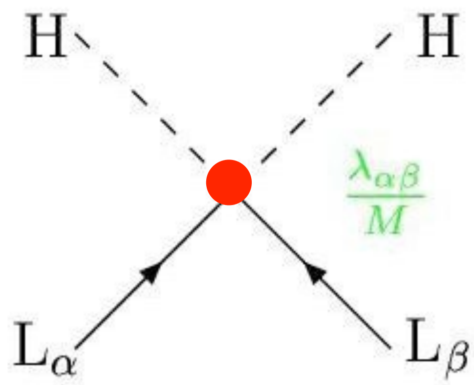
It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

$$\lambda/M\ \underbrace{(L\ L\ H\ H)}_{O^{d=5}} \rightarrow \lambda v^2/M\ (\nu\nu)$$



It's unique $\rightarrow$ very special role of ν masses:
lowest-order effect of higher energy physics

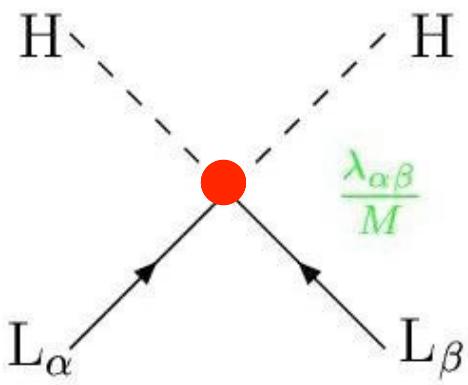
This mass term violates lepton number (B-L)
$\rightarrow$ Majorana neutrinos

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

$$\lambda/M\ (\underbrace{L\ L\ H\ H}_{O^{d=5}}) \rightarrow \lambda v^2/M\ (\nu\nu)$$

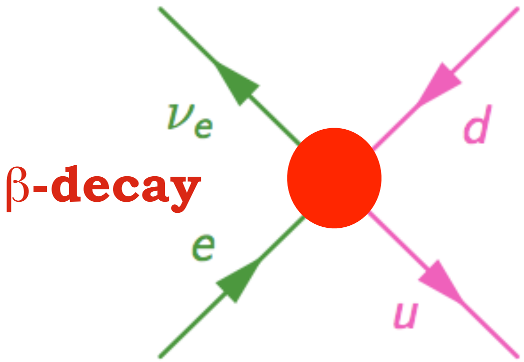


It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

This mass term violates lepton number (B-L)
→ Majorana neutrinos

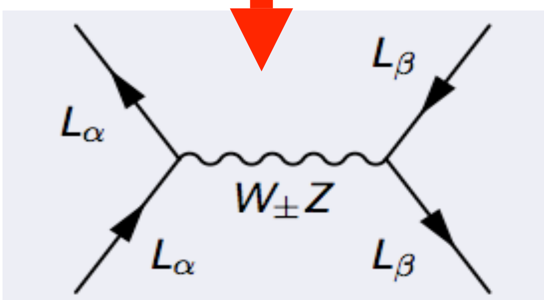
$O^{d=5}$ *is common to all models of Majorana* ν*s*

From the Fermi theory to SM



$$G_F \quad (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$$

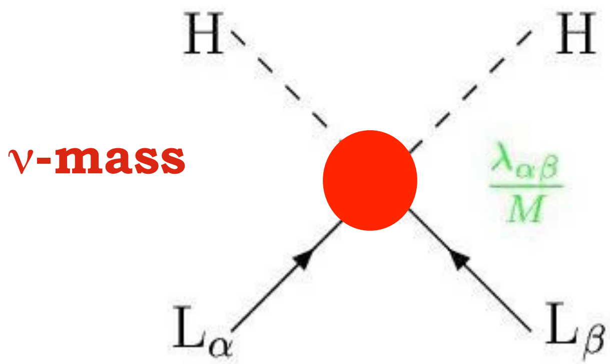
$U(1)_{em}$ invariant



$$\frac{g^2}{M_W^2} \; (L_\alpha \gamma_\mu L_\alpha)\; (Q_{L\beta} \gamma_\mu Q_\beta)$$

$SU(2) \, xU(1)_{em}$ gauge invariant

From Majorana masses to Seesaw

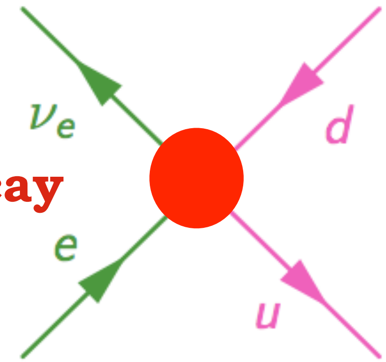


$$\lambda / M \; (L\ L\ H\ H)$$

$SU(2) \, xU(1)_{em}$ inv.

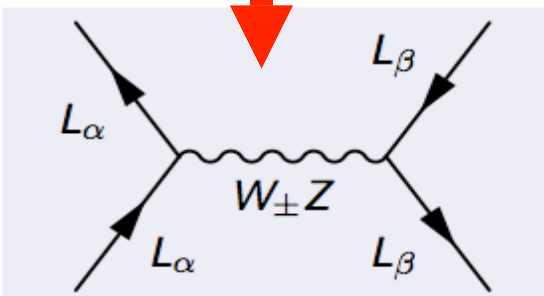
From the Fermi theory to SM

β-decay



$G_F \quad (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$

$U(1)_{em}$ invariant

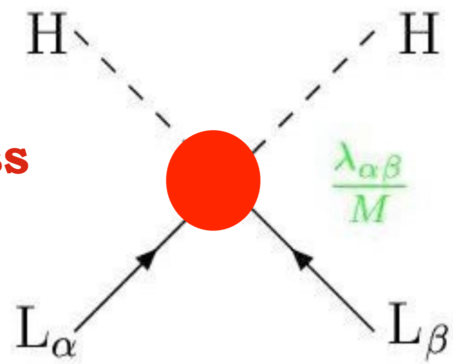


$$\frac{g^2}{M_W^2} \; (L_\alpha \gamma_\mu L_\alpha) \; (Q_{L\beta} \gamma_\mu Q_\beta)$$

$SU(2) \; x U(1)_{em}$ gauge invariant

From Majorana masses to Seesaw

ν-mass

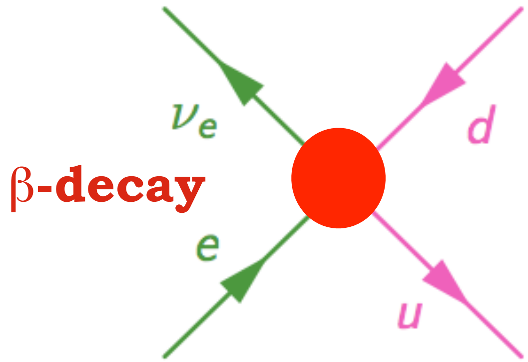


λ / M (L L H H)

$SU(2) \; x U(1)_{em}$ inv.

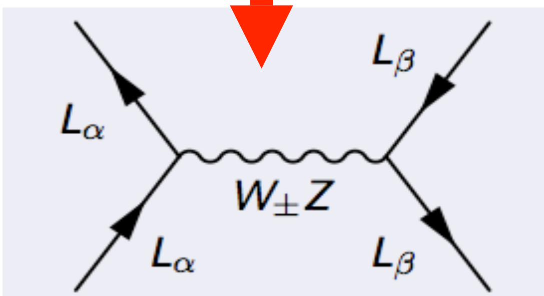
2 x 2 = 1 + 3

From the Fermi theory to SM



$G_F \ (\bar{e}_L \gamma^\mu \nu_L^e)(\bar{u}\gamma_\mu d_L)$

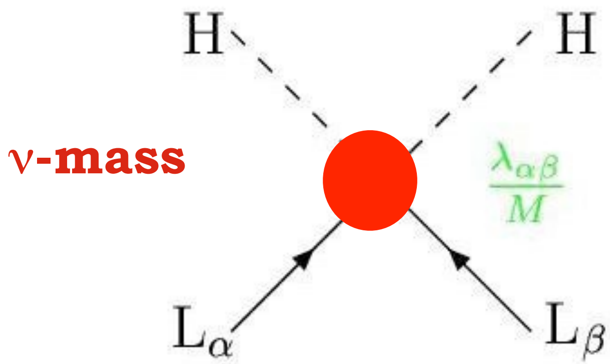
$U(1)_{em}$ invariant



$$\frac{g^2}{M_W^2} \ (L_\alpha \gamma_\mu L_\alpha) \ (Q_{L\beta} \gamma_\mu Q_\beta)$$

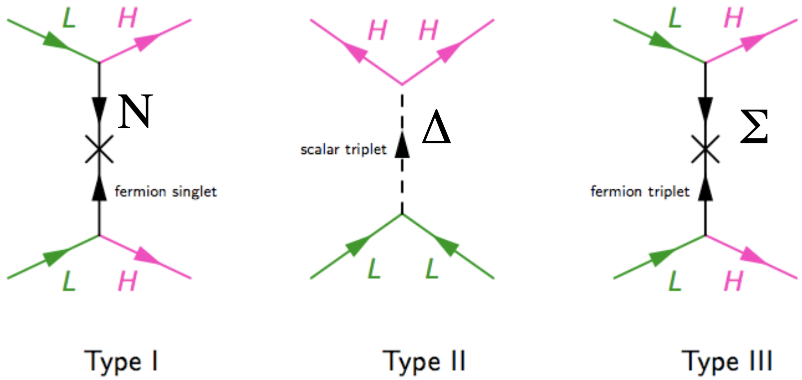
$SU(2) \, xU(1)_{em}$ gauge invariant

From Majorana masses to Seesaw



$\lambda/M \ (L \, L \, H \, H)$

$SU(2) \, xU(1)_{em}$ inv.



Seesaw models

Gonzalez-Alonso

Minimal Flavour violation (MFV)

•Unitarity of CKM first row:

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2=0.9999\pm0.0006$$

•*Restrict to flavour blind ops.-> 4 operators

•Correction is only multiplicative to β and μ decay rate

- **The direct experimental limit puts strong constraints on all 4 operators, at the level of the colliders constraints or better.**

$$\Delta_{CKM} = -(0.1\pm0.6)\cdot10^{-3} \Rightarrow \Lambda_i^{eff} > 11\,\mathrm{TeV}\ (90\%\,\mathrm{CL})$$

* 2 generations: our results may apply directly to models in which the third is decoupled

* 3 generations