The Potential of Minimal Flavour Violation

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Today I will discuss flavour:

* for quarks
* for leptons

and then focus on Minimal Flavour Violation (MFV) for both sectors

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

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:

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

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

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* The **electroweak** vaccuum: 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

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

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The Higgs excitation has the quantum numbers of the EW vacuum

BSM because

1) **Experimental evidence** for new <u>**particle**</u> 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
d e

c ν_μ
s μ

t ν_τ
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
d e

c ν_μ
s μ

t ν_τ
b τ

Why so diferent masses and mixing angles?

The Flavour Puzzle

u ν_e
d e

c ν_μ
s μ

t ν_τ
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

$\longrightarrow$ $\Lambda_{\text{electroweak}} \sim$ **1 TeV** ?

* **FLAVOUR PUZZLE**: no progress

Understanding stalled since 30 years.
Only new B physics data AND neutrino masses and mixings

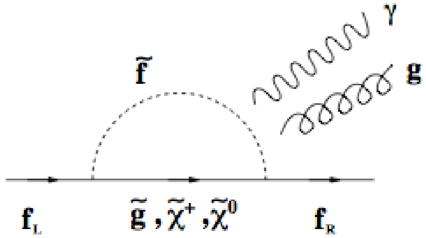
$\longrightarrow$ $\Lambda_f \sim$ **100's TeV** ???

BSMs tend to worsen the favour puzzle

The FLAVOUR WALL for BSM

i) Typically, BSMs have **electric dipole moments** at one loop

i.e susy MSSM:

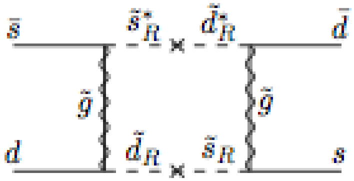


< 1 loop in SM ---> **Best (precision) window of new physics**

ii) **FCNC**

i.e susy MSSM:

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



$\mu \rightarrow e\gamma$

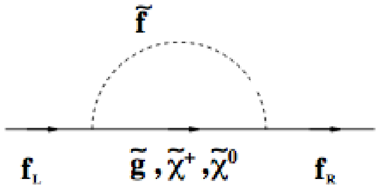
competing with SM at one-loop

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)

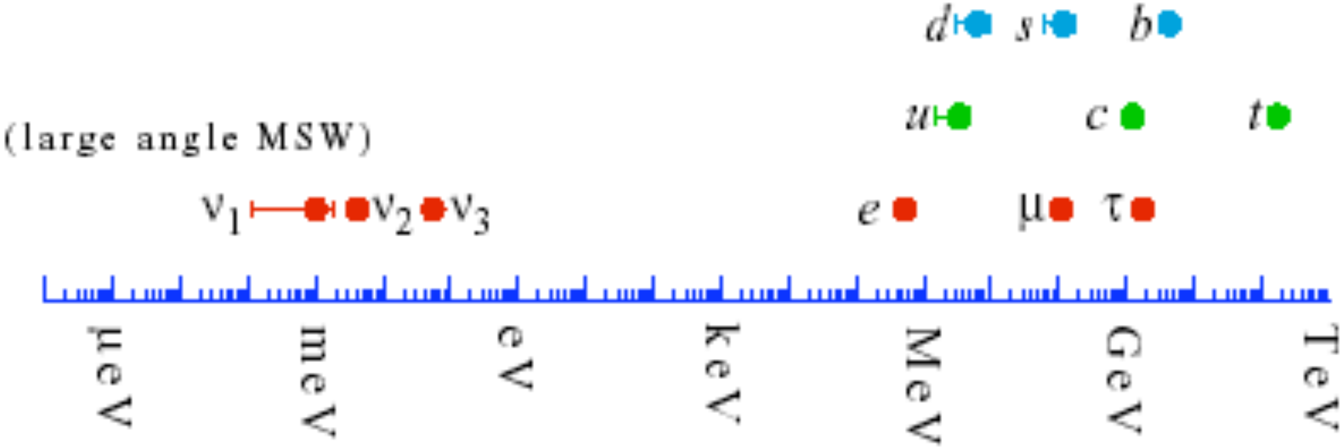
Neutrino light on flavour ?

* 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 .....

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



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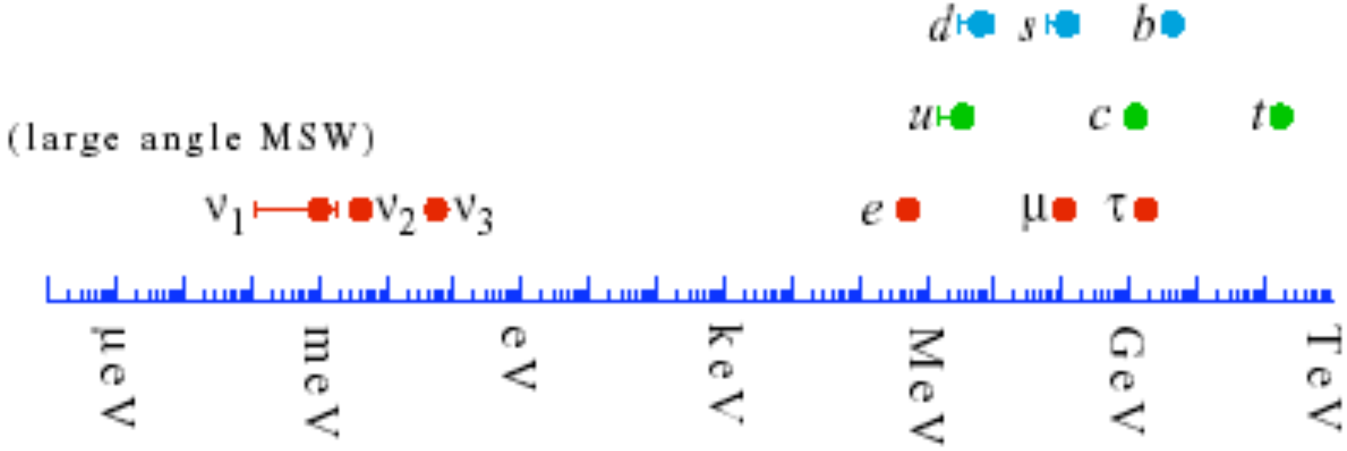
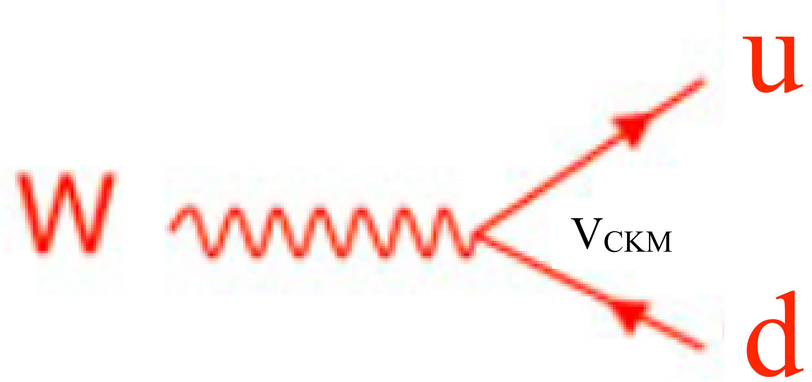


Maybe because of Majorana neutrinos?

Lepton mixing in charged currents

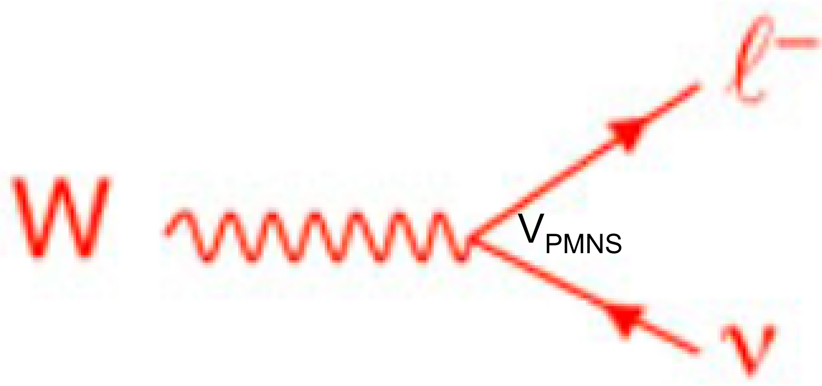
Quarks



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

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

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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

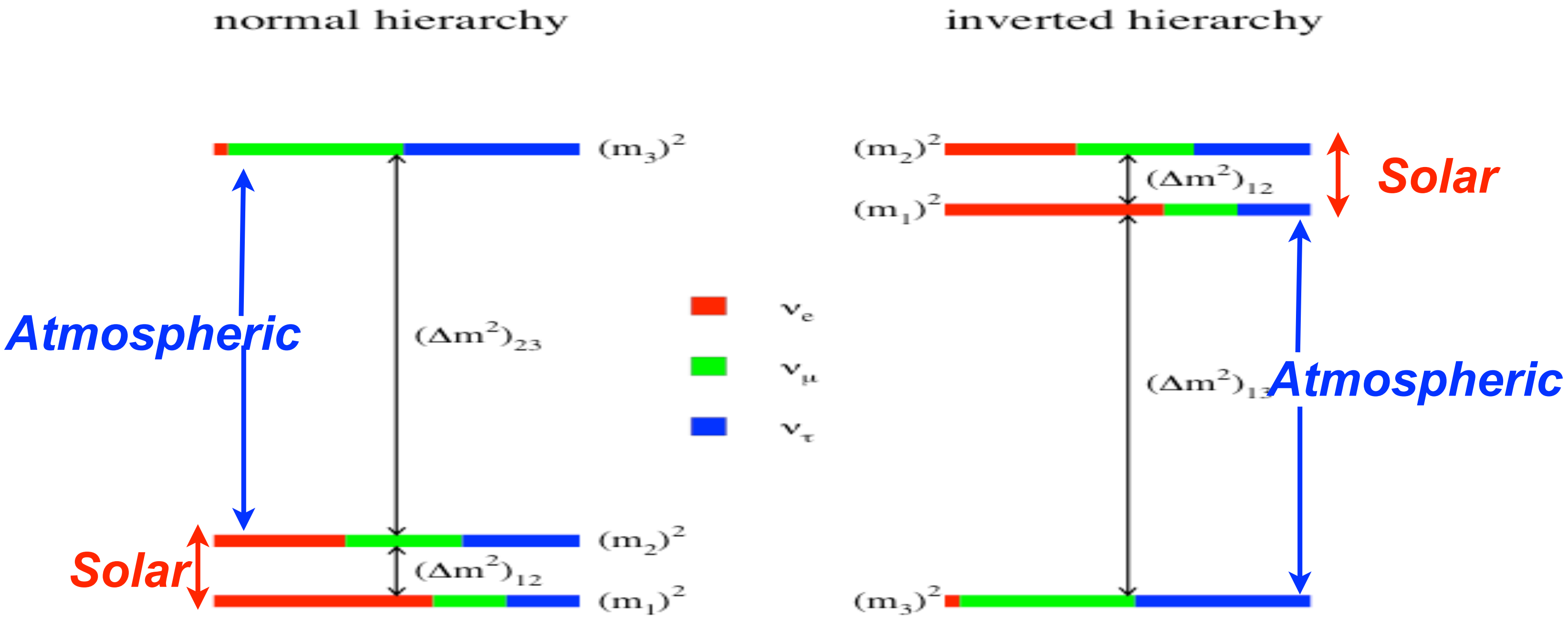
What are the main physics goals in ν physics?

- To determine the absolute scale of masses
- To determine whether they are Majorana

* To discover Leptonic CP-violation

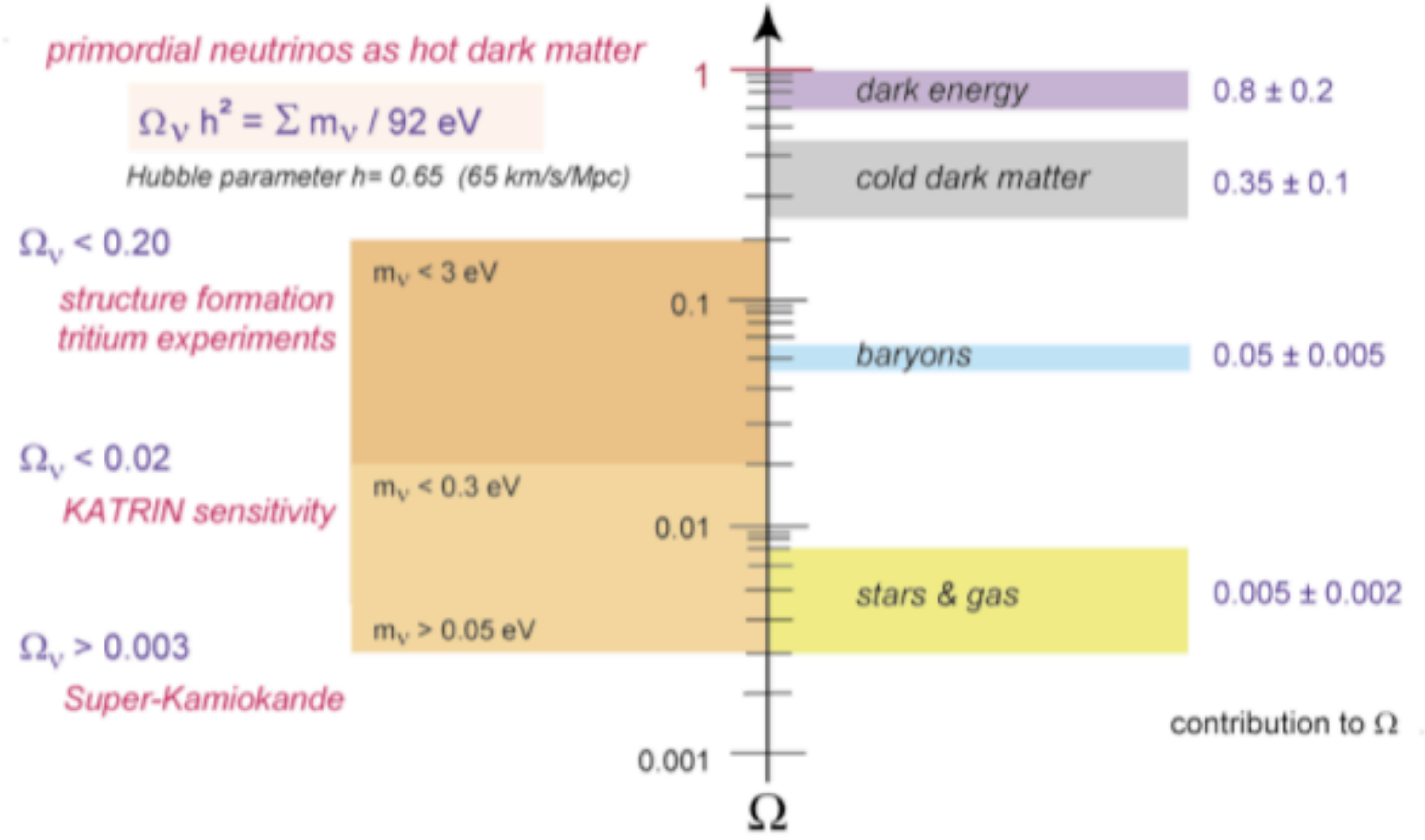
The art of the possible:

We should at least measure the 3 active ν mass matrix



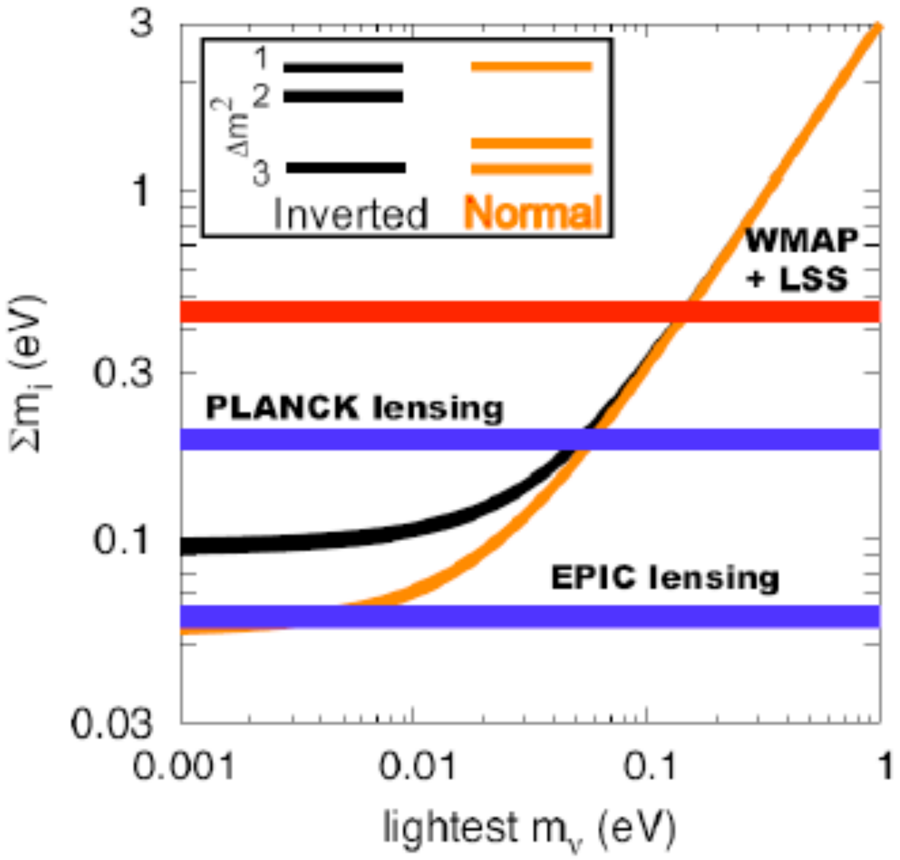
Masses
$m_1^2 < m_2^2$, m_3^2

Absolute mass scale



(Karlsruhe Katrin web page)

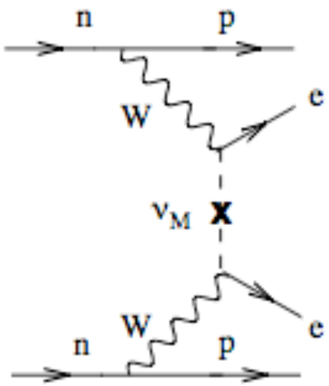
Neutrino mass hierarchy from cosmology

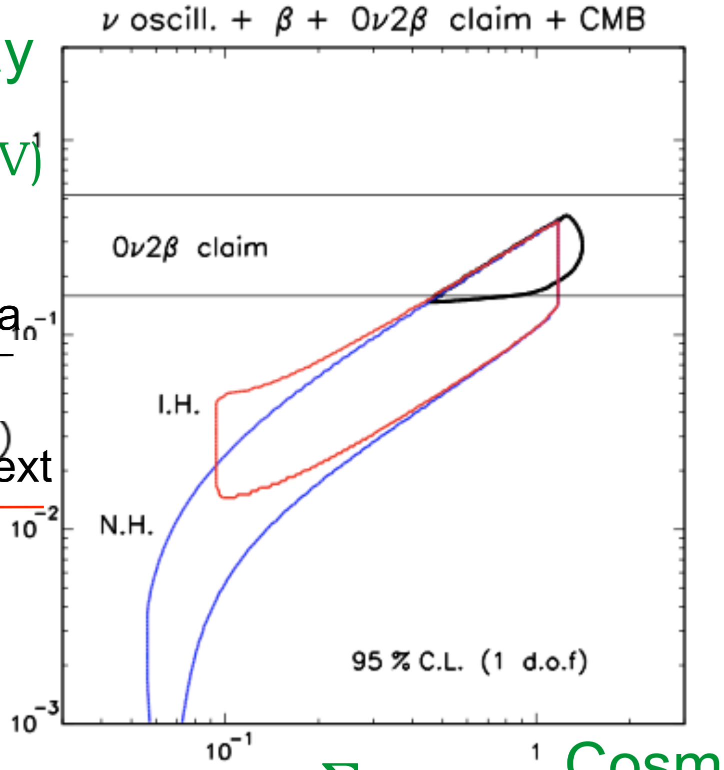


Cooray Now2010

Majorananess and ν mass scale

$0\nu\beta\beta$ decay





$m_{\beta\beta}$(eV)

Next era

(eV)

Next-to-next

Σ(eV)

Cosmo

Figure 6. Present constraints on $m_{\beta\beta}$ and Σ from neutrino experiments and CMB data. Take from [64]. **Fogli et al**

CP violation

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

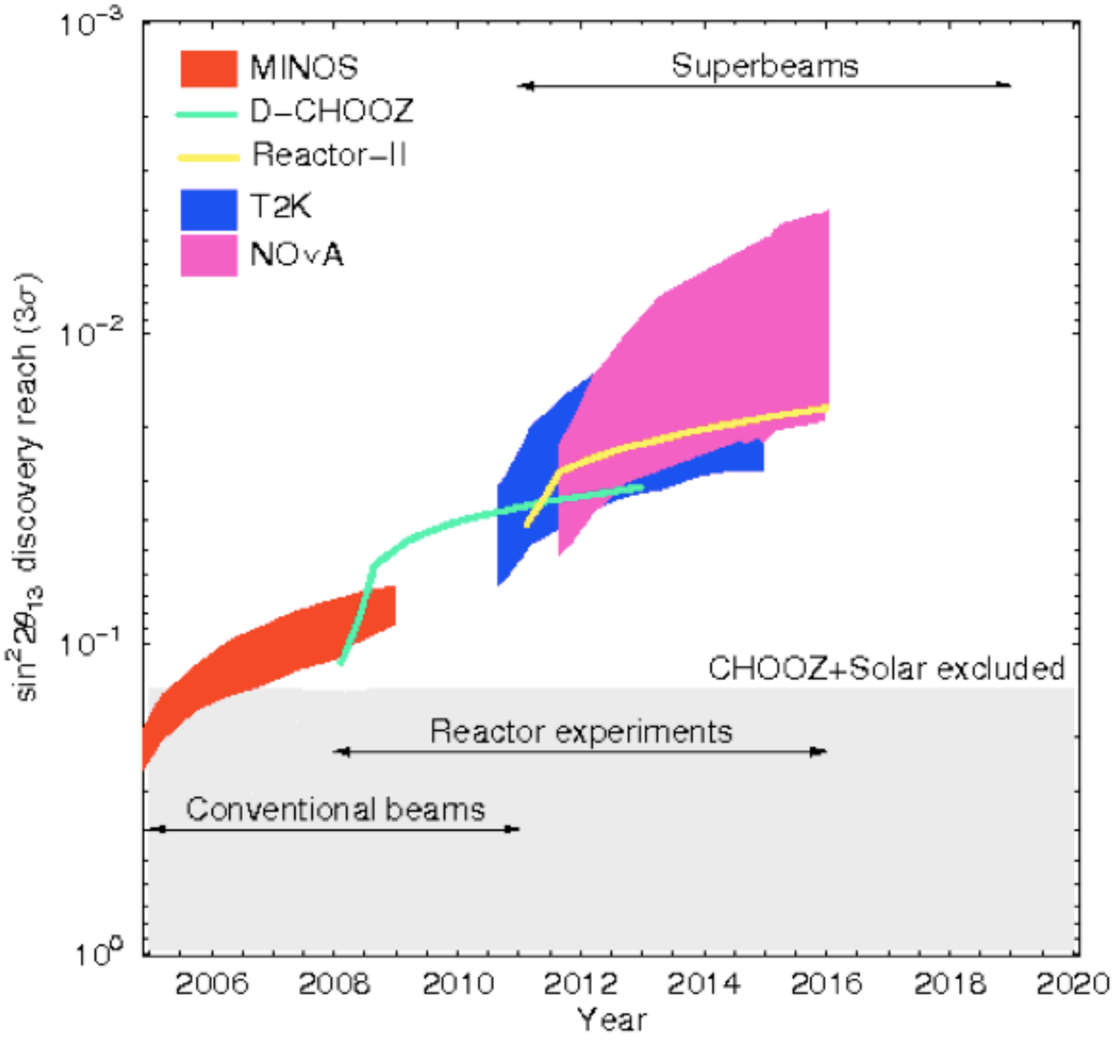
$\theta_{13} \neq 0$ is the key to CP violation

Entering the era of precision neutrino oscillation physics

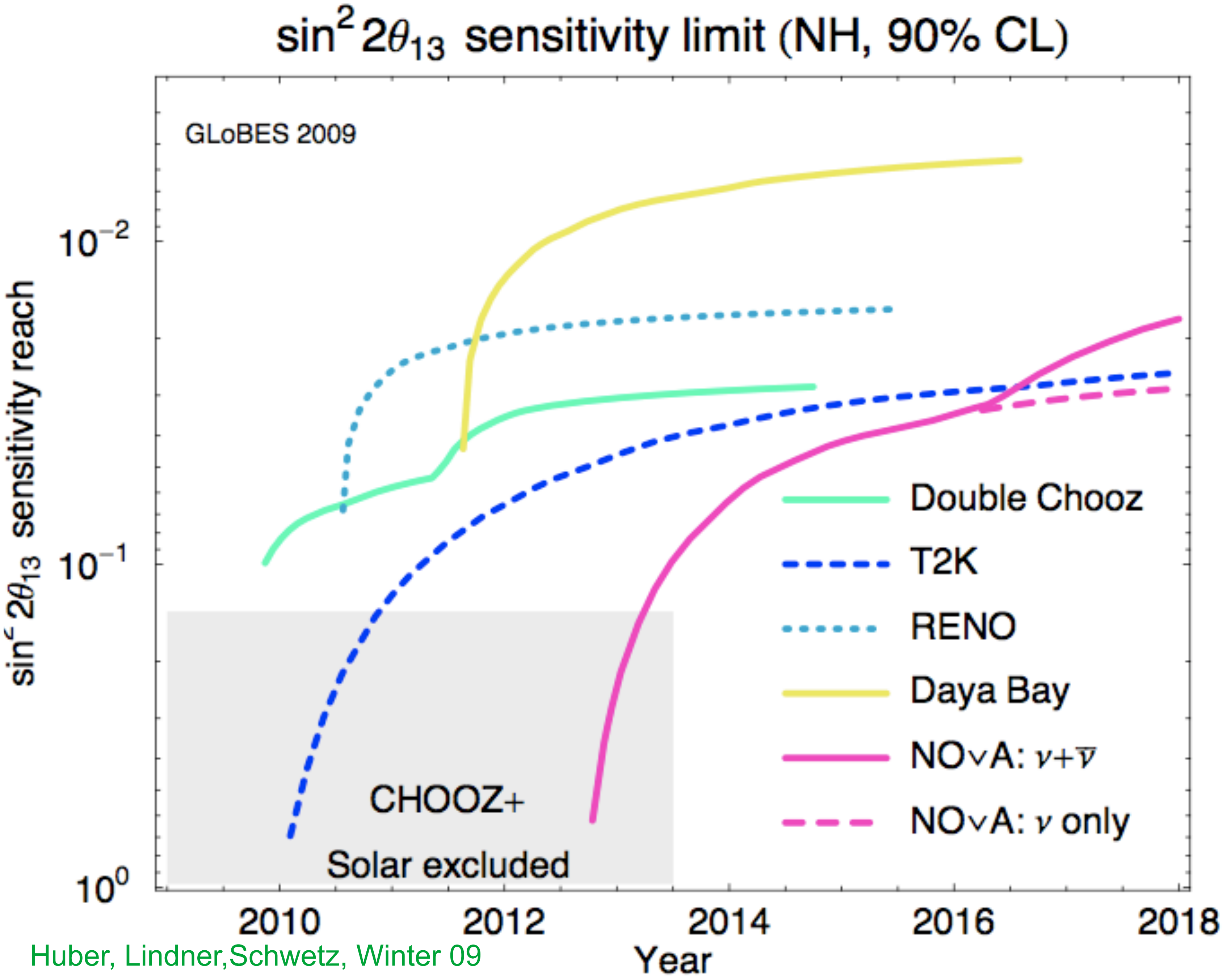
~ % level

ν_μ<--->ν_e golden channel...

θ_{13} future sensitivities



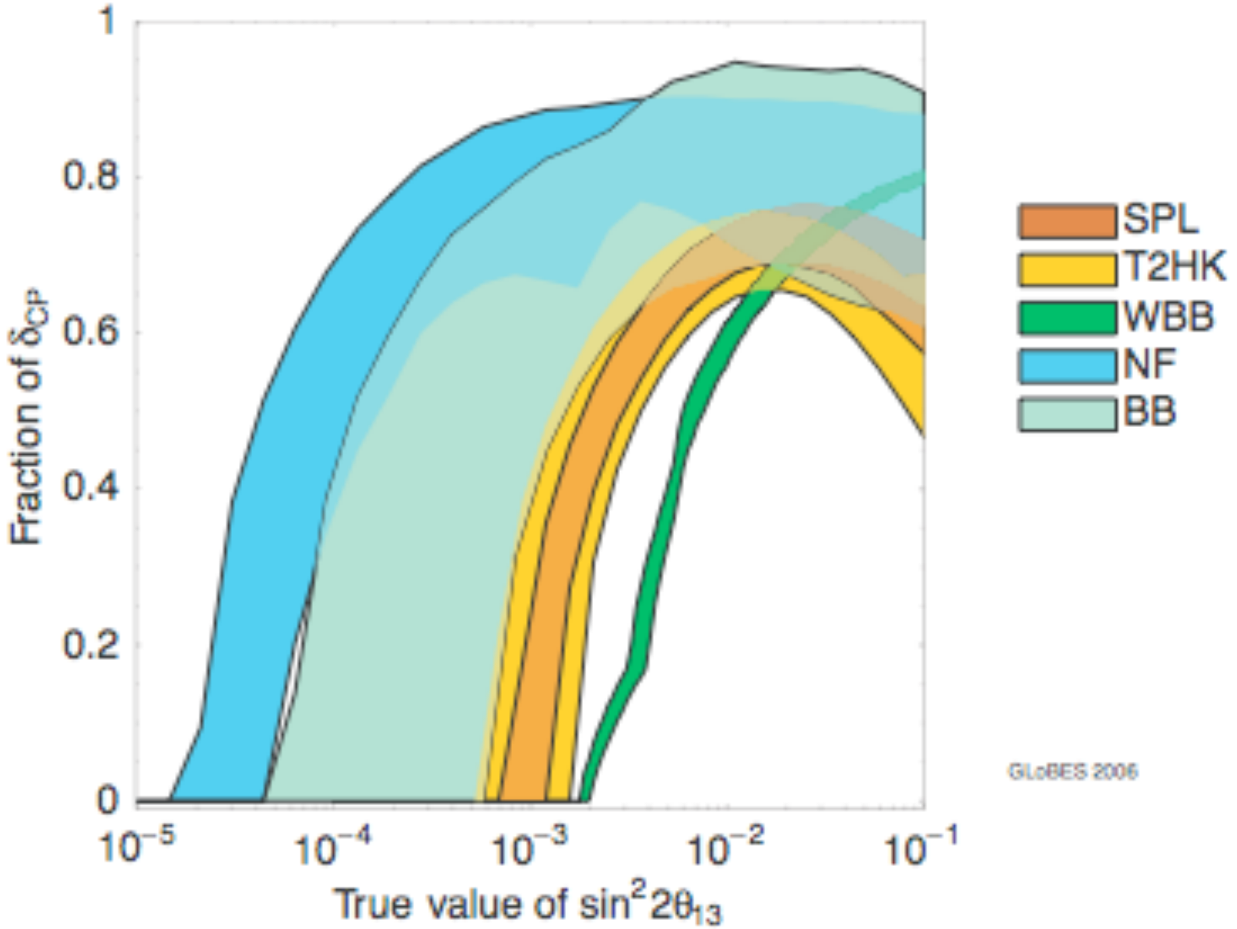
Example with
fixed atmosph.
parameters
(Albrow et al. 06)



Huber, Lindner,Schwetz, Winter 09

Race for the CP phase δ…

ISS report 06



Work of many people …

Plenty of possibilities to reach the $\sin^2 2\theta_{13} \sim 10^{-4}$ realm …

What are the main physics goals in ν physics?

- To determine the absolute scale of masses
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* To discover Leptonic CP-violation

They would not “prove” leptogenesis,
but they would give a strong argument for it

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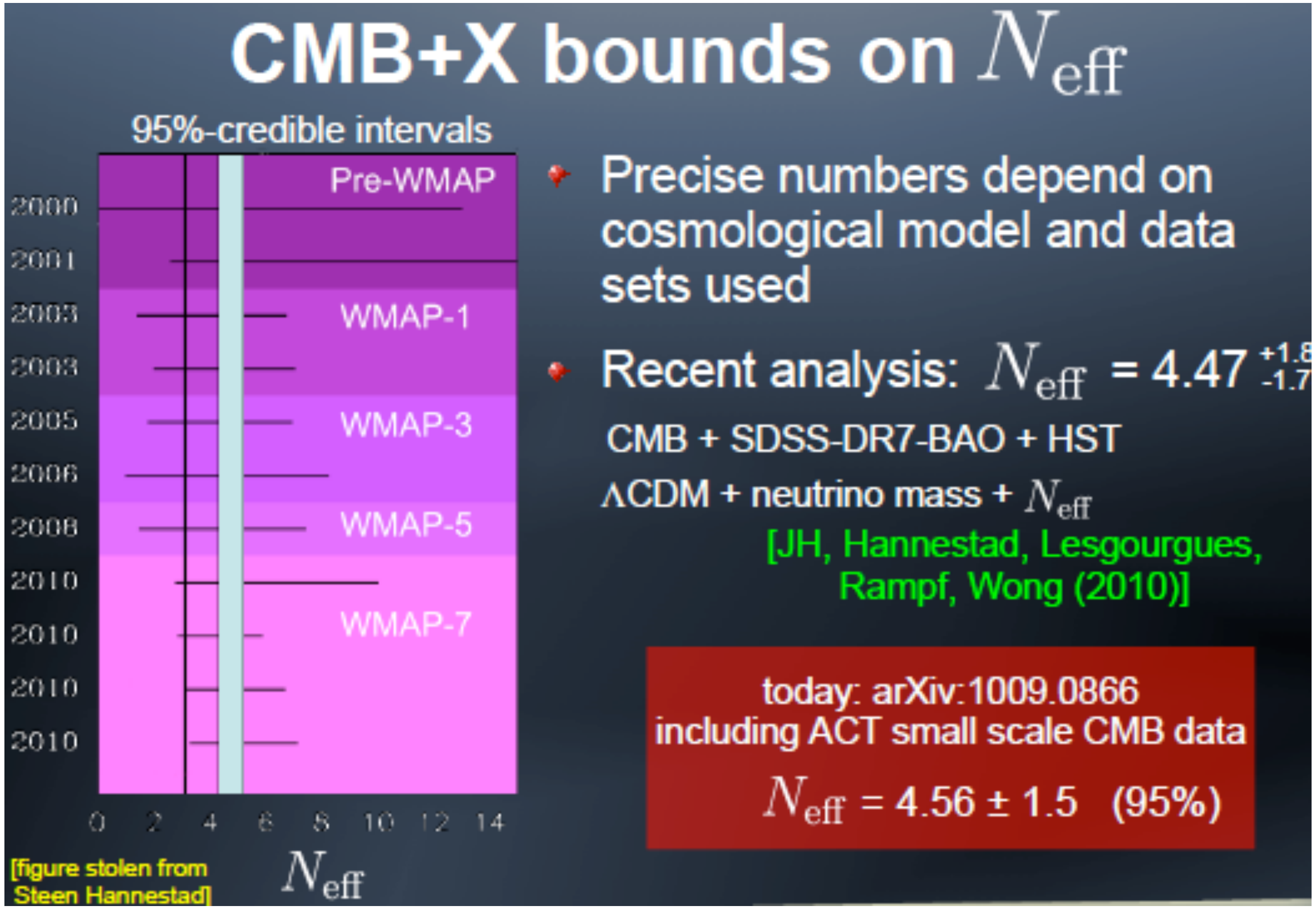
Go for those discoveries !

Can we foresee how to go beyond?

Experimentally? i.e. beyond 3...

- * Miniboone-like...
- * Or rather cosmo?:



CMB+X bounds on $N_{\rm eff}$

[figure stolen from Steen Hannestad]

- Precise numbers depend on cosmological model and data sets used
- Recent analysis: $N_{\rm eff} = 4.47^{+1.8}_{-1.7}$

CMB + SDSS-DR7-BAO + HST

ΛCDM + neutrino mass + $N_{\rm eff}$

[JH, Hannestad, Lesgourgues, Rampf, Wong (2010)]

today: arXiv:1009.0866
including ACT small scale CMB data

$N_{\rm eff} = 4.56 \pm 1.5$ (95%)

Haman
NOW2010

Experimentally? i.e. beyond 3...

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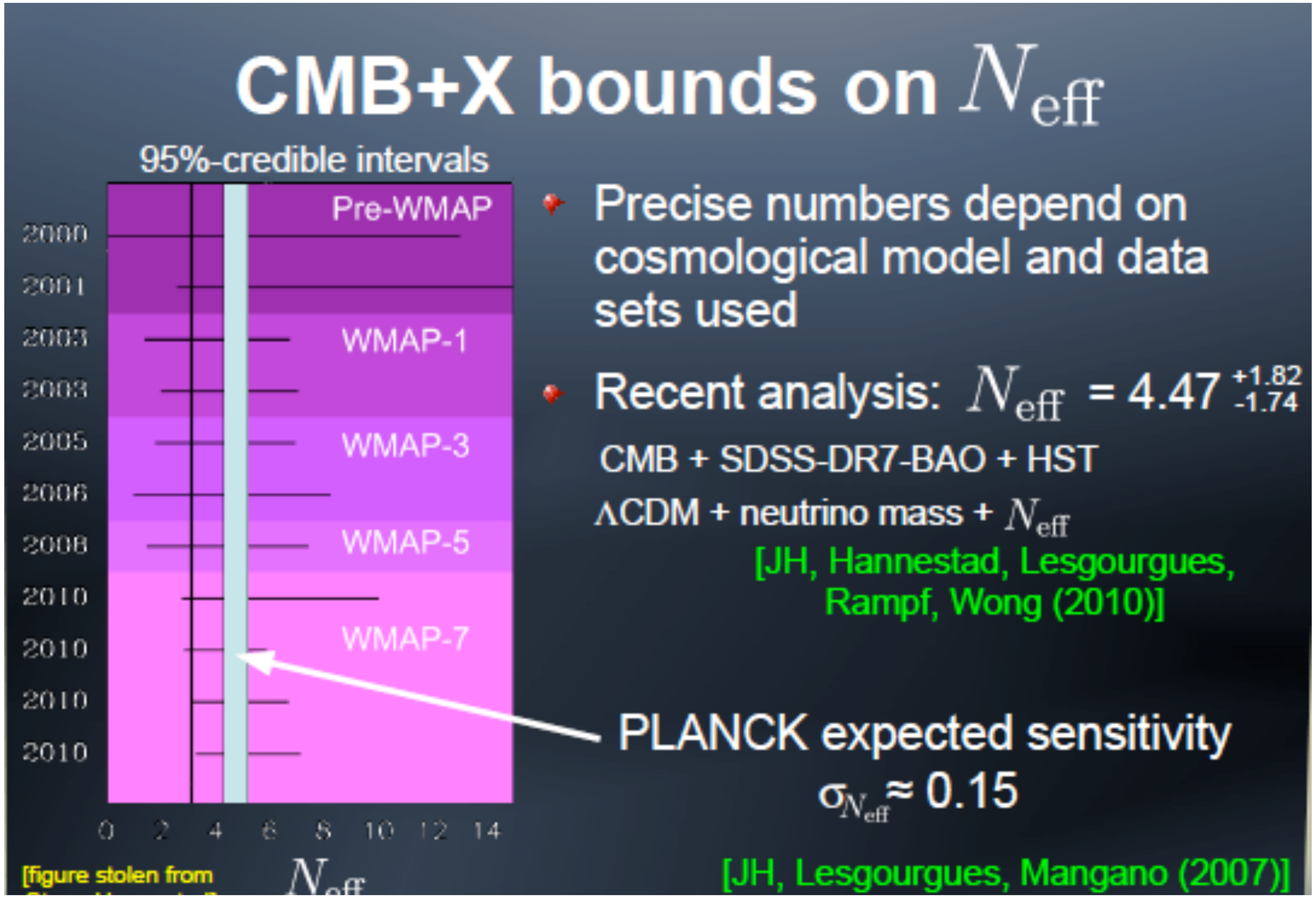

CMB+X bounds on N_{eff}

95%-credible intervals

- Precise numbers depend on cosmological model and data sets used
- Recent analysis: $N_{\text{eff}} = 4.47^{+1.82}_{-1.74}$

CMB + SDSS-DR7-BAO + HST

ΛCDM + neutrino mass + N_{eff}

[JH, Hannestad, Lesgourgues, Rampf, Wong (2010)]

PLANCK expected sensitivity

$\sigma_{N_{\text{eff}}} \approx 0.15$

[JH, Lesgourgues, Mangano (2007)]

[figure stolen from

Haman
NOW2010

Assume only 3:

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- To determine whether they are Majorana

* To discover Leptonic CP-violation

Can we foresee how to go beyond?

Neutrino masses indicate new physics beyond the SM

Maybe new flavour physics could appear also in neutrino couplings ?

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?

Maybe new flavour physics could appear also in neutrino couplings ?

How to advance in a model-independent way?

- In quark flavour puzzle

- In lepton flavour puzzle

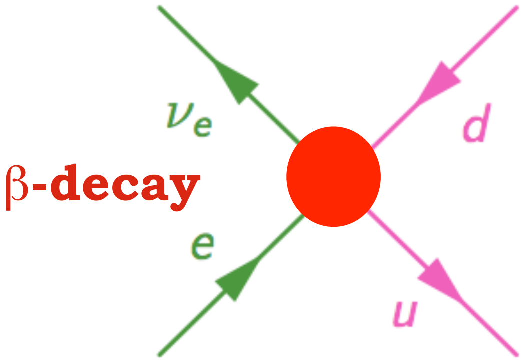
How to go about it model-independent ?....

Effective field theory

Mimic travel from Fermi’s beta decay to SM

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

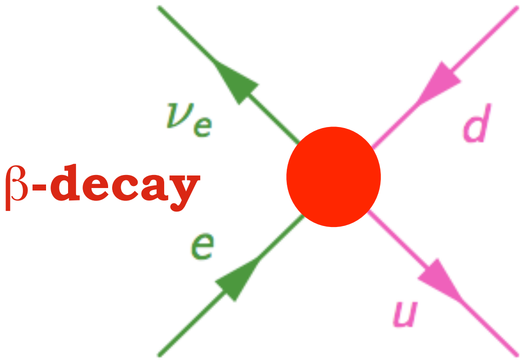
From the Fermi theory to SM



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

U(1)$_{em}$ invariant

From the Fermi theory to SM



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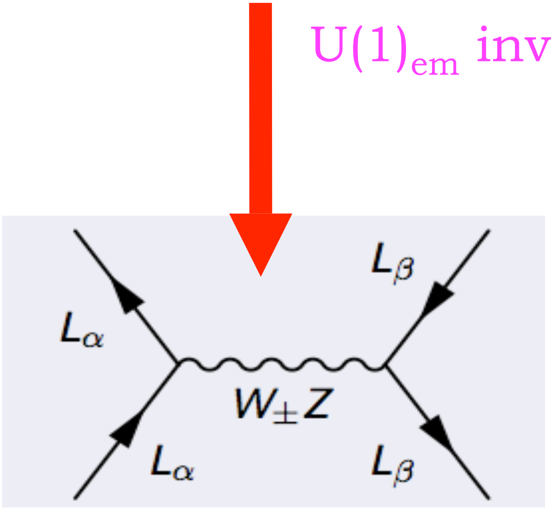


$$\frac{g^2}{M_W^2} \ (L_\alpha \, \gamma_\mu \, L_\alpha) \ (Q_{L\beta} \, \gamma_\mu Q_\beta)$$

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

If new physics scale M > v

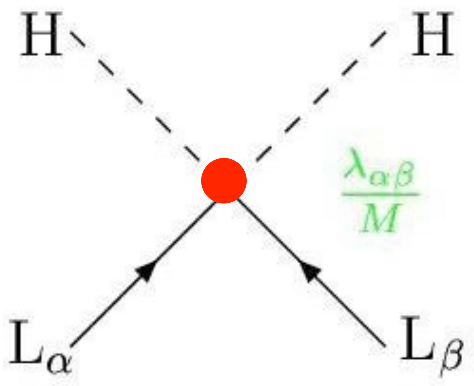
$$\mathcal{L} = \mathcal{L}_{SU(3)xSU(2)xU(1)} + \frac{O^{d=5}}{M} + \frac{O^{d=6}}{M^2} + \ldots\ldots$$

ν masses beyond the SM

The Weinberg operator

Dimension 5 operator:

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



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

ν masses beyond the SM

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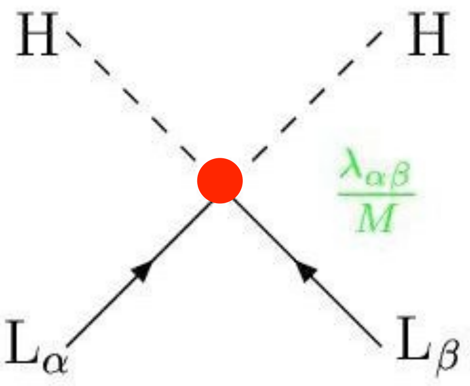

It's unique → very special role of ν masses:
lowest-order effect of higher energy physics

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

ν masses beyond the SM

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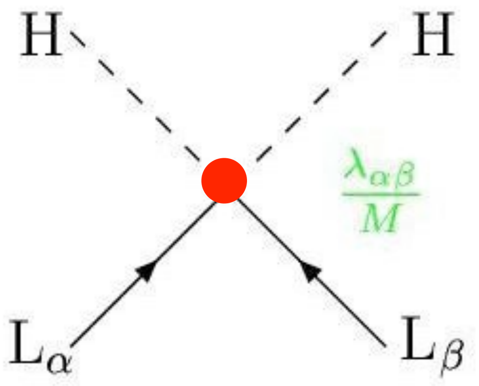

It’s unique → very special role of ν masses:
lowest-order effect of higher energy physics

This mass term violates lepton number (B-L)
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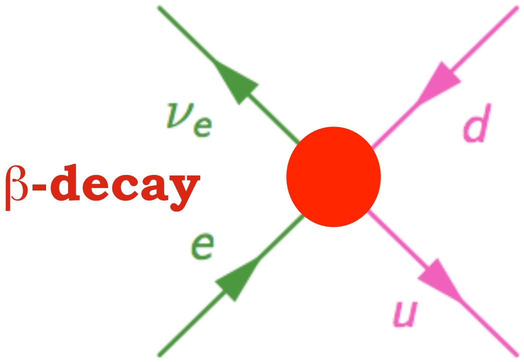
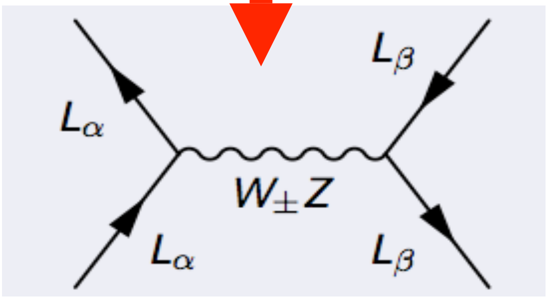
$O^{d=5}$ *is common to all models of Majorana* νs

From the Fermi theory to SM



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

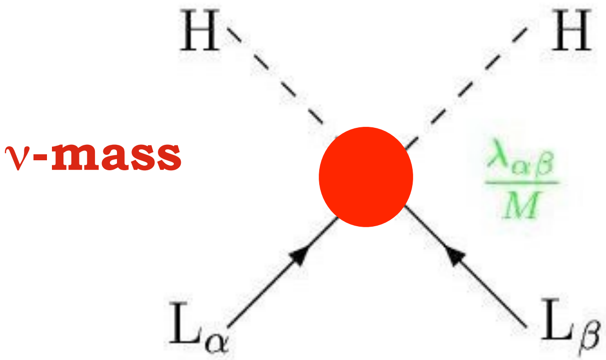
U(1)$_{em}$ invariant



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

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

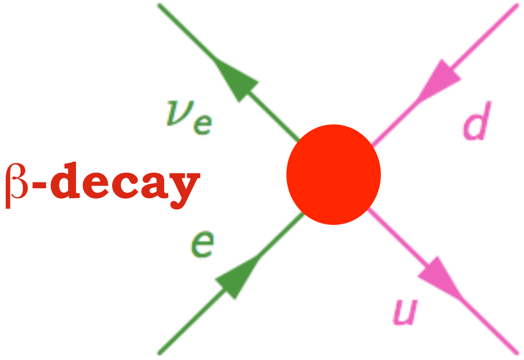
From Majorana masses to Seesaw



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

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

From the Fermi theory to SM



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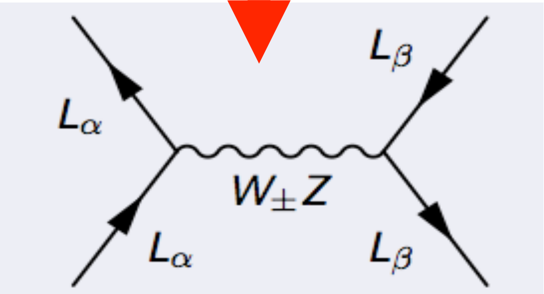
U(1)$_{em}$ invariant



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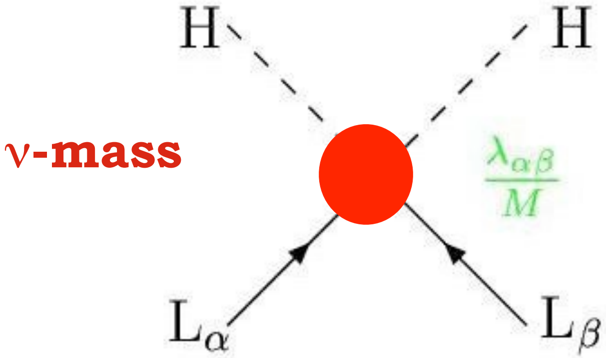
From Majorana masses to Seesaw



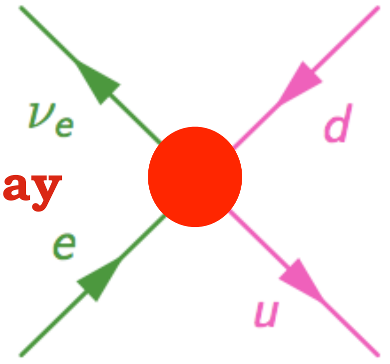
$\lambda/M\ (L\ L\ H\ H)$

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

2 x 2 = 1 + 3

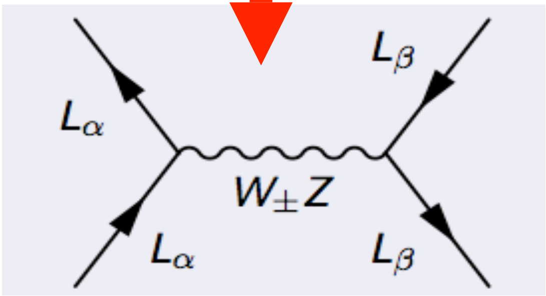
From the Fermi theory to SM

β-decay



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

$U(1)_{em}$ invariant

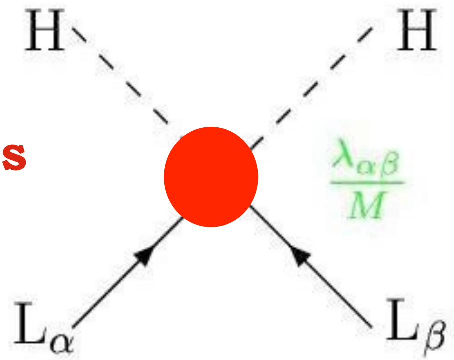


$\frac{g^2}{M_W^2}\;(L_\alpha\, \gamma_\mu\, L_\alpha)\;(Q_{L\beta}\, \gamma_\mu Q_\beta)$

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

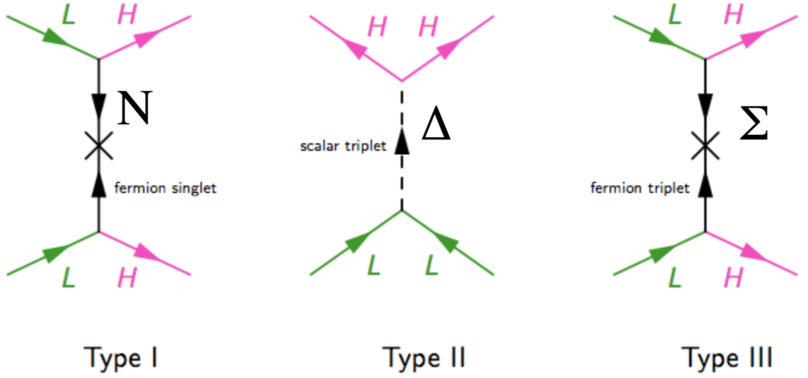
From Majorana masses to Seesaw

ν-mass



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

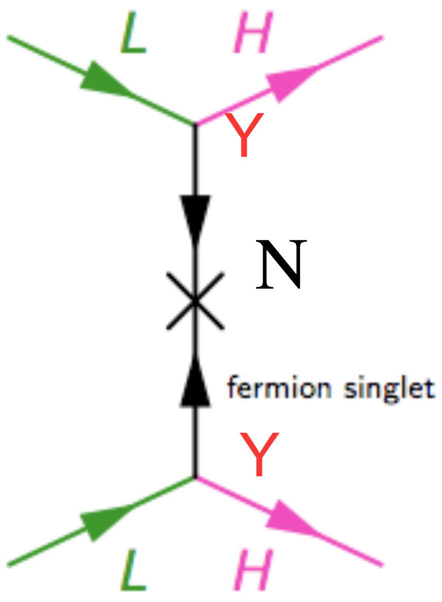
$SU(2)\ xU(1)_{em}$ inv.



Seesaw models

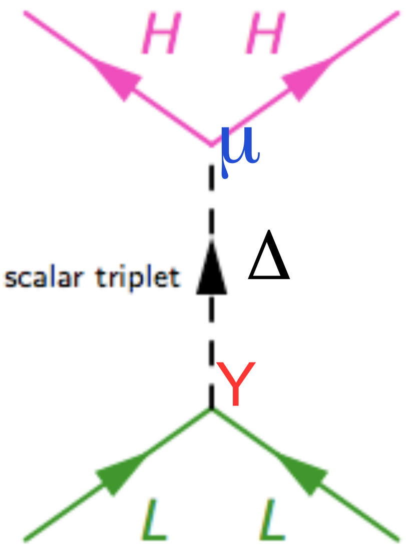
The Seesaw models

- Three types of models yield the Weinberg operator at tree level



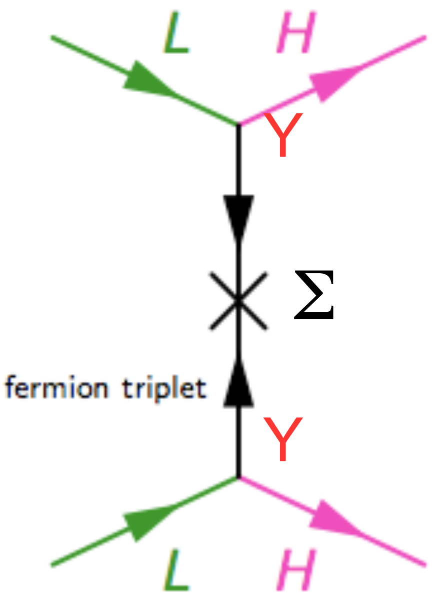
Type I

$$m_\nu \sim v^2 \; Y_N^T \frac{1}{M_N} Y_N$$



Type II

$$m_\nu \sim v^2 \; Y_\Delta \frac{\mu}{M_\Delta^2}$$

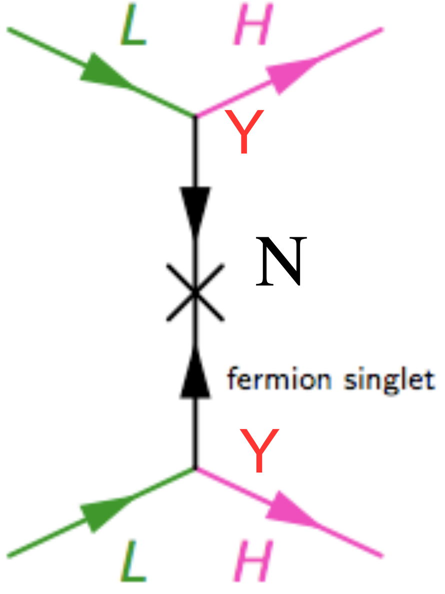


Type III

$$m_\nu \sim v^2 \; Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

The Seesaw models

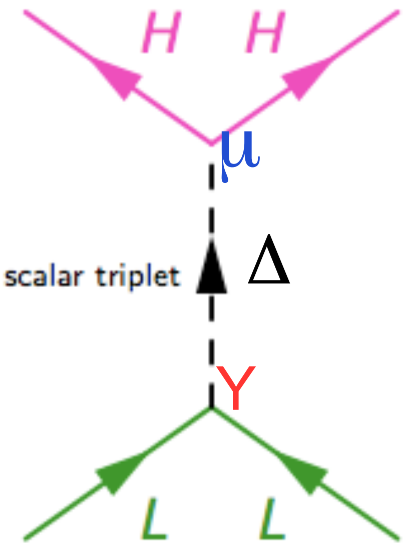
- Three types of models yield the Weinberg operator at tree level



Type I

Heavy fermion singlet N_R

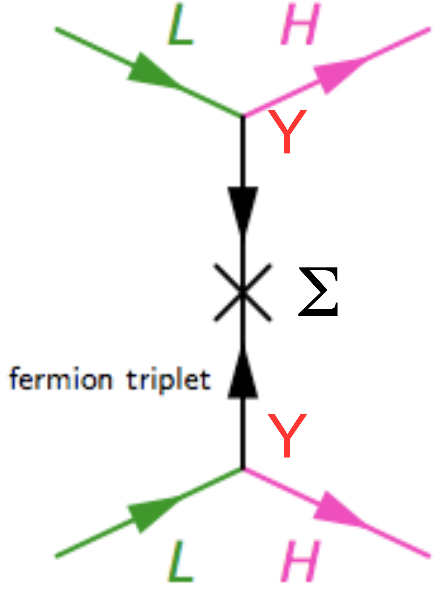
Minkowski, Gell-Mann, Ramond, Slansky, Yanagida, Glashow, Mohapatra, Senjanovic



Type II

Heavy scalar triplet Δ

Magg, Wetterich, Lazarides, Shafi, Mohapatra, Senjanovic, Schecter, Valle



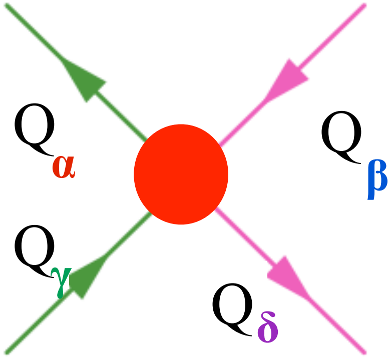
Type III

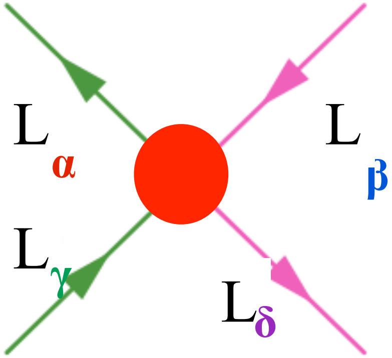
Heavy fermion triplet Σ_R

Ma, Roy, Senjanovic, Hambye et al.,

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

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





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

A humble ansatz:

- Minimal Flavour Violation

(Chivukula. Georgi)
(Ambrosio, Giudice, Isidori, Strumia)

A humble ansatz:

- Minimal Flavour Violation

....taking laboratory data at face value

(Chivukula. Georgi)
(Ambrosio, Giudice, Isidori, Strumia)

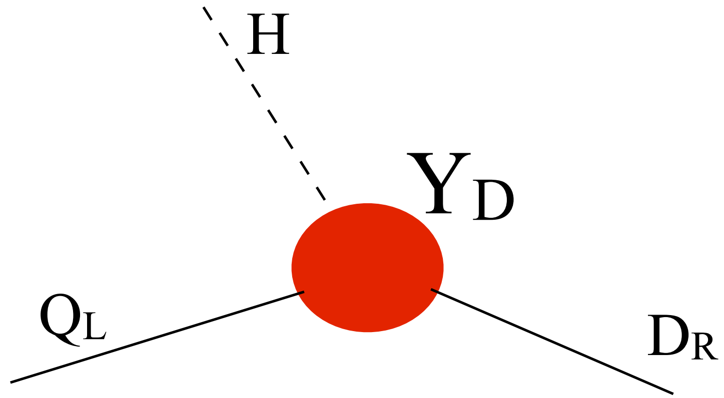
* All quark flavour data are consistent with SM

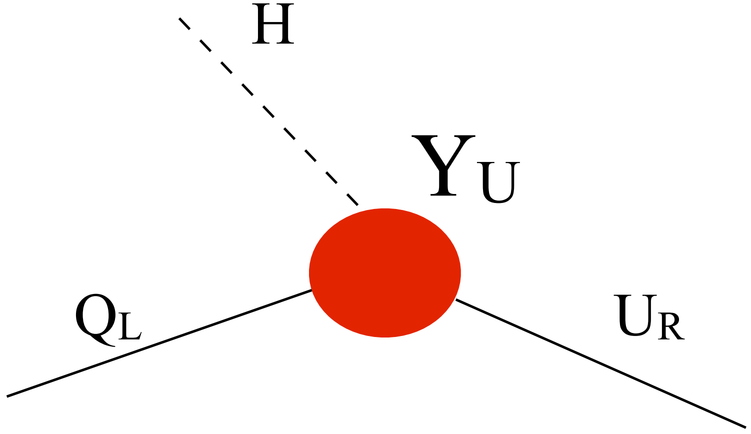
Kaon sector, B-factories, accelerators....

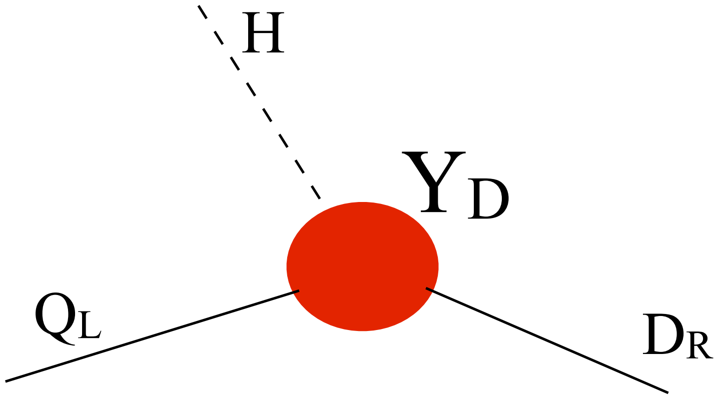
There are some ~2-3 sigma anomalies around, though: i.e. Fermilab's anomalous like-sign dimuon charge asymmetry in B_S decays

= consistent with CKM

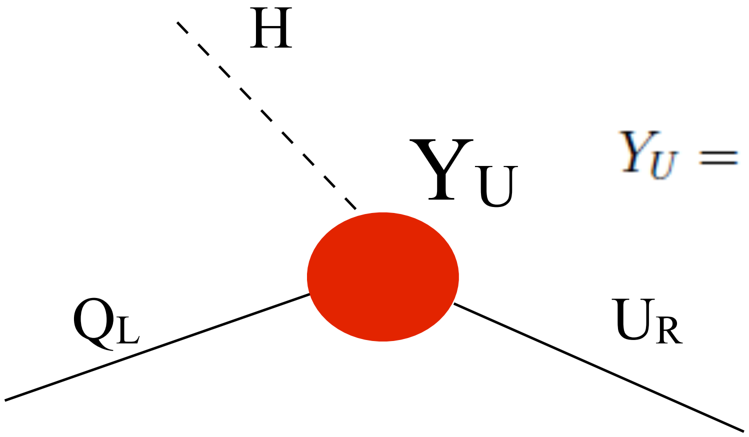
= consistent with all flavour effects due to Yukawas


H
Y_D
Q_L
D_R


H
Y_U
Q_L
U_R



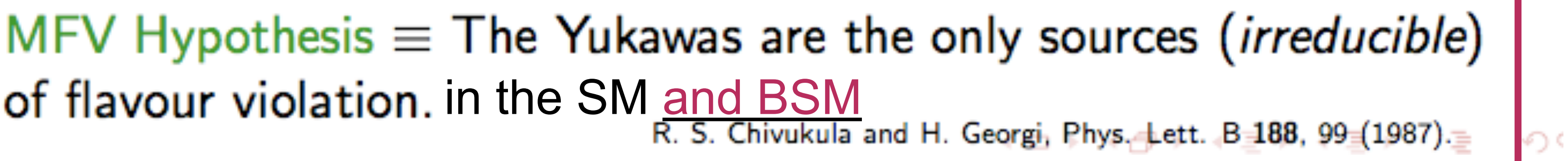
$$Y_D = \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix}$$



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

Minimal Flavour violation (MFV)

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

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The global Flavour symmetry of the SM with massless fermions:

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

$$Q_L \to L\ Q_L \qquad D_R \to R_d\ D_R \quad \ldots$$

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

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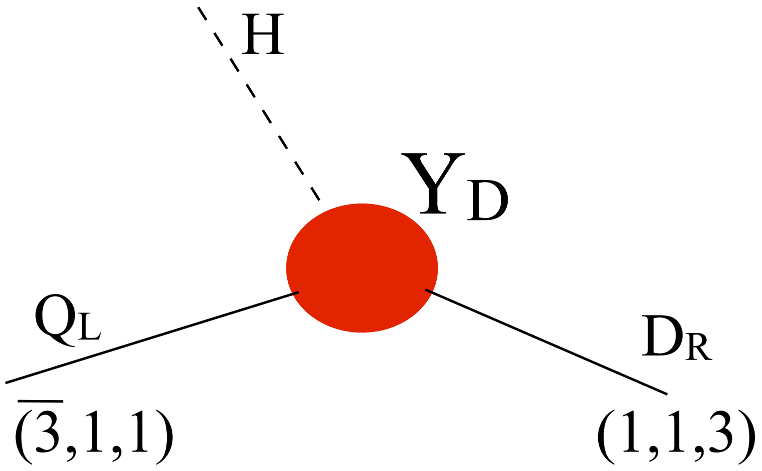
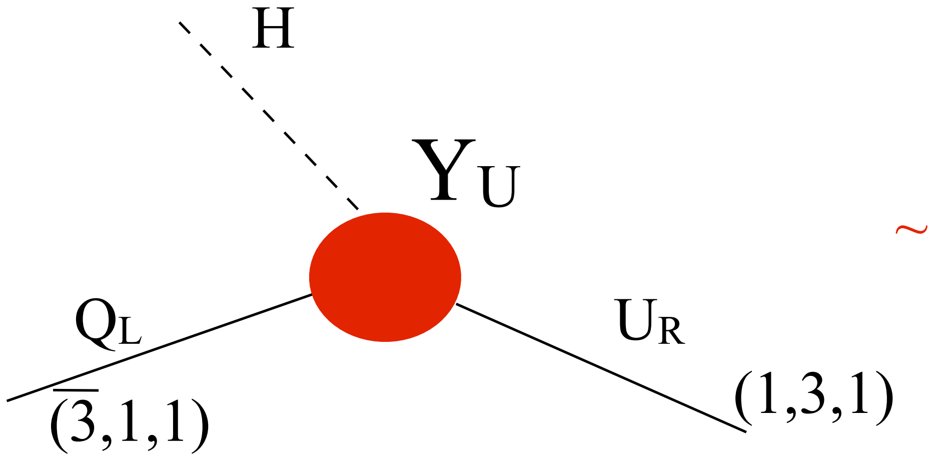
$$G_f = SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$$



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



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

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

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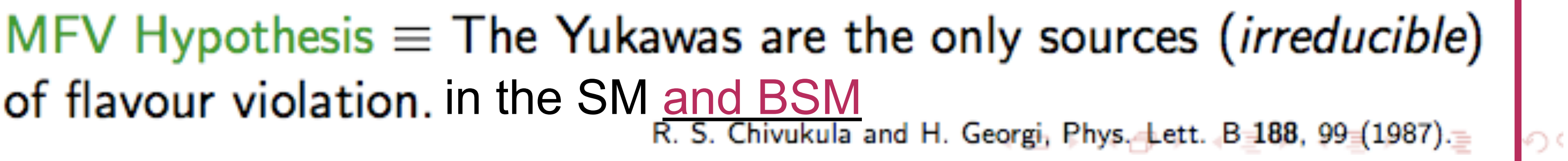
$$Q_L \rightarrow L\ Q_L \qquad D_R \rightarrow R_d\ D_R \quad \ldots \boxed{Y_d \rightarrow L_u Y_u R_d^\dagger}, \ldots$$

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

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

Minimal Flavour violation (MFV)

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



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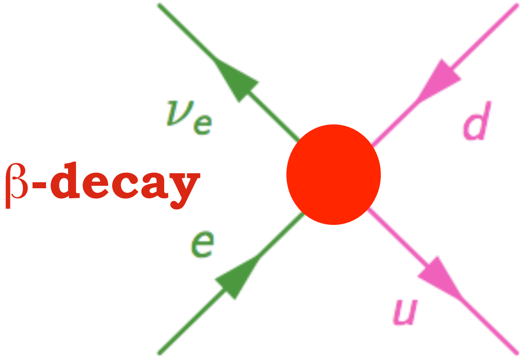
It is very predictive for quarks: $O^{d=6} \sim \overline{Q}_{\alpha} Q_{\beta} \overline{Q}_{\gamma} Q_{\delta}$

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

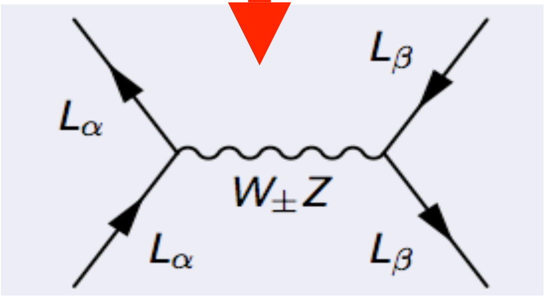
i.e. $C^{d=6} \sim \frac{Y^{+}_{\alpha\beta} Y_{\gamma\delta}}{\Lambda^{2}_{\text{flavour}}}$ $O^{d=6} \sim \overline{Q}_{\alpha} Q_{\beta} \overline{Q}_{\gamma} Q_{\delta}$

From the Fermi theory to SM



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

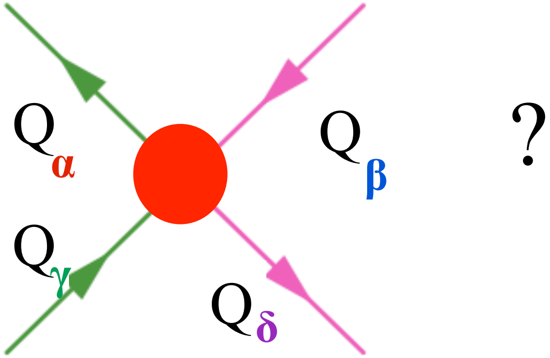
$U(1)_{em}$ invariant



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

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

From the SM to the theory of flavour



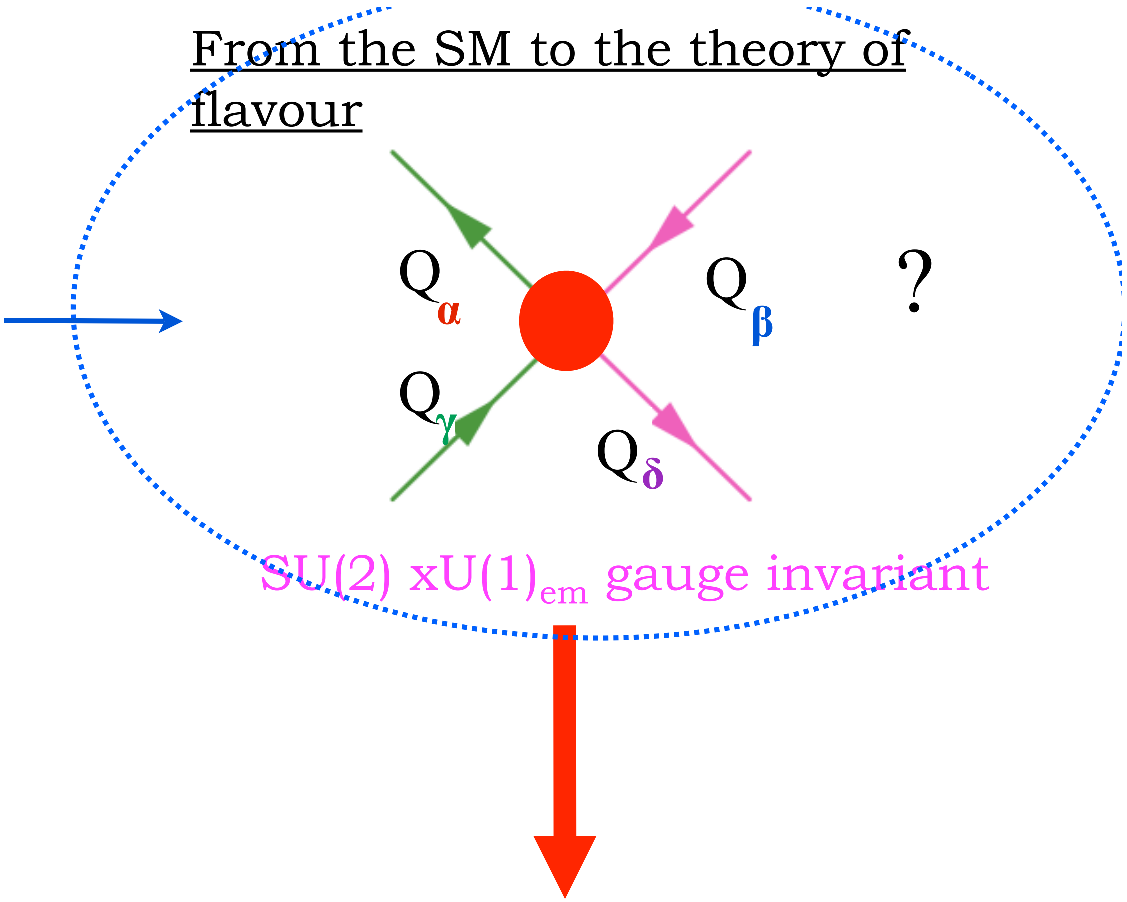
$SU(2) \; xU(1)_{em}$ gauge invariant

?

The Theory of Flavour

MFV IS NOT A MODEL OF FLAVOUR

IT REMAINS AT THIS LEVEL



From the SM to the theory of flavour

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?

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

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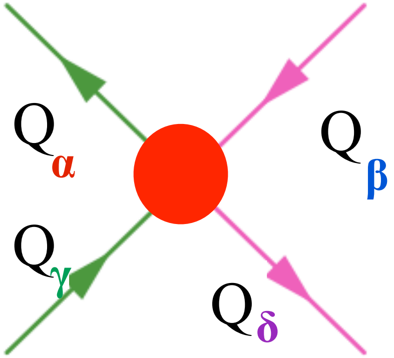


?

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

?

The Theory of Flavour

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

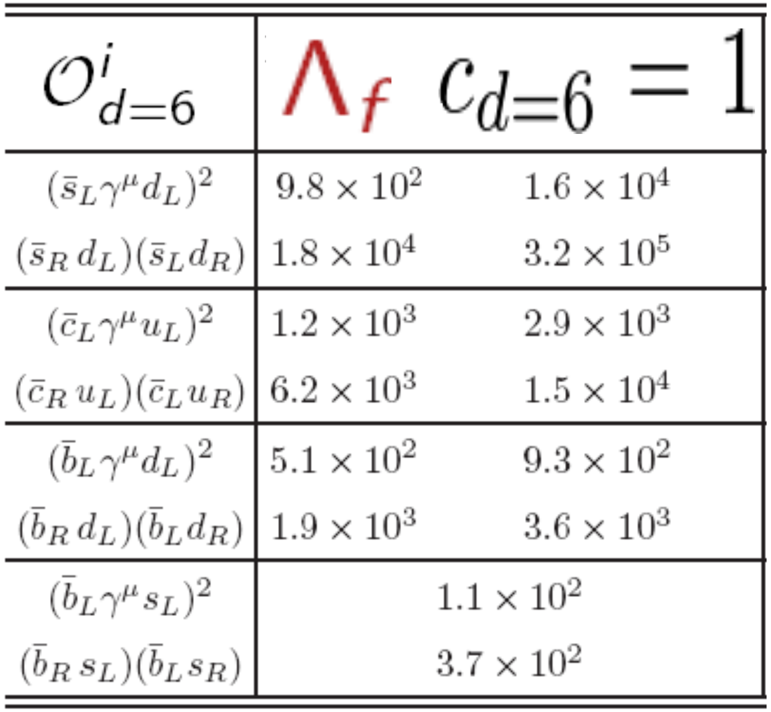
$$\Lambda_f \sim \Lambda_{electroweak} \sim \text{TeV}$$

... and induce observable flavour changing effects

WHY MFV?

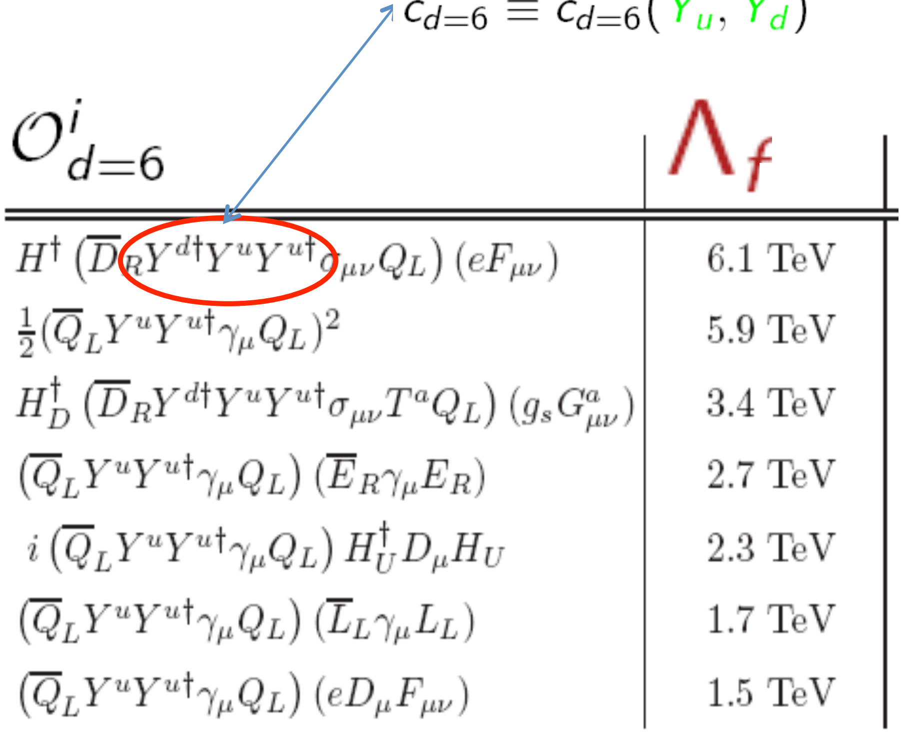
FOR QUARKS

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



$\mathcal{O}^i_{d=6}$	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	

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



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

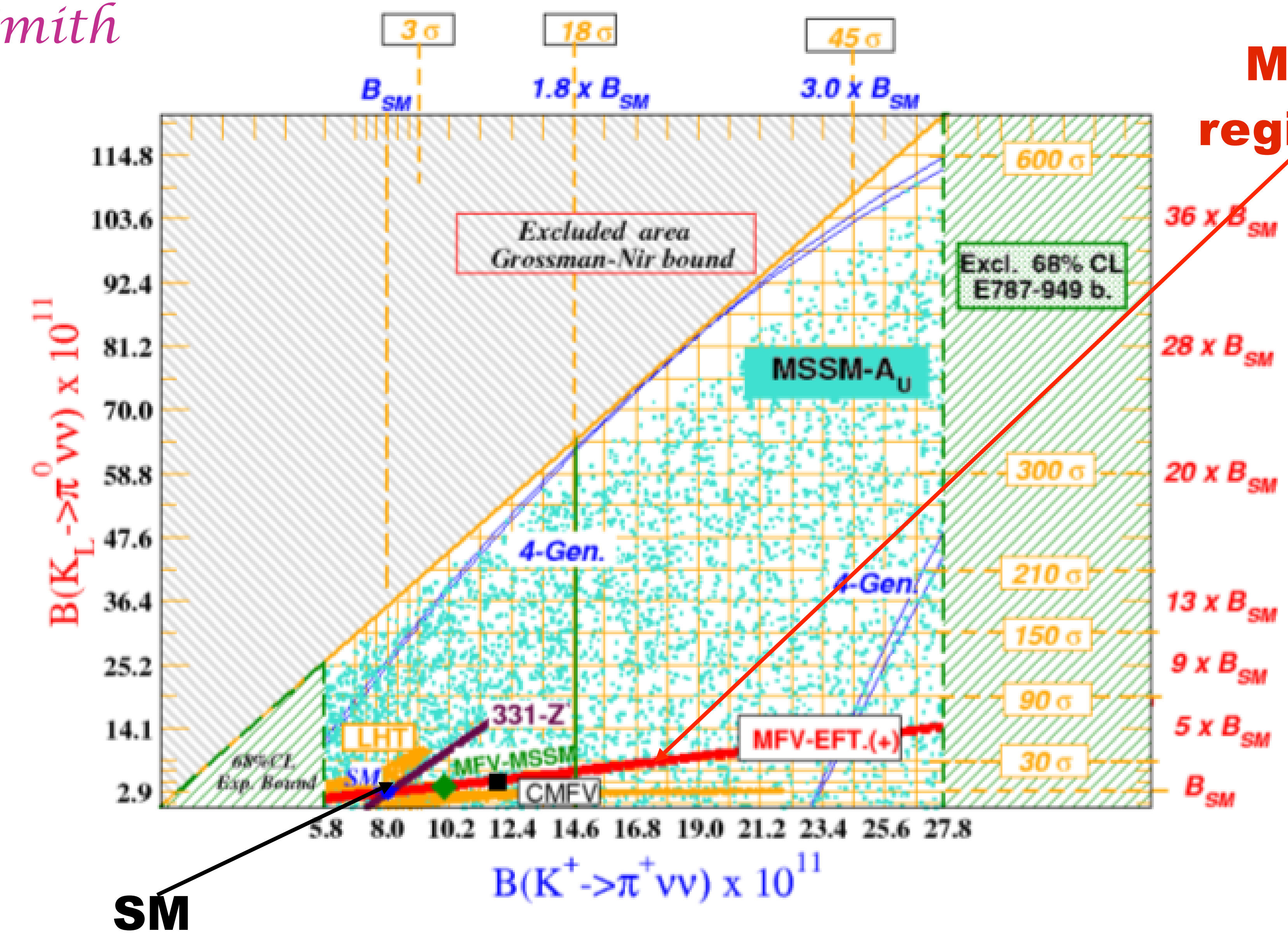
WITHOUT MFV: $\Lambda_f \overset{>}{\sim} 10^2$ TeV

WITH MFV: $\Lambda_f \overset{>}{\sim}$ 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



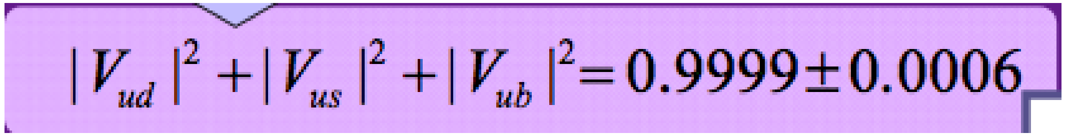
MFV region

SM

Gonzalez-Alonso

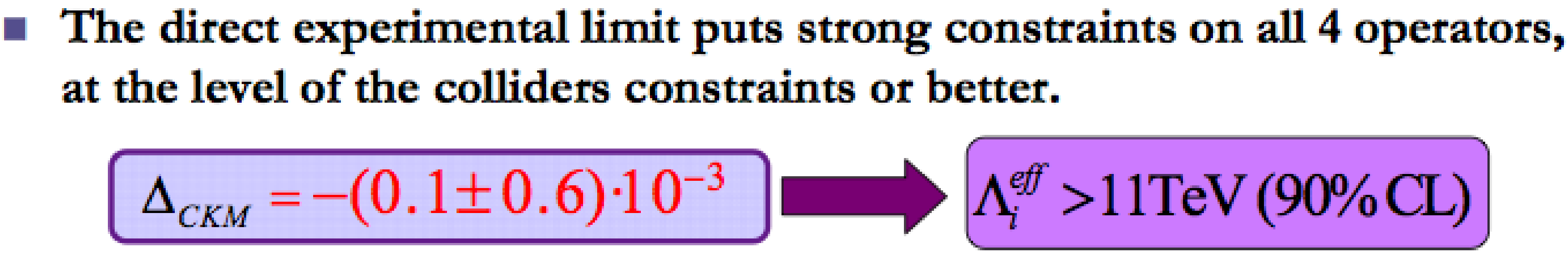
Minimal Flavour violation (MFV)

- 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.**

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

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 ~ $<\Psi\overline{\Psi}>^n/\Lambda_f^n$, rather than in susy-like options

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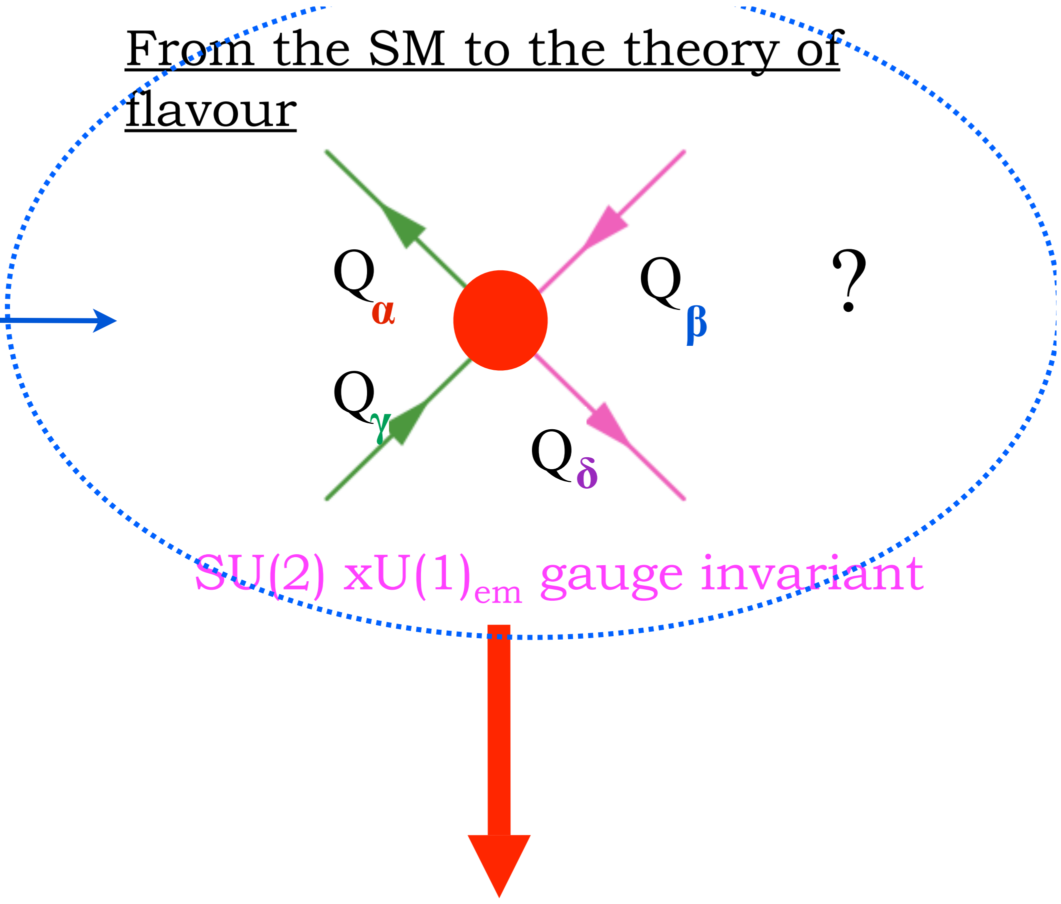
$$C^{d=6} \sim \frac{Y^{+}_{\alpha\beta}\, Y_{\gamma\delta}}{\Lambda^{2}_{\text{flavour}}}$$



From the SM to the theory of flavour

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

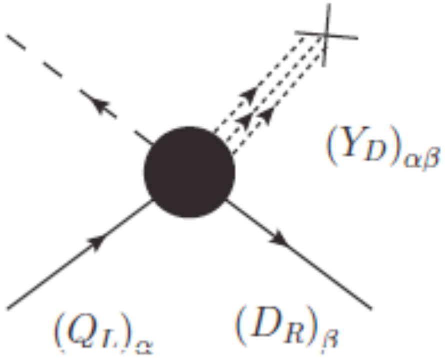
?

The Theory of Flavour

The Dynamics Behind MFV

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

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



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

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Spontaneous breaking of flavour symmetry dangerous

--> i.e. gauge it (Grinstein, Redi, Villadoro, 2010)

The Dynamics Behind MFV

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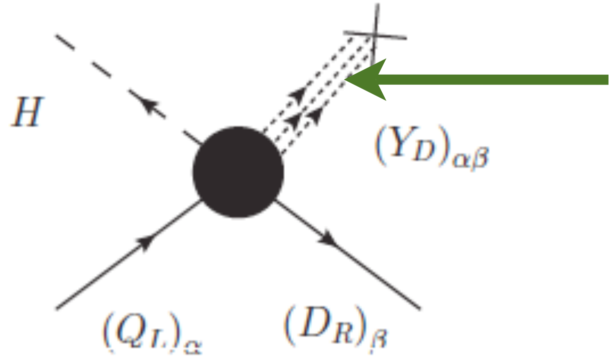

$(3, 1, \overline{3})$

That scalar field or aggregate of fields may have a potential

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

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What is the potential of Minimal Flavour Violation ?

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

The Dynamics Behind MFV

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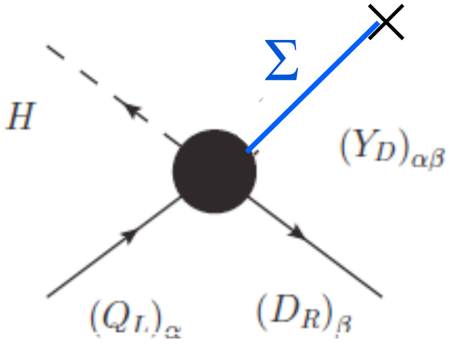
What is the potential of Minimal Flavour Violation ?

Can its minimum correspond to the observed masses and mixings?

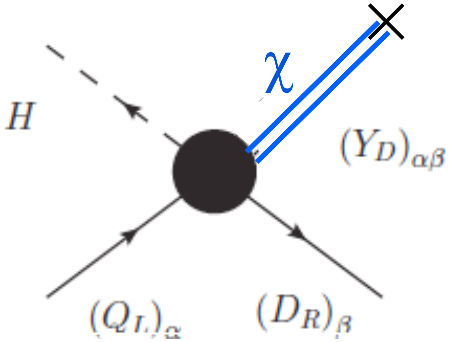
(Alonso, Gavela, Merlo, Rigolin, arXiv 1103.2915)

We analyzed the scalar potential for both 2 and 3 families, two cases:

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



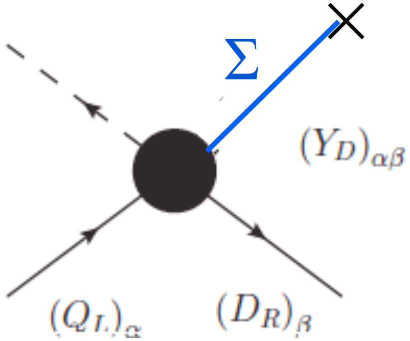
2) Y -- > two fields $\chi\, \chi^+ \sim (3, 1, \overline{3})$



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

1) Y --> one single field Σ

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



Y --> one single field Σ

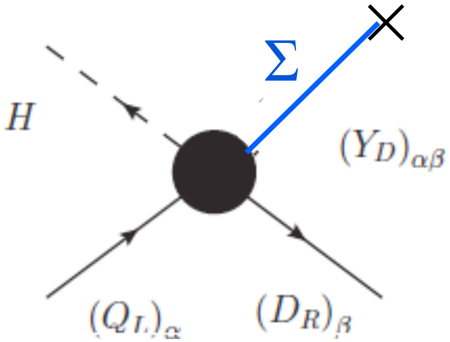
Dimension 5 Yukawa operator

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 --> one single field Σ

Construction of the Potential

Dimension 5 Yukawa Operator

The potential will also respect the flavour symmetry, so it will be built with the G_f invariants:

$$Tr\left(\Sigma_u\Sigma_u^\dagger\right)\,, \quad \det\left(\Sigma_u\right)\,, \quad Tr\left(\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right)\,,$$
$$Tr\left(\Sigma_d\Sigma_d^\dagger\right)\,, \quad \det\left(\Sigma_d\right)\,, \quad \ldots$$

These invariants can be expressed in terms of masses and mixing angles (2 generations):

$$\langle\Sigma_u\rangle = \Lambda \cdot V^\dagger Diag\{y_{u_i}\}\,, \qquad \langle\Sigma_d\rangle = \Lambda \cdot Diag\{y_{d_i}\}\;;$$

$$Y_D = \begin{pmatrix} y_d & 0 \\ 0 & y_s \end{pmatrix}\,, \qquad Y_U = \mathcal{V}_C^\dagger \begin{pmatrix} y_u & 0 \\ 0 & y_c \end{pmatrix}$$

$$\mathrm{V} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Y --> one single field Σ

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Dimension 5 Yukawa Operator

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$$Tr\left(\Sigma_u \Sigma_u^\dagger\right)\,, \quad \det\left(\Sigma_u\right)\,, \quad Tr\left(\Sigma_u \Sigma_u^\dagger \Sigma_d \Sigma_d^\dagger\right)\,,$$
$$Tr\left(\Sigma_d \Sigma_d^\dagger\right)\,, \quad \det\left(\Sigma_d\right)\,, \qquad \cdots$$

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$$\langle \Sigma_u \rangle = \Lambda \cdot V^\dagger Diag\{y_{u_i}\}\,, \qquad \langle \Sigma_d \rangle = \Lambda \cdot Diag\{y_{d_i}\}\;;$$

$$\mathrm{Tr}\left(\Sigma_u \Sigma_u^\dagger\right) = \Lambda_f^2\,(y_u^2 + y_c^2) \qquad \det\left(\Sigma_u\right) \;=\; \Lambda_f^2\, y_u\, y_c$$

Y --> one single field Σ

Construction of the Potential

Dimension 5 Yukawa Operator

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$$Tr\left(\Sigma_u\Sigma_u^\dagger\right)\,,\quad \det\left(\Sigma_u\right)\,,\quad Tr\left(\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right)\,,$$
$$Tr\left(\Sigma_d\Sigma_d^\dagger\right)\,,\quad \det\left(\Sigma_d\right)\,,\qquad \cdots$$

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$$\langle\Sigma_u\rangle = \Lambda\cdot V^\dagger Diag\{y_{u_i}\}\,,\qquad \langle\Sigma_d\rangle = \Lambda\cdot Diag\{y_{d_i}\}\;;$$
$$Tr\left(\left\langle\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right\rangle\right) = \frac{1}{2}\Lambda^4\left[\left(y_c^2 - y_u^2\right)\left(y_s^2 - y_d^2\right)\cos 2\theta_c + \cdots\right]$$

Y --> one single field Σ

Construction of the Potential

Dimension 5 Yukawa Operator

The potential will also respect the flavour symmetry, so it will be built with the G_f invariants:

$$Tr\left(\Sigma_u\Sigma_u^\dagger\right)\,,\quad \det\left(\Sigma_u\right)\,,\quad Tr\left(\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right)\,,$$
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The most general Potential is:

$$V = \sum_{i=u,d}\left(-\mu_i^2\,Tr\left(\Sigma_i\Sigma_i^\dagger\right)-\tilde{\mu}_i^2\det\left(\Sigma_i\right)\right)+$$
$$\sum_{i,j=u,d}\left(\lambda_{ij}\,Tr\left(\Sigma_i\Sigma_i^\dagger\right)Tr\left(\Sigma_j\Sigma_j^\dagger\right)+\tilde{\lambda}_{ij}\det\left(\Sigma_i\right)\det\left(\Sigma_j\right)+\cdots\right)\cdots$$

Y --> one single field Σ

Construction of the Potential

Dimension 5 Yukawa Operator

The potential will also respect the flavour symmetry, so it will be built with the G_f invariants:

$$Tr\left(\Sigma_u\Sigma_u^\dagger\right)\,, \quad \det\left(\Sigma_u\right)\,, \quad Tr\left(\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right)\,,$$
$$Tr\left(\Sigma_d\Sigma_d^\dagger\right)\,, \quad \det\left(\Sigma_d\right)\,, \qquad \cdots$$

These invariants can be expressed in terms of masses and mixing angles (2 generations):

$$\langle\Sigma_u\rangle = \Lambda\cdot V^\dagger Diag\{y_{u_i}\}\,, \qquad \langle\Sigma_d\rangle = \Lambda\cdot Diag\{y_{d_i}\}\;;$$
$$Tr\left(\left\langle\Sigma_u\Sigma_u^\dagger\Sigma_d\Sigma_d^\dagger\right\rangle\right) = \frac{1}{2}\Lambda^4\left[\left(y_c^2-y_u^2\right)\left(y_s^2-y_d^2\right)\cos 2\theta_c+\cdots\right]$$

The most general Potential is:

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$$\sum_{i,j=u,d}\left(\lambda_{ij}\,Tr\left(\Sigma_i\Sigma_i^\dagger\right)Tr\left(\Sigma_j\Sigma_j^\dagger\right)+\tilde{\lambda}_{ij}\det\left(\Sigma_i\right)\det\left(\Sigma_j\right)+\cdots\right)\cdots$$

Y --> one single field Σ

Minimum of the Potential

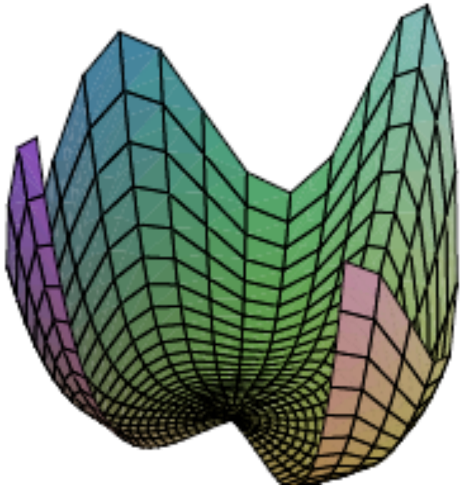
Dimension 5 Yukawa Operator

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 !

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

Y --> one single field Σ

Minimum of the Potential

Dimension 5 Yukawa Operator

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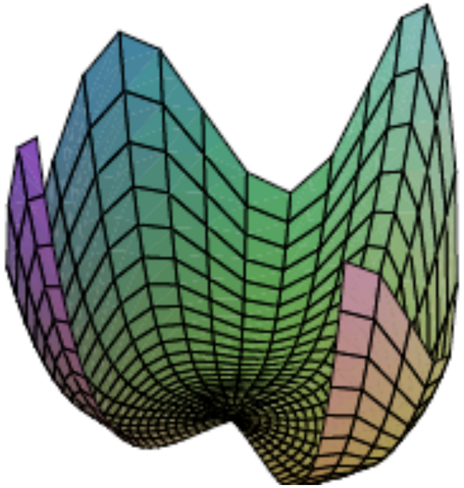


Non-degenerate masses $\longrightarrow \sin 2\theta_c = 0$ No mixing !

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

- Not only we have to input the hierarchy of masses in the potential parameters, wich was to expect but $\cdots$
- To accommodate the mixing we must introduce wild fine tunnings of $O(10^{-10})$ and nonrenormalizable terms of dimension 8

Y --> one single field Σ

three families

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

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

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

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

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

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

$$Det\left(\Sigma_u\right) \overset{vev}{=} \Lambda_f^3 y_u y_c y_t ,$$

$$Det\left(\Sigma_d\right)\Big| \overset{vev}{=} \Lambda_f^3 y_d y_s y_b ,$$

Interesting angular dependence:

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

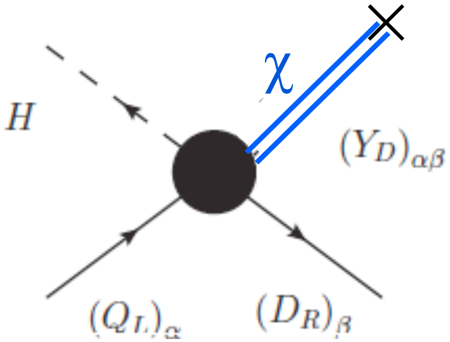
$$\begin{aligned} P_{int} \equiv & \sum_{i<j,k}\left(y_{d_i}^2-y_{d_k}^2\right)\left(y_{u_j}^2-y_{u_k}^2\right)\sin^2\theta_{ik}\sin^2\theta_{jk} + \\ & -\left(y_d^2-y_s^2\right)\left(y_c^2-y_t^2\right)\sin^2\theta_{12}\sin^2\theta_{13}\sin^2\theta_{23} + \\ & +\frac{1}{2}\left(y_d^2-y_s^2\right)\left(y_c^2-y_t^2\right)\cos\delta\,\sin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

Sad conclusions as for 2 families:

need non-renormalizable + super fine-tuning

1) Y --> quadratic in fields χ

$$Y \sim \frac{<\chi\chi^{\dagger}>}{\Lambda_f^2}$$



→ **Automatic strong mass hierarchy and one mixing angle !**

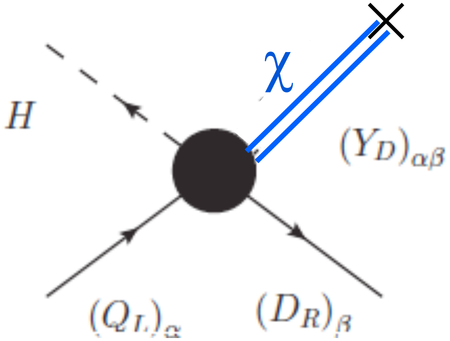
Holds for 2 and 3 families !

Y --> quadratic in fields χ

Dimension 6 Yukawa operator

χ are fundamentals of G_f : vectors under, 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. $Y_D \sim \dfrac{\chi^L{}_d \, (\chi^R{}_d)^+}{\Lambda_f{}^2} \sim (3, 1, 1)\,(1, 1, \overline{3}) \sim (3, 1, \overline{3})$

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

Y --> quadratic in fields χ

It is very simple:

- a square matrix built out of 2 vectors

$$\begin{pmatrix} d \\ e \\ f \\ \ddots \end{pmatrix} \quad (\,a\,,\,b\,,\,c\;.......)$$

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

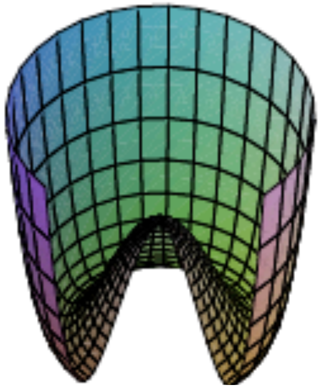
Y --> quadratic in fields χ

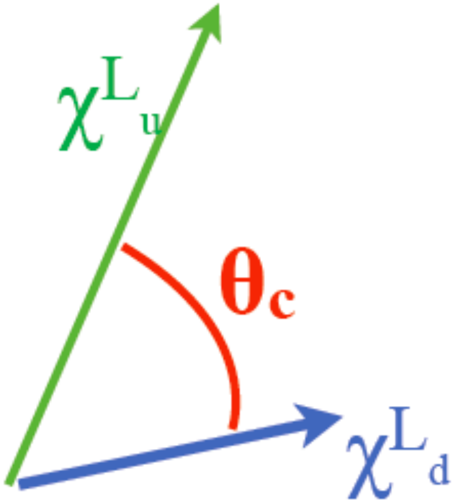
Minimum of the Potential

Dimension 6 Yukawa Operator

The invariants are:

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





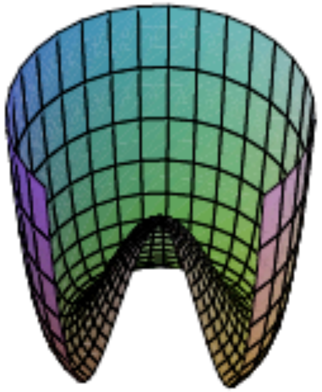
θ_c is the angle between up and down L vectors

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):

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

Towards a realistic 3 family spectrum

e.g. replicas of $\chi^{L}\ ,\ \chi^{R}_{u}\ ,\ \chi^{R}_{d}$

???

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:

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

* 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 replicas ?

In summary

* We constructed the general scalar potential for MFV

* The flavor symmetry imposes strong restrictions on the MFV potential: just a few invariants allowed at the renormalizable and non-renormalizable level. In general, to obtain realistic masses and mixing requires strong fine-tuning.

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

-strong mass hierarchy
- non-trivial mixing

Leptonic Minimal Flavour Violation

T. Hambye, D. Hernández, P. Hernández, MBG

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 ~ $<\Psi\overline{\Psi}>^n/\Lambda_f^n$, rather than in susy-like options

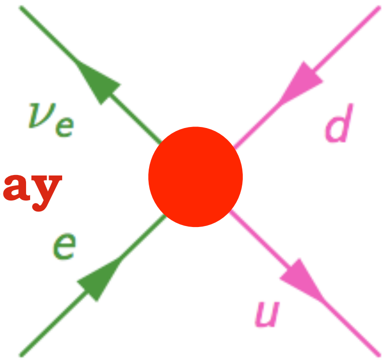
- It makes you think on the relation between scales:
  electroweak vs. flavour vs lepton number scales

What happens in the presence of neutrino masses?

Cirigliano, Isidori, Grinstein, Wise

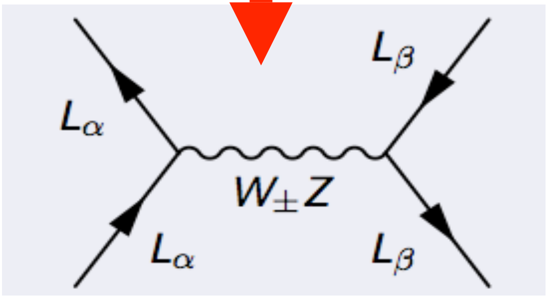
From the Fermi theory to SM

β-decay



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

$U(1)_{em}$ invariant

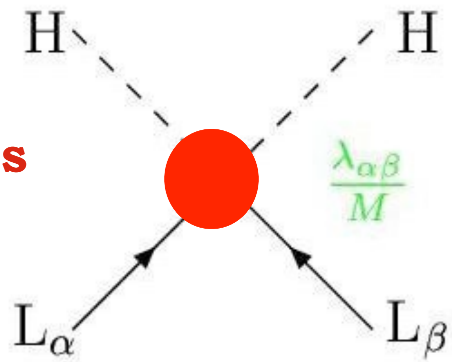


$\frac{g^2}{M_W^2} \; (L_\alpha \, \gamma_\mu \, L_\alpha) \; (Q_{L\beta} \, \gamma_\mu Q_\beta)$

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

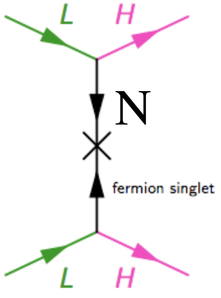
From Majorana masses to Seesaw

ν-mass

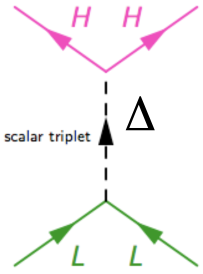


$\lambda / M \ (L \ L \ H \ H)$

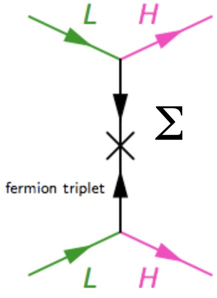
$SU(2) \ xU(1)_{em}$ inv.



Type I



Type II

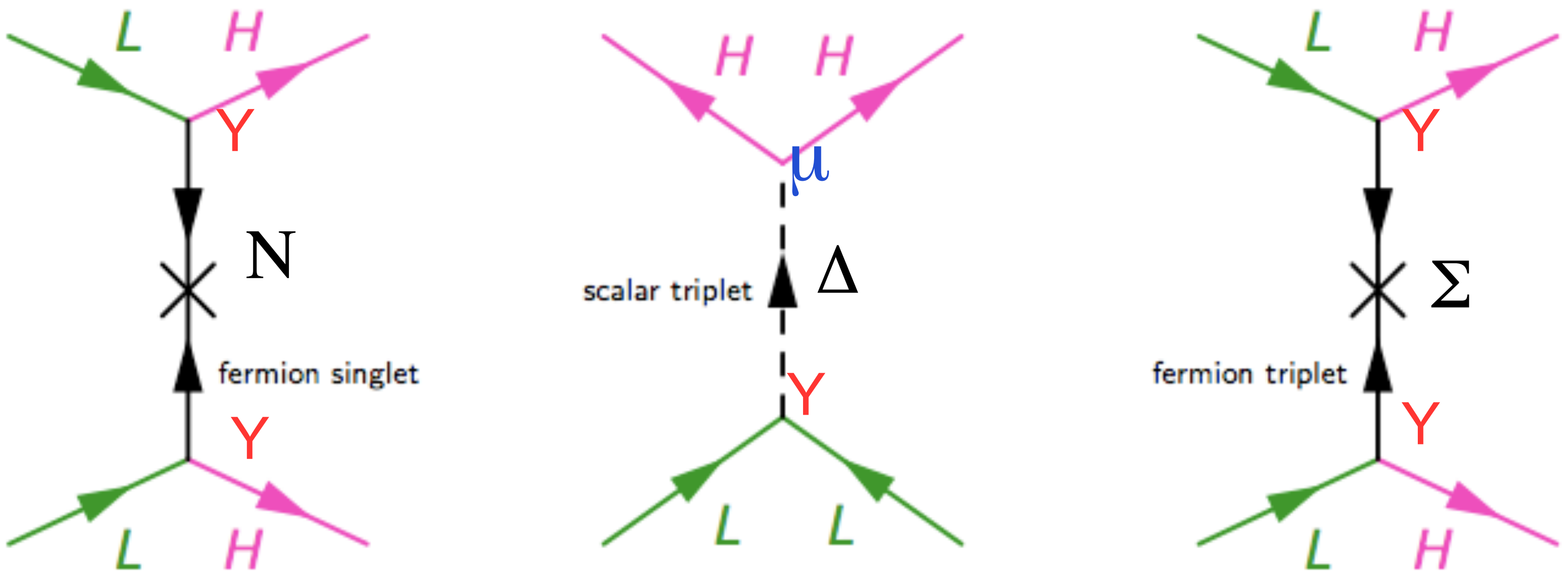


Type III

Seesaw models

The Seesaw models

- Three types of models yield the Weinberg operator at tree level



Type I

Type II

Type III

$m_\nu \sim v^2 \; Y_N^T \frac{1}{M_N} Y_N$

$m_\nu \sim v^2 \; Y_\Delta \frac{\mu}{M_\Delta{}^2}$

$m_\nu \sim v^2 \; Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$

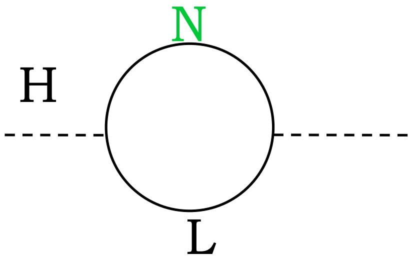
Seesaws are favorite
lepton number theories

Are they MFV theories?

First condition for it:

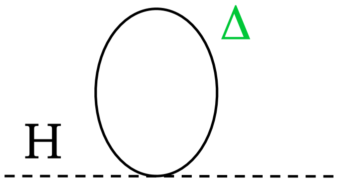
* Λ_f must be ~O (TeV), to have observable effects

M~1 TeV is suggested by electroweak hierarchy problem



$$\delta m_H^2 = -\frac{Y_N^\dagger Y_N}{16\pi^2}\left[2\Lambda^2 + 2M_N^2 \log\frac{M_N^2}{\Lambda^2}\right]$$

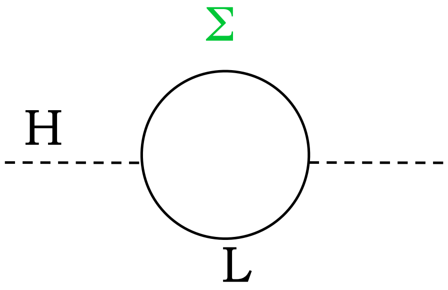
(Vissani, Casas et al., Schmaltz)



$$\delta m_H^2 = -3\frac{\lambda_3}{16\pi^2}\left[\Lambda^2 + M_\Delta^2\left(\log\frac{M_\Delta^2}{\Lambda^2} - 1\right)\right]$$

$$-\frac{\mu_\Delta^2}{2\pi^2}\log\left(\left|\frac{M_\Delta^2 - \Lambda^2}{M_\Delta^2}\right|\right)$$

(Abada, Biggio, Bonnet, Hambye, M.B.G.)



$$\delta m_H{}^2 = -3\frac{Y_\Sigma^\dagger Y_\Sigma}{16\pi^2}\left[2\Lambda^2 + 2M_\Sigma^2 \log\frac{M_\Sigma^2}{\Lambda^2}\right]$$

First condition for it:

to separate the effective lepton number scale Λ_{LN} from the flavour scale Λ_f

* Λ_f must be ~O (TeV), to have observable effects

* Λ_{LN} effective ~O (Grand Unif.) for tiny m_ν

First condition for it:

to separate the effective lepton number scale Λ_{LN} from the flavour scale Λ_f

* Λ_f must be ~O (TeV) ← d=6 operators

* Λ_{LN} effective ~O (Grand Unif.) for tiny m_ν ← d=5 op.

(Weinberg)

Could d=6 be stronger than d=5 ?

* Two independent scales in d=5, d=6 may result from a symmetry principle: lepton number

Cirigliano et al; Kersten,Smirnov; Abada et al

* d=5 requires to violate lepton number

* d=6 does not violate any symmetry

Λ_{LN} >> Λ_{fl} ~TeV ?

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{\alpha}{\Lambda_{LN}} O_i^{d=5} + \sum_i \frac{\beta_i}{\Lambda^2_{\text{flavour}}} O_i^{d=6} + \dots$$

Cirigliano, et al

There is a sensible physics motivation:

- Origin of lepton/quark flavour violation linked/close to the EW scale

- (Effective) Lepton number breaking scale higher and responsible for the gap between ν and other fermion

What happens in the presence of neutrino masses?

Cirigliano, Isidori, Grinstein, Wise

In the lepton sector

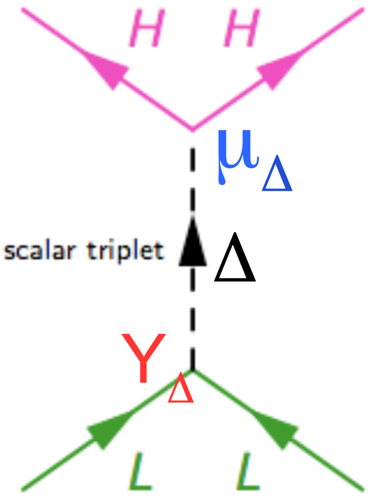
$$\mathcal{L} = \underbrace{\cdots + Y_e \bar{L} \phi e_R}_{\mathcal{L}_{SM}} + \sum_i \underset{\boxed{\Lambda_{LN}}}{c^i_{d=5}} \mathcal{O}^i_{d=5} + \underset{\boxed{\Lambda_{flavour}}}{c^i_{d=6}} \mathcal{O}^i_{d=6} \cdots$$

Delicate:

* Majorana masses are model dependent : $c^{d=5}(Y_e,?)$, $c^{d=6}(Y_e,?)$

* Requires to separate lepton number from flavour origin

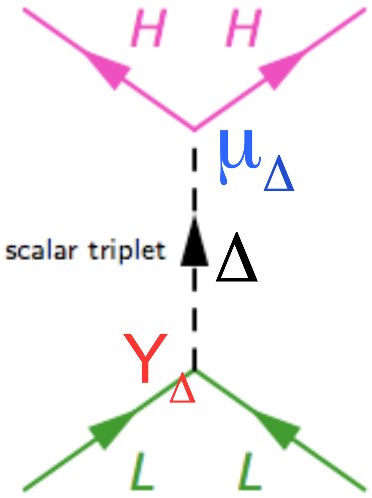
A successful model: Scalar-triplet Seesaw (type II)



$$\mathscr{L}_\Delta = \cdots + (D_\mu\Delta)^\dagger(D^\mu\Delta) - M_\Delta{}^2\,\Delta^\dagger\Delta + +$$

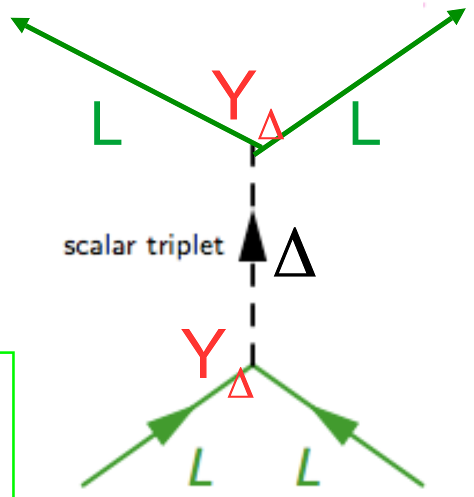
$$+\, Y_\Delta^{\alpha\beta}\,\overline{\widetilde{L}}\,(\tau\cdot\Delta)\,L + \mu_\Delta\widetilde{\phi}^\dagger(\tau\cdot\Delta)^\dagger\phi + \ldots$$

A successful model: Scalar-triplet Seesaw (type II)



$\Lambda_{fl} = M_\Delta$

$\Lambda_{LN} = M_\Delta^2 / \mu_\Delta$



$$\mathscr{L}_\Delta = \cdots + (D_\mu \Delta)^\dagger (D^\mu \Delta) - M_\Delta^2 \, \Delta^\dagger \Delta + +$$

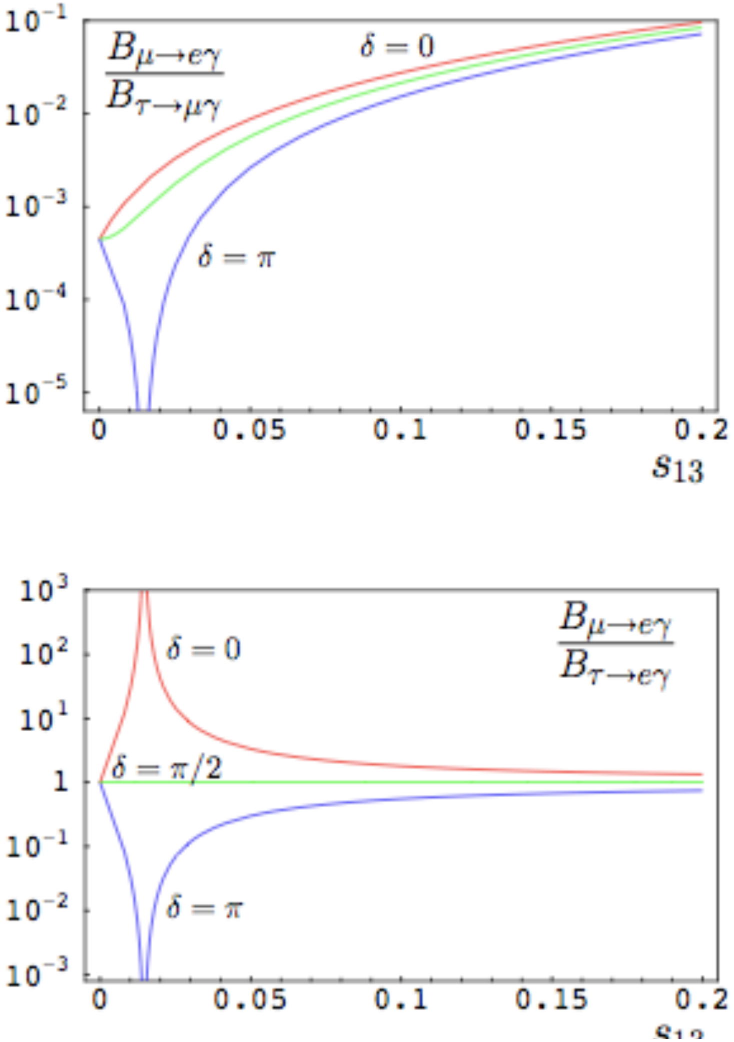
$$+ Y_\Delta^{\alpha\beta} \, \overline{\widetilde{L}} (\tau \cdot \Delta) \, L + \mu_\Delta \widetilde{\phi}^\dagger (\tau \cdot \Delta)^\dagger \phi + \ldots$$

Correlations among

weak processes, i.e.

$\mu \longrightarrow e\gamma$ / $\tau \longrightarrow e\gamma$ / $\tau \longrightarrow \mu\gamma$

- * Neutrino masses OK
- * Measurable flavour OK
- * Predictivity OK

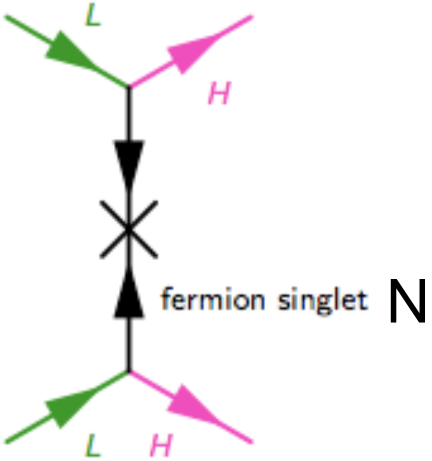


V. Cirigliano, B. Grinstein, G. Isidori, M. Wise, hep-ph/050700
M. B. Gavela, T. Hambye, P. Hernández, D.H., 0906.1

An unsuccessful model: simplest type I

Standard Seesaw (Type I) doesn't work

$$\mathscr{L} = \cdots - Y_N \bar{N} \phi^\dagger L_L - \Lambda_{LN} \bar{N}^c N \ldots$$



- Neutrino masses: Ok. $m_\nu \propto Y_N^T \frac{1}{\Lambda_{LN}} Y_N$
- Measurable flavour: NOT OK!. $\Lambda_{fl} \equiv \Lambda_{LN}$
- Predictivity: More or less Ok. $c_{d=5} \propto c_{d=6}$ *if no CP*

Hambye, Hernandez[2], Gavela

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

Instead of $$\mathcal{L}_m = \begin{pmatrix} 0 & Y_N^T v \\ Y_N v & M_N \end{pmatrix}$$

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \end{array}\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \end{array}$$

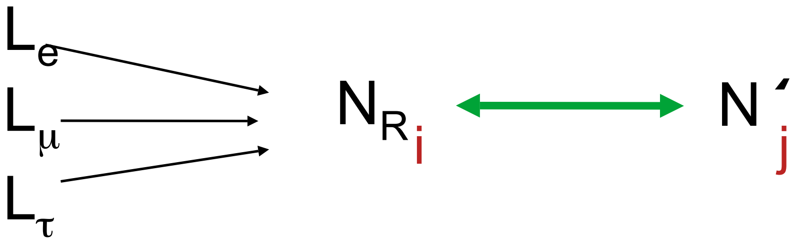
$$\mathscr{L}_{M_\nu} = \left(\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ 0 & Y_N^T v & 0 \\ Y_N v & 0 & \Lambda^T \\ 0 & \Lambda & 0 \end{array} \right)$$

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \end{array}$$

$$\mathscr{L}_{M_\nu} = \begin{array}{cccc} & \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ & 0 & Y_N^T v & 0 \\ & Y_N v & 0 & \Lambda^T \\ & 0 & \Lambda & 0 \end{array}$$



L_e

L_μ

L_τ

N_{R_i}

N'_j

Successful fermionic-mediated Seesaws:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \end{array}\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \end{array}$$

$$\mathscr{L}_{M_\nu} = \left(\begin{array}{ccc} 0 & Y_N^T v & 0 \\ Y_N v & 0 & \Lambda^T \\ 0 & \Lambda & 0 \end{array} \right)$$

Lepton number conserved

$U(1)_{LN}$

$$\boxed{\begin{array}{l} \Lambda_{fl} = \Lambda \\ \Lambda_{LN} = \infty \end{array}}$$

$$C^{d=6} \sim \frac{Y^+ Y}{\Lambda^2}$$

Successful fermionic-mediated Seesaw:

One more mediator, one more scale…. i.e. Inverse seesaws

$$\mathcal{L}_{M_\nu} = \begin{array}{c} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array} \\ \left(\begin{array}{ccc} 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{array} \right) \end{array}$$

Lepton number violated

by any of those 3 entries

Λ may be ~ TeV and Ys ~1, and be ok with m_ν

Wyler, Wolfenstein; Mohapatra,Valle, Branco,Grimus,Lavoura,Malinsky, Romao…

Small parameters (μ, μ', Y') unpleasant?

- They are technically natural
- There exist UV completions with only high scales

(Bonnet, Hernandez(D), Ota, Winter 09)

Particular surprising case

Three light active families + one N_R + one $N_R{}'$

$$\mathcal{L}_{M_\nu} = \begin{array}{c} \\ \\ \\ \end{array} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \end{array}$$

$$\mathcal{L}_{M_\nu} = \left(\begin{array}{ccc} 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y'_N v & \Lambda & \mu \end{array}\right)$$

μ´ is irrelevant (at tree-level)

-- one massless neutrino
-- just one low-energy Majorana phase

arguably the simplest model of neutrino mass

Hambye, Hernandez^2, B.G. 09

Particular surprising case

Three light active families + one N_R + one $N_R{}'$

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \left(\begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{array} \right) \end{array}$$

μ' is irrelevant (at tree-level)

$$\mathbf{m_\nu} \sim c^{d=5}_{\alpha\beta} = \left(Y_N'^T \frac{1}{\Lambda^T} Y_N + Y_N^T \frac{1}{\Lambda} Y_N' \right)_{\alpha\beta} - \left(Y_N^T \frac{1}{\Lambda} \mu \frac{1}{\Lambda^T} Y_N \right)_{\alpha\beta}$$

$$\textbf{flavour effects} \sim c^{d=6}_{\alpha\beta} \equiv \left(Y_N^\dagger \frac{1}{\Lambda^\dagger \Lambda} Y_N \right)_{\alpha\beta} + \cdots$$

Hambye, Hernandez^2, B.G. 09

Particular surprising case

Three light active families + one N_R + one N_R'

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \\ \\ \\ \end{array} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \\ \end{array}$$

$$\mathscr{L}_{M_\nu} = \left(\begin{array}{ccc} 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{array} \right)$$

μ' is irrelevant (at tree-level)

FUNDAMENTAL

	moduli	phases
Y_N	3	3
Y_N'	3	3
Λ	1	1

vs

LOW ENERGY

- 3 angles and 2 phases in the U_{PMNS}
- 2 masses and 0 phases in M_ν
- 2 overall factors and 5 phases absorbed.

***Yukawas are completely determined from U_{PMNS}+m_ν**, except for a normalization + a degeneracy in the Majorana phase

Hambye, Hernandez[2], B.G. 09

Particular surprising case

Three light active families + one N_R + one $N_R{}'$

$$\mathscr{L}_{M_\nu} = \begin{array}{c} \begin{array}{ccc} \bar{L}_i & \bar{N}^c & \bar{N}'^c \end{array} \\ \left(\begin{array}{ccc} 0 & Y_N^T v & Y_N'^T v \\ Y_N v & \mu' & \Lambda^T \\ Y_N' v & \Lambda & \mu \end{array}\right) \end{array}$$

μ' is irrelevant (at tree-level)

i.e.

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta}s_{13} + e^{-i\alpha}s_{12}r^{1/4} \\ s_{23}\left(1-\frac{\sqrt{r}}{2}\right) + e^{-i\alpha}r^{1/4}c_{12}c_{23} \\ c_{23}\left(1-\frac{\sqrt{r}}{2}\right) - e^{-i\alpha}r^{1/4}c_{12}s_{23} \end{pmatrix} \qquad r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

Normal hierarchy

***Yukawas are completely determined from U_{PMNS}+m_ν**, except for a normalization + a degeneracy in the Majorana phase (+ 1 phase if μ present)

Hambye, Hernandez^2, B.G. 09

Normal hierarchy:

Up to terms of $\mathcal{O}(\sqrt{r}, s_{13})$, we find

$$r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

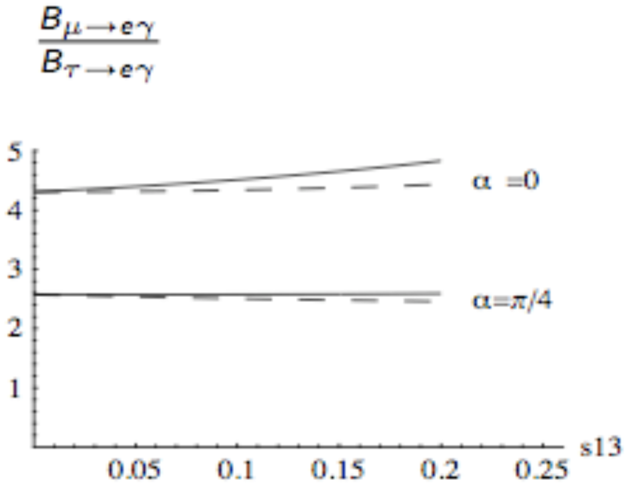
$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix} .$$

Inverted hierarchy:

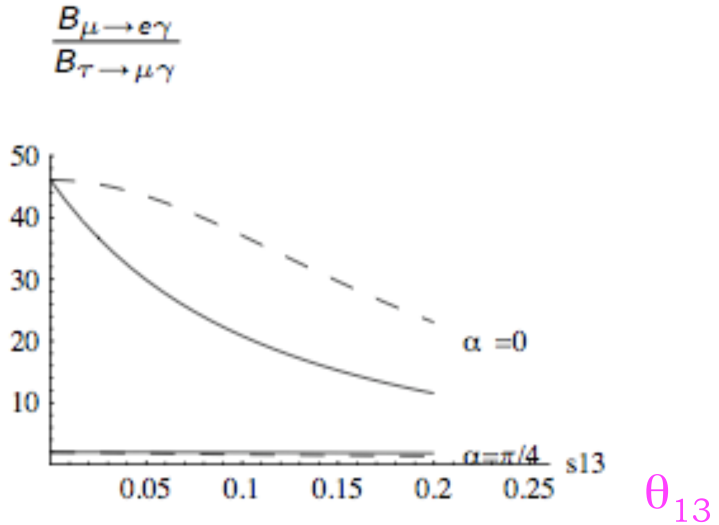
$$Y_N^T \simeq \frac{y}{\sqrt{2}} \begin{pmatrix} c_{12} e^{i\alpha} + s_{12} e^{-i\alpha} \\ c_{12}\left(c_{23} e^{-i\alpha} - s_{23} s_{13} e^{i(\alpha-\delta)}\right) - s_{12}\left(c_{23} e^{i\alpha} + s_{23} s_{13} e^{-i(\alpha+\delta)}\right) \\ -c_{12}\left(s_{23} e^{-i\alpha} + c_{23} s_{13} e^{i(\alpha-\delta)}\right) + s_{12}\left(s_{23} e^{i\alpha} - c_{23} s_{13} e^{-i(\alpha+\delta)}\right) \end{pmatrix}$$

$$\boxed{B_{\mu\to e\gamma} \propto |Y_{N_e} Y_{N_\mu}|^2}$$

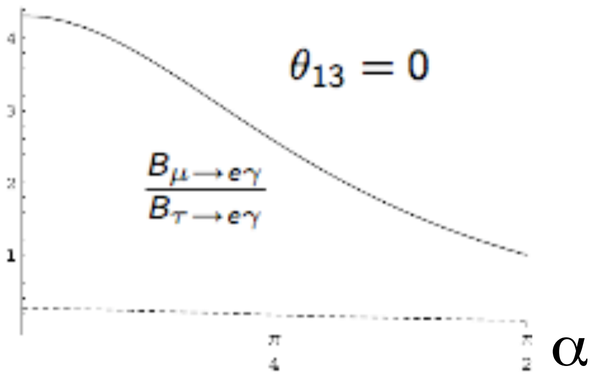
NORMAL HIERARCHY

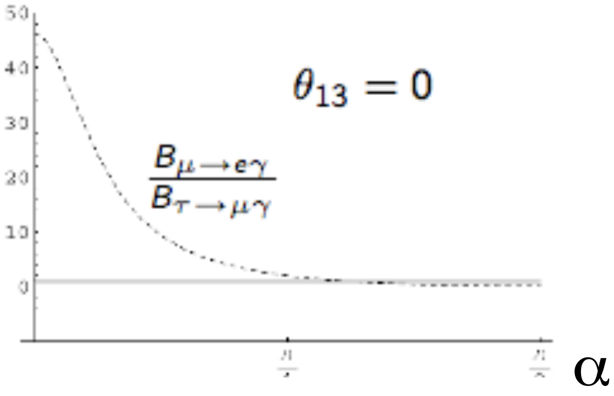


INVERTED HIERARCHY



Strong dependence on the Majorana phase!





Degeneracy in the Majorana phase α

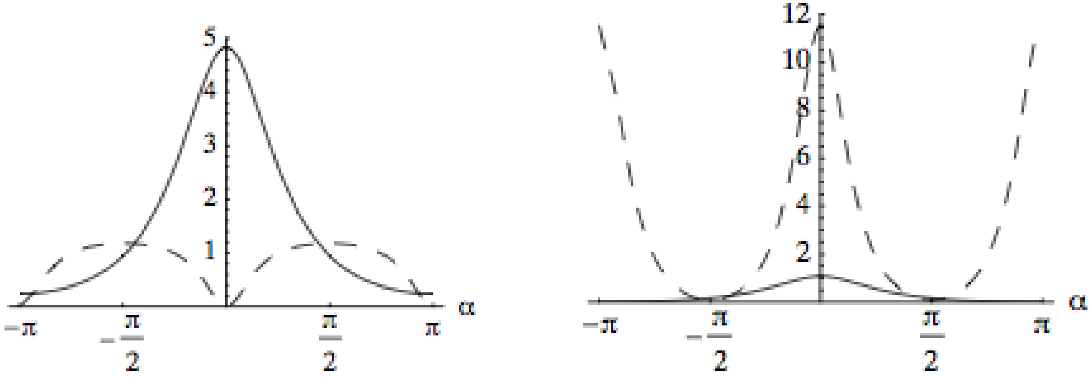
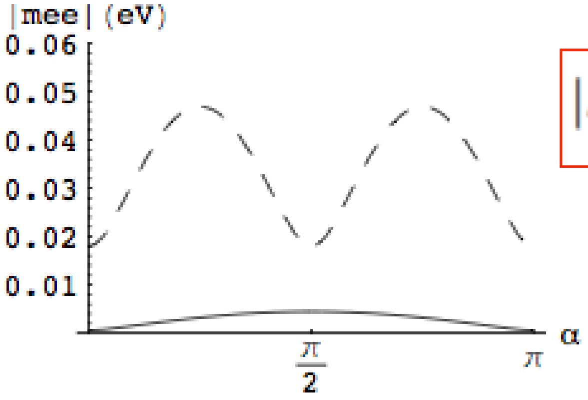


Figure 3: Left: Ratio $B_{e\mu}/B_{e\tau}$ for the normal hierarchy (solid) and the inverse hierarchy (dashed) as a function of α for $(\delta, s_{13}) = (0, 0.2)$. Right: the same for the ratio $B_{e\mu}/B_{\mu\tau}$.



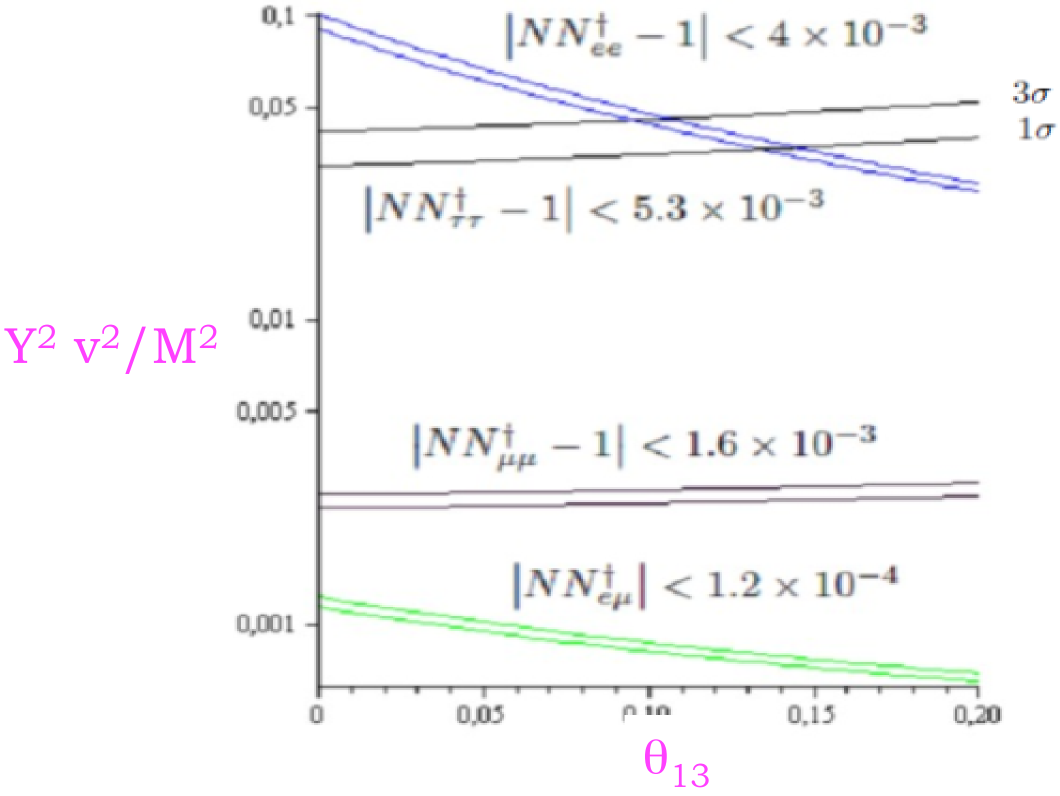
$$\boxed{|m_{ee}|_{IH} \simeq |s_{12}^2 e^{-2i\alpha} - c_{12}^2 e^{2i\alpha}|}$$

Figure 5: m_{ee} as a function of α for the normal (solid) and inverted (dashed) hierarchies, for $(\delta, s_{13}) = (0, 0.2)$.

Normal hierarchy:

$Y^2\ v^2/M^2$ vs θ_{13}

$N \sim U_{PMNS} + Y^{+}Y\ v^2/M^2$



Actual Data

To date, the best Bound comes from the rare decay $\mu \to e\gamma$ $\sim< 10^{-4}$

(Alonso, Gavela, Hernandez,Li …ongoing)

* It is a fermionic seesaw: bounds on non-unitarity apply

At present, best bound on $Y^2 v^2/M^2 < 10^{-4}$ is from **μ --> e γ**

$$B_{\mu\to e\gamma} \propto |Y_{N_e} Y_{N_\mu}|^2$$

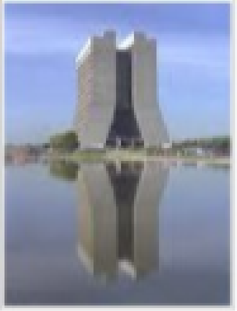
i.e.

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix} \qquad r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

Normal hierarchy

μ-e conversion being computed now

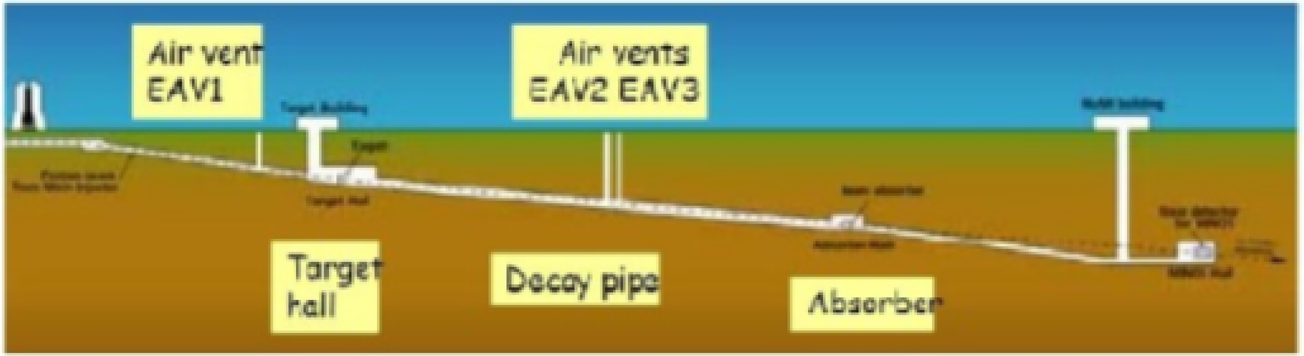
But in some regions the mu-tau sector can be stronger



MINSIS

Main
Injector
Non **S**tandard
Interaction**S**

Minsis is a project for a **short baseline** experiment in Fermilab

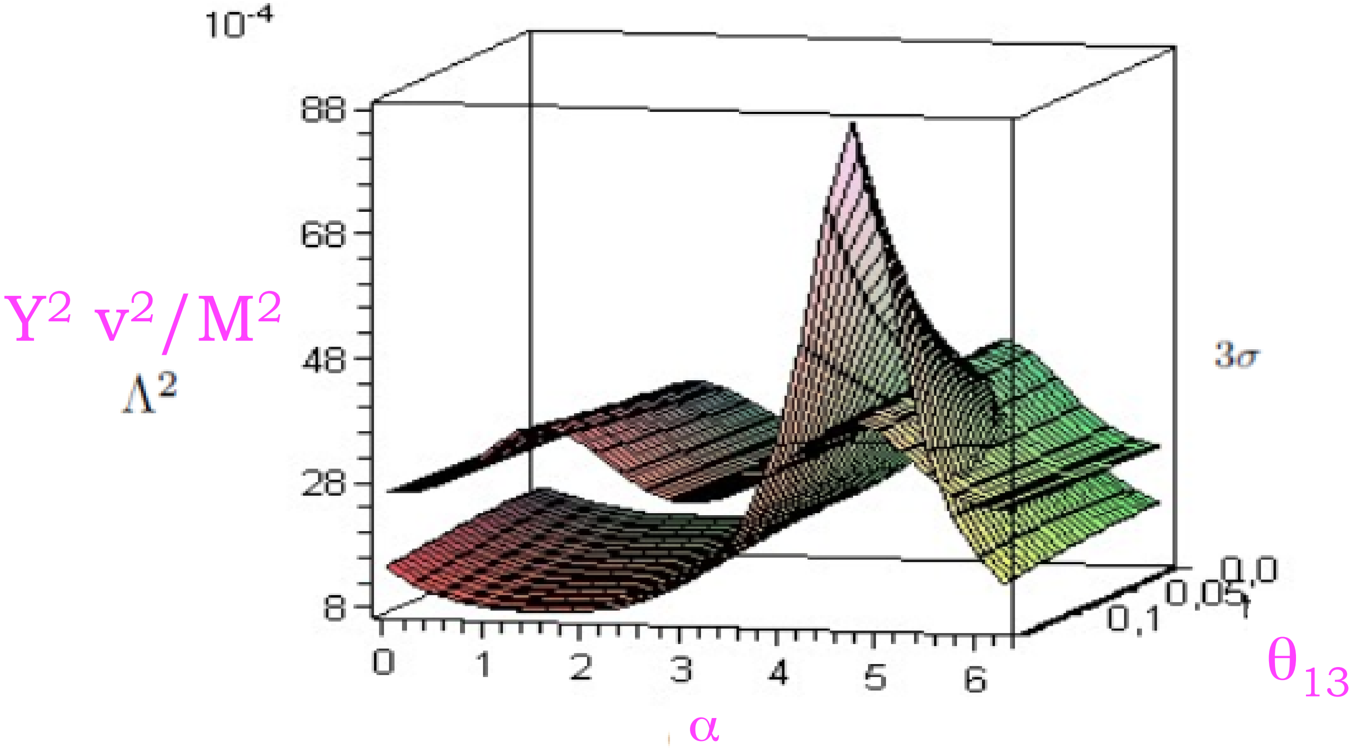


That would look for ν_μ dissappearance

ν_μ --> ν_τ

Normal hierarchy: MINSIS and MFV

If we explore a wider range of parameters



We find that there are regions where an experiment as MINSIS would improve the present bounds on our Model

(Alonso, Gavela, Hernandez,Li …ongoing)

Ongoing:

- * **Bounds on non-unitarity apply**

$\mu \dashrightarrow e\,\gamma$

(Alonso, Gavela, Hernandez,Li …ongoing)

- * **Impact on** $\nu_\mu \dashrightarrow \nu_\tau$ **can be very important**

- * **Leptogenesis possible** (Blanchet, Hambye, Josse-Michaux 09)

The Yukawas themselves are flavour vectors here!!

Normal hierarchy:

Up to terms of $\mathcal{O}(\sqrt{r}, s_{13})$, we find

$$r = \frac{|\Delta m^2_{12}|}{|\Delta m^2_{13}|}$$

$$Y_N^T \simeq y \begin{pmatrix} e^{i\delta} s_{13} + e^{-i\alpha} s_{12} r^{1/4} \\ s_{23}\left(1 - \frac{\sqrt{r}}{2}\right) + e^{-i\alpha} r^{1/4} c_{12} c_{23} \\ c_{23}\left(1 - \frac{\sqrt{r}}{2}\right) - e^{-i\alpha} r^{1/4} c_{12} s_{23} \end{pmatrix} .$$

Inverted hierarchy:

$$Y_N^T \simeq \frac{y}{\sqrt{2}} \begin{pmatrix} c_{12} e^{i\alpha} + s_{12} e^{-i\alpha} \\ c_{12}\left(c_{23} e^{-i\alpha} - s_{23} s_{13} e^{i(\alpha-\delta)}\right) - s_{12}\left(c_{23} e^{i\alpha} + s_{23} s_{13} e^{-i(\alpha+\delta)}\right) \\ -c_{12}\left(s_{23} e^{-i\alpha} + c_{23} s_{13} e^{i(\alpha-\delta)}\right) + s_{12}\left(s_{23} e^{i\alpha} - c_{23} s_{13} e^{-i(\alpha+\delta)}\right) \end{pmatrix}$$

The Yukawas themselves are flavour vectors here!!

Is this model is automatically of the “fundamental” (χ)   type….

… with 2 χ replicas ??

What is the scalar potential of MFV including Majorana νs?

- Work ongoing right now
- It should allow an answer to the question of whether leptonic mixing differs from quark mixing because of the different nature of mass

Conclusions

1) Scalar Potential for MFV

-- We constructed it for quarks and explored the minima

-- Quark masses and mixings difficult to accomodate

Scalar fields in the fundamental induce naturally:
strong quark mass hierarchy + mixing !

2) MFV vs Seesaw

-- Scalar mediated Seesaw ("type II") is automatically MFV

-- Fermionic Seesaws (I and III) are NOT in minimal version
but with approximate $U(1)_{LN}$ - e.g. inverse seesaws-
they can be MFV

We found maybe the simplest model of neutrino masses:
add just 2 heavy right-handed neutrinos to SM:
extremely predictiv, and it is MFV

... and Yukawas are in the fundamental of the flavour group

-- We are exploring the leptonic MFV scalar potential

Back-up slides

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

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

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

O(1)

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

→ d-d ~ s-d ~ b-s transitions of ~ equal strength

while it may not be so...

for instance for SM+ 2 Higgses and Z_3. light quarks dominate

(Branco, Grimus, Lavoura)

All this underlies the importance

of searching for ν_μ <--> ν_τ transitions

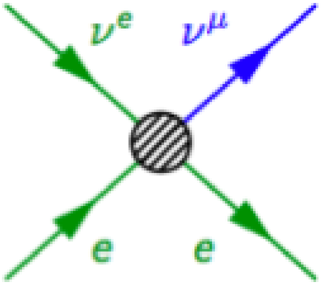
or NSI involving those flavours in general

(i.e. at near detectors)

“Why not” NSIs

(Non-Seesaw NSIs)

i.e., purely matter NSI?



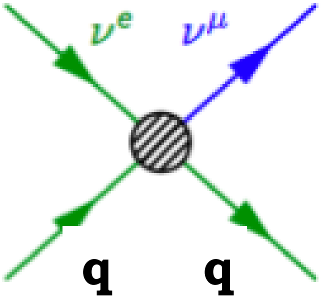
Extra effects in matter propagation

$$\mathscr{L}_{\rm NSI} \propto -\epsilon^{\ell}_{\alpha\beta}(\bar{\nu}^{\alpha}\gamma^{\rho}P_L\nu_{\beta})(\bar{\ell}\gamma_{\rho}\ell)$$

$$\mathscr{H}_F = U \begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E} \end{pmatrix} U^{\dagger} + V \begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^m_{\mu e} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^m_{\tau e} & \epsilon^m_{\tau\mu} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

$$V \propto N_e$$

i.e., purely matter NSI?



Extra effects in matter propagation

$$\mathscr{L}_{\mathrm{NSI}} \propto -\epsilon^{\ell}_{\alpha\beta}(\bar{\nu}^{\alpha}\gamma^{\rho}P_L\nu_{\beta})\ (\bar{q}\ \gamma_{\mu}\ q)$$

$$\mathscr{H}_F = U\begin{pmatrix} 0 & & \\ & \frac{\Delta m^2_{21}}{2E} & \\ & & \frac{\Delta m^2_{31}}{2E} \end{pmatrix}U^{\dagger} + V\begin{pmatrix} 1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau} \\ \epsilon^m_{\mu e} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau} \\ \epsilon^m_{\tau e} & \epsilon^m_{\tau\mu} & \epsilon^m_{\tau\tau} \end{pmatrix}$$

$$V \propto N_e$$

BOUNDS

*Absolute maxima:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

from ν scattering
in NuTev
and in CHARM II

C. Biggio, M. Blennow, E. Fdez-Mtnez, 0907.0097

BOUNDS

*Absolute maxima:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & \boxed{0.33} \\ 3.0 & \boxed{0.33} & 21 \end{pmatrix}$$

from ν scattering
in NuTev
and in CHARM II

C. Biggio, M. Blennow, E. Fdez-Mtnez, 0907.0097

•Also from atmospheric data, unless cancellations among epsilons:

$$|\varepsilon_{\mu\tau}| < 5\ 10^{-2}$$

Fornengo, Maltoni, Tomás-Bayo, Valle,hep-ph 0108043
Gonzalez-García, Maltoni, Phys. Ret. 460, 2008

Potential Trouble:

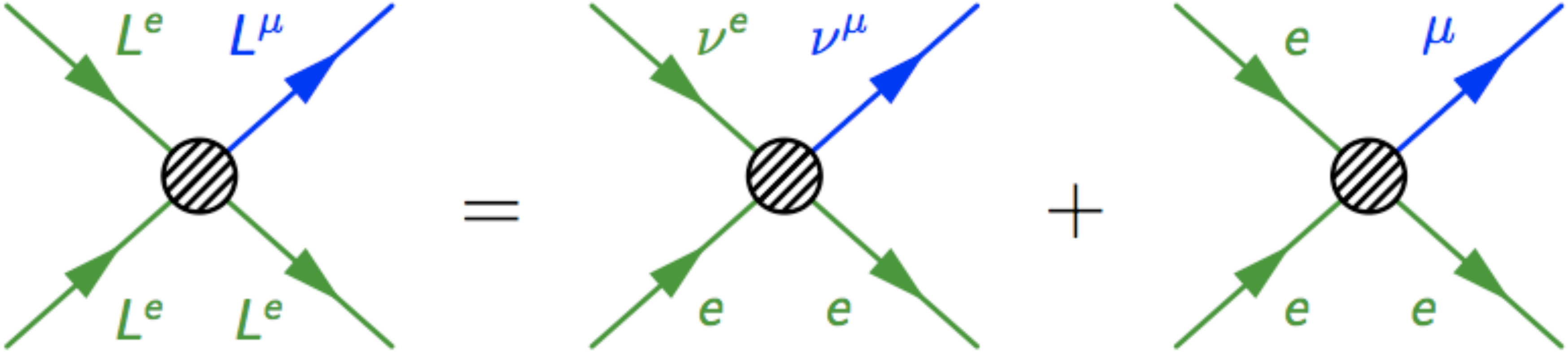
SU(2) x U(1) gauge invariance

NSI ------------------------------>Dangerous four
charged lepton
couplings

- **Gauge invariance** $(SU(3) \times SU(2) \times U(1))$

$$\frac{1}{\Lambda^2}(\bar{\nu}^e \gamma^\rho P_L \nu^\mu)(\bar{e}_L \gamma_\rho e_L) \rightarrow \frac{1}{\Lambda^2}(\bar{L}^e \gamma^\rho L^\mu)(\bar{L}_e \gamma_\rho L_e)$$

Trouble, for instance $\mu \longrightarrow eee$



$\mu \longrightarrow eee$

Systematical analysis

Two possibilities

A) There could be NO lepton charged processes involved

Ex: For $d = 6$

(Davidson, Kuypers) $$(\bar{L^c} i\tau^2 L)(\bar{L} i\tau^2 L^c) \rightarrow (\bar{\nu^c_\tau}\ e_L)(\bar{\nu}_\mu e^c_L)$$

Ex: For $d = 8$

$$O_{NSI} = (\bar{L}H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \rightarrow v^2(\bar{\nu}_\tau\ \gamma^\mu \nu^\mu)(\bar{e}_L \gamma_\mu e)$$

(Berezhiani, Rossi)

Systematical analysis

Two possibilities

A) There could be NO lepton charged processes involved

Ex: For $d = 6$

(Davidson, Kuypers) $(\overline{L^c} i\tau^2 L)(\bar{L} i\tau^2 L^c) \to (\overline{\nu^c_\tau}\ e_L)(\bar{\nu}_\mu e^c_L)$

But it also produces $\tau \dashrightarrow \mu\ \nu_e\bar{\nu}_e$!

Ex: For $d = 8$

And $\mu \dashrightarrow e\ \nu_\tau\bar{\nu}_e$

$$\boxed{\varepsilon_{\mu\tau} < 3\ 10^{-2}}$$

Fdez-Martinez

$$O_{NSI} = (\bar{L}H)\gamma^\mu(H^\dagger L)(\bar{E}\gamma_\mu E) \to v^2(\bar{\nu}_\tau\ \gamma^\mu\nu^\mu)(\bar{e}_L\gamma_\mu e)$$

(Berezhiani, Rossi)

Systematical analysis

Two possibilities

B) In general, "fine tune" some of them to obtain desired suppression

Ex:

$$\mathcal{L}_{\text{eff}} = \frac{\mathcal{C}^1}{\Lambda^2}(\bar{L}^e \gamma^\rho L^\mu)(\bar{L}^e \gamma_\rho L^\mu) + \frac{\mathcal{C}^3}{\Lambda^2}(\bar{L}^e \gamma^\rho \vec{\tau} L^\mu)(\bar{L}^e \gamma_\rho \vec{\tau} L^\mu)$$

We can avoid charged lepton interactions $(\bar{e}_L \gamma^\mu P_L \mu)(\bar{e} \gamma_\mu P_L e)$ if

$$\mathcal{C}^1 + \mathcal{C}^3 \simeq 0$$

ALL cancellation conditions examined

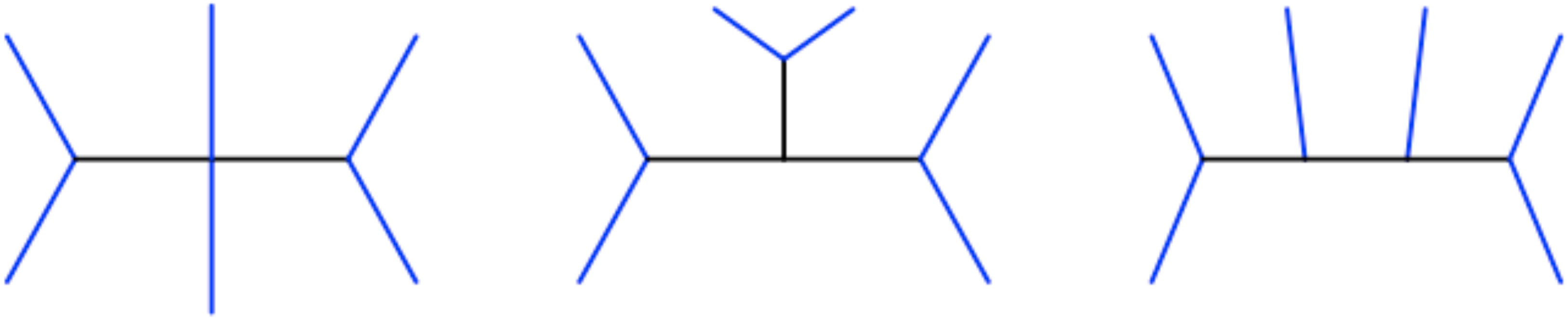
(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

Bottom line: $d = 6$ doesn't look promising

Maybe things get better at $d = 8$

Is it possible to generate $d = 8$ and NO $d = 6$ operators??

Several possibilities



Require at least 2 new fields (and unrelated to seesaw)

(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

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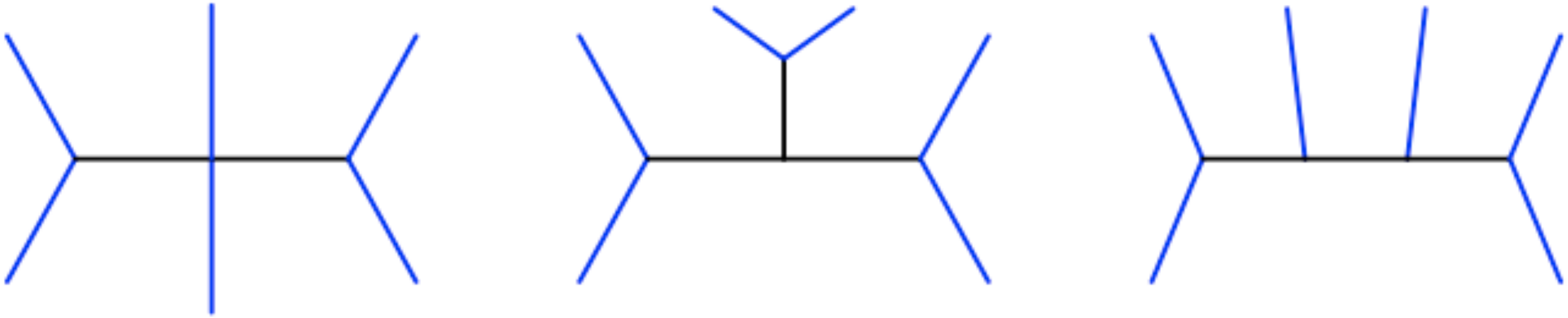
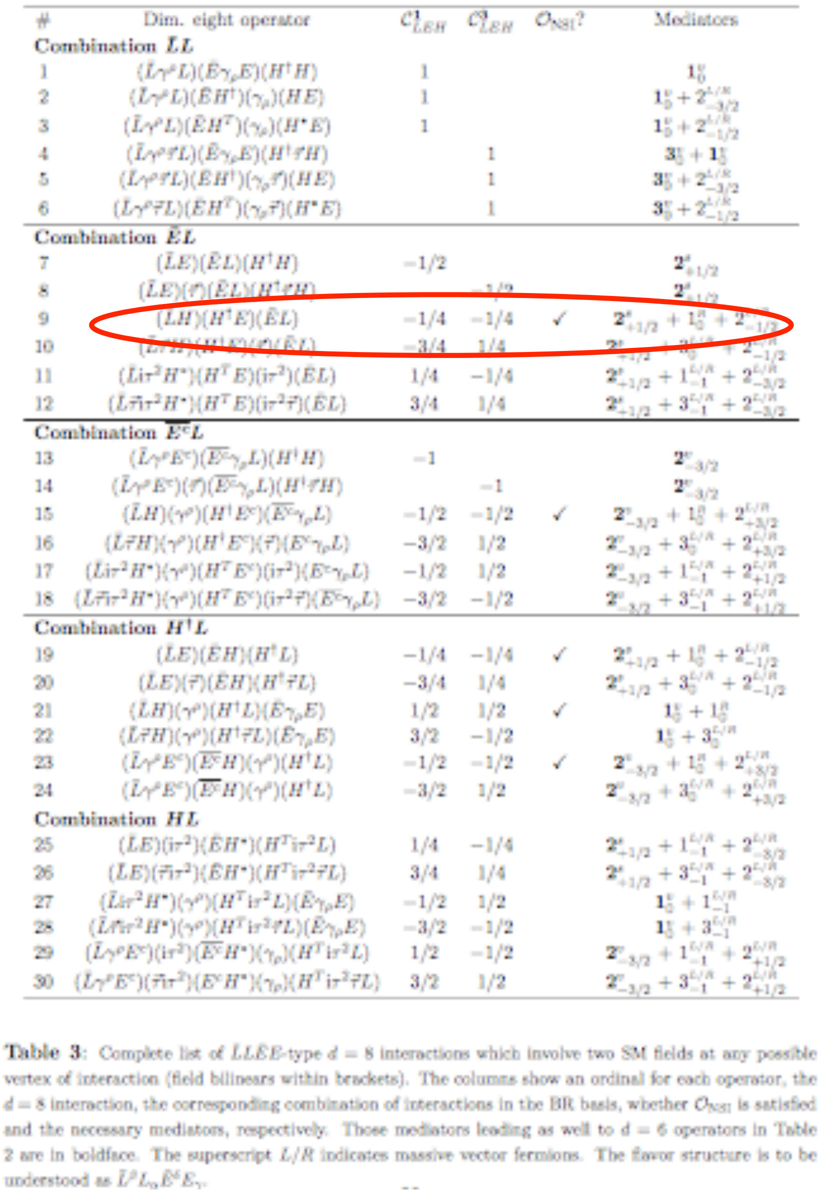


TERRIBLY COMPLICATED

(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

Complete list of d=8 operators and their mediators



#	Dim. eight operator	C^1_{LEH}	C^3_{LEH}	$\mathcal{O}_{NSI}$?	Mediators
Combination $\bar L L$					
1	$(\bar L\gamma^\rho L)(\bar E\gamma_\rho E)(H^\dagger H)$	1			$\mathbf{1}^v_0$
2	$(\bar L\gamma^\rho L)(\bar E H^\dagger)(\gamma_\rho)(H E)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-3/2}$
3	$(\bar L\gamma^\rho L)(\bar E H^T)(\gamma_\rho)(H^* E)$	1			$\mathbf{1}^v_0 + 2^{L/R}_{-1/2}$
4	$(\bar L\gamma^\rho\vec\tau L)(\bar E\gamma_\rho E)(H^\dagger\vec\tau H)$		1		$\mathbf{3}^v_0 + \mathbf{1}^v_0$
5	$(\bar L\gamma^\rho\vec\tau L)(\bar E H^\dagger)(\gamma_\rho\vec\tau)(H E)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-3/2}$
6	$(\bar L\gamma^\rho\vec\tau L)(\bar E H^T)(\gamma_\rho\vec\tau)(H^* E)$		1		$\mathbf{3}^v_0 + 2^{L/R}_{-1/2}$
Combination $\bar E L$					
7	$(\bar L E)(\bar E L)(H^\dagger H)$	−1/2			$\mathbf{2}^s_{+1/2}$
8	$(\bar L E)(\vec\tau)(\bar E L)(H^\dagger\vec\tau H)$		−1/2		$\mathbf{2}^s_{+1/2}$
9	$(\bar L H)(H^\dagger E)(\bar E L)$	−1/4	−1/4	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
10	$(\bar L\vec\tau H)(H^\dagger E)(\vec\tau)(\bar E L)$	−3/4	1/4		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
11	$(\bar L i\tau^2 H^*)(H^T E)(i\tau^2)(\bar E L)$	1/4	−1/4		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
12	$(\bar L\vec\tau i\tau^2 H^*)(H^T E)(i\tau^2\vec\tau)(\bar E L)$	3/4	1/4		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
Combination $\overline{E^c} L$					
13	$(\bar L\gamma^\rho E^c)(\overline{E^c}\gamma_\rho L)(H^\dagger H)$	−1			$\mathbf{2}^v_{-3/2}$
14	$(\bar L\gamma^\rho E^c)(\vec\tau)(\overline{E^c}\gamma_\rho L)(H^\dagger\vec\tau H)$		−1		$\mathbf{2}^v_{-3/2}$
15	$(\bar L H)(\gamma^\rho)(H^\dagger E^c)(\overline{E^c}\gamma_\rho L)$	−1/2	−1/2	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
16	$(\bar L\vec\tau H)(\gamma^\rho)(H^\dagger E^c)(\vec\tau)(\overline{E^c}\gamma_\rho L)$	−3/2	1/2		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
17	$(\bar L i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2)(\overline{E^c}\gamma_\rho L)$	−1/2	1/2		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
18	$(\bar L\vec\tau i\tau^2 H^*)(\gamma^\rho)(H^T E^c)(i\tau^2\vec\tau)(\overline{E^c}\gamma_\rho L)$	−3/2	−1/2		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$
Combination $H^\dagger L$					
19	$(\bar L E)(\bar E H)(H^\dagger L)$	−1/4	−1/4	✓	$\mathbf{2}^s_{+1/2} + 1^R_0 + 2^{L/R}_{-1/2}$
20	$(\bar L E)(\vec\tau)(\bar E H)(H^\dagger\vec\tau L)$	−3/4	1/4		$\mathbf{2}^s_{+1/2} + 3^{L/R}_0 + 2^{L/R}_{-1/2}$
21	$(\bar L H)(\gamma^\rho)(H^\dagger L)(\bar E\gamma_\rho E)$	1/2	1/2	✓	$\mathbf{1}^v_0 + 1^R_0$
22	$(\bar L\vec\tau H)(\gamma^\rho)(H^\dagger\vec\tau L)(\bar E\gamma_\rho E)$	3/2	−1/2		$\mathbf{1}^v_0 + 3^{L/R}_0$
23	$(\bar L\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	−1/2	−1/2	✓	$\mathbf{2}^v_{-3/2} + 1^R_0 + 2^{L/R}_{+3/2}$
24	$(\bar L\gamma^\rho E^c)(\overline{E^c}H)(\gamma^\rho)(H^\dagger L)$	−3/2	1/2		$\mathbf{2}^v_{-3/2} + 3^{L/R}_0 + 2^{L/R}_{+3/2}$
Combination $H L$					
25	$(\bar L E)(i\tau^2)(\bar E H^*)(H^T i\tau^2 L)$	1/4	−1/4		$\mathbf{2}^s_{+1/2} + 1^{L/R}_{-1} + 2^{L/R}_{-3/2}$
26	$(\bar L E)(\vec\tau i\tau^2)(\bar E H^*)(H^T i\tau^2\vec\tau L)$	3/4	1/4		$\mathbf{2}^s_{+1/2} + 3^{L/R}_{-1} + 2^{L/R}_{-3/2}$
27	$(\bar L i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2 L)(\bar E\gamma_\rho E)$	−1/2	1/2		$\mathbf{1}^v_0 + 1^{L/R}_{-1}$
28	$(\bar L\vec\tau i\tau^2 H^*)(\gamma^\rho)(H^T i\tau^2\vec\tau L)(\bar E\gamma_\rho E)$	−3/2	−1/2		$\mathbf{1}^v_0 + 3^{L/R}_{-1}$
29	$(\bar L\gamma^\rho E^c)(i\tau^2)(\overline{E^c}H^*)(\gamma_\rho)(H^T i\tau^2 L)$	1/2	−1/2		$\mathbf{2}^v_{-3/2} + 1^{L/R}_{-1} + 2^{L/R}_{+1/2}$
30	$(\bar L\gamma^\rho E^c)(\vec\tau i\tau^2)(E^c H^*)(\gamma_\rho)(H^T i\tau^2\vec\tau L)$	3/2	1/2		$\mathbf{2}^v_{-3/2} + 3^{L/R}_{-1} + 2^{L/R}_{+1/2}$

Table 3: Complete list of $\bar L L \bar E E$-type $d = 8$ interactions which involve two SM fields at any possible vertex of interaction (field bilinears within brackets). The columns show an ordinal for each operator, the $d = 8$ interaction, the corresponding combination of interactions in the BR basis, whether $\mathcal{O}_{NSI}$ is satisfied and the necessary mediators, respectively. Those mediators leading as well to d = 6 operators in Table 2 are in boldface. The superscript L/R indicates massive vector fermions. The flavor structure is to be understood as $\bar L^\beta L_\alpha \bar E^\delta E_\gamma$.

D. Hernandez, Ota, Winter + MBG

$(\bar{L}H)(H^\dagger E)(\bar{E}L)$	$-1/4$	$-1/4$	✓	$\mathbf{2}^{s}_{+1/2} + 1^{R}_{0} + 2^{L/R}_{-1/2}$

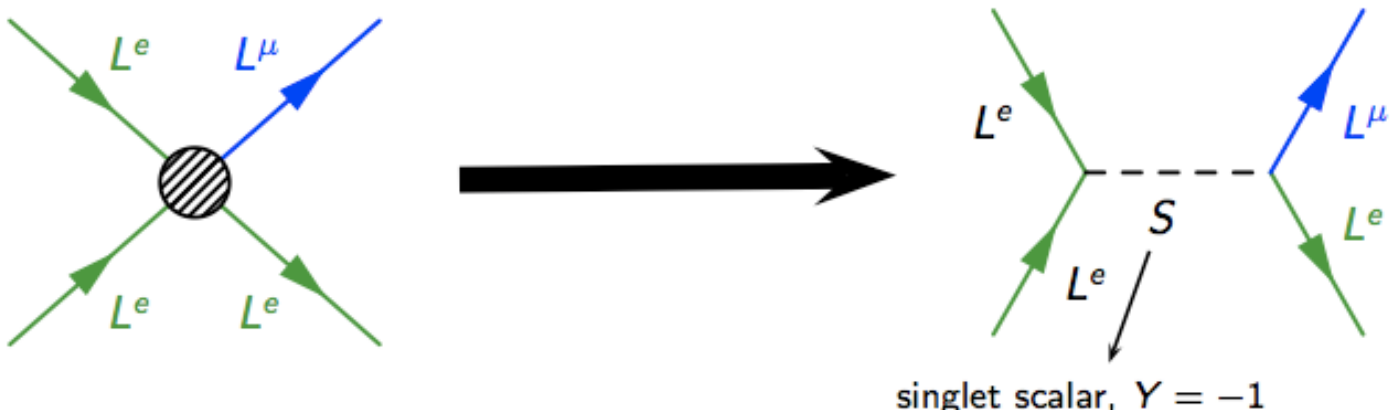
Finally, gauge invariance implies:

- **From d=6 ops.:** $\varepsilon_{\mu\tau} < 3\ 10^{-2}$

- **Or avoid altogether d=6 ops. and fine-tune cancellations between d=8 ones**
- **-unbelievable- !**

(check cancellantions in our table if you have the stomach for it)

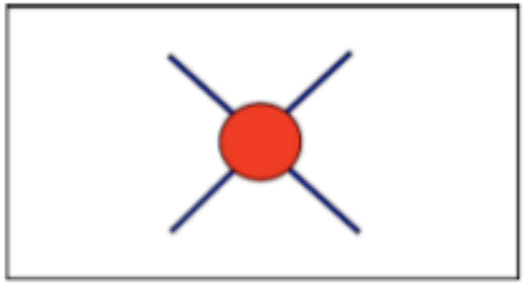
TREE-LEVEL MEDIATOR DECOMPOSITION



(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

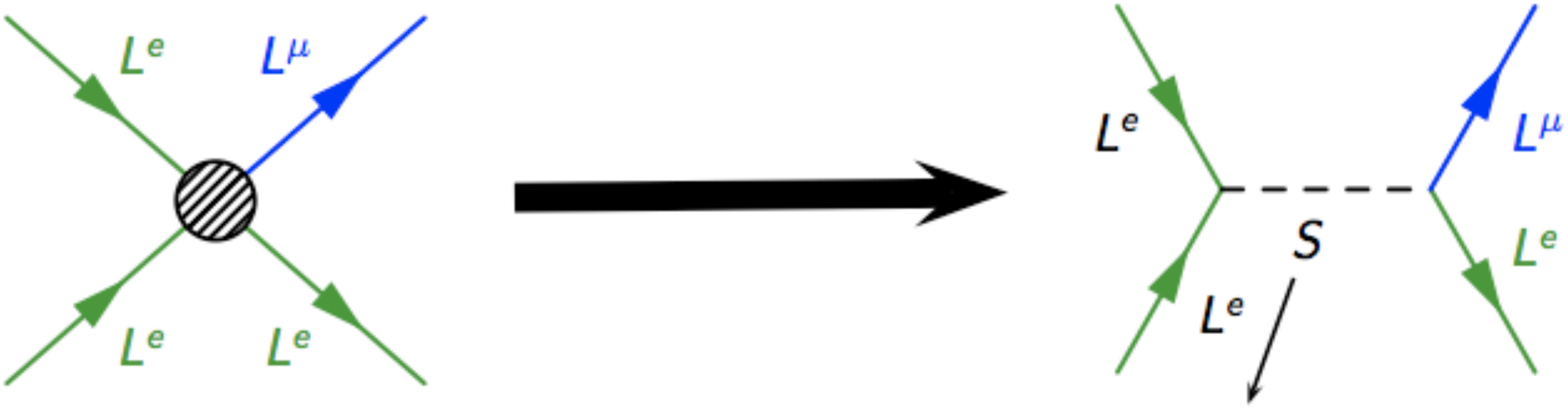
Mediator analysis of NSI

Constraints are then stronger and odds even worse:



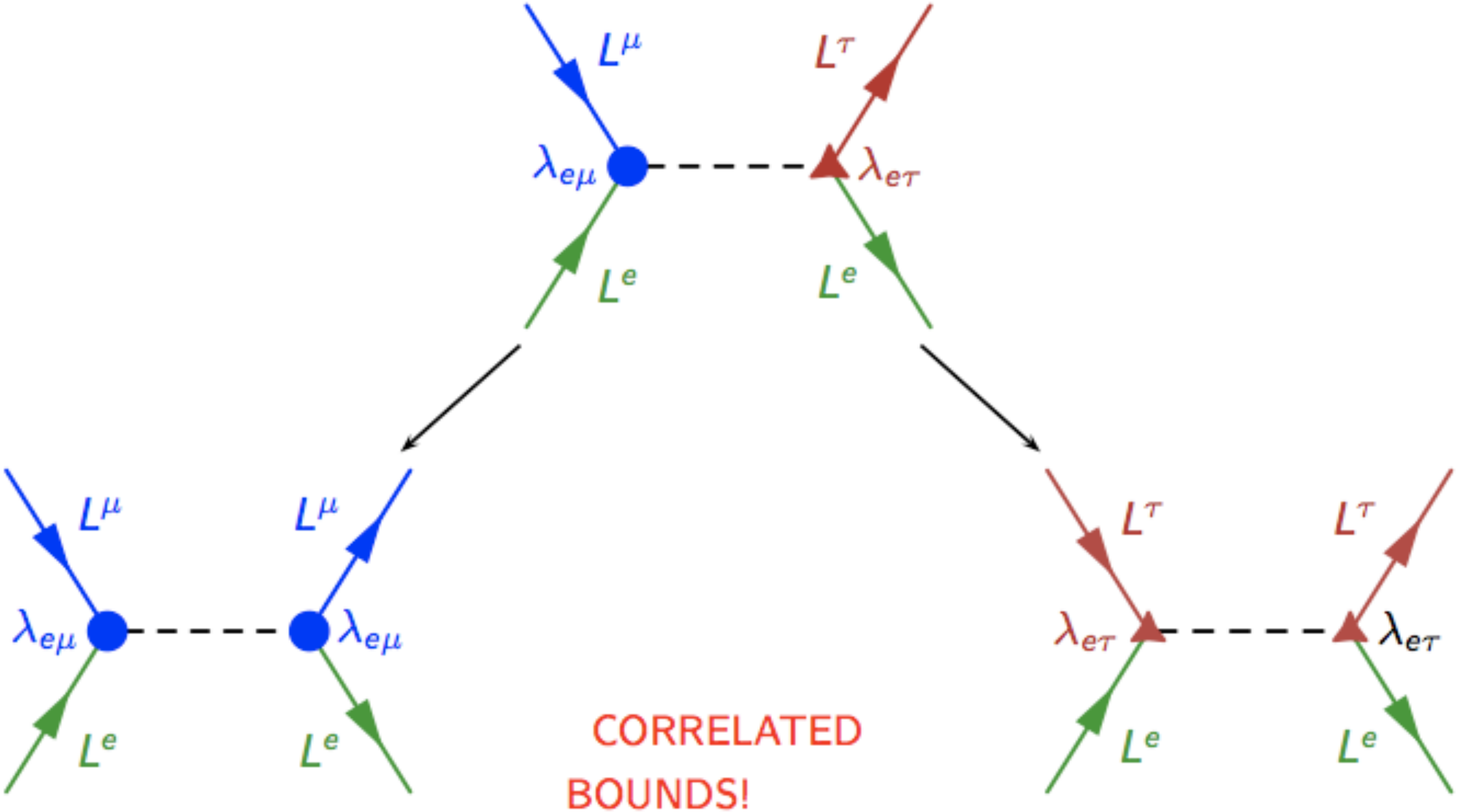
We can open the $d = 6$ vertex (remember Fermi, Weinberg?)

Ex: For instance, take the $(\bar{L^c} i\tau^2 L)(\bar{L} i\tau^2 L^c)$ Davidson+Kuypers



singlet scalar, $Y = -1$

BUT... you might run into troubles

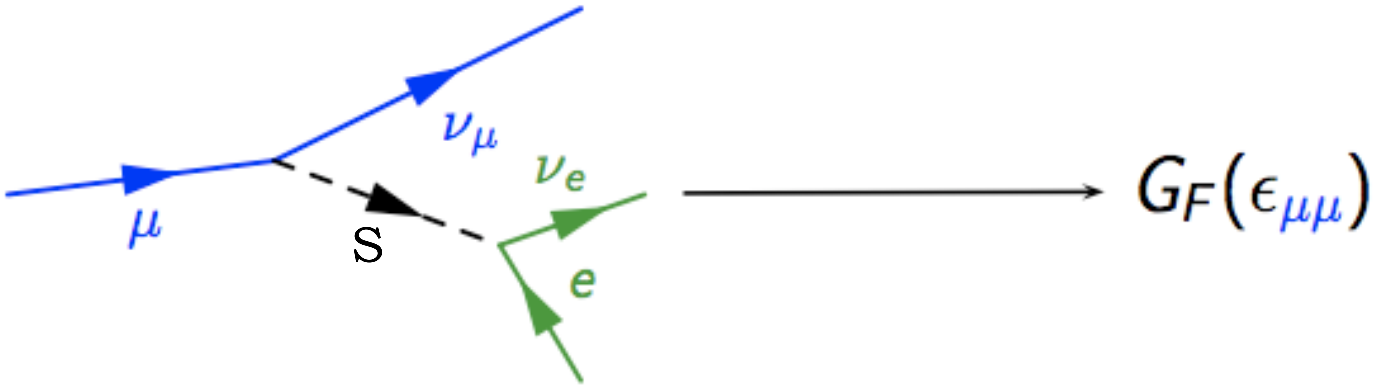


CORRELATED BOUNDS!

SEVERELY CONSTRAINED:

S. Antusch, J. P. Baumann, E. Fdez-Mtnez; 0807.1003
F. Cuypers, S. Davidson; hep-ph/ 9609487

Moreover...



Davidson+Kuypers….. Antusch,Baumann, Fdez.-Martinezz

$$\boxed{\varepsilon_{\mu\tau} < 2\ 10^{-3}}$$

- This S is disconnected from the seesaw mechanism… although connected to radiatively generated masses -Zee model-

- d=6 NSI are very very constrained.

TREE-LEVEL MEDIATOR DECOMPOSITION

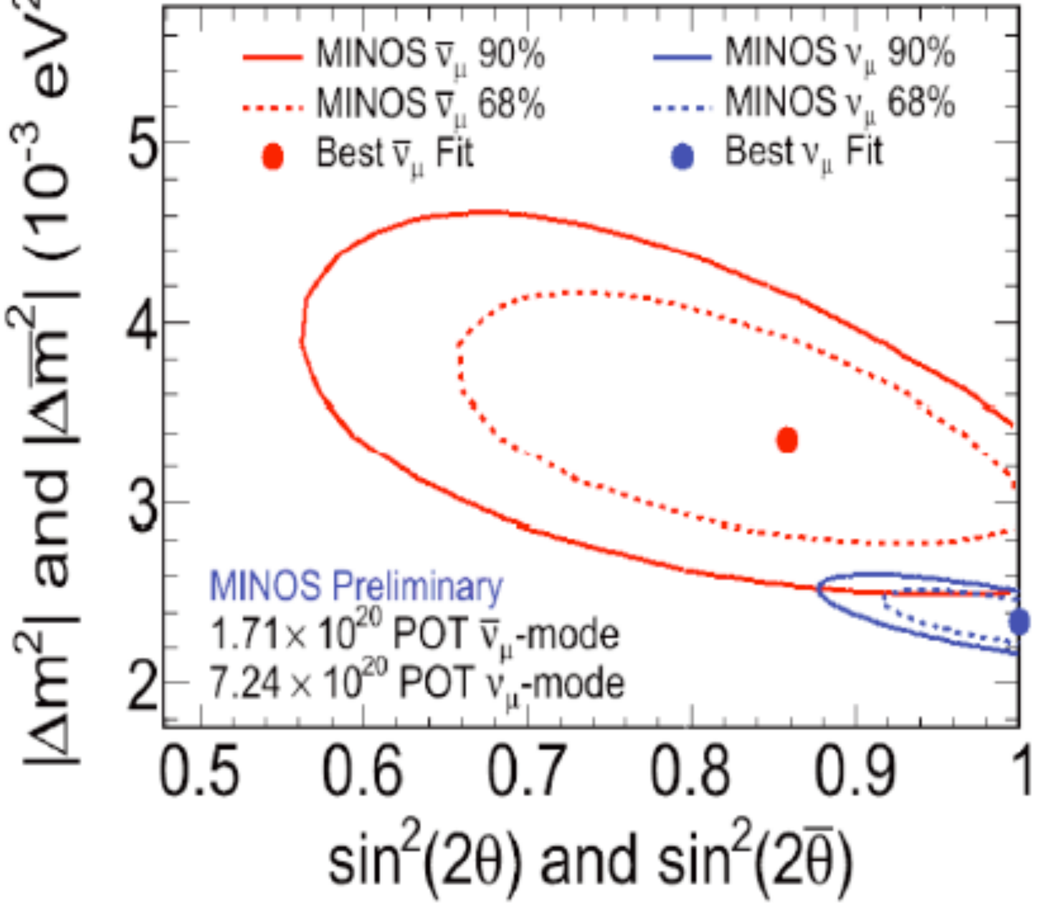
Would give even stronger bounds…

- $\varepsilon_{\mu\tau} < 10^{-3}$

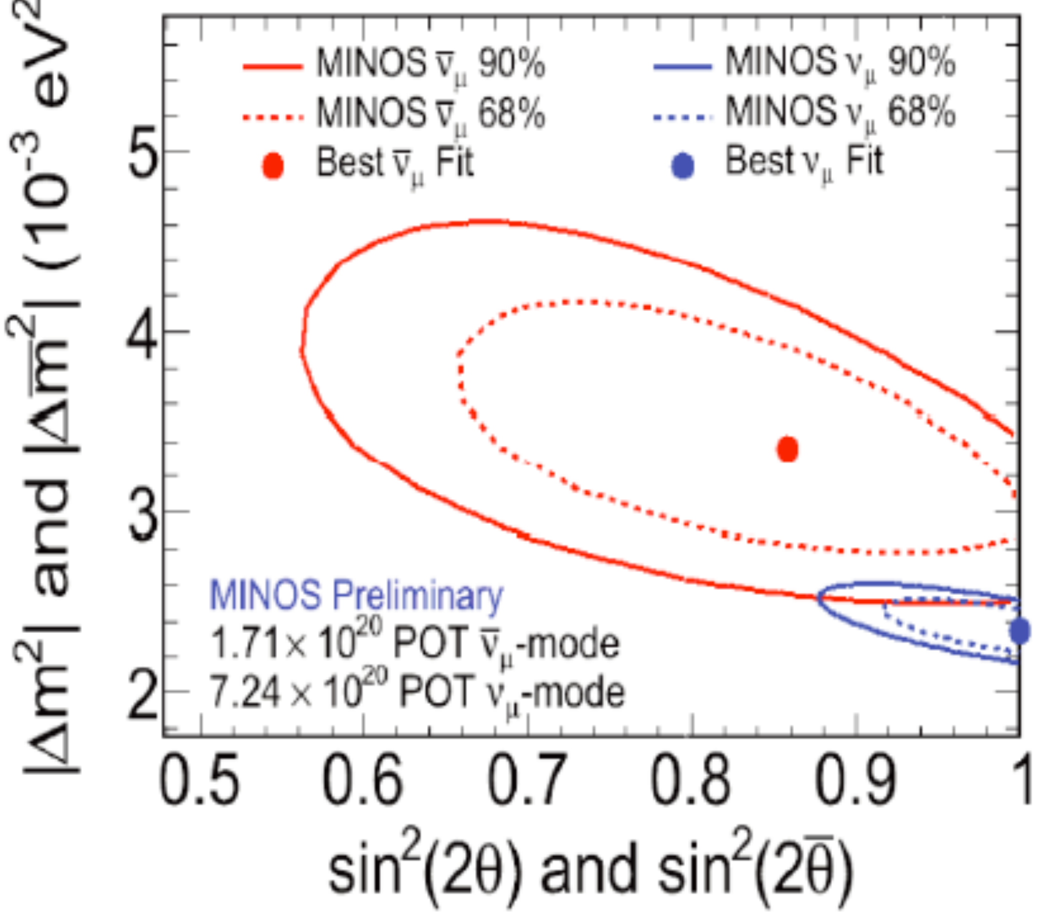
(Antusch, Baunman, Fdez-Martinez; D. Hernandez, Ota, Winter + MBG)

MINOS: neutrinos versus antineutrino difference??

MINOS (P. Vahle @Nu2010)



Could MINOS effect, if ever it becomes a signal (which is NOT), be matter NSI?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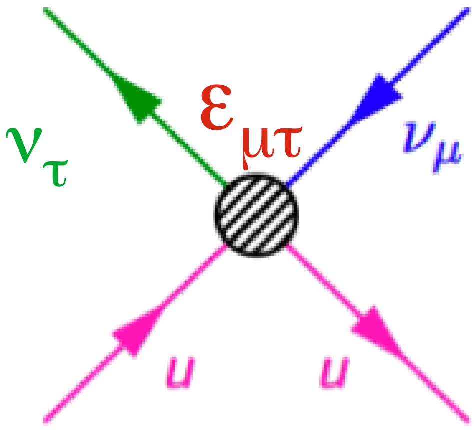
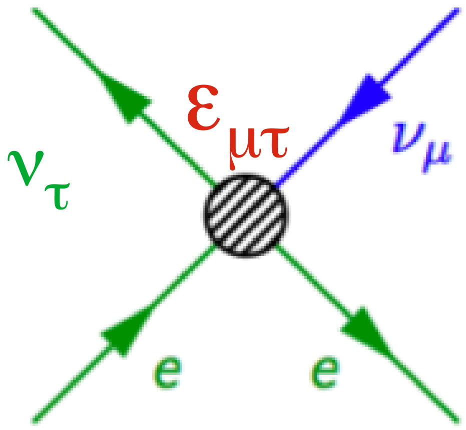
Mann et al. arXiv:1006.5720 $\varepsilon_{\mu\tau}$





$$\frac{1}{\Lambda^2}\bar{\nu}_\tau \nu_\mu \bar{u} u$$

$$\frac{1}{\Lambda}\bar{\nu}_\tau \nu_\mu \bar{e} e$$

Could MINOS effect, if ever it becomes a signal (which is NOT), be matter NSI?

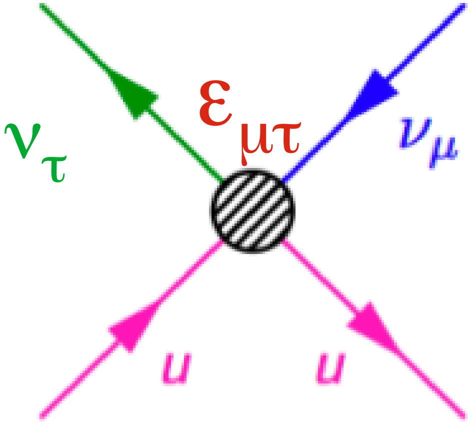
Mann et al. arXiv:1006.5720 $\varepsilon_{\mu\tau}$

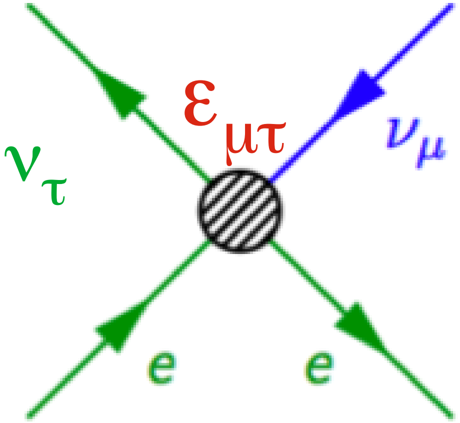
$$\mathcal{P}\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu\right) \simeq$$

$$1 - \sin^2\left(\left|\frac{\Delta m^2_{32}}{4E_\nu} \mp \varepsilon_{\mu\tau}|V_e|\right| L\right).$$

Could MINOS effect, if ever it becomes a signal (which is NOT), be matter NSI?

Mann et al. arXiv:1006.5720 $\varepsilon_{\mu\tau}$





They claim $\varepsilon_{\mu\tau} = -(0.12 \pm 0.21),\ \Delta m^2_{32} = 2.56^{+0.27}_{-0.24} \times 10^{-3}\ \mathrm{eV}^2$

$$\sin^2 2\theta_{23} = 0.90 \pm 0.05.$$

Kopp, Machado,Parke

arXiv:0076594

“Could it be $\varepsilon_{\mu\tau}$ matter NSI?”

* Similar analysis, but simulating MINOS event spectrum:

They claim

$$\epsilon^m_{\mu\tau} = -0.40 = 0.40\, e^{1.0 i\pi} \qquad \sin^2\theta_{23} = \quad 0.38$$

$$\epsilon^m_{\tau\tau} = -2.16 \qquad \Delta m^2_{32} = +2.86 \times 10^{-3}\ \mathrm{eV}^2$$

(Signs can be changed, eightfold degeneracy)

* Discovery at NOνA in less than one nominal year

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Plausible? NO! : gauge invariance -> $\varepsilon_{\mu\tau} < 3\ 10^{-2}$ from d=6,

or d=8 ops. with ad hoc cancellat.

Kopp, Machado,Parke

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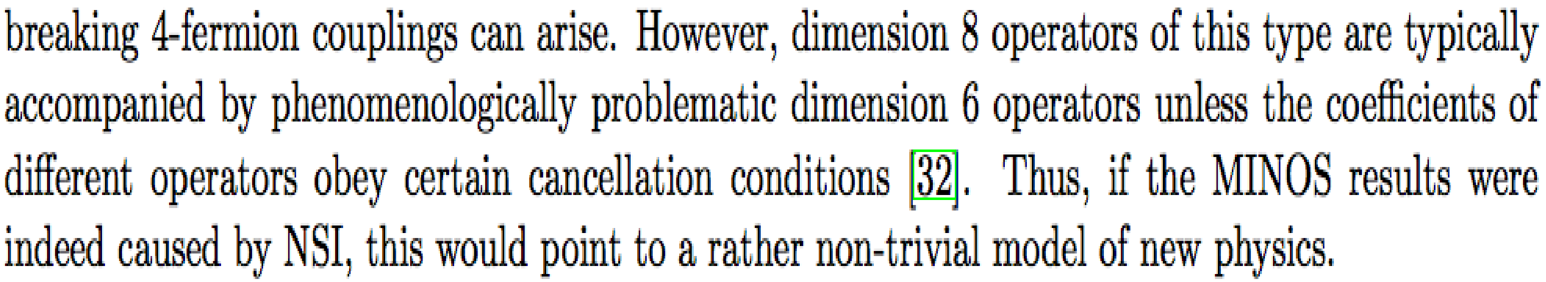
* They acknowledge that gauge invariance disfavours d=6 ops., and d=8 ops. unlikely:



breaking 4-fermion couplings can arise. However, dimension 8 operators of this type are typically accompanied by phenomenologically problematic dimension 6 operators unless the coefficients of different operators obey certain cancellation conditions [32]. Thus, if the MINOS results were indeed caused by NSI, this would point to a rather non-trivial model of new physics.

Kopp, Machado,Parke

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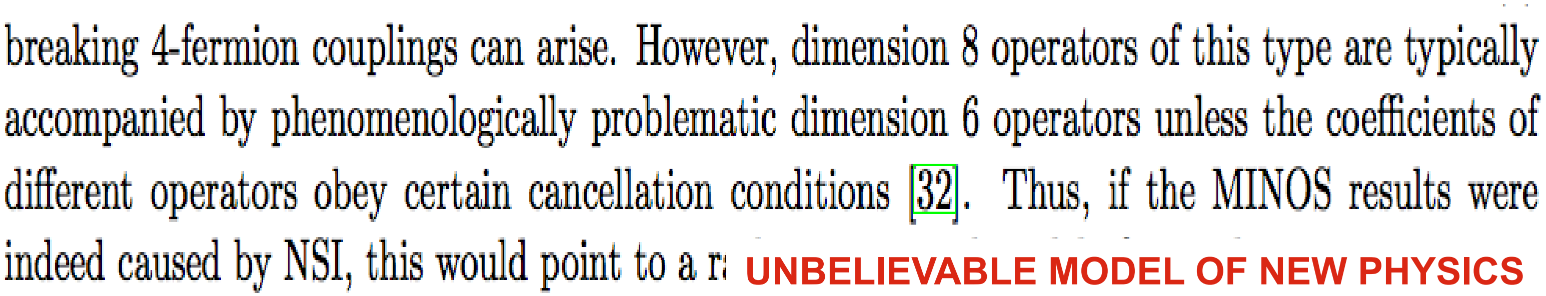

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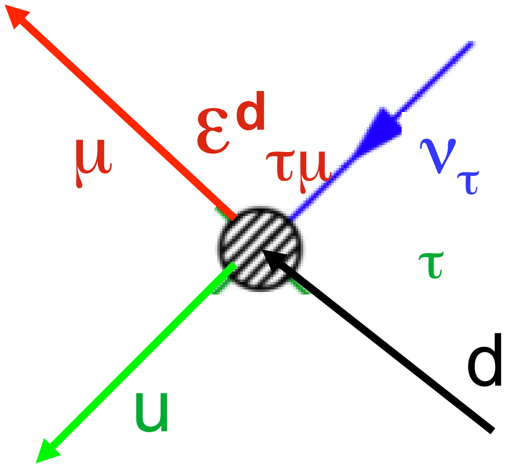
UNBELIEVABLE MODEL OF NEW PHYSICS

One week ago:

Kopp, Machado,Parke “Could it be <u>charged</u> NSI + CP-viol.?”



Interference of

SM $\nu_\mu + N \rightarrow X + \mu$

with $\nu_\mu \xrightarrow{\text{osc.}} \nu_\tau + N \rightarrow X + \mu$

$\varepsilon^{d}_{\tau\mu} \longrightarrow (\varepsilon^{d}_{\tau\mu})^*$ for antineutrinos

They claim

$$\epsilon^d_{\tau\mu} = 0.12\,i = 0.12\,e^{0.5i\pi}\,, \qquad \sin^2\theta_{23} = 0.41\,, \qquad \Delta m^2_{32} = +2.74 \times 10^{-3}\ \mathrm{eV}^2$$

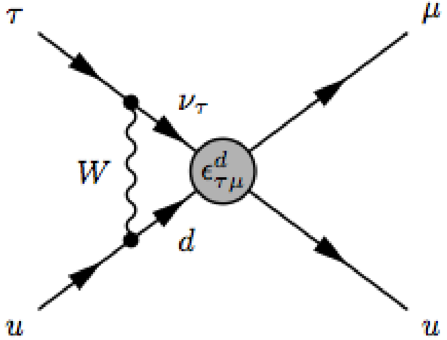
They say OK with bound $|\epsilon^d_{\tau\mu}| \lesssim 0.20$ from $\tau^\pm \rightarrow \mu^\pm\pi^0$

But....

But gauge invariance strikes again

* Their bound $|\epsilon^{d}_{\tau\mu}| \lesssim 0.20$ obtained from one loop contrib. to

Kopp, Machado,Parke



$$\tau^{\pm} \to \mu^{\pm}\pi^{0}$$

$$\mathcal{L}_{\rm NSI} \supset -2\sqrt{2}G_F \epsilon^{d}_{\tau\mu} V_{ud} \left[\bar{u}\gamma^{\rho}d\right]\left[\bar{\mu}\gamma_{\rho}P_L\nu_{\tau}\right].$$

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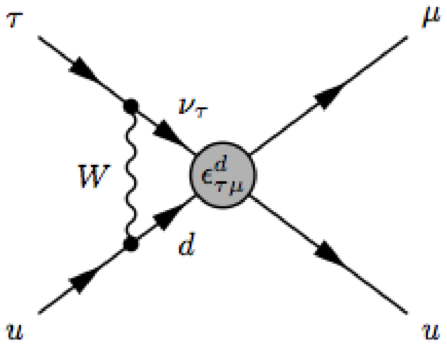
Kopp, Machado,Parke



$\tau^\pm \to \mu^\pm \pi^0$

* But a d=6 gauge inv. formulat. of the coupling

$$\mathcal{L}_{\rm NSI} \supset -2\sqrt{2}G_F\epsilon^d_{\tau\mu}V_{ud}\,(\overline{Q}\,\gamma^\rho\tau Q)(\overline{L}_\mu\,\gamma_\rho\,\tau\,L_\tau)$$

TREE LEVEL $\tau^\pm \to \mu^\pm\pi^0$ and $\mu^\pm\,\rho$ $\longrightarrow$ $\boxed{|\epsilon^d_{\tau\mu}| \lesssim 10^{-4}}$

and cannot explain "data"

(Blennow, Fernandez-Martinez arXiv:1005.0756)

My conclusion:

a ν_μ/ν_μ difference in MINOS

based on matter NSI ($\Lambda > v$)

is terribly unlikely

because of gauge invariance

and/or Atmospheric ---> $\varepsilon_{\mu\tau} < 3\ 10^{-2}$ unless brutal cancellations

More promising ? :

What about lighter states? … ie light steriles?

Steriles lighter than M_W evade non-unitarity bounds -if light enough- and some of the pure matter NSI bounds

Ie. Ann Nelson and collab.; light steriles, gauged B-L

Engelhardt, Nelson and Walsh 2010

(Heeck, Rodejohan 2010 for gauging L_μ-L_τ and light Z' ?)

And light steriles for the new MiniBoone data?

•Interesting: Same L/E than LSND, but different L and E
--> different backgrounds

CP in vacuum?:CP does not depend on L/E if matter effects negligible, but differs for neutrinos and antineutrinos

seems difficult (arXiv:0906.1997 and arXiv:0705.0107)

* **Combination of 3+1 and NSI ?** Akhmedov+Schwetz 2010
A. Nelson and colab. 2010

And light s ta?

Anyway,

- Interesti nd E

all those Fnal data are only 2 σ !!!

CP i atter effects

only combined they are intriguing ntineutrinos

5.0107)

Combination of 3+1 and NSI ? Akhmedov+Schwetz 2010

And light s ta?

•Interesti nd E

Recall: Paul the octopus predictions

are a 2.6 σ effect!!!

CP i atter effects

ntineutrinos

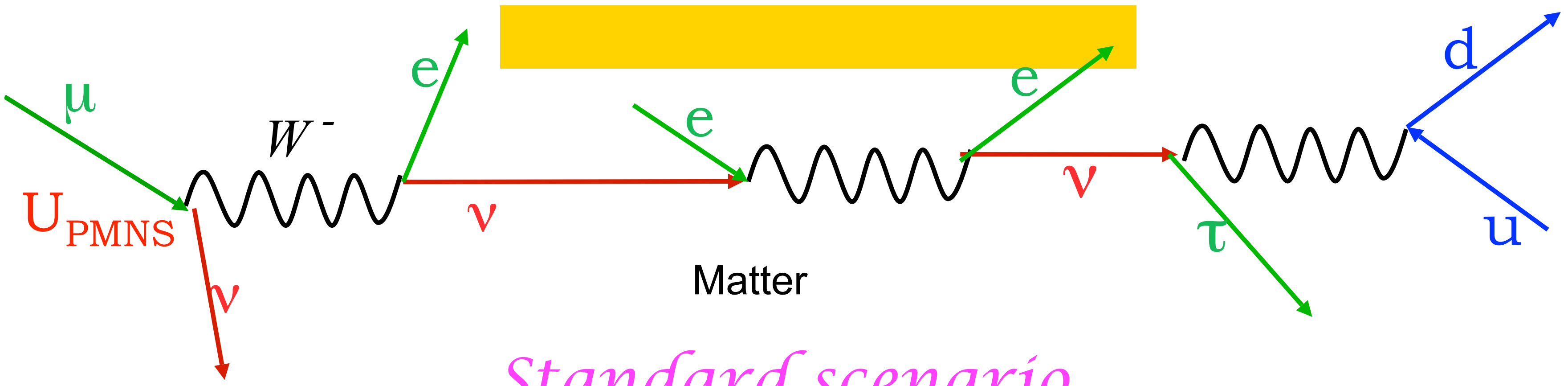
5.0107)

Combination of 3+1 and NSI ? Akhmedov+Schwetz 2010

2.6 σ effect for the world cup ! (Marc Sher)

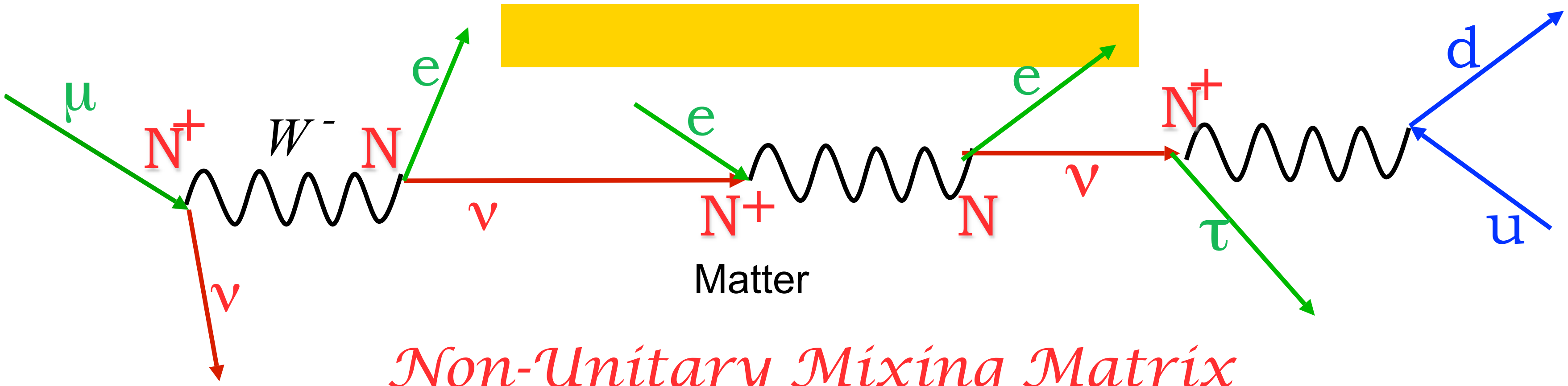
It is an appearance experiment (Spain)

YES! These effects ARE non-standard neutrino interactions



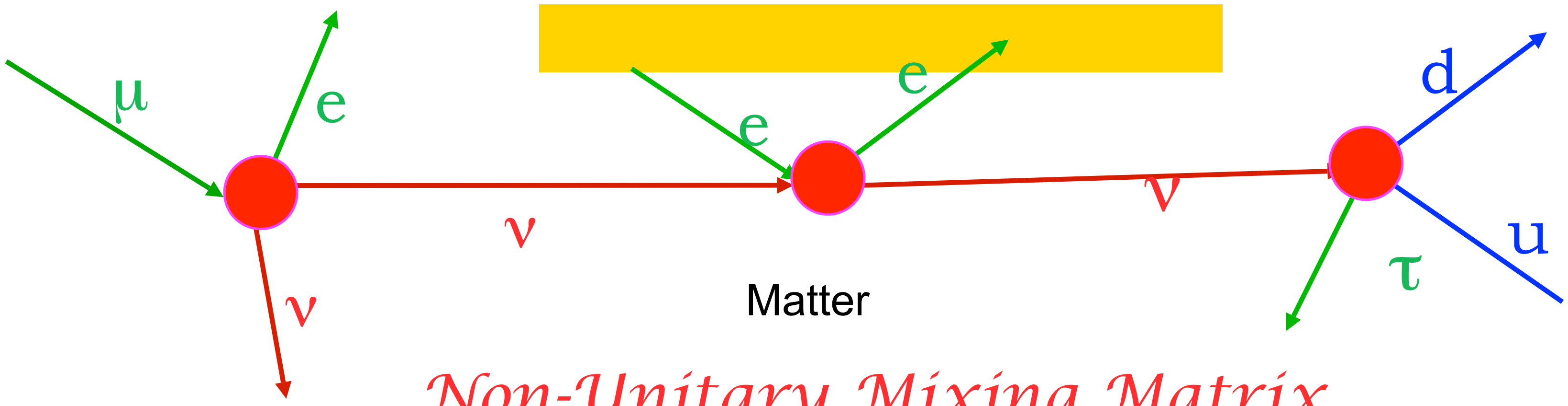
Standard scenario

YES! These effects ARE non-standard neutrino interactions



Non-Unitary Mixing Matrix

YES! These effects ARE non-standard neutrino interactions…



Non-Unitary Mixing Matrix

…affecting <u>simultneously</u> *production, propagation and detection.*

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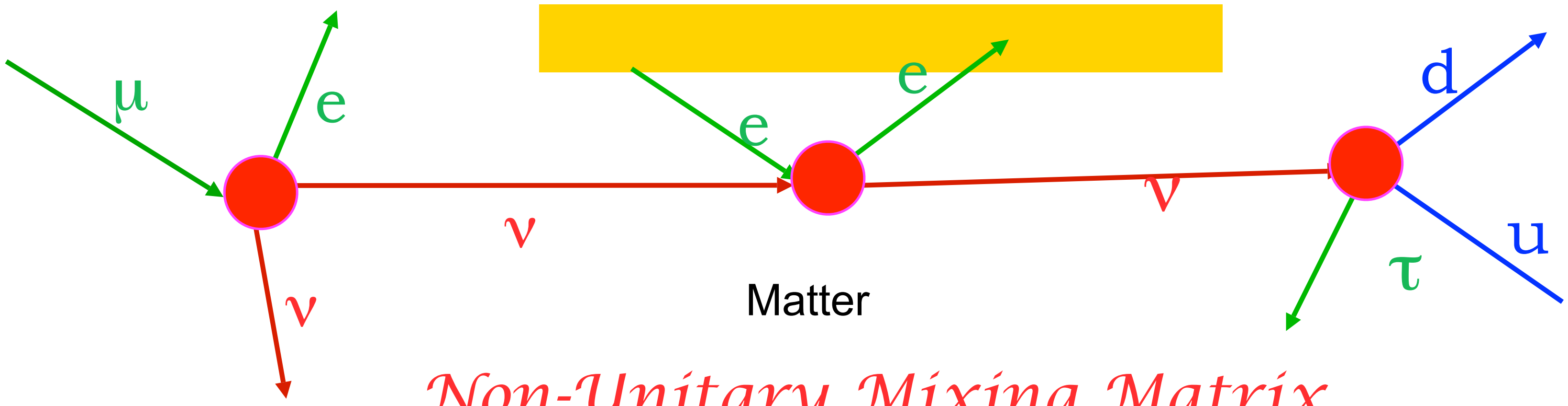

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These NSI are a generic signature
of fermionic Seesaws

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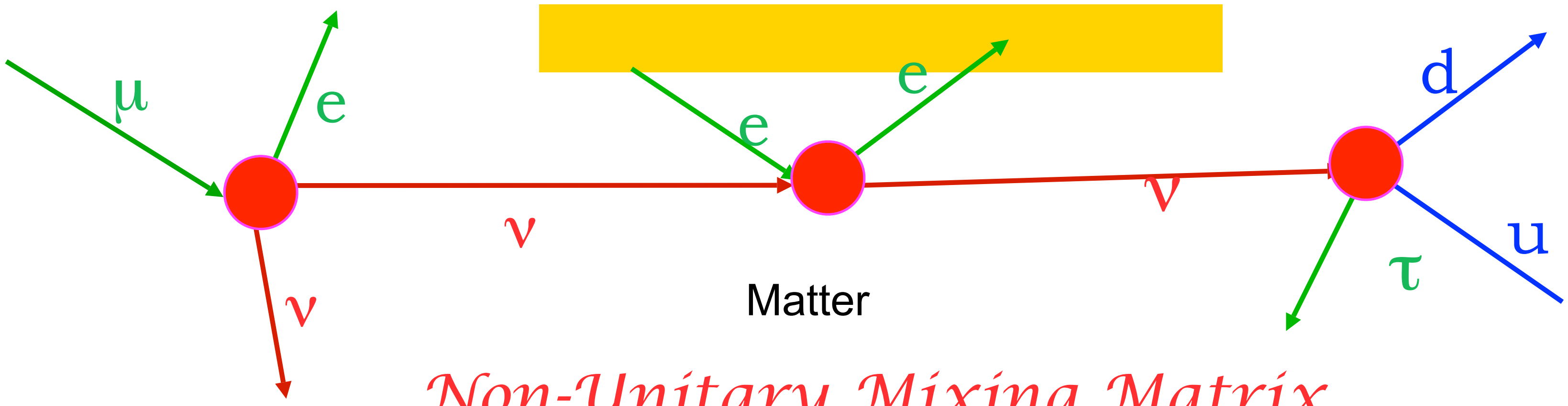

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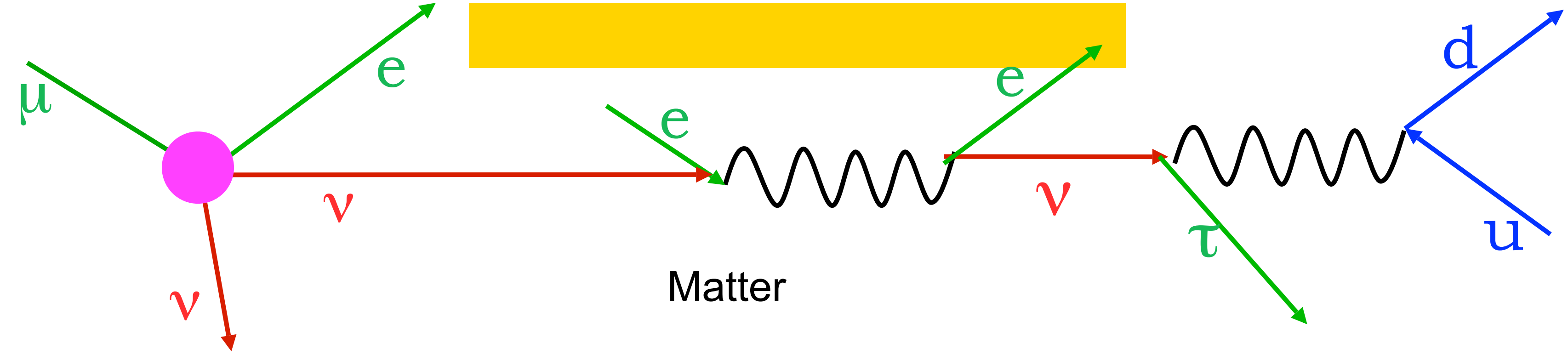
…affecting simultneously *production, propagation and detection.*

To be compared with popular non-standard interactions, with either:



Exotic production

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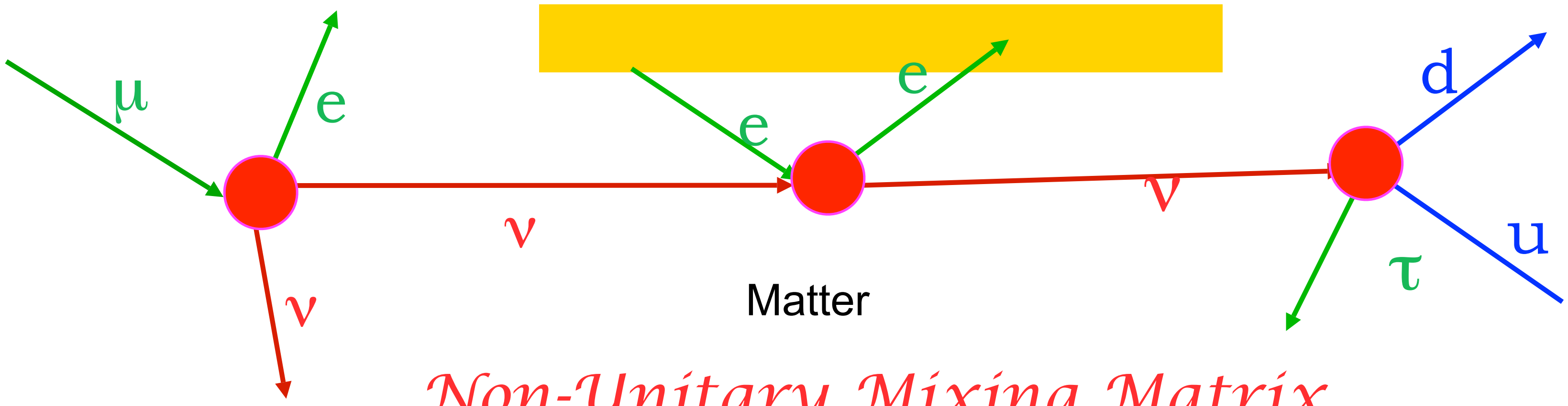

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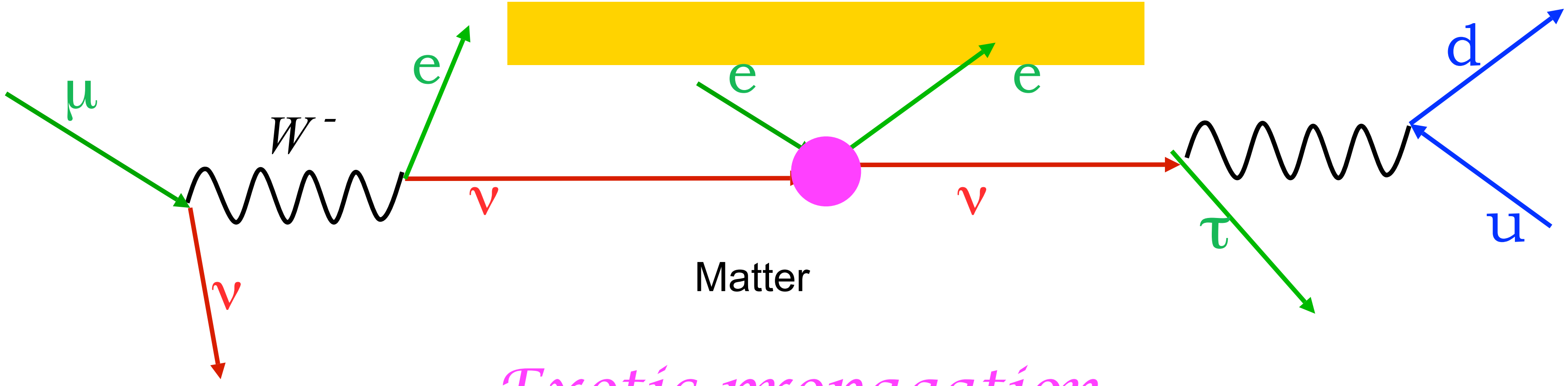
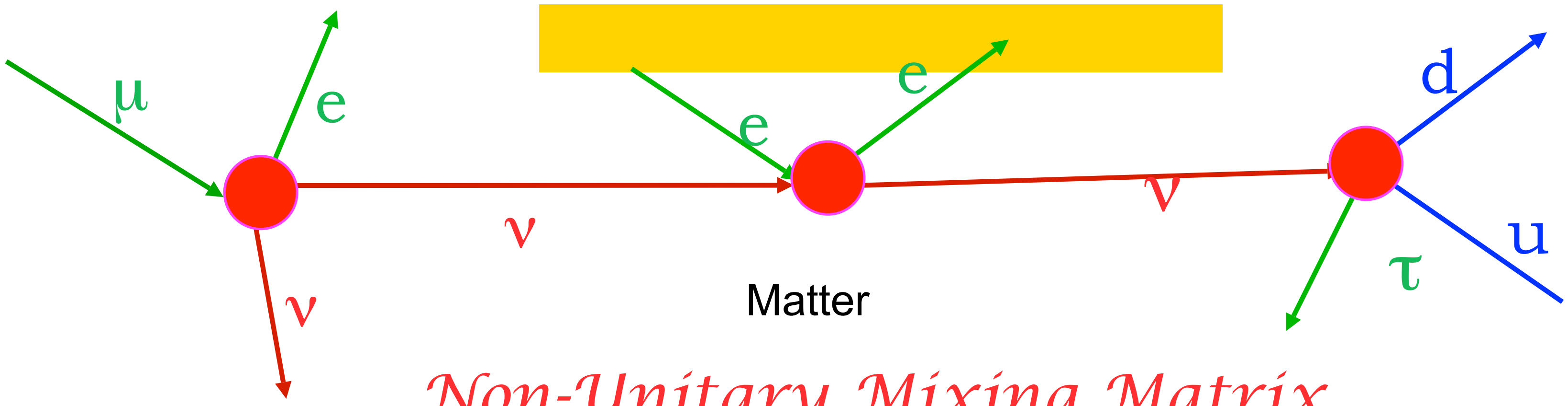
…affecting simultneously *production, propagation and detection.*



Exotic propagation

YES! These effects ARE non-standard neutrino interactions…



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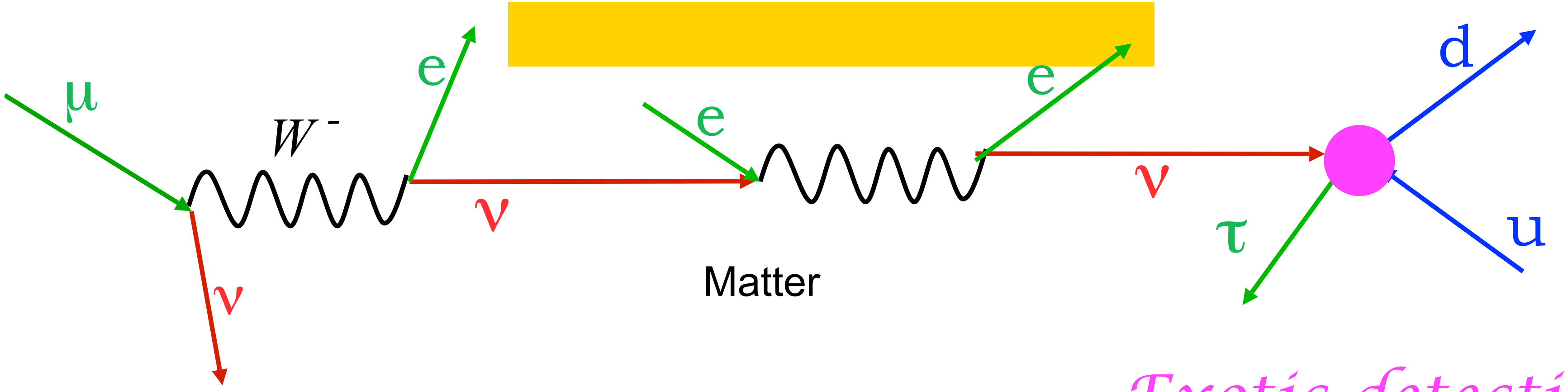

Exotic detection

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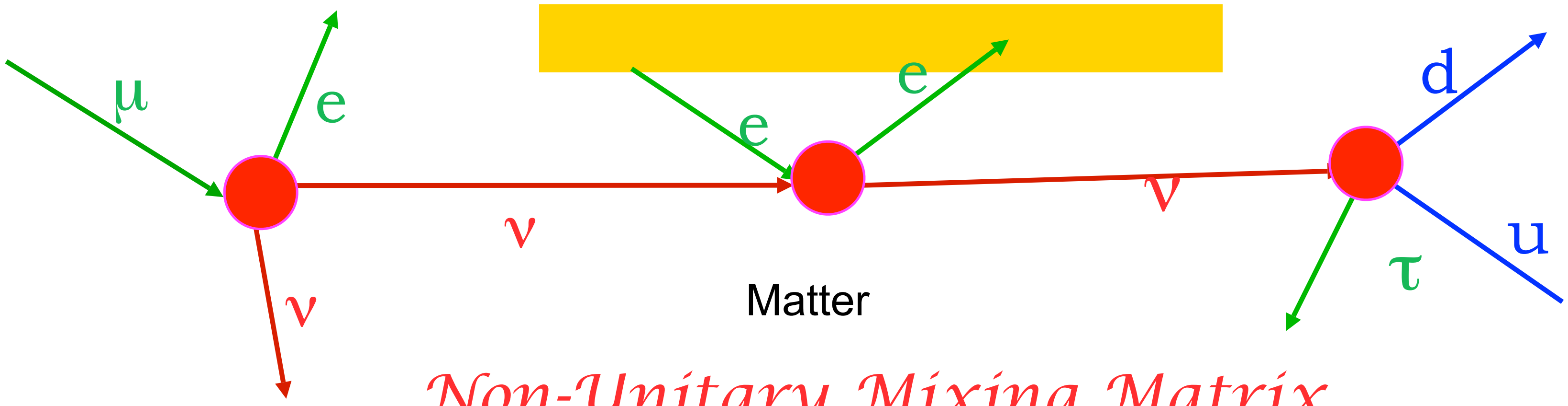


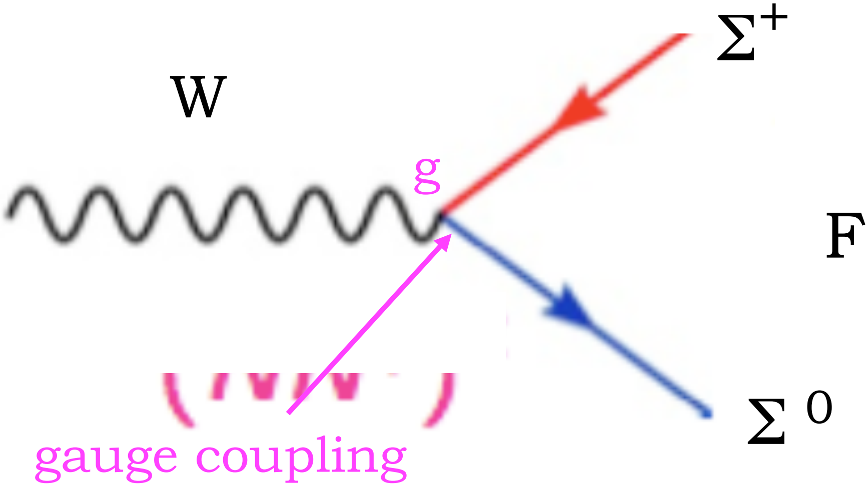
Non-Unitary Mixing Matrix

…affecting simultneously *production, propagation and detection.*

These NSI are a generic signature
of fermionic Seesaws

Fermion-triplet seesaws:

similar - although richer! - analysis



(Abada et al. 07))

For $M \approx TeV \rightarrow |Y| < 10^{-2}$

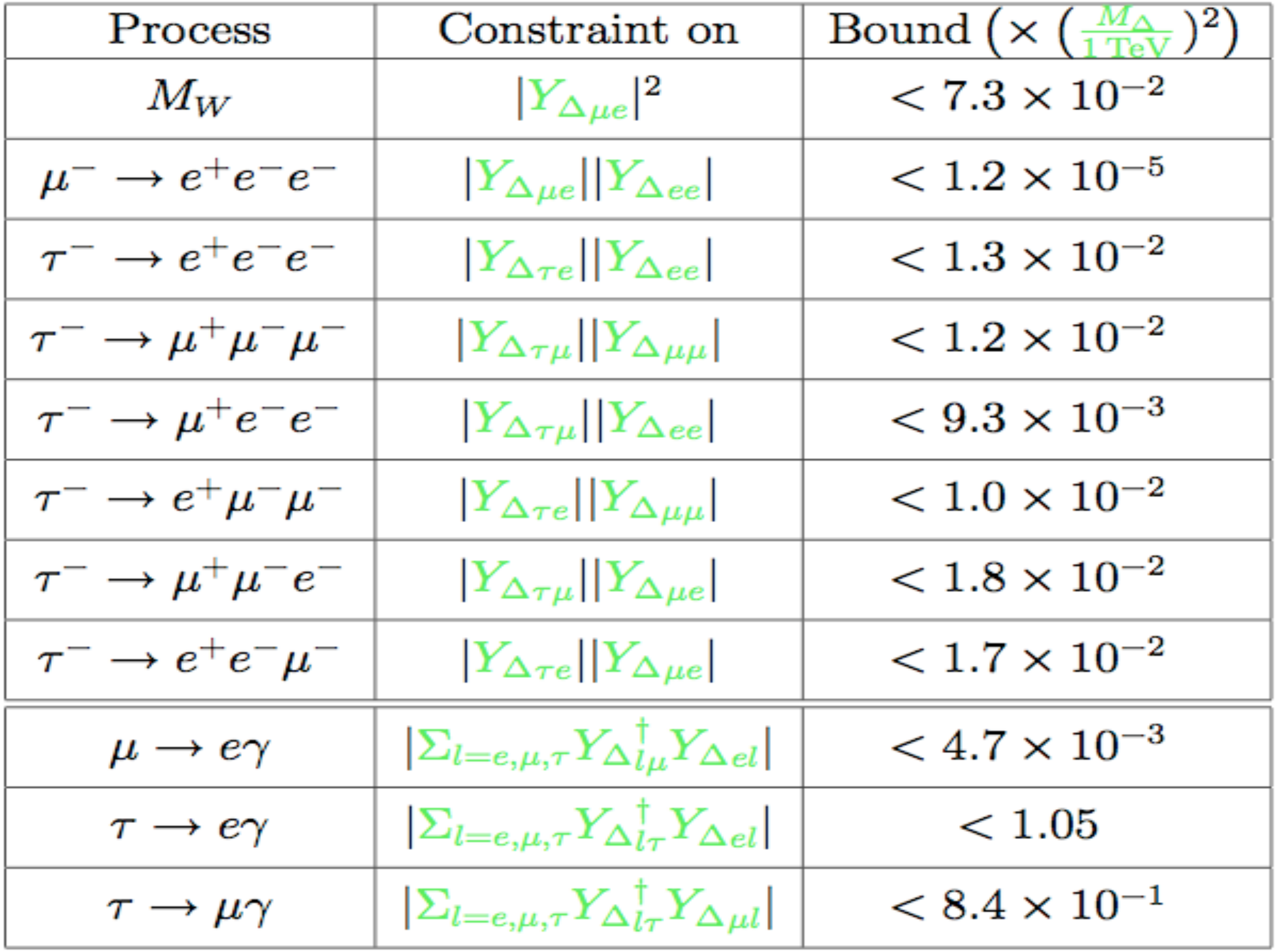
➡ For the Triplet-fermion Seesaws (type III):

$$(NN^{+}-1)_{\alpha\beta} = \frac{v^2}{2}\,|c^{d=6}|_{\alpha\beta} = \frac{v^2}{2}\,|Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger}\frac{1}{M_\Sigma} Y_\Sigma|_{\alpha\beta} \lesssim \begin{pmatrix} 3\cdot 10^{-3} & < 1.1\cdot 10^{-6} & < 1.2\cdot 10^{-3} \\ < 1.1\cdot 10^{-6} & 4\cdot 10^{-3} & < 1.2\cdot 10^{-3} \\ < 1.2\cdot 10^{-3} & < 1.2\cdot 10^{-3} & 4\cdot 10^{-3} \end{pmatrix}$$

(Abada et al 07)

Scalar triplet seesaw

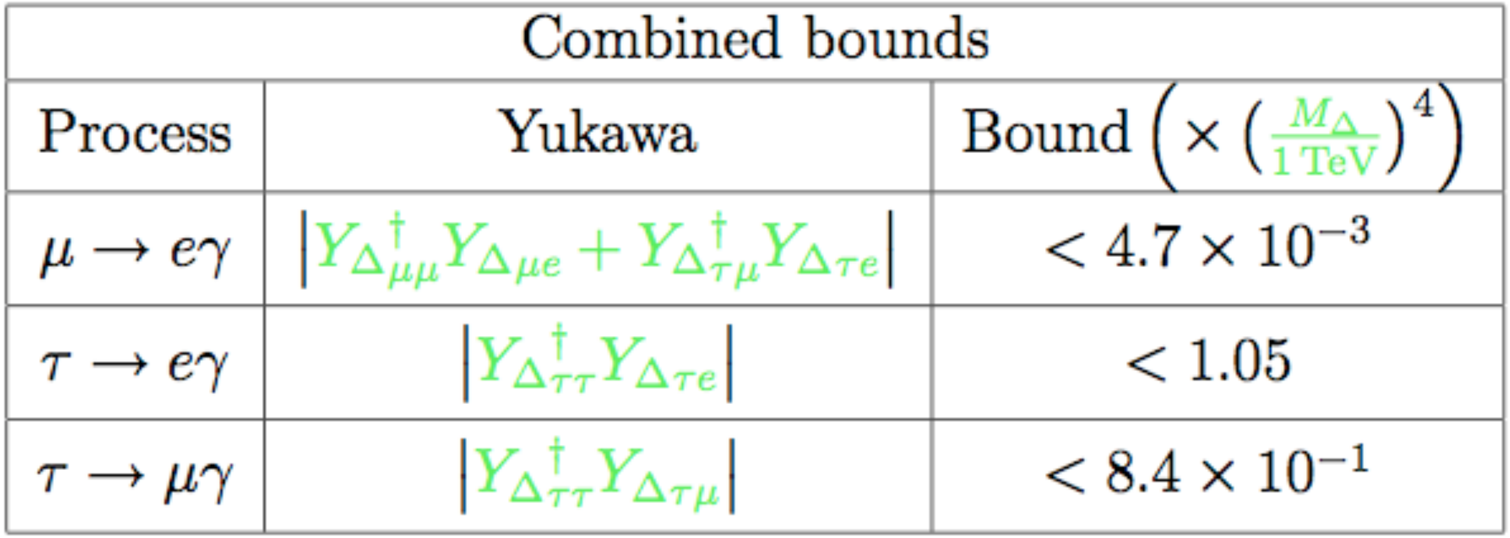
Bounds on $c^{d=6}$



Process	Constraint on	Bound $(\times (\frac{M_\Delta}{1\,\mathrm{TeV}})^2)$
M_W	$\lvert Y_{\Delta \mu e} \rvert^2$	$< 7.3 \times 10^{-2}$
$\mu^- \to e^+ e^- e^-$	$\lvert Y_{\Delta \mu e} \rvert \lvert Y_{\Delta ee} \rvert$	$< 1.2 \times 10^{-5}$
$\tau^- \to e^+ e^- e^-$	$\lvert Y_{\Delta \tau e} \rvert \lvert Y_{\Delta ee} \rvert$	$< 1.3 \times 10^{-2}$
$\tau^- \to \mu^+ \mu^- \mu^-$	$\lvert Y_{\Delta \tau \mu} \rvert \lvert Y_{\Delta \mu\mu} \rvert$	$< 1.2 \times 10^{-2}$
$\tau^- \to \mu^+ e^- e^-$	$\lvert Y_{\Delta \tau \mu} \rvert \lvert Y_{\Delta ee} \rvert$	$< 9.3 \times 10^{-3}$
$\tau^- \to e^+ \mu^- \mu^-$	$\lvert Y_{\Delta \tau e} \rvert \lvert Y_{\Delta \mu\mu} \rvert$	$< 1.0 \times 10^{-2}$
$\tau^- \to \mu^+ \mu^- e^-$	$\lvert Y_{\Delta \tau \mu} \rvert \lvert Y_{\Delta \mu e} \rvert$	$< 1.8 \times 10^{-2}$
$\tau^- \to e^+ e^- \mu^-$	$\lvert Y_{\Delta \tau e} \rvert \lvert Y_{\Delta \mu e} \rvert$	$< 1.7 \times 10^{-2}$
$\mu \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\mu} Y_{\Delta el} \rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta el} \rvert$	< 1.05
$\tau \to \mu\gamma$	$\lvert \Sigma_{l=e,\mu,\tau} Y_{\Delta}{}^{\dagger}_{l\tau} Y_{\Delta \mu l} \rvert$	$< 8.4 \times 10^{-1}$

Scalar triplet seesaw

Combined bounds on $c^{d=6}$



Combined bounds		
Process	Yukawa	Bound $\left(\times\left(\frac{M_\Delta}{1\,\mathrm{TeV}}\right)^4\right)$
$\mu \to e\gamma$	$\left\lvert Y_{\Delta}{}^{\dagger}_{\mu\mu} Y_{\Delta\,\mu e} + Y_{\Delta}{}^{\dagger}_{\tau\mu} Y_{\Delta\,\tau e}\right\rvert$	$< 4.7 \times 10^{-3}$
$\tau \to e\gamma$	$\left\lvert Y_{\Delta}{}^{\dagger}_{\tau\tau} Y_{\Delta\,\tau e}\right\rvert$	< 1.05
$\tau \to \mu\gamma$	$\left\lvert Y_{\Delta}{}^{\dagger}_{\tau\tau} Y_{\Delta\,\tau\mu}\right\rvert$	$< 8.4 \times 10^{-1}$

Obervable non-standard interactions from

$\boxed{Y_\Delta^{+} Y_\Delta / M^2 \; (\bar{L}_\alpha L_\beta) \; (\bar{L}_\gamma L_\delta)}$ in scalar triplet seesaw ???

Barely so ! (Malisnky Ohlsson and Zhang 08):

--- Require Yukawa couplings are almost diagonal--> *degenerate neutrino spectrum*

--- Not excluded are

$\mu^- \text{-->} e^- \nu_e \bar{\nu}_\mu \ldots$ *Wrong sign muons at near detector*

No ν **masses** in the SM

because the SM *accidentally* preserves B-L

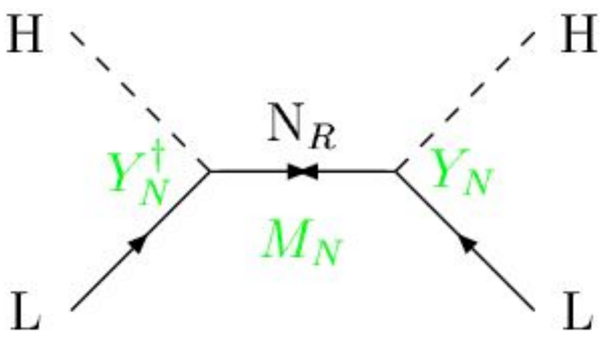
i.e. Adding singlet neutrino fields N_R

- right-handed N_R → $Y_N \tilde{H} \bar{L} N_R + h.c.$ ® $m_D \bar{\nu}_L N_R + h.c.$

Would require $Y_N \sim 10^{-12}$!!! Why ν_s are so light???

Why N_R does not acquire large Majorana mass? $\delta \mathcal{L} \sim M\ (N_R N_R)$

OK with gauge invariance



Seesaw model

Which allows $Y_N \sim 1$ --> $M \sim M_{Gut}$

N elements from oscillations & decays

MUV

without unitarity

OSCILLATIONS

+DECAYS

$$|N| = \begin{pmatrix} .75 - .89 & .45 - .65 & <.20 \\ .19 - .55 & .42 - .74 & .57 - .82 \\ .13 - .56 & .36 - .75 & .54 - .82 \end{pmatrix}$$

Antusch, Biggio, Fernández-Martínez,
López-Pavón, M.B.G. 06

3σ

with unitarity

OSCILLATIONS

$$U| = \begin{pmatrix} .79 - .88 & .47 - .61 & < .20 \,| \\ .19 - .52 & .42 - .73 & .58 - .82 \\ .20 - .53 & .44 - .74 & .56 - .81 \end{pmatrix}$$

M. C. Gonzalez Garcia hep-ph/0410030