Prague v13, May 24 2013

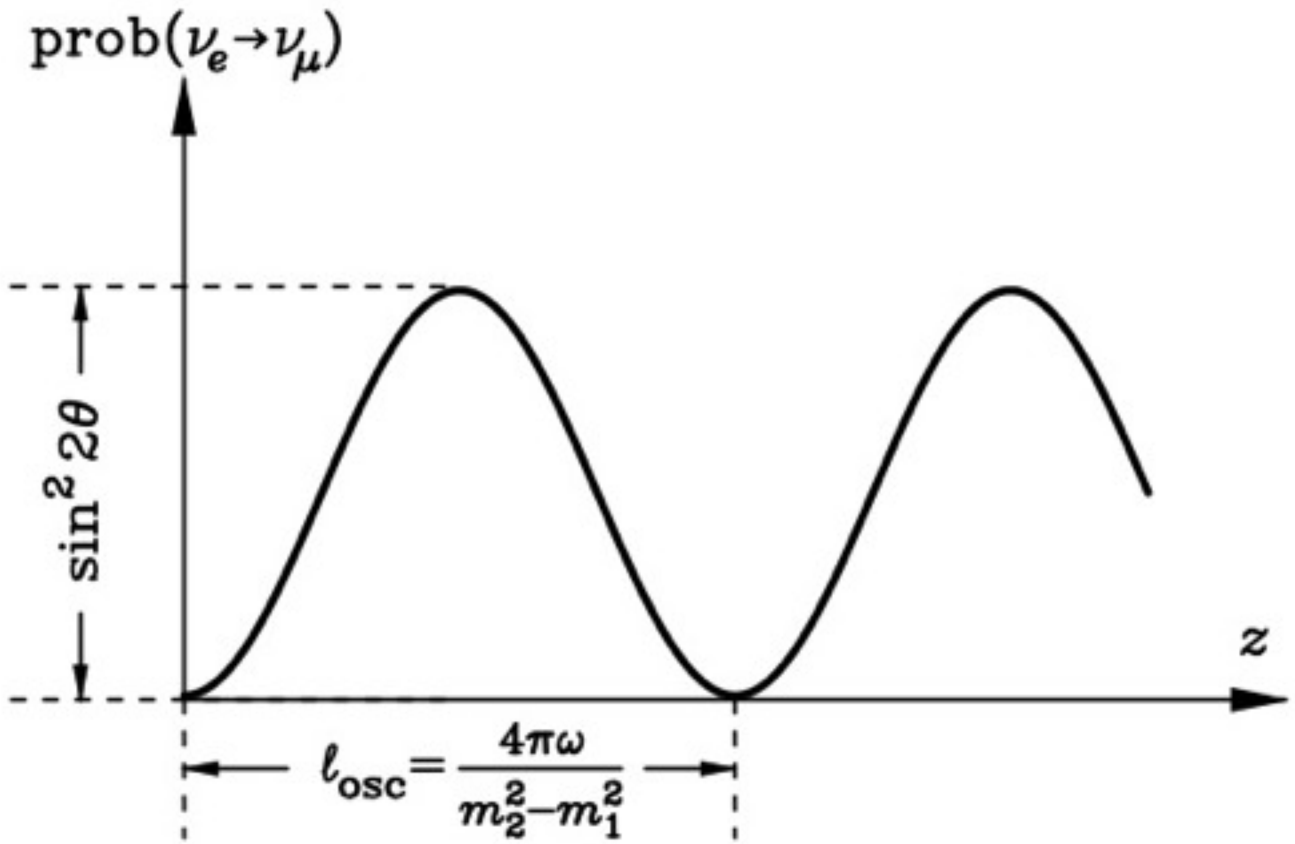
Neutrinos and L (and B) violation

Michal Malinský

IPNP, Charles University in Prague

The classical neutrino oscillations' ingredients

Flavour mixing



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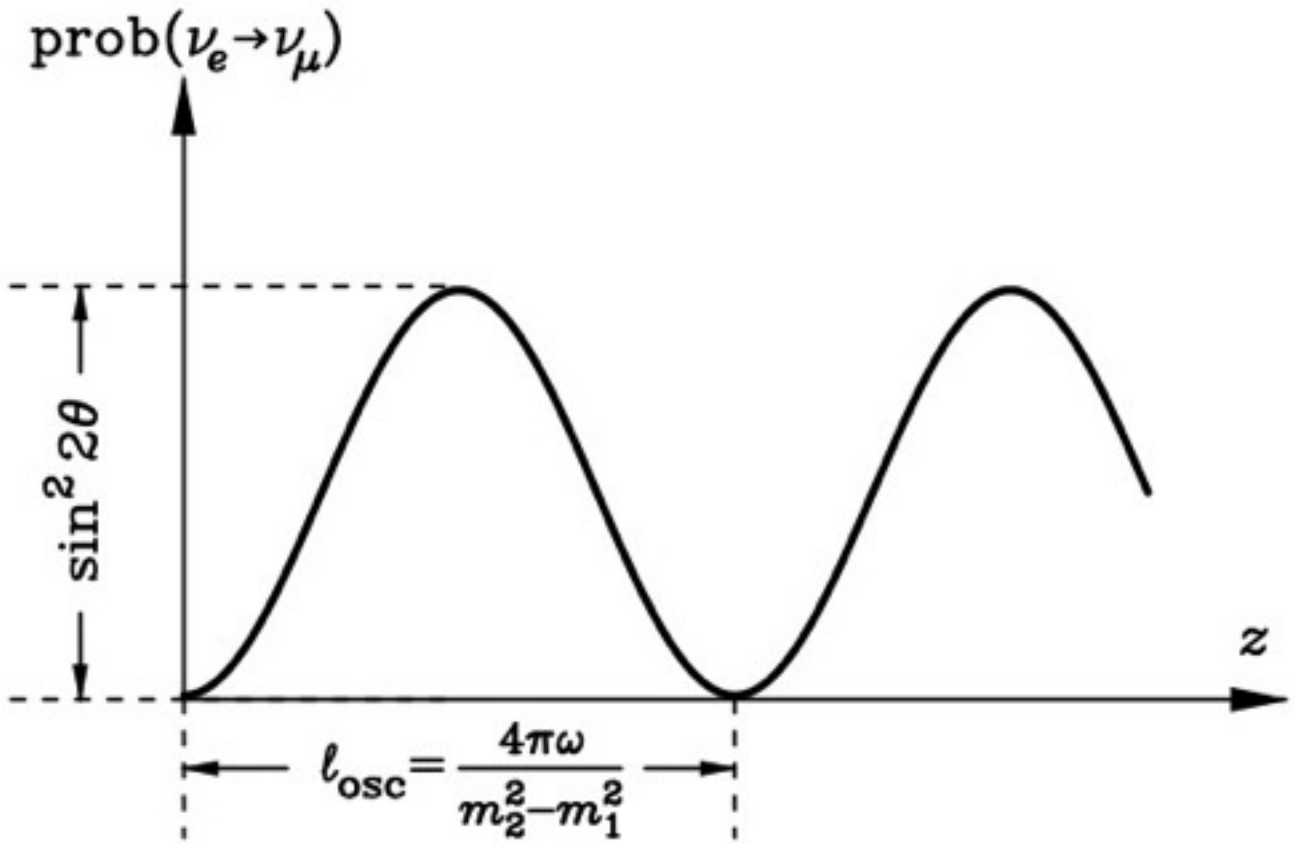

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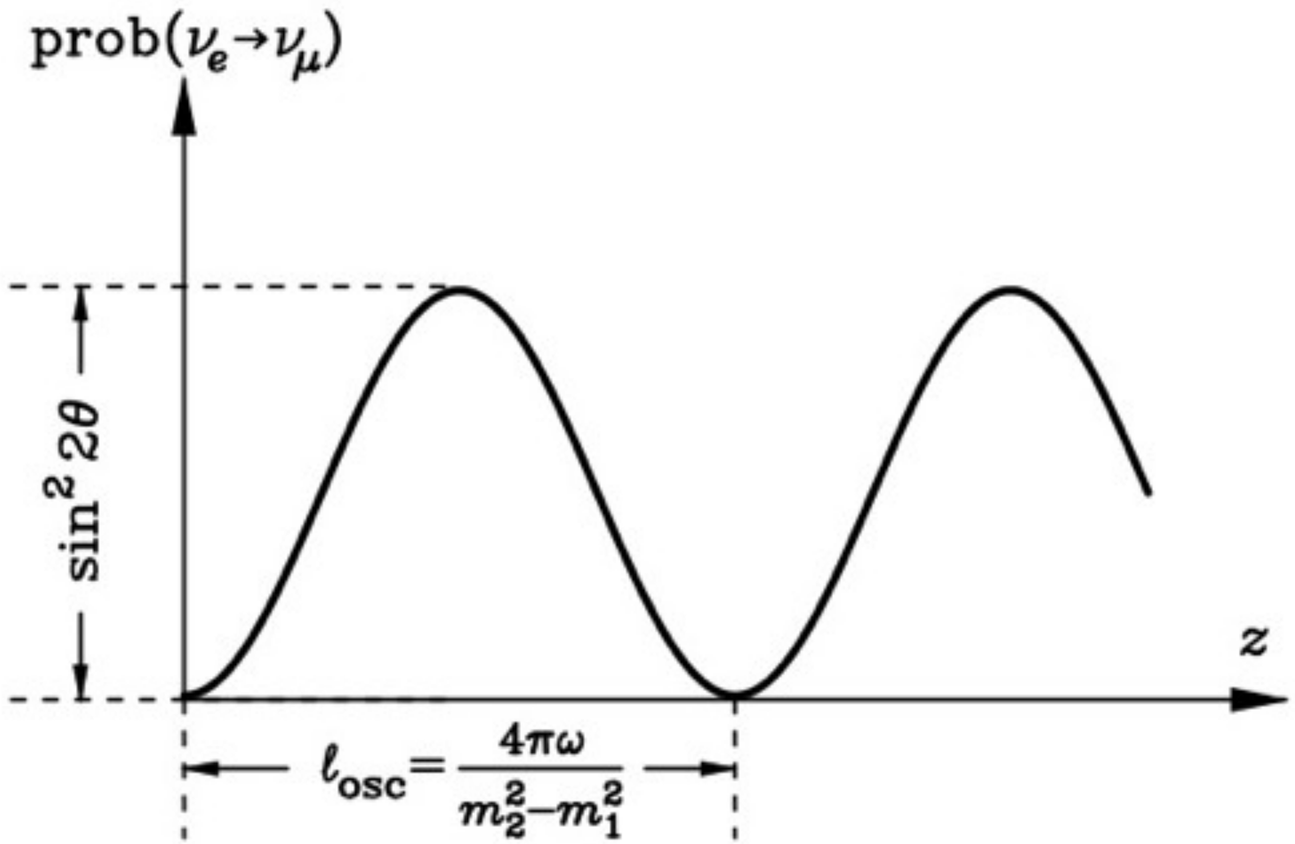

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Neutrino masses

- need for an oscillatory pattern
- very tiny compared to the other SM masses
- tiny Yukawas kosher but rather boring...

The seesaw origin of small neutrino masses(?)

Weinberg's d=5 operator $$\mathcal{L} \ni \frac{LLHH}{\Lambda}$$

S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979)

Seesaw: smallness related to the large scale in the denominator

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BTW: good to have the "complete Higgs doublet" :-)

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Expected at some point: it's even in the SM (non-perturbatively)...

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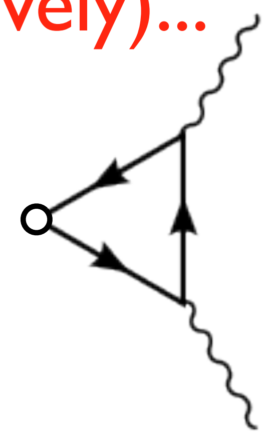

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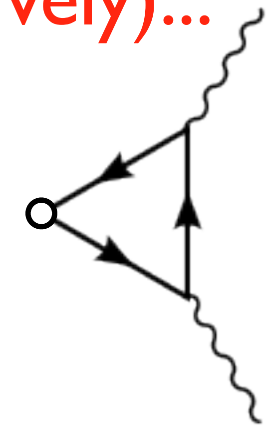

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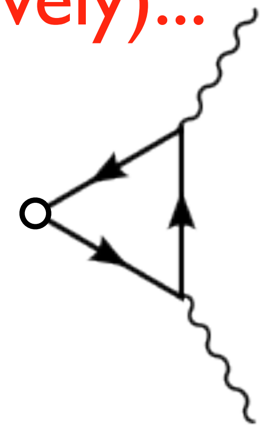

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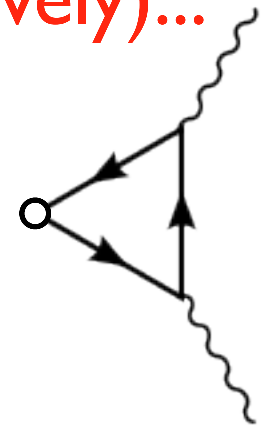

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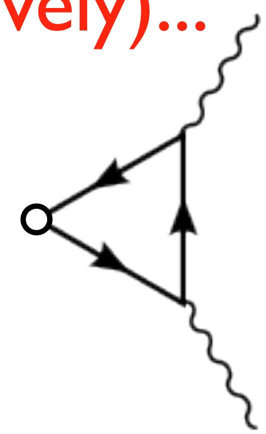

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$${}^3He \to e^+ \mu^+ \overline{\nu}_\tau \qquad \mathcal{A} \sim e^{-2\pi/\alpha_w} \sim 10^{-80}$$

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- with RH neutrinos charge quantization lost unless Majorana

Babu, Mohapatra, Phys.Rev. D41 (1990) 271

Foot, Lew, Volkas 1993

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Perturbative + nonperturbative LNV very handy for baryogenesis

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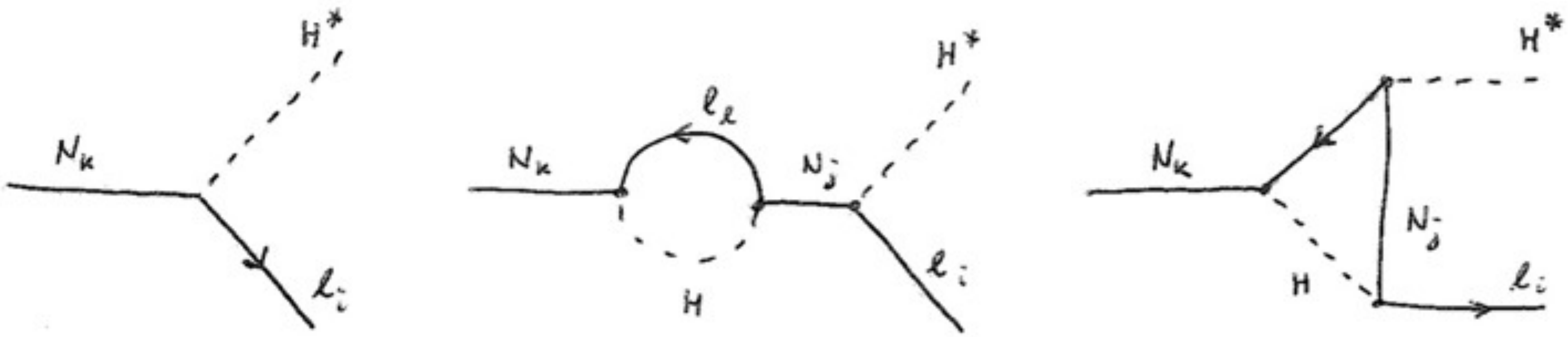
Generating net L:

CP asymmetry: $$\epsilon_1 = \frac{\sum_\alpha [\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})]}{\sum_\alpha [\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})]}$$



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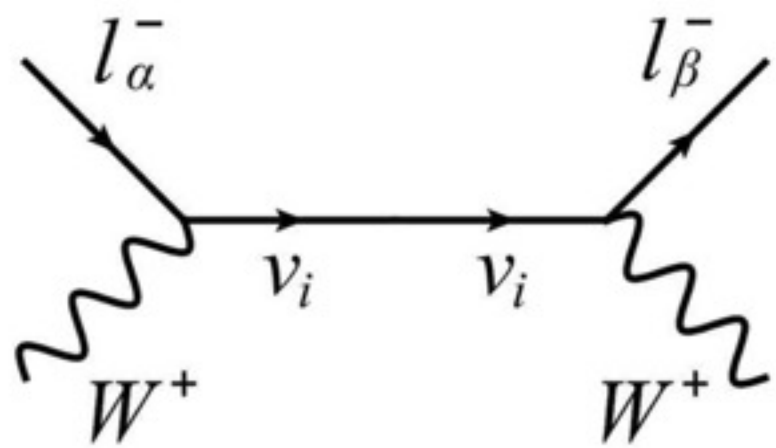

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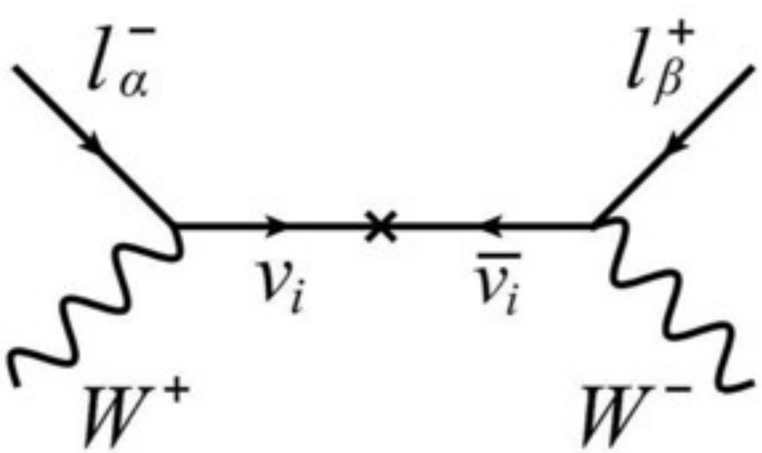

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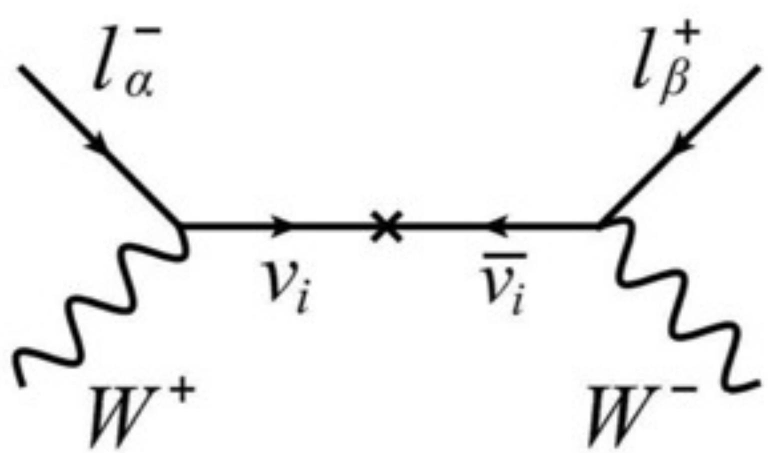

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Nowadays mostly academic...

see e.g. Z-z. Xing, arXiv:1301.7654v2

How to test lepton number violation?

How to test Majorana / seesaw nature of neutrino masses?

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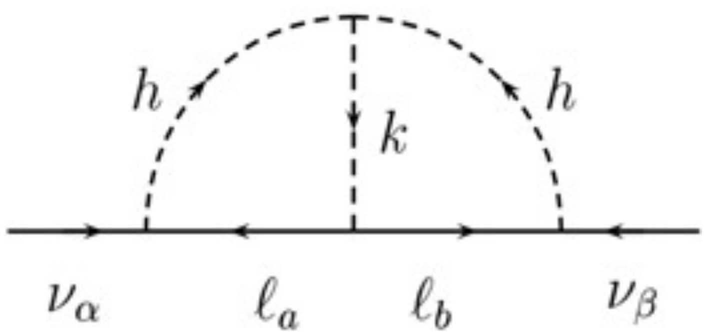

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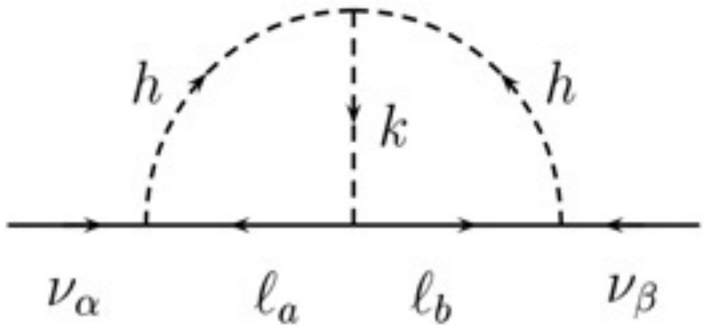

- R-parity violation in SUSY
- ...

A. Zee, Nucl. Phys. B 264 (1986) 99

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Neutrinoless double beta decay?

Colliders?

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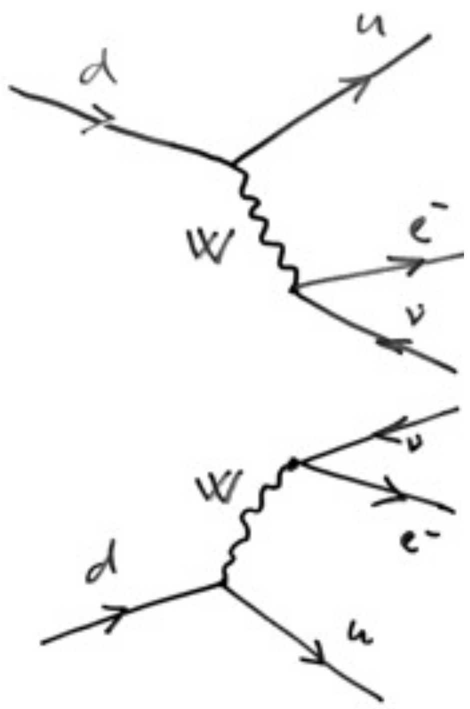

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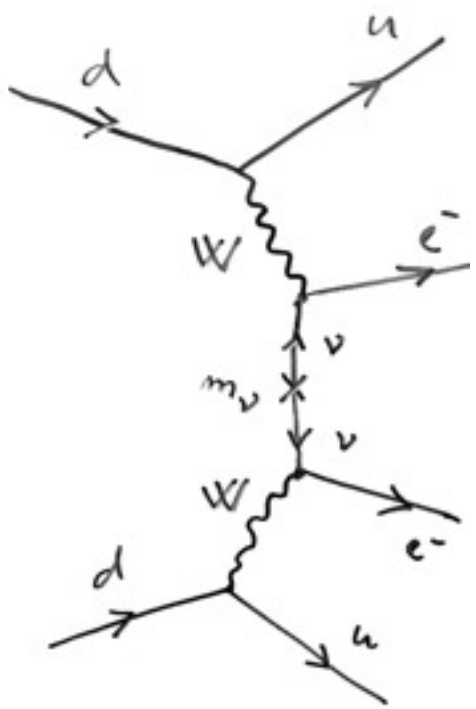

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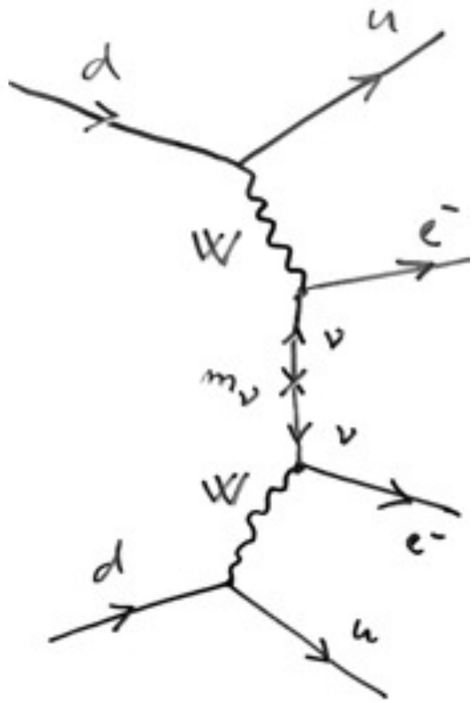

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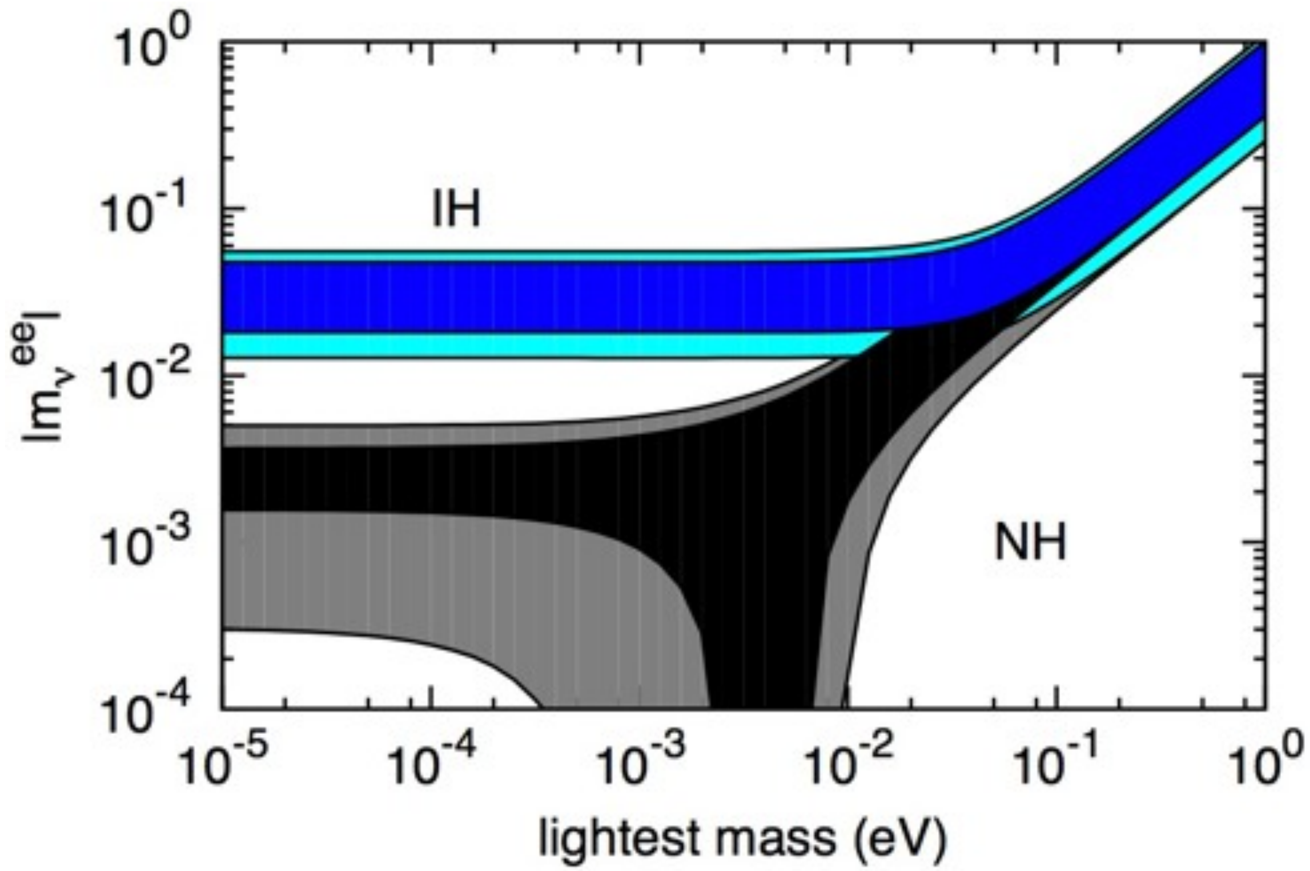

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Figures from Chakrabortty et al., 2012

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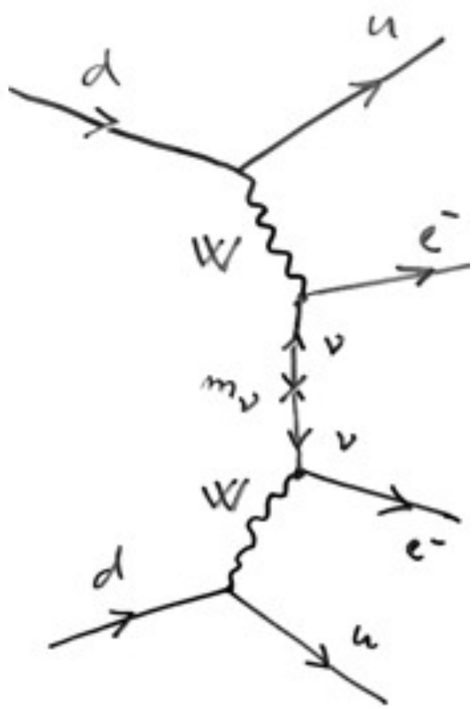

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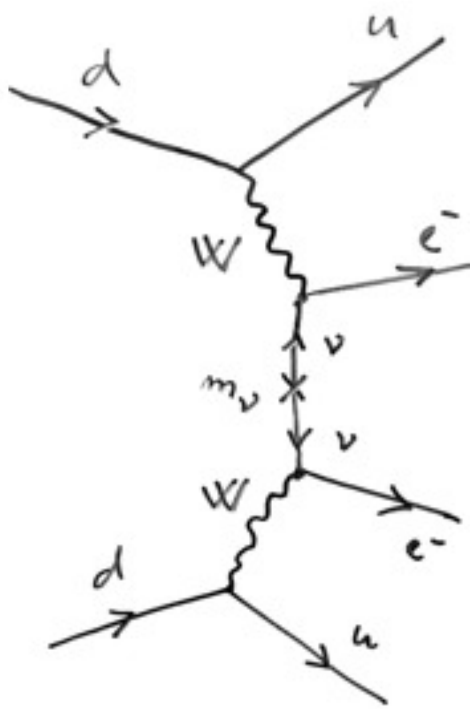

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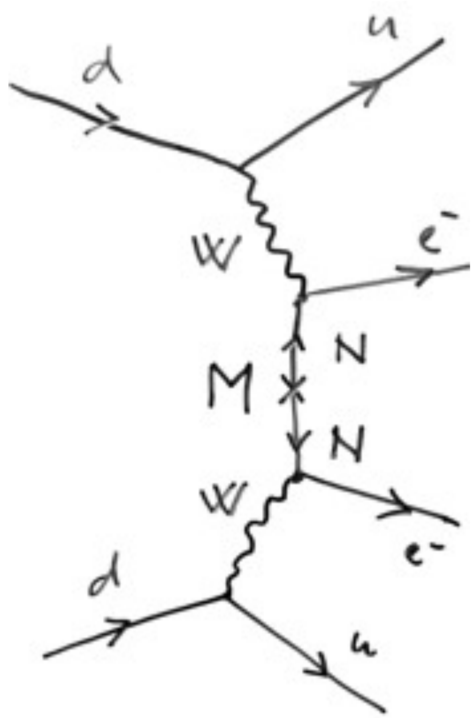

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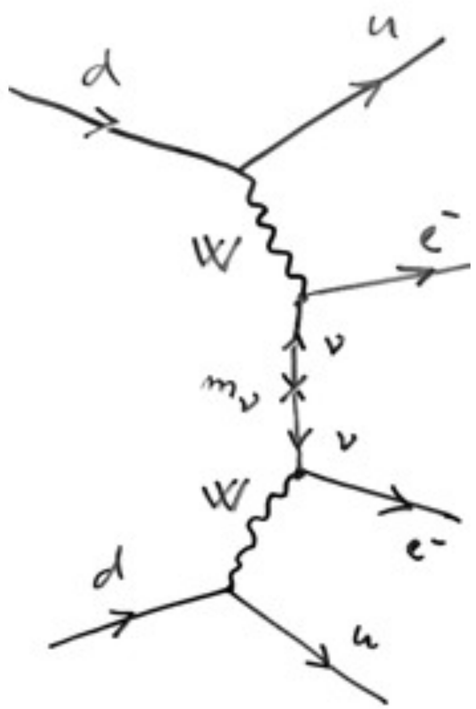

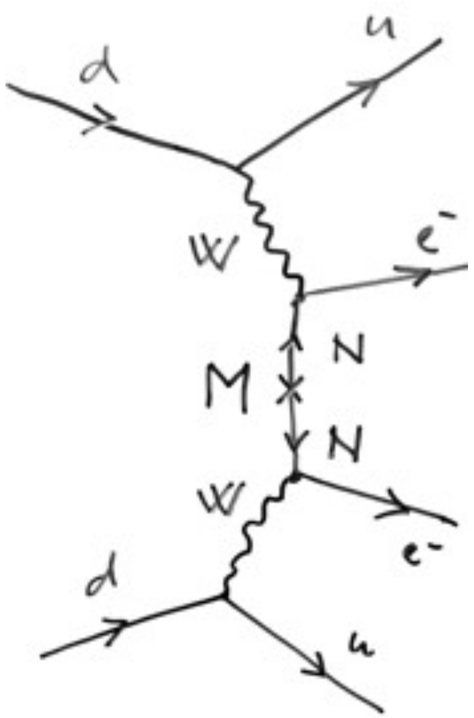

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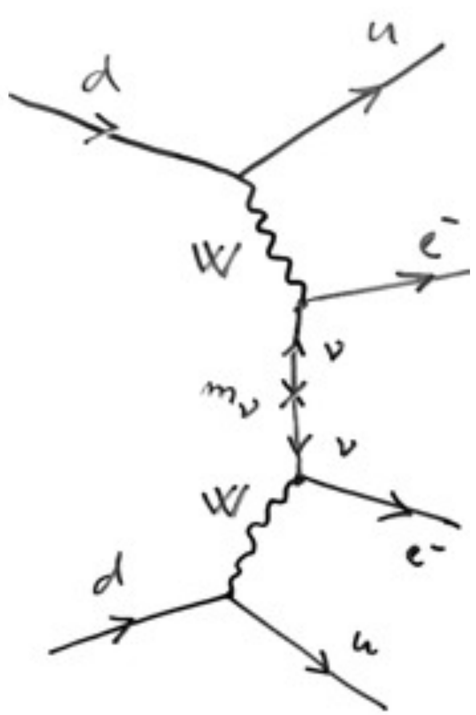

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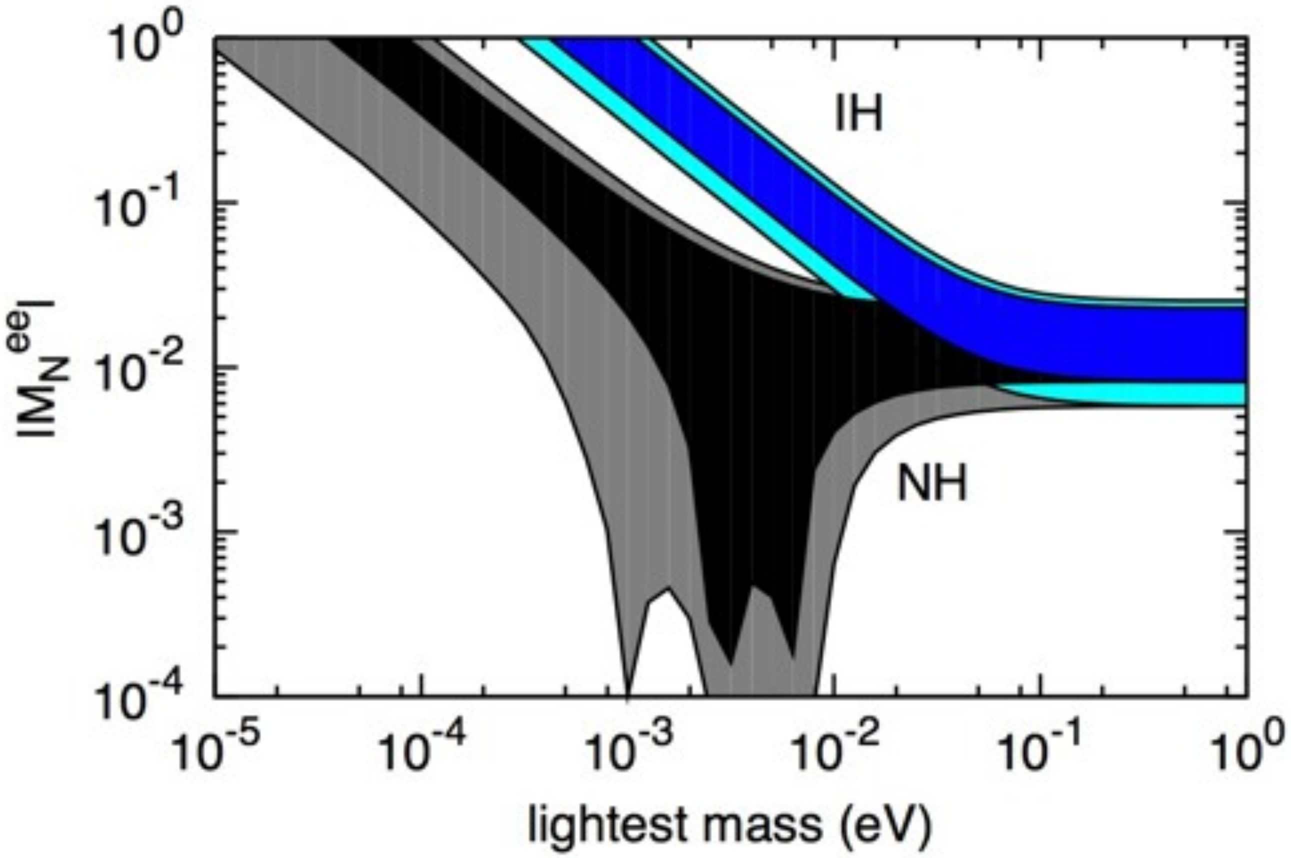

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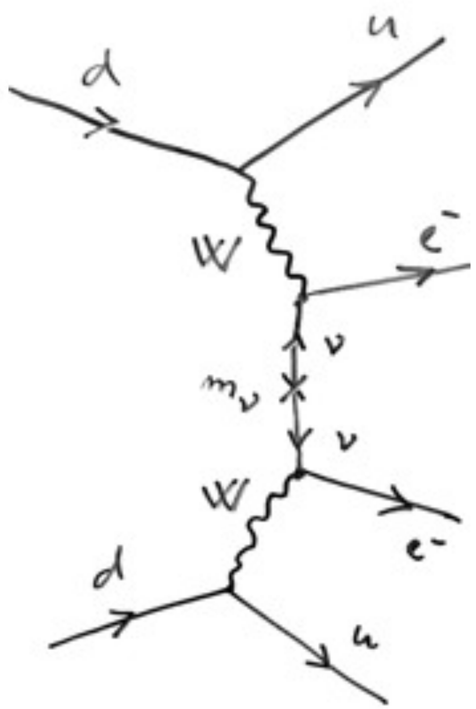

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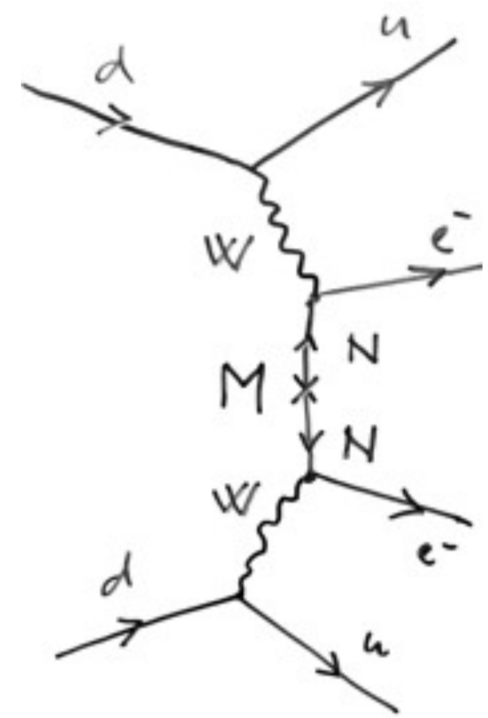

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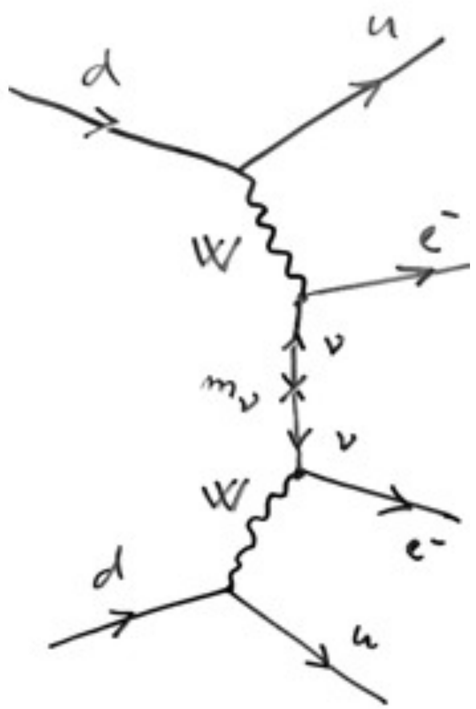

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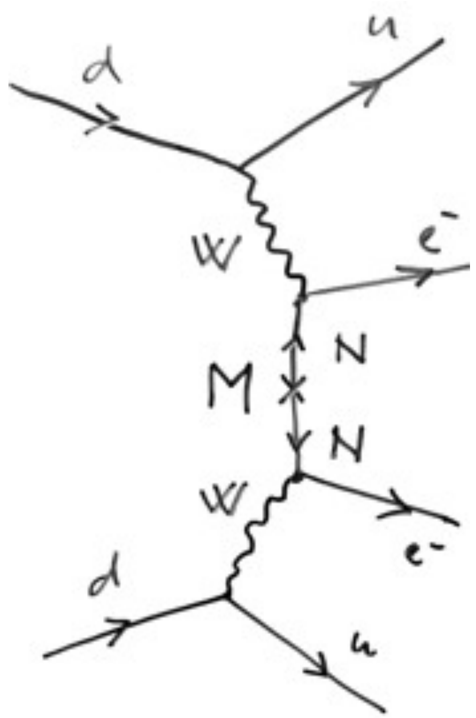

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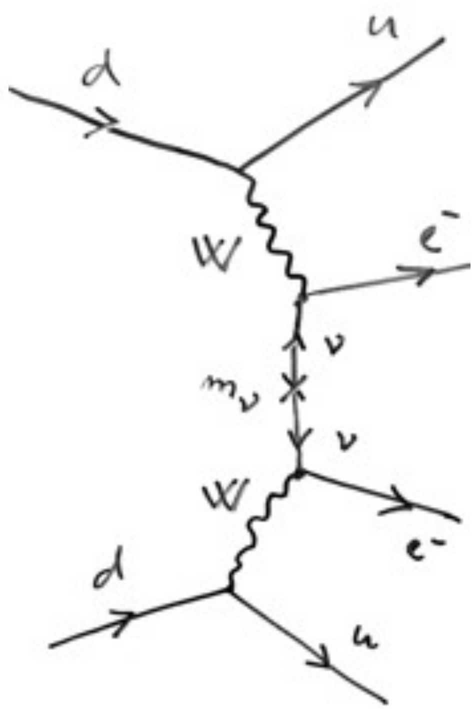
This may even dominate if M is in the TeV region or if there are RH currents around TeV

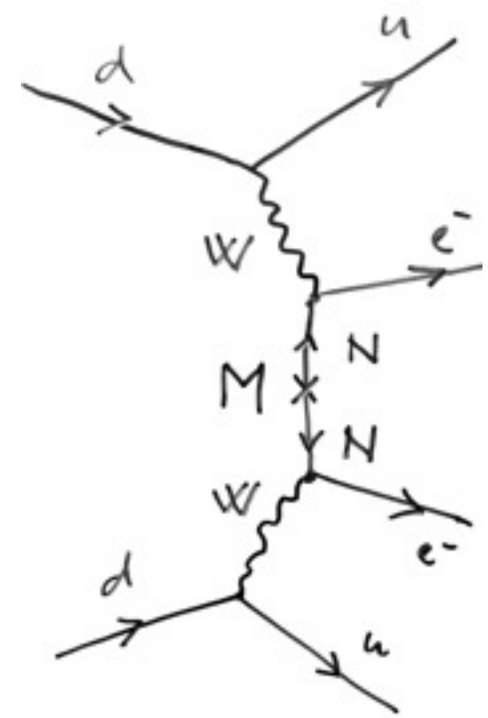
Neutrinoless double beta decay

Diagrammatics:



$$\mathcal{A} \propto g^4 \frac{\langle m \rangle}{q^2}$$

Heavy neutrinos also feel gauge interactions!



$$F = \sqrt{m_\nu M^{-1}}$$

$$\mathcal{A} \propto g^4 \sum_i F^2 \frac{\kappa}{M_i}$$

This may even dominate if M is in the TeV region or if there are RH currents around TeV

$$m_{W_R} \gtrsim 1.3 \left(\frac{\langle m_N \rangle}{[1\text{TeV}]} \right)^{-1/4} \text{TeV}$$

Neutrinoless double beta decay

But what if there is something else?

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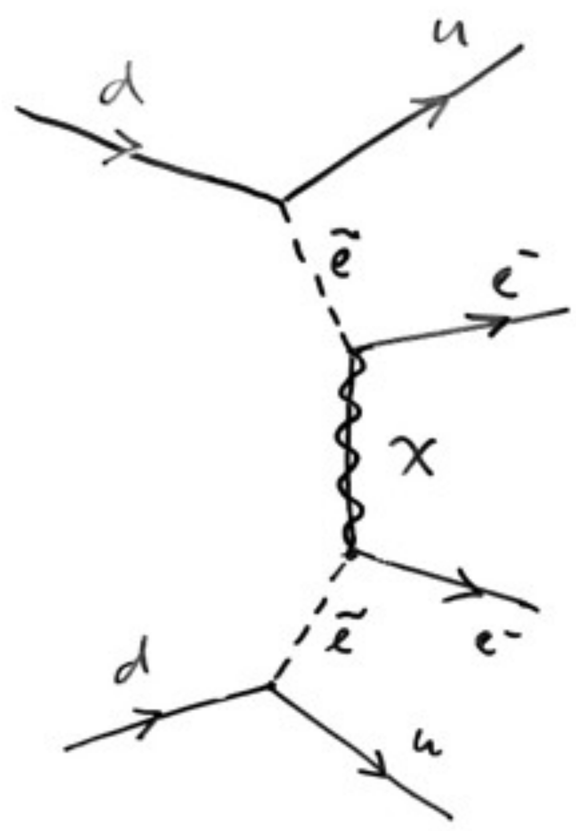

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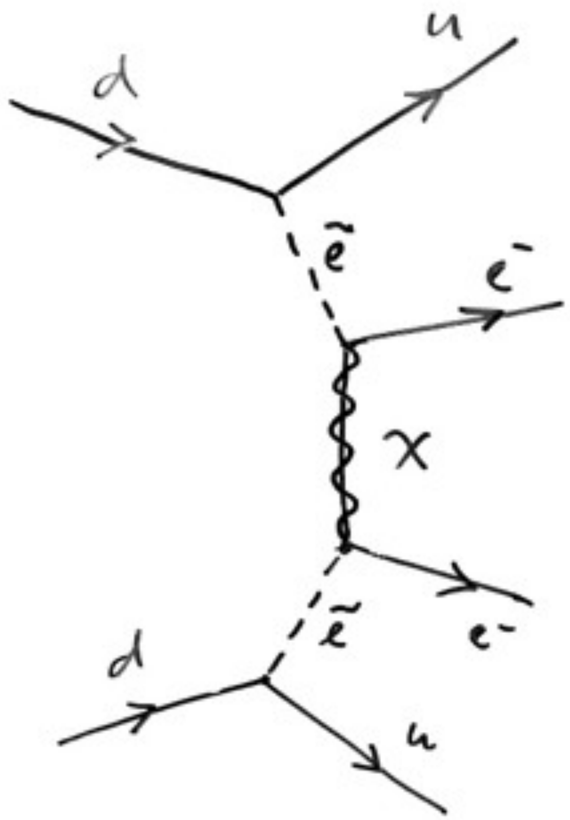
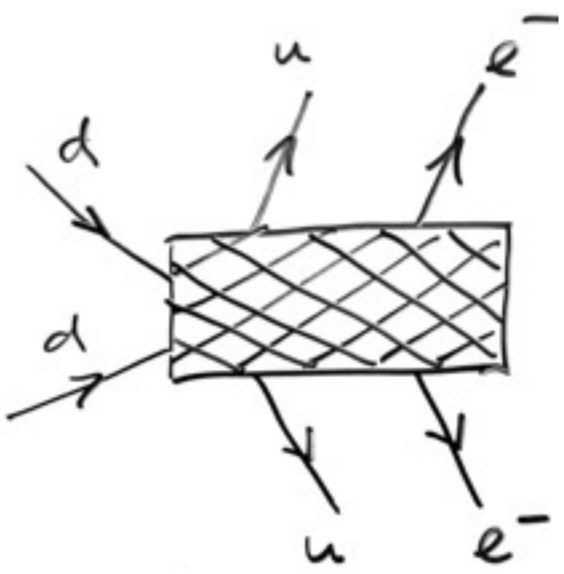


Schechter - Valle mechanism:



J. Schechter, J. F. W. Valle, PRD 1982
Takasugi, PLB 1984

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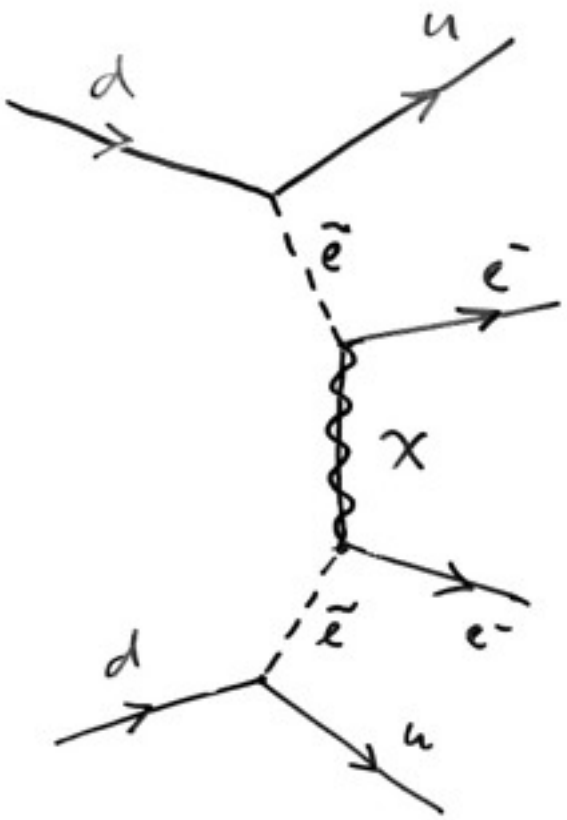

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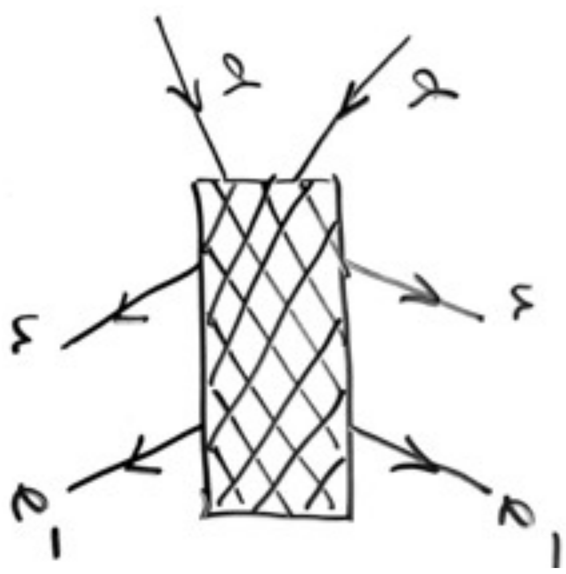

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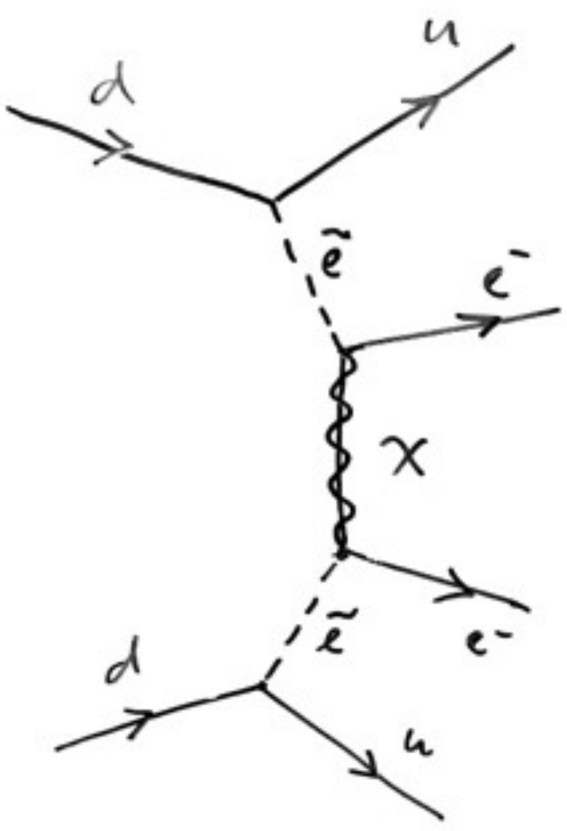

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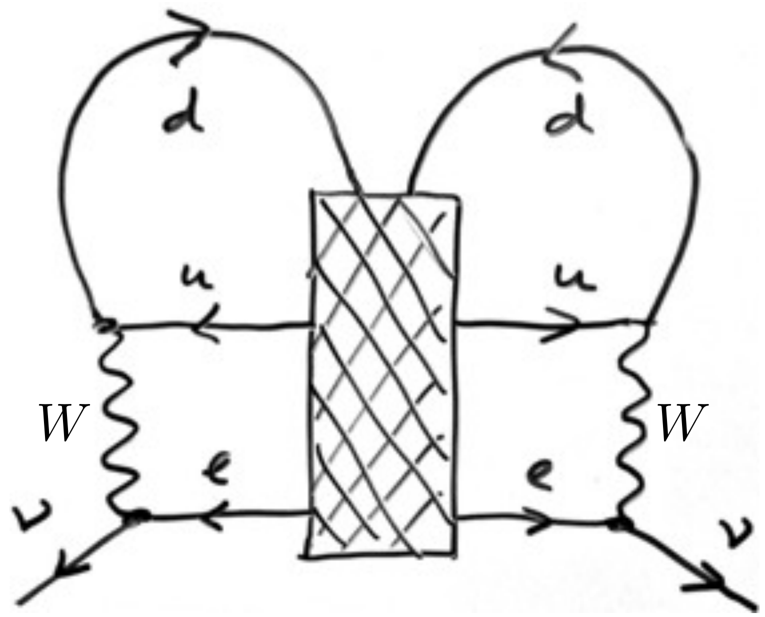

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If neutrinoless double beta decay is seen, neutrinos should be Majorana...

How to test Majorana / seesaw nature of neutrino masses?

Seesaw as a framework can be truly tested if and only if the underlying dynamics (i.e., a specific opening of the seesaw operator) or a specific and strong correlation in new physics signals can be revealed

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Colliders?

Lepton flavour violation?

Collider tests of the underlying dynamics?

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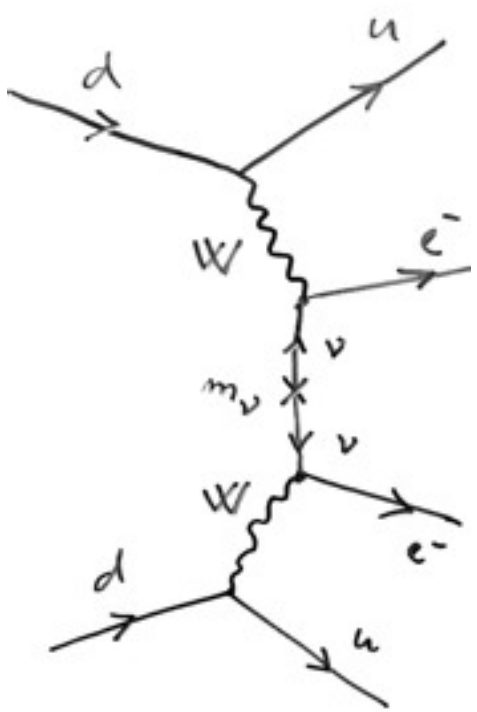

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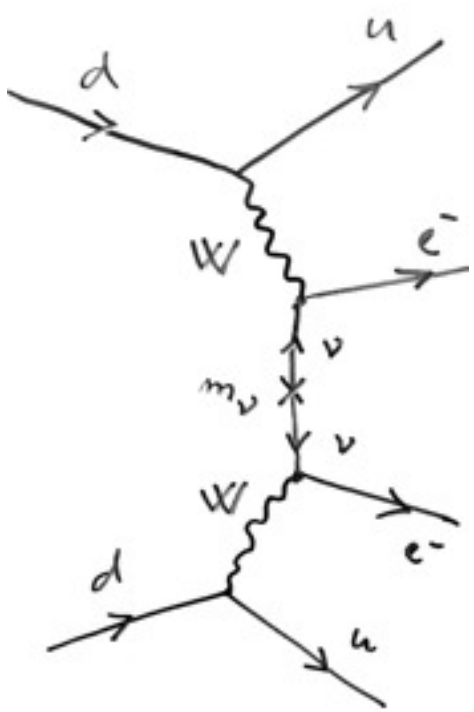

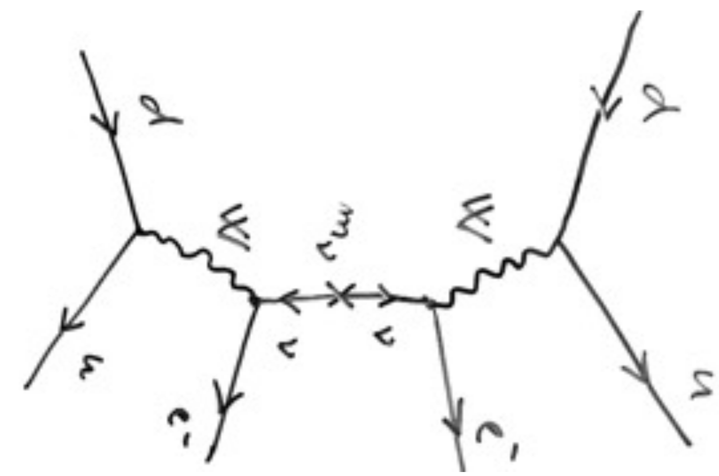

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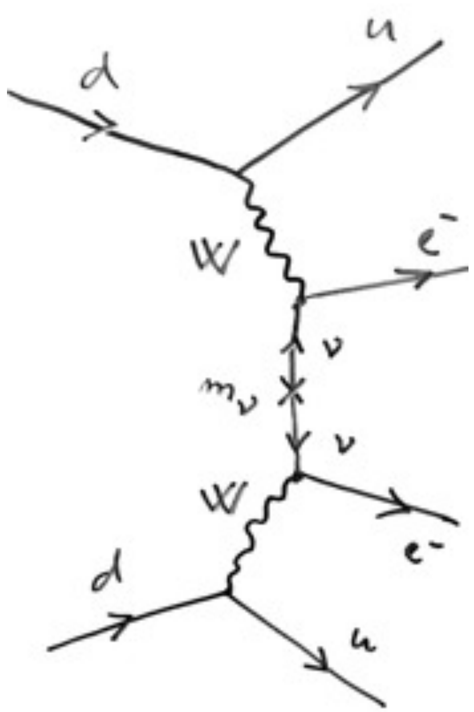

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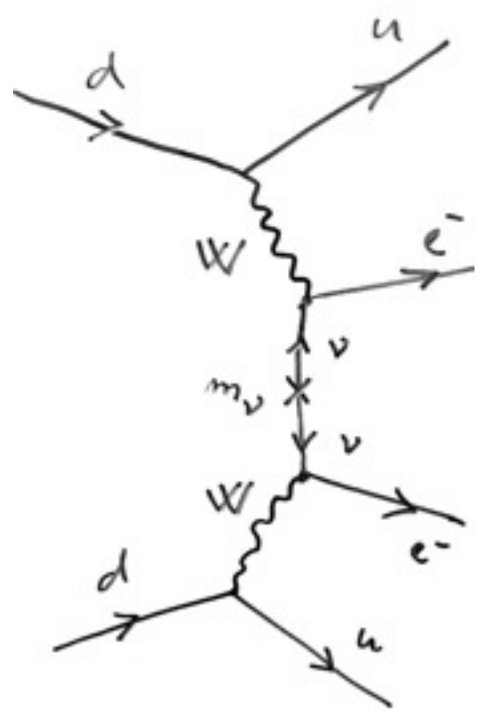

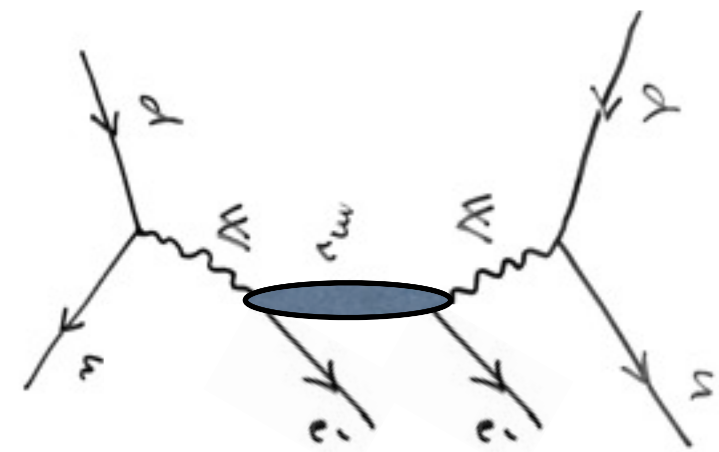

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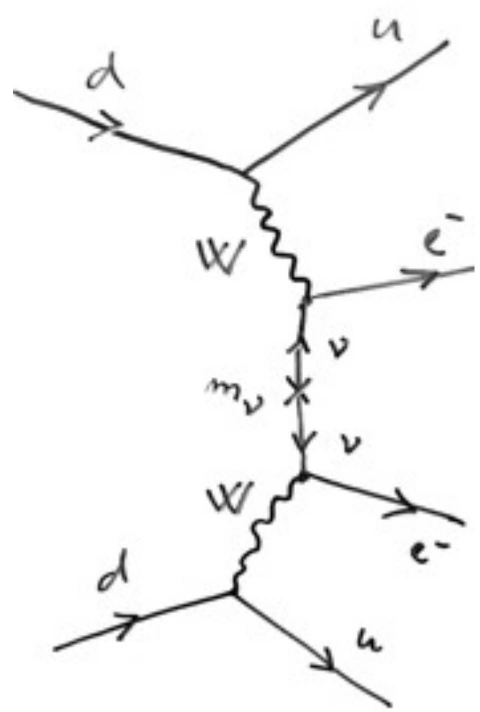

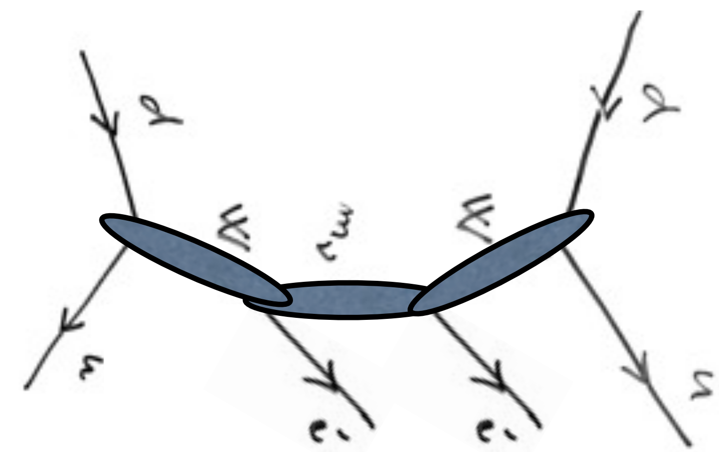

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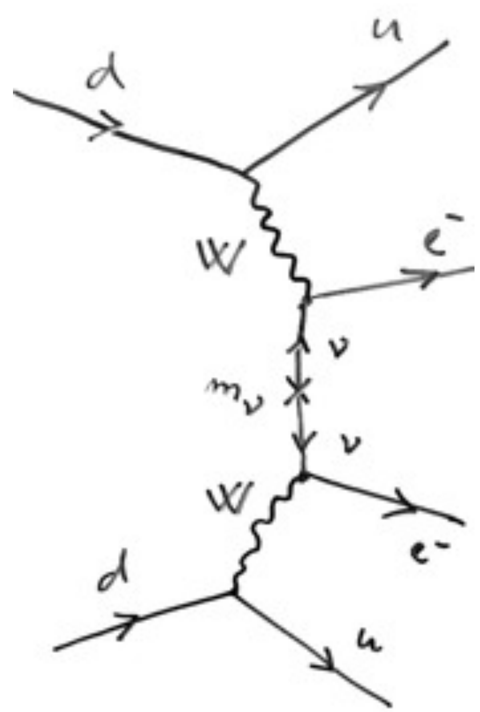

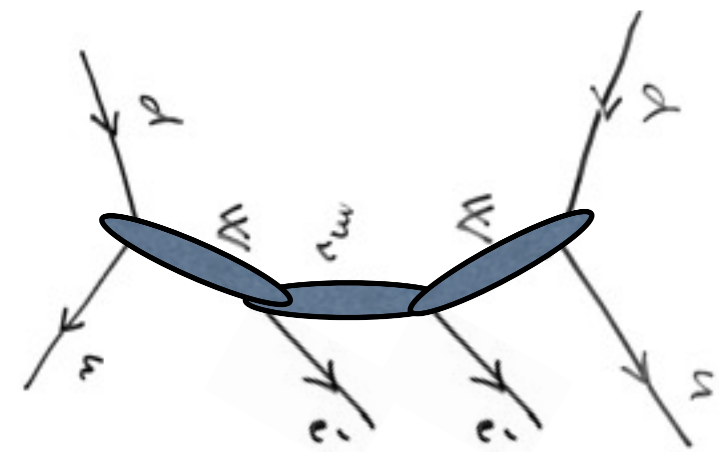

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etc.

The scale

$$\mathcal{L} \ni \frac{LLHH}{\Lambda}$$

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Lower bounds for light neutrino masses:

- Neutrino oscillations: $\Delta m^2_{\odot} = (8.0 \pm 0.3) \times 10^{-5}\mathrm{eV}^2$

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Upper bounds for light neutrino masses:

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Hopeless?

The mediators

Renormalizable "openings" of the Weinberg operator

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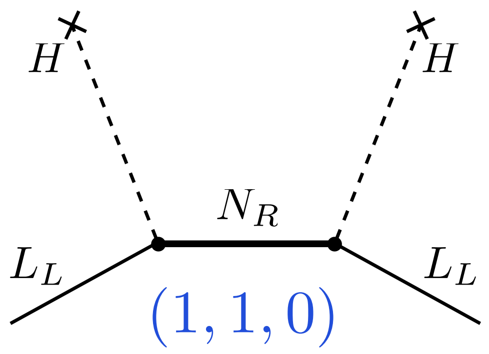
type-I seesaw



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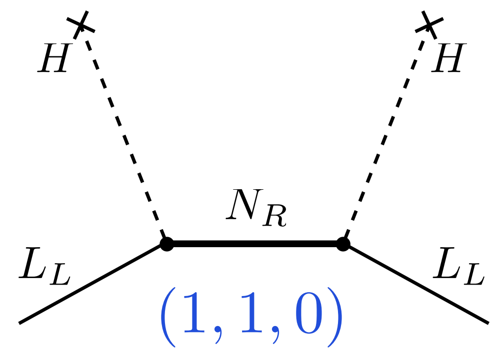

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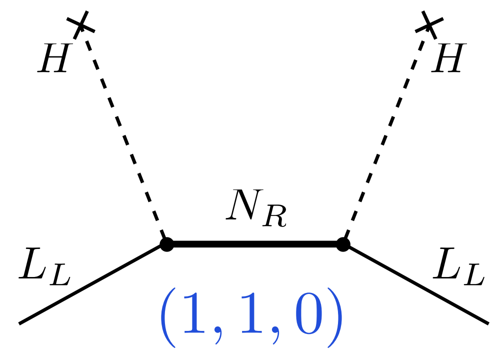

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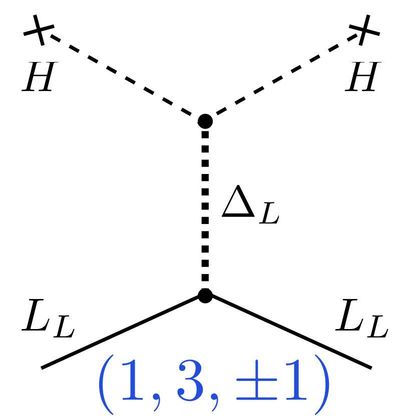

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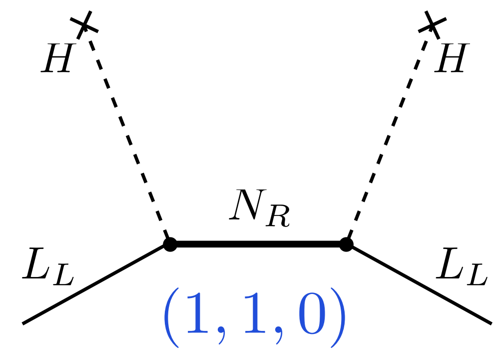

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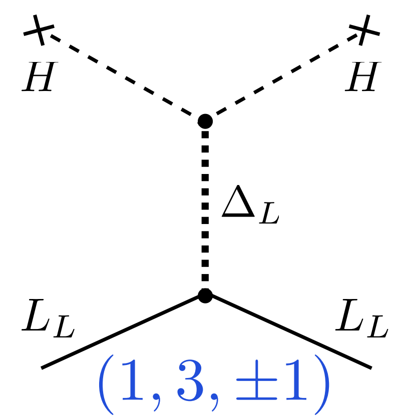

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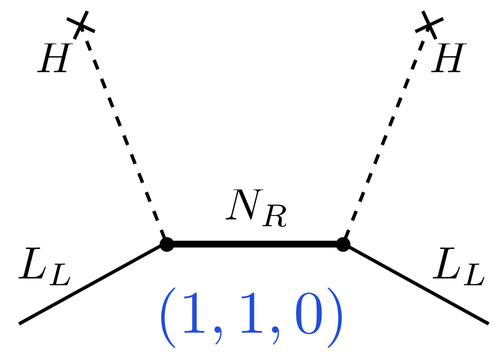

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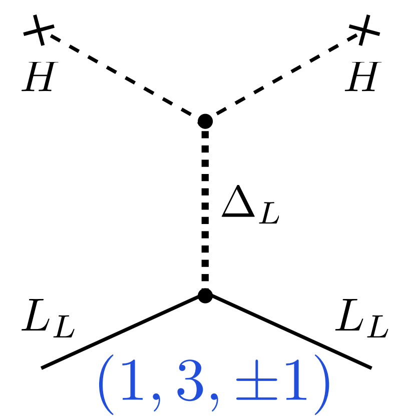

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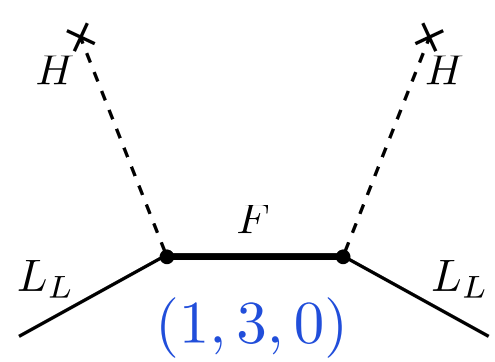

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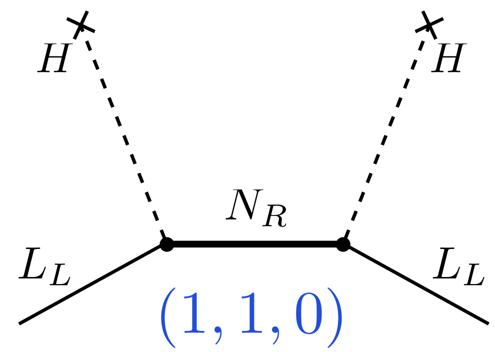

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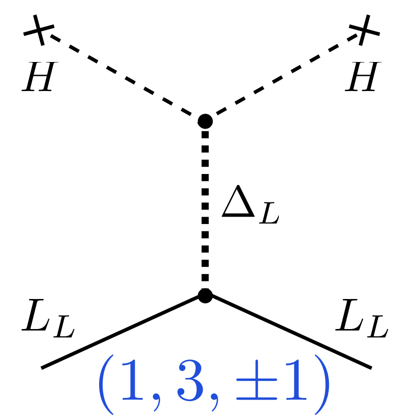

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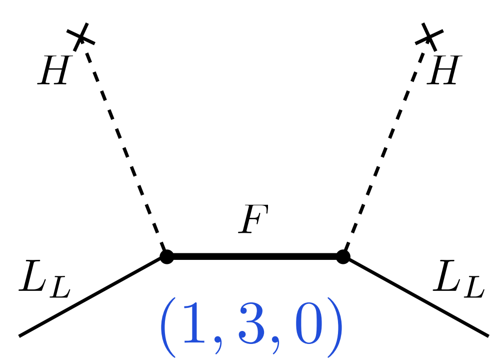
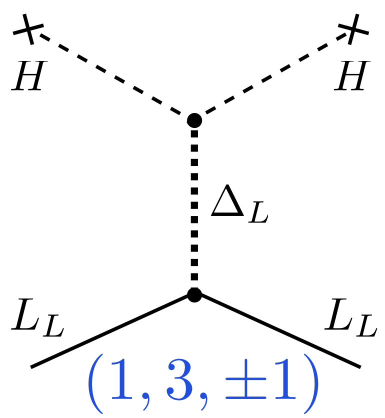


tiny Yukawas?
gauge interactions!

Type-II seesaw at collider(s)

review: arXiv:1001.2693 [hep-ph]

Type-II seesaw: - doubly-charged scalar in the spectrum!



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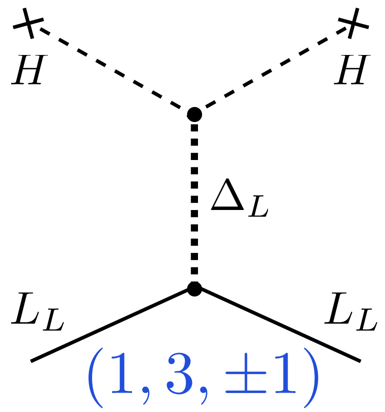

$$Z^* \to \Delta^{++}\Delta^{--} \to (l^+ l^+)(l^- l^-)$$

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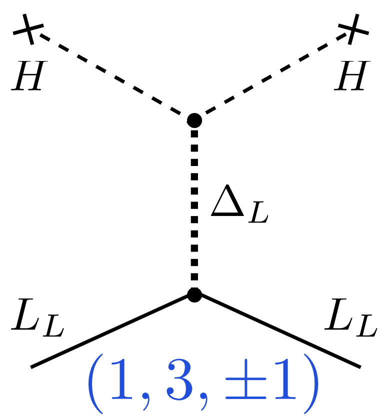

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$$Z^* \rightarrow \Delta^{++}\Delta^{--} \rightarrow (l^+ l^+)(l^- l^-)$$

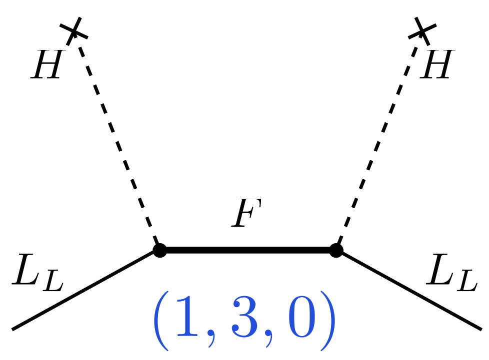
- decays rely on the size of the triplet Yukawa couplings

- flavour structure correlated to neutrino mixing

"Light" type-III seesaw at collider(s)?

review: arXiv:1001.2693 [hep-ph]

Type-III seesaw: - neutral and charged fermions



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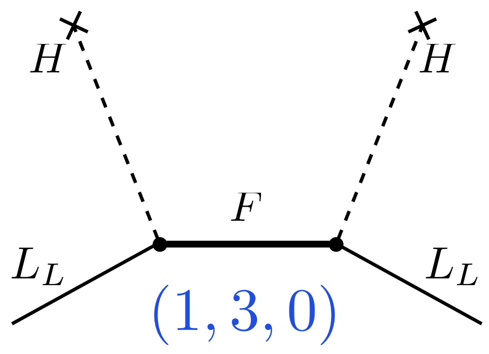

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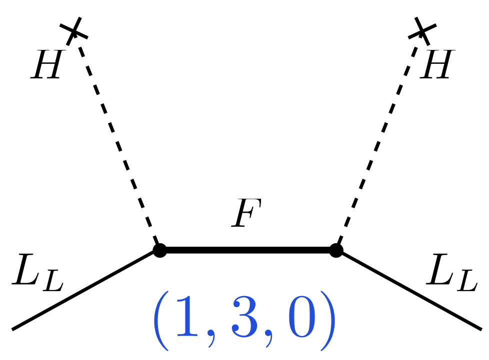


- multi-lepton channels as in type-II

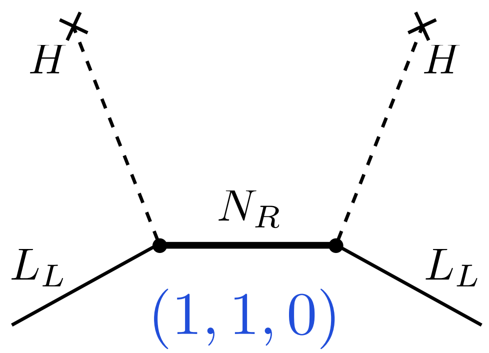
$$F^+ \to Z^* l^+ \to (l^+ l^-) l^+$$

- kinematics different, not so spectacular...

“Light” type-I seesaw at collider(s)?

review: arXiv:1001.2693 [hep-ph]

Type-I seesaw:



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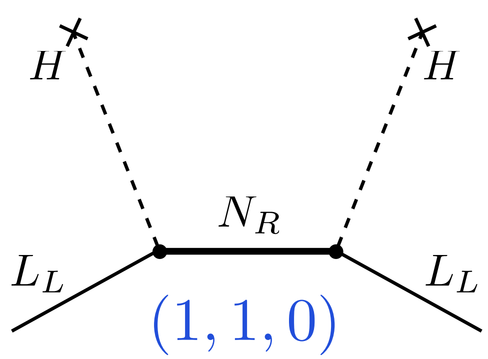
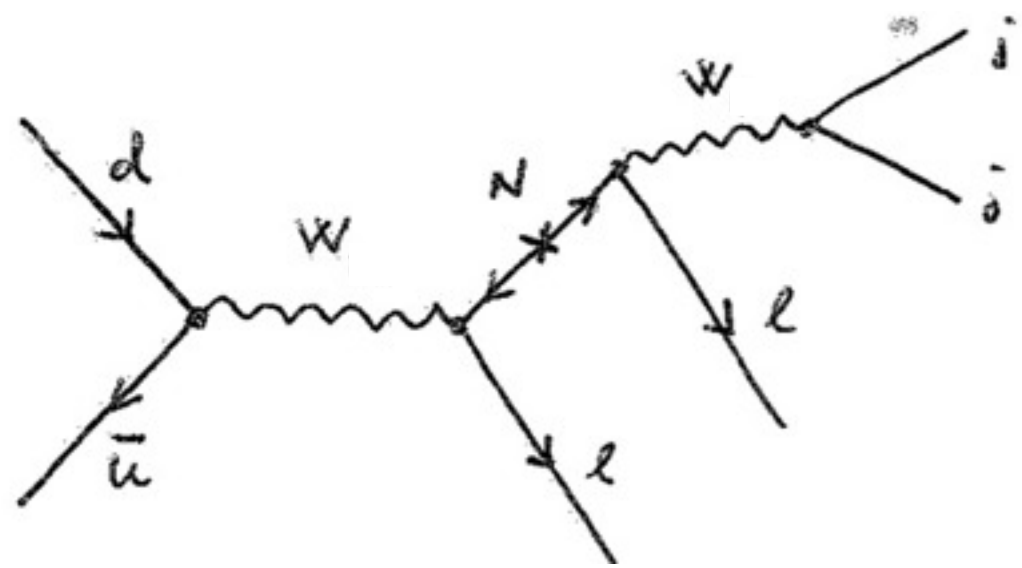
Type-I seesaw: - generally problematic, RHN couplings are too small!





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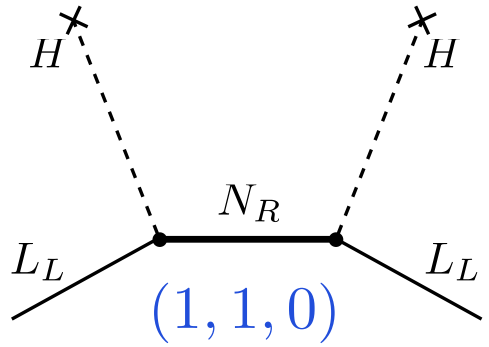

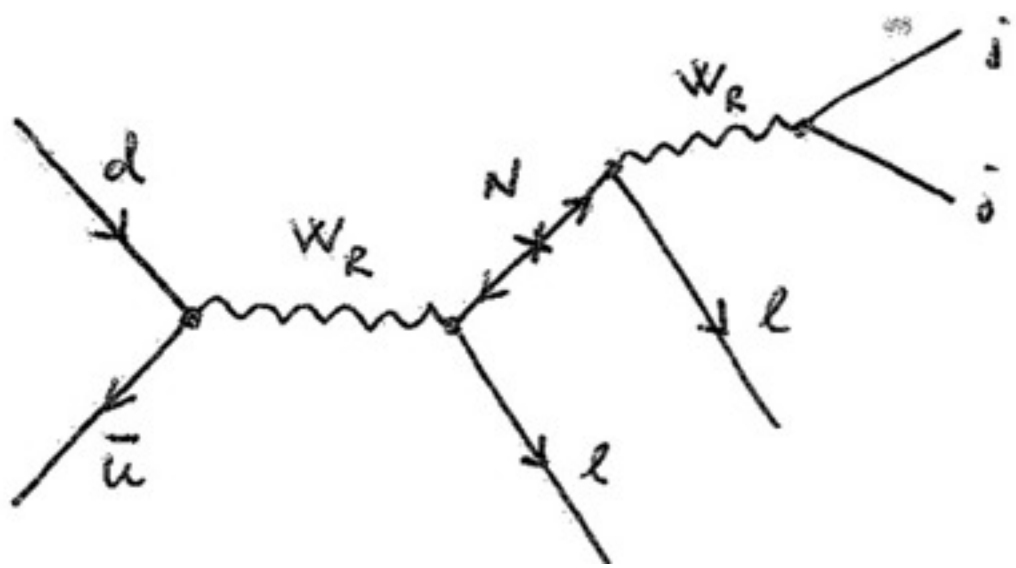

- again, much better with right-handed currents

W.Y. Keung and G. Senjanovic, Phys. Rev. Lett. 50, 1427 (1983)

Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1
ν_R	0	0	0
e_R	0	-1	-1

Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q	$(B-L)/2$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$, $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$, $-\frac{1}{3}$	$+\frac{1}{6}$
u_R	0	$+\frac{2}{3}$	$+\frac{2}{3}$	$+\frac{1}{6}$
d_R	0	$-\frac{1}{3}$	$-\frac{1}{3}$	
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$, $-\frac{1}{2}$	$-\frac{1}{2}$	0, -1	$-\frac{1}{2}$
ν_R	0	0	0	$-\frac{1}{2}$
e_R	0	-1	-1	

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u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$	

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	T_L^3	Y	Q	$(B-L)/2$	
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u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$ $-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$

Standard model matter fields + 3 RH neutrinos

	T^3_L	Y	Q	$(B-L)/2$	T^3-like generator for RH fields!
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$+\frac{1}{6}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	0
u_R d_R	0 0	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{2}{3}$ $-\frac{1}{3}$	$+\frac{1}{6}$	$+\frac{1}{2}$ $-\frac{1}{2}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$+\frac{1}{2}$ $-\frac{1}{2}$	$-\frac{1}{2}$	0 -1	$-\frac{1}{2}$	0
ν_R e_R	0 0	0 -1	0 -1	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$

Left-right models

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$u_R$$

$$d_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$\color{red}{\nu_R}$$

$$e_R$$

Left-right models

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

$$\begin{matrix} u_R \\ d_R \end{matrix} \longrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$$

$$\begin{matrix} \color{red}{\nu_R} \\ e_R \end{matrix} \longrightarrow \begin{pmatrix} \color{red}{\nu} \\ e \end{pmatrix}_R$$

Left-right models

$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ gauge group

recent review: G. Senjanovic, Riv. Nuovo Cim. 034, 2011

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High-scale parity restoration

- $SU(2)_R$ x $U(1)_{B-L}$ broken by a scalar triplet

$$\{\Delta^0, \Delta^+, \Delta^{++}\}$$

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Yukawa "unification"

$$V_{CKM} \approx 1$$

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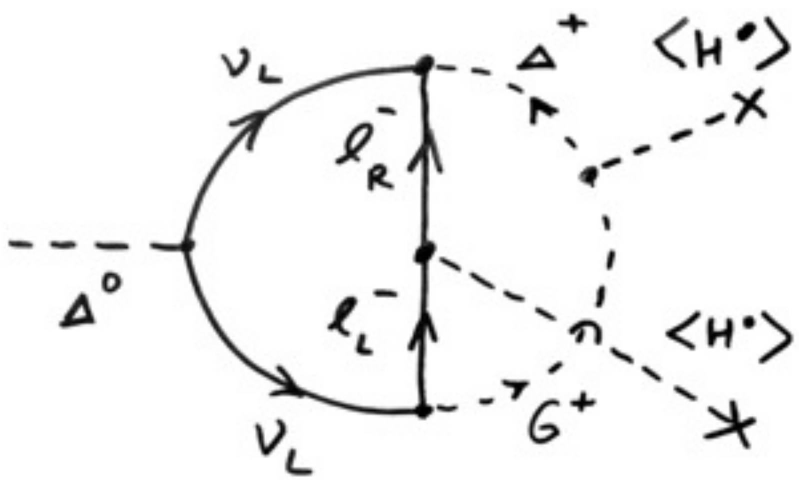
recent review: G. Senjanovic, Riv. Nuovo Cim. 034, 2011

Triplet VEV likely to be generated, type-II contribution expected



T. P. Cheng, L.-F. Li, PRD22 (1980) 2860

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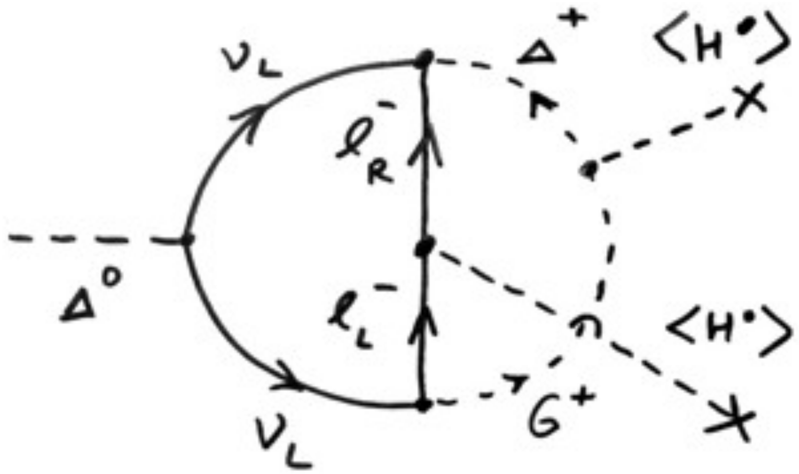

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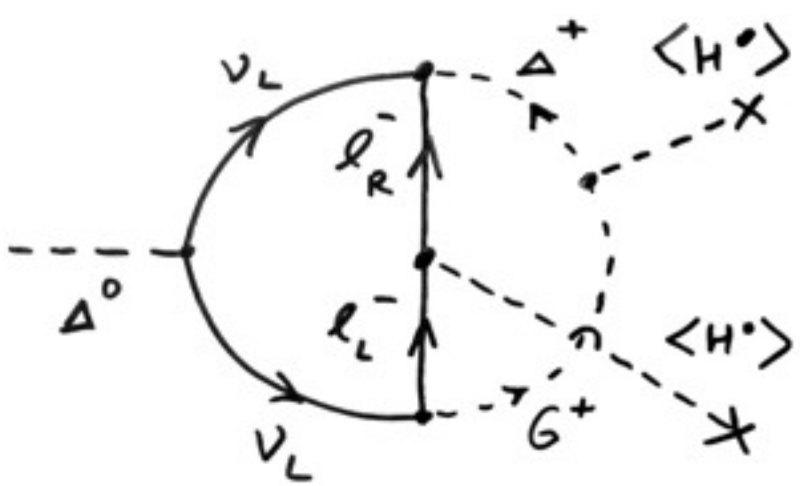

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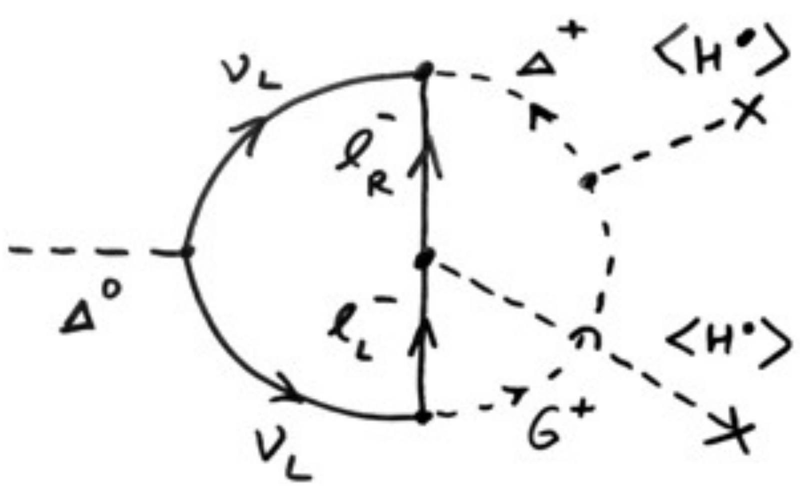

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- still no particular understanding of the flavour pattern
- electric charge quantized only through anomalies...

Pati-Salam as a prototype Q-L unification

"Lepton number as a fourth color", J. C. Pati, A. Salam, Phys. Rev. D 10, 275–289 (1974)

$$\begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R} = (4,2,1) \oplus (\overline{4},1,2)^* \quad \text{of} \quad SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$$

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Heavy singlet and coloured scalars

⇨ perturbative B and L violation

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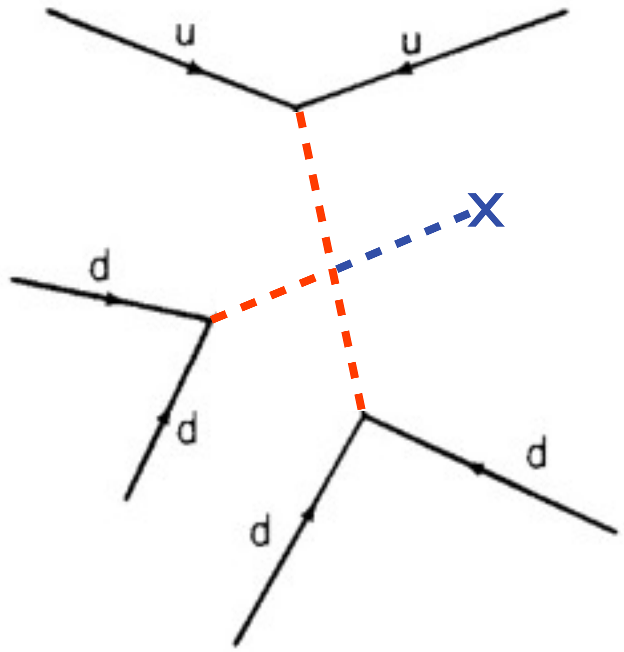

Majorana neutrino implies Majorana neutron!

cf. M. Yokoyama's talk

Pauli was sorry for a "neutron"!

Original - Photocopie of PLC 0393
Abschrift/15.12.56 FM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}\ \mathrm{cm})$.

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Pauli was sorry for a "neutron"!

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}$ cm).

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J. Chadwick 1932

Neutron-antineutron oscillations

$$H = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix}$$ in the $\{|n\rangle, |\bar{n}\rangle\}$ basis

Y. Kamyshkov, hep-ex/0211006

R. Mohapatra, J.Phys. G36 (2009) 104006

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Indirect searches: nuclear stability

Super-K, SNO

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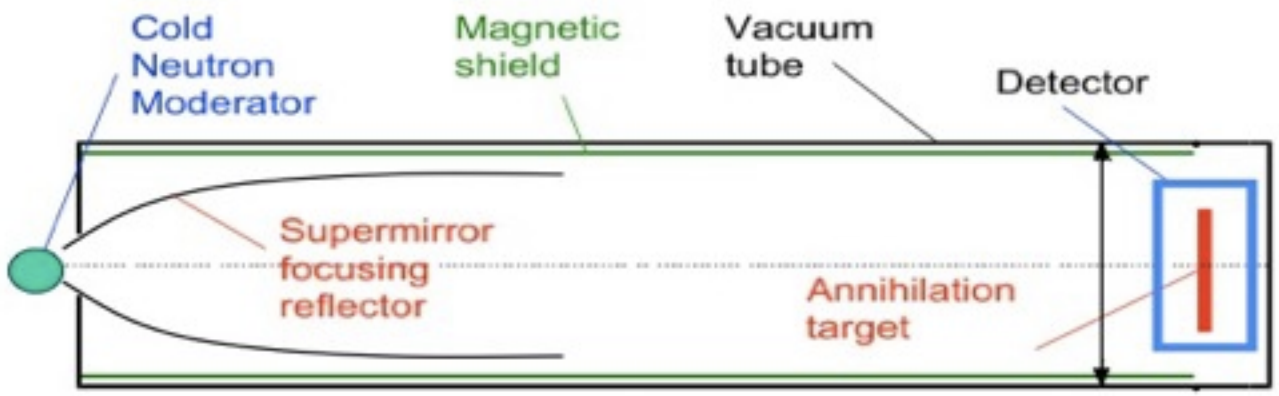
Direct searches with free neutrons:

ILL experiment, Z.Phys.C63



similar results

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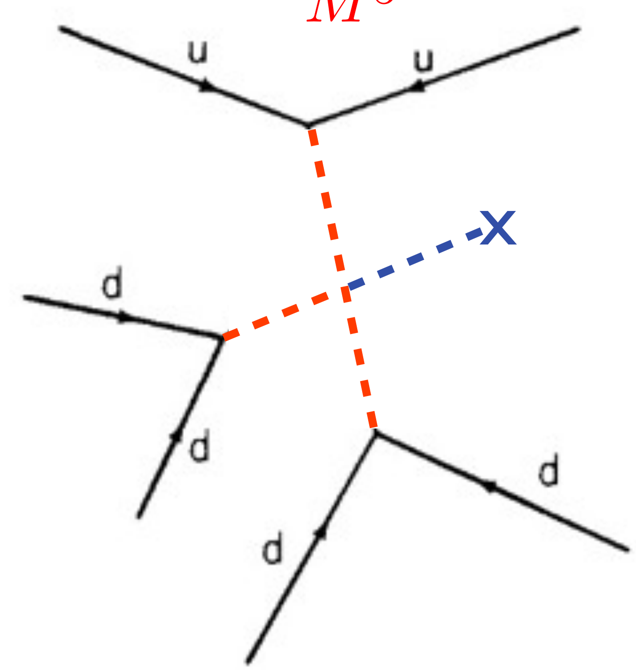

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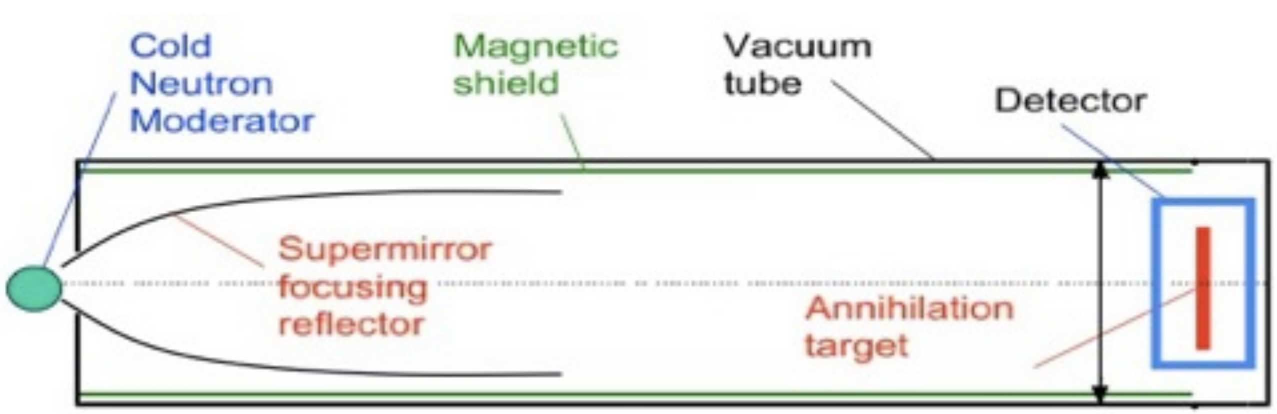

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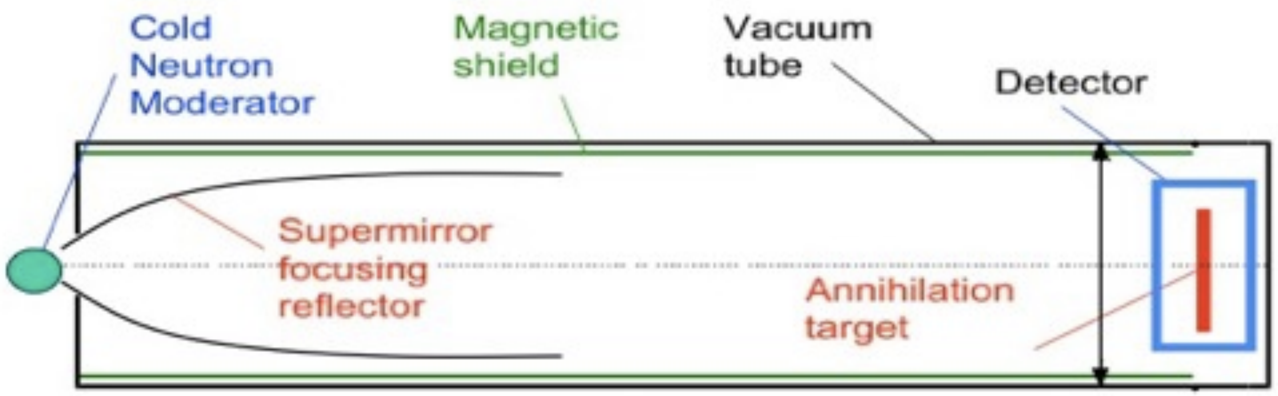

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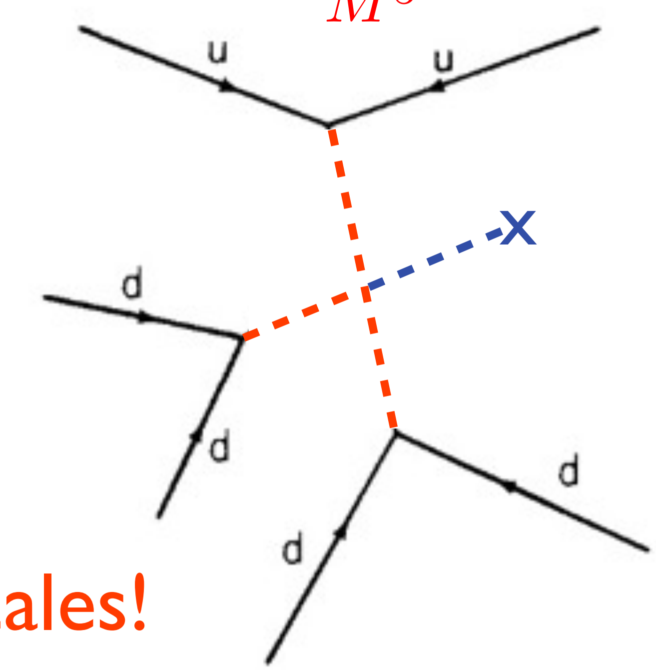

Neutron-antineutron oscillations probe O(100 TeV) scales!

Thanks for your kind attention!

Leptogenesis?

CP asymmetry:

$$\epsilon_1 \approx -\frac{3}{8\pi}\frac{1}{(Y_N Y_N^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{1i}\right]\frac{M_1}{M_i}$$

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$$\epsilon_1 \approx -\frac{3}{8\pi}\frac{1}{(Y_N Y_N^\dagger)_{11}}\sum_{i=2,3}\mathrm{Im}\left[(Y_N Y_N^\dagger)^2_{1i}\right]\frac{M_1}{M_i}$$

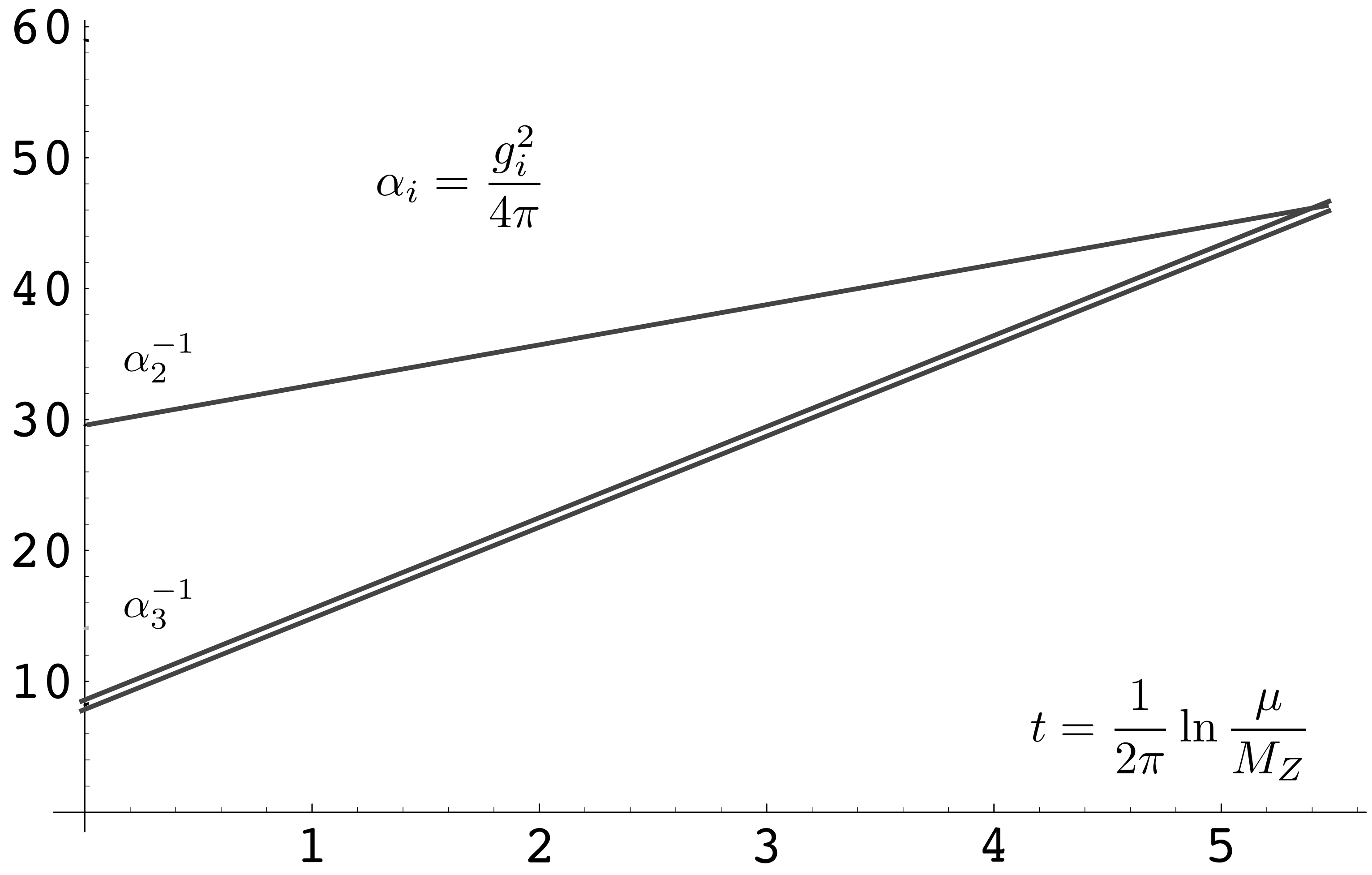
Davidson-Ibarra bound: S. Davidson and A. Ibarra, Phys. Lett. B535, 25 (2002)

$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1(m_3-m_2)}{v^2}$$

$$M_1 \gtrsim 10^9\,\mathrm{GeV}$$

Even stronger gauge symmetries?

Nonabelian SM gauge couplings seem to converge at high energies



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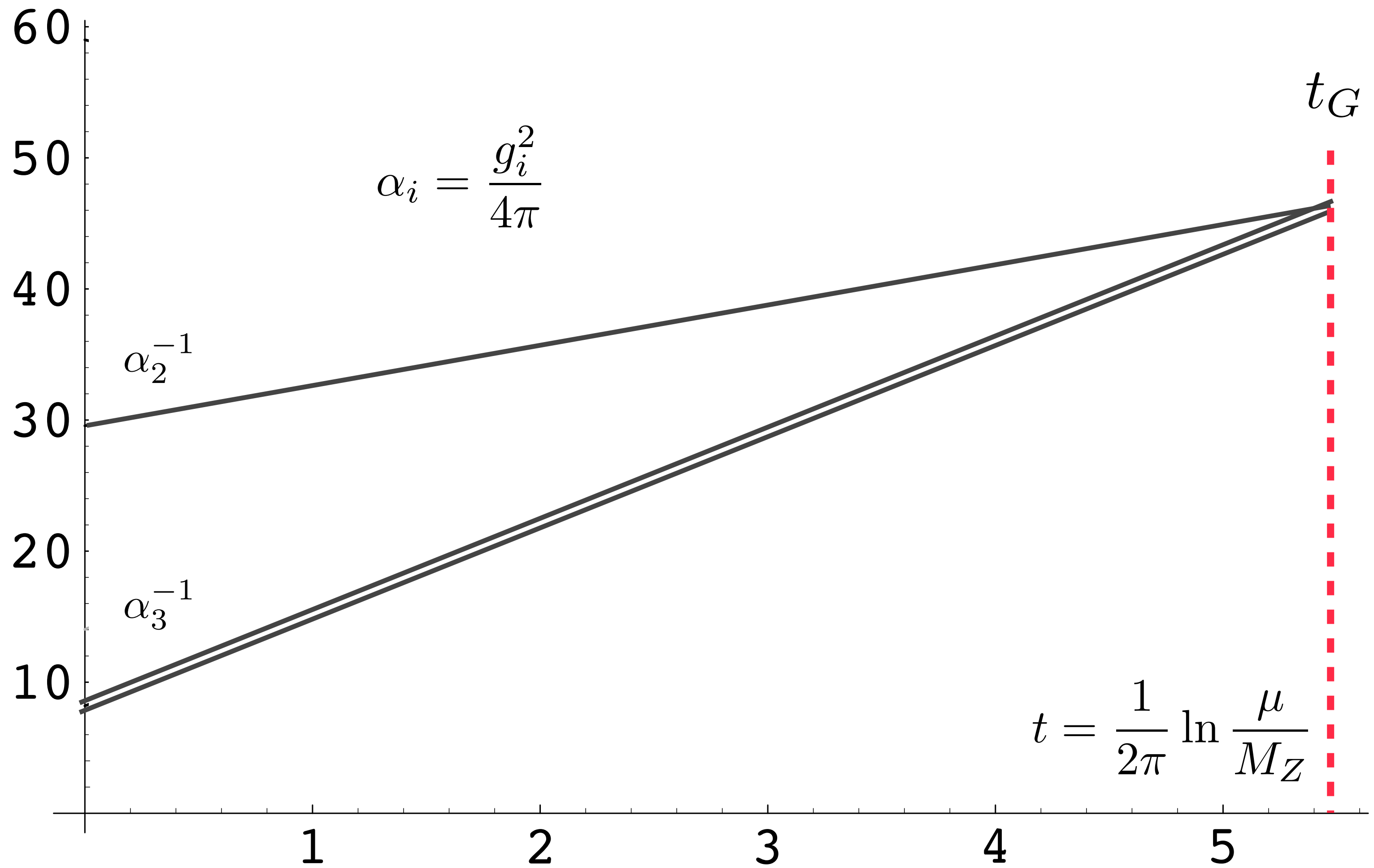

$M_G \sim 10^{16}\mathrm{GeV}$

Grand Unifications

H.Georgi, S.Glashow, Phys.Rev.Lett. 30 (1974)

GUTs are spontaneously broken BSM gauge theories based on simple compact gauge groups

The GUT physics case

- charge quantization
- monopoles
- baryon AND lepton number violation
- partly flavour

The fate of B-L (global/gauged?)

global B-L?

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	explicit breaking	spontaneous breaking
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Majoron

Gelmini, Roncandelli 1980

$U(1)$

$$J_\mu = \Phi^* \partial_\mu \Phi - \Phi \partial_\mu \Phi^* + \overline{\psi} \gamma_\mu \psi$$

$$\partial^\mu J_\mu = 0$$

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$U(1) \to \emptyset$ $\quad \langle \Phi \rangle = \Lambda \quad G = \mathrm{Im}\Phi$ Goldstone boson!

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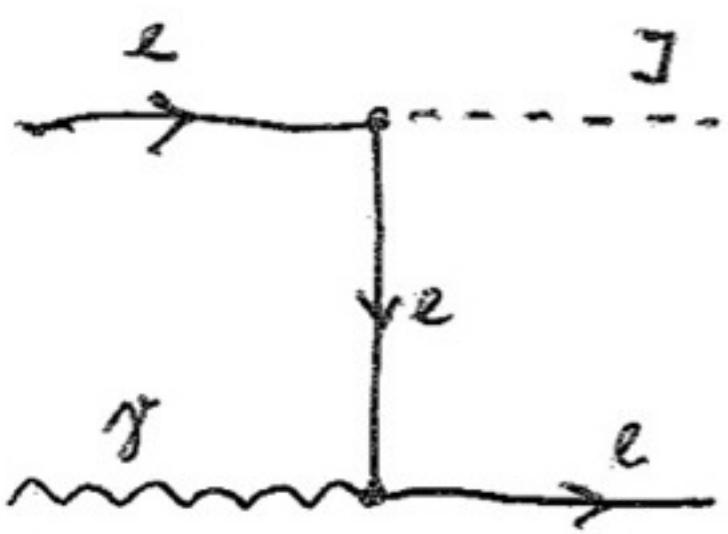
Majoron

Stellar photoproduction of Majorons (J)

$$\gamma + e \to e + J$$



$$L_J \propto \frac{\alpha g^2 T^6}{m_e^4 m_p}$$

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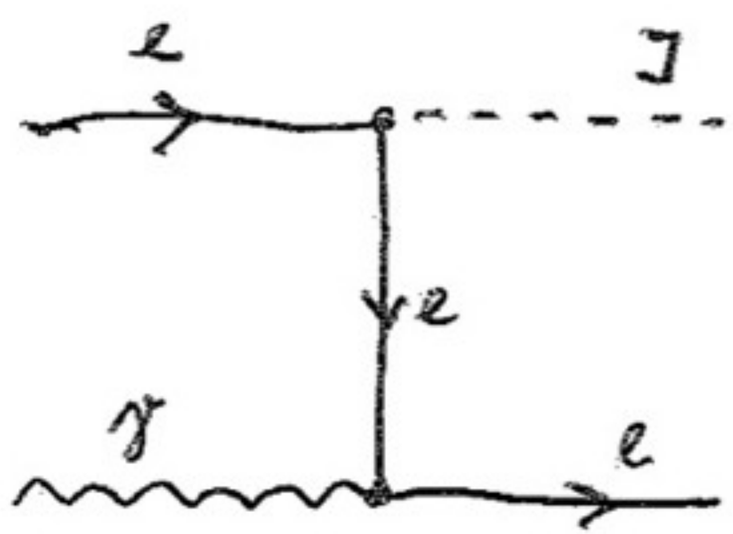

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Red giants: $g < 10^{-12}$

Chanda, Nieves, Pal, PRD37, 1988

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In order to ever gauge B-L three RH neutrinos are needed!

GUT basics

Georgi-Glashow model - a prototype GUT

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

We present a series of hypotheses and speculations leading inescapably to the conclusion that SU(5) is the gauge group of the world—that all elementary particle forces (strong, weak, and electromagnetic) are different manifestations of the same fundamental interaction involving a single coupling strength, the fine-structure constant. Our hypotheses may be wrong and our speculations idle, but the uniqueness and simplicity of our scheme are reasons enough that it be taken seriously.

of the GIM mechanism with the notion of colored quarks[4] keeps the successes of the quark model and gives an important bonus: Lepton and hadron anomalies cancel so that the theory of weak and electromagnetic interactions is renormalizable.[5]

The next step is to include strong interactions. We assume that *strong interactions are mediated by an octet of neutral vector gauge gluons* associated with local color SU(3) symmetry, and that there are no fundamental strongly interacting scalar-meson fields.[6] This insures that

- Actually, what Georgi and Glashow have shown was uniqueness of SU(5) for rank=4 GUTs

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$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

$$(1,2,-\tfrac{1}{2}) \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}$$

$$(1,1,+1) \quad e^c \quad \mu^c$$

$$(3,2,+\tfrac{1}{6}) \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix}$$

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$$(8,1,0) \quad G^\mu$$

$$\left.\begin{array}{ll}(1,3,0) & A^\mu \\ (1,1,0) & B^\mu\end{array}\right\} W^\pm, Z, \gamma$$

$$24 = (8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-\tfrac{5}{6}) \oplus (\overline{3},2,+\tfrac{5}{6})$$

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G^μ A^μ B^μ $\begin{pmatrix} X^\mu \\ Y^\mu \end{pmatrix}$

new gauge bosons

Higgs sector: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \to SU(3)_c \otimes U(1)_Q$

$(1,2,-\frac{1}{2})$ H

$$\overline{5} = (1,\overline{2},+\tfrac{1}{2}) \oplus (\overline{3},1,-\tfrac{1}{3})$$

$i\tau_2 H^*$ Δ

new coloured Higgs bosons

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new gauge bosons

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$(1,2,-\frac{1}{2})$ H

$$\overline{5} = \underset{i\tau_2 H^*}{(1,\overline{2},+\tfrac{1}{2})} \oplus \underset{\Delta}{(\overline{3},1,-\tfrac{1}{3})}$$

new coloured Higgs bosons

GUT-breaking Higgs: $SU(5) \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

variety of extra Higgses

$$24 = (8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-\tfrac{5}{6}) \oplus (\overline{3},1,-\tfrac{1}{3})$$

Baryon and lepton number violation in GUTs

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  - gauge bosons coupled to a universal charge

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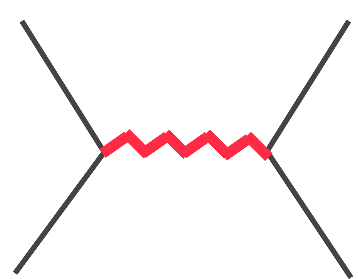
- Proton decay

d=6

gauge-induced



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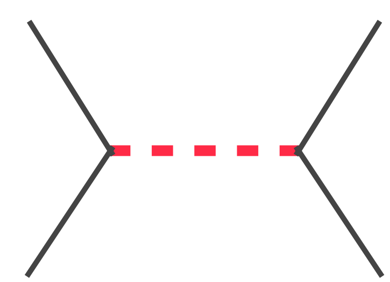

$$\frac{f_1}{M_G^2}\overline{Q}u^c\overline{Q}e^c, \quad \frac{f_2}{M_G^2}u^c\overline{Q}d^c\overline{L}$$

$$\frac{f_3}{M_G^2}QQQL, \quad \frac{f_4}{M_G^2}u^cu^cd^ce^c$$

Monopoles

No way to produce in lab, only cosmics + Callan-Rubakov effect

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Theory: $$\Phi_M(\mathrm{Earth})_{\mathrm{theory}} \lesssim 10^{-22} \sim 10^{-27}\ \mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}$$

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N.B. early (fake) monopole-like events — Price et al., 1975 PRL August 25