Prague, September 6 2012

Neutrinos from the Beyond-Standard-Model perspective

Michal Malinský

AHEP group of IFIC, CSIC/University of Valencia

Standard model matter fields

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} c \\ s \end{pmatrix}_L \qquad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$u_R \qquad c_R \qquad t_R$$

$$d_R \qquad s_R \qquad b_R$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

$$e_R \qquad \mu_R \qquad \tau_R$$

Neutrino mass generation in the SM?

Weinberg's d=5 operator

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- violates the lepton number global symmetry of the SM!

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

Baryon and lepton number violation in the SM

Anomalies: $$\mathcal{A} \propto \frac{1}{32\pi^2}\mathrm{Tr}\left(\{T_a, T_b\}T\right)\tilde{F}^a_{\mu\nu}F^{b\mu\nu}$$

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$$\nu_R^1 \qquad \nu_R^2 \qquad \nu_R^3$$

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$$Y_{Dij}\overline{Q_{L}}_i\langle H\rangle D_{Rj}+Y_{Uij}\overline{Q_{L}}_i\langle\tilde{H}\rangle U_{Rj}+Y_{Eij}\overline{L_{L}}_i\langle H\rangle E_{Rj}+Y_{Nij}\overline{L_{L}}_i\langle\tilde{H}\rangle N_{Rj}+h.c.$$

$$+\tfrac{1}{2}M_{Rij}\overline{N^c_{Ri}}N_{Rj}+h.c.$$

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$$M_\nu = \begin{pmatrix} 0 & Y_N v \\ Y_N^T v & M_R \end{pmatrix}$$

$$m_\nu = Y_N {M_R}^{-1} v^2 Y_N^T$$

Seesaw systematics

Renormalizable "openings" of the Weinberg operator

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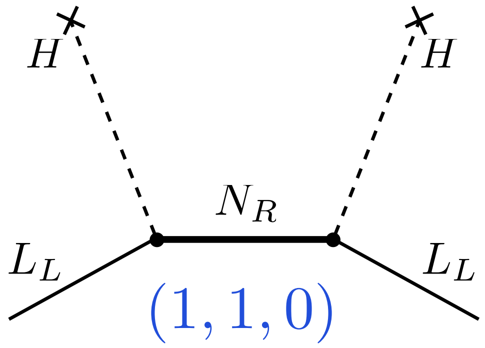

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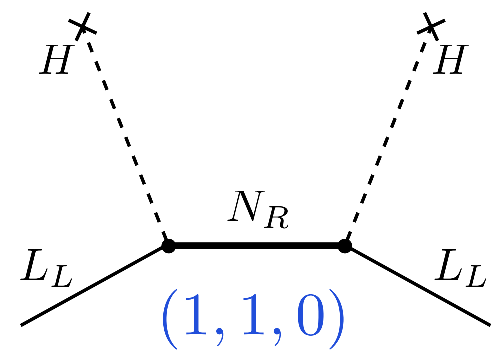

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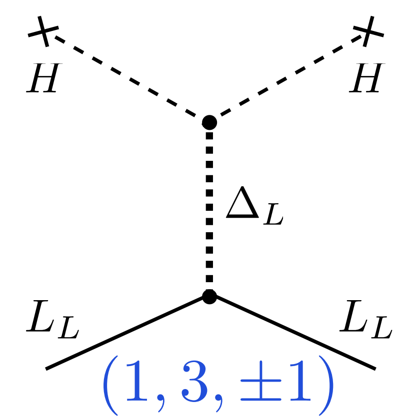

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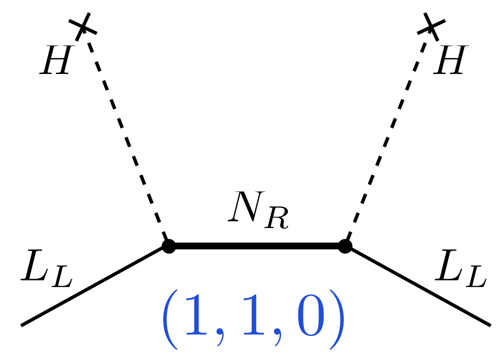

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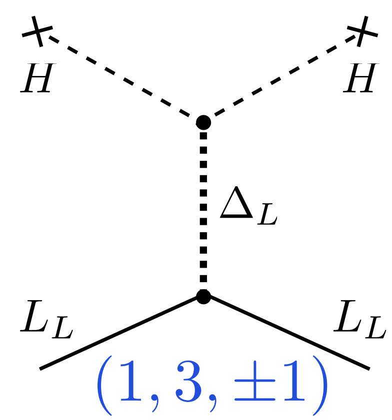
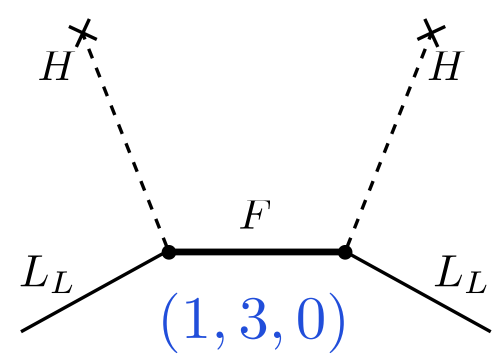


type-III seesaw



Seesaw scale?

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Lower bounds:

- Neutrino oscillations:

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

$$|\Delta m^2_A| = (2.5 \pm 0.3) \times 10^{-3} \mathrm{eV}^2$$

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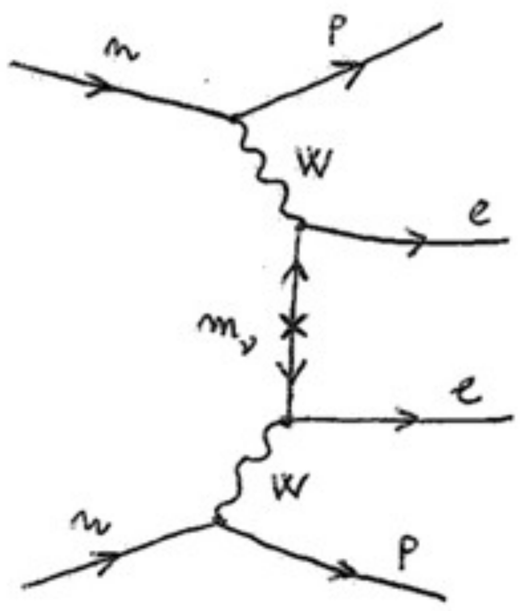
- Cosmology (structure): $\sum_i m_i \lesssim 1\mathrm{eV}$
- $0\nu 2\beta$: $\langle m^{ee} \rangle \lesssim 1\mathrm{eV}$



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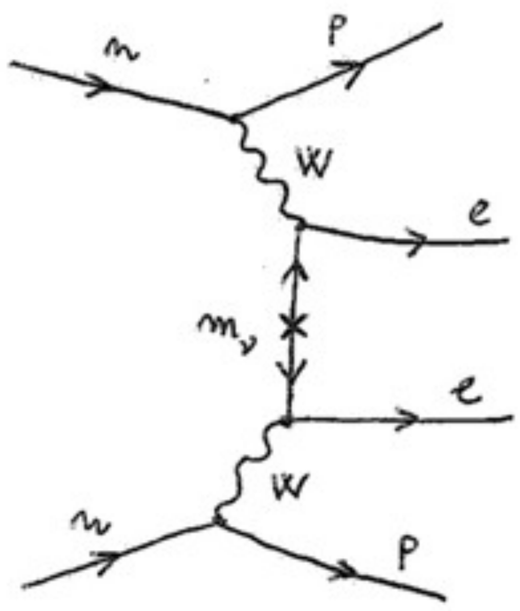

$$\Lambda \sim (10^{12} - 10^{14})\ \mathrm{GeV}$$

Leptogenesis?

$$\frac{n_B}{n_\gamma} \equiv \eta_B = (6.1 \pm 0.3) \times 10^{-10}$$

Fukugita, Yanagida, PLB174, 1986

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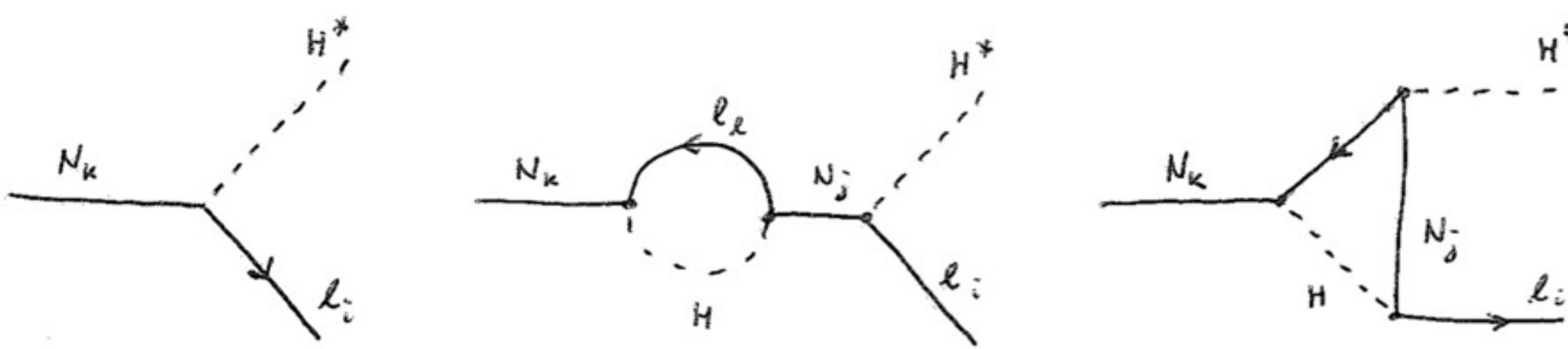
Generating net L: $$\epsilon_1 = \frac{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})\right]}{\sum_\alpha \left[\Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \bar{\ell}_\alpha \overline{H})\right]}$$



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

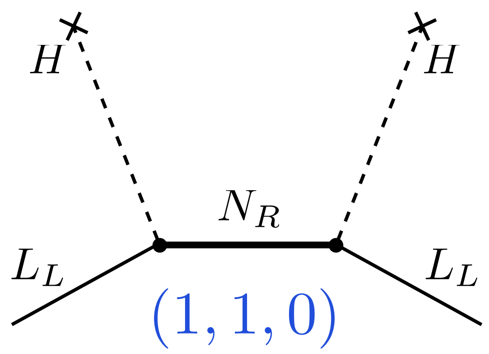
$$|\epsilon_1| \leq \frac{3}{16\pi}\frac{M_1(m_3 - m_2)}{v^2}$$

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

“Light” seesaw?

LHC phenomenology(?) - mediators review: arXiv:1001.2693 [hep-ph]

Type-I seesaw: - generally problematic, Yukawa’s are too small!



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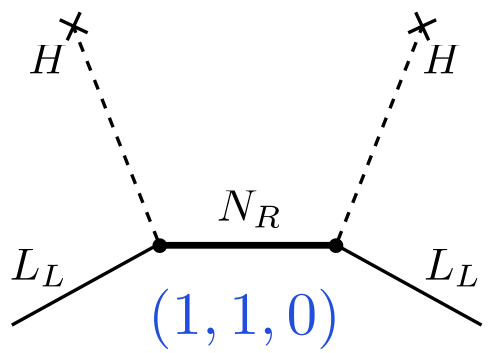
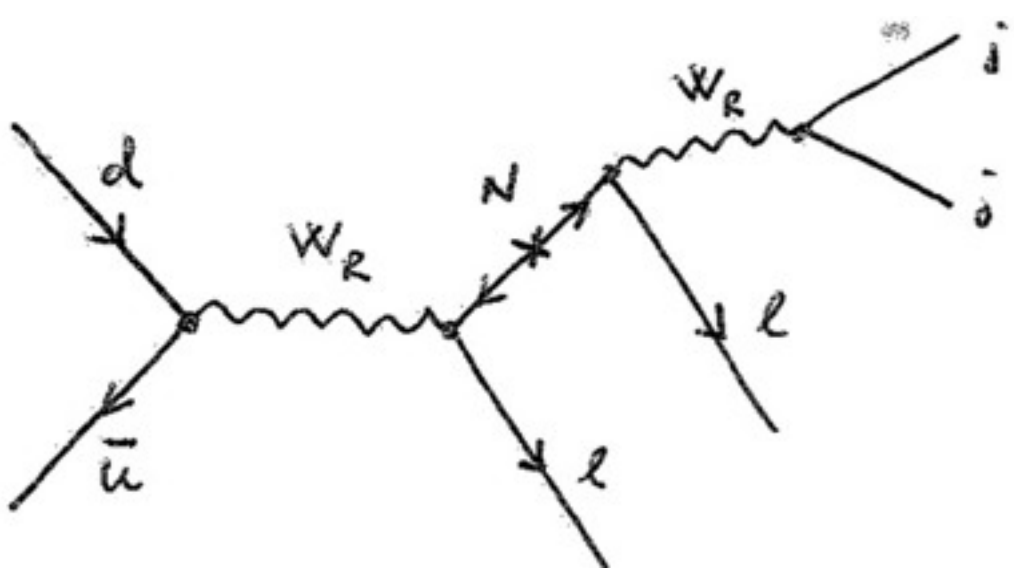
- Much better with extended gauge symmetries



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



- “essentially background-free” same-sign dilepton signal

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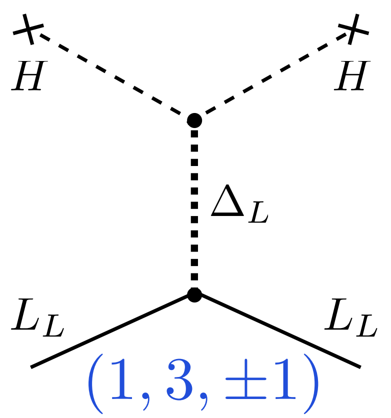
Type-II seesaw: - doubly-charged scalar in the spectrum!



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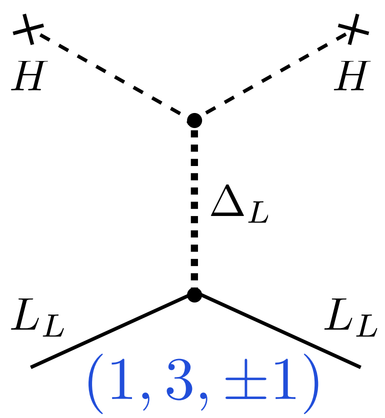

- same sign dilepton pairs (boosted)

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

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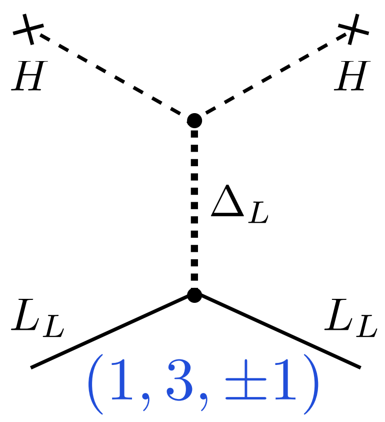

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- decays rely on the Yukawa couplings

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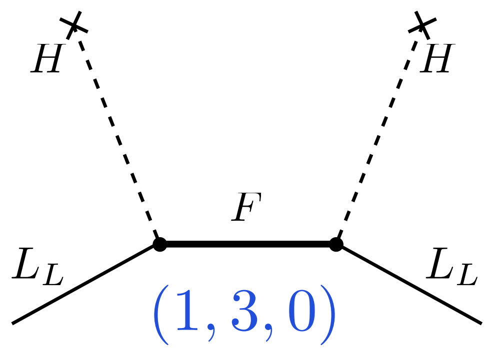
Type-III seesaw:

- neutral and charged fermions
- triplet feels the SM gauge interactions - better!



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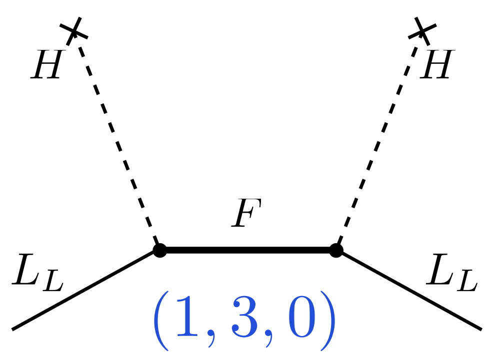

- multi-lepton channels as in type-II, different kinematics!

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

$$E^- \to Z^* l^- \to (\nu \bar{\nu}) l^-$$

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

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explicit breaking

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Majoron

Gelmini, Roncandelli 1980

$U(1)$

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

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

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Goldstone boson!

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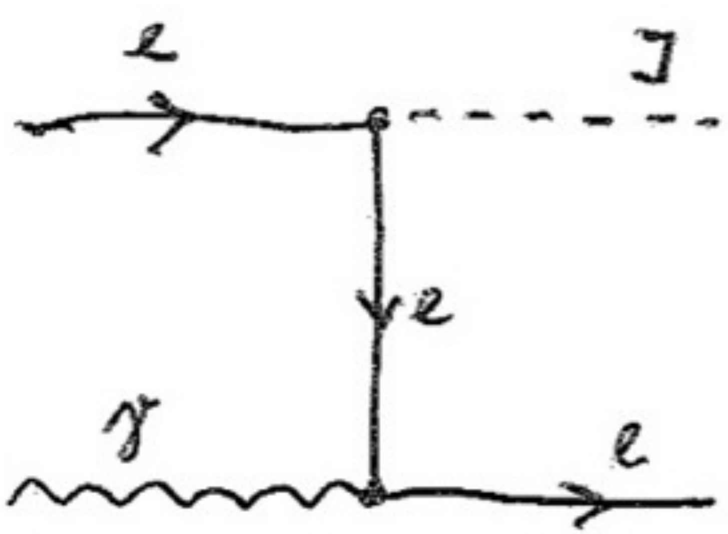
$$\mathcal{L} \ni \partial^\mu G \partial_\mu G - \frac{G}{\Lambda}\partial^\mu(\overline{\psi}\gamma_\mu\psi)$$

Majoron

Stellar photoproduction of Majorons (J)

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



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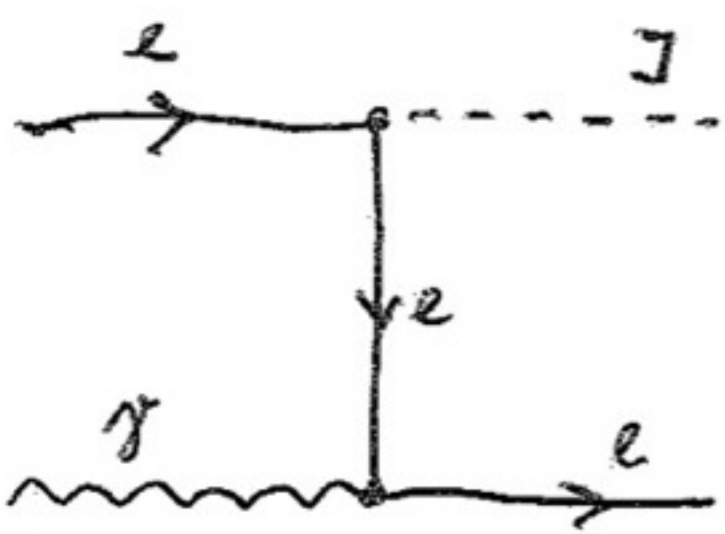

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Red giants: $g < 10^{-12}$

Chanda, Nieves, Pal, PRD37, 1988

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

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

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 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	$-\frac{1}{2}$
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Standard model matter fields + 3 RH neutrinos

	T_L^3	Y	Q	$(B-L)/2$	Another T^3-like generator?
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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	$-\frac{1}{2}$	$+\frac{1}{2}$ $-\frac{1}{2}$

Left-right models

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

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

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

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- high-scale parity restoration

- Z',W' gauge bosons

- Yukawa "unification" $V_{CKM} \approx 1$

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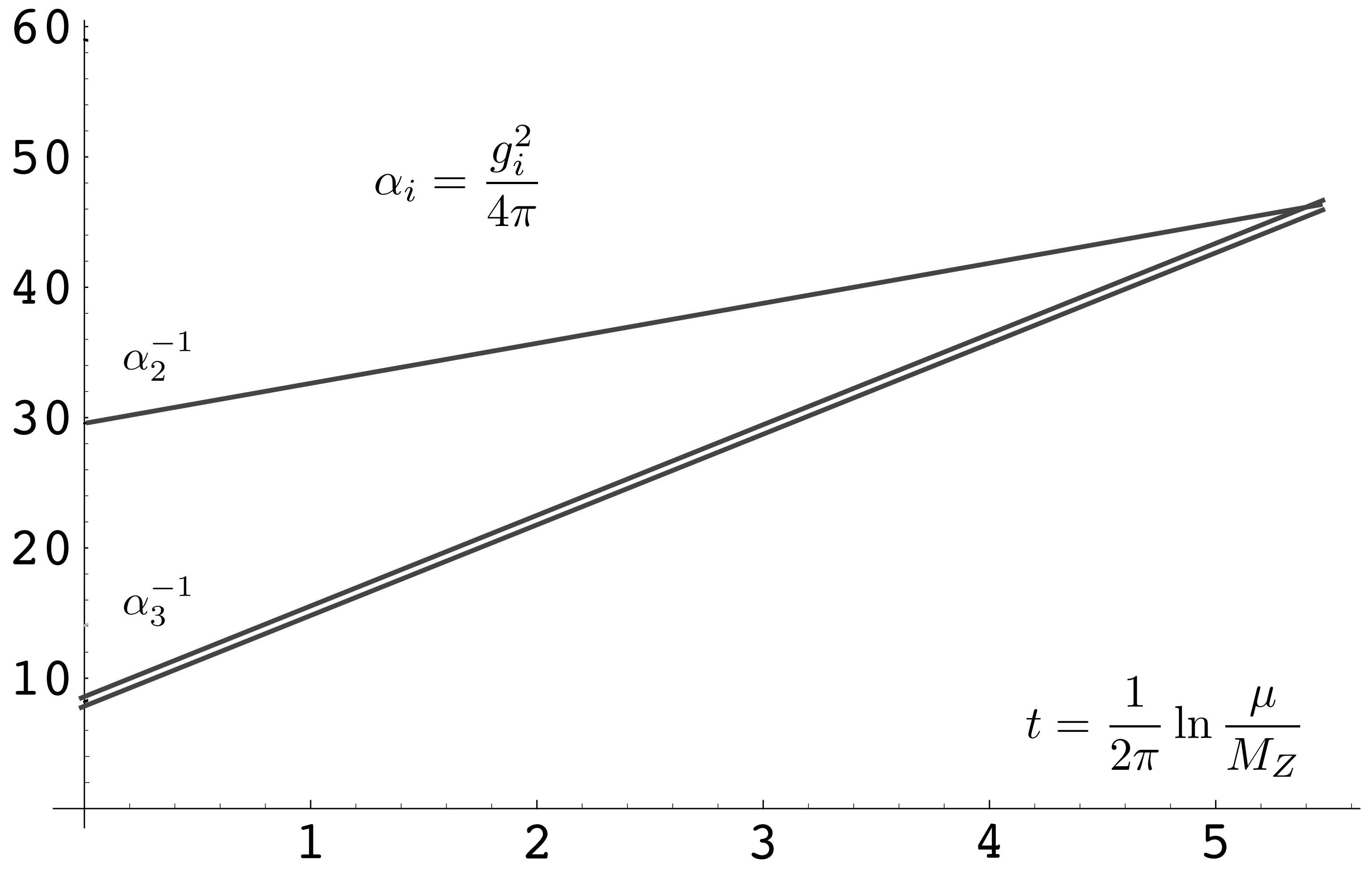
Unfortunately, not strong enough to tell us much about neutrinos

Even stronger gauge symmetries?

the SM gauge couplings seem to converge at high energies



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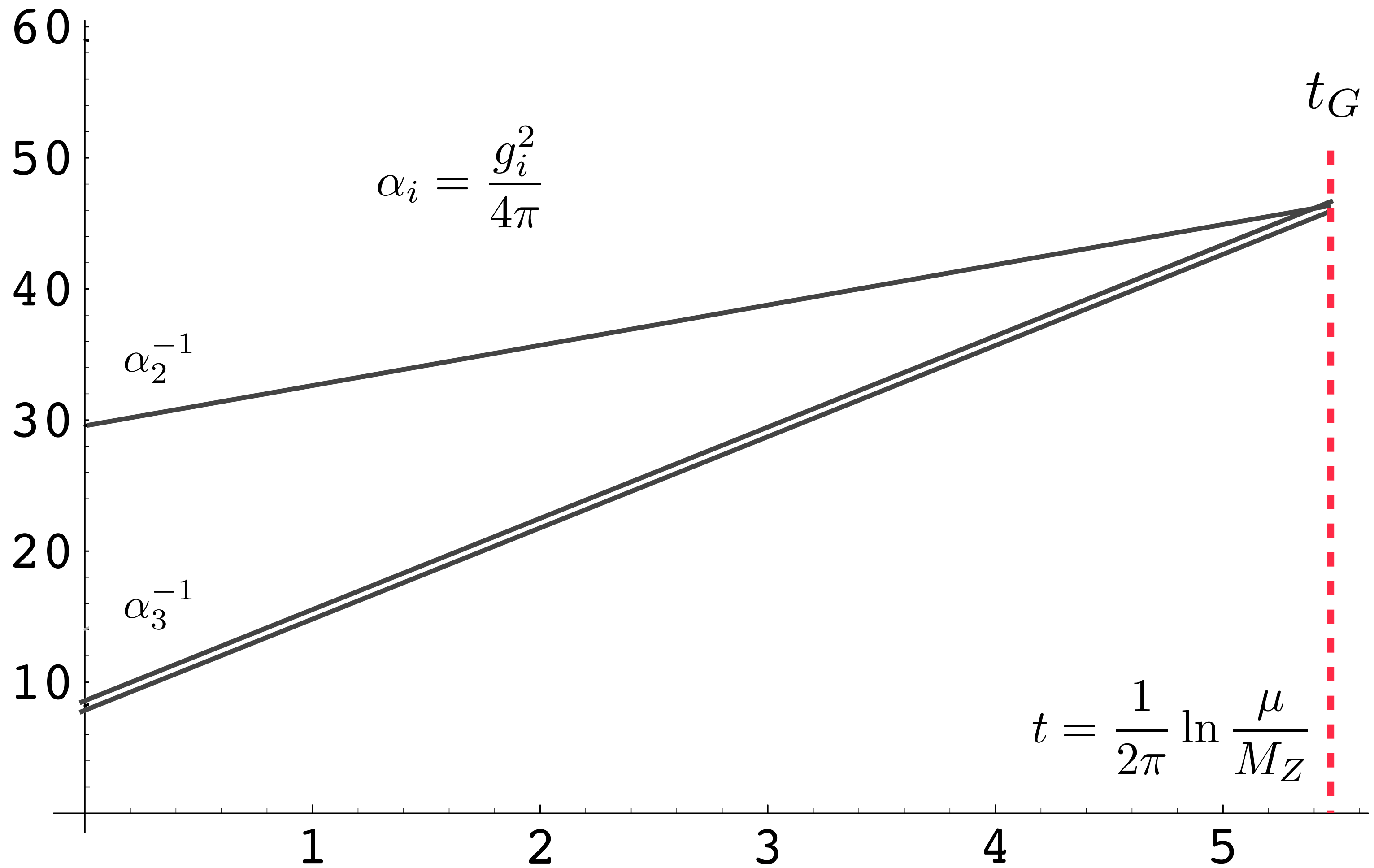

$M_G \sim 10^{16}\text{GeV}$

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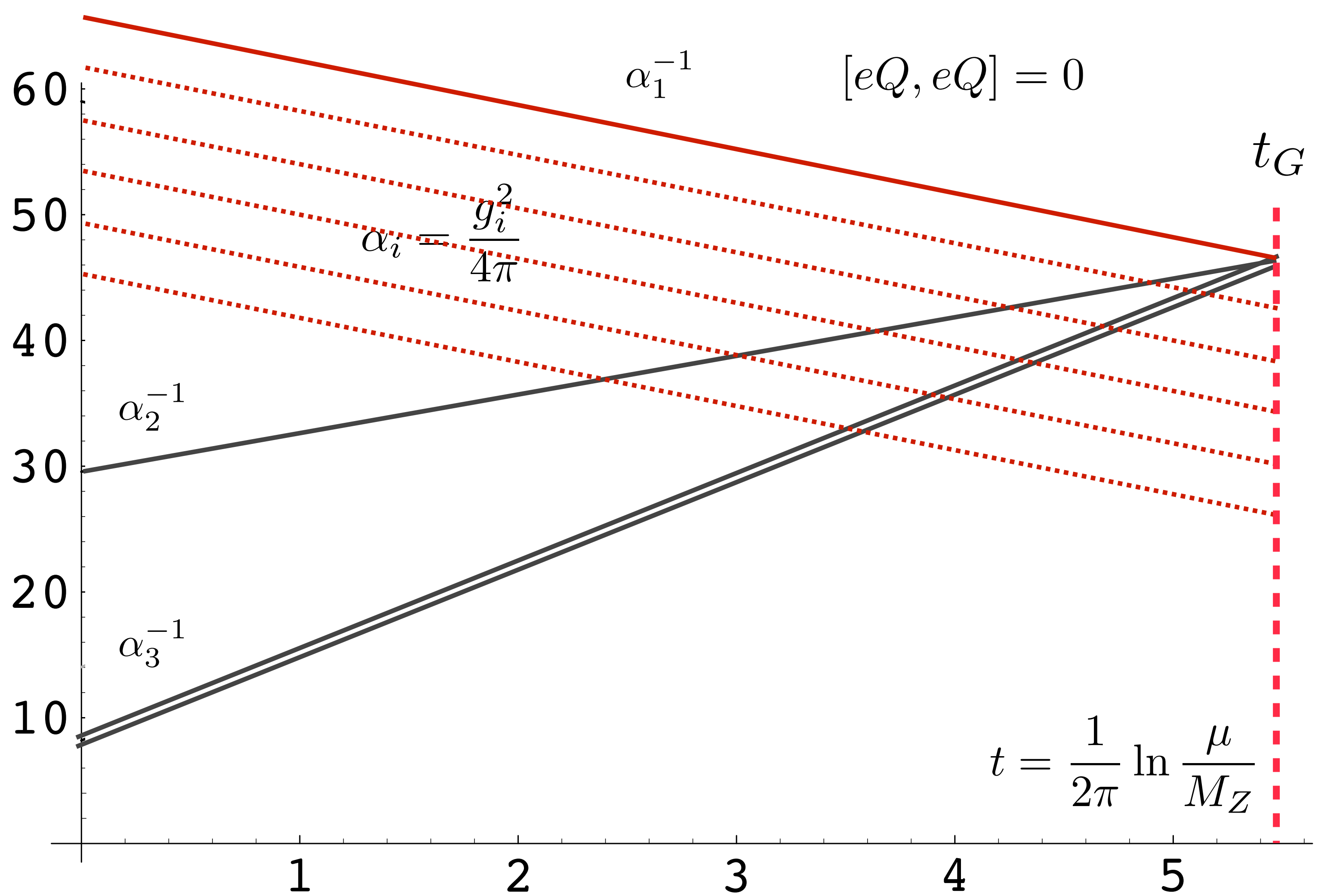

$M_G \sim 10^{16}\text{GeV}$

GUT basics

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

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

The physics case

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

GUT basics

Georgi-Glashow model - a prototype GUT

- 1974 - The first SU(5) grandunified model by Georgi and Glashow

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Gauge sector:

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

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

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

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new gauge bosons

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

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

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$i\tau_2 H^*$ Δ

new coloured Higgs bosons

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

variety of extra Higgses

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Baryon and lepton number violation in GUTs

- Quarks and leptons share common GUT multiplets

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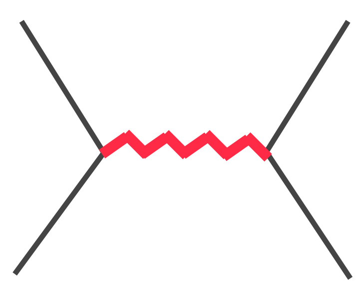
- Proton decay

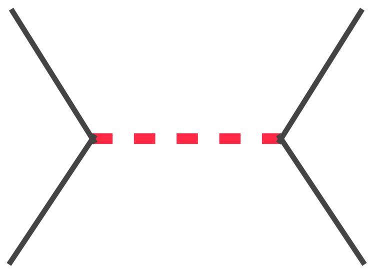
d=6

gauge-induced



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

Higgs-induced



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

SO(10) GUT completion of the L-R model

- all matter in a single IRREP of SO(10)

Fritzsch & Minkowski 1975

$$SO(10) \supset\supset SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\underbrace{}_{}\quad Q_L \qquad\qquad Q_R \qquad\qquad L_L \qquad\qquad L_R$$

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RH neutrino mandatory!

- very simple Yukawa sector

$$\Phi$$

$$10_H = (3,1,1,-2/3) \oplus (3,1,1,+2/3) \oplus (1,2,2,0)$$

$$\mathcal{L} \ni 16_F Y_{10} 16_F 10_H$$

all Dirac masses correlated!

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- extra piece needed: $16 \otimes 16 = 10 \oplus 126 \oplus 120$

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$$\mathcal{L} \ni 16_F Y_{126} 16_F 126_H$$

Majorana and extra Dirac masses generated!

SO(10) “flavour miracle”

Assuming dominant type II seesaw:

B.Bajc, G.Senjanovic and F.Vissani
Phys.Rev.Lett. 90 (2003) 051802

$$
\begin{aligned}
M_u &= Y_{10} v_u^{10} + Y_{126} v_u^{126} \\
M_d &= Y_{10} v_d^{10} + Y_{126} v_d^{126} \\
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$$

$$\theta_{23} \sim \frac{\pi}{4}$$

$$\theta_{13} \sim \mathcal{O}(\lambda)$$

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Daya-Bay: $\sin^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

$$U_{e3} \sim 0.15$$

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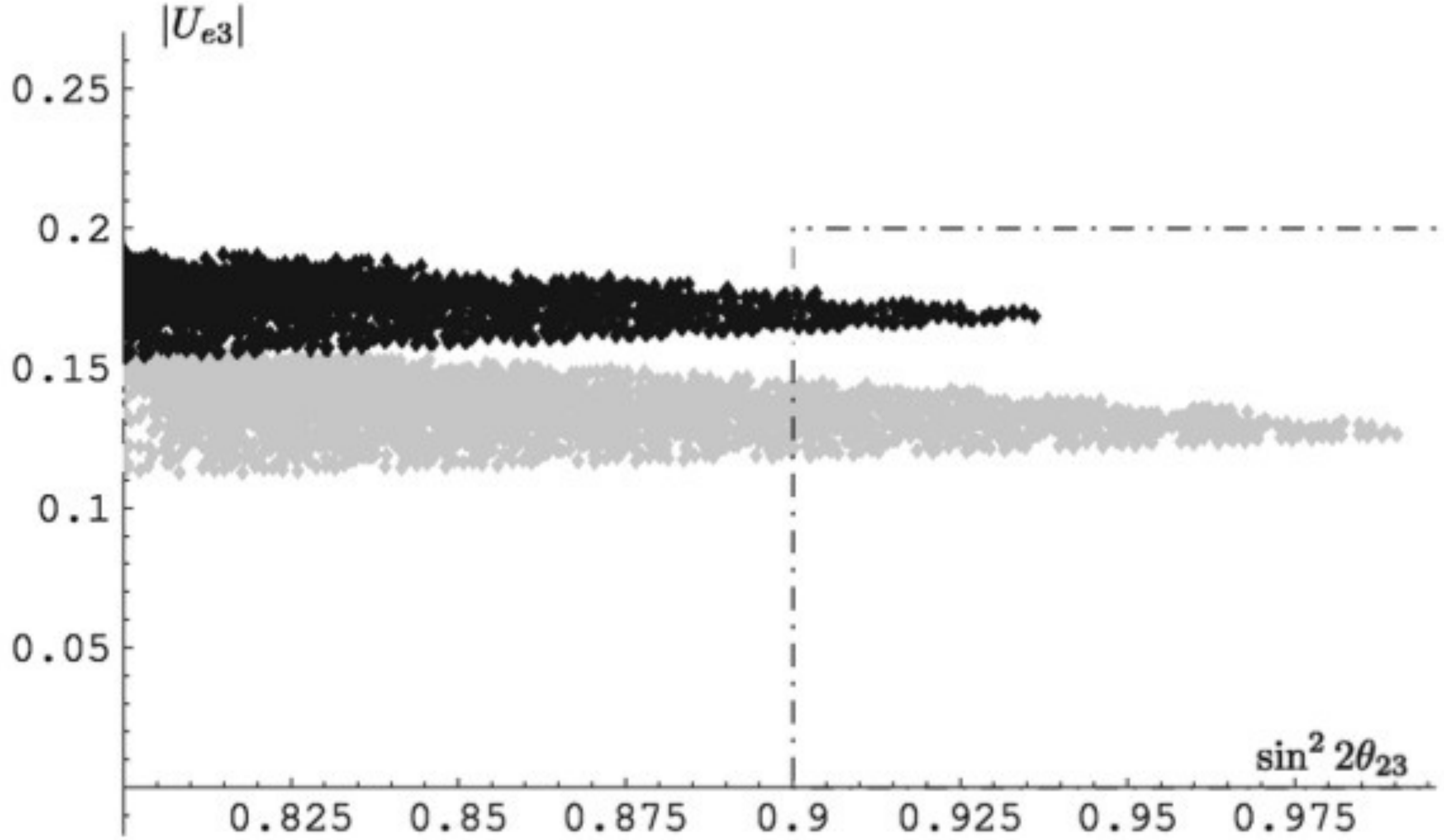

!!!

figure from: S. Bertolini, M. Frigerio, MM, Phys. Rev. D70, 2004


Thanks for your kind attention!

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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

Monopoles

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

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- galactic magnetic field depletion
- pulsar stability — Freese, Turner
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Upper limits on the flux density around Earth

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

Experiment: $$\Phi_M(\text{Earth})_{\text{exp.}} \lesssim 10^{-16}\ \text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$$ MACRO 2001 (Gran Sasso)

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