Reflections on Baryon and Lepton Number Violation

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BLV circa 2020

BNV & LNV

touch into the core of it all

generic features & motivation

how to capture the essential?

genuine theory: GUT

hard after SU(5) failure

effective operator analysis

Fermi -> V - A -> SM

Minimal SU(5) theory

Georgi, Glashow '74

remarkably predictive - a great surprise for the fathers

- predicts proton decay scale — *Georgi, Quinn, Weinberg '74*
- relates weak mixing to strong coupling — *Georgi, Quinn, Weinberg '75*
- predicts down quark - lepton mass ratios
- predicts proton decay branching ratios — *Mohapatra '79*

basically all wrong

- couplings do not unify
- neutrino massless

Minimal realistic SU(5)

add 24F

Bajc, GS 2006

↓

light fermion triplet@LHC?

but

says nothing precise about p decay

↓

add 45H

Dorsner, Fileviez Perez 2006

baroque, also tailor ordered

GUT and gravity: scales

Dvali

$$\Lambda_{strong} = \frac{M_P}{\sqrt{N}}$$ (N ~100's) $< 10^{17}\, GeV$

# of real degrees of freedom

non-perturbative, not fine tuneable

$$\Lambda_{strong} \gg M_{GUT} \gtrsim 10^{16}\, GeV$$ proton stability

no room?

GUT - which representations

smaller repr -> bigger strong coupling scale → need d=5 operators - additional assumptions

bigger repr -> smaller strong coupling scale ← no need d=5 operators

bigger repr -> non -perturbative problem with *N* *Dvali , GS in progress*

↓

SO(10) with 126H, 210H, …
in trouble?

Aulakh, Mohaptra '82

Babu, Mohapatra '92

Bajc, Melfo, GS, Vissani 2002 -2005

Goh, Mohapatra, NG 2002

Aulakh et. al. 2002 -today

In constructing a new theory, we shall be careful to insist that they should be precise theories, giving a description from which definite conclusions can be drawn. We do not want to proceed in a fashion that would allow us to change the details of the theory at every place that we find it in conflict with experiment, or with our initial postulates. Any vague theory that is not completely absurd can be patched up by more vague talk at every point that brings up inconsistencies—and if we begin to believe in the talk rather than in the evidence we will be in a sorry state.

and yet often

- assumption on parameter space (MSSM)
- additional ad-hoc symmetries: flavour
- when no prediction, appeal to ill understood strings:
  F-theory, M-theory, orbifolds …

BNV - effective

Weinberg '79

$$\frac{1}{\Lambda_{\not B}^2}\, q\, q\, q\, \ell$$ → proton decay

↓

UV completion = gauge $\qquad \Lambda_{\not B} \gtrsim 10^{16}\, GeV$

describes many processes - sum and selection rules

↓

B-L conserved

↓

neutron cannot decay into Kaon

LNV - effective

Weinberg '79

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$$O_{\not L} = \frac{c_W}{\Lambda} \ell\,\ell\,\Phi\,\Phi$$

Φ = SM Higgs

UV completion - small Yukawa

$c_W \ll 1$ natural

- large scale claim $(c_W = 1)$ unjustified

Weinberg 'SM50 ...

- no direct physical process → only message: neutrino = Majorana

Cirigliano talk

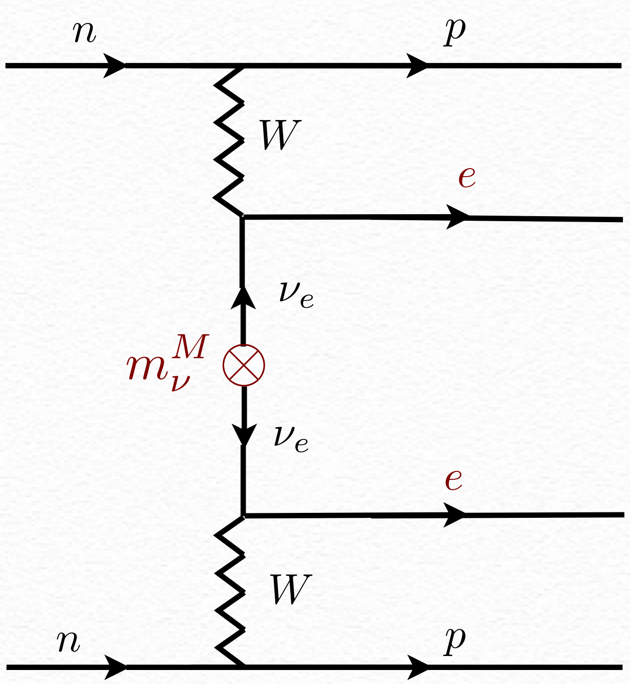
not the right operator

right operator → $\frac{1}{\Lambda^5}(e\,e\,u\,u\,\bar{d}\,\bar{d})$ 0nu2beta

Lepton Number Violation (LNV)

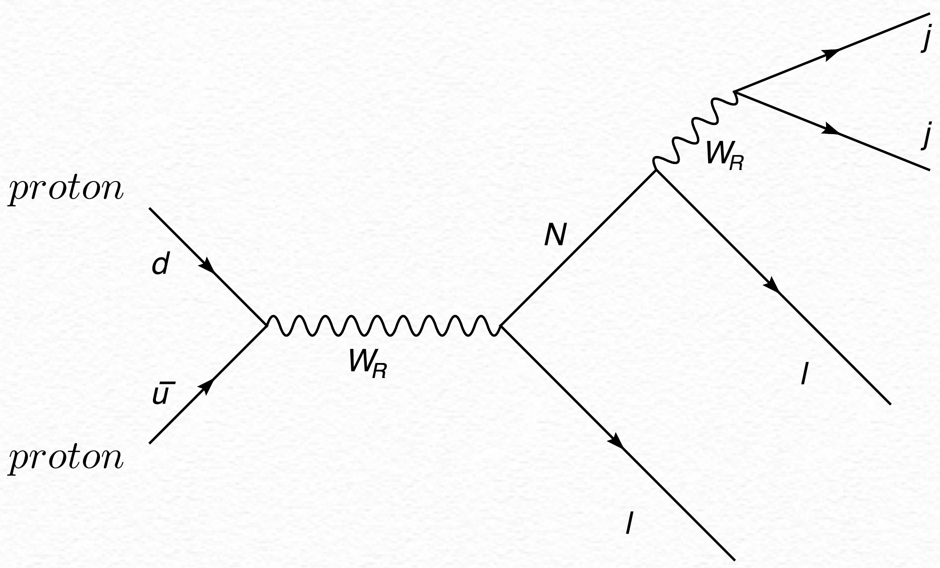
- neutrinoless double beta decay

Furry '38



- LNV@hadron colliders: KS process

Keung. GS '83



0nu2beta: new physics

Feinberg, Goldhaber '59

$$\frac{1}{\Lambda_{\not L}^5}(e\,e\,u\,u\,\bar{d}\,\bar{d})$$

d = 9 operator

$$\Lambda_{\not L} \gtrsim TeV$$

LHC

measure electron polarisation

- e = RH ➔ new physics
- both e = LH ➔ new physics or neutrino?

Effective operator analysis

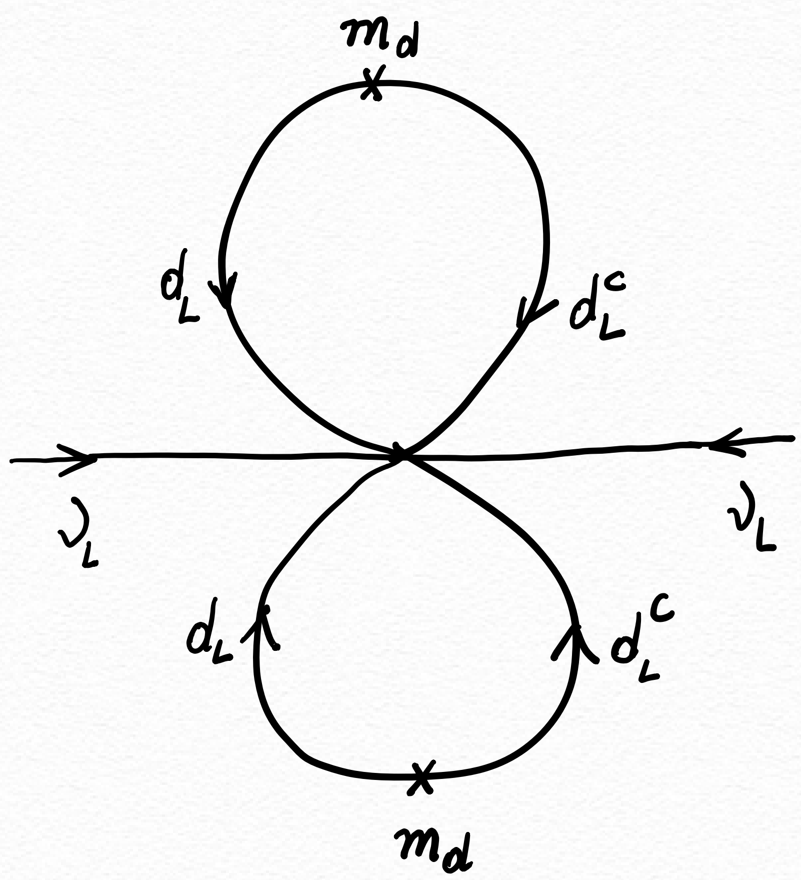
Bonnet et. al. 2013

$$O = \frac{1}{\Lambda^5}(e_L e_L)(u_L u_L d_L^c d_L^c)$$

typical operator

SU(2) weak

$$O = \frac{1}{\Lambda^5}(\nu_L \nu_L)(d_L d_L d_L^c d_L^c)$$



neutrino mass

$$m_\nu \simeq (\frac{\alpha}{4\pi})^2 \frac{m_d^2}{\Lambda}$$

$$\Lambda \simeq TeV$$

$$m_\nu \simeq 10^{-1}\, eV$$

too close for comfort?

Dvali, GS in progress

(1)

$$(e_L \, e_L) \times \begin{cases} u_L u_L \, d^c_L d^c_L \\ u_R u_R \, d^c_R d^c_R \end{cases} \qquad (O_1)$$

$+ \quad \updownarrow$

$$(\nu_L \, \nu_L) \times \begin{cases} d_L d_L \, d^c_L d^c_L \\ u_R u_R \, u^c_R u^c_R \end{cases} \qquad (O_2)$$

(1'1')

$$(e_L \, u_L)(e_L \, d^c_L)(u_R \, d^c_R) \qquad (O_3)$$

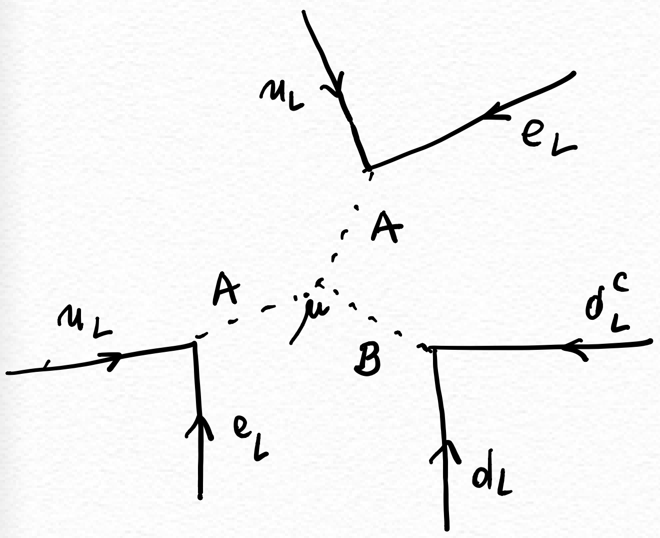
$SU(2) \updownarrow \qquad +$

$$(\nu_L \, d_L)(\nu_L \, d^c_L)(u_R \, u^c_R)$$

$$\Rightarrow \boxed{m_\nu = \left(\frac{\alpha}{\pi}\right)^2 \frac{m_u m_d}{\Lambda}}$$

(Poor person's) UV completion

$$\mathcal{L}_{new} = A(u_L e_L + d_L \nu_L) + B\, d_L^c d_L^c + \mu\, A\, A\, B$$



A = scalar leptoquark

B = scalar di-quark

$$\frac{1}{\Lambda^5} = \frac{\mu}{m_A^4\, m_B^2}$$

$m_B \gg m_A$ helps

$$m_A \gtrsim 2\, TeV$$

ATLAS 2006.05872

$$\frac{\mu}{m_B^2} \gtrsim 10^{-6}\, GeV^{-1}$$

$$m_\nu \simeq (\frac{\alpha}{4\pi})^2 \mu \frac{m_d^2}{m_B^2} \simeq 10^{-4}\, eV$$

negligible

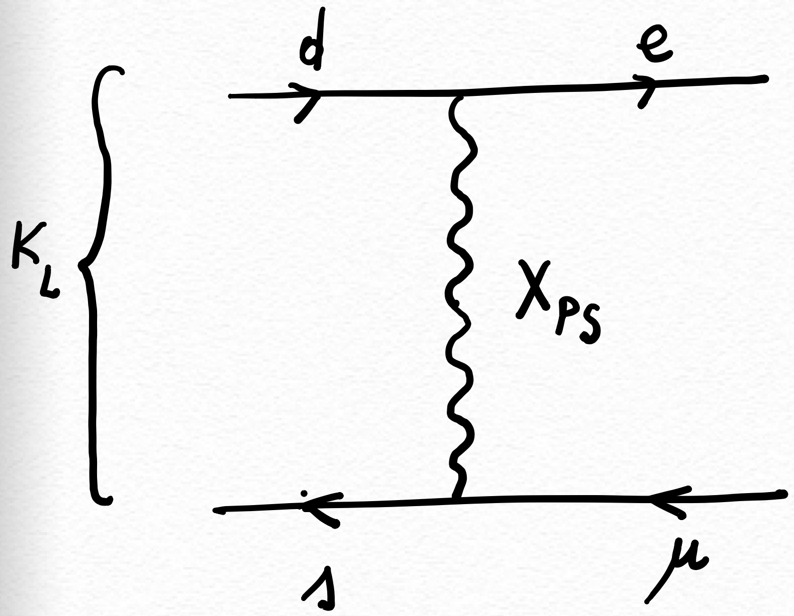
UV completion: theory

quark - lepton unification

Pati - Salam $SU(2) \times SU(2) \times SU(4)$

$$U = \begin{pmatrix} u \\ u \\ u \\ \nu \end{pmatrix} \quad D = \begin{pmatrix} d \\ d \\ d \\ e \end{pmatrix}$$

LFV in gauge boson interactions



$K_L \to \mu \bar{e}$

scale large

$\Lambda \gtrsim 10^5 GeV$ assume scalar leptoquarks light?

also n - n bar talk by Babu

LR symmetric PS - scale huge → give up LR?

GUT and neutron oscillations

A general discussion of mass scales in grand unified theories is presented, with special emphasis on Higgs scalars which mediate neutron-antineutron (n-$\bar{n}$) and hydrogen-antihydrogen (H-$\bar{H}$) oscillations. It is shown that the analogue of survival hypothesis for fermions naturally makes such particles superheavy, thus leading to unobservable lifetimes. If this hypothesis is relaxed, an interesting possibility of potentially observable n-$\bar{n}$ and H-$\bar{H}$ transitions, mutually related arises in the context of SU(5) theory with spontaneously broken B-L symmetry.

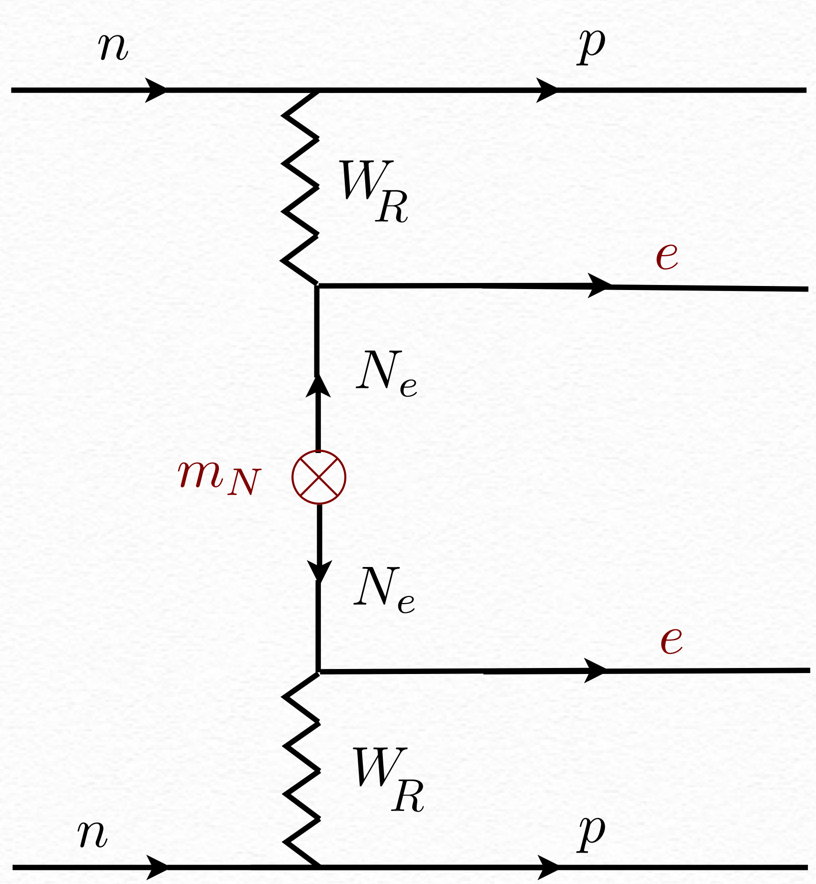
GS, talk at n-n bar Harvard '82

way to make 'predictions' = assume survival principle for scalars too

Mohapatra, GS '82

e = RH ➡ new physics

natural candidate: LR model Mohapatra, GS '79 -'81



N = RH neutrino

Left-Right Symmetric Model

Mohapatra, Pati, Salam, GS '74-'75

W_L $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ $\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ | $\begin{pmatrix} u_R \\ d_R \end{pmatrix}$ $\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$ W_R $M_{W_R} \gg M_{W_L}$

seesaw $M_\nu = -M_D^T \frac{1}{M_N} M_D$ ⬅ $M_N \propto M_{W_R}$ $N \equiv \nu_R^*$

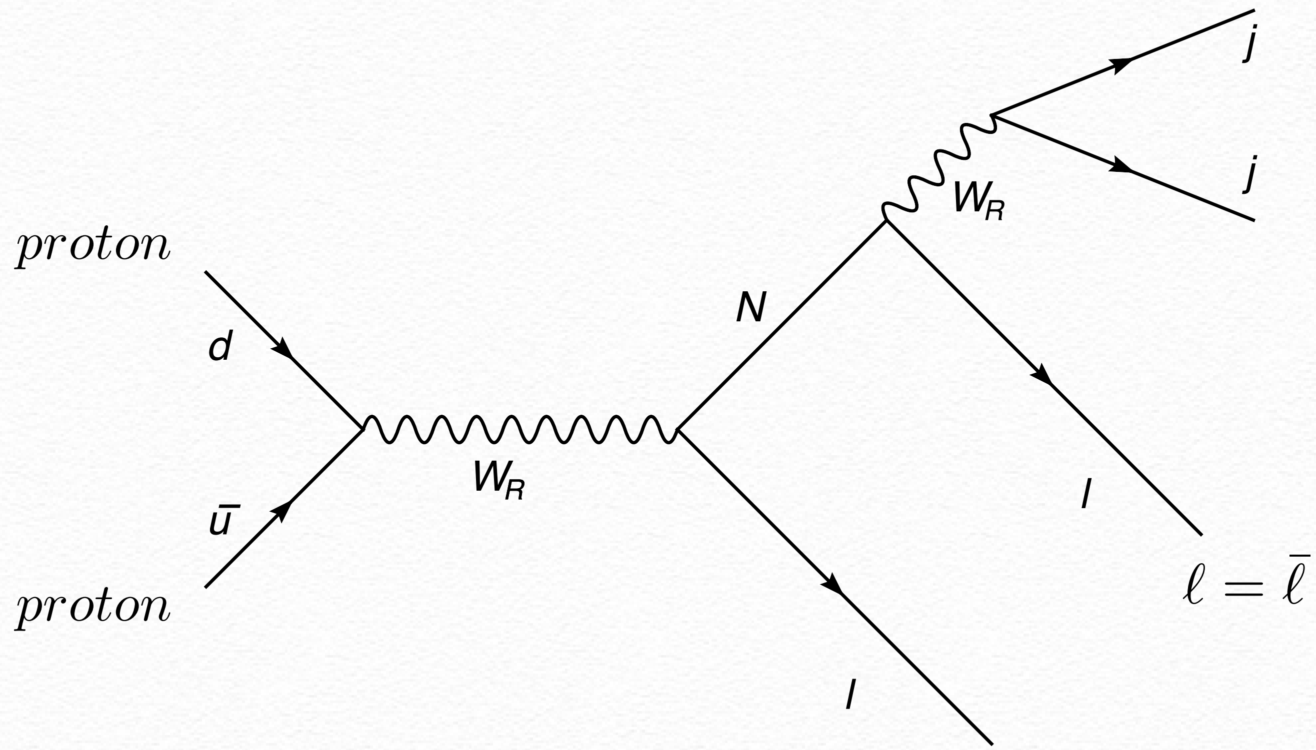
⬇

neutrino light ~ parity broken strongly

SM: $M_{W_R} \to \infty$

LNV @ LHC

Keung, GS '83



measure $M_N = V_R m_N V_R^T$

- connection with $0\nu 2\beta$
- connection with LFV

Tello et. al. 2011

Tello PhD thesis 2012

Lepton flavour violation

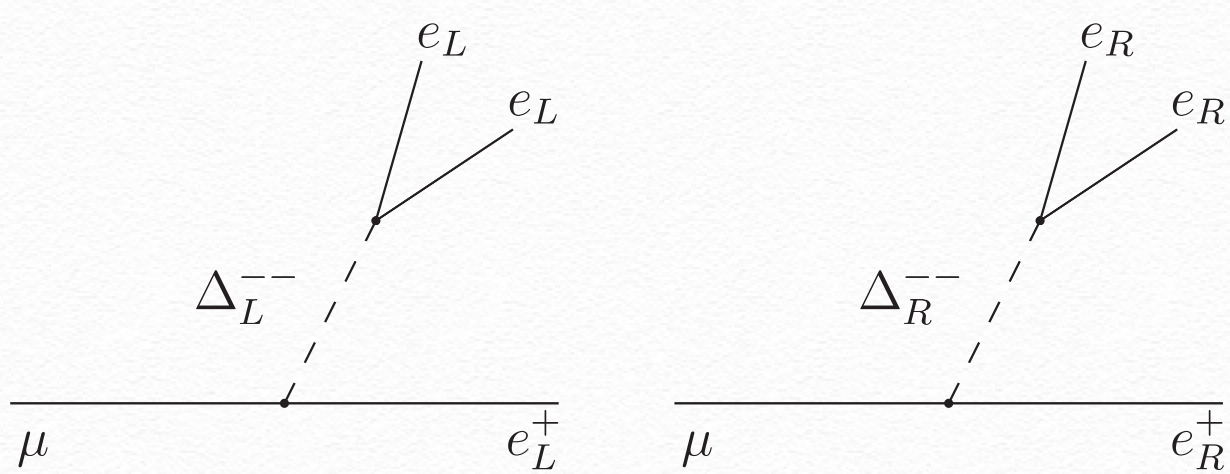
- mu -> 3 e

Cirigliano, Kurylov, Ramsey-Musolf, Vogel ‘04

Tello PhD thesis ‘12

$B_{\mu\to 3e} \lesssim 10^{-12}$

SINDRUM



$$BR(\mu \to e e \bar{e}) = \frac{1}{2} \frac{M_W^4}{M_{W_R}^4} \left| \frac{M_N M_N}{m_{\Delta^{++}}^2} \right|_{e\mu}^2$$

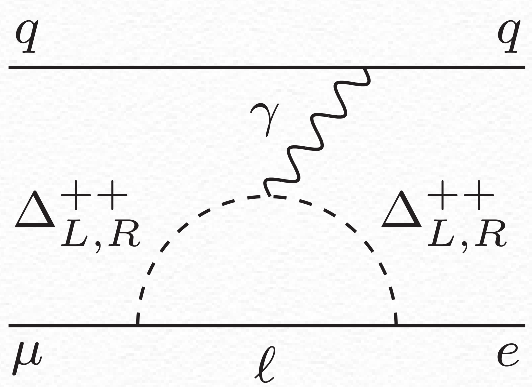
N light ~ charm quark light

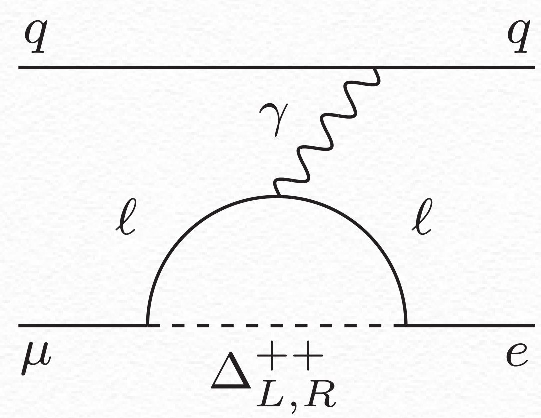
$$M_N = V_R m_N V_R^T$$

probed in KS process

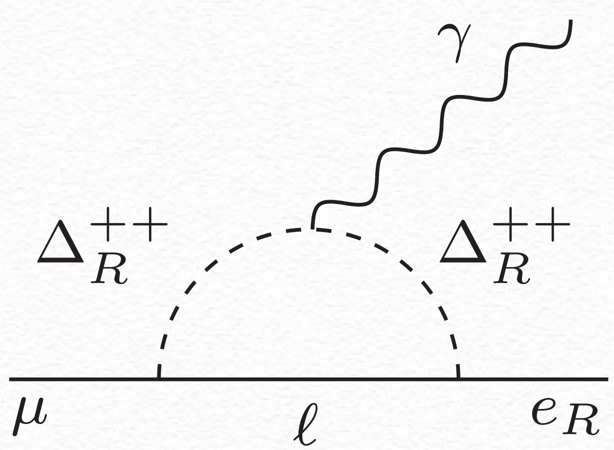
Cirigliano, Kurylov, Ramsey-Musolf, Vogel ‘04

- mu -> e conversion $B_{\mu\to e} < 7 \times 10^{-13}$ SINDRUM II





- mu -> e gamma $B_{\mu\to e\gamma} < 4 \times 10^{-13}$ MEG ‘16



$$\Gamma(\mu X \to e X) \simeq \Gamma(\mu \to e\gamma)$$

Tello PhD thesis ‘12

LR needed?

produce *N* through W -> needs nu - *N* mixing

↓

not the seesaw

$$\begin{matrix} \nu \\ N \end{matrix} \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \xrightarrow{M_D \ll M_N} M_\nu = -M_D^T \frac{1}{M_N} M_D$$

Minkowski; Mohapatra, GS;
Glashow; Gell-Mann et. al.; Yanagida

↓

nu - *N* mixing $\Theta = M_D/M_N$ negligible

Seesaw ambiguity

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$ → $$M_D = i\sqrt{M}_N \, O \, \sqrt{M}_\nu$$

$OO^T = 1$ arbitrary complex orthogonal matrix

↓

produce N through arbitrary mixing $\Theta = M_D / M_N$

↓

not the seesaw

LR = charge conjugation

Nemevsek, GS, Tello 2012

$$Y_D = Y_D^T \quad \Rightarrow \quad M_D = M_D^T$$

$$M_\nu = -M_D^T \frac{1}{M_N} M_D \quad \rightarrow \quad M_D = i\sqrt{M_N}\sqrt{\frac{1}{M_N} M_\nu}$$

$$O = \sqrt{M_N}\sqrt{M_N^{-1} M_\nu}\sqrt{M_\nu}^{-1}$$

seesaw untangled

LR = parity

GS, Tello 2016 - 2020

P: $M_D = M_D^\dagger$

$$M_\nu = M_D^T \frac{1}{M_N} M_D$$ ➔ $$\frac{1}{\sqrt{M_N}} M_\nu^* \frac{1}{\sqrt{M_N}} = X X^*$$ **with** $$X = \frac{1}{\sqrt{M_N}} M_D \frac{1}{\sqrt{M_N^*}}$$

$$X = X^\dagger$$

$$X X^* = O S\, O^T$$ O = orthogonal

$$X = O \sqrt{S}\, O^\dagger$$ all fixed as in the case of C

LR = self-contained

Nemevsek, GS, Tello 2012

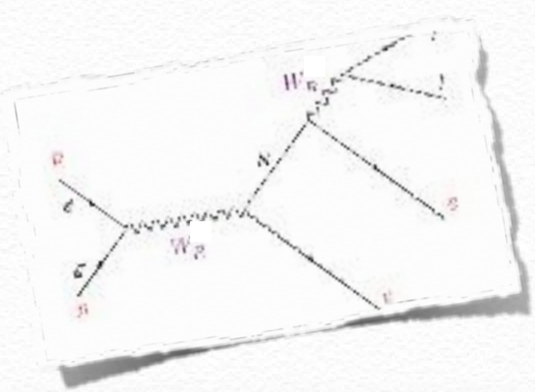
GS, Tello 2016, 2018, 2019

$$\Gamma(h \to \bar{f} f) \propto \frac{m_f^2}{M_W^2} m_h$$

SM for charged fermions

$$\Gamma(N \to W e) \propto \frac{m_N^2}{M_W^2} m_\nu$$

LRSM for neutrino

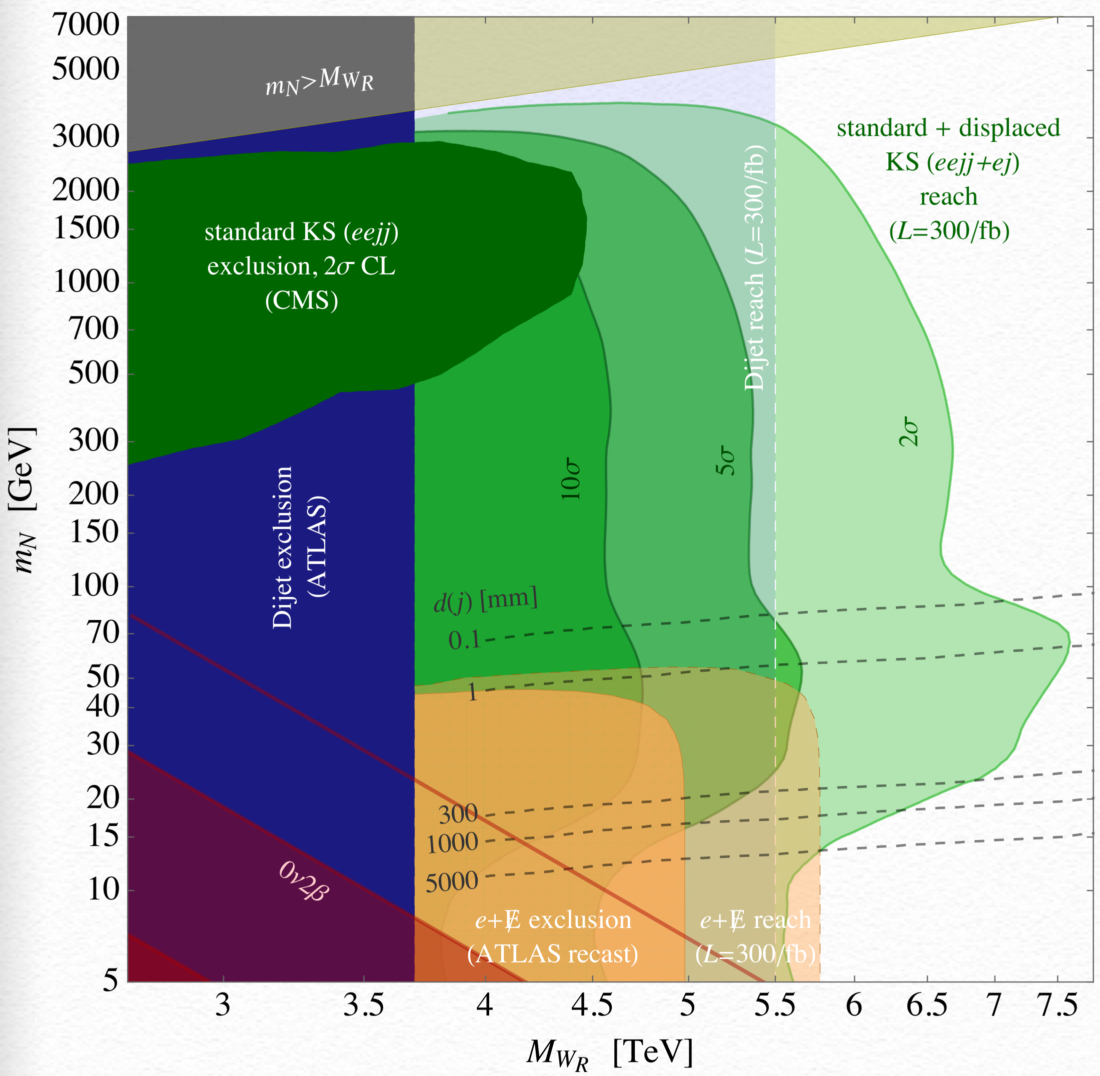


$$M_{W_R} \gtrsim 4 - 5\, TeV$$

depends on m_N

ATLAS 2019

neutrinos (N_R). A search for W_R boson and N_R neutrino production in a final state containing two charged leptons and two jets ($\ell\ell jj$) with $\ell = e, \mu$ is presented here. The exact process of interest is the Keung–Senjanović (KS) process [10], shown in Figure 1. When the W_R boson is heavier than



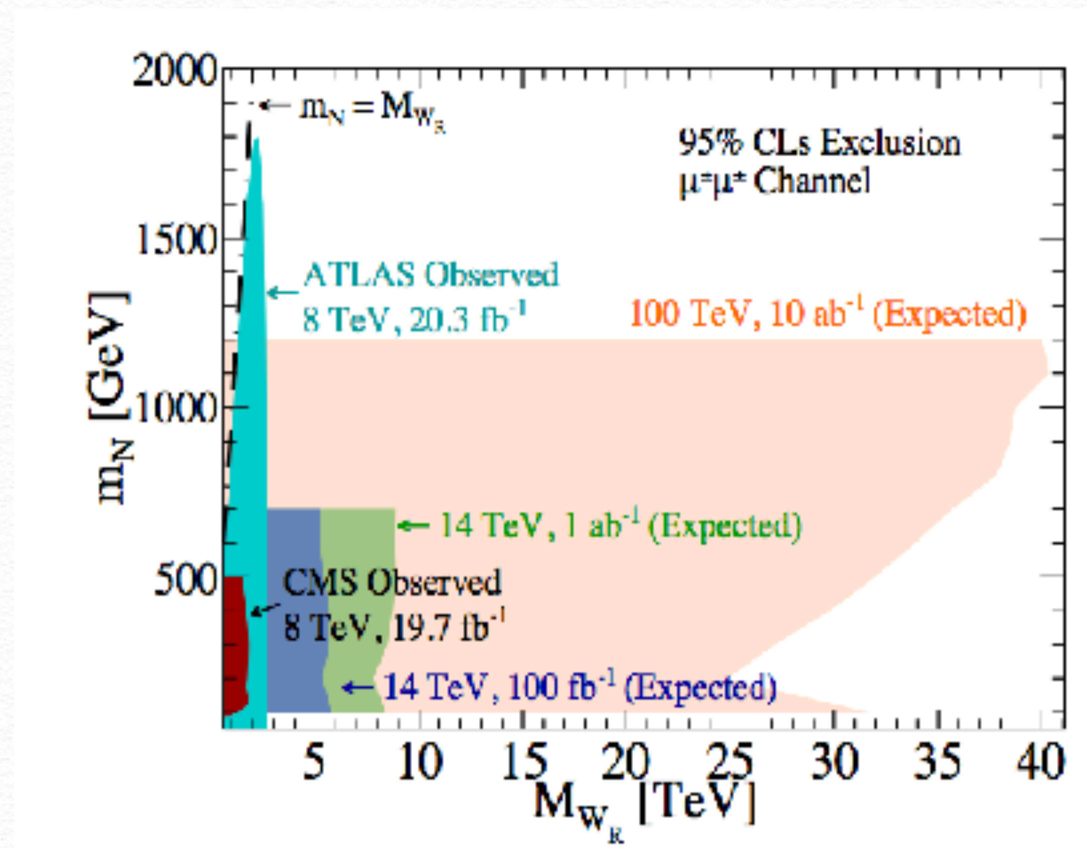
Nemevsek, Nesti, Popara 2018

LHC reach

$M_{W_R} \gtrsim 4\,TeV$ dijets ATLAS 2019

100 TeV collider reach

Ruiz 2017



Outlook

- p decay expected as we all know
- other BNV a gamble - stakes high
- no predictive, self-contained theory of BNV
- LNV expected in 0nu2beta
- LNV at hadron colliders possible
  - expected if e is RH in 0nu2beta
- LRSM - predictive, self-contained theory of neutrino mass and LNV (and LFV) both at low and high energy

Thank you

discussion yesterday

Goran: non n-n bar in GUT (generically)

Rabi: Babu and I have a model 2012

model: assume miracle - light leptoquarks and show you can embed it

only way to make ‘predictions’ = assume survival principle for scalars too

Mohapatra, GS ‘82

not a theory

Warning

Feynman

Somebody makes up a theory: The proton is unstable. They make a calculation and find that there would be no protons in the universe anymore! So they fiddle around with the numbers, putting a higher mass into the new particle, and after much effort they predict that the proton will decay at a rate slightly less than the last measured rate the proton has been shown not to decay at.

When a new experiment comes along and measures the proton more carefully, the theories adjust themselves to squeeze out from the pressure. The most recent experiment showed that the proton doesn't decay at a rate that is five times slower than what was predicted in the *last stand* of the theories. What do you think happened? The phoenix just rose again with a new modification of the theory that requires even more accurate experiments to check it. Whether the proton decays or not is not known. To prove that it does not decay is very difficult.

True theory = miracle

- not tailor ordered to fix a bug

- predictions = surprises

example: Dirac equation ➔ positron

example: GR ➔ BH, gravitational waves

example: SM ➔ neutral currents, Higgs
origin of fermion masses

https://inference-review.com/article/the-yang-mills-model

- not a personal model, modified as one goes along

GUT theory self-contained

it's like coming with GR, but much more amazing

14 orders of magnitude above SM - and predictive?

SUSY 2019 - Corpus Christi, Texas - bar ~ midnight

Babu: theory is what you write down -
and leave for others to make predictions for all seasons

Einstein ‘15

Glashow ’61

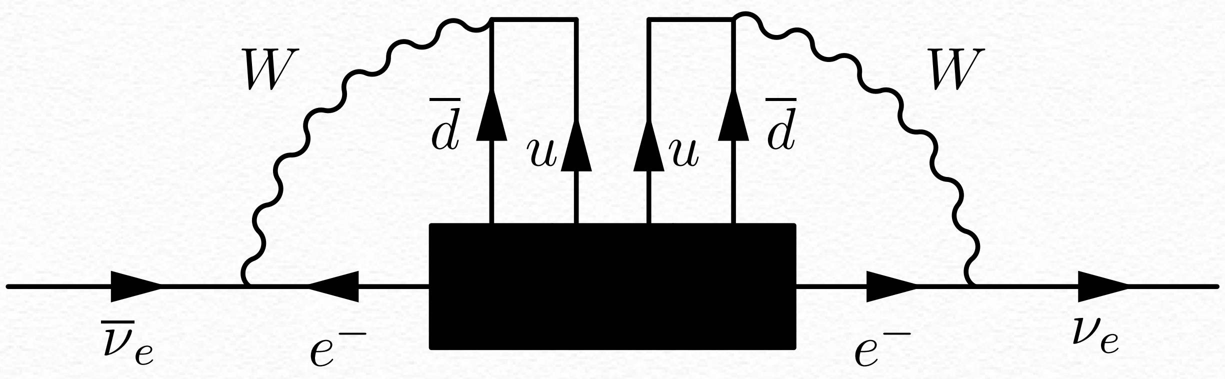
Weinberg ’67

0nu2beta -> Neutrino = Majorana?

Schechter, Valle '82

Cirigliano talk

new physics behind 0nu2beta ➔ Majorana mass



➔

$$\delta m_\nu \simeq 10^{-24}\, eV$$

Duerr, Lindner, Merle ' 11

effectively = 0

Planck scale seesaw $m_\nu \simeq 10^{-5}\, eV$

Feinberg, Goldhaber '59

example $$\frac{g_{LNV}}{m_e}\pi^+\,\pi^+ e\,e$$

use electron mass cutoff - instead of say Fermi scale

↓

coupling almost vanishing $g_{LNV} \lesssim 10^{-25}$

effective field theory took time

Generations - Lepton Flavour Violation?

$$O_\mu = \frac{1}{\Lambda^5}(\mu_L \mu_L)(c_L c_L d_L^c d_L^c) \qquad O_e = \frac{1}{\Lambda^5}(e_L e_L)(u_L u_L d_L^c d_L^c)$$

expect

$$\frac{1}{\Lambda^2}(c\,\mu)(\bar{u}\bar{e}) \rightarrow \Gamma(D^0 \to \mu\bar{e}) \simeq \frac{m_D^5}{\Lambda^4} \rightarrow \Lambda \gtrsim 10^5 GeV$$

$0\nu 2\beta$ hopelessly small

flavour could be conserved → mass suppression can save it

$$(V_R)_{ij} \simeq (V_L)_{ij} - i\epsilon \frac{(V_L)_{ik}(V_L^\dagger m_u V_L)_{kj}}{m_{d_k} + m_{d_j}}$$

$$\langle \Phi \rangle = v \, \mathrm{diag}(\cos\beta, -\sin\beta e^{-ia})$$

$$\epsilon = s_a t_{2\beta}$$

↓

$$\theta_R^{12} - \theta_L^{12} \simeq -s_a t_{2\beta} \frac{m_t}{m_s} s_{23} s_{13} s_\delta$$

$$\theta_R^{23} - \theta_L^{23} \simeq -s_a t_{2\beta} \frac{m_t}{m_b} \frac{m_s}{m_b} s_{12} s_{13} s_\delta$$

$$\theta_R^{13} - \theta_L^{13} \simeq -s_a t_{2\beta} \frac{m_t}{m_b} \frac{m_s}{m_b} s_{12} s_{23} s_\delta$$

GS, Tello 1408.3835 (hep-ph)

GS, Tello 1502.05704 (hep-ph)

long history

Zhang, An, Ji, Mohapatra '07

conspiracy of small mixings suppression

justifies quoted limits on

- assume same L & R mixings

EW genesis similar to SM

Dark matter $m_N \simeq keV$ spectrum and VR fixed

$$M_{W_R} \gtrsim 20\, TeV \quad \text{or} \quad M_{W_R} \simeq 5\, TeV$$

Nemevsek, GS, Zhang ‘2012

Bezrukov, Hettmansperger, Lindner ’2009