Baryon Number, Lepton Number

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B&L: why so important?

Attempt: extract the essence of both BLV

Focus: predictive framework from fundamental principles

Messages:

LNV
fundamental theory, accessible in principle at colliders,
connection with low energy processes: 0nu2bta, LFV, …

BNV
no fundamental theory. Nucleon decay: effective theory
surprisngly predictive but unreachable energies

Concept of B, L

1930's: why is proton stable? ➔ B number conserved?

Stueckelberg; Wigner ‘39

Useful bookkeeping, says also other processes suppressed: $n \to \bar{n}$

Similarly L conserved? $p \to \gamma + e^+$ $p \to \pi^0 + e^+$

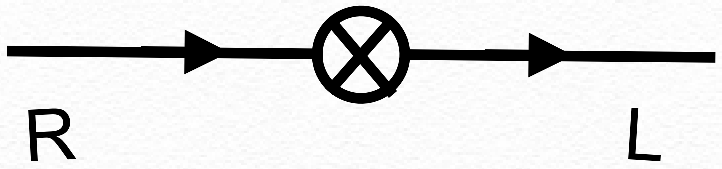
LNV: Neutrino = anti neutrino?

Majorana ‘37

$$\psi_M = \psi_\nu + \psi_\nu^*$$

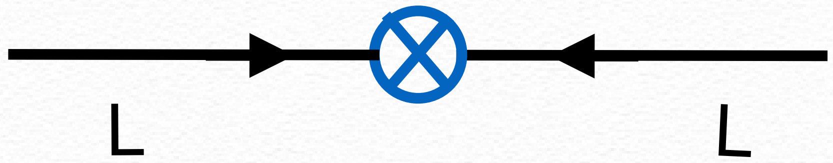
Dirac mass

$$m_D(\bar{\psi}_R \psi_L + h.c.)$$



Majorana mass

$$m_M(\psi_L^T C \psi_L + h.c.)$$



Lepton Number Violation

- nuclear beta decay $n + n \to p + p + e + e$ *Furry ‘38*
- hadron colliders $p + p(\bar{p}) \to \ell + \ell + jets$ *Keung, GS ‘83*

$$\ell = e.\mu, \tau$$

Majorana mass

$$\psi_L = \begin{pmatrix} u \\ 0 \end{pmatrix} \quad \rightarrow \quad \psi_L^T C \psi_L = u^T i\sigma_2 u$$

u = spin 1/2 state

mass term = bilinear in u

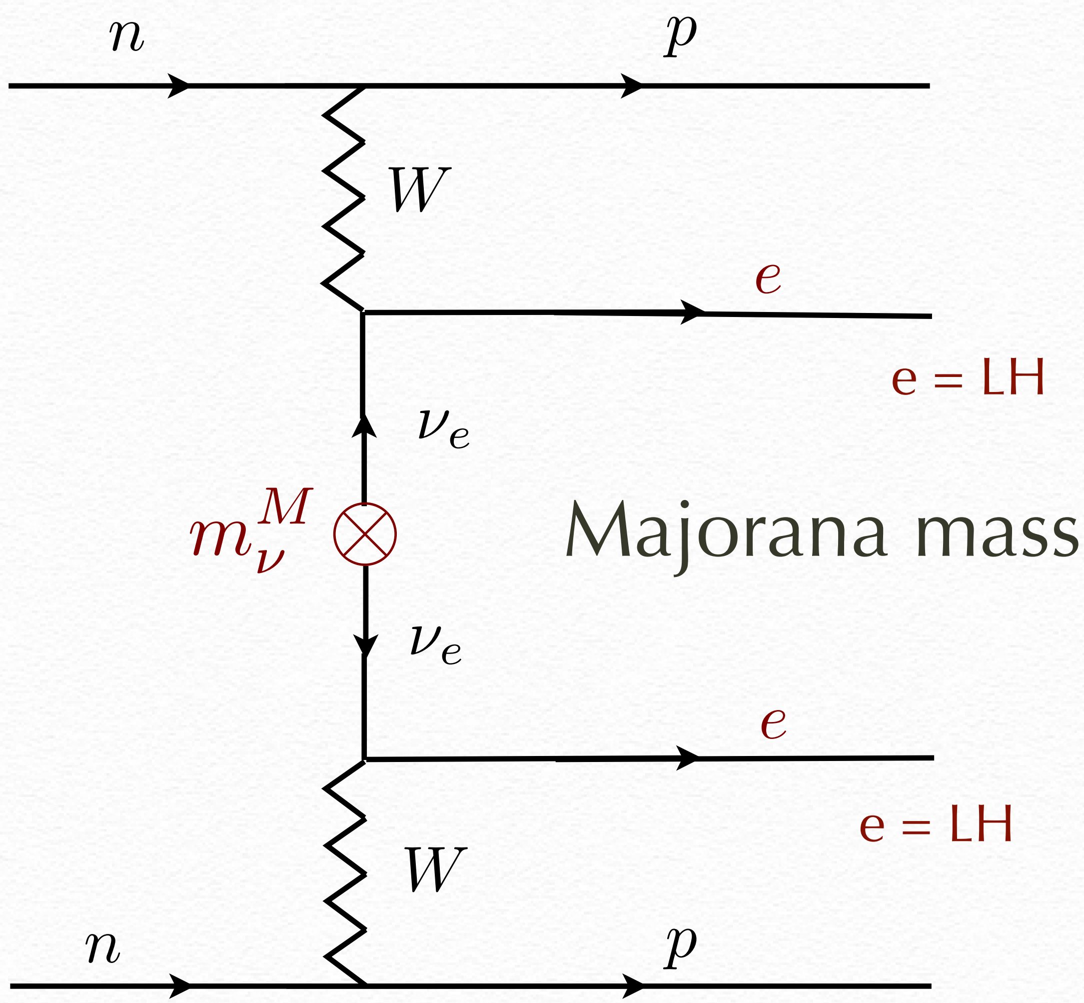
$$u^T i\sigma_2 u \quad \rightarrow \quad |\uparrow\downarrow - \downarrow\uparrow\rangle$$

spin 0 = Lorenz invariant state

if charged particle, then uu carries charge

Neutrinoless double beta decay

Furry 1938



Majorana mass

$$\tau_{0\nu2\beta} \gtrsim 10^{26} yr$$

↓

$$m_\nu^M \lesssim 1(0.3)eV$$

probe of neutrino Majorana mass?

NO

Caveat: new physics involved?

Feinberg, Goldhaber '59

Pontecorvo '64

Mohapatra, GS '79

Mohapatra, GS '81

d=9 operator $$\mathcal{H}_{eff} = \frac{1}{\Lambda^5}\,\bar{p}\,\bar{p}\,\bar{e}\,\bar{e}\,n\,n$$

$\tau_{0\nu 2\beta} \gtrsim 10^{26} yr$ ➔ $\Lambda \gtrsim 3\, TeV$

tailor made for LHC

neutrino = RH ➔ new physics (not neutrino mass itself)

probe of the theory of neutrino mass?

SM and neutrino Majorana mass

SM: neutrino massless

d = 5 $$\mathcal{L}_{eff} \propto \frac{1}{\Lambda}(\ell_L^T i\sigma_2 \Phi) C (\Phi^T i\sigma_2 \ell_L)$$ *Weinberg '79*

$$\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \Phi = \begin{pmatrix} 0 \\ h+v \end{pmatrix}_L$$

$$\Downarrow$$

$$m_\nu = \frac{v^2}{\Lambda} \qquad y_\nu = \frac{v}{\Lambda} = \frac{m_\nu}{v}$$

Not very useful → Need UV completion: theory

Left-Right Symmetric Model

Pati, Mohapatra, Salam   1974

Mohapatra, GS   1975

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

neutrino is massive

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \Bigg| \qquad \begin{pmatrix} \boxed{\nu_R} \\ e_R \end{pmatrix} \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$W_L \qquad\qquad \boxed{W_R}$$

$$m_{W_R} \gg m_{W_L}$$

Neutrino mass long before experiment

Seesaw mechanism for neutrino mass

N= RH neutrino

$$M_\nu = -M_D^T \frac{1}{M_N} M_D$$

LR spontaneously broken: $m_N \propto M_{W_R}$

Minkowski 1977

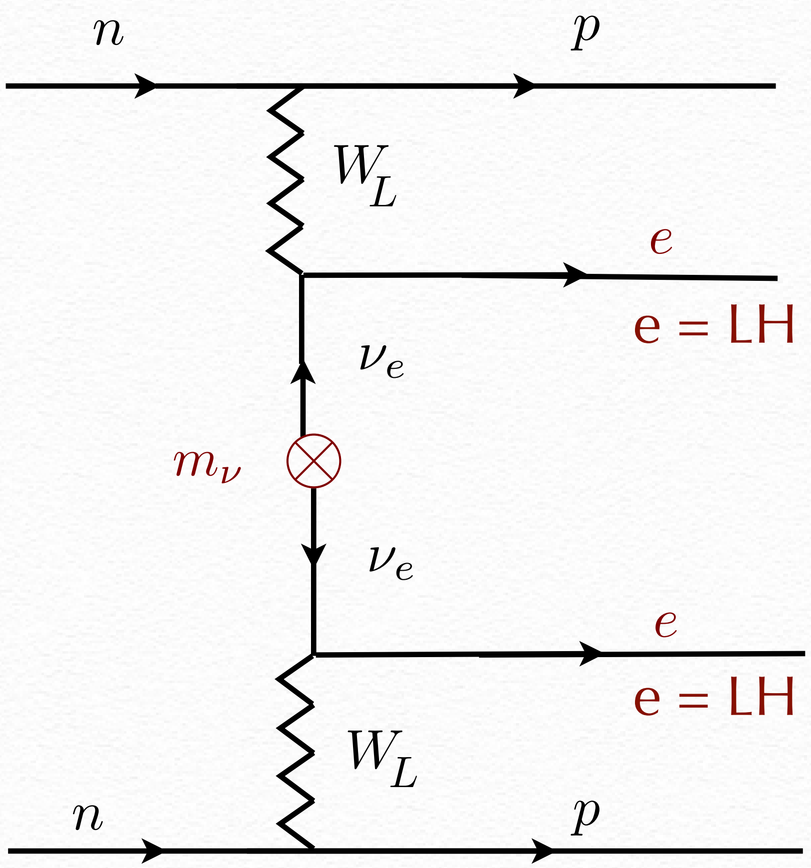
Mohapatra, GS 1979

neutrino is light, since N is heavy

neutrino mass ~ parity violation in nature

New source for double beta

Mohapatra, GS '79 Mohapatra, GS '81



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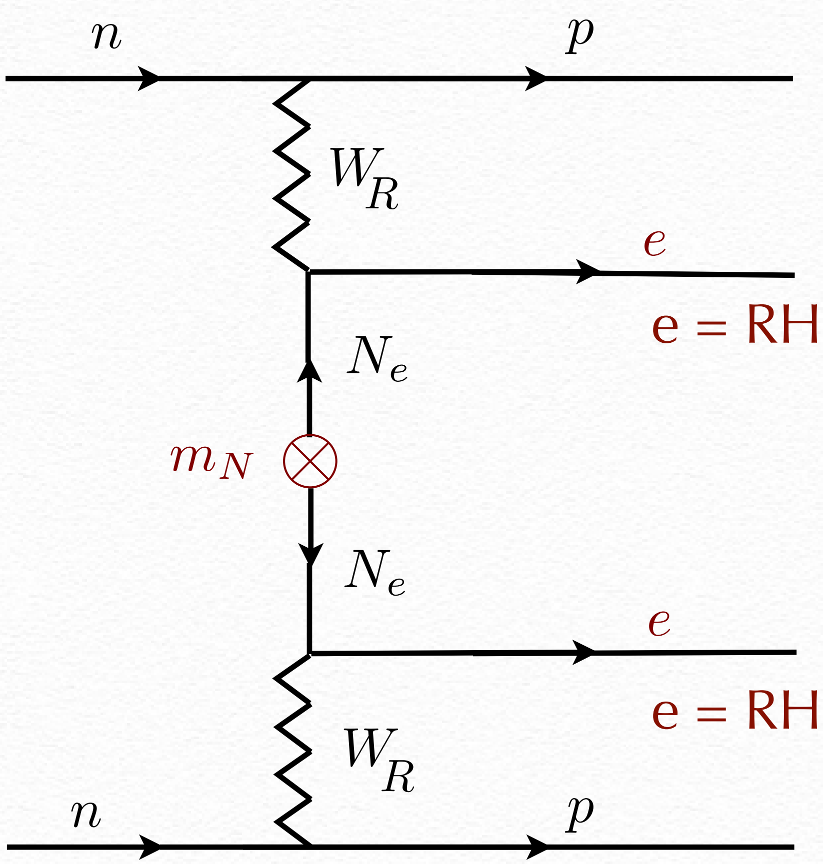


e = RH → $M_{W_R} \lesssim 10\,TeV$ LHC?

Nemevsek, Nesti, GS, Tello 2011

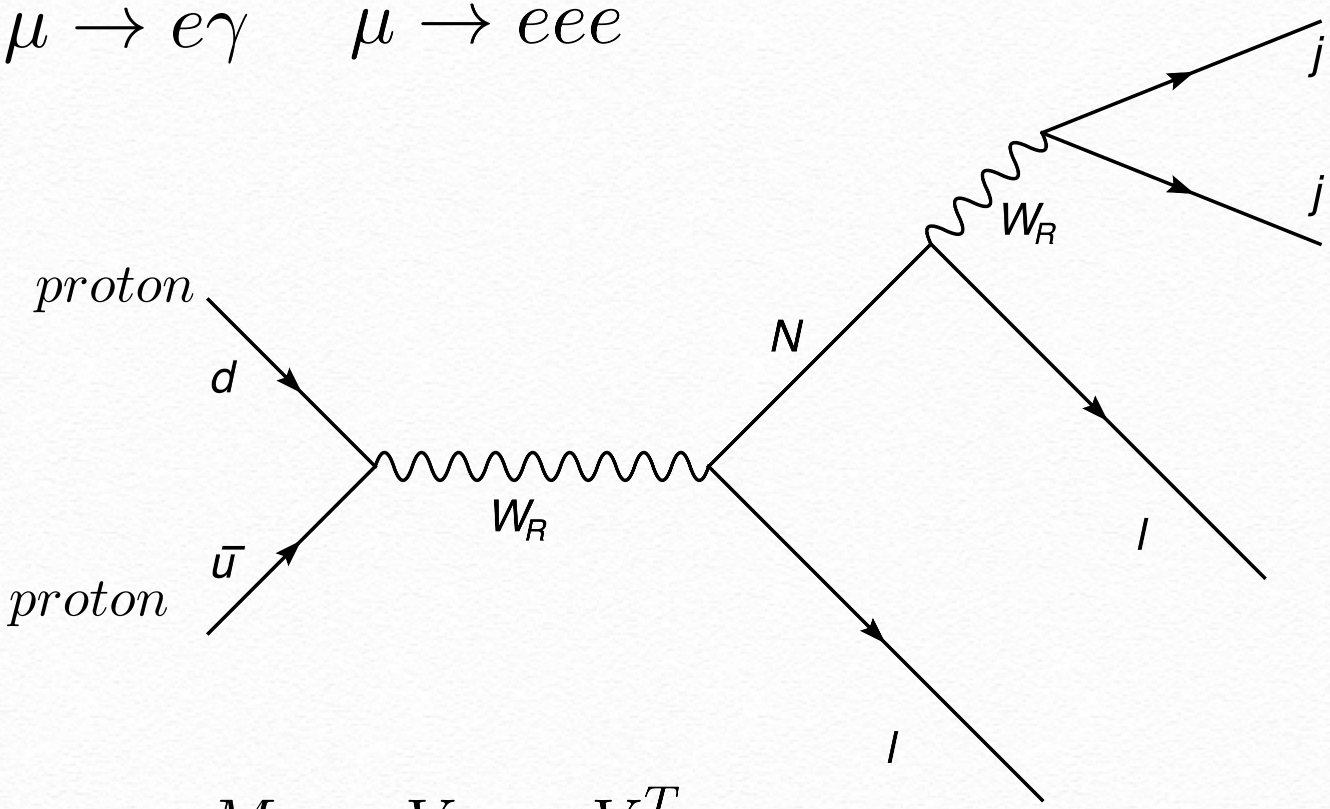
LNV @ hadron colliders

Keung, G.S. ’83

moreover, LFV

Tello PhD thesis ‘12

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



probe of Majorana nature of N

50% lepton - 50 % antileptons

$$M_N = V_R m_N V_R^T$$

0nu2beta connection

Ferrari et al ’00

Nemevsek, Nesti, GS, Zhang ’11

Vasquez ‘14

Nemevsek, Nesti, Popara ’18

ATLAS hep-ex 1904.12679

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

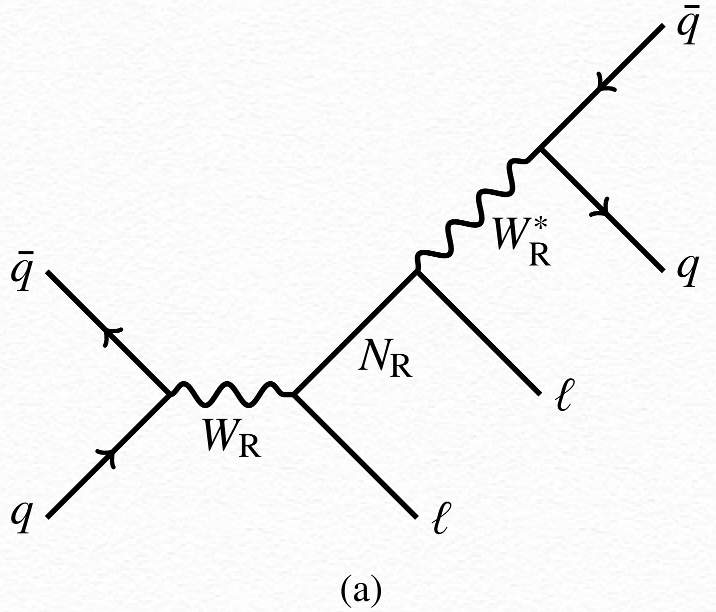


Figure 1: The KS process, for (a) the $m_{W_R} > m_{N_R}$ case

$M_{W_R} \gtrsim 5\, TeV$ for $m_N \lesssim M_{W_R}$

di-jet $M_{W_R} \gtrsim 5\, TeV$

Neutrino mass: Higgs mechanism

$$\Gamma(N \to We) \propto m_\nu m_N^2$$

Nemevsek, GS, Tello   2012

and a number of similar decays

GS, Tello   2015 - 2020

testable at LHC?

also the quark sector predictive:

LH mixing -> RH mixings

GS, Tello   2015, 2016

SM for charged fermions

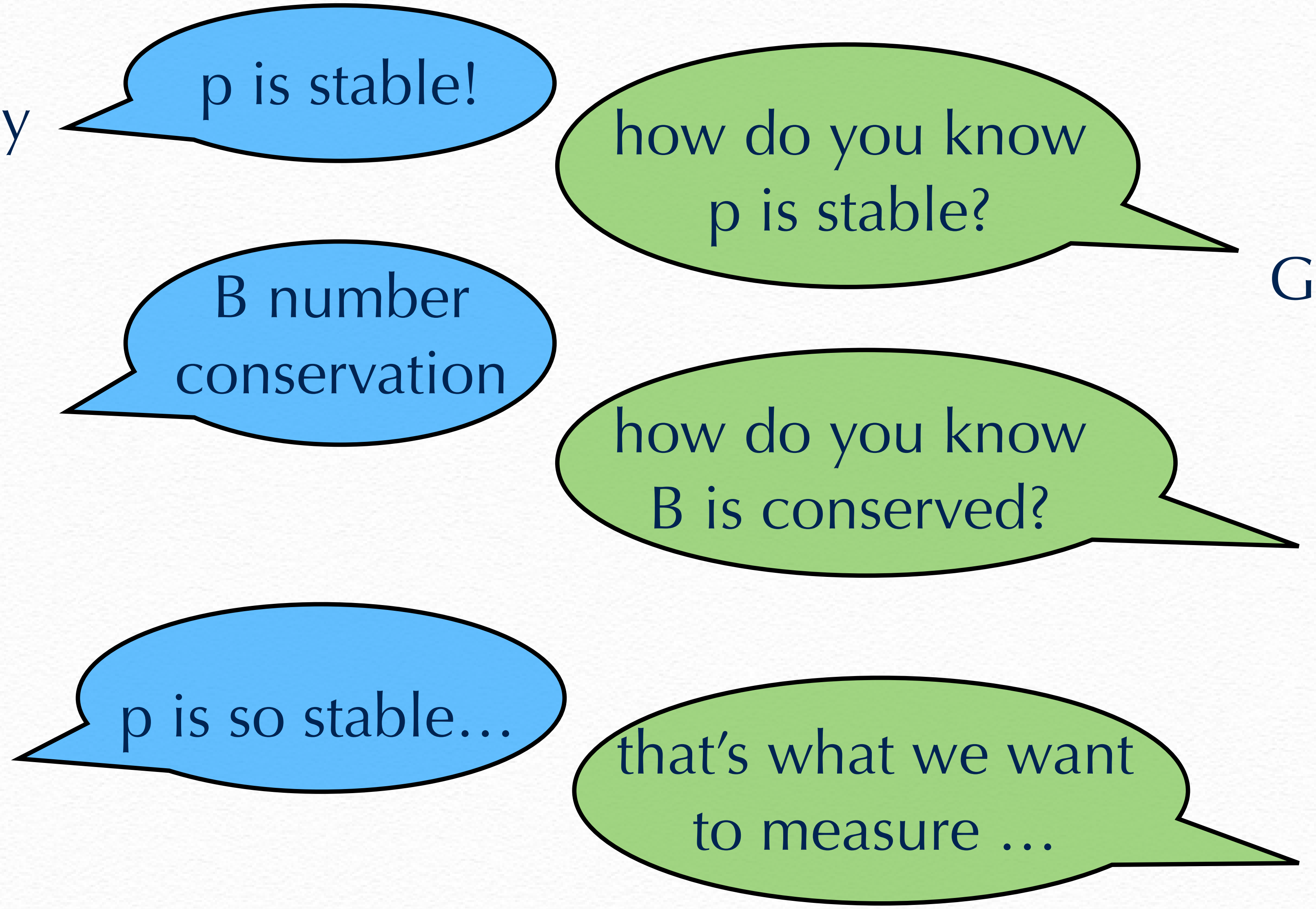
$$\Gamma(h \to f\bar{f}) \propto m_h m_f^2$$

Weinberg ‘67

BNV: proton decay

Feel in the bones: $\tau_p \gtrsim 10^{18} yr$ *Goldhaber ‘59s*

Goldhaber, Reines ‘56 large water detectors to measure p lifetime



Funding agency

p is stable!

how do you know p is stable?

G & R

B number conservation

how do you know B is conserved?

p is so stable…

that’s what we want to measure …

Proton decay: effective

Weinberg ‘79

Lorentz and color $\mathcal{H}_{eff} \propto \frac{1}{\Lambda^2} q\, q\, q\, \ell(\bar{\ell})$

SK: $\tau_p \gtrsim 10^{34} yr$ ➜ $\Lambda \gtrsim 10^{16} GeV$

Why talk about it? ➜ Grand Unification:

$\Lambda \simeq M_{GUT} \simeq 10^{16} GeV$ *Georgi, Quinn, Weinberg ‘74*

No truly predictive theory

Nucleon decay predictions from effective theory

Lorentz, color, ew: $\mathcal{H}_{eff} \propto \frac{1}{\Lambda^2} q\, q\, q\, \ell$

Weinberg ‘79

GS ‘09

↓

- B-L = conserved → $N \to \ell^+ + ...$ $(n \not\to K^+ + \ell)$
- if q = s → $n \not\to K^- + \bar{\ell}$ $(K^- = \bar{u}s)$

Neutron: no two-body Kaon decay

And more

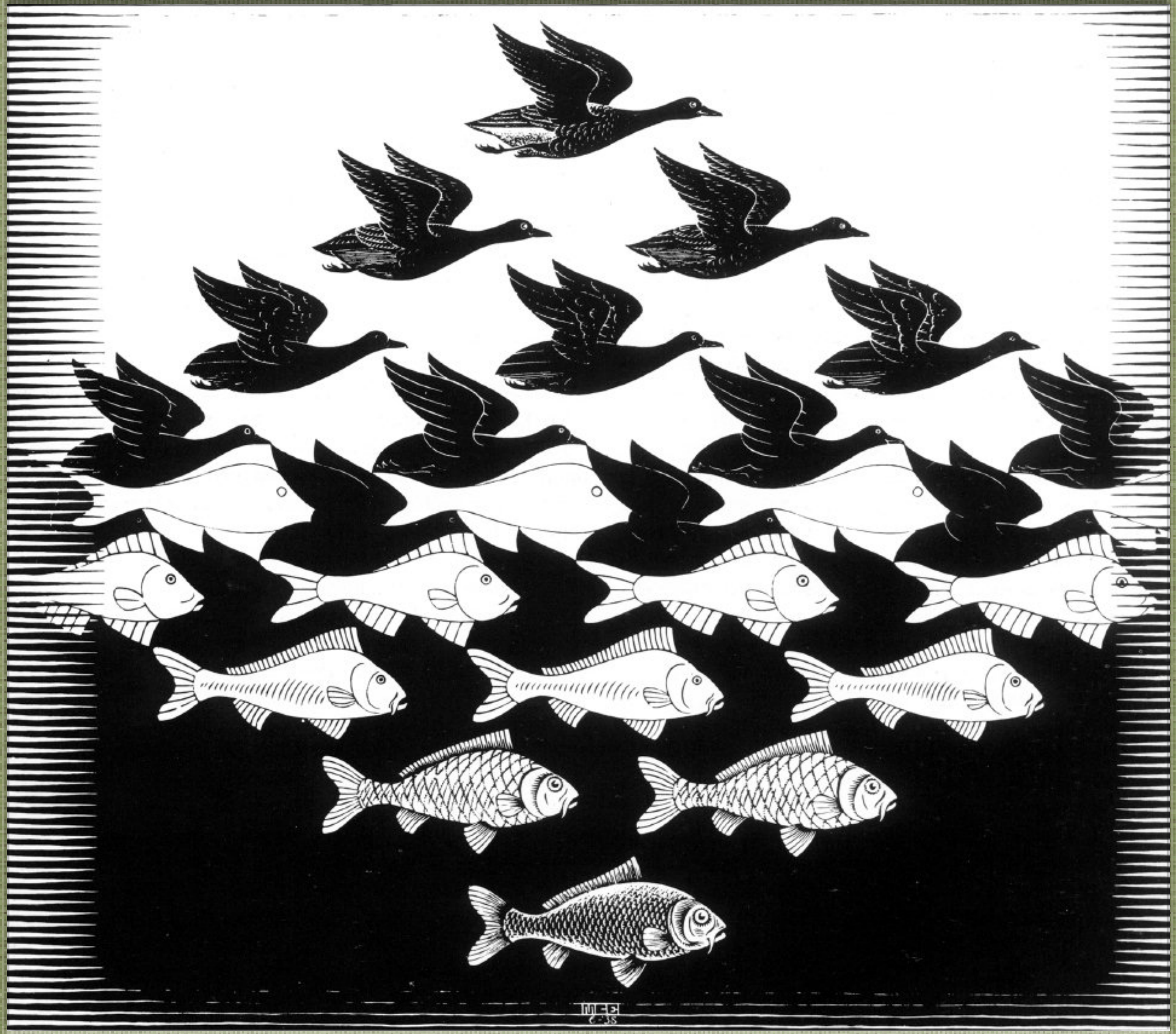
$$\Gamma(p \to \ell_R^+ \pi^0) = \tfrac{1}{2}\Gamma(n \to \ell_R^+ \pi^-)$$

$$= \tfrac{1}{2}\Gamma(p \to \bar{\nu}\pi^+) = \Gamma(n \to \bar{\nu}\,\pi^0)$$

$$\Gamma(p \to \ell_L^+ \pi^0) = \tfrac{1}{2}\Gamma(n \to \ell_L^+ \pi^-)$$

Clear tests of high energy - GUT inspired - predictions

Thank you



Does gravity matter?

- One needs: $M_{GUT} \ll M_{Pl}$ $\quad M_{Pl} = \sqrt{G_N^{-1}}$

$$\Lambda_{strong} = \frac{M_{Pl}}{N_{species}}$$

Dvali …

- There is more to it: gravitational anomaly

$$\langle \bar{\nu}\nu \rangle = \Lambda^3_{gravity} \lesssim M^3_{Pl}\, e^{-N_{species}}$$

Dvali ‘05

real degrees of freedom $\quad N^{SM}_{species} = 118$

$\Lambda_{gravity} \lesssim GeV$ $\quad$ can impact neutrino mass

Minimal SU5

$M_{GUT} \lesssim 10^{15}\, GeV$ ➔ $\tau_p \lesssim 10^{30}\, yr$

Georgi, Quinn, Weinberg ‘74

“Everybody rushed underground” *Goldhaber ?*

Proton decay: predictions?

Minimal SU(5) → N decay branching ratios = f(CKM)

Georgi, Glashow ‘74

Mohapatra ‘79

but wrong fermion mass relations: $m_e = m_d$

↓

Cure with d=5 terms → lose predictions

GUT problems

- Small Higgs representations: need d> 4

↓

Too many couplings

- Large Higgs representations: huge thresholds

↓

Spectra almost completely arbitrary

Predictive GUT -> a great challenge

Thresholds: Survival principle

Many scalar particles

↓

Assume scalars masses: largest value consistent with symmetries

$m_p = \lambda M$ → $m_p \simeq M$

del Agiola, Ibanez ‘81

Mohapatra, GS ‘82

Fails completely in minimal SO10 with small
Higgs representations = spectrum predicted

Preda, GS, Zantedeschi ‘22

Weak triplet, color octet, leptoquark doublet ~ TeV

$\langle 3_W \rangle = v_T$ modifies W-mass → CDF *GS, Zantedeschi ‘22*