Large Hadron Collider and Left-Right Symmetry in Nature

Goran Senjanović
ICTP, Trieste

prepared for Univ. of Nova Gorica

Symmetries and Particles

- Standard Model of all interactions

  (but gravity*)

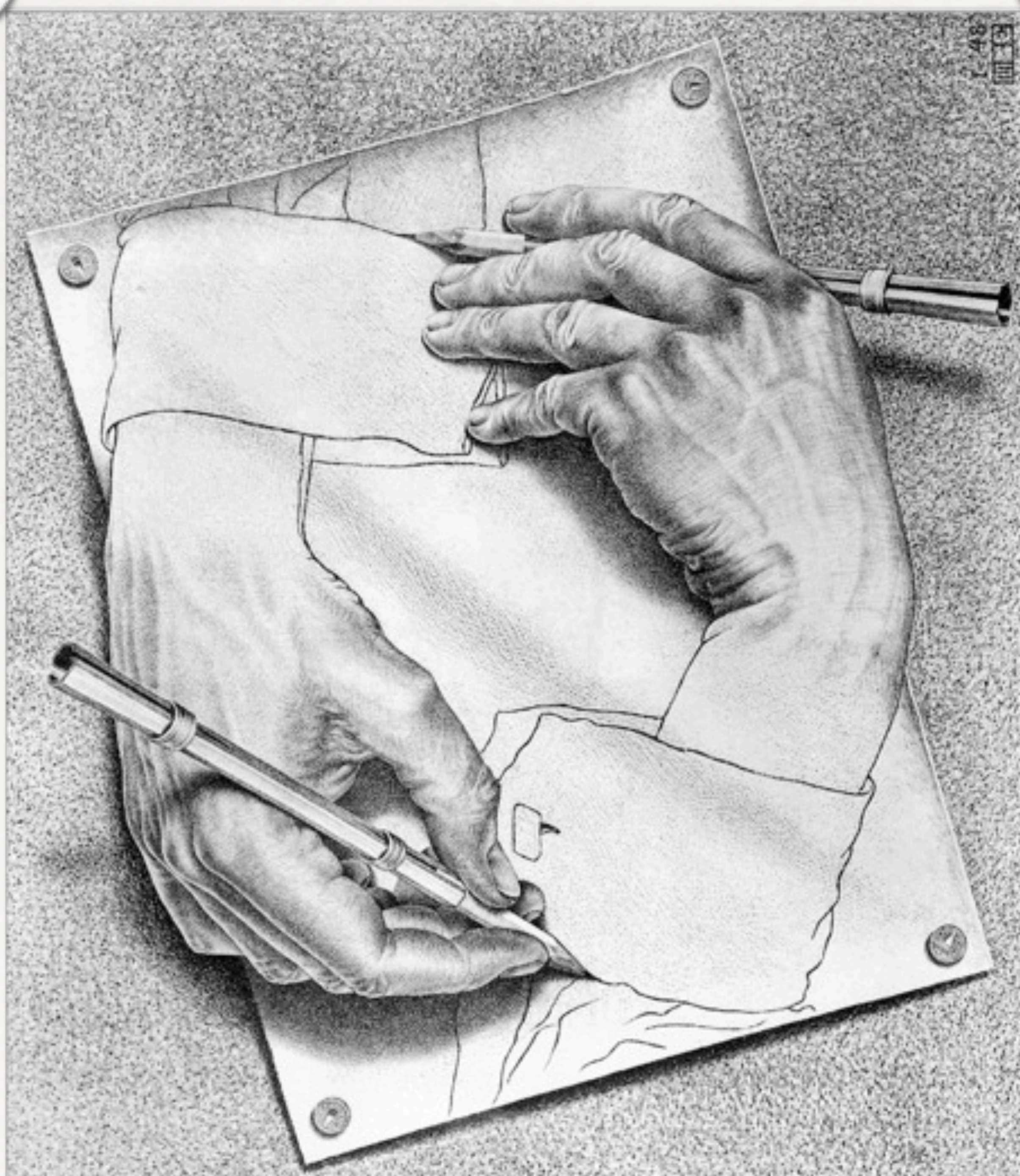
  based on symmetries: local gauge

* gravity negligible:

  38 orders of magnitude weaker than em

⊙ sun - 10^{50} particles zero charge

Theme 1



Parity :

left - right symmetry

images in the mirror

P: all interactions?

Fall and Rise(?)
of Parity

LHC - timely

- [ ] elementary particles - mass, charge, .. spin

angular momentum at rest

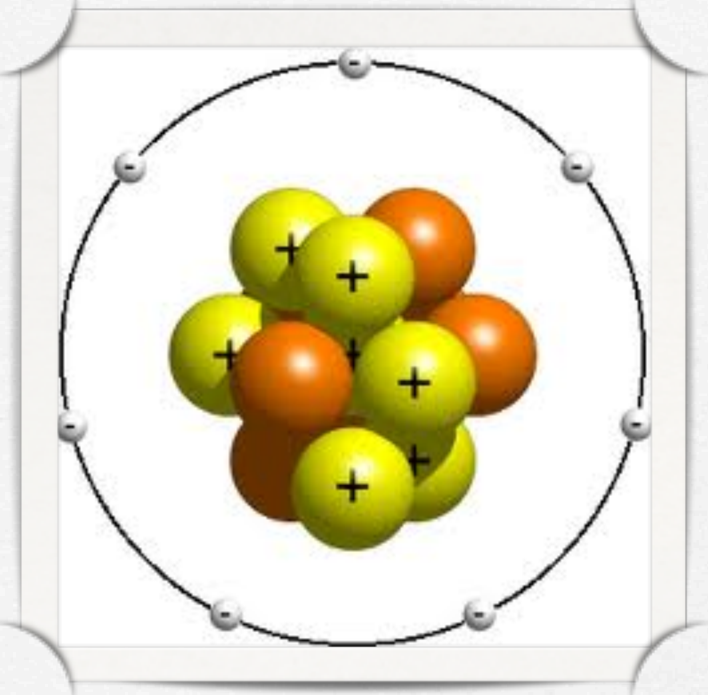
- [ ] Quantum Mechanics:

$s = n/2$

particles keep spinning

- electron (e), proton (p), neutron (n)

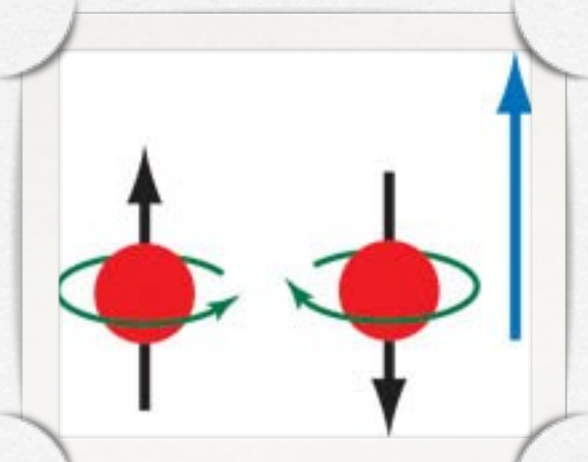
  neutrino (ν)



matter

s = 1/2

(fermions)



$$m_p \simeq m_n \simeq 1\,\mathrm{GeV} \simeq 10^{-24} gr$$

$$m_e \simeq 10^{-3} m_p$$

neutrino mass ?

- "messengers" of forces:

s=1

Force	Mediator	Q_{em}	Spin	Mass
~~Gravitational~~	~~graviton~~	~~0~~	~~2~~	~~0~~
Electro-magnetic	photon	0	1	0
Strong	gluons	0	1	0
Weak	W^+	+1	1	80 GeV
	W^-	-1	1	80 GeV
	Z^0	0	1	91 GeV

- proton and neutron: quarks   Gell-Mann '64

proton

spin s=1/2

neutron

electron, neutrino

relativistic equation for s=1/2

Dirac '28

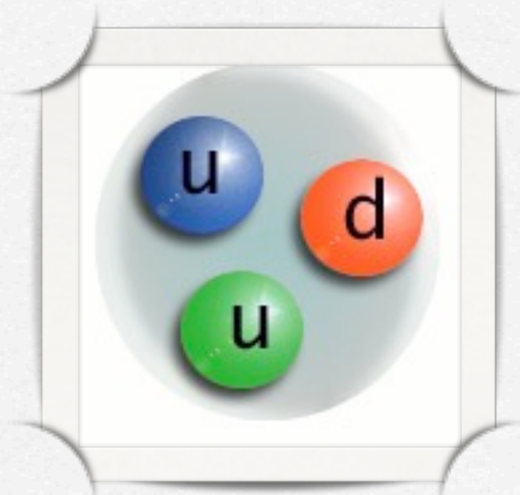
- proton and neutron: quarks

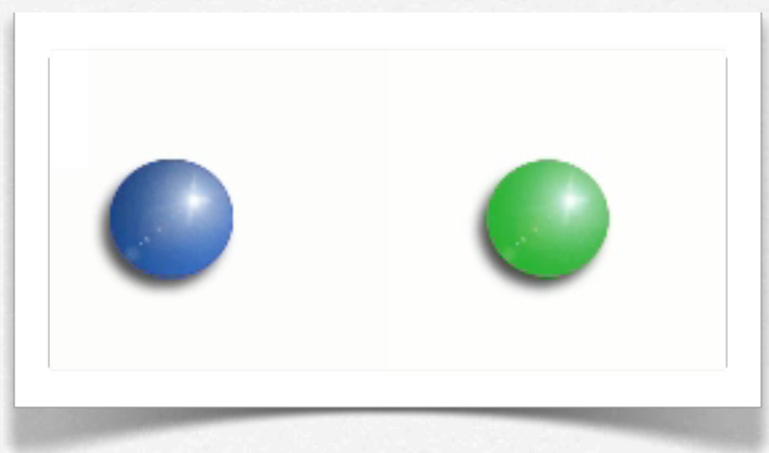
Gell-Mann '64

proton

spin s=1/2

neutron





electron, neutrino

relativistic equation for s=1/2

Dirac '28

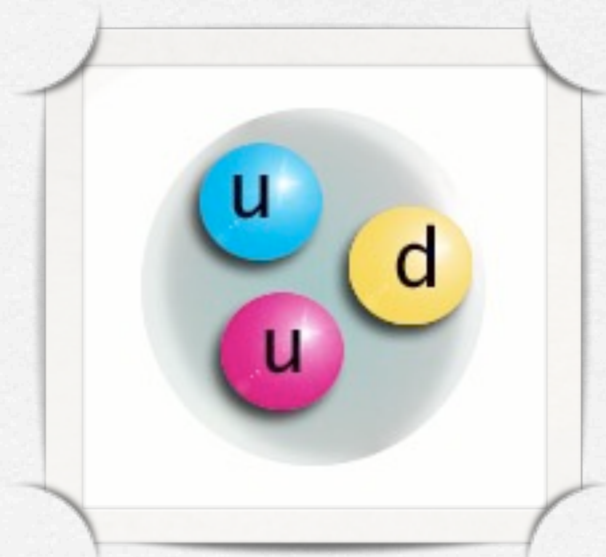
☐ bombshell: anti-particles — Dirac '31

Skobeltsyn '23 — Chao '29

Joliot-Curie ?

$\bar{e}$ — positron = anti electron — Anderson '32

$\bar{p}$ — anti proton — Segre', Chamberlain '55



☐ `theorem':

anti-particle for every fermion (s=1/2)

- `theorem': massive charged fermions

Dirac '28

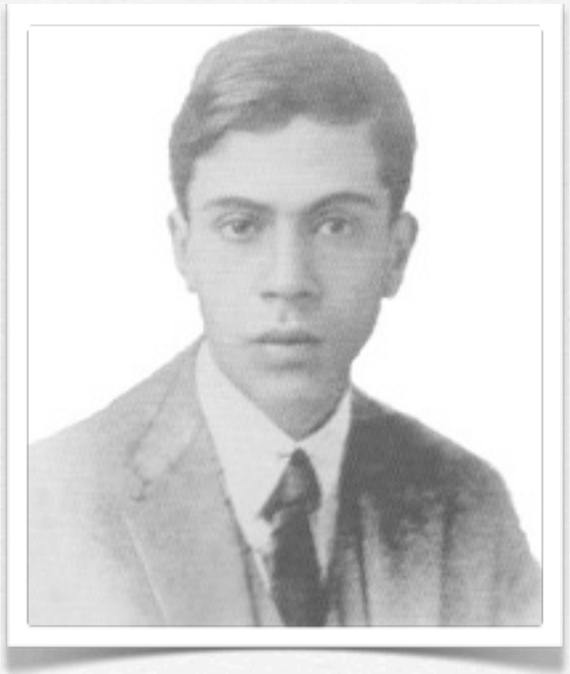
Left and Right

not neutrino ?

Majorana '37

Teoria simmetrica dell'elettrone e del positrone

Il Nuovo Cimento Vol. 14 (1937) p. 171

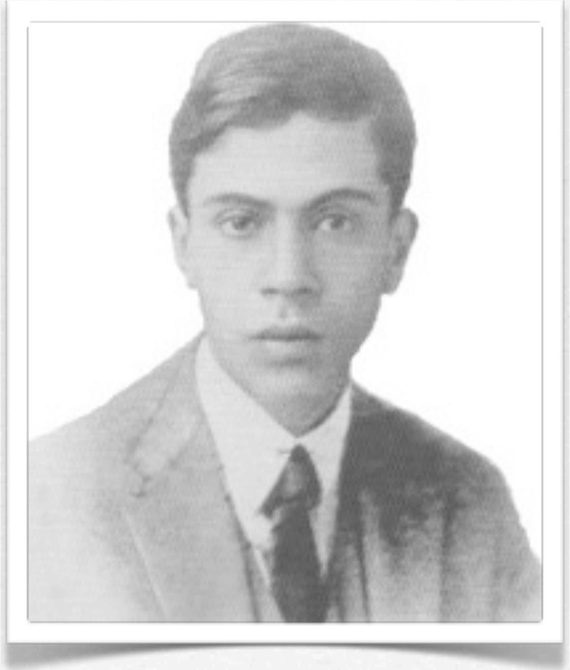


Ettore Majorana

only 32

Teoria simmetrica dell'elettrone e del positrone

Il Nuovo Cimento Vol. 14 (1937) p. 171



Ettore Majorana

last paper before his disappearance

only 32

Teoria simmetrica dell'elettrone e del positrone

Il Nuovo Cimento Vol. 14 (1937) p. 171

Ettore Majorana

last paper before his disappearance

only 32

Fermi:

there are various types of scientists

.

Second, third rank - do their best, but do not go far.

First rank, make great discoveries, fundamental for the development of science.

And then, there are geniuses, like Galileo and Newton. Ettore Majorana was one of them; unfortunately he lacked common sense.

Theme 2

- Neutrinos `real' particles?

The creation of electrons out of "nothing"

- Neutrino-less double beta decay

Racah '37

- LHC - pp collisions can create electrons

Keung, GS '83

- Why are neutrinos so special?

- The most aloof particles

A probe of new physics

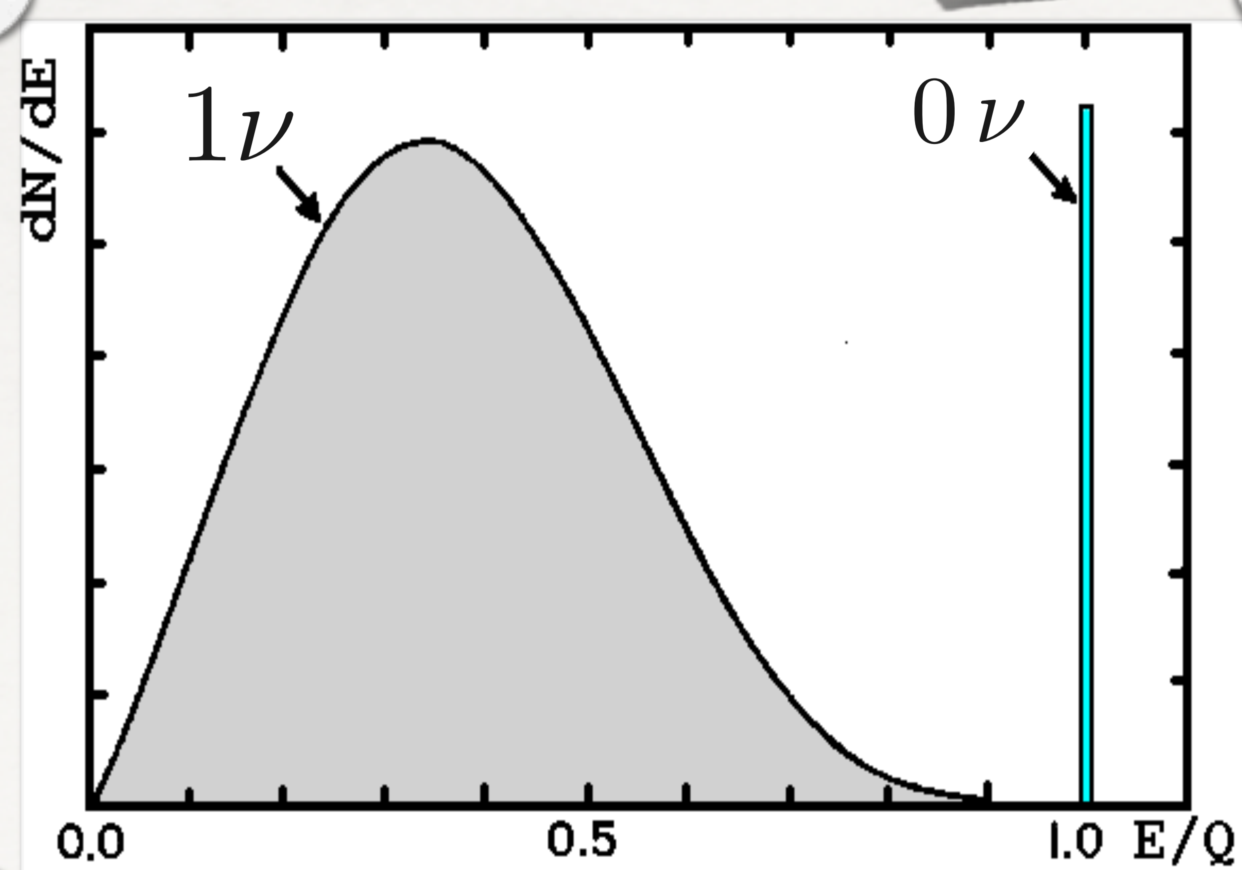
Discovering neutrinos

- produced in beta decay $n \rightarrow p + e + \bar{\nu}$

Continuous electron spectrum instead of a mono-energetic electron

expected: $E = Q$

$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + e^- + \bar{\nu}_e$



Chadwik '14

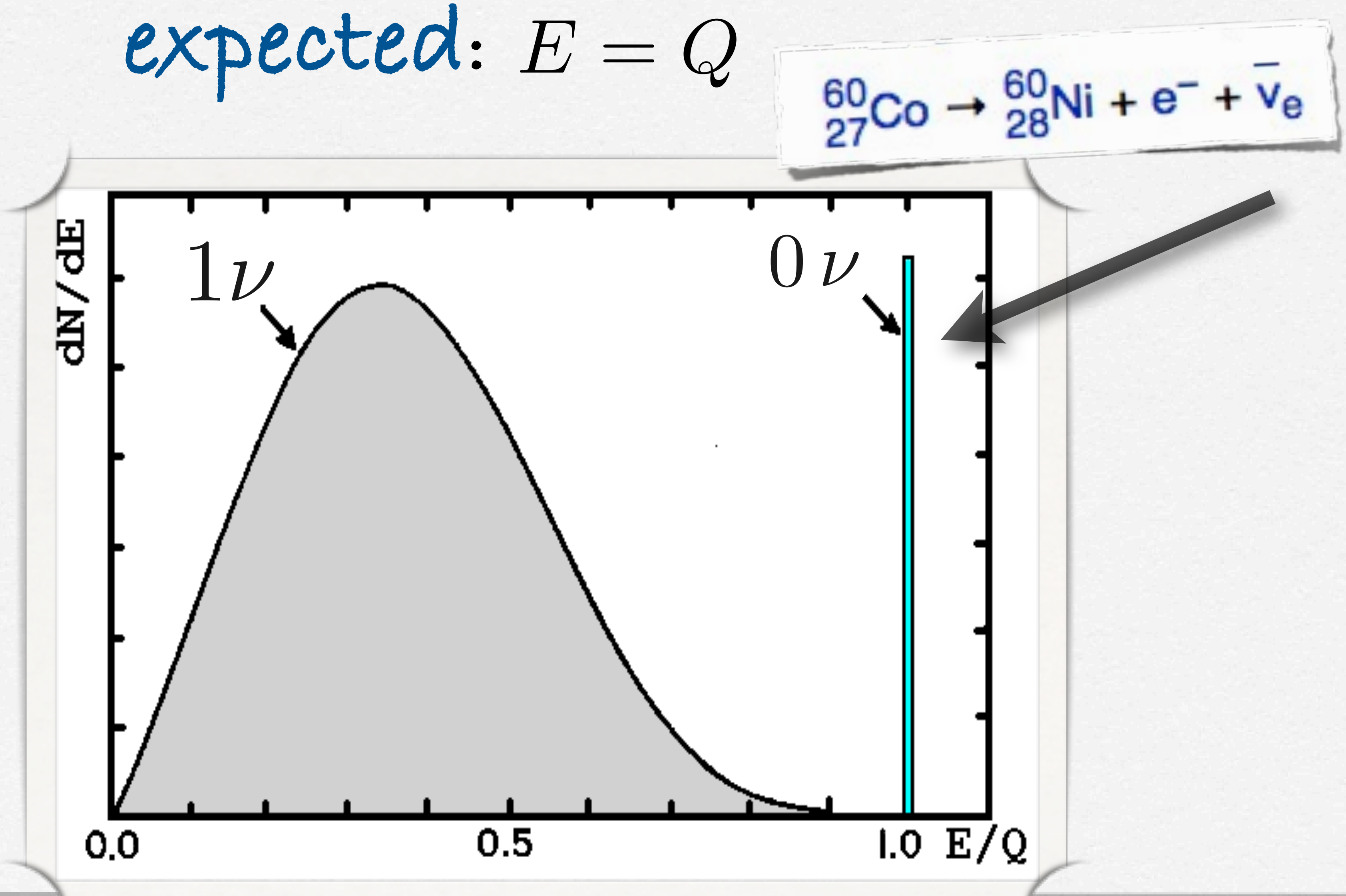
confusion and confirmation in the late 20's

Discovering neutrinos

- produced in beta decay $n \rightarrow p + e + \bar{\nu}$

Continuous electron spectrum instead of a mono-energetic electron

expected: $E = Q$



Chadwik '14

confusion and confirmation in the late 20's

☐ conservation of energy

Pauli '30

a new neutral particle

Chadwick '32

neutron

\`brother' of electron

neutrino (small neutron)

leptons (light)

Fermi (Amaldi)

- how to see it? $p + \bar{\nu} \rightarrow n + \bar{e}$

cross section tiny: $\simeq 10^{-44}\,\mathrm{cm}^2$

compare with electron: $\sigma \simeq 10^{-22}\,\mathrm{cm}^2$

- mean free path $\simeq 10^{20}\mathrm{cm}$

70 million times distance earth-sun

helps understand John Updike

Cosmic Gall

by John Updike

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

Cosmic Gall

by John Updike

NEUTRINOS, they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold shoulder steel and sounding brass,
Insult the stallion in his stall,
And scorning barriers of class,
Infiltrate you and me! Like tall
and painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
and pierce the lover and his lass
From underneath the bed-you call
It wonderful; I call it crass.

wrong

- great pessimism

Pauli regrets inventing a particle that “will never be seen”

- Cowan and Reines ‘56

large flux of neutrinos

Savannah River reactor

$$\Phi = 10^{13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

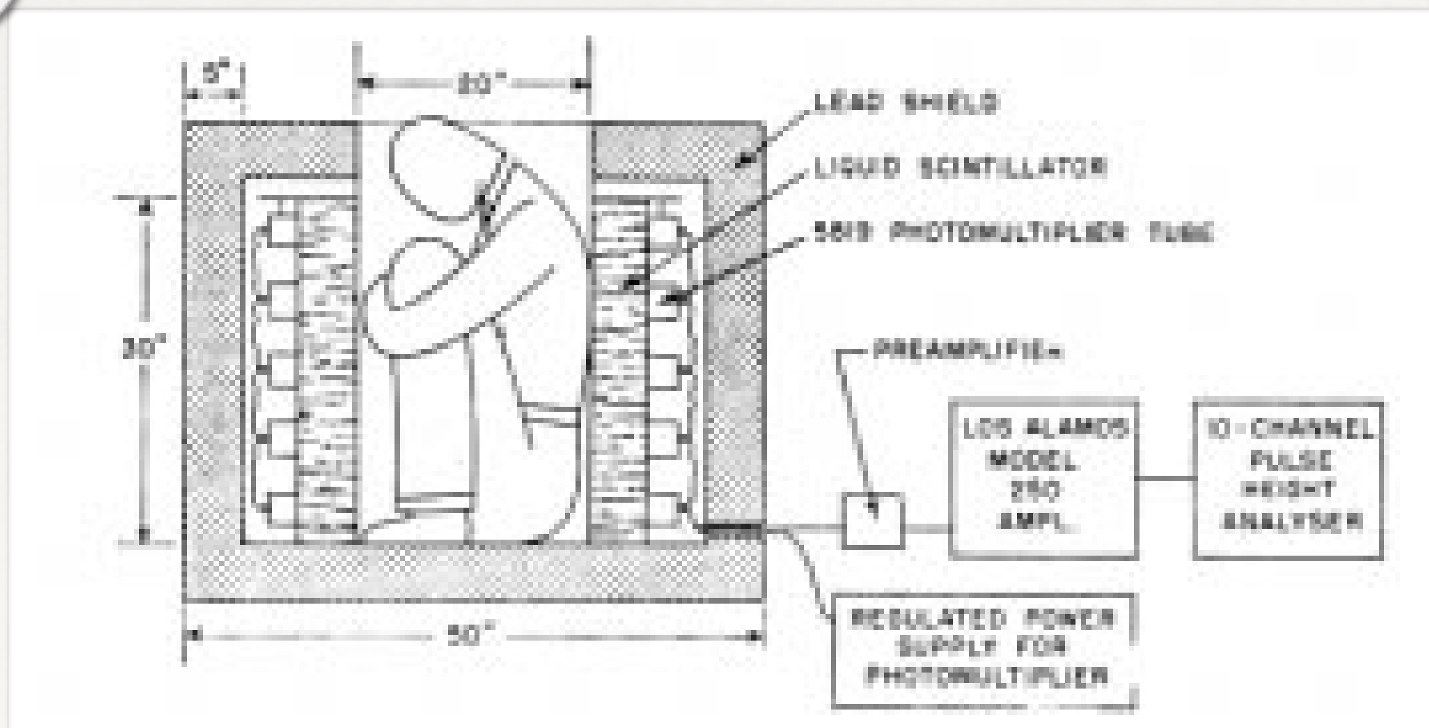
$$\#\,\mathrm{events} = \Phi\sigma \mathrm{nV}$$

$$V = 10^{5}\,\mathrm{cm}^{3}$$

about **10** per hour :)

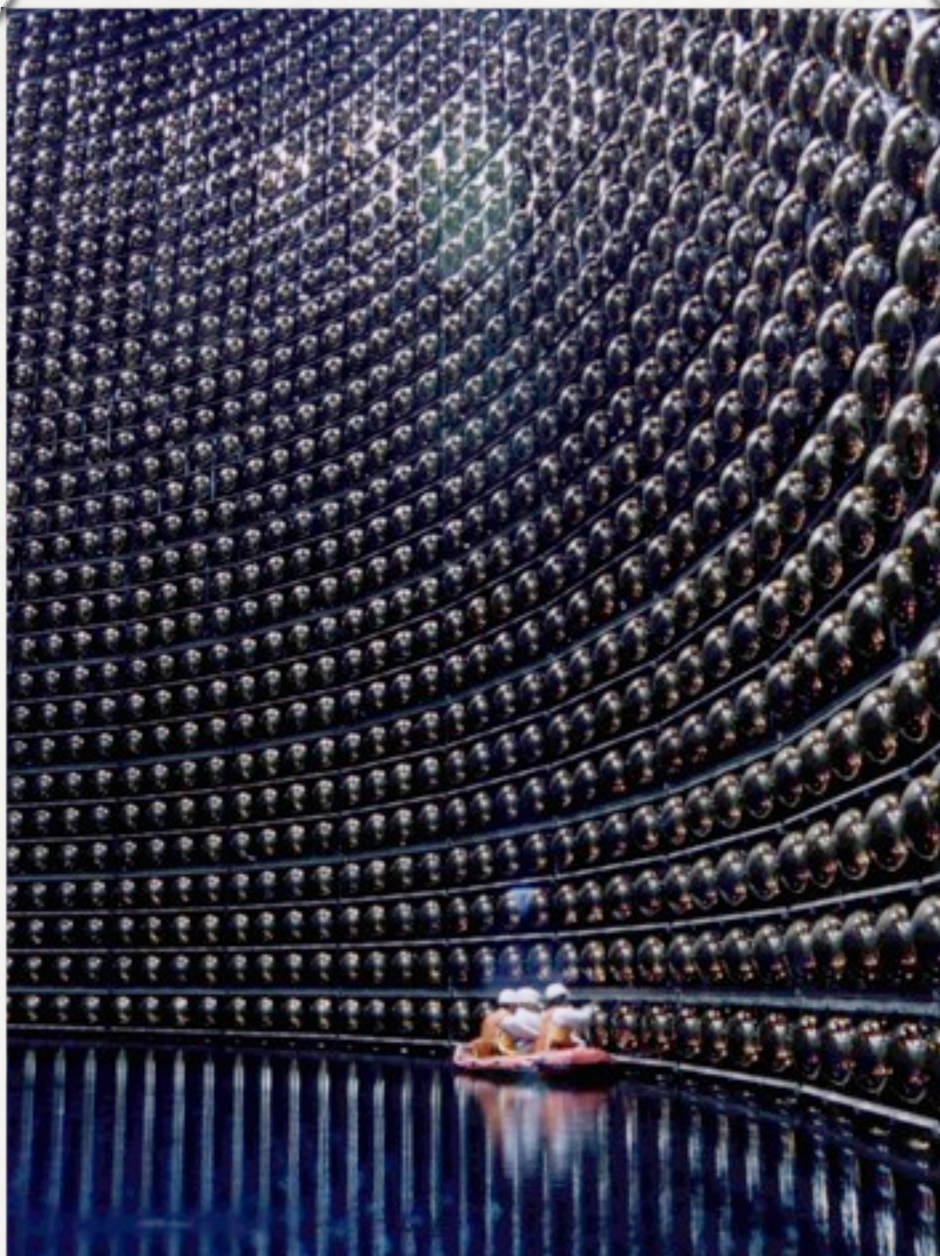
☐ detector : water (protons)

good old days



8 people

Atmospheric neutrinos   modern times



Super Kamiokande

neutrino mass $m_\nu \gtrsim 10^{-1}\ eV$

'98 $(m_p \simeq 10^9\ \mathrm{eV})$

- flux $\Phi = 0.1\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

10^{14} times smaller than reactor flux

needs huge detectors

110 people

- 1956: bombshell of Lee and Yang

parity violation in weak interaction

(not known: they argue it is eventually restored at high energies *)

* mirror fermions

GS, Wilczek, Zee '84

GS, Martinez, Melfo, Nesti '11

- experiment: polarized Co atoms

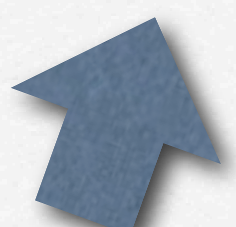
$${}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$$

Wu et al '56

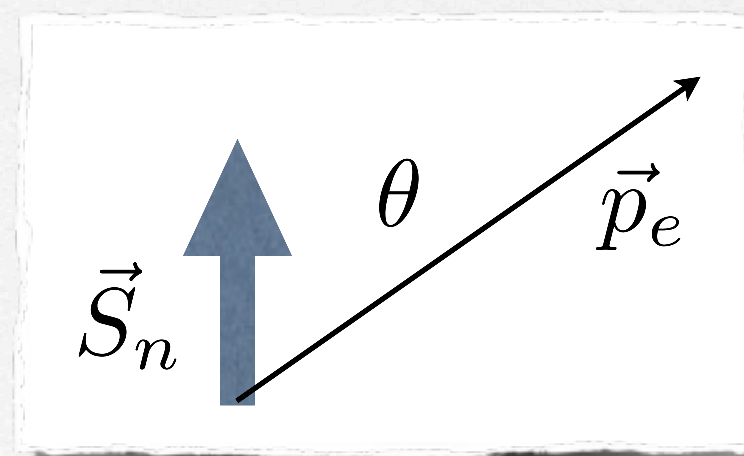
Lederman et al '56

spin up (magnetic field) - parity invariant

but electrons prefer to go down



$$I(\theta) = (1 - \cos\theta)$$



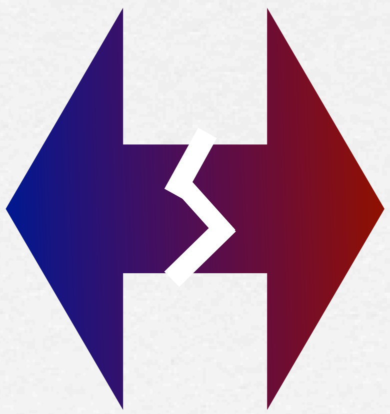
1956 - a great year

Marshak, Sudarshan '56

Gell-Mann, Feynman '57

- only left particles in beta decay

V - A theory



L-R symmetry maximally broken

Dirac: electron charged $\Rightarrow$ complex

$$e = e_L + e_R$$

parity:

$$e_L \leftrightarrow e_R$$

antiparticle = positron

$$\bar{e}_R = (e_L)^*$$

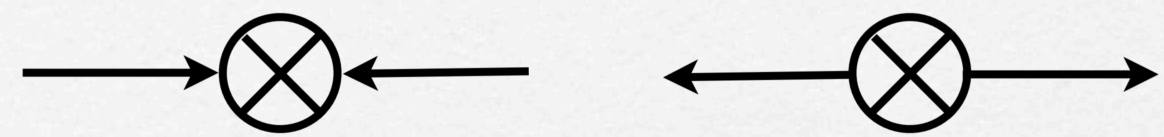
Majorana: neutrino neutral

$\Rightarrow$ real

The Majorana Program

neutrino mass

$$\nu_M = \nu_L + \nu_L^* \quad \Leftrightarrow \quad m_\nu^M (\nu_L \nu_L + h.c.)$$



$$\Rightarrow \quad \Delta L = 2$$ lepton number violation

create electrons out of 'nothing'

- beta decay :

$$n \to p + e + \bar{\nu}$$

sometimes impossible :

$$^{76}_{32}Ge \not\to ^{76}_{33}As + e + \bar{\nu}$$

Ge lighter than **As**

- double beta decay dominant :

$$^{76}_{32}Ge \to ^{76}_{34}Se + e + e + \bar{\nu} + \bar{\nu}$$

Goeppert-Mayer '35

- search from '48
- geochemical observation '50
- laboratory '86

$$\tau_{1/2} \simeq 10^{21}\ \mathrm{yr}$$

- if neutrino Majorana

$$^{76}_{32}Ge \rightarrow ^{76}_{34}Se + e + e$$

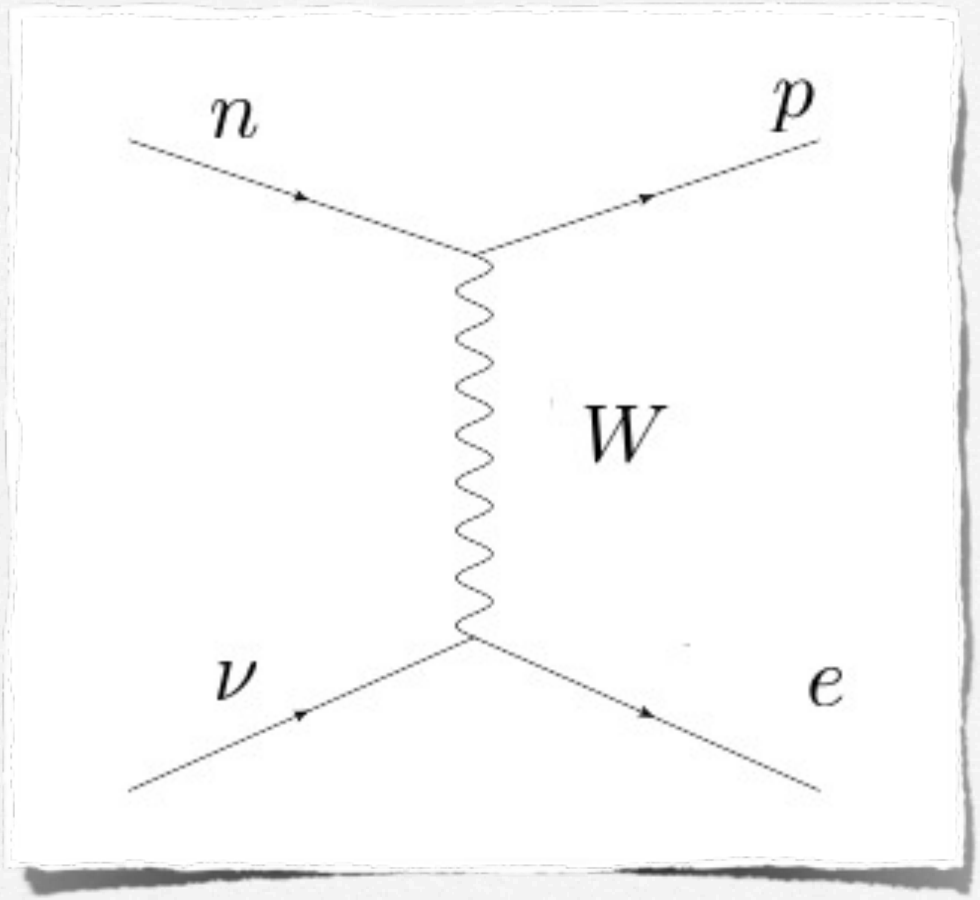
neutrino-less double beta decay

$$\tau_{1/2} \gtrsim 10^{24}\, yr$$

Majorana '37

Racah '37, Furry '38

beta decay : messenger *W* boson



Parity violation

only left particles interact with ***W***

discovered at CERN in $p - \bar{p}$ collider '83

studied at LEP: $e - \bar{e}$ '90 -ties → $M_W \simeq 80\,GeV$

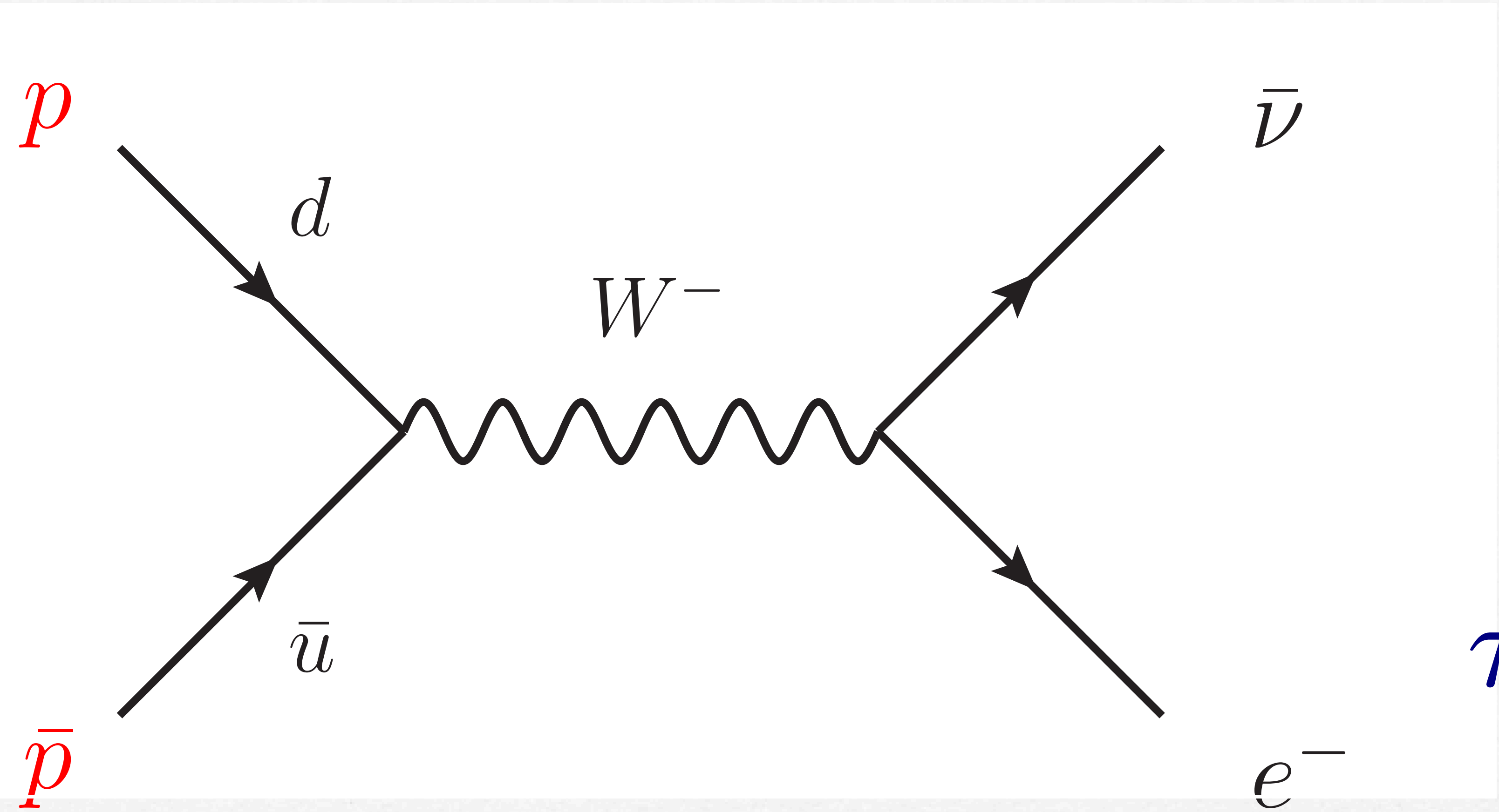
SPS experiment

modern times

Super Proton Synchrotron

137 people

'81-'84



7 km circumference

$$\tau_W \simeq 10^{-24}\ sec$$

LEP experiment

Large Electron-Positron collider

modern times

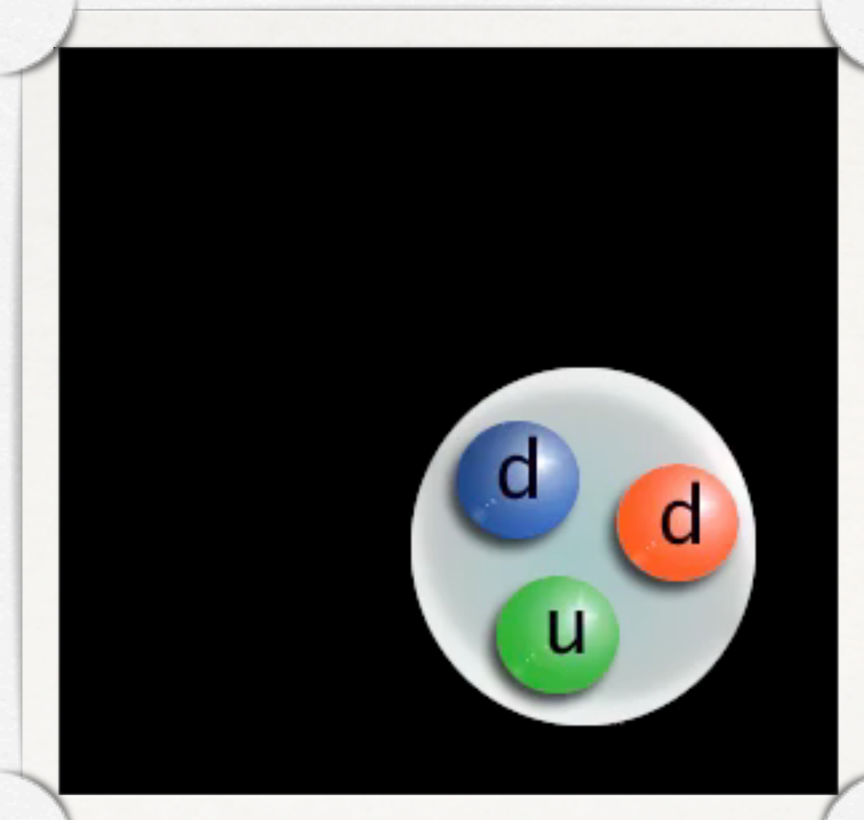
'89 - '00

- 1500 people
- 4 detectors: ALEPH, LEP 3, OPAL, DELPHI
- 27 km circumference

Standard Model $\Longleftarrow 10^9$ W bosons

W boson: the shiny (hairy) guy

W boson: the shiny (hairy) guy

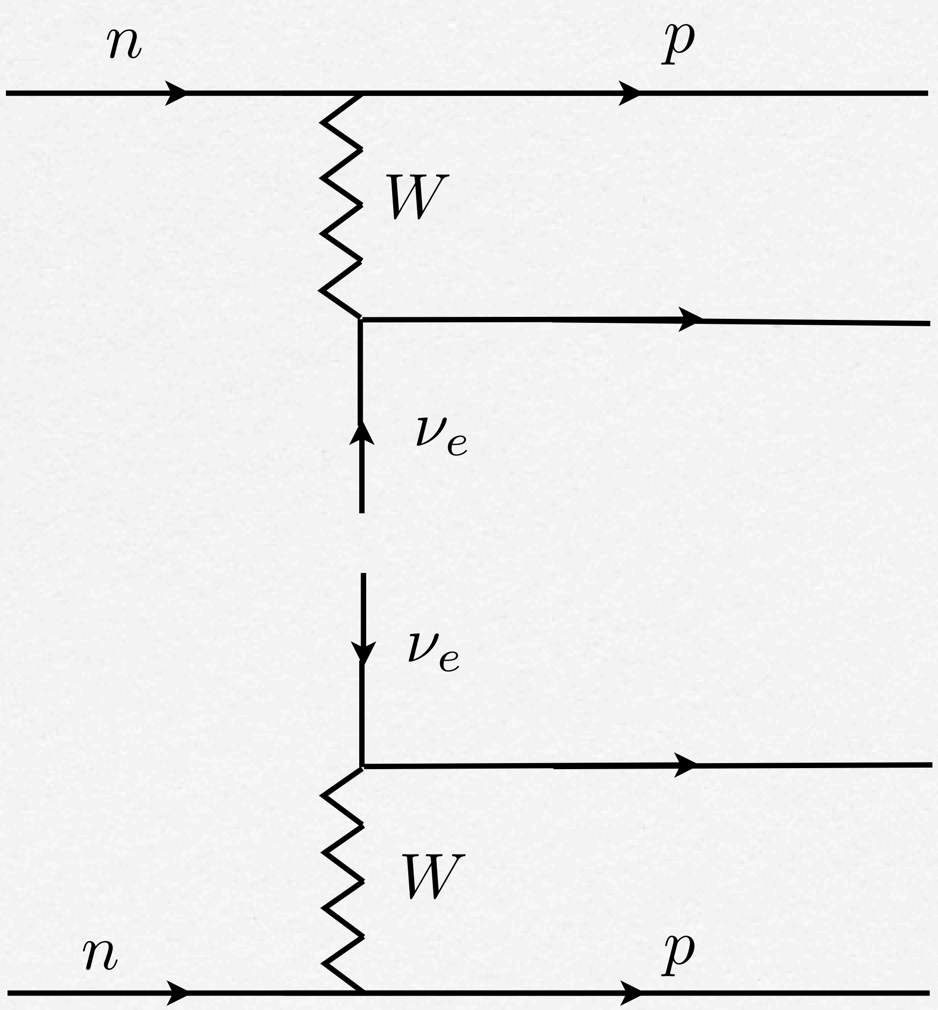


Double-beta decay

$$^{76}Ge \not\rightarrow \, ^{76}As + e + \bar{\nu}_e$$

Göppert-Mayer, '35

$$^{76}Ge \rightarrow \, ^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$



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

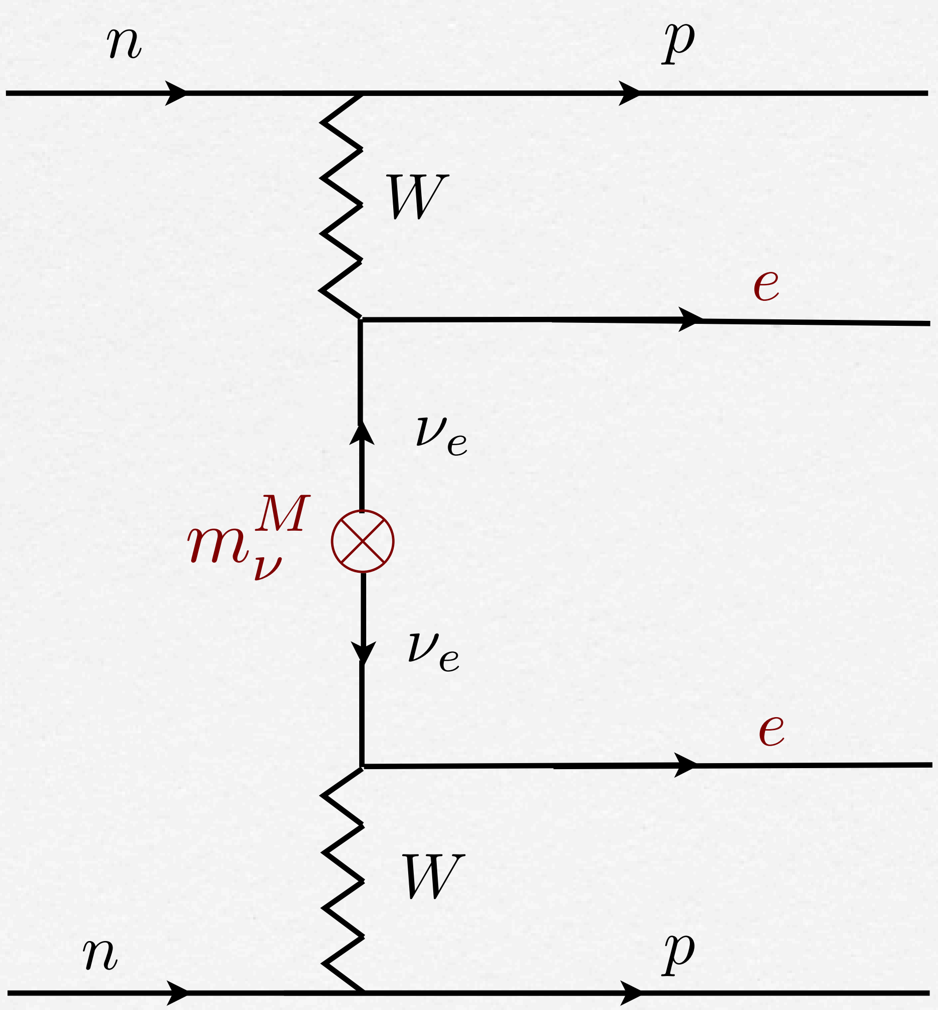
$$(m_p \simeq 10^9 \, \text{eV})$$

Double-beta decay

$$^{76}Ge \not\to \, ^{76}As + e + \bar{\nu}_e$$

Göppert-Mayer, '35

$$^{76}Ge \to \, ^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$



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

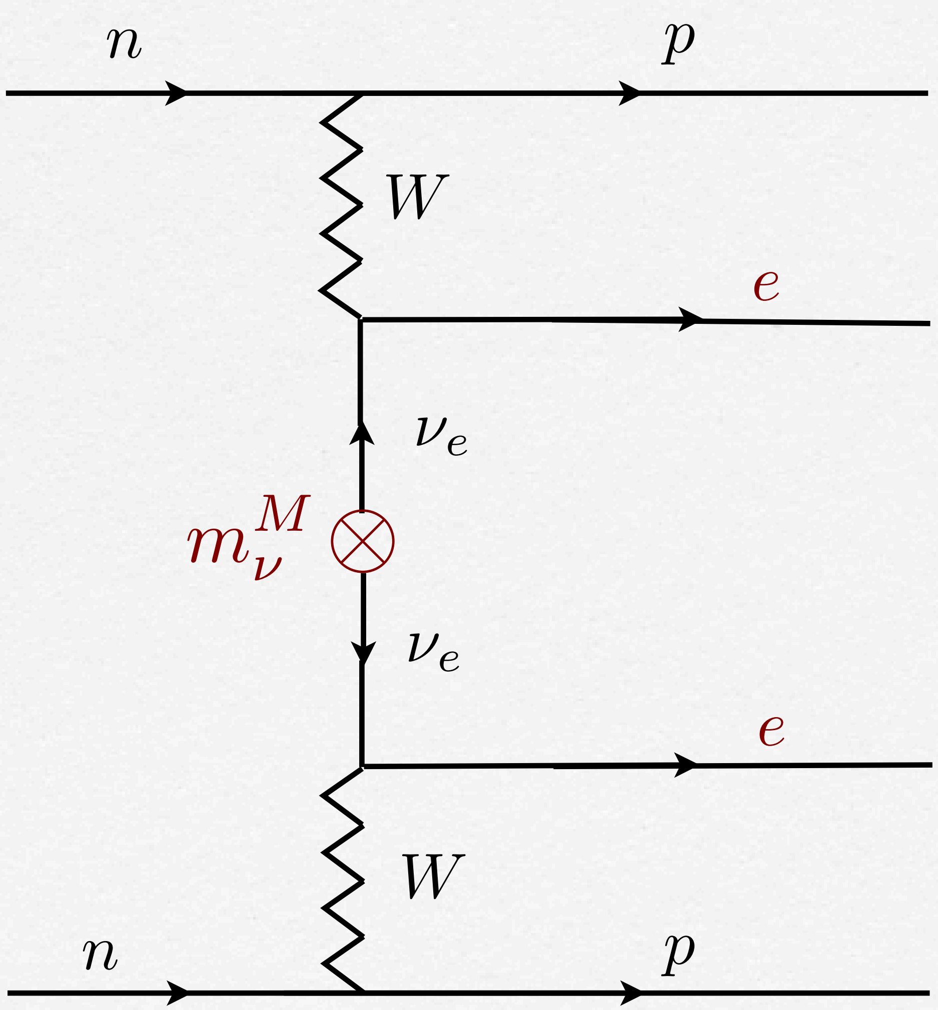
$$(m_p \simeq 10^9 \, \text{eV})$$

Double-beta decay

$$^{76}Ge \not\to\ ^{76}As + e + \bar{\nu}_e$$

Göppert-Mayer, '35

$$^{76}Ge \to\ ^{76}Se + e + e + \bar{\nu}_e + \bar{\nu}_e$$



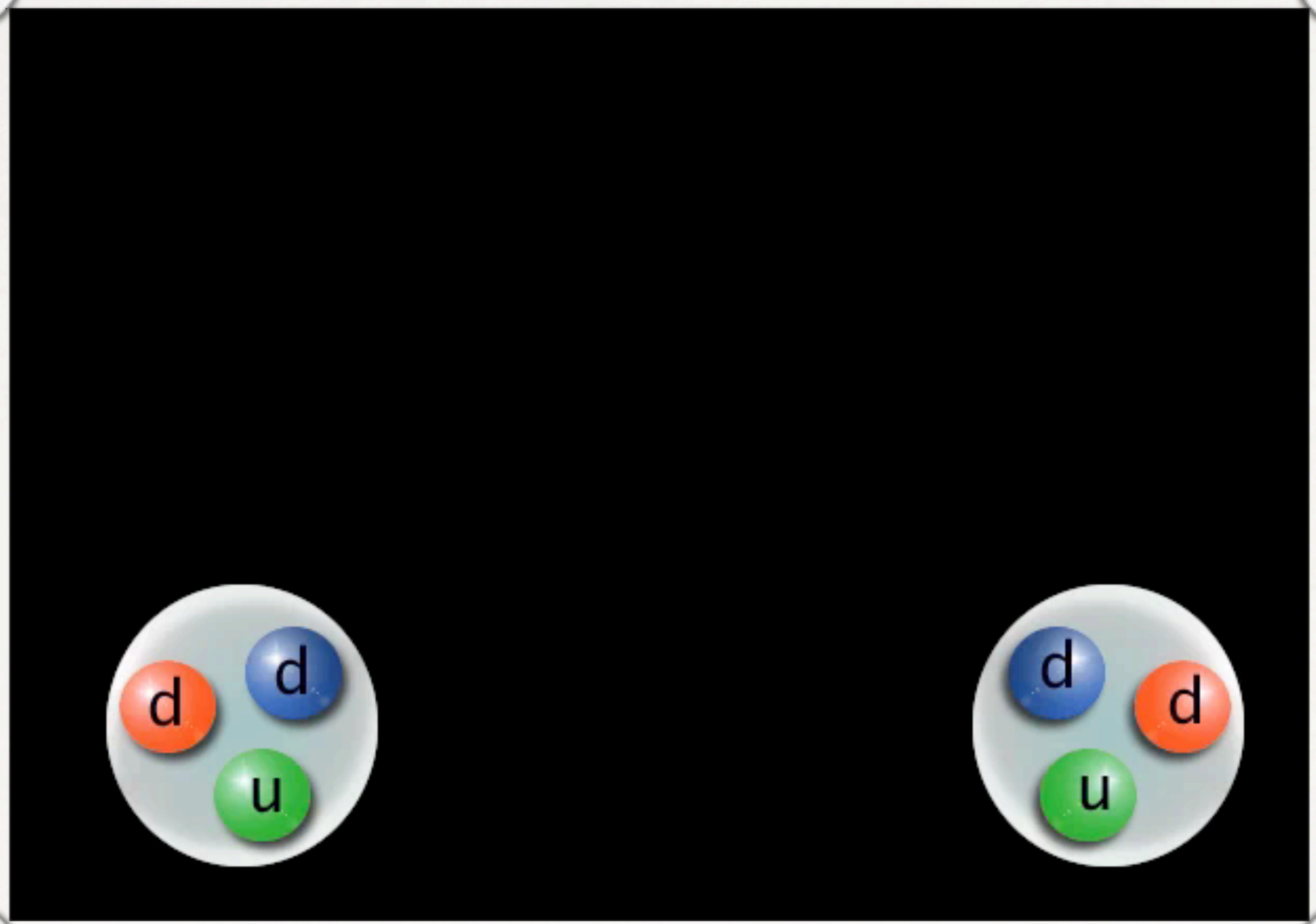
$$^{76}Ge \to\ ^{76}Se + e + e$$

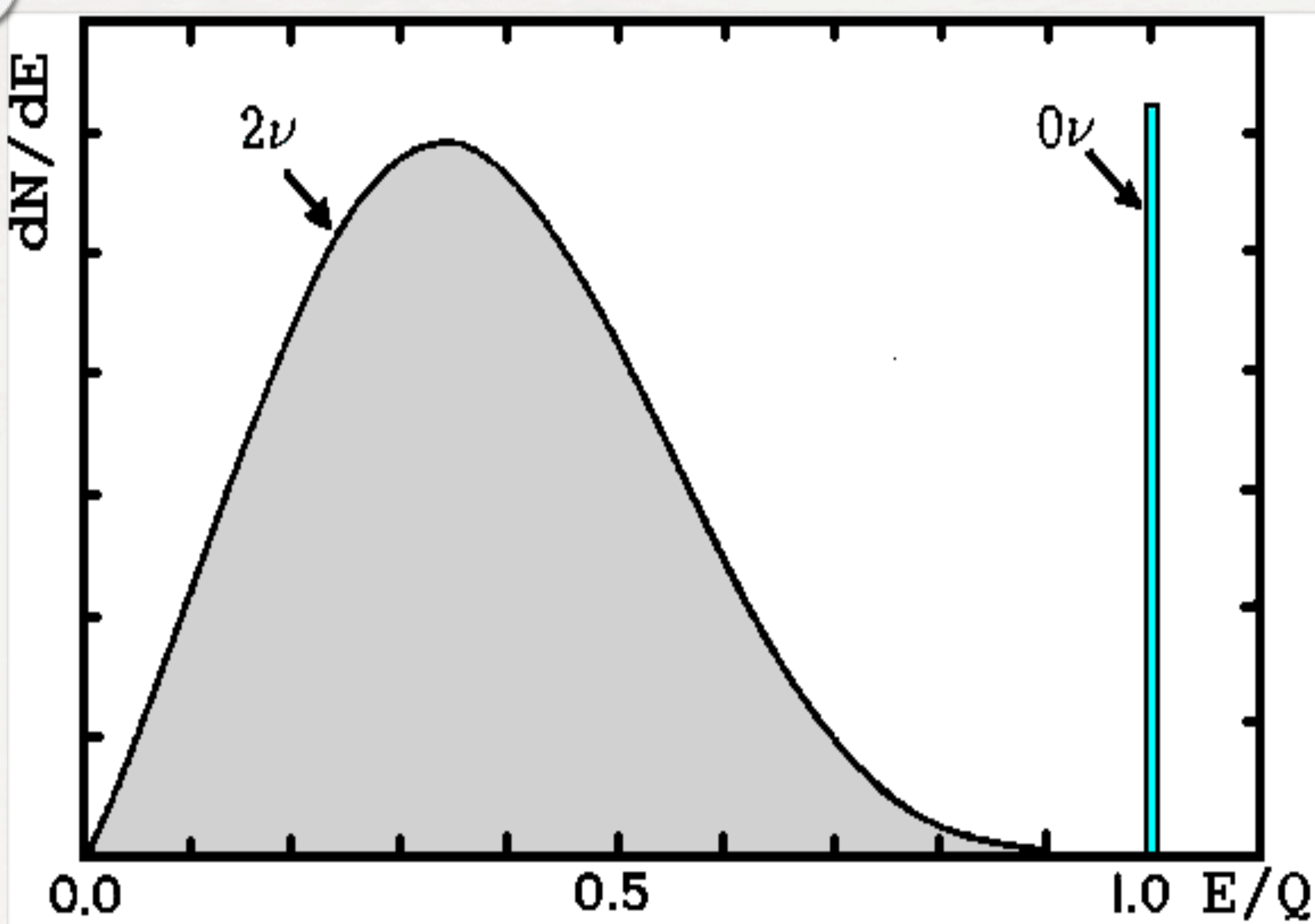
proportional to neutrino mass

$$t_{1/2} \geq 10^{24}\, yr \implies m_\nu^M \lesssim 1\, eV$$

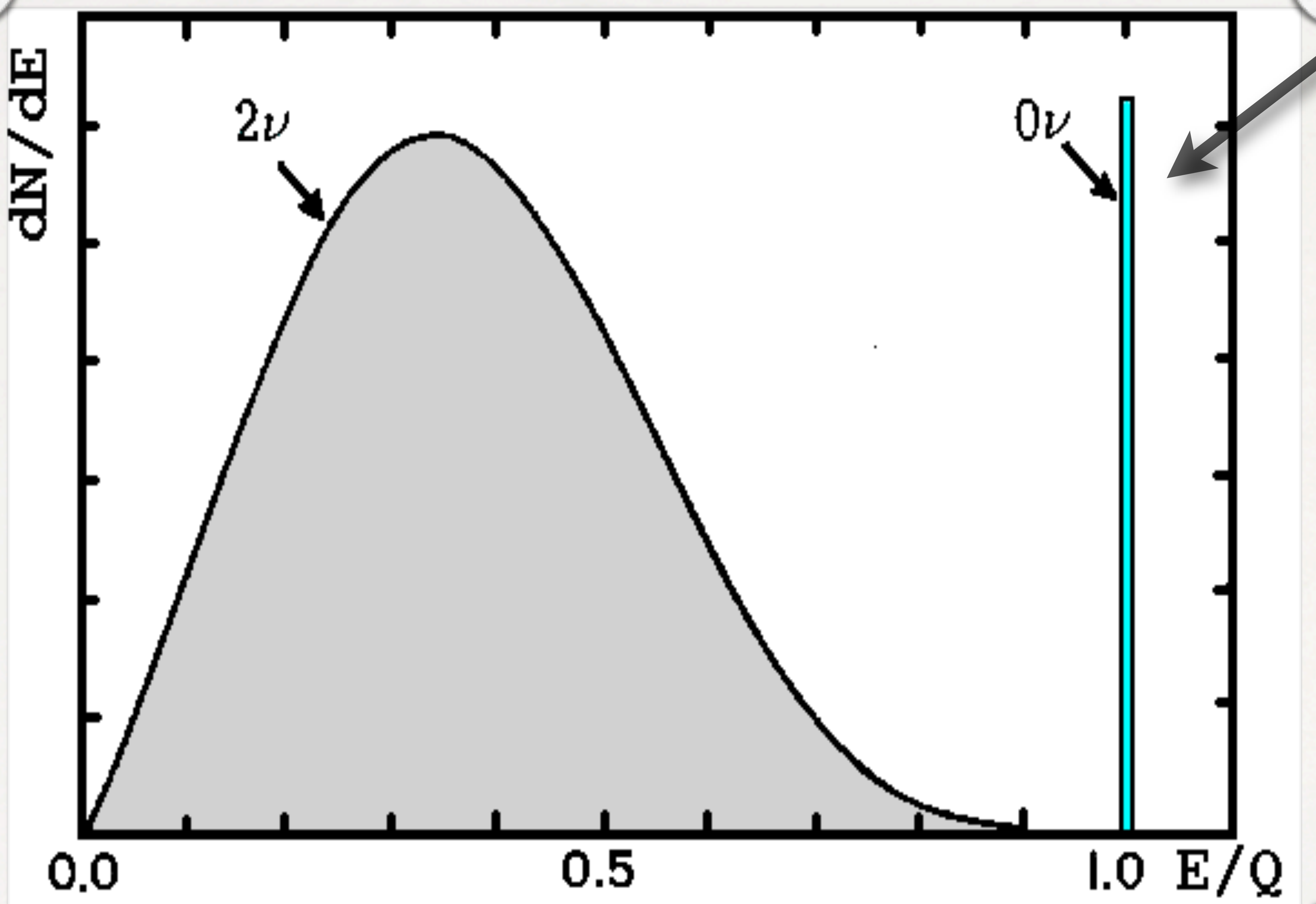
$$m_\nu \gtrsim 10^{-1}\, eV$$

$$(m_p \simeq 10^9\, \mathrm{eV})$$


d
d
u
d
d
u



sum of electron energies



sum of electron energies

past experiments:

IGEX International Germanium EXperiment

NEMO (Mo) Neutrino Ettore Majorana Observatory

1 in '89 - 3 January 11, 2011 Frejus, France

CUORICINO (Te) Gran Sasso Laboratory, Italy
(little heart)

*HMBB (Ge) Gran Sasso Laboratory '90 - - '00

* claims a result !

- HMBB experiment:

Klapdor-Kleingrothaus '01-10

$*$ Majorana neutrino mass ~ 0.4 eV

- cosmology:

Seljak '05

sum of neutrino masses $< 0.4 - 1$ eV

Fogli et al '08

new physics necessary?

CUORE = heart (Te)

Cryogenic Underground Observatory for Rare Events

2012

COBRA

Cadmium 0-neutrino Beta Research Apparatus

2014 ?

MAJORANA (Ge) 2015

Super NEMO (Mo) 2014

MOON

Molybdenum Observatory Of Neutrinos

modern times

GERDA experiment

GERmanium Detector Array

Gran Sasso Laboratory

order of magnitude better than HMBB

expect:
a few years

Standard Model

Glashow Weinberg Salam

'61-67

$SU(2)_L \times U(1)$ gauge theory

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

no L-R symmetry

no ν_R

$\nu_L \nu_L$

Standard Model

Glashow Weinberg Salam
'61-67

$SU(2)_L \times U(1)$ gauge theory

$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R

no L-R symmetry

no ν_R

$\nu_L \nu_L$

forbidden by $SU(2)$ symmetry

- Why parity : $L \leftrightarrow R$ broken ?

- Standard Model :

don't ask: parity broken for all seasons

Unacceptable:

God may be left-handed, but not an invalid

L-R symmetry

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$W_L$$

$$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$W_R$$

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

Pati Salam '74

Mohapatra GS '75

L-R symmetry

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$W_L \qquad W_R$$

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

Pati Salam '74

$E \gg m_{W_R}$ parity restored?

Mohapatra GS '75

neutrino mass

*seesaw

Minkowski '77

Mohapatra, GS '79

*Gell-Mann et al '79

$m_\nu \lesssim 1\,\mathrm{eV}$ ⟷ $M_{W_R} \gtrsim 10^3\,\mathrm{GeV}$

$M_{W_L} \simeq 80\,\mathrm{GeV}$

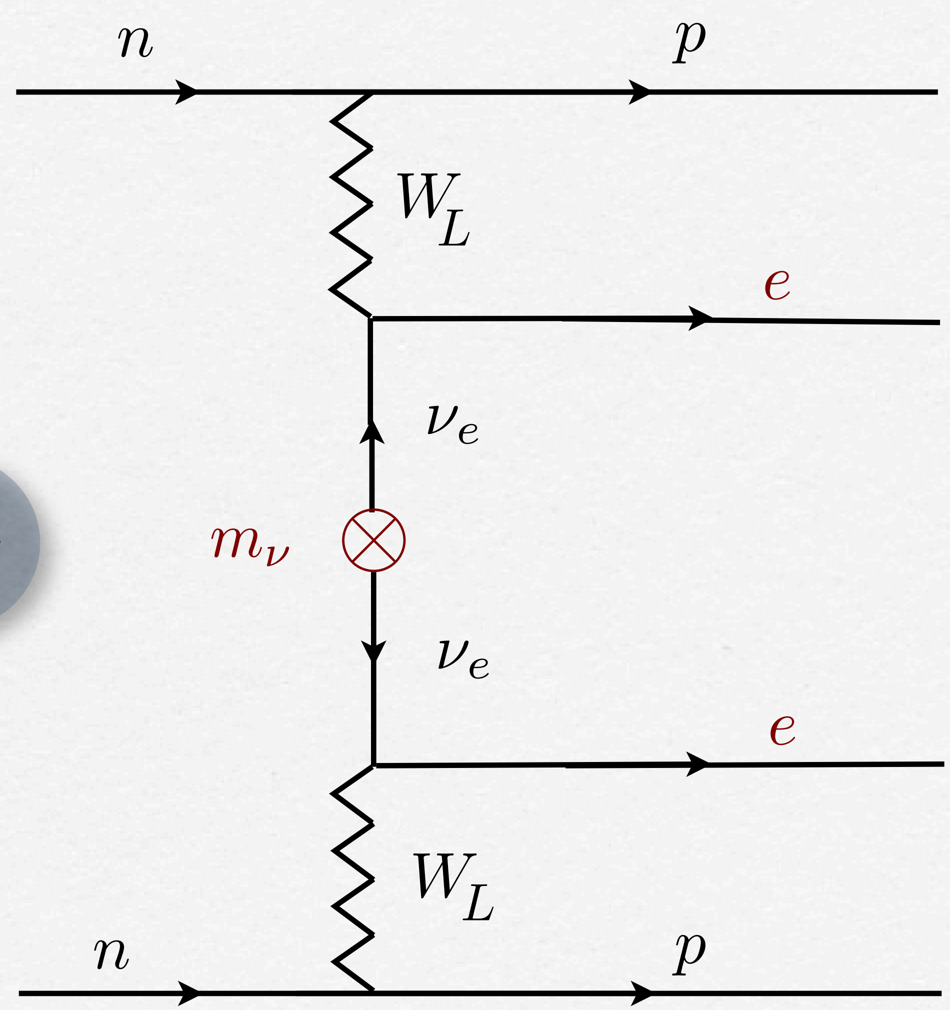
Minimal model:

Theoretical limit → $M_{W_R} \gtrsim 2500\,\mathrm{GeV}$

Maiezza, Nemevsek, Nesti, GS '2010

New source for $0\nu 2\beta$

Mohapatra, GS '81



LL

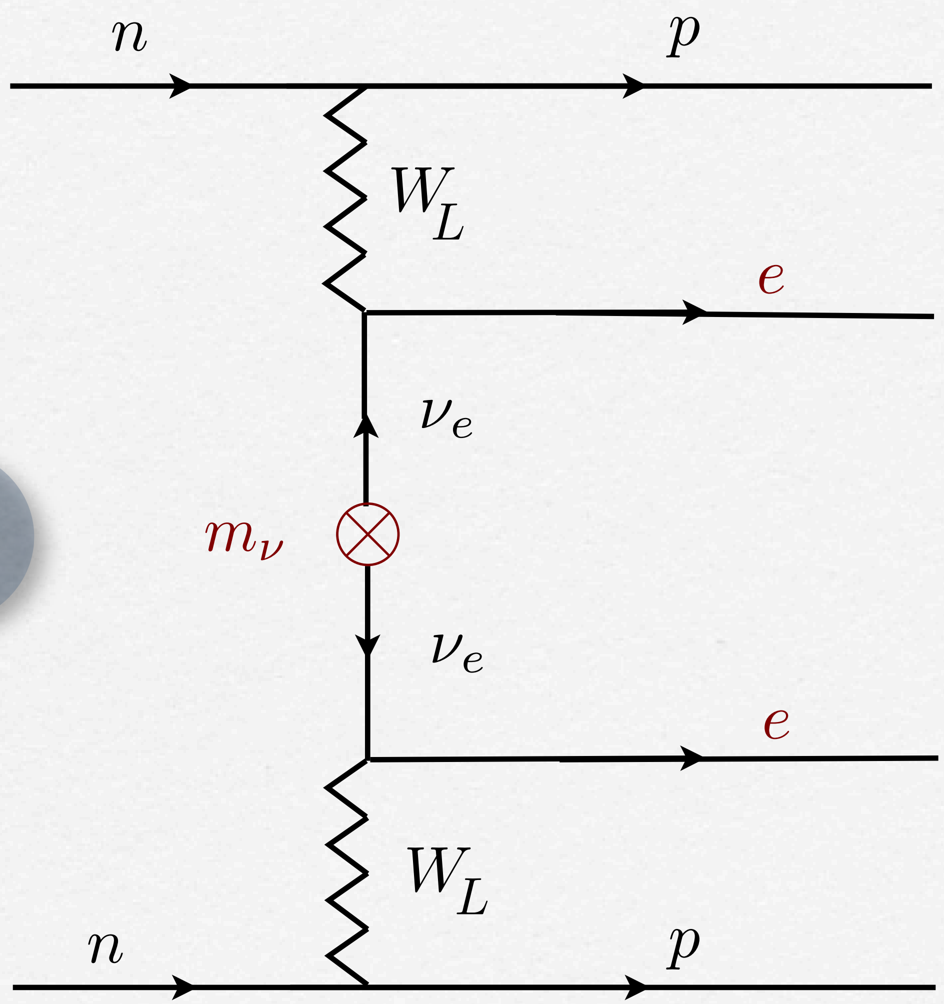
$$LL \propto \frac{1}{M^4_{W_L}} \frac{m_\nu}{p^2}$$

$$p \simeq 100 MeV$$

New source for $0\nu 2\beta$

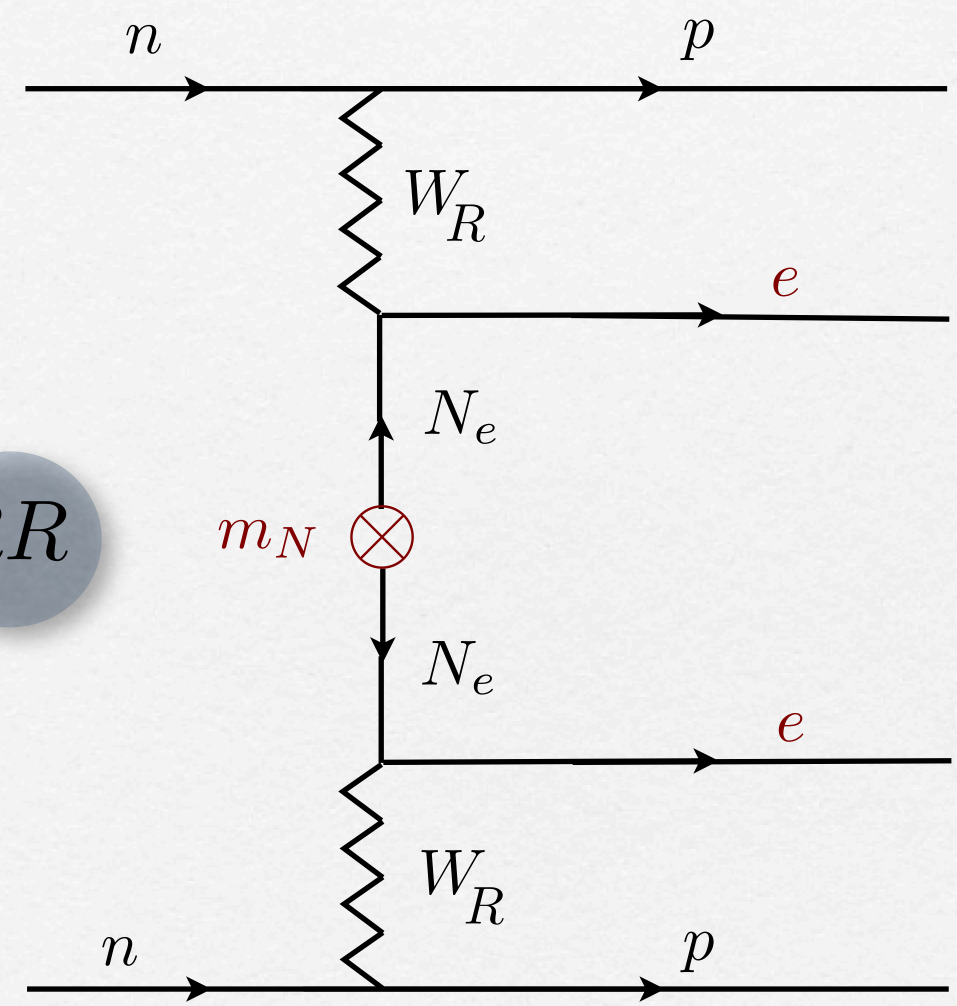
Mohapatra, GS '81

LL



+

RR



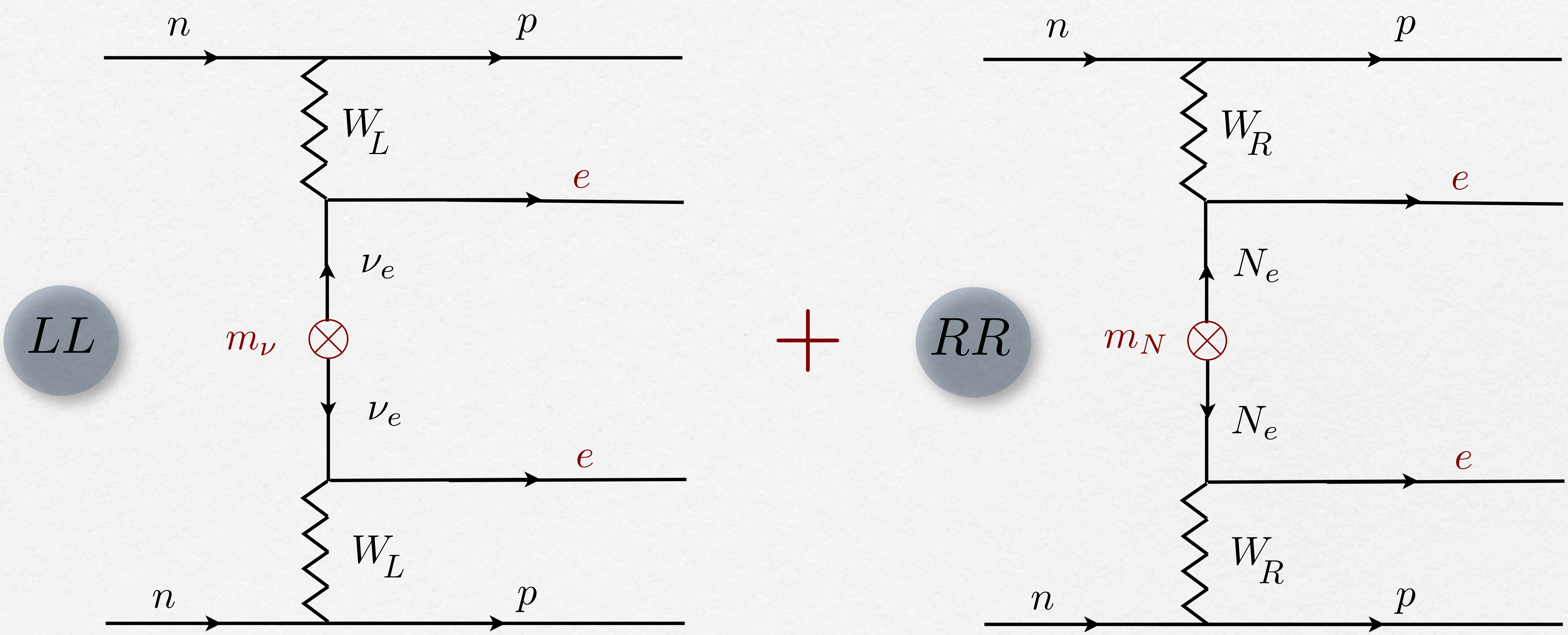
$$LL \propto \frac{1}{M_{W_L}^4} \frac{m_\nu}{p^2}$$

$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$p \simeq 100 MeV$

New source for $0\nu 2\beta$

Mohapatra, GS '81



$$LL \propto \frac{1}{M_{W_L}^4} \frac{m_\nu}{p^2}$$

$$p \simeq 100 MeV$$

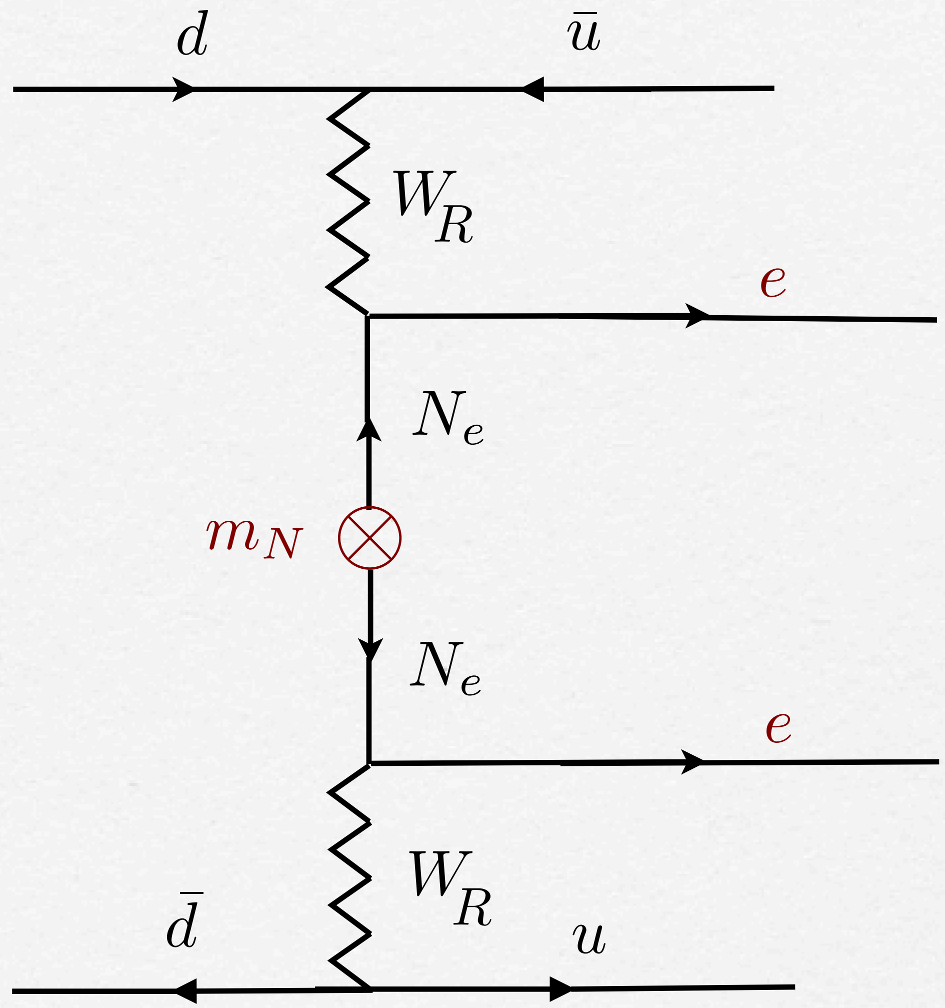
$$\frac{RR}{LL} \simeq O(1)$$

$$M_{W_R} \simeq m_N \simeq 10 M_{W_L}$$

$$m_\nu \simeq 1\, eV$$

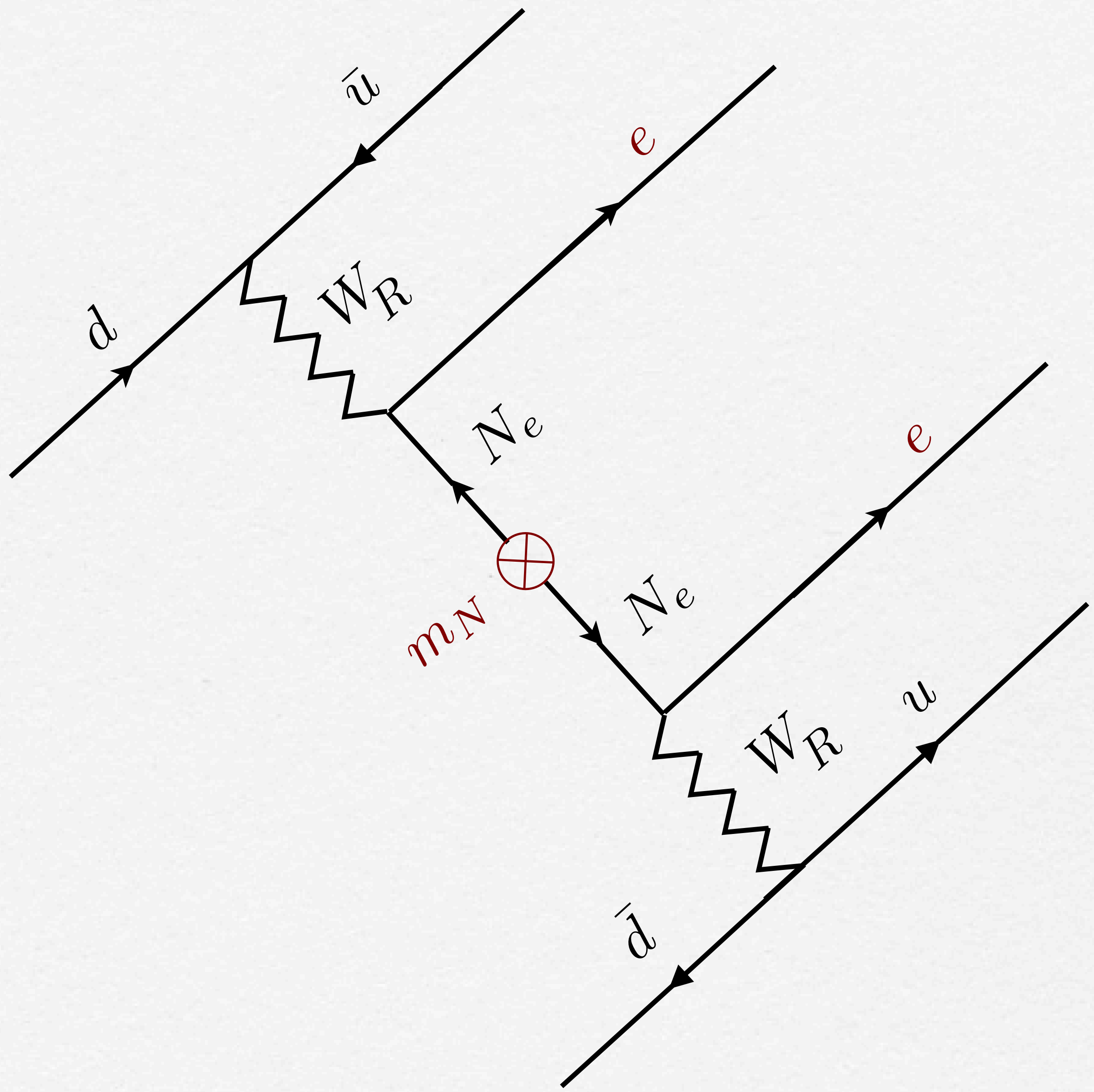
$$RR \propto \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

Tello, Nemevsek, Nesti, GS, Vissani '11

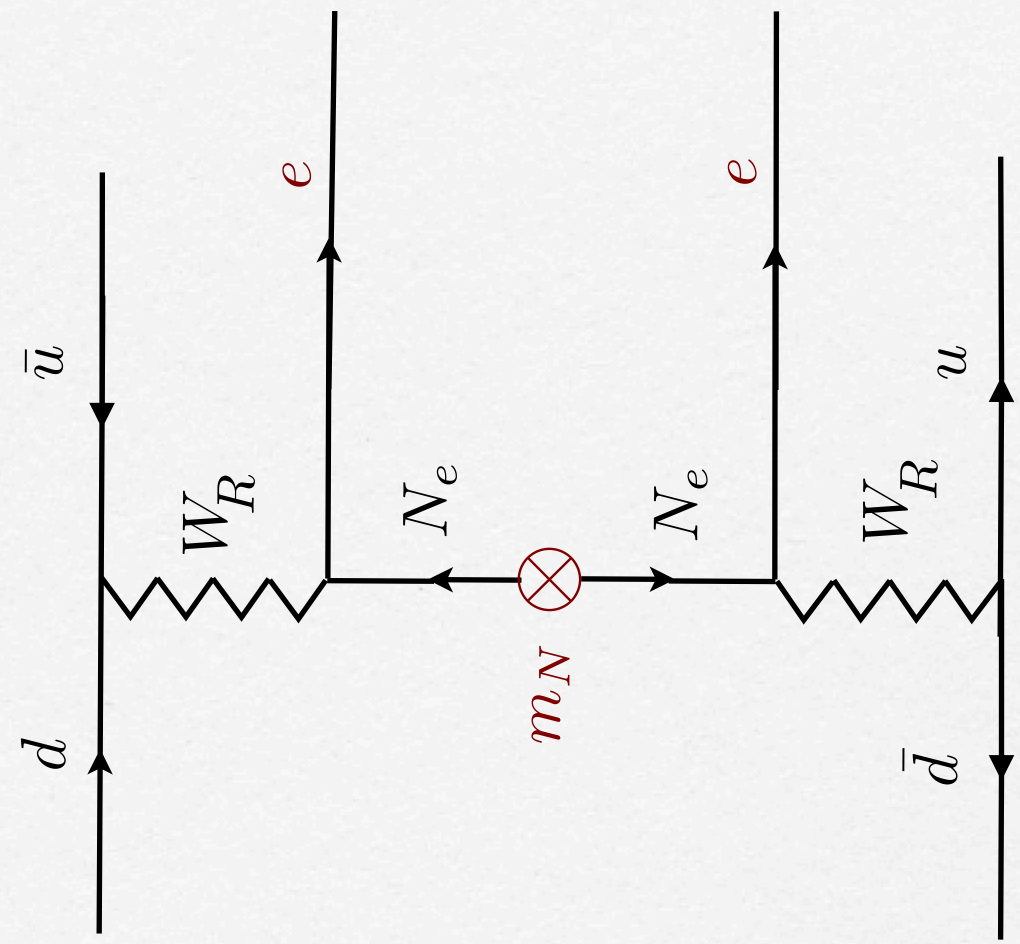


If HMBB claim true and neutrino mass small (cosmology) ⇒ W_R @ TeV = 1000 GeV

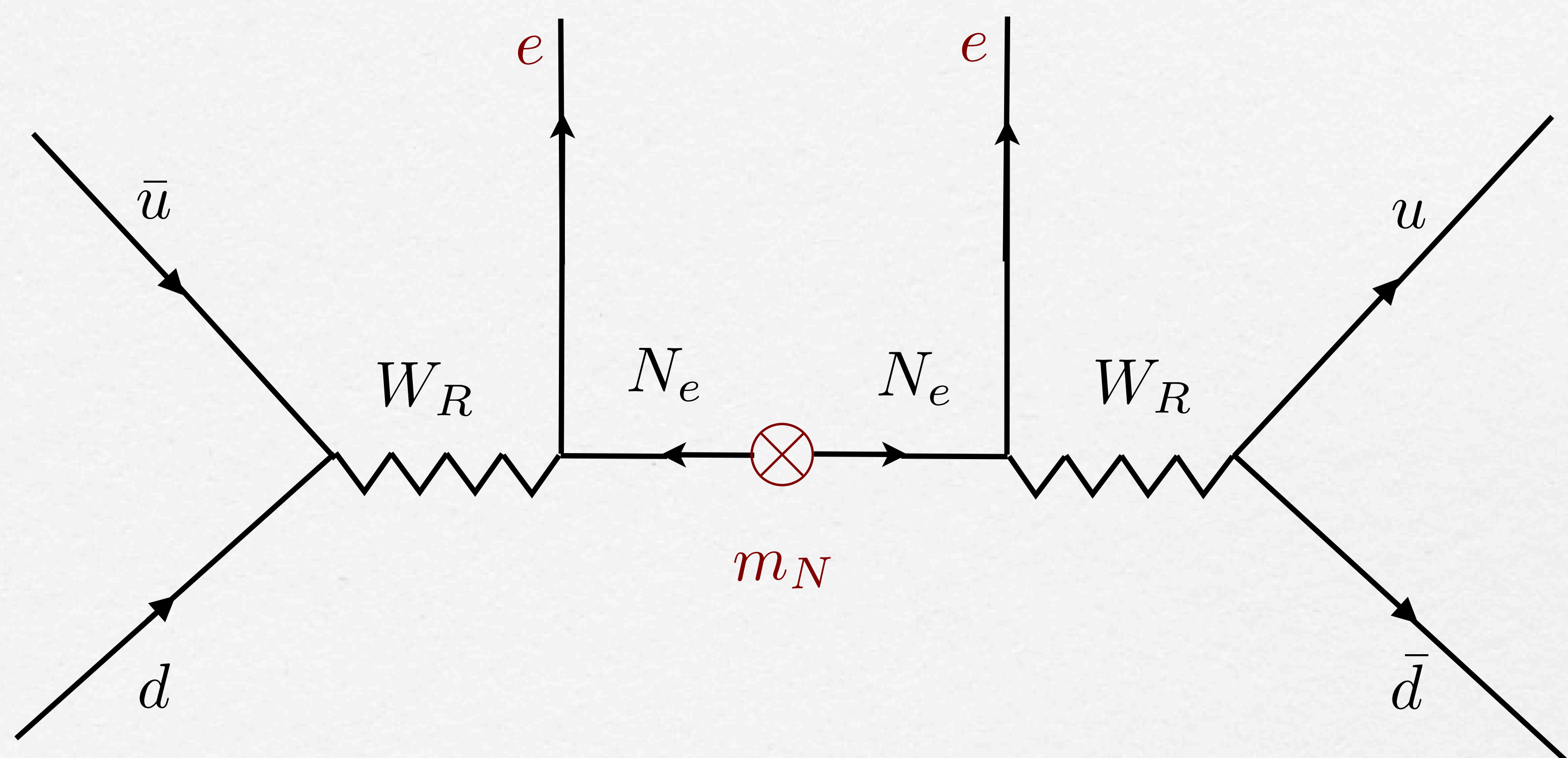
LHC energies



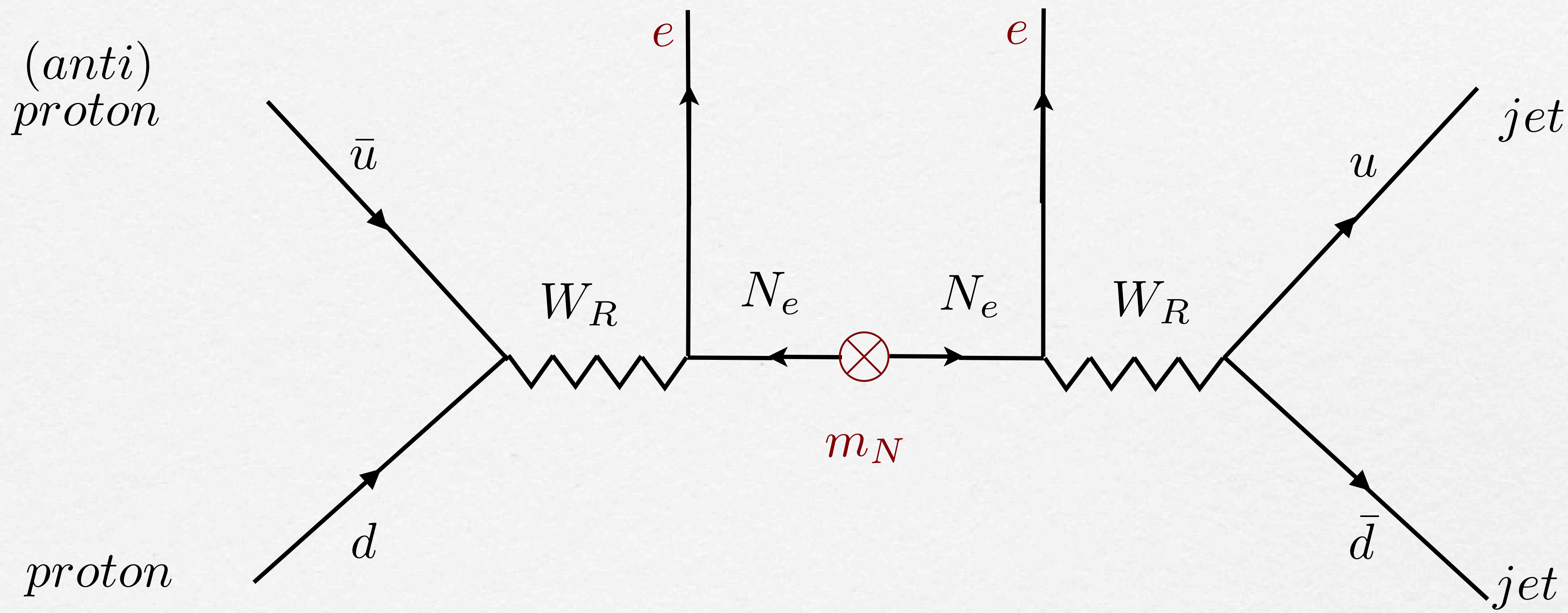
$\bar{u}$
e
d
W_R
N_e
m_N
N_e
e
W_R
u
$\bar{d}$



$\bar{u}$
d
W_R
e
N_e
m_N
N_e
e
W_R
u
$\bar{d}$


e
e
$\bar{u}$
u
W_R
N_e
N_e
W_R
m_N
d
$\bar{d}$

W_R production @ colliders



- Parity restoration
- electrons + jets

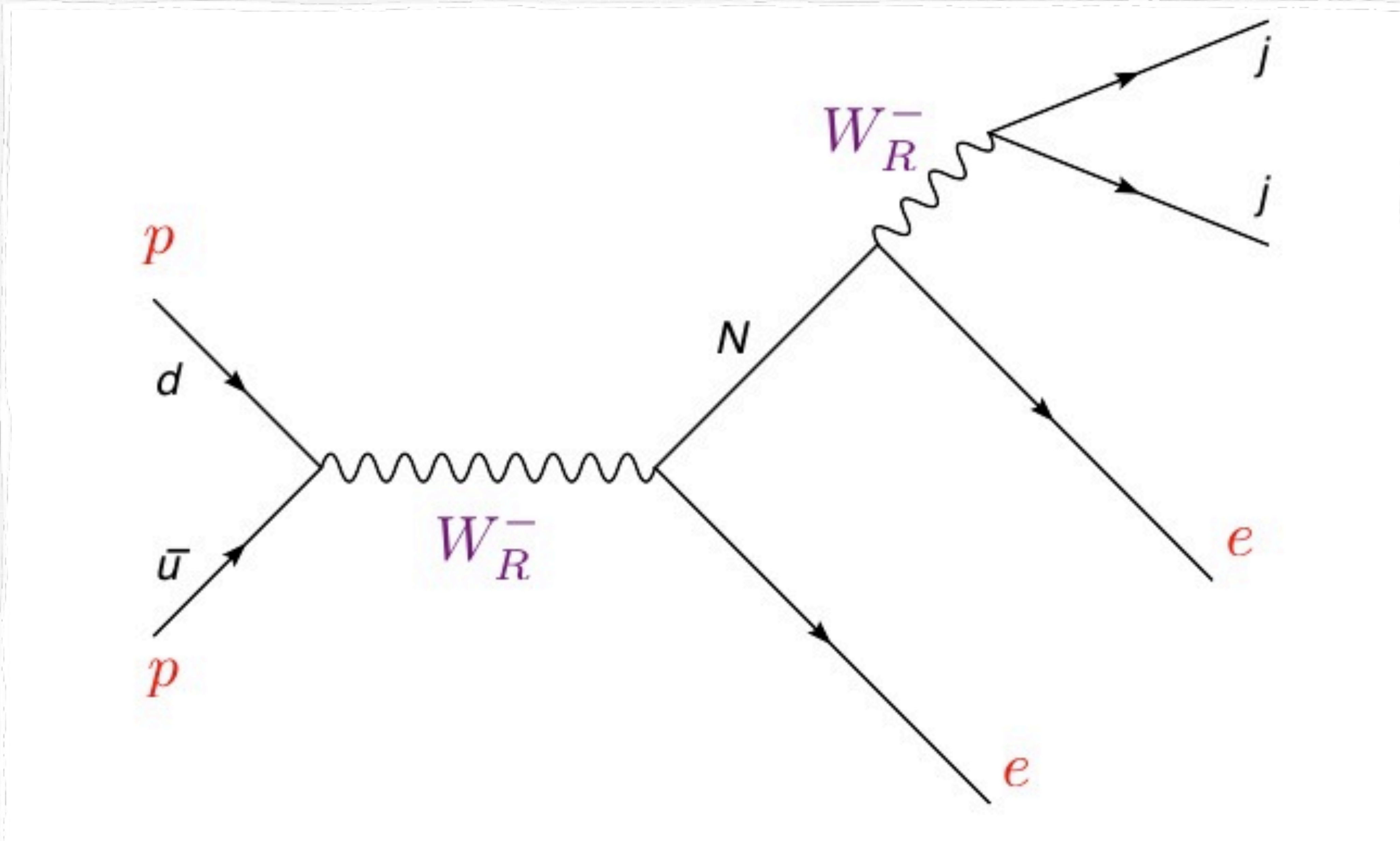
Keung, G.S. '83

LHC

proton = $u\ u\ d$

$q_d = -1/3$

$q_u = 2/3$



N = ν_R

j = hadronic jet

Keung, GS '83

LHC air view

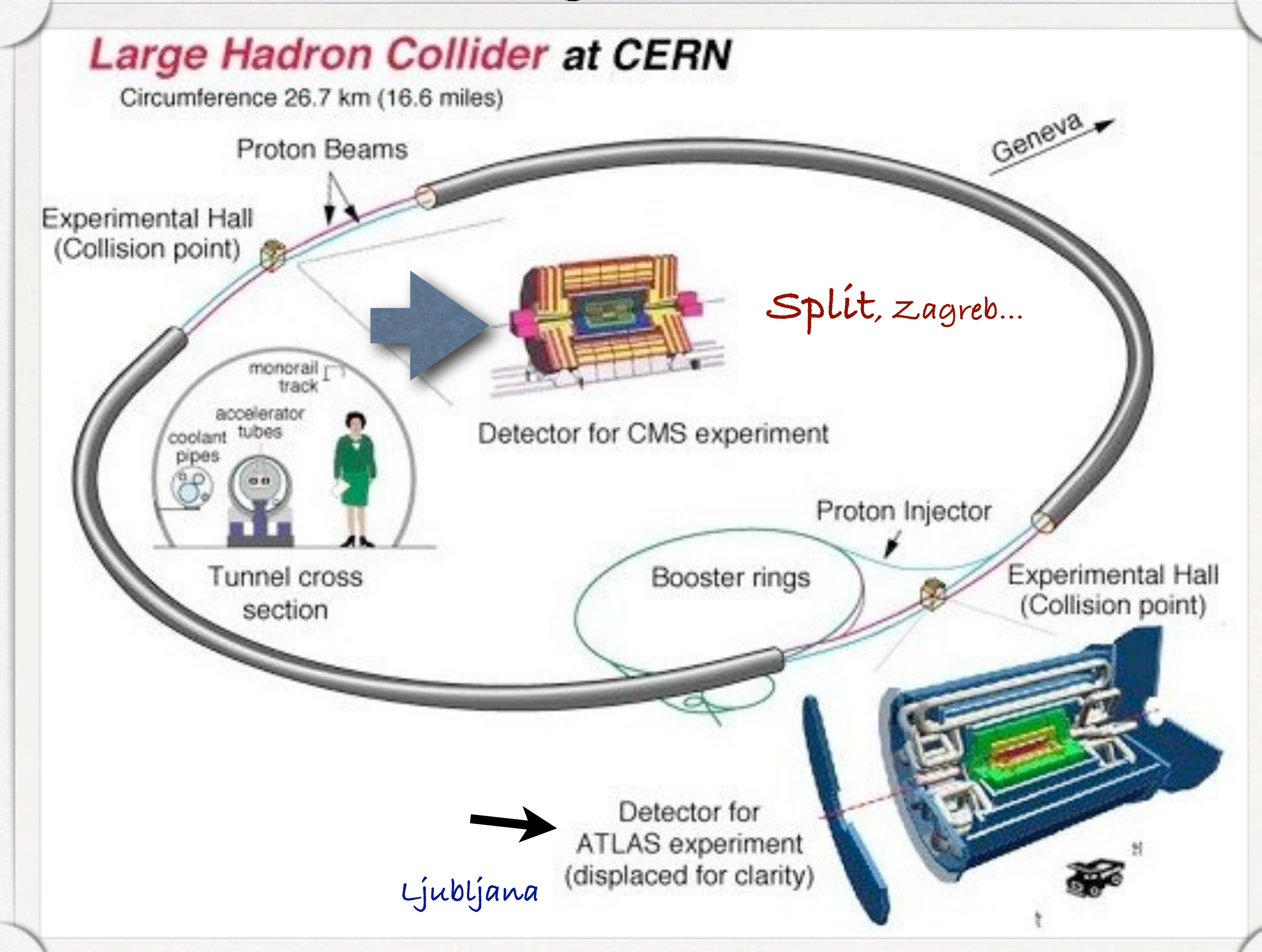
modern times

CERN

- 27 km
- 175 m deep

proton - proton scattering

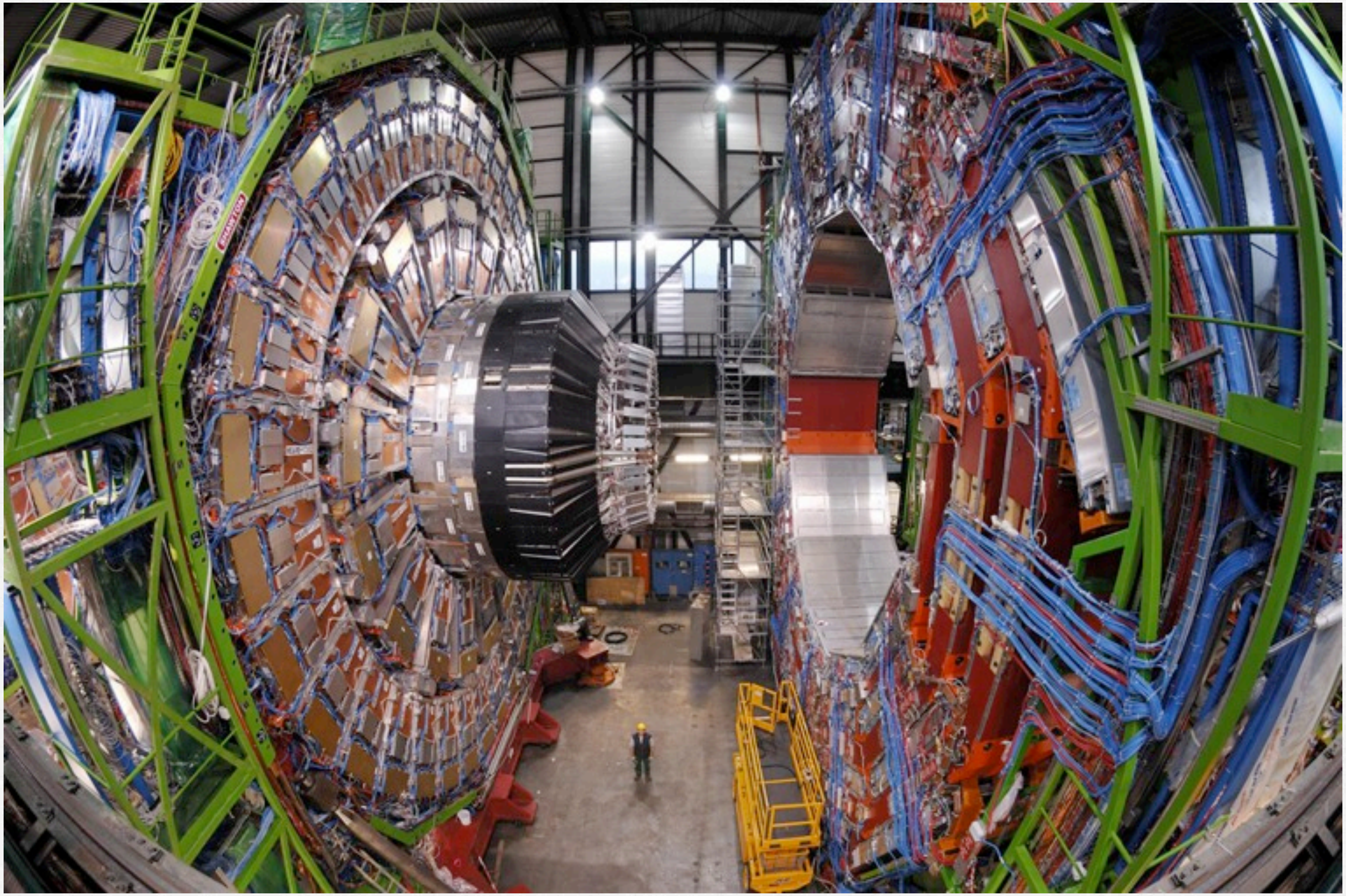
E=3500 GeV



total

E=7000 GeV

will double



modern times:

3600 people

CMS detector

Compact Muon Solenoid

both CMS and ATLAS:

dedicated search for W_R

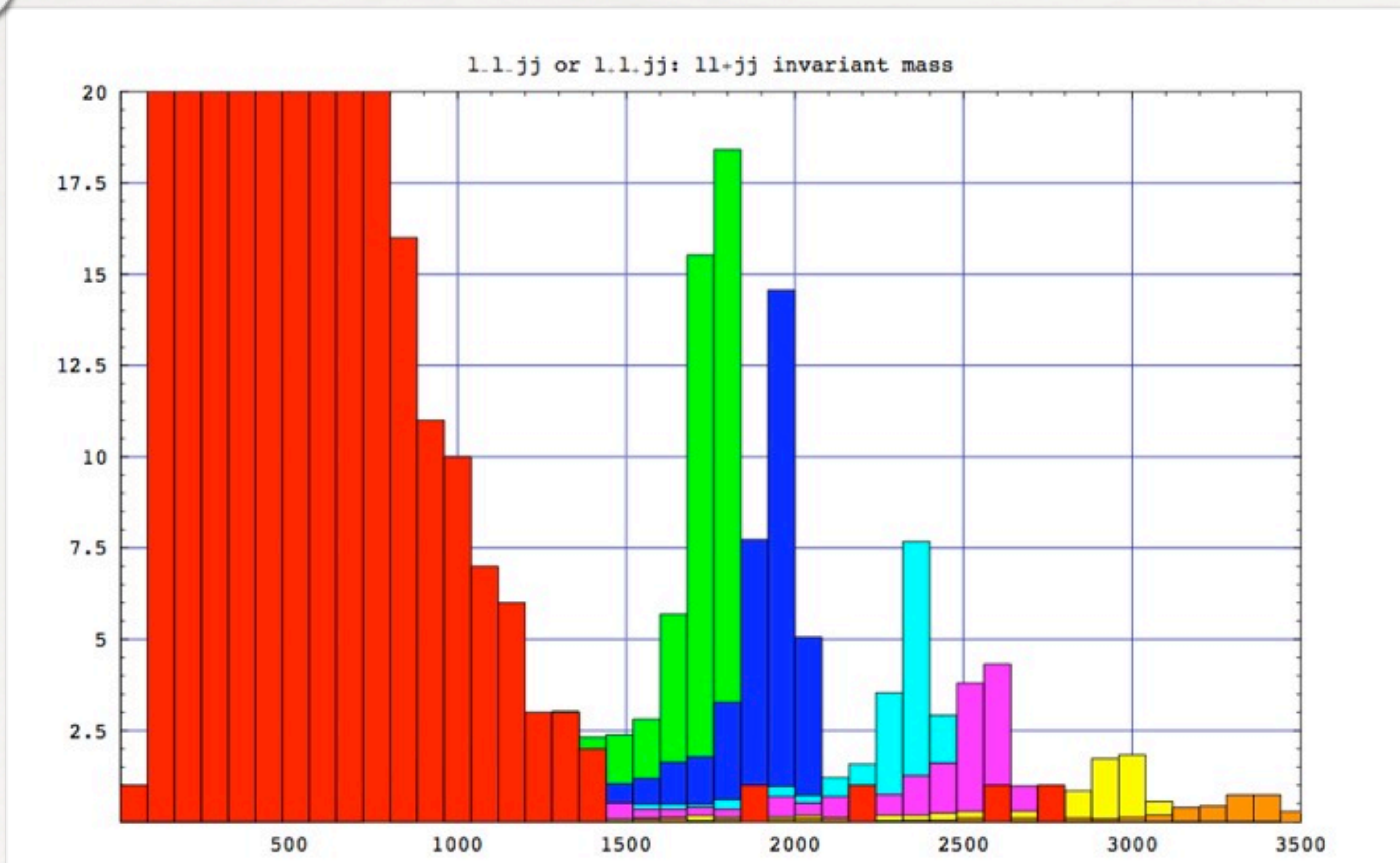
@ 14 TeV:

W_R up to 4 TeV mass

14 TeV LHC

Nesti

# of events as a function of energy (GeV) for $L = 8 fb^{-1}$



red = background   peaks = mass of W_R

- becoming reality as we speak, after two decades of waiting

- first data already here and more to come this year

- @ E = 3.5 TeV already a limit:

$$M_{W_R} \gtrsim 1700\ GeV$$

Nemevsek, Nesti, GS, Zhang, next week

LHC and Left-Right Symmetry

- ☑ direct test of restoration of parity
- ☑ direct production of electrons

spectacular LHC
signatures !!

Message:

LHC

- can probe the origin of neutrino mass
- can resolve the mystery of L-R symmetry in nature

STAY TUNED

Hvala

Thank you