

Neutrino Paradigm and LHC

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ICTP, Trieste

JSI lecture, April 4, 2012

Is Nature Left-Right Symmetric?

Alessio Maiezza, Miha Nemevsek,
Fabrizio Nesti, Vladimir Tello,
Francesco Vissani, Yue Zhang

Wai-Yee Keung, Rabi Mohapatra

Symmetries and Particles

Standard Model of all interactions

(but gravity*)

based on symmetries: local gauge

* gravity negligible:

38 orders of magnitude weaker than em

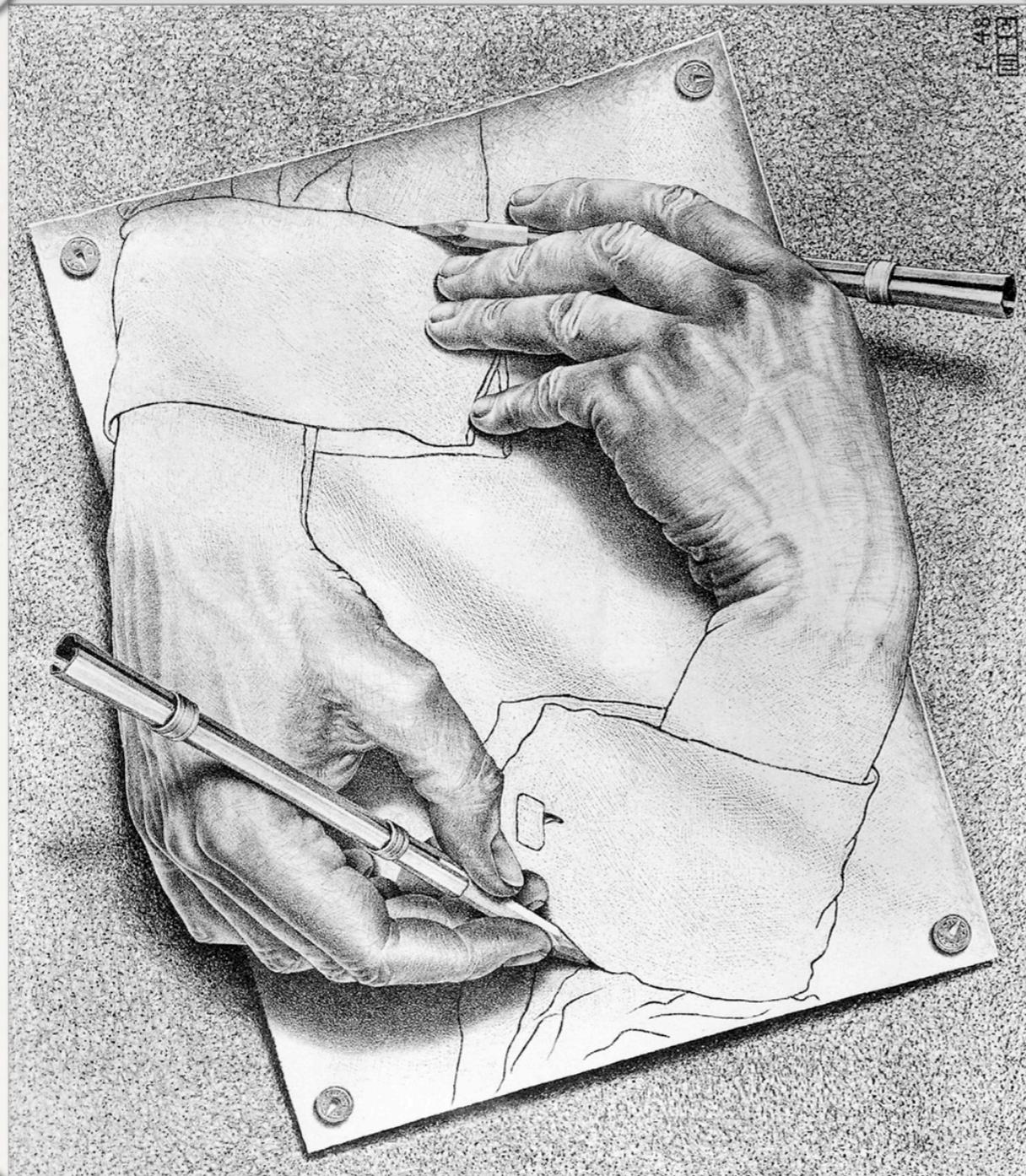
Why does gravity matter?

Why does matter gravitate?

⊙ sun - 10^{50} particles

zero charge

Theme 1

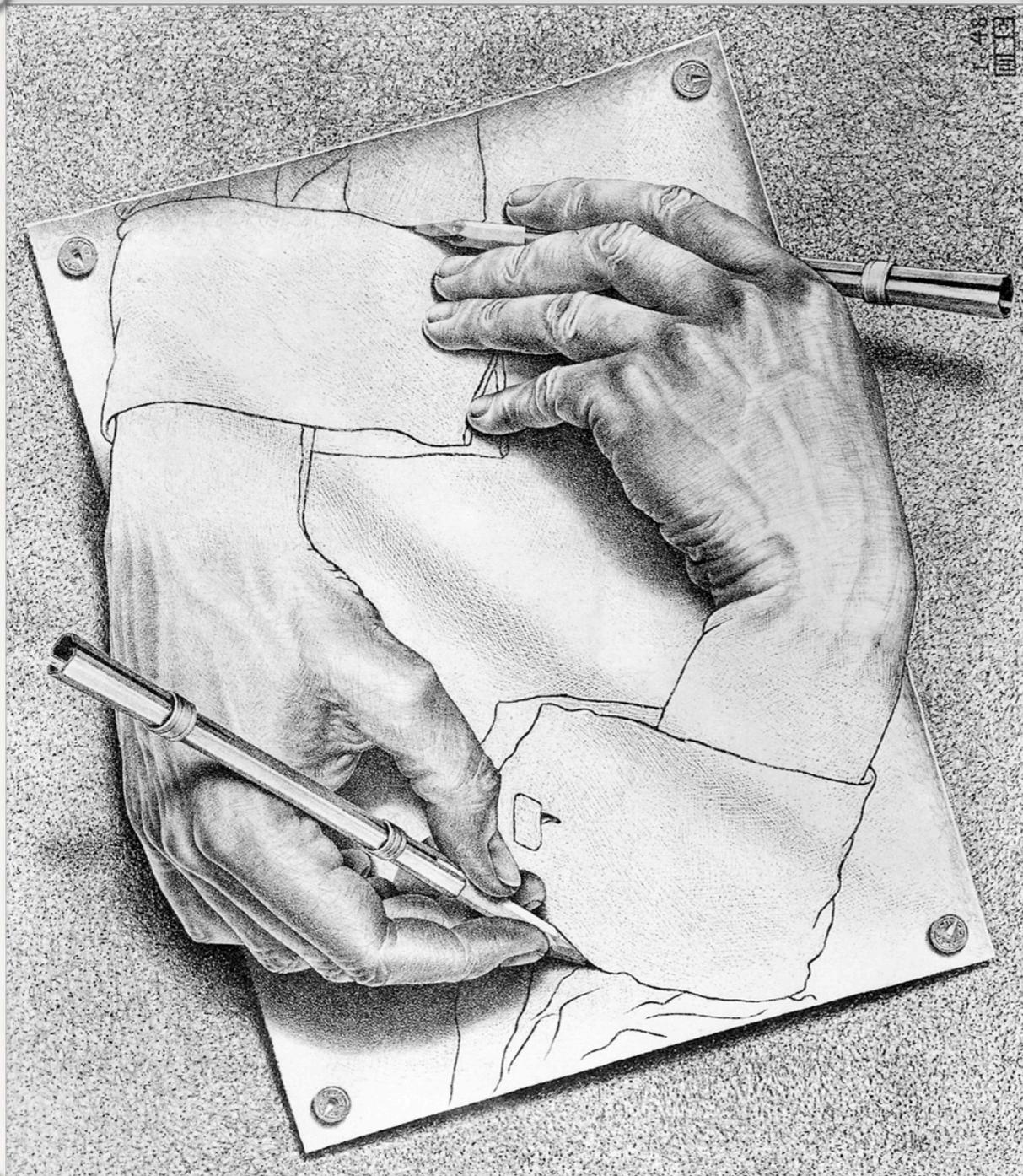


Parity:

left - right symmetry

images in the mirror

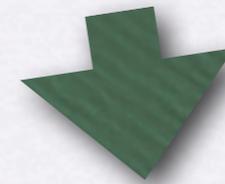
Theme 1



Parity:

left - right symmetry

images in the mirror



Large Hadron Collider

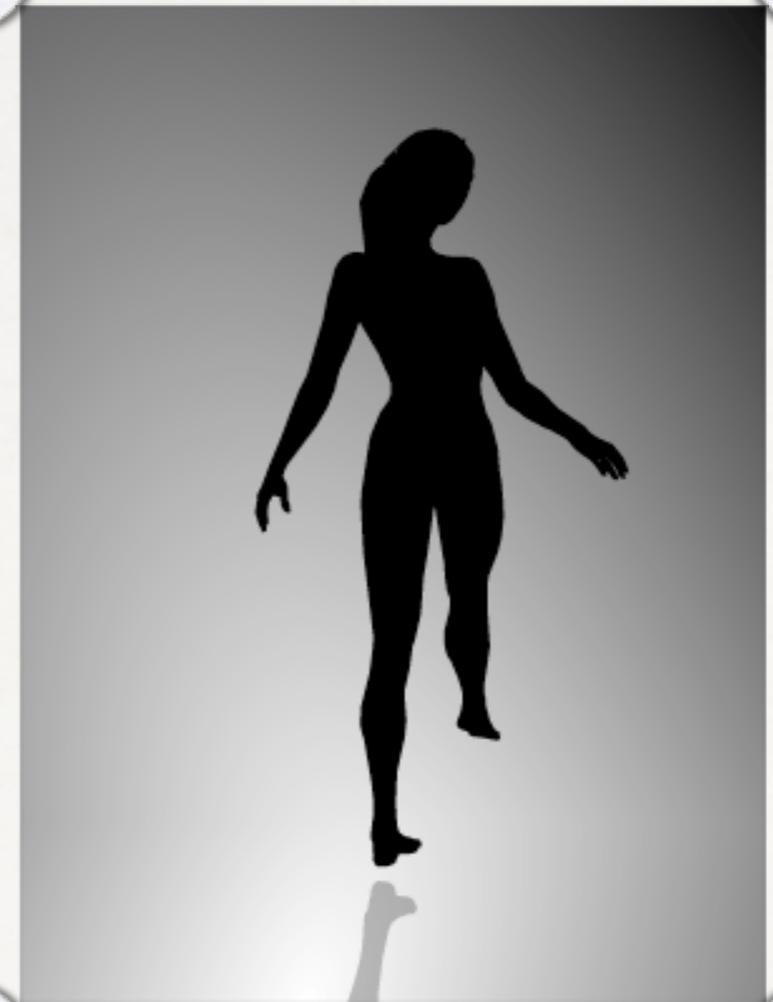
- elementary particles - mass, charge, spin



angular momentum at rest

particles keep spinning

- Quantum Mechanics:
 $s=n/2$



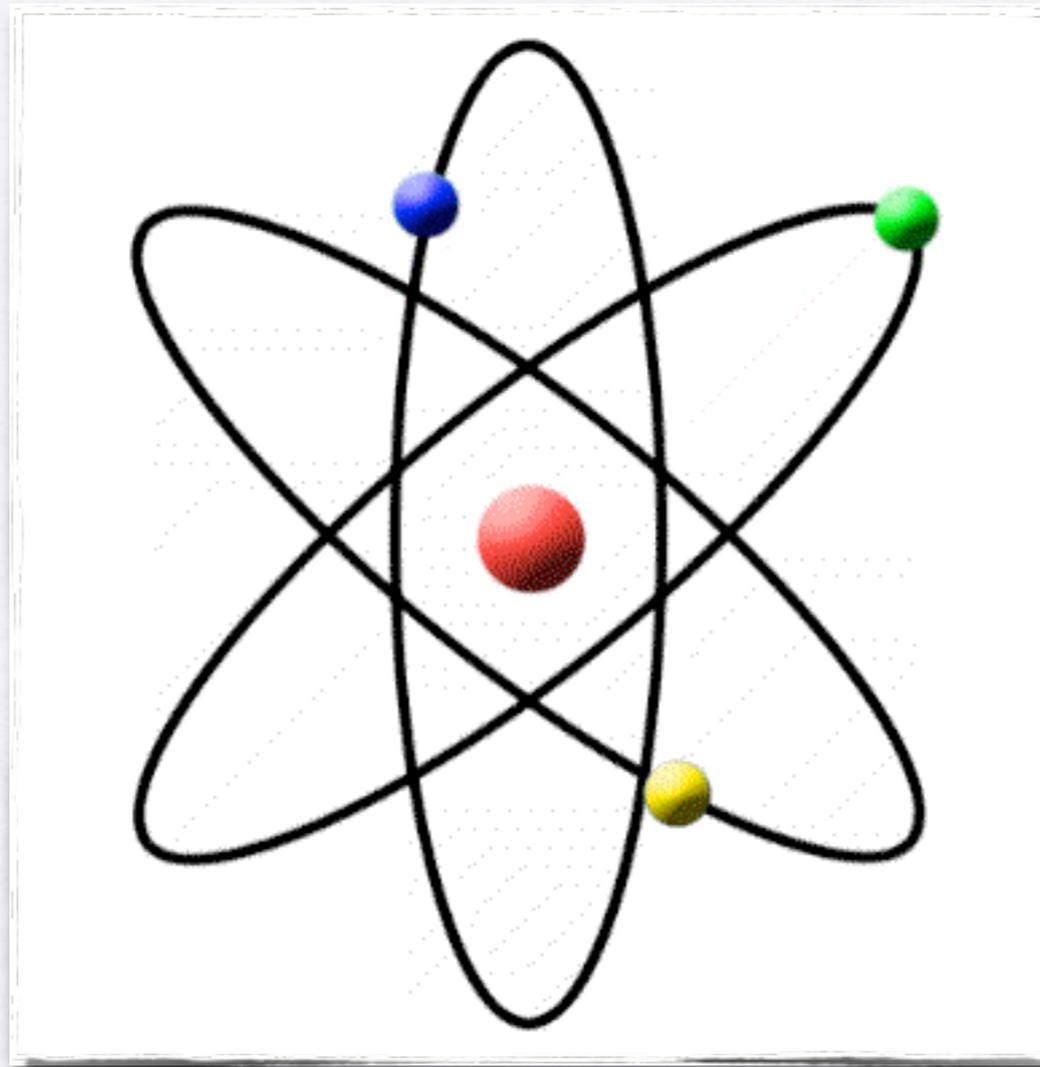
Matter = atoms

 nucleus



electrons

Matter = atoms



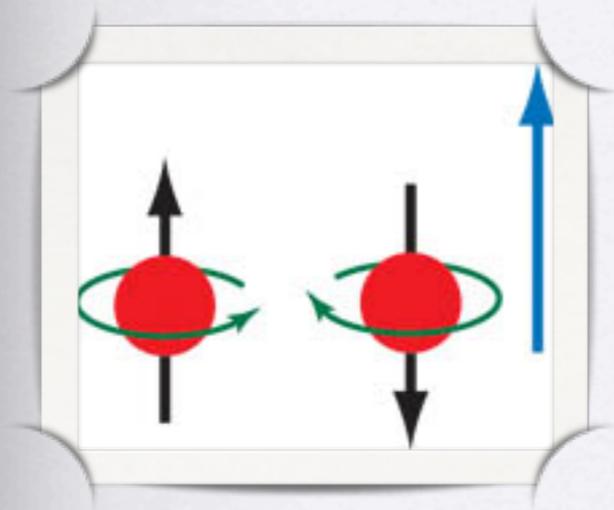
electrons



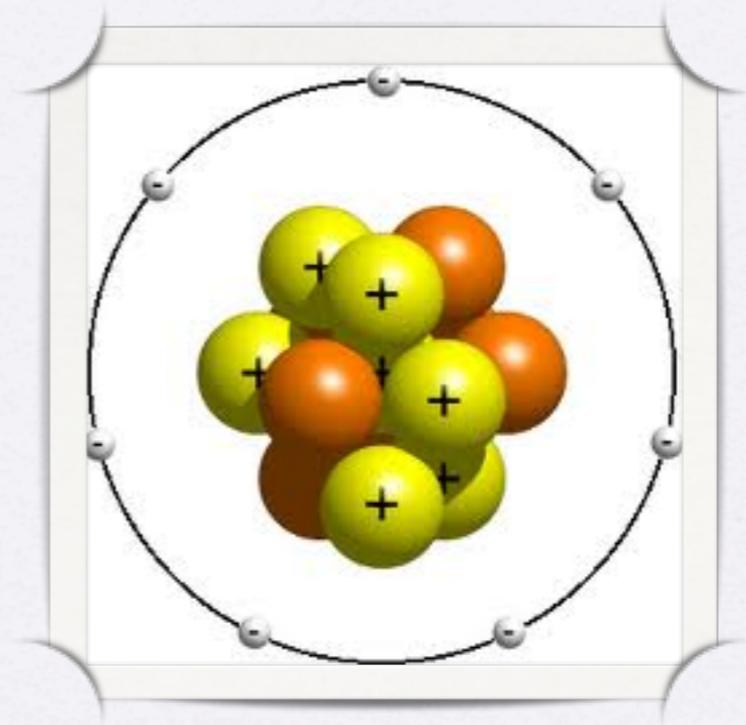
nucleus

Nucleus = protons and neutrons

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



$s = 1/2$
(fermions)



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

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

relativistic equation: $s=1/2$

Dirac '28

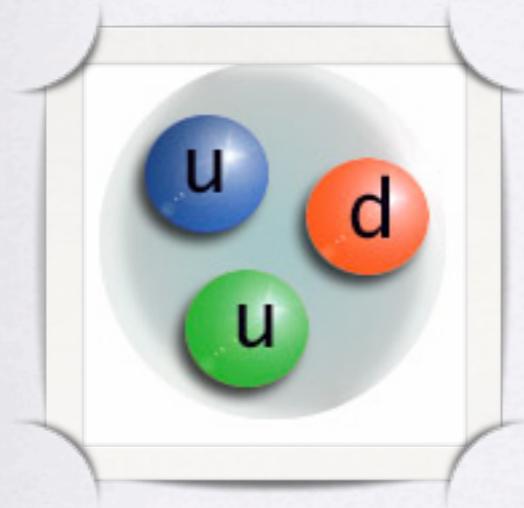
Protons and neutrons

$s=1/2$

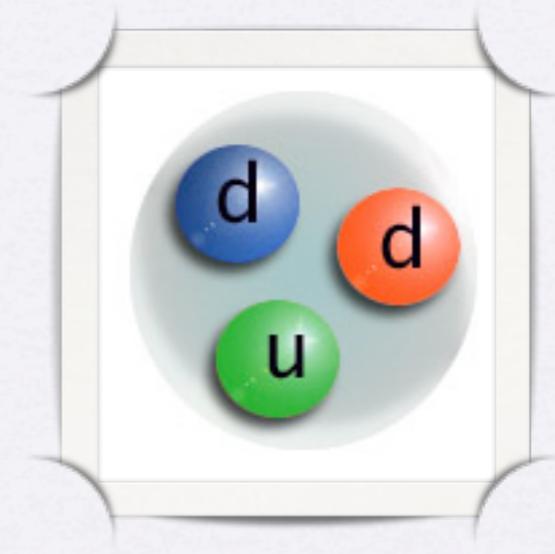
aces

Zweig '64

proton



neutron



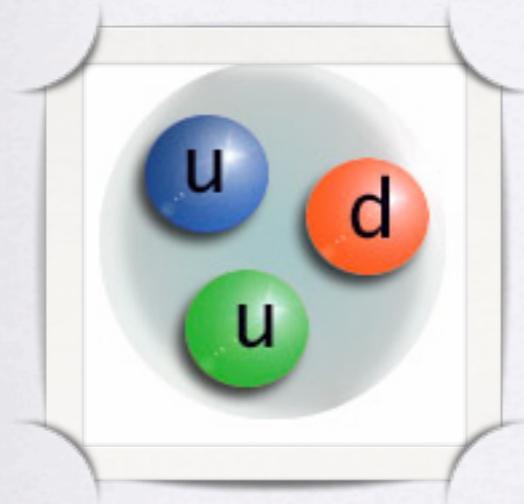
Protons and neutrons

$s=1/2$

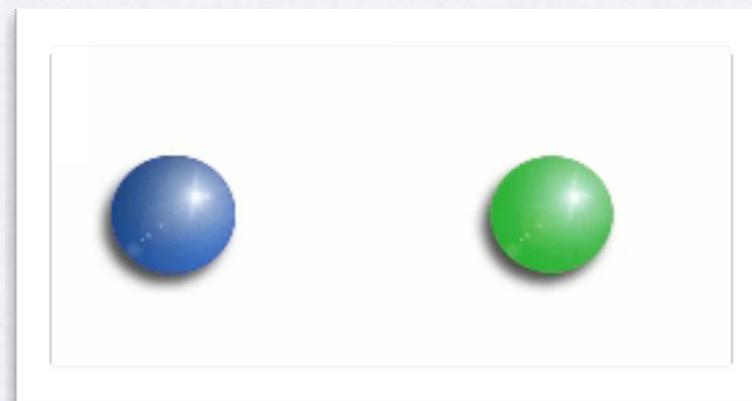
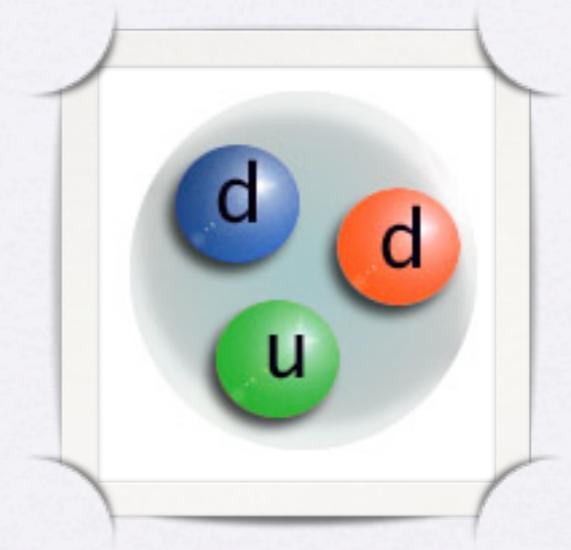
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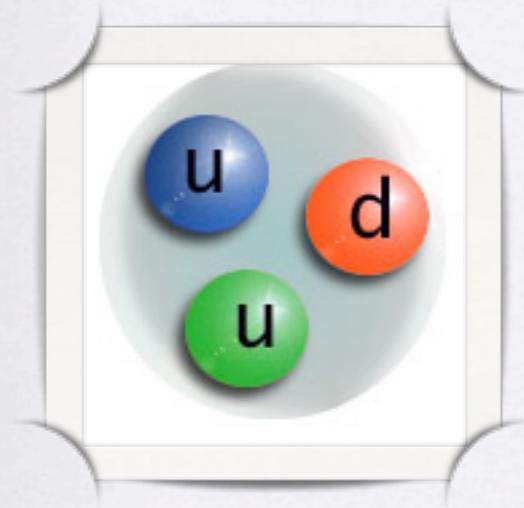
Protons and neutrons

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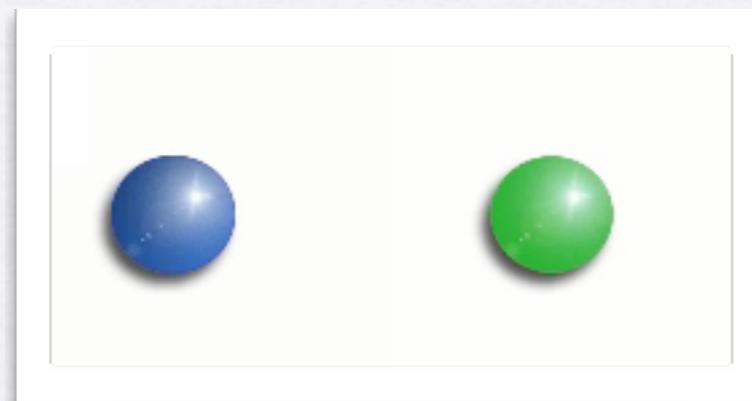
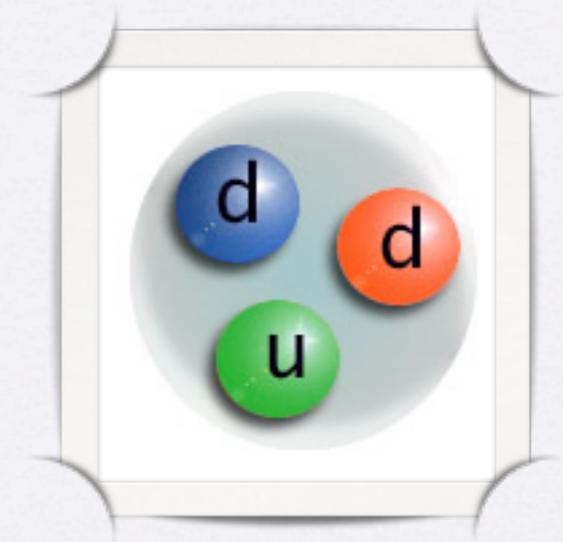
quarks

Gell-Mann '64

proton



neutron



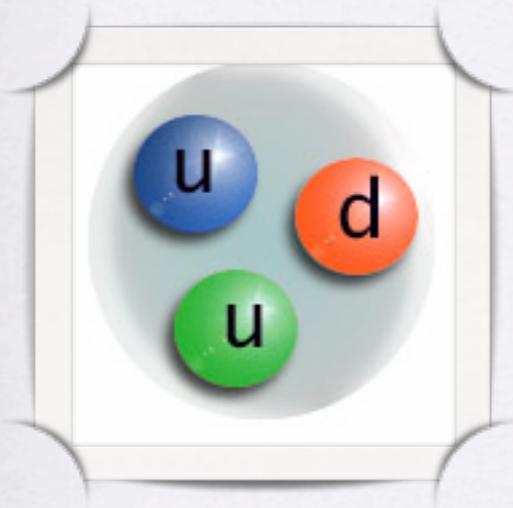
Protons and neutrons

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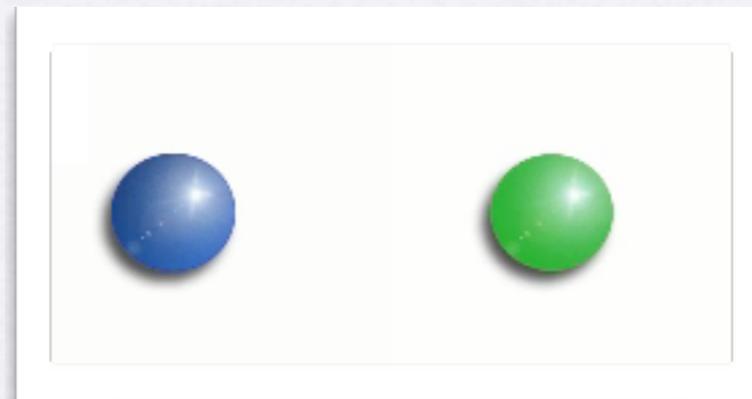
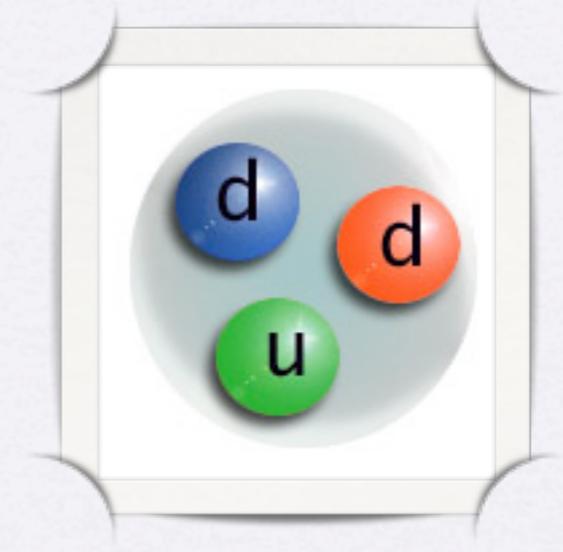
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proton



neutron

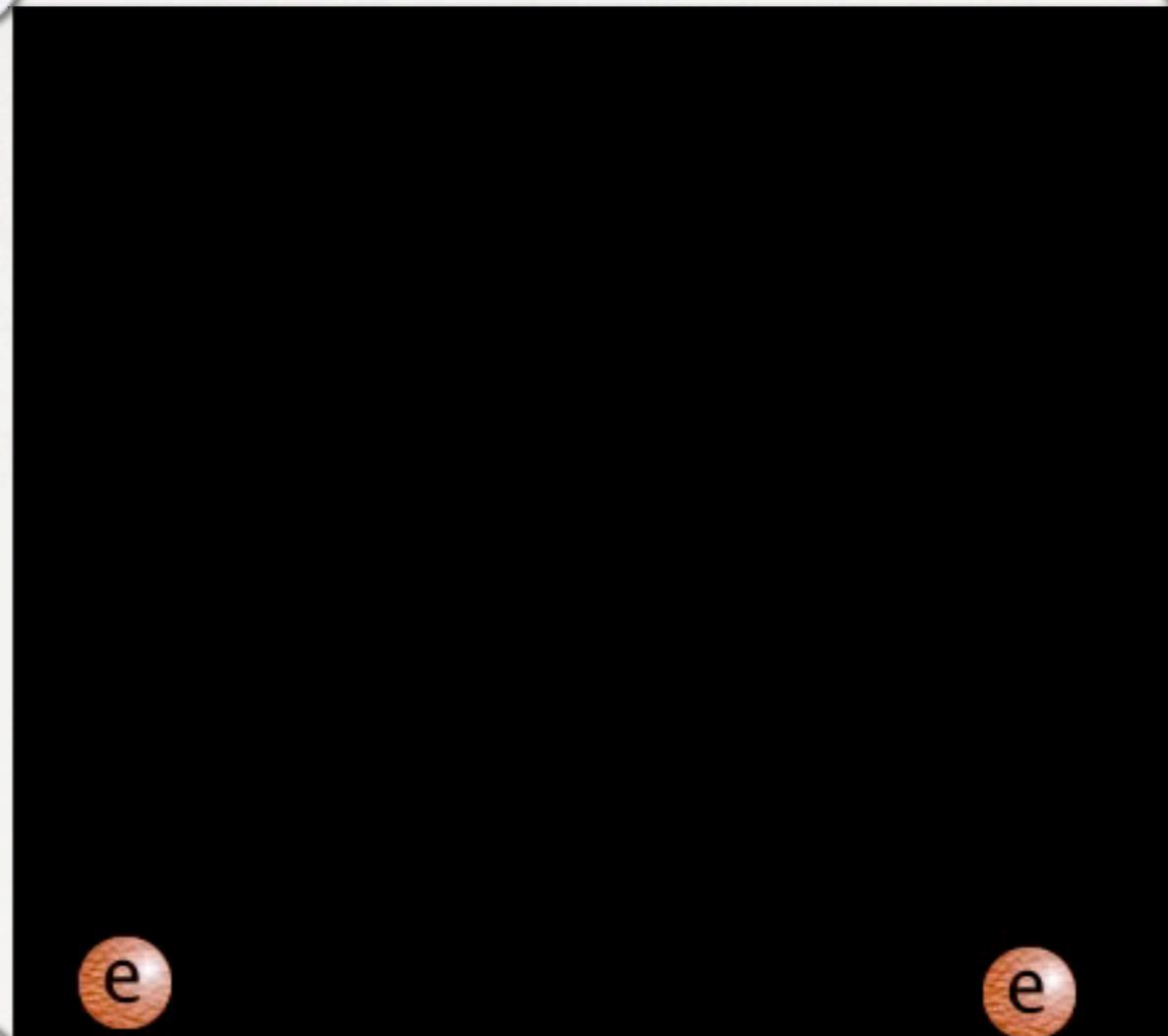


our hero:

neutrino

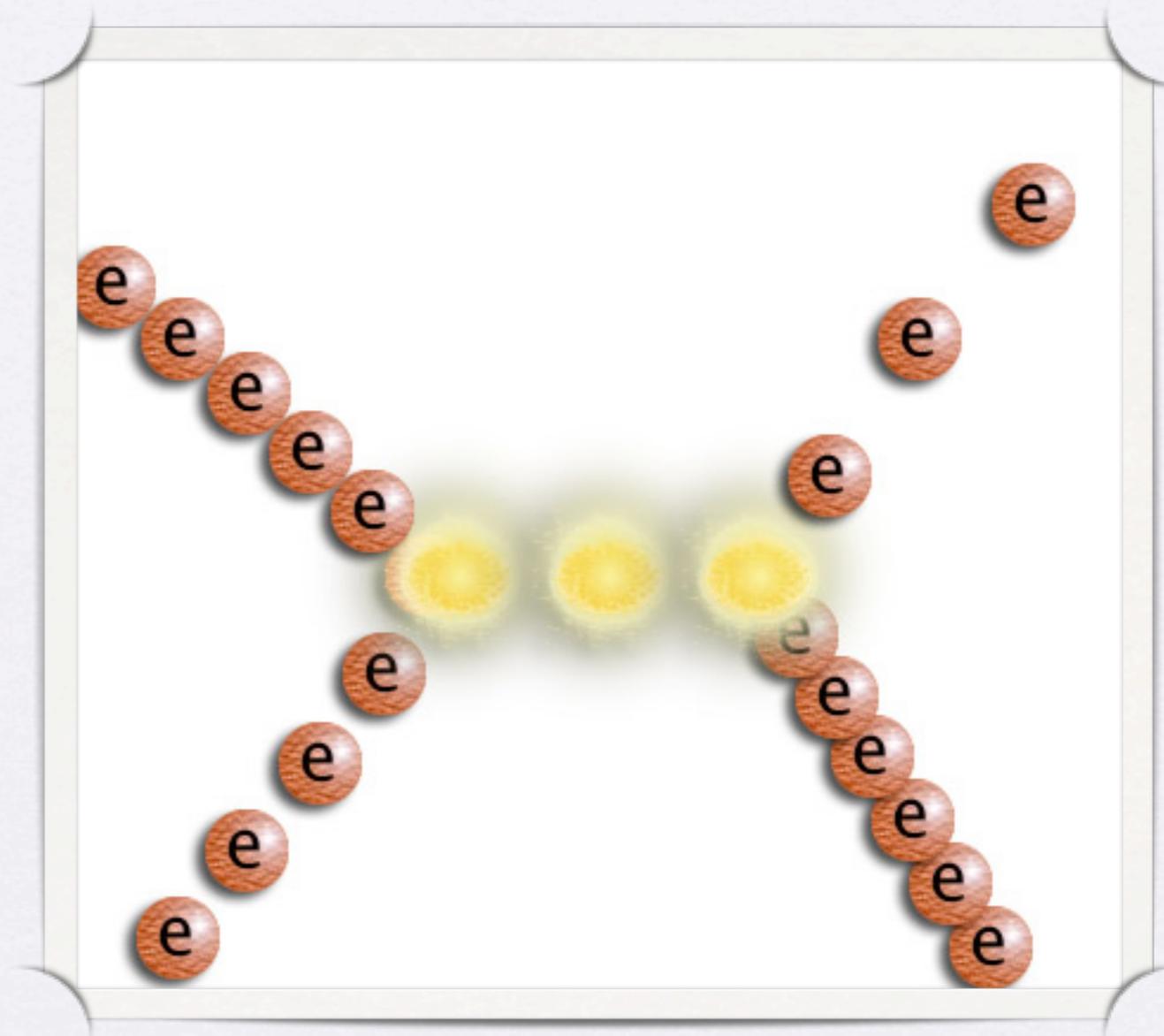
Forces: messengers

photon =
messenger of em



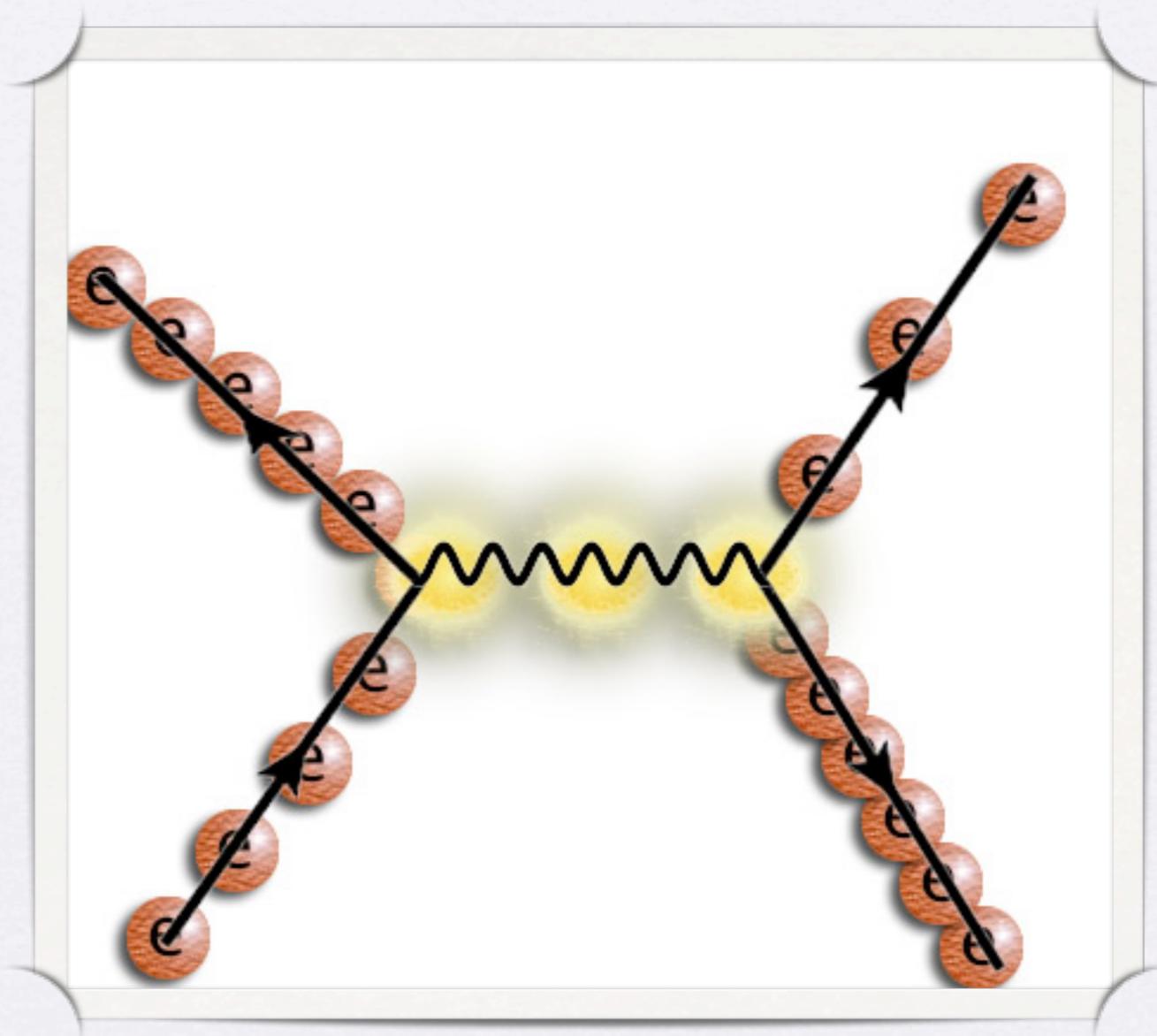
Forces: messengers

Feynman '48



Forces: messengers

Feynman '48

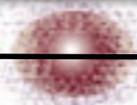


messengers of forces:

feeble →

$s=1$

central →

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

$$m_p \simeq GeV$$



- bombshell: anti-particles

Dirac '31

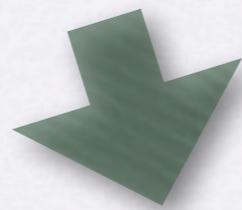
\bar{e} positron = anti electron

Chao '29

Anderson '32

\bar{p} anti proton

Segre', Chamberlain '55



different anti-particle for every fermion



- bombshell: anti-particles

Dirac '31

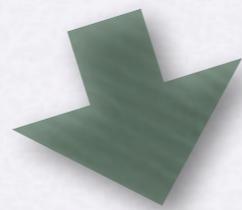
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different anti-particle for every fermion

not necessarily,



- bombshell: anti-particles

Dirac '31

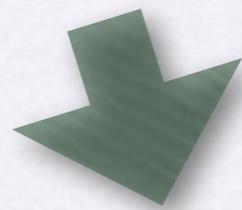
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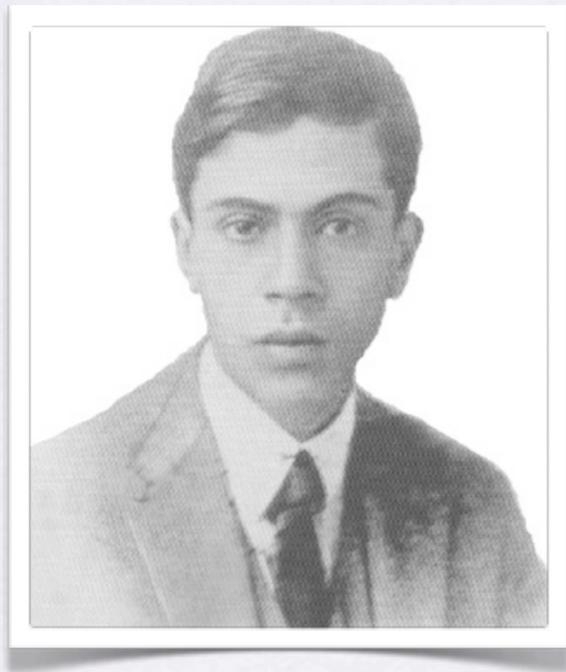
different anti-particle for every fermion

not necessarily,

says Majorana

not neutrino ?

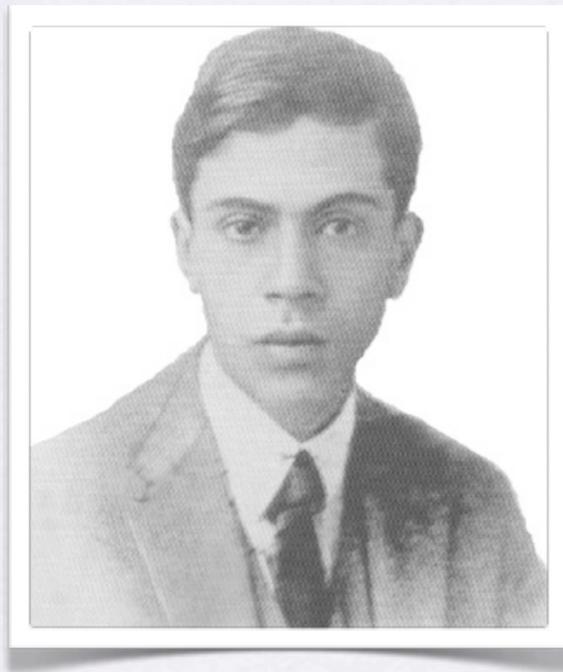
it's own antiparticle



Ettore Majorana

not neutrino ?

it's own antiparticle



Ettore Majorana

last paper before his disappearance

not neutrino ?

it's own antiparticle

Ettore Majorana

last paper before his disappearance

Ettore Majorana

March 26

1938

took a boat from Palermo to Napoli -
never seen afterwards

only 32



"A slightly uncertain destination"

beautiful novel,
physics remarkably correct

Who saw him?

Chi l'ha visto?



Ettore Majorana, ordinario di fisica teorica all'Università di Napoli, è misteriosamente scomparso dagli ultimi di marzo. Di anni 31, alto metri 1,70, snello, con capelli neri, occhi scuri, una lunga cicatrice sul dorso di una mano. Chi ne sapesse qualcosa è pregato di scrivere al R. P. E. Maria-

necci, Viale Regina Margherita 66 - Roma.

Ettore Majorana - Questo annuncio della famiglia Majorana apparve sulla «Domenica del Corriere» del 17 luglio 1938.

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

The creation of electrons out of “nothing”

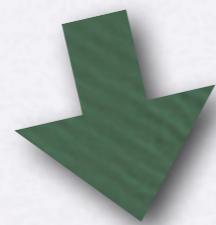
- Neutrino-less double beta decay

Racah '37 Furry '38

- LHC - pp collisions can create electrons

Keung, GS '83

- neutrinos: why so special?
- The most aloof particles



A probe of new physics

Discovering neutrinos

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

Pauli '30

conservation of energy



a new neutral particle:

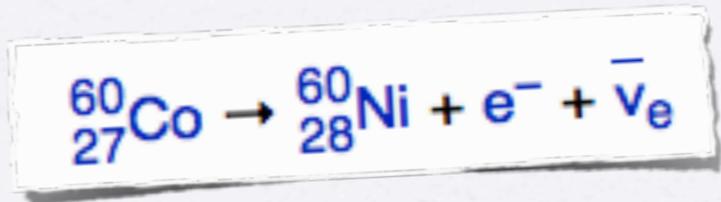
neutrino (small neutron)

Fermi '32

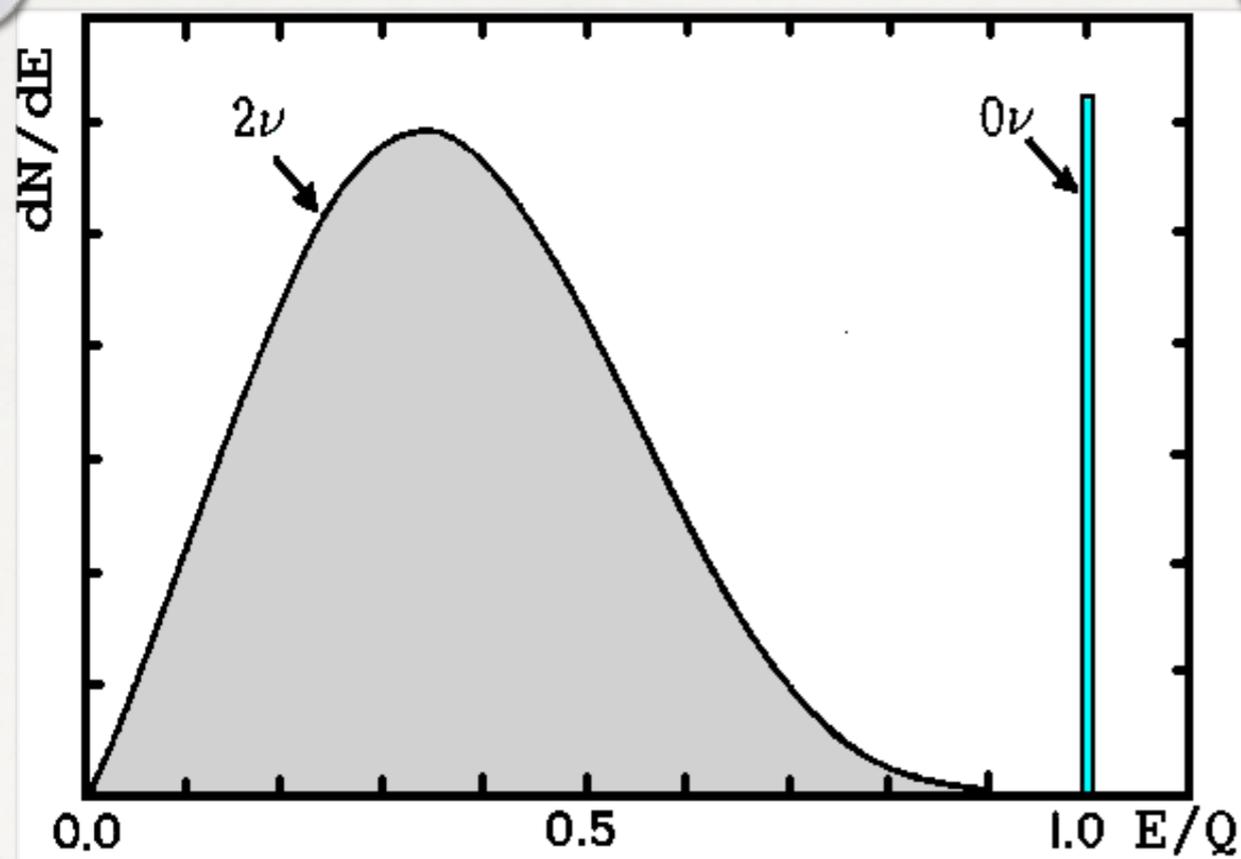
'brother' of electron

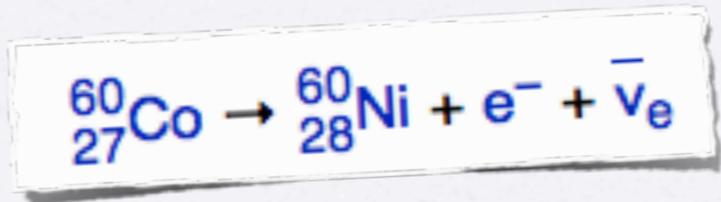
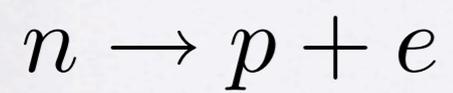
leptons (light)

$$n \rightarrow p + e$$

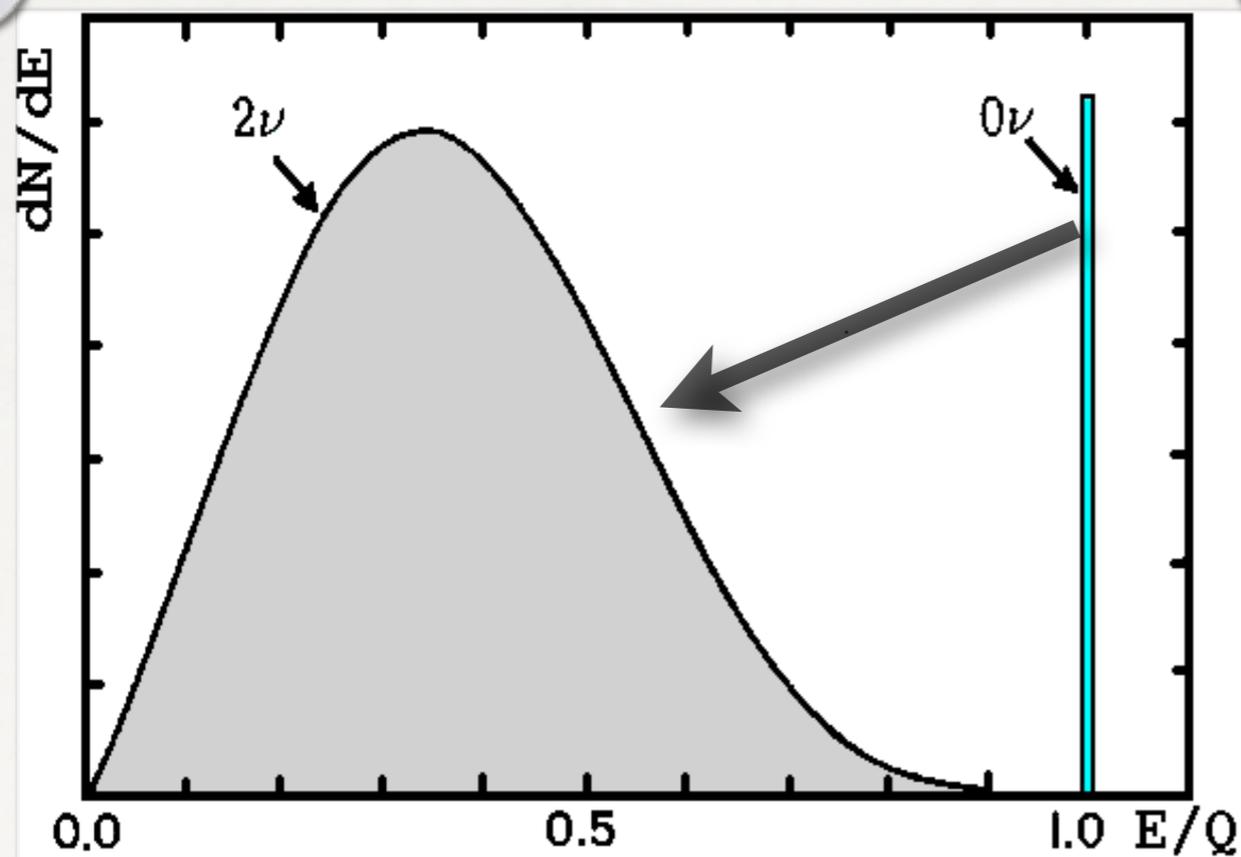


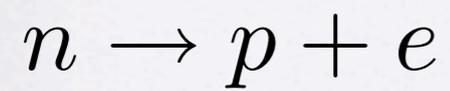
expected $E = Q$



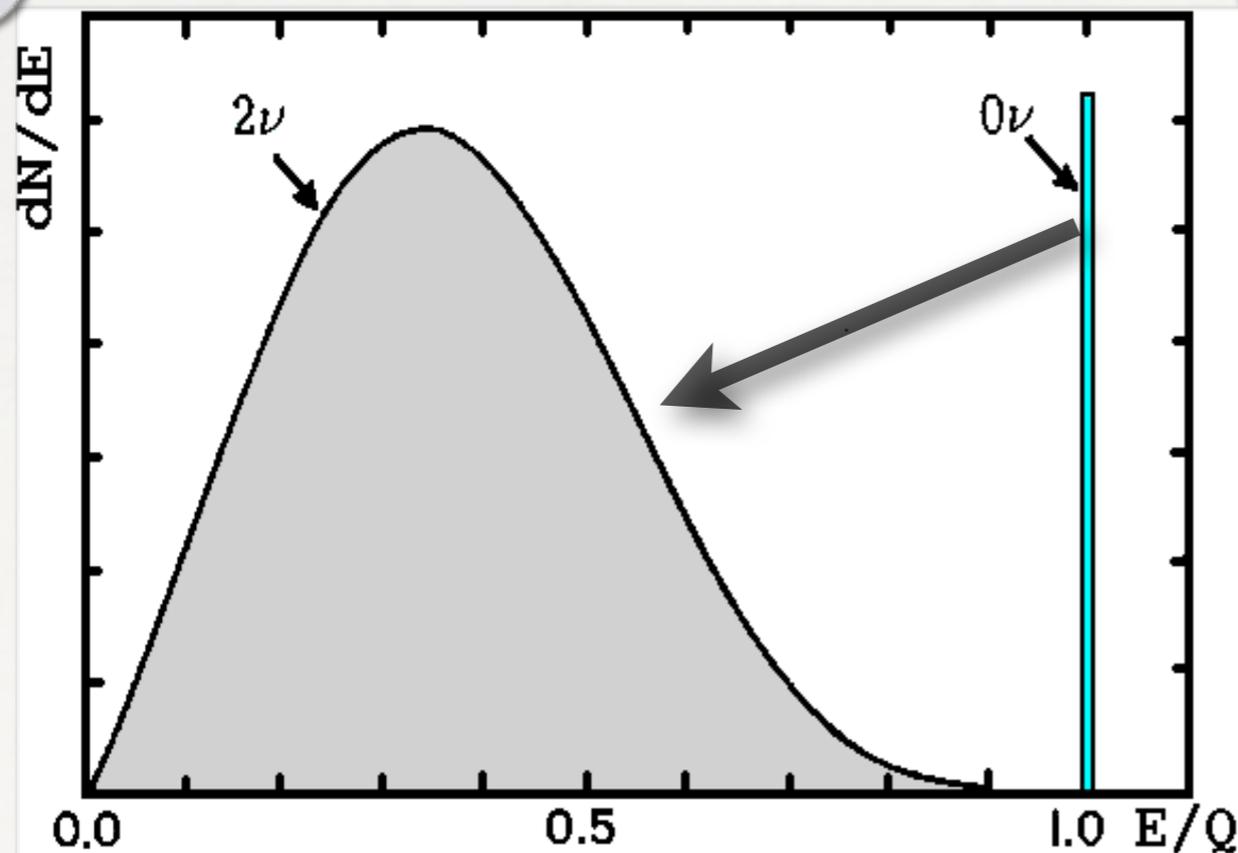


expected $E = Q$





expected $E = Q$



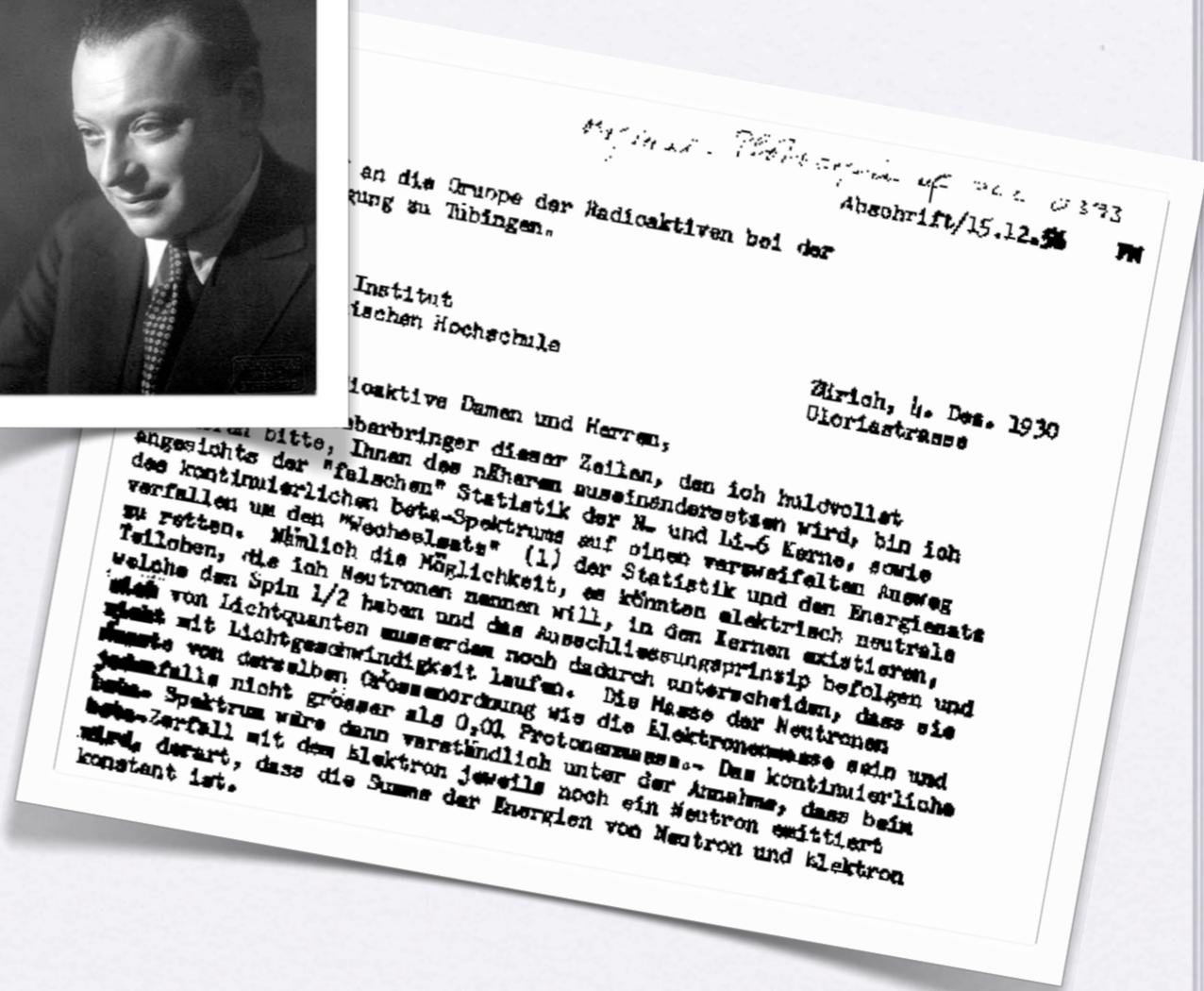
Continuous spectrum

Dear Radioactive Ladies and Gentlemen,

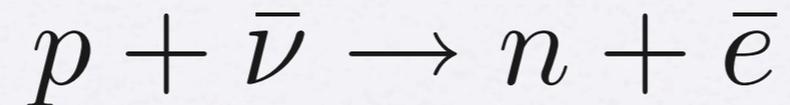
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a **desperate** remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $1/2$ and obey the exclusion principle and which 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 masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen those neutrons very earlier if they really exist. But only the one who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "**Oh, It's well better not to think to this at all, like new taxes**". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately, I cannot appear in Tübingen personally since **I am indispensable here in Zurich because of a ball on the night of 6/7 December**. With my best regards to you, and also to Mr Back.

Your humble servant
. W. Pauli



- how to see it?



- mean free path $\simeq 10^{20}$ cm Fermi '34

70 million times distance earth-sun

helps understand 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

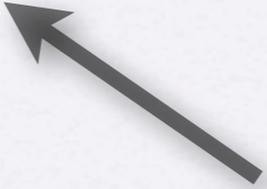
by John Updike

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Cosmic Gall

by John Updike

wrong



Savannah River reactor

Cowan and Reines '56



large flux of neutrinos

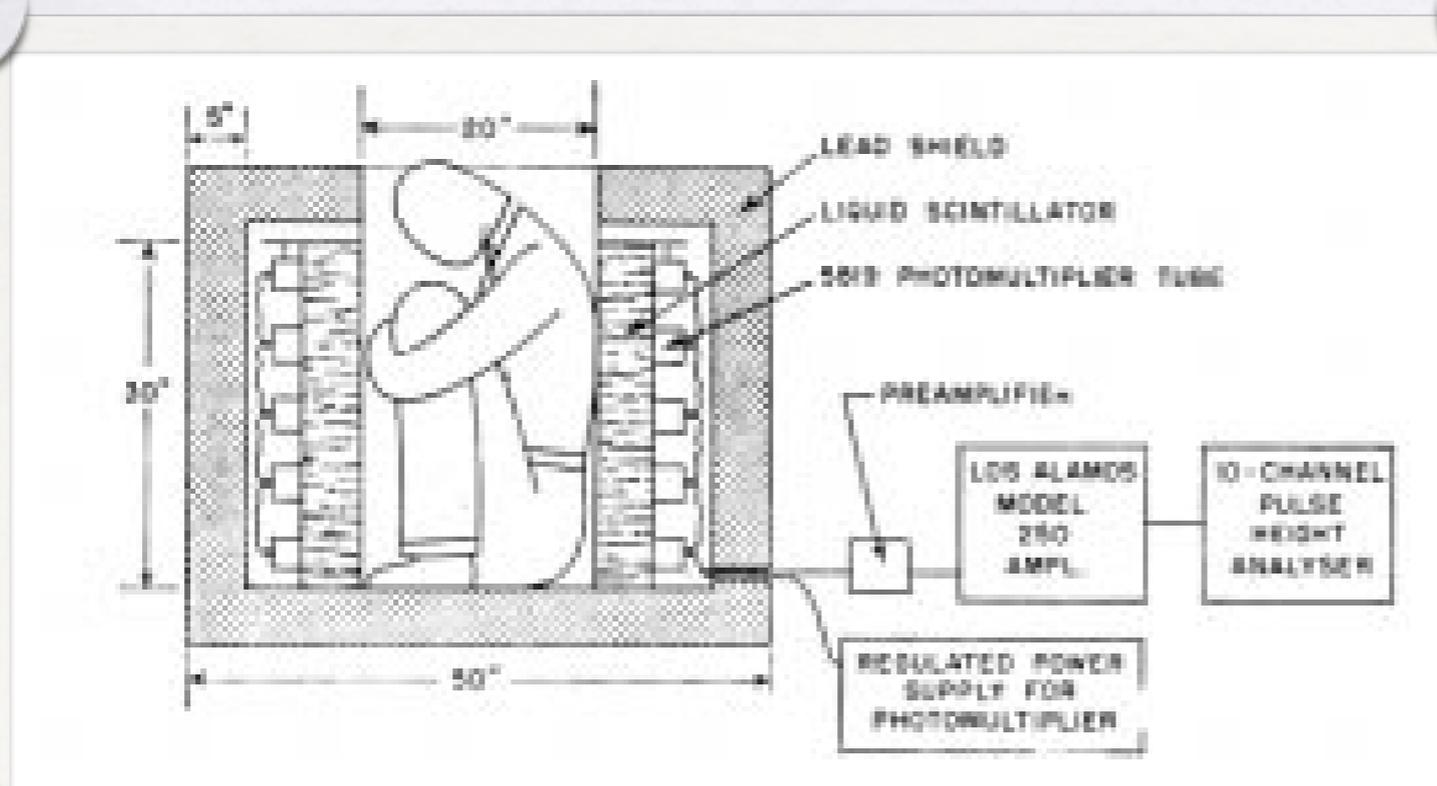
detector : **water** (protons)

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

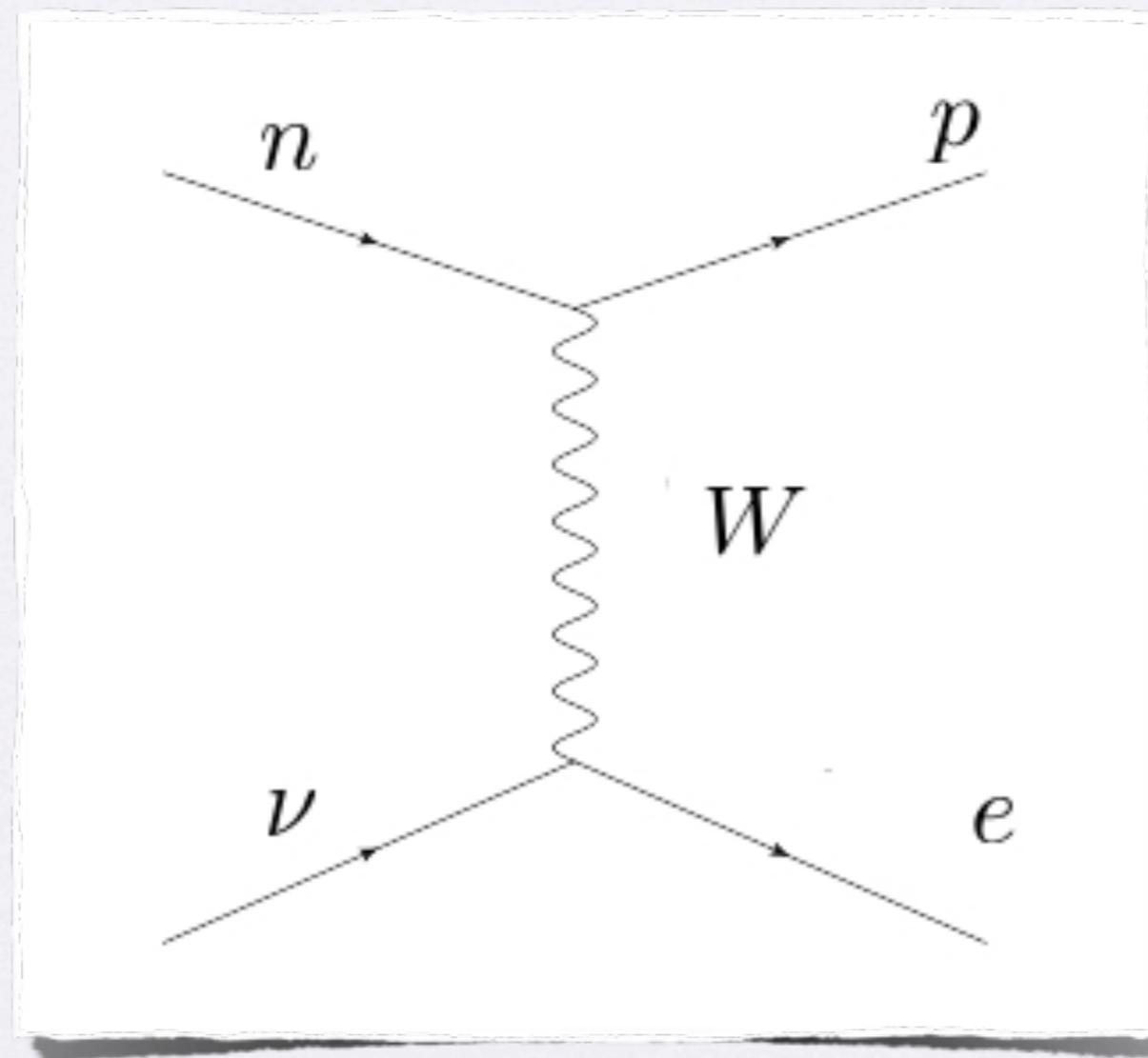
(ten thousand billions)

good old days

8 people



Beta decay : messenger W boson



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

W boson: the shiny (hairy) guy

$$d \rightarrow u + e + \bar{\nu}$$

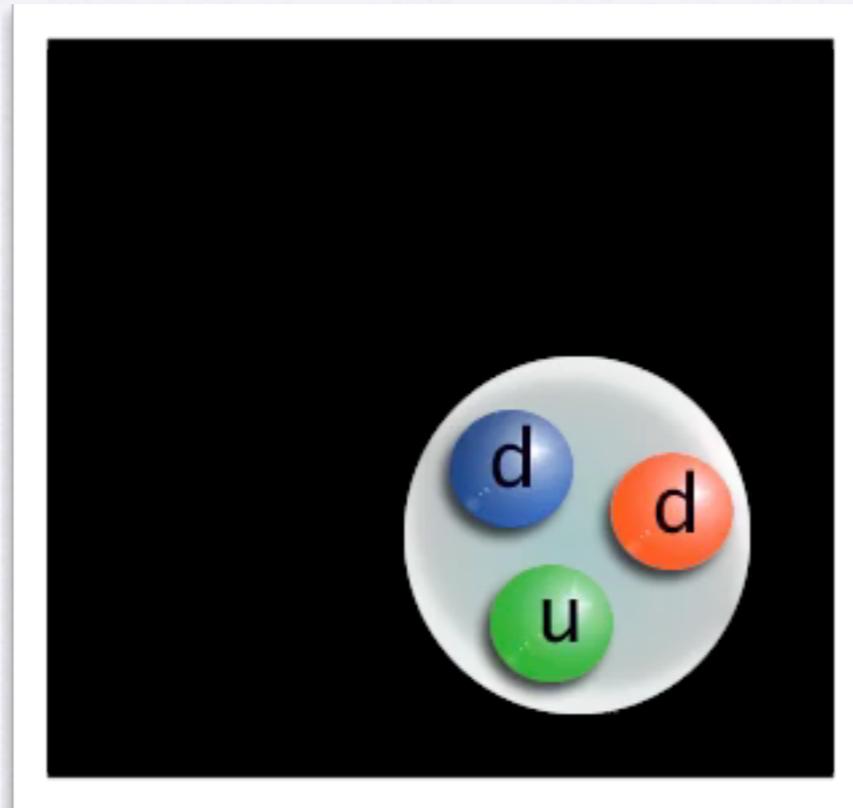
$$p = u u d$$

$$n = u d d$$

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

W boson: the shiny (hairy) guy

$$d \rightarrow u + e + \bar{\nu}$$



$$p = u u d$$

$$n = u d d$$

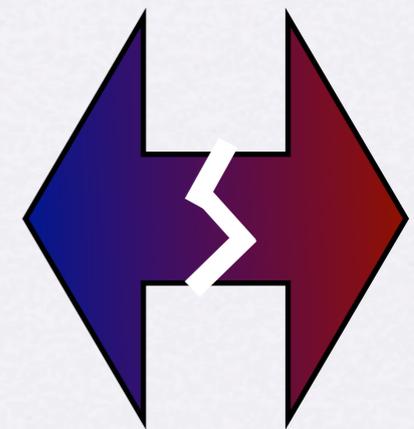


- 1956: bombshell of Lee and Yang

parity violation in weak interaction

- only left particles in beta decay

L-R symmetry broken



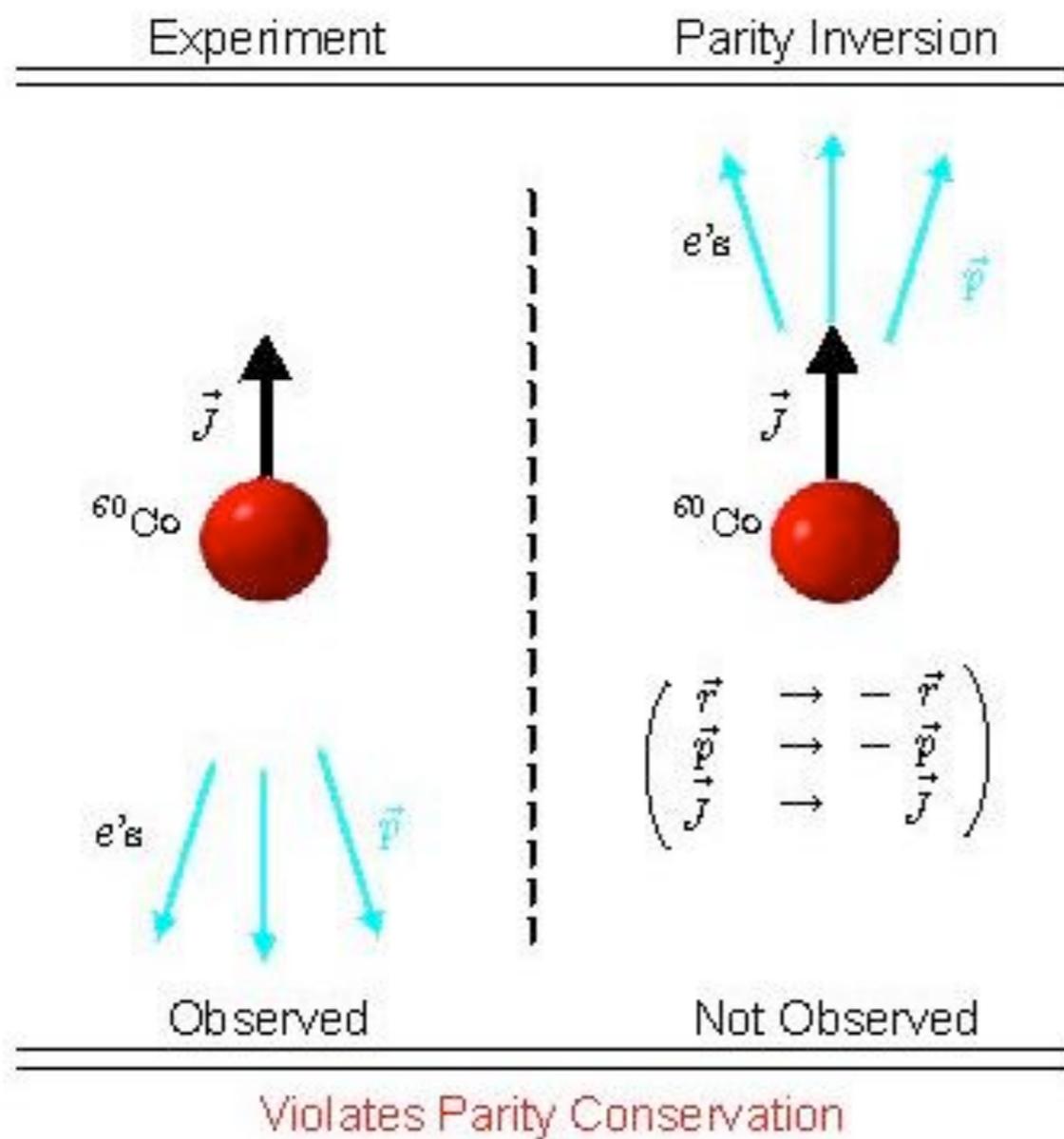
Discovery of P violation

good old days

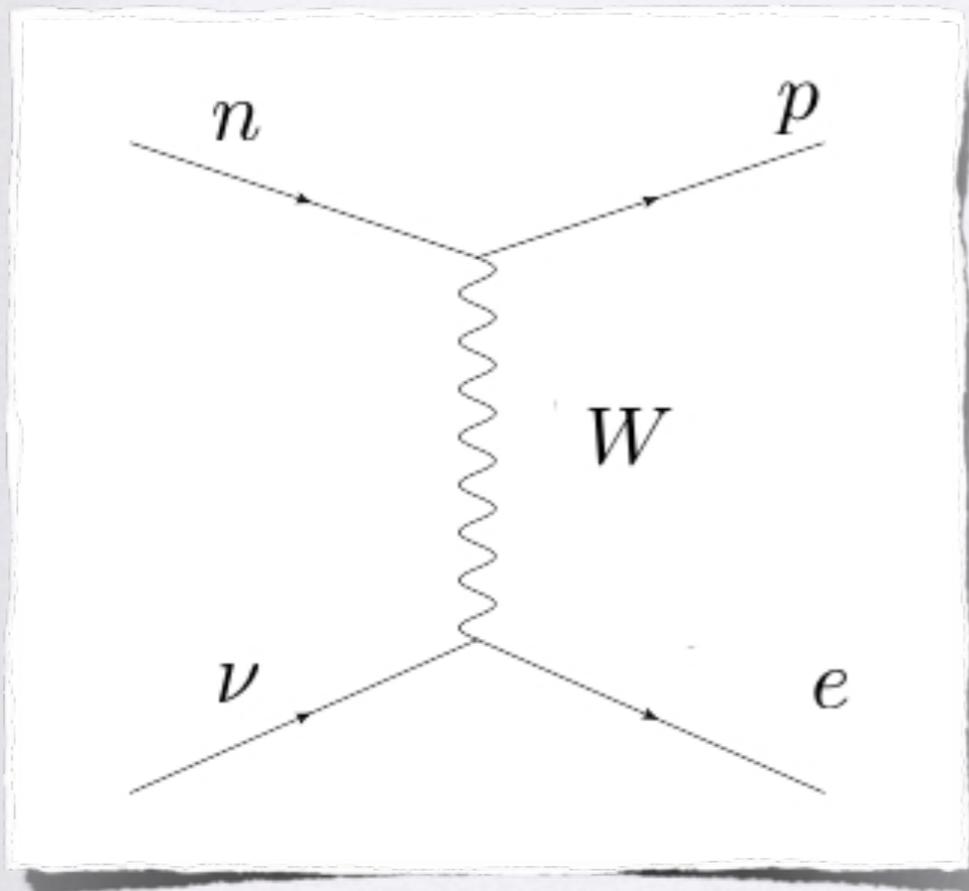
5 people



C.S. Wu
'56



beta decay : messenger W boson



Parity violation



only left particles
interact with W

confirmed when
discovered

Discovering W bosons

SPS: Super Proton Synchrotron

7 km circumference

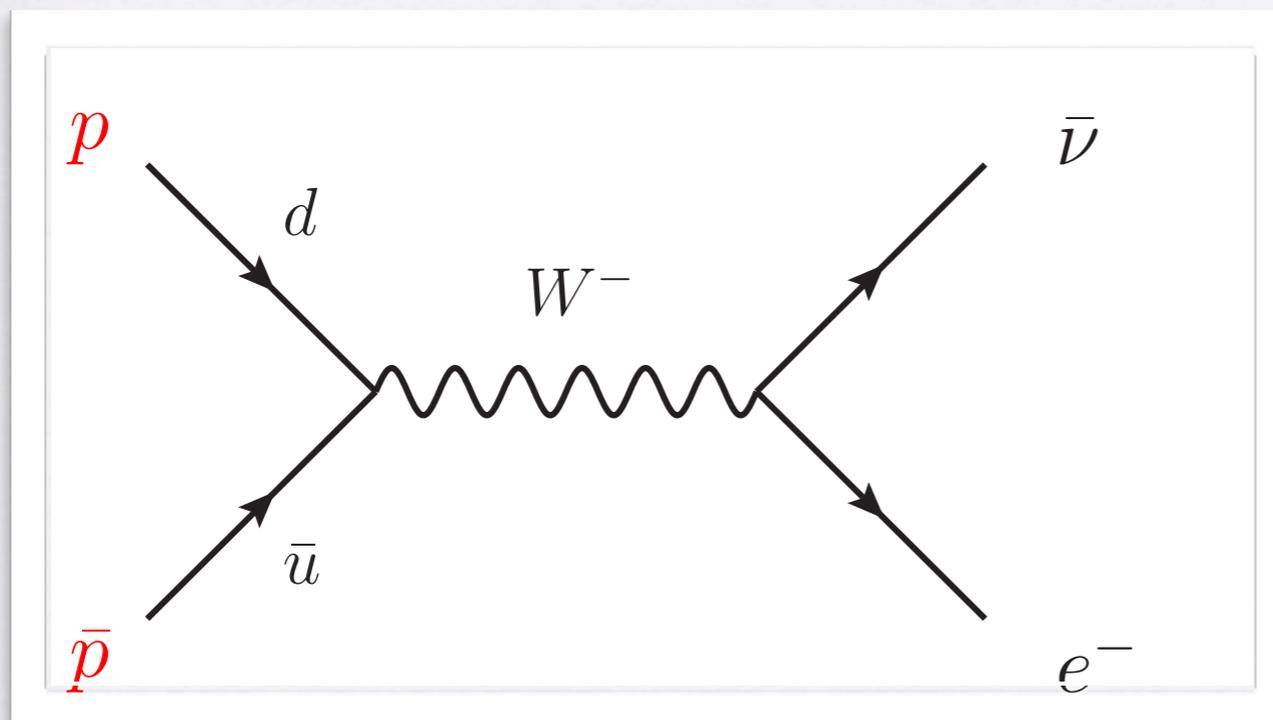
modern times

137 people

'81-'84



C. Rubbia



$$M_W \simeq 80 \text{ GeV}$$

$$m_p \simeq \text{GeV}$$

LEP experiment

modern times

'89 - '00

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

10^9 W bosons \Rightarrow Standard Model

LEP experiment

modern times

'89 - '00

- 1500 people



- 4 detectors: ALEPH, LEP 3, OPAL, DELPHI

- 27 km circumference

10^9 W bosons \Rightarrow Standard Model

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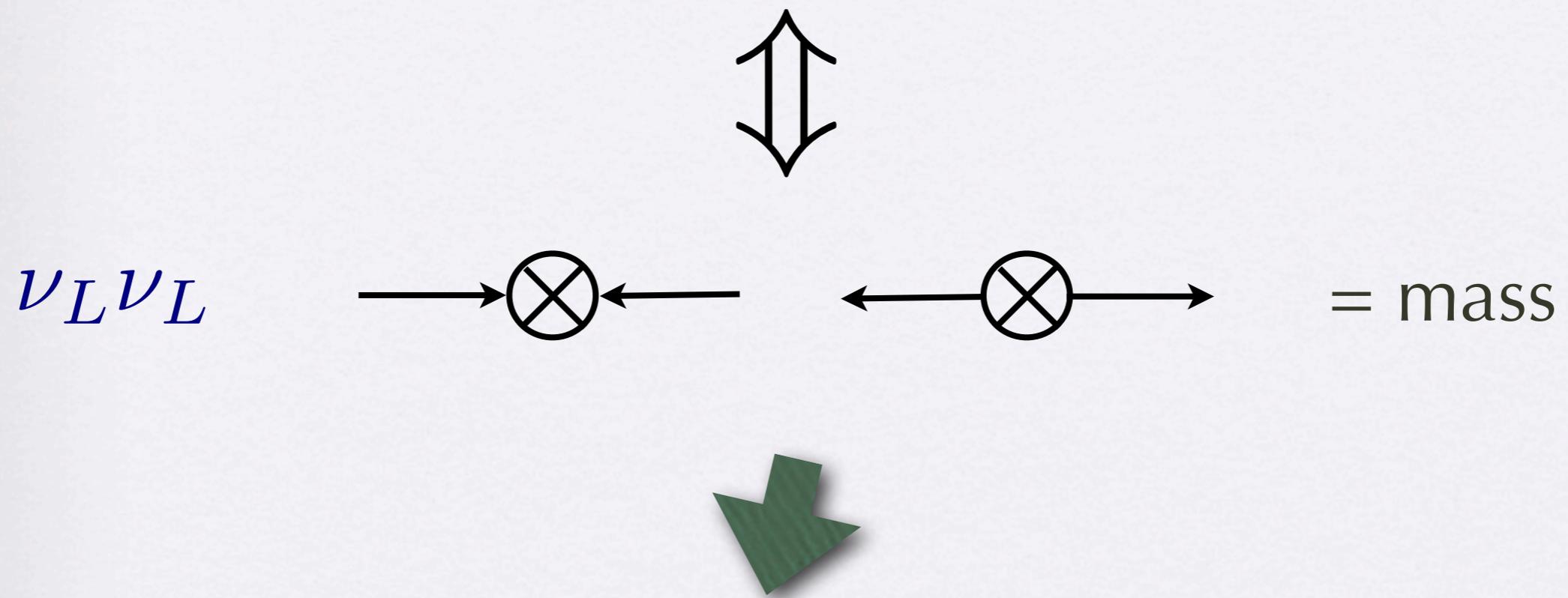
- 4 detectors: ALEPH, LEP 3, OPAL, DELPHI

- 27 km circumference

10^9 W bosons \Rightarrow Standard Model

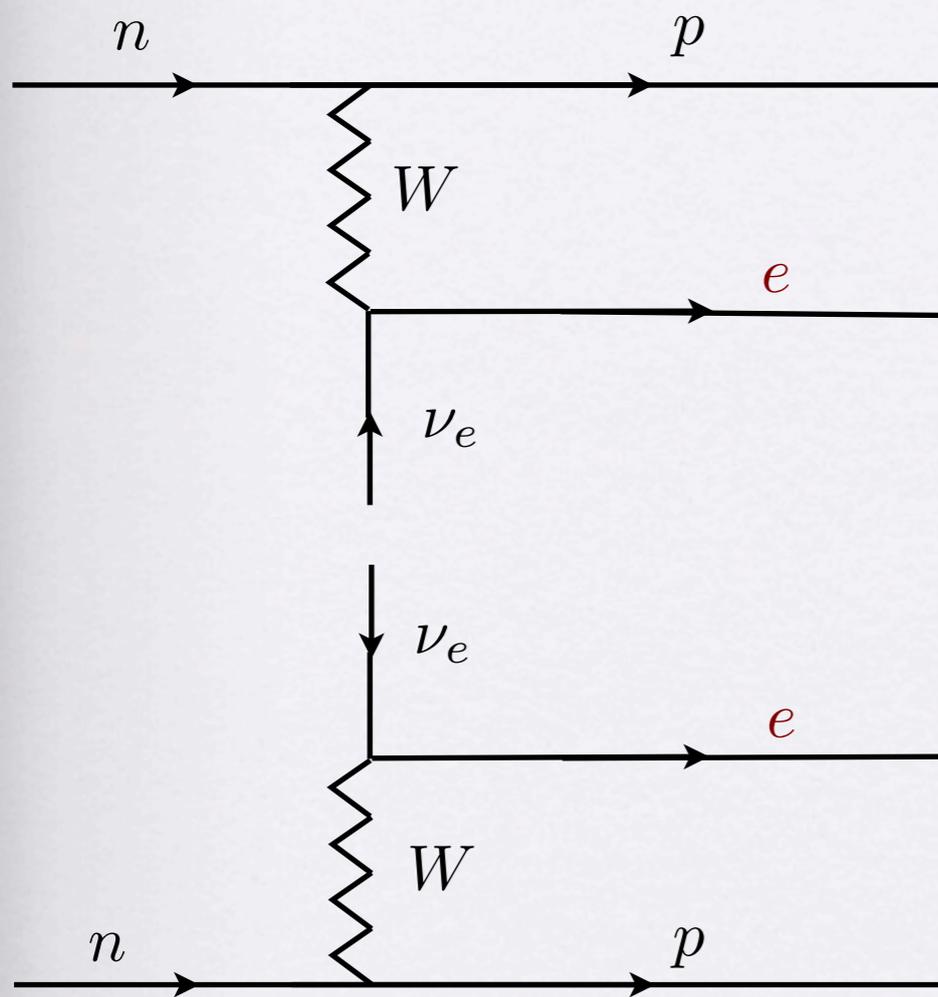
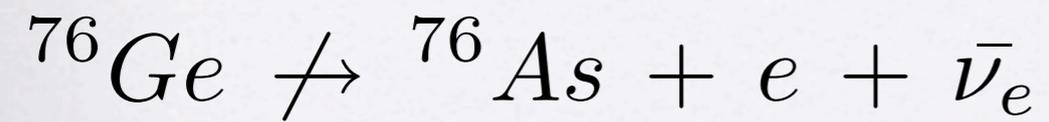
Majorana Program:

neutrino = anti neutrino

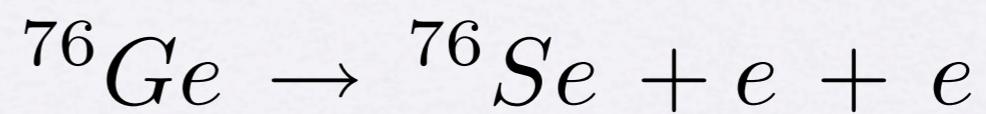
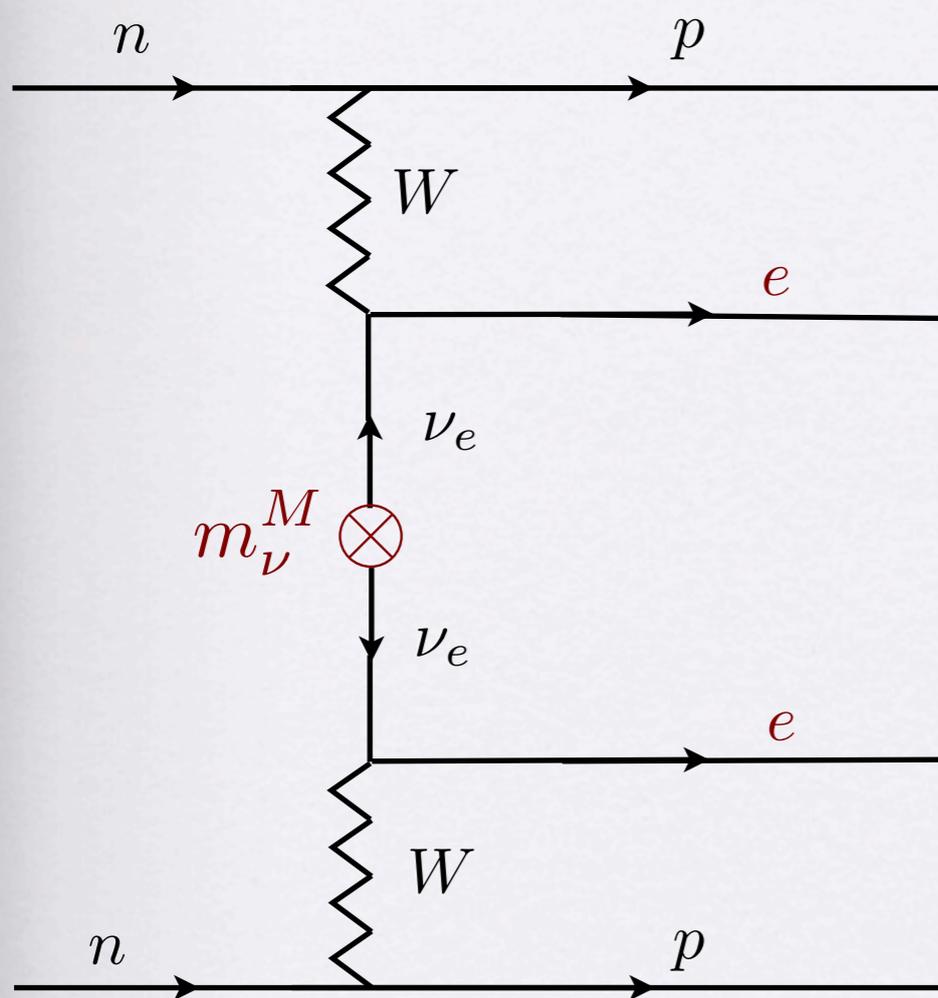
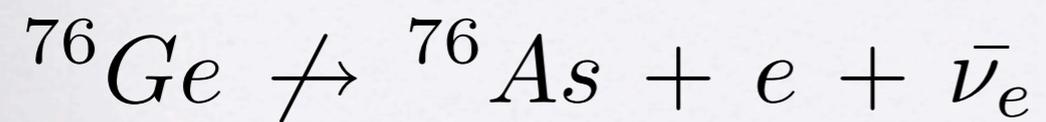


create electrons out of
'nothing'

Double-beta decay



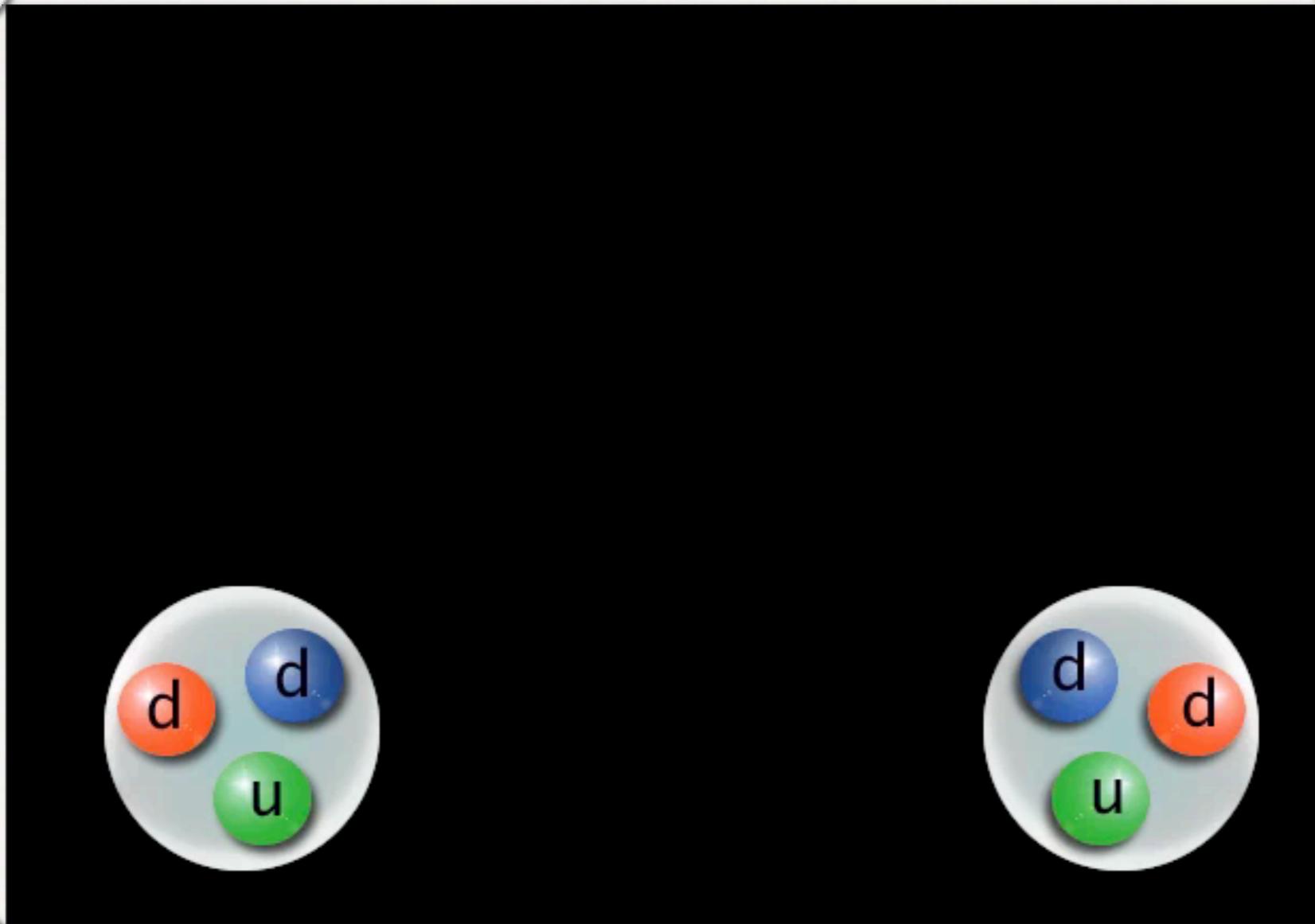
Double-beta decay



only if neutrino massive

Neutrino-less double beta decay

Neutrino-less double beta decay



GERDA experiment

GERmanium Detector Array

Gran Sasso Laboratory

modern times

about 100 people

expect:
a few years



future is here



Standard Model

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

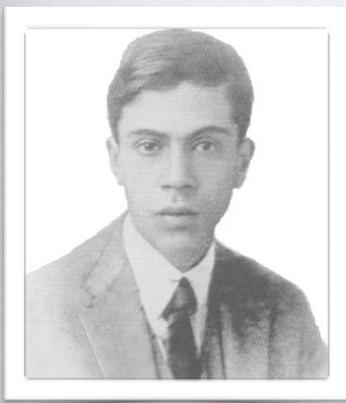
Glashow Weinberg Salam '61-67

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

e_R

no ν_R

L-R asymmetry



$\nu_L \nu_L$

forbidden by symmetry

Standard Model

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

Glashow Weinberg Salam '61-67

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

e_R

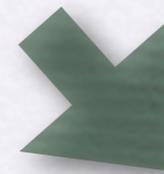
no ν_R

L-R asymmetry



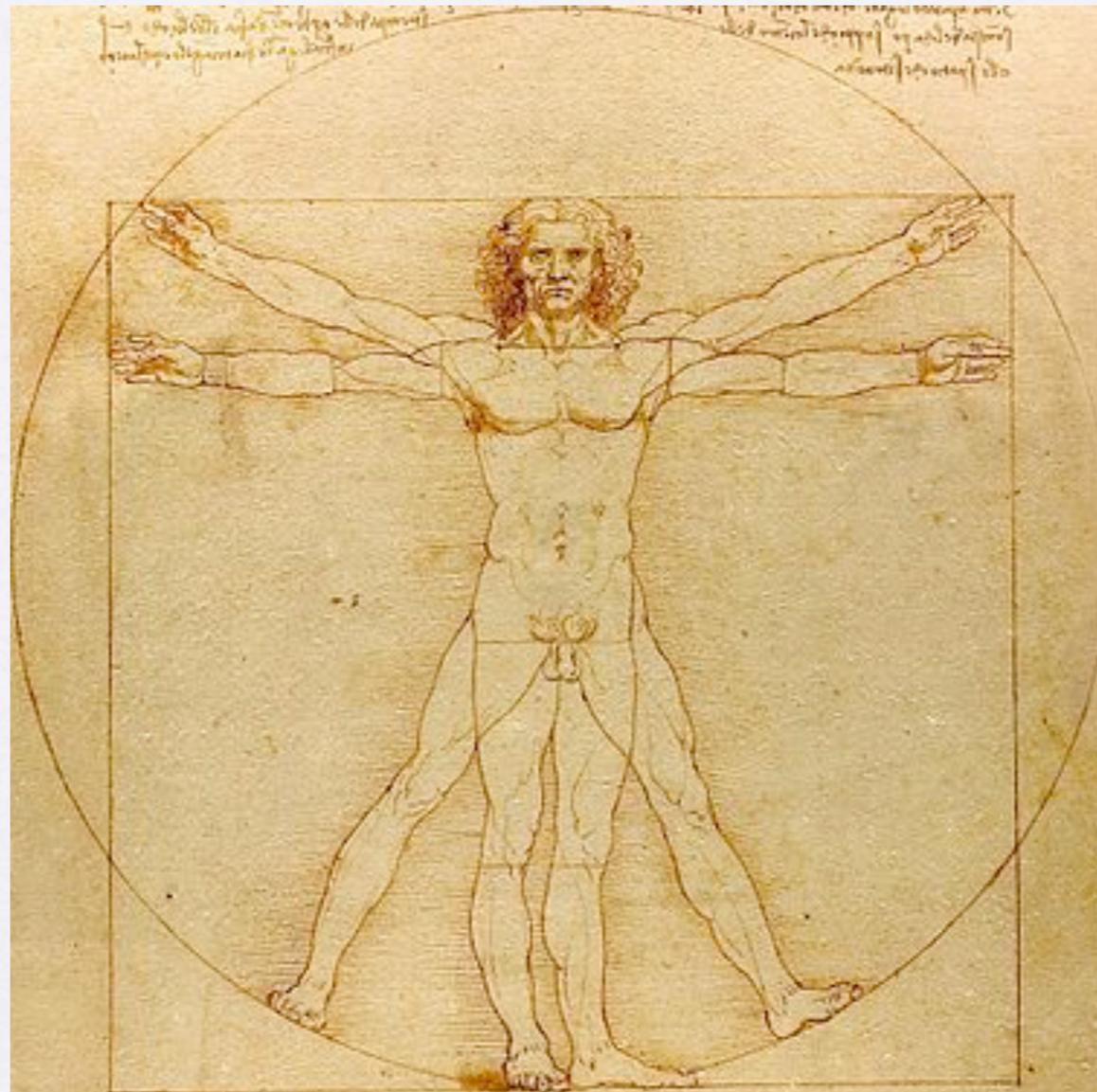
$\nu_L \nu_L$

forbidden by symmetry

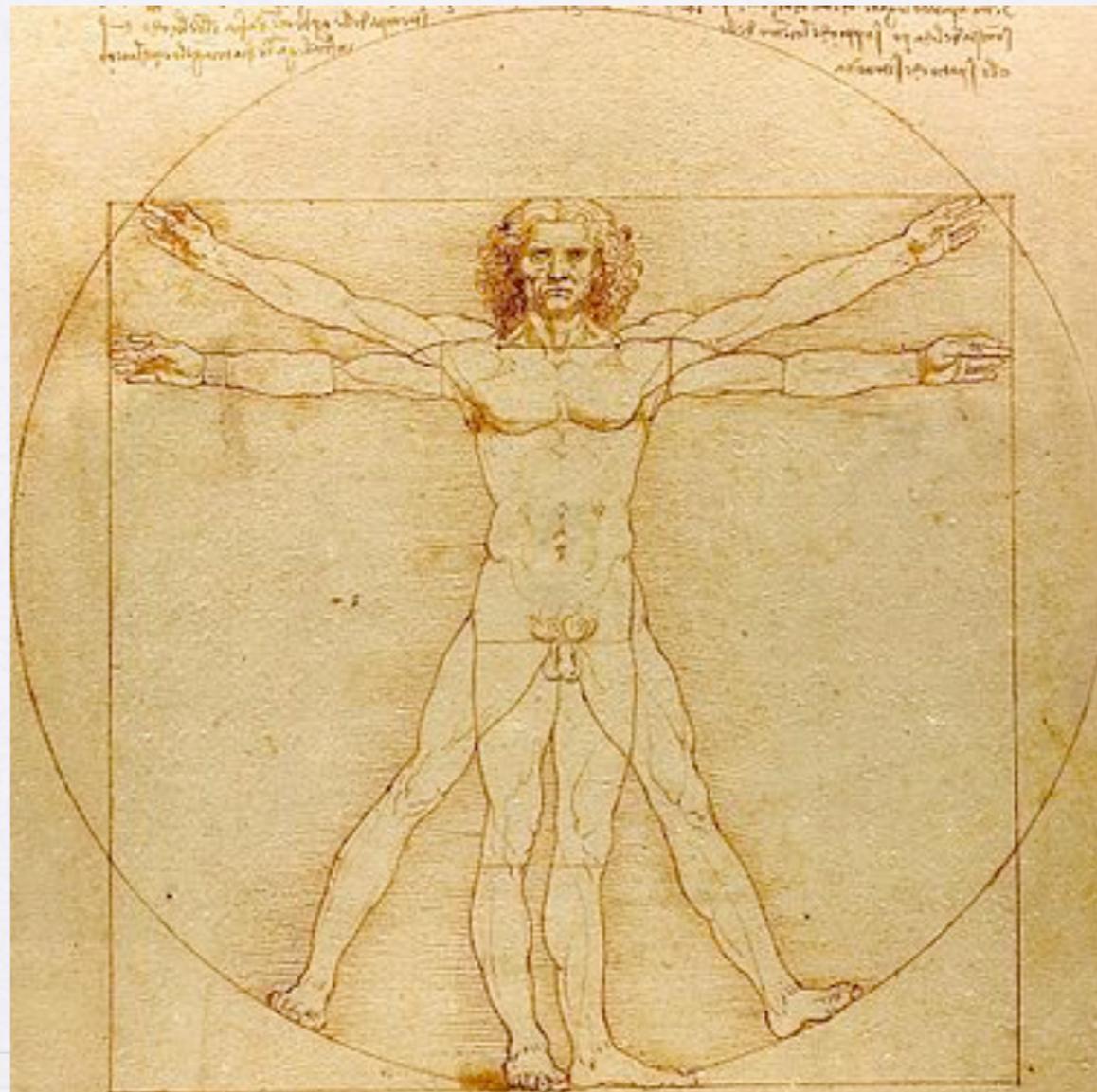


no neutrino mass

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



- Why parity : $L \leftarrow \rightleftarrows \rightarrow R$ broken ?



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



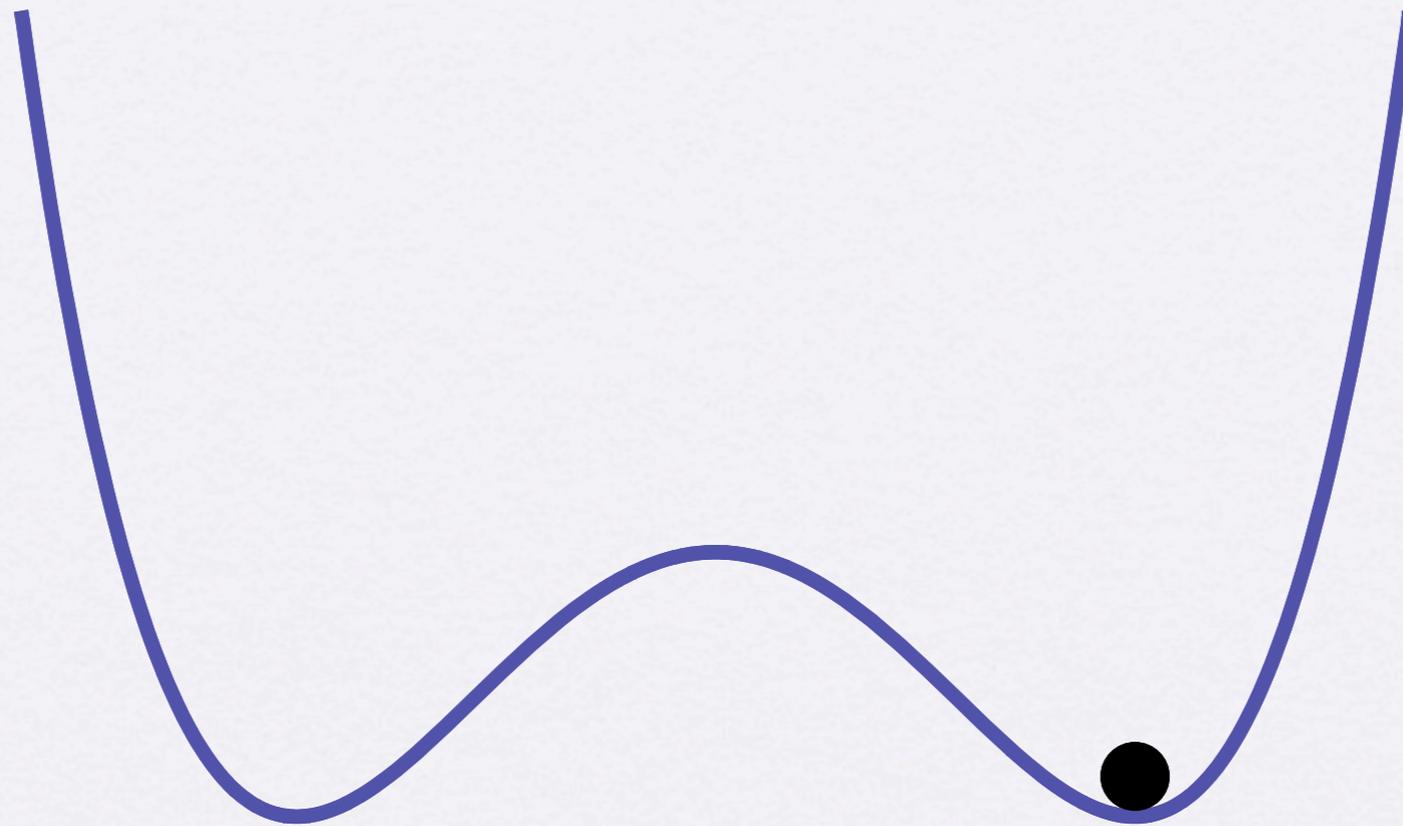
$$m_{W_R} \gg m_{W_L}$$

Pati Salam '74

Mohapatra GS '75

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

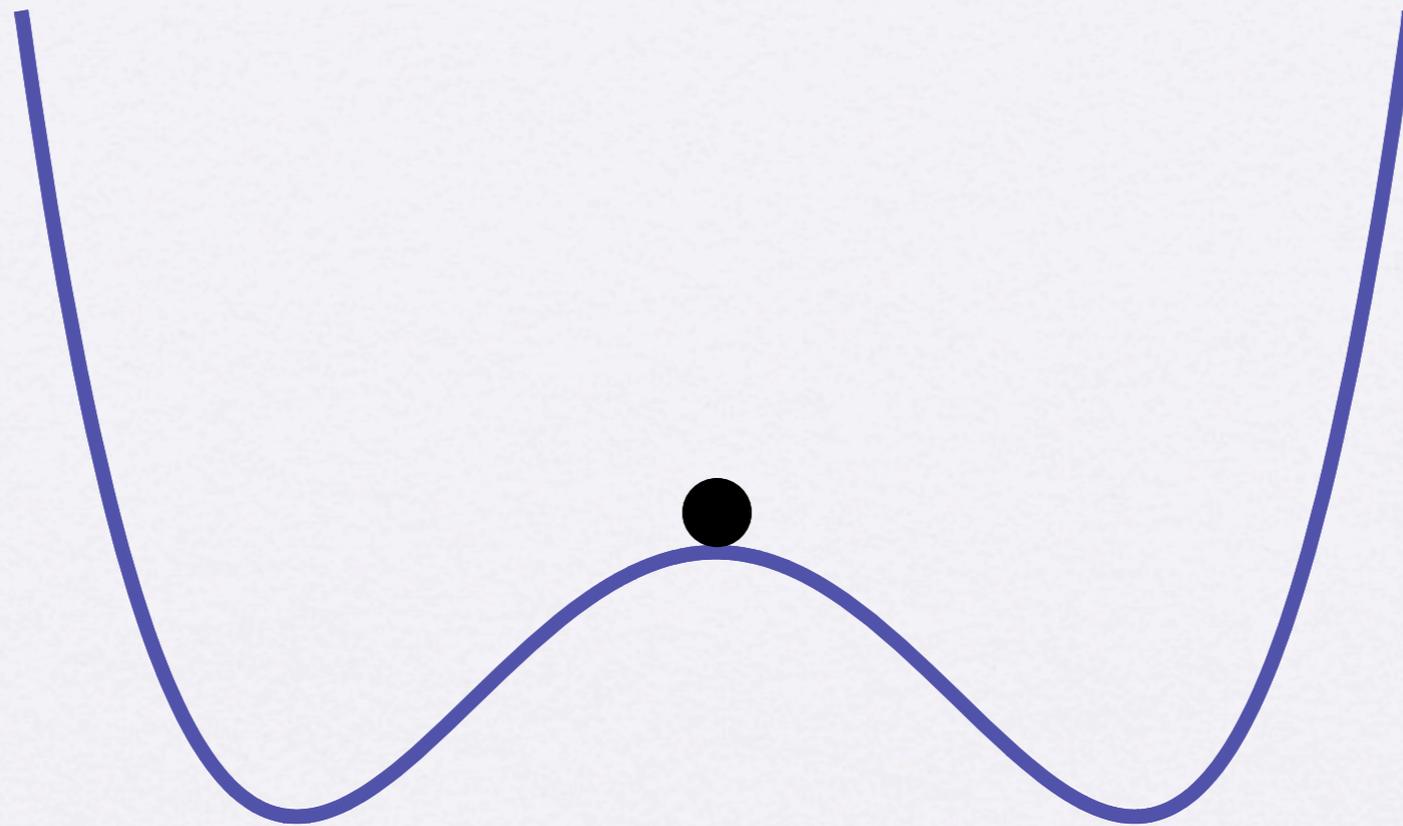
L-R symmetry breaking



Spontaneous

GS '75

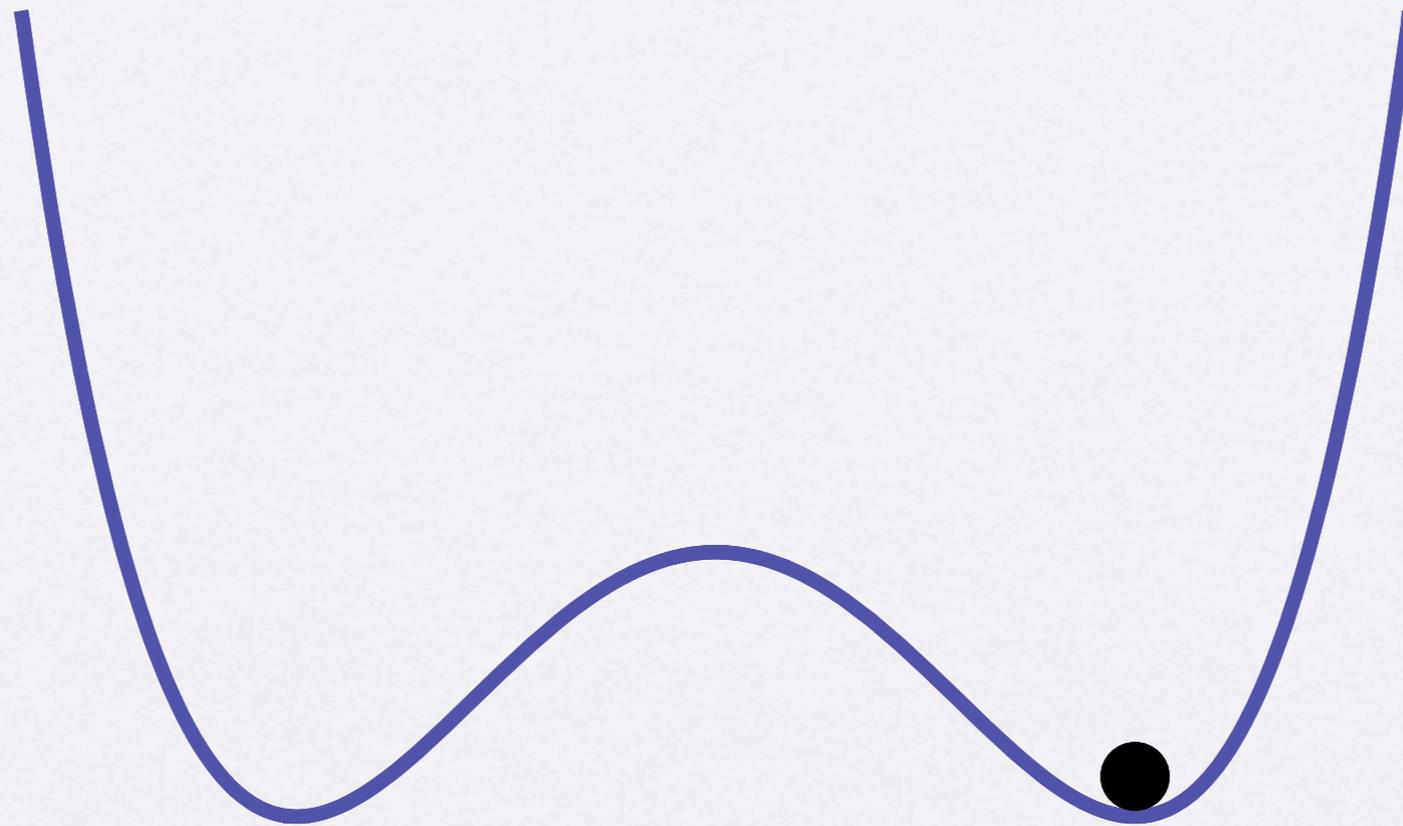
L-R symmetry breaking



Spontaneous

GS '75

L-R symmetry breaking



Spontaneous

GS '75

Neutrino: Majorana mass



seesaw

Minkowski '77

Mohapatra, GS '79

$$M_{W_R} \simeq 3000 - 5000 \text{ GeV}$$

$$m_p \simeq \text{GeV}$$

Maiezza, Nemevsek, Nesti, GS '2010

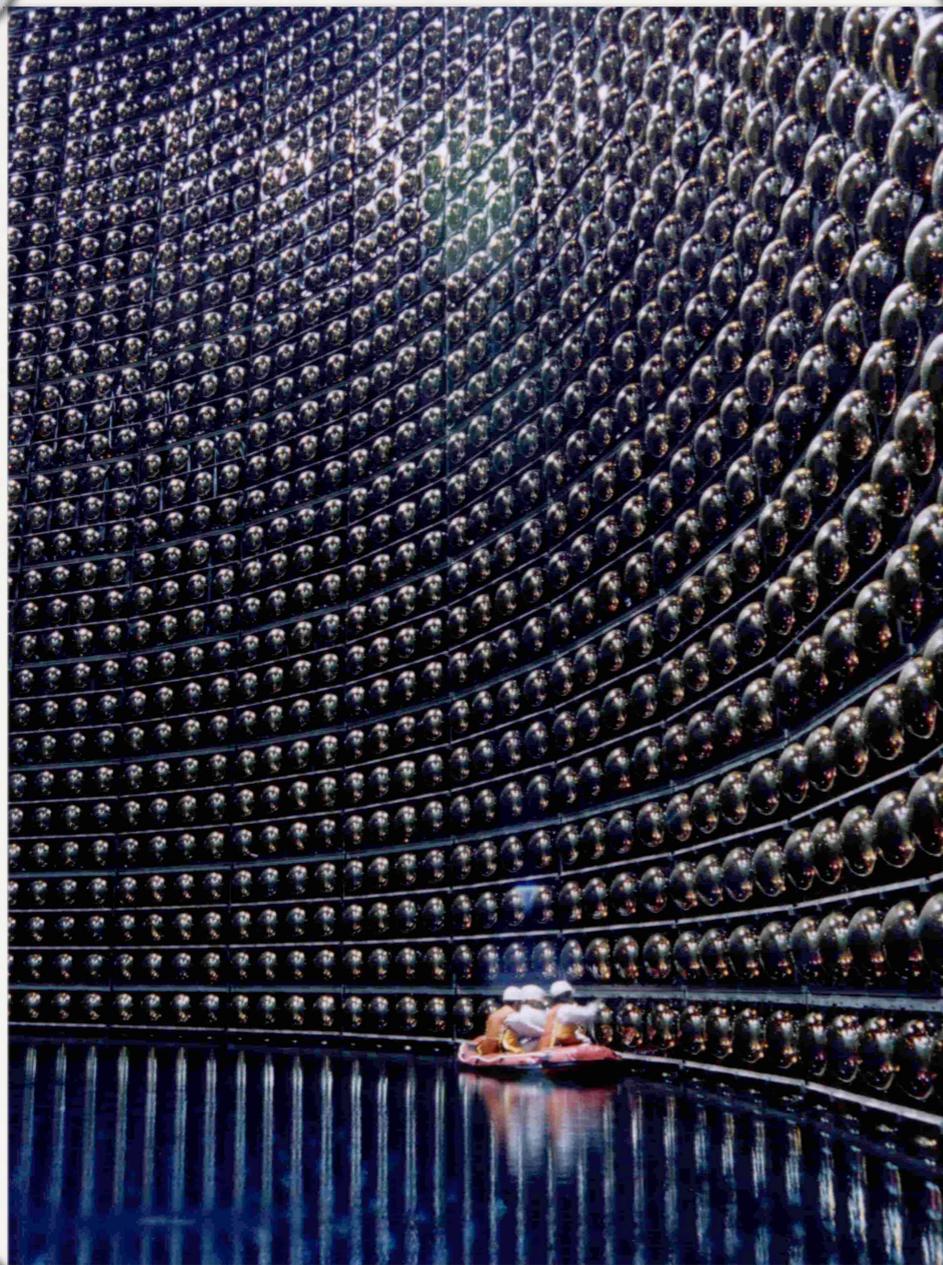


$W_R = \text{big dog}$

Atmospheric neutrinos

Super Kamiokande '98

modern times



neutrino mass

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

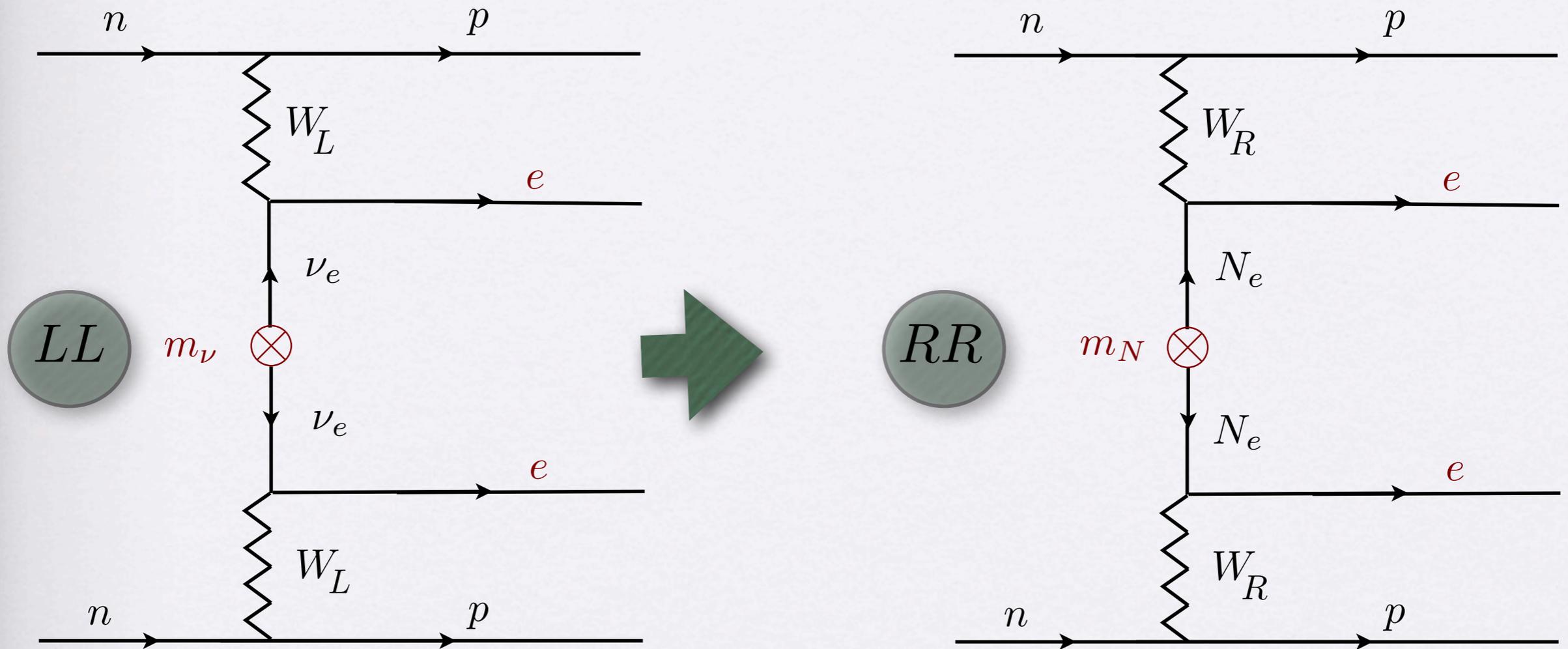
$$(m_p \simeq 10^9 \text{ eV})$$

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

needs huge detectors

New source for $0\nu 2\beta$

Mohapatra, GS '81

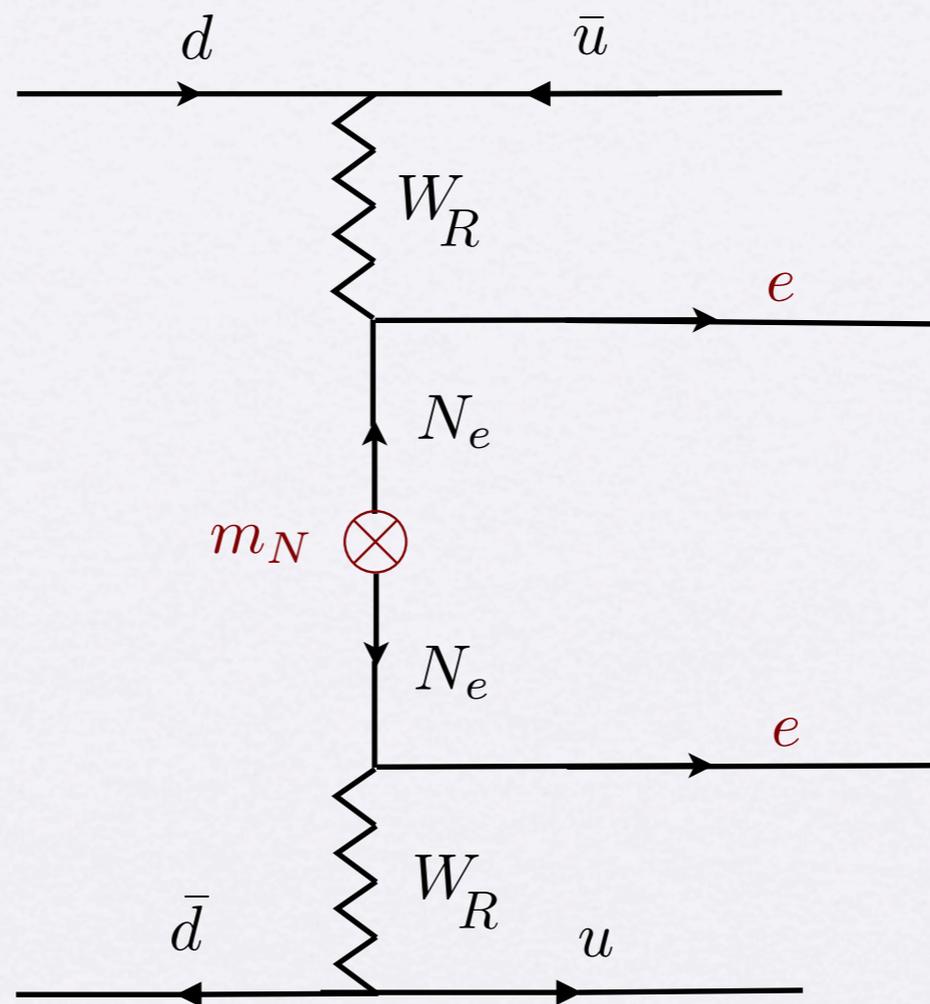


$N = RH$ neutrino

Tello, Nemevsek, Nesti, GS, Vissani '11

Nemevsek, Nesti, GS, Tello '11

$$W_R @ \text{TeV} = 1000 \text{ GeV}$$

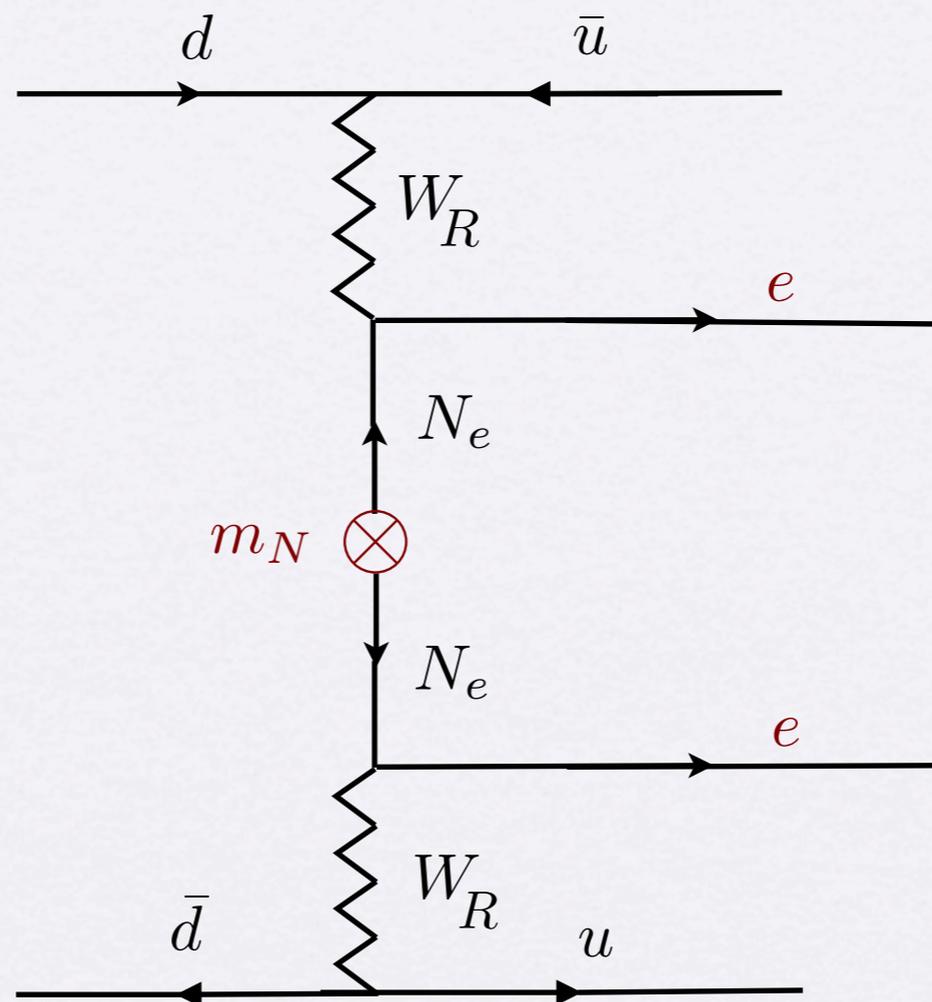


$$m_p \simeq \text{GeV}$$

Tello, Nemevsek, Nesti, GS, Vissani '11

Nemevsek, Nesti, GS, Tello '11

$W_R @ \text{TeV} = 1000 \text{ GeV}$

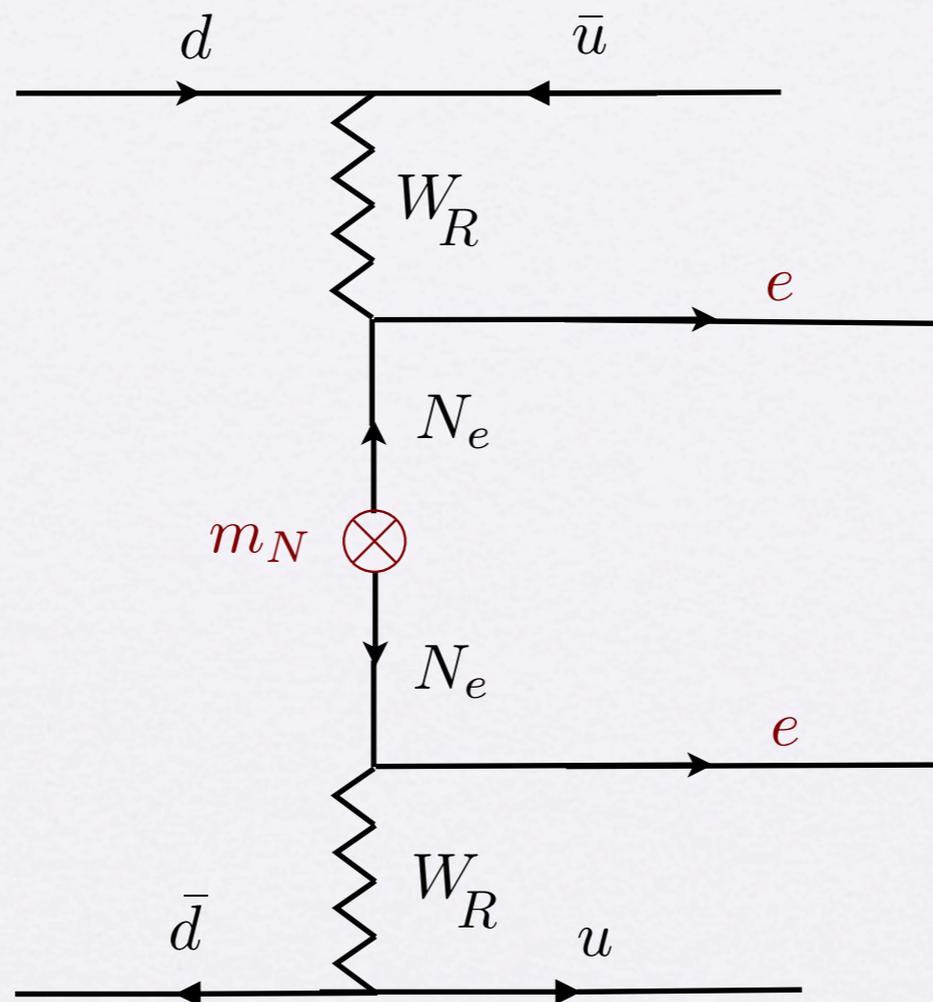


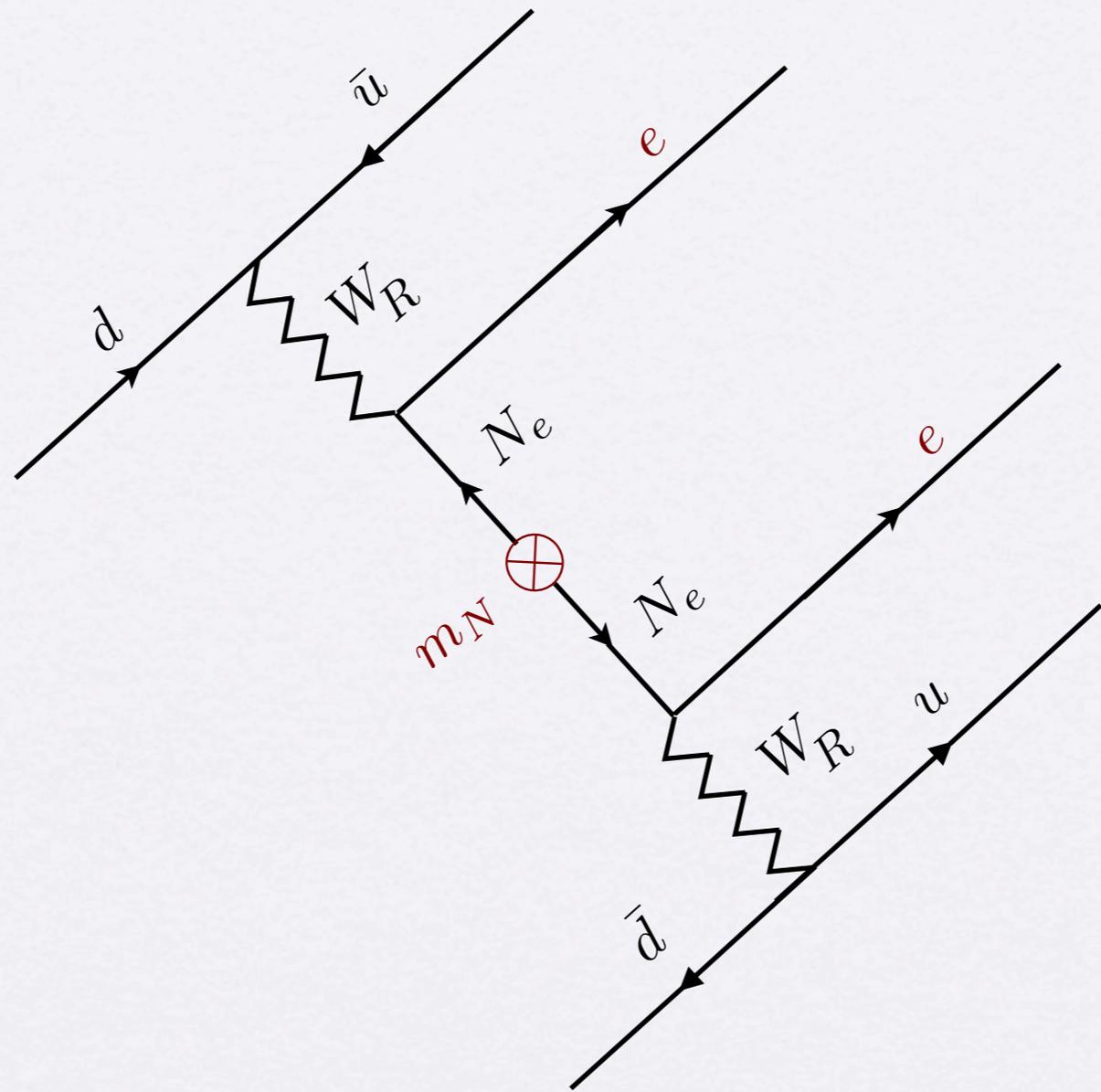
connection with LHC?

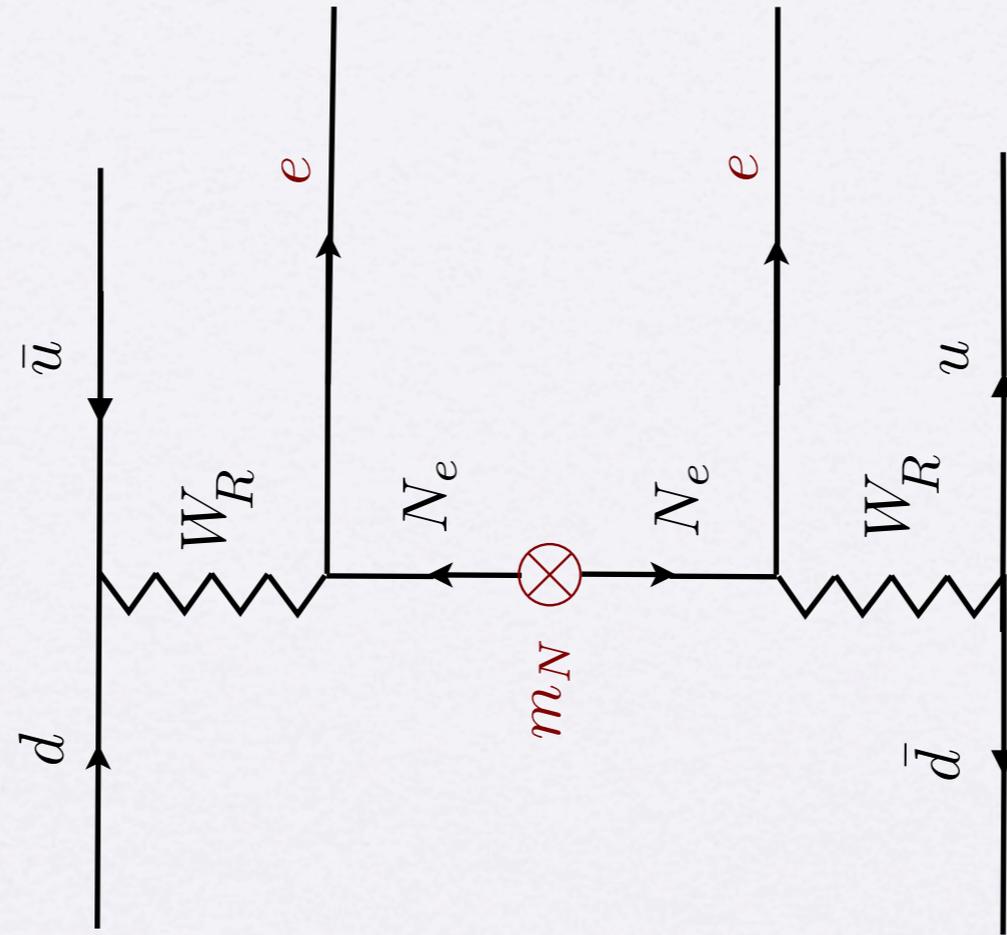
$m_p \simeq \text{GeV}$

rotation in a plane

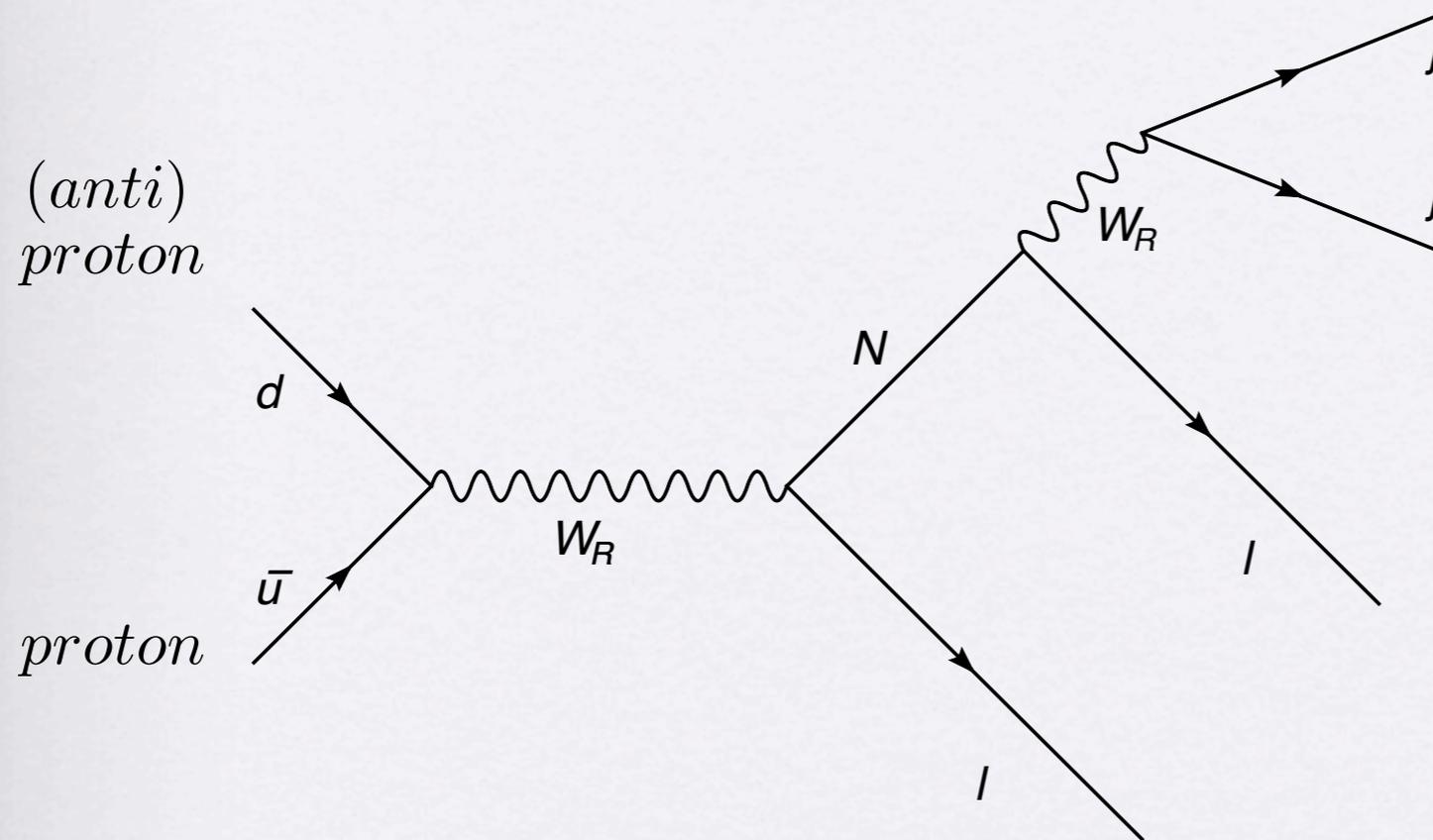
Keung, G.S. '83







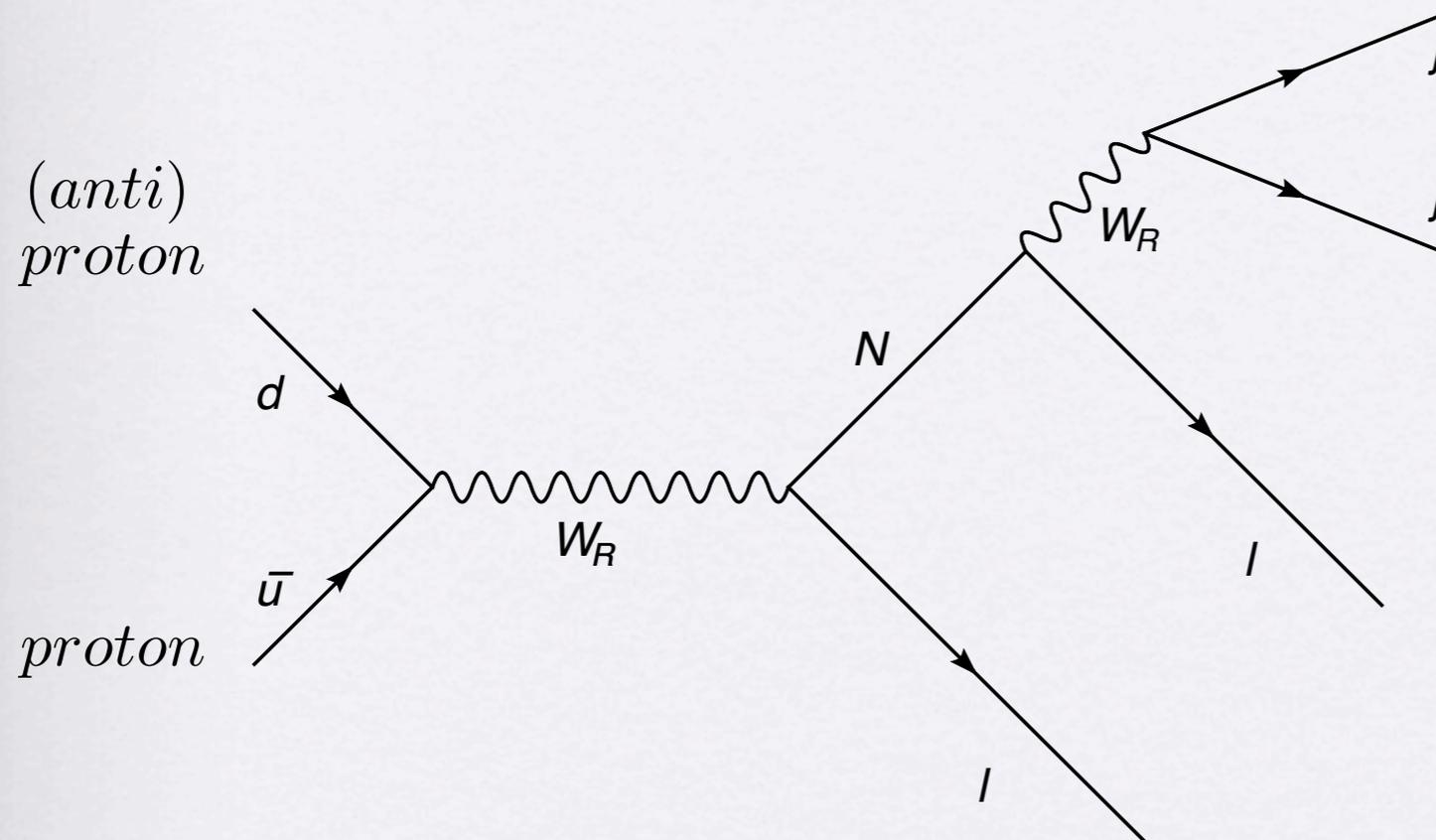
Production @ colliders



- Parity restoration
- Lepton Number Violation: same sign leptons

Production @ colliders

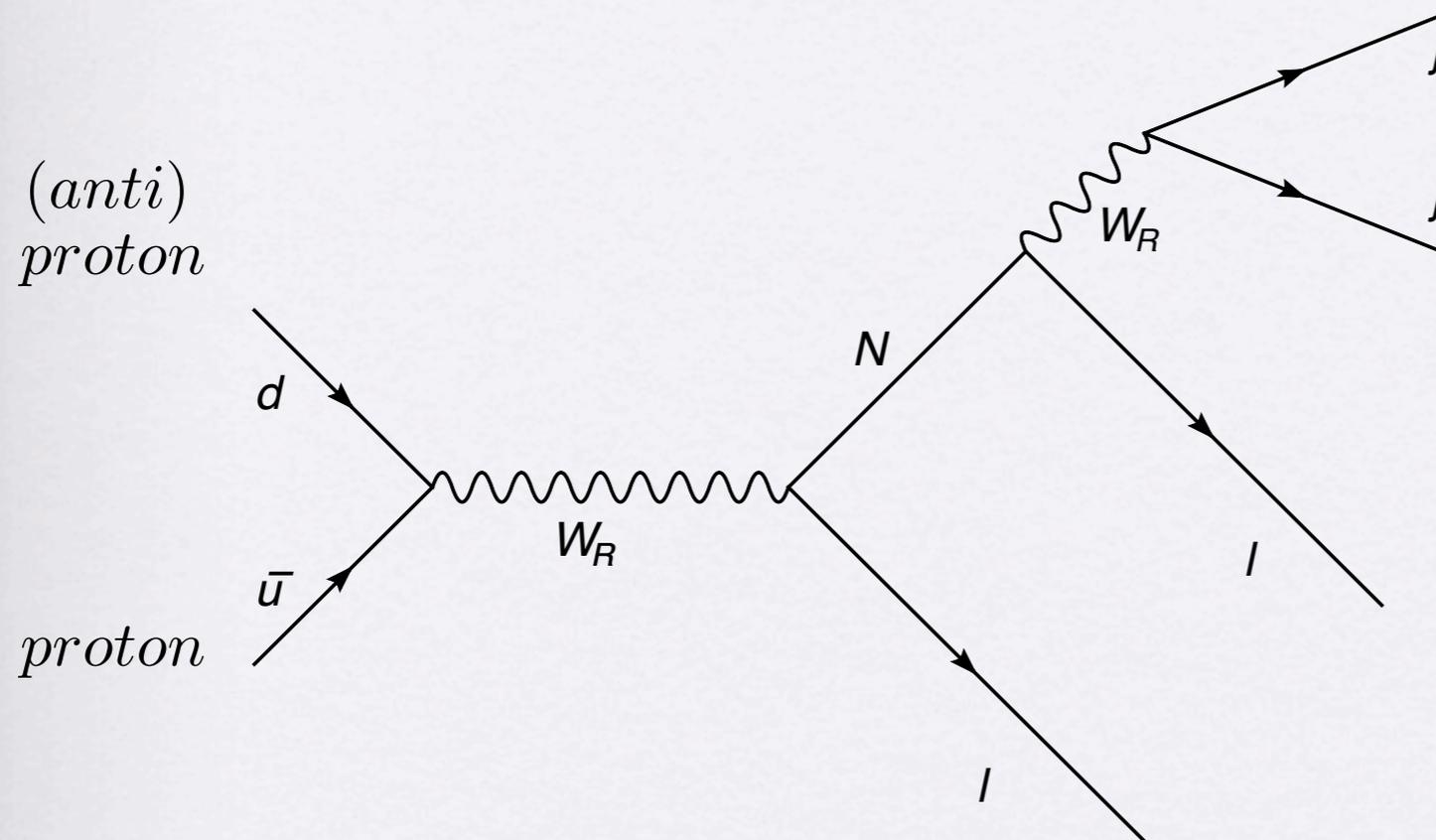
- direct probe of Majorana nature:



- Parity restoration
- Lepton Number Violation: same sign leptons

Production @ colliders

- direct probe of Majorana nature:



- 50% electrons -
- 50 % positrons

- Parity restoration
- Lepton Number Violation: same sign leptons

Large Hadron Collider

CERN

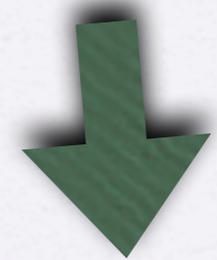
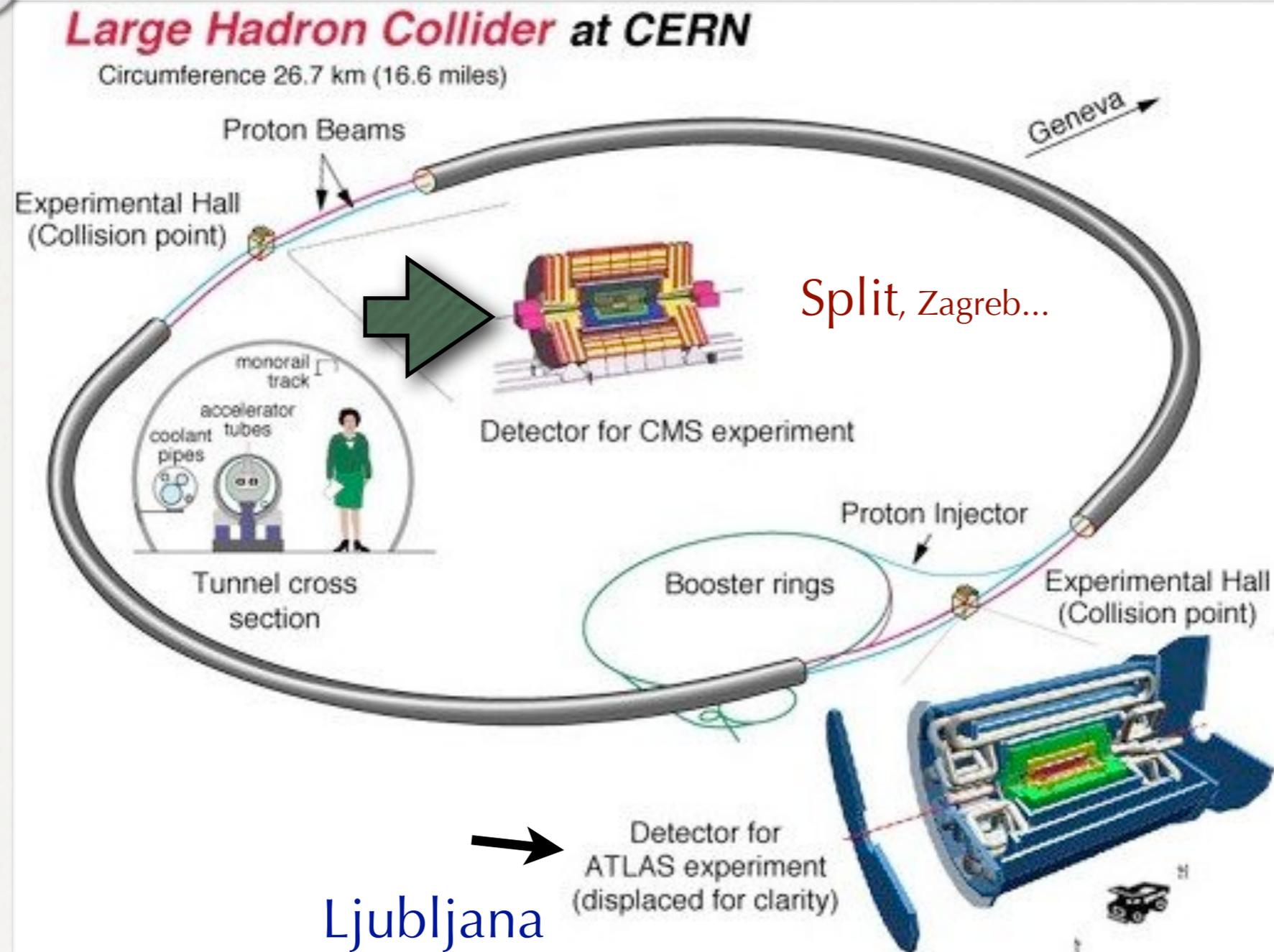
modern times

- 27 km
- up to 175 m deep



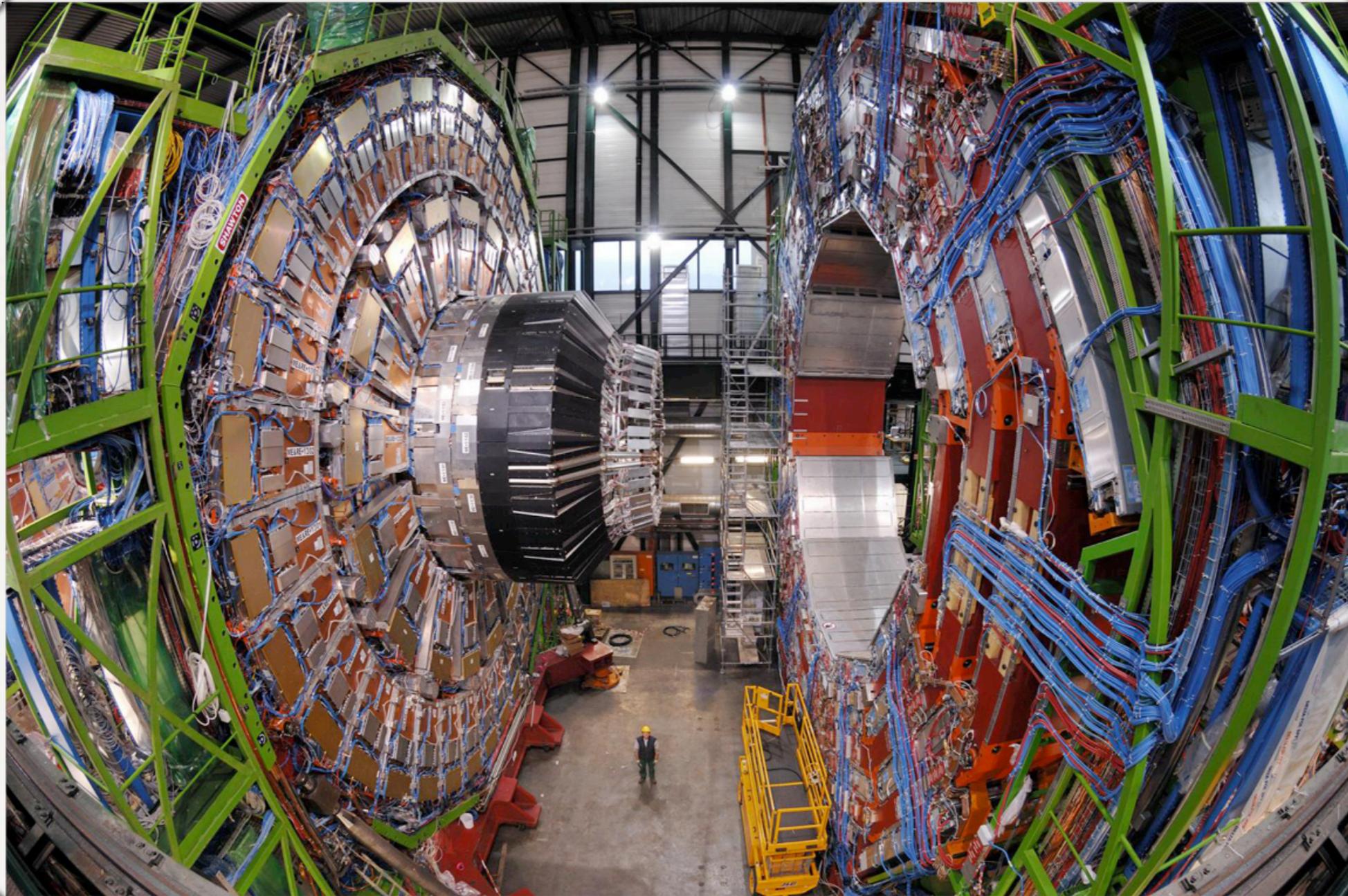
proton - proton scattering

$E=7000$
GeV



will double
in 2014

modern times: 3600 people



CMS detector

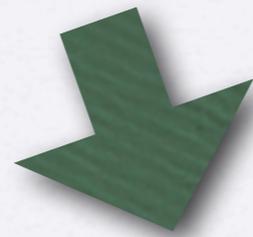
Compact *Muon Solenoid*

both CMS and ATLAS: dedicated search for W_R

- becoming reality as we speak, after three decades of waiting
- first data already here and more to come this year
- a number of papers, limit ~ 2500 GeV: closing up on theory

stay tuned

Large Hadron Collider



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

Hvala

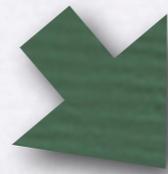




anti-particles

not around us :

particle + anti-particle



annihilate