Particle Physics
The Standard Model

Antonio Pich

IFIC, CSIC – Univ. Valencia

Antonio.Pich@cern.ch

The Standard Model

1. Constituents & Interactions
2. Quarks
3. Gauge Invariance
4. Quantum Chromodynamics
5. Electroweak Unification
6. Symmetry Breaking
7. Electroweak Phenomenology
8. Flavour Dynamics

1. Constituents & Interactions

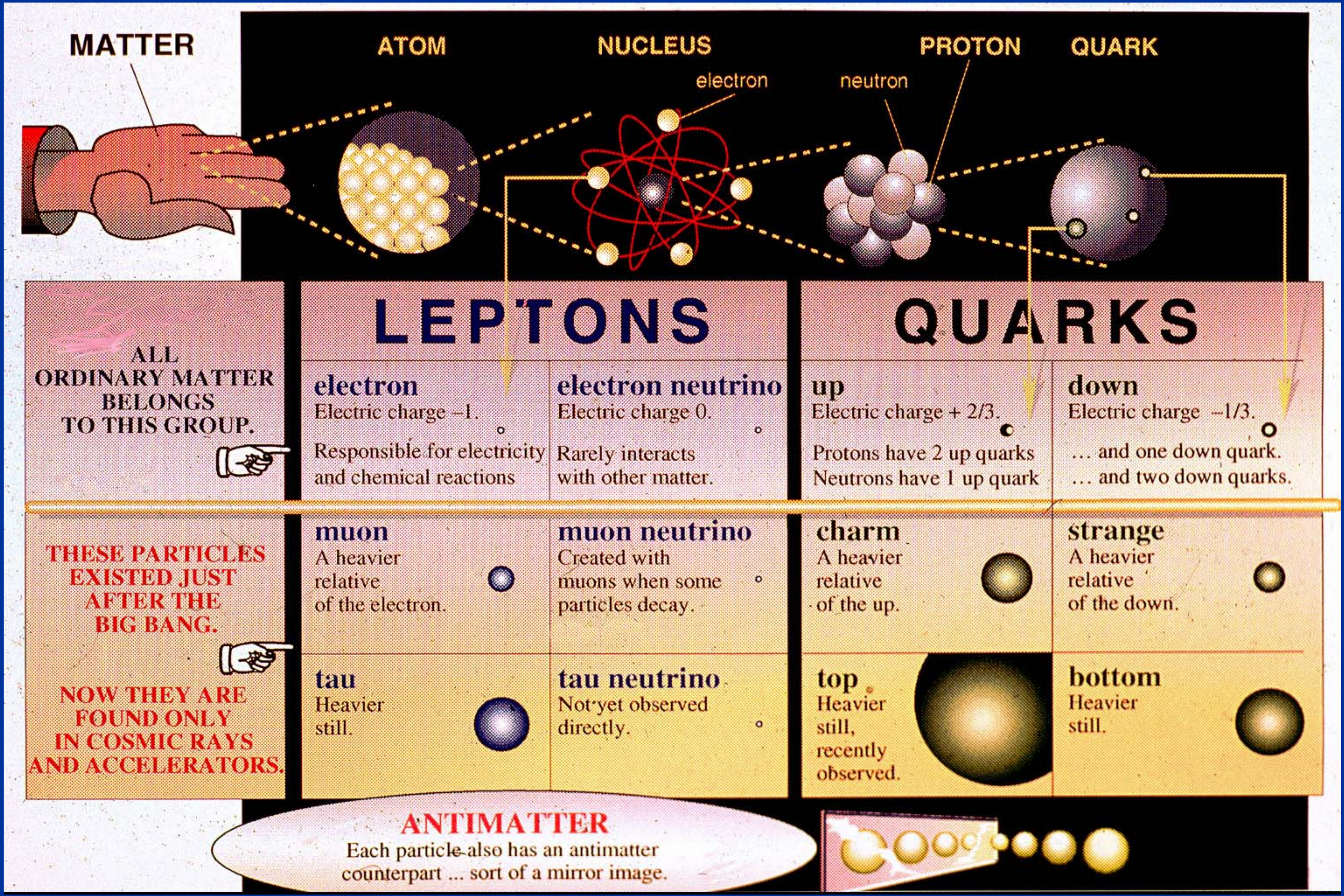
- Table of Elementary Fermions
- Interactions: Gauge Bosons
- Charged Leptons
- Neutrinos

Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110	111 111	112 112						

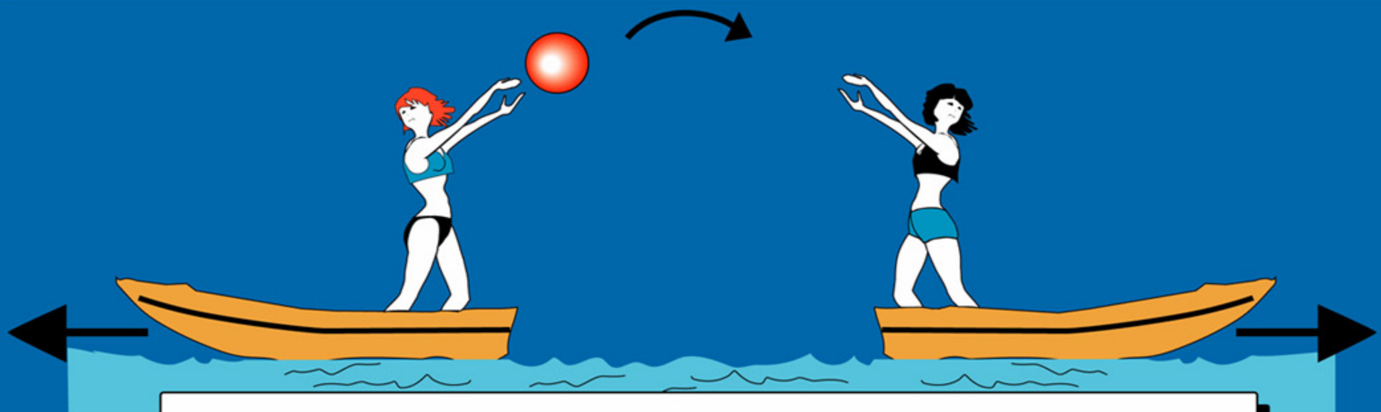
Naming conventions of new elements

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr


MATTER
ATOM
NUCLEUS
electron
neutron
PROTON
QUARK
LEPTONS
QUARKS
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
electron
Electric charge –1.
Responsible for electricity and chemical reactions
electron neutrino
Electric charge 0.
Rarely interacts with other matter.
up
Electric charge + 2/3.
Protons have 2 up quarks
Neutrons have 1 up quark
down
Electric charge –1/3.
... and one down quark.
... and two down quarks.
THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.
NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.
muon
A heavier relative of the electron.
muon neutrino
Created with muons when some particles decay.
charm
A heavier relative of the up.
strange
A heavier relative of the down.
tau
Heavier still.
tau neutrino
Not yet observed directly.
top
Heavier still, recently observed.
bottom
Heavier still.
ANTIMATTER
Each particle also has an antimatter counterpart ... sort of a mirror image.

The forces in Nature

TYPE	INTENSITY OF FORCES (DECREASING ORDER)	BINDING PARTICLE (FIELD QUANTUM)	OCCURS IN :
STRONG NUCLEAR FORCE	~ 1	GLUONS (NO MASS)	ATOMIC NUCLEUS
ELECTRO -MAGNETIC FORCE	$\sim 10^{-3}$	PHOTONS (NO MASS)	ATOMIC SHELL ELECTROTECHNIQUE
WEAK NUCLEAR FORCE	$\sim 10^{-5}$	BOSONS Z^0 , $W+$, $W-$ (HEAVY)	RADIOACTIVE BETA DESINTEGRATION
GRAVITATION	$\sim 10^{-38}$	GRAVITONS (?)	HEAVENLY BODIES



THE EXCHANGE OF PARTICLES IS RESPONSIBLE FOR THE FORCE

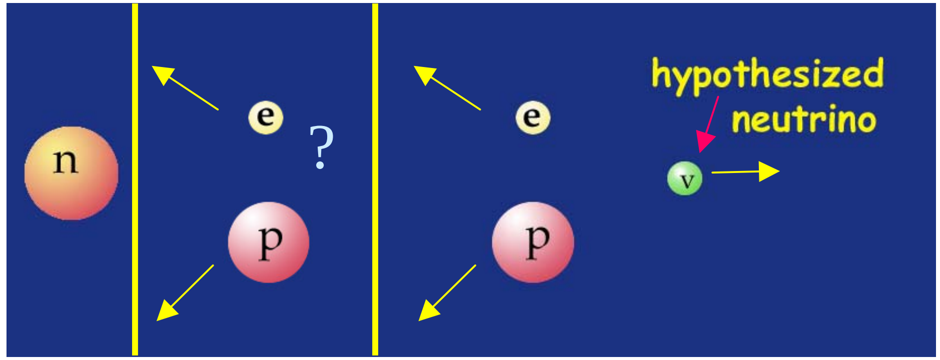
CERN AC Z04 V25/8/1992

RADIOACTIVITY

(β Decay) $\quad {}^{14}_{6}C \to {}^{14}_{7}N + e^- + \overline{\nu}_e$

$$n \to p + e^- + \overline{\nu}_e$$

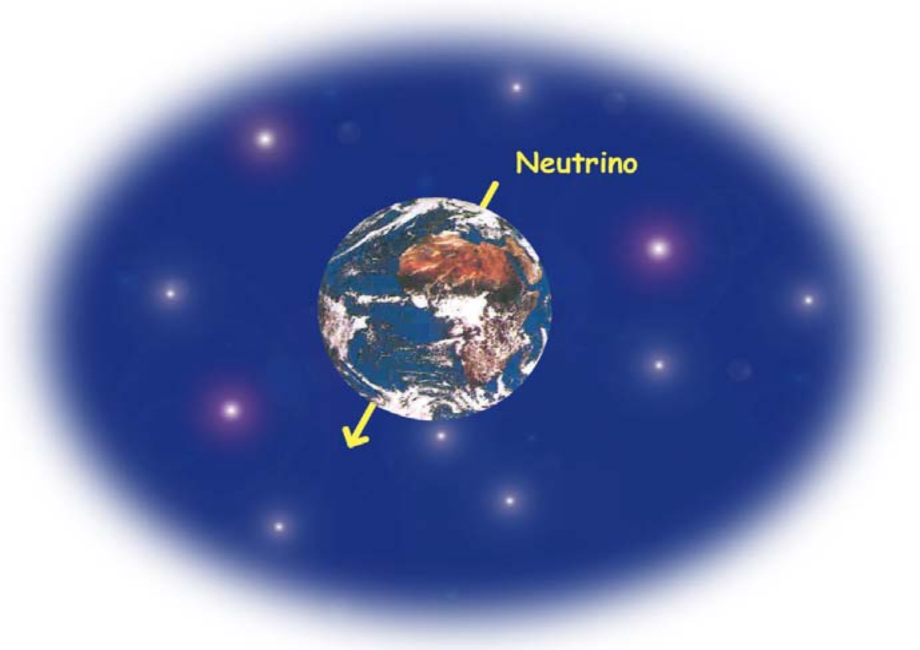
$$" p \to n + e^+ + \nu_e "$$



$$Q_{\nu_e} = Q_{\overline{\nu}_e} = 0$$

$$m_{\nu_e} = m_{\overline{\nu}_e} \approx 0$$

$\nu_e \equiv$ Neutrino ; $\overline{\nu}_e \equiv$ Anti-Neutrino



Weak Interaction

$$W^\pm, \; Z^0$$

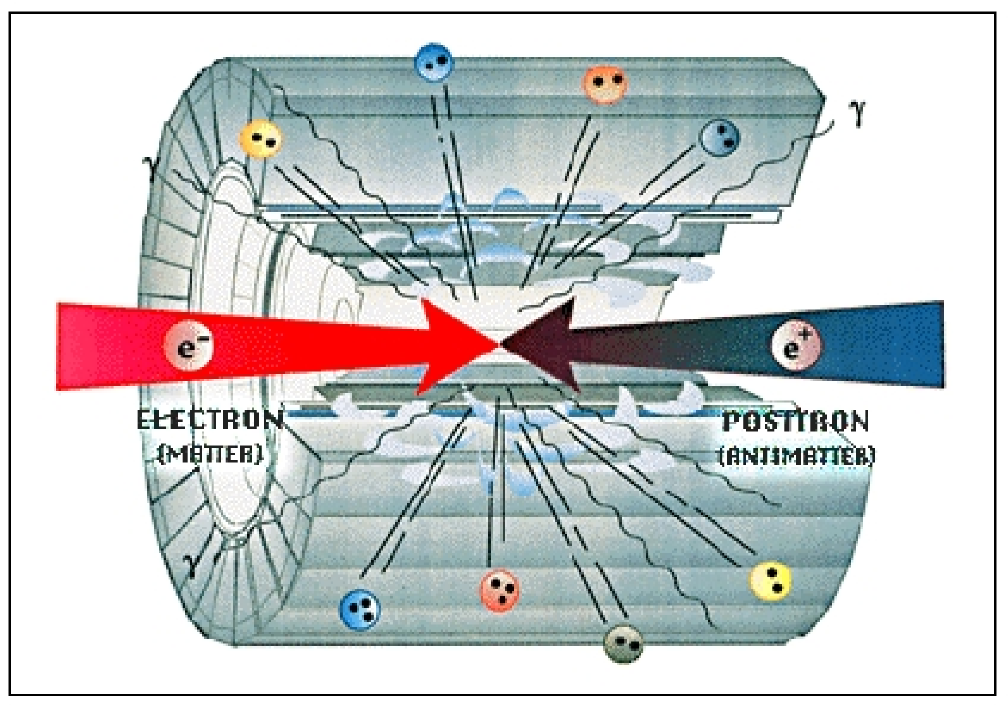
$$M_W \sim M_Z \approx 100 \; m_p$$

Quarks Leptons Bosons

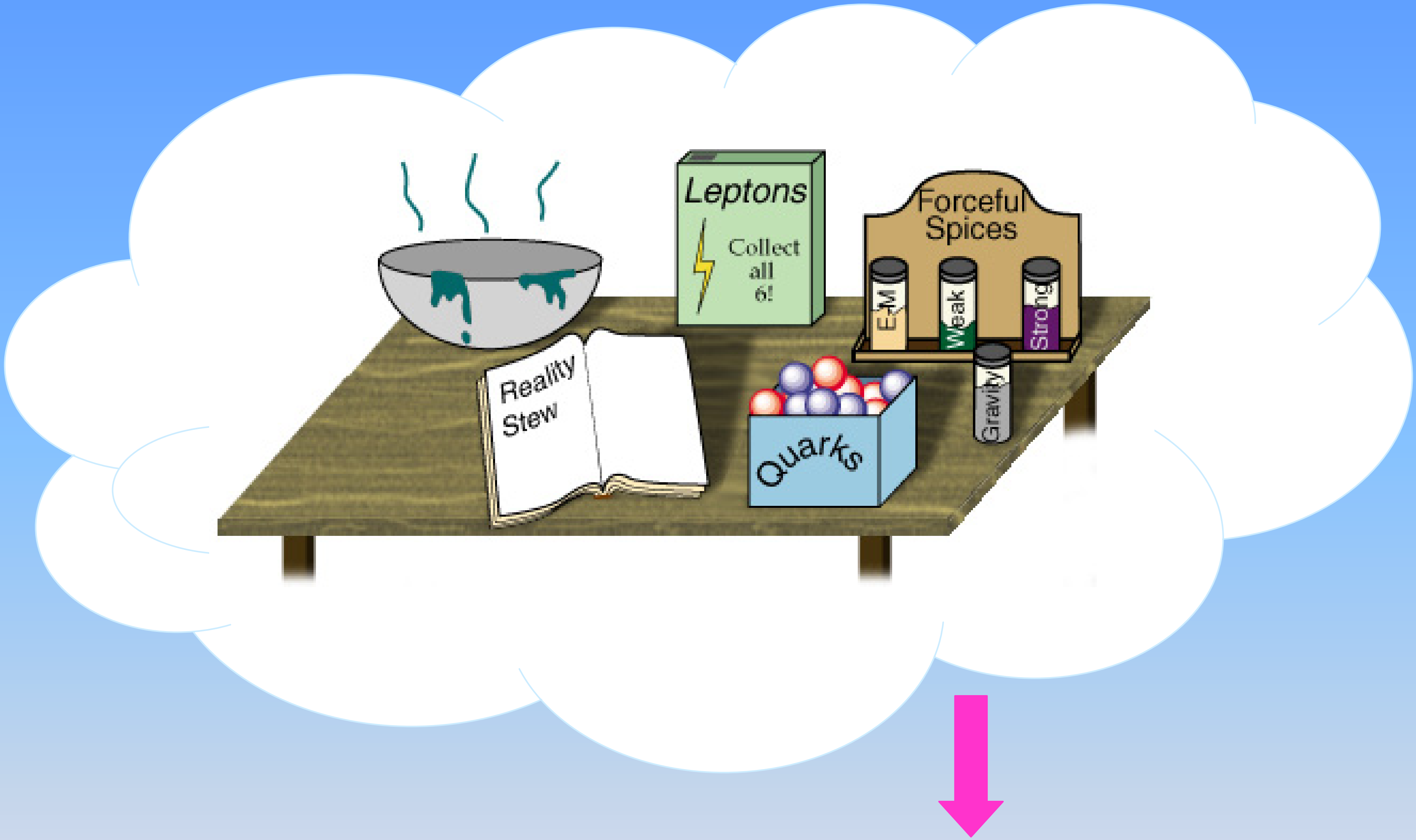
QM + Relativity → Antiparticles (Dirac)

ANTIMATTER

u	d	ν_e	e^-
$\bar{u}$	$\bar{d}$	$\bar{\nu}_e$	e^+



$$E = m\,c^2$$



STANDARD MODEL

THEORETICAL FRAMEWORK

Quantum Mechanics $(\hbar)$ + Special Relativity (c)

⇒ Quantum Field Theory

STANDARD THEORY:

1) Electricity + Magnetism + Optics (light): γ
   Quantum Electrodynamics (QED)

2) QED + Weak Interaction: $\gamma, Z, W^{\pm}$
   Electroweak Theory $SU(2)_L \otimes U(1)_Y$

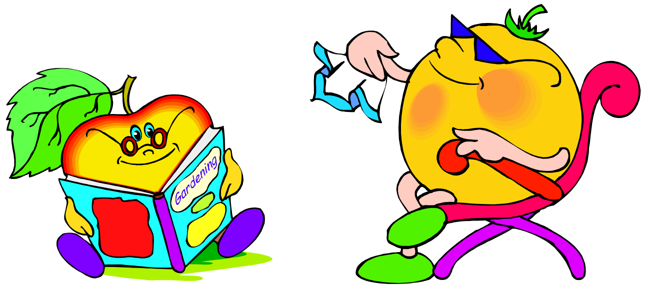
3) Strong Interaction:: 8 Gluons
   Quantum Chromodynamics (QCD)

OPEN QUESTIONS:

- The Higgs Boson (Mass scales)
- Gran Unification (Electroweak + Strong)
- SuperSymmetry
- Gravitation: SuperGravity, Strings, ...

LEPTONS

- Do not have Strong Interactions
- Spin ½
- Seen as Free Particles
- Pointlike $\quad (r < \text{few} \times 10^{-17}\ \text{cm})$



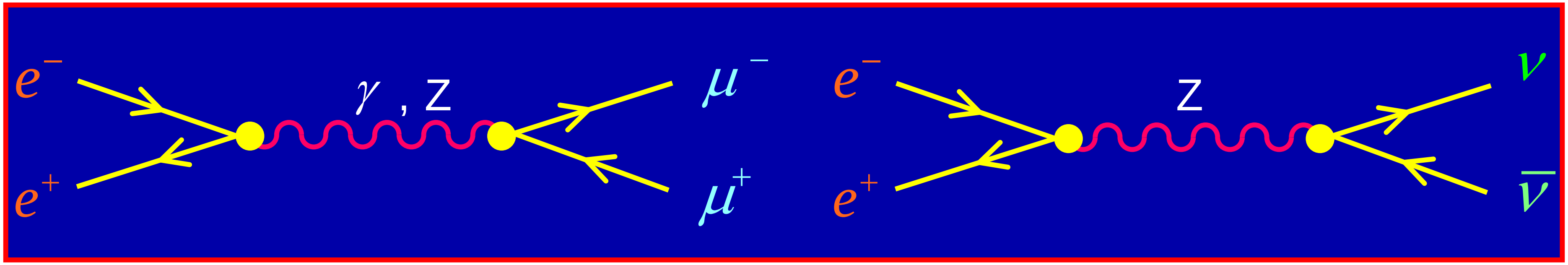
Family Structure:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$m_e = 0.5\ \text{MeV}$ $\tau_e > 4 \cdot 10^{24}\ \text{y}$	$m_\mu = 106\ \text{MeV}$ $\tau_\mu = 2 \cdot 10^{-6}\ \text{s}$	$m_\tau = 1777\ \text{MeV}$ $\tau_\tau = 3 \cdot 10^{-13}\ \text{s}$
$m_{\nu_e} < 3\ \text{eV}$	$m_{\nu_\mu} < 0.2\ \text{MeV}$	$m_{\nu_\tau} < 18\ \text{MeV}$

Why 3 ?

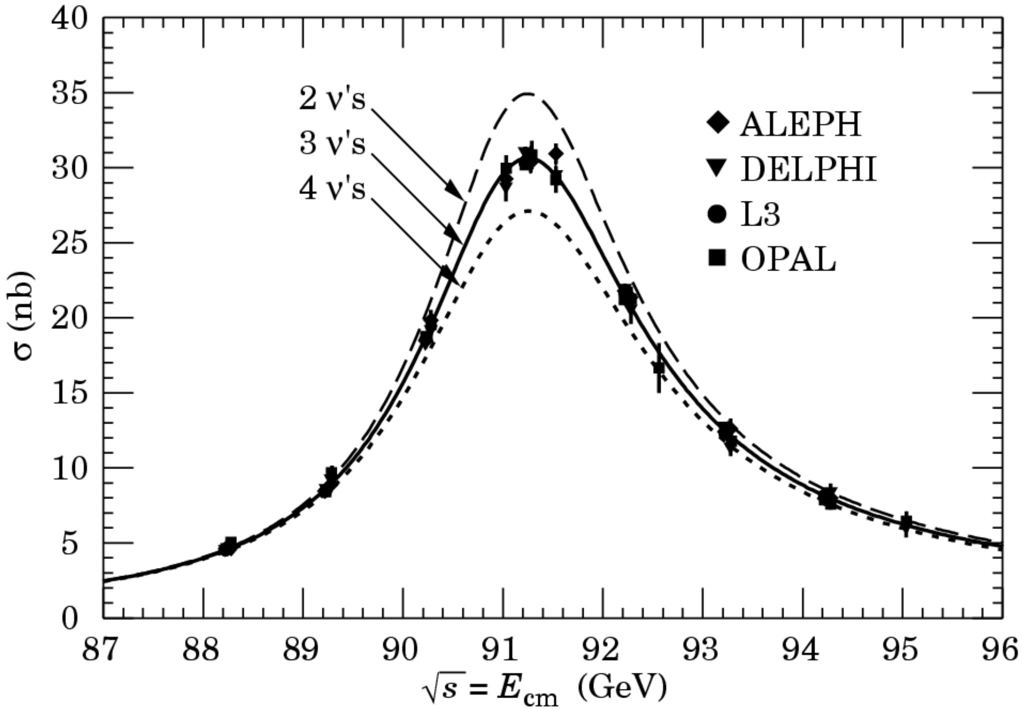
NEUTRAL CURRENTS



- Flavour Conserving $\mu \not\to e\,\gamma \quad ; \quad Z \not\to e^{\mp}\mu^{\pm}$
- $g_\gamma \sim Q_l$ $\quad (Q_e = Q_\mu = Q_\tau \;\; ; \;\; Q_\nu = 0)$
- Same γ interaction for both lepton helicities
- NC Universality: $g_{Zee} = g_{Z\mu\mu} = g_{Z\tau\tau} \neq g_{Z\nu\nu}$
- Different Z coupling to l_R and l_L
- Left-handed neutrinos only
- 3 Families with light (massless ?) neutrinos

HOW MANY NEUTRINOS ?

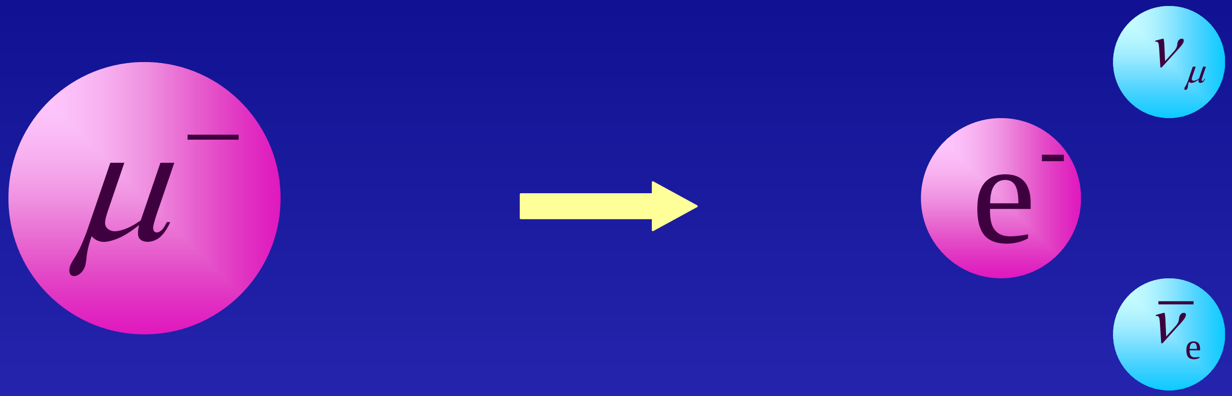
$$\sigma\,(Z \to \text{hadrons})$$

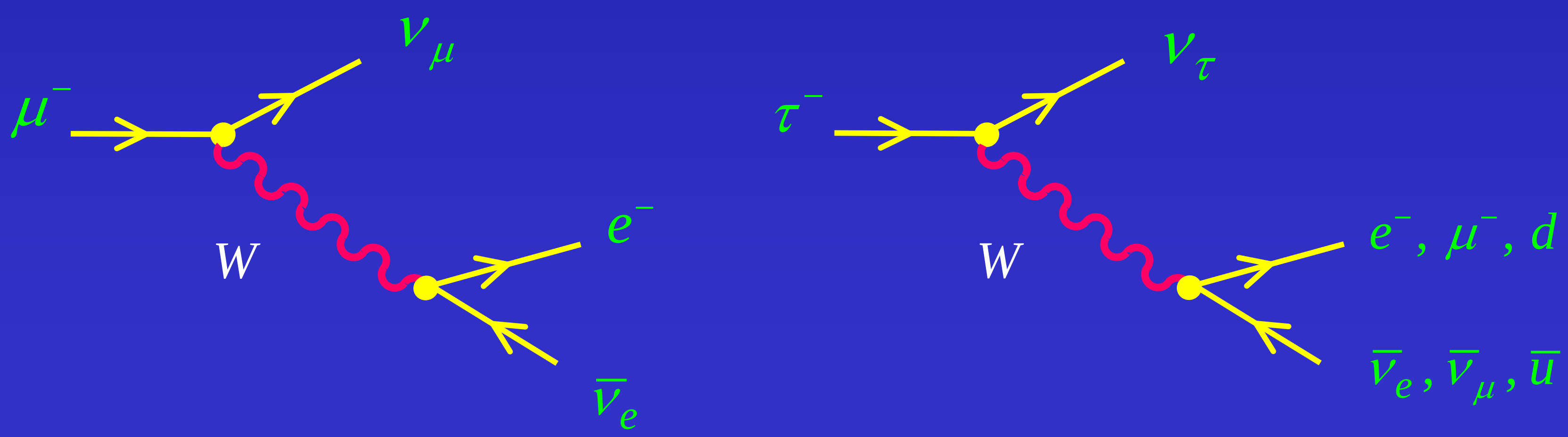


$$N_\nu = \frac{\Gamma(Z \to \text{invisible})}{\Gamma(Z \to \nu_i \bar{\nu}_i)_{\text{Th}}} = 2.9841 \pm 0.0083$$

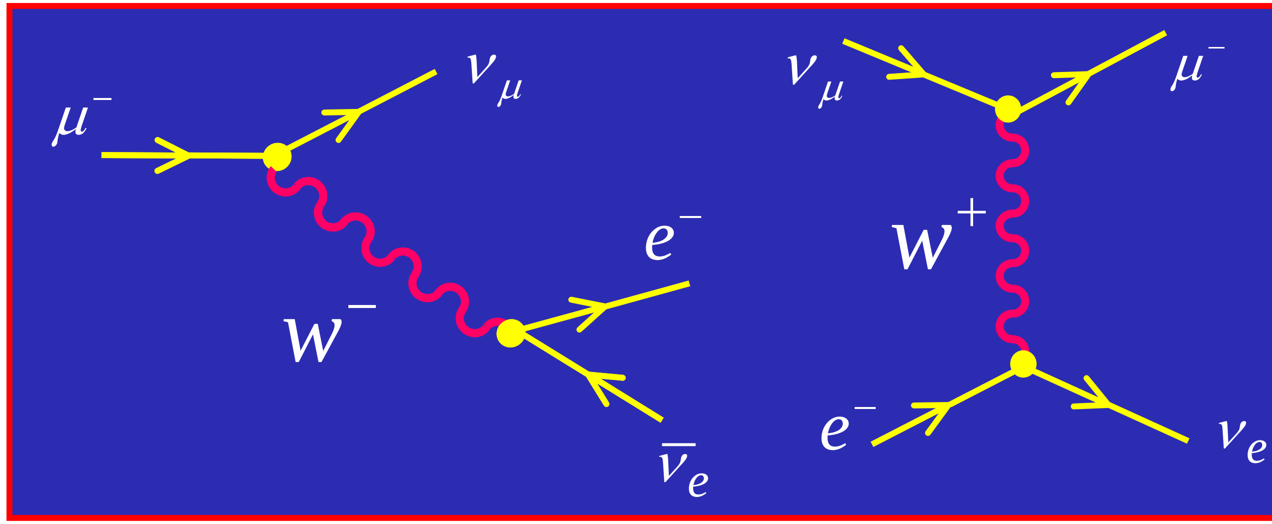
$$\Gamma(Z \to \text{invisible}) \equiv \Gamma(Z \to \text{all}) - \Gamma(Z \to \text{visible})$$

The heavier leptons μ and τ are unstable

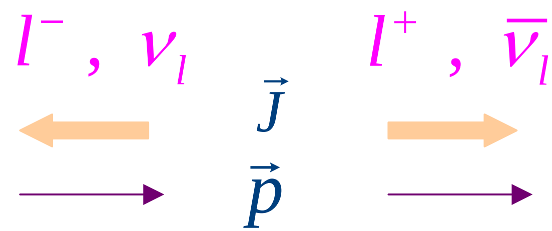


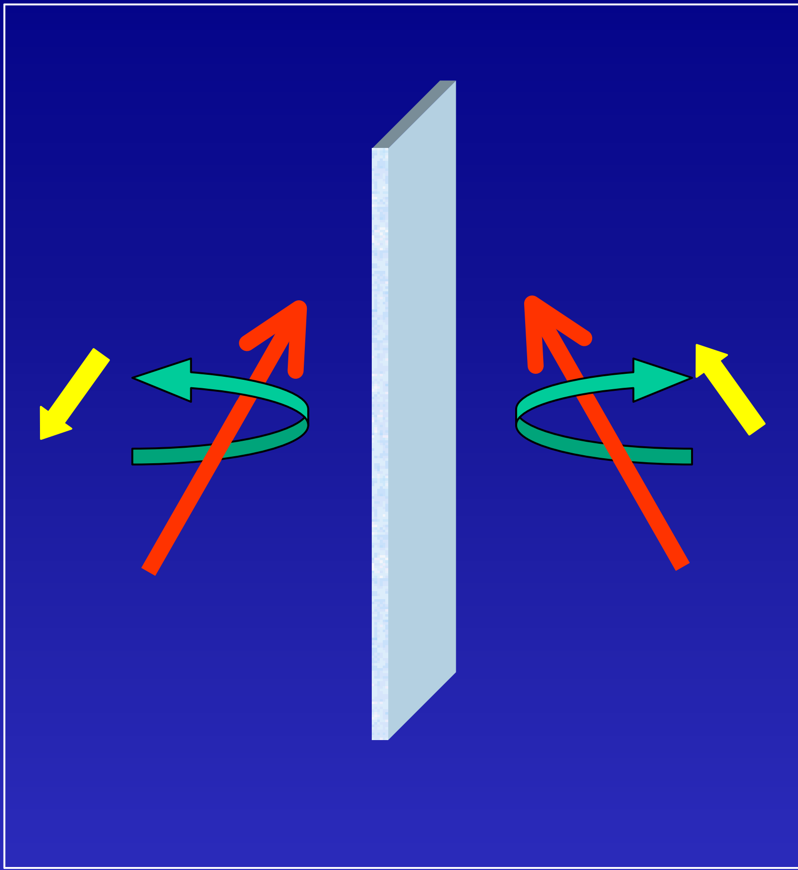


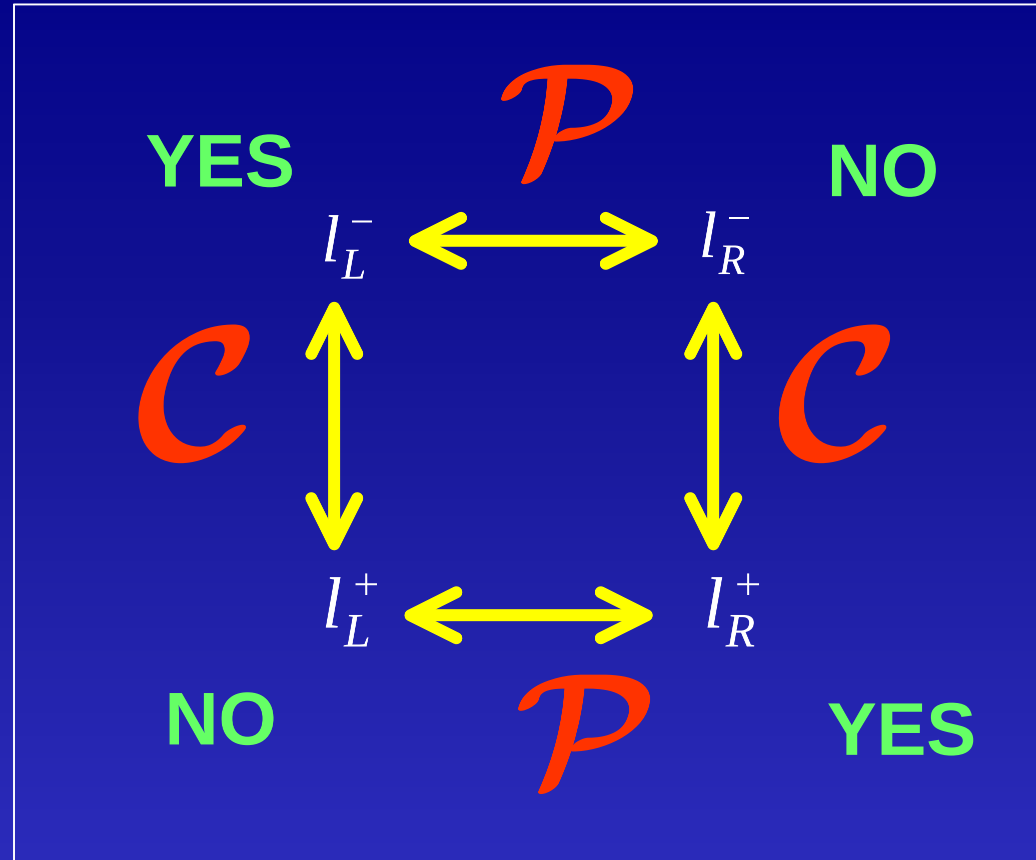
CHARGED CURRENTS



- Left-handed leptons (Right-handed antileptons)



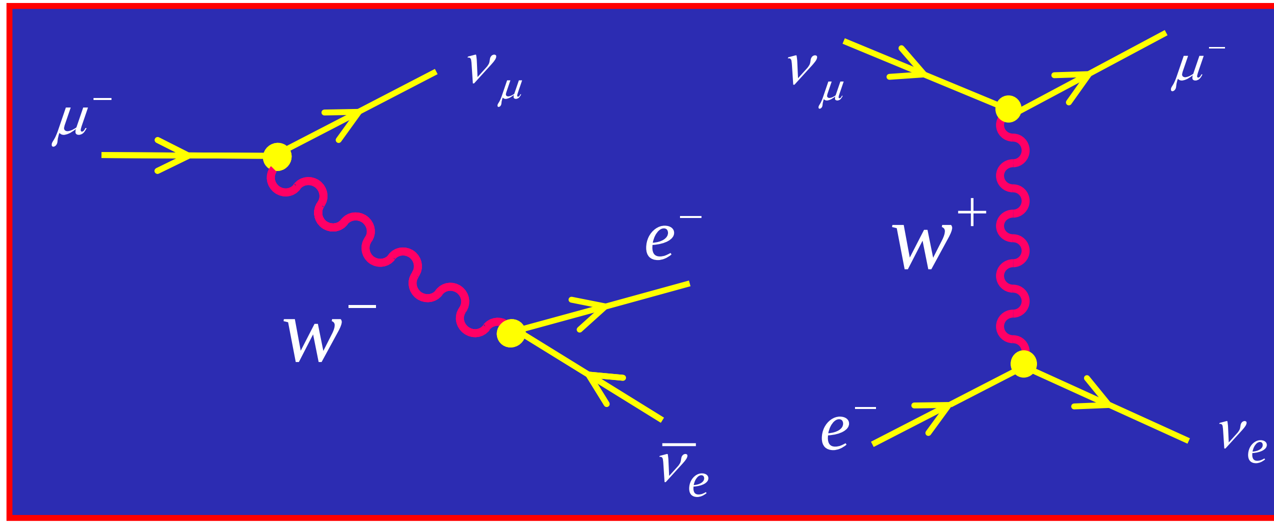




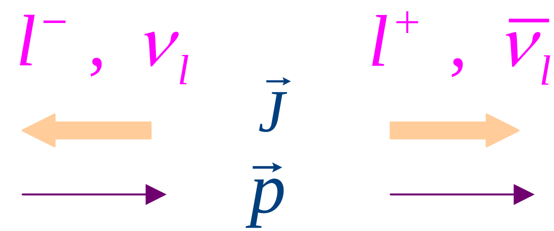
$\not{\mathcal{P}}$ and $\not{\mathcal{C}}$ in Weak Interactions

$\mathcal{CP}$ still a good symmetry

CHARGED CURRENTS



- Left-handed leptons (Right-handed antileptons)



- Doublet partners: $l^- \Leftrightarrow \nu_l$

$$\nu_\mu X \to \mu^- X' \quad ; \quad \nu_\mu X \not\to e^- X'$$

- Universal Strength

$$T(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim \frac{g_W^2}{M_W^2 - q^2} \xrightarrow{q^2 << M_W^2} \frac{g_W^2}{M_W^2} \sim G_F \quad \Longrightarrow \quad \Gamma(l \to \nu_l\, l' \bar{\nu}_{l'}) \sim G_F^2\, m_l^5$$

$$\Gamma(\tau \to \nu_\tau\, e\, \bar{\nu}_e) / \Gamma(\mu \to \nu_\mu\, e\, \bar{\nu}_e) \approx (m_\tau / m_\mu)^5$$

NEUTRINOS

- Weakly Interacting Particles
- Among most abundant particles in the Universe
- Each second pass through your body

$\sim 10^{14}\ \nu_e$ from the SUN

$(p\, p \rightarrow d\ e^+ \nu_e\ ,\ \ldots)$

NEUTRINOS

Each second pass through your body

$\sim 10^{14}\ \nu_e$ from the SUN

$(\, p\, p \to d\, e^+ \nu_e\ ,\ \ldots)$

They also come

from below!

NEUTRINOS

are produced in the atmosphere by

COSMIC RAYS

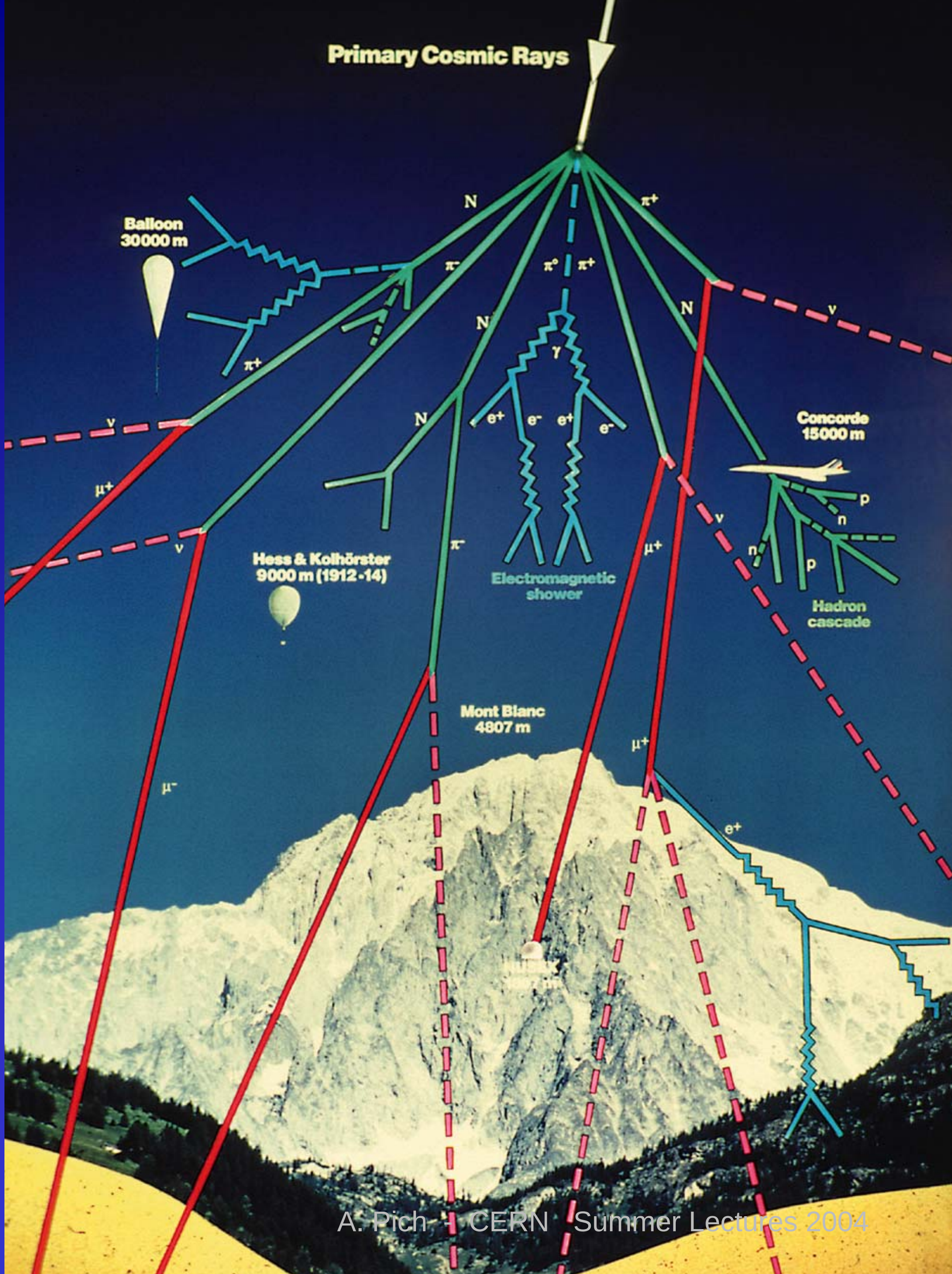
$$p\,X \to \pi\,X'$$

$$\pi^- \to \mu^- \,\overline{\nu}_\mu \quad ; \quad \mu^- \to \nu_\mu \, e^- \,\overline{\nu}_e$$

- Produced by Nuclear Reactors

$$n \to p\, e^- \,\overline{\nu}_e$$

- Produced at CERN



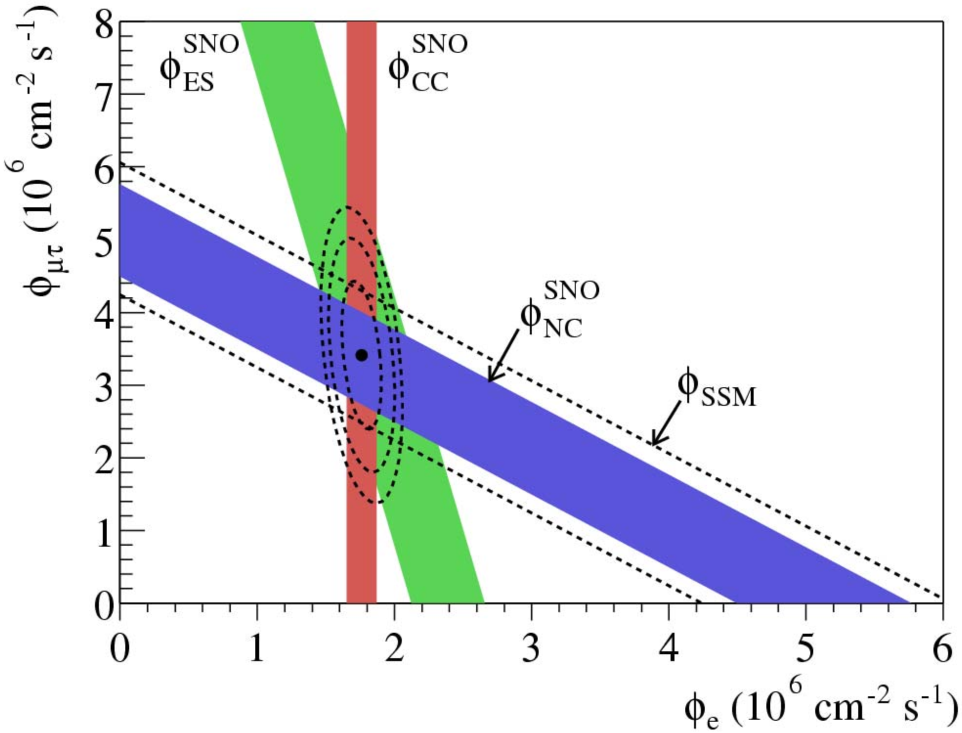
SOLAR NEUTRINO PROBLEM

ν_e Measured $<$ ν_e Predicted

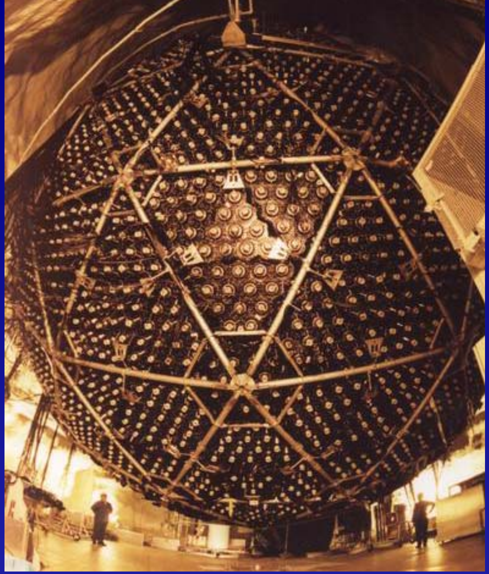
SNO

- CC: $\nu_e + d \rightarrow p + p + e^-$
- ES: $\nu_x + e^- \rightarrow \nu_x + e^-$
- NC: $\nu_x + d \rightarrow p + n + \nu_x$

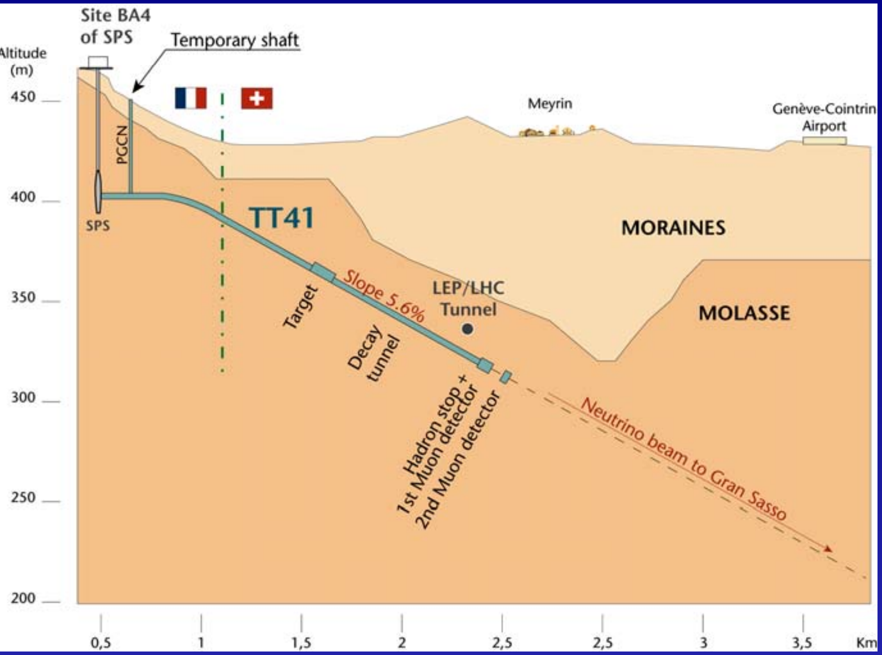
$(x = e, \mu, \tau)$

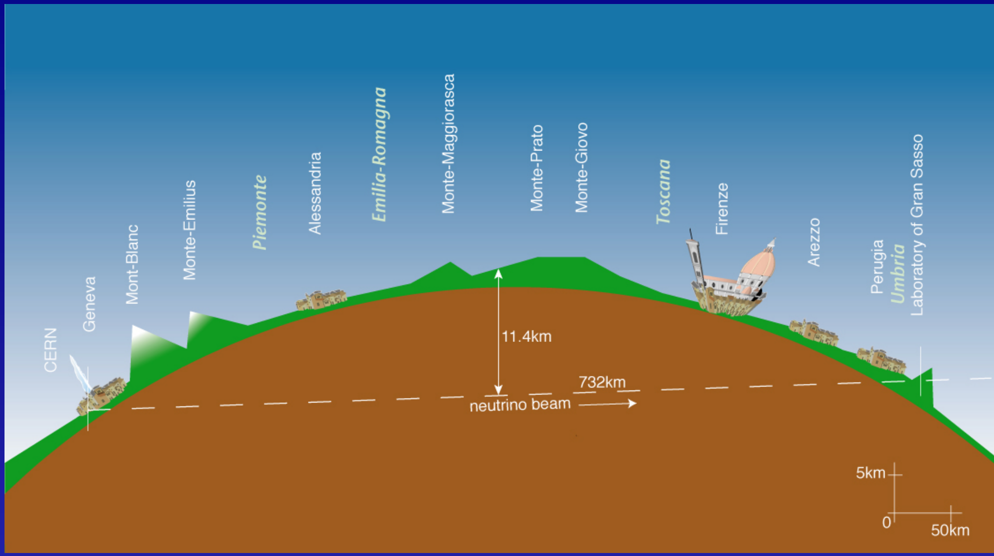


Neutrino Oscillations $\nu_e \rightarrow \nu_{\mu,\tau}$



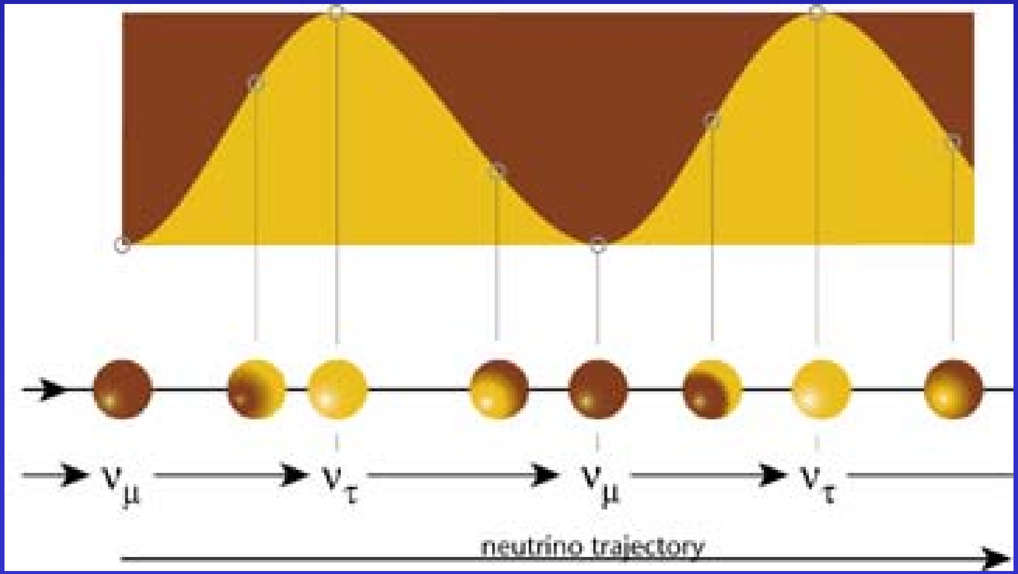
Sudbury Neutrino Observatory





CNGS

CERN Neutrinos To Gran Sasso



Quarks Leptons Bosons