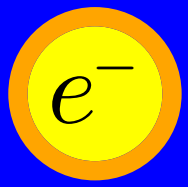
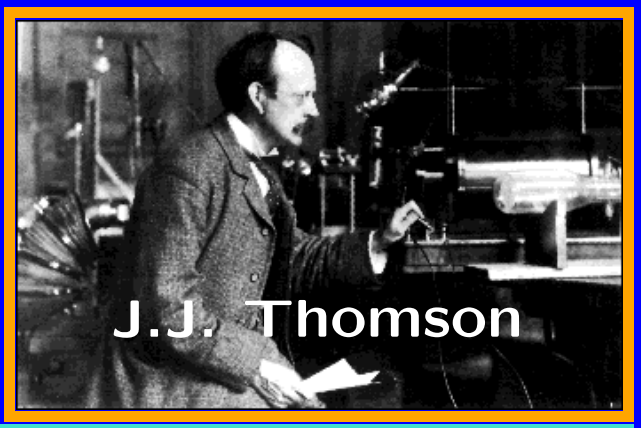
Particles of the Standard Model:

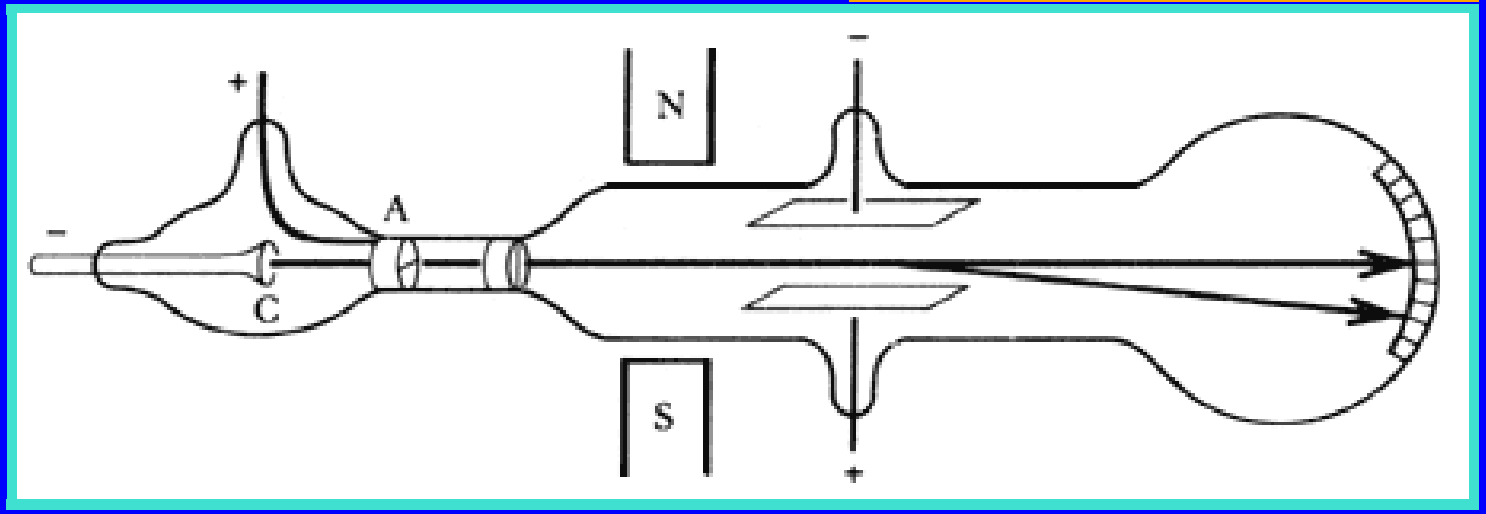
Fermions

1. reminder about the particles
   - from the historical introduction
2. the ordering principle
   - example: electron and neutrino
3. the systematics
   - extending the ordering to all fermions
   - counting the degrees of freedom
4. overview



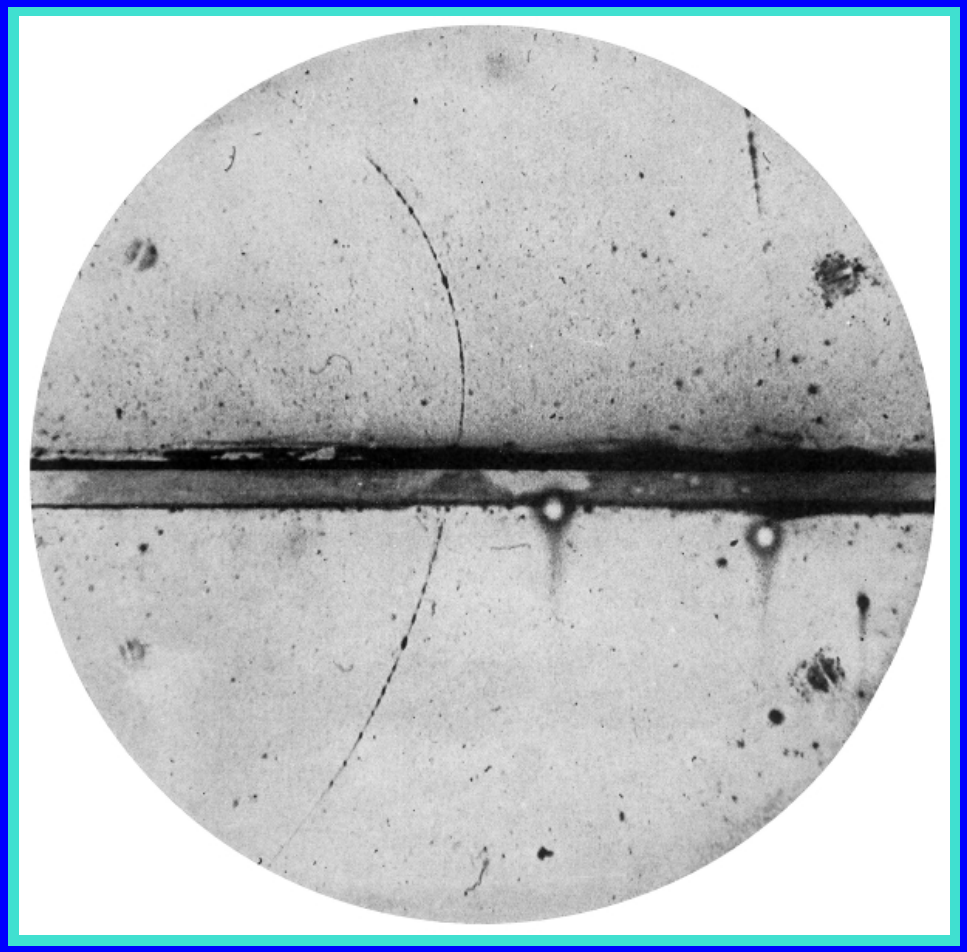
the electron



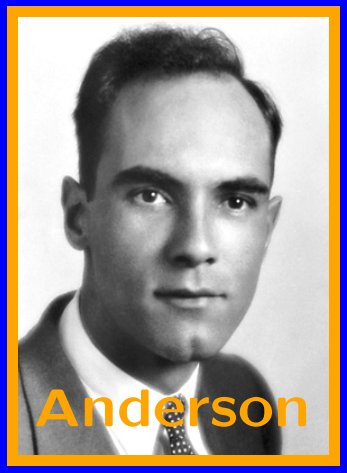


1897

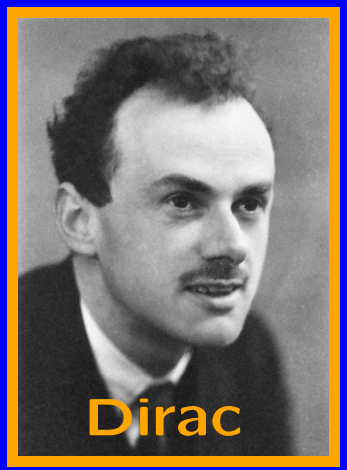
e^+ the positron

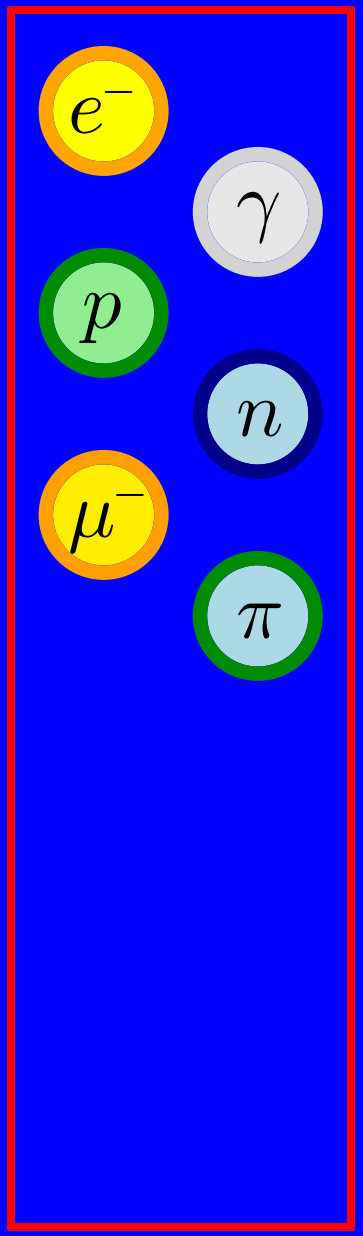


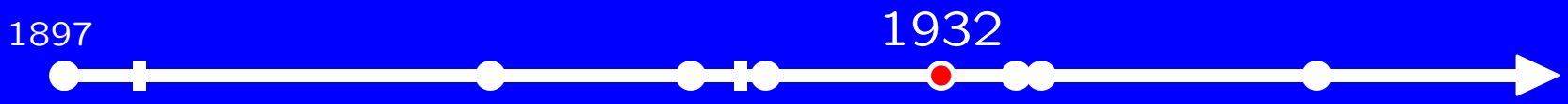
Discovery



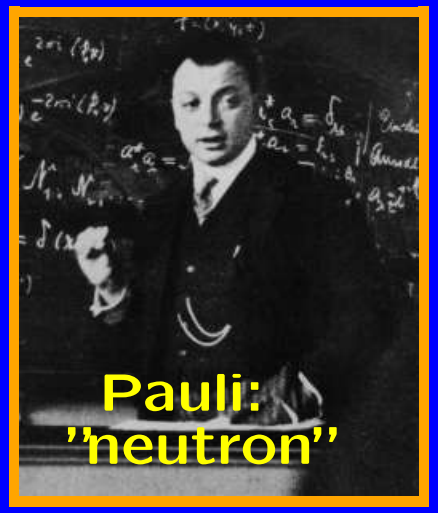
Prediction

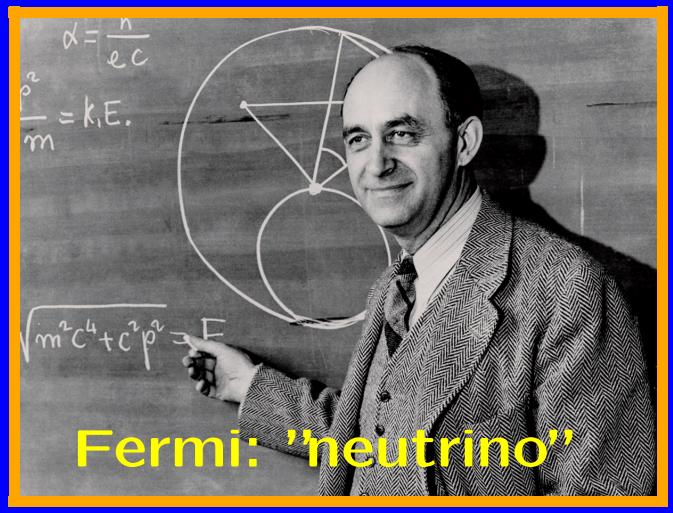


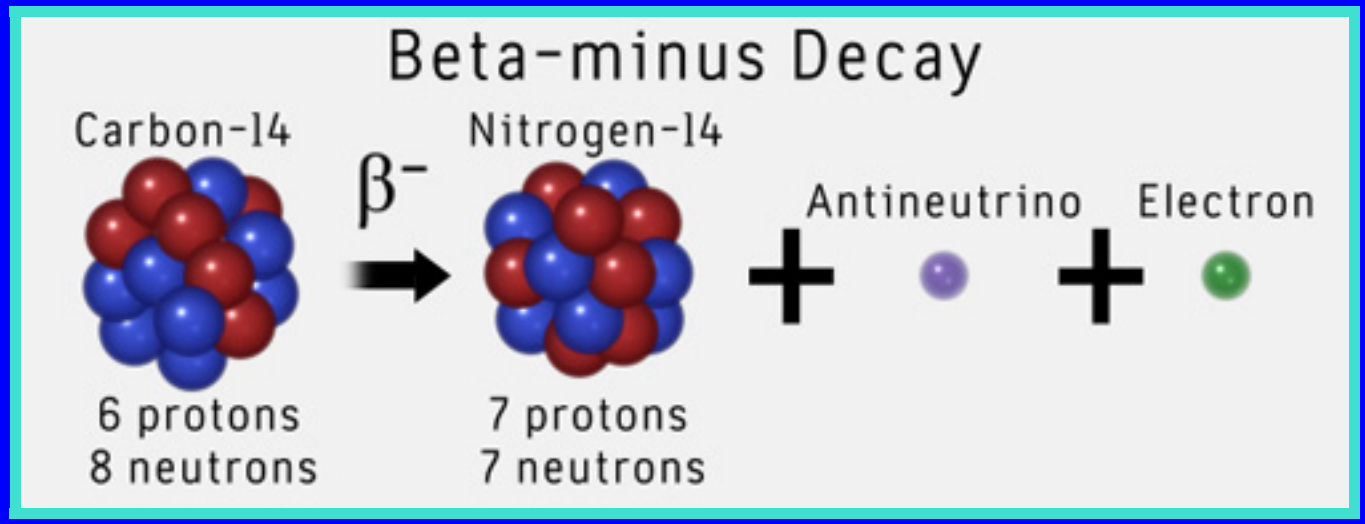


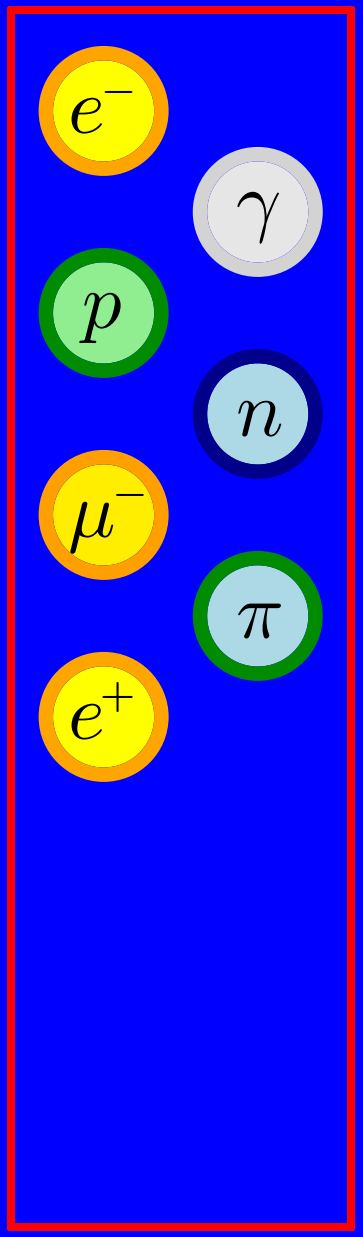


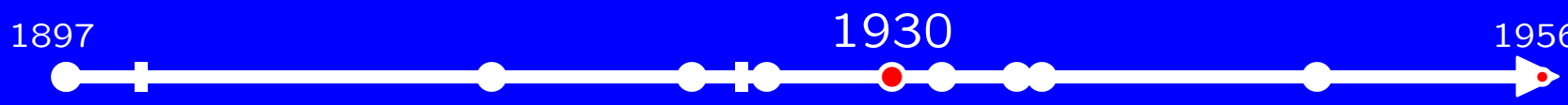
ν the neutrino – theory prediction











Reminder: Are symmetries perfect?

★ Parity violation – but maybe a CP symmetry?

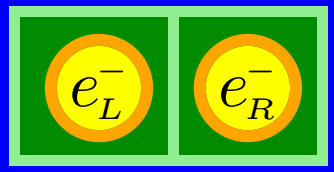
right-handed anti-neutrino | left-handed anti-neutrino | left-handed neutrino

- there is no left-handed anti-neutrino, but there is a left-handed neutrino (and only a such-handed!)
- obviously, this violates C-symmetry (Charge conjugation, the symmetrie between matter and anti-matter)
- BUT: the combined symmetry transformation CP (exchange matter/anti-matter plus mirroring) works:

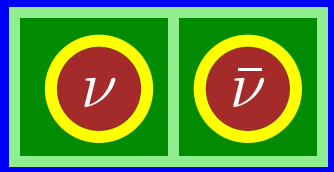
right-handed anti-neutrino | left-handed neutrino

Ordering principle:
discreet symmetries

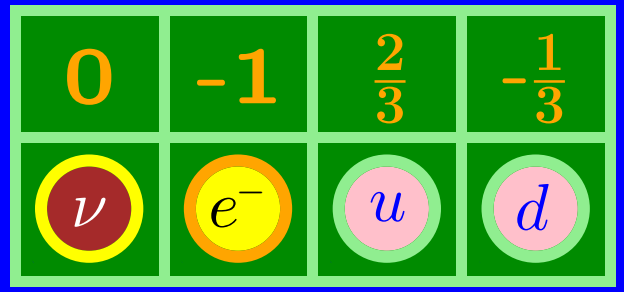
- **Parity P**
  - left-handed or right-handed



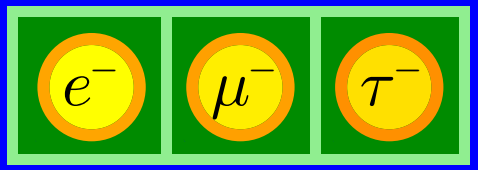
- **Charge Conjugation C**
  - particle or antiparticle



- **Charge Q or Flavour**
  - possible values:

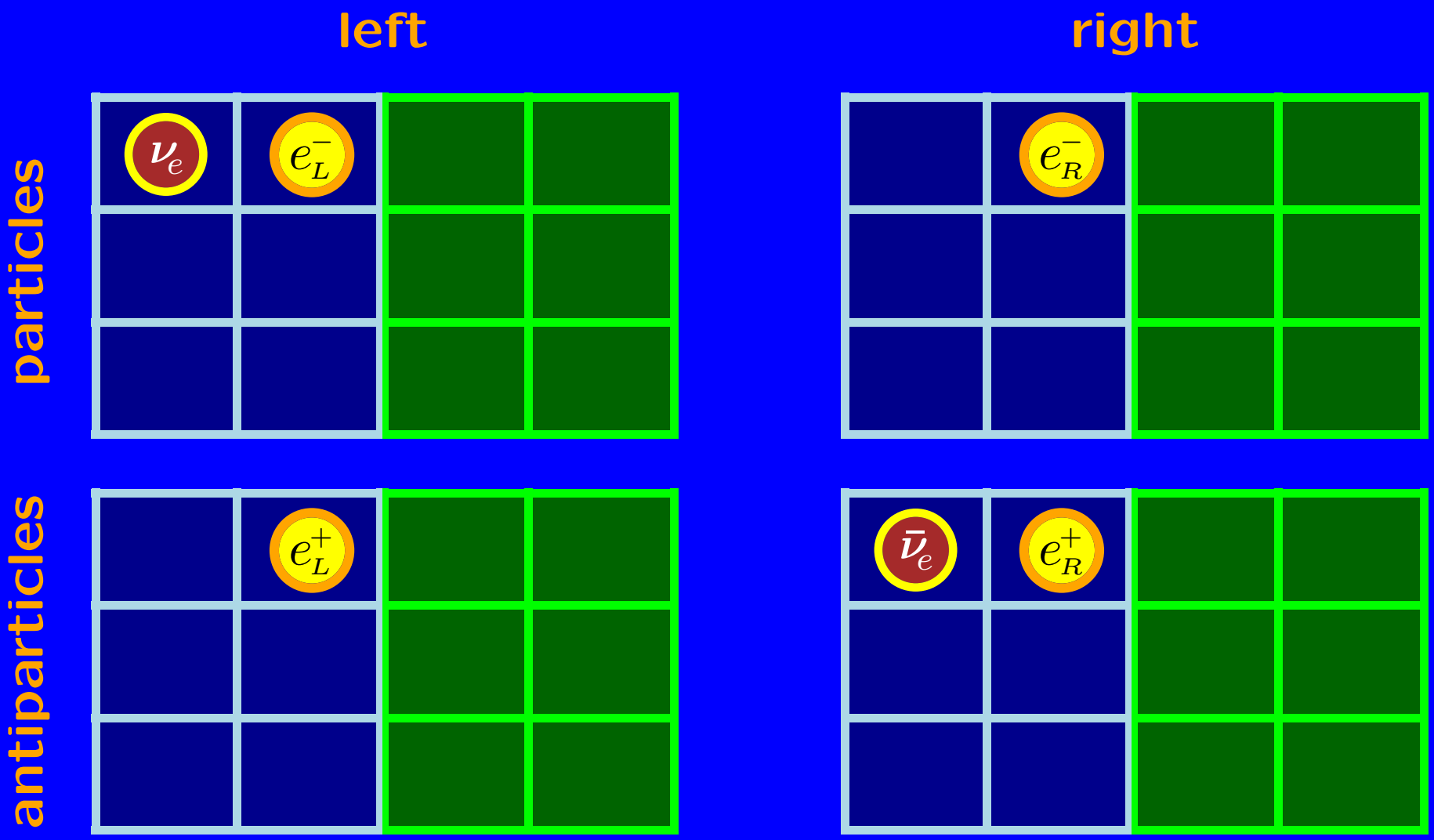


- **Generation**
  - first – second – third

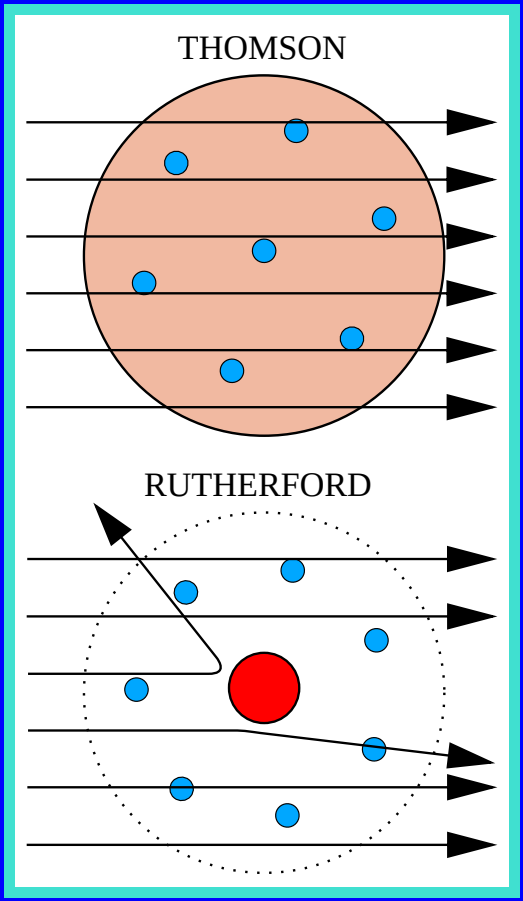


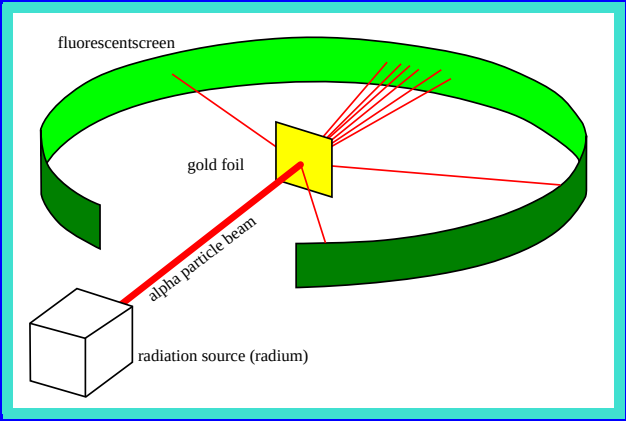
Particles of the Standard Model:

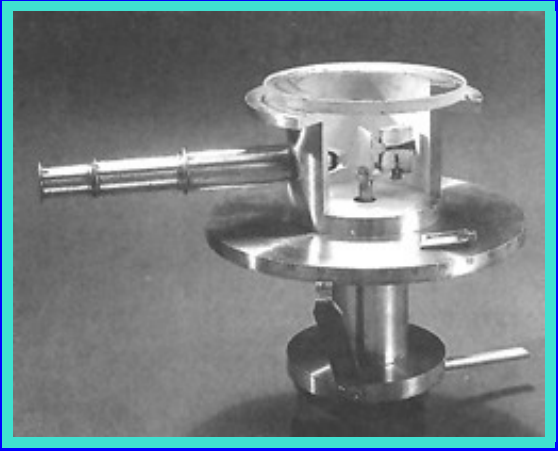
Fermions

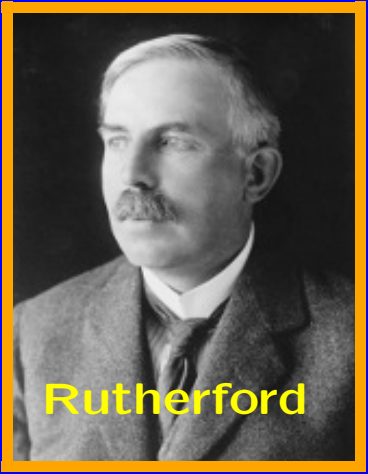


p the proton – the atomic nucleus







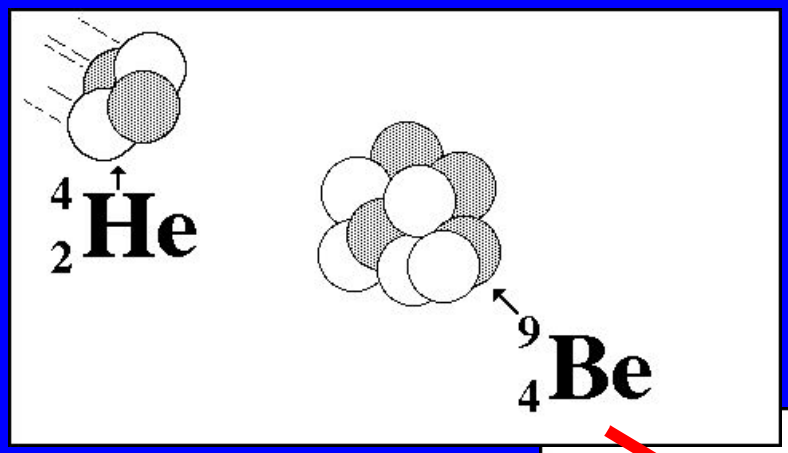


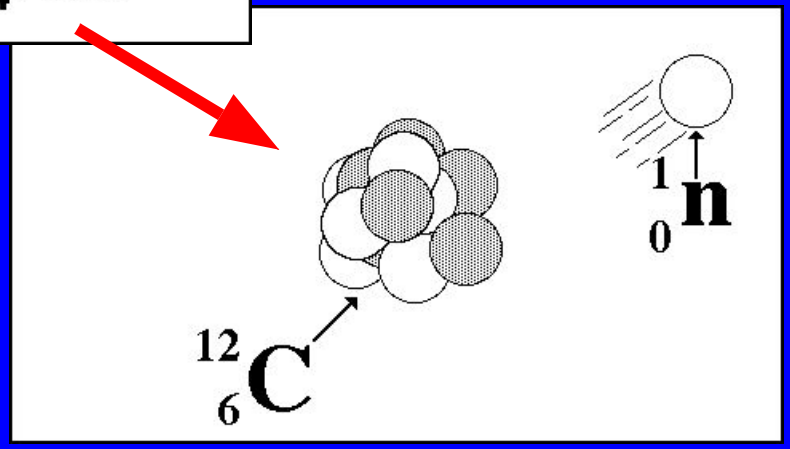
e^-

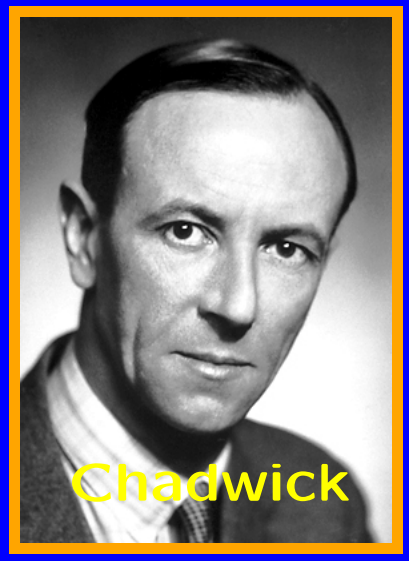
γ

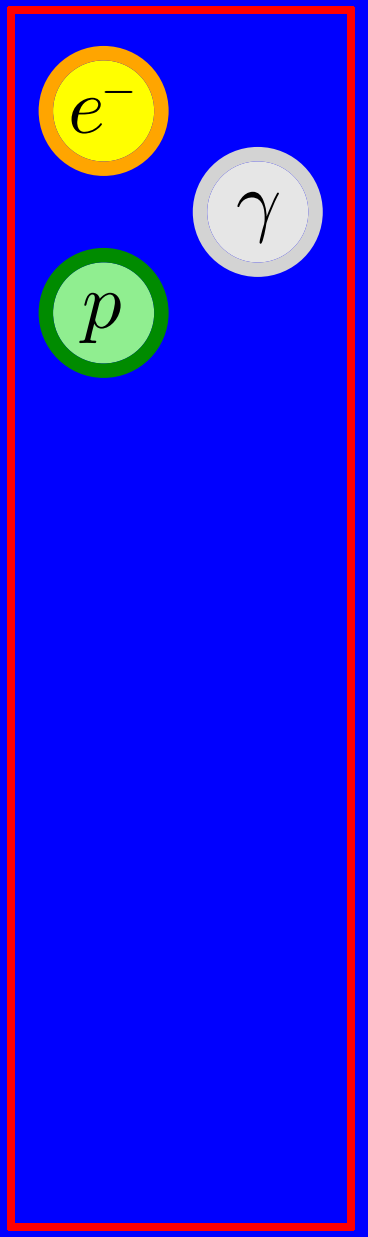
1897 1914

n the neutron





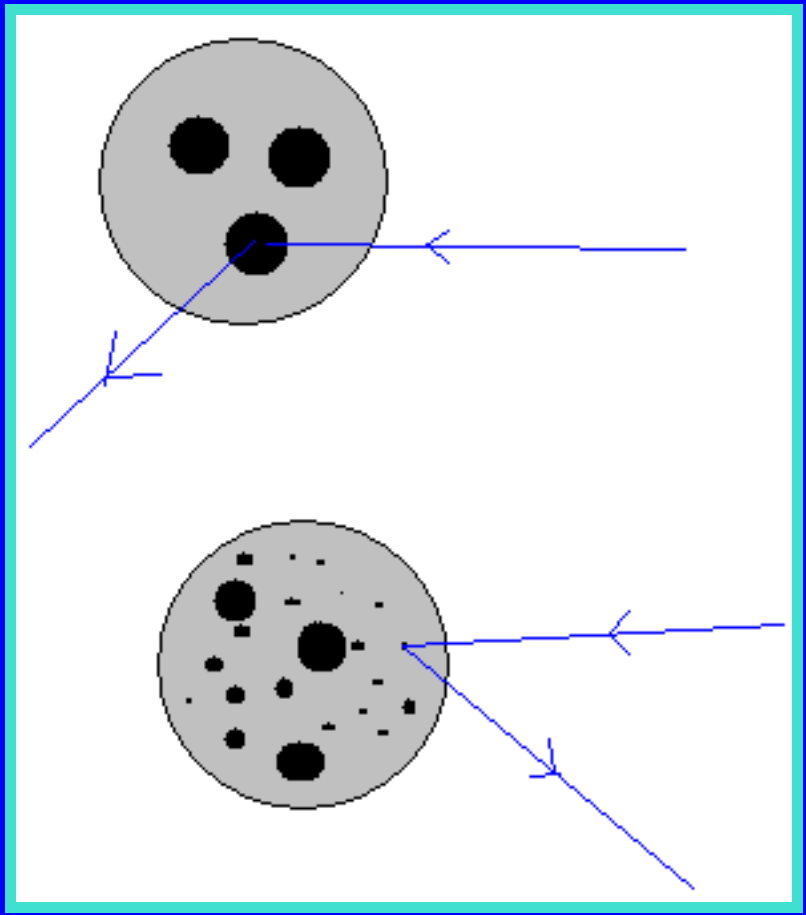


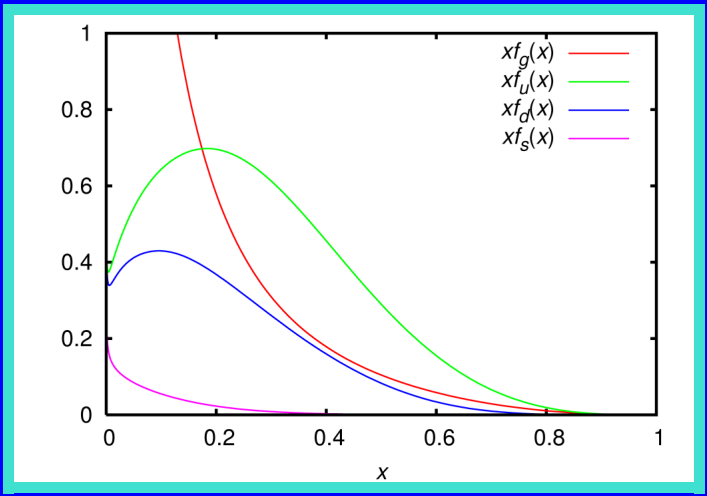


1897 1932

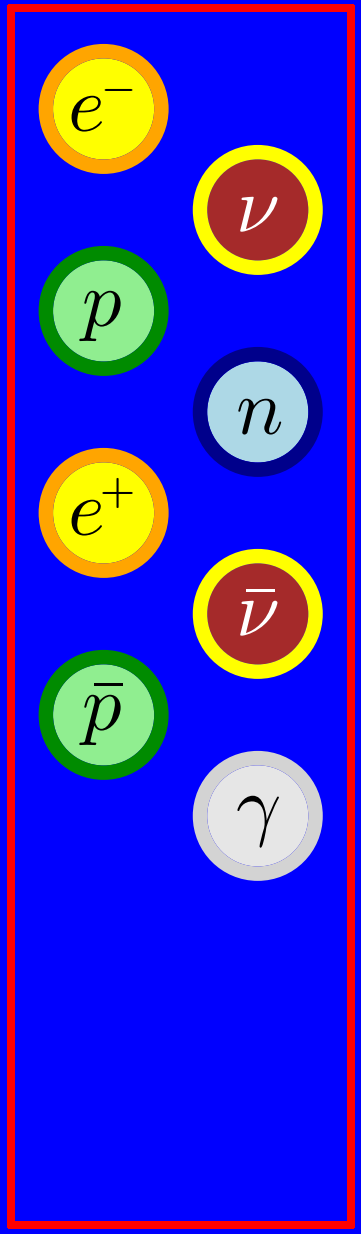
partons / parton model

Richard Feynman 1969



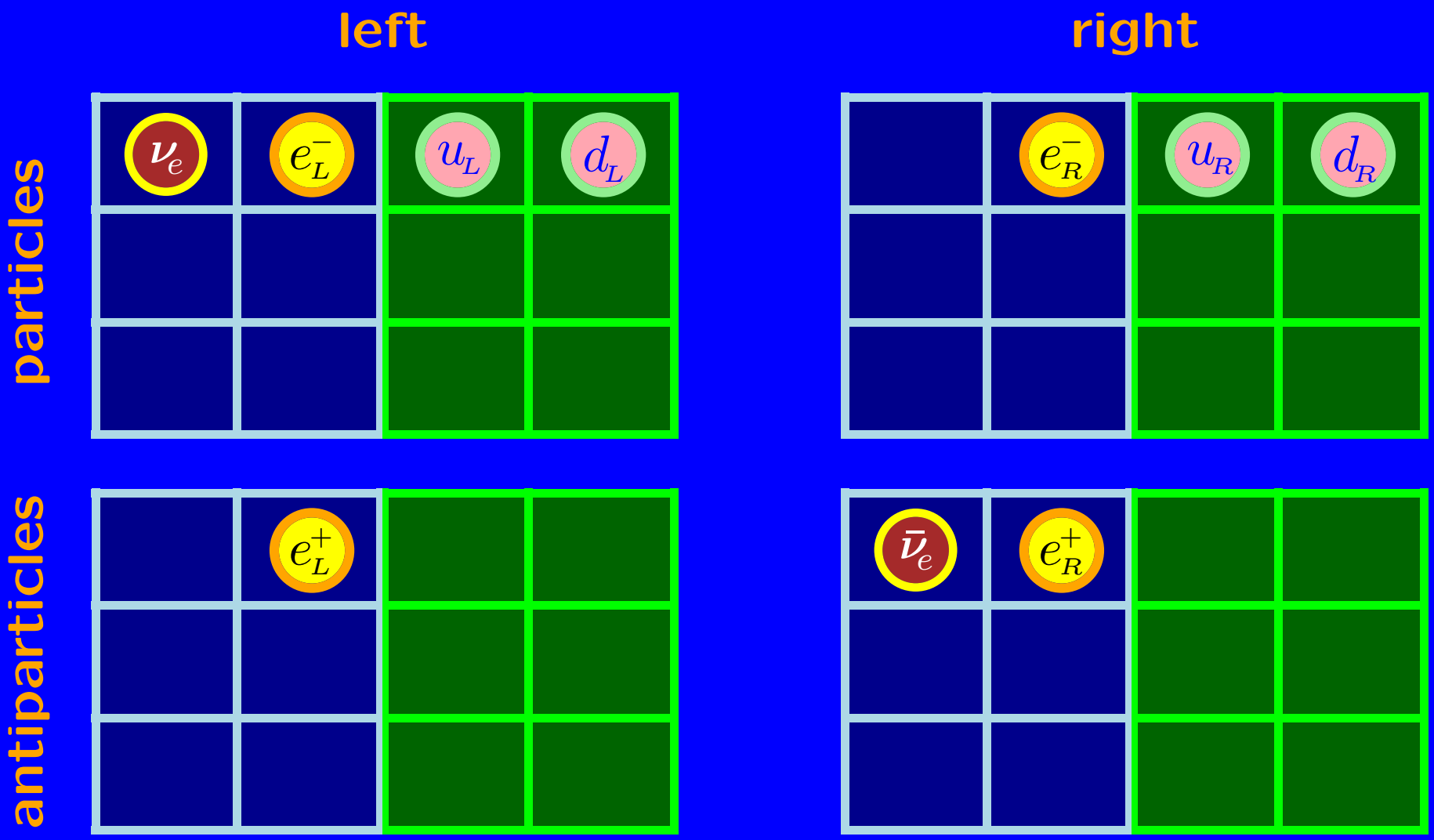


a hadron is composed of point-like constituents, called "partons". The number of partons depends on the probing energy ⇒ **parton distribution functions**

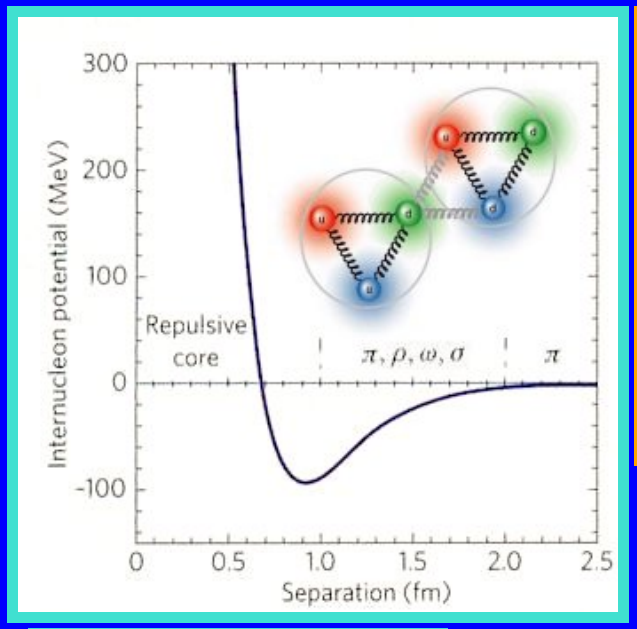


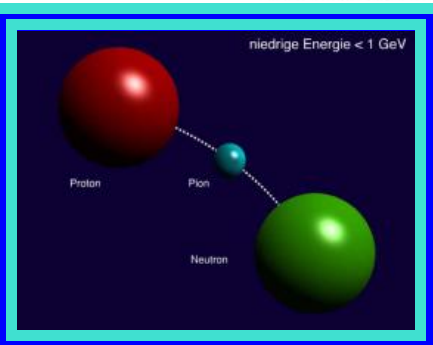
Particles of the Standard Model:

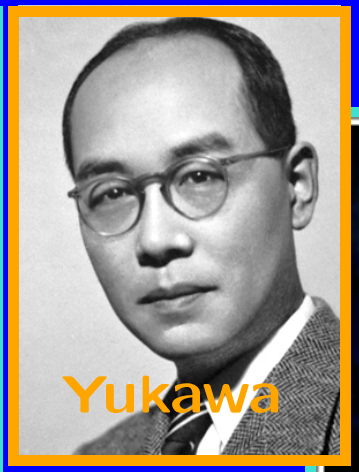
Fermions

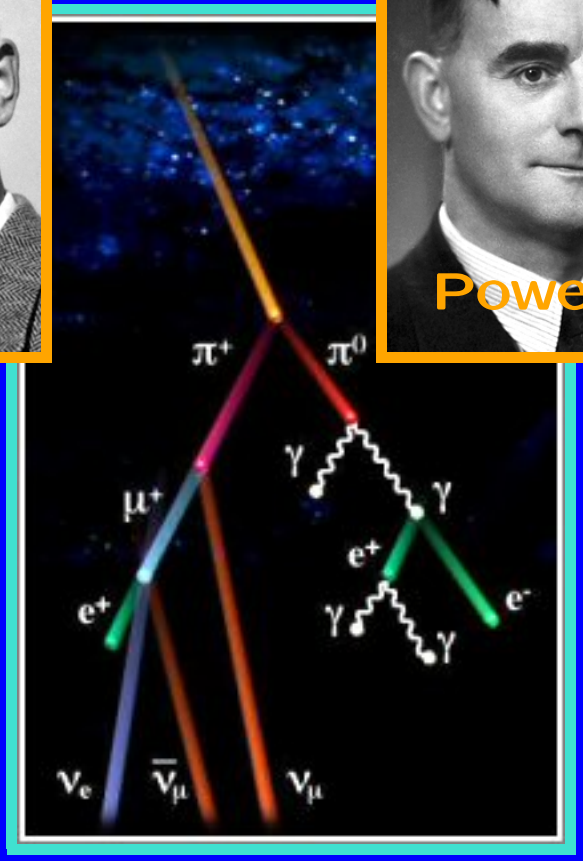


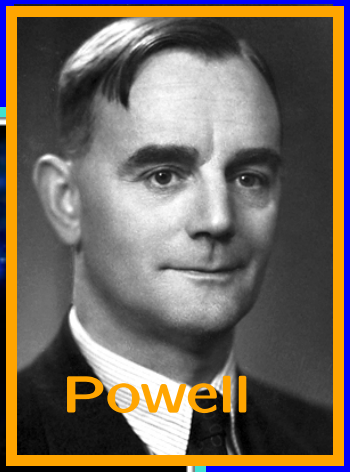
π the pion

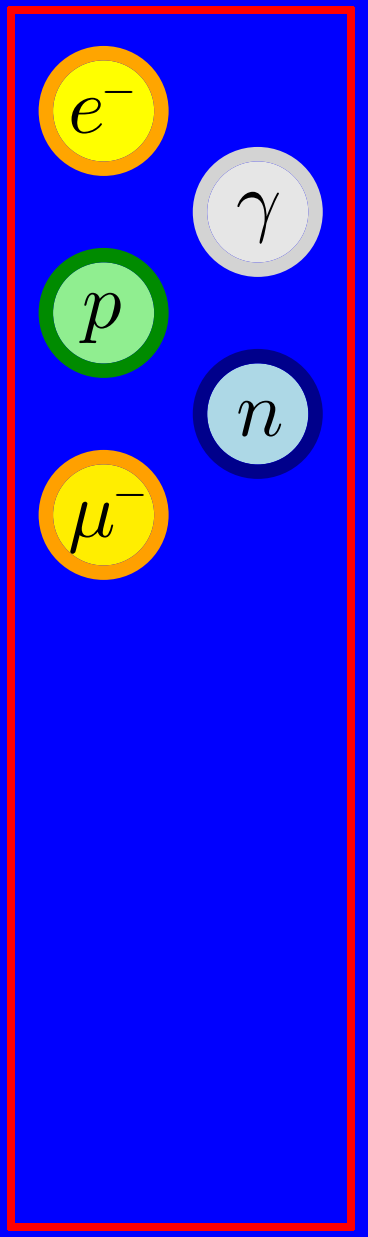








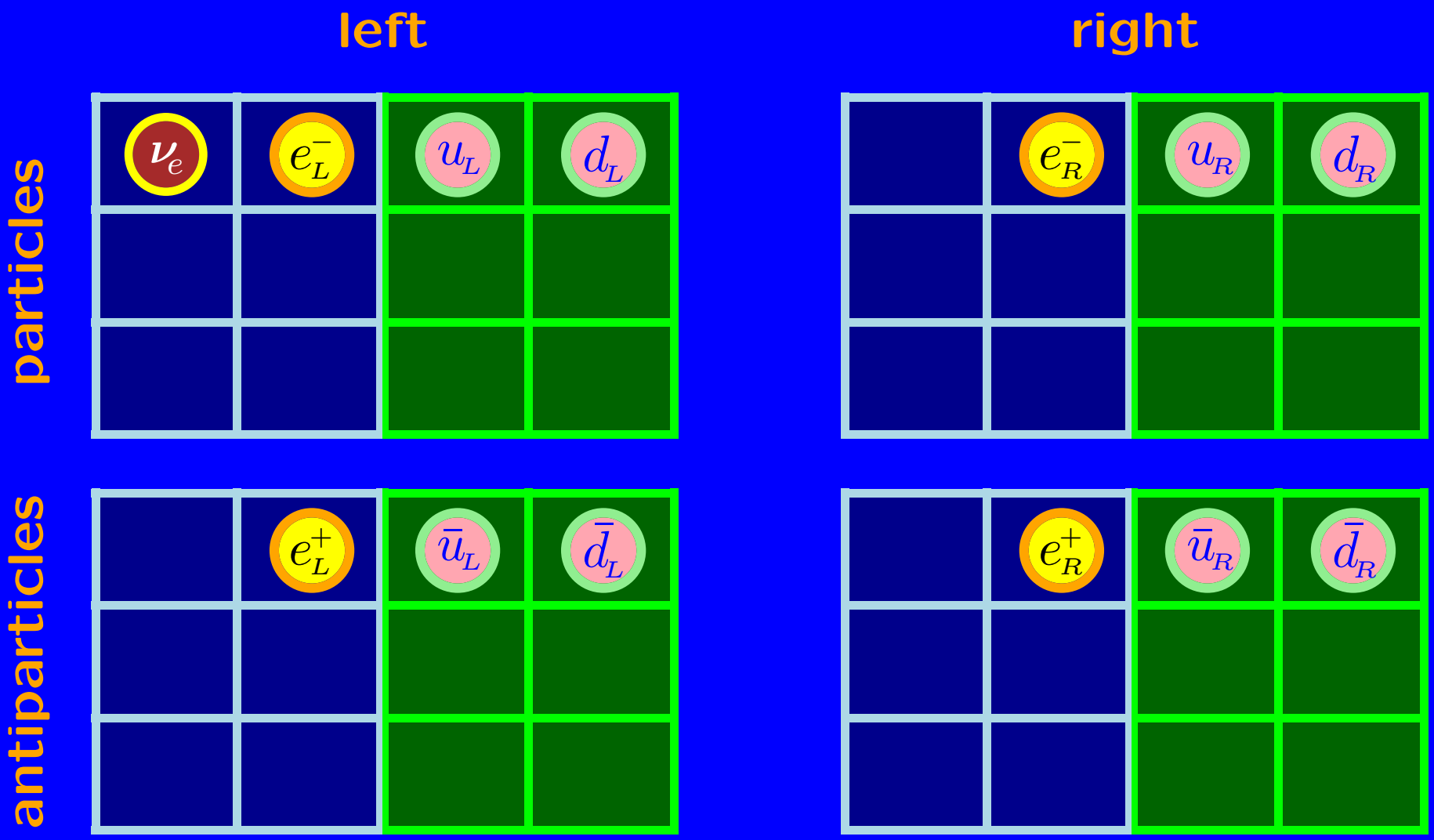




1897 1935 1947

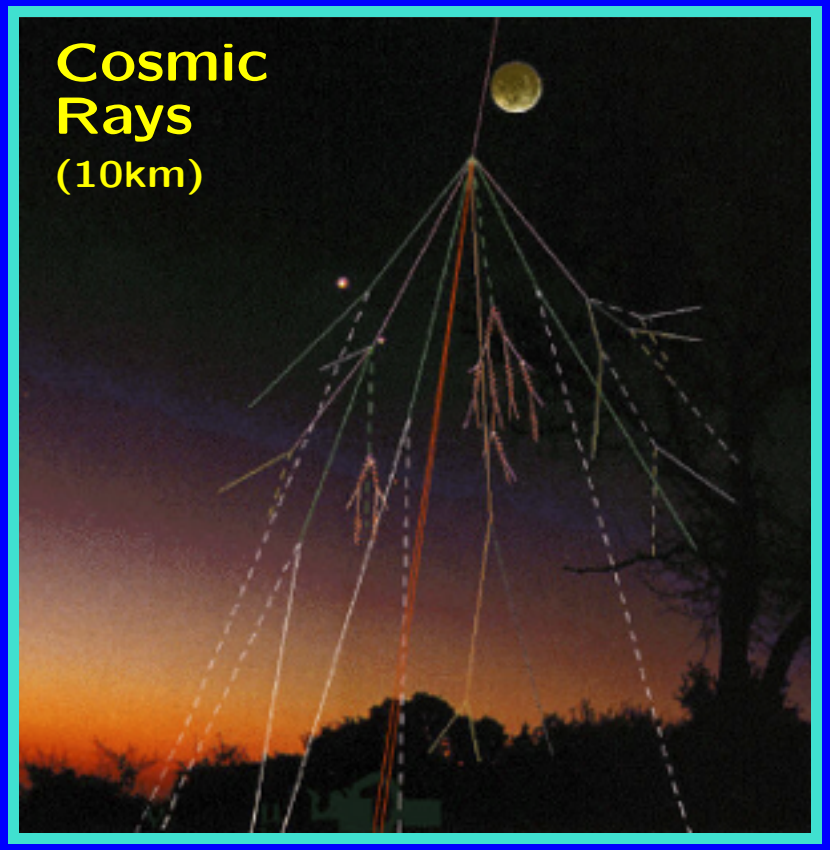
Particles of the Standard Model:

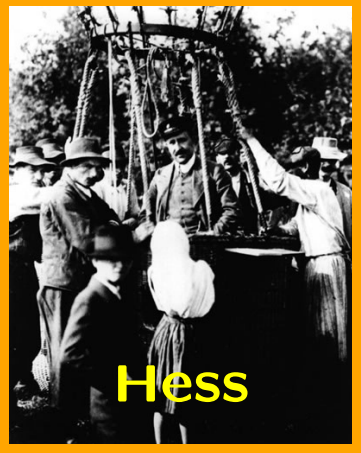
Fermions

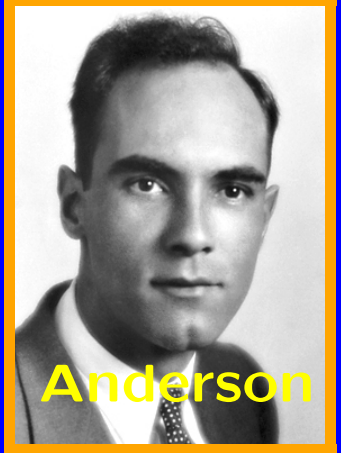


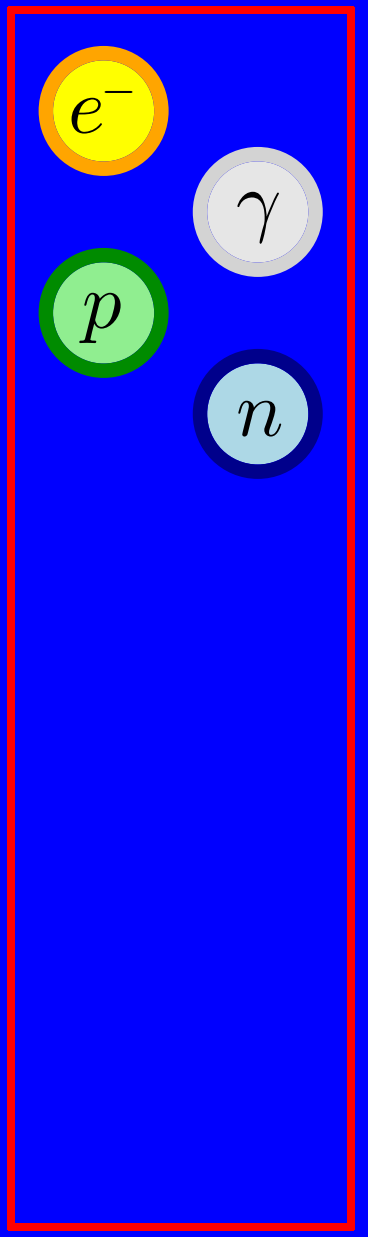
the muon

Raby: "Who ordered that one?"





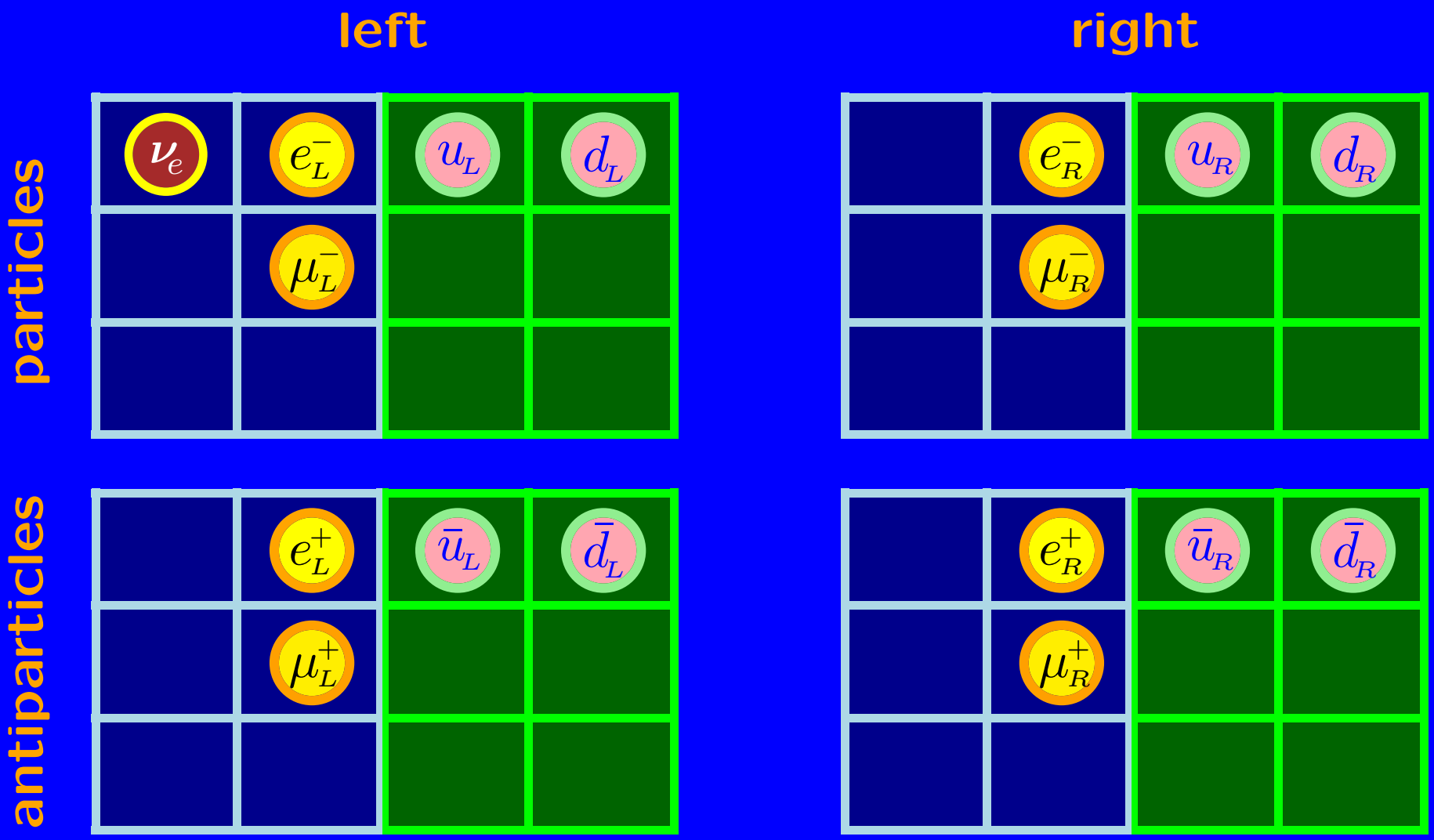




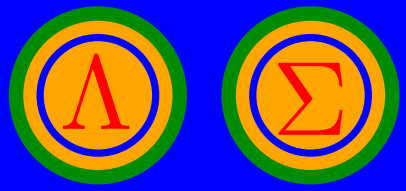
1897 1936

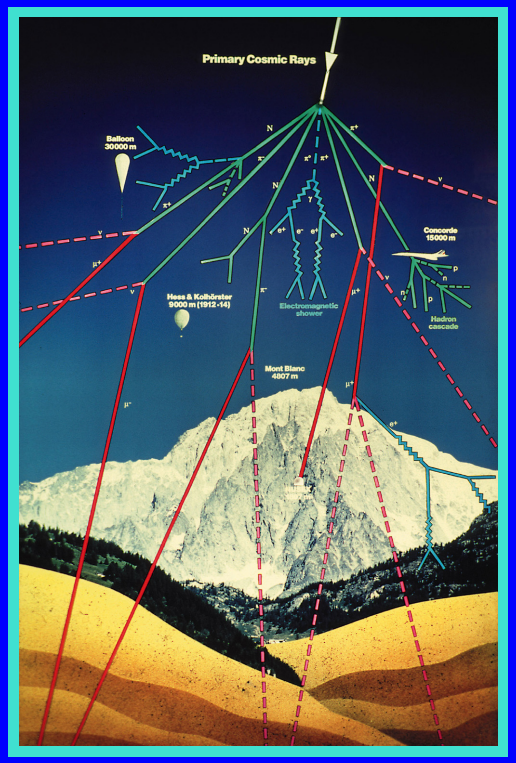
Particles of the Standard Model:

Fermions



strange particles



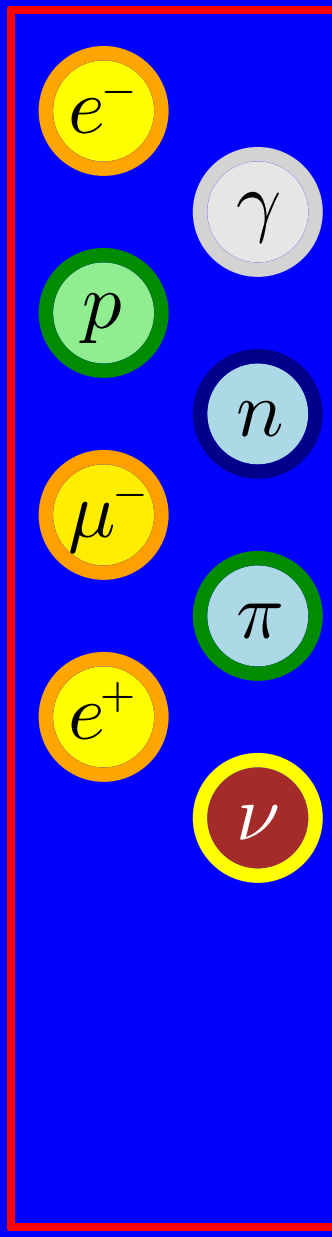


Pic du Midi

K: **Rochester** and **Butler** (Univ. of Manchester)

Λ: **Hopper** and **Biswas** (Univ. of Melbourne)

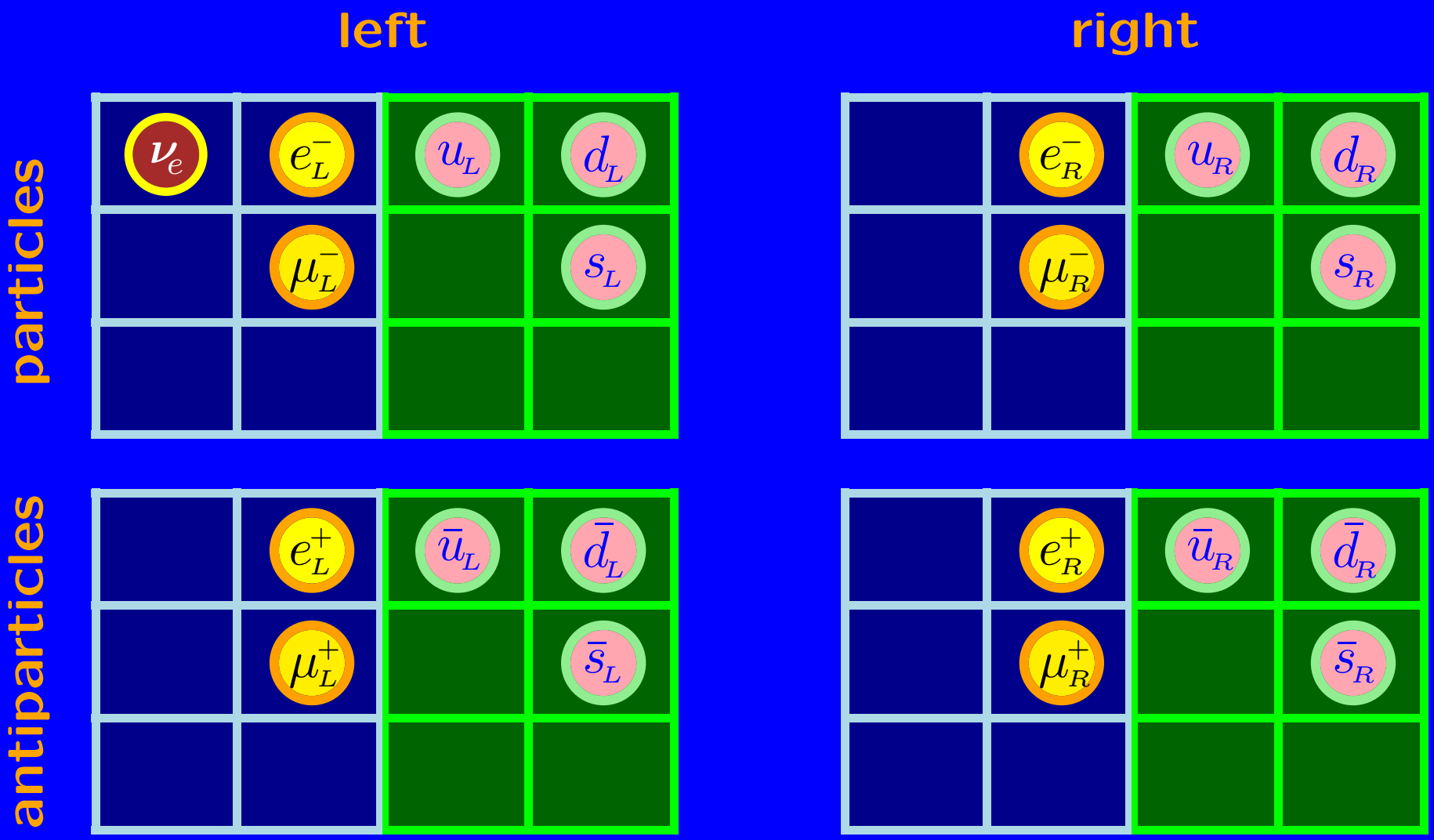
particles in a cloud chamber



1897 1947 . . .

Particles of the Standard Model:

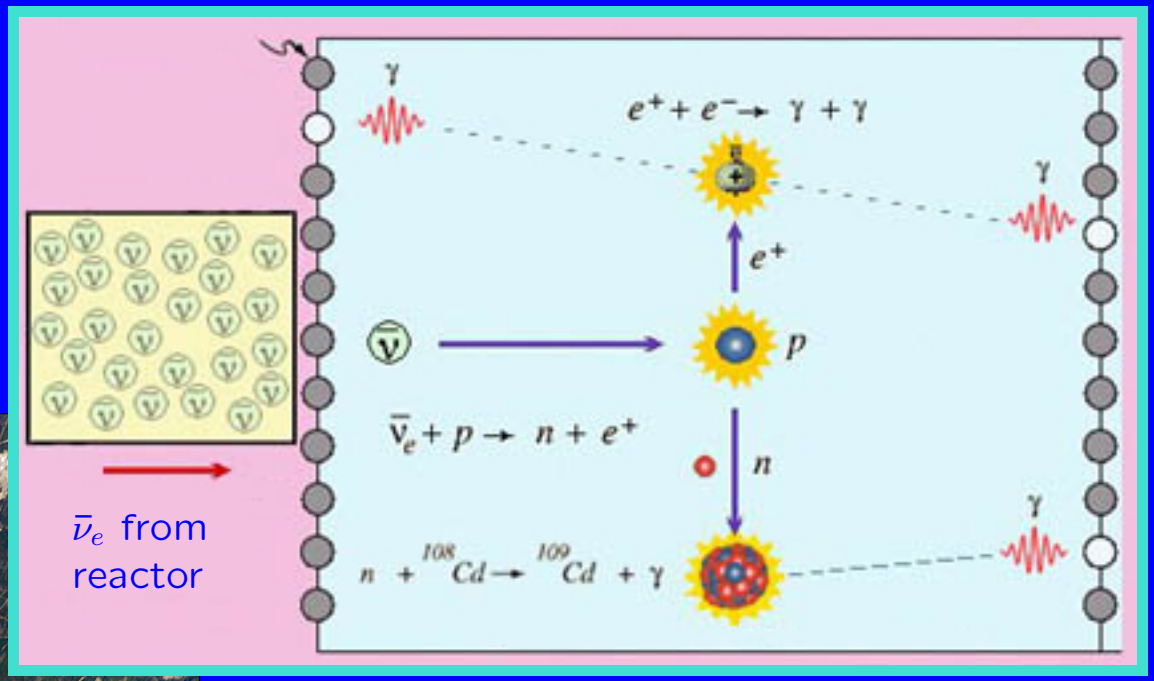
Fermions



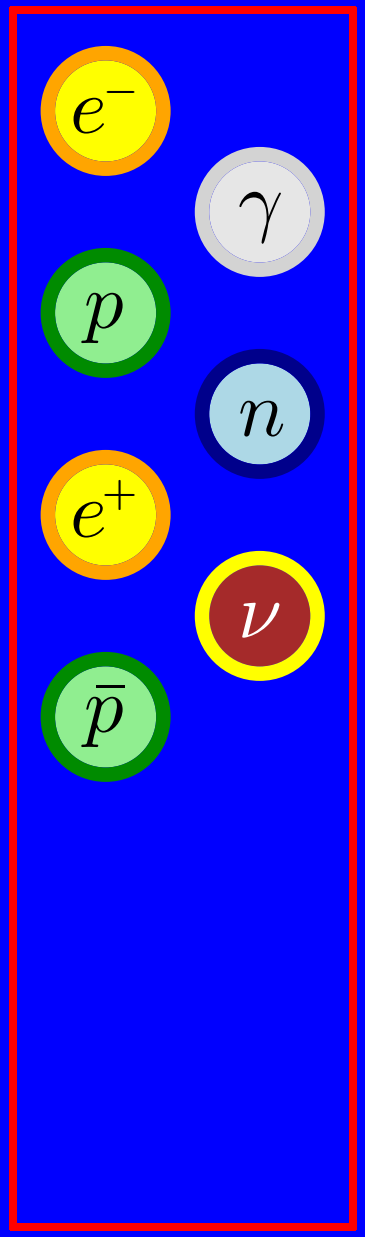
$\bar{\nu}$ antineutrino

Cowan–Reines neutrino experiment

Savannah River Site



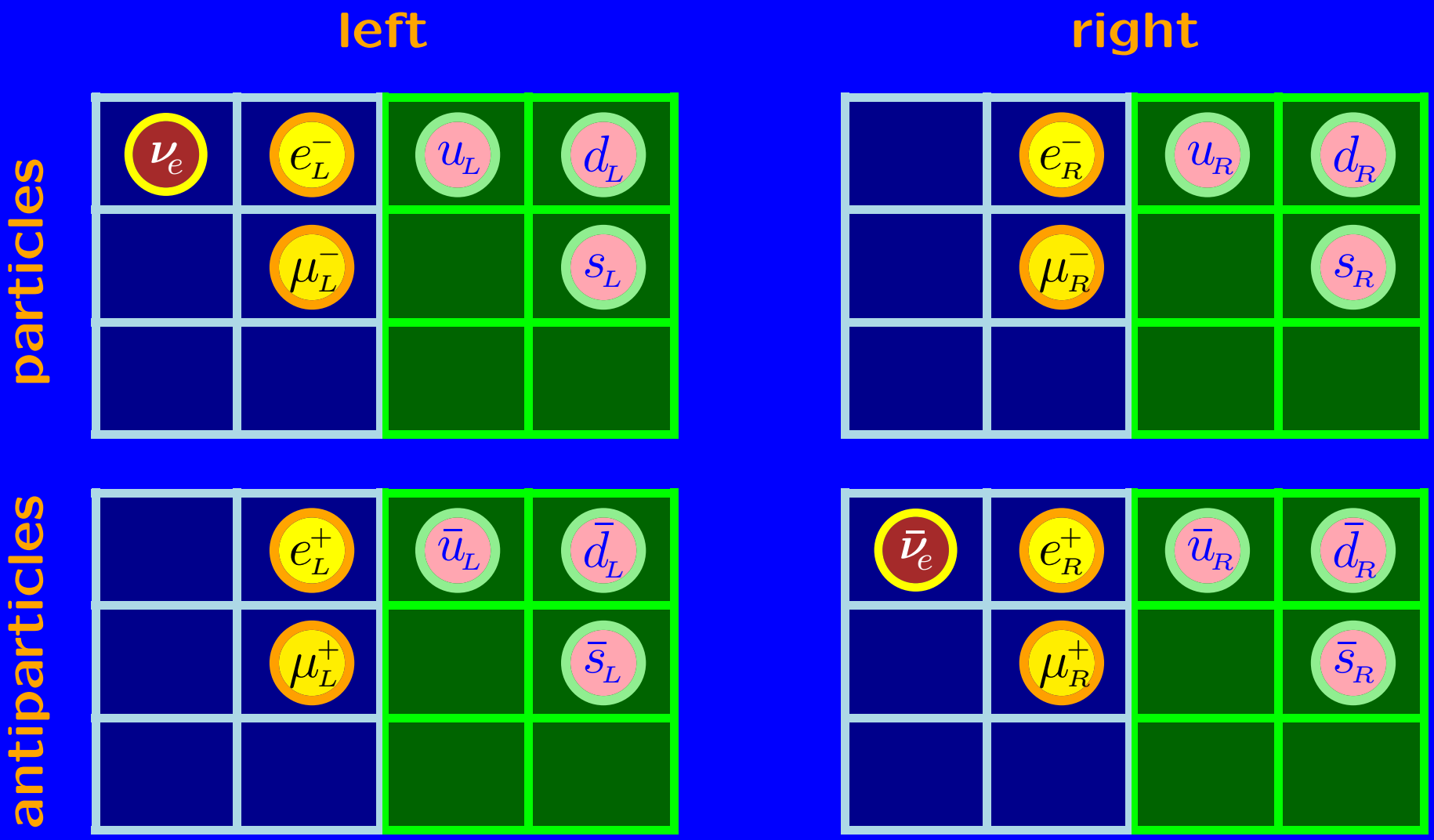
used the antineutrino flux from the nuclear reactors of the Savannah River Site (South Carolina).



...1956

Particles of the Standard Model:

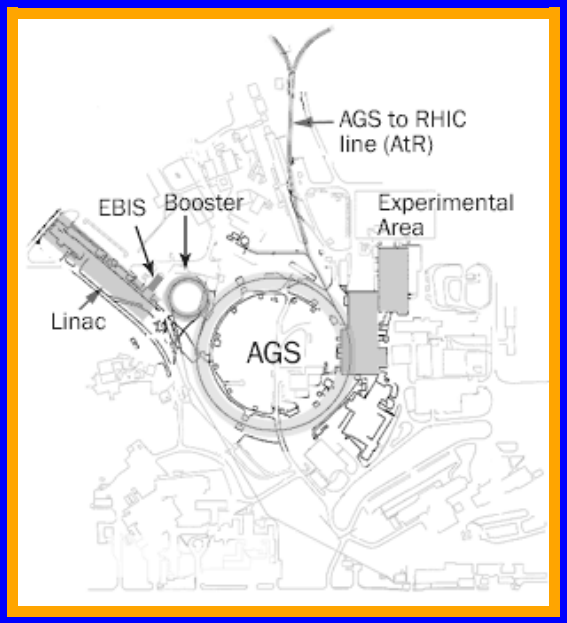
Fermions



muon neutrino

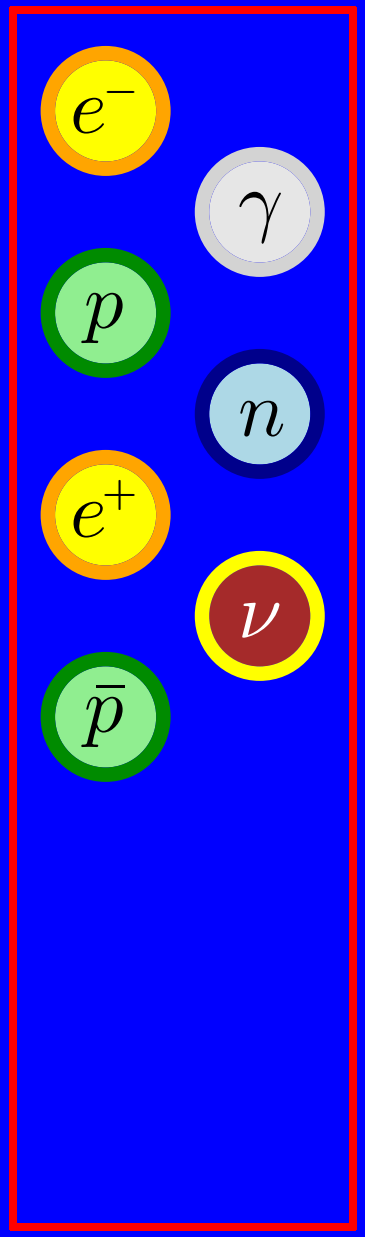
the Alternating Gradient Synchrotron (AGS)

1962
Leon Lederman
Melvin Schwartz
Jack Steinberger



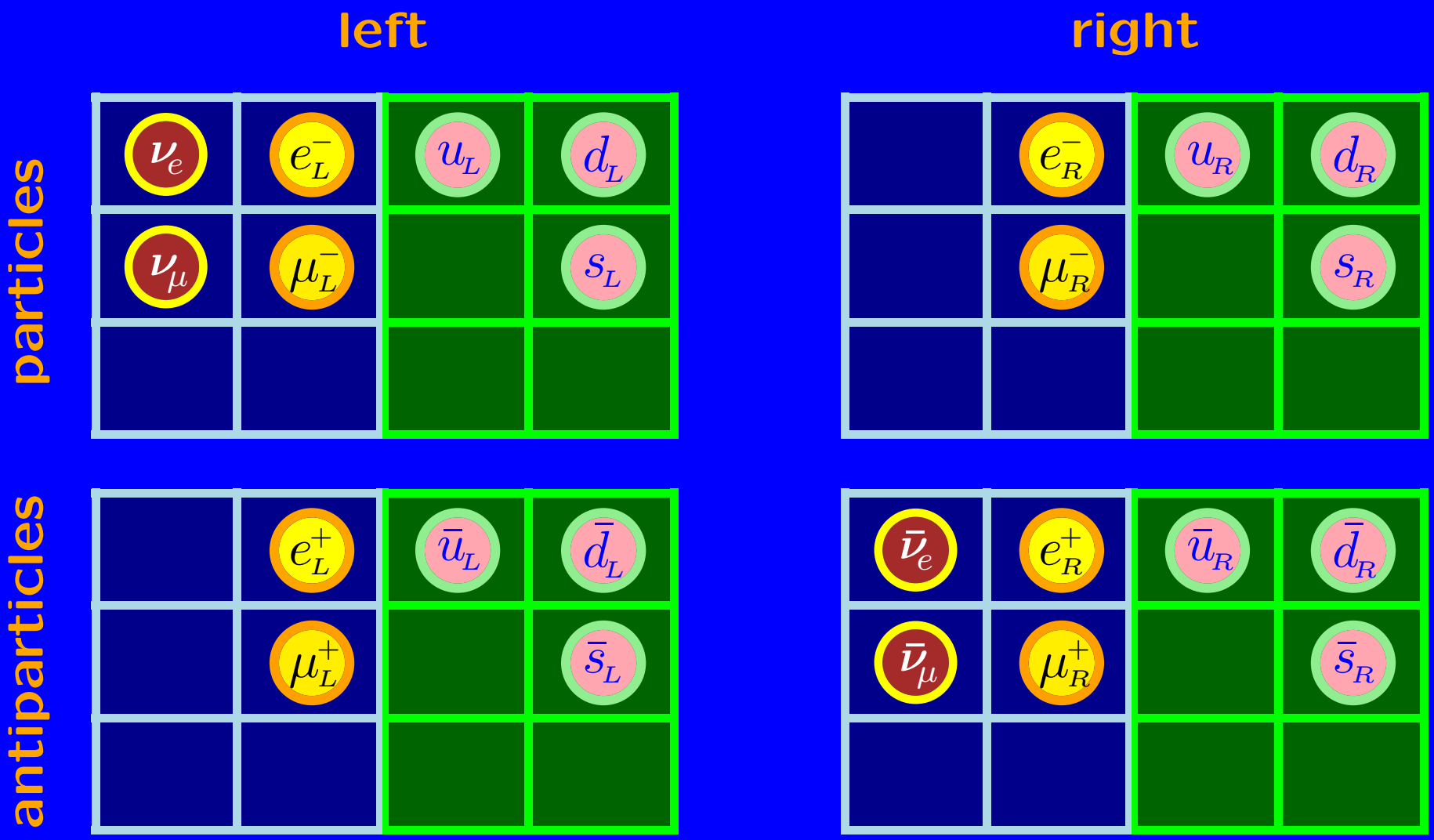
use the pions and kaons of the AGS. These dacays produce also (anti)neutrinos; with a similar setup like the Cowan–Reines experiment they detect muons, but no electrons

$\Rightarrow$ the neutrinos coming from pions and kaons have to differ from the neutrinos coming from the reactors.



Particles of the Standard Model:

Fermions



c charm quark: J/ψ

SLAC with detector complex at the right (east) side

BNL: NSLS-II under construction

Burt Richter (SLAC)

Samuel Ting (BNL)

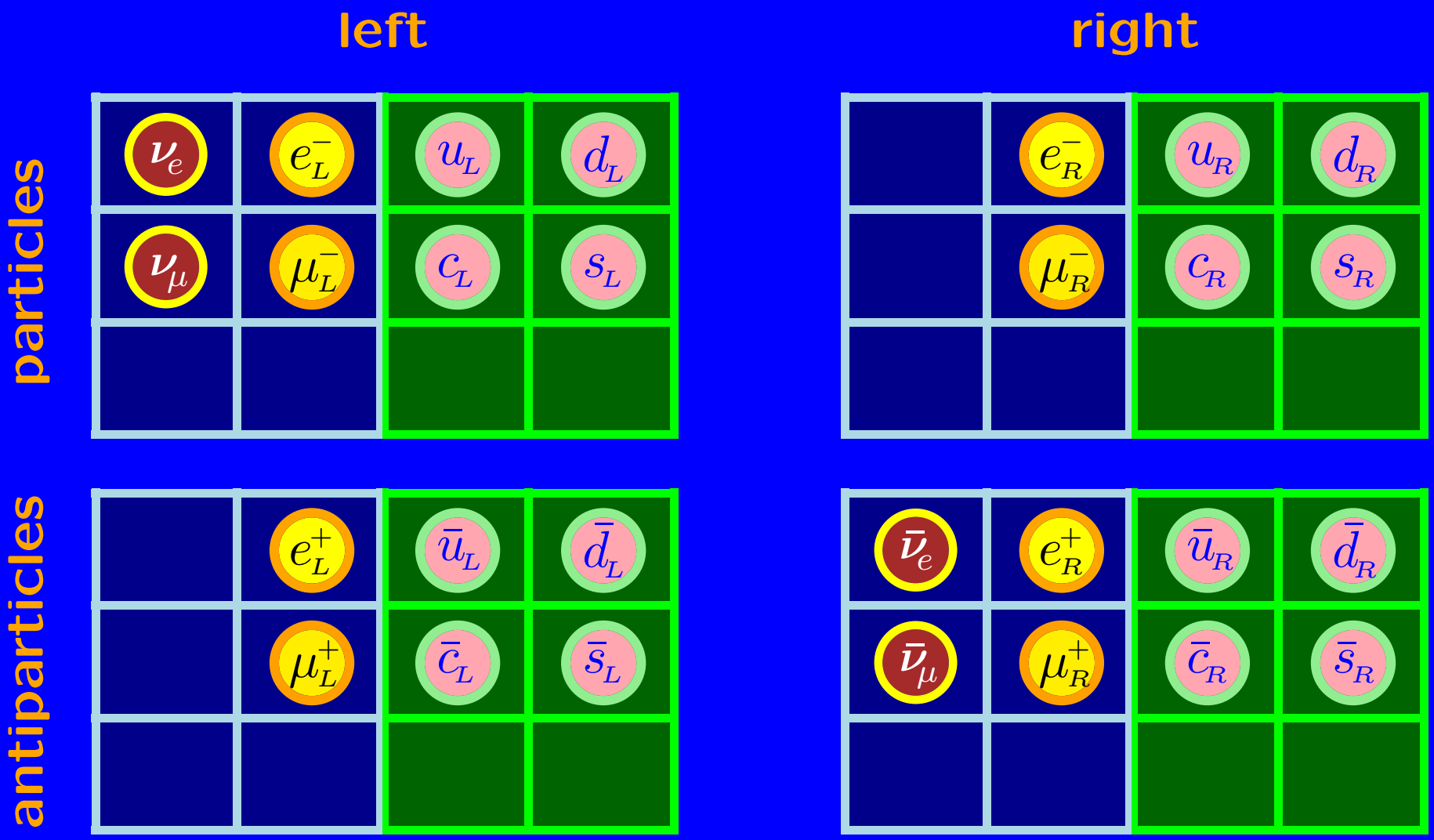
1974

. . 1955 — 1974

γ ν e^- c d

Particles of the Standard Model:

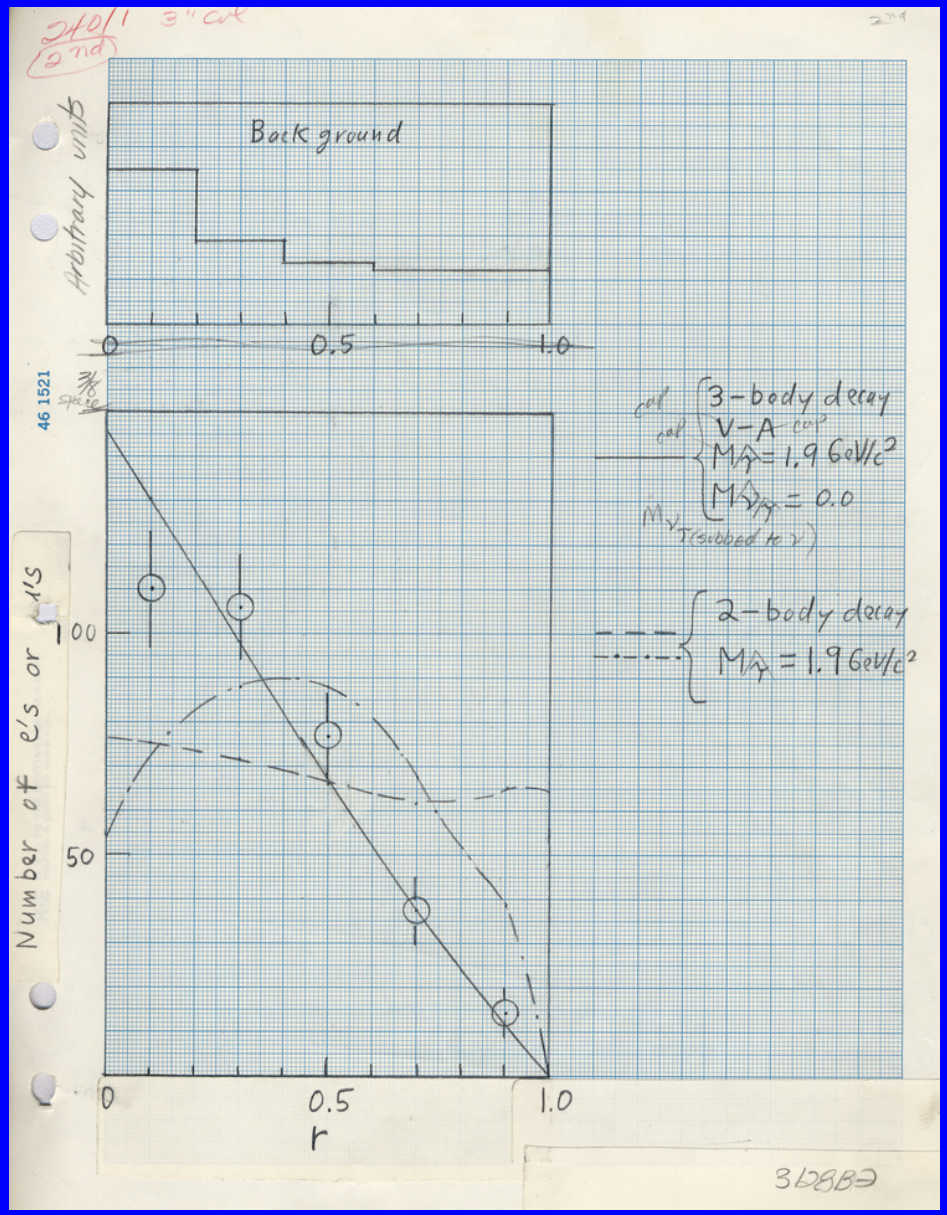
Fermions

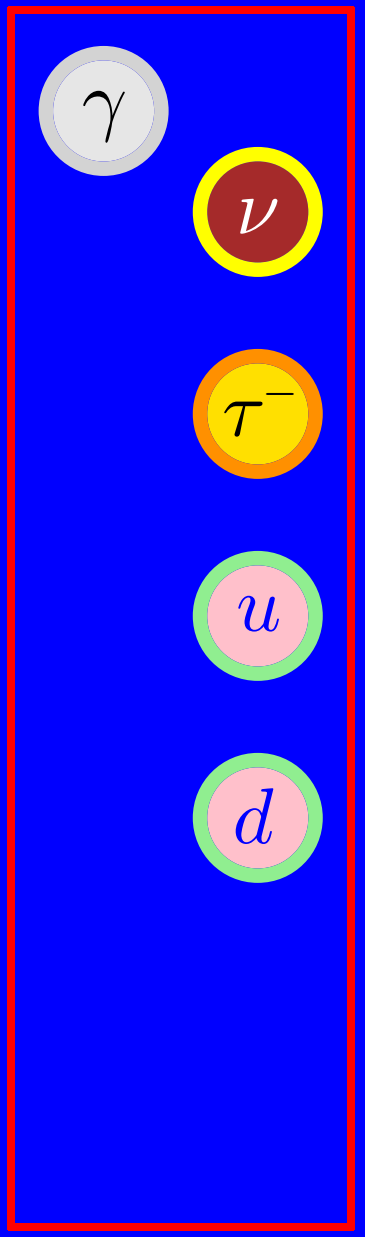


τ lepton

Martin Perl
(SLAC-LBL)
1975

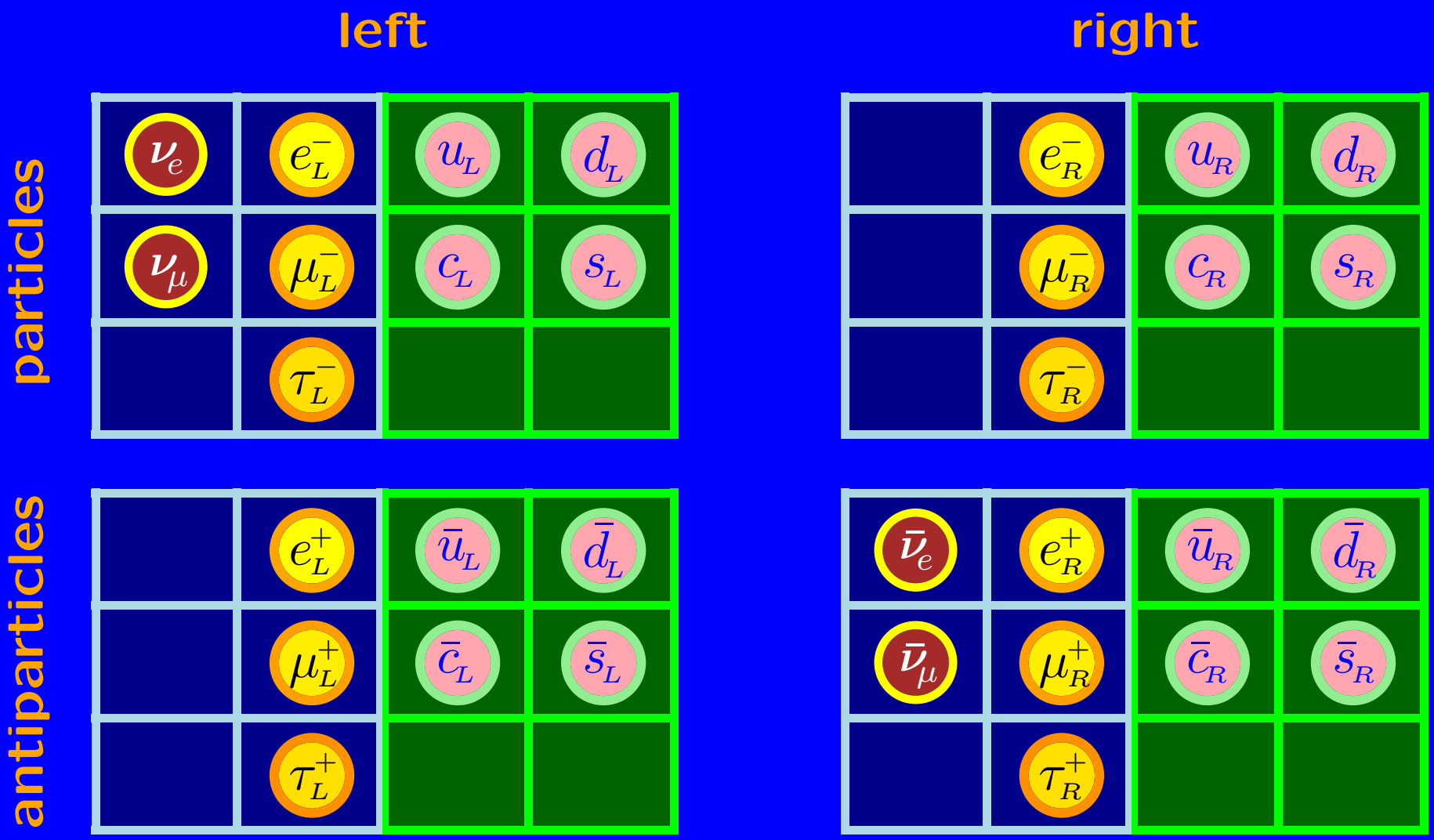
- using Mark I
  (SLAC-LBL Magnetic Detector)
  – first 4π-detector
- comparing **signal** to **background**



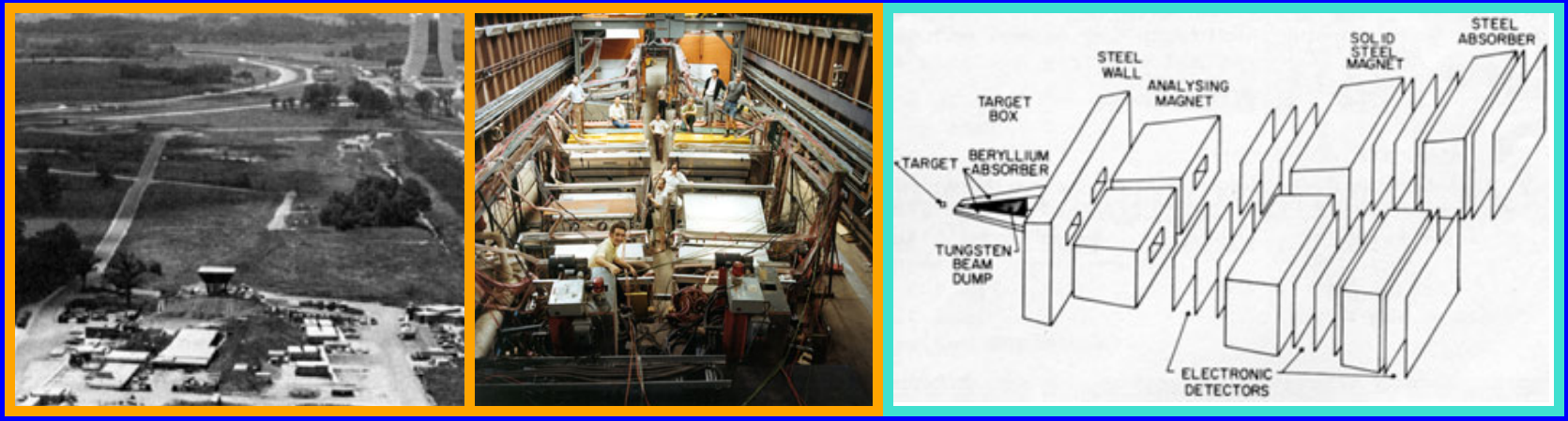


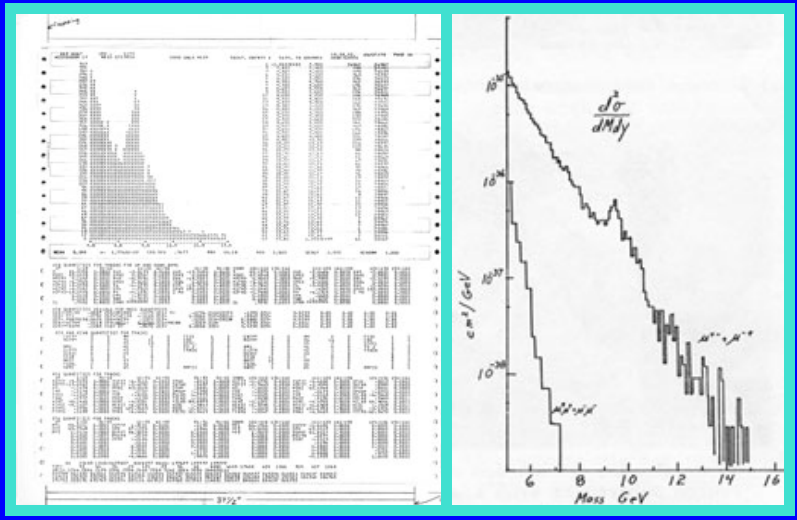
Particles of the Standard Model:

Fermions



b bottom quark: Υ





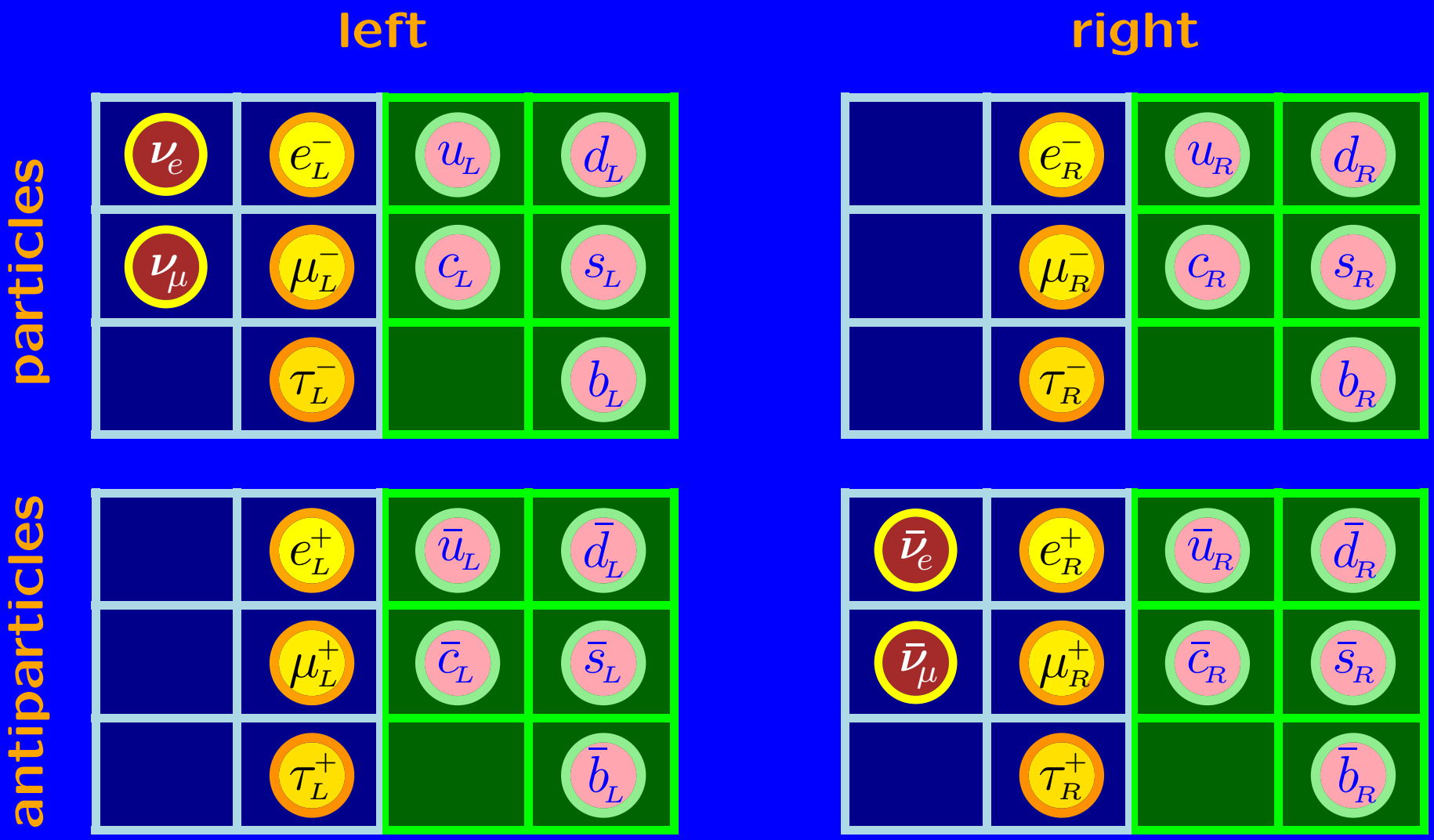
background suppression and computer aided statistical analysis lets the **Fermilab E288** experiment discover the Upsilon meson **1974**

. . 1955 1977

γ ν e^- u b

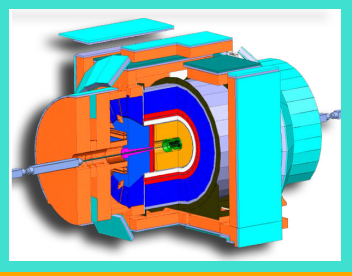
Particles of the Standard Model:

Fermions



t top quark

CDF



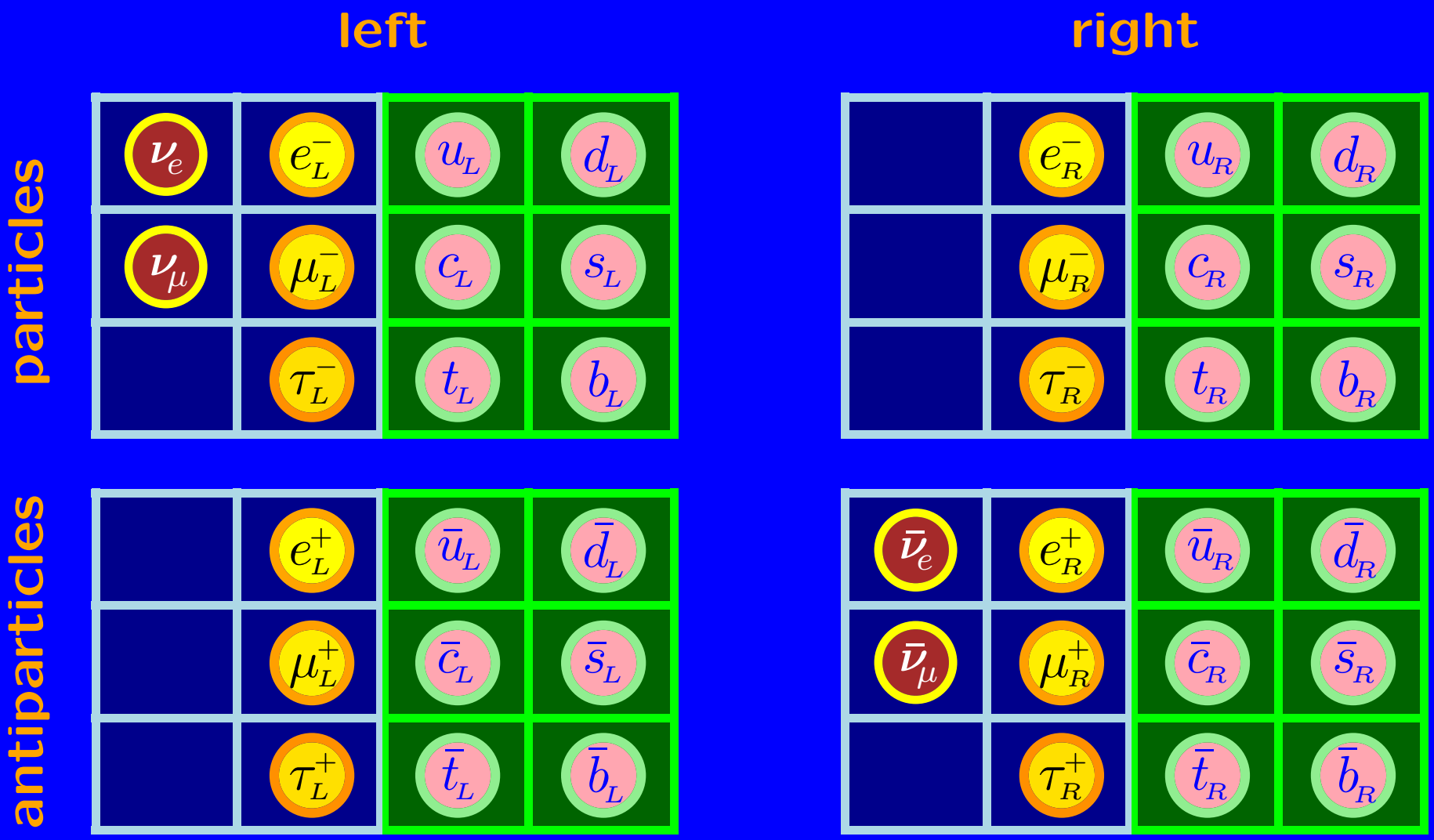
DØ

γ ν_τ W τ^- Z t g b

. . 1955 1995

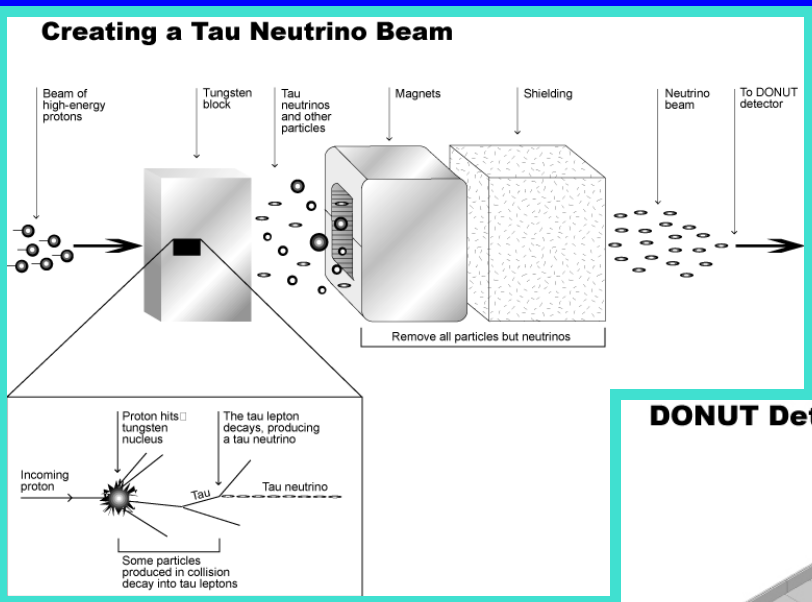
Particles of the Standard Model:

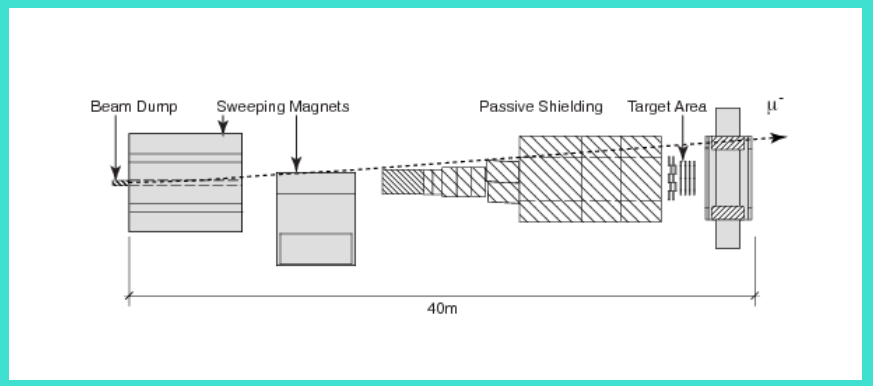
Fermions

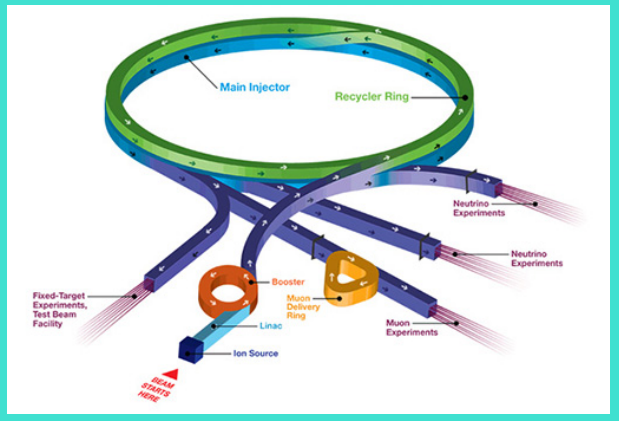


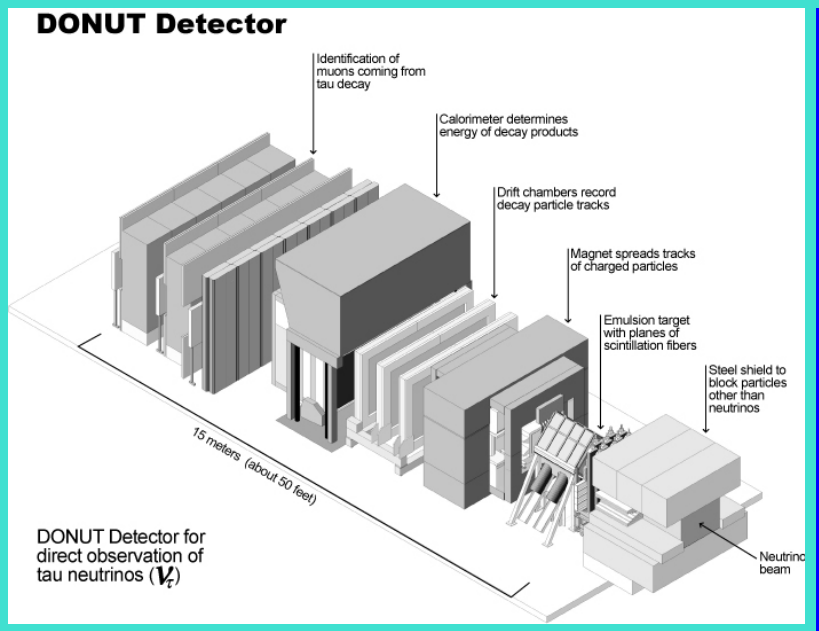
tau neutrino

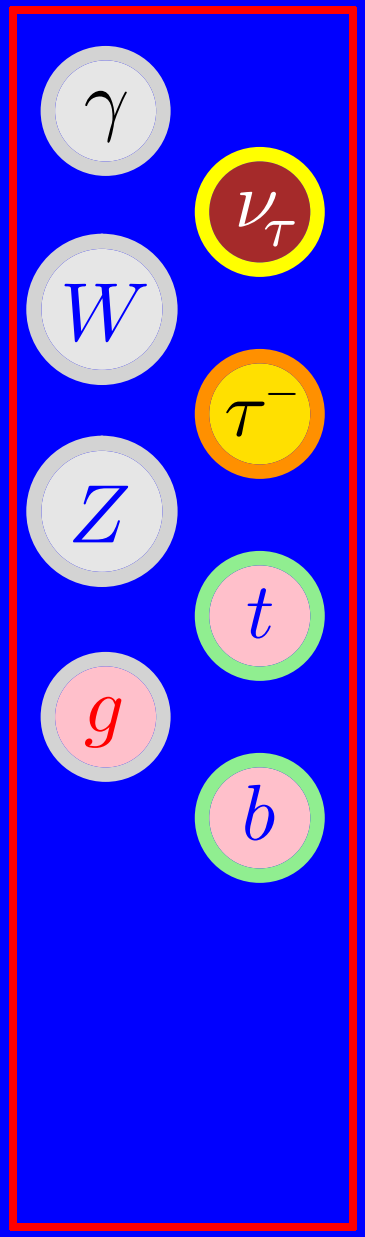
Discovery by the DONUT collaboration (E872 Fermilab)





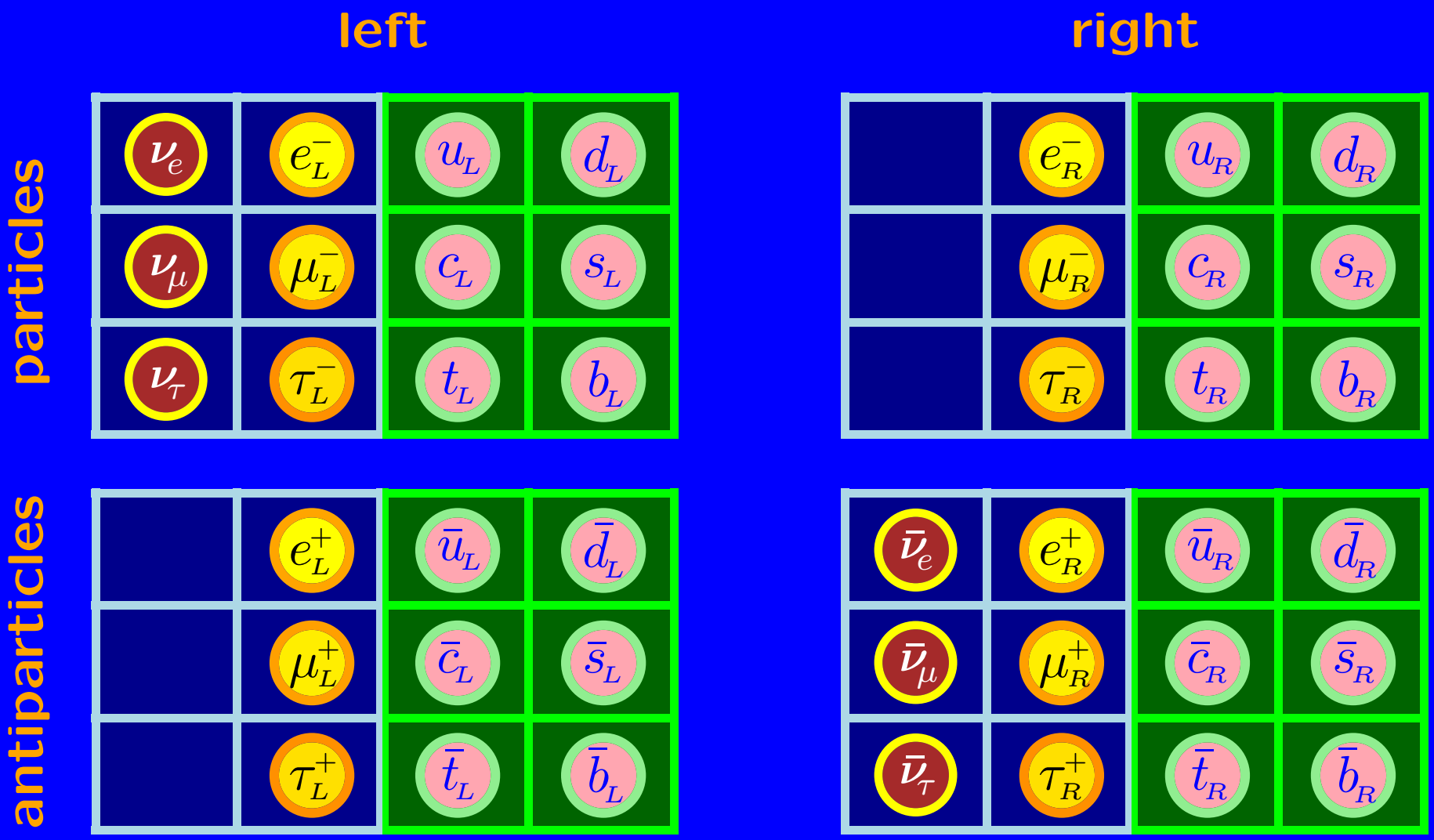


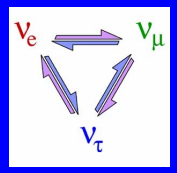




Particles of the Standard Model:

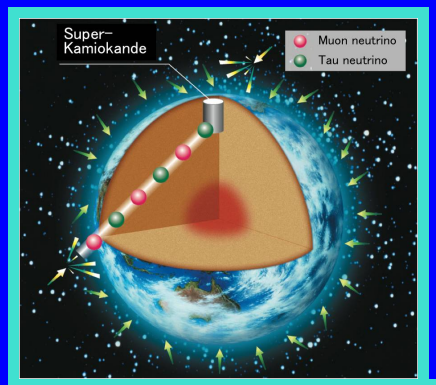
Fermions





neutrino oscillations

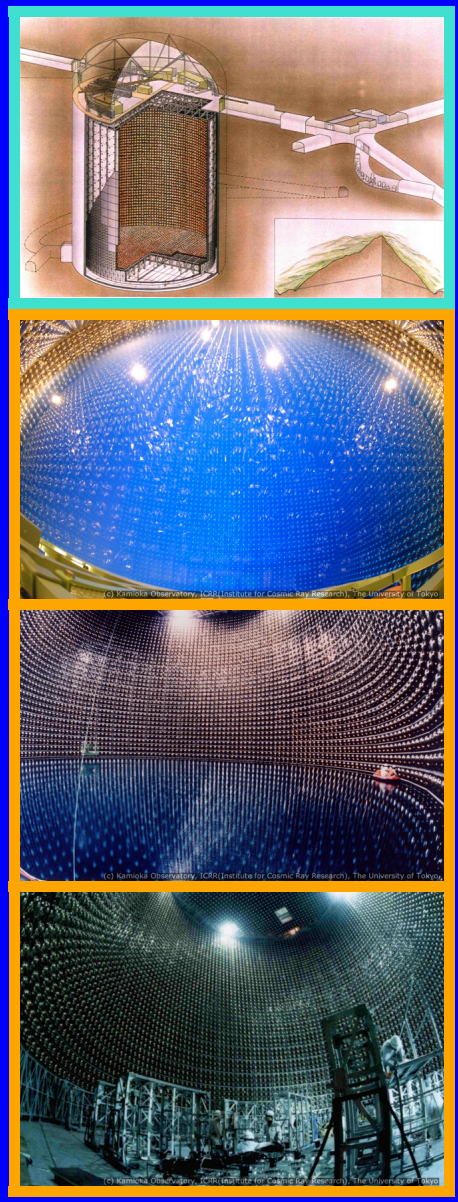
1957 predicted by **B. Pontecorvo**

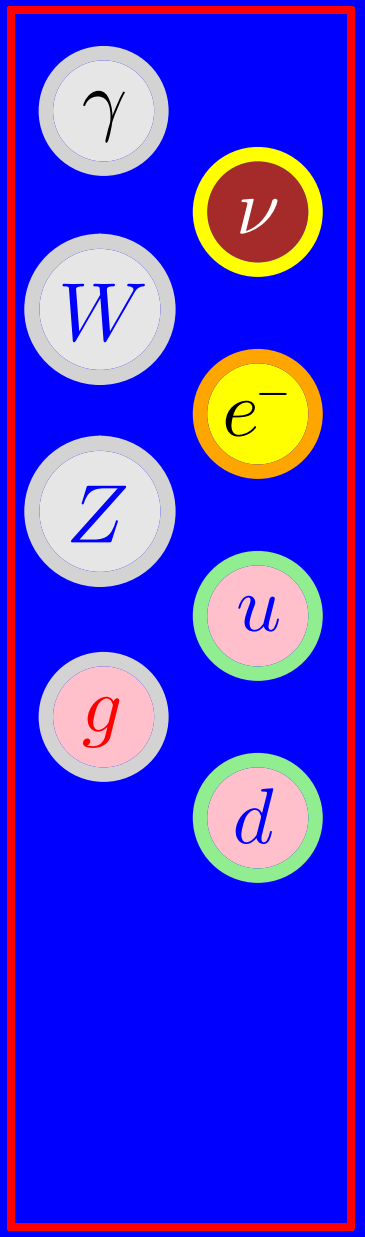


Super Kamiokande (SK) announces first experimental evidence for **atmospheric neutrino oscillations** in **1998**

Sudbury Neutrino Observatory (SNO) provides clear evidence of neutrino flavor change in solar neutrinos in **2001**

only then the solar neutrino puzzle was solved





. . . 1957 1998 2001

Neutrino oscillations: $\nu_e \longleftrightarrow \nu_\mu \longleftrightarrow \nu_\tau$

★ solve the solar neutrino puzzle

→ neutrinos have a tiny mass

↳ there exist also right-handed neutrinos ν_{eR}

★ but they have

★ no charge, no hypercharge, and no color

↳ no interaction except the mass-term

→ their existence does not change

(the predictions of) the Standard Model !

Particles of the Standard Model:

Fermions