Introduction to Particle Physics

- The Particle Zoo
- Symmetries
- The Standard Model

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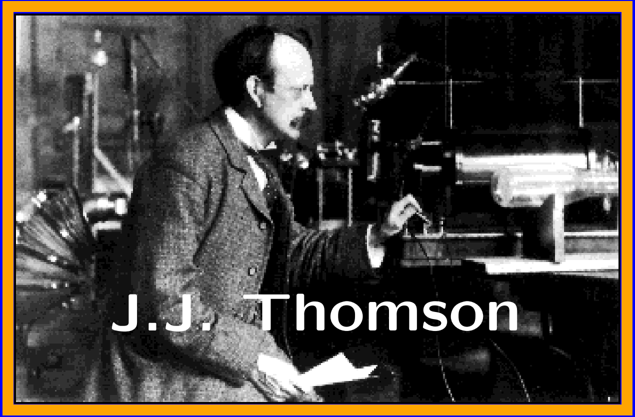
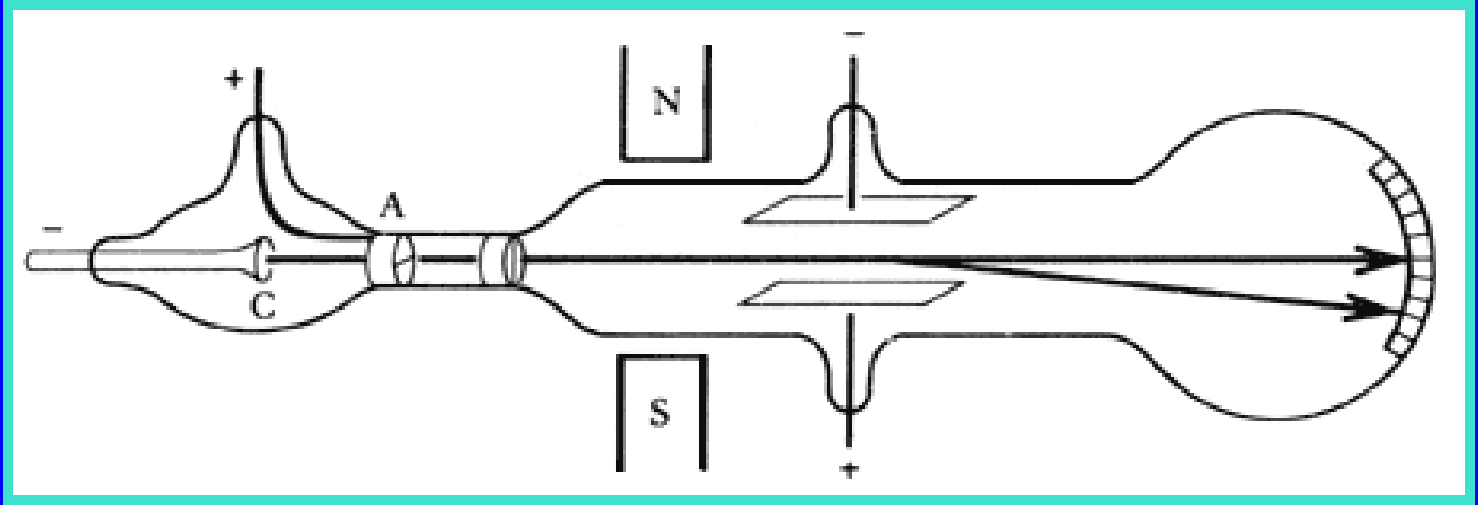
The Particle Zoo

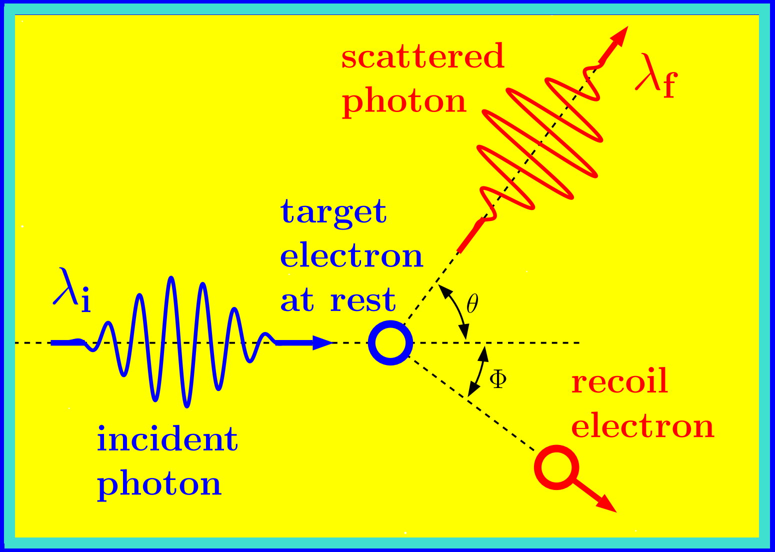
e^- the electron

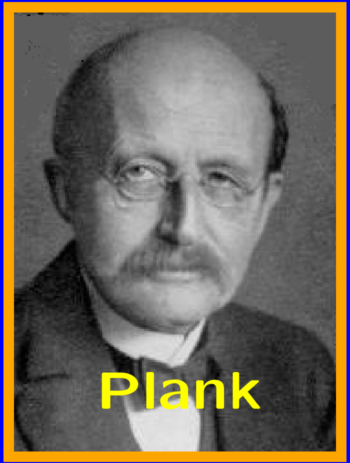




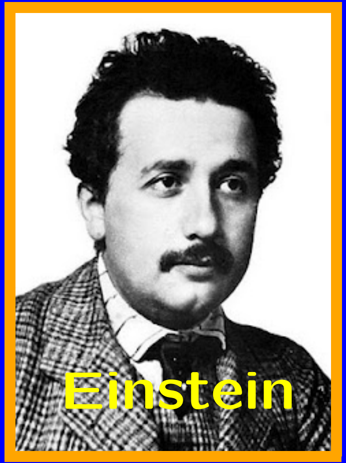
1897

γ the photon

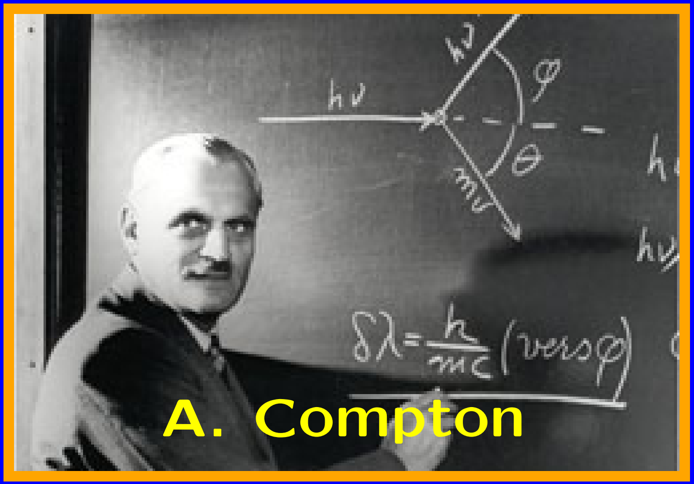




Plank



Einstein



A. Compton

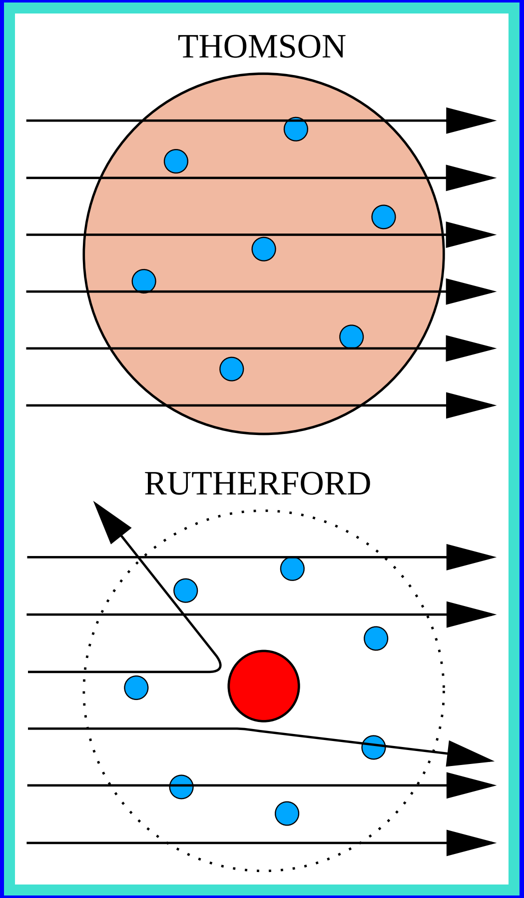
e^-

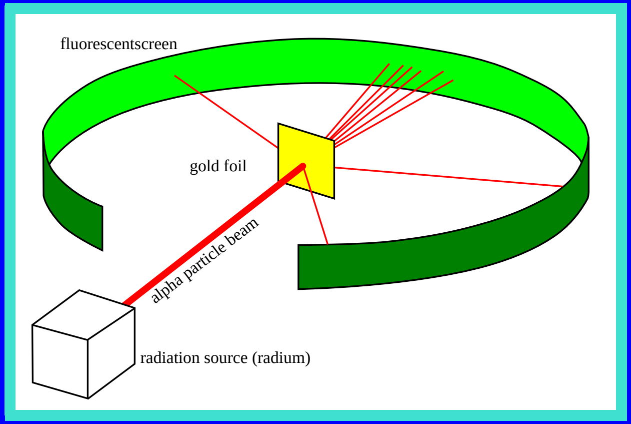
1897 1900 – 1924

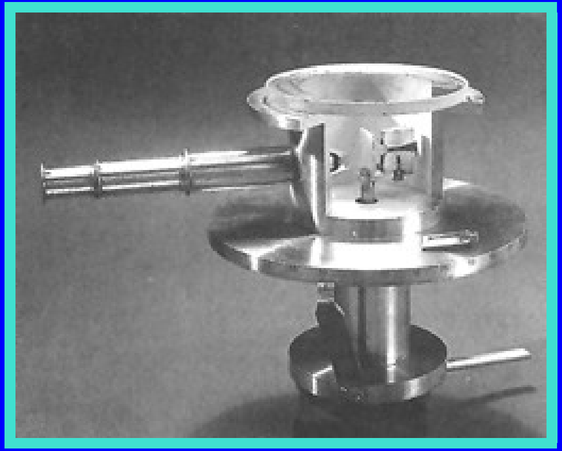
p the proton – the atomic nucleus

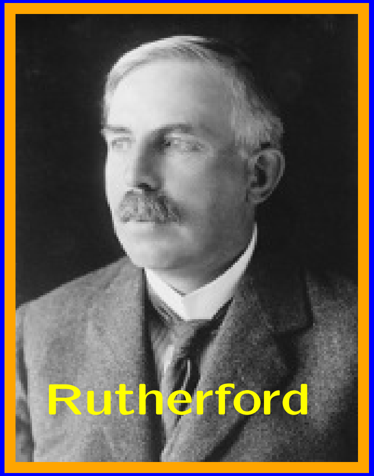
e^-

γ





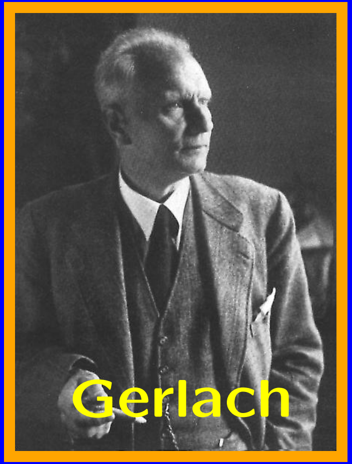


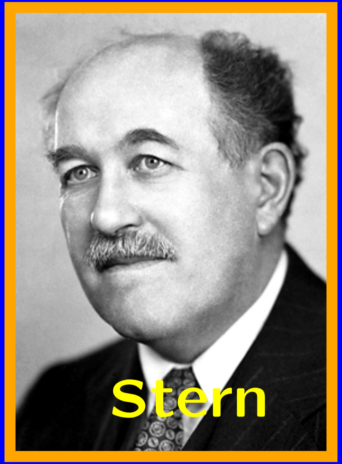


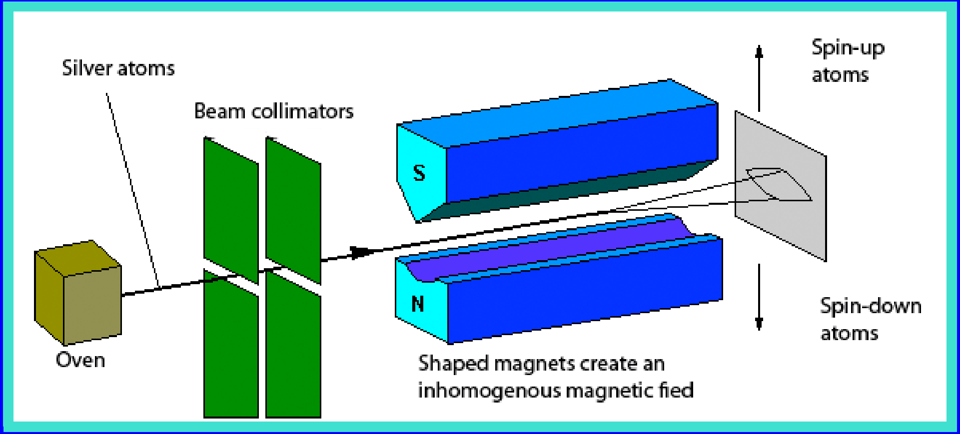
1897

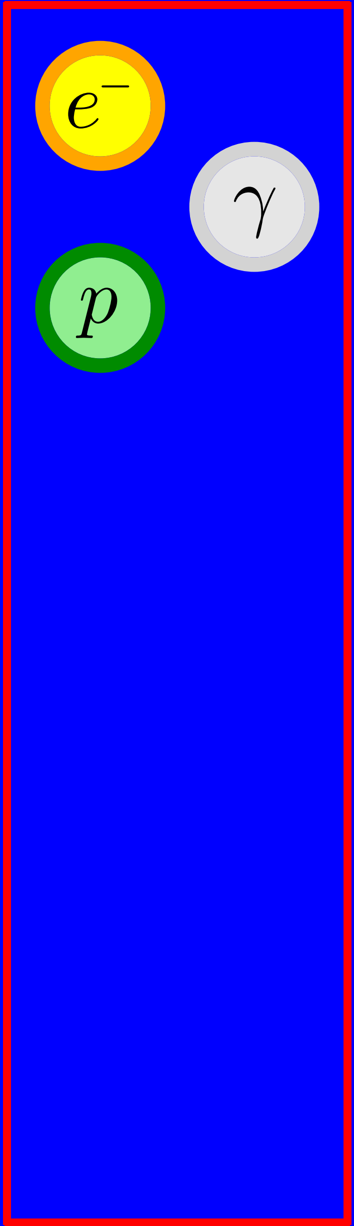
1914

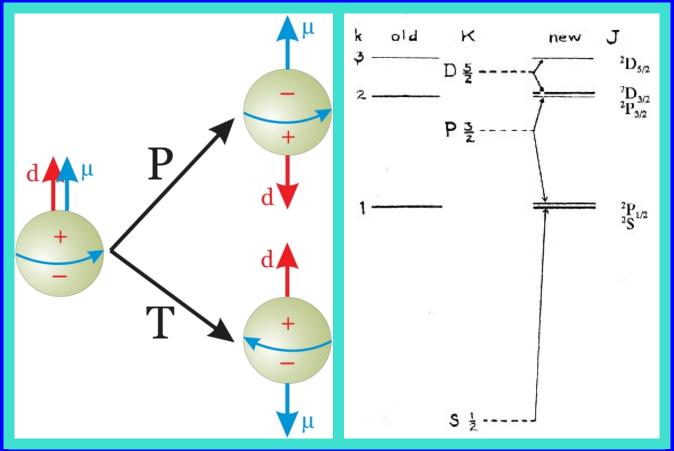
Stern-Gerlach experiment → Spin

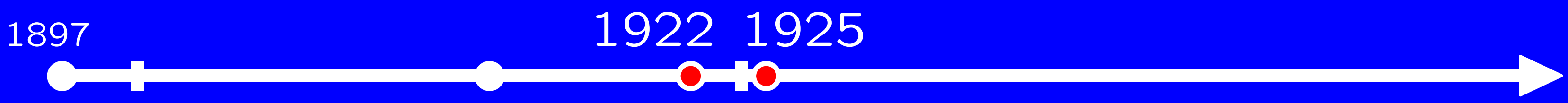




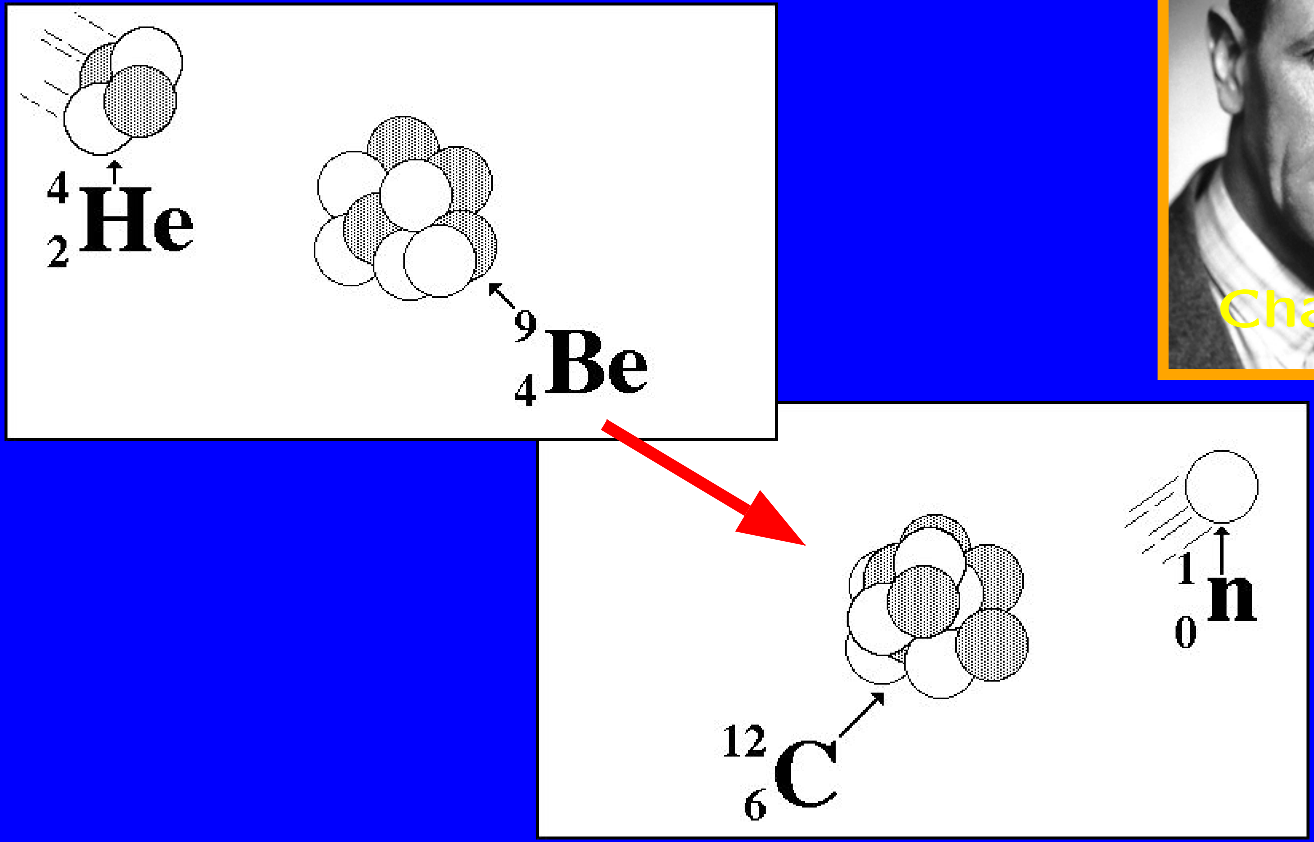


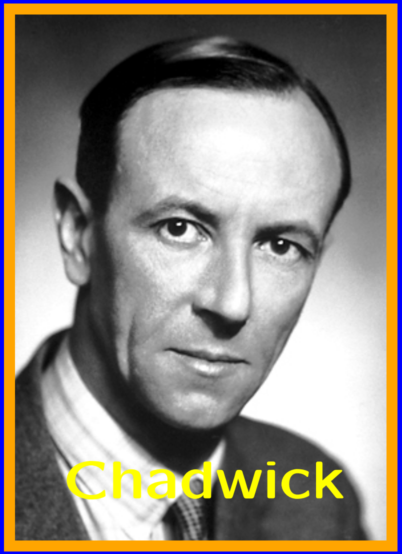


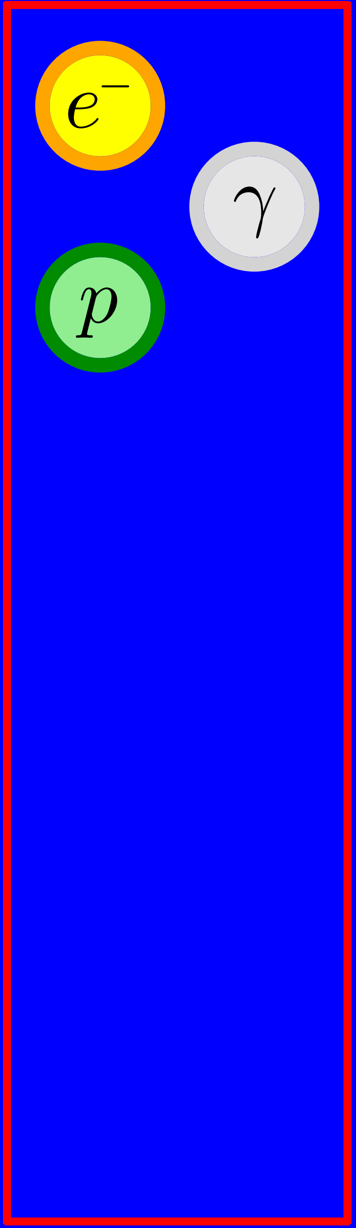


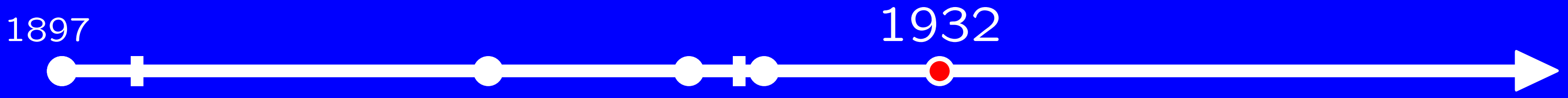


n the neutron



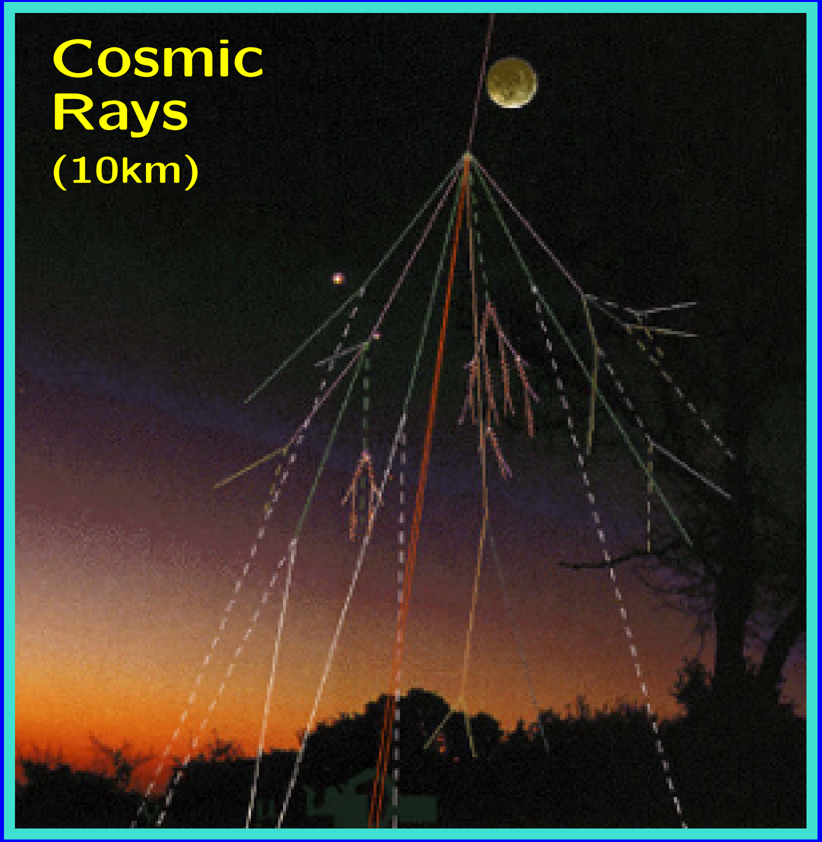


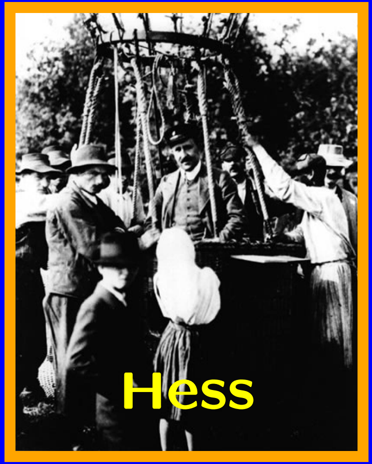


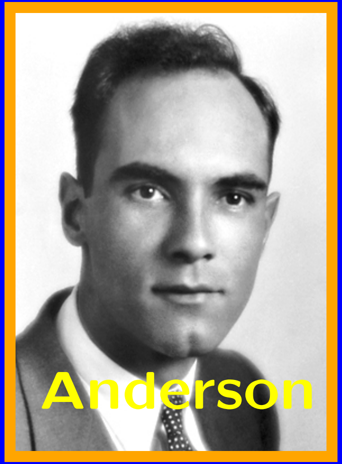


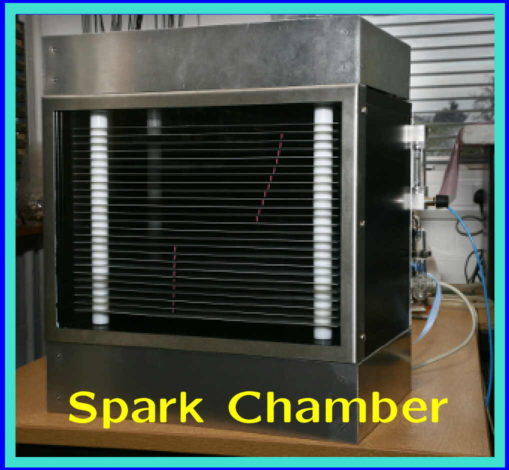
μ^- the muon

Raby: ”Who ordered that one?”

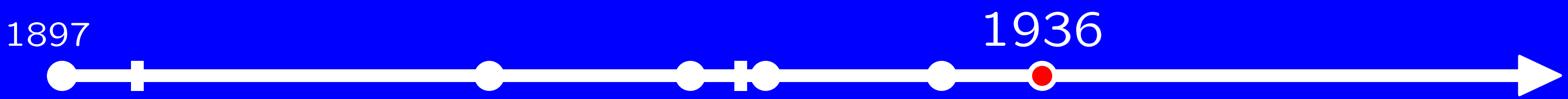




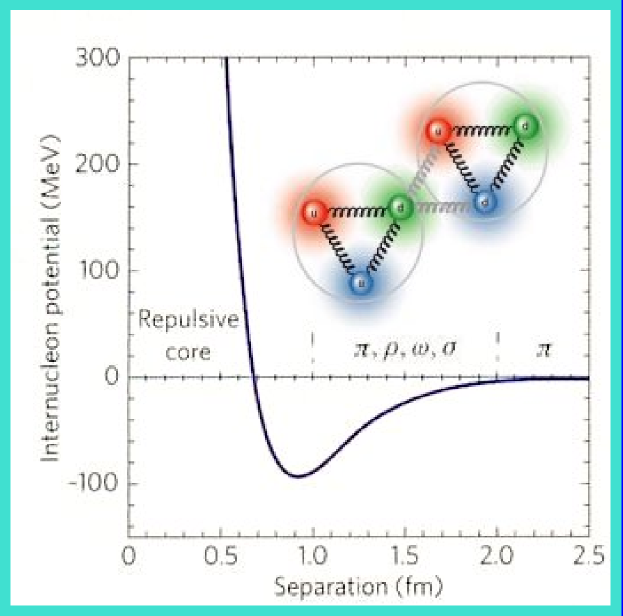


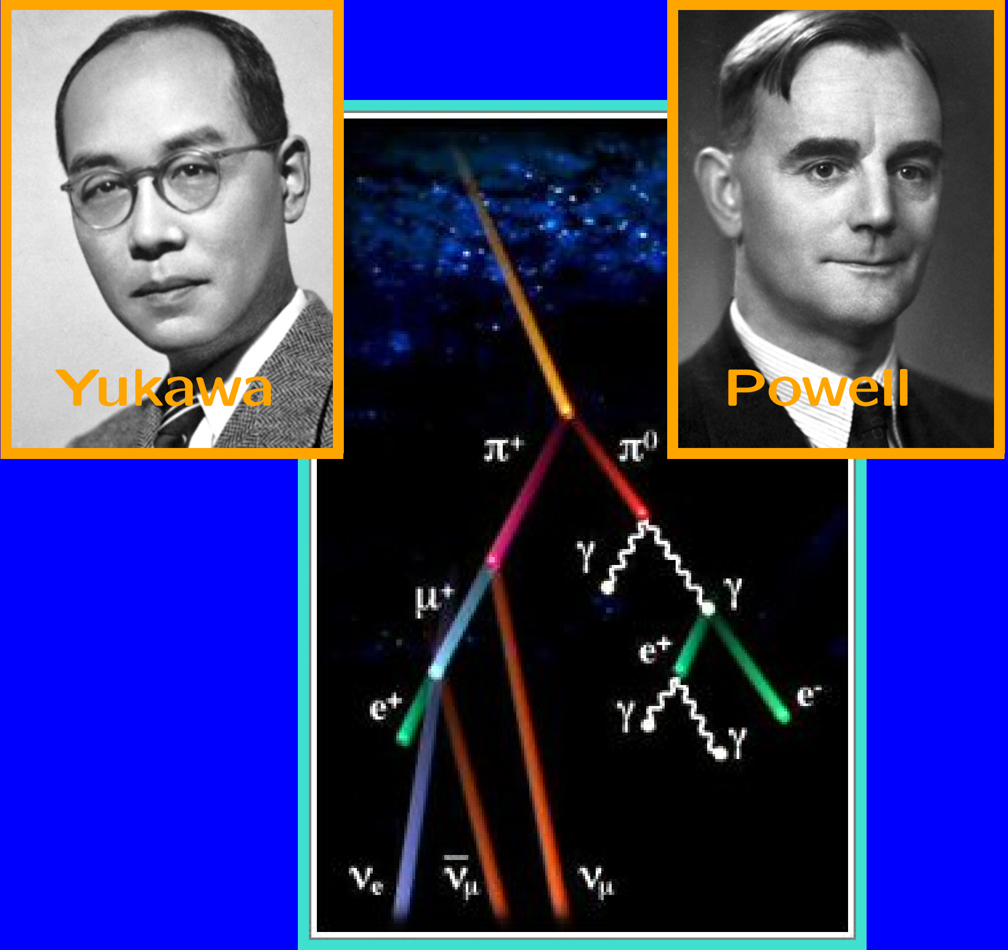


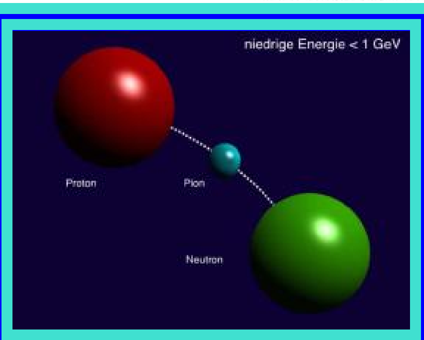
e^- γ p n

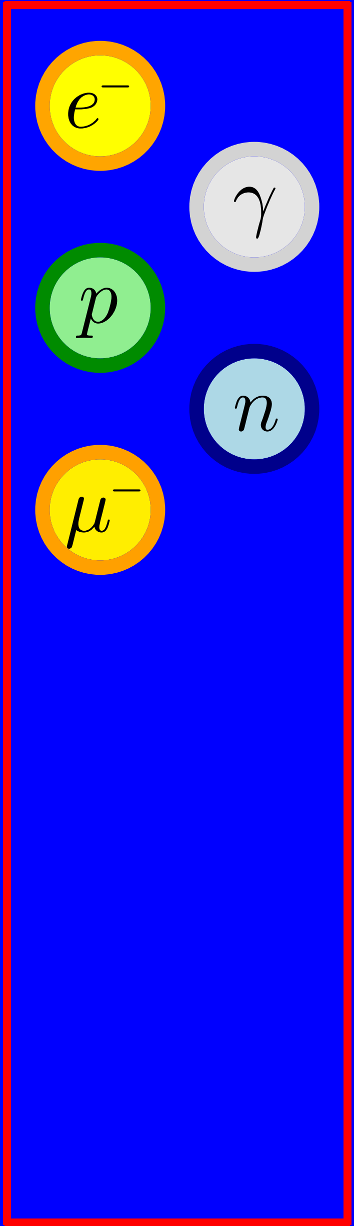


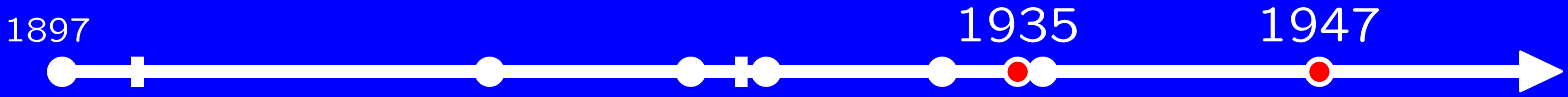
π the pion


300
200
100
0
-100
Internucleon potential (MeV)
0
0.5
1.0
1.5
2.0
2.5
Separation (fm)
Repulsive core
$\pi, \rho, \omega, \sigma$
π
u
d

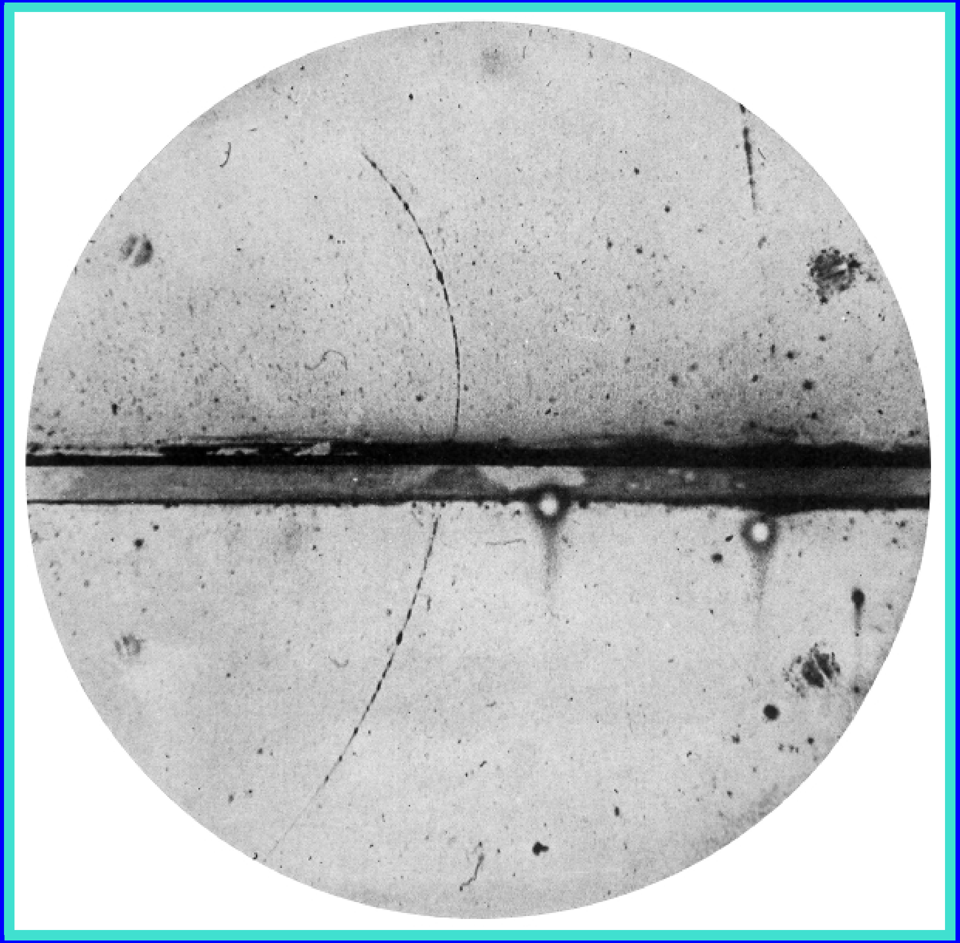

Yukawa
Powell
π^+
π^0
γ
γ
μ^+
e^+
e^+
γ
γ
e^-
ν_e
$\bar{\nu}_\mu$
ν_μ


niedrige Energie < 1 GeV
Proton
Pion
Neutron

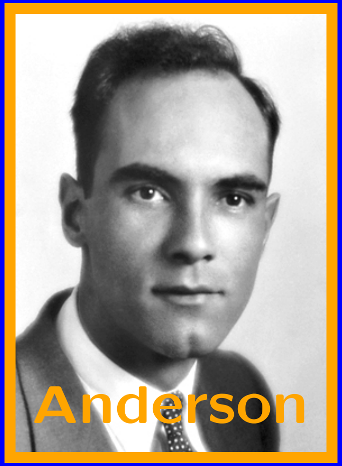

e^-
γ
p
n
μ^-


1897
1935
1947

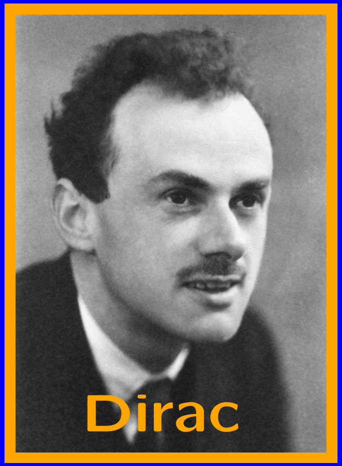
e^+ the positron



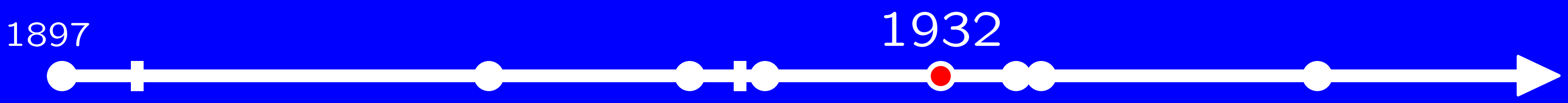
Discovery



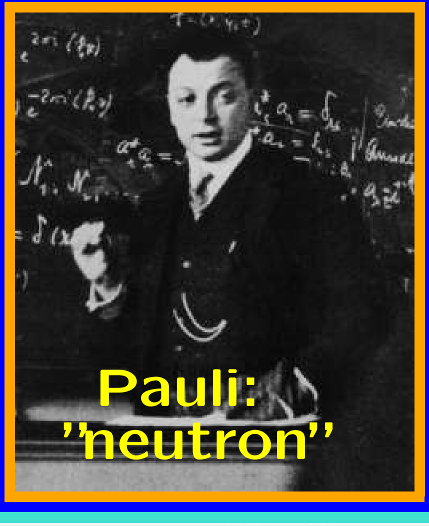
Prediction

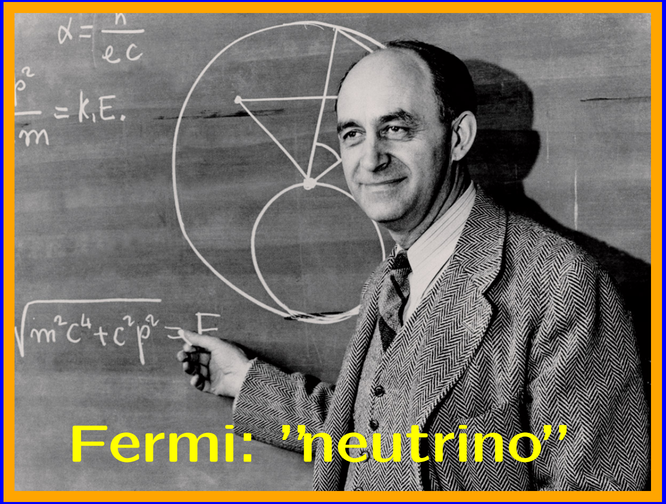


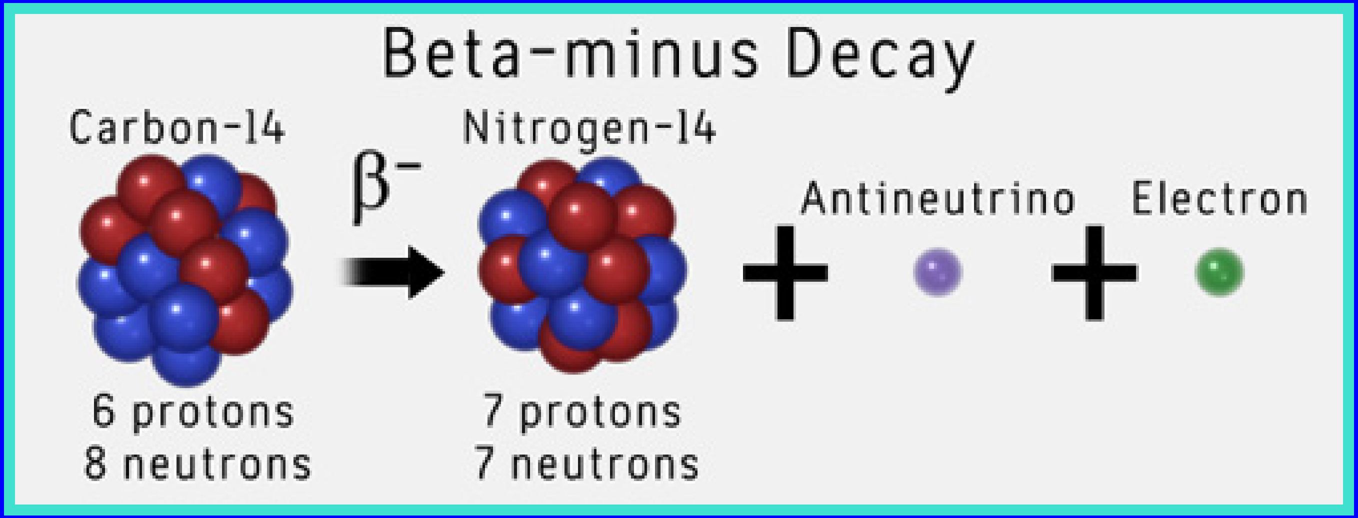
e^- γ p n μ^- π



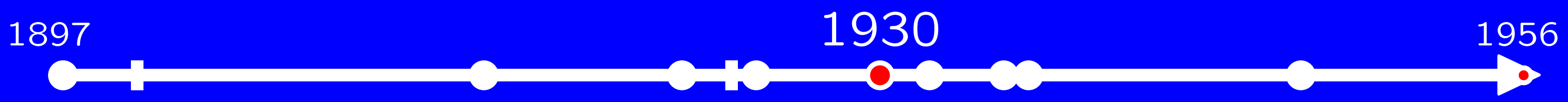
ν the neutrino – theory prediction





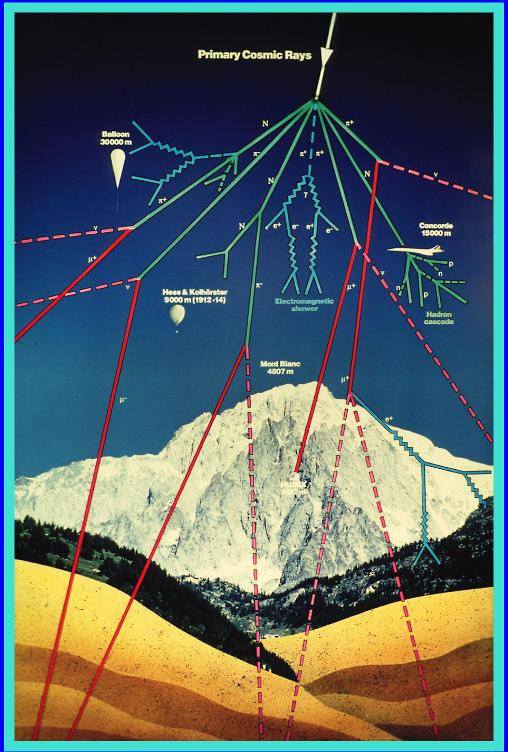


e^- γ p n μ^- π e^+

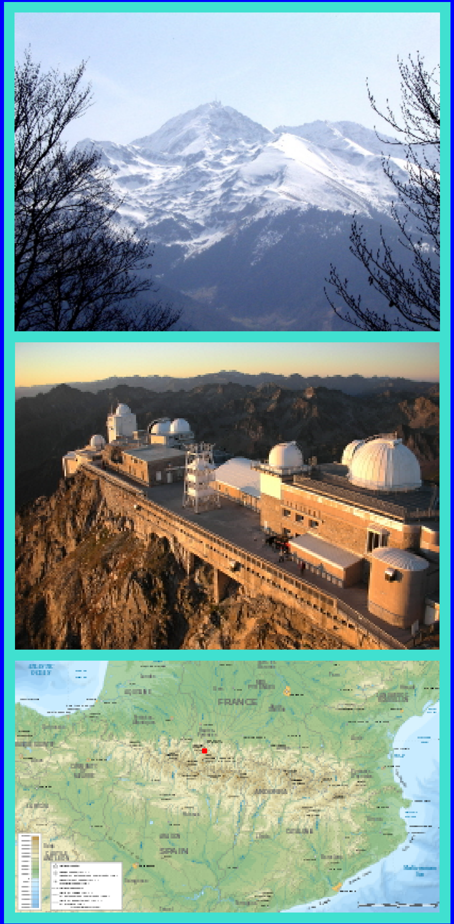


K strange particles

Λ Σ



Pic du Midi

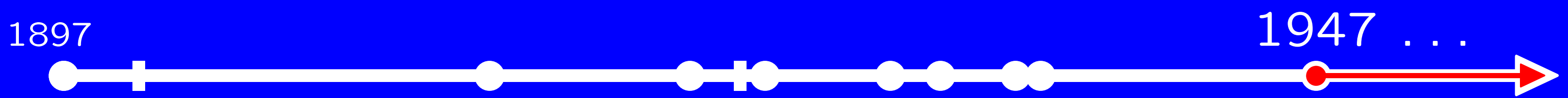


K: **Rochester** and **Butler**
(Univ. of Manchester)

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

particles in a cloud chamber

e^- γ p n μ^- π e^+ ν

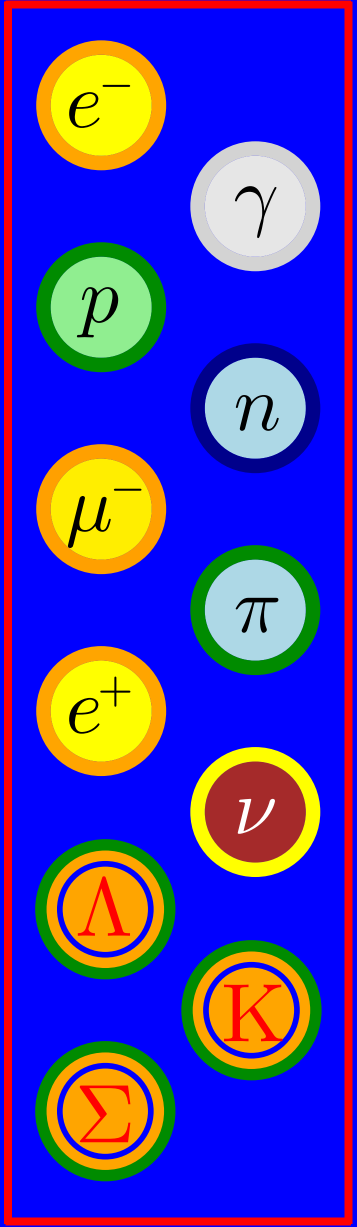


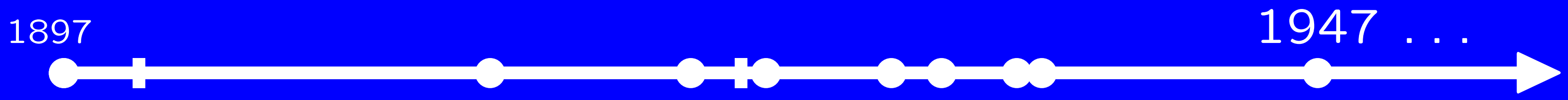
Willis E. Lamb, Jr.

Fine structure of the hydrogen atom

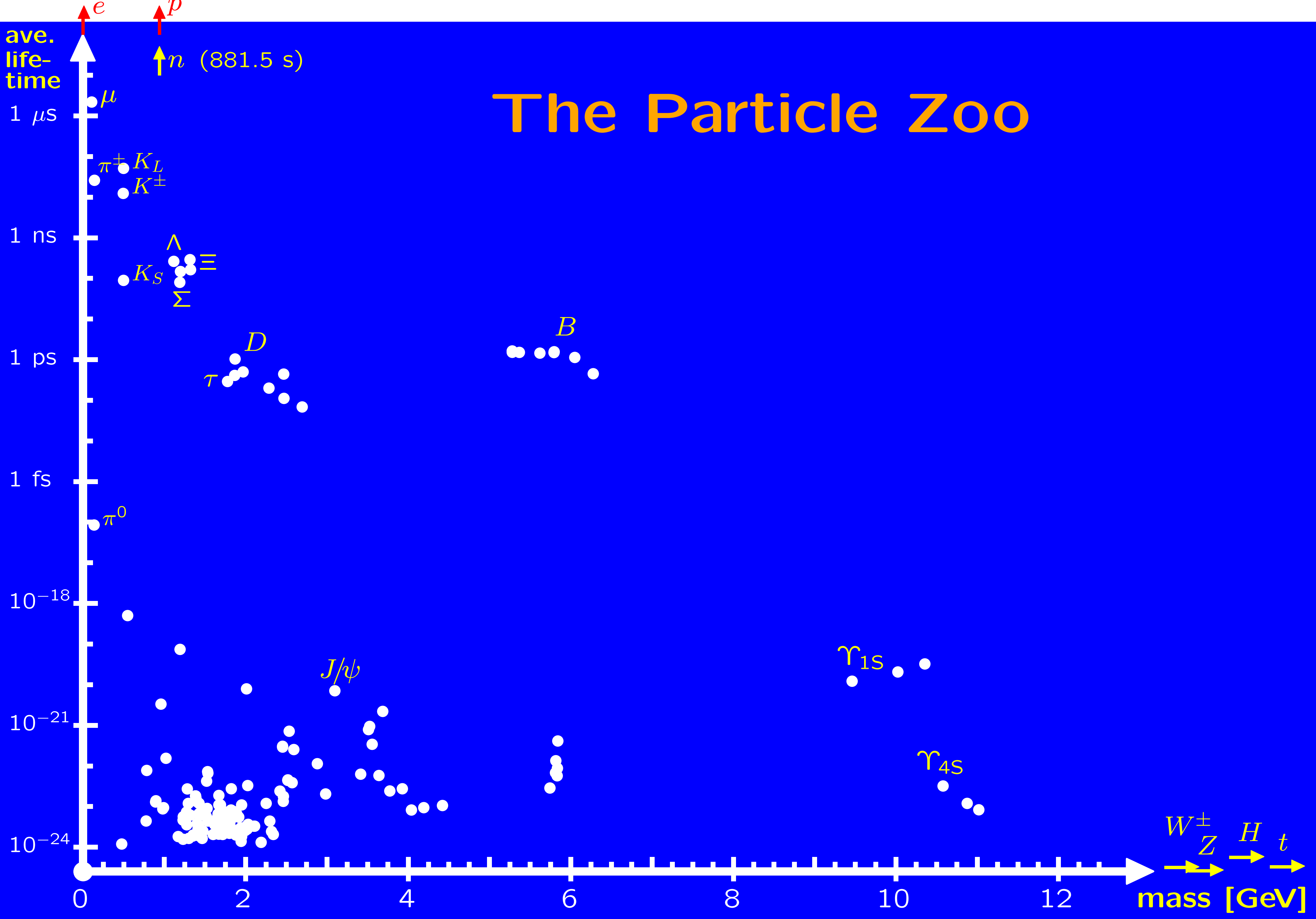
Nobel Lecture, December 12, 1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called «elementary particles»: the electron and the proton. A deluge of other «elementary» particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. **I have heard it said that «the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine».**





The Particle Zoo



Looking for some order in this ”chaos” . . .

1. properties of particles:

- order by **mass** (approximately, rather to be seen historically):

leptons	(Greek: ”light”)	electrons, muons, neutrinos, . . .
mesons	(”medium-weight”)	pions, kaons, . . .
baryons	(”heavy”)	protons, neutrons, lambda, . . .

- order by **charge**:

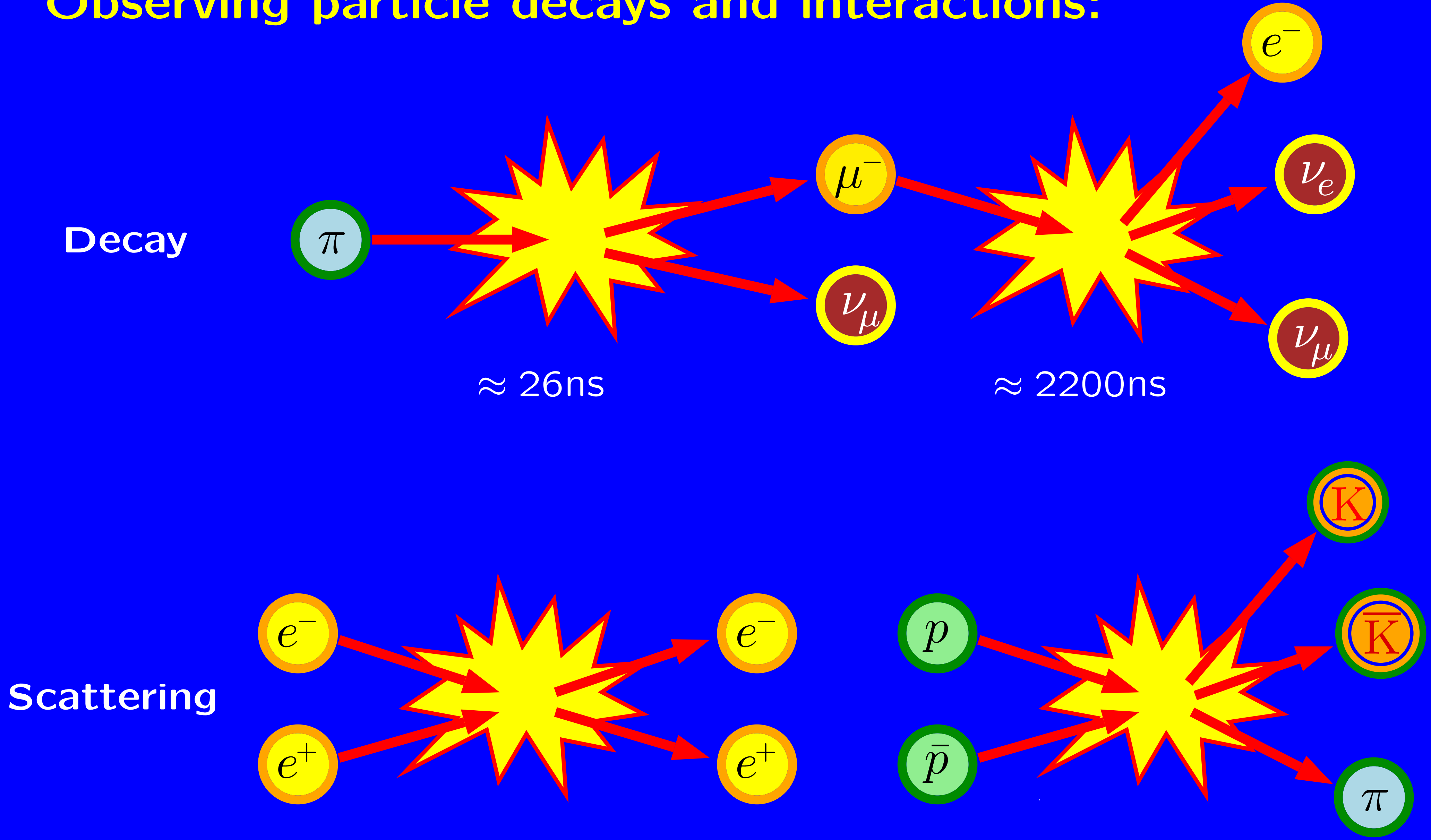
neutral	neutrons, neutrinos, photons, . . .
±1 elementary charge	proton, electron, muon, . . .
±2 elementary charge	Δ^{++}, Σ_c^{++}, . . .

- order by **spin**:

fermions	(spin $\frac{1}{2}$, $1\frac{1}{2}$, . . .)	electrons, protons, neutrinos, . . .
bosons	(spin 0, 1, . . .)	photons, pions, . . .

- order by **”strangeness”**, **parity**, . . .

Observing particle decays and interactions:



Decay

≈ 26ns

≈ 2200ns

Scattering

Looking for some order in this "chaos" . . .

2. conservation laws for particles:

- conservation of **energy**:

  $n \to p + \ldots$ but not $\pi^0 \to \pi^\pm + \ldots$

- conservation of **charge**:

  $n \to p + e^- + \ldots$ but not $n \to p + e^+ + \ldots$

- conservation of **lepton number**:

  $n \to p + e^- + \bar{\nu}_e$ but not $n \to p + e^- + \nu_e$

- conservation of **baryon number**:

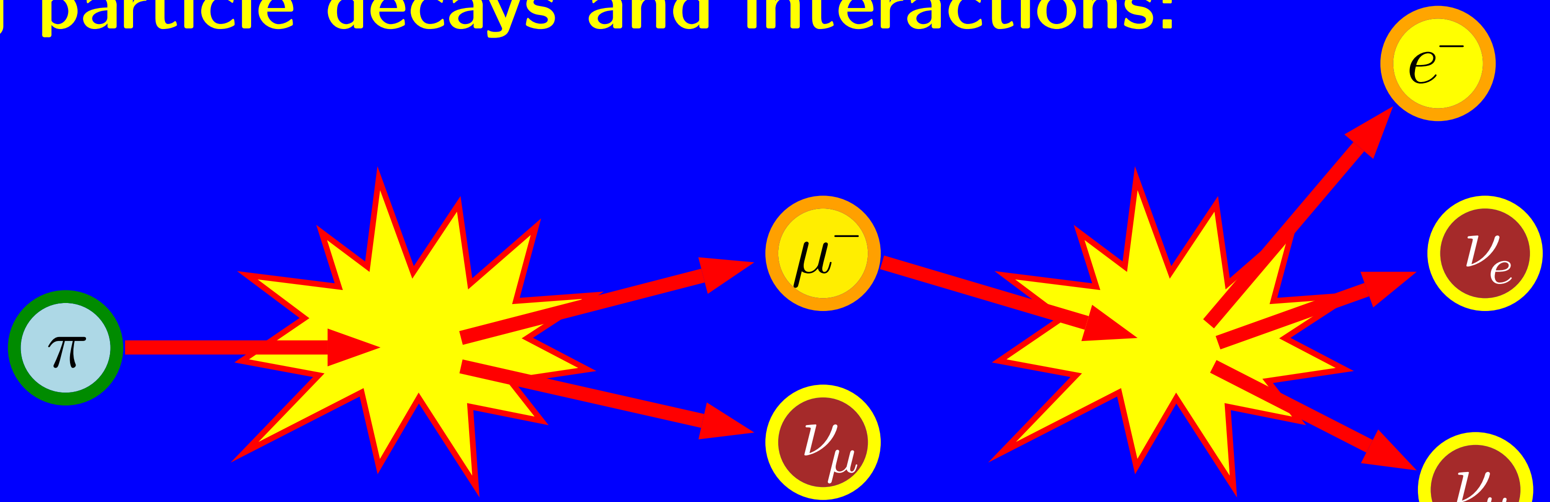
  $n \to p + \ldots$ but not $n \to \pi^+ + \pi^- + \ldots$

- conservation of **strangeness** (only in "fast" processes):

  fast $K^* \to K + \pi$ but only "slow" $K \to \pi + \pi$

Observing particle decays and interactions:

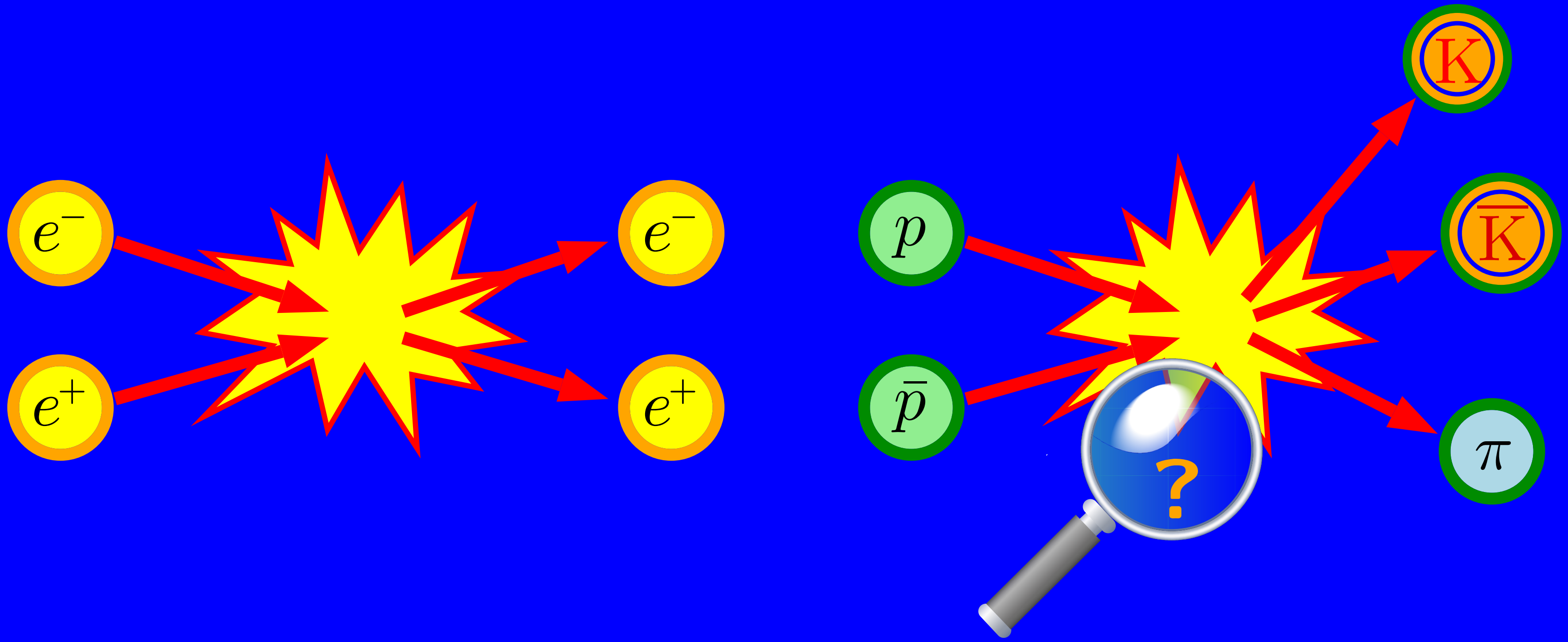
Decay



$\approx$ 26ns

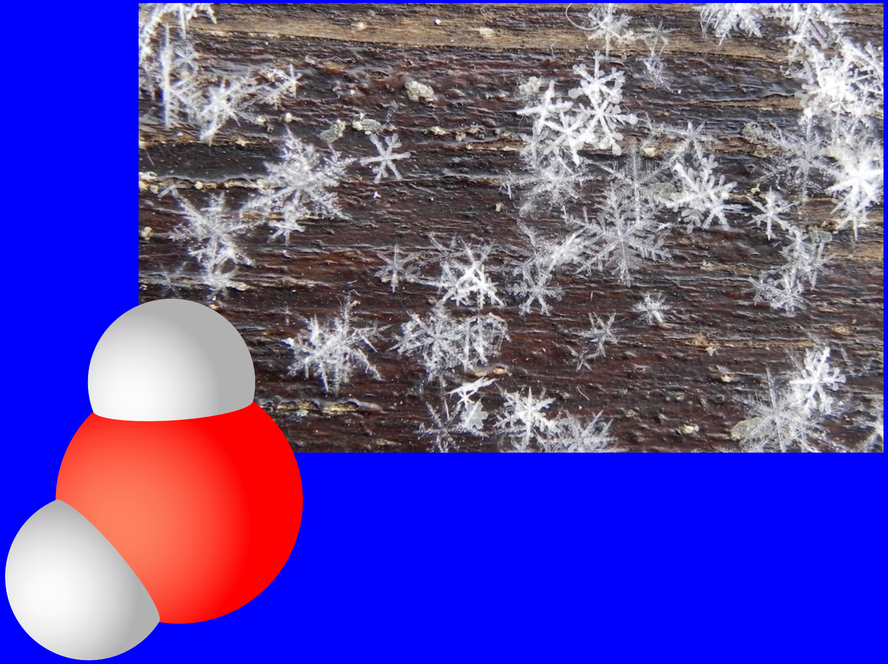
$\approx$ 2200ns

Scattering



Symmetries & where do we find them?

→ **everywhere in nature:**



- **snowflakes exhibit a 6-fold symmetry**

- **crystals build lattices**

→ **symmetries of the microcosm are also visible in the macrocosm**

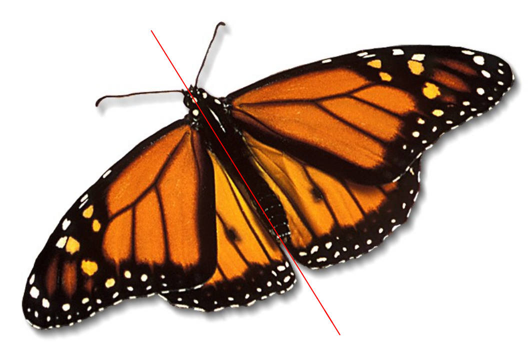
How do symmetries look like in theory?

★ symmetries are described by symmetry transformations:

Example 1: Butterfly

symmetry transformation S_0:

mirror all points at a line



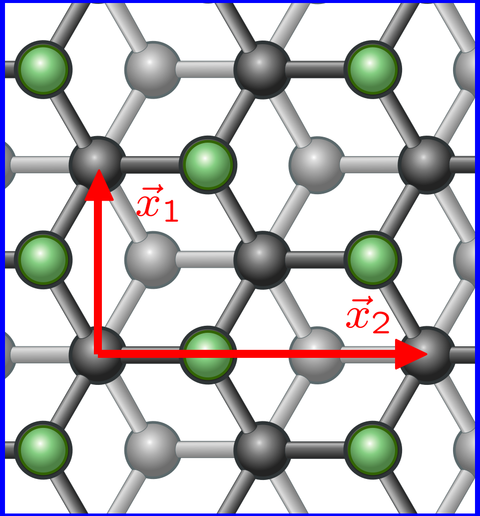
formally: $W =$ ''original picture'' $\Rightarrow$ $W' =$ ''mirrored picture''

apply symmetry in operator notation: $S_0 W = W'$

a symmetry is given <u>if and only if</u> $S_0 W = W$!

How do symmetries look like in theory?

★ symmetries are described by symmetry transformations:



Example 2: crystal lattice

symmetry transformations S_i:

move all points

by the same vectors ($\vec{x}_1$ or $\vec{x}_2$)

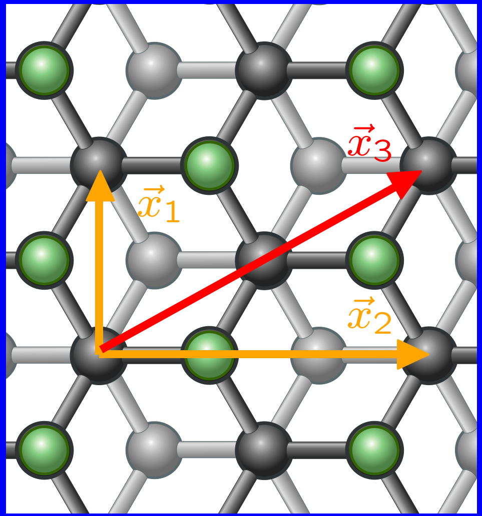
formally: $W =$ "original picture" $\Rightarrow$ $W' =$ "moved picture"

apply symmetry in operator notation: $S_i W = W'$

a symmetry is given <u>if and only if</u> $S_i W = W$!

How do symmetries look like in theory?

★ symmetry transformations form **group structures**



Example: translations

symmetry transformations S_1 and S_2:

move all points

by the same vector ($\vec{x}_1$ or $\vec{x}_2$)

movement of all points by the vector

$$\vec{x}_3 = \vec{x}_1 + \vec{x}_2$$

is also a symmetry transformation !

$$S_3 = S_1 \circ S_2$$

Groups, mathematically:

a **group** $(G, \circ)$ is a **set** $G = \{a, b, c, \dots\}$ with a **binary operation** $\circ$ that fulfills (the axioms)

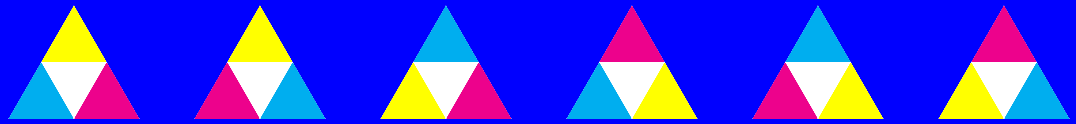
- **closure:** $c = a \circ b \in G \quad \Leftrightarrow \quad a, b \in G$
- **associativity:** $(a \circ b) \circ c = a \circ (b \circ c)$
- **identity:** $\exists\, e$ with $a \circ e = e \circ a = a \quad \forall a \in G$
- **inverse:** $\forall a \in G \quad \exists\, b = a^{-1}$ (the inverse)
  with $a \circ b = b \circ a = e$

an **Abelian group** fulfills an additional relation

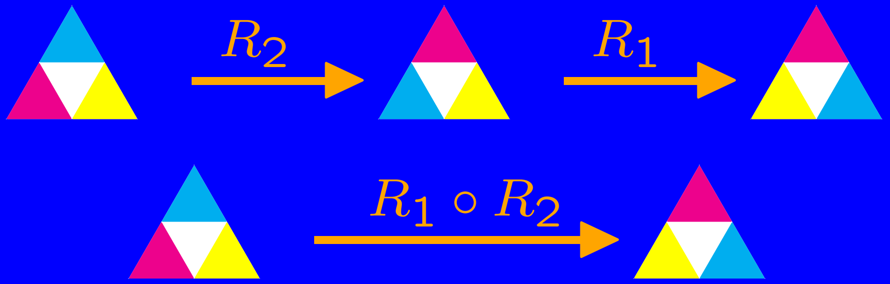
- **commutativity:** $a \circ b = b \circ a \quad \forall a, b \in G$

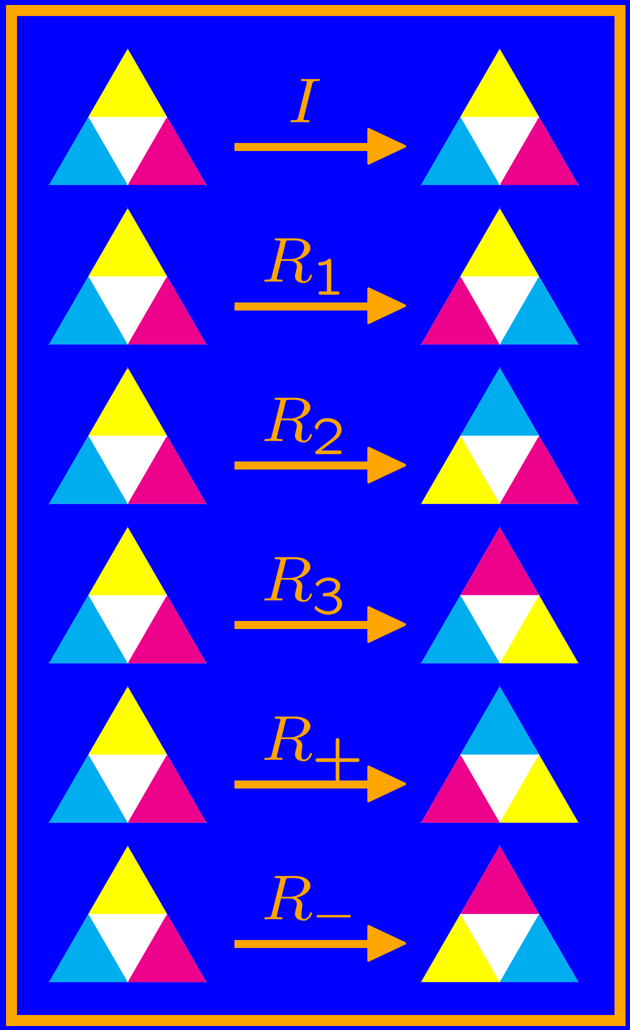
Groups, an example:

using these six triangles,
we can construct a group:



- the triangles themselves will not be elements
  - as we have no clue, how to connect them
- their **relations** will be elements of a group!
  - we know, how we can transform one triangle into the other
  - then the set is $\{I, R_1, R_2, R_3, R_+, R_-\}$
- then these transformations can be connected:
  - do first one, then the other:
    $R_1 \circ R_2 =$ doing first R_2, then R_1





Which symmetries do we encounter in particle physics?

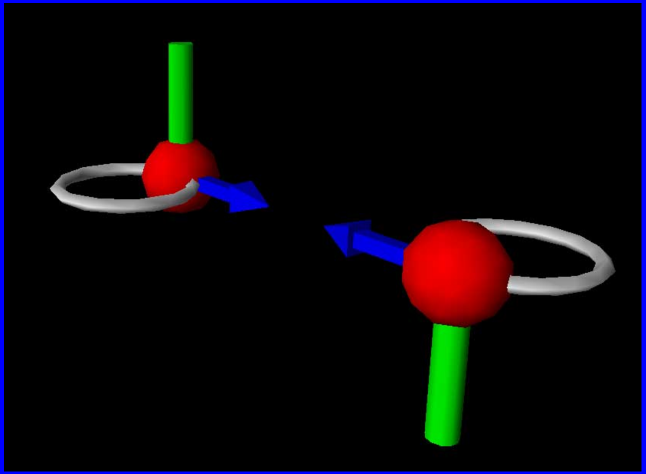
★ **discrete** symmetry transformations:

parity transformation P

- to mirror at a plane (a mirror) is easy to understand, but depends on the (arbitrary) position and orientation of the plane.
- a more general definition: **mirror at the origin**

  (space inversion, parity transformation):

$$\mathbf{P}W(t,x,y,z) := W(t,-x,-y,-z)$$



- the parity transformation corresponds to a rotation followed by a mirroring at a plane

Which symmetries do we encounter in particle physics?

★ **discrete** symmetry transformations:

time reversal T (reversal of the ”arrow of time”)

- corresponds to a movie played backwards
- in case of a movie (= everday physics), this is spotted at once
  (i.e. there is no symmetry)
- however, the laws of mechanics are time-symmetric (example: billiard)

- definition:

$$\mathbf{T}W(t,x,y,z) := W(-t,x,y,z)$$

Which symmetries do we encounter in particle physics?

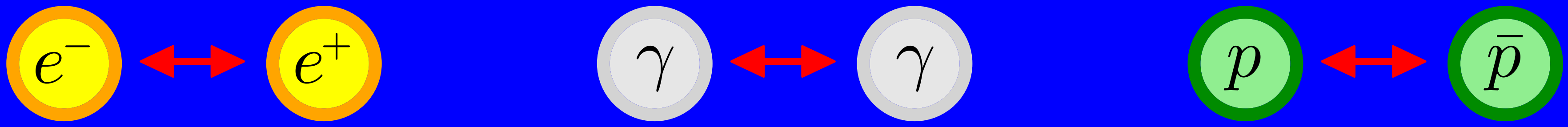
★ **discrete** symmetry transformations:

charge conjugation C (exchanging matter and anti-matter)

- for every known particle, there is also a anti-partner
- anti particles are identical to their partners with respect to some properties (e.g. mass), and opposite w.r.t. others (e.g. charge)
- charge conjugation exchanges all particles with their (anti)partners (and vice versa)

- definition:

$$\mathrm{C}W(t,x,y,z) := \bar{W}(t,x,y,z) = W^{\dagger}(t,x,y,z)$$



Which symmetries do we encounter in particle physics?

★ **continuous** symmetry transformations:

- they can be performed in **arbitrary small steps**

- **time shift**: physics(today) ➡ physics(tomorrow)
  - more accurately: shift by a time-step Δt

$$e^{\Delta t \frac{\partial}{\partial t}} W(t, x, y, z) = W(t + \Delta t, x, y, z)$$

- **space shift**: physics(here) ➡ physics(there)
  - more accurately: shift in space by a vector $\Delta\vec{r} = (\Delta x, \Delta y, \Delta z)$

$$e^{\Delta\vec{r}\cdot\vec{\nabla}} W(t, x, y, z) = W(t, x + \Delta x, y + \Delta y, z + \Delta z)$$

Which symmetries do we encounter in particle physics?

★ **continuous** symmetry transformations:

– they can be performed in **arbitrary small steps**

- **orientation**: physics(north) ➡ physics(west)
  – more accurately: rotation around an arbitrary axis in space

$$DW(t,x,y,z) = W(t,x',y',z')$$

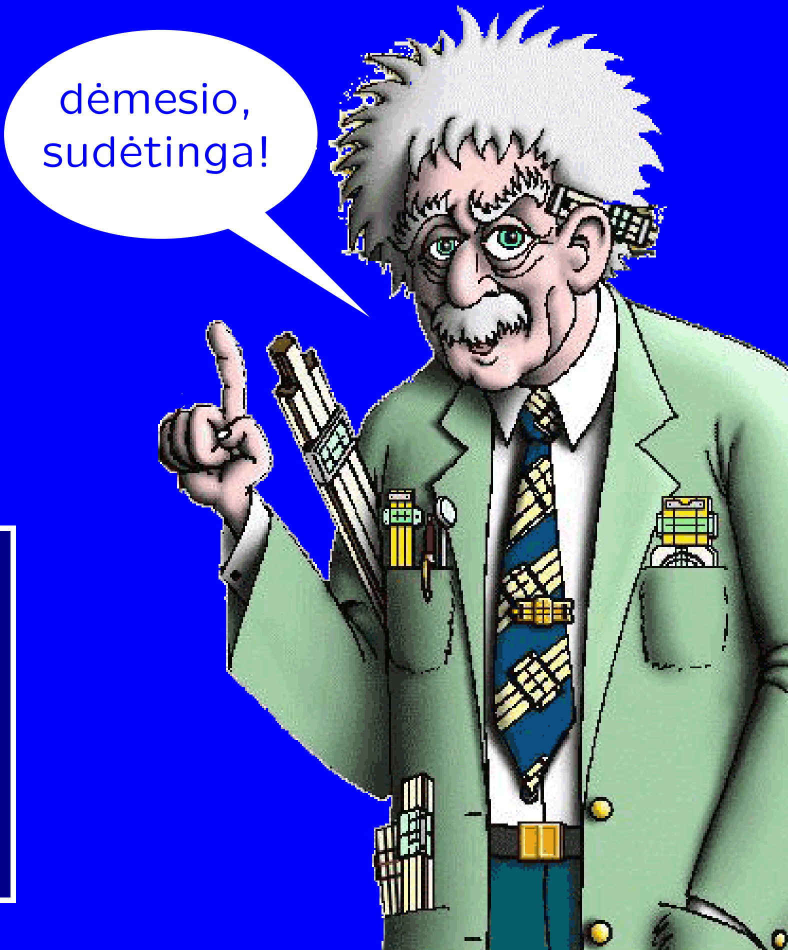
Which symmetries do we encounter in particle physics?

★ **continuous** symmetry transformations:

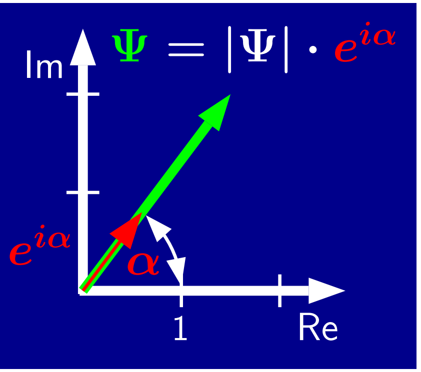
- they can be performed in **arbitrary small steps**

- $U(1)$ **transformation**:
  - does not affect the outer coordinates (t, x, y, z), but inner properties of particles
  - $U(1)$ is a transformation, which rotates the phase of a particle field (denoted as Ψ) by an angle α:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha}\Psi(t,x,y,z)$$



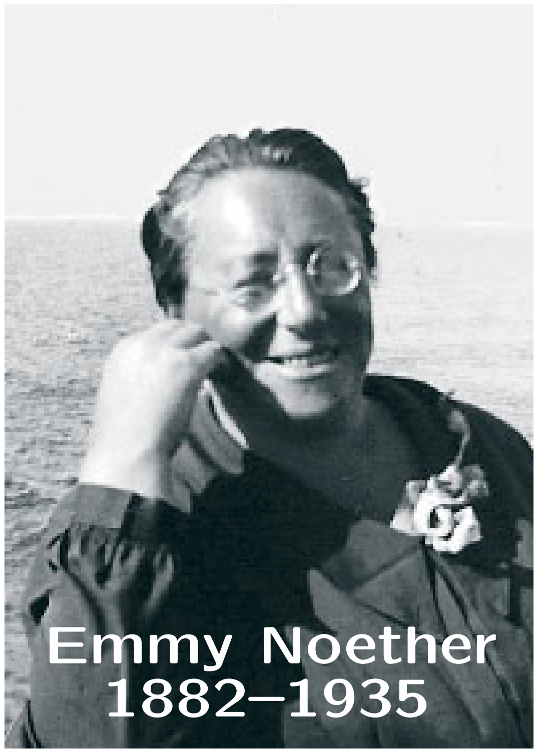
insertion: **particles** are represented by fields in quantum field theory. At each point in space and time, the field Ψ can have a certain complex phase.



The fundamental importance of symmetries

★ Noether's theorem:

to each symmetry of a field theory corresponds a certain conserved quantity → conservation law


Emmy Noether
1882–1935

that means: if a field theory remains unchanged under a certain symmetry transformation S, then there is a mathematical procedure to calculate a property of the field which does not change with time, whatever complicated processes are involved.

The fundamental importance of symmetries

★ applications of Noether's theorem:

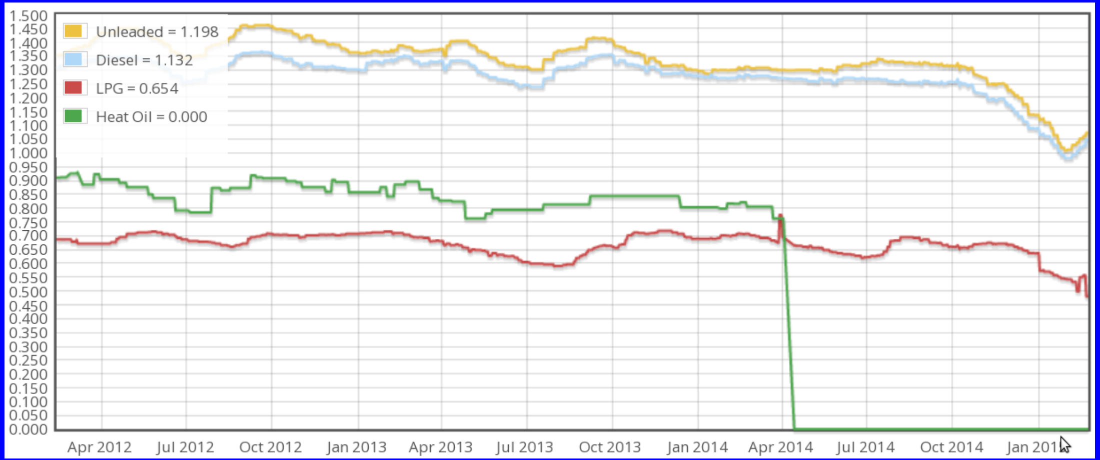
”also tomorrow the sun will rise”

→ conservation of energy

- the laws of physics do not change with time
- more accurate: the corresponding field theory is invariant under time shifts:

$$e^{\Delta t\frac{\partial}{\partial t}}W(t,x,y,z) = W(t+\Delta t,x,y,z) \doteq \boldsymbol{W(t,x,y,z)}$$

From Noether's theorem follows the conservation of a well-known property: energy!



The fundamental importance of symmetries

★ applications of Noether's theorem:

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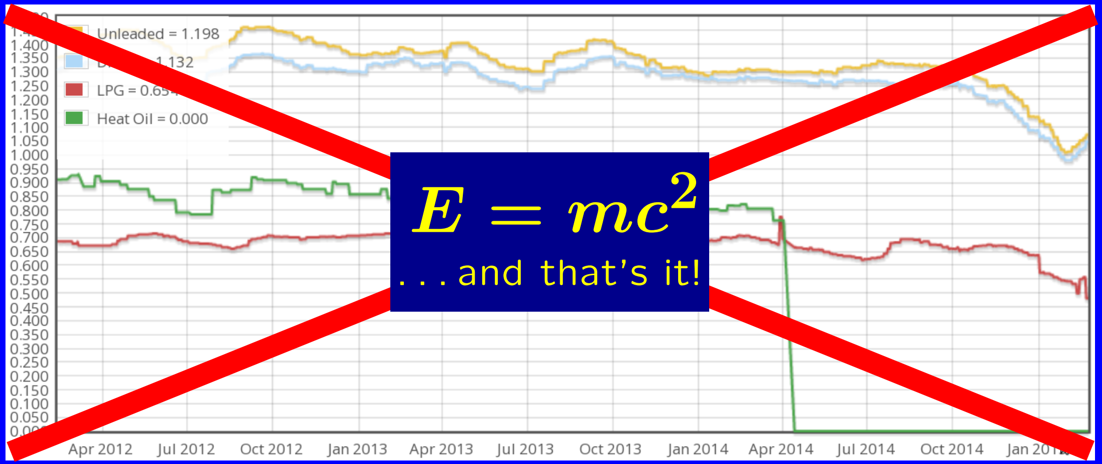


$$E = mc^2$$

. . . and that's it!

just to be clear:

★ we are talking **about properties of the underlying theory, not a certain physics scenario**:

Example: **chess**:

- there is **virtually an infinite number of ways** a game of chess can develop
- a game **tomorrow** can be **completely different** from a game **today**

but:

- the **rules** of chess **remain the same**, they are **invariant under time shifts!**

The fundamental importance of symmetries

★ applications of Noether’s theorem:

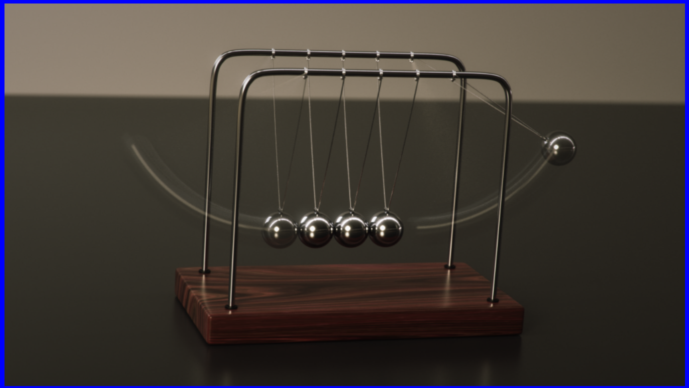
”it’s the same everywhere”

$\longrightarrow$ conservation of momentum

- the laws of physics do not depend on where you are
- more accurate: the corresponding field theory is invariant under space shifts:

$$e^{\Delta\vec{r}\cdot\vec{\nabla}}W(t,\vec{r}) = W(t,\vec{r}+\Delta\vec{r}) \doteq \boldsymbol{W(t,\vec{r})}$$

From Noether’s theorem follows the conservation of a well-known property: momentum!



The fundamental importance of symmetries

★ applications of Noether's theorem:

''going round and round''

→ conservation of angular momentum

- the laws of physics do not depend on which way you look
- more accurate: the corresponding field theory is invariant under rotations:

$$DW(t,\vec{r}) = W(t,\vec{r}\,') \doteq \boldsymbol{W}(\boldsymbol{t},\vec{\boldsymbol{r}})$$

From Noether's theorem follows the conservation of a well-known property: angular momentum!

The fundamental importance of symmetries

★ applications of Noether's theorem:

even more abstract symmetries get a meaning:

★ conservation of charge

- as it turns out, the field theory of electro-dynamics is invariant under a global* U(1) transformation:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha}\Psi(t,x,y,z)$$
$$\Rightarrow W'(t,x,y,z) \doteq W(t,x,y,z)$$

* global means: affecting all space-points (t,x,y,z) in the same way

From Noether's theorem follows the conservation of charge!

Overview

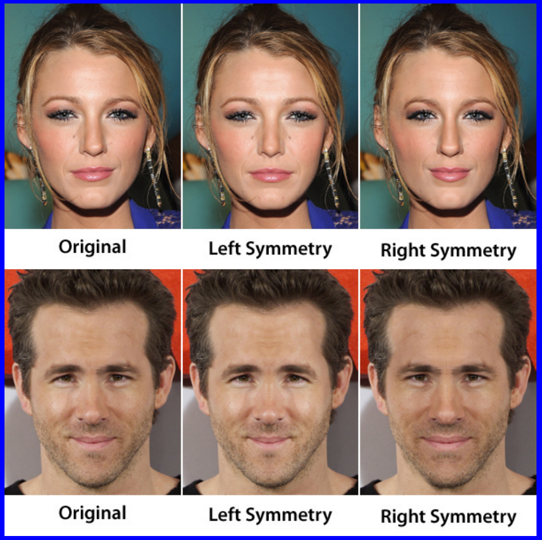
symmetries and conservation laws

symmetry	conservation law
time shift	energy
space shift	momentum
rotation	angular momentum
$U(1)$ phase	charge

Are symmetries perfect?

★ the small imperfections make it more interesting . . .

is physics really perfectly symmetric?



- obviously, many things in our macroscopic world are not symmetric
- but is this also true for the fundamental laws of physics?

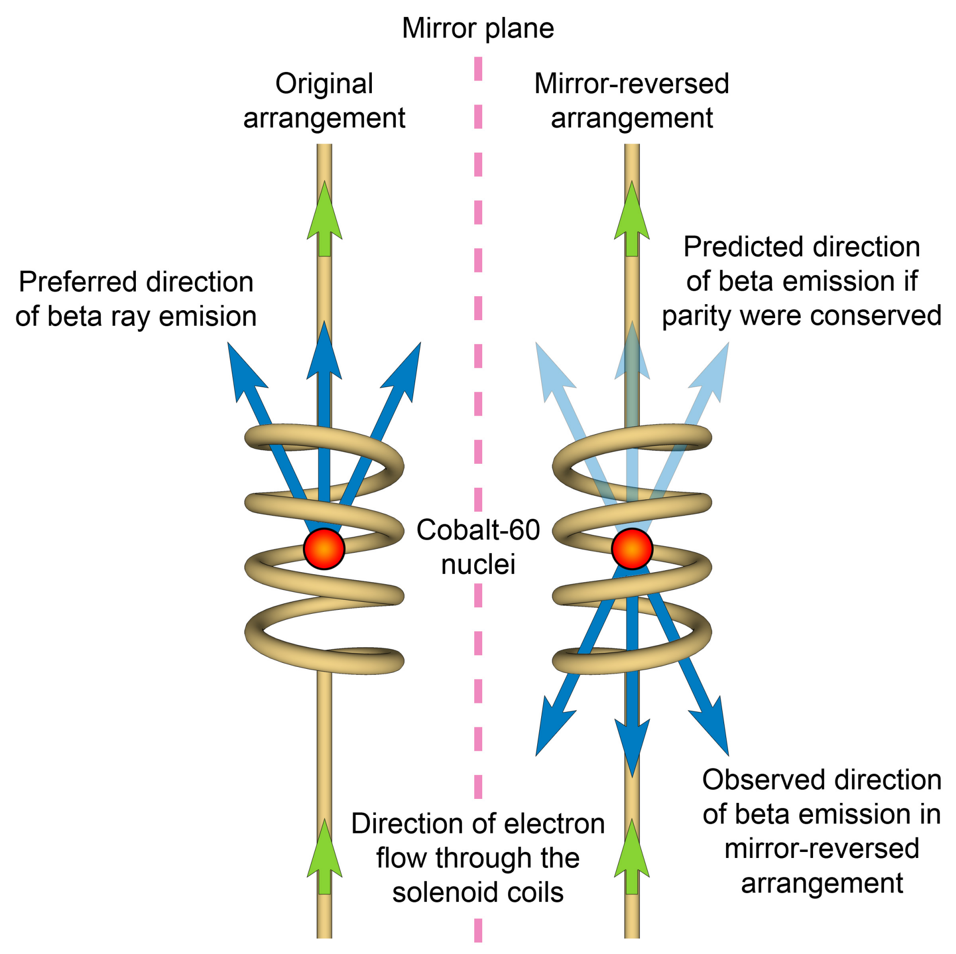
★ Originally it seemed that nature does not only exhibit the previously discussed continuous symmetries, but the discrete symmetries as well:

- P (parity transformation = mirror symmetry)
- T (time reversal)
- C (charge conjugation)

Are symmetries perfect?

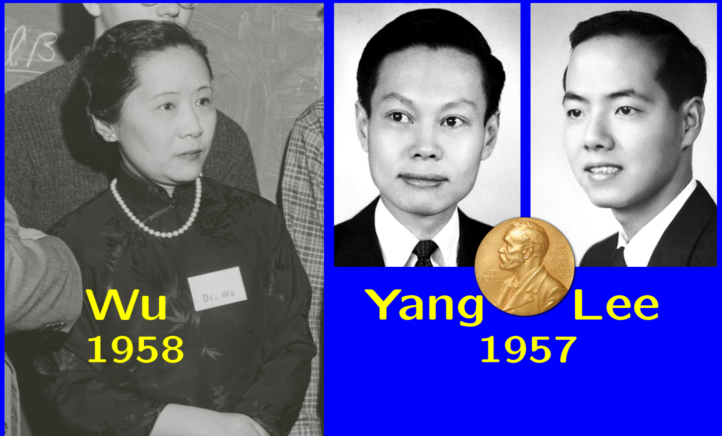
★ the Wu experiment

- originally, all experiments indicated that the microcosmic world is perfectly mirror-symmetric
- 1956 Tsung-Dao Lee and Chen Ning Yang postulated a violation of parity for the weak interaction
- in the same year, Chien-Shiung Wu demonstrated the violation experimentally



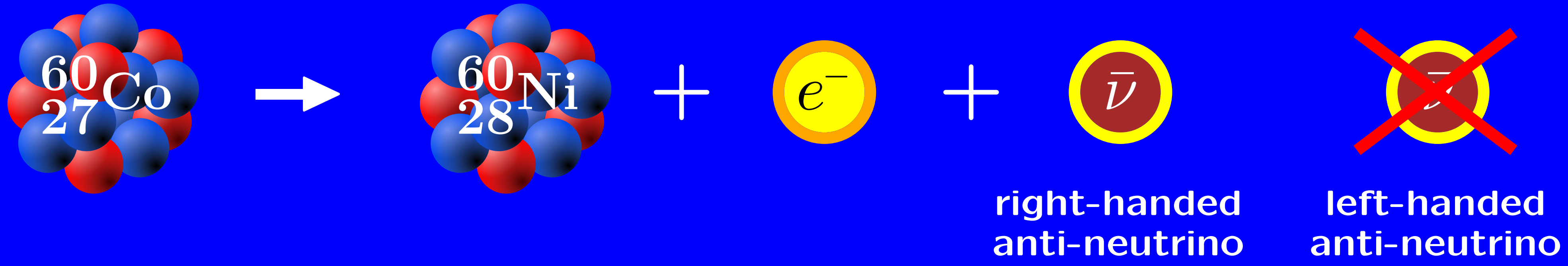
→ nature is not mirror-symmetric,

P-symmetry (parity) is violated



Are symmetries perfect?

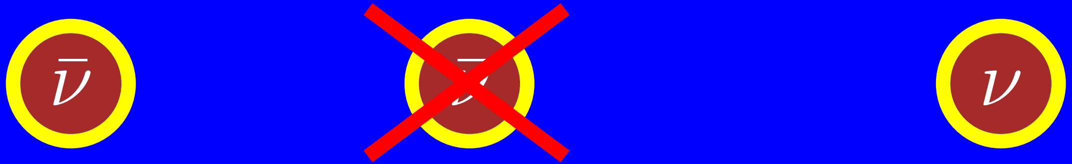
★ a deeper understanding of the Wu experiment



- also (undetected) anti-neutrinos are emitted
- anti-neutrinos have a spin that is always orientated in the direction of movement (they are "right-handed")
- since a P-transformation changes the direction of movement, but not the spin, it produces a "left-handed" anti-neutrino
- as it turns out, we do not see a left-handed anti-neutrino in nature at all!
- therefore, Parity is said to be maximally violated

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 <u>neutrino</u> (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:

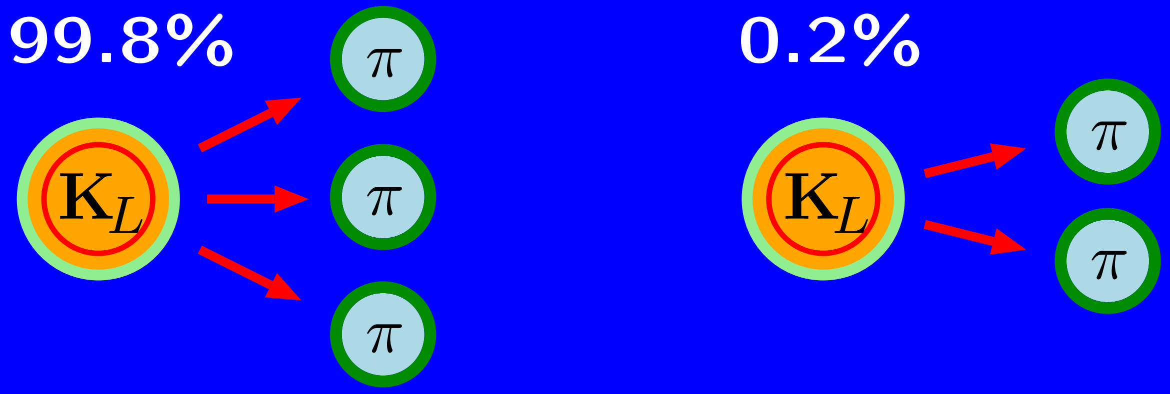
right-handed anti-neutrino

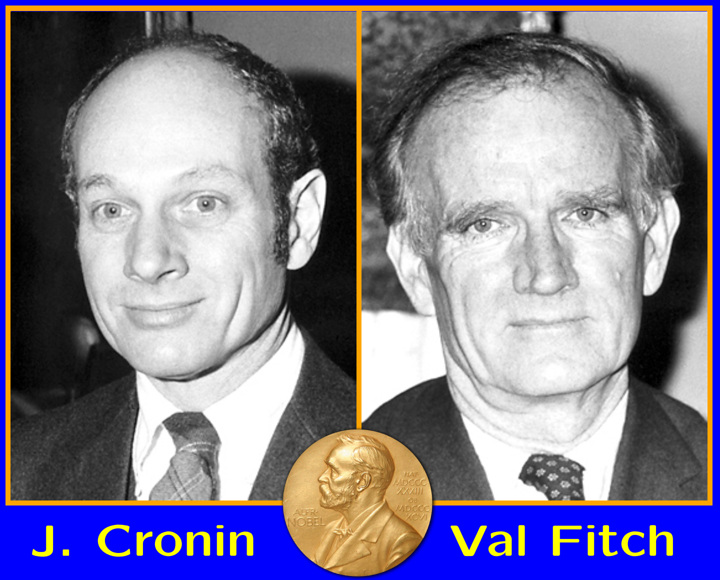
$\Leftarrow$ CP $\Rightarrow$

left-handed neutrino

Are symmetries perfect?

★ the kaon experiment of 1964





J. Cronin Val Fitch

1980

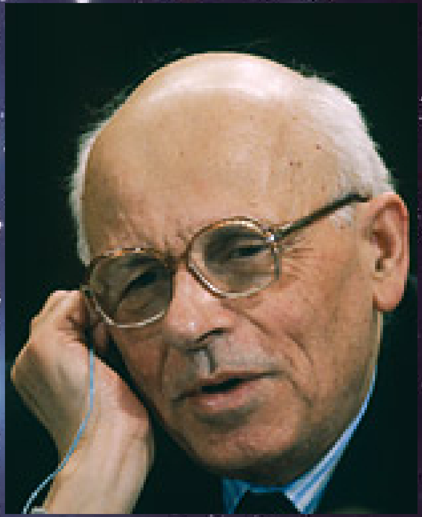
- if there is a CP-symmetry in nature, by Noether's theorem there is also a corresponding conserved quantum number "CP"
- kaons and pions are pseudo-scalars

  $\Rightarrow \quad \mathrm{P}\mathrm{K} = -\mathrm{K}$ and $\mathrm{P}\pi = -\pi$
- therefore, CP is conserved for the decay of the long-lived kaon into three pions, but not for the decay into two

→ CP is (slightly) <u>violated</u>

Are symmetries perfect?

★ implications of CP-violation in Cosmology



why CP-violation is important for our existence:

- our universe consists – as far as we know – almost completely of matter
- but where is the anti-matter?
- and why haven't matter and anti-matter just annihilated?

possible explanation:

- at the big bang, there were large amounts of matter and anti-matter
- almost all of them annihilated
- but smallest asymmetries in the laws of nature for matter and anti-matter left a tiny excess of matter: the matter of our universe
- 1967, Andrej Sacharow gave a list of conditions for this explanation
  - ▶ one of it is CP-violation

Without CP-violation, our universe would not be the one we know!

Are symmetries perfect?

★ ”last hope” CPT ?

the CPT-theorem states:

- under very general conditions

  i.e.: transformations of the Poincaré group

  are symmetries of microscopic physics
- quantum field theories (the ”language” of particle physics)

  always have CPT as a symmetry

. . . also experimentally, no violations have been observed so far

⟶ CPT is (as far as we know today) not violated

interesting side remark:

- CPT-symmetry together with CP-violation, gives also T-violation
- that means: the fundamental laws of nature are not time-symmetric,
  there is a special direction of time even at the microscopic level

”the future IS different from the past, after all!”

Overview

discrete symmetries

symmetry	valid in the universe?
P (parity: ”mirroring”)	✗
C (charge conjugation)	✗
T (time reversal)	✗
CP (combination of C and P)	✗
CPT (combination of C, P, & T)	✓

How symmetries make theories

★ QED, the quantum theory of light

remember:

- physics is invariant under a global U(1)-transformation of the field Ψ:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha}\Psi(t,x,y,z)$$

- global means a synchronous phase transformation of all particles in the whole universe!

the idea:

- replace the global transformation by a local one:

$$U(1)\Psi(t,x,y,z) = e^{i\alpha(t,x,y,z)}\Psi(t,x,y,z)$$

(different particles at different positions get transformed independently)

How symmetries make theories

★ QED, the quantum theory of light

result of a local U(1) transformation:

- **if only particles are transformed**
  - ★ not changing the electromagnetic interaction
  - ➡ **the theory is not invariant** under local U(1) transformations!
- **if the electromagnetic interaction is included in the transformation**
  - ➡ **the theory becomes invariant** under local U(1) transformations!

- **this works only, because the electromagnetic interaction has ”just the right form”**

”coincidence or deeper truth?”

How symmetries make theories

★ QED, the quantum theory of light

the modern viewpoint
("gauge principle"):

- a non-interacting theory,
  - invariant under a global symmetry

  can be made locally symmetric
  - by introducing
    - ★ additional fields
    - ★ and interactions

➡ **the full theory is now** for QED:

- ★ **locally symmetric** invariant under local phase transformations
- ★ **and interacting** the electro-magnetic gauge field A_μ, describing photons

each local symmetry produces an interaction plus new particles which mediate it

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force

- experiments show that protons (and neutrons) have an inner structure
- observations suggest the existence of
  - ★ fermions (quarks) with
  - ★ 3 inner degrees of freedom (color)

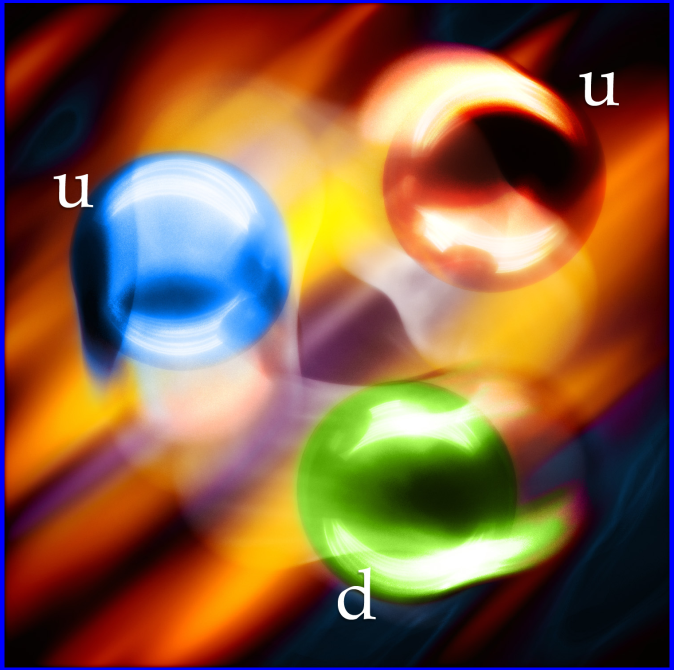
  inside the nucleon

there are three color states:

red, green, blue

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force



- we do not see "color"
- color states can be redefined
  - ★ without changing the theory!

"new colors" = mixture of old colors

$$q = A_{rr}\, q + A_{rg}\, q + A_{rb}\, q$$

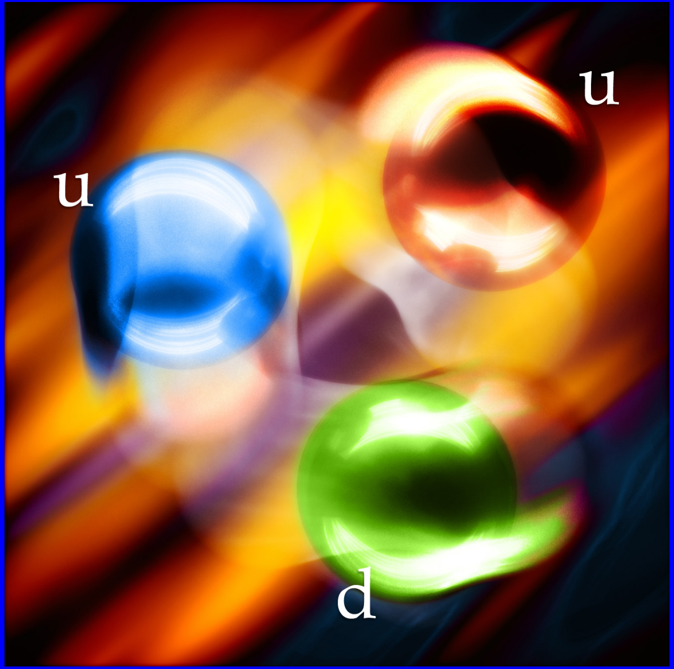
$$q = A_{gr}\, q + A_{gg}\, q + A_{gb}\, q$$

$$q = A_{br}\, q + A_{bg}\, q + A_{bb}\, q$$

- mathematically, this corresponds to a **unitary** 3 × 3 **matrix A**
- the symmetry group is called $SU(3)$

How symmetries make theories

★ Quantum-Chromo-Dynamics (QCD) the theory of the strong force



gauge principle:

- making the $SU(3)_{\text{color}}$-symmetry **local**
  we get
  - ★ the **strong force** with
  - ★ the **gluon** as the force carrier
- the **strong force** binds the quarks into mesons and baryons
- it is also (indirectly) responsible for the stability of nuclei
  (binding of proton and neutron, the nuclear force)

the color symmetry of quarks enables the existence of atoms!

How symmetries make theories

★ sketch of electro-weak interaction

- proton and neutron behave similar inside the nucleus
  - ★ **iso-spin symmetry**
- **extending this iso-spin symmetry to all left-handed fermions**
  - ★ **groups them in pairs (doublets)**
  - ★ **is a symmetry of the free theory**

"new flavor" = mixture of old flavors

$$\nu_e' = A_{uu}\,\nu_e + A_{ud}\,e_L^-$$

$$e_L'^- = A_{du}\,\nu_e + A_{dd}\,e_L^-$$

$$u_L' = A_{uu}\,u_L + A_{ud}\,d_L$$

$$d_L' = A_{du}\,u_L + A_{dd}\,d_L$$

gauge principle:

- **making the $SU(2)_L$-symmetry local**
  (and "mixing" it with a local $U(1)_Y$-symmetry) we get
  - ★ **the electro-weak force**
  - ★ **with W- and Z-bosons (and photons) as force carriers**

Overview

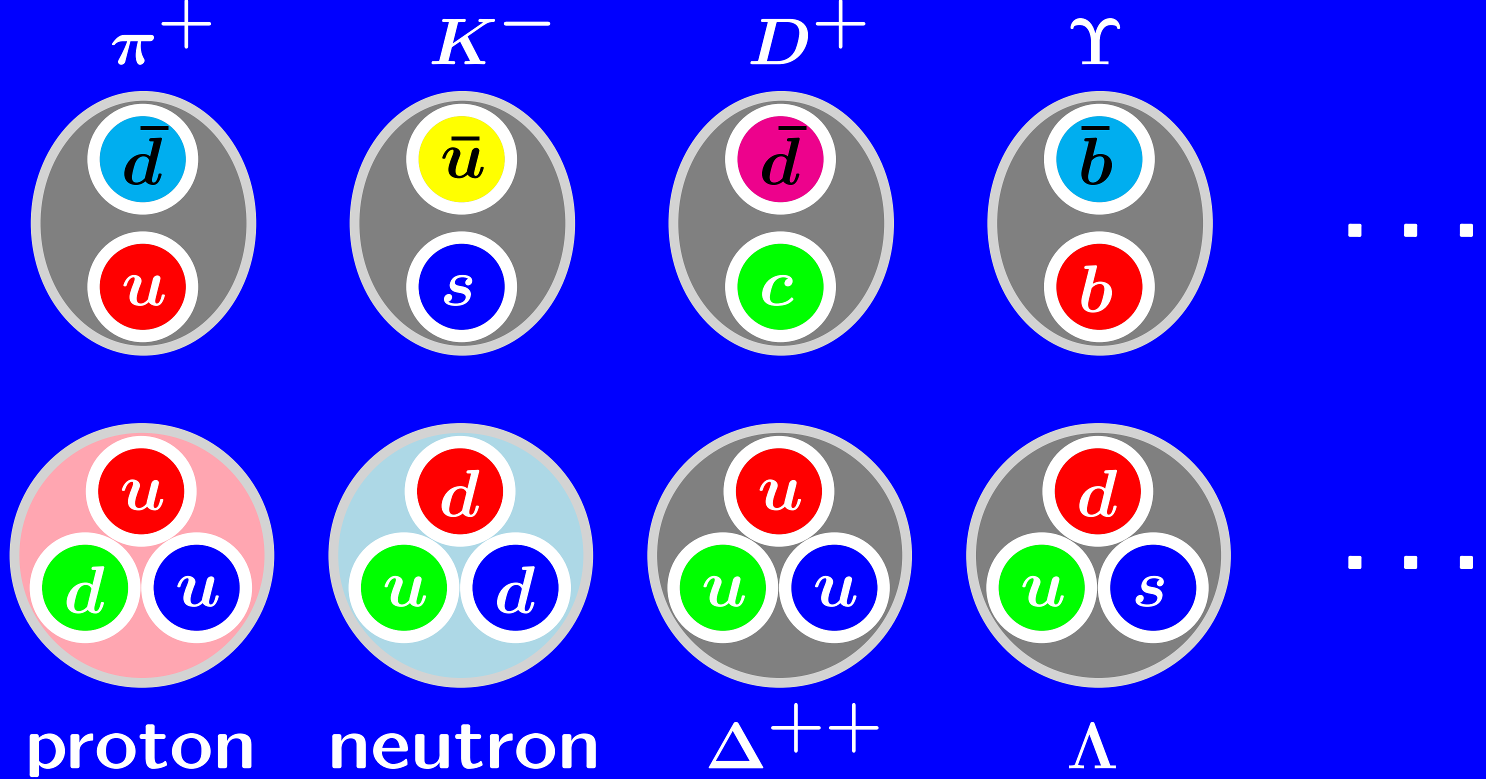
Symmetries and Interactions

symmetry		interaction	
$\boldsymbol{U(1)}$	symmetry of all leptons and quarks	$U(1)_Y$	electro-weak
$\boldsymbol{SU(2)}$	symmetry of left-handed leptons and quarks	weak	
$\boldsymbol{SU(3)}$	symmetry of quarks alone	strong	
?	is it a symmetry of space-time geometry itself, or something qualitatively different?	(quantum-) gravity	

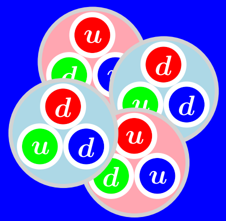
Taxonomie: composing matter

mesons

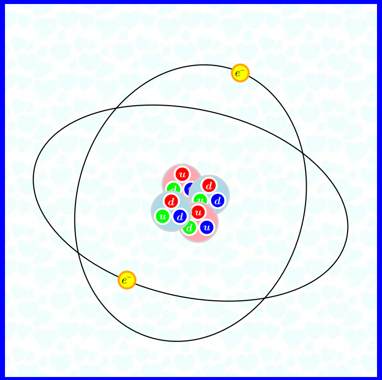
baryons



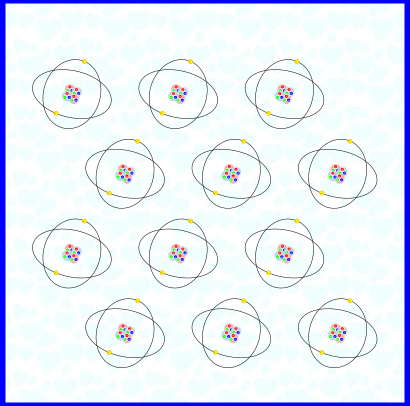
nucleus



He-nucleus
(α-particle)



atom



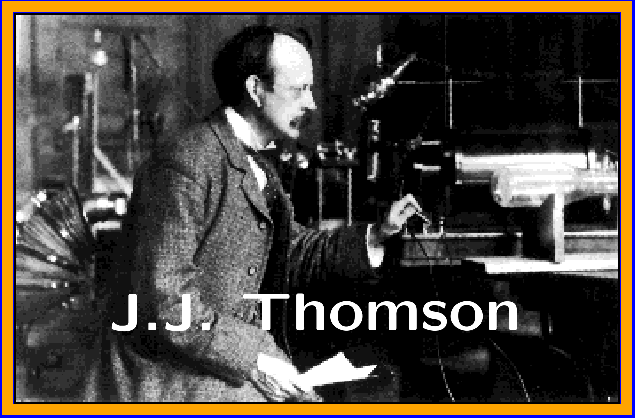
matter

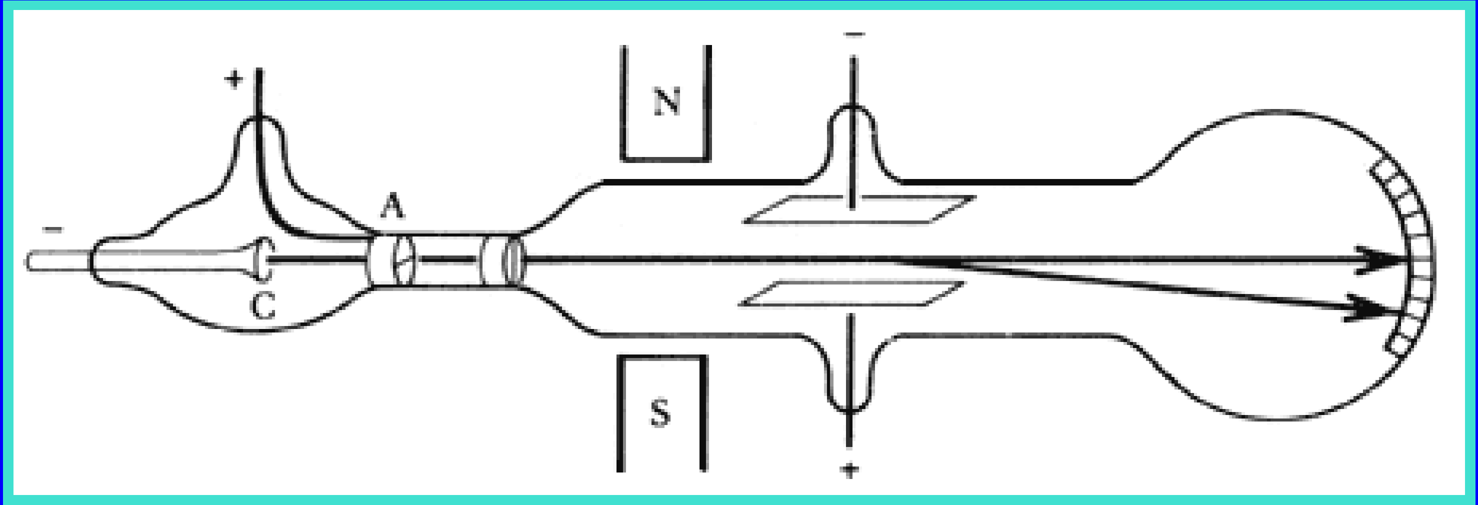
Particles of the Standard Model:

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

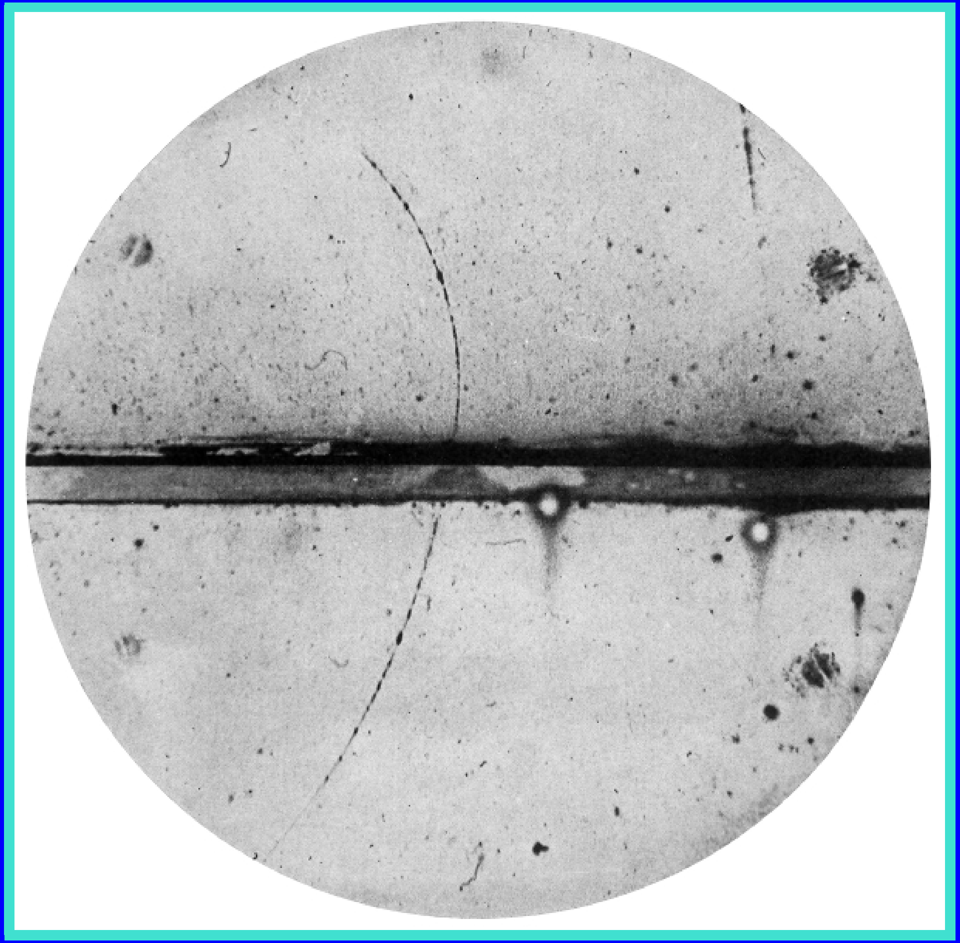
e^- the electron


J.J. Thomson

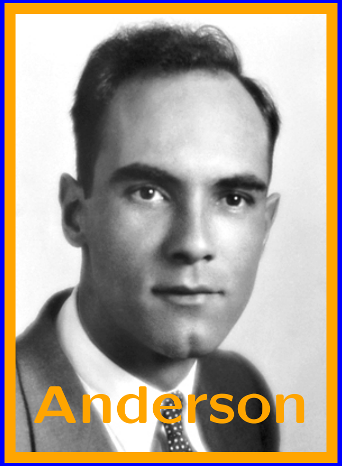


1897

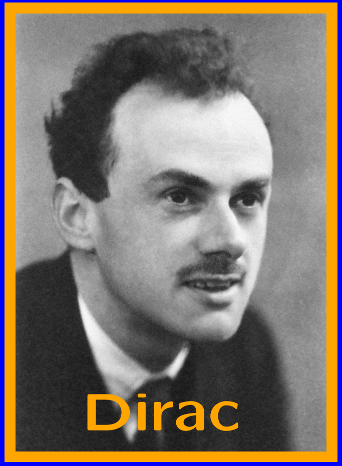
e^+ the positron



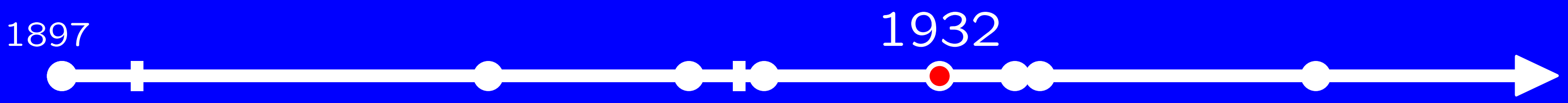
Discovery



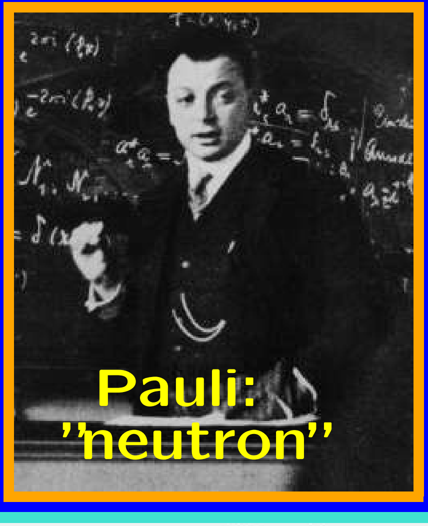
Prediction



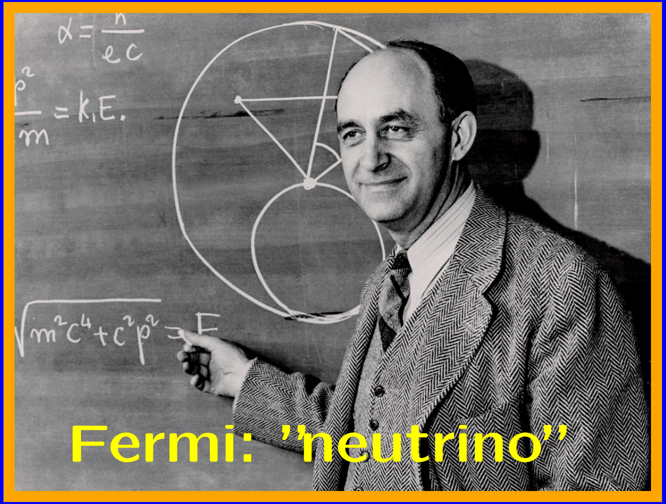
e^- γ p n μ^- π



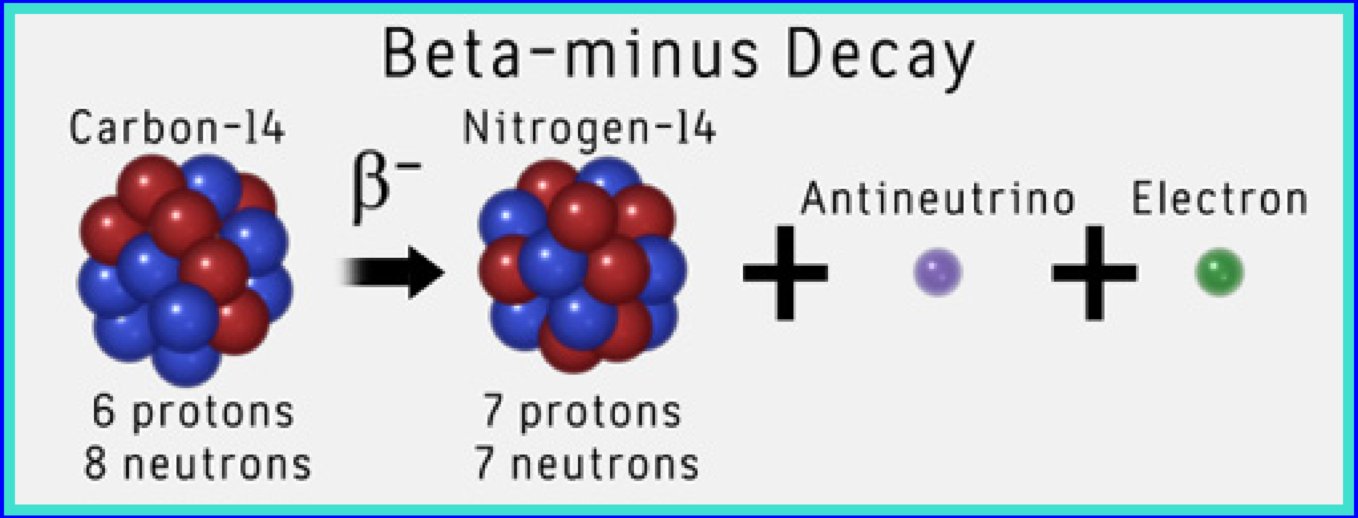
ν the neutrino – theory prediction

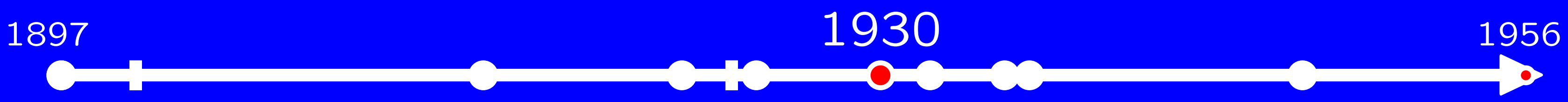


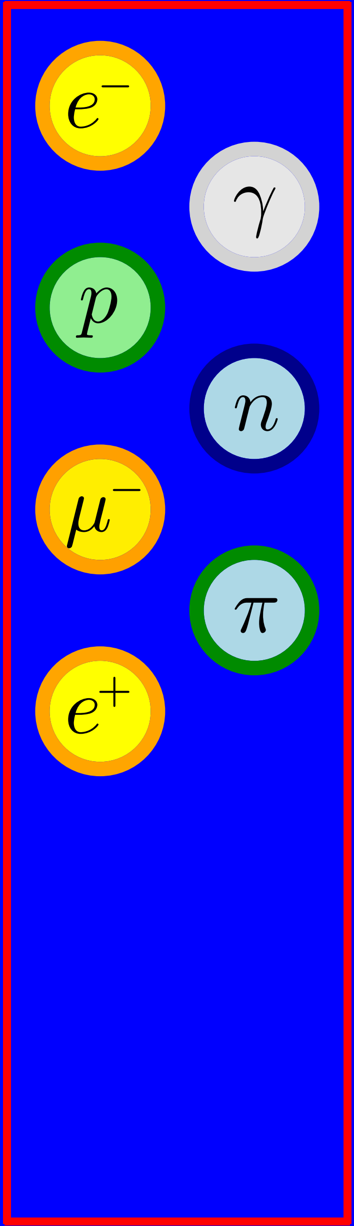
Pauli: ''neutron''



Fermi: ''neutrino''







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 <u>neutrino</u> (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:

$\Leftarrow$ CP $\Rightarrow$

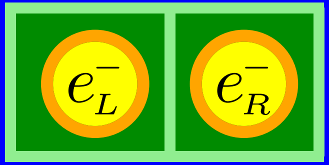
right-handed
anti-neutrino

left-handed
neutrino

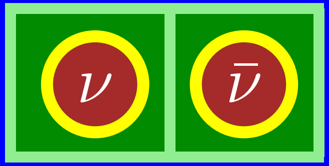
Ordering principle:

discreet symmetries

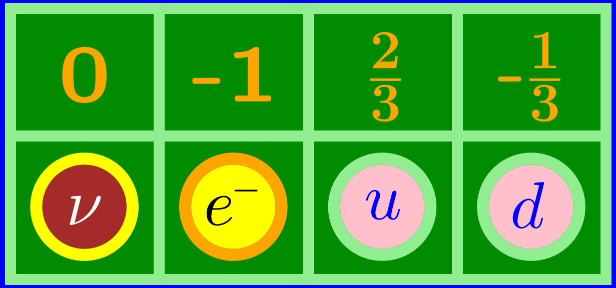
- **Parity** P
  - left-handed or right-handed



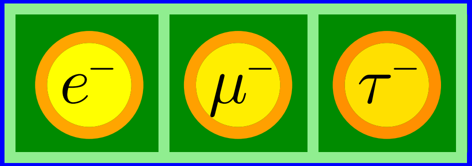
- **Charge Conjugation** C
  - particle or antiparticle



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

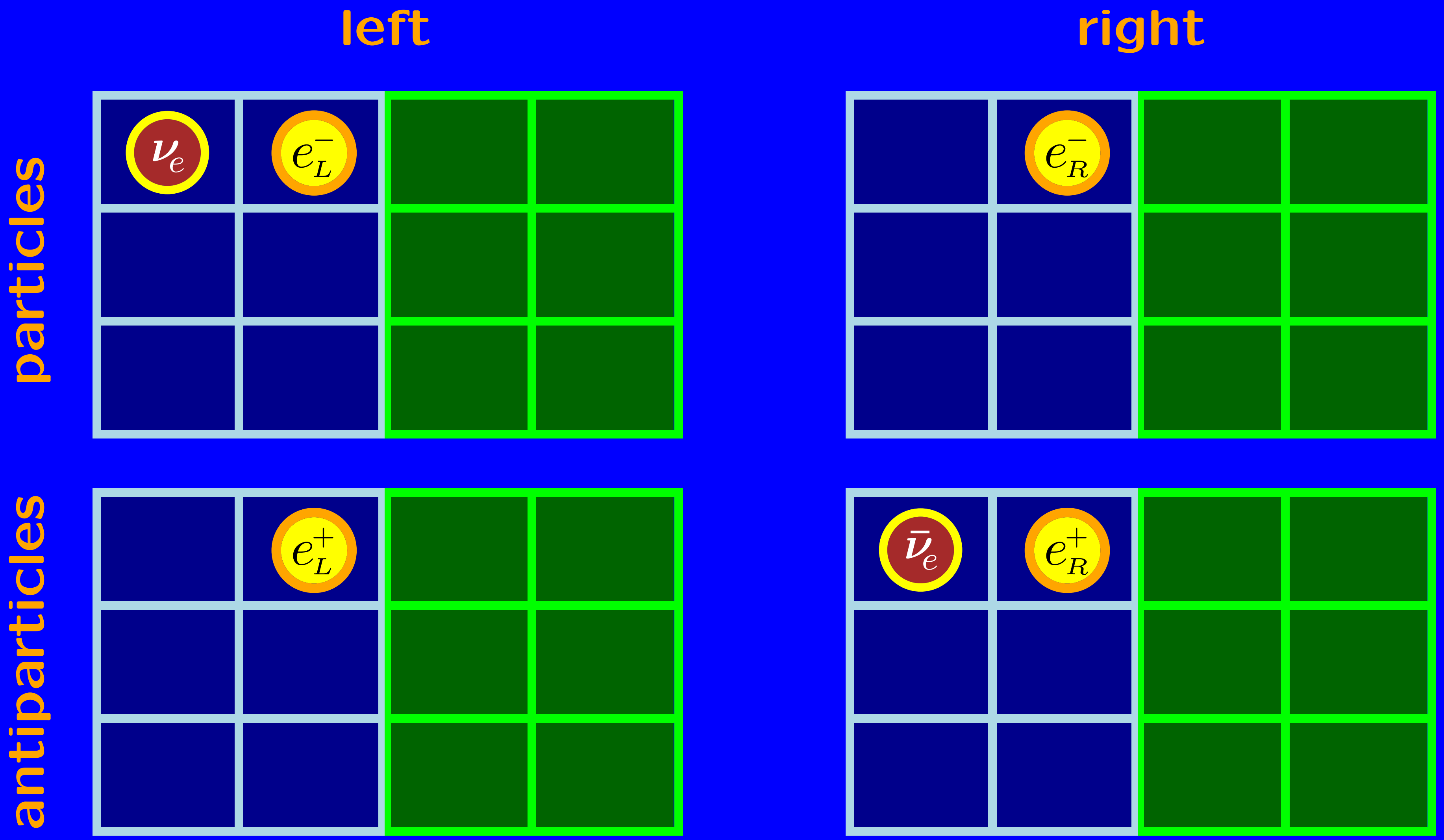


- **Generation**
  - first – second – third



Particles of the Standard Model:

Fermions



left

right

particles

antiparticles

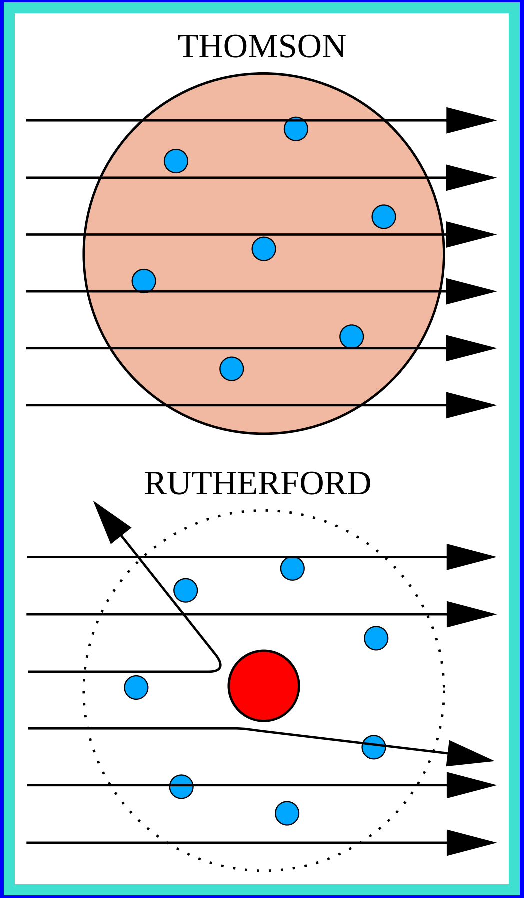
ν_e e^-_L

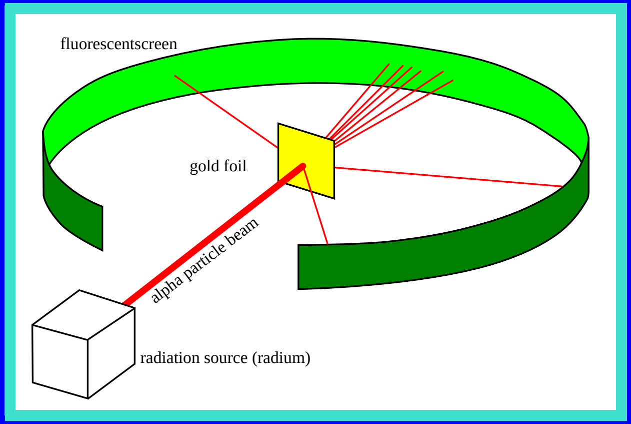
e^-_R

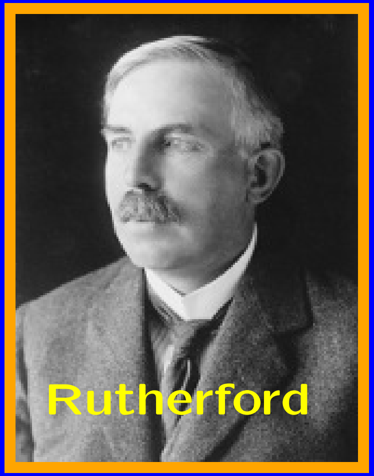
e^+_L

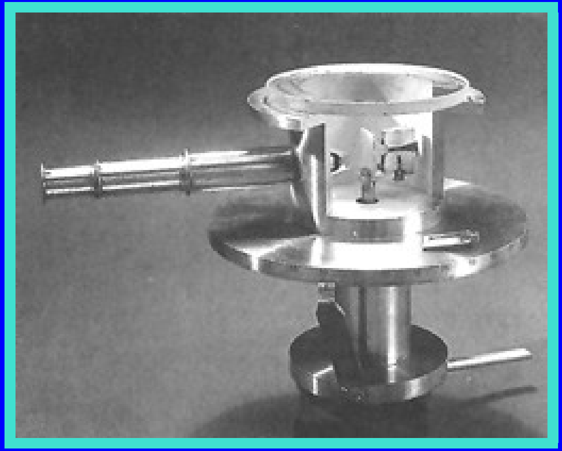
$\bar{\nu}_e$ e^+_R

p the proton – the atomic nucleus









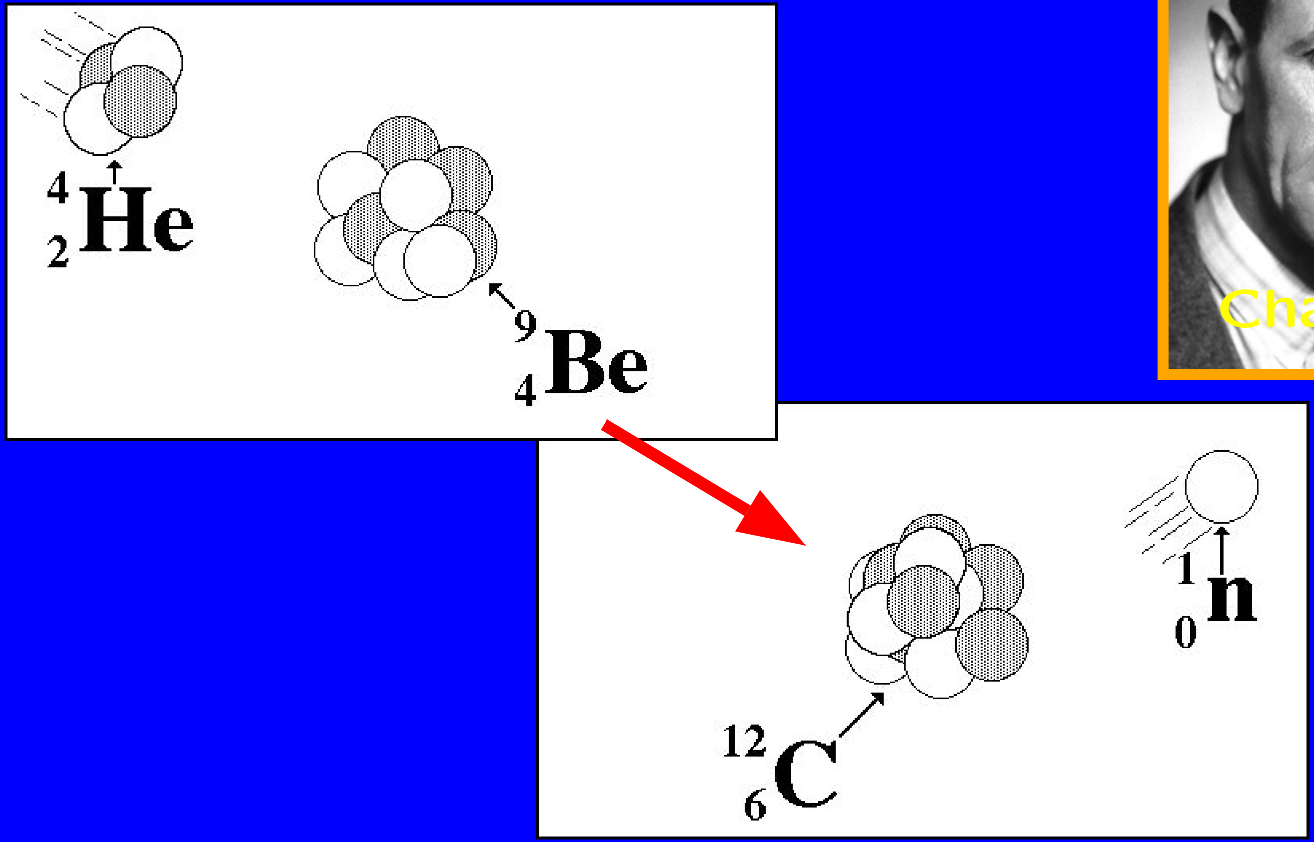
e^-

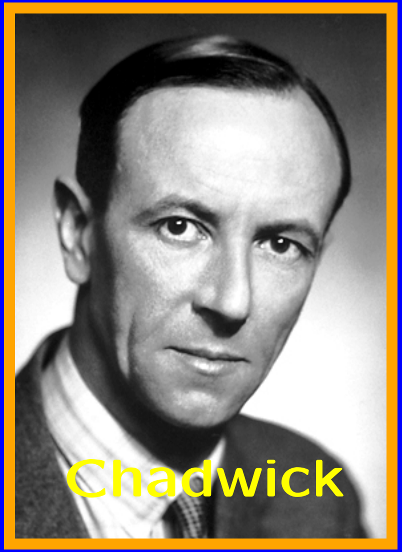
γ

1897

1914

n the neutron

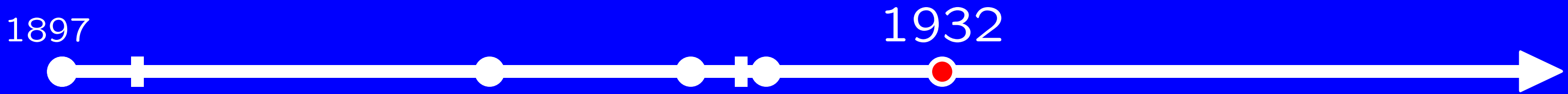




e^-

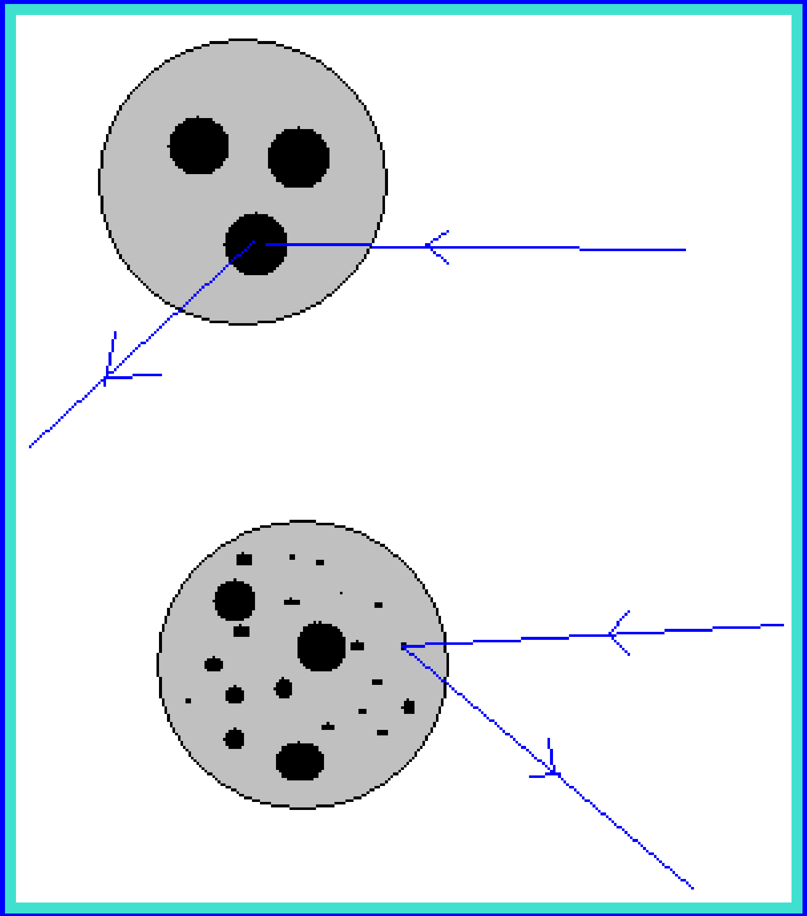
γ

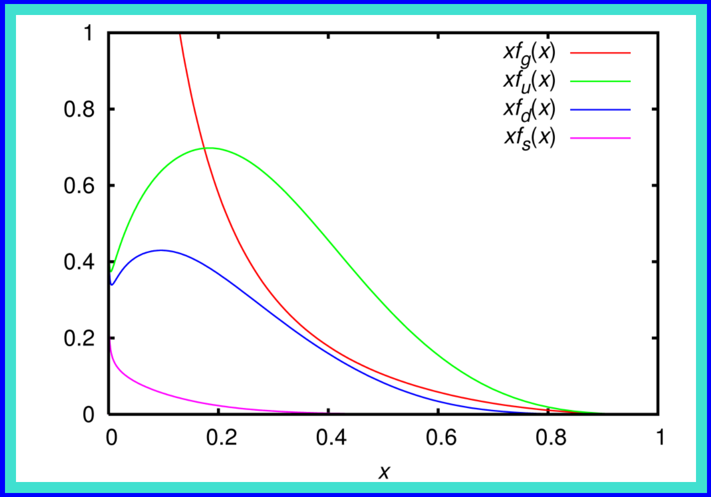
p



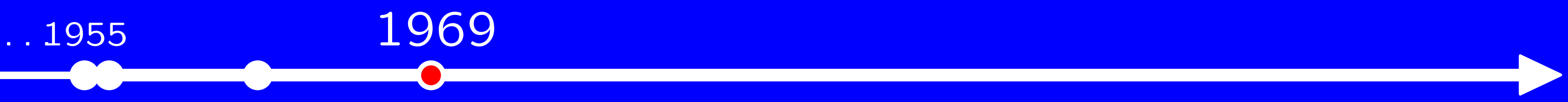
partons / parton model

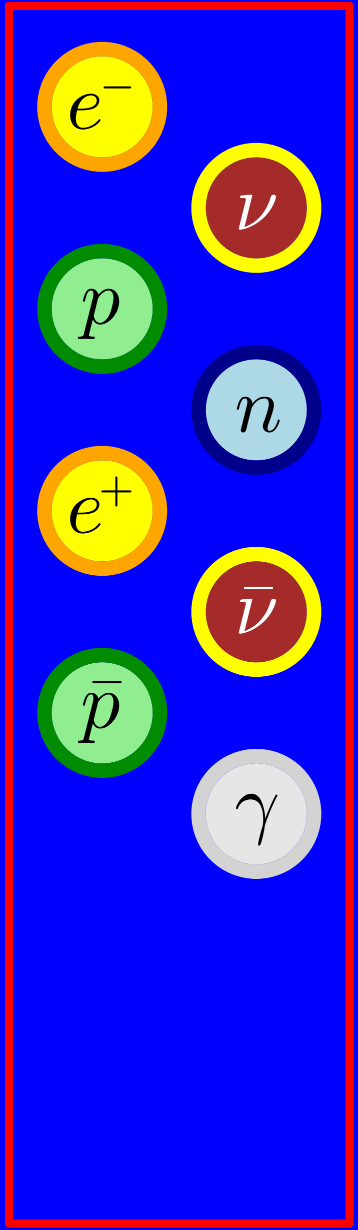
Richard Feynman 1969





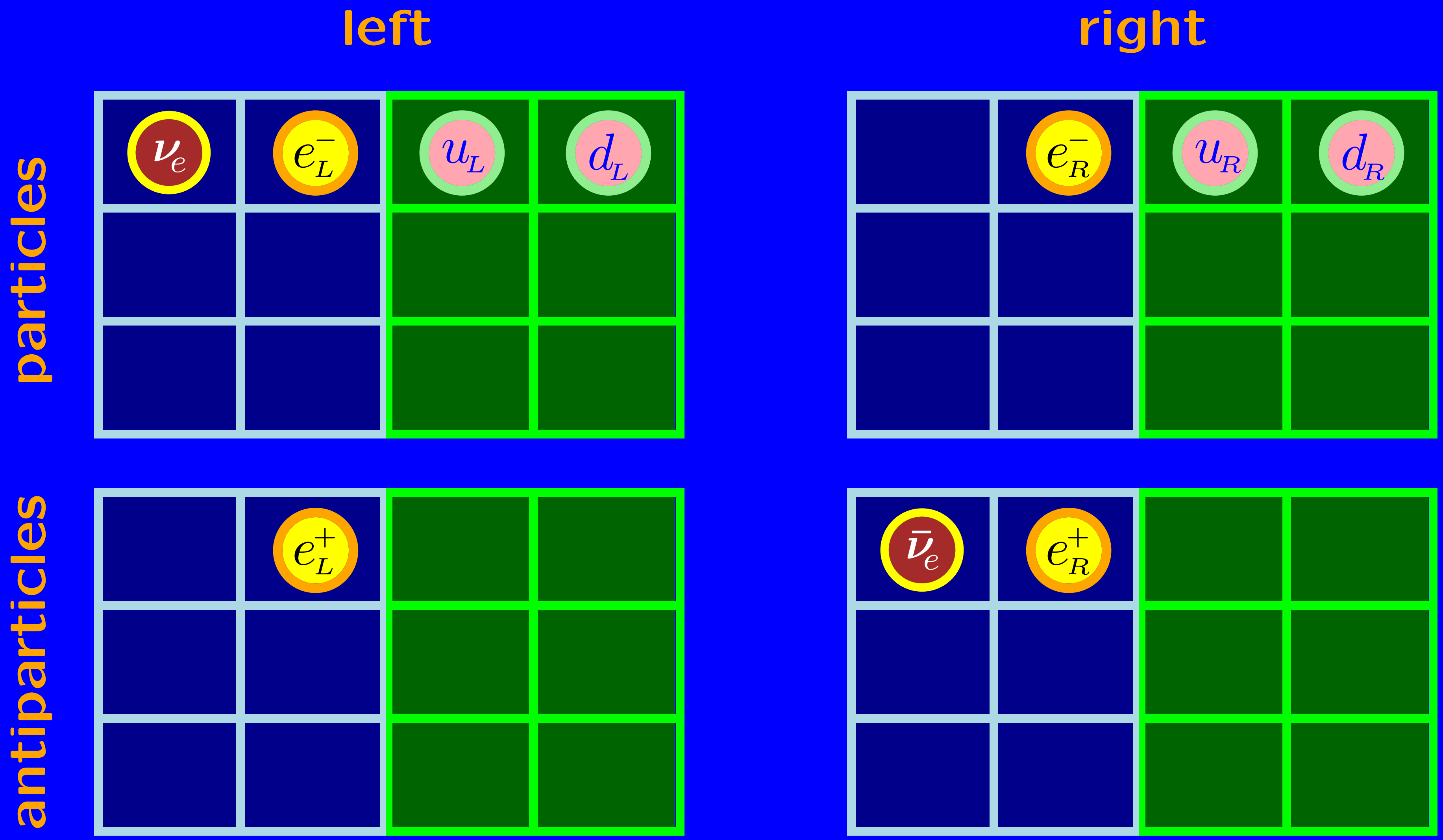
a hadron is composed of point-like constituents, called ”partons”. The number of partons depends on the probing energy ⇒ **parton distribution functions**



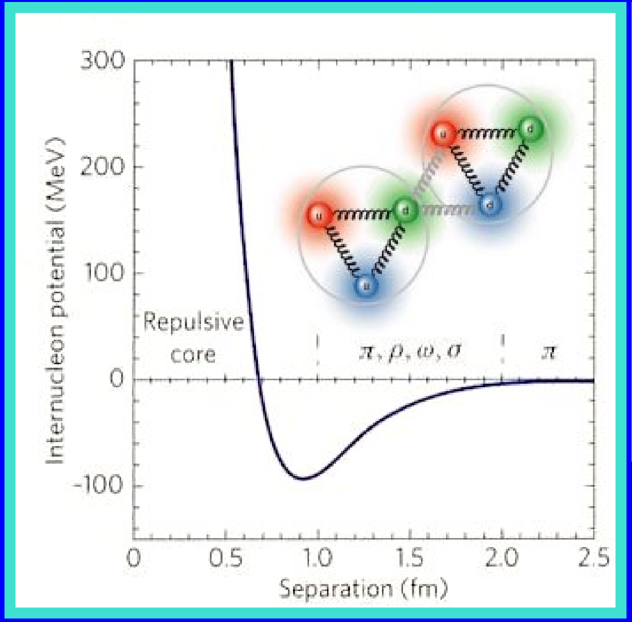


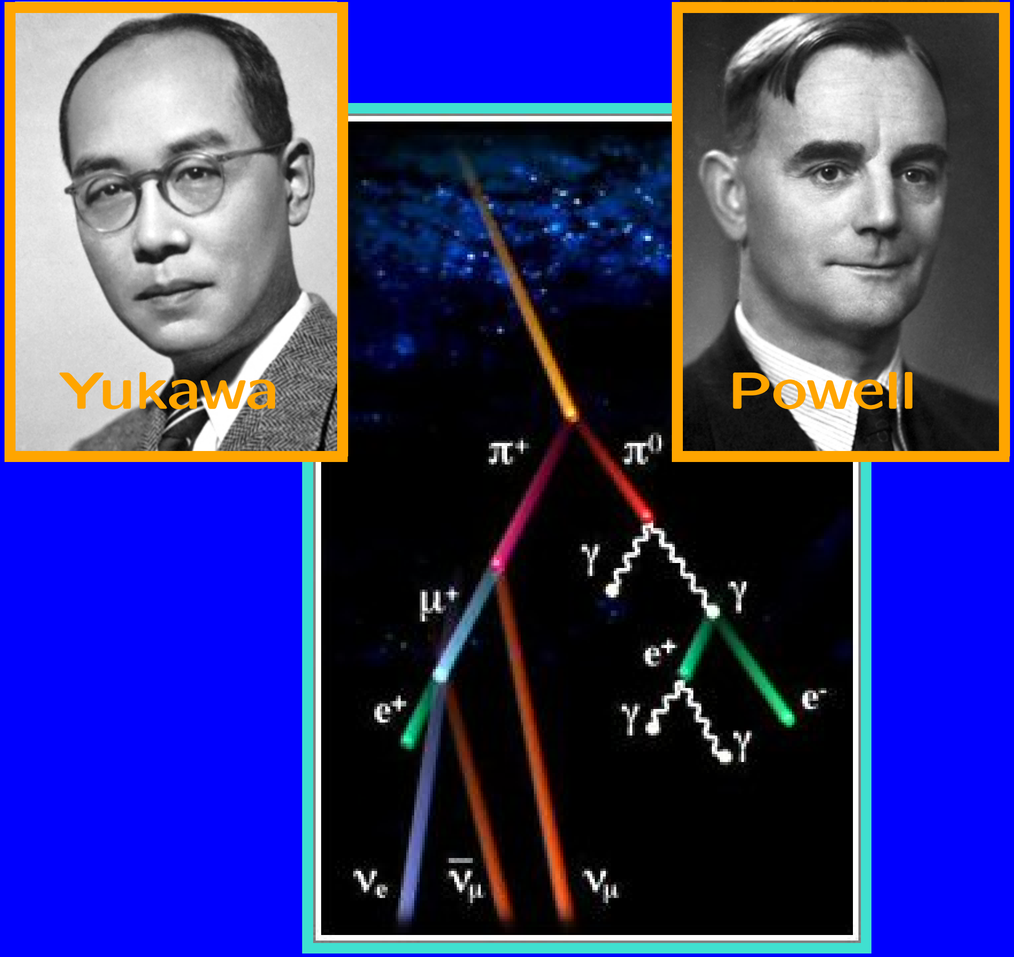
Particles of the Standard Model:

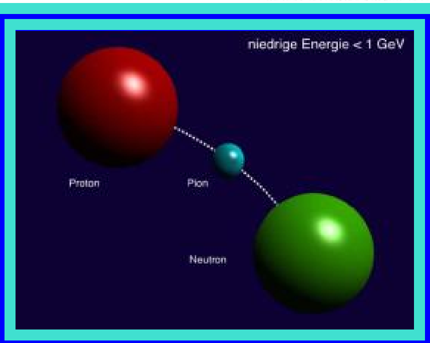
Fermions



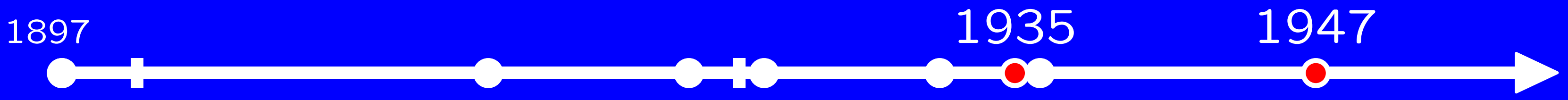
π the pion





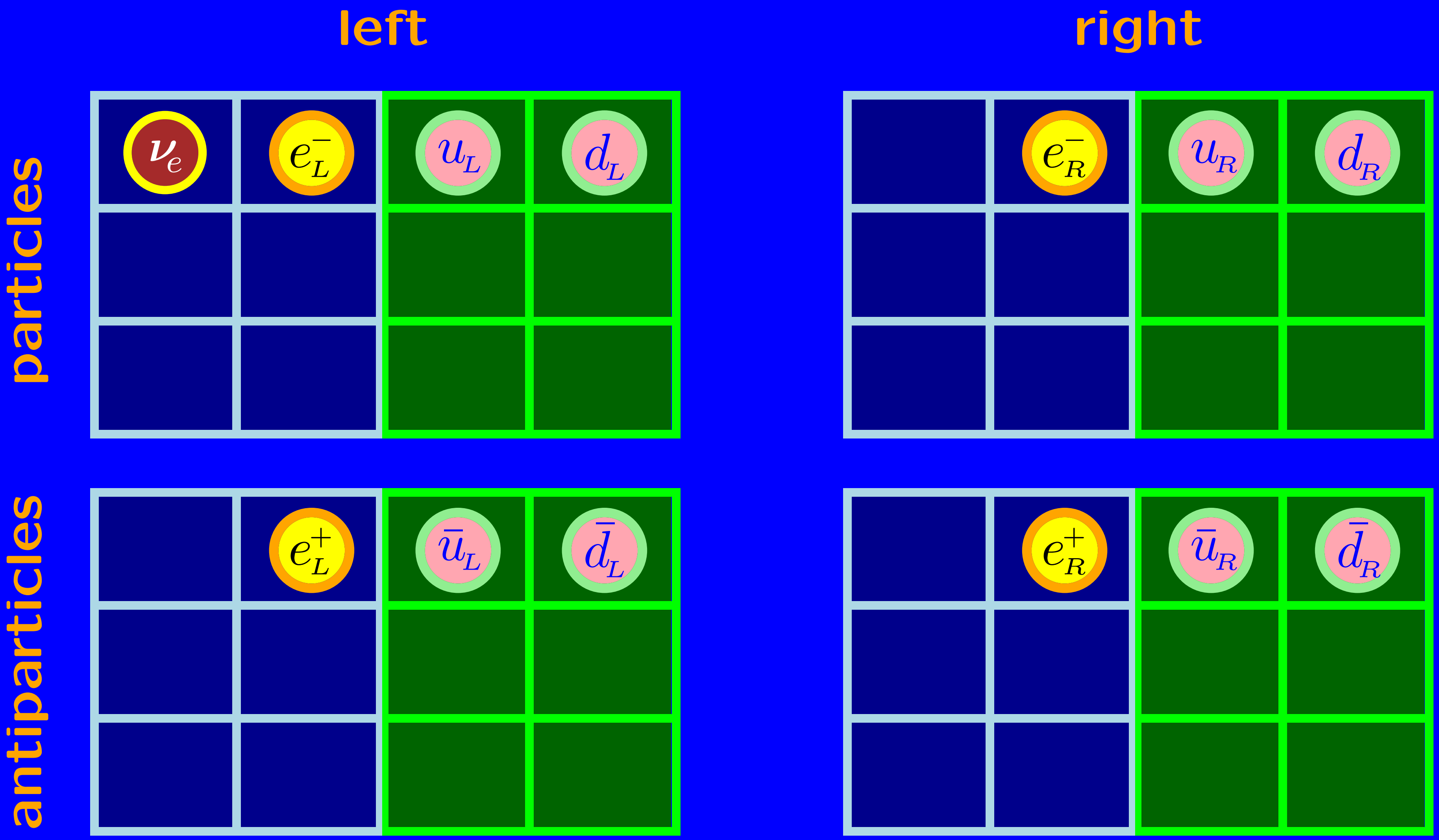


e^- γ p n μ^-



Particles of the Standard Model:

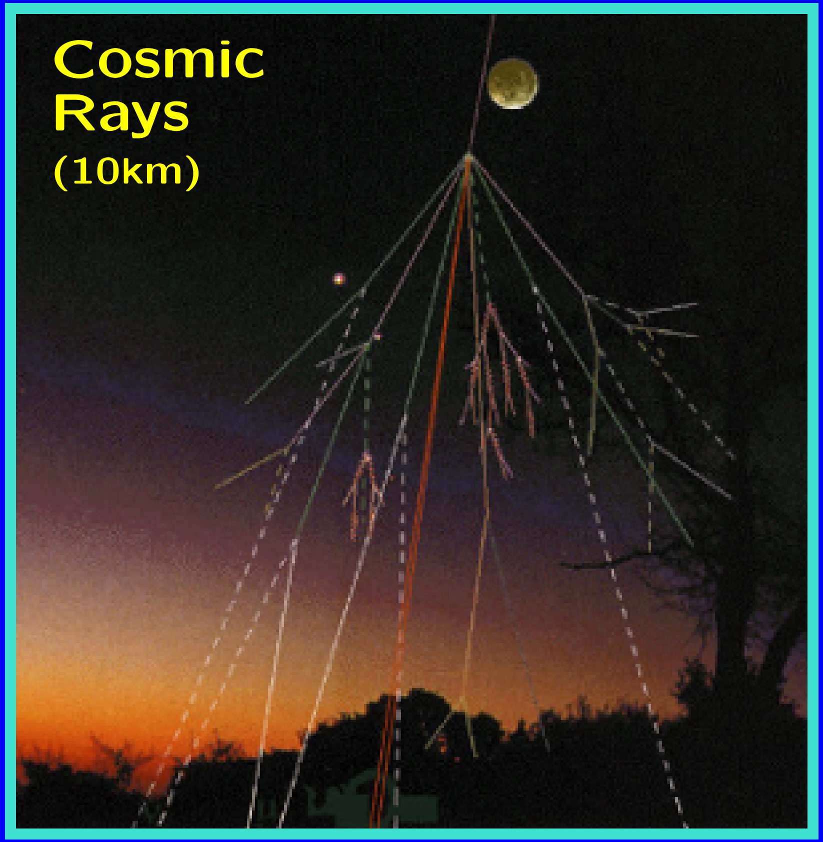
Fermions

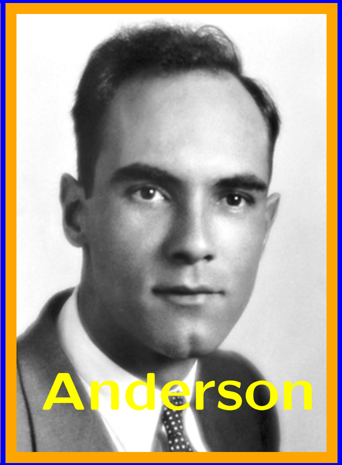


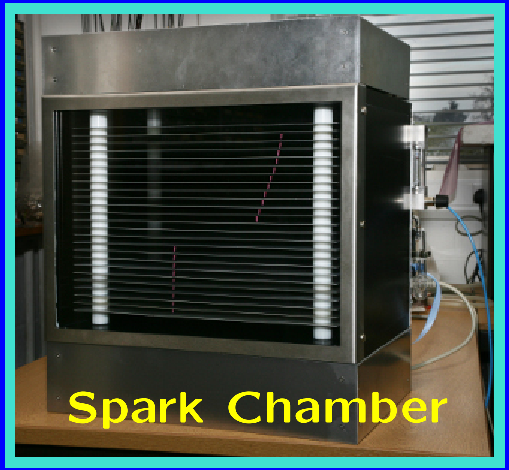
	left				right			
particles	ν_e	e_L^-	u_L	d_L		e_R^-	u_R	d_R
antiparticles		e_L^+	$\bar{u}_L$	$\bar{d}_L$		e_R^+	$\bar{u}_R$	$\bar{d}_R$

μ^- the muon

Raby: "Who ordered that one?"





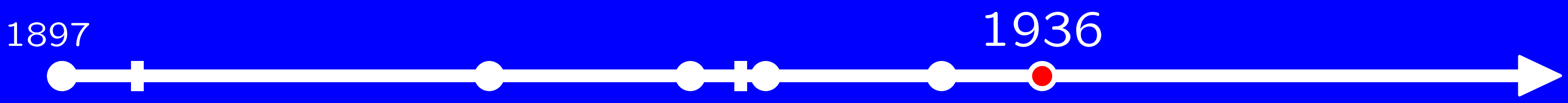


e^-

γ

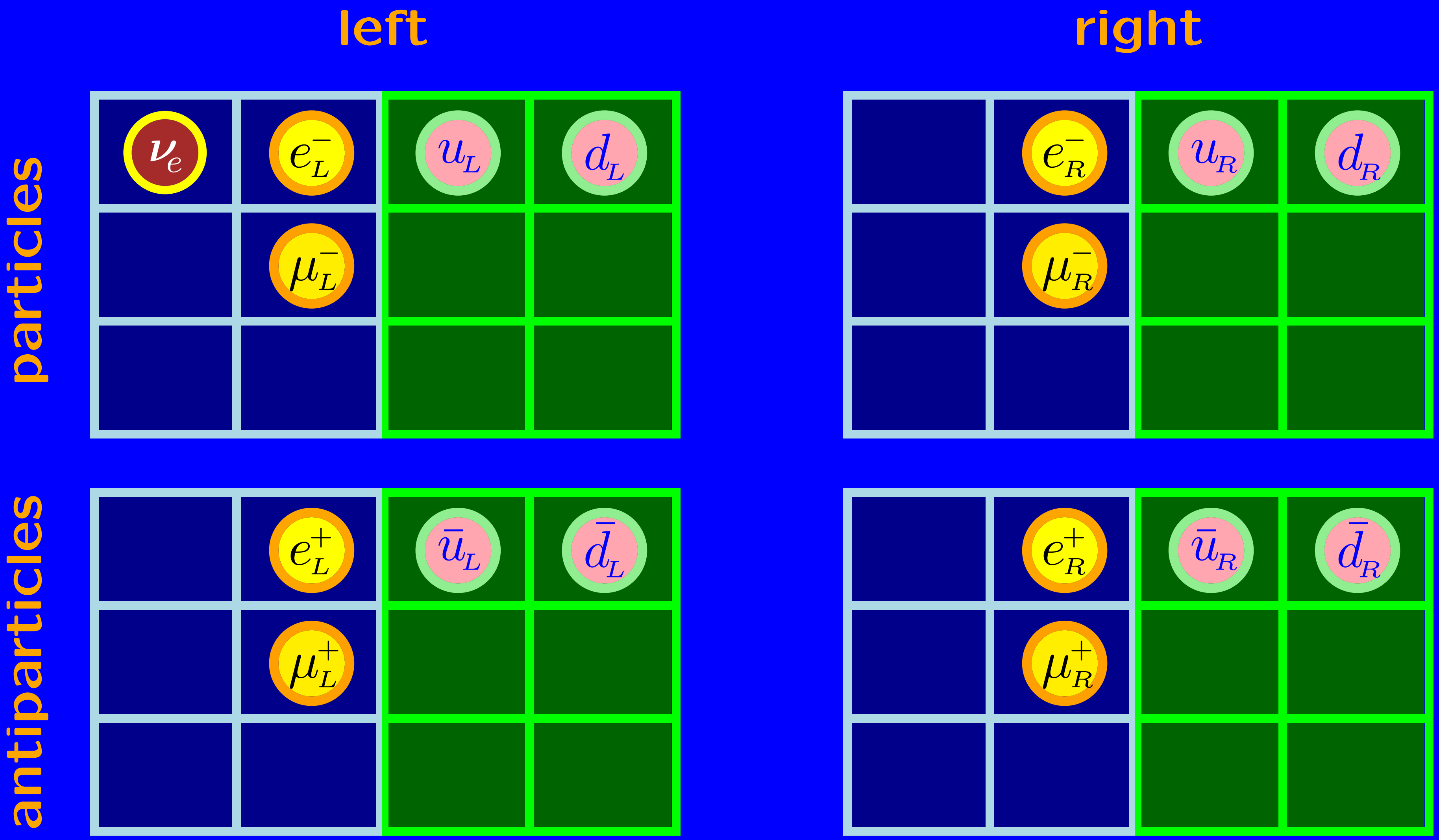
p

n



Particles of the Standard Model:

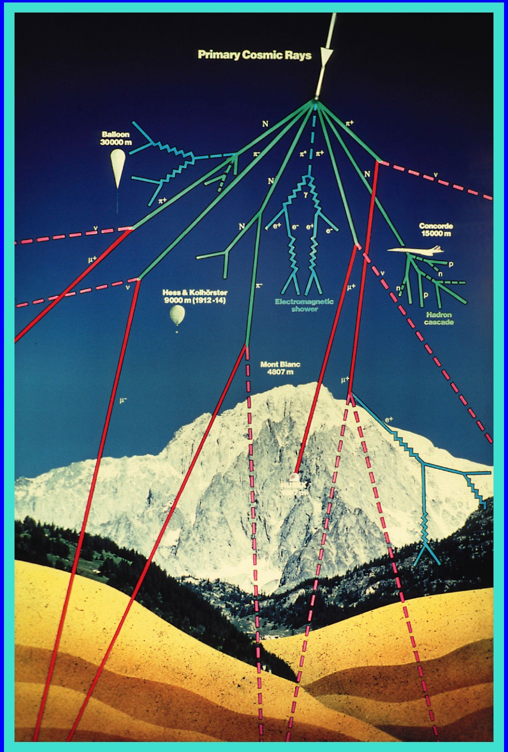
Fermions



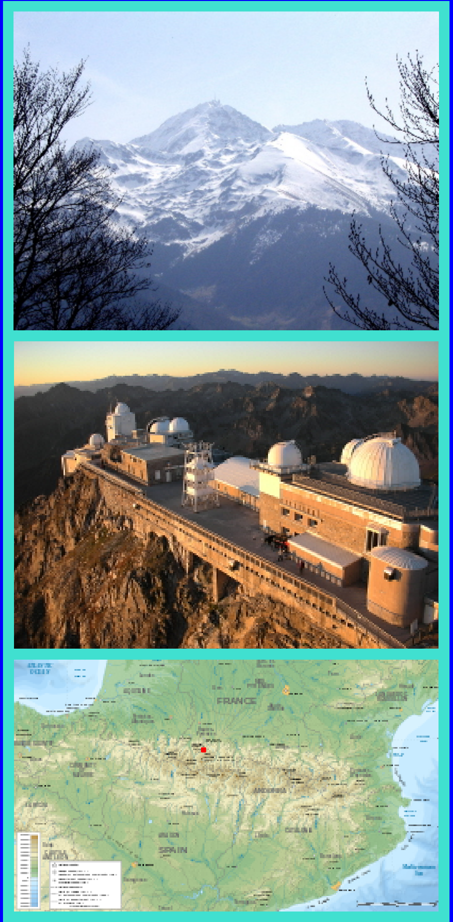
	left				right			
particles	ν_e	e_L^-	u_L	d_L		e_R^-	u_R	d_R
		μ_L^-				μ_R^-		
antiparticles		e_L^+	$\bar{u}_L$	$\bar{d}_L$		e_R^+	$\bar{u}_R$	$\bar{d}_R$
		μ_L^+				μ_R^+		

K strange particles

Λ Σ



Pic du Midi

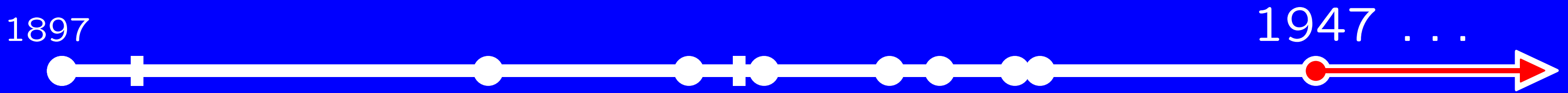


K: **Rochester**
and **Butler**
(Univ. of Manchester)

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

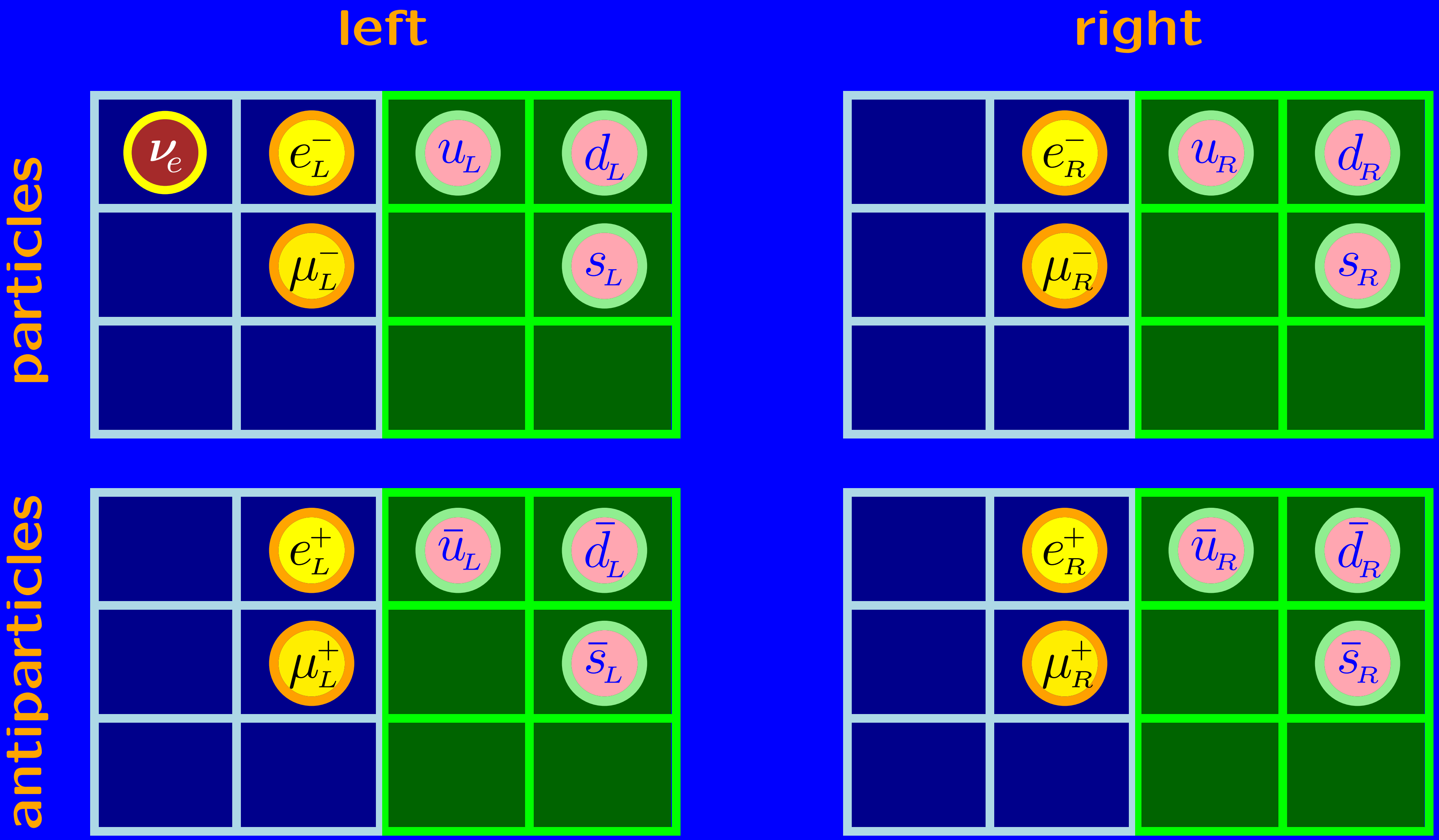
particles in a cloud chamber

e^- γ p n μ^- π e^+ ν



Particles of the Standard Model:

Fermions



left

right

particles

ν_e	e_L^-	u_L	d_L
	μ_L^-		s_L

	e_R^-	u_R	d_R
	μ_R^-		s_R

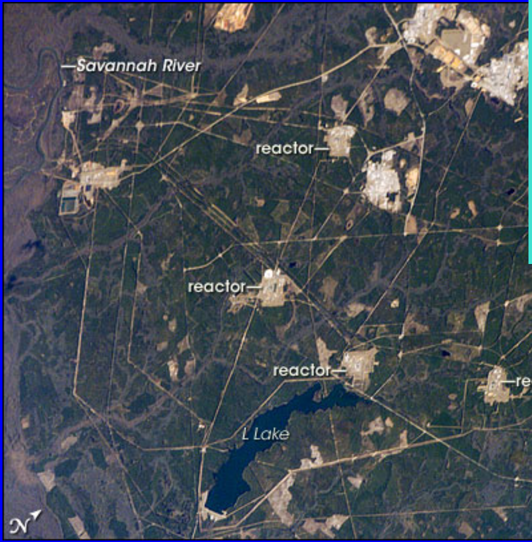
antiparticles

	e_L^+	$\bar{u}_L$	$\bar{d}_L$
	μ_L^+		$\bar{s}_L$

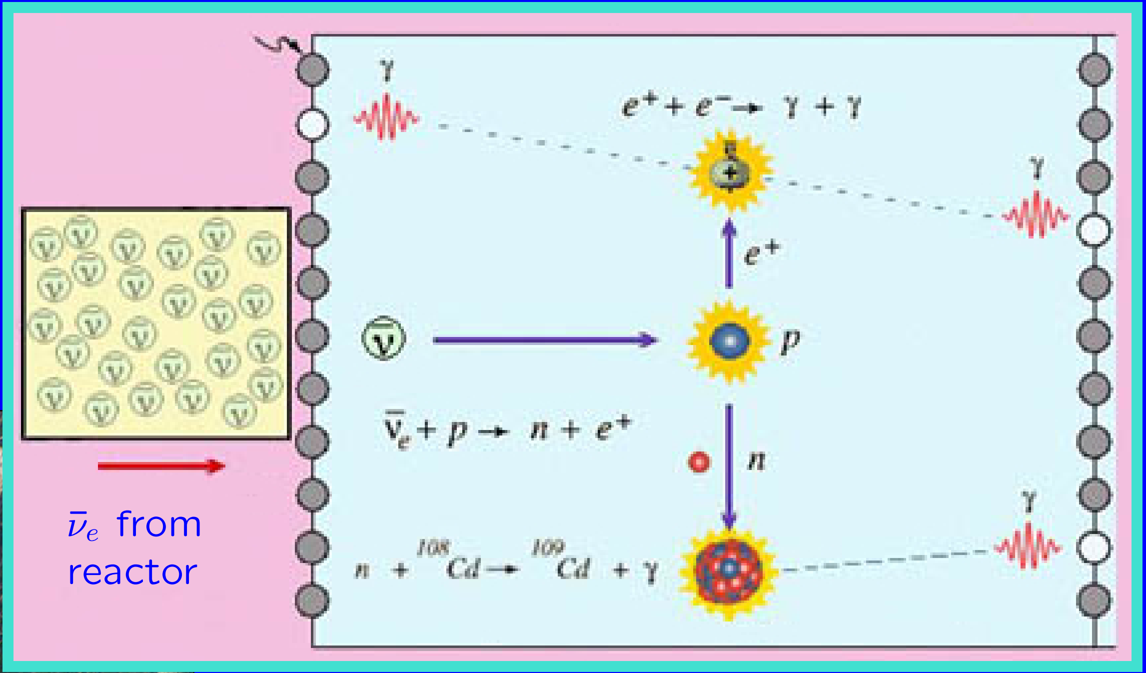
	e_R^+	$\bar{u}_R$	$\bar{d}_R$
	μ_R^+		$\bar{s}_R$

$\bar{\nu}$ antineutrino

Savannah River Site



Cowan–Reines neutrino experiment



$\bar{\nu}_e$ from reactor

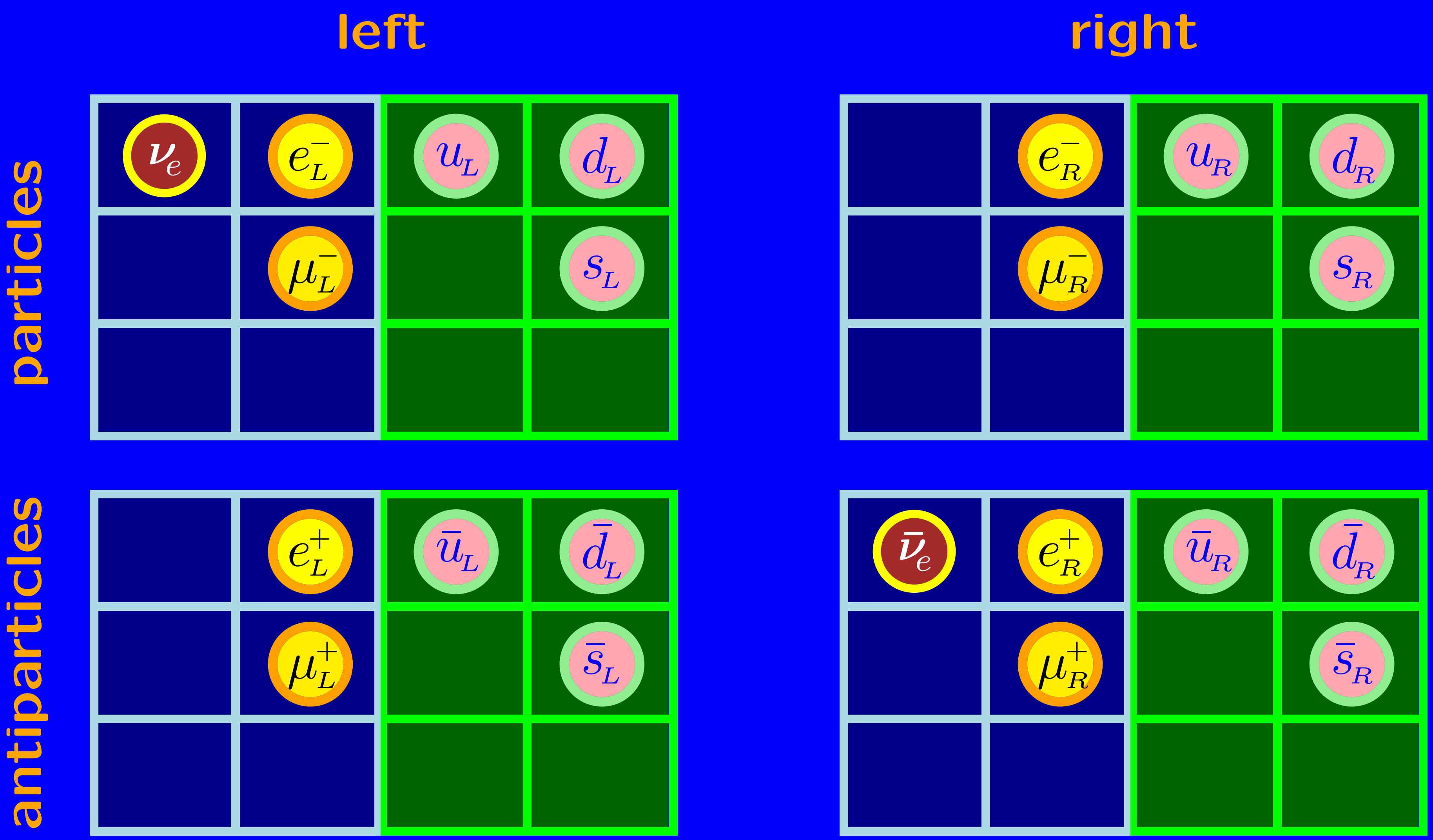
used the antineutrino flux from the nuclear reactors of the Savannah River Site (South Carolina).

e^- γ p n e^+ ν $\bar{p}$

. . . 1956

Particles of the Standard Model:

Fermions



left

right

particles

ν_e	e^-_L	u_L	d_L
	μ^-_L		s_L

	e^-_R	u_R	d_R
	μ^-_R		s_R

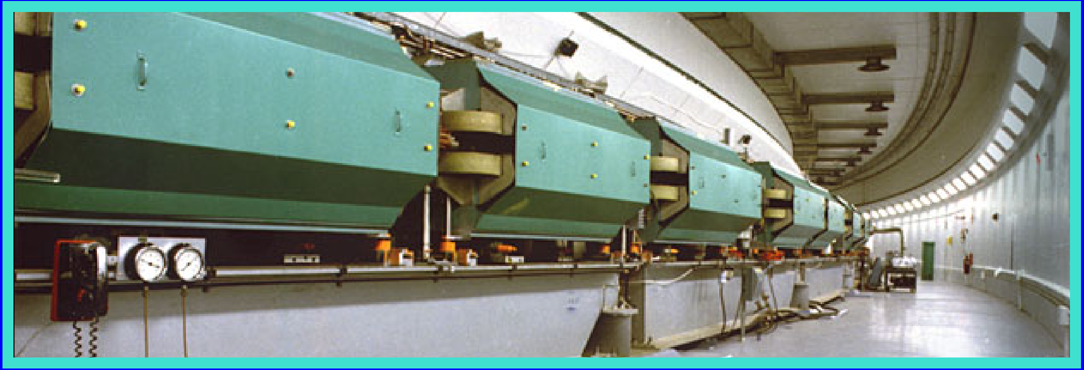
antiparticles

	e^+_L	$\bar{u}_L$	$\bar{d}_L$
	μ^+_L		$\bar{s}_L$

$\bar{\nu}_e$	e^+_R	$\bar{u}_R$	$\bar{d}_R$
	μ^+_R		$\bar{s}_R$

ν_μ muon neutrino

the Alternating Gradient Synchrotron (AGS)

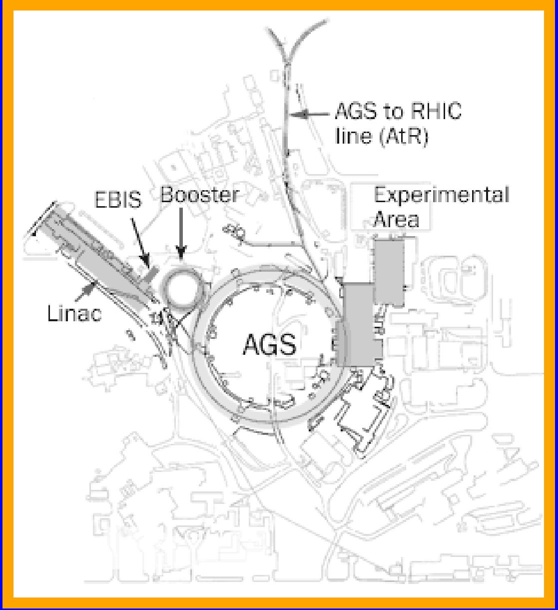


1962

Leon Lederman

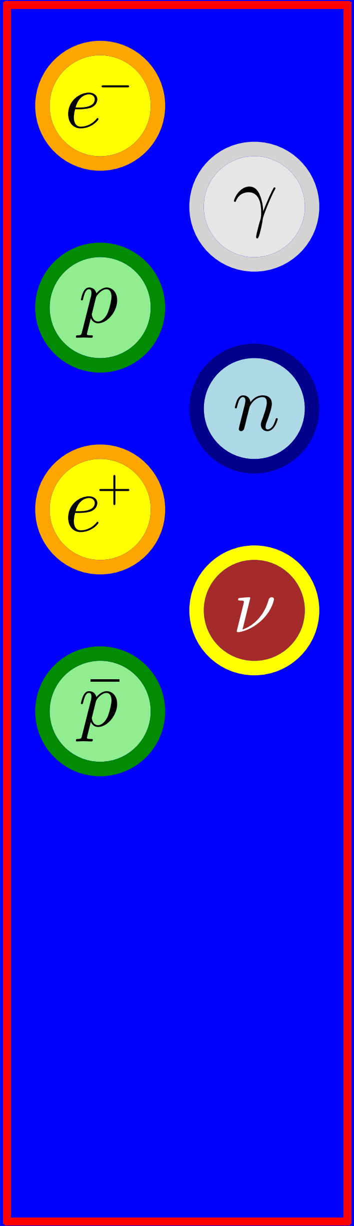
Melvin Schwartz

Jack Steinberger



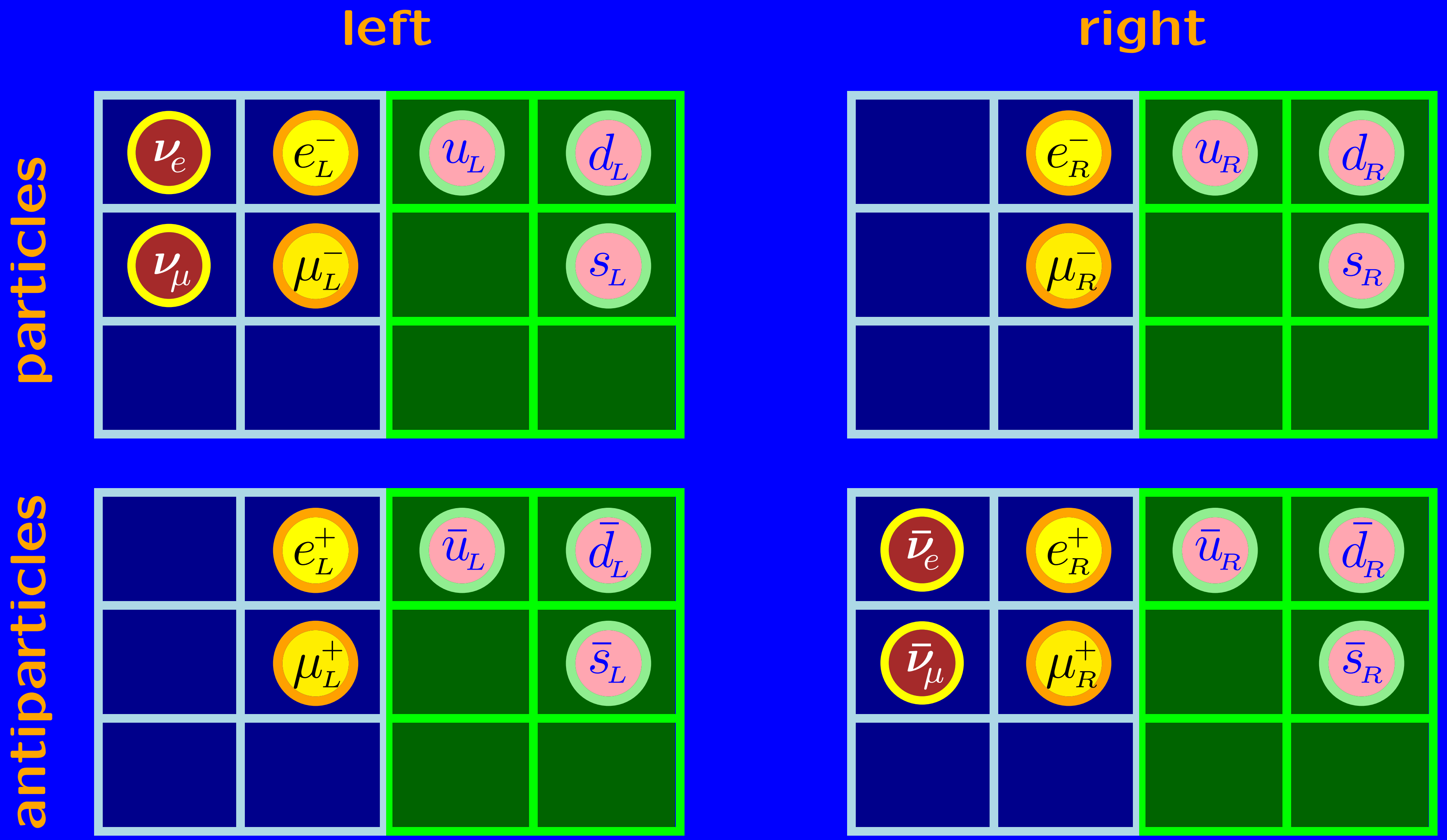
use the pions and kaons of the AGS. These dacays produce also (anti)neutrinos; with a similar setup like the Cowan–Reines experiment they detect muons, but no electrons

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



Particles of the Standard Model:

Fermions



left **right**

particles

ν_e	e^-_L	u_L	d_L
ν_μ	μ^-_L		s_L

	e^-_R	u_R	d_R
	μ^-_R		s_R

antiparticles

	e^+_L	$\bar{u}_L$	$\bar{d}_L$
	μ^+_L		$\bar{s}_L$

$\bar{\nu}_e$	e^+_R	$\bar{u}_R$	$\bar{d}_R$
$\bar{\nu}_\mu$	μ^+_R		$\bar{s}_R$

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

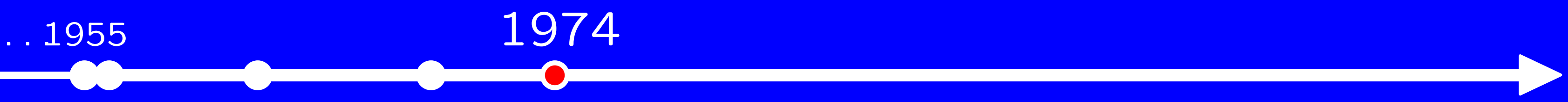
γ

ν

e^-

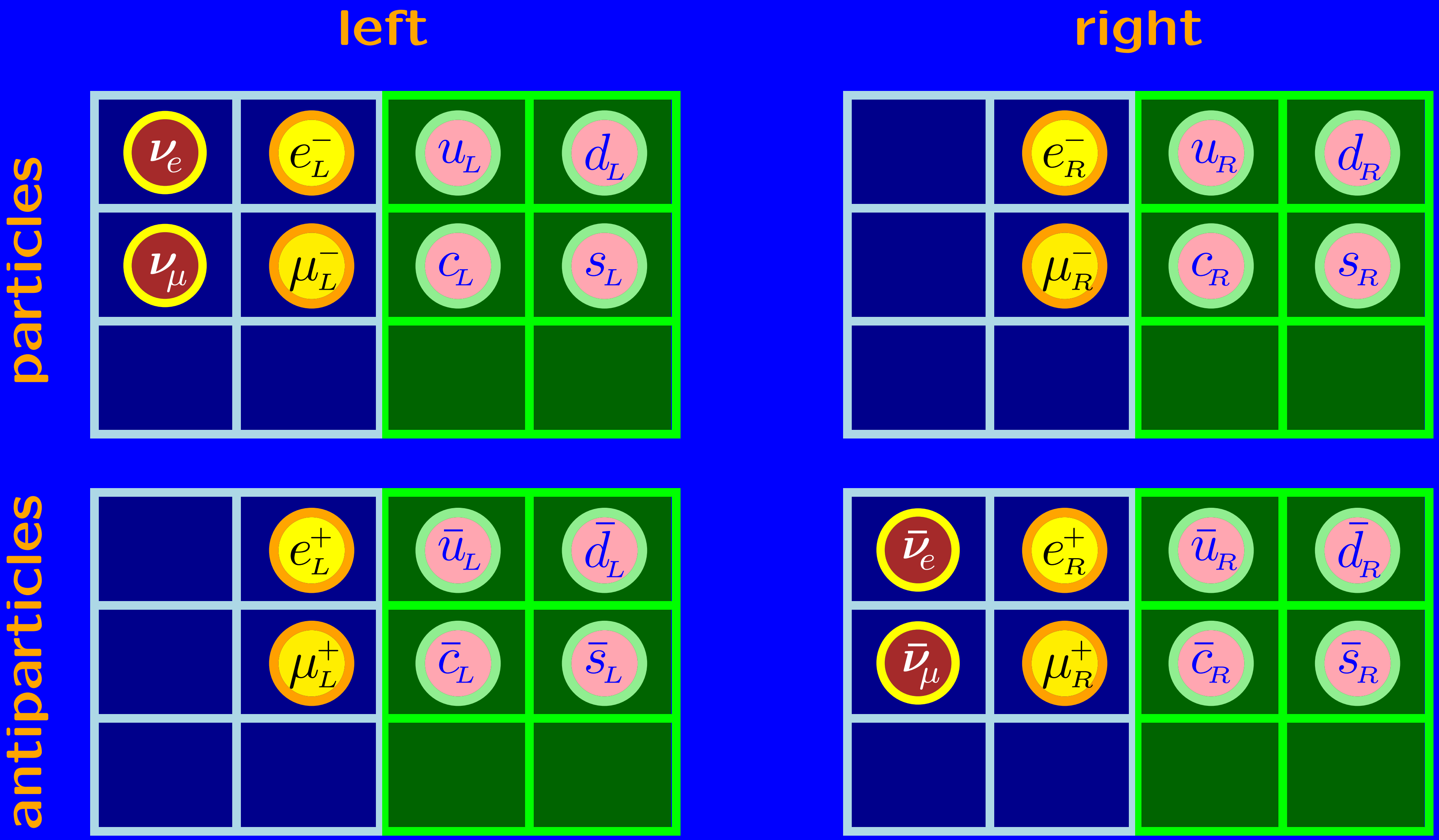
c

d



Particles of the Standard Model:

Fermions



left

right

particles

ν_e	e_L^-	u_L	d_L		e_R^-	u_R	d_R
ν_μ	μ_L^-	c_L	s_L		μ_R^-	c_R	s_R

antiparticles

	e_L^+	$\bar{u}_L$	$\bar{d}_L$	$\bar{\nu}_e$	e_R^+	$\bar{u}_R$	$\bar{d}_R$
	μ_L^+	$\bar{c}_L$	$\bar{s}_L$	$\bar{\nu}_\mu$	μ_R^+	$\bar{c}_R$	$\bar{s}_R$

τ^- τ lepton

Martin Perl

(SLAC-LBL)

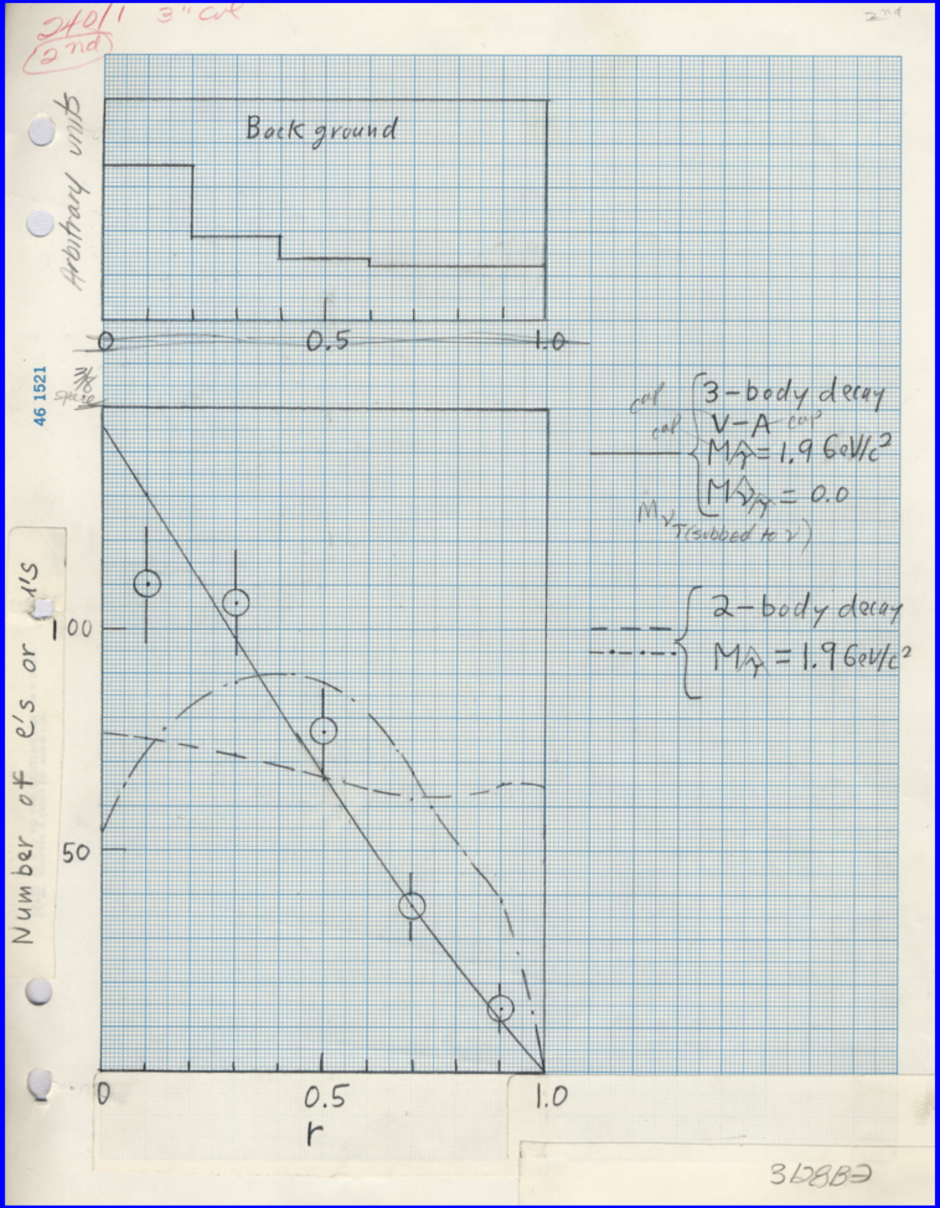
1975

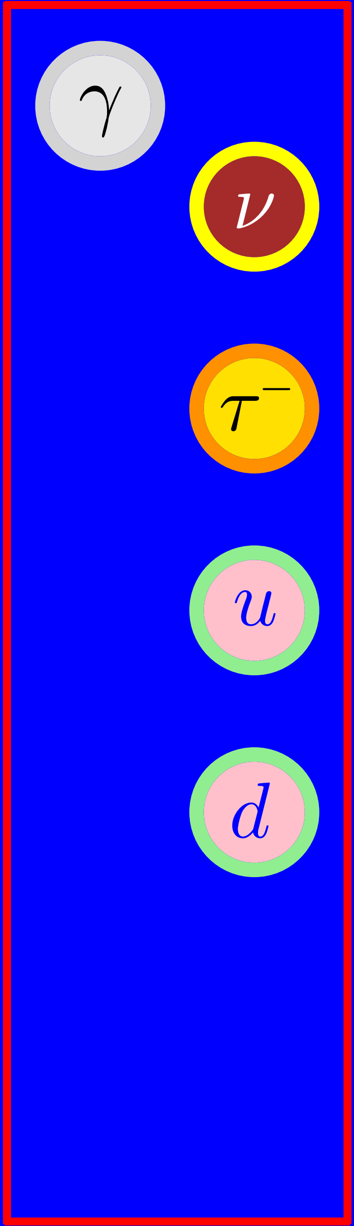
- using Mark I

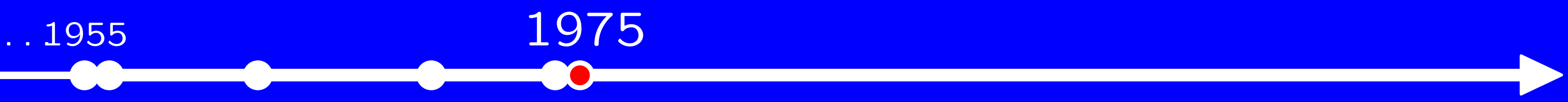
  (SLAC-LBL Magnetic Detector)

  - first 4π-detector

- comparing **signal** to **background**

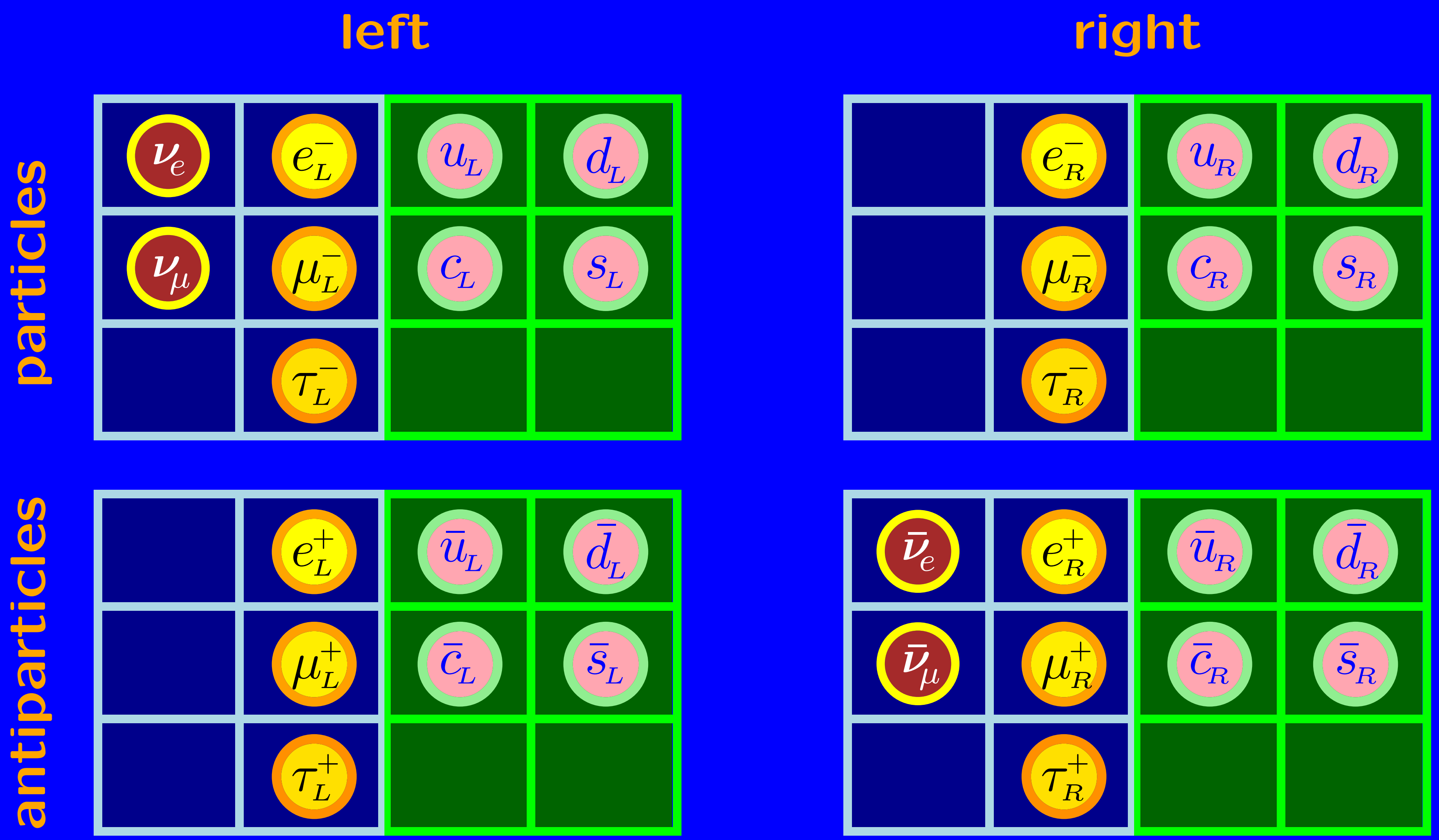






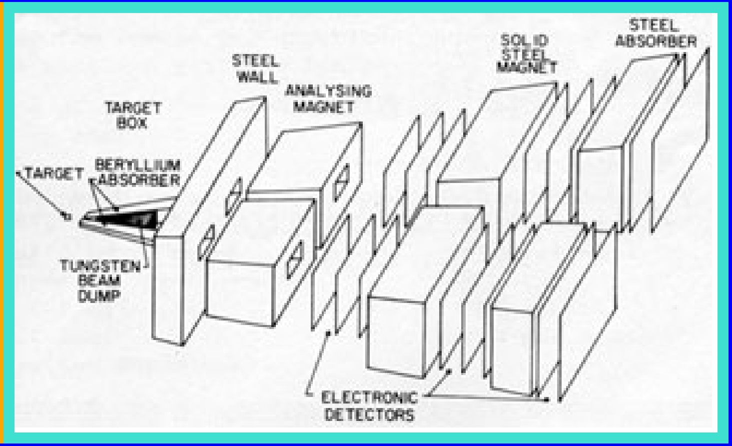
Particles of the Standard Model:

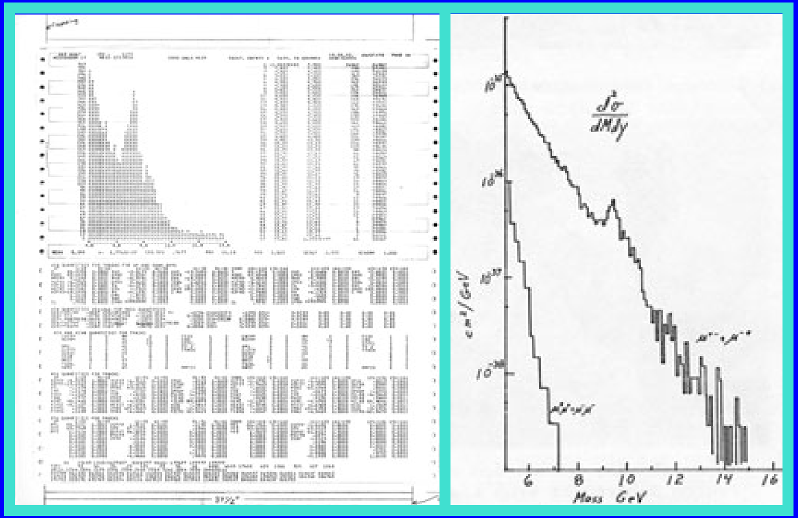
Fermions



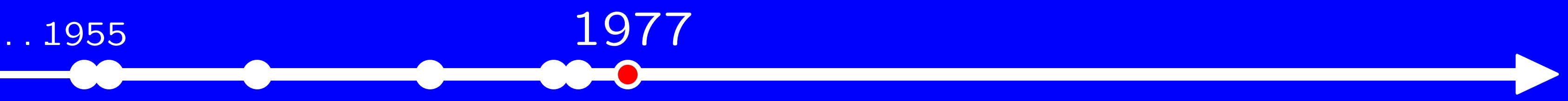
	left				right			
particles	ν_e	e^-_L	u_L	d_L		e^-_R	u_R	d_R
	ν_μ	μ^-_L	c_L	s_L		μ^-_R	c_R	s_R
		τ^-_L				τ^-_R		
antiparticles		e^+_L	$\bar{u}_L$	$\bar{d}_L$	$\bar{\nu}_e$	e^+_R	$\bar{u}_R$	$\bar{d}_R$
		μ^+_L	$\bar{c}_L$	$\bar{s}_L$	$\bar{\nu}_\mu$	μ^+_R	$\bar{c}_R$	$\bar{s}_R$
		τ^+_L				τ^+_R		

b bottom quark: Υ





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



γ

ν

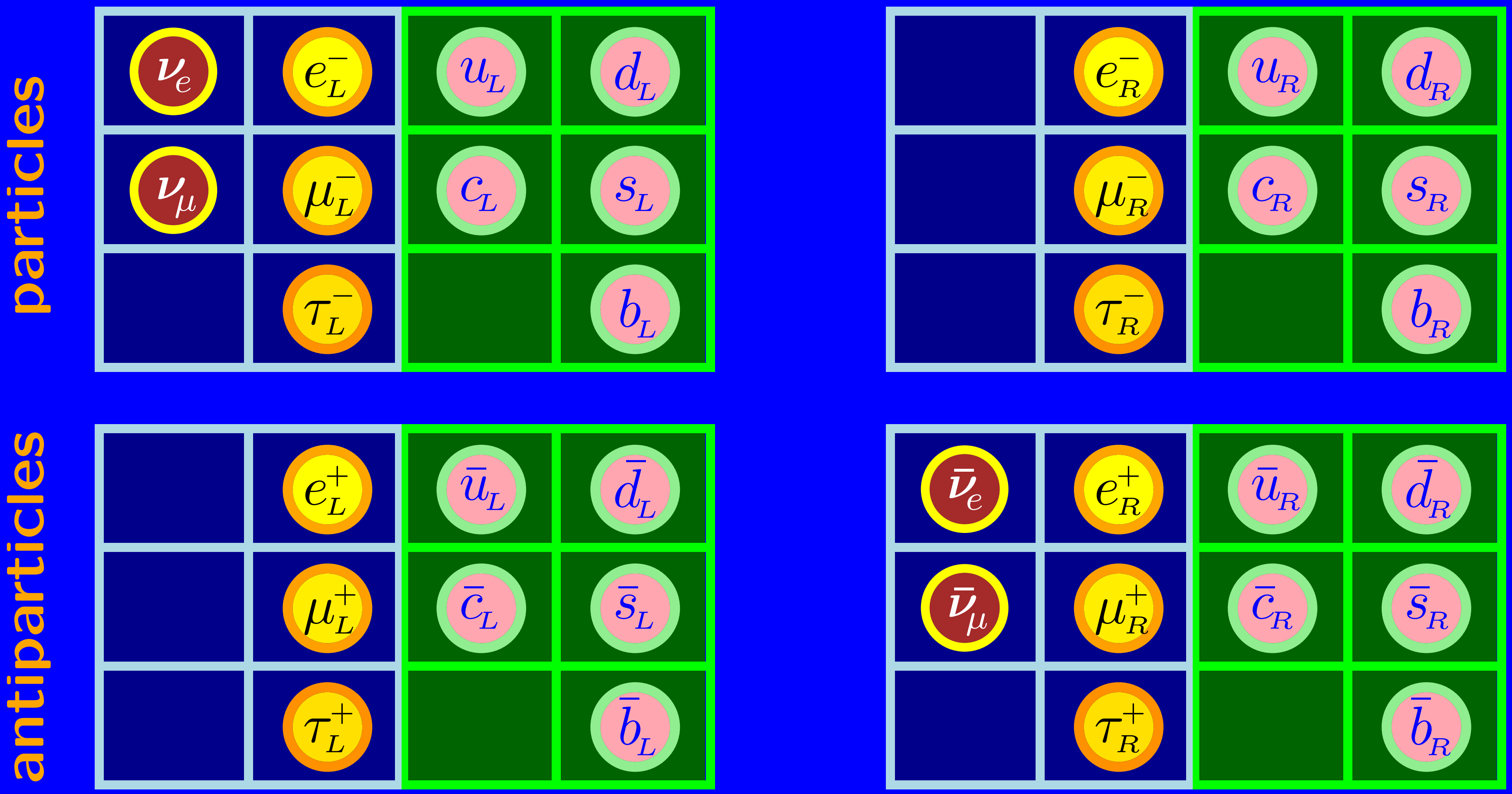
e^-

u

b

Particles of the Standard Model:

Fermions



particles

left

ν_e	e_L^-	u_L	d_L
ν_μ	μ_L^-	c_L	s_L
	τ_L^-		b_L

right

	e_R^-	u_R	d_R
	μ_R^-	c_R	s_R
	τ_R^-		b_R

antiparticles

left

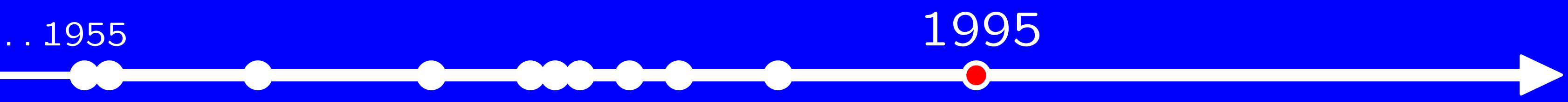
	e_L^+	$\bar{u}_L$	$\bar{d}_L$
	μ_L^+	$\bar{c}_L$	$\bar{s}_L$
	τ_L^+		$\bar{b}_L$

right

$\bar{\nu}_e$	e_R^+	$\bar{u}_R$	$\bar{d}_R$
$\bar{\nu}_\mu$	μ_R^+	$\bar{c}_R$	$\bar{s}_R$
	τ_R^+		$\bar{b}_R$

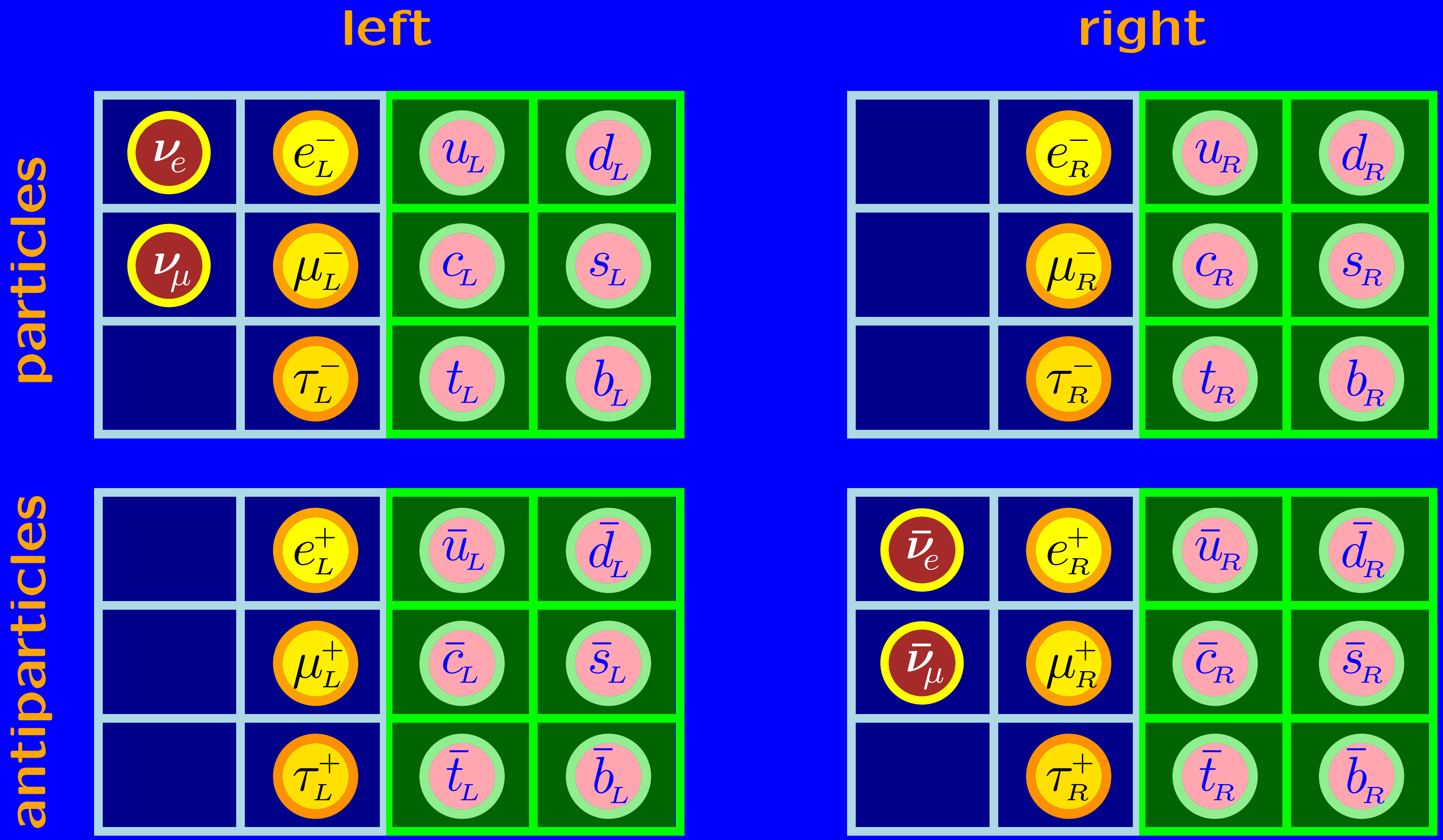
t top quark

γ ν_τ W τ^- Z t g b



Particles of the Standard Model:

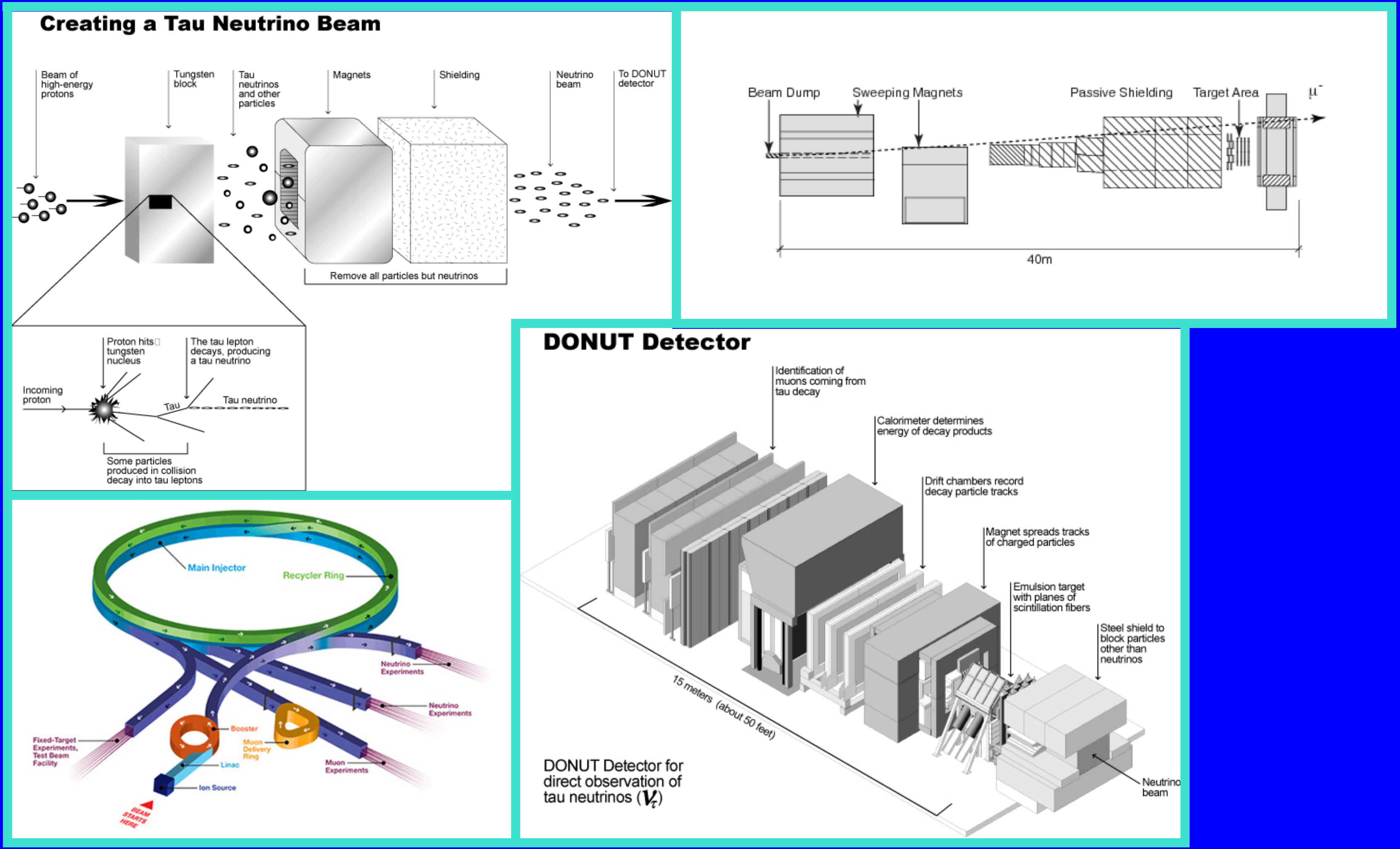
Fermions



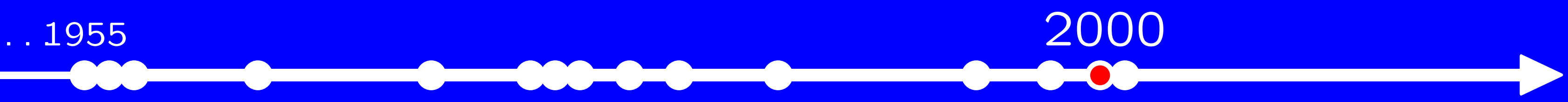
	left				right			
particles	ν_e	e_L^-	u_L	d_L		e_R^-	u_R	d_R
	ν_μ	μ_L^-	c_L	s_L		μ_R^-	c_R	s_R
		τ_L^-	t_L	b_L		τ_R^-	t_R	b_R
antiparticles		e_L^+	$\bar{u}_L$	$\bar{d}_L$	$\bar{\nu}_e$	e_R^+	$\bar{u}_R$	$\bar{d}_R$
		μ_L^+	$\bar{c}_L$	$\bar{s}_L$	$\bar{\nu}_\mu$	μ_R^+	$\bar{c}_R$	$\bar{s}_R$
		τ_L^+	$\bar{t}_L$	$\bar{b}_L$		τ_R^+	$\bar{t}_R$	$\bar{b}_R$

ν_τ tau neutrino

Discovery by the DONUT collaboration (E872 Fermilab)

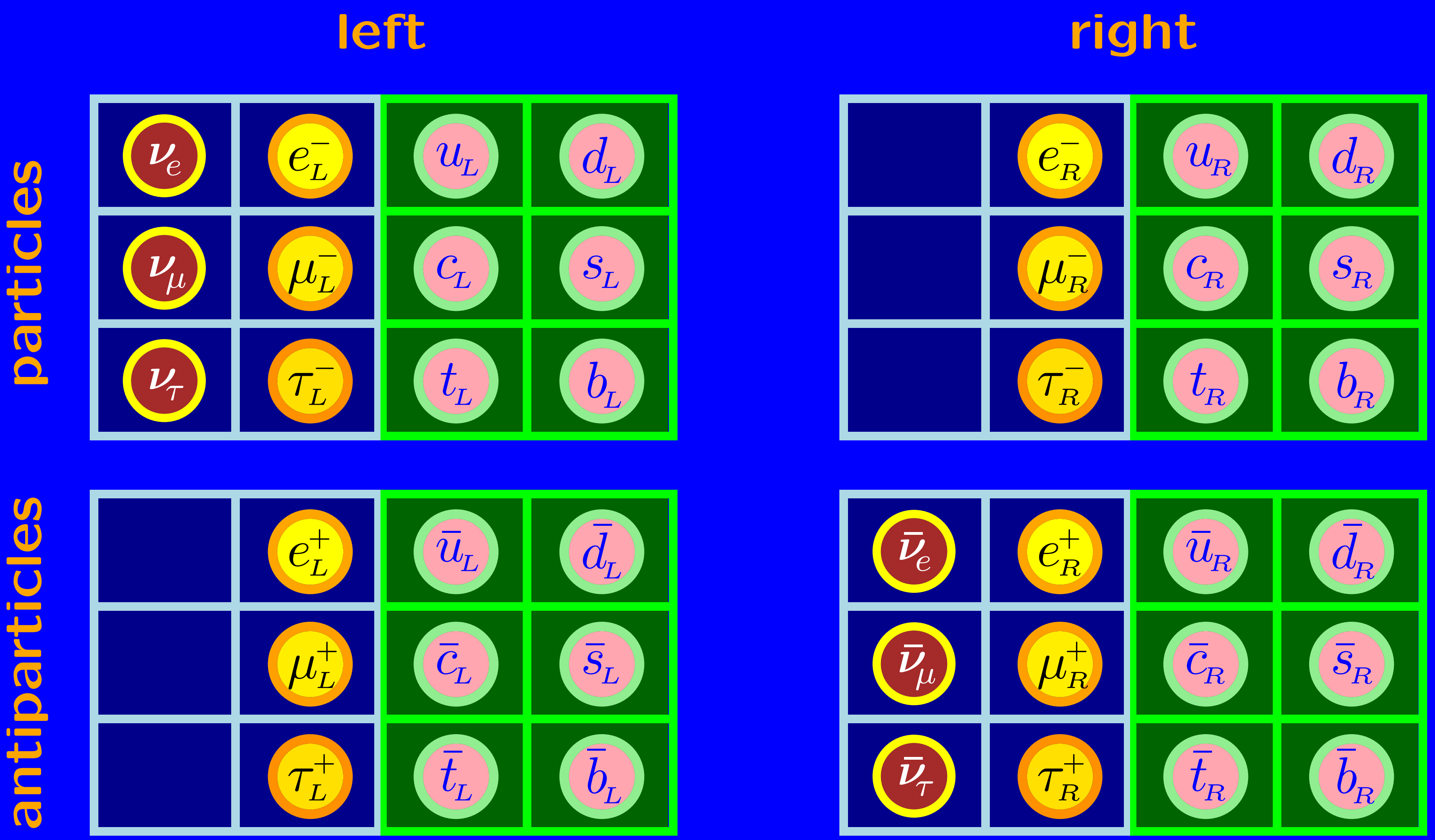


γ ν_τ W τ^- Z t g b

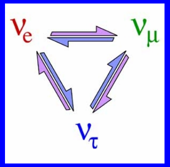


Particles of the Standard Model:

Fermions

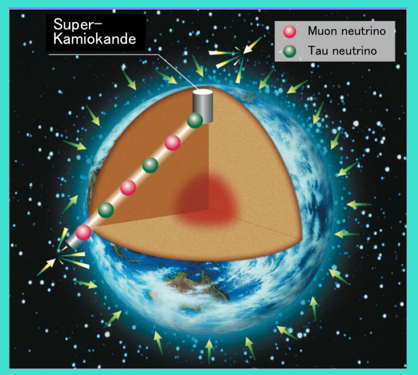


	left				right			
particles	$\boldsymbol{\nu}_e$	e^-_L	u_L	d_L		e^-_R	u_R	d_R
	$\boldsymbol{\nu}_\mu$	μ^-_L	c_L	s_L		μ^-_R	c_R	s_R
	$\boldsymbol{\nu}_\tau$	τ^-_L	t_L	b_L		τ^-_R	t_R	b_R
antiparticles		e^+_L	$\bar{u}_L$	$\bar{d}_L$	$\bar{\boldsymbol{\nu}}_e$	e^+_R	$\bar{u}_R$	$\bar{d}_R$
		μ^+_L	$\bar{c}_L$	$\bar{s}_L$	$\bar{\boldsymbol{\nu}}_\mu$	μ^+_R	$\bar{c}_R$	$\bar{s}_R$
		τ^+_L	$\bar{t}_L$	$\bar{b}_L$	$\bar{\boldsymbol{\nu}}_\tau$	τ^+_R	$\bar{t}_R$	$\bar{b}_R$

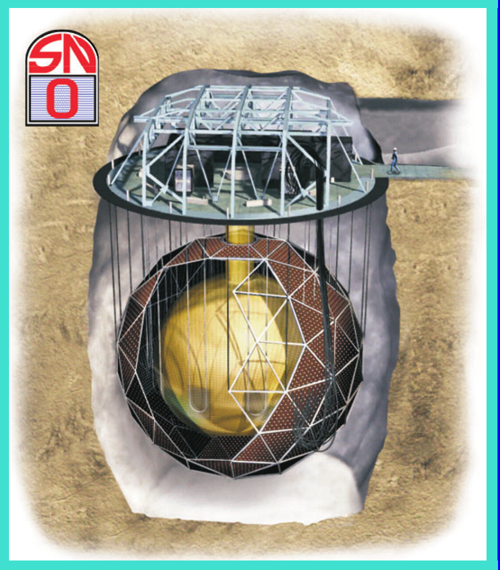


neutrino oscillations

1957 predicted by **B. Pontecorvo**

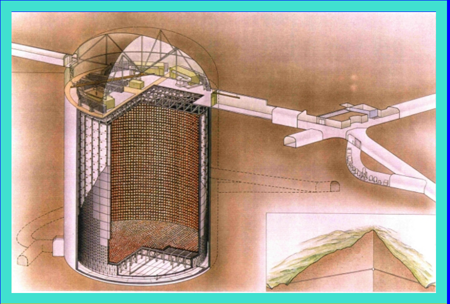


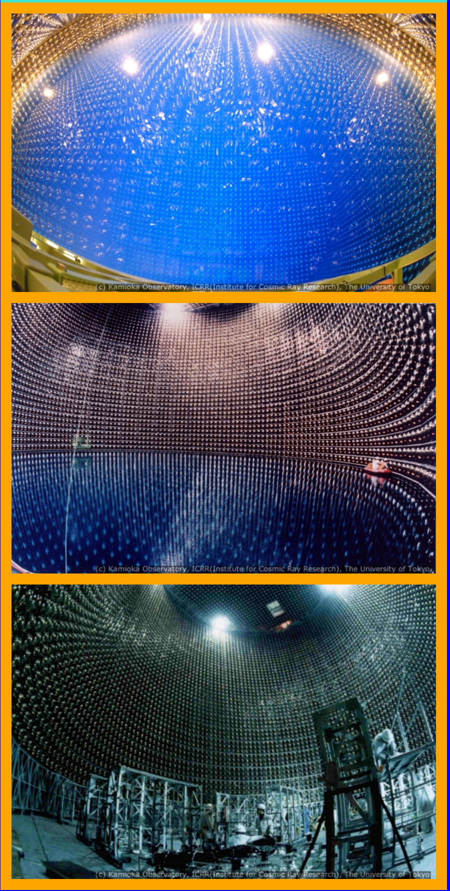
Super Kamiokande (SK) announces first experimental evidence for **atmospheric neutrino oscillations** in **1998**



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

only then the solar neutrino puzzle was solved





(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

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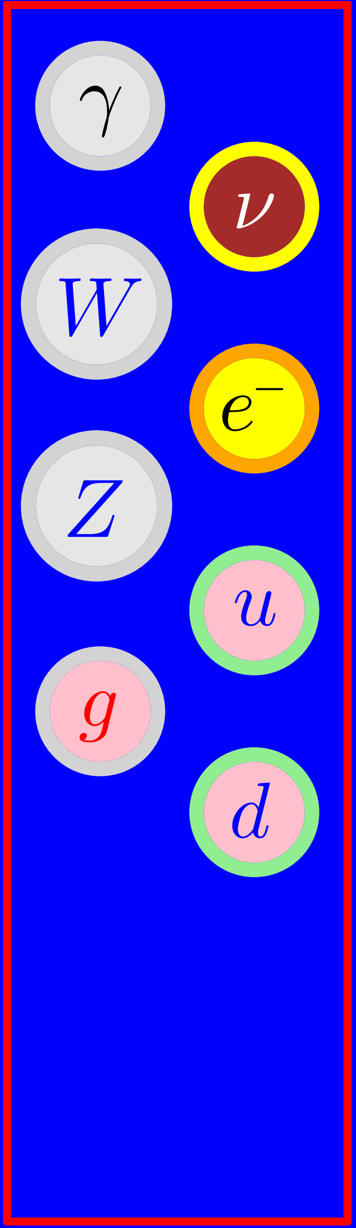
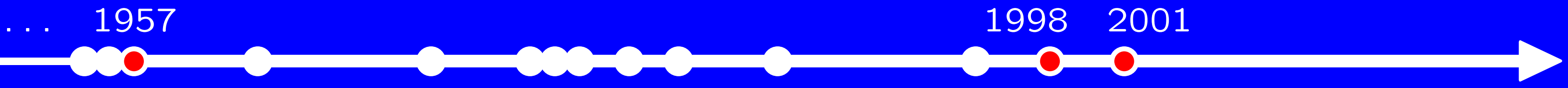




Neutrino oscillations: $\nu_e \longleftrightarrow \nu_\mu \longleftrightarrow \nu_\tau$

★ 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

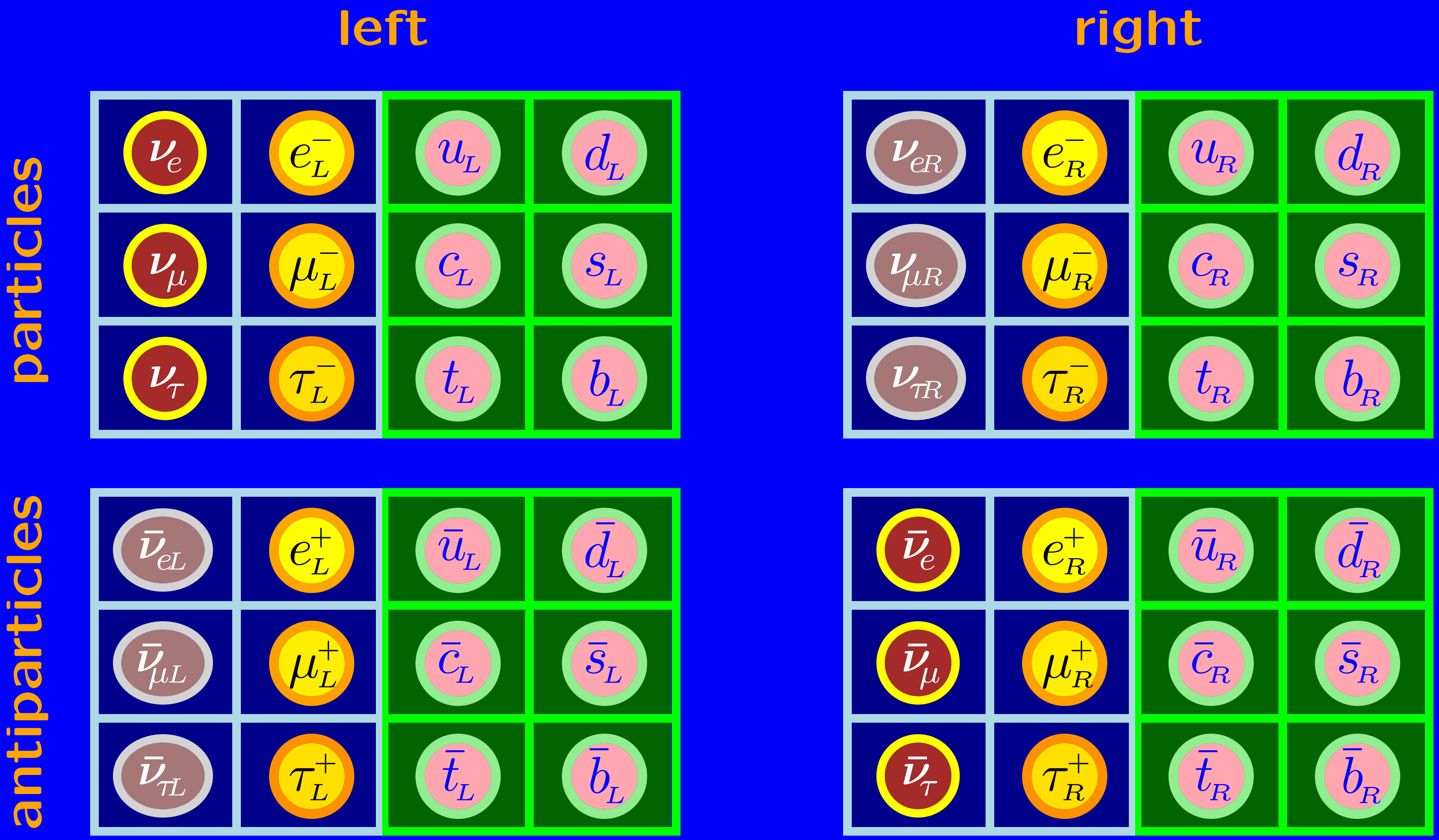
↳ no interaction except the mass-term

→ their existence does not change

(the predictions of) the Standard Model !

Particles of the Standard Model:

Fermions



	left				right			
particles	ν_e	e_L^-	u_L	d_L	ν_{eR}	e_R^-	u_R	d_R
	ν_μ	μ_L^-	c_L	s_L	$\nu_{\mu R}$	μ_R^-	c_R	s_R
	ν_τ	τ_L^-	t_L	b_L	$\nu_{\tau R}$	τ_R^-	t_R	b_R
antiparticles	$\bar{\nu}_{eL}$	e_L^+	$\bar{u}_L$	$\bar{d}_L$	$\bar{\nu}_e$	e_R^+	$\bar{u}_R$	$\bar{d}_R$
	$\bar{\nu}_{\mu L}$	μ_L^+	$\bar{c}_L$	$\bar{s}_L$	$\bar{\nu}_\mu$	μ_R^+	$\bar{c}_R$	$\bar{s}_R$
	$\bar{\nu}_{\tau L}$	τ_L^+	$\bar{t}_L$	$\bar{b}_L$	$\bar{\nu}_\tau$	τ_R^+	$\bar{t}_R$	$\bar{b}_R$

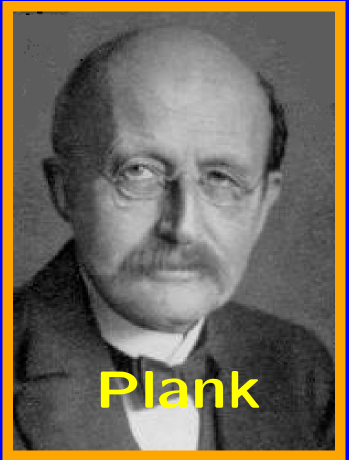
Particles of the Standard Model:

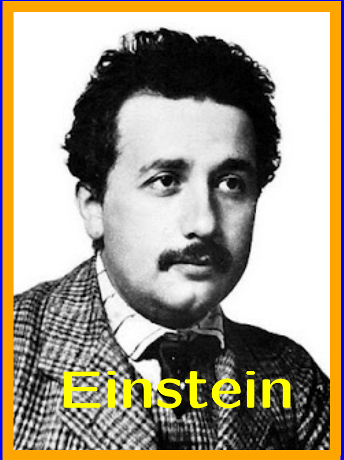
Gauge Bosons

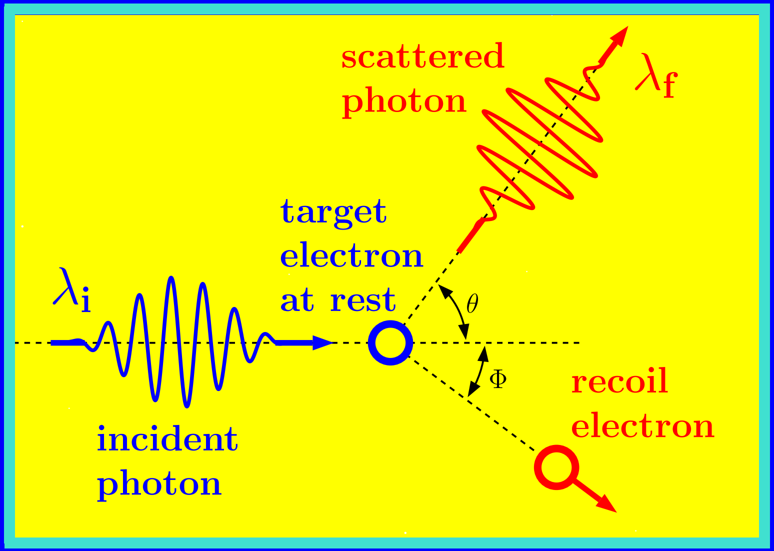
1. screening in QED
    - Vacuum polarization
    - running coupling constant
2. anti-screening in QCD
    - asymptotic freedom
    - confinement
3. massive vector bosons

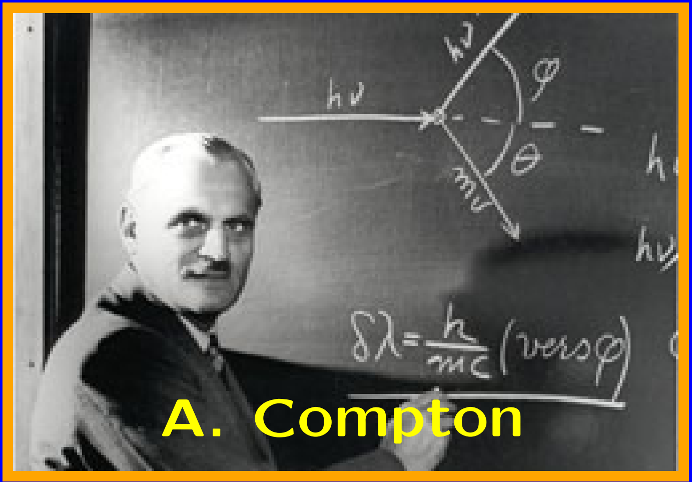
γ the photon

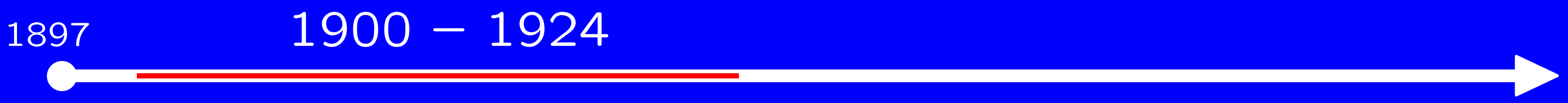
e^-





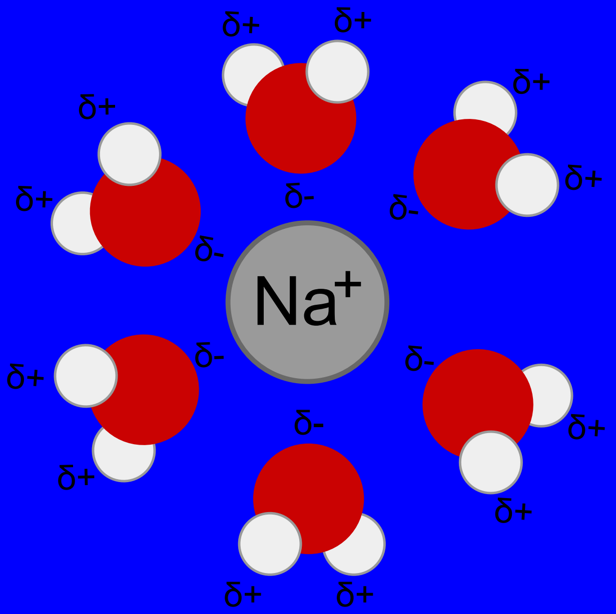






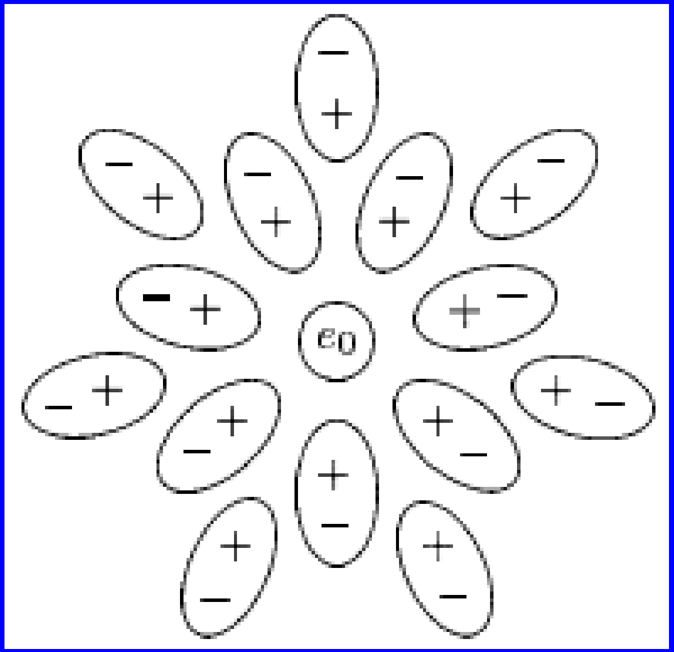
screening

- the effective charge of an ion in a dielectric medium is reduced by the dielectric molecules surrounding the charge



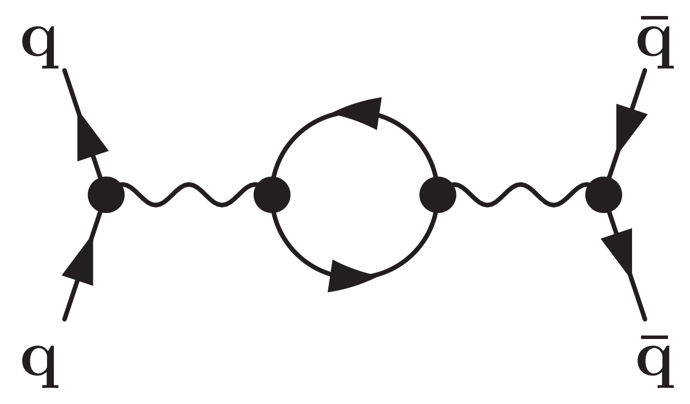
- the same happens in the vacuum:
  - if one looks at the charge with sufficient energy to see virtual electron-positron pairs

→ Vacuum polarization !



screening

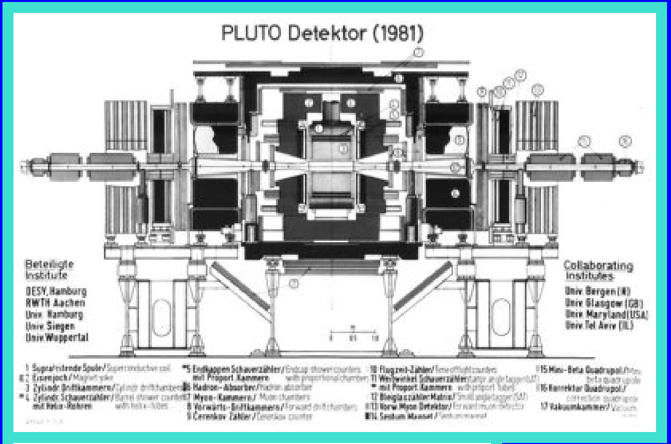
- the energy dependence of the effective charge in the vacuum due to the Vacuum polarization is described by the

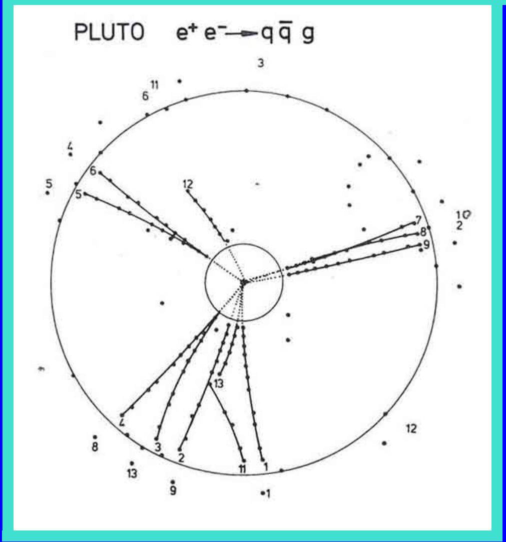


★ running coupling

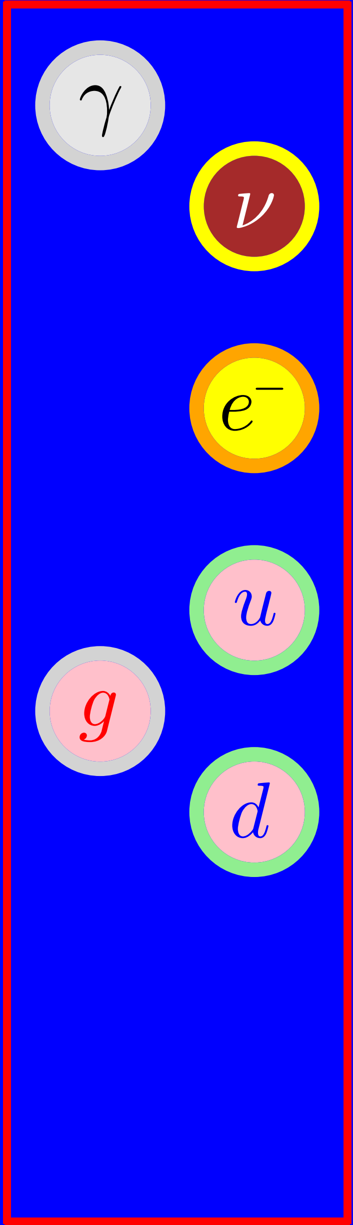
$$\alpha_{\mathrm{em}}(Q^2) = \frac{\alpha_0}{1 - \frac{\alpha_0}{3\pi} \ln[\frac{Q^2}{m_e^2}]}$$

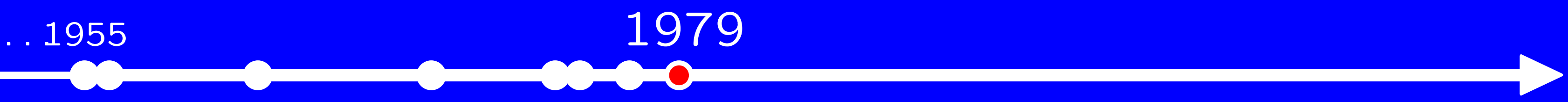
g gluon





the consistent interpretation of **3-jet events** as **gluon bremsstrahlung** in the framework of QCD, done in PLUTO, TASSO, MARK-J, and JADE (experiments at PETRA, DESY), marks the discovery of the gluon **1979**

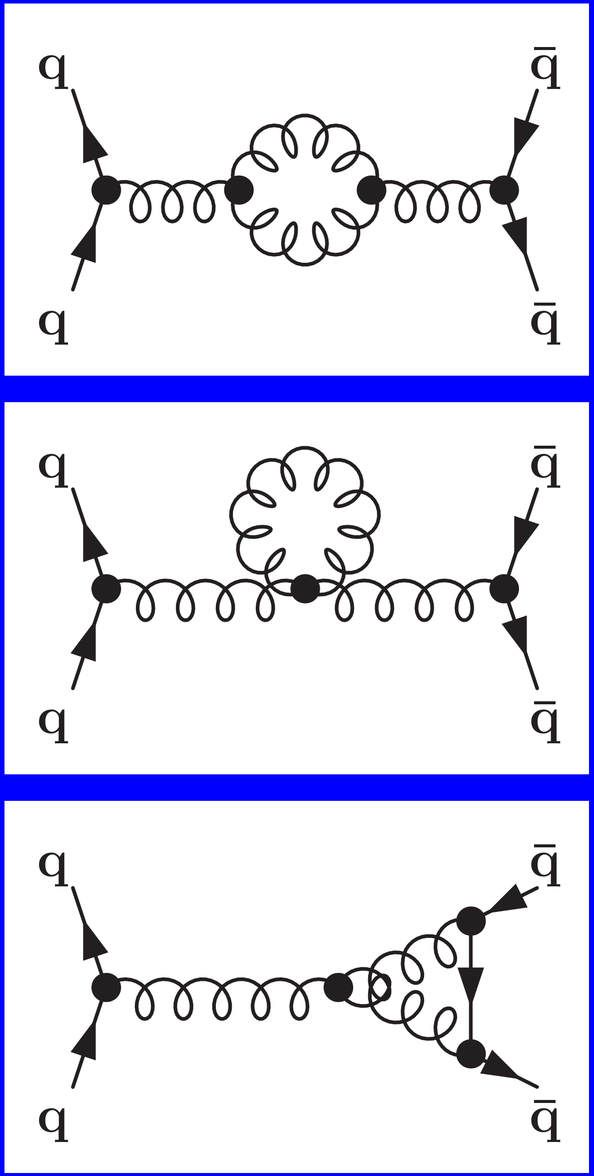




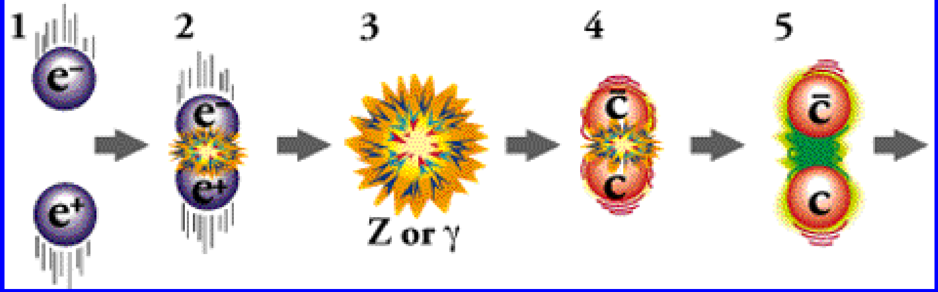
anti-screening

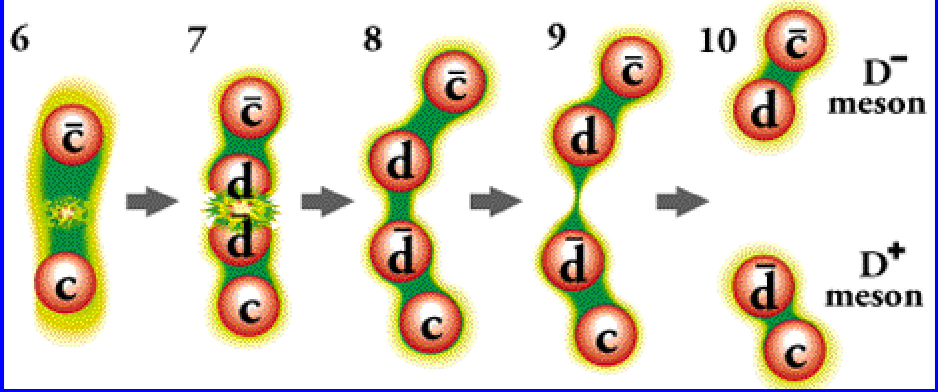
- the self couplings in QCD have the opposite effect for the color charges
  - the closer one looks, the weaker the charges seem to become

➡ asymptotic freedom !



anti-screening





- at high energies (colliders)
  - we have no problem to separate color charges
- at lower energies
  - the force connecting the charges seems to become stronger

→ strong enough that the potential (= force * distance) creates a quark-antiquark pair, that restores color neutrality

→ color confinement !

color confinement

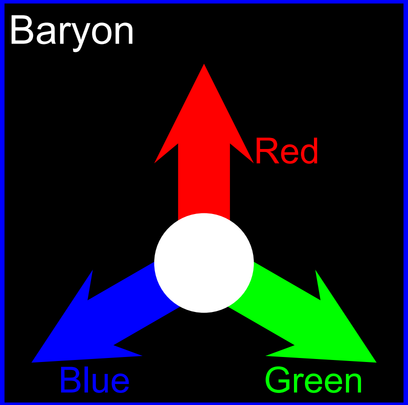
- low energy states have to be color neutral

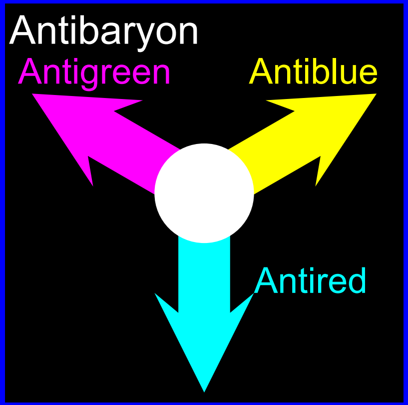
➡ we can only observe color neutral particles

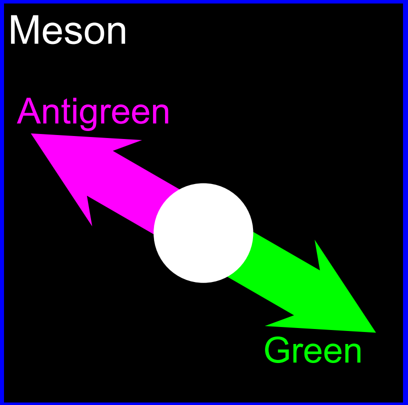
- the strong force hides inside the nucleons

- the nuclear force is more like a van der Waals force:
  - mediated by mesons (quark – antiquark pairs)

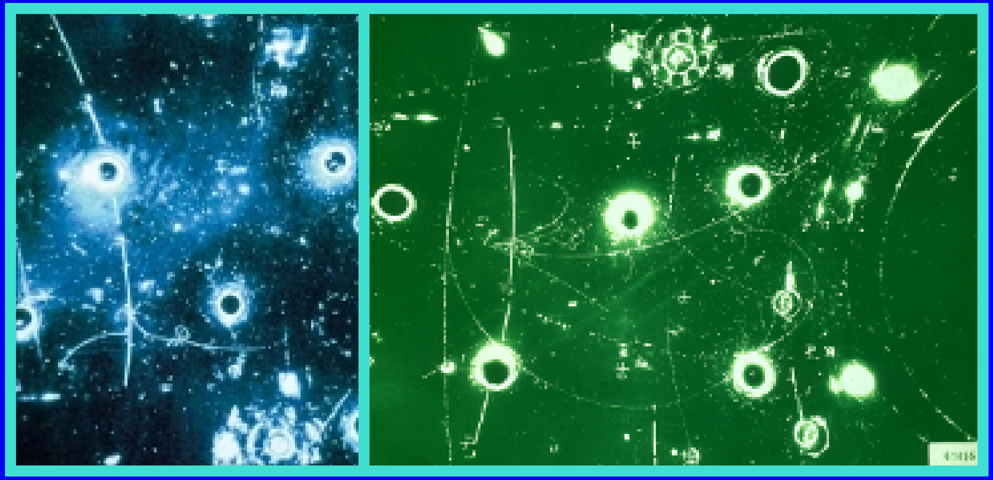
➡ Baryons and Mesons are color singlets





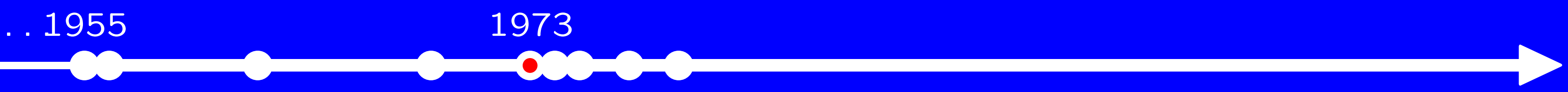


W Z hints for $W^{\pm}$- and Z-boson



Weak charged currents were known from neutrino detection.

CERN announced the experimental observation of **weak neutral currents**, shortly after they were predicted by the electroweak theory of Abdus Salam, Sheldon Glashow and Steven Weinberg.

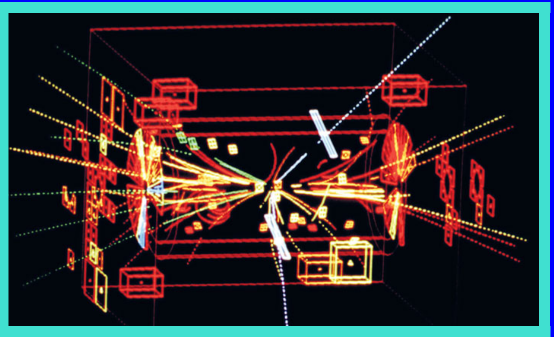


γ ν W e^- u g d

W Z $W^{\pm}$- and Z-boson

event in the UA1 detector

Z-event in UA1

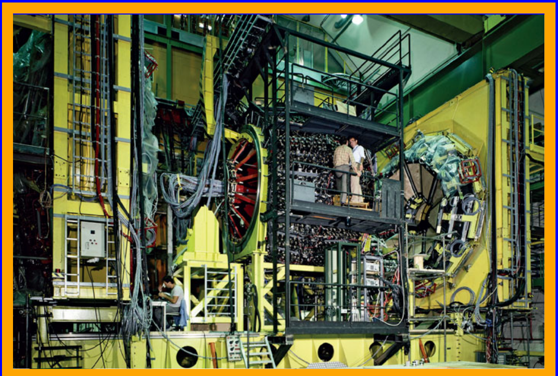


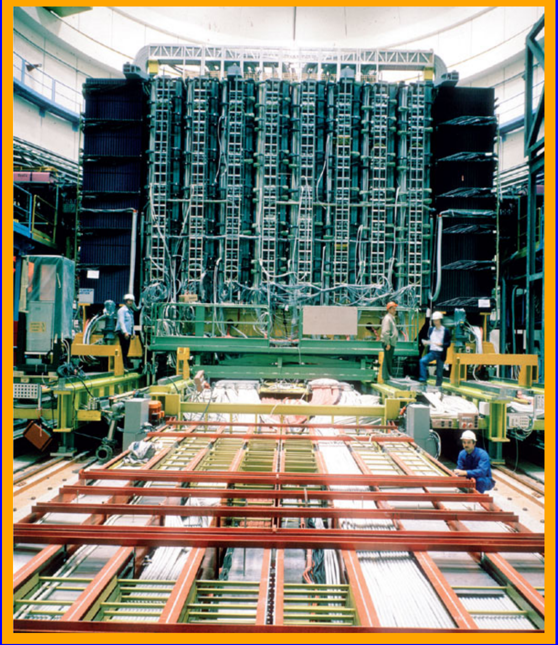
January 1983:

Rubbia: "They look like Ws, they feel like Ws, they smell like Ws, they must be Ws".

4 Z-events by end of June 1983

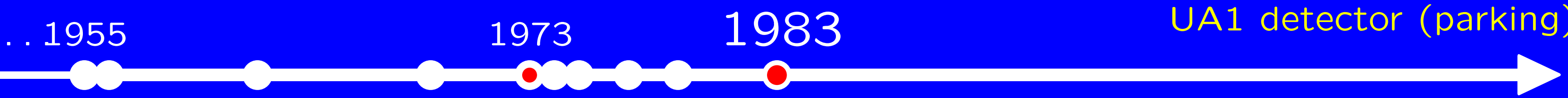
UA2 detector



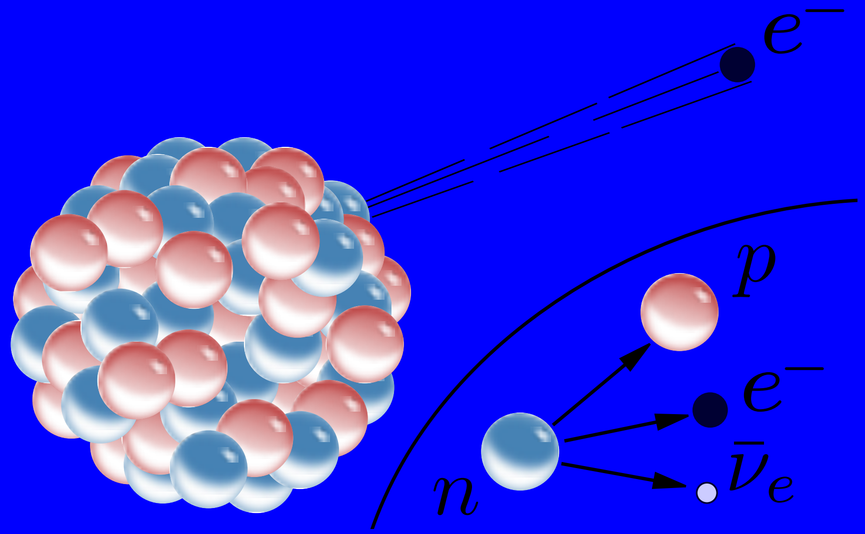


UA1 detector (parking)

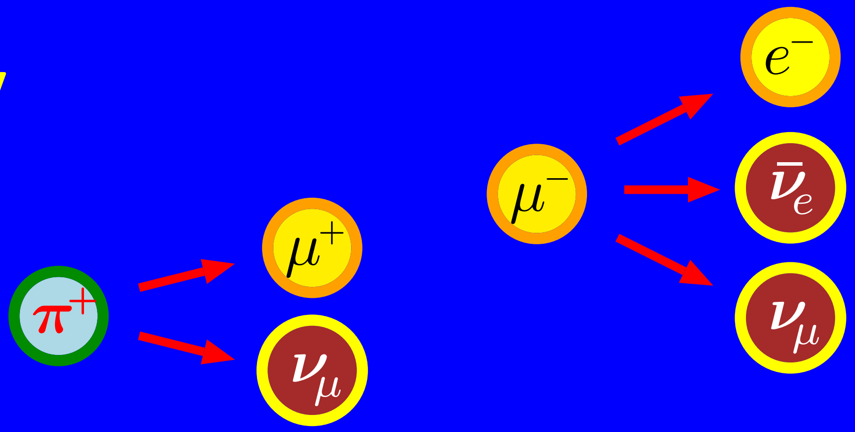
γ ν W e^- Z u g d



Weak Interactions



- 1933 Enrico Fermi explained the radioactive beta decay
  - by coupling four fermions
- the same coupling constant $G_F = \frac{1.16637 \times 10^{-5}}{\mathrm{GeV}^2}$ describes
  - radioactive beta-decay
  - muon decay
  - charged pion decay
  - neutrino interactions



★ but it cannot work for energies bigger than ∼100 GeV

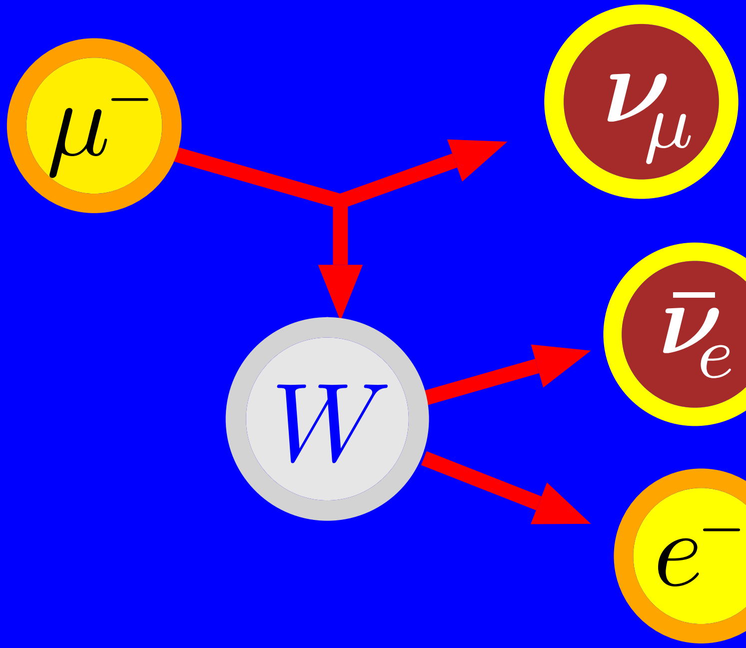
Weak Interactions: modern explanation

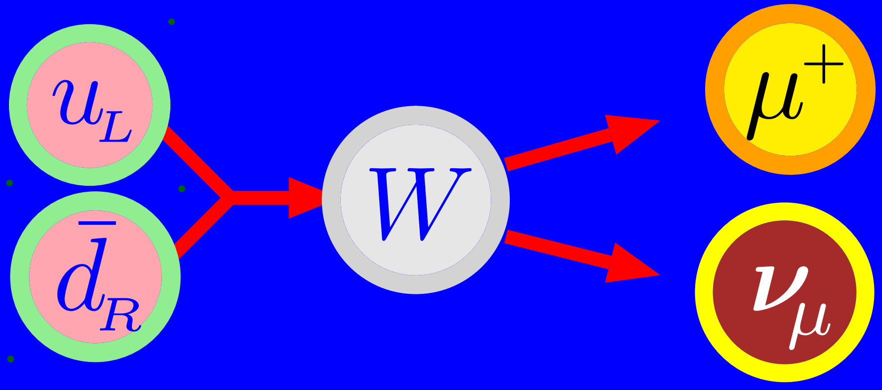
- weak interactions couple a pair of fermions with another pair
  - via vector bosons
- the Fermi coupling constant

$$G_F = \frac{\sqrt{2}}{8}\frac{g^2}{m_W^2}$$

is independent of energy

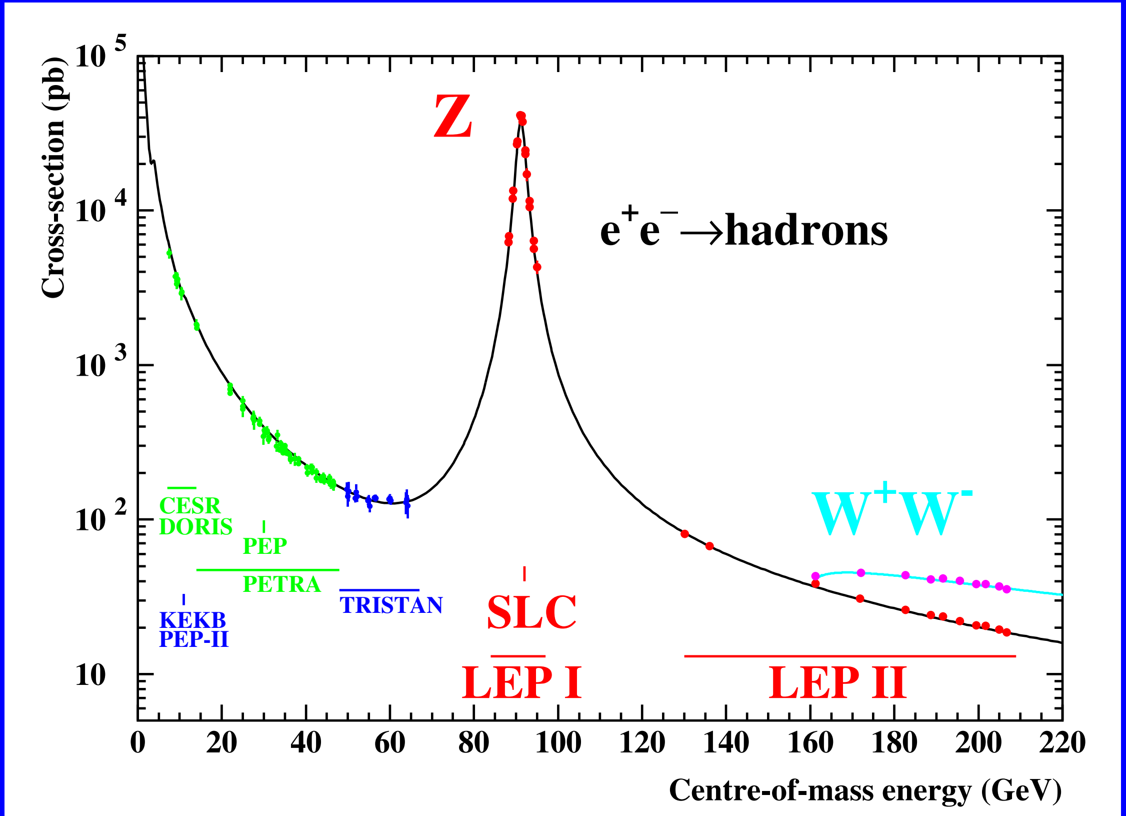
★ only if the energy is (much) smaller than the mass of the W-boson (80 GeV)





Weak Interactions: LEP

- electron-positron colliders can produce Z-bosons or pairs of W-bosons
  - ★ which decay to hadrons and leptons

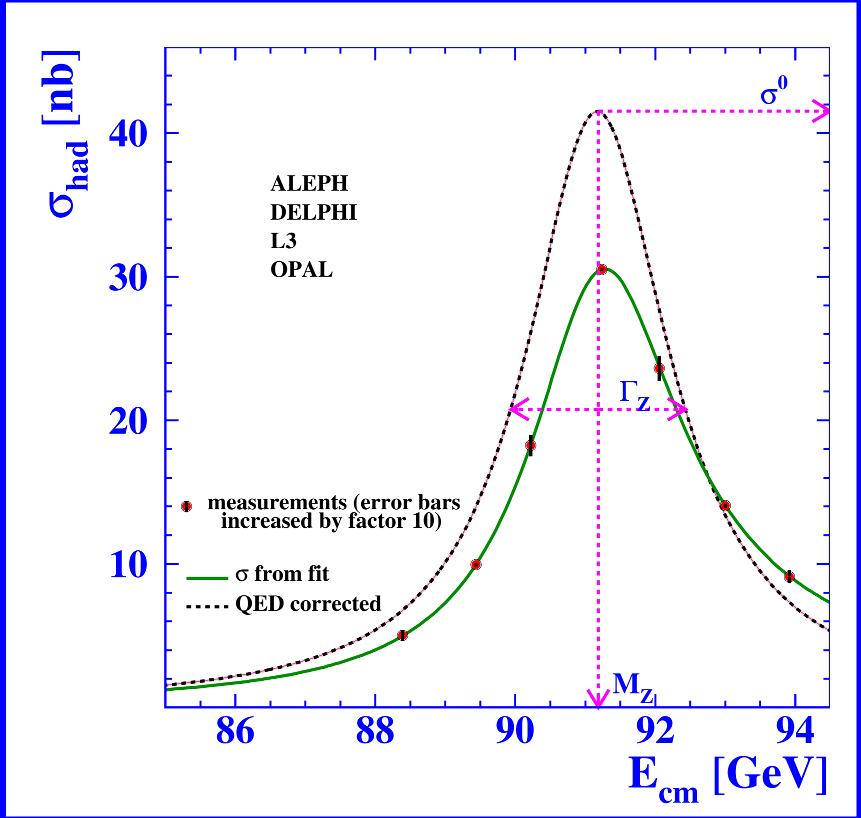


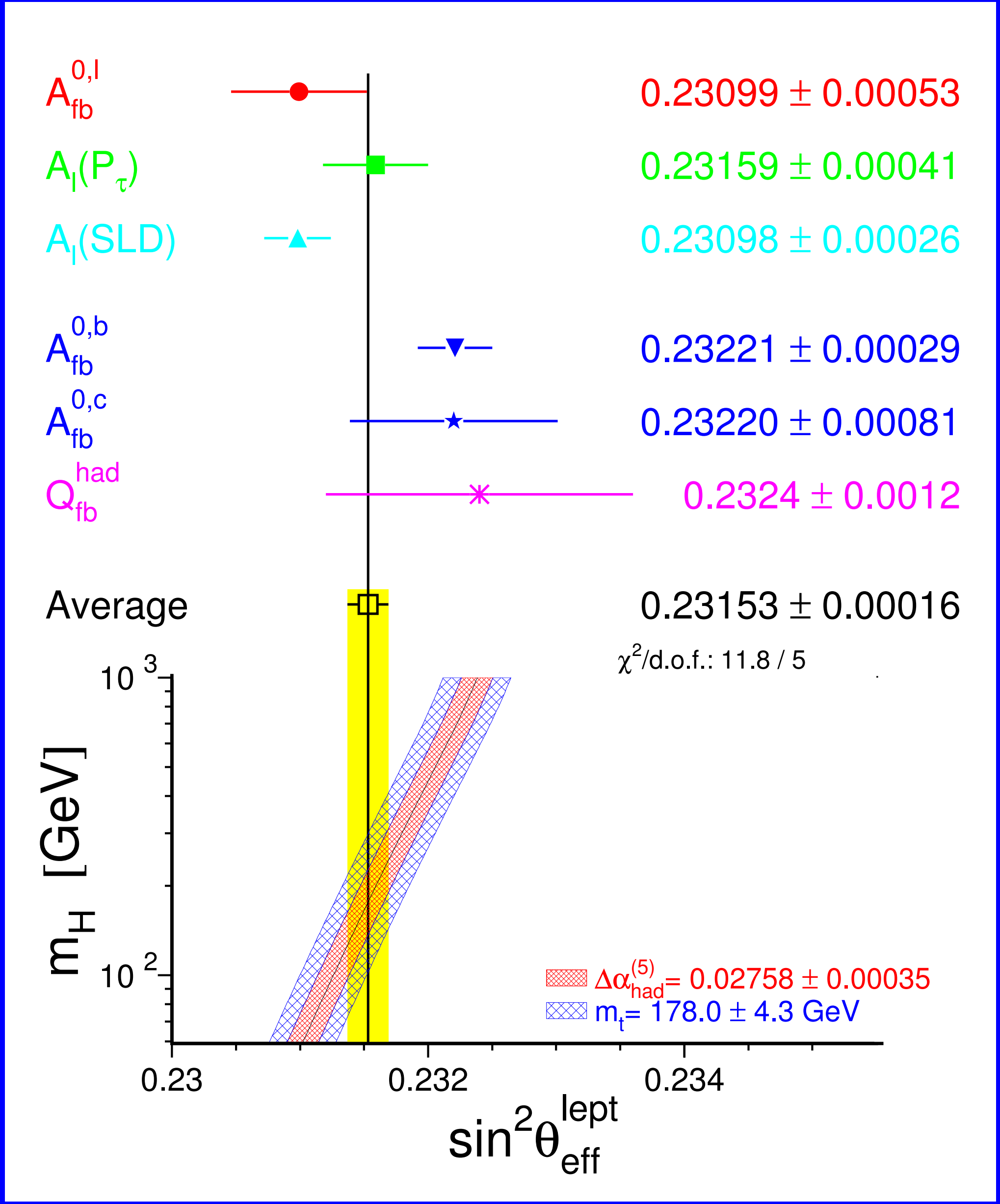
LEP

Weak Interactions: LEP

- electron-positron colliders determine the energy of collisions very accurately

➡ precision measurements

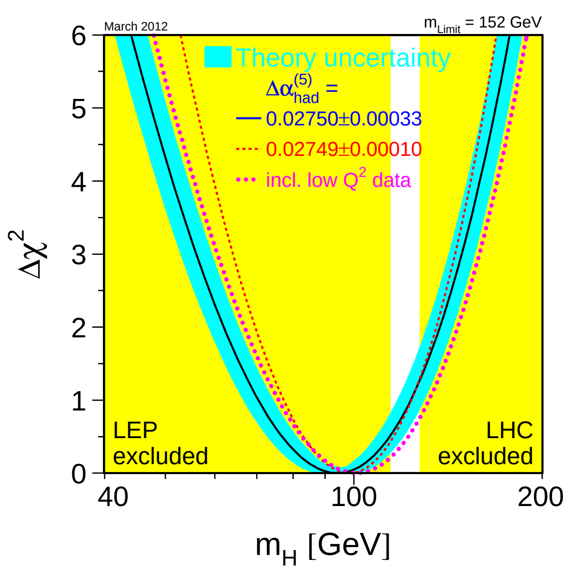




Weak Interactions: LEP

- measuring more predictions than there are parameters in a theory

→ consistency check for the Standard Model



	Measurement	Fit
$\Delta\alpha^{(5)}_{\text{had}}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{\text{fb}}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{\text{fb}}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{\text{fb}}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{\text{lept}}_{\text{eff}}(Q_{\text{fb}})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26

Particles of the Standard Model:

Higgs Boson

1. Why a Higgs Boson?
2. The Higgs mechanism
   - . . . no formulas . . .   . . . only handwaving
3. Systematics:
   - counting the degrees of freedom
4. Experimental evidence
   - History of the discovery

Why a Higgs Boson ?

- The Standard Model is a chiral gauge field theory

→ it is described with massless fermion fields

- the gauge symmetries enforce massless vector bosons
- But we have
  - ★ massive fermions: leptons and quarks
  - ★ massive vector bosons: $W^{\pm}$ and Z^0
- Solution: the Higgs mechanism

The Higgs Mechanism

- **Ingredients:**
  - ★ scalar fields
  - ★ continuous local symmetries = gauge symmetries
  - ★ the vacuum
- **Result**
  - ★ gauge symmetries are spontaneously broken
  - ★ the scalar fields develop
    a vacuum expectation value (vev)
  - ★ other fields can acquire masses due to the vev

symmetry breaking

Example: chess:

- the rules of chess are in principle
  - absolutely symmetric
  - for both players
- i.e. the rules how the pieces move are the same for black and white

but:

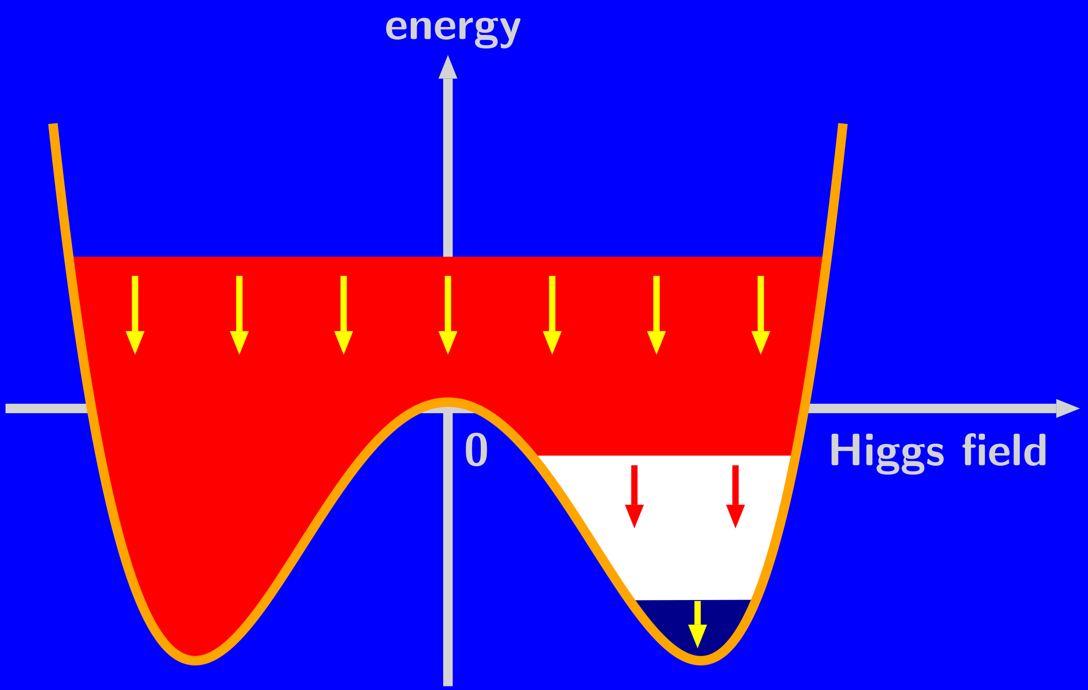
- the symmetry is broken at the beginning due to the initial setup of the pieces
- therefore
  - ➡ a bishop never can change the color of the field it is standing on

symmetry breaking

★ the origin of mass

In the SM, masses of particles are an effect of symmetry breaking:

- originally, all particles are massless, but interact with the Higgs field
- due to spontaneous symmetry breaking
  - ★ the value of the Higgs field is non-zero in the vacuum (=vev)
- the interaction with this vev produces the mass of particles



★ hot universe

- shortly after the big bang

particles are massless

★ cold universe

- condensed into an asymmetric state

particles get a mass

spontaneous symmetry breaking

degrees of freedom

only $SU(2) \times U(1)$ bosons

massless theory

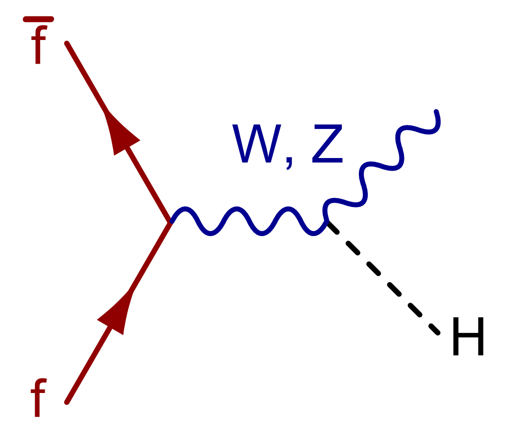
#	particles	dof
1	complex scalar doublet	4
4	massless gauge bosons (B, W^i)	8
0	massive gauge bosons	0
		12

massive theory

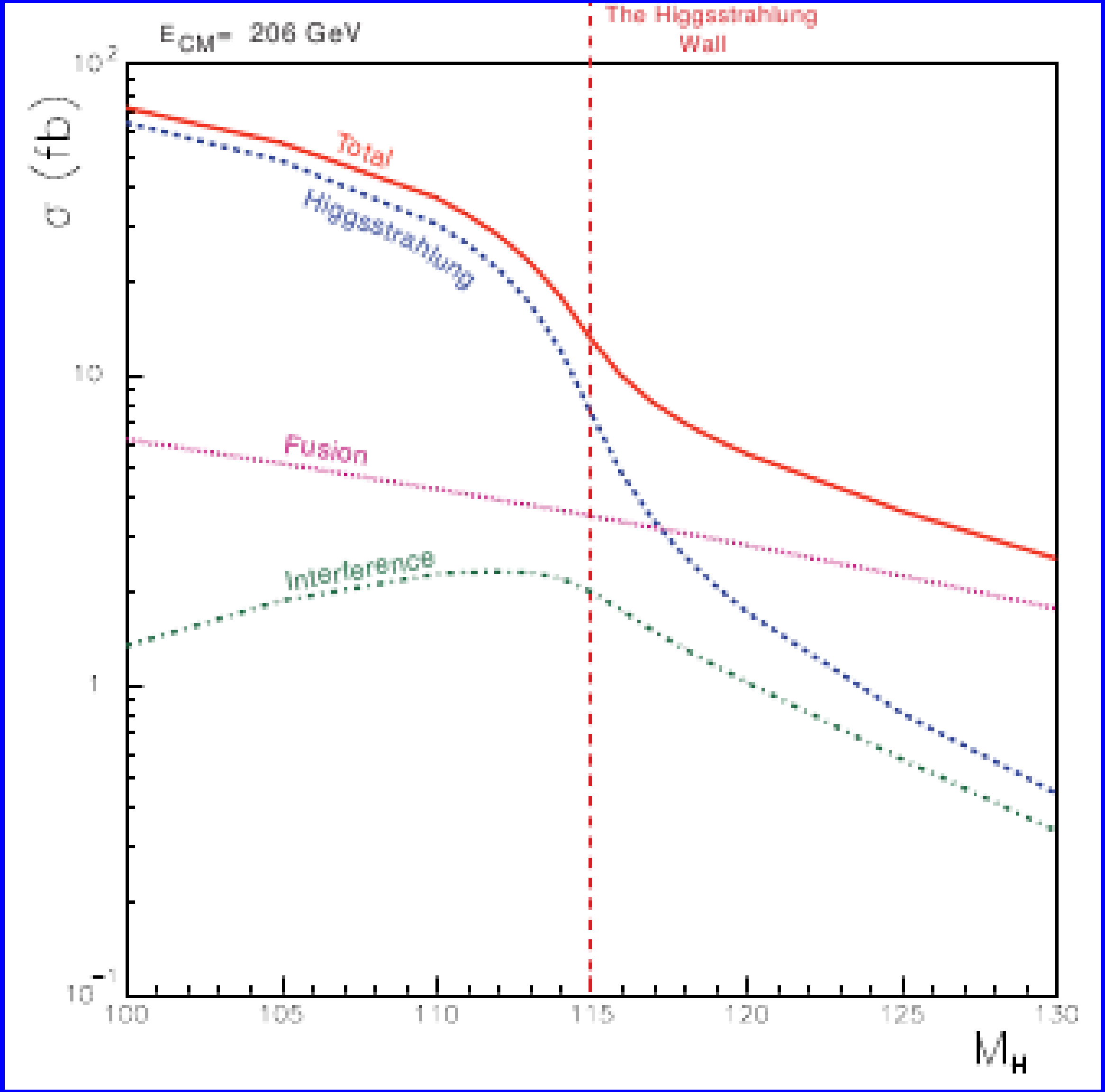
#	particles	dof
1	real scalar field (Higgs)	1
1	massless gauge boson (photon)	2
3	massive gauge bosons ($W^{\pm}$, Z^0)	9
		12

production at LEP

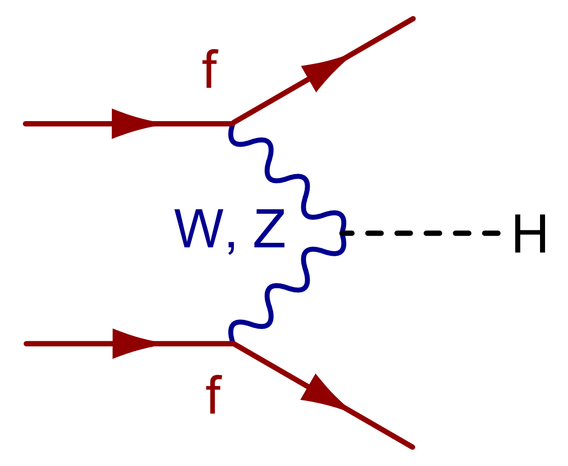
Higgs-strahlung



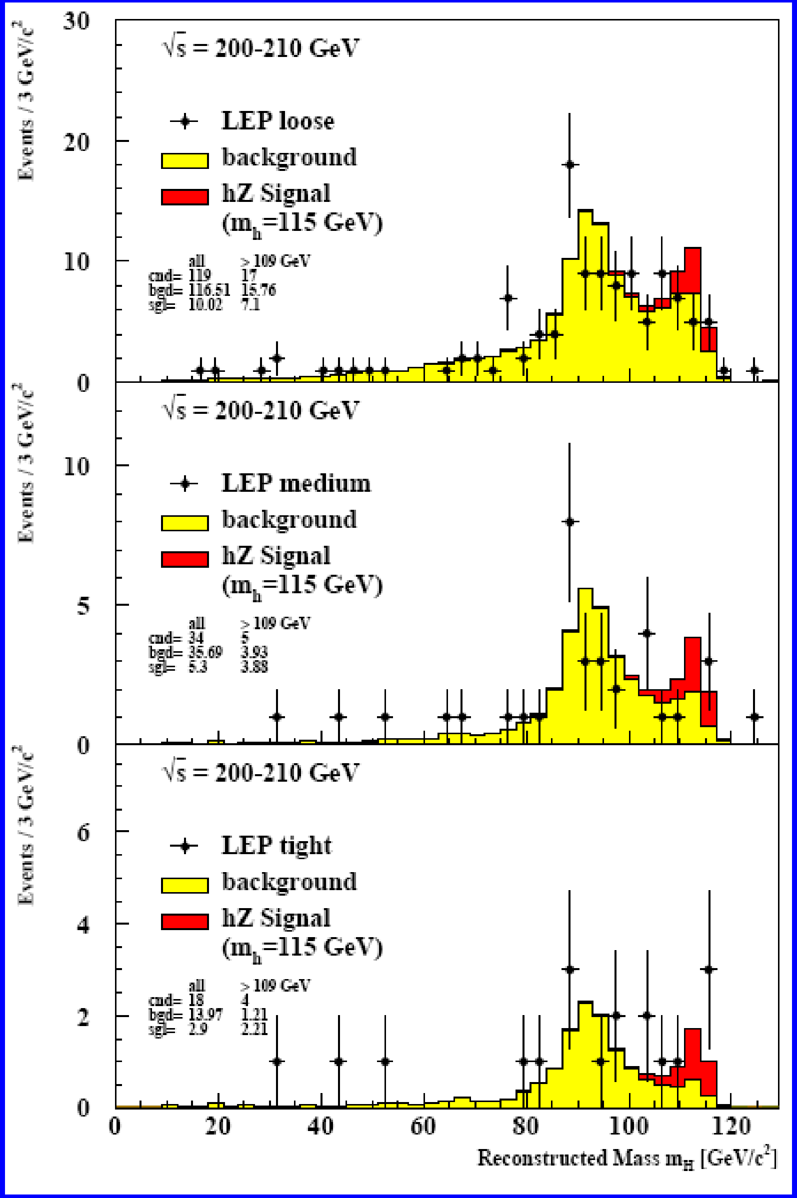
Higgs production cross section



Higgs-fusion



exclusion by LEP I & II



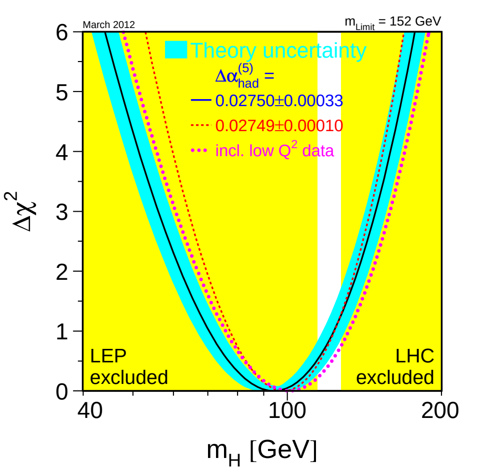
→ comparison between an expected (calculated) distribution and the measured distribution of events

← measured mass distribution

hints: electroweak precision measurements

- very precise measurements allow the comparison with precise calculations
- all loop calculations depend on the masses of all the particles in the loop!

→ sensitivity to particles, that can not yet be produced!



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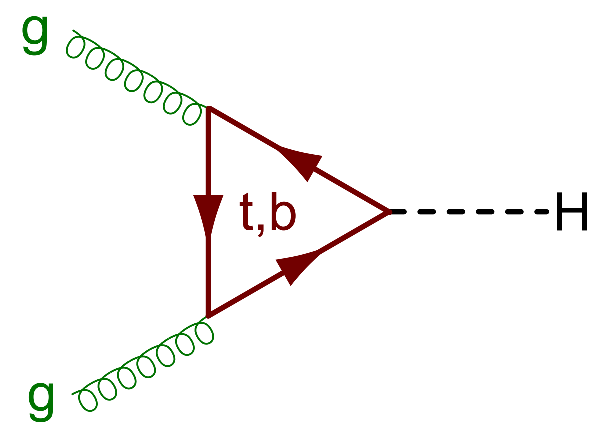
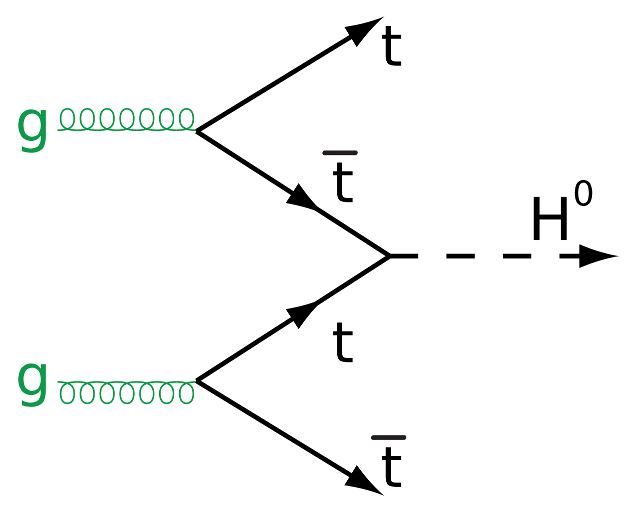
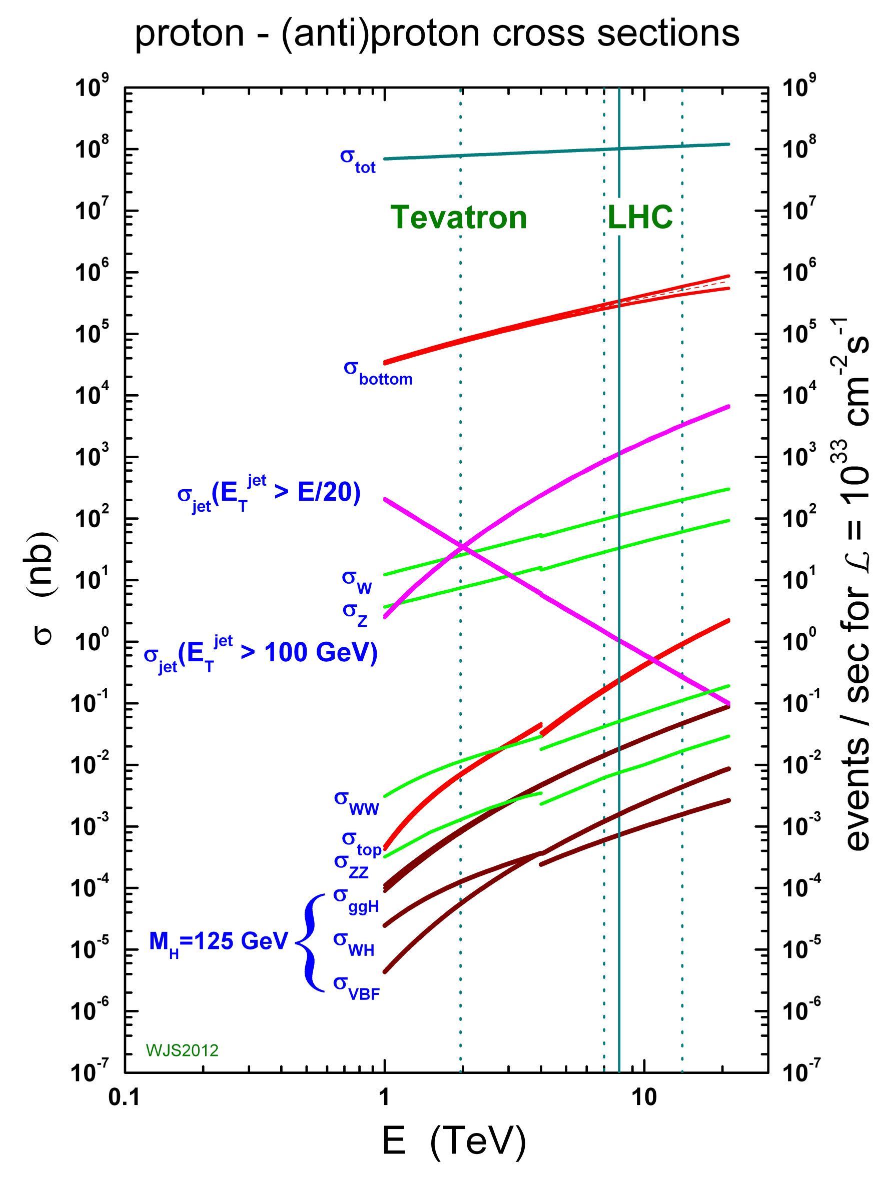
production at LHC

Higgs-gluon-fusion



top-associated-production





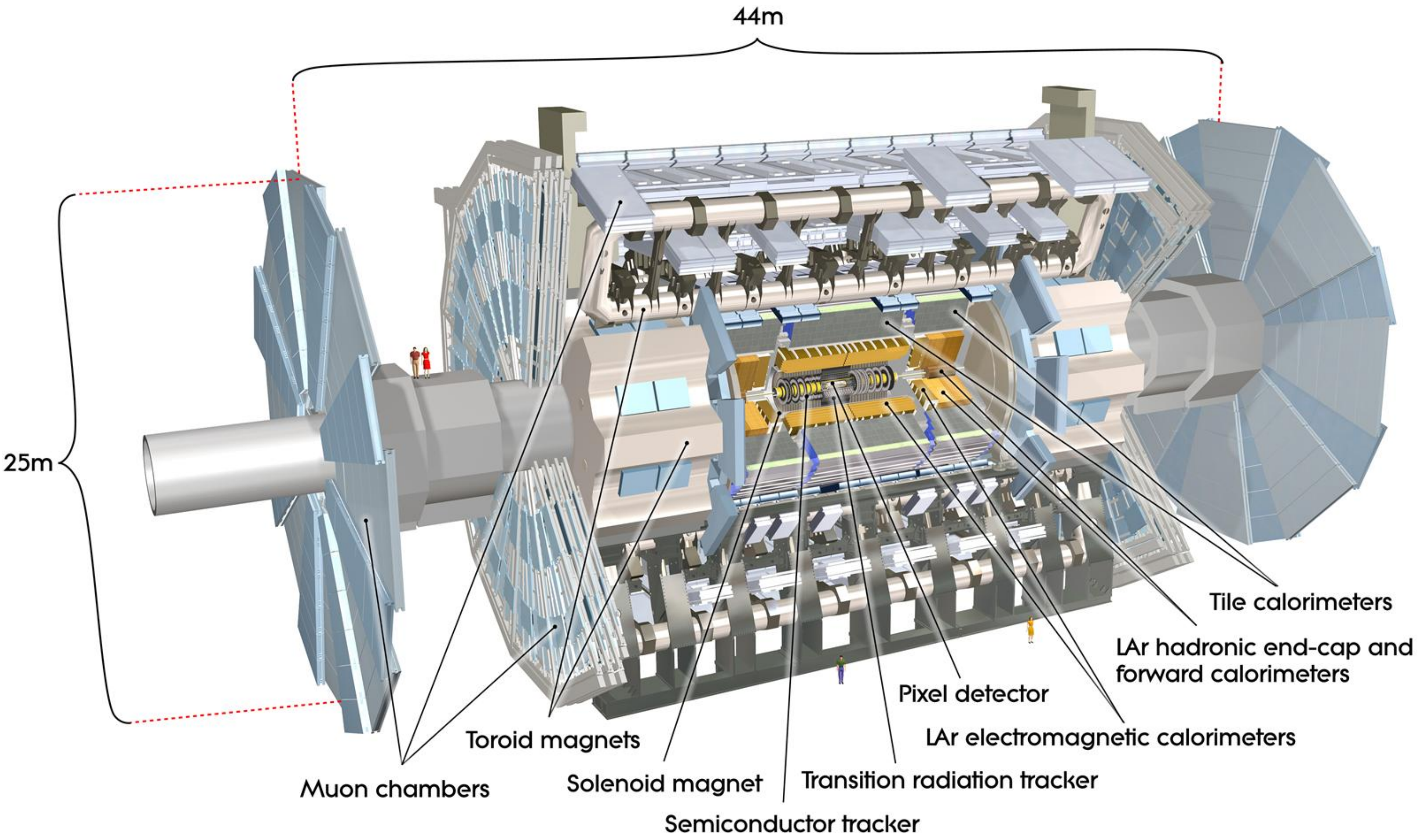
The Higgs particle — history of the experimental search

reduction of the allowed mass range

- 2004 LEP limit: $m_H > 114.4\,\text{GeV}$
  - uses data, collected from the LEP experiments until 2000
- 2010 Tevatron exclusion: $158 < m_H/\text{GeV} < 175$ is excluded
  - data from the Fermilab experiments CDF and D0
- July 2011 LHC exclusion: $145 < m_H/\text{GeV} < 466$ is excluded
  - data from the ATLAS and CMS from 2010 and 2011
- December 2011 LHC limits the allowed mass range
  - ATLAS: $116 < m_H/\text{GeV} < 130$
  - CMS: $115 < m_H/\text{GeV} < 127$
- July 4th 2012 CERN announces the detection of
  a boson compatible with the SM Higgs boson
  - ATLAS: $m_H \sim 126.5\,\text{GeV}$ @ 5 σ significance
  - CMS: $m_H = 125.3 \pm 0.6\,\text{GeV}$ @ 4.9 σ significance

The Higgs particle — experimental search

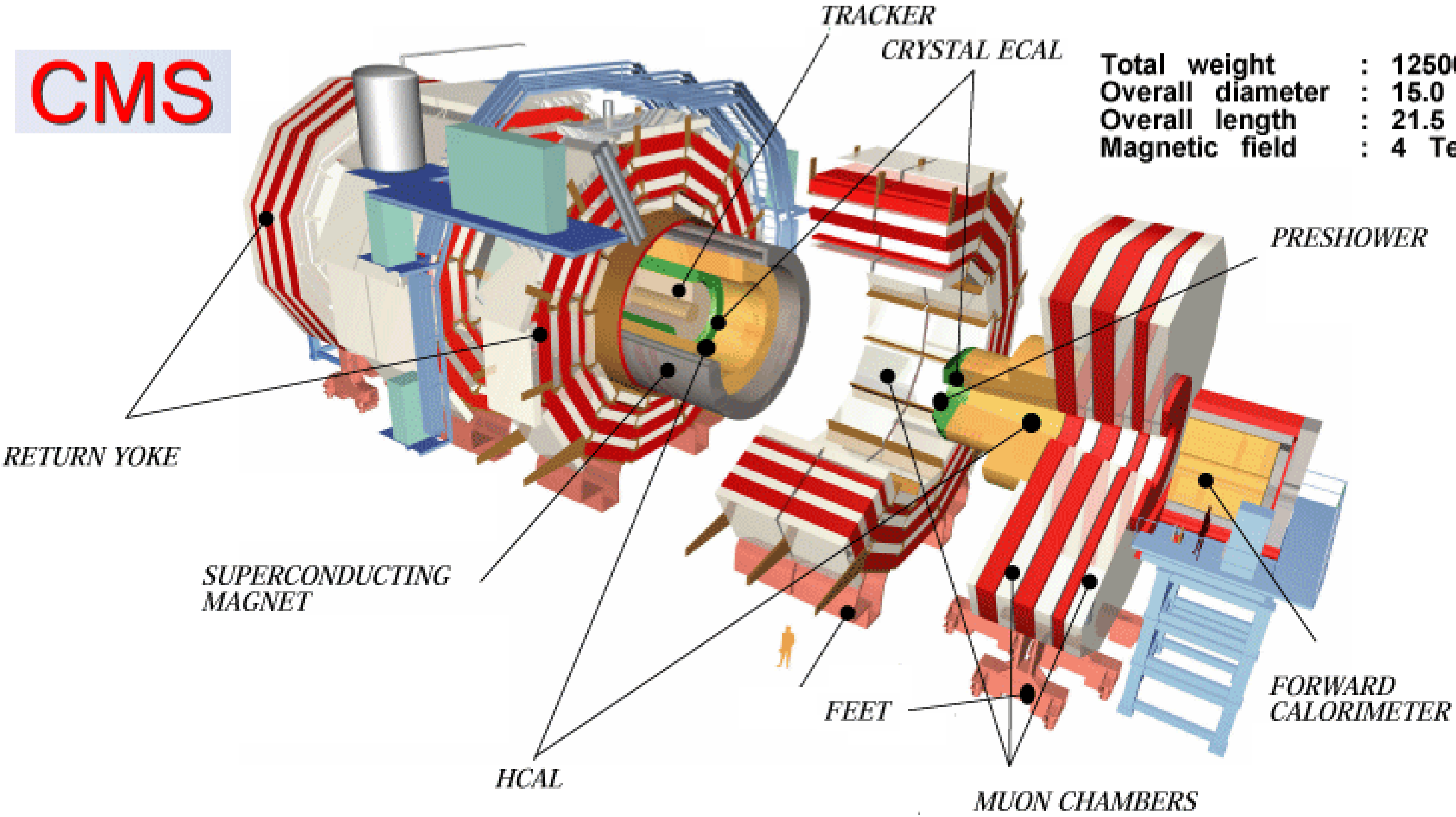
by the Atlas detector



The Higgs particle — experimental search

by the CMS detector

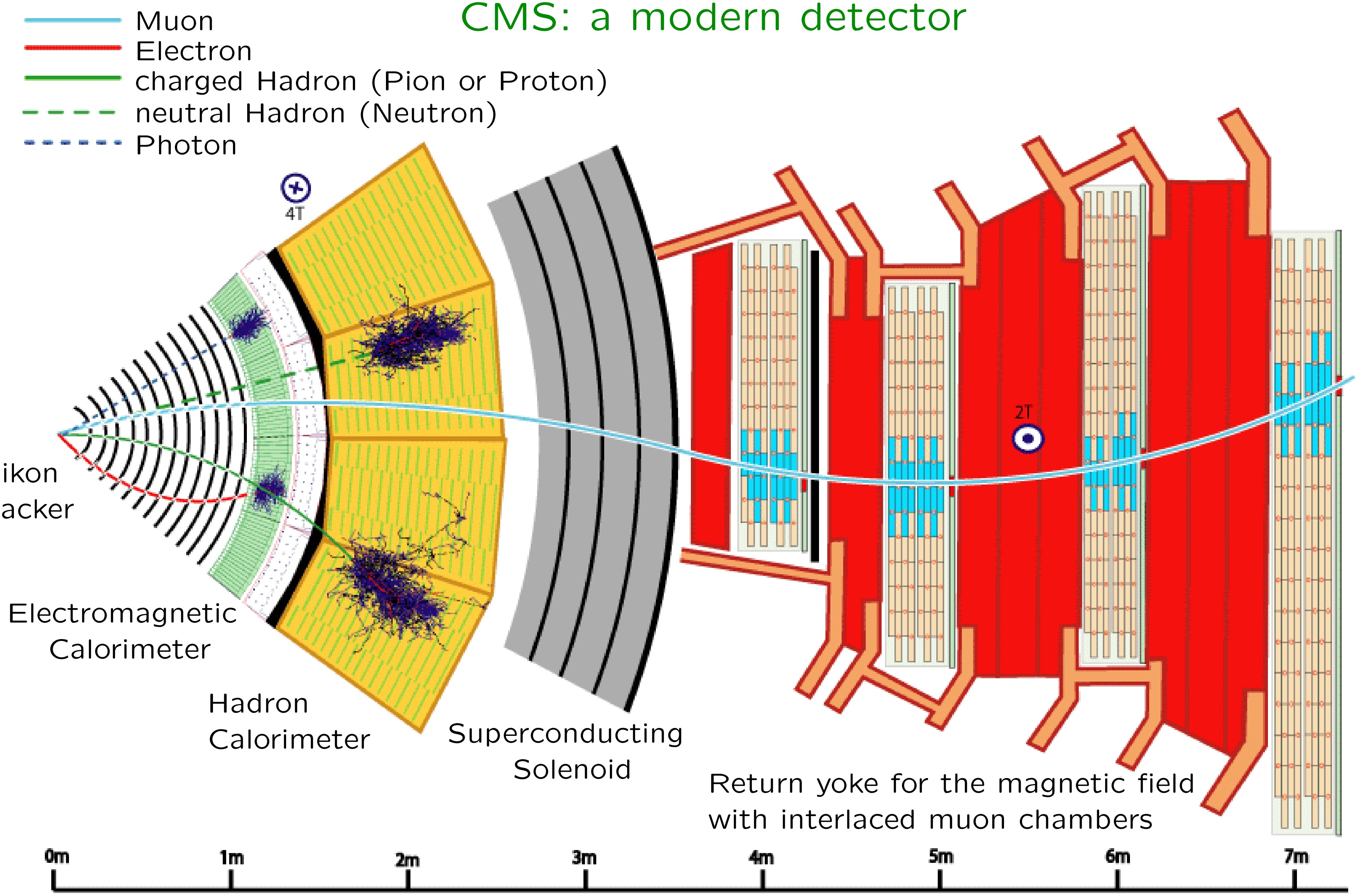
CMS



Total weight : 12500 T
Overall diameter : 15.0 m
Overall length : 21.5 m
Magnetic field : 4 Tesla

The Higgs particle — experimental search

CMS: a modern detector



Muon
Electron
charged Hadron (Pion or Proton)
neutral Hadron (Neutron)
Photon

Silikon Tracker

Electromagnetic Calorimeter

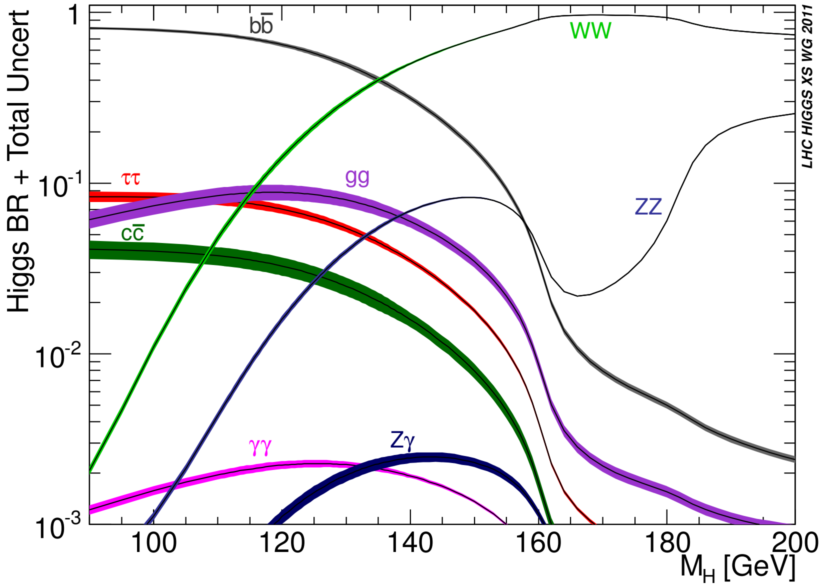
Hadron Calorimeter

Superconducting Solenoid

Return yoke for the magnetic field with interlaced muon chambers

The Higgs particle — experimental search

How was that measurement achieved?



combining production- with decay-channels of the Higgs boson

largest branching ratios

- $b\bar{b}$, $\tau^-\tau^+$, $c\bar{c}$, and gg
  - hard to distiguish from background
- $WW \to 4q$
  - similar: also hard to distiguish from background
- $WW \to 2\ell 2\nu$
  - neutrinos are not measured ⇒ bad reconstruction

⇒ looking for $\gamma\gamma$ and $ZZ \to 4\ell$

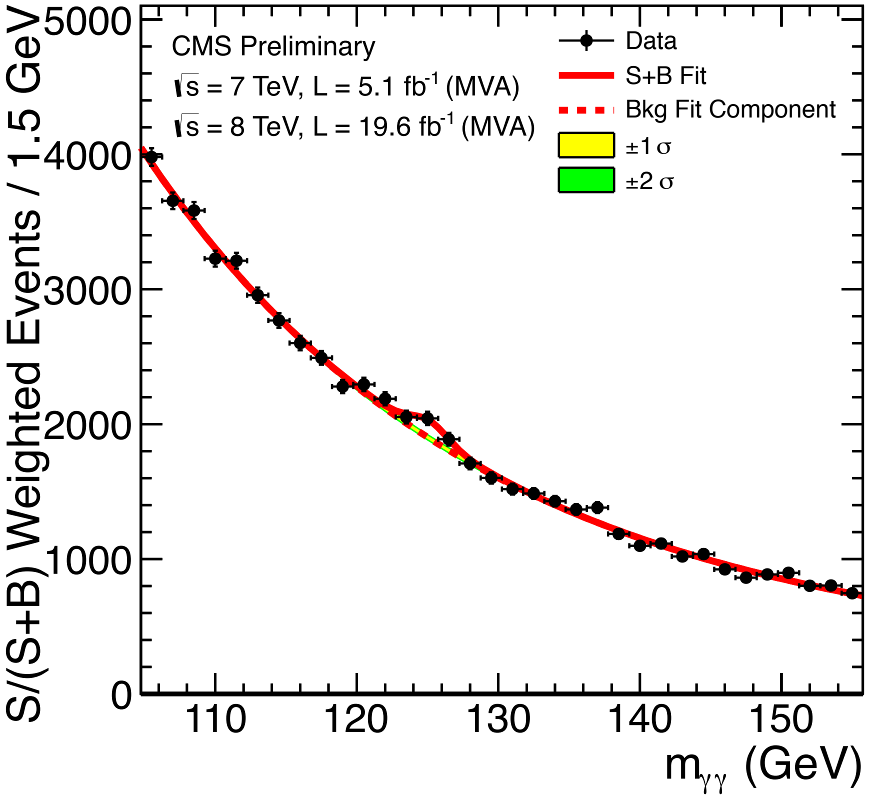
- has also very good mass resolution

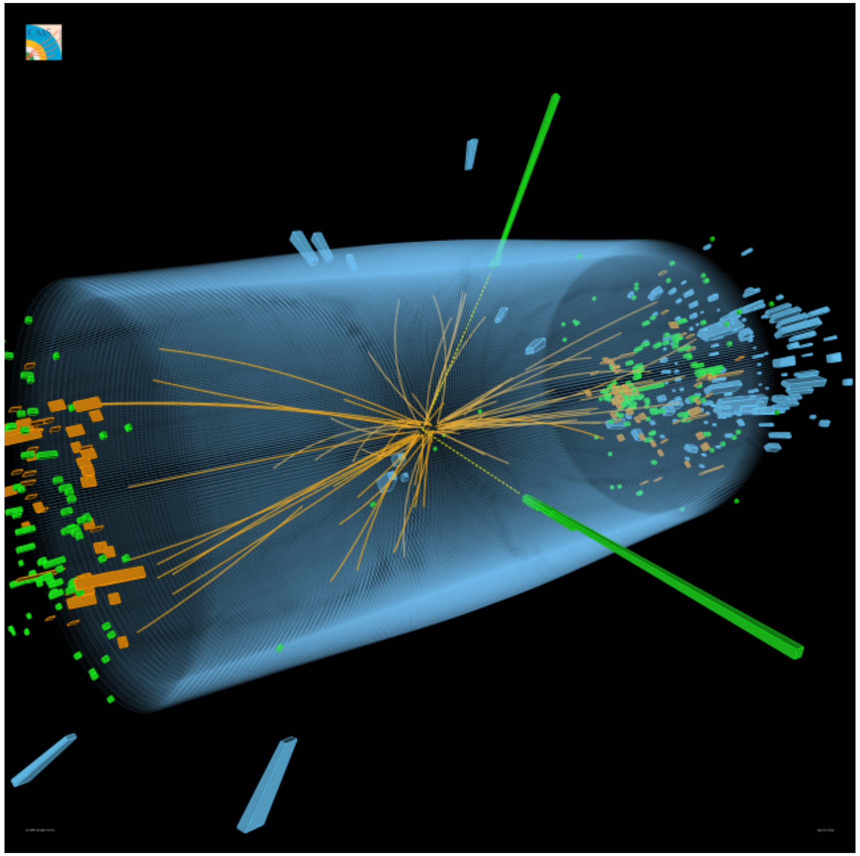
  ⇒ ”golden channel”

The Higgs particle — experimental search

$H \to \gamma\gamma$

- Monte Carlo and data:
  - gives a signal on a background



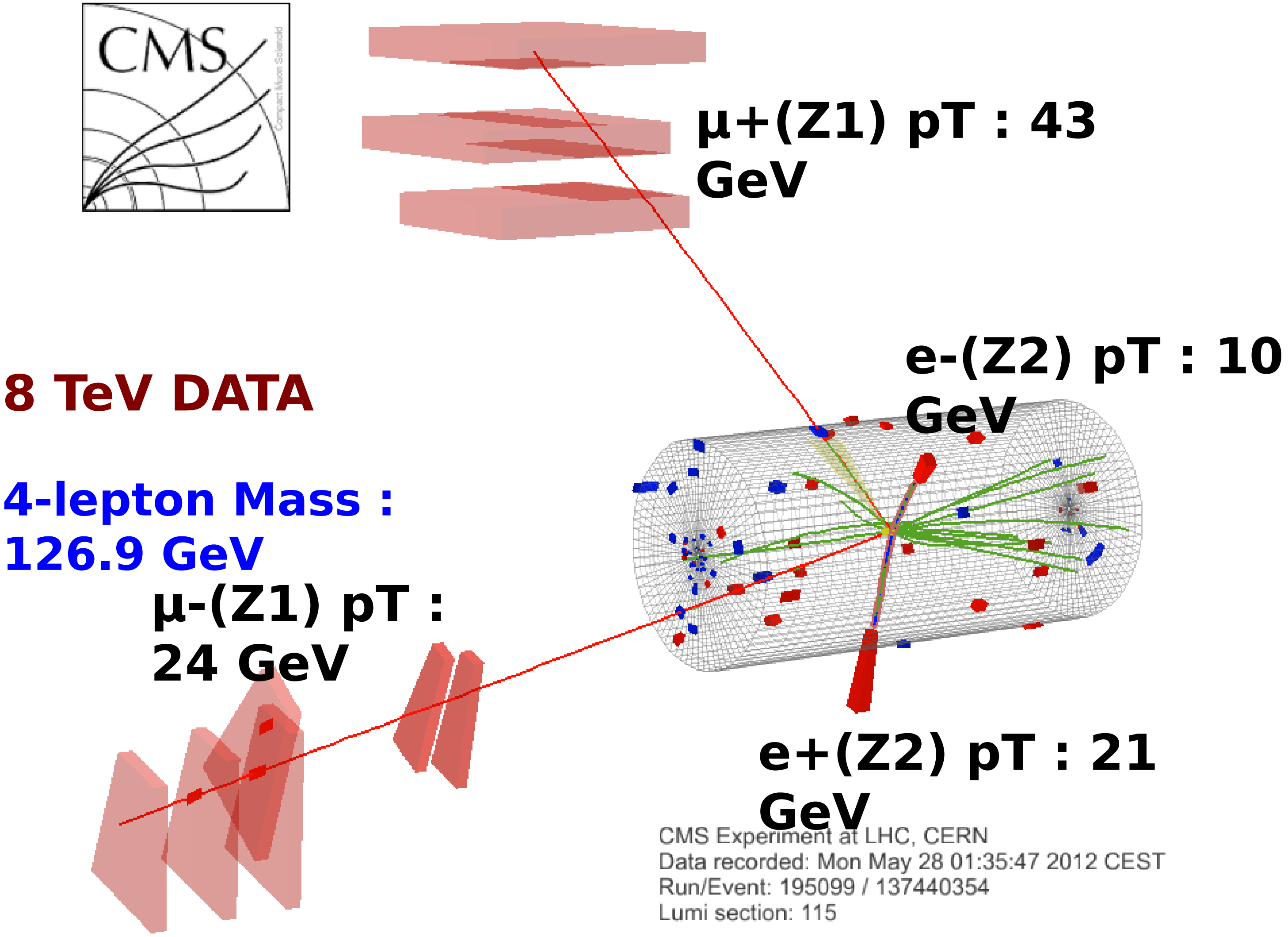


a possible $H \to \gamma\gamma$ event

with local p-value at 125 GeV with a local significance of 4.1 σ

The Higgs particle — experimental search

$$H \to ZZ^* \to \mu^-\mu^+ + e^-e^+$$



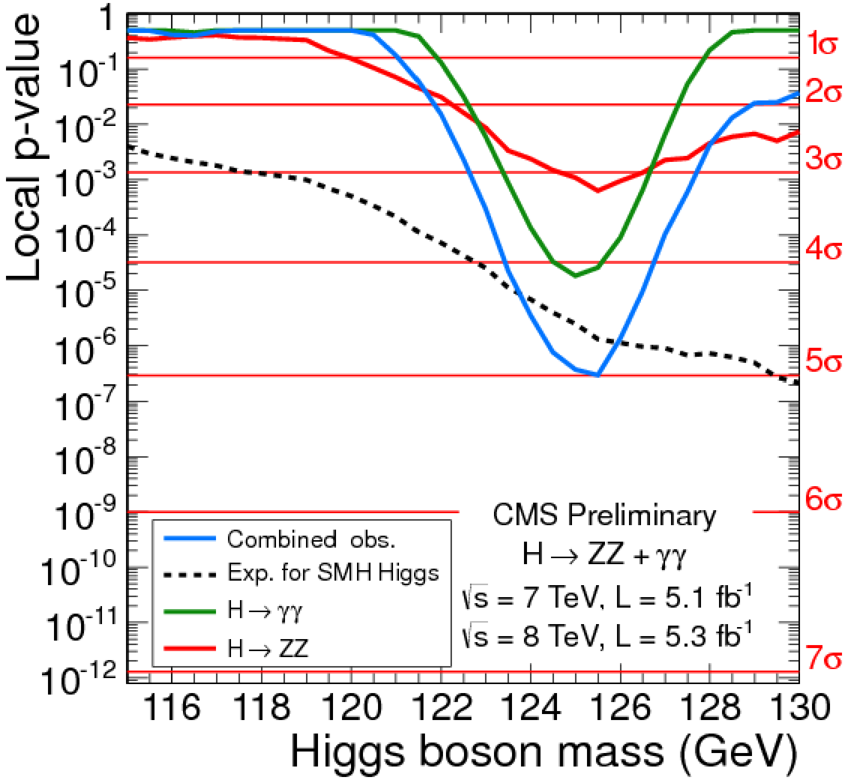
The Higgs particle — experimental search

Combining $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

- combining the high sensitivity, high mass resolution channels: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$
  - $\gamma\gamma$ has 4.1 σ excess
  - 4ℓ has 3.2 σ excess
- near the same mass of 125 GeV

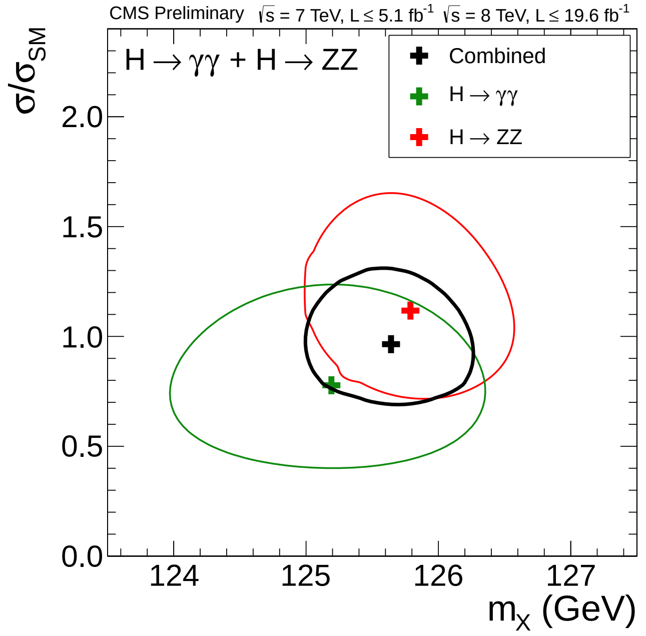
$\Rightarrow$ combined significance of 5 σ

(as of 2012 . . . now it is more)



The Higgs particle — experimental search

Characterising the excess in all channels

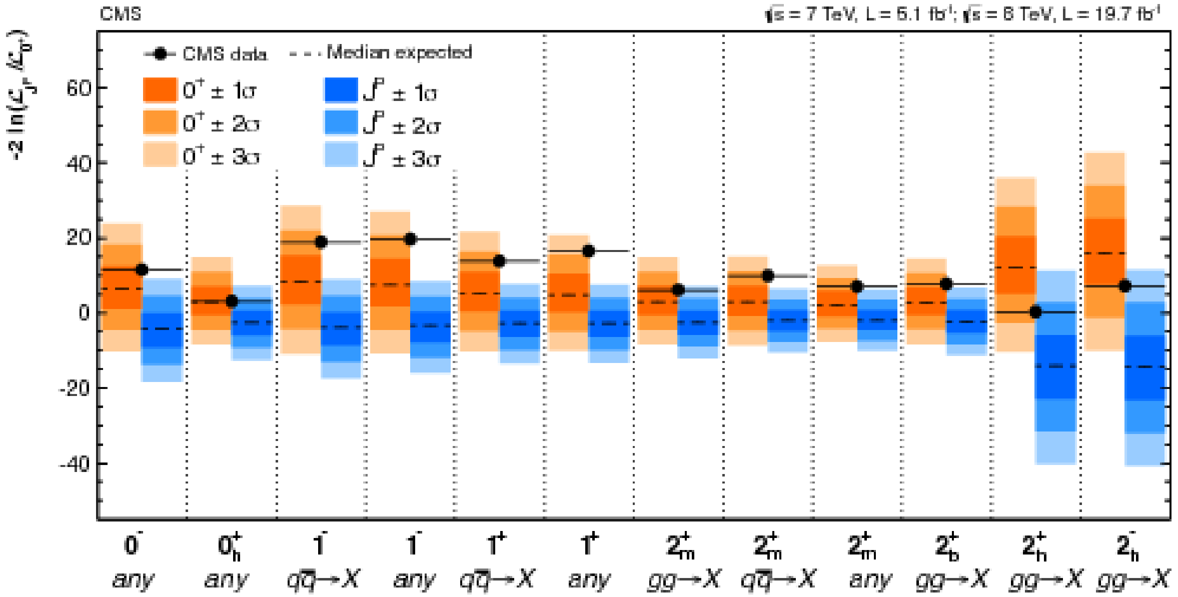


- results for the mass are self consistent
- and can be combined

  $\Rightarrow$ $m_X = 125.9 \pm 0.4\,\text{GeV}$

- But is it the SM Higgs boson?

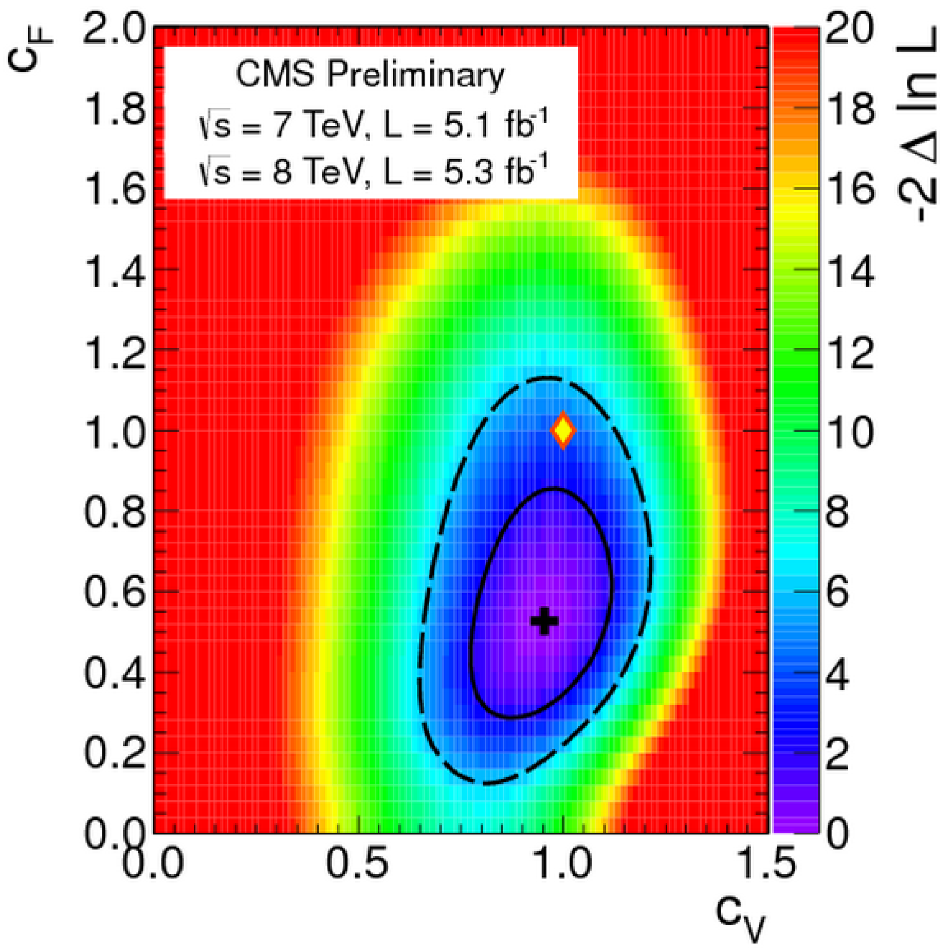
  $\Rightarrow$ comparing to other hypotheses:



The Higgs particle — experimental search

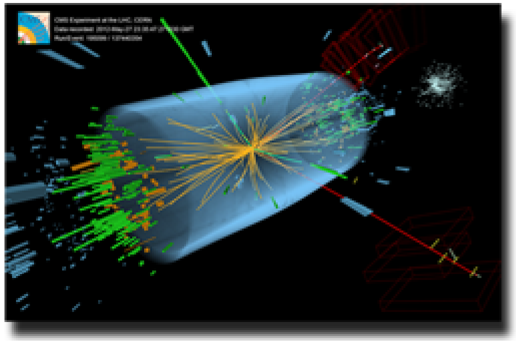
Comparing couplings to fermions and to vector bosons

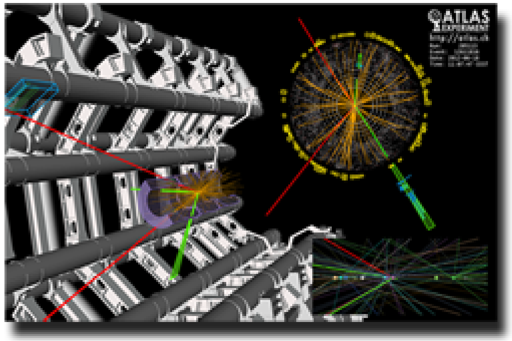
- Group the Higgs couplings into ''Vectorial'' and ''Fermionic'' sets.
- with coupling strength relative to the SM value
  - c_V for vectors
  - c_F for fermions
- use theoretical LO prediction for the loop-induced $H \to \gamma\gamma$ and $H \to gg$ vertices
- agreement with SM in 95% range
  - fermio-phobic Higgs ? . . . statistics



⇒ We need more data! . . . and they will come

Nobelprize in Physics 2013





Francois Englert and Peter W. Higgs

Energy Scales