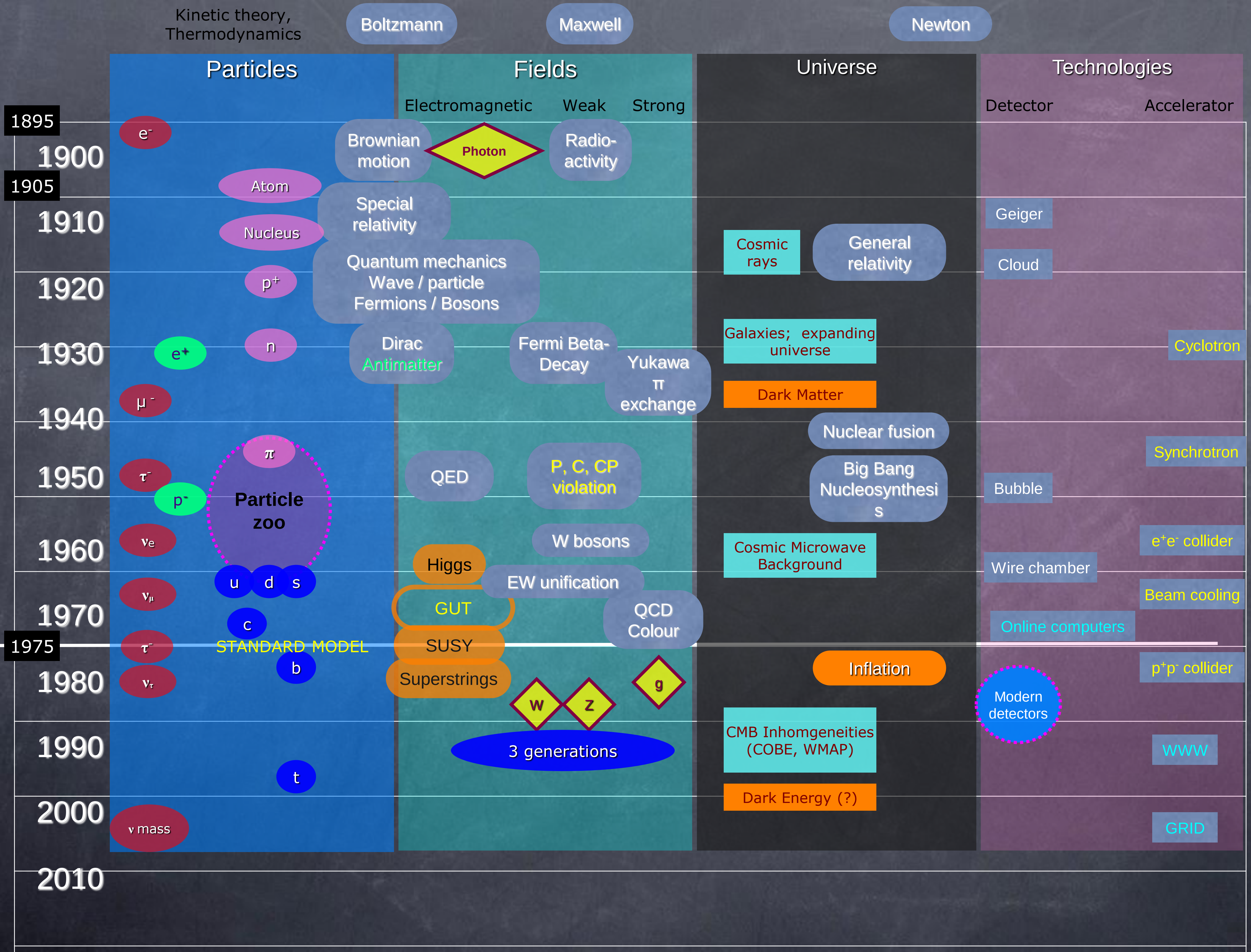
Kinetic theory, Thermodynamics
Boltzmann
Maxwell
Newton
Particles
Fields
Electromagnetic
Weak
Strong
Universe
Technologies
Detector
Accelerator
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e^-
Atom
Nucleus
p^+
e^+
n
μ^-
π
τ^-
p^-
Particle zoo
ν_e
u
d
s
ν_μ
c
STANDARD MODEL
τ^-
ν_τ
b
t
ν mass
Brownian motion
Photon
Radio-activity
Special relativity
Quantum mechanics
Wave / particle
Fermions / Bosons
Dirac
Antimatter
Fermi Beta-Decay
Yukawa
π
exchange
QED
P, C, CP violation
W bosons
Higgs
EW unification
GUT
QCD
Colour
SUSY
Superstrings
W
Z
g
3 generations
Cosmic rays
General relativity
Galaxies; expanding universe
Dark Matter
Nuclear fusion
Big Bang
Nucleosynthesis
Cosmic Microwave Background
Inflation
CMB Inhomgeneities (COBE, WMAP)
Dark Energy (?)
Geiger
Cloud
Cyclotron
Synchrotron
Bubble
e^+e^- collider
Wire chamber
Beam cooling
Online computers
p^+p^- collider
Modern detectors
WWW
GRID

PARTICLE SPECTRUM

n

1932

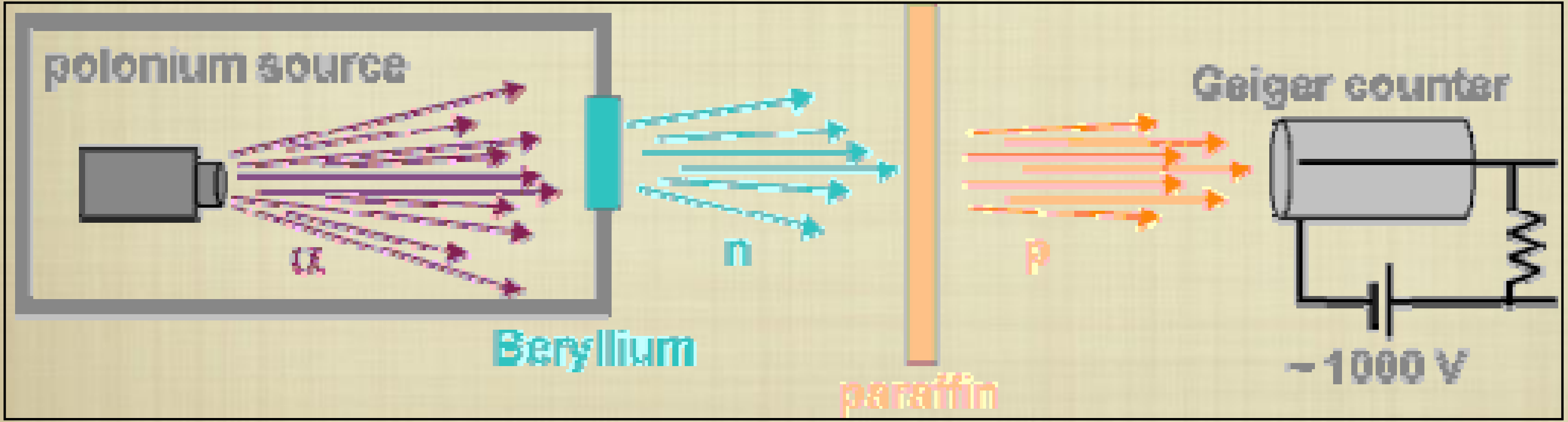
What is the nucleus made of ?

For example: He-4 has only Z=2; what are the other two units of mass due to ?

Heisenberg: Protons and electrons (4 protons and 2 electrons)?

Did not work - the uncertainty relation forbids the presence of electrons in the nucleus!

Chadwick (1932): The neutron

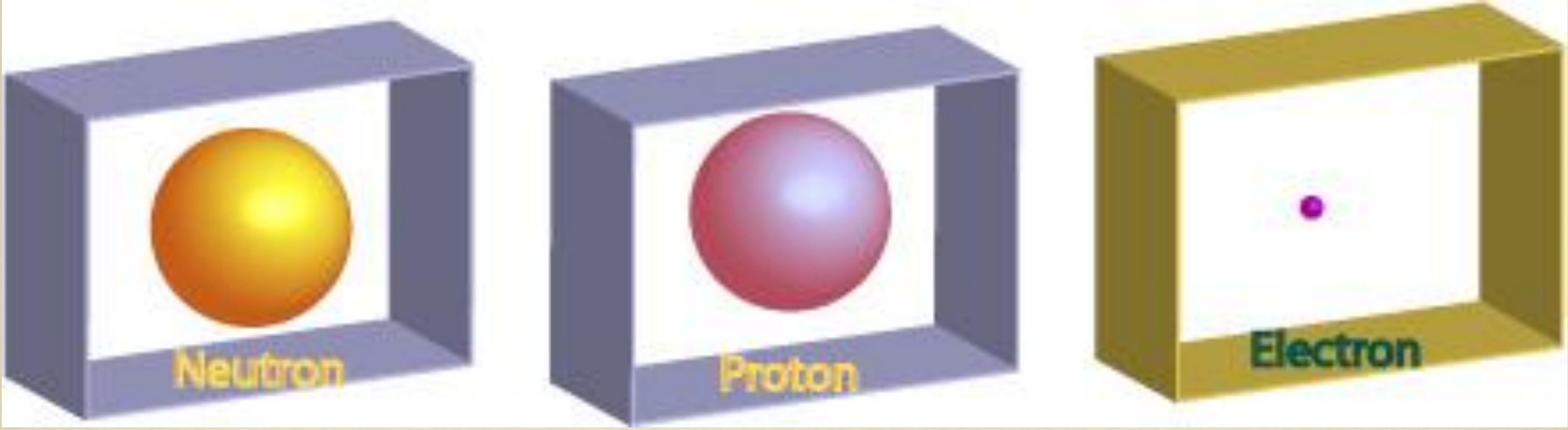


From kinematics: Mass of neutron ~ mass of proton

What keeps everything together? Strong short-range interaction?

PARTICLE SPECTRUM

Fundamental particle spectrum (1932)



Simple, easy to remember
Still taught at schools
(usually in chemistry lessons)

The "Strong Interaction" - Nuclear forces

Yukawa (1934)

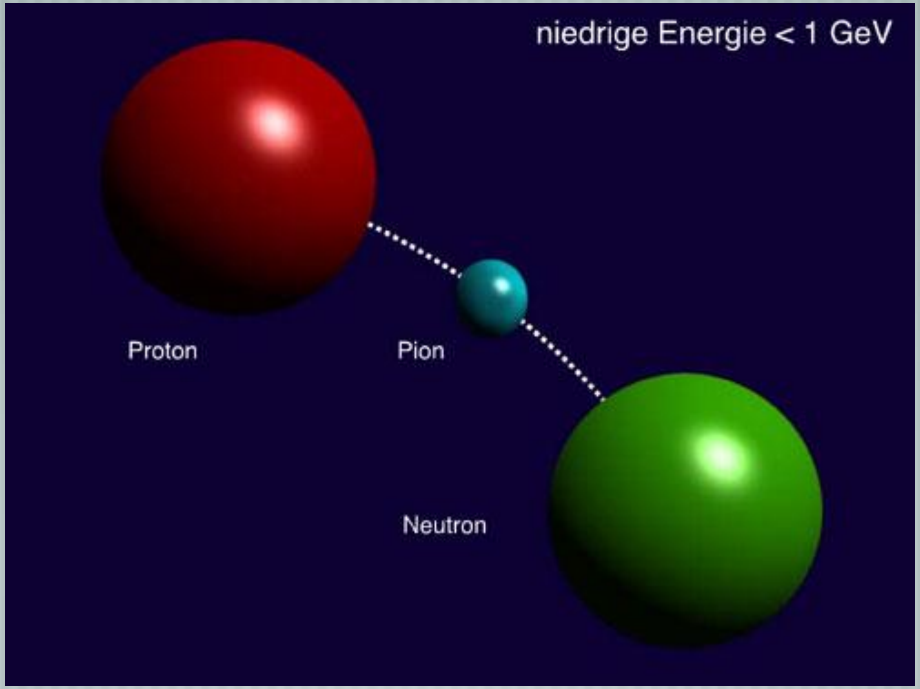
What keeps the protons and neutrons together in the nucleus?

1) This force must be stronger than the electromagnetic repulsion

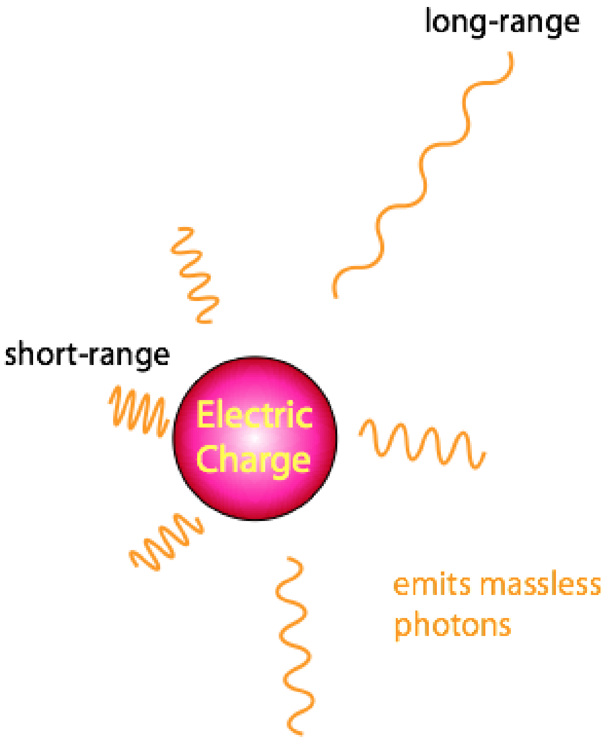
2) It must be of short range (~ 1-2 fm) to explain the size of nuclei

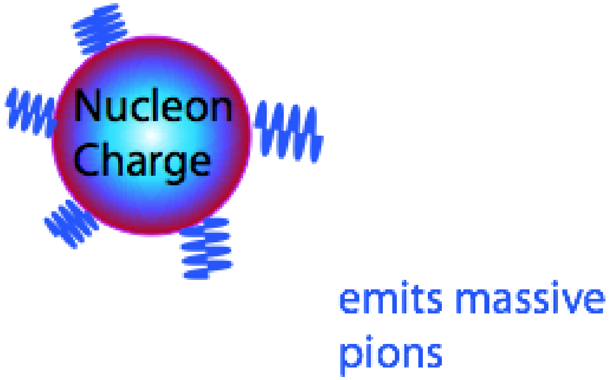
Yukawa's idea:

a massive particle ("pion") is exchanged between two nucleons



Electromagnetic vs Nuclear





$$\Delta E\,\Delta t \geq \hbar \qquad (\Delta E \sim m)$$

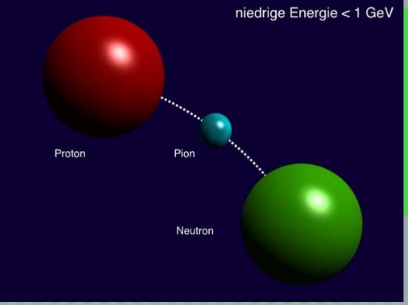
$$r = c\,\Delta t = \frac{\hbar c}{m} \sim \frac{200\ \mathrm{MeV\ fm}}{m}$$

$$V(r) = -e^2\,\frac{1}{r}$$

Coulomb law

$$V(r) = -g^2\,\frac{e^{-mr}}{r}$$

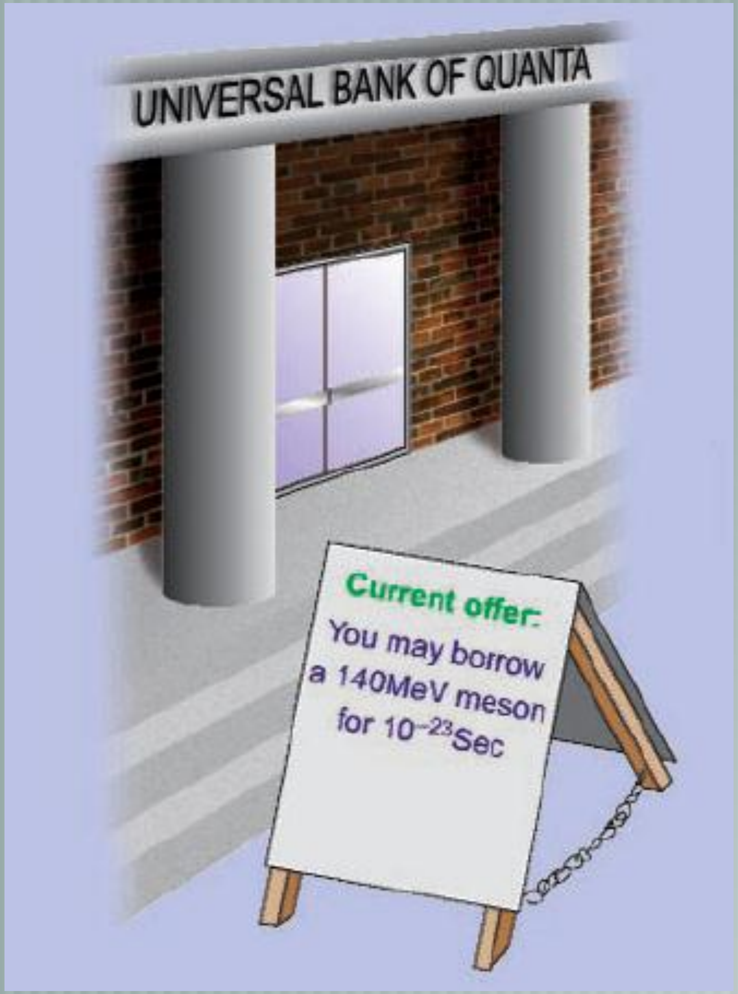
Yukawa potential ~ Modified “Coulomb” law

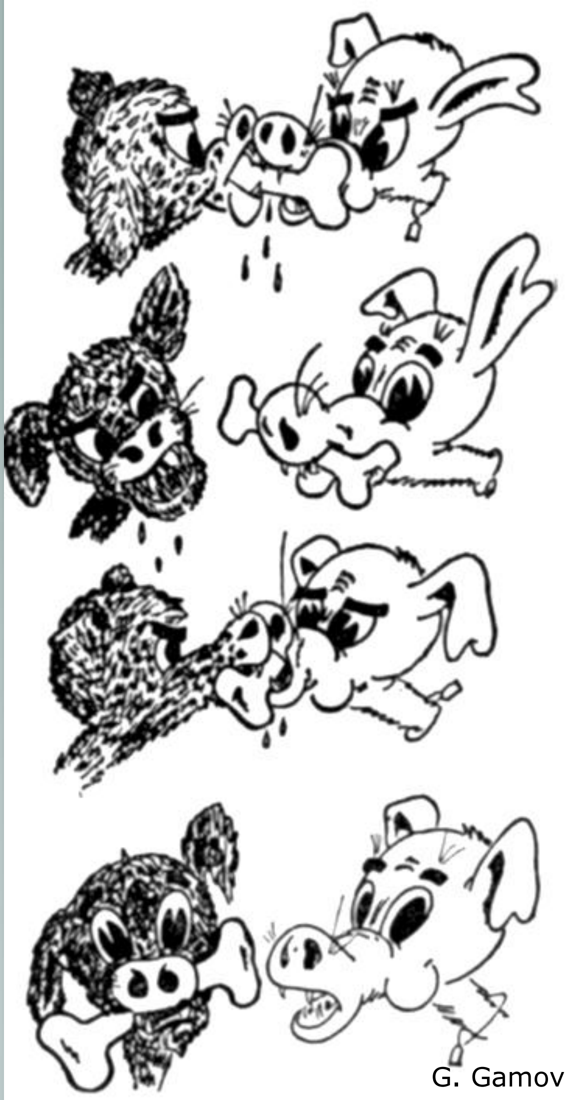


Fields

‘Strong’ interaction

Metaphors for ‘particle exchange’



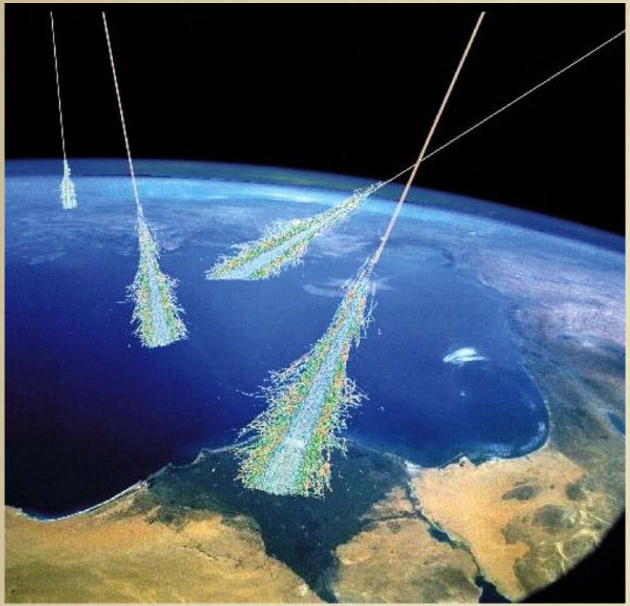

G. Gamov

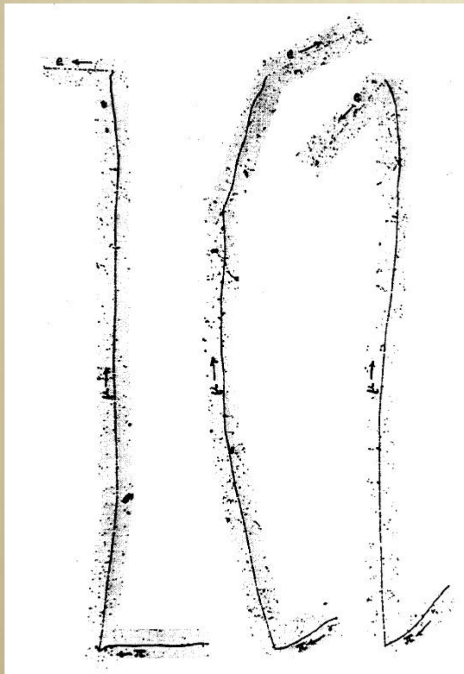
Allowed by uncertainty relation: 1.4 fm ~ 140 MeV

PARTICLE SPECTRUM

μ^-

1937





1913: Cosmic Rays were discovered

Physicists went on mountain tops for experiments!

1937: New particle discovered: negative charge, ~ 200 m_e

Very longe range in matter !? Not Yukawa's "pion" !

Muon = 'heavy electron'

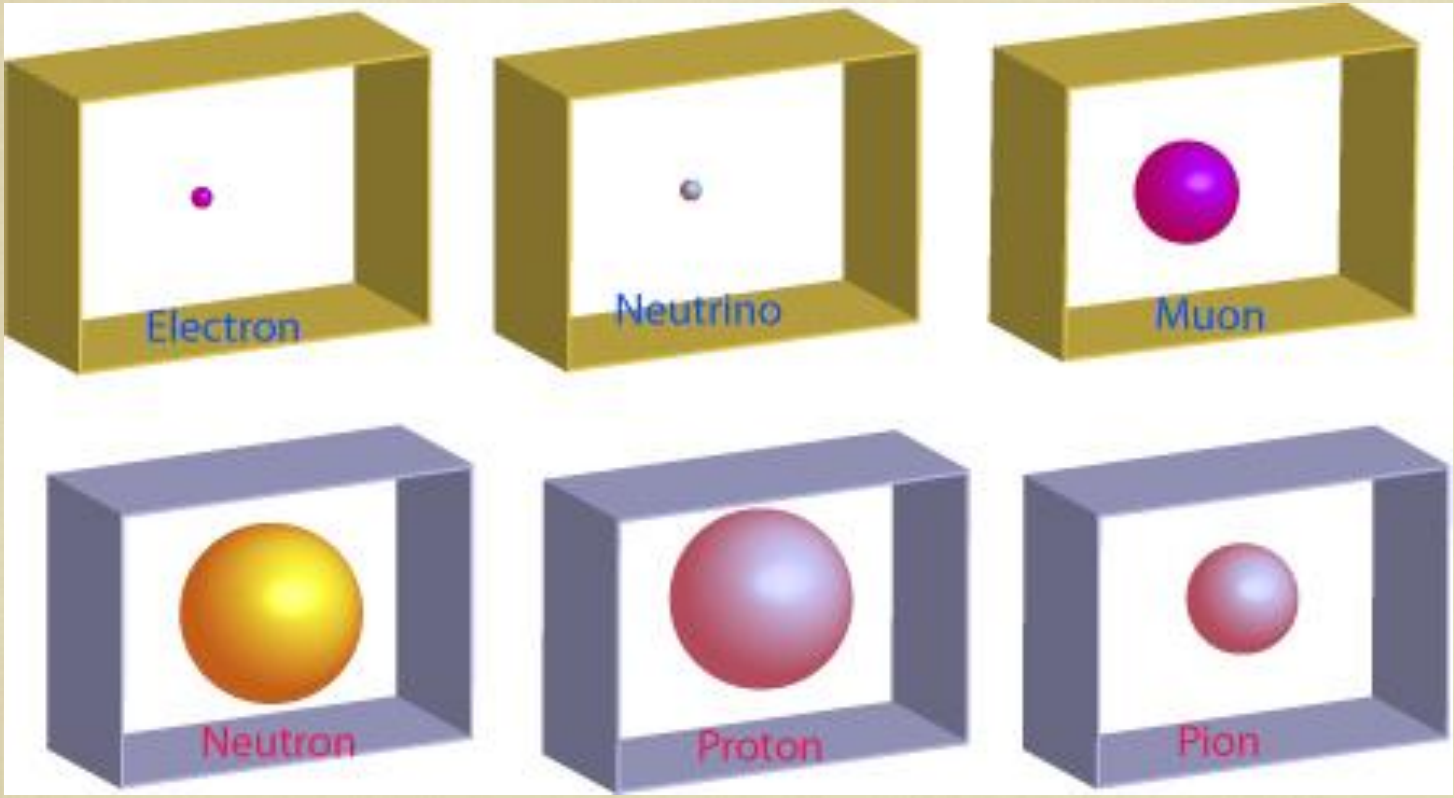
I. Rabi: "Who ordered that ?"

1948: The "pion" was finally discovered (emulsions)

PARTICLE SPECTRUM

1948

In 1948, the particle spectrum started to look ugly:



Fields

‘Weak’ interaction

Back to the beginning of the century - another interaction was being discovered

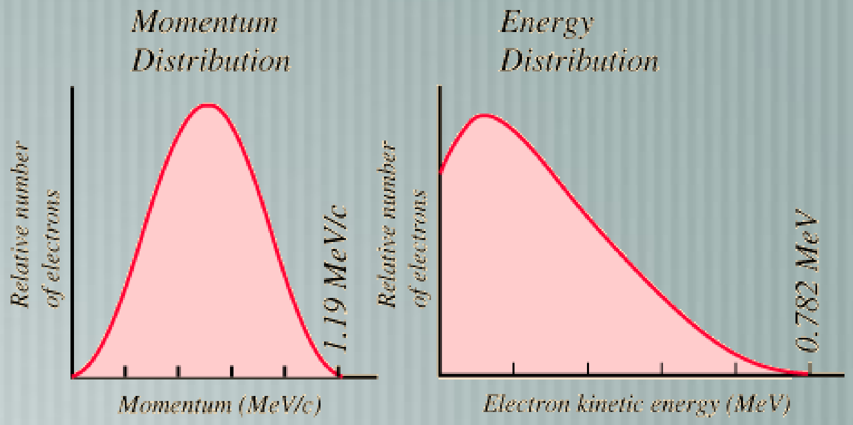
The “Weak Interaction” - Radioactivity

1896: Henri Becquerel discovered radiation from U crystals

1898: Marie and Pierre Curie : ionizing radiation from ‘Pechblende’ (U + Polonium)

1911: Continuous (?) energy spectrum of ‘beta’-rays (electrons) - energy conservation?

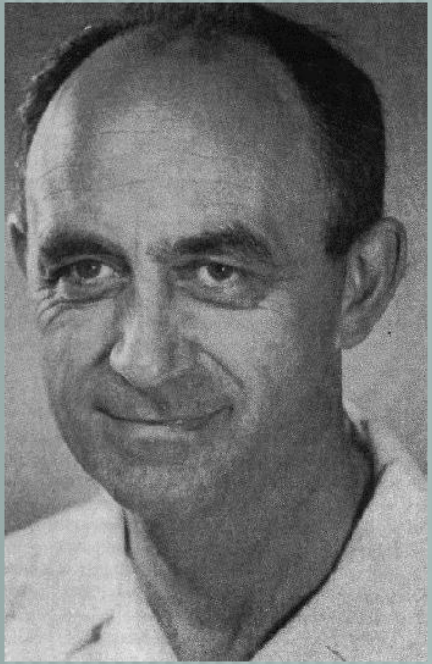
Z --> (Z+1) + e ?



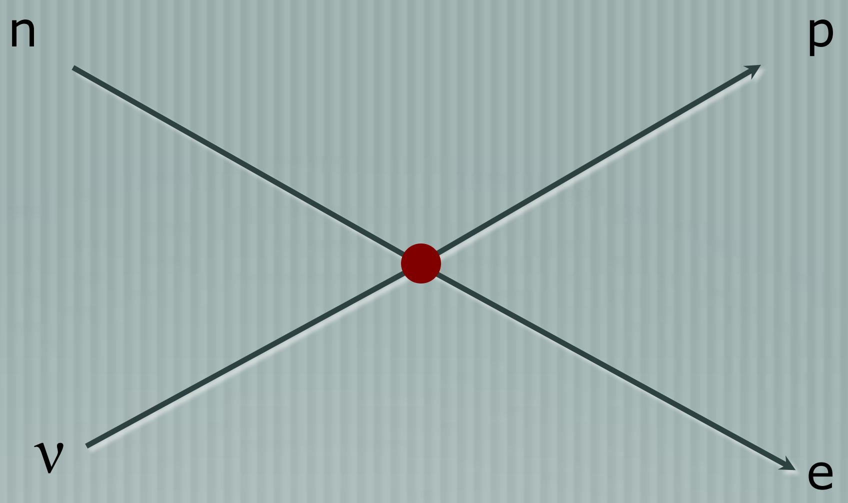
1930: Wolfgang Pauli postulates existence of ‘neutrino’: **n --> p + e + ν**

Fields

'Weak' interaction



Enrico Fermi
(1934)



Proposed a **phenomenological** model of weak interaction

Point-like coupling with strength $G_F \sim 10^{-5}$ of e.m. interaction

Coupling of two 'currents' (proton-neutron / electron-neutrino)

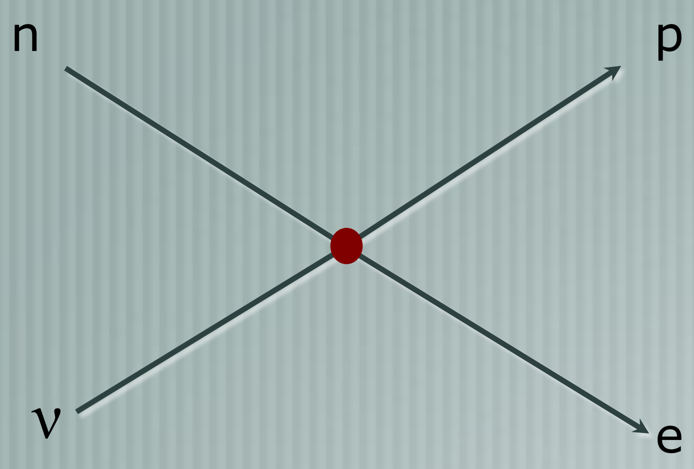
Ok until ~1960

Fields

1958 Glashow

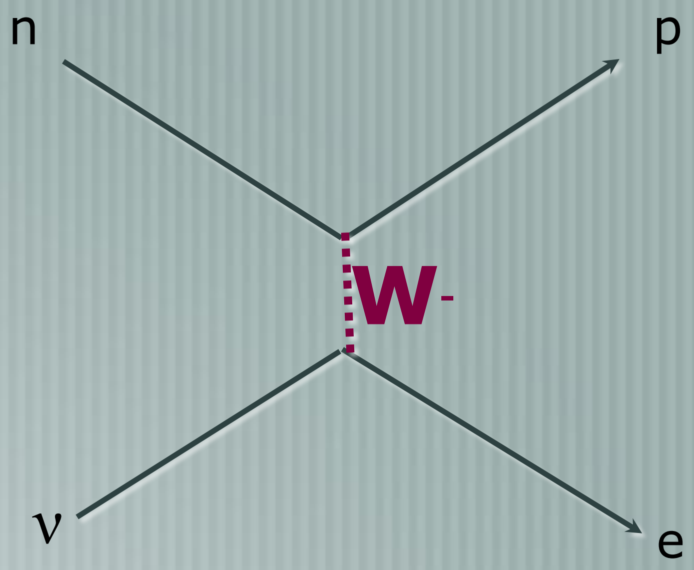
Back to the weak interaction: there was a big (theoretical) problem

probability of this reaction > 100% for E > 300 GeV



Fermi model

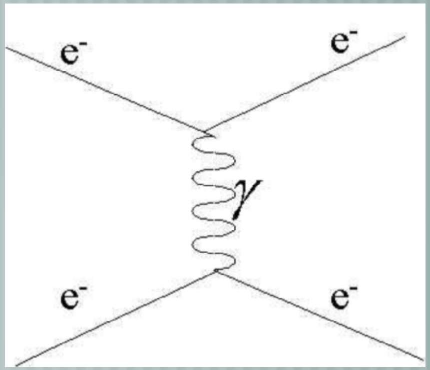
New Idea



Glashow model

Weak interaction transmitted by massive vector bosons (in analogy to photon exchange!)

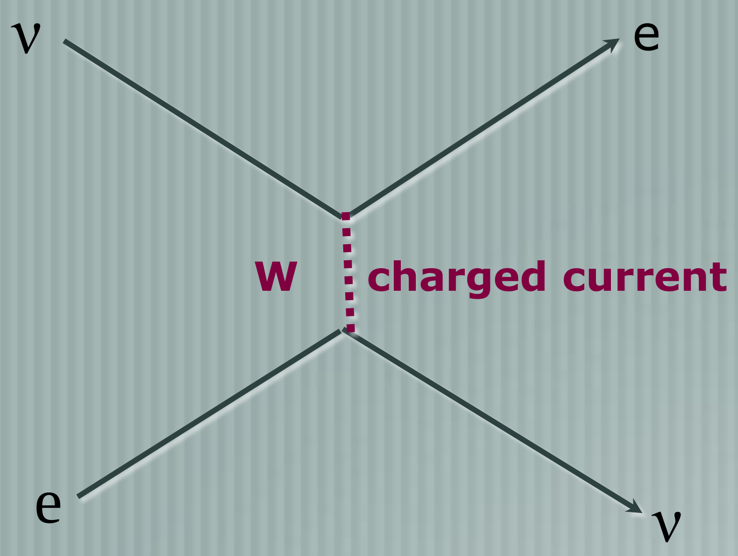
Large mass (80 GeV) explains short range ($2\cdot10^{-18}$ m) and small cross-sections

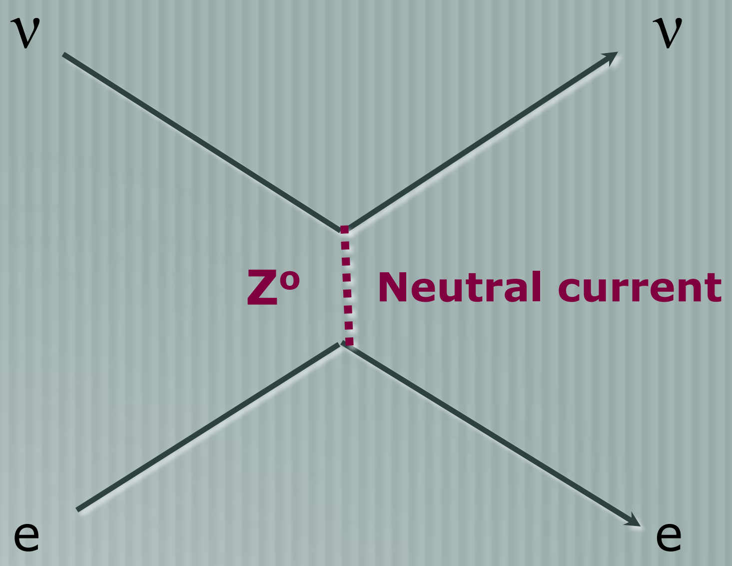


Fields

Electroweak Interaction

1968





Glashow, Salam, Weinberg (1968) - Electroweak Force

- The electromagnetic and weak interaction are different aspects of the same 'electroweak' force
- All quarks and leptons have a 'weak' charge
- There should be a 'heavy photon' (Z^o) and two charged vector boson ($W^\pm$) of mass ~ 50-100 GeV
- **The W,Z bosons acquire their mass by interacting with the "Higgs field" (1964)**

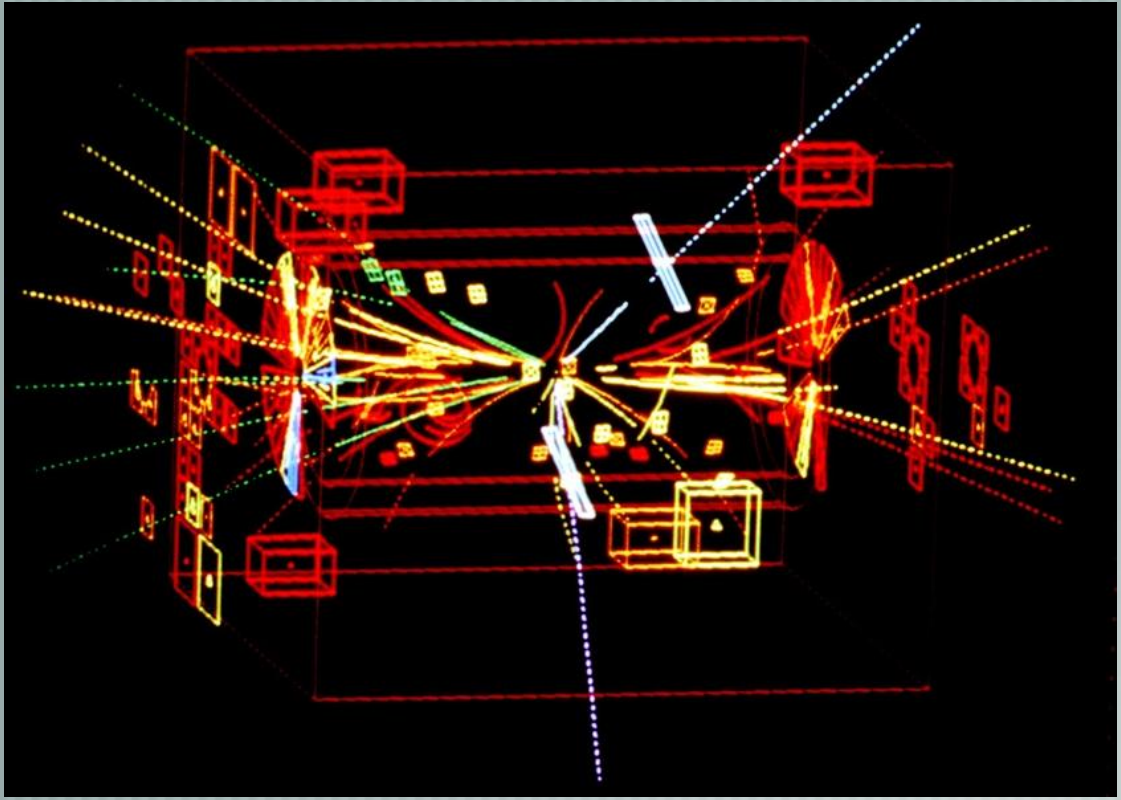
Fields

Electroweak Interaction

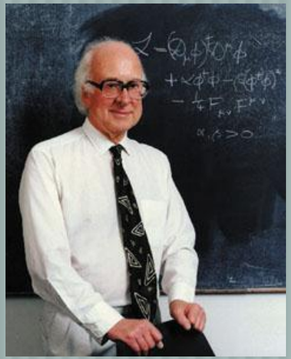
1983

“They really exist” : Discovery of the W, Z bosons at CERN (1983)

(Carlo Rubbia - leader of UA1 collaboration, and proponent of proton-antiproton collider in SpS)
(Simon van der Meer - inventor of stochastic beam cooling)



Higgs



Sir Peter Higgs

The Higgs field fills the entire Universe, since the Big Bang

By interacting with the field, some particles acquire mass

(The Higgs field represents some kind of ‘cosmic DNA’)

A cocktail party

The Higgs field...

.. a famous guest wants to walk through the room...

... a new (massless) particle enters ...

but a cluster of guests forms and he acquires ‘inertia’ ...

... interacts with the Higgs field and acquires mass ...

Higgs

***All* particles obtain their mass by the Higgs field**

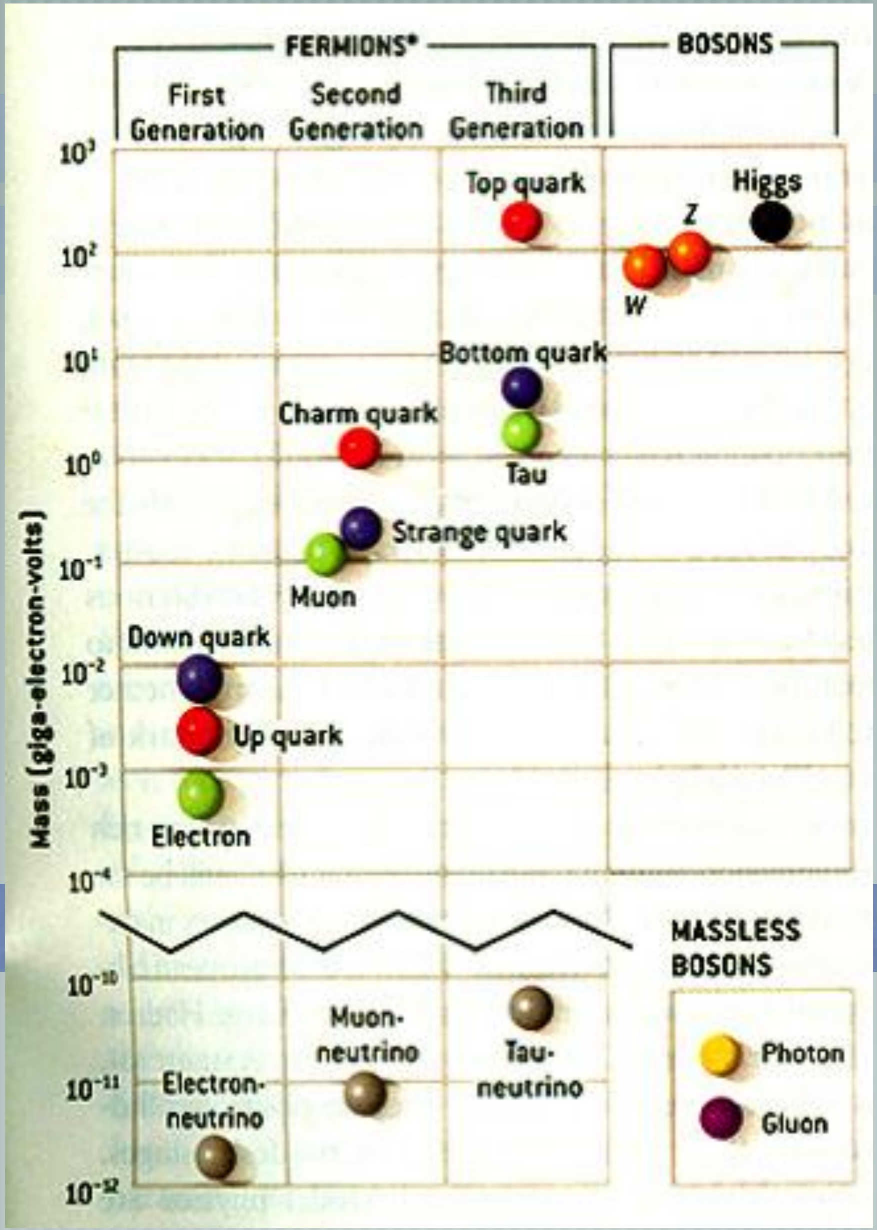
1 TeV →

100 GeV →

1 GeV →

1 MeV →

0.01 eV →



Higgs

The Higgs boson

A rumour originates ...

The energy of a particle collision...

.. the party guests cluster together and form a ‘clump’.

... excites the Higgs field and creates the Higgs boson.

Number of events

$$N_{ev} = \sigma \int_{\text{LHC run}} \text{Luminosity} \bullet dt$$

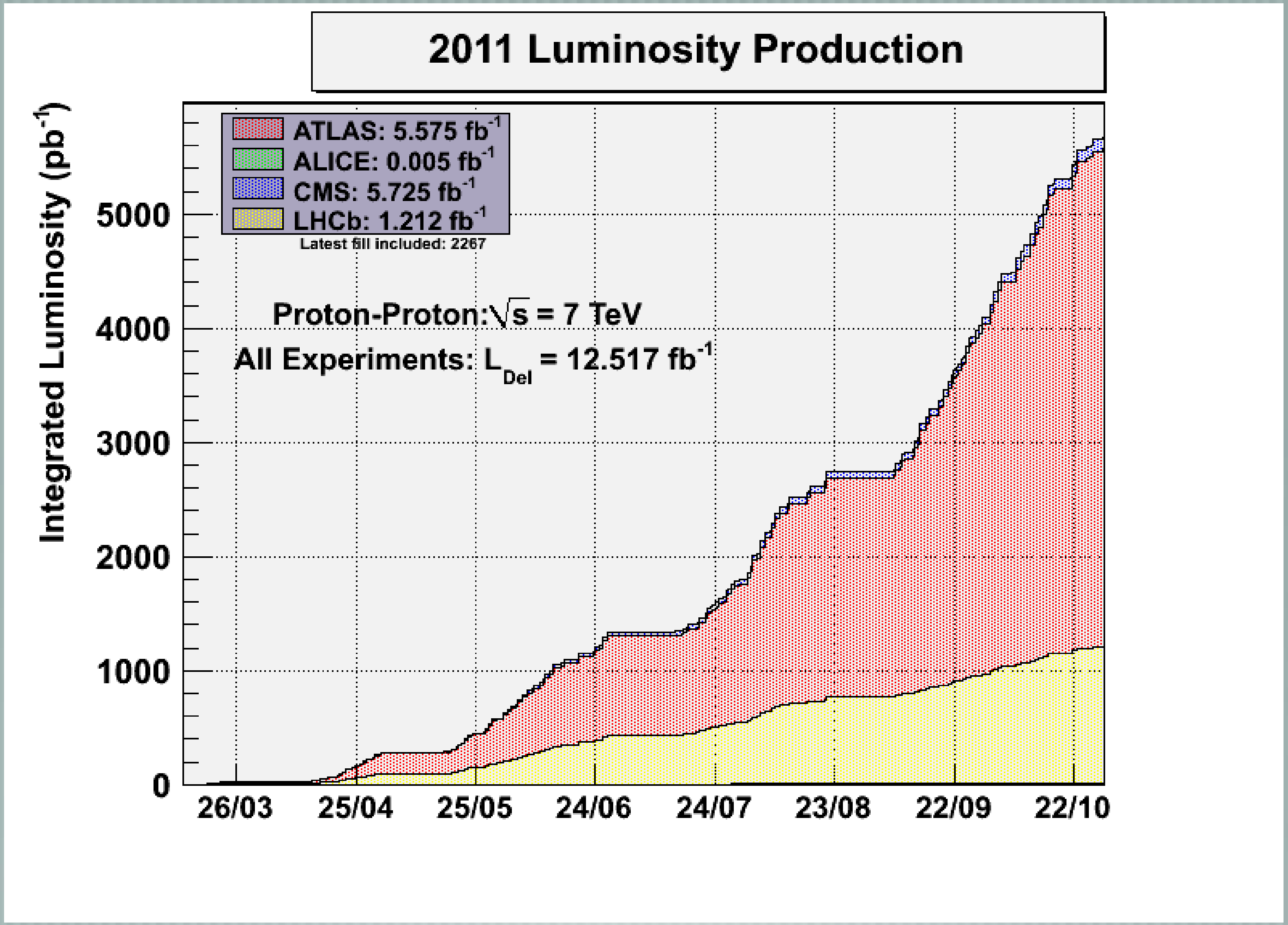
σ = cross-section ~ 100 milli-barn = 10^{-25} cm^2
Luminosity = “intensity” of collision between beams

1 femto-barn = 10^{-15} barn = 10^{-39} cm^2

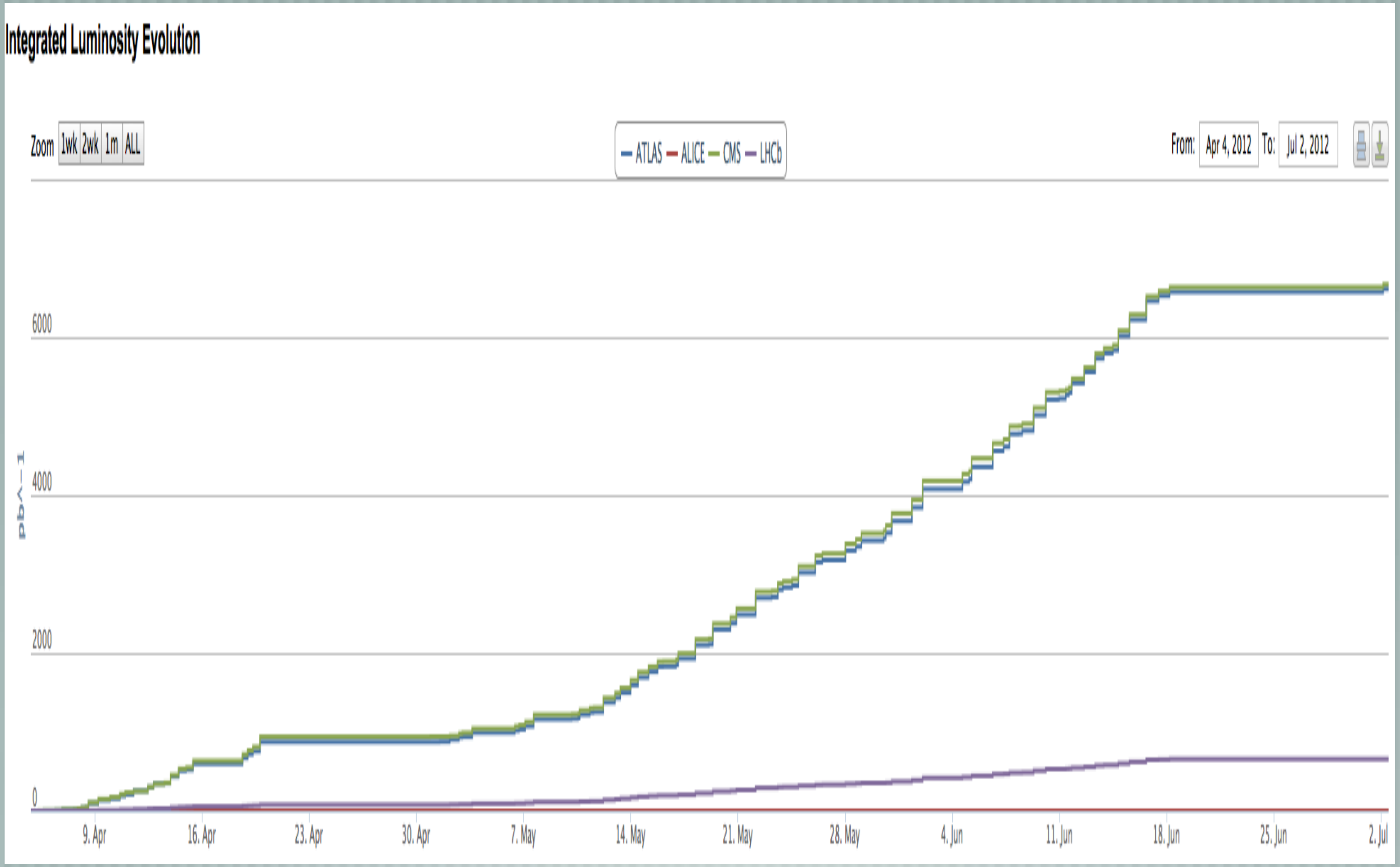
1 ‘inverse femto-barn’ = 1 fb^{-1} =

= 100,000,000,000,000 events

Luminosity and number of events

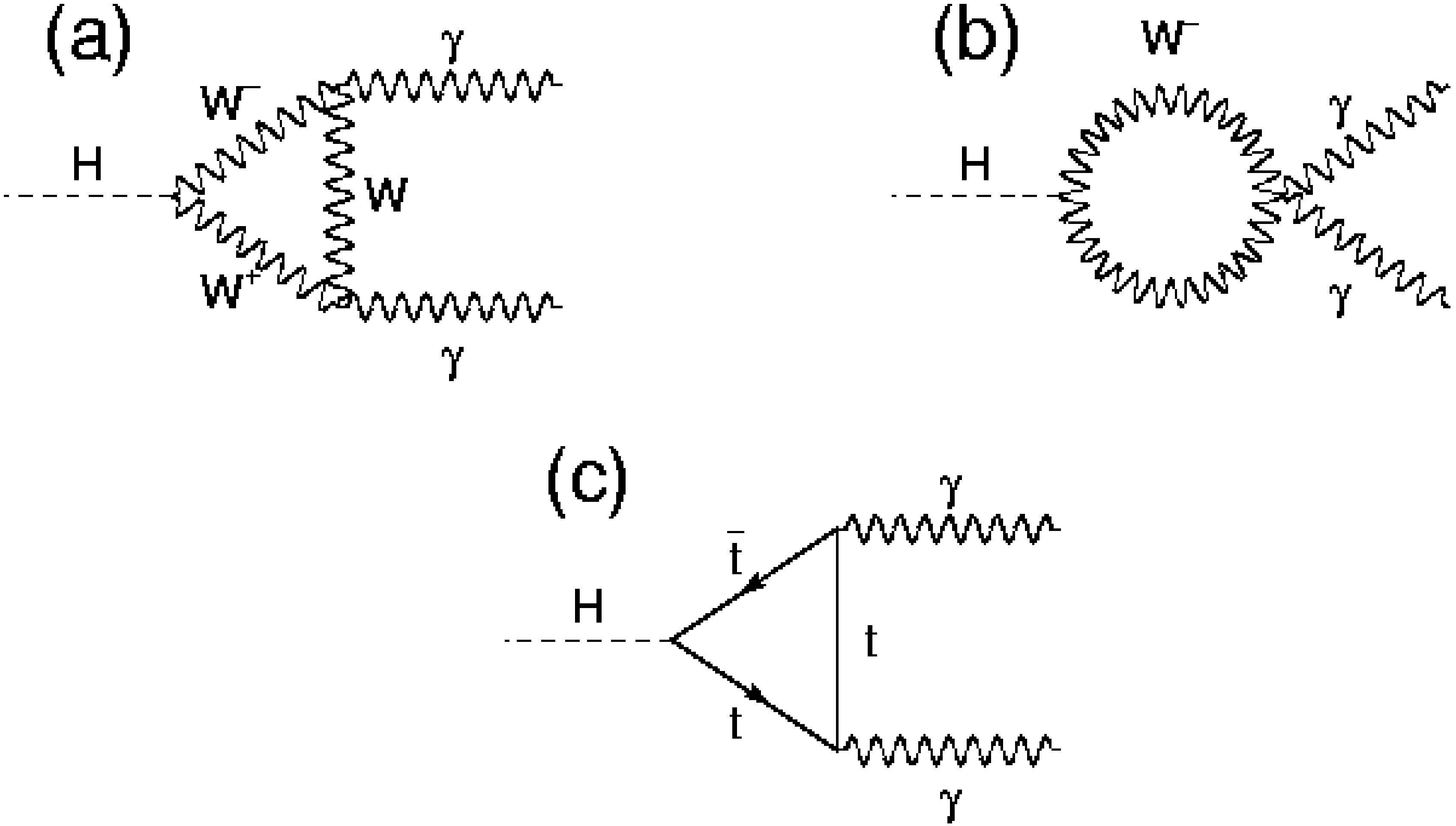


Luminosity and number of events 2012



How can a Higgs boson decay into two massless particles ?

Figure 2.9: Feynman diagrams in the Standard Model for the Higgs decay to two photons in lowest order.



Answer: through intermediate ‘loops’ of heavy particles

Higgs

The last update on 13 December 2011

Higgs boson decay

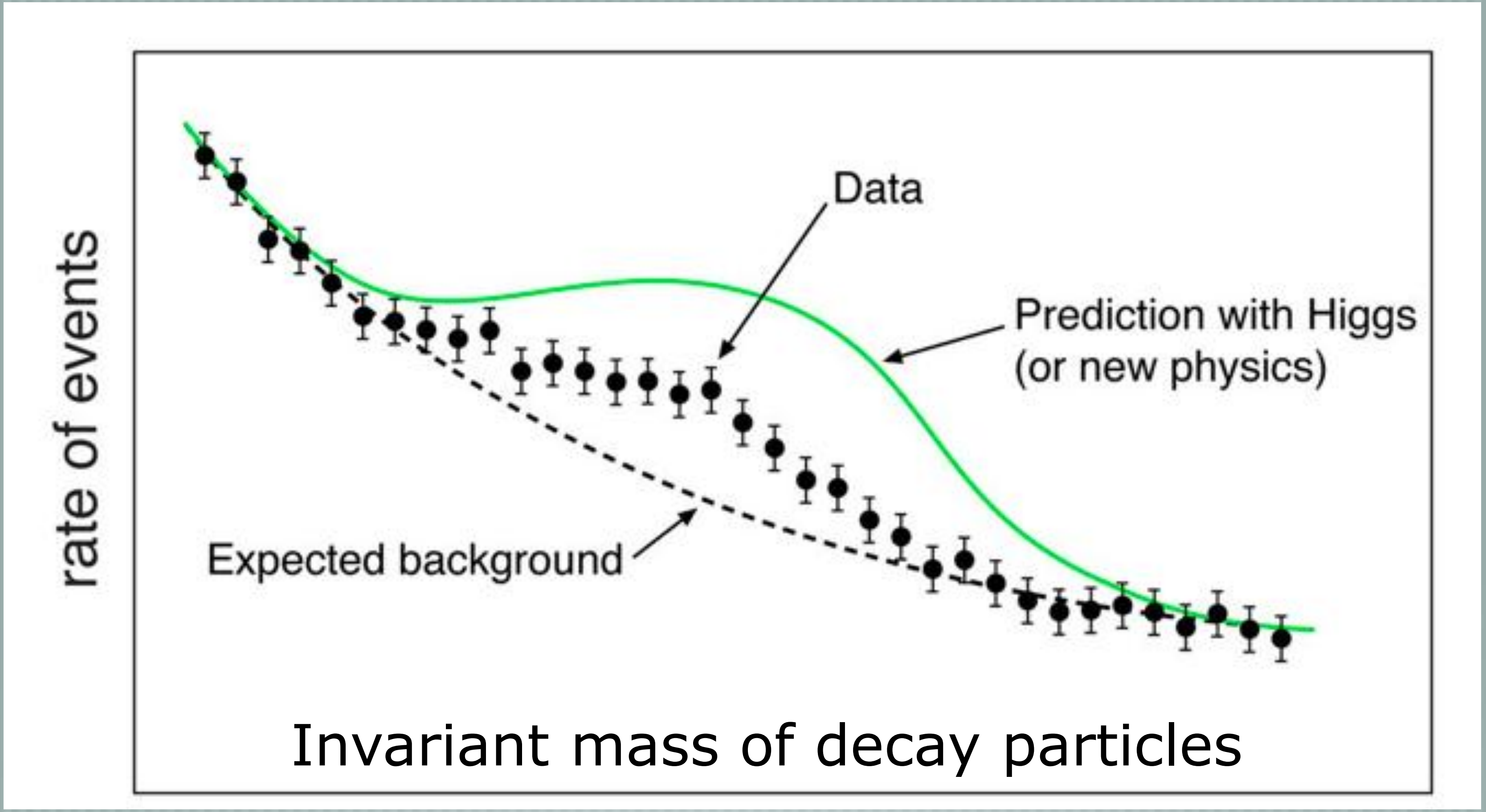
Since the interaction of particles with the Higgs field is proportional to their mass:

- the Higgs boson decays preferably into particles with large mass
- provided the Higgs mass is sufficient

- **not** into top-antitop, since m=350 GeV

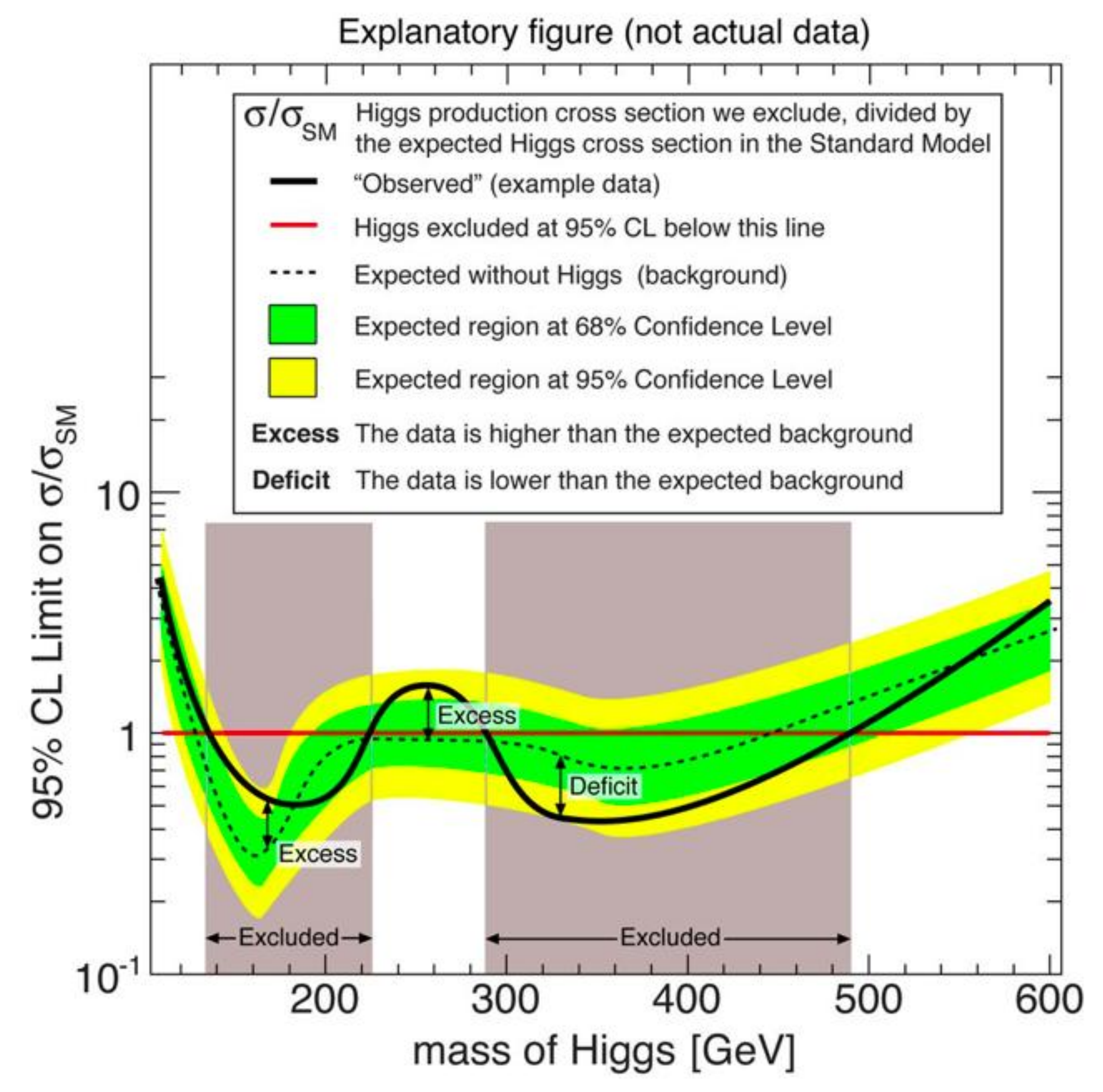
- **$Z^o Z^o$ --> $\mu^+\mu^-\mu^+\mu^-$ or $\mu^+\mu^-e^+e^-$** (only for m > 180 GeV, but o.k. via Z*)
- $W^+ W^-$ (difficult to detect)
- b + anti-b quark
- c + anti-c quark
- tau + anti-tau lepton
- **gamma + gamma** (only 0.2% probability, but little background)

How are the data presented?



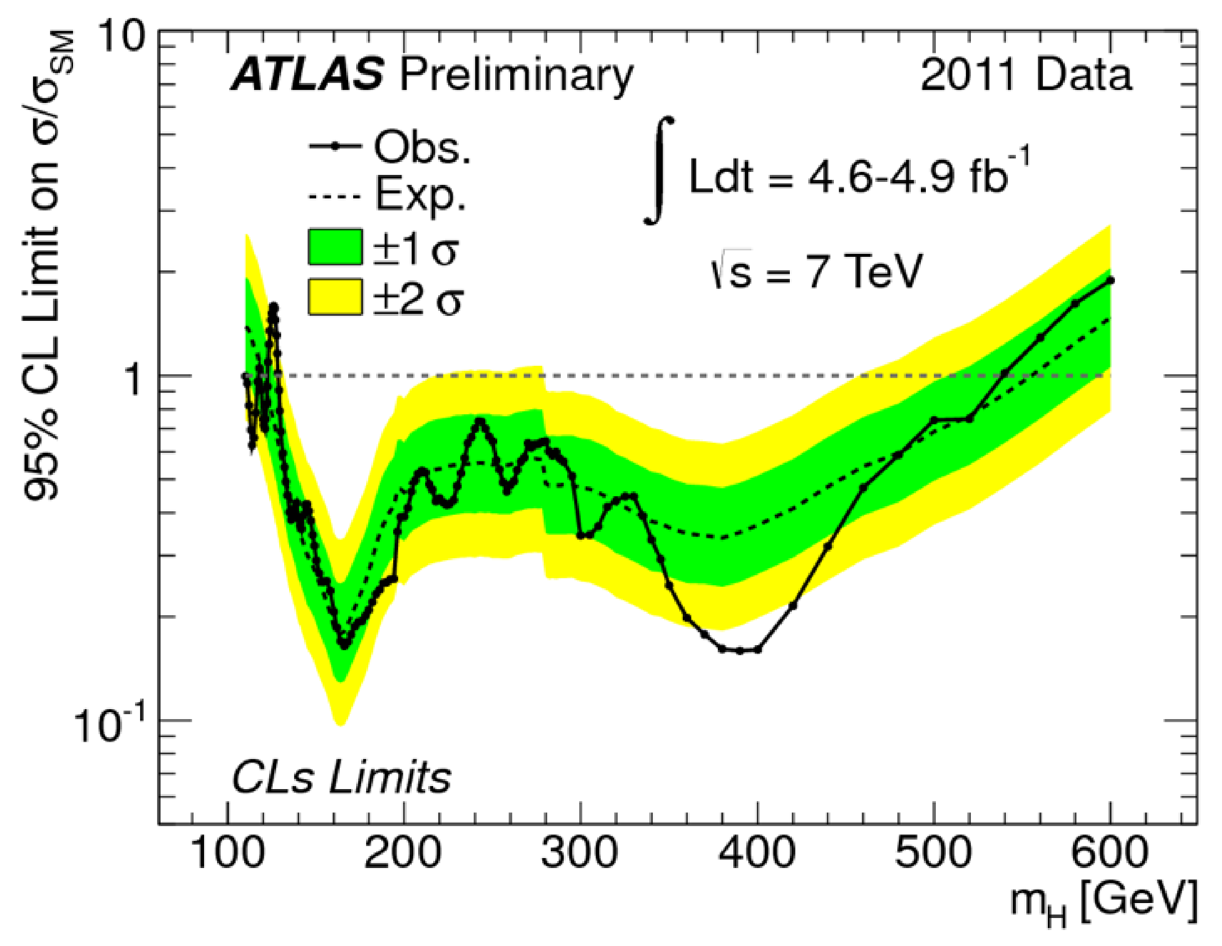
Three possible explanations:

1. It is a statistical fluctuation above the expected background processes.
2. It is a systematic problem due to an imperfect understanding of the background processes.
3. The excess is due to some different new physics (than that hypothesized) that would predict a smaller excess


Explanatory figure (not actual data)
σ/σSM Higgs production cross section we exclude, divided by the expected Higgs cross section in the Standard Model
"Observed" (example data)
Higgs excluded at 95% CL below this line
Expected without Higgs (background)
Expected region at 68% Confidence Level
Expected region at 95% Confidence Level
Excess The data is higher than the expected background
Deficit The data is lower than the expected background
Excess
Deficit
Excess
Excluded
Excluded
95% CL Limit on σ/σSM
10
1
10-1
200
300
400
500
600
mass of Higgs [GeV]

Higgs

The last update on 13 December 2011



2012: 20 fb^{-1} (8 TeV) = Final verdict on existence (or not) of Higgs boson