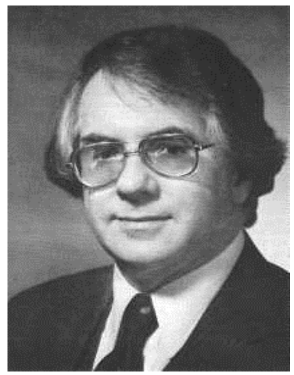
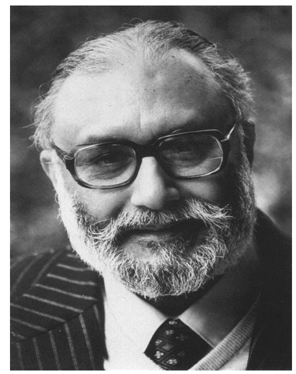
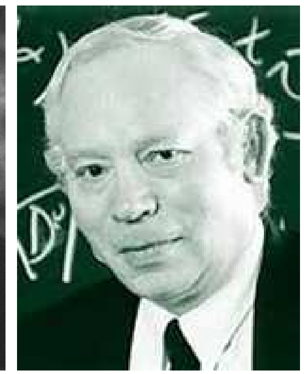
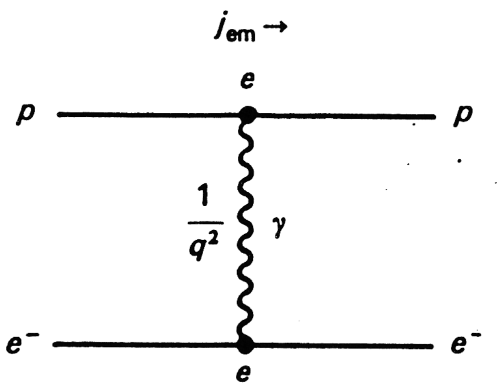
Weak Interactions

The Theory of GLASHOW, SALAM and WEINBERG ~ 1959-1968

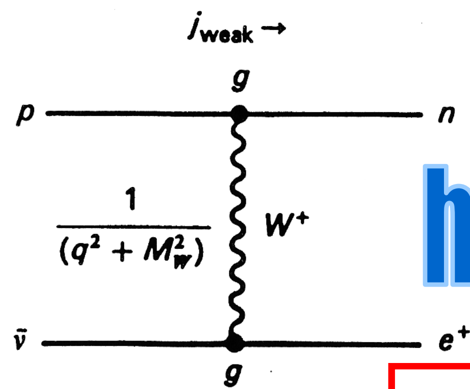




(Nobel 1979)

Theory of the unified weak and electromagnetic interaction, transmitted by exchange of "intermediate vector bosons"



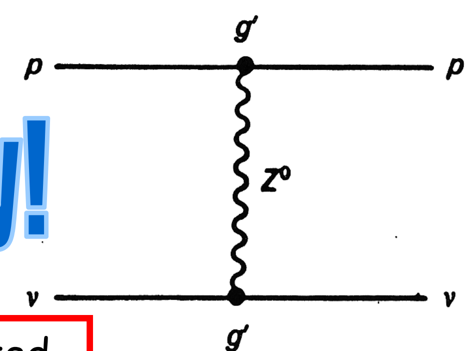
(a) Electromagnetic scattering



(b) Weak scattering (charged current)

heavy!

mass generated by Higgs field



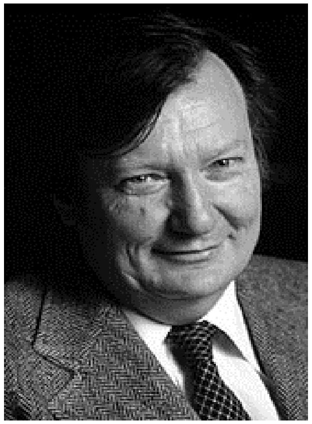
(c) Weak scattering (neutral current)

Discovery of the W and Z (1983)

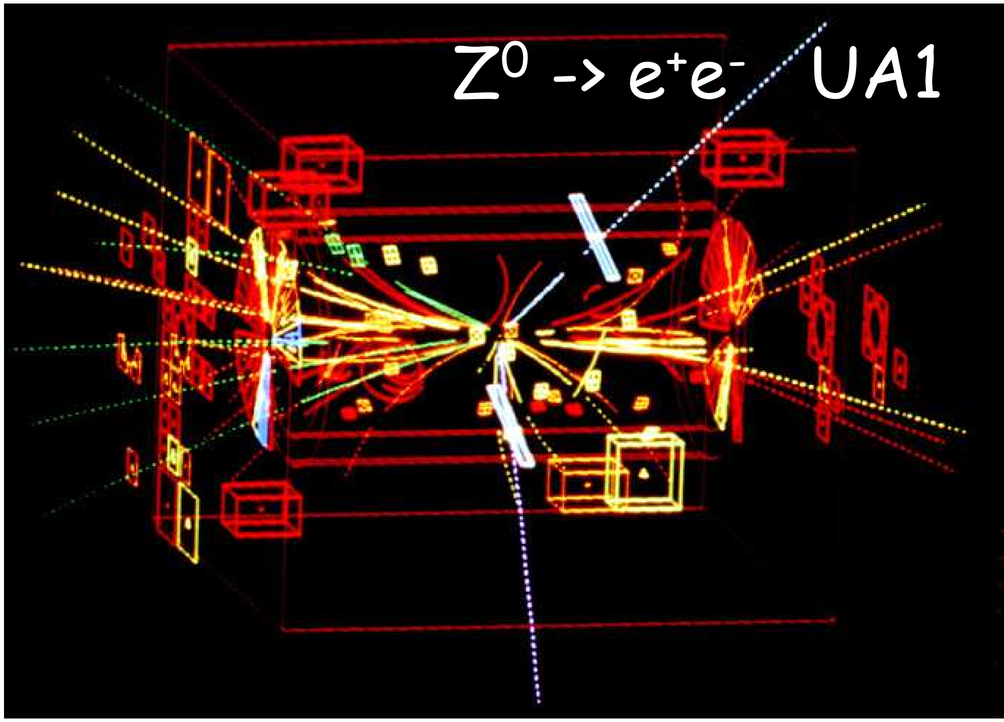
- To produce the heavy W and Z bosons (m ~ 80-90 GeV) need high energy collider!
- 1978-80: conversion of SPS proton accelerator at CERN into proton-antiproton collider
  challenge: make antiproton beam!
- success!
  -> first W and Z produced 1982/83

(Nobel 1984)

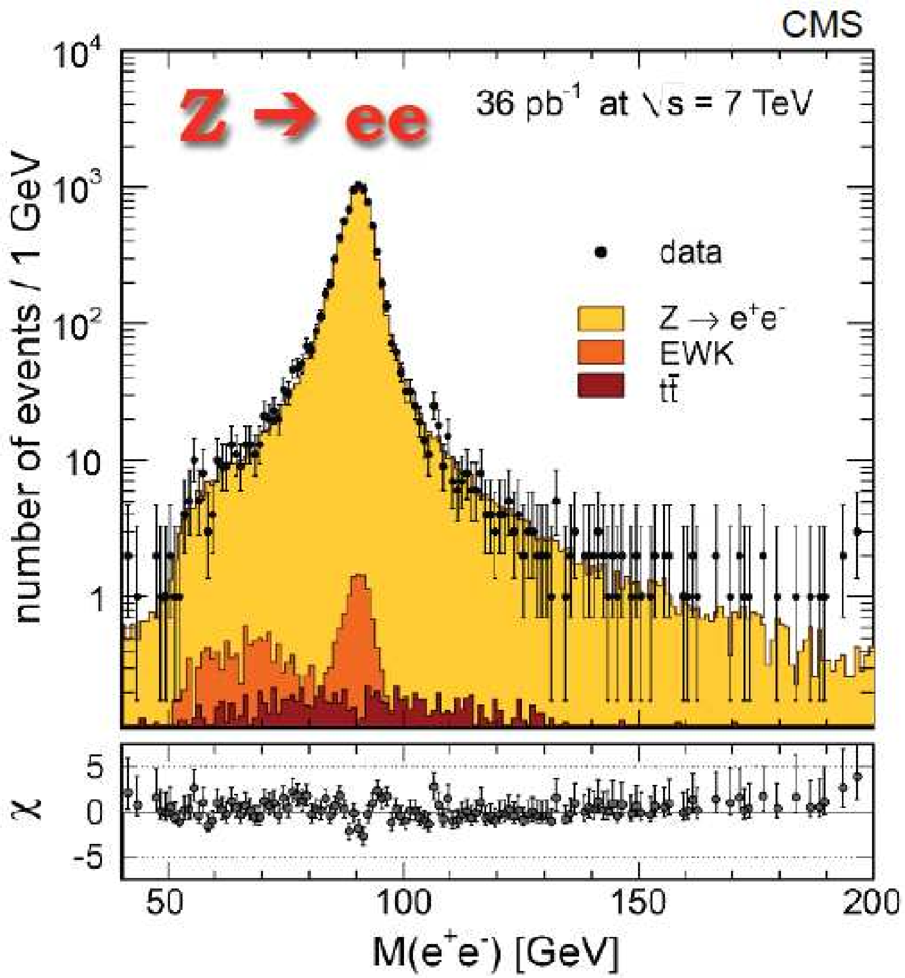
Carlo Rubbia

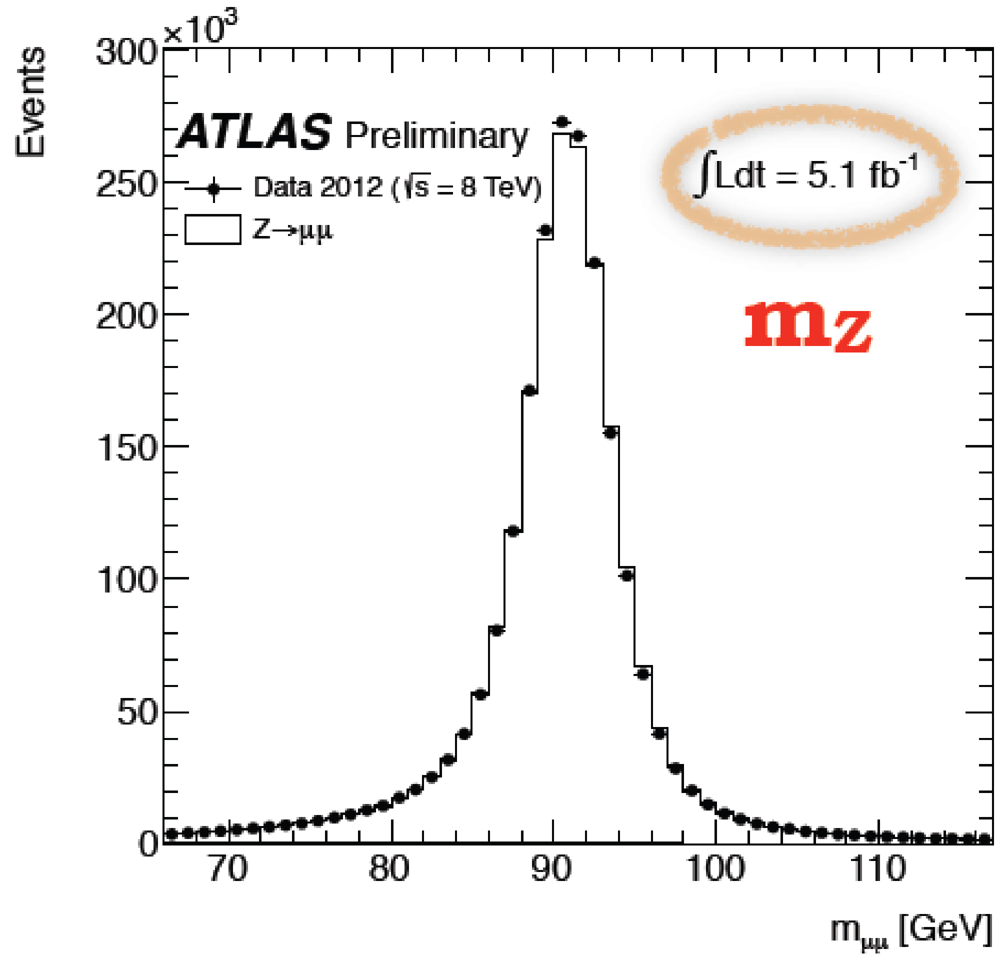


Simon van der Meer



Z production at LHC





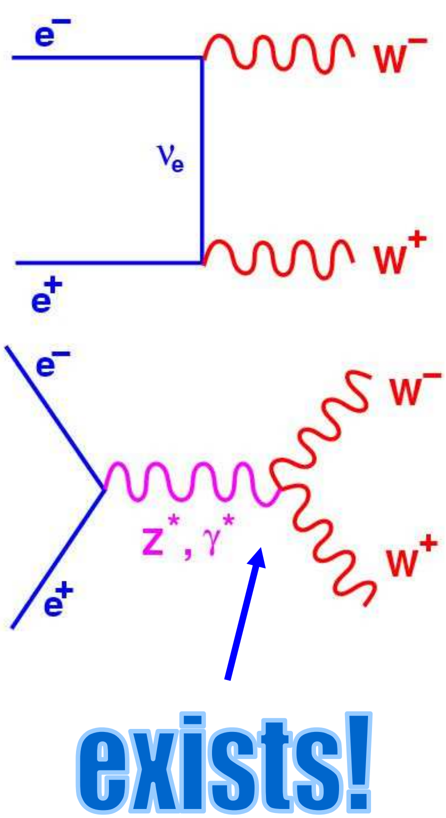
Now millions of events …

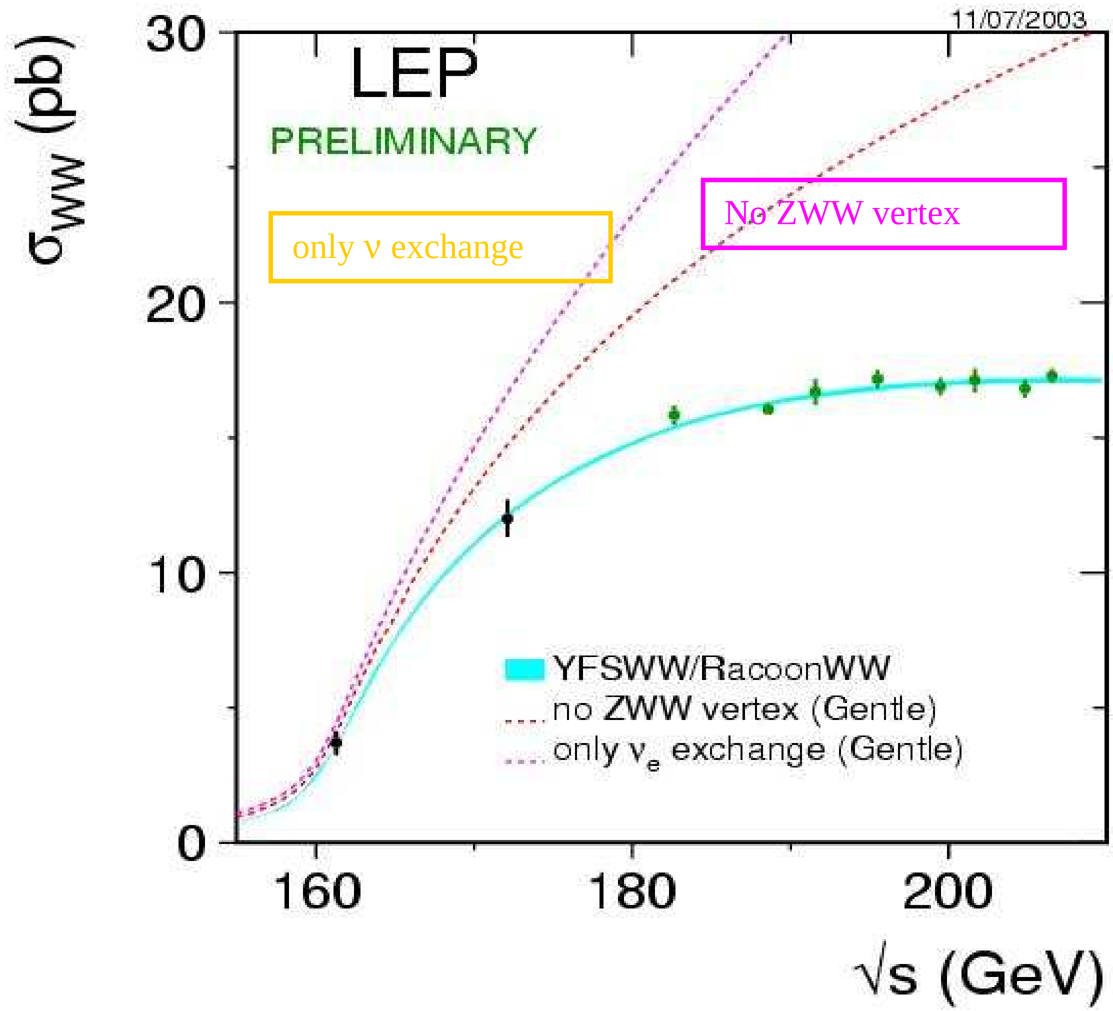
yesterday's signal is today's background and tomorrow's calibration

Three Boson Coupling @ LEP

W/Z bosons carry electroweak charge (like colour for gluons)

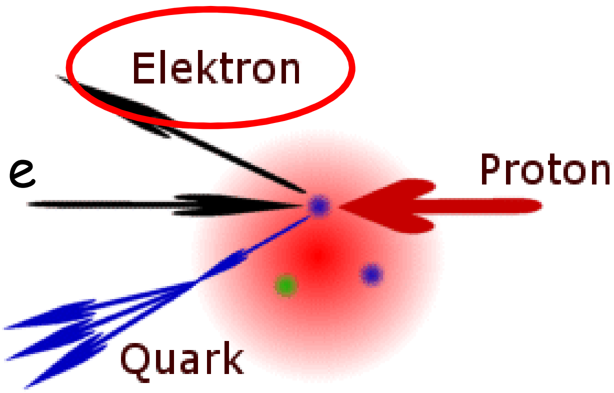
-> measure rate of W pair production at LEP II

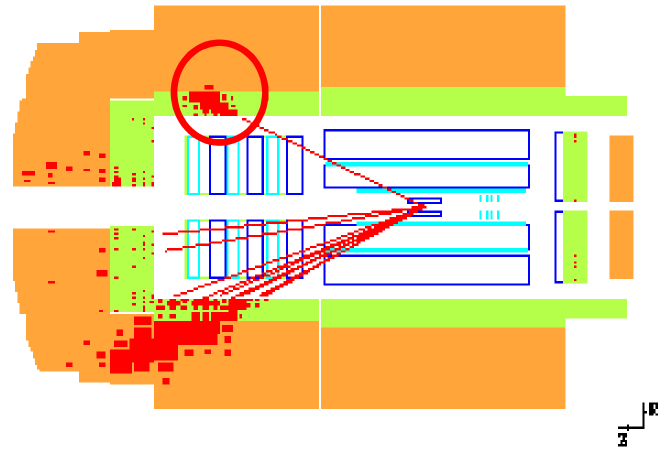


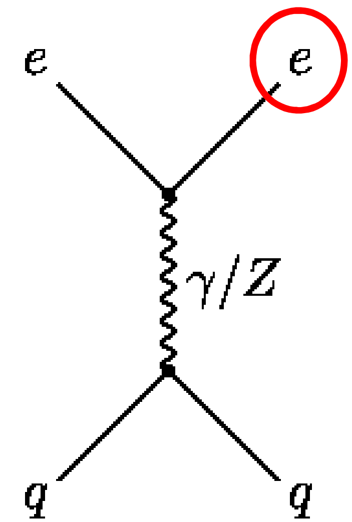


Electroweak Physics at HERA

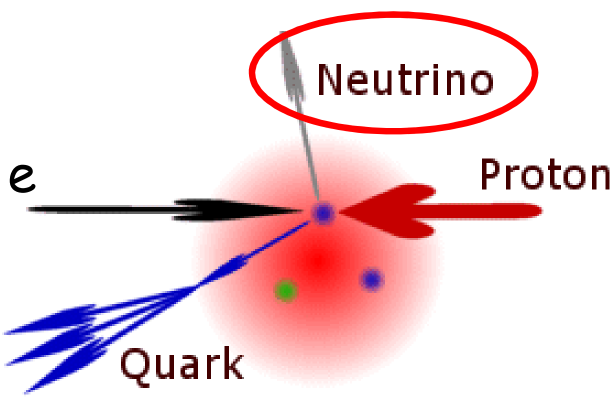
Neutral Current (NC) interactions

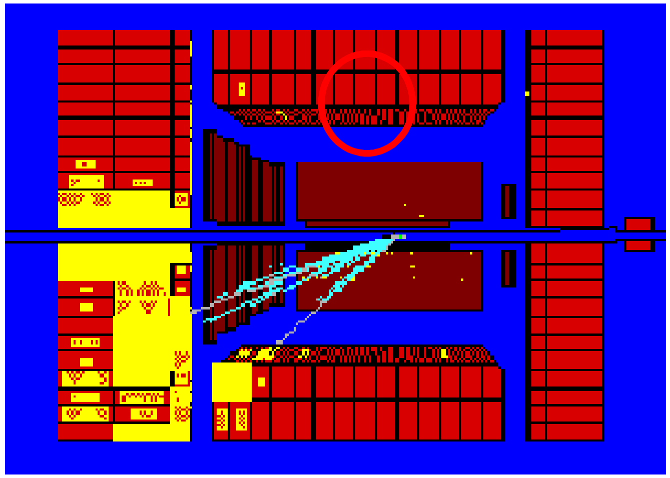


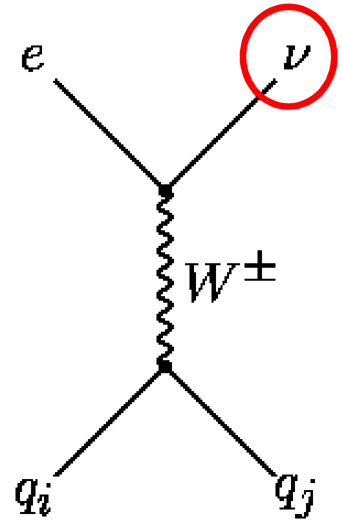




Charged Current (CC) interactions

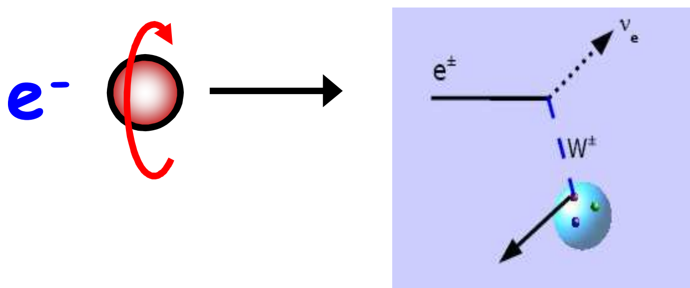




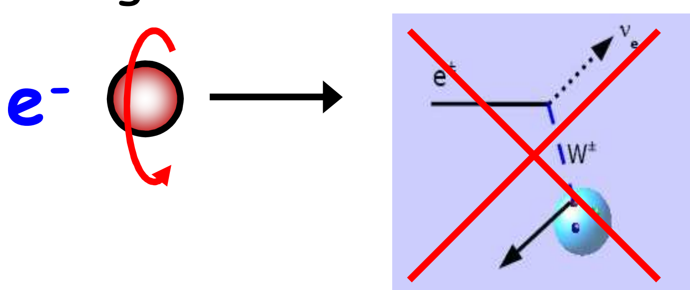


Weak interactions are "left-handed"

- lefthanded electrons interact (CC)

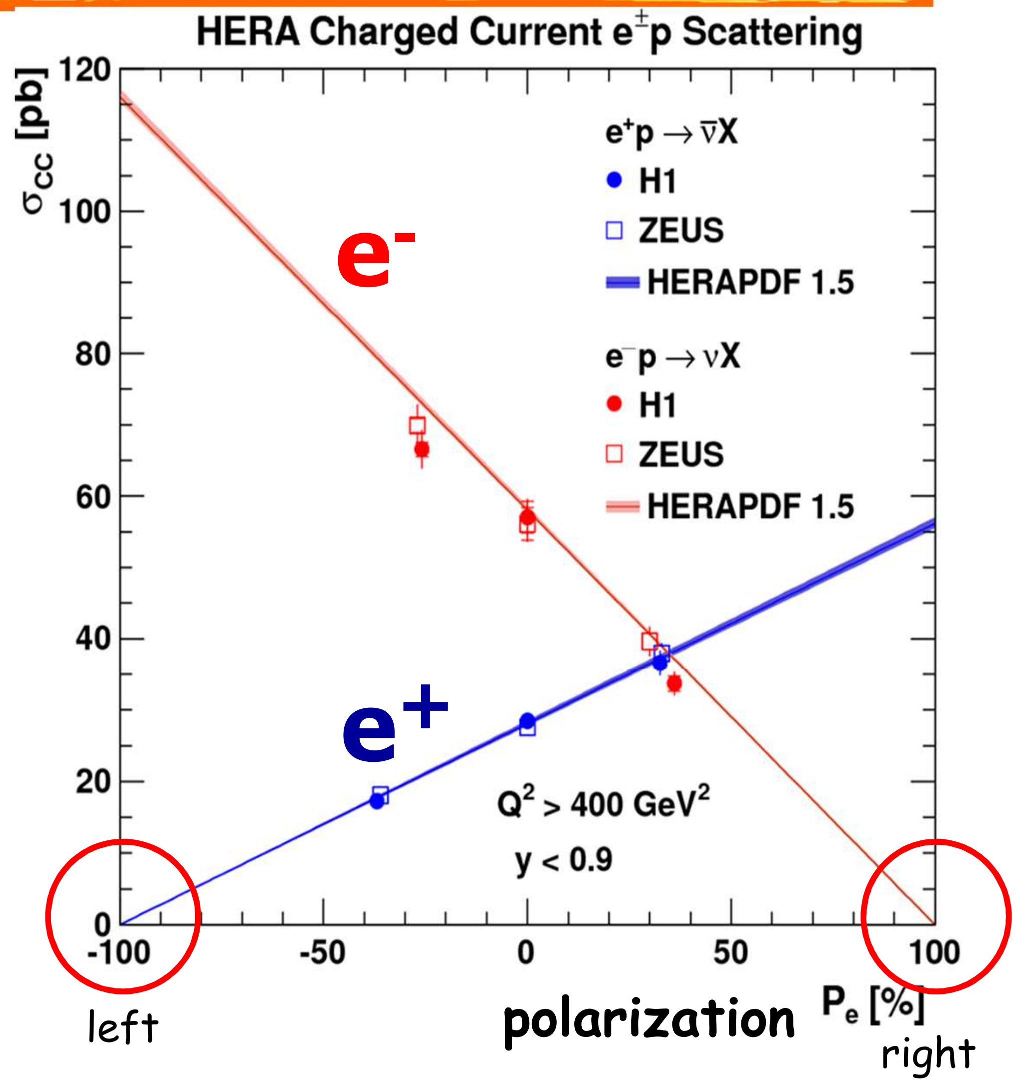


- righthanded electrons do not!



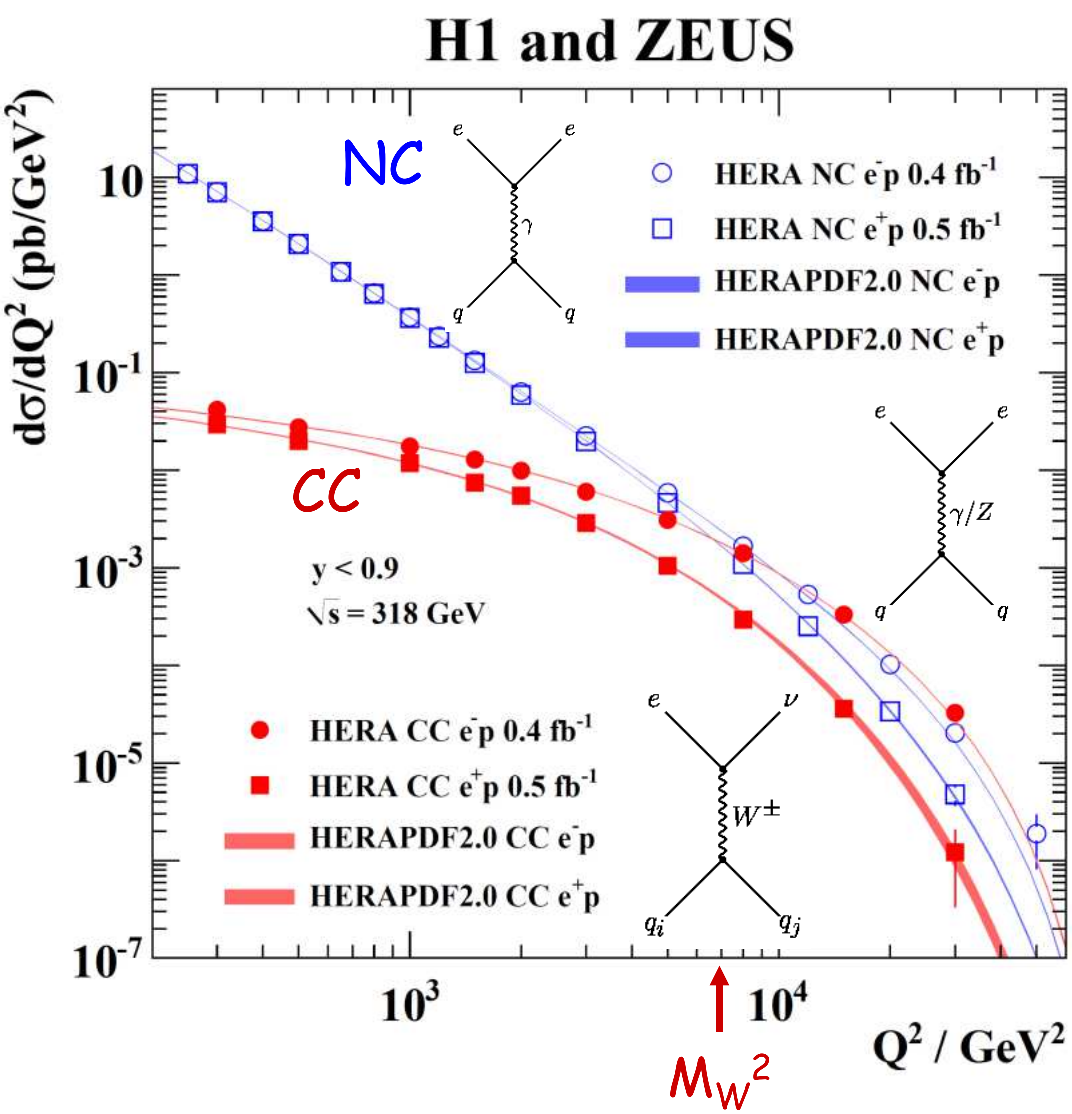
- cross section linearly proportional to polarization

$$\boxed{\sigma^{e^{\pm}p}_{polCC} = (1 \pm P_e) \cdot \sigma^{e^{\pm}p}_{unpolCC}}$$



It works!

Electroweak Unification

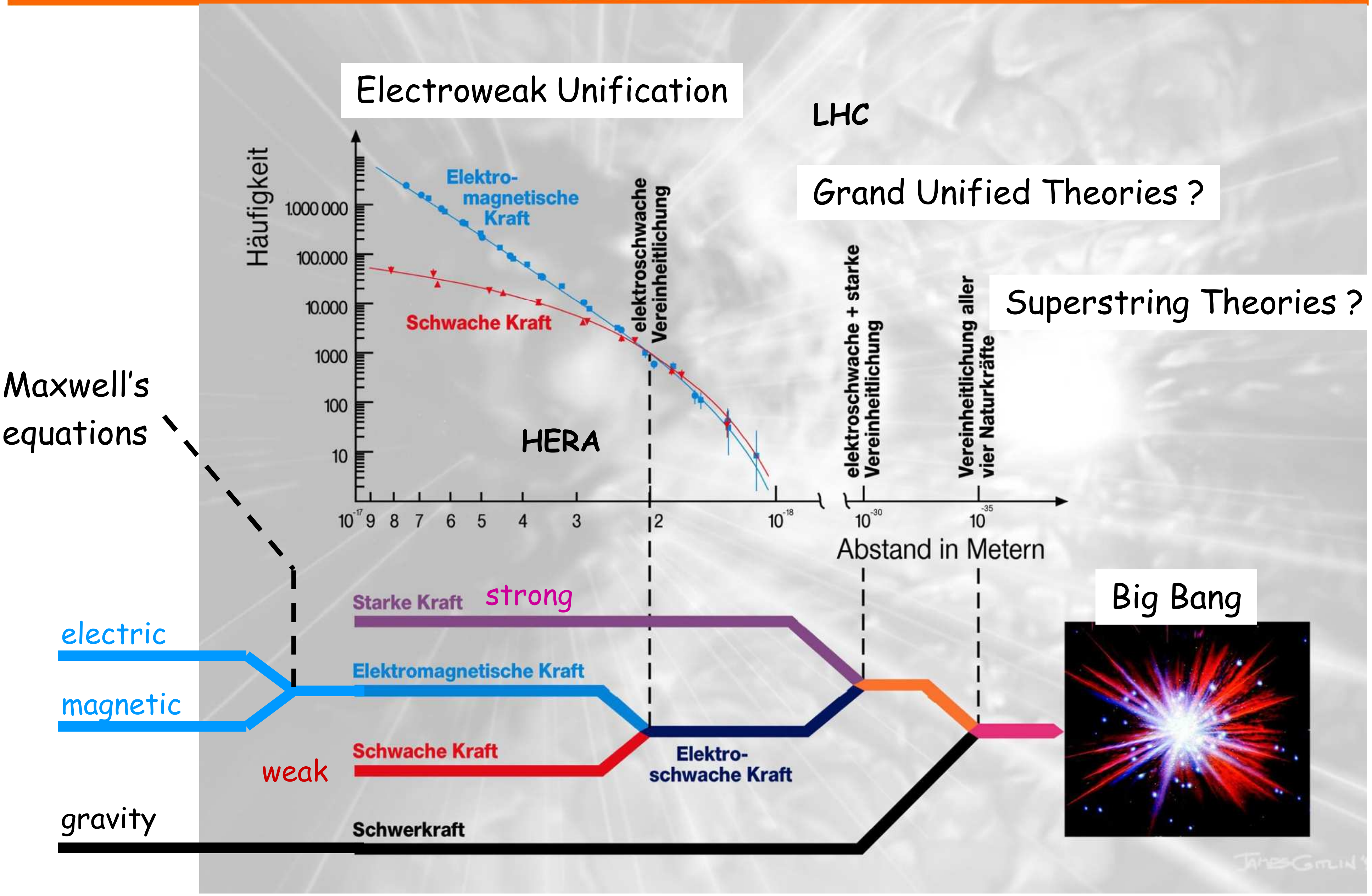


Strength of weak and electromagentic forces become similar at scale $Q^2 \sim M_W^2$

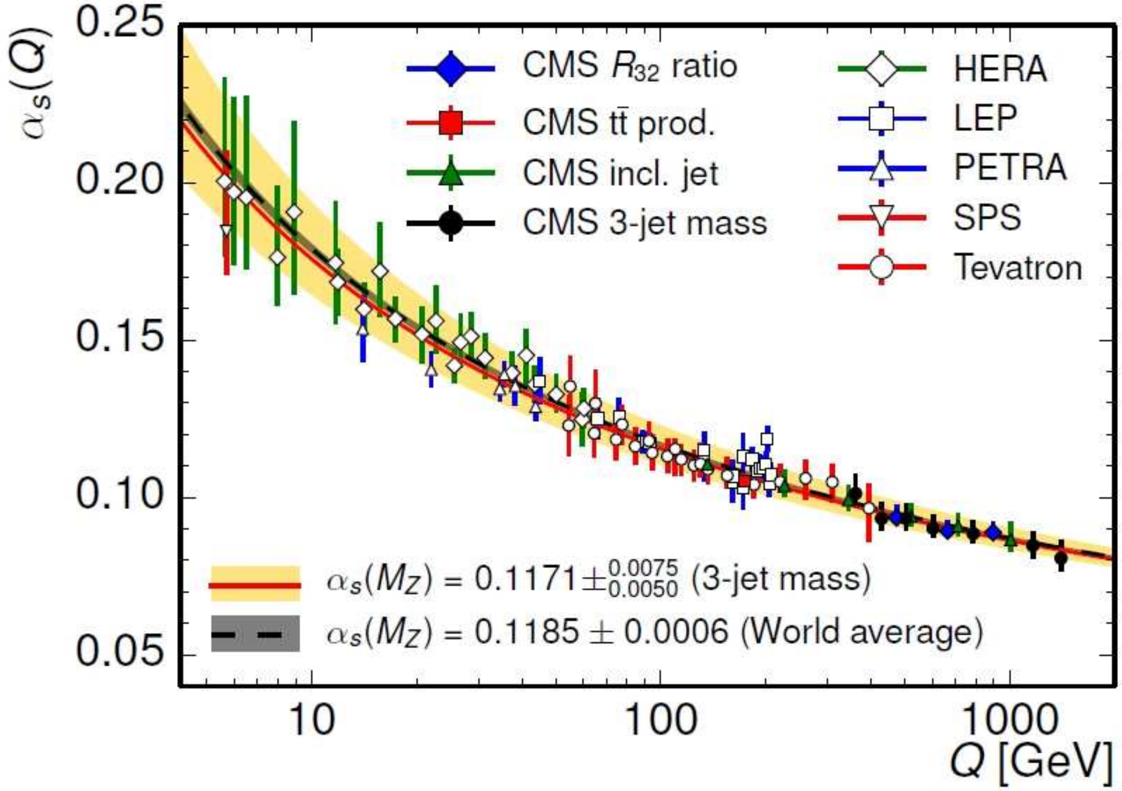
$$\frac{d^2\sigma_{NC}}{dQ^2\,dx} \sim \alpha^2 \frac{1}{Q^4} \frac{1}{x} \Phi_{NC}(x,Q^2)$$

$$\frac{d^2\sigma_{CC}}{dQ^2\,dx} \sim G_F^2 \left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \frac{1}{x} \Phi_{CC}(x,Q^2)$$

The Quest for Unification of Forces

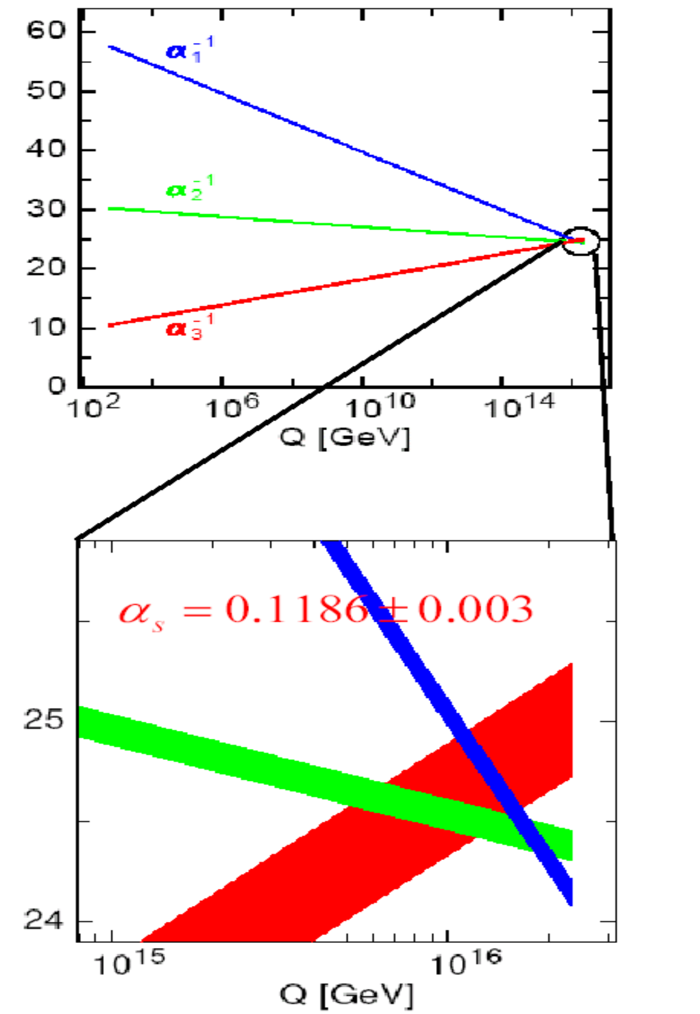


α_s running and Grand Unification



?

with SUSY (see later):



hep-ph/0407067 B.Allanach ... P.Zerwas

Antimatter

P.A.M. Dirac
(Nobel 1933)

relativistic Schrödinger equation
(Dirac equation)
two solutions:
one with positive, one with negative energy
Dirac: interpret negative solution as **antiparticle**

1932 antielectrons (positrons) found in conversion of energy into matter


C.D.Anderson
(Nobel 1936)

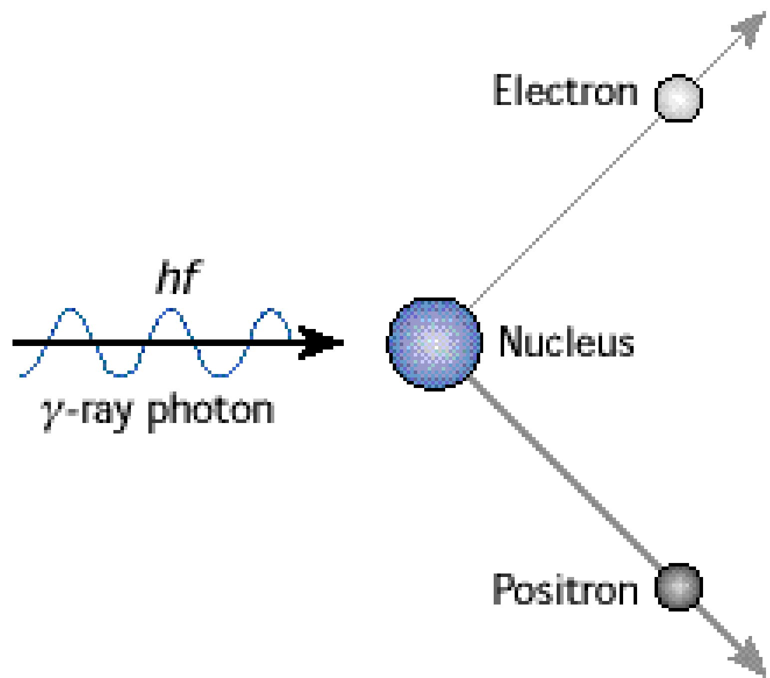
1995 antihydrogen consisting of antiprotons and positrons produced at CERN

In principle: antiworld can be built from antimatter
In practice: produced only in accelerators and in cosmic rays

Why???

Pair Production

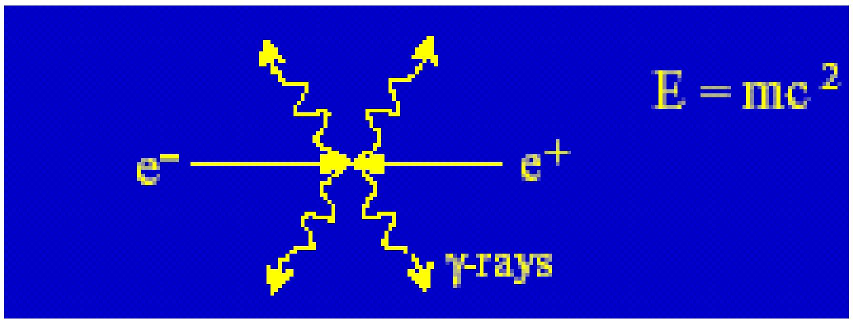
e.g. $$\gamma \rightarrow e^{+} + e^{-}$$

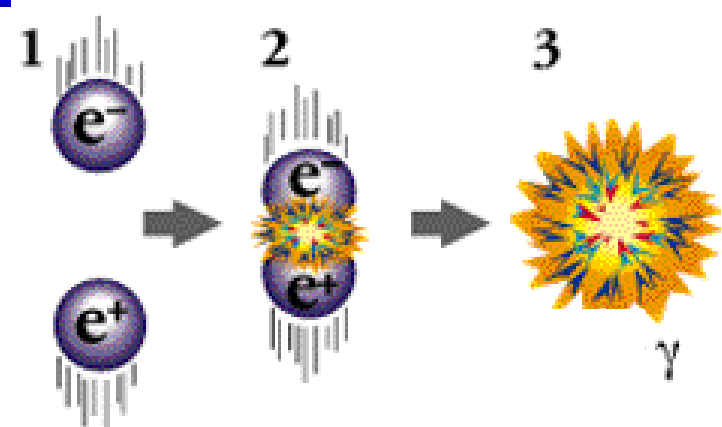


Equal amounts of matter and antimatter are produced when radiation is converted to matter

Annihilation

$$e^{+} + e^{-} \rightarrow 2hf$$

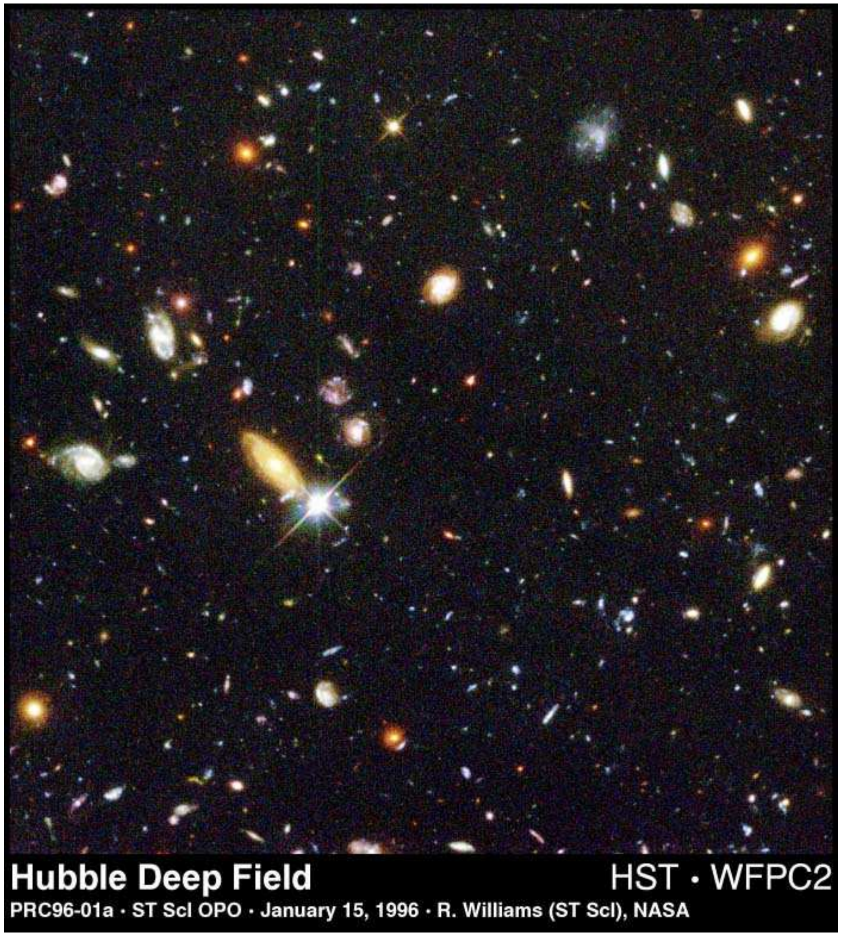


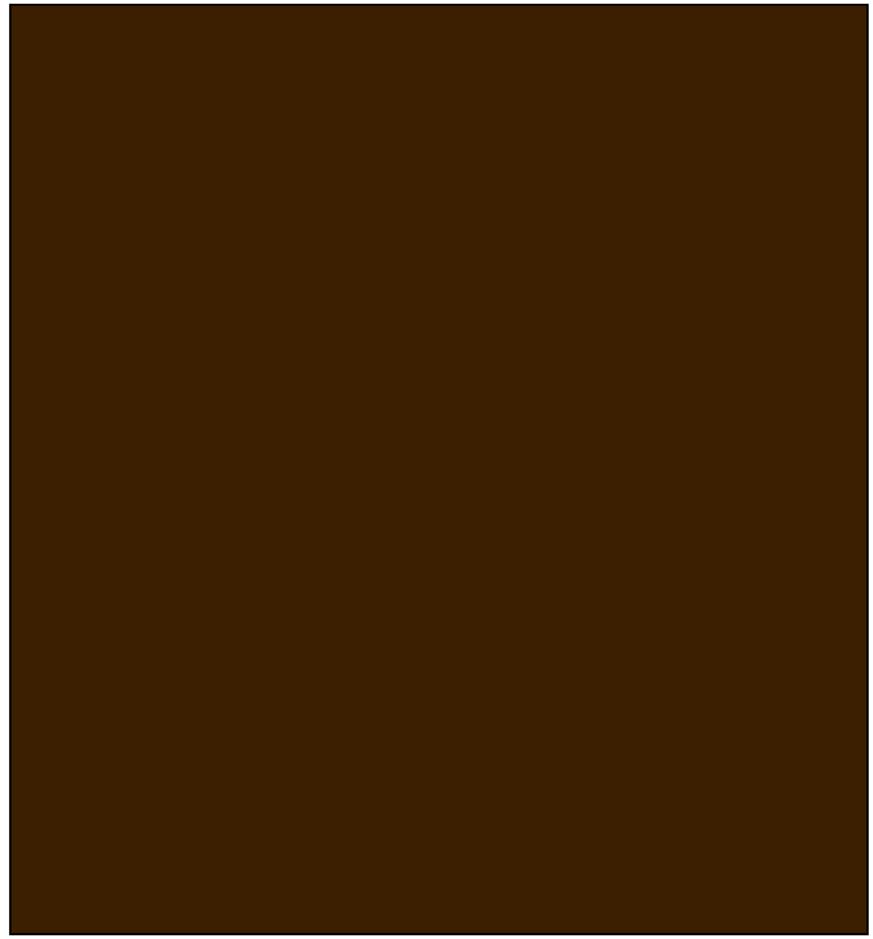


Antimatter can be produced.
It annihilates with matter to produce radiation

The Matter Antimatter Puzzle

Why does the Universe look like
this not that?

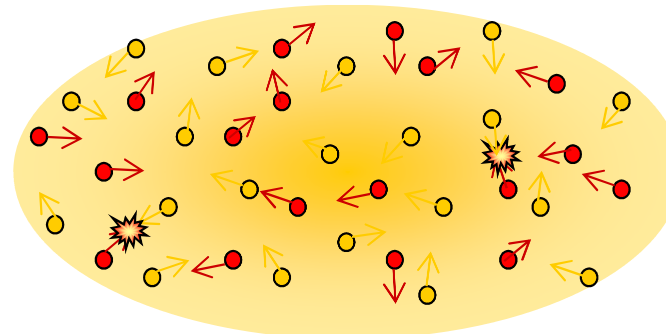




As far as we can see in universe, no large-scale antimatter.
-> need CP violation!

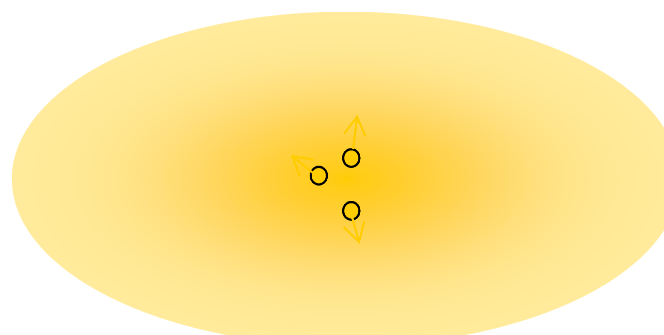
The Matter Antimatter Puzzle

Early Universe



-> particles, anti-particles and photons in thermal equilibrium
– colliding, annihilating, being re-created etc.

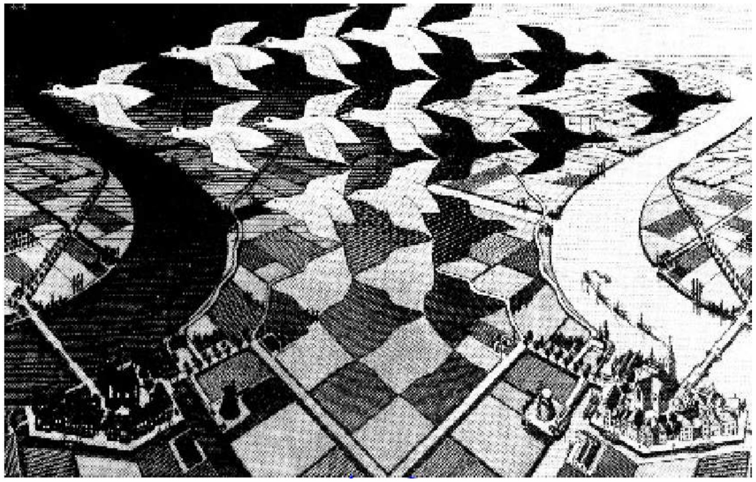
Slight difference in fundamental interactions between matter and antimatter ("CP violation") ?
-> matter slightly more likely to survive



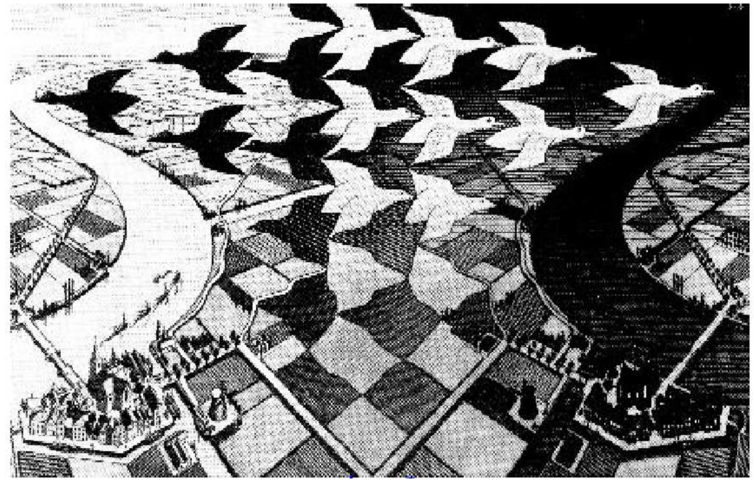
Ratio of baryons (e.g. p, n) to photons today tells us about this asymmetry - it is about $1:10^9$

CP symmetry

graphics: M.C. Escher

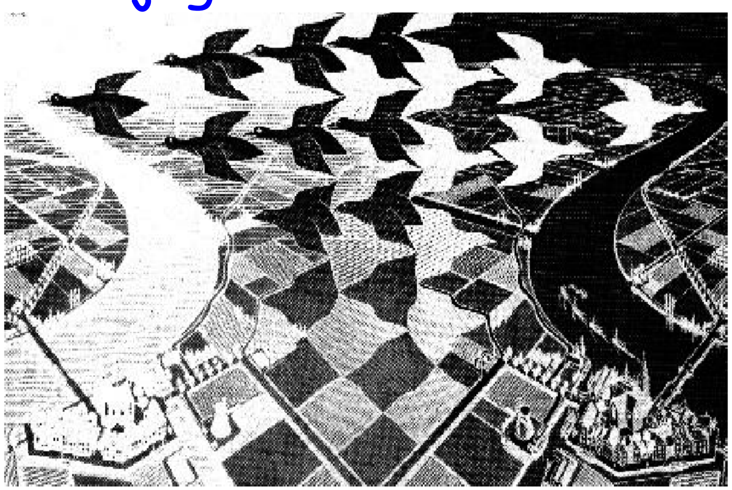


Parity (reflection) →

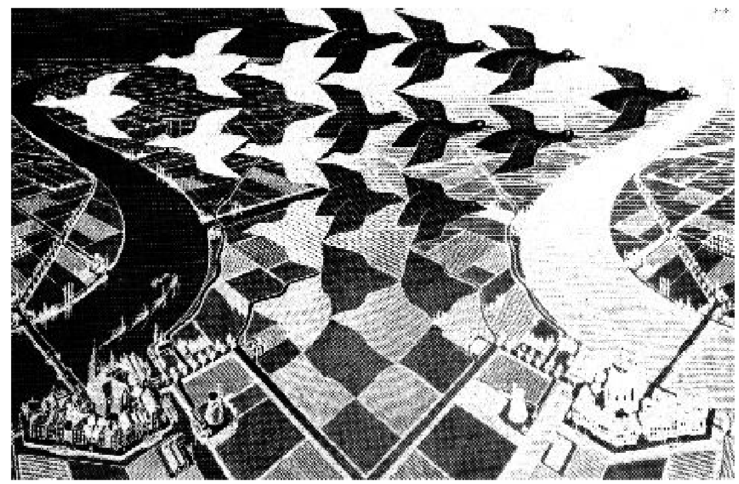


Charge Conjugation ↓ (black → white)

C ↓

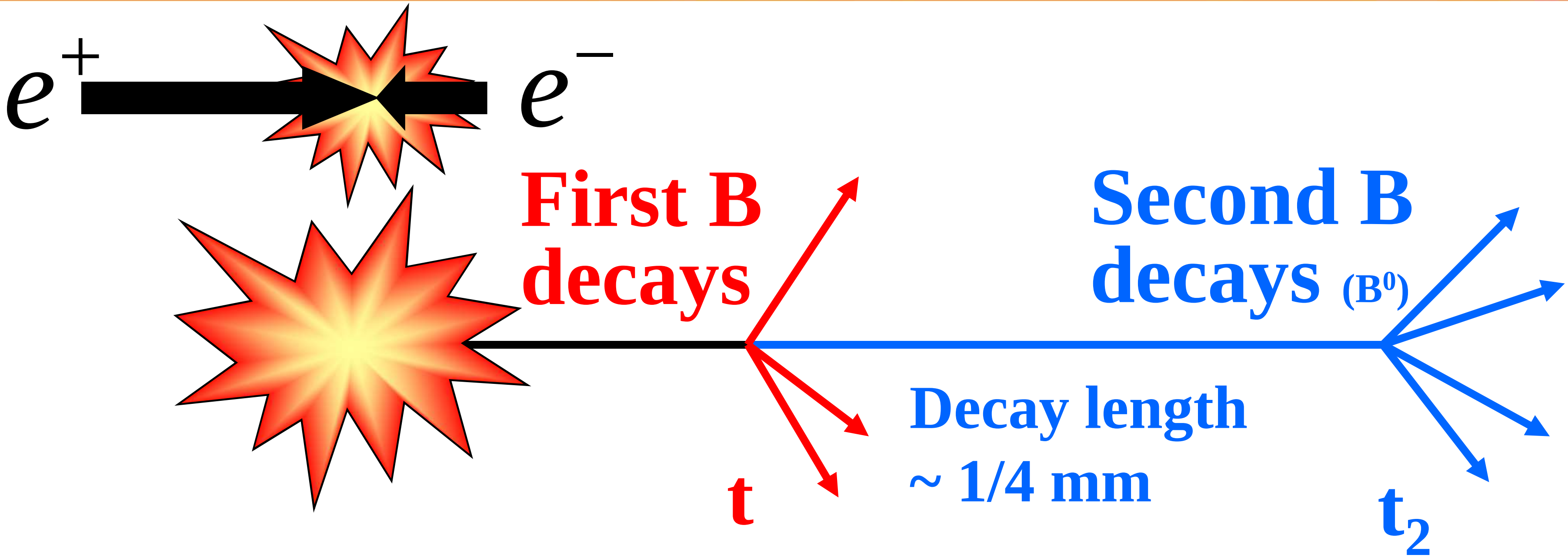


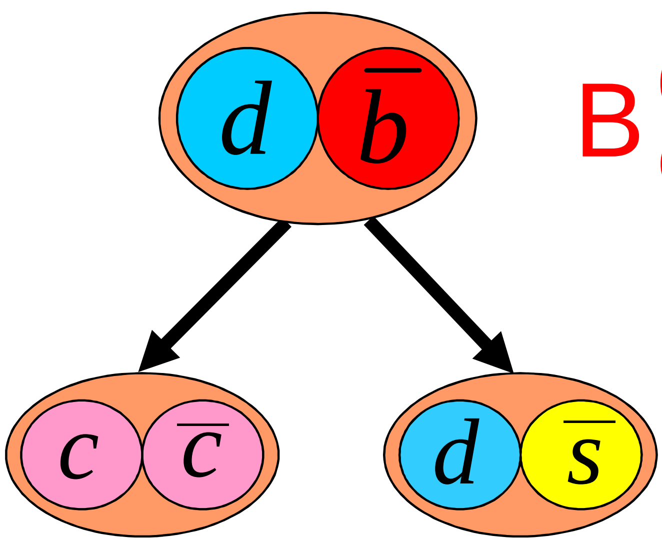
P →



Like weak interaction, symmetric under CP (at first sight!)
Can there be small deviations from this symmetry?

CP violation in B meson decays





B_d^0 (or $\overline{B_d^0}$)

$$Asymmetry(t) = \frac{\overline{B^0} - B^0}{\overline{B^0} + B^0}$$

Simply count decays as function of t!

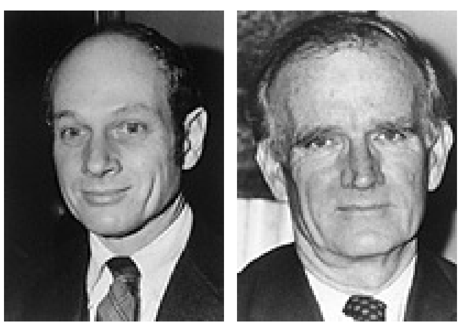
CP violation in B meson decays

Example: measurement from BaBar at SLAC

(also Belle
at KEK)

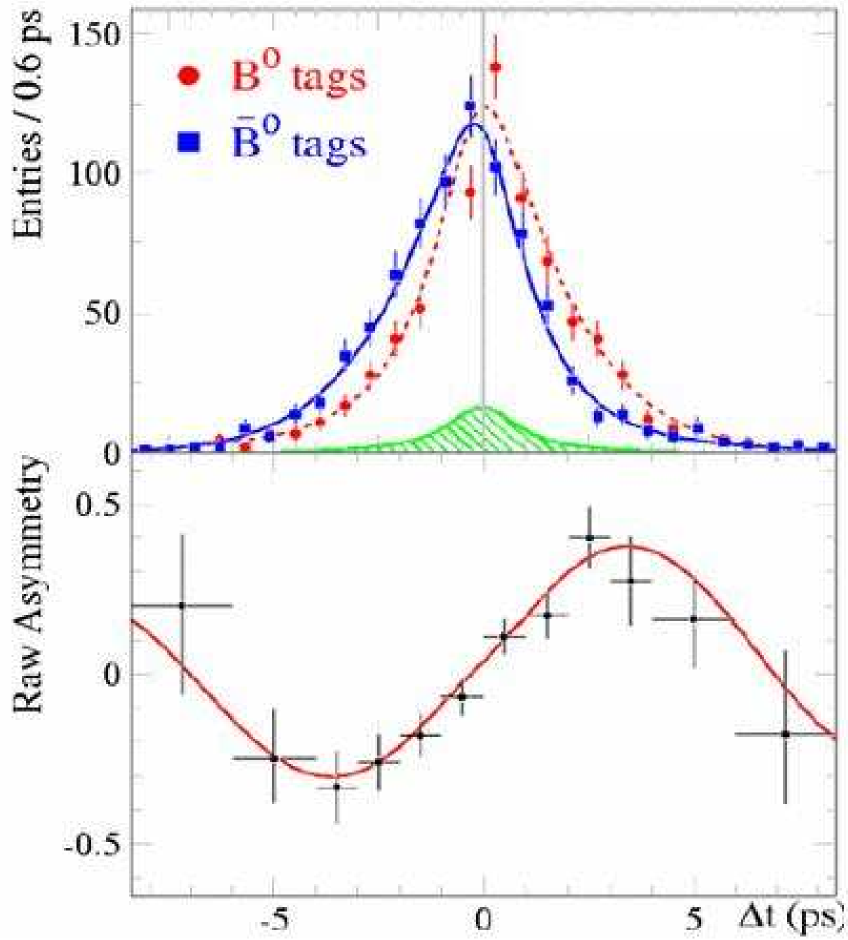
B and anti-B are indeed different

(also found earlier for K decays:)



Val L. Fitch

James W. Cronin (Nobel 1980)

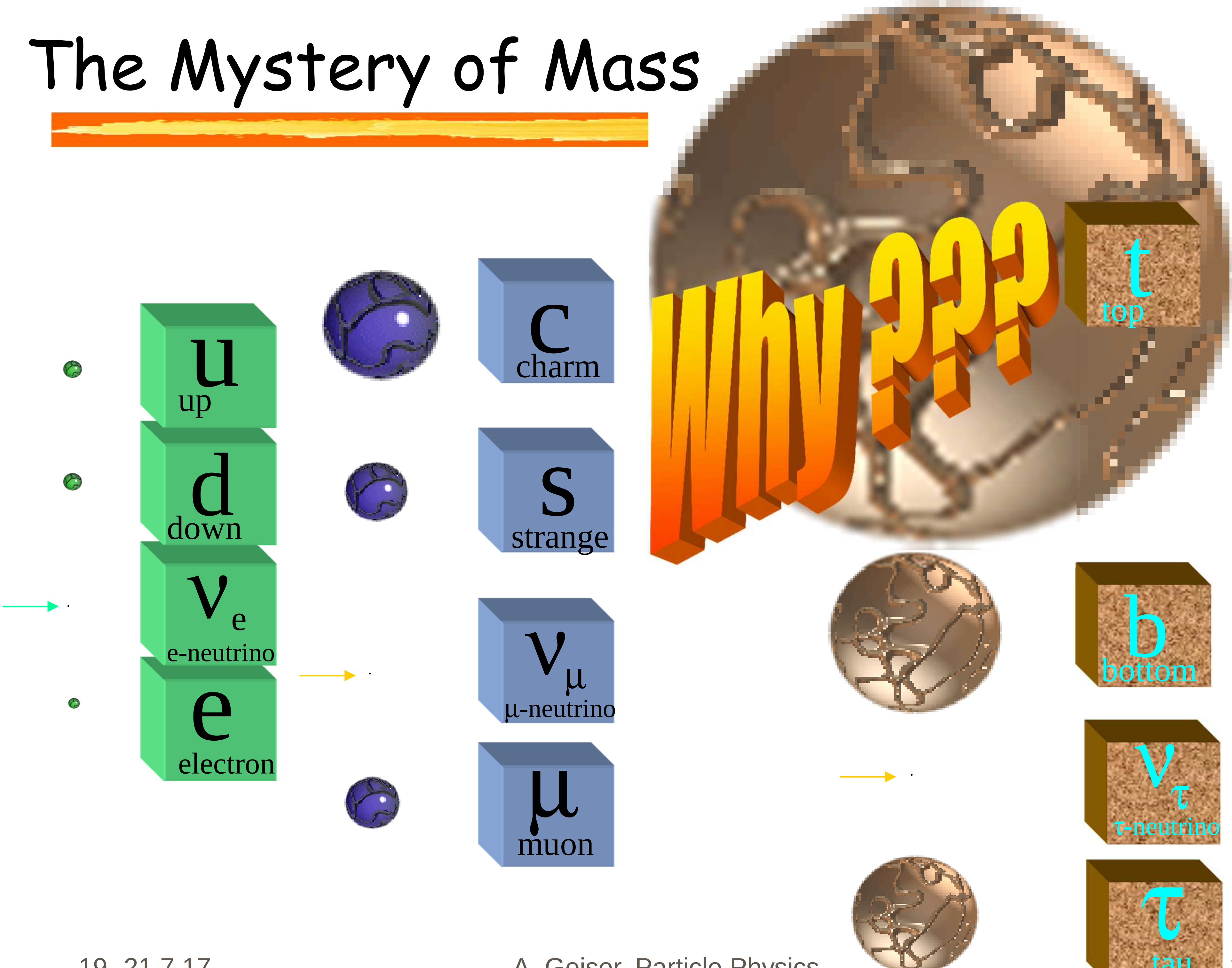


data taking stopped
Belle/**Super-Belle continuing (DESY!)**

Weak Interactions violate CP!

M. Kobayashi T. Maskawa
(Nobel 2008)

The Mystery of Mass



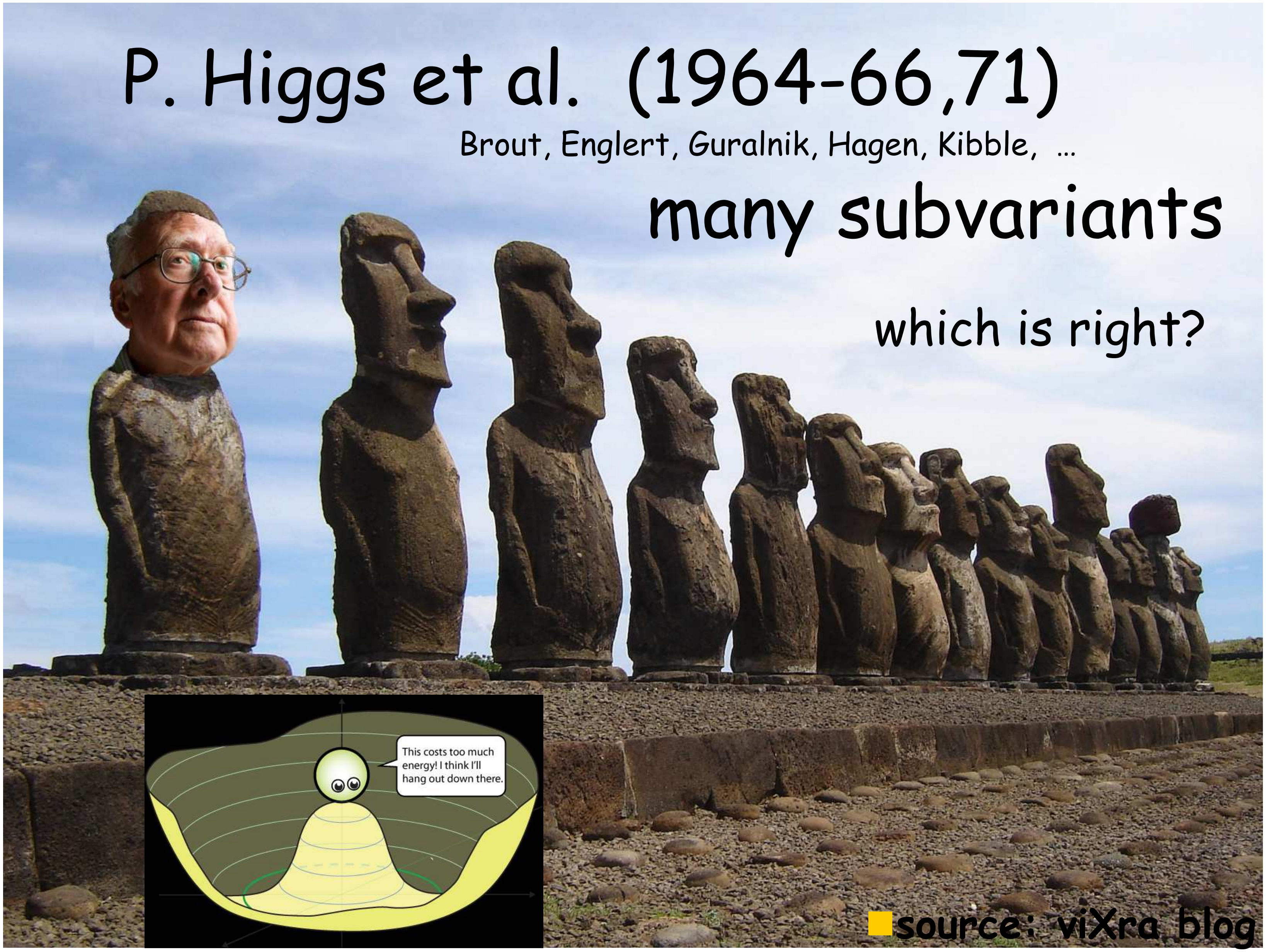
The Mass (BEH) Mechanism

P. Higgs et al. (1964-66,71)

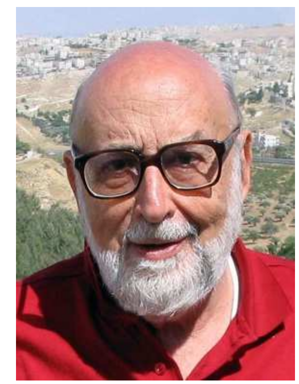
Brout, Englert, Guralnik, Hagen, Kibble, ...

many subvariants

which is right?



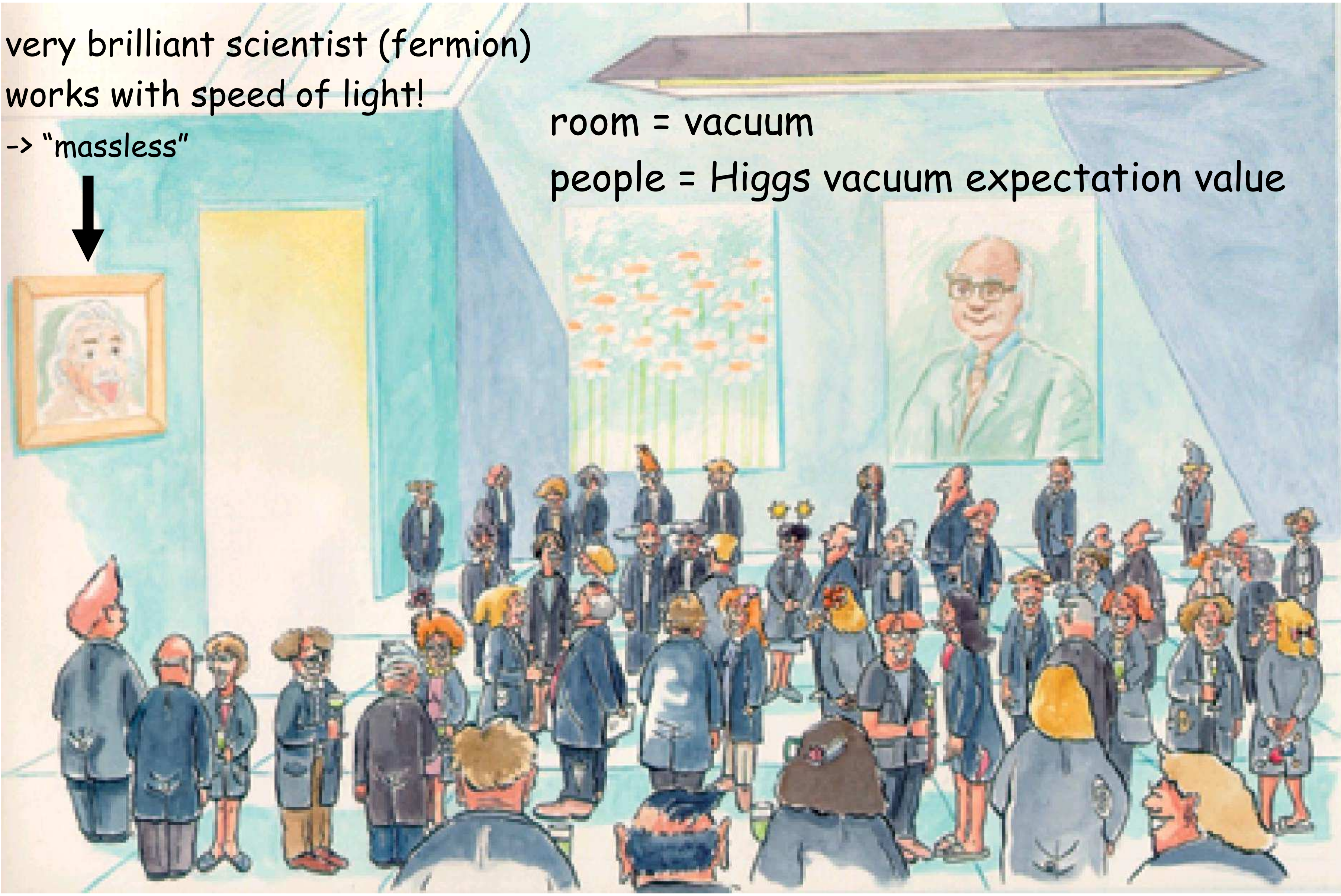
Peter Higgs



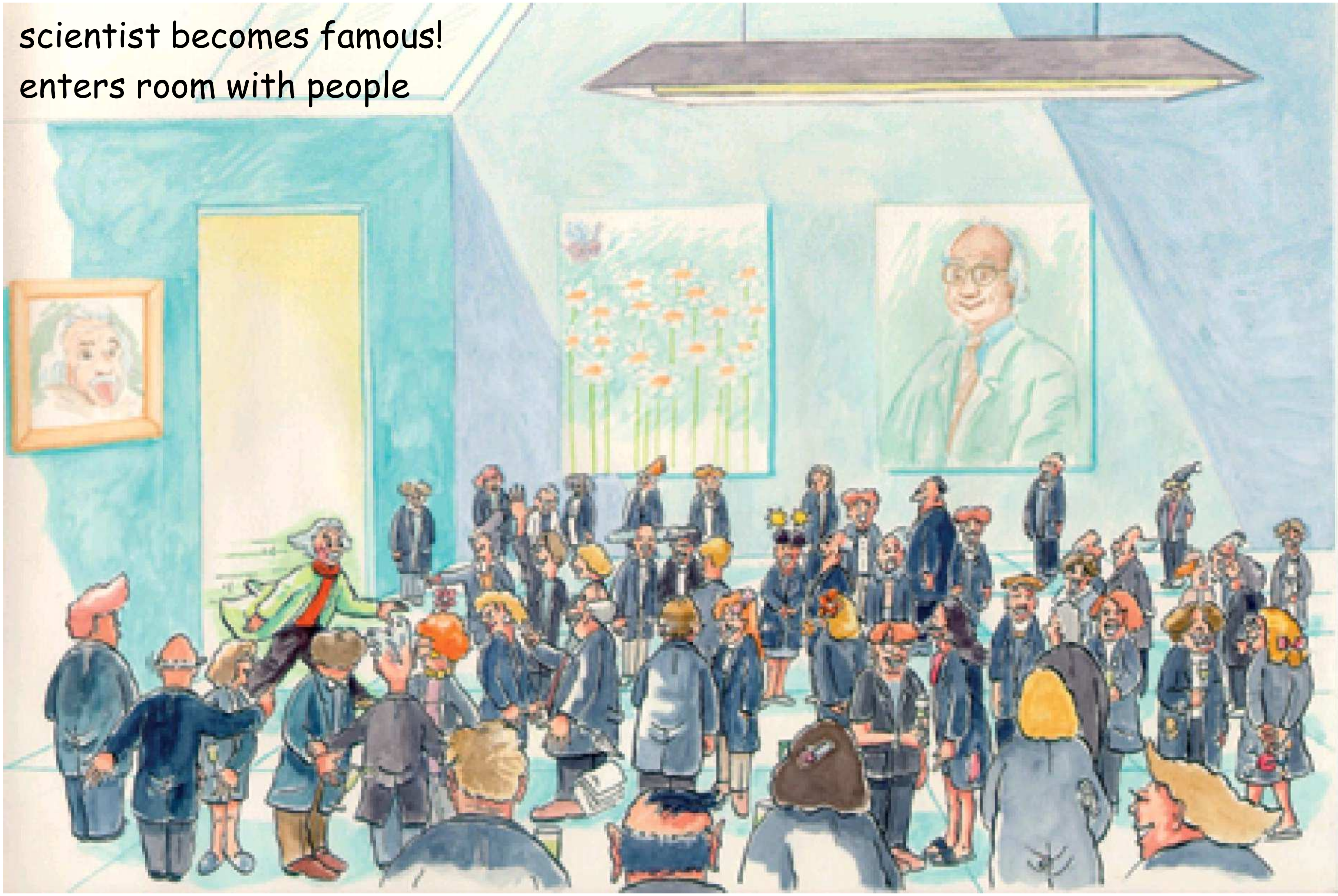
François Englert

(Nobel 2013)

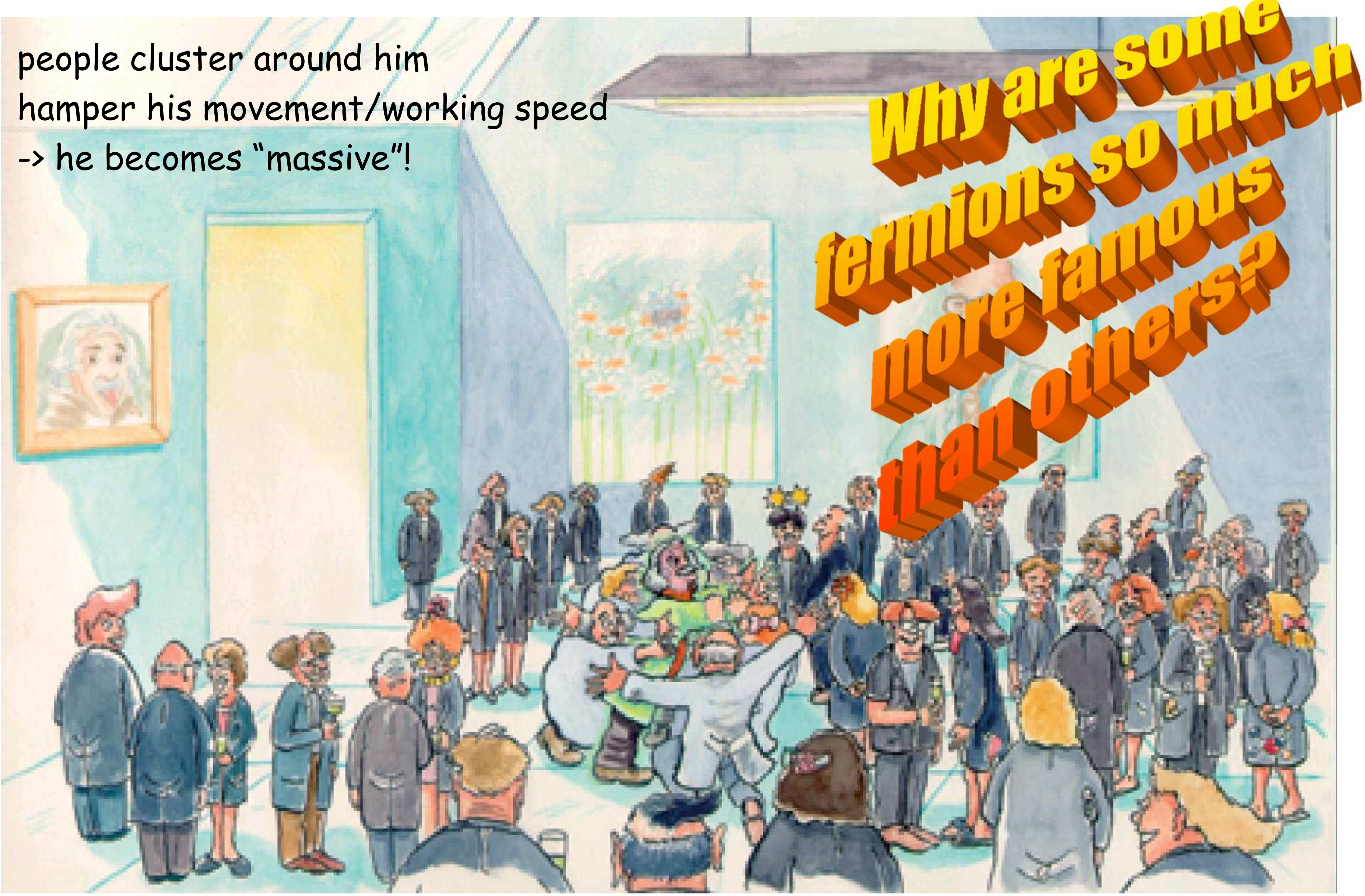
Fermion Mass from Higgs field?



Fermion Mass from Higgs field?

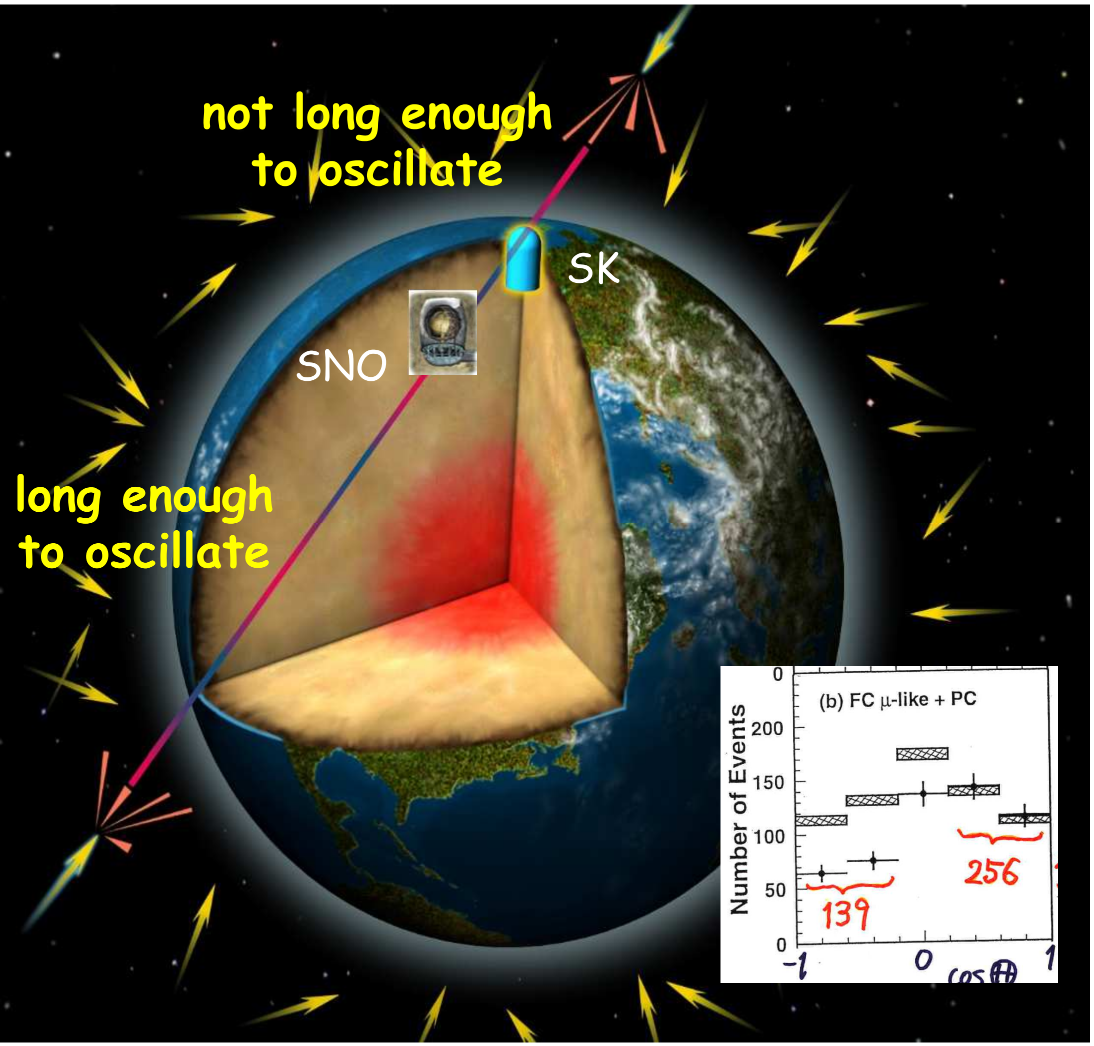


Fermion Mass from Higgs field?

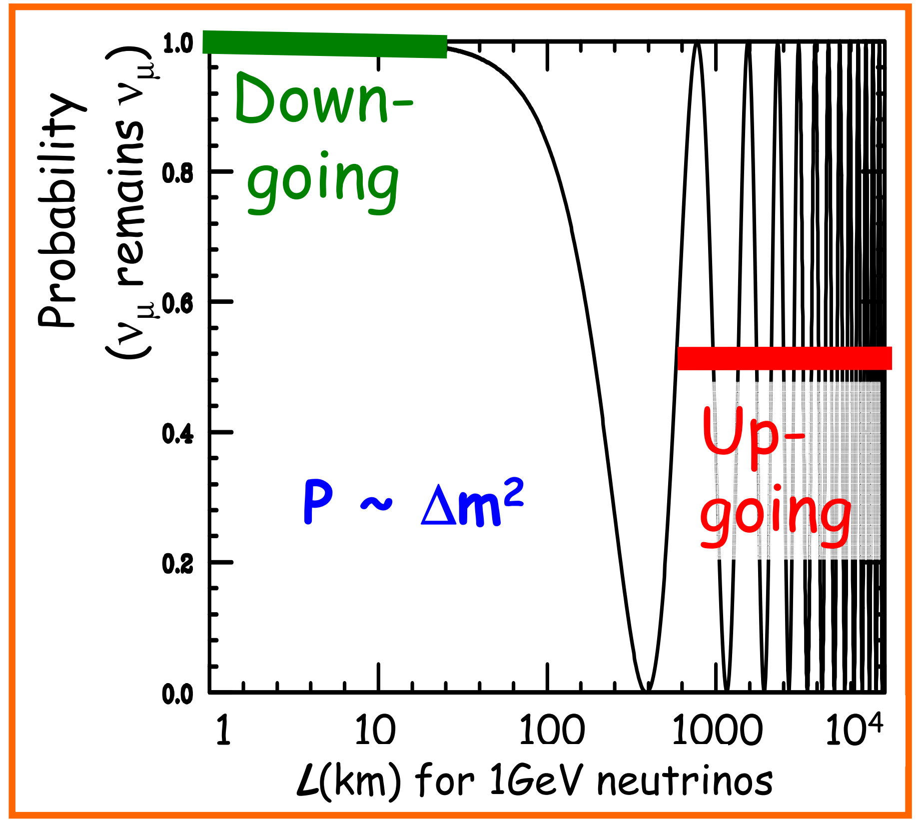


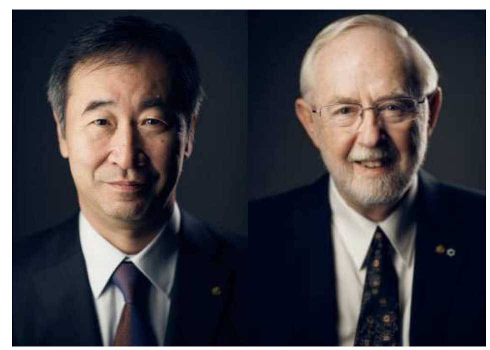
Neutrino oscillations: neutrinos are massive!

Cosmic ray



1998

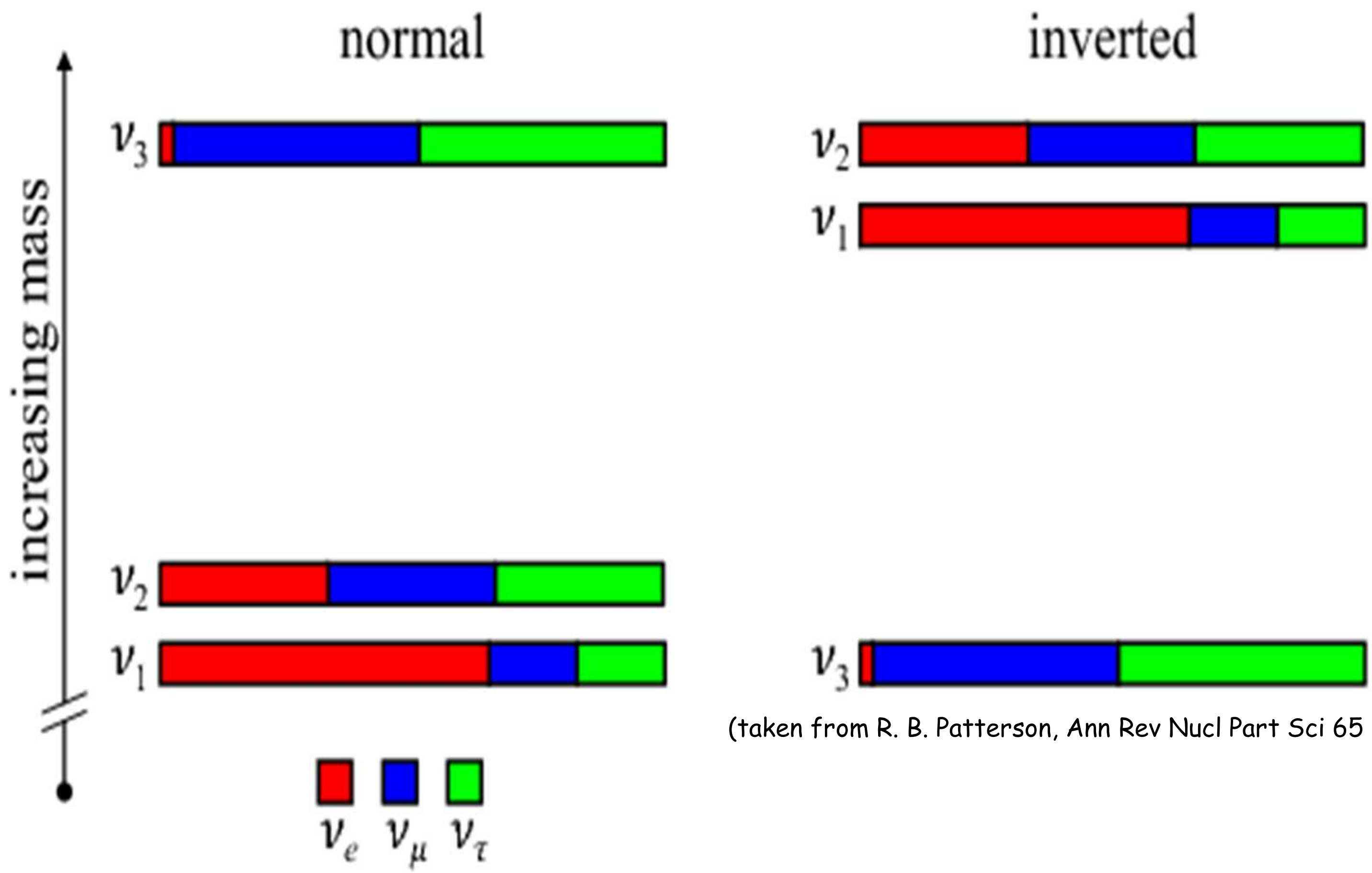




Takaaki Kajita Arthur McDonald

(Nobel 2015)

What do we know about Neutrino mass?



< 2.2 eV

Why???

> 1 meV

(taken from R. B. Patterson, Ann Rev Nucl Part Sci 65 (2015) 177-192.)

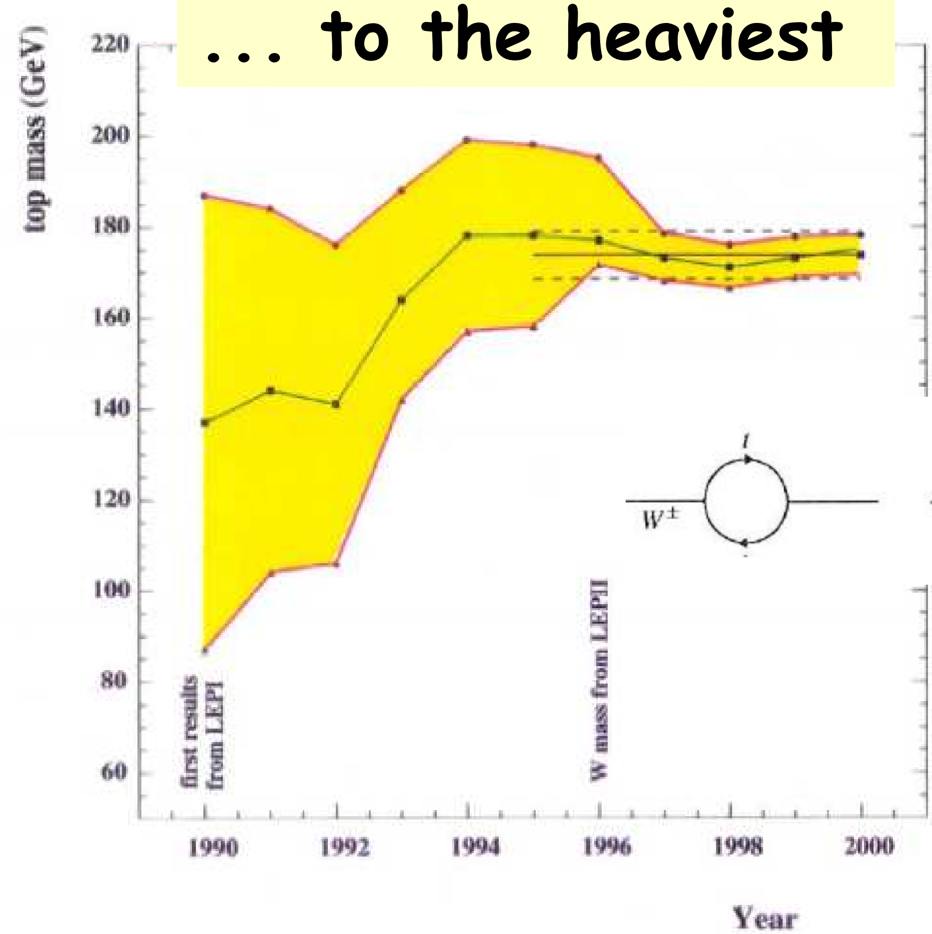
- are the masses of Dirac type (generated by Higgs)?
  or of Majorana type (ν's are their own antiparticles,
  masses have non-Standard Model origin)?
- CP violation?

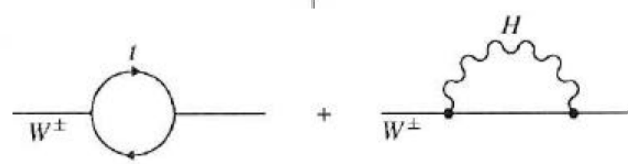
possibly first evidence
for physics
beyond Standard Model

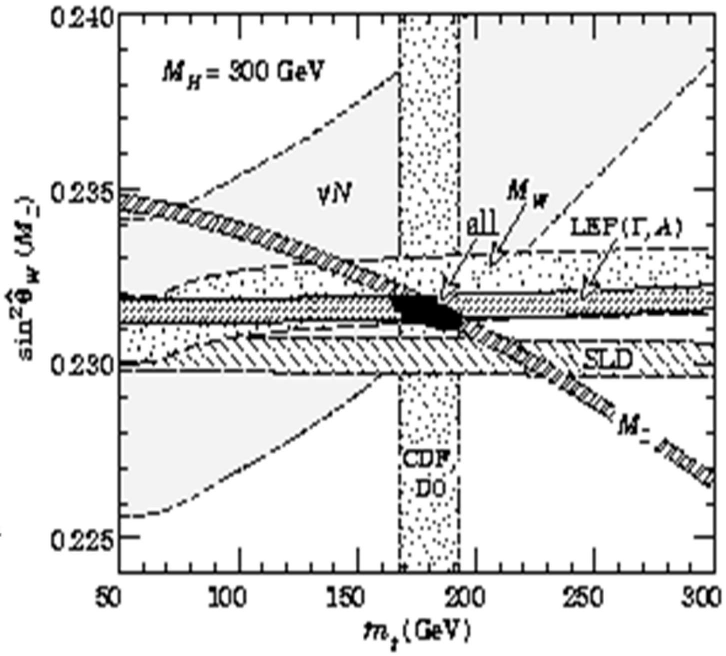
The quest for the top quark

Electroweak precision measurements at LEP/CERN
sensitive to top quark mass and Higgs mass (indirect effects)

... to the heaviest



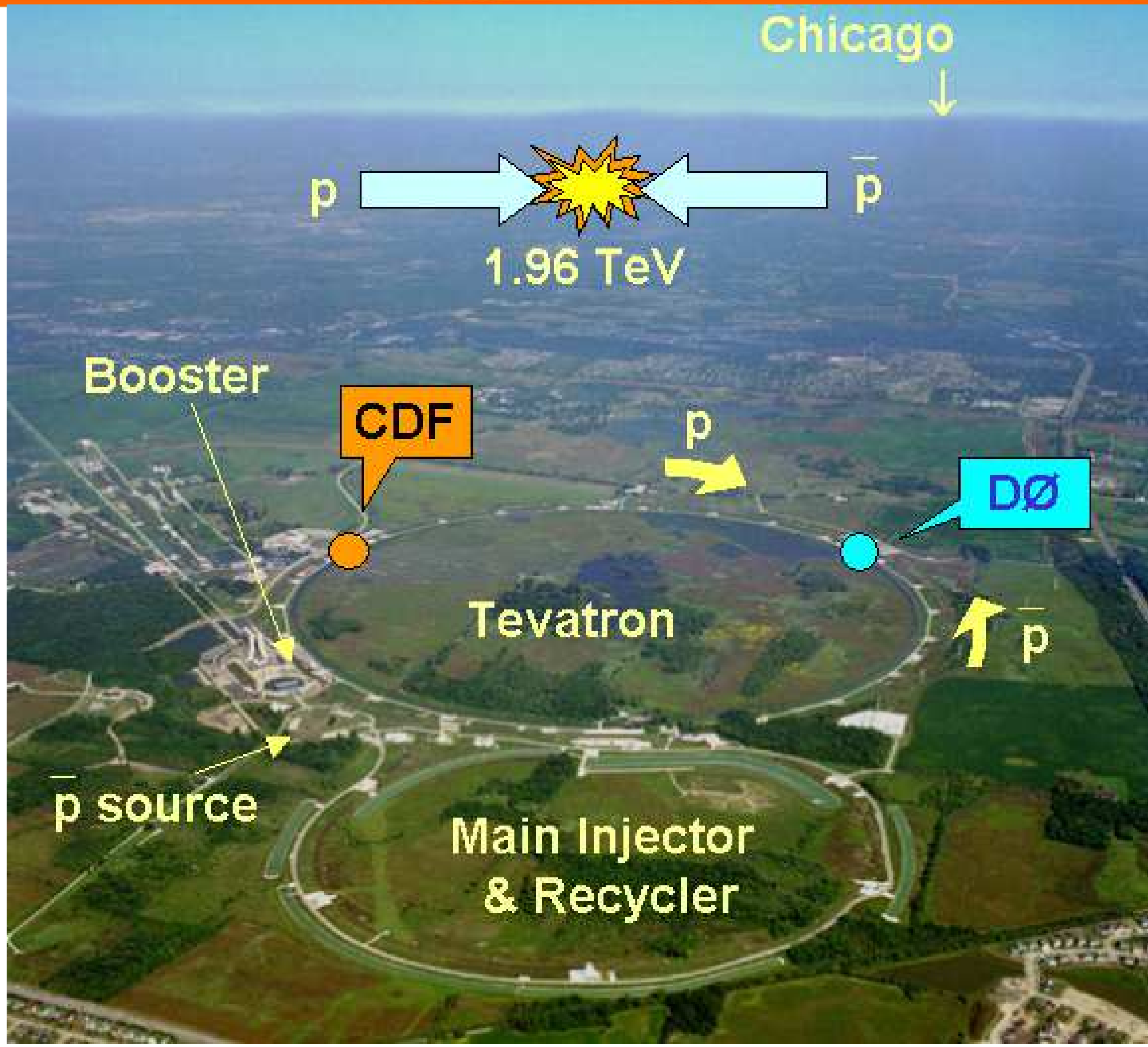




$$\propto \left(\boxed{\frac{M_t}{M_W}}\right)^2, \ln\left(\boxed{\frac{M_h}{M_W}}\right)$$

-> M_t ~ 170 GeV

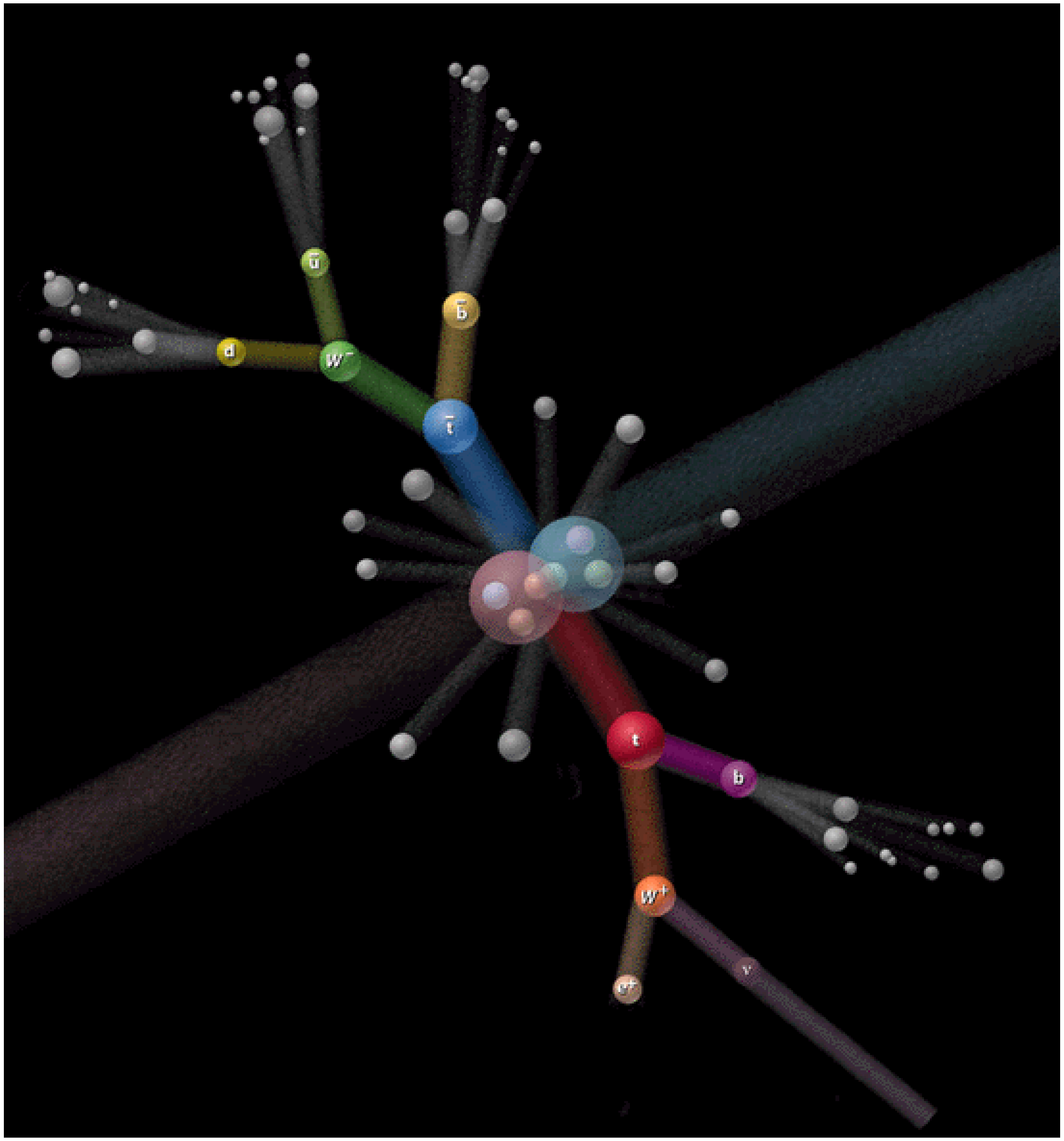
The Tevatron (Fermilab)



data taking ended in 2011

analysis still ongoing

Top quark discovery (Fermilab 1995)



Top quark actually found where expected!

Tevatron at Fermilab (CDF + D0)

measured mass value: (PDG16)

M_{top} = 173.2 ± 0.9 GeV

it works!