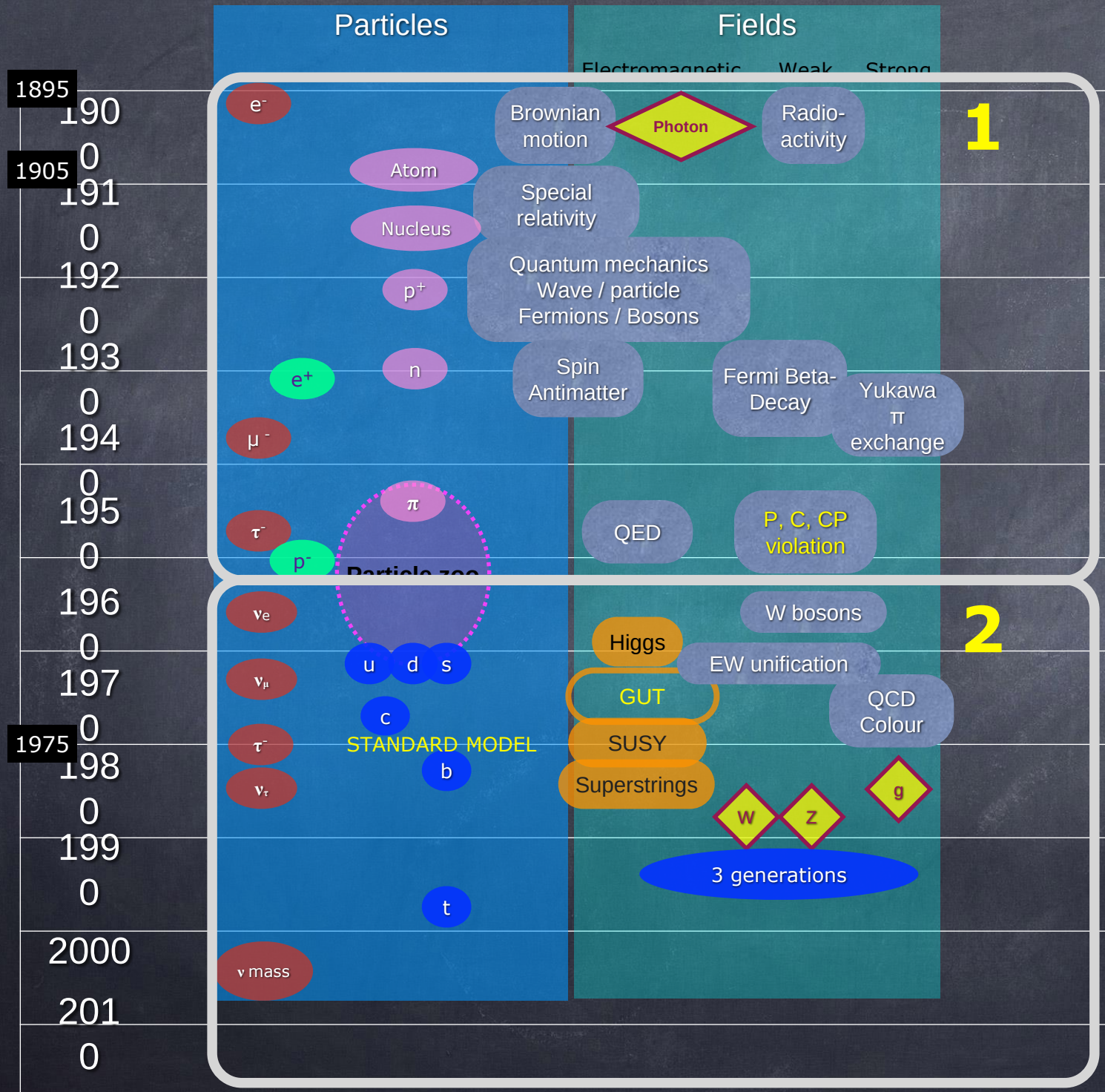
STRUCTURE OF MATTER

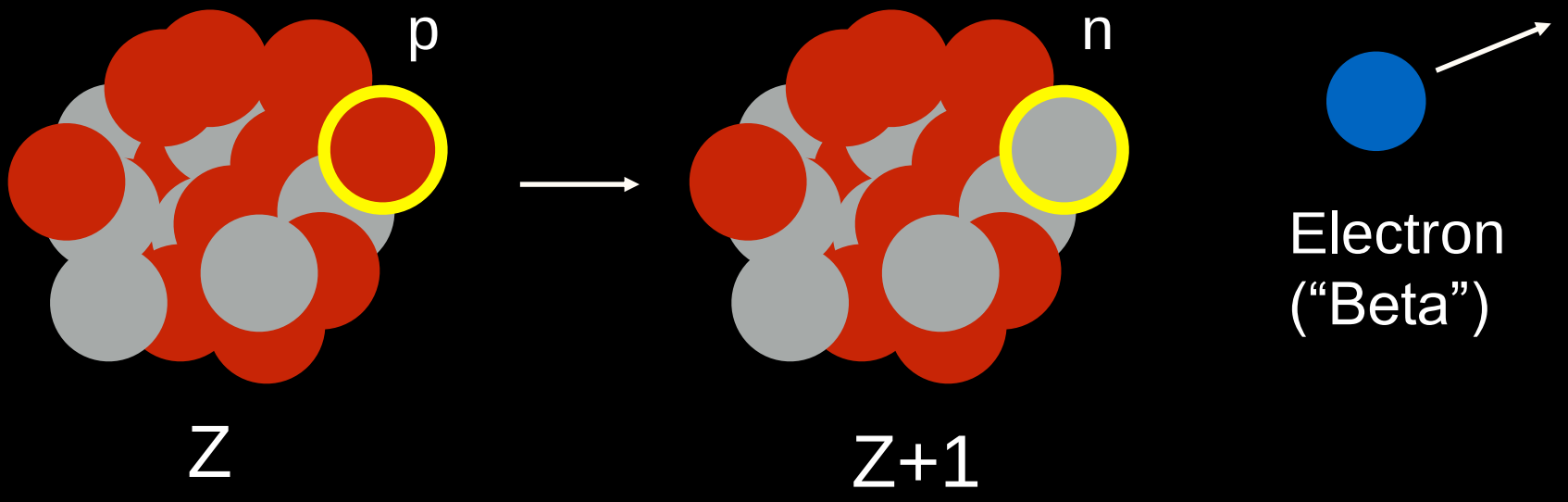
Discoveries and Mysteries

Part 2

Rolf Landua
CERN

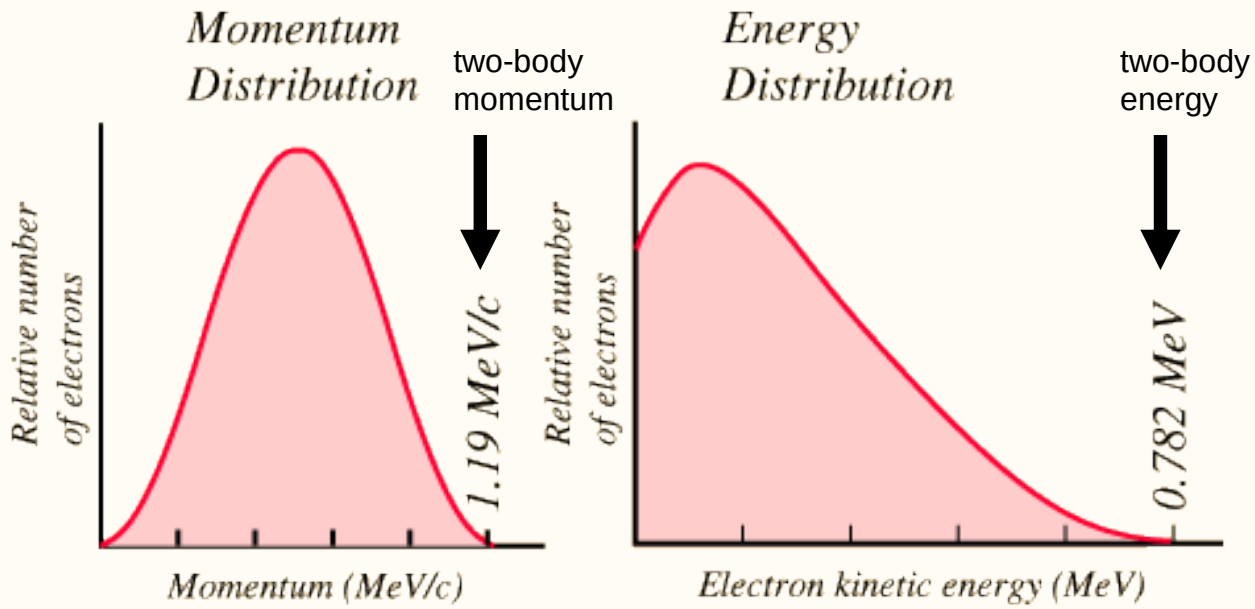

Particles
Fields
Electromagnetic
Weak
Strong
1895
1900
1905
1910
1920
1930
1940
1950
1960
1970
1975
1980
1990
2000
2010
e⁻
Brownian motion
Photon
Radio-activity
1
Atom
Special relativity
Nucleus
Quantum mechanics
Wave / particle
Fermions / Bosons
p⁺
n
e⁺
Spin
Antimatter
Fermi Beta-Decay
Yukawa π exchange
μ⁻
π
τ⁻
p⁻
QED
P, C, CP violation
Particle zoo
νe
W bosons
Higgs
2
EW unification
u
d
s
νμ
GUT
QCD Colour
c
τ⁻
STANDARD MODEL
SUSY
b
Superstrings
g
W
Z
ντ
3 generations
t
ν mass

WEAK INTERACTION



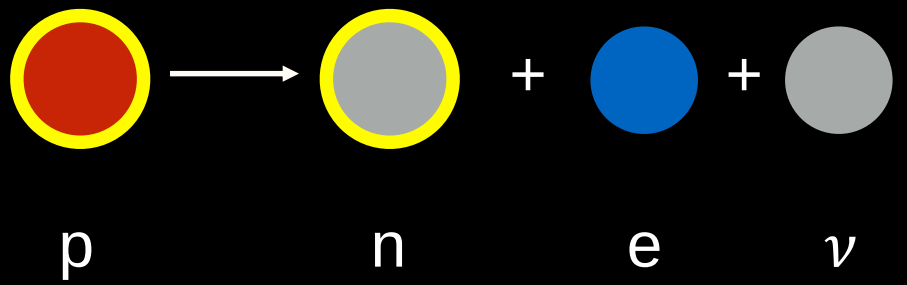
Henri Becquerel (1900): Beta-radiation = electrons

Two-body reaction? But electron energy/momentum is continuous:

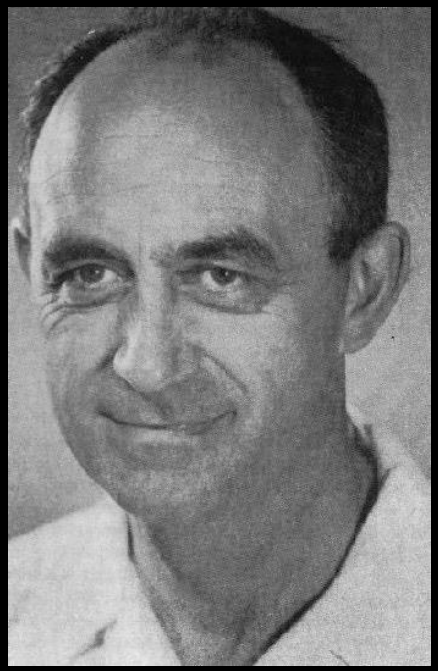


W. Pauli (1930) postulate:

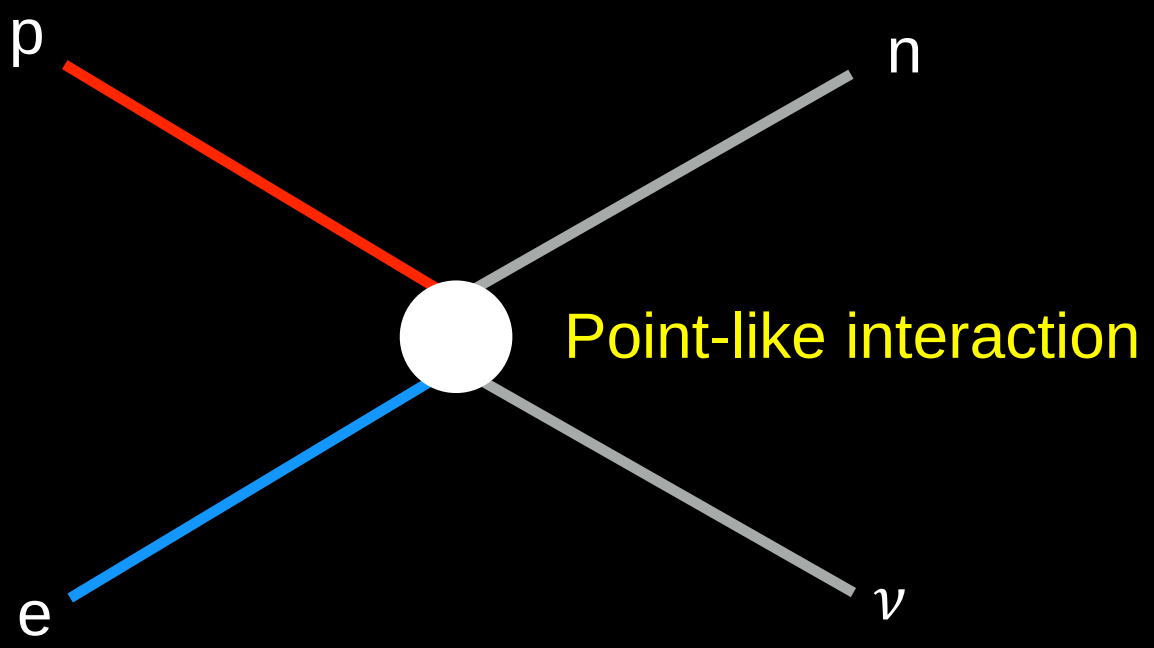
- there is a third particle involved
- neutral
- very small or zero mass
- “Neutrino” (Fermi)



FERMI THEORY (1934)



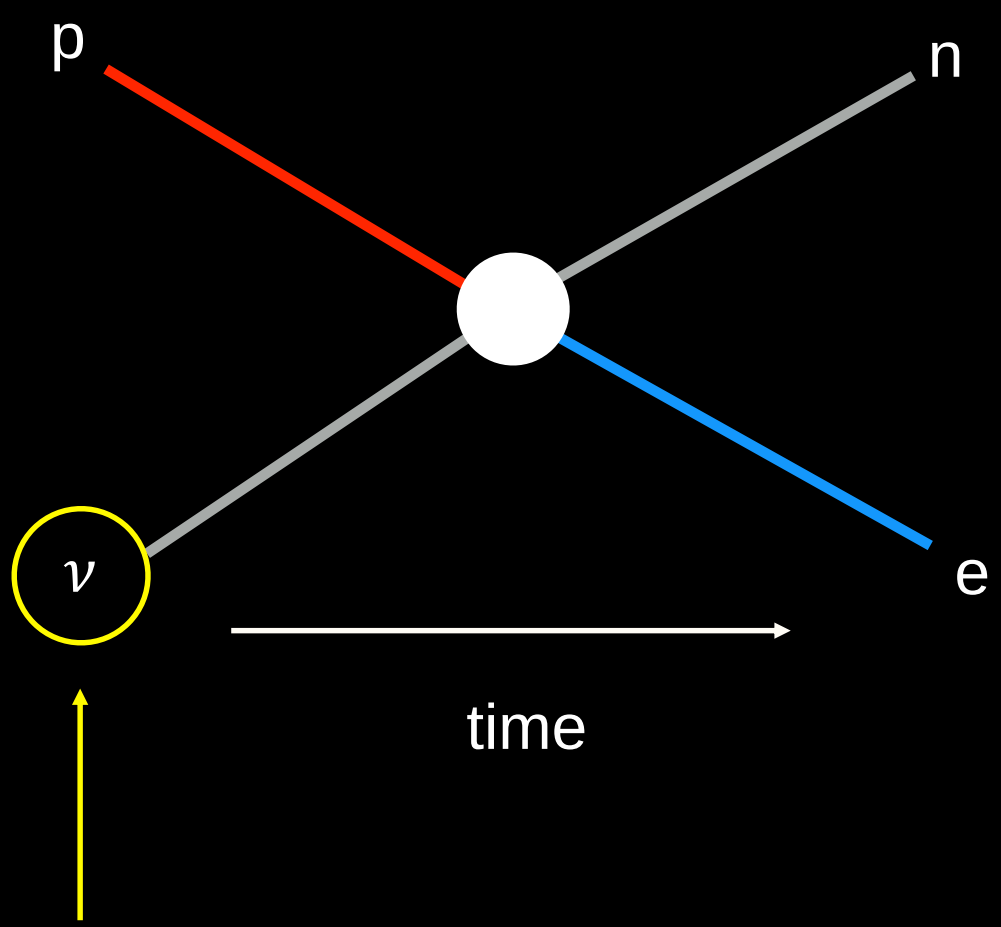
Enrico Fermi



W = Overlap of the four wave functions x Universal constant G

$G \sim 10^{-5} / M^2_p$ = “Fermi constant”

FERMI: PREDICTION ABOUT NEUTRINO INTERACTIONS



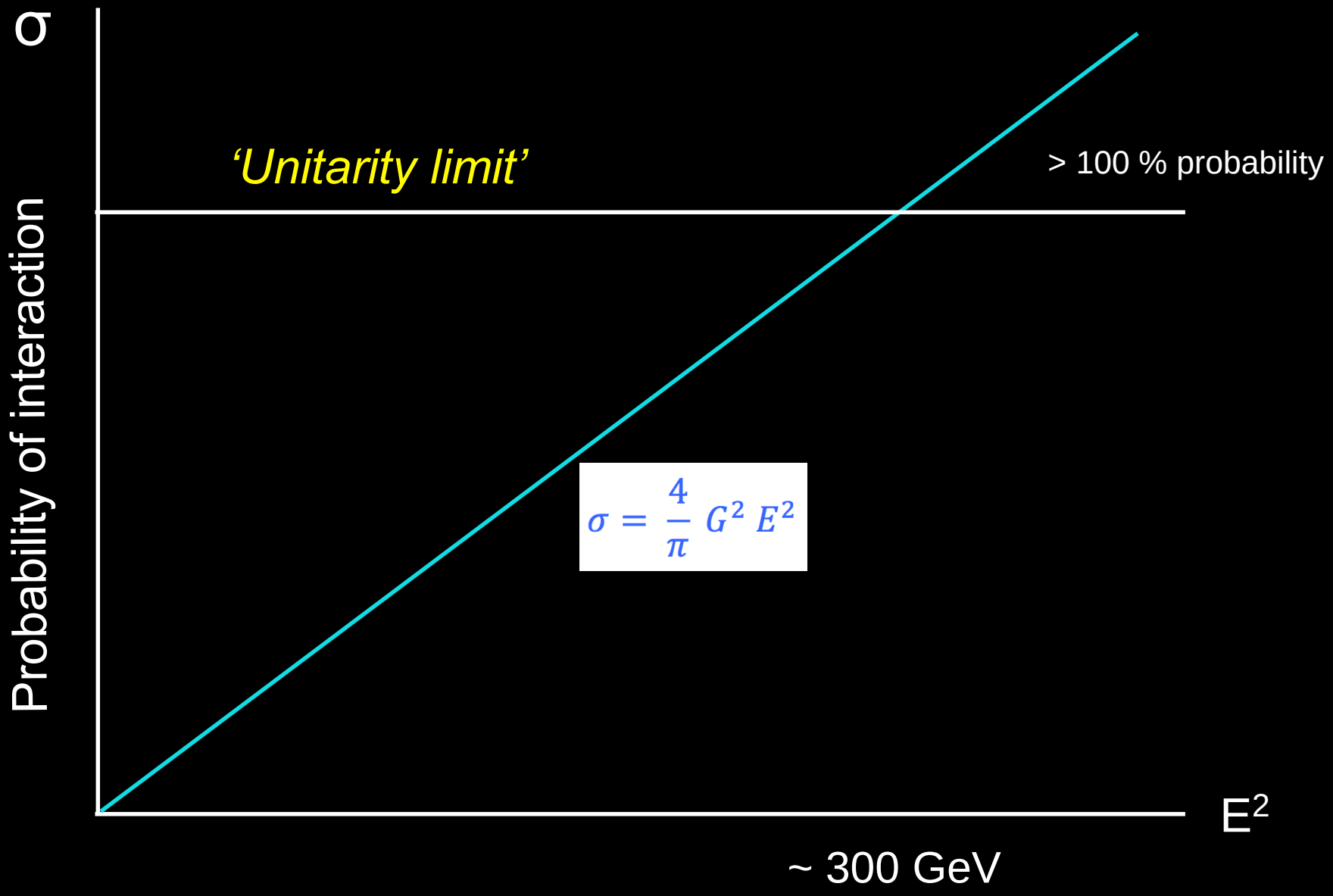
$$\sigma = \frac{4}{\pi} G^2 E^2$$

E = 1 MeV: $\sigma = 10^{-43}$ cm^2

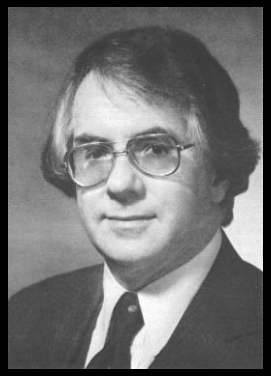
(Range: 10^{20} cm ~ 100 l.yr)

Reines, Cowan (1956):
Neutrino ‘beam’ from reactor
Reactions prove existence of neutrinos

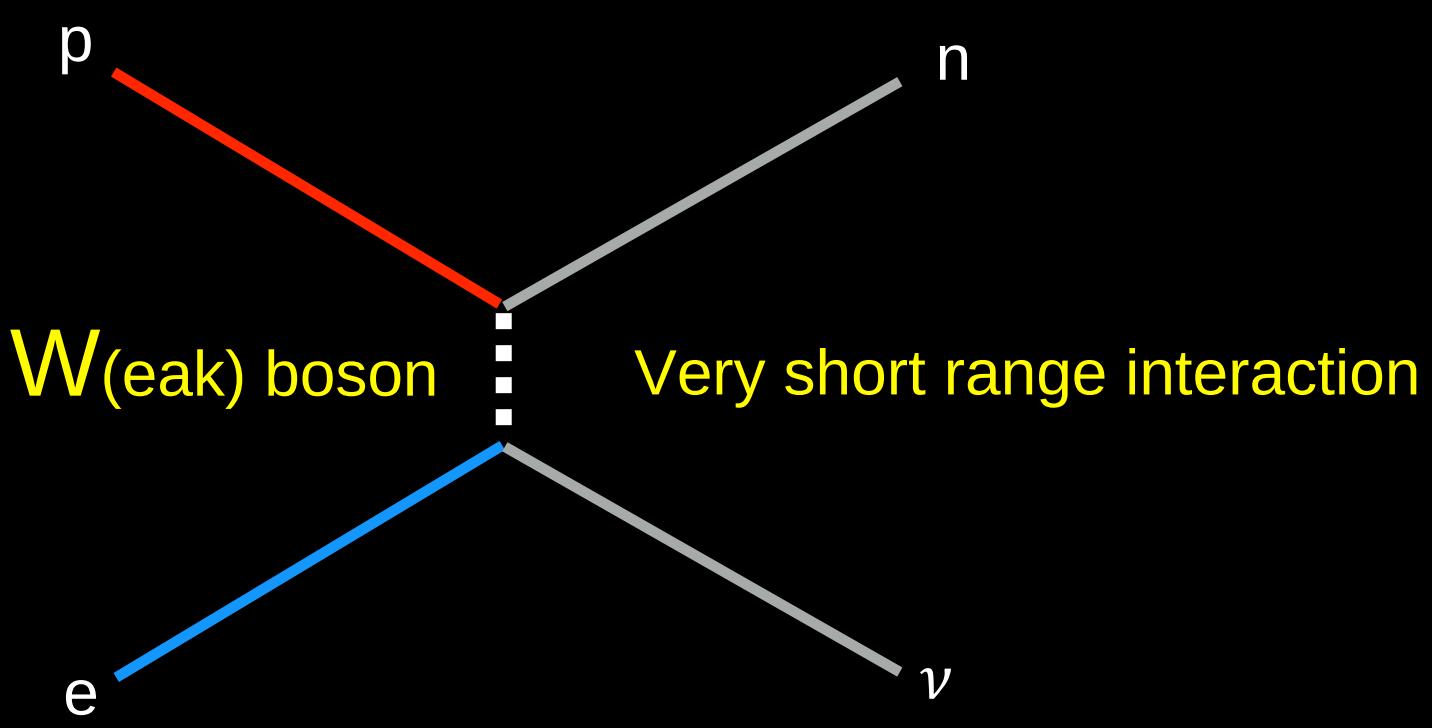
and then ….. THE PREDICTION FAILED !!



GLASGOW REFORMULATES FERMI THEORY (1958)

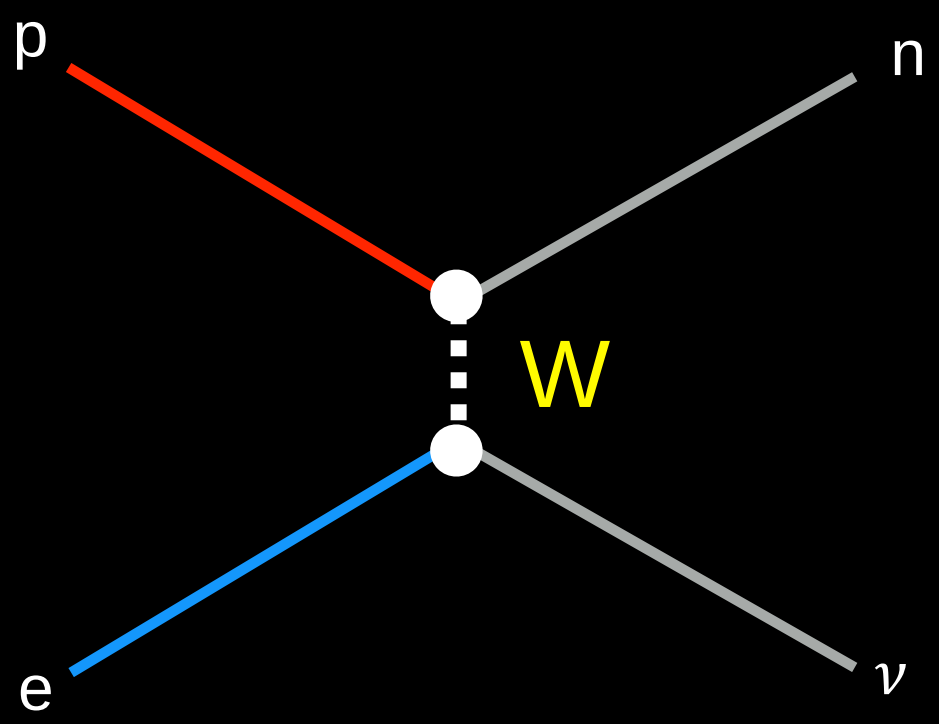


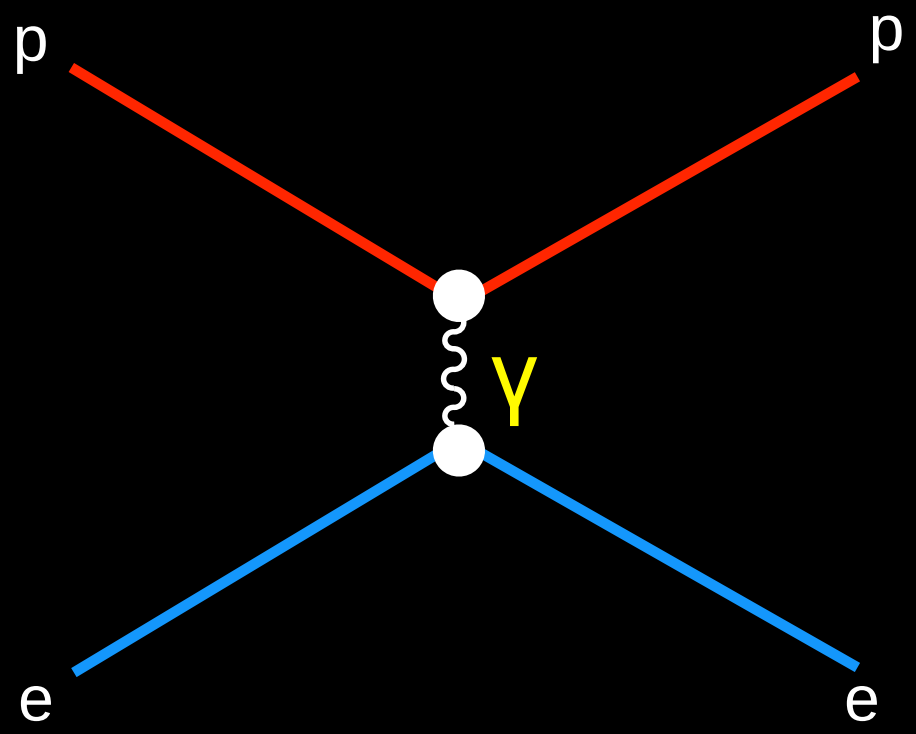
S. Glashow



If mass of W boson ~ 100 GeV : theory o.k.

Interesting: at high energies, coupling of weak and e.m. interaction similar !

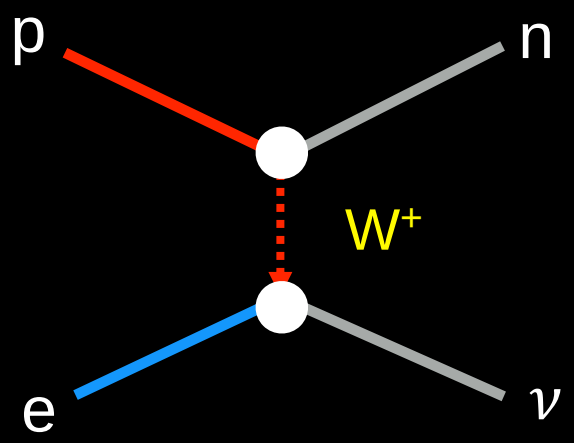


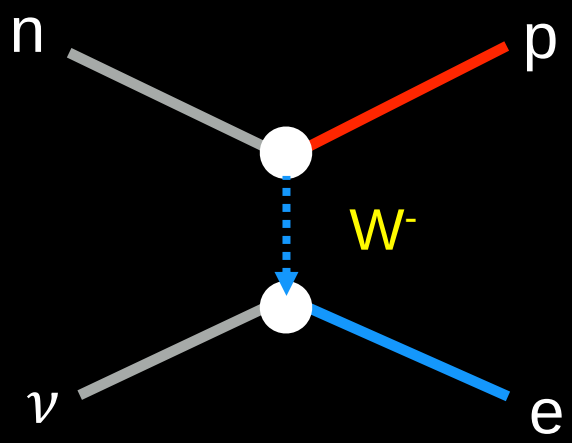


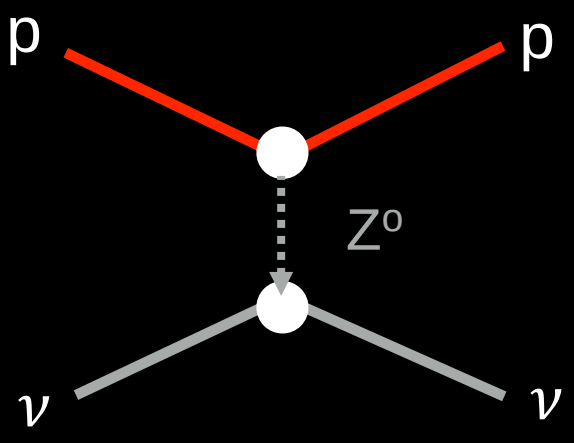
Leads to idea of ELECTRO-WEAK UNIFICATION
(Glashow, Salam, Weinberg)

ELECTRO-WEAK UNIFICATION

"Charged currents" ($W^{\pm}$) and "Neutral Current" (Z^o)







p + e —> n + ν

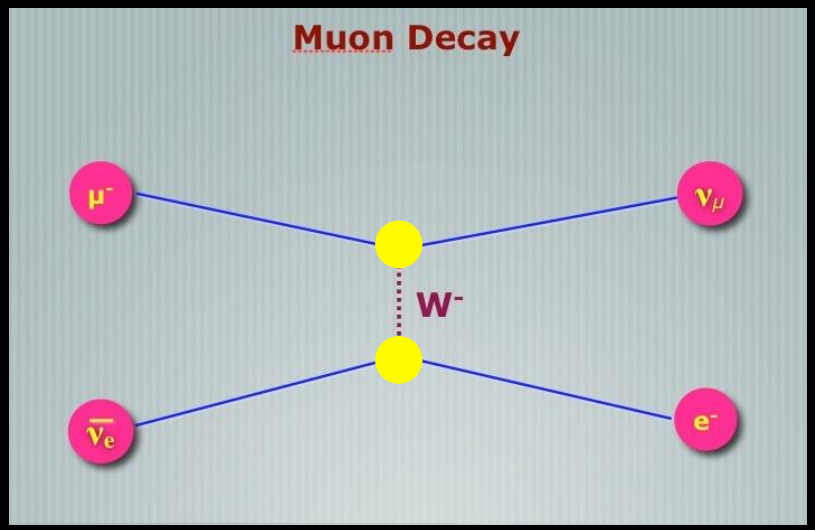
n + ν —> p + e

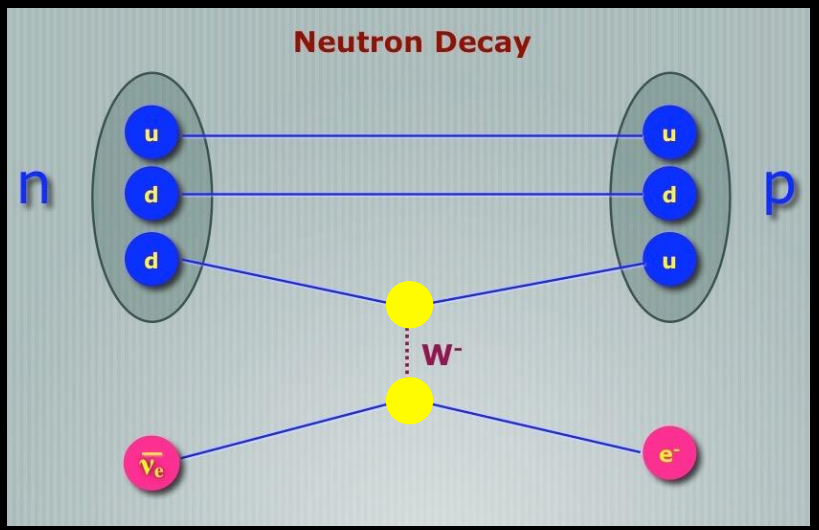
p + ν —> p + ν

Z^o is the 'massive' brother of the photon

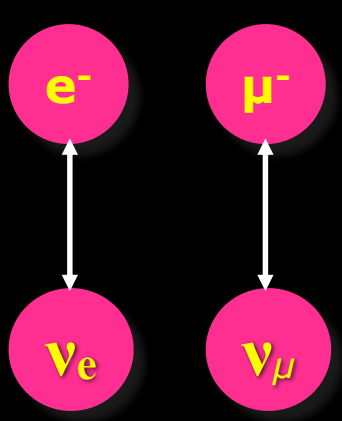
Idea of "weak symmetry breaking" through 'Higgs mechanism'

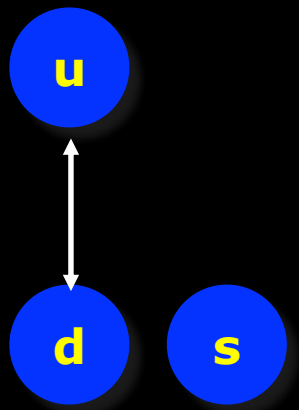
Interesting: electroweak interaction is (approx.) the same for leptons and quarks !



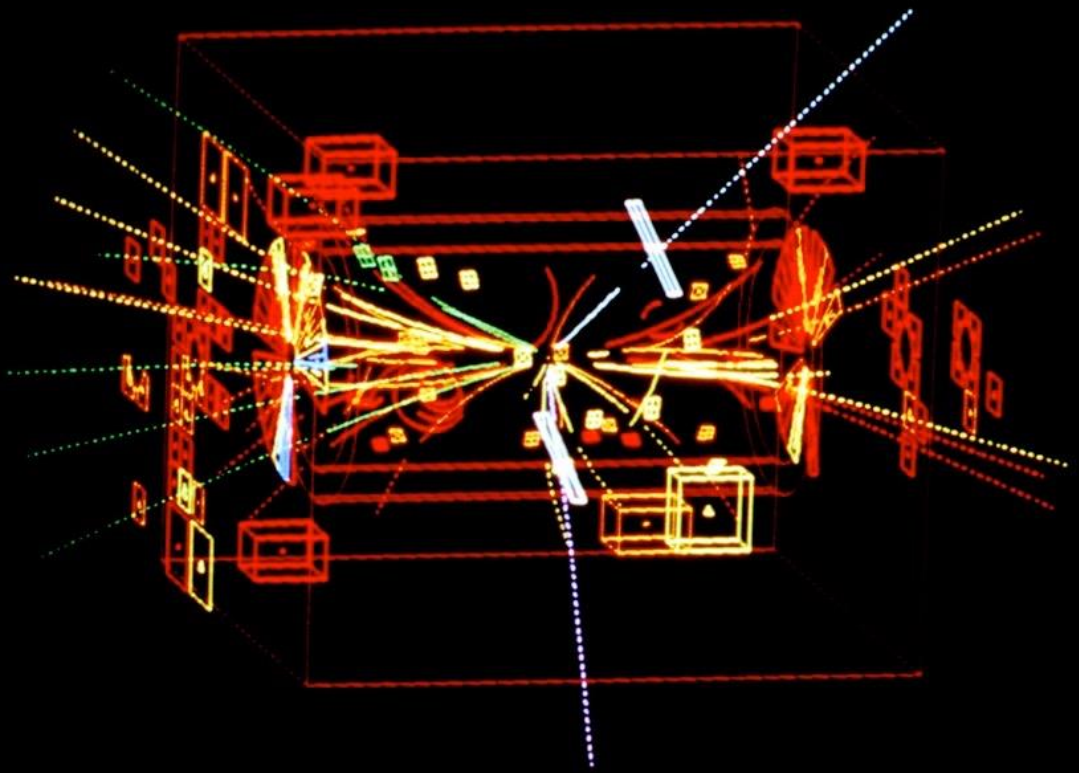


"Universality*" - transmitted by W, Z bosons, same strength!





DISCOVERY OF THE WEAK BOSONS AT CERN (1983)



(C. Rubbia, S. van der Meer)

THE CHARM QUARK

A legendary paper, predicting the 'charm' quark (Glashow, Iliopoulos, Maiani)

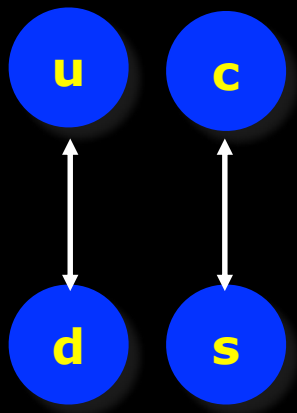
PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

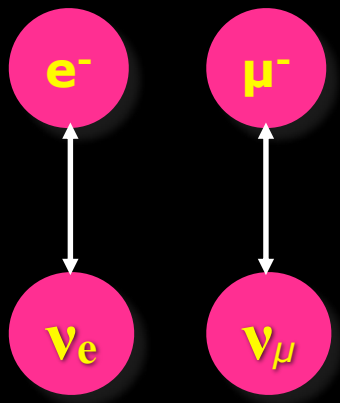
S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

Quarks



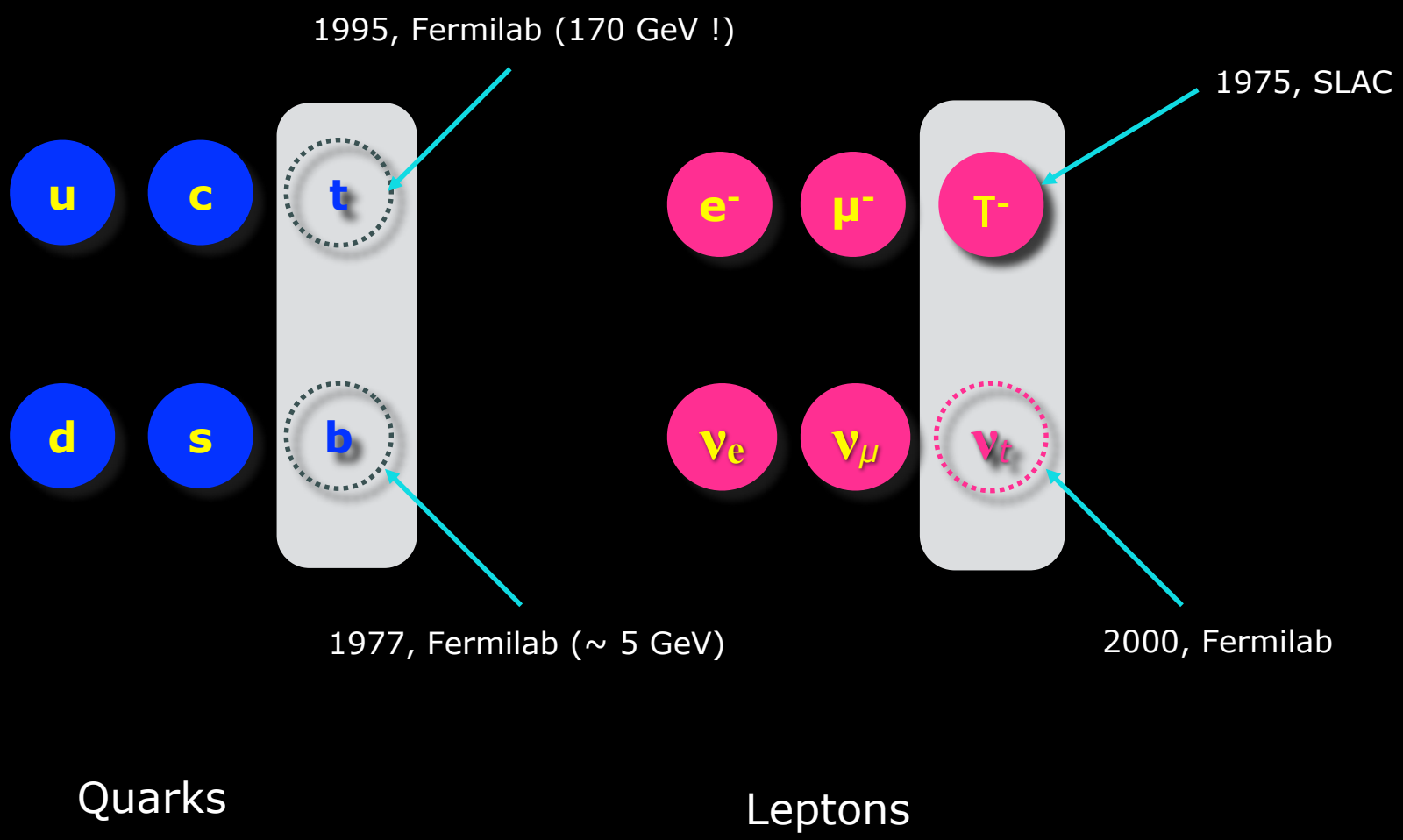
Leptons



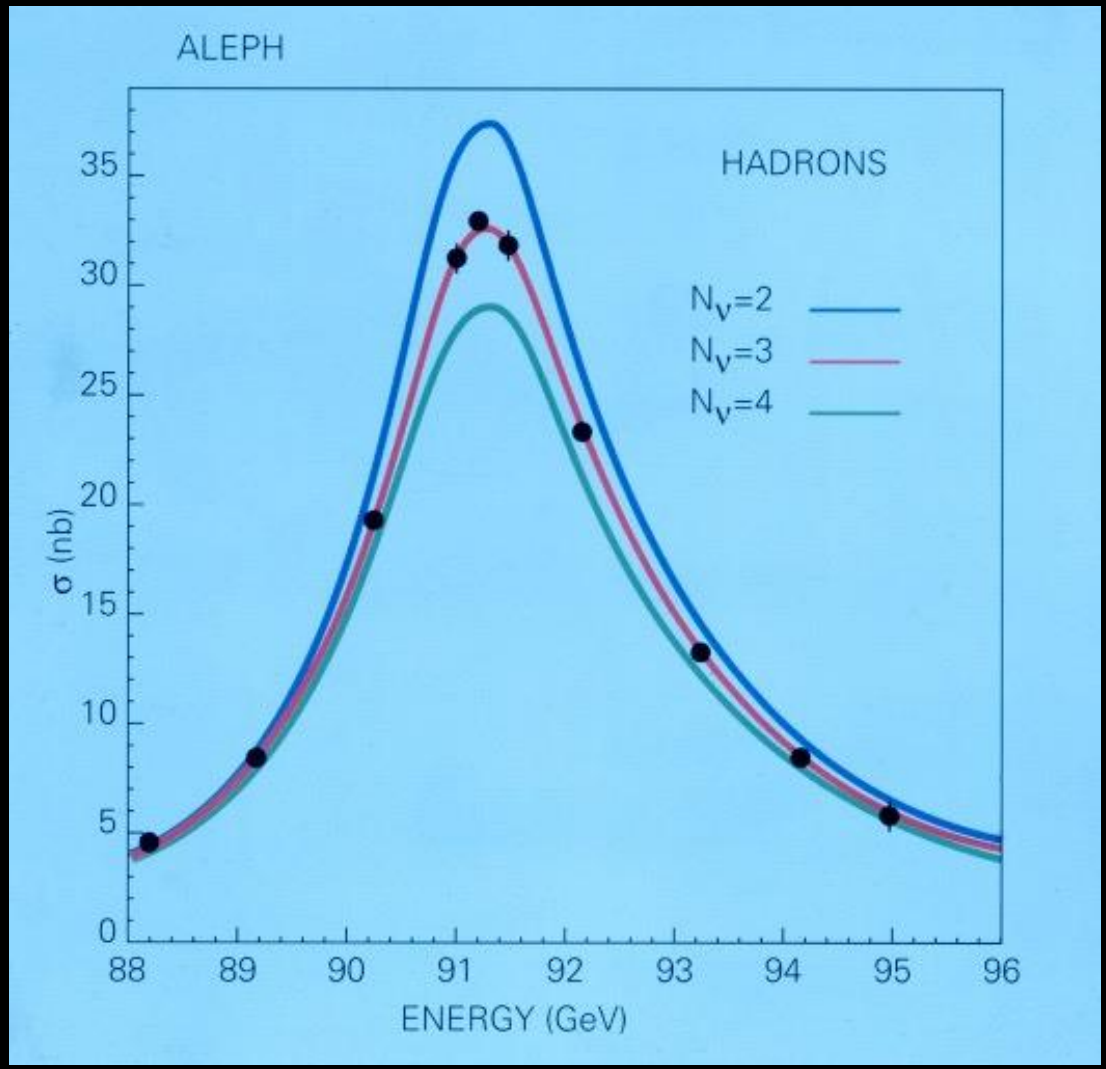
The charm quark was discovered (J/ψ meson = charm-anticharm bound state) in November 1974

Surprise, surprise: enter the THIRD FAMILY

A new lepton (called "tau") is discovered (heavy brother of e and μ)

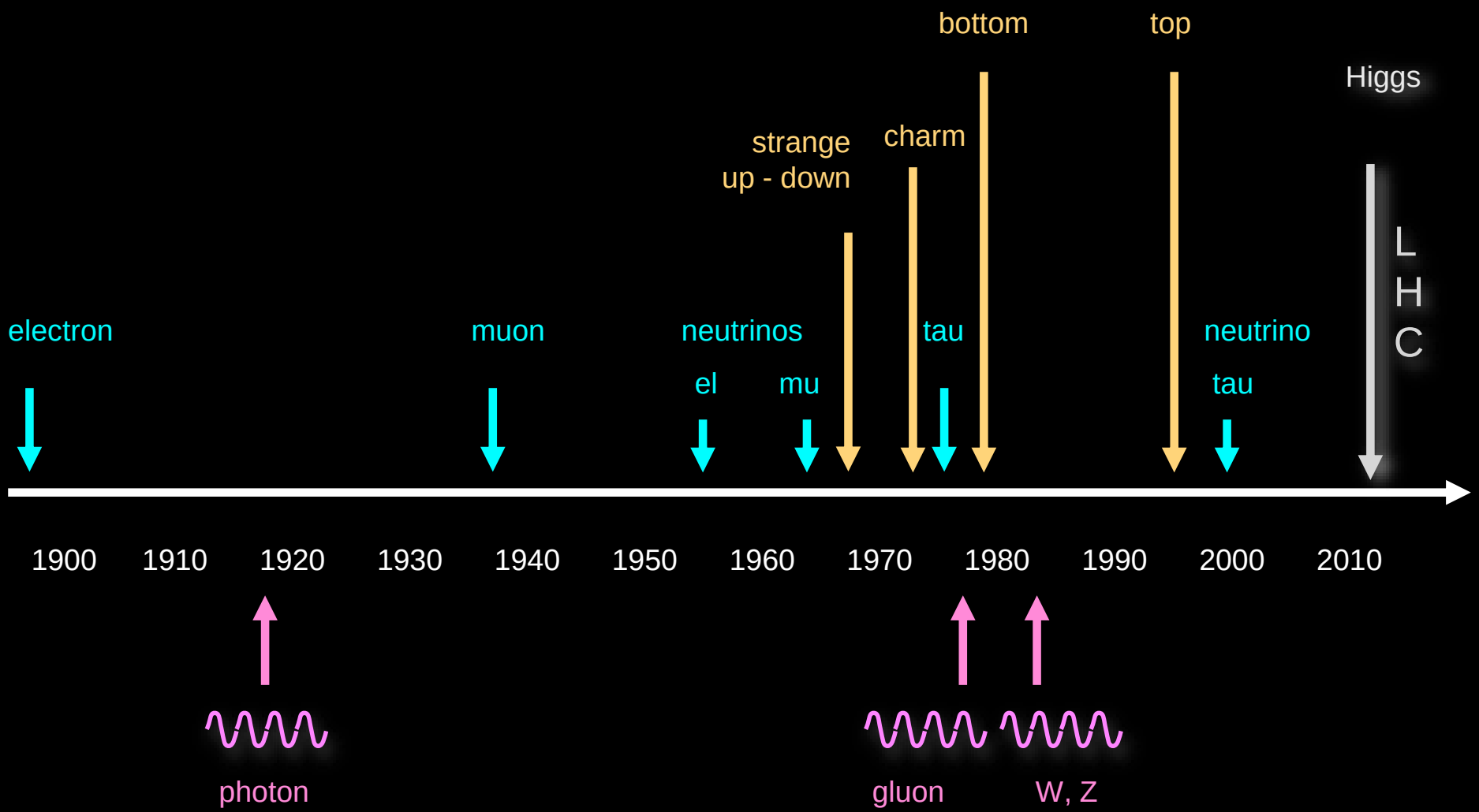


There are exactly 3 families



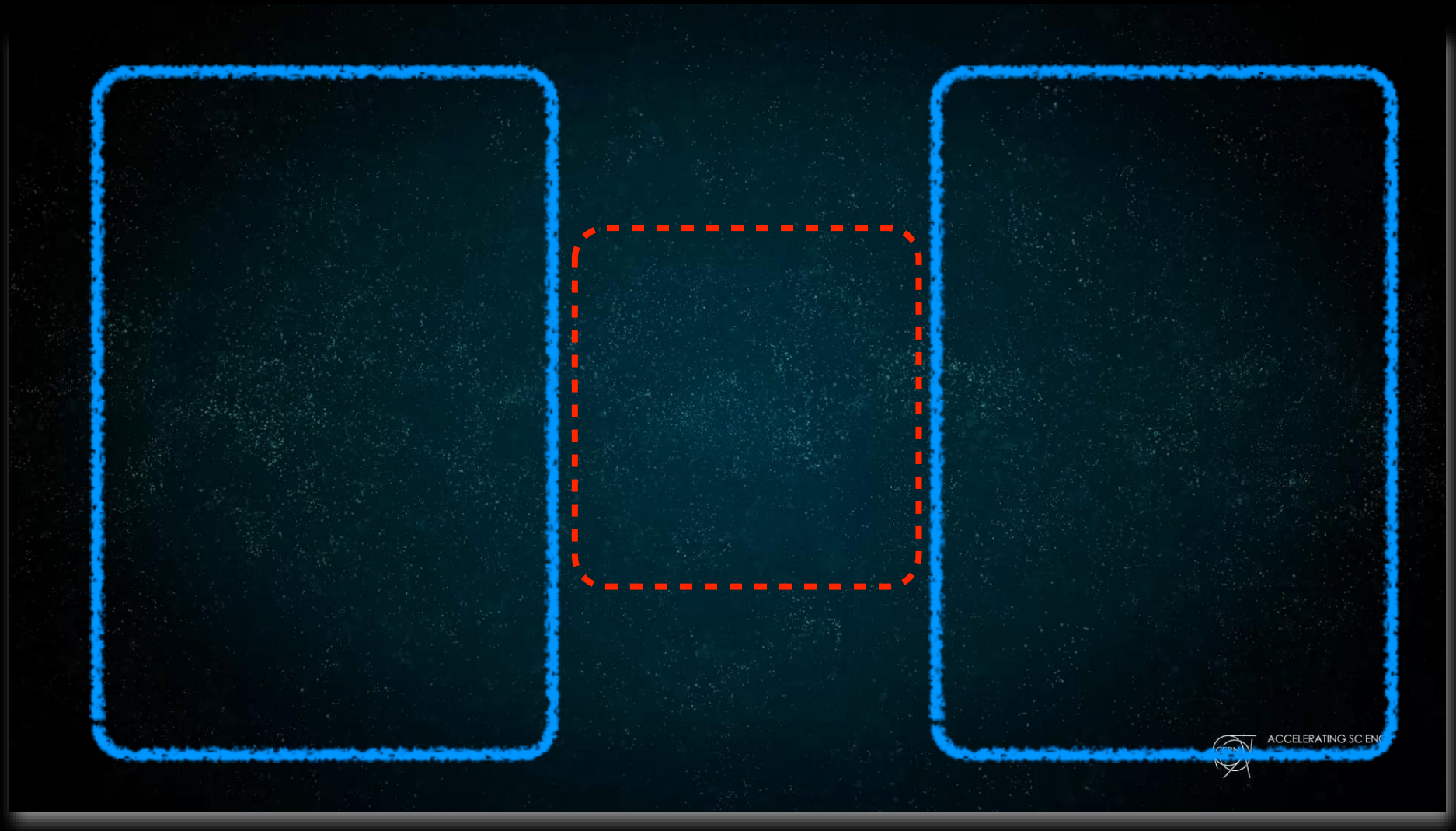
LEP measures the decay width of the Z^o particle

Experiments at accelerators have discovered the whole set of fundamental particles



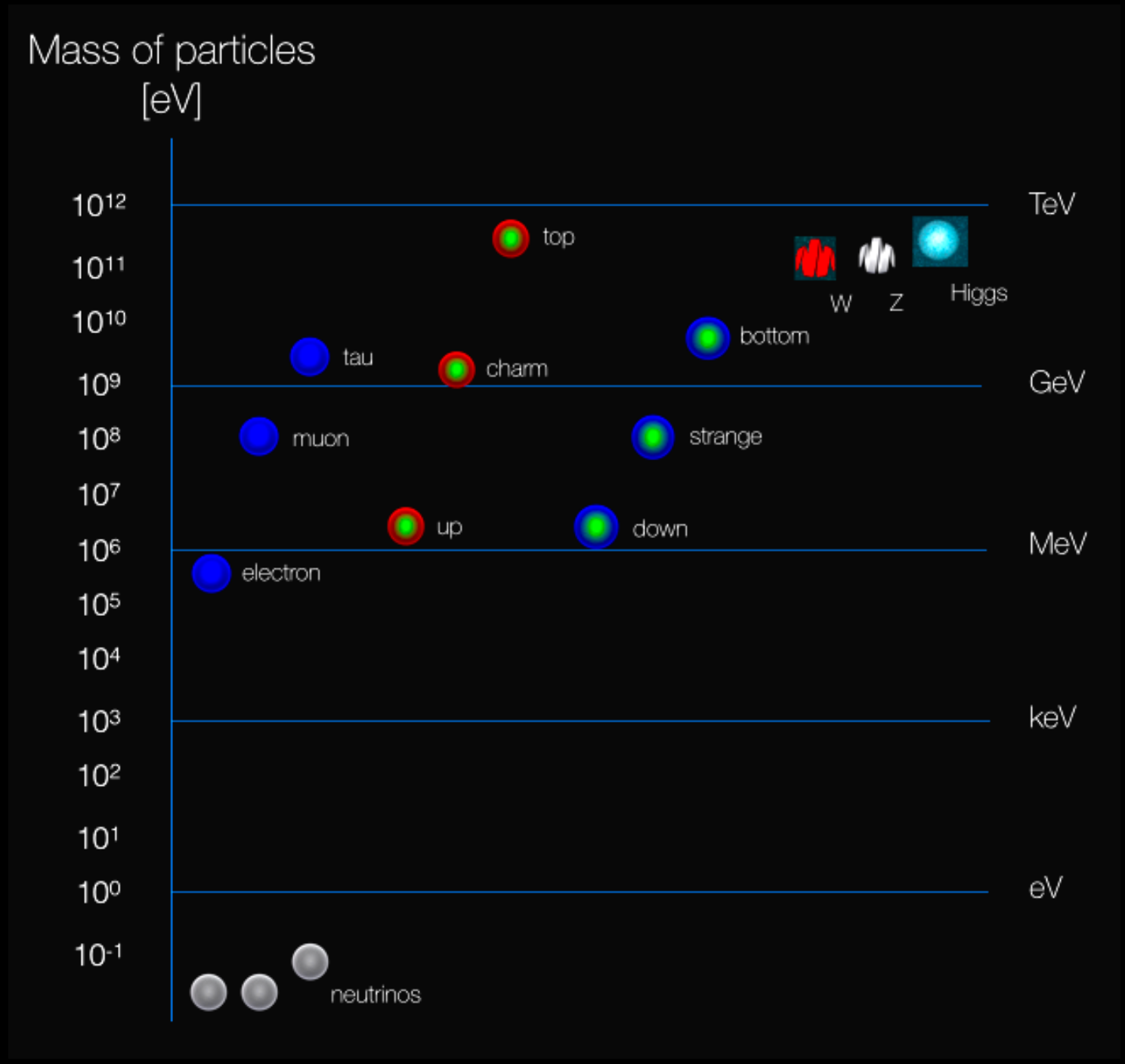
Particle physics of the 21st century

Standard model = ‘periodic system’ of elementary particles



Particles Higgs Fields

How do particles obtain their mass ?

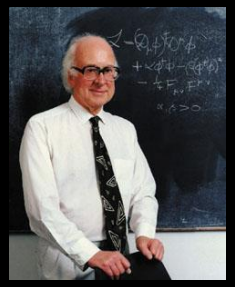


The mystery of mass

Massless particles have to move with the speed of light

THEY CANNOT FORM SOLID OBJECTS

The Brout-Englert-Higgs (BEH) field idea



Sir Peter Higgs

the entire Universe is filled with a homogeneous field

particles interacting with this field obtain inertia (=rest mass)

the BEH field interaction is proportional to the mass of the particle

The ‘cocktail party’ explanation of the Higgs mechanism

A cocktail party ...

The BEH field ....

.. a famous person wants to traverse the room...

... a massless particle enters...

.. but the guests cluster around and slow down its movement...

... the interaction with the BEH field produces the inertia of the particle ...

The ‘Higgs boson’

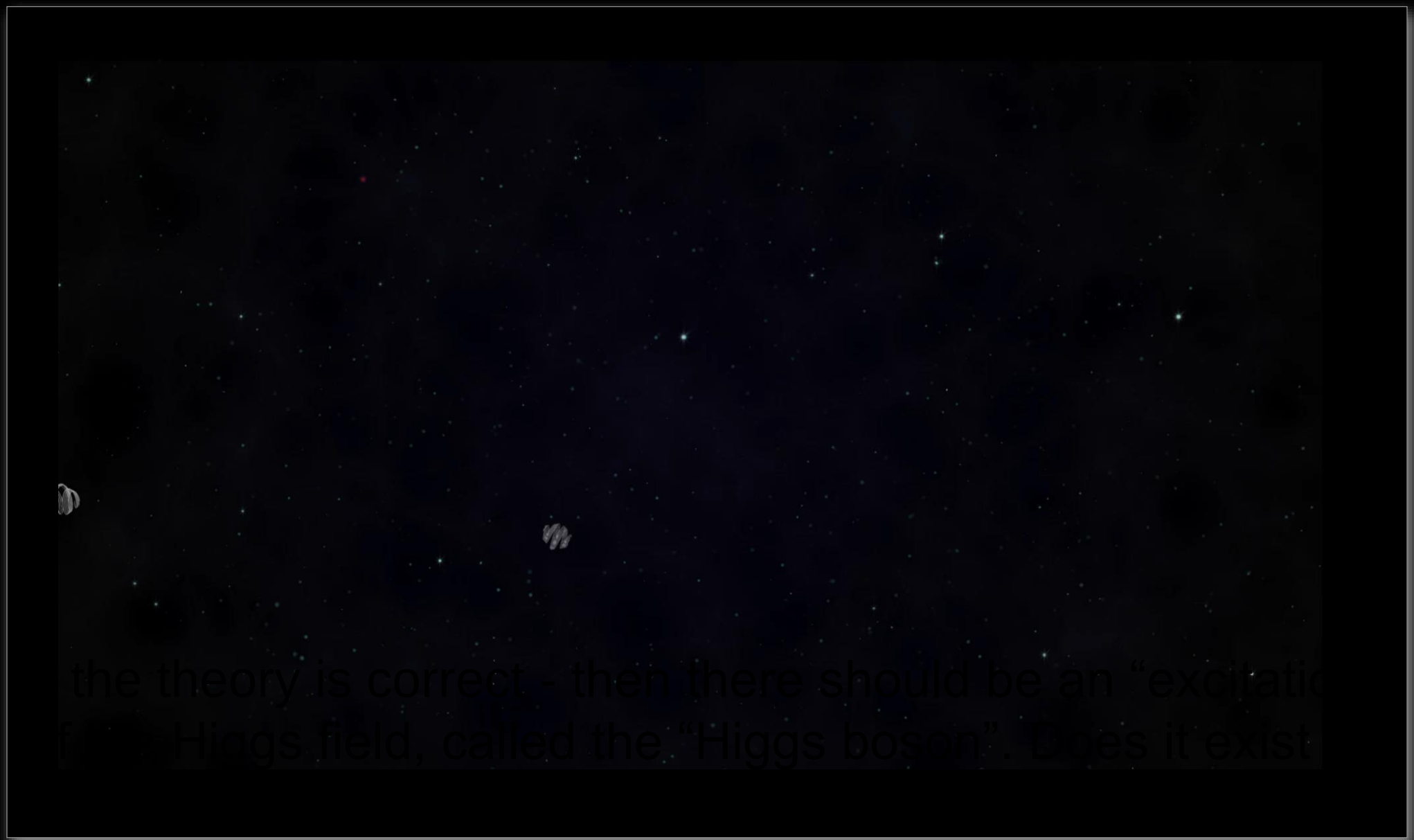
A rumour is spreading among the guests ...

.. they cluster together to exchange the information among themselves...

The BEH field ...

... is excited by an energy concentration and forms an excitation by self-interaction ...

Animation: the Higgs mechanism

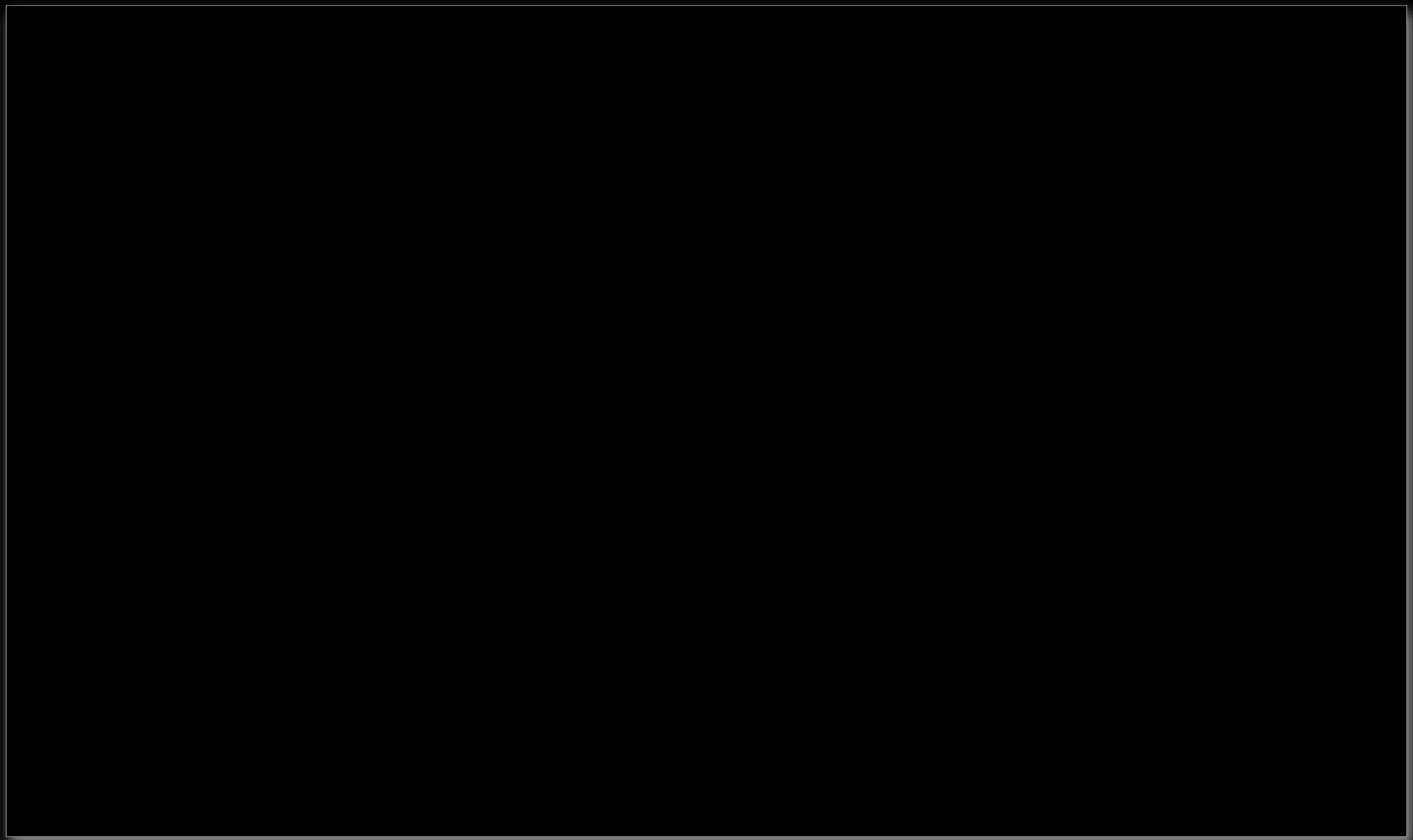


Exciting the Brout-Englert-Higgs field: the “Higgs boson”

... but this happens on average once per 10,000,000,000 (10^{10}) collisions !

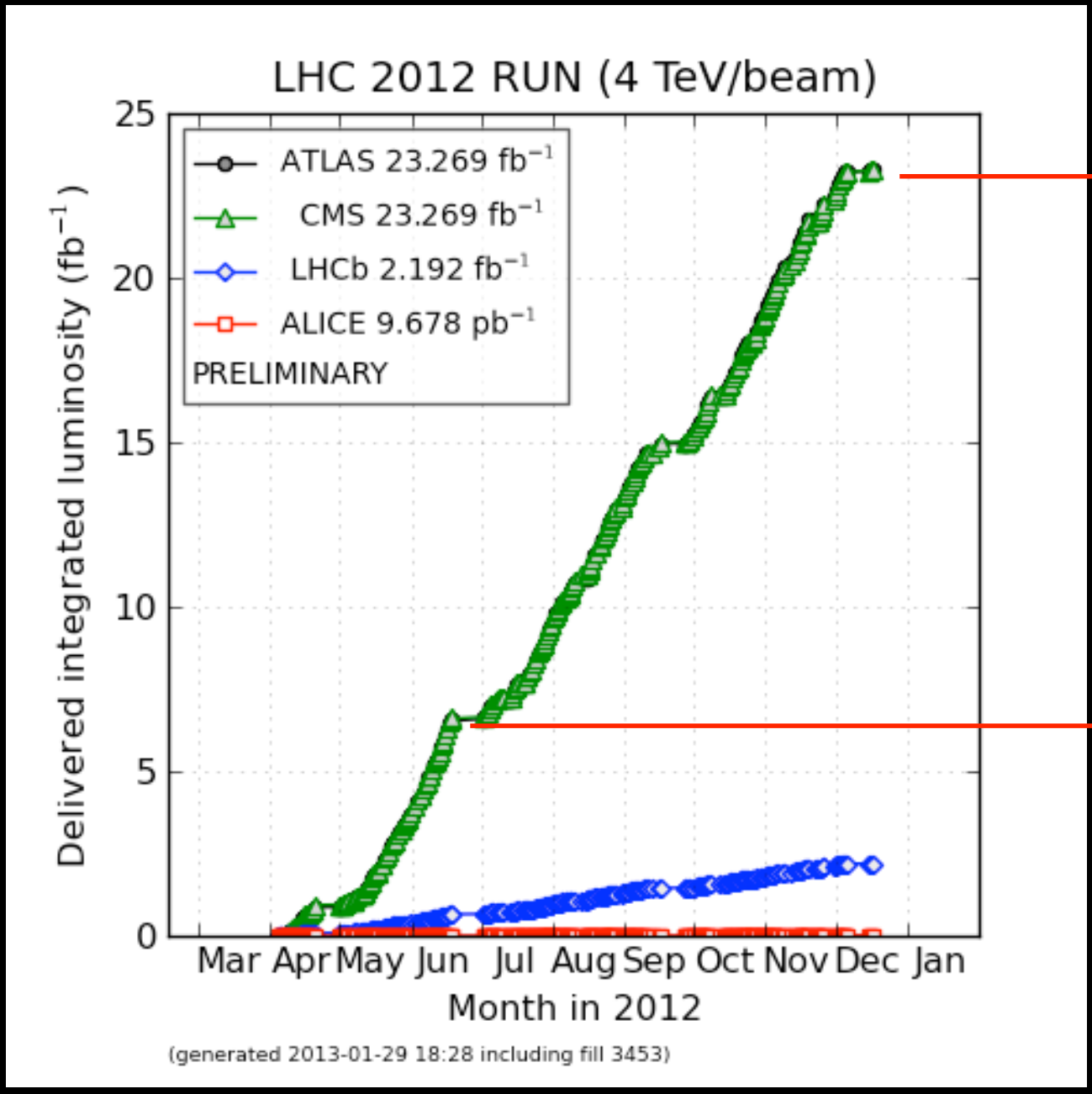
The Higgs boson can decay in two photons

...



but only with a probability of 0.2 %

The CERN hunt for the Higgs boson

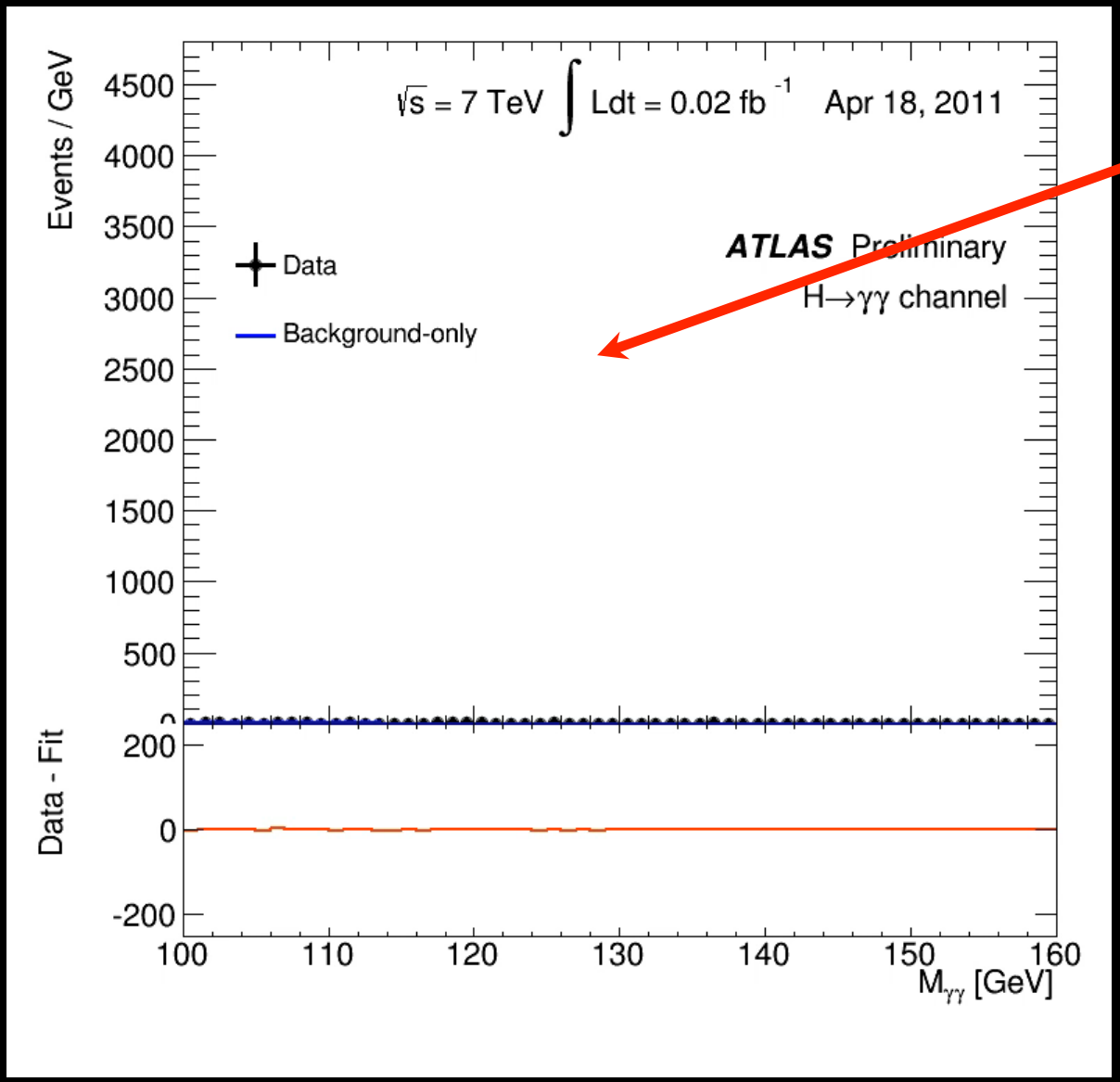


15.12.2012

3,000,000,000,000,000 ($3 \cdot 10^{15}$)
(3000 trillion events !)

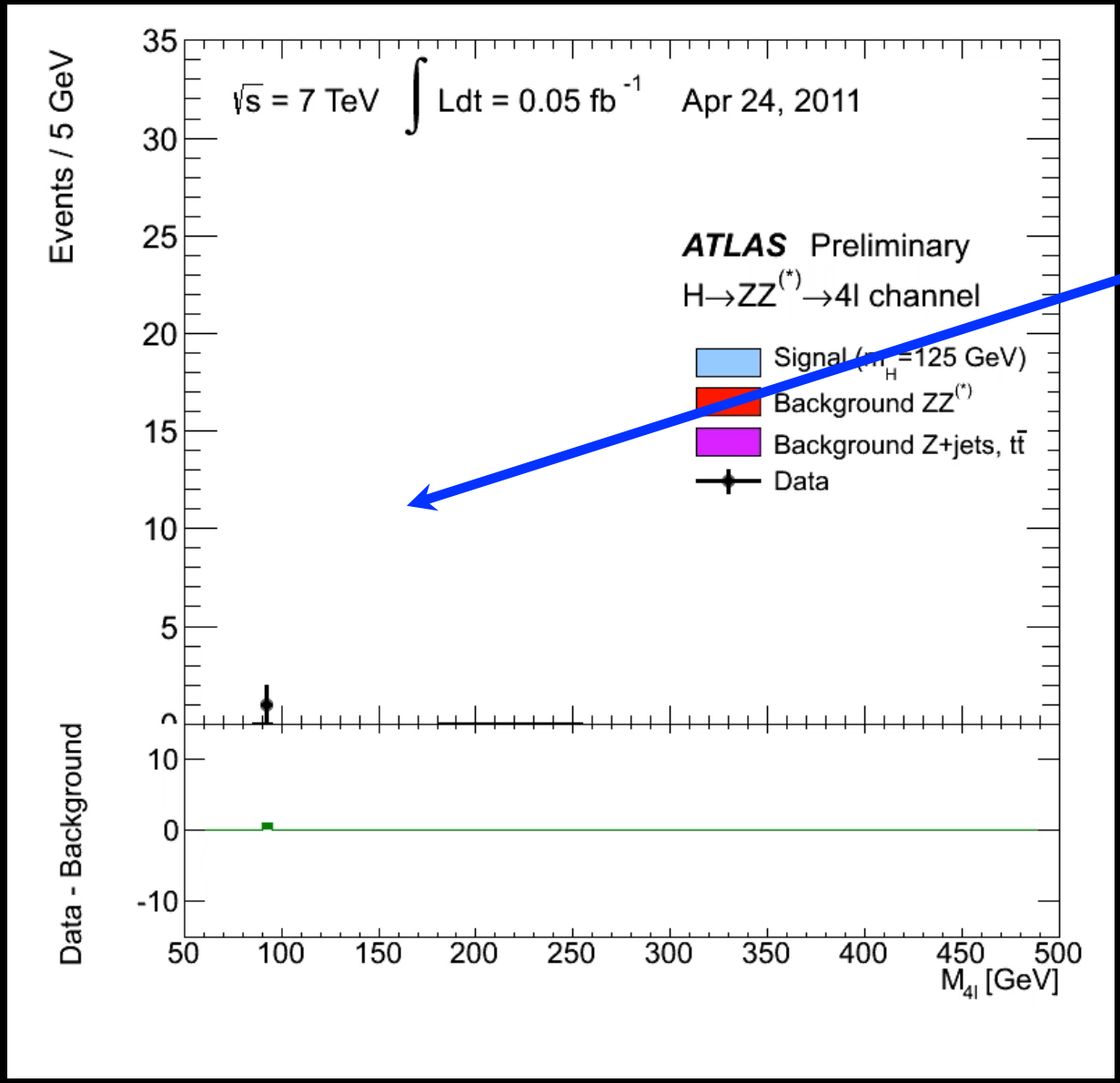
4.7.2012

The evolution of the histogram with two-photon events



Higgs boson

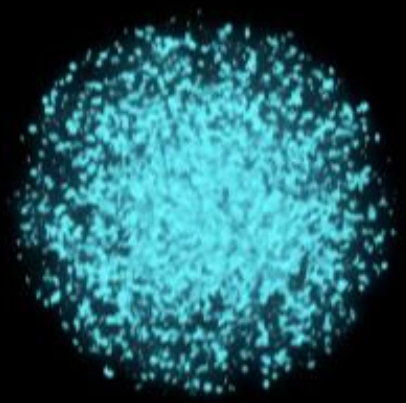
The evolution of the histogram with four leptons

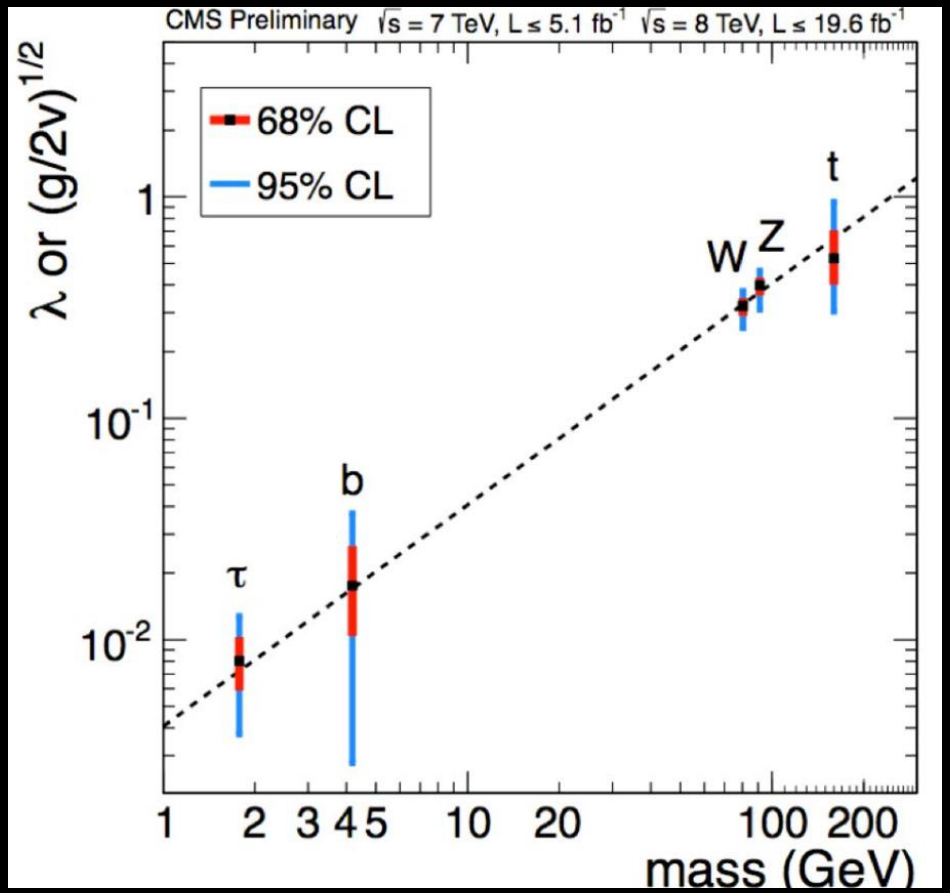


Higgs boson

Status 2014: the new particle is the Higgs boson

Higgs boson decay probability is predicted to be
proportional to the mass of the decay particles





Theoretical expectations compatible with observations

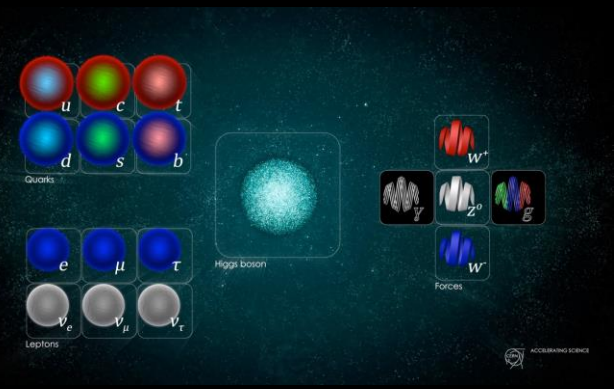
What does this mean?

- the Higgs boson exists, therefore ...
- the Brout-Englert-Higgs field exists
- we know how particles obtain their mass
- the “Standard model” is complete

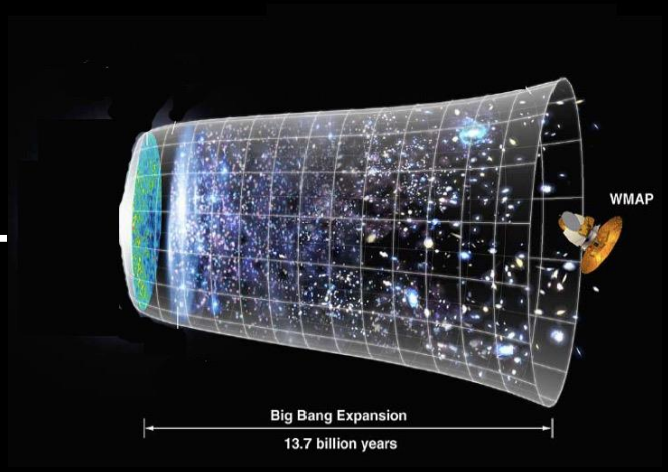
Even more:

- empty space is not ‘empty’
- perhaps a connection to ‘dark energy’ ?

Particle physics + Cosmology = Universe ?



+



No !

Less than 5% of the energy content of the universe are understood!

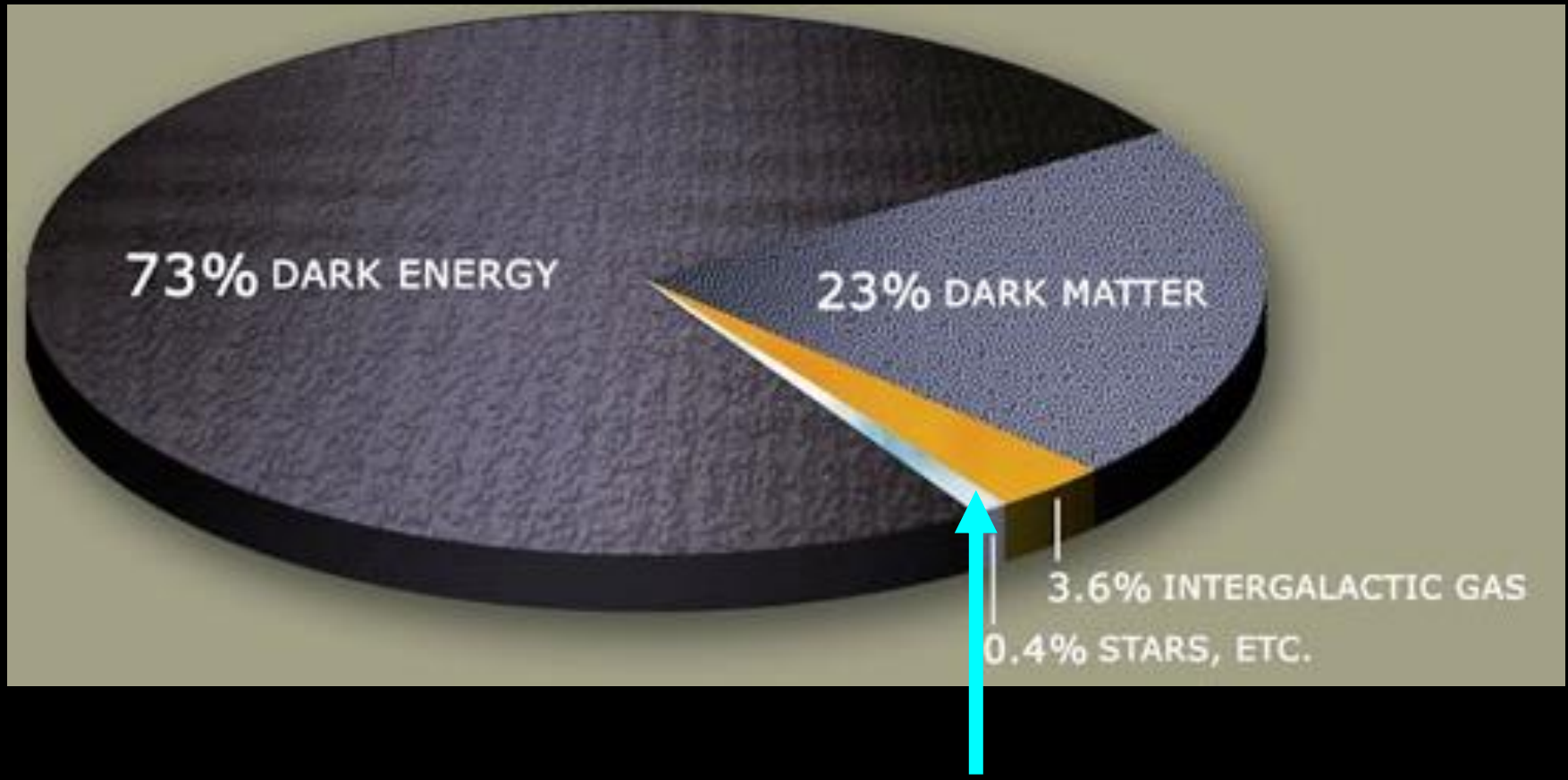
Dark matter ...?

Galaxies rotate too fast

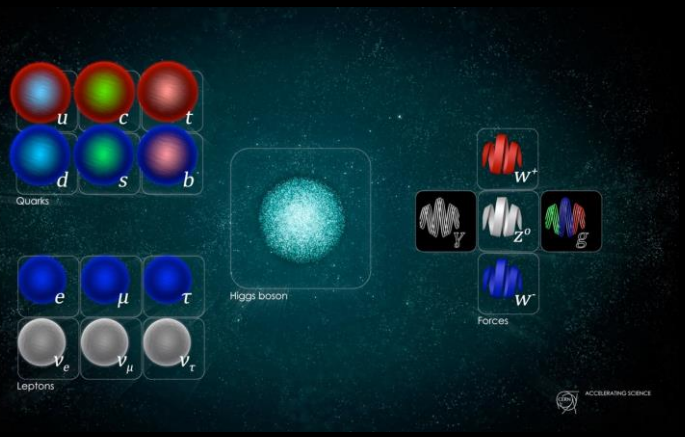
Dark energy ...?

The expansion of the Universe accelerates ...

The “dark Universe”: 96 % of its energy content are hidden in ‘dark energy’ and ‘dark matter’

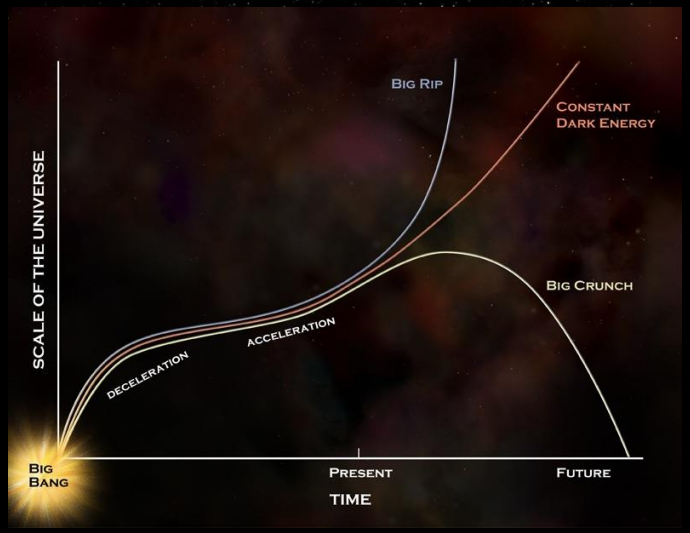


The big questions:



Is the Higgs boson alone?
Connection to ‘dark energy’ ?

What is dark matter?



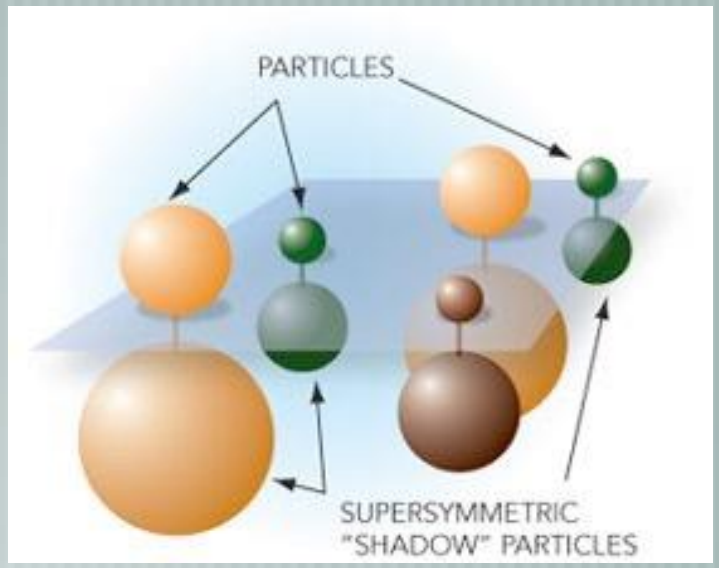
What is dark energy?

SUPERSYMMETRY - connection to Dark Matter ?

A connection between particles (spin 1/2) and fields (spin 1) ?

FERMIONS (quarks, electrons, neutrinos) interact through the exchange of BOSONS (gluons, photon, W/Z bosons)

"SUPERSYMMETRY" predicts a complete symmetry between FERMIONS AND BOSONS: each fermion has a boson partner, and vice versa:

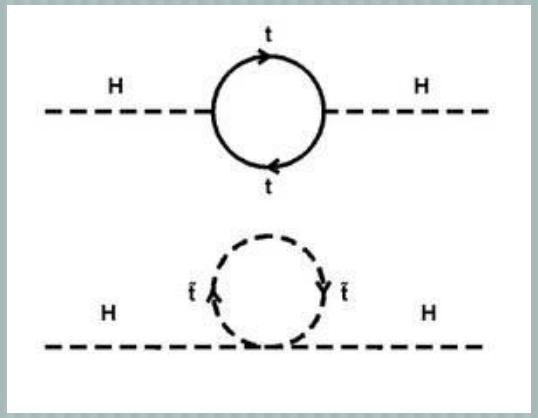


Spin 1/2	Spin 0, Spin 1
electron	selectron (S=0)
quark	squark (S=0)
photino	photon (S=1)
gluino	gluon (S=1)
gaugino (Wino, Zino)	W, Z (S=1)

But: no such SUSY partner has ever been seen. So ...
if they exist, they must have a large mass (> 1 TeV)

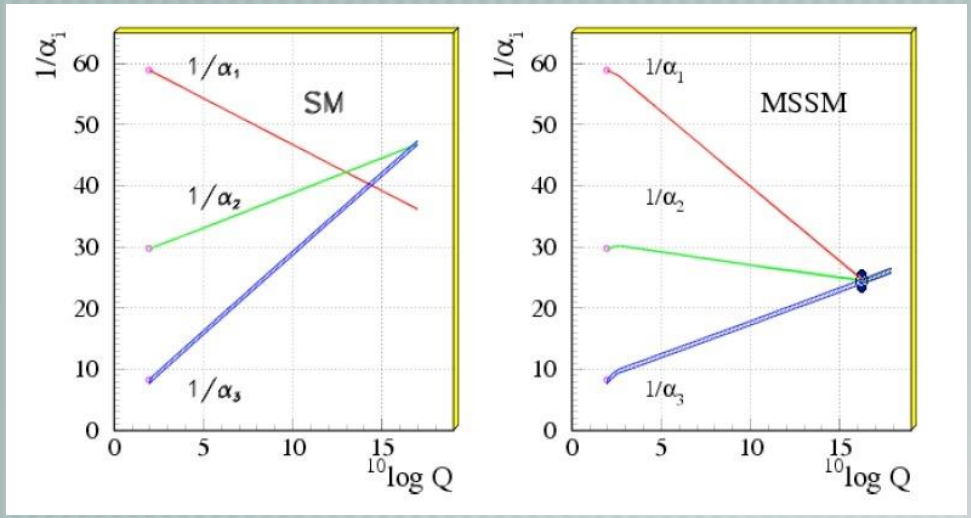
Why SUSY?

1) A fundamental space-time-symmetry



2) "Protection of the Higgs boson mass (M ~ 10^2 GeV)
from vacuum fluctuations up to Planck mass (~10^{19} GeV)

3) Predicts unification of electroweak and strong interaction at ~10^{17} GeV

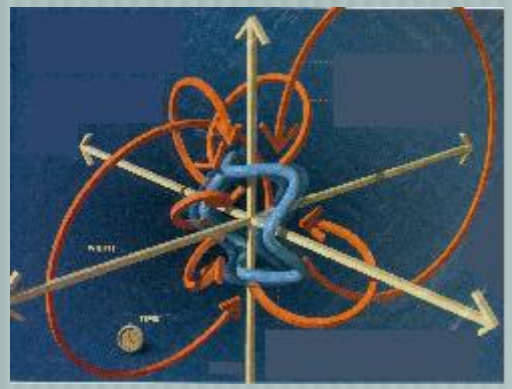


4) May explain the cosmological matter-antimatter asymmetry

5) **Lightest supersymmetric particle = dark matter ??**

MORE MYSTERIES

What is a particle?

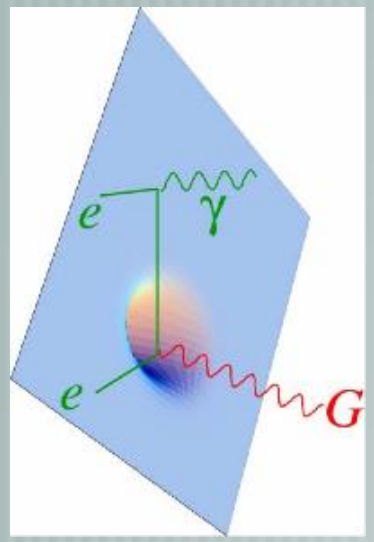


Superstrings in 9+1 dimensions?

Little strings of string energy vibrating in a 9+1 dimensional space ?
L ~10^{-35} m (Planck length)
Standard model particles: different vibration modes, open/closed strings
GRAVITON-like particle contained (unification of SM and gravity?)

BUT: why did 6 dimensions disappear? how did they disappear?
is there a unique way to go from 10 to 4 dimensions?

Extra dimensions ?



More than 3 macroscopic dimensions of space?

Is the graviton propagating in 4- or more dimensions of space?

Micro-black holes ?

Mysteries of the 21st century

1900 - 2000: Phantastic progress in understanding matter and the Universe

We know what matter is made of.
We know the principle steps in the evolution of the Universe.

Some of the big physics questions of the 21st century

What is the structure of empty space: the BEH field? dark energy?
What is dark matter?
What is the origin/nature of particle families? Why three? What are particles?
Where is the connection between quarks and leptons (identical electroweak charges!!)
How did the antimatter disappear?
The origin and value of the constants of Nature? Is life in the Universe an 'accident' ?

The Large Hadron Collider - 2015

New discoveries are waiting !