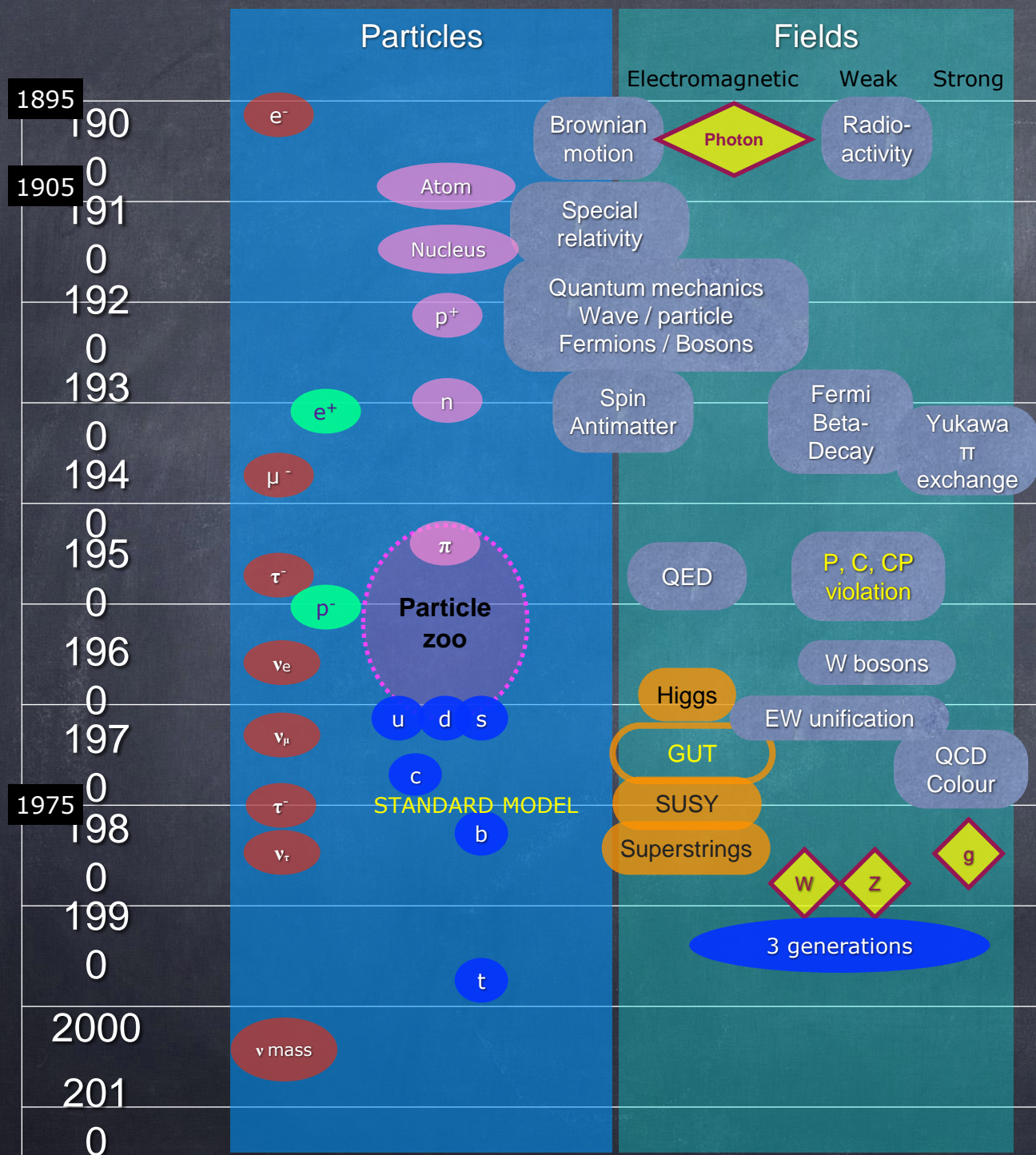


# **STRUCTURE OF MATTER**

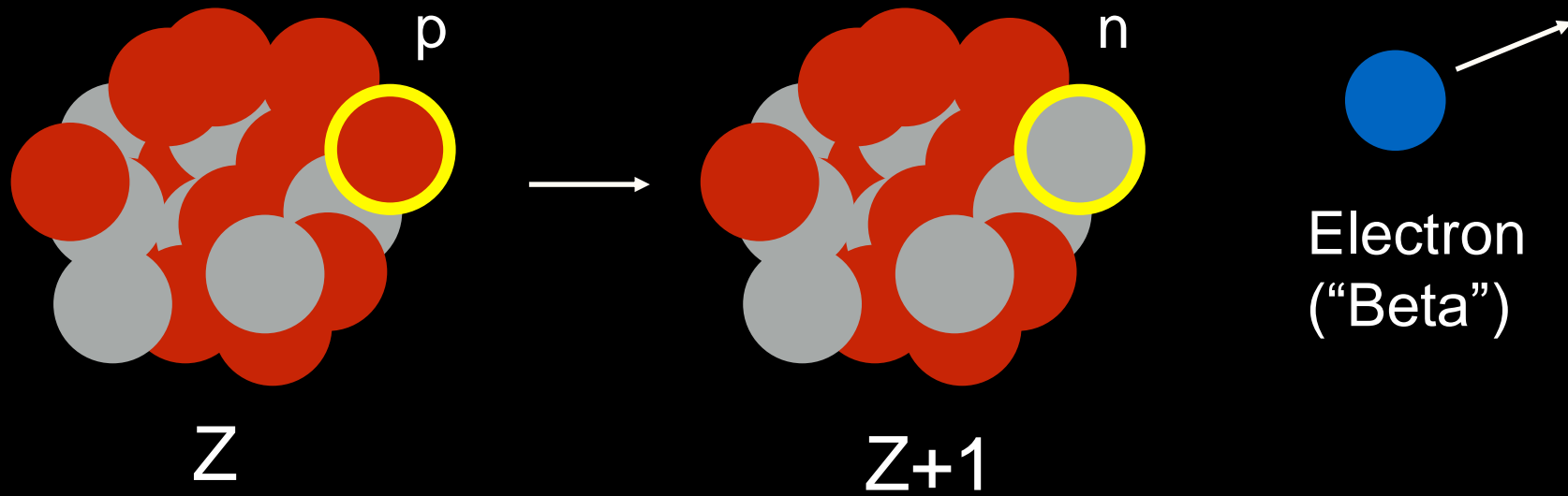
Discoveries and Mysteries

Part 2

Rolf Landua  
CERN

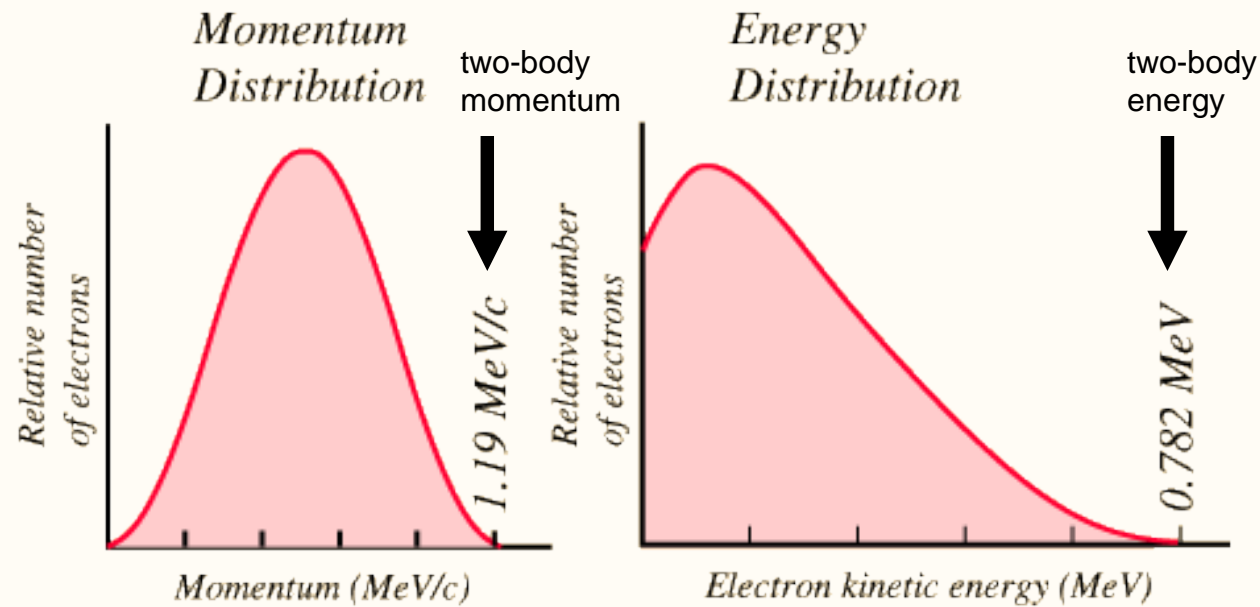


# WEAK INTERACTION



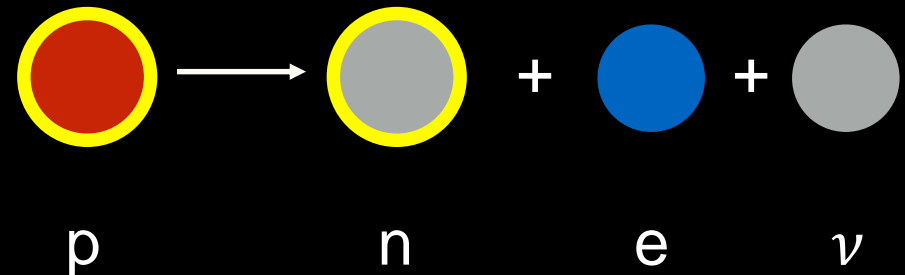
Henri Becquerel (1900): Beta-radiation = electrons

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

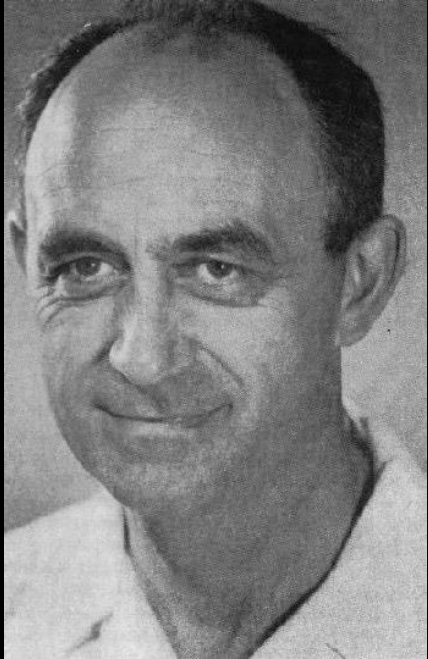


W. Pauli (1930) postulate:

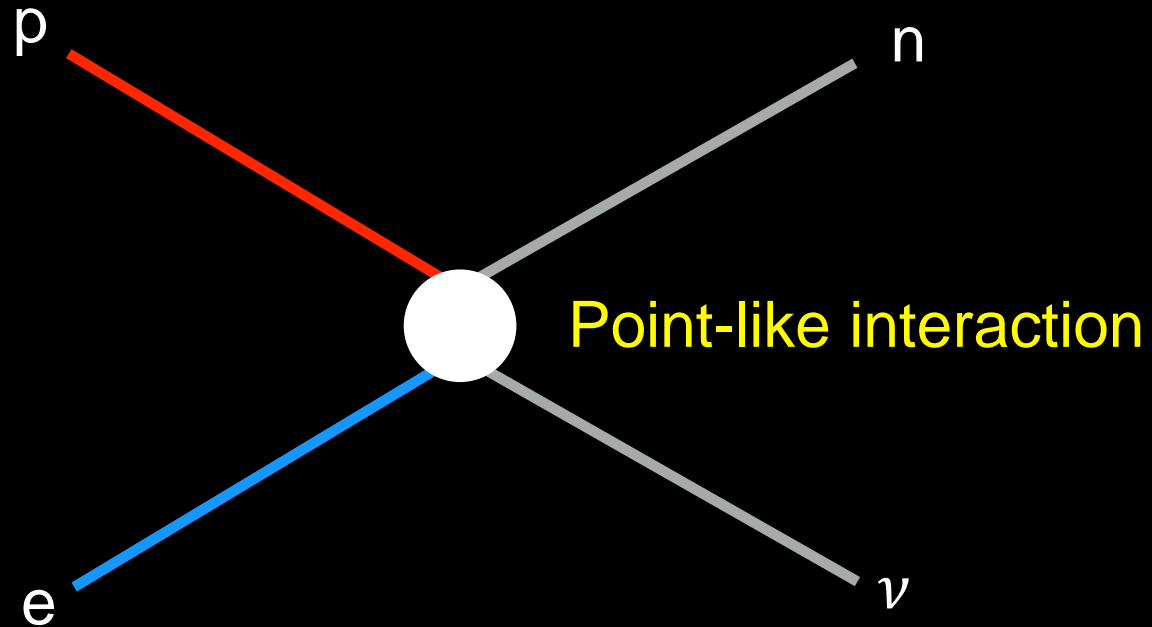
- there is a third particle involved
- neutral
- very small or zero mass
- "Neutrino" (Fermi)



# FERMI THEORY (1934)



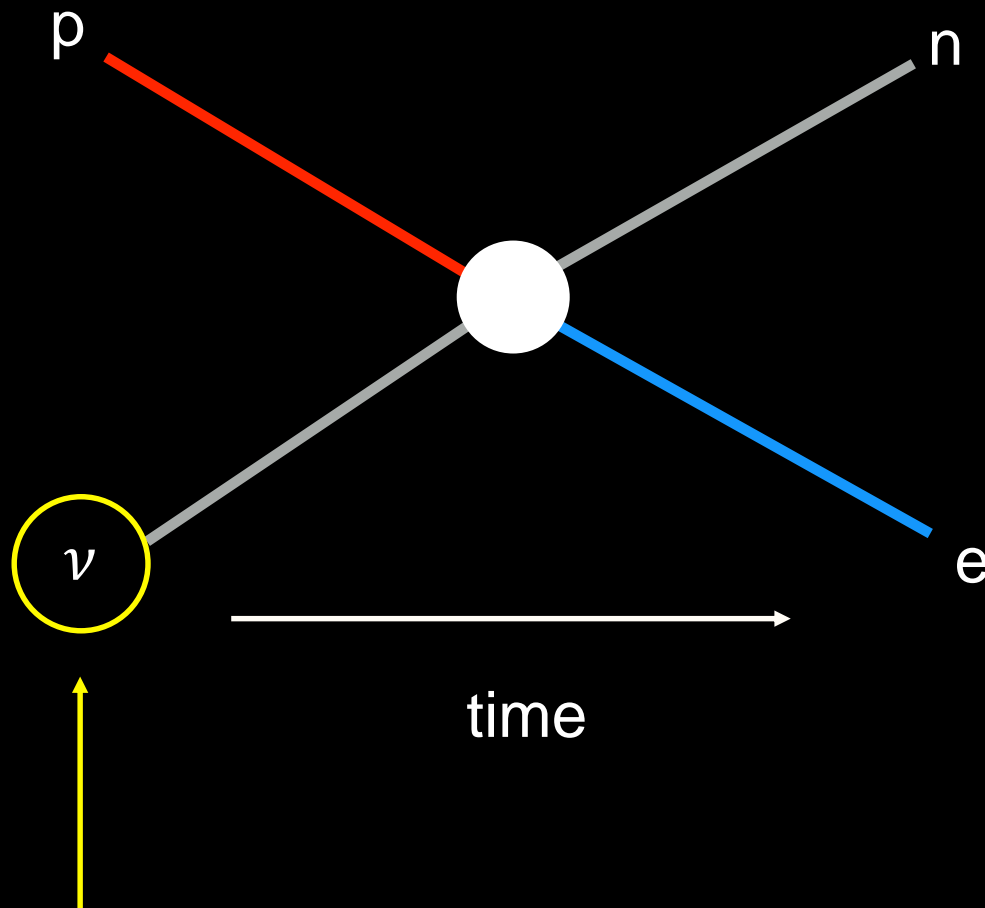
Enrico Fermi



$W = \text{Overlap of the four wave functions} \times \text{Universal constant } G$

$G \sim 10^{-5} / M_p^2 = \text{"Fermi constant"}$

# FERMI: PREDICTION ABOUT NEUTRINO INTERACTIONS



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

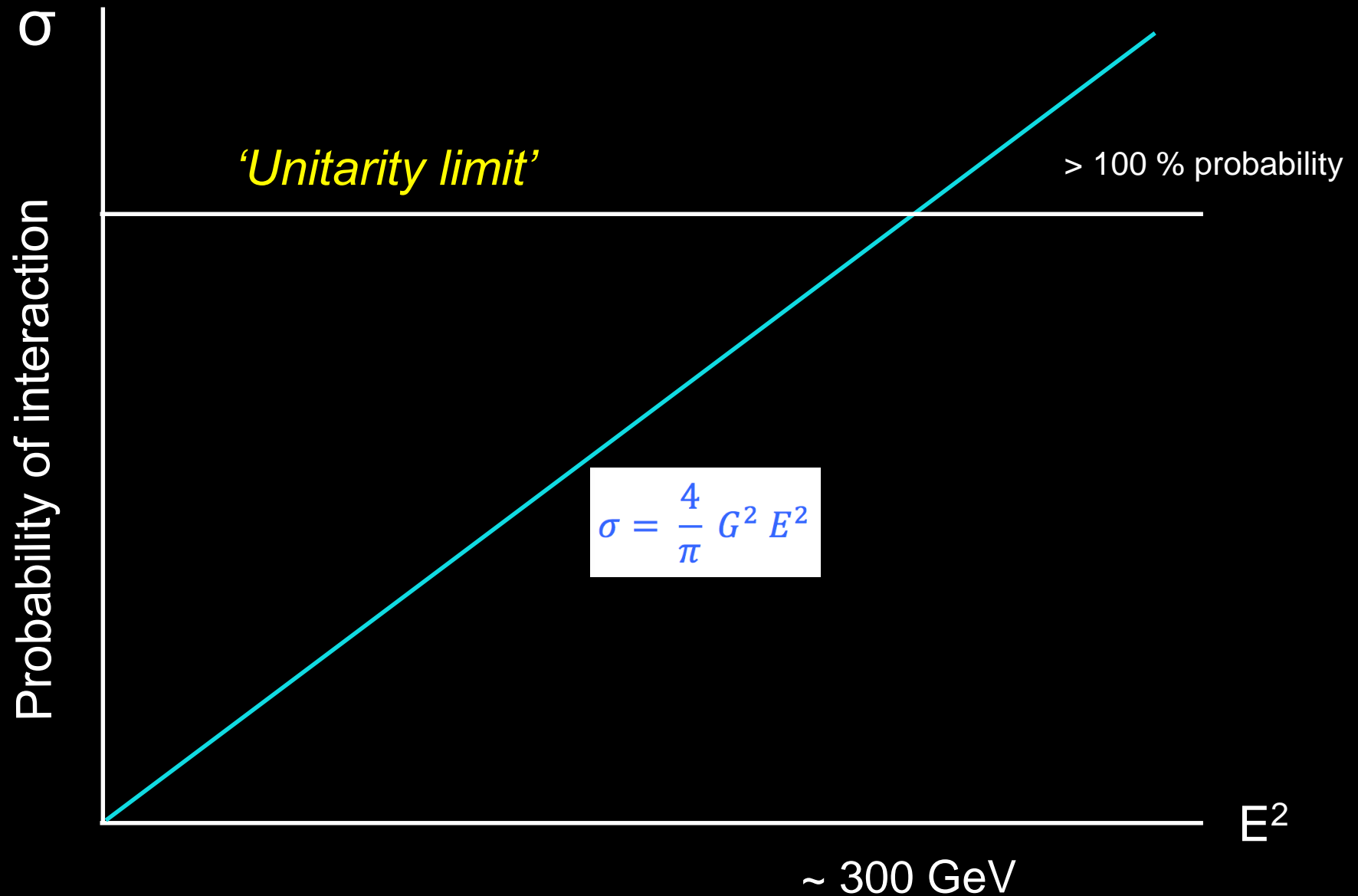
$$E = 1 \text{ MeV: } \sigma = 10^{-43} \text{ cm}^2$$

(Range:  $10^{20}$  cm  $\sim$  100 l.yr)

Reines, Cowan (1956):  
Neutrino 'beam' from reactor

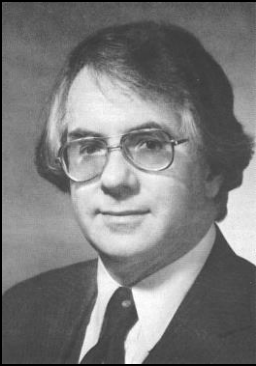
Reactions prove existence of neutrinos

and then ..... THE PREDICTION FAILED !!

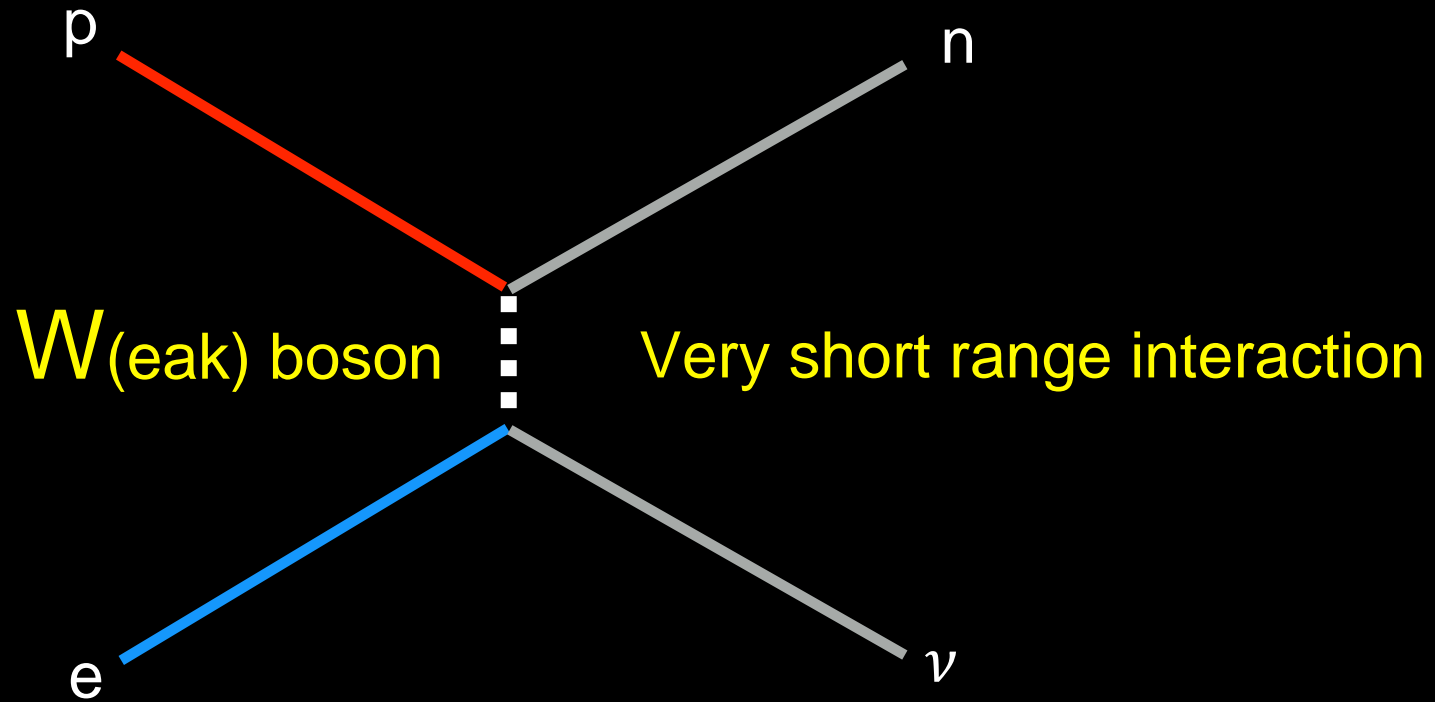




# GLASGOW REFORMULATES FERMI THEORY (1958)



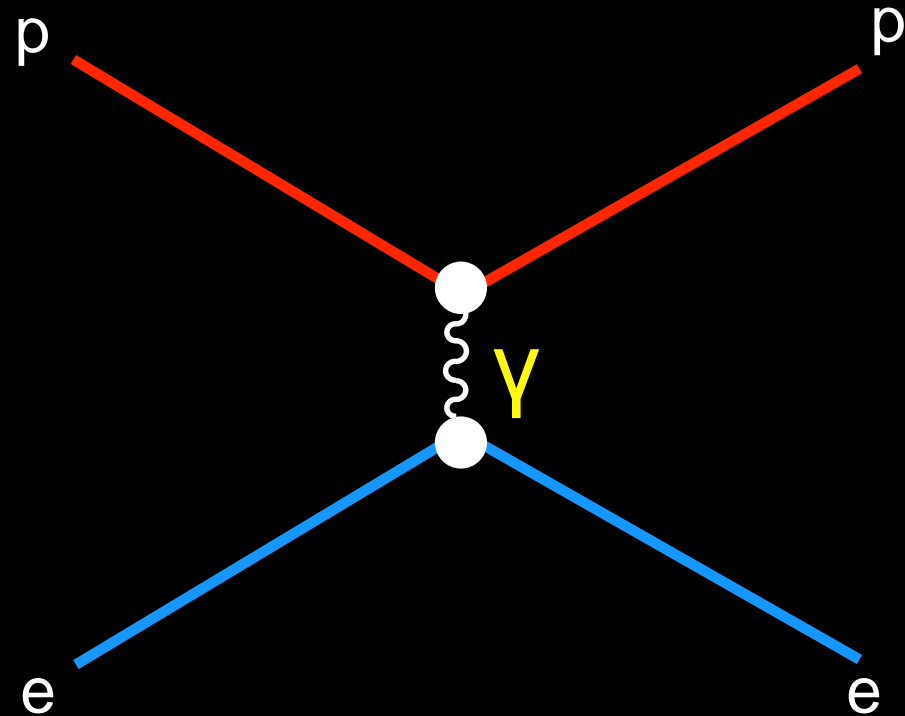
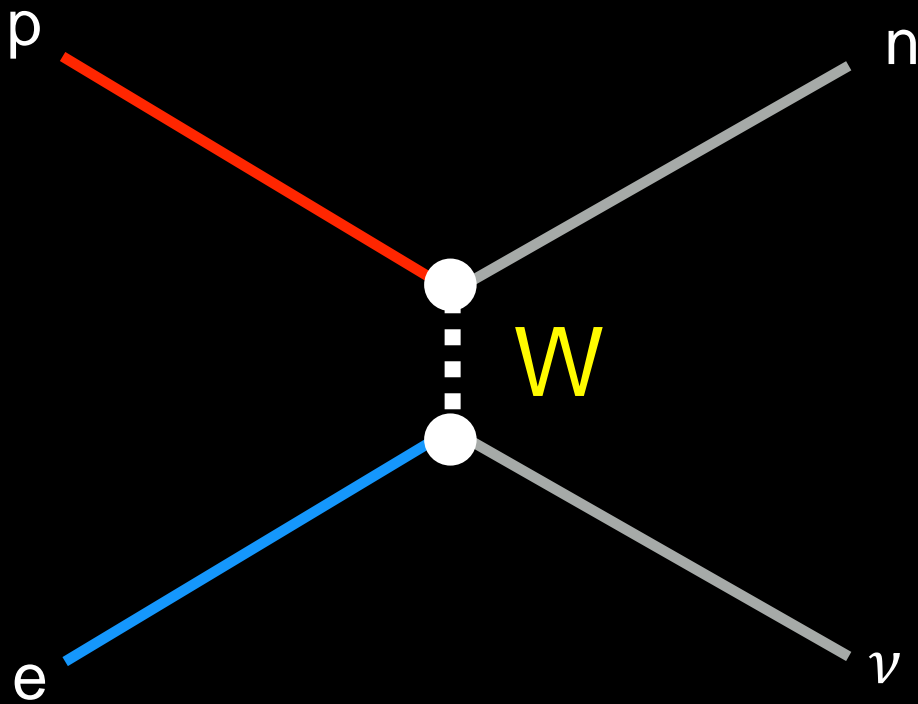
S. Glashow



If mass of  $W$  boson  $\sim 100$  GeV : theory o.k.



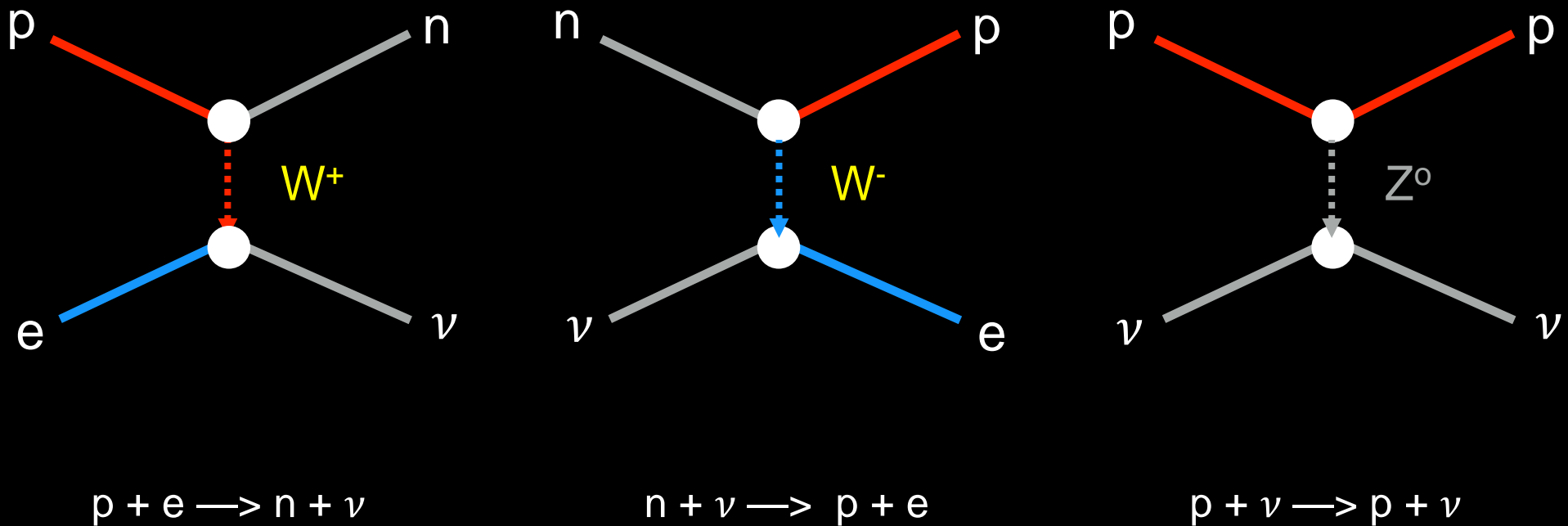
Interesting: at high energies, coupling of weak and e.m. interaction similar !



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

# ELECTRO-WEAK UNIFICATION

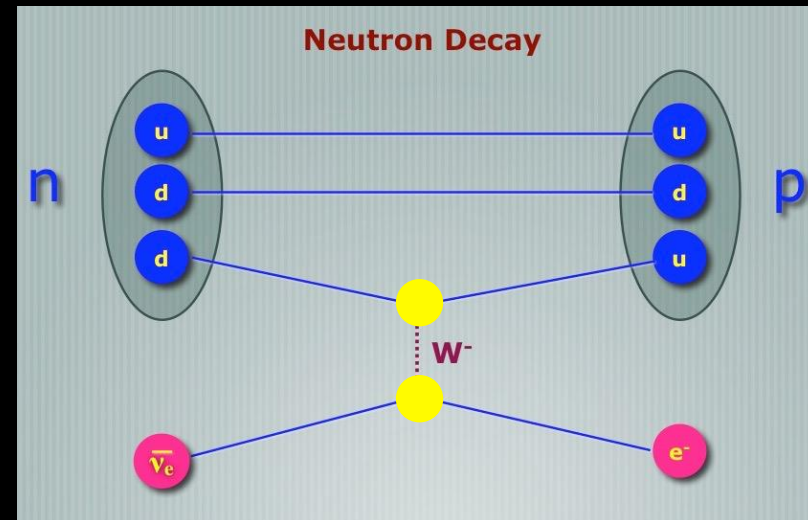
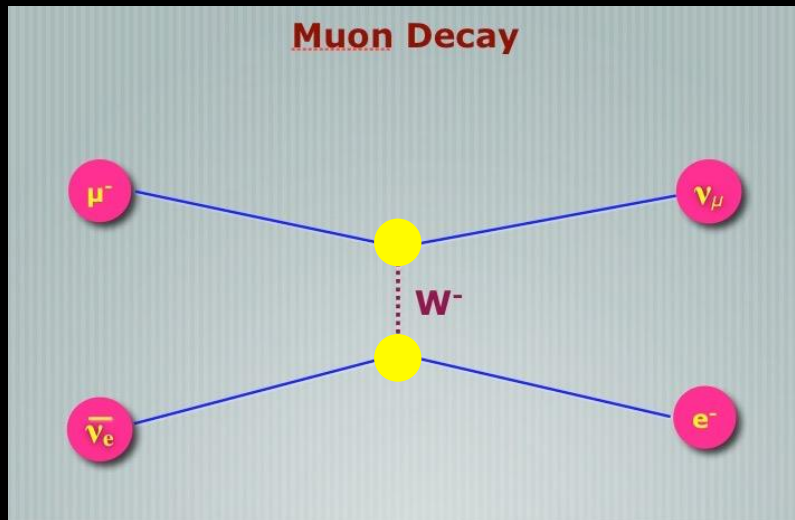
“Charged currents” ( $W^\pm$ ) and “Neutral Current” ( $Z^0$ )



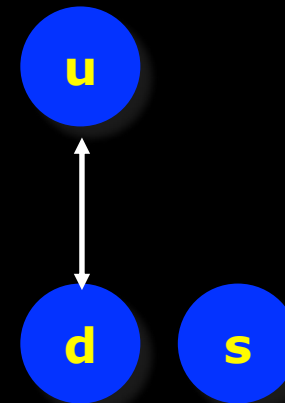
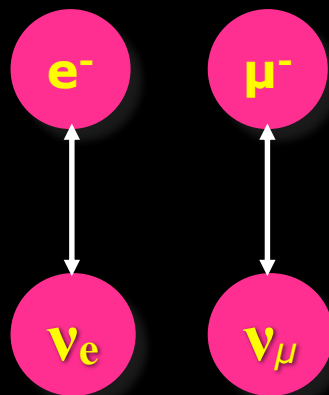
$Z^0$  is the ‘massive’ brother of the photon

Idea of “weak symmetry breaking” through ‘Higgs mechanism’

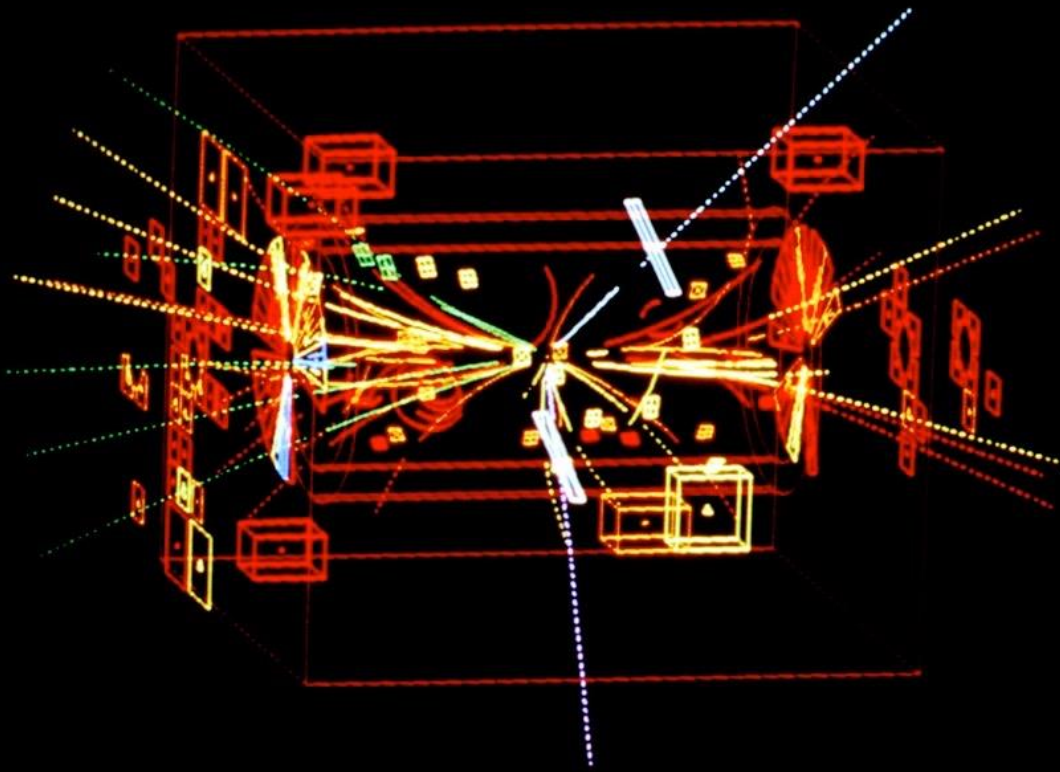
Interesting: electroweak interaction is (approx.) the same for leptons and quarks !



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



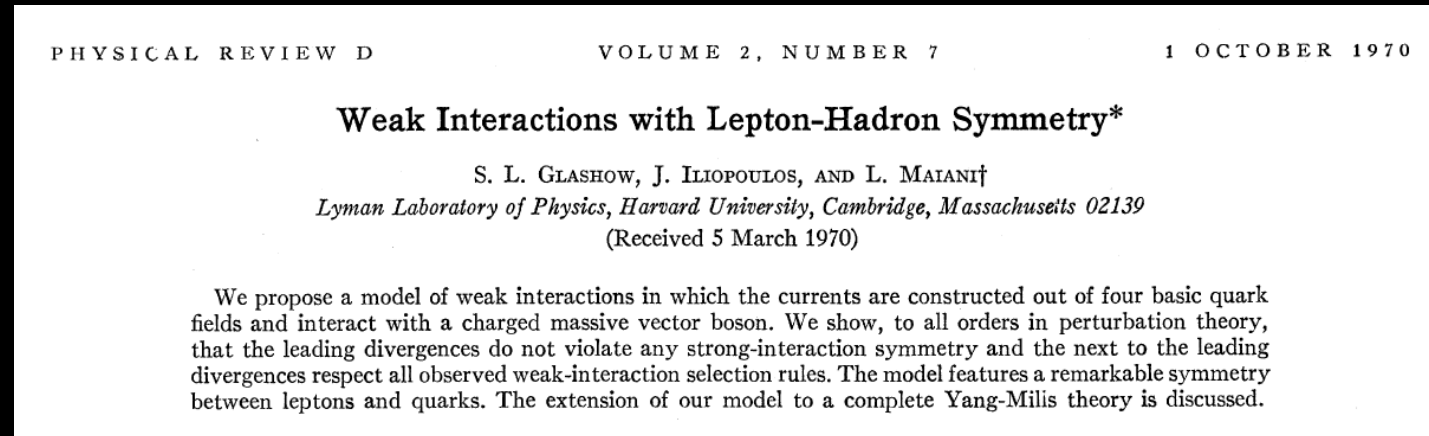
# DISCOVERY OF THE WEAK BOSONS AT CERN (1983)



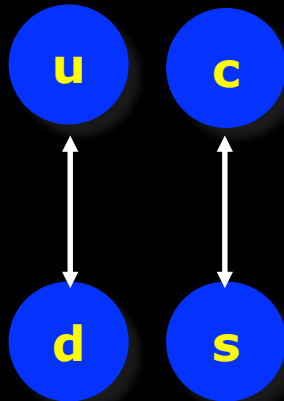
(C. Rubbia, S. van der Meer)

# THE CHARM QUARK

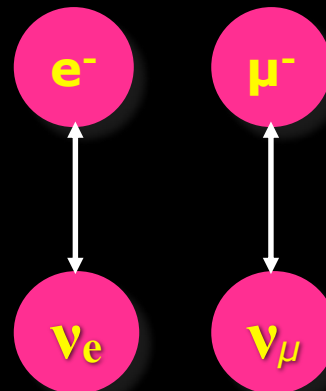
A legendary paper, predicting the 'charm' quark (Glashow, Iliopoulos, Maiani)



Quarks



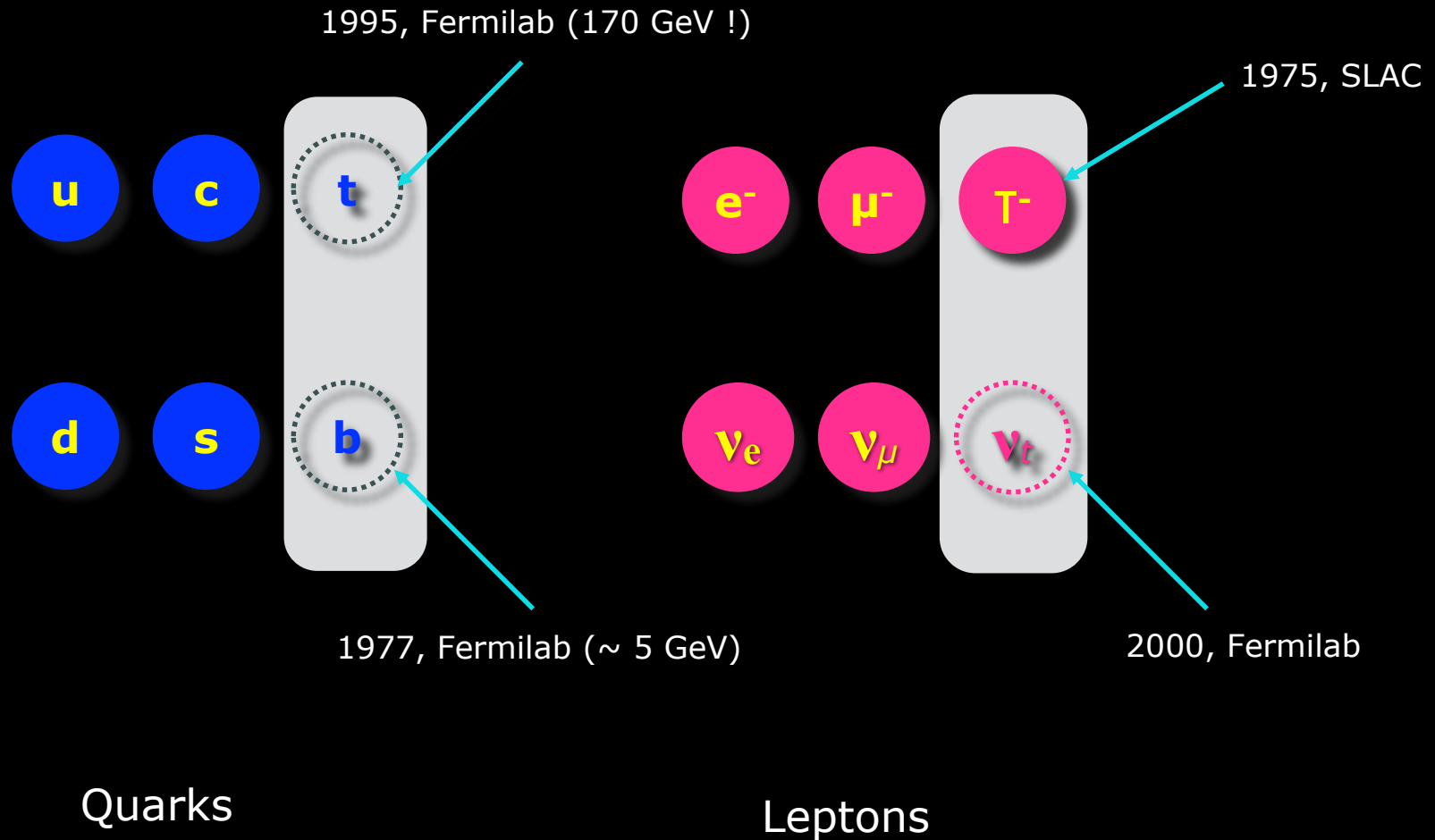
Leptons



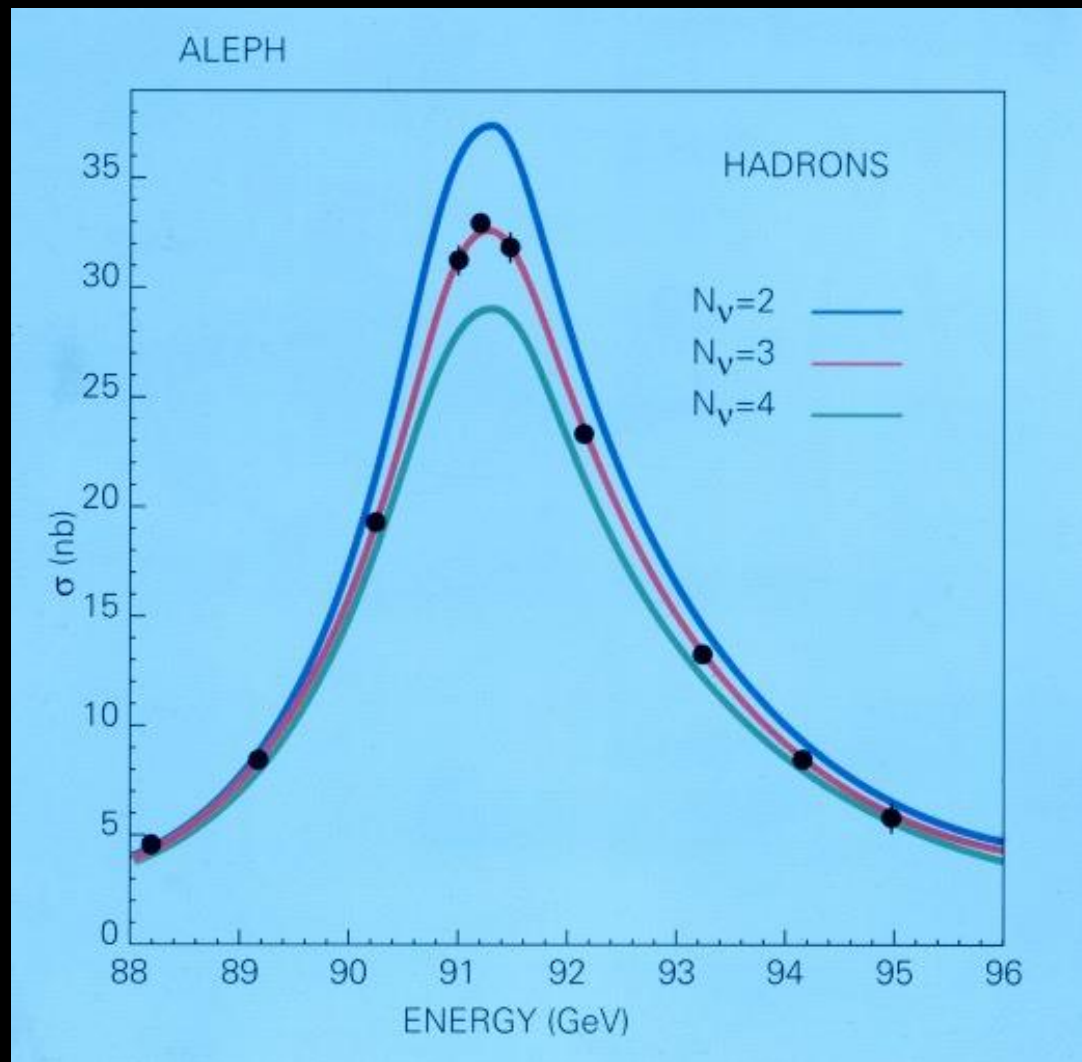
The charm quark was discovered  
( $J/\psi$  meson =  
charm-anticharm bound  
state)  
in November 1974

# Surprise, surprise: enter the THIRD FAMILY

*A new lepton (called “tau”) is discovered ( heavy brother of  $e$  and  $\mu$  )*



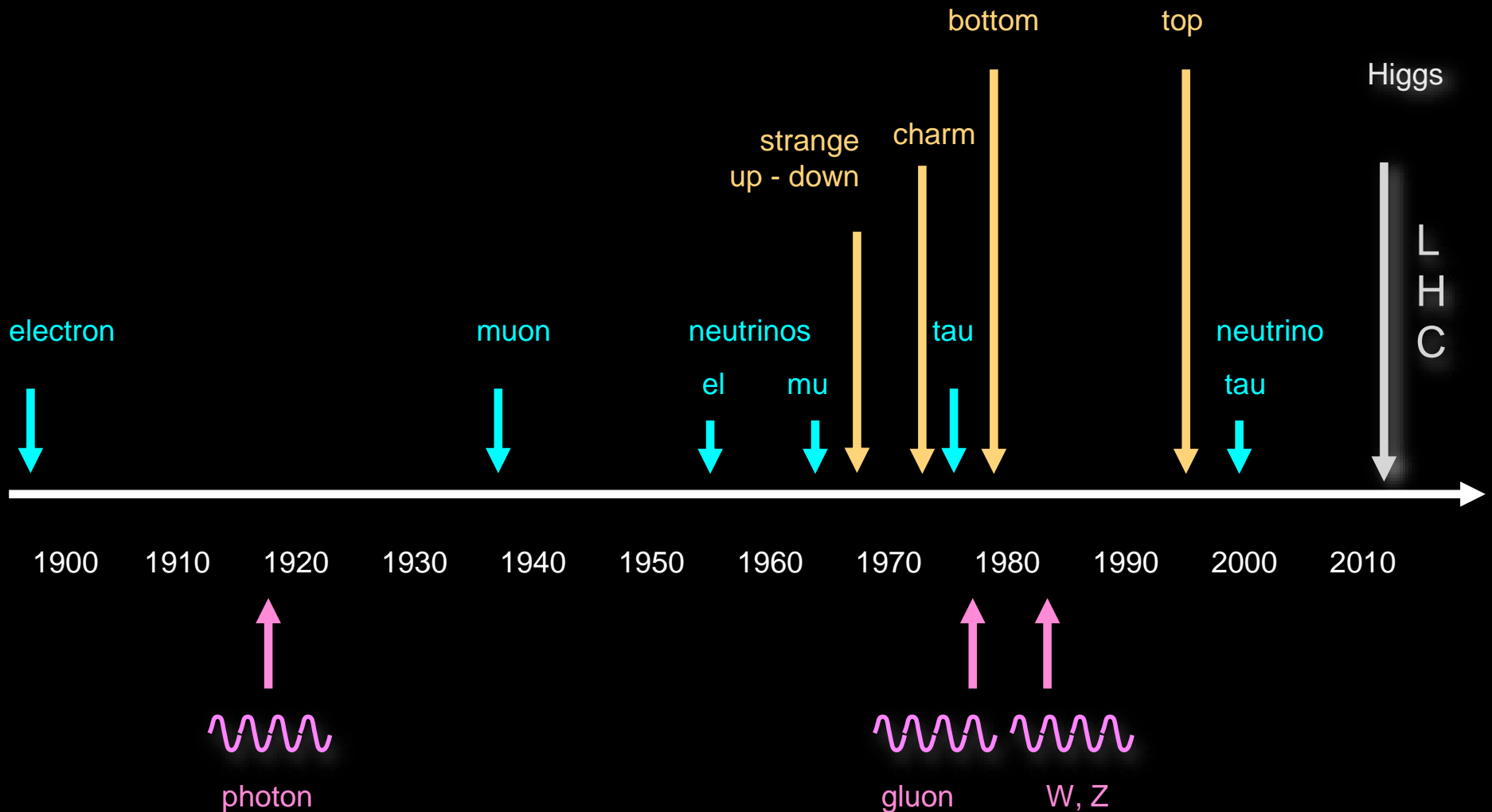
There are exactly 3 families



LEP measures the decay width of the  $Z^0$  particle

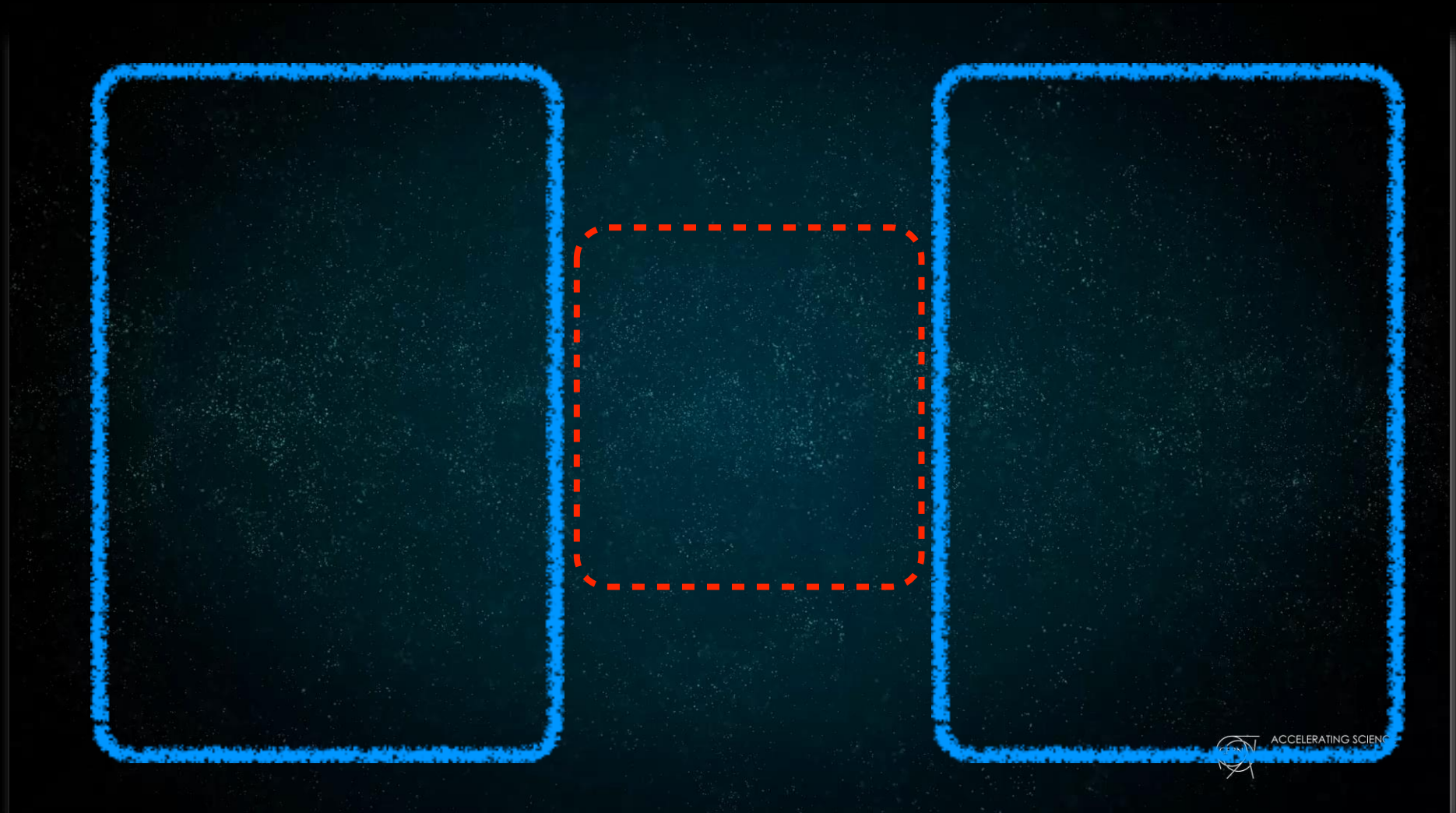


# Experiments at accelerators have discovered the whole set of fundamental particles



# Particle physics of the 21<sup>st</sup> century

Standard model = 'periodic system' of elementary particles



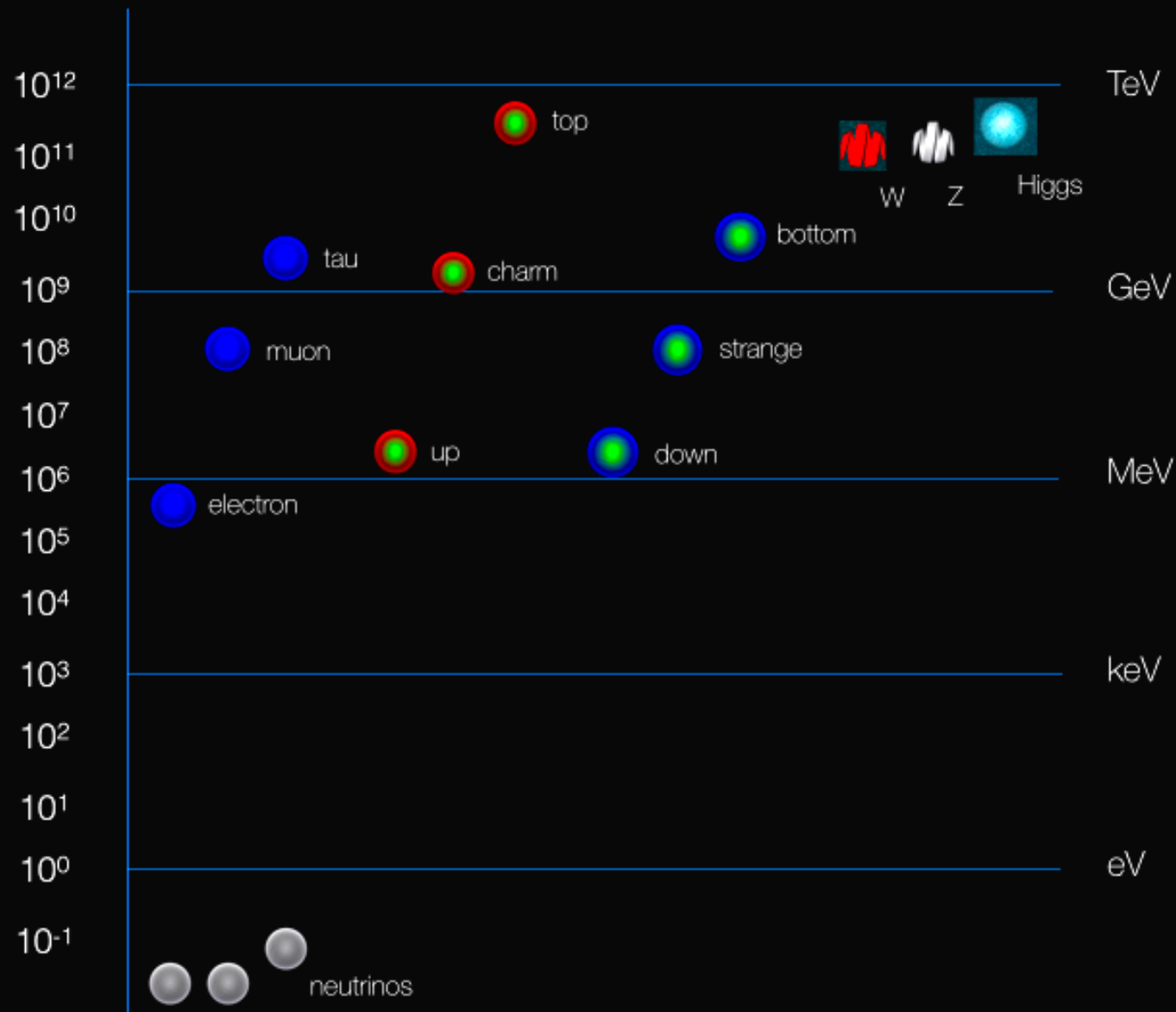
Particles

Higgs

Fields

# How do particles obtain their mass ?

Mass of particles  
[eV]



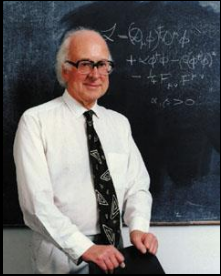
# The mystery of mass



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



the theory is correct - then there should be an “excitation” of the Higgs field, called the “Higgs boson”. Does it exist?

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



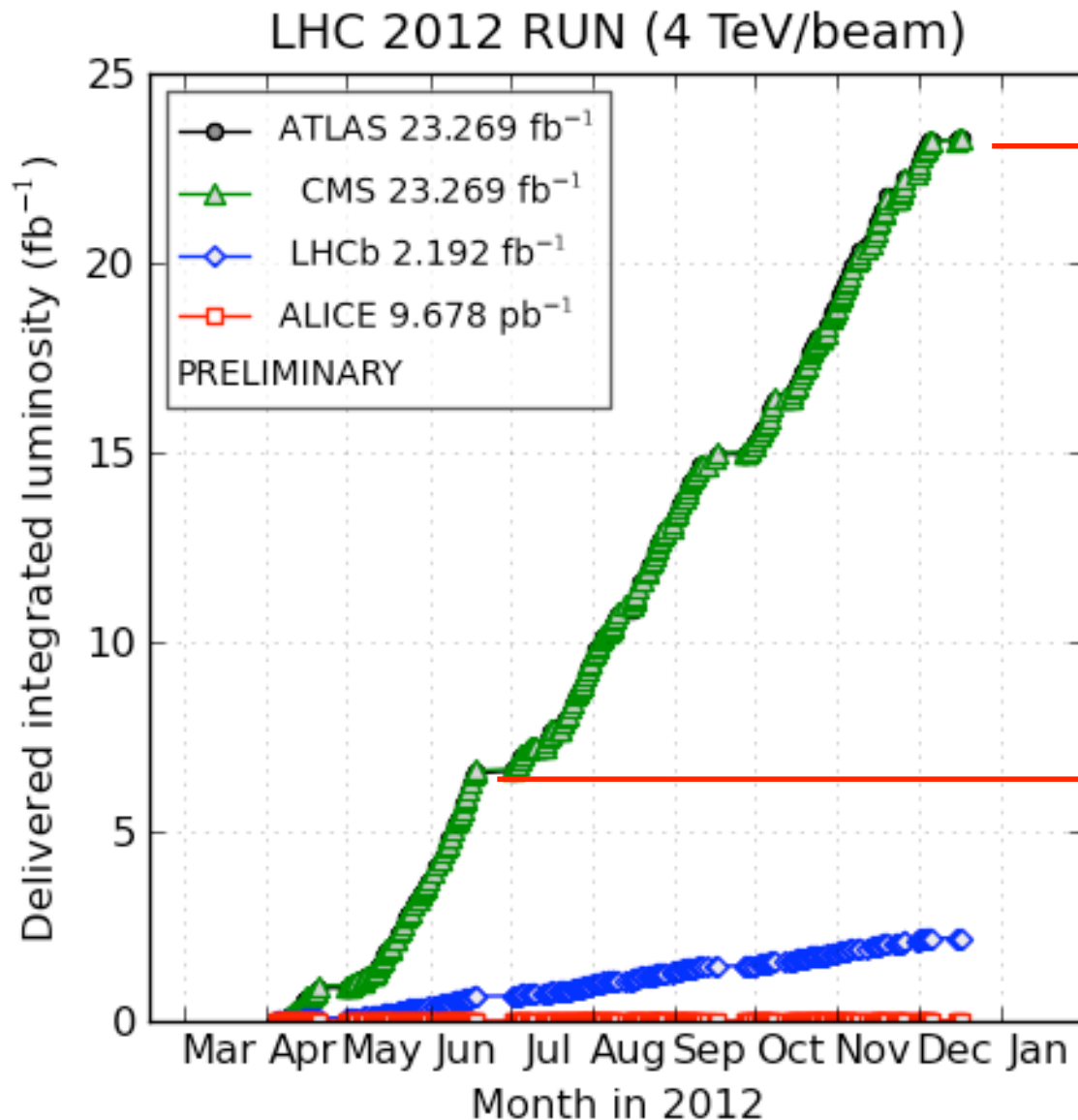
... but this happens on average once per 10,000,000,000 ( $10^{10}$ ) collisions !

# The Higgs boson can decay in two photons

...

but only with a probability of 0.2 %

# The CERN hunt for the Higgs boson



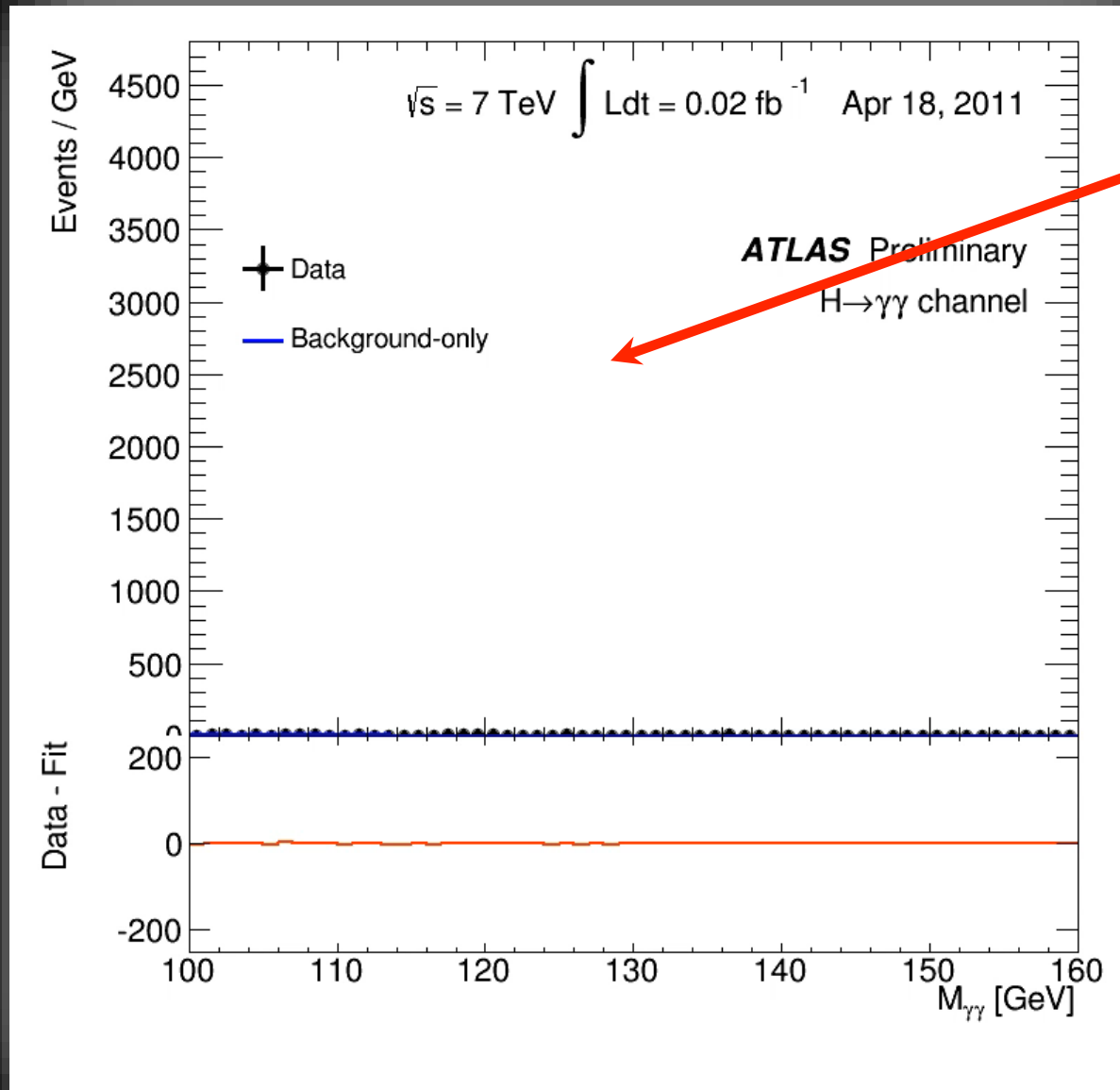
(generated 2013-01-29 18:28 including fill 3453)

15.12.2012

3,000,000,000,000,000 (3·10<sup>15</sup>)  
(3000 trillion events !)

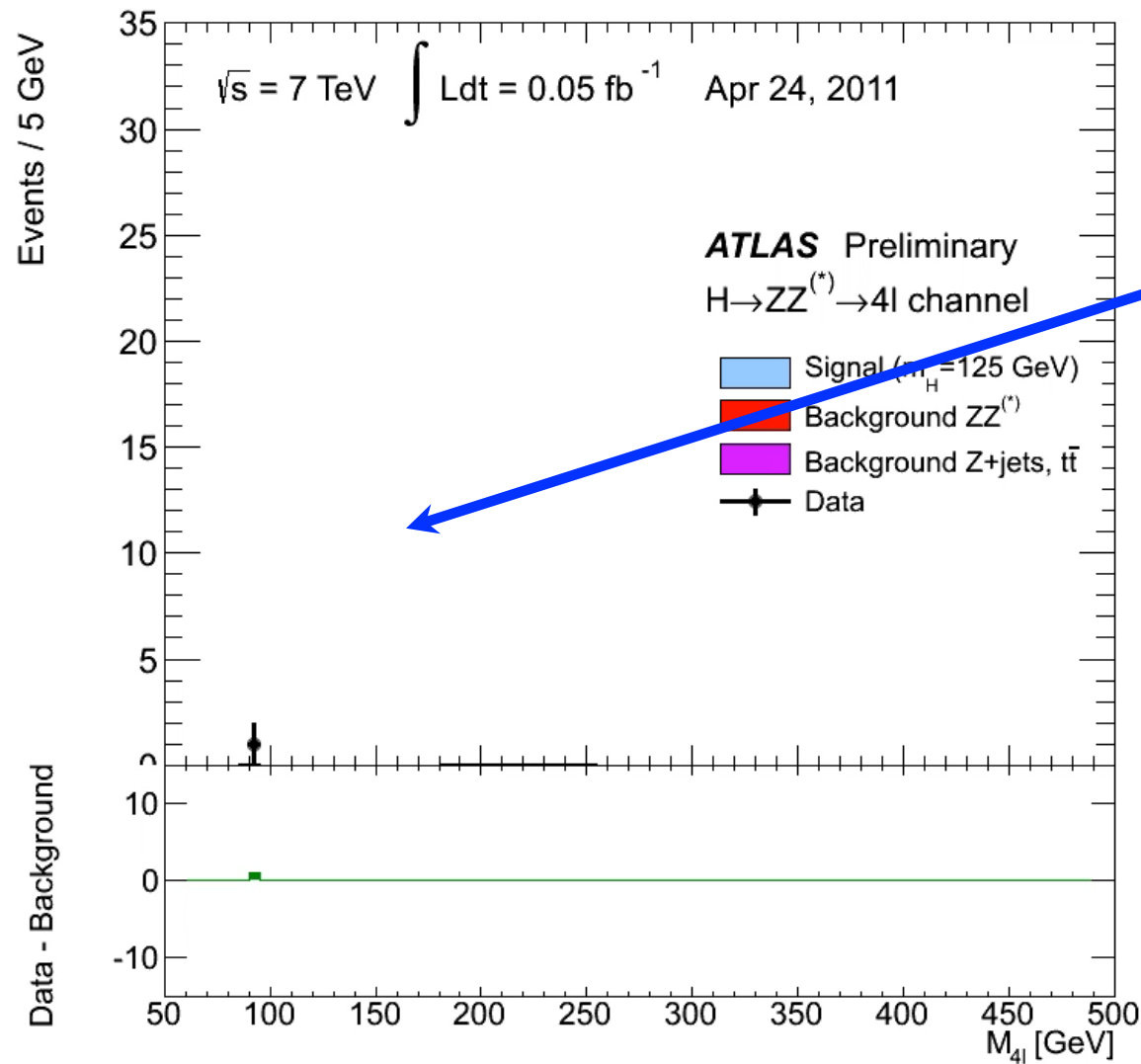
4.7.2012

# The evolution of the histogram with two-photon events



Higgs boson

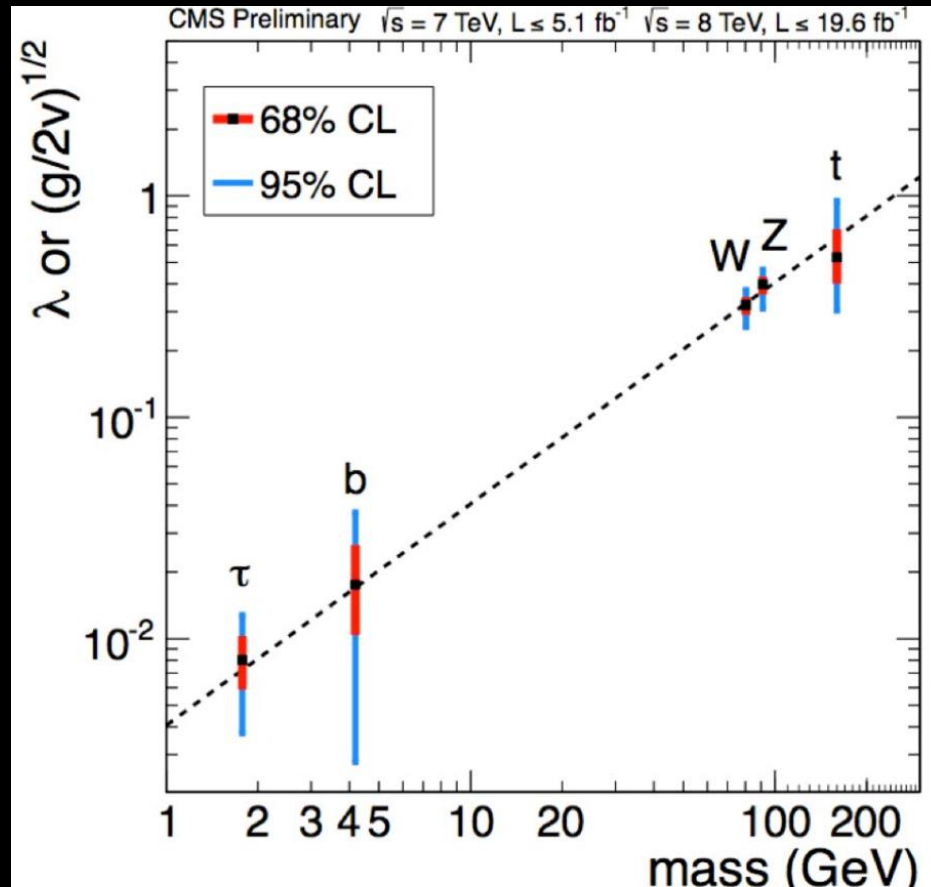
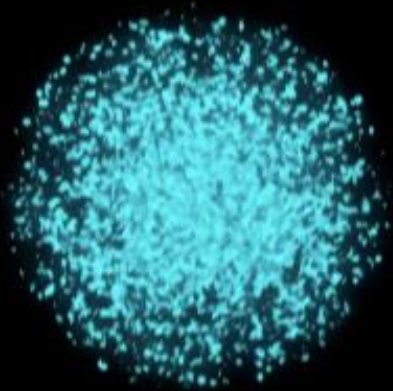
# The evolution of the histogram with four leptons



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?*

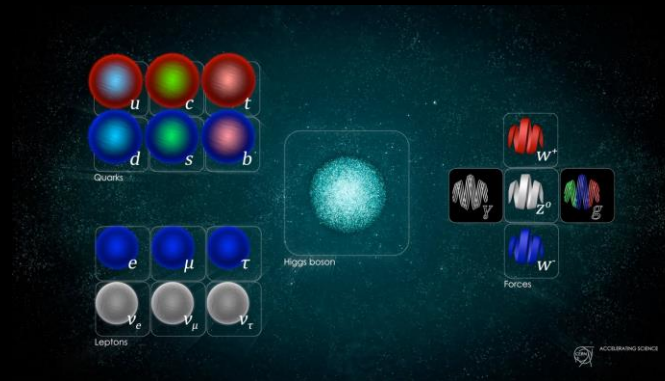
- the Higgs boson exists, therefore ...
- the Brout-Englert-Higgs field exists
- we know how particles obtain their mass
- the “Standard model” is complete

## *Even more:*

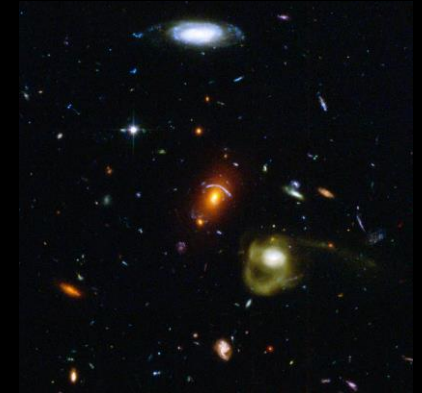
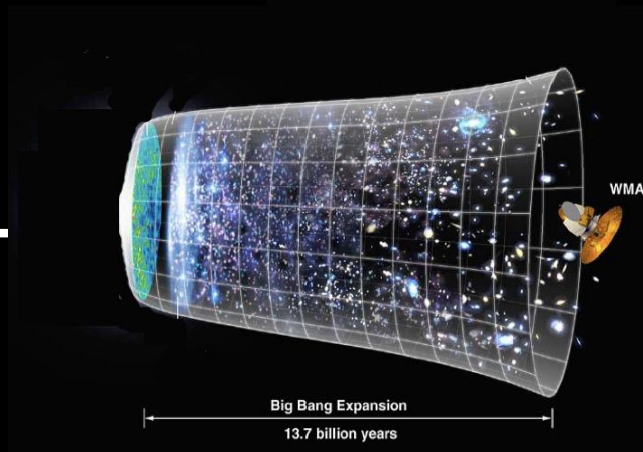
- empty space is not ‘empty’
- perhaps a connection to ‘dark energy’ ?

Particle  
physics

+ Cosmology = Universe ?



+



No !

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

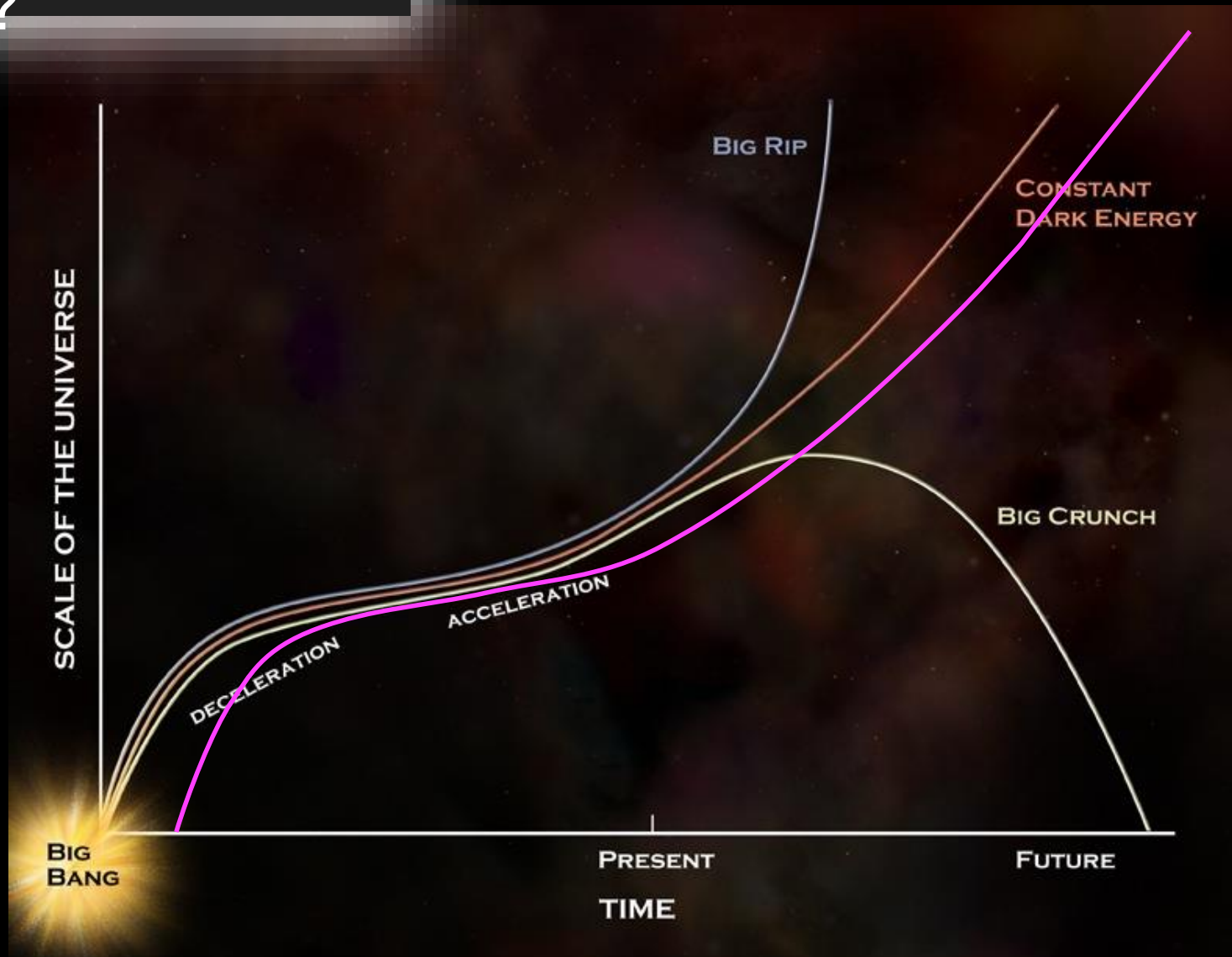
## Dark matter ...?



Galaxies rotate too fast

# Dark energy

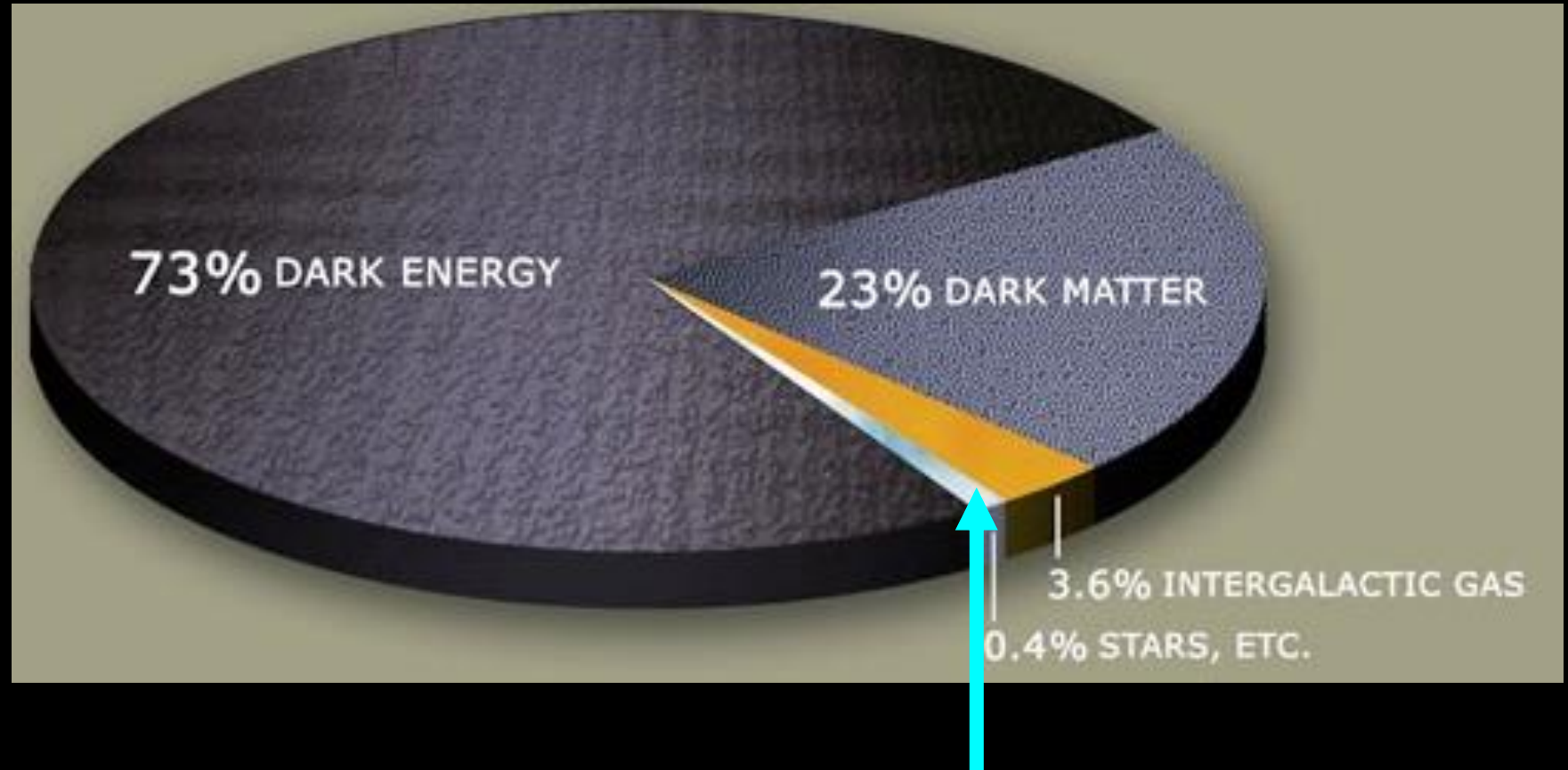
...?



The expansion of the Universe accelerates ...

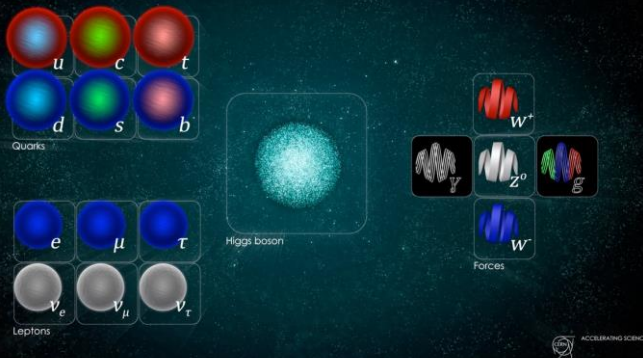


The “dark Universe”: 96 % of its energy content are hidden in ‘dark energy’ and ‘dark matter’



You are here

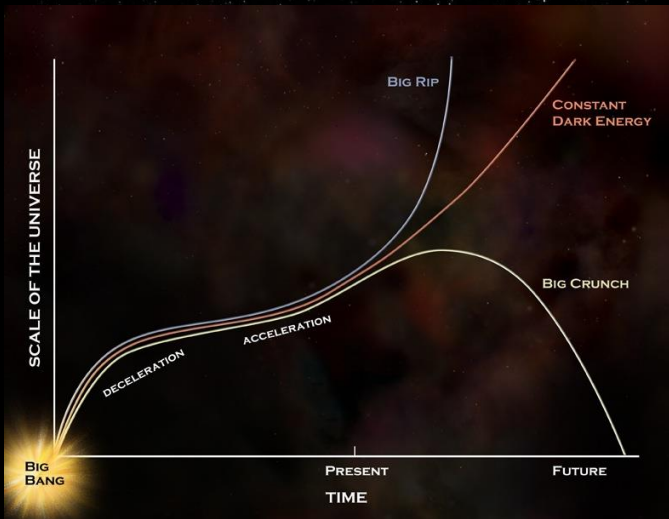
# The big questions:



Is the Higgs boson alone?  
Connection to 'dark energy' ?



What is dark matter?



What is dark energy?

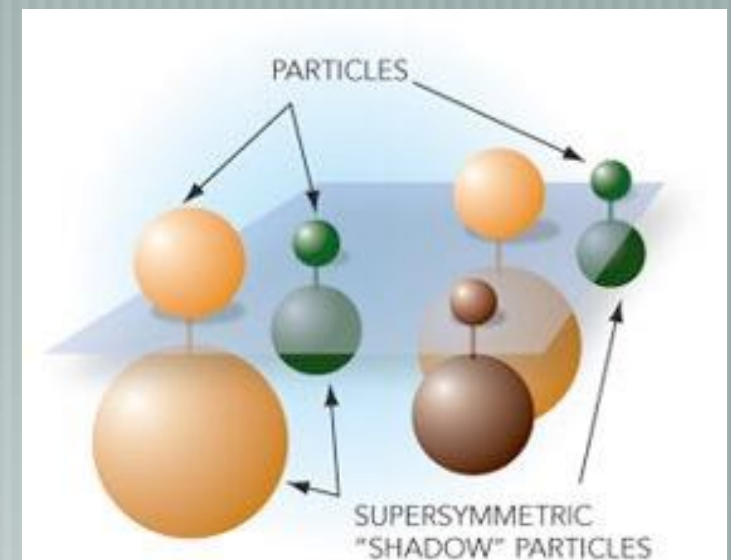
# SUPERSYMMETRY - connection to Dark Matter ?

**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)



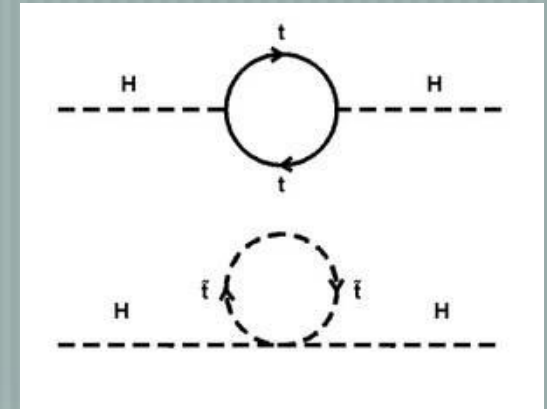
But: no such SUSY partner has ever been seen. So ...  
if they exist, they must have a large mass ( $> 1$  TeV)



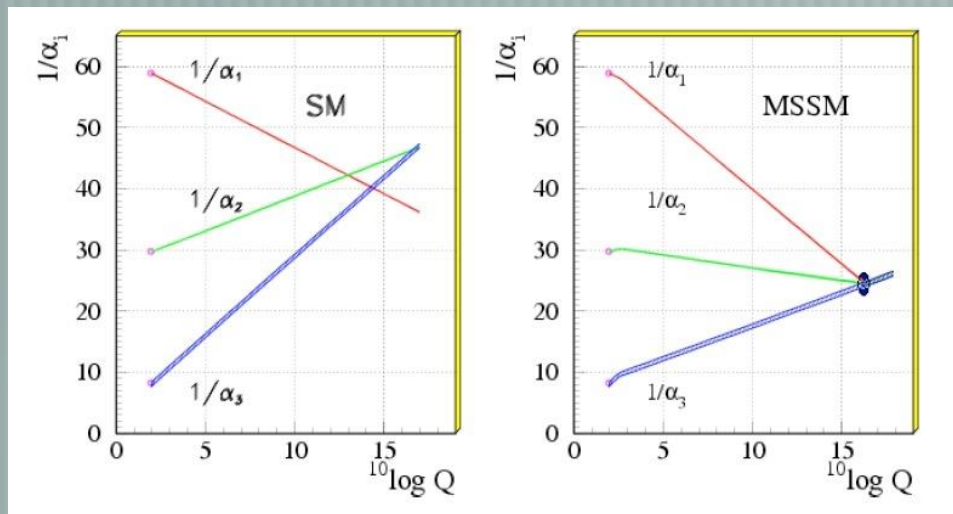
# Why SUSY?

1) A fundamental space-time-symmetry

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



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

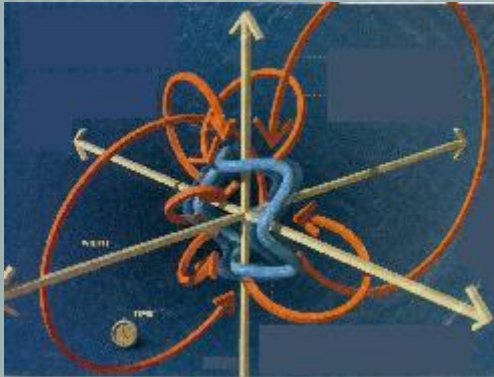


4) May explain the cosmological matter-antimatter asymmetry

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

# MORE MYSTERIES

## What is a particle?



## Superstrings in 9+1 dimensions?

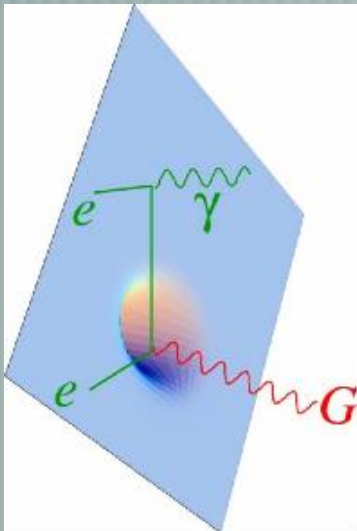
Little strings of string energy vibrating in a 9+1 dimensional space ?

$L \sim 10^{-35}$  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 !**