Particles and Universe

Lecture 8 Symmetry and SM

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I. Theory of elementary particles – role of symmetry

II. Standard Model, generation of mass, Higgs particle

III. P, C, CP symmetry and matter-antimatter asymmetry

GOAL

.. dotrzeć do tych uniwersalnych elementarnych praw przyrody,

z których kosmos może być zbudowany przez czyste wnioskowanie.

I want to know how God created this world. I am not interested in this or that phenomenon.. I want to know His thoughts, the rest are details.

Albert Einstein

Laws and *laws*

Many phenomenological laws like Hooke's law:

… the more force we apply to a metal spring, the more it stretches…F = k x

In 30 XXw → it arises from properties of electromag. interaction in the metal

At the fundamental level we expect

a minimal set of the simplest laws

Beauty in physics = symmetry

„Oh, how ugly" - Einstein on a equation

Paul Dirac (1902-1984)

The beauty of an equation is more important than its correctness, in the sense that if an equation is beautiful, sooner or later it will be demonstrated to be correct.

Herman Weyl (1885-1955)

„Symmetry, as wide or as narrow as you may define its meaning, is one idea by which man through the ages has tried to comprehend and create order, beauty, and perfection.”

H. Weyl, Symetria (Prószyński i S-ka 1997)

Emmy Noether (1882 – 1935)

from L. Molt blog

In April 1915, Emmy Noether was completing her groundbreaking theorem that links conservation laws with the symmetries of Nature.

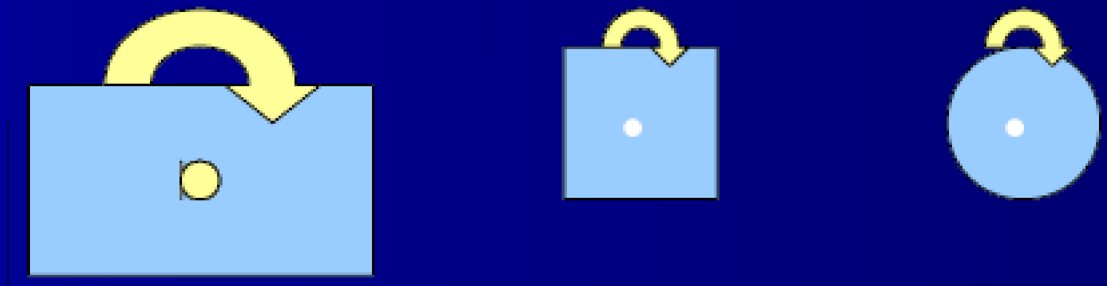
In Spring 1915, Hilbert and Klein invited her to Göttingen... very shortly after she arrived to Göttingen, she proved Noether's theorem (published in 1918).

Fortunately, in 1971, a guy named Tavel translated it to English and in 2005, Frank Wang typed it in and submitted it to the arXiv:
https://arxiv.org/abs/physics/0503066

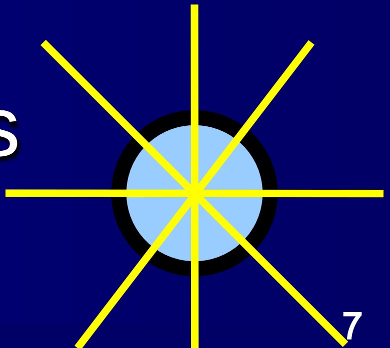
Symmetry or invariance in geometry

Geometrical figure is symmetric, with respect to some operations, if these operations do not change it, eg.

-rotation around origin



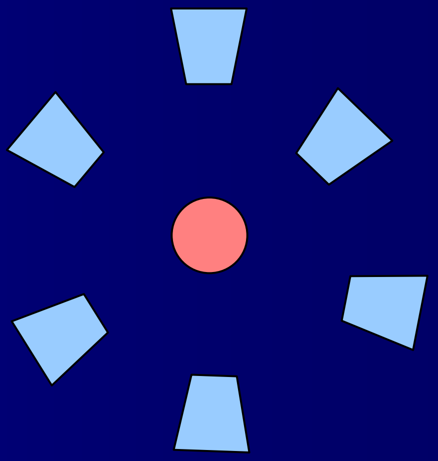
-reflection with respect to planes, lines



Symmetry of laws
- other names: invariance, independence

E. Wigner 1930r – does emission of light by
an atom depends on the direction?

Experiment: detectors around the emitting atom
If the same results
→ spherical symmetry



Similarly, one can consider invariance
of laws on a shift of position or time

Fundamental laws of nature are related to symmetry *Emma Noether, 1918*

- Momentum and energy conservation laws

Related to symmetry (invariance) of *equations of motion* under the transformation of the system:

conservation of momentum - symmetry under space translation
conservation of energy - symmetry under time translation
conservation of anglular momentum - symmetry under rotation

- Electric charge conservation law

related to a symmetry? Later…

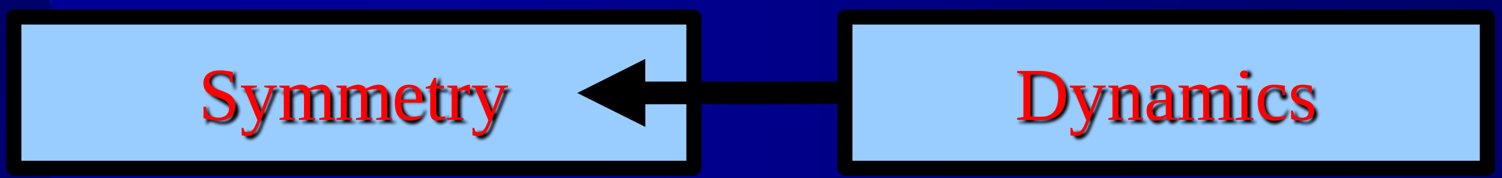
These laws are valid in microworld as well, in addition there are other conservation laws (quantum numbers, like baryonic B)

SYMMETRY

D. Gross

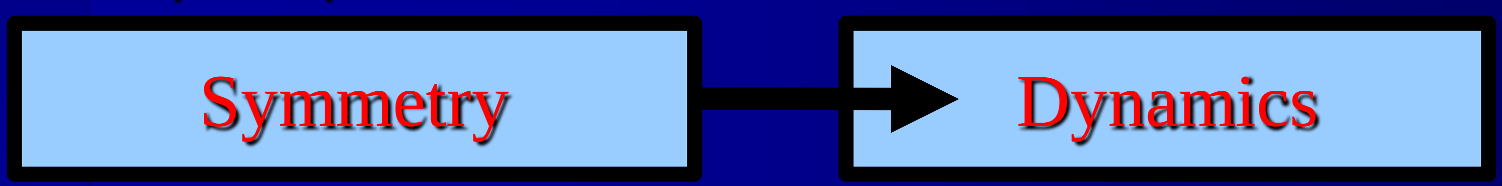
Before EINSTEIN

Symmetry as a consequence of dynamic laws



After EINSTEIN

Einstein realized relativistic symmetry of Maxwell laws (under Lorentz transformation) and promoted it to a symmetry of space-time.



Today: Symmetry is an primary property of nature, which determines possible dynamic laws of nature.

SYMMETRY or INVARIANCE

▪GLOBAL (does not depend on time and space):

Regularity of the laws of motion; global symmetry transformation leads to a different physical situation, but observation are invariant – eg. in laboratory on an orbit the distance between desk and window is constant. Traditional symmetry in nature this type.

▪LOCAL (depands on time, space):

Totally different, related to the laws themselves. Symmetry transformation do not yield to different physical situations. It means on independence on gauge used to measure (gauge symmetry). Observed for el-magn. interaction - for years without consequences ...

Gauge - a standard or scale of measurement: The capacity of barrels was measured according to the gauge in use at the time.

1912-17 symmetry of space-time under local transformation of reference frame → graviation

1968-73 gauge symmetry → electroweak and strong interaction

Weyl – gauge symmetry (1918)

…………… independence on gauge of physical device

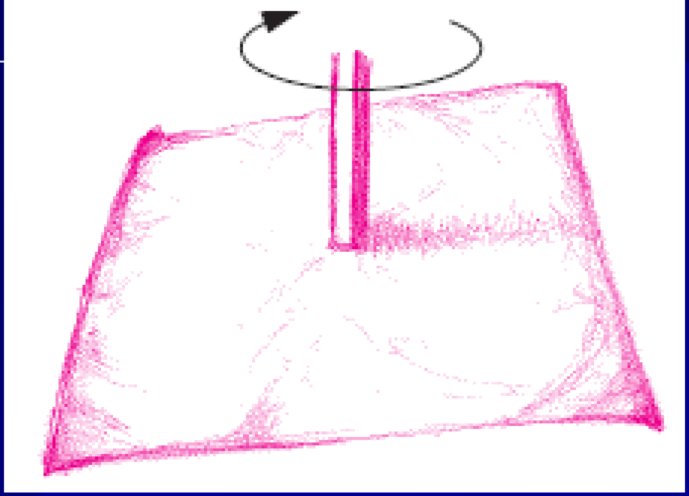
- Global changes of: calendar, temperatur scale, position of zeroth meridian, etc do not change: time distance, heat needed to boil water, time of travel. Profit and loss are fixed, if the money is denominated.

Greenwich

- Situation is totally different if changes are local

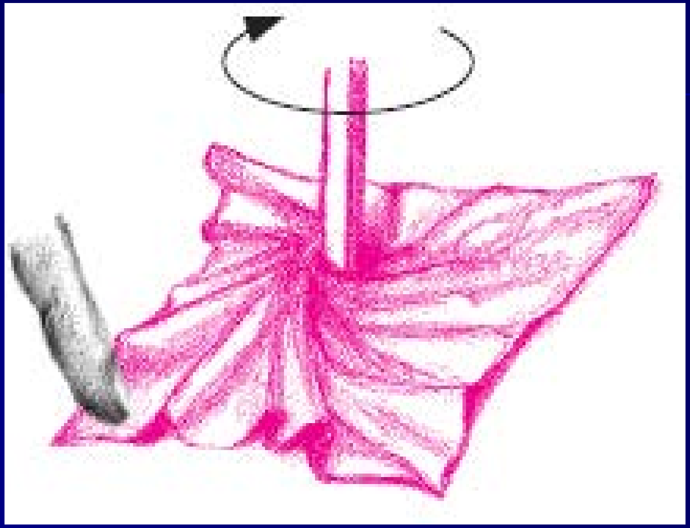
→ eg. speculation if local differences in values

Symmetry
global and local



Rotation of the whole tablecloth – symmetry

Symetria materii-materia symetrii
M. Krawczyk
DELTA 5 (312) 2000



Local rotation around a point - there appear wavelets - they can be removed by force restauring the symmetry…

We need to introduce a particular interaction everywhere
→ massless carriers of interaction – gauge bosons !

Local symmetry for physical systems

- In every case:

  two types of objects and interaction between them

  to ensure symmetry in each point of space

→ only massless carriers of interaction!

- Relation between a type of interaction and particular type of a local symmetry

Gauge principle

Symmetry – main idea in modern particle physics

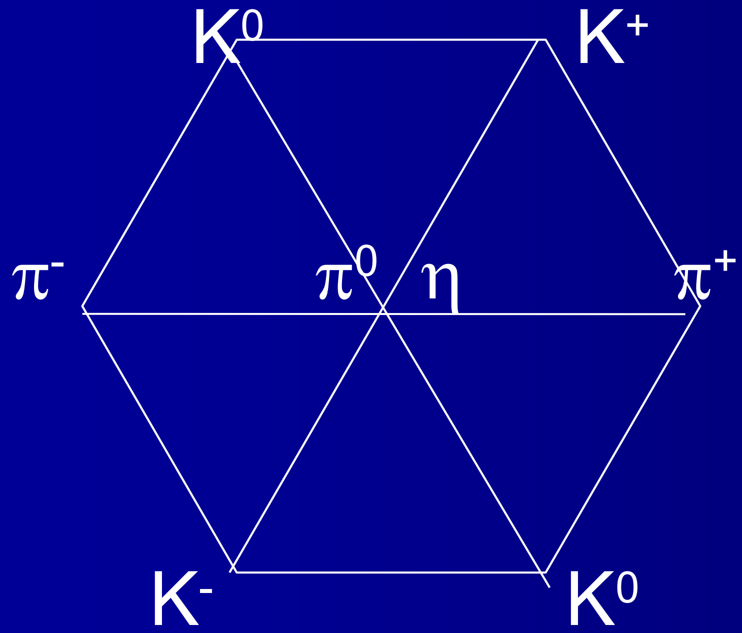
- Earlier used only for classification of particles (-> *multiplets*)
- From 60' XX – also in the description of interaction

Types symmetries:

- Global and local symmetries (Note: if system has a local symmetry then it has also a global one (NOT vice versa)
- Continuous and discrete (under a continuous (eg. rotation over an arbitrary small angle) and a discrete transformation (eg. reflection off a mirror))

Multiplets of elementary particles → quark diagrams

dziwność S



+1

0 η'

-1

isospin I: -1, -½ , 0, ½ , 1

Symmetry and its violation

In physics important are all: exact and approximate, explicite or hidden symmetries

- Exact symmetry

- Violated (broken) symmetry:

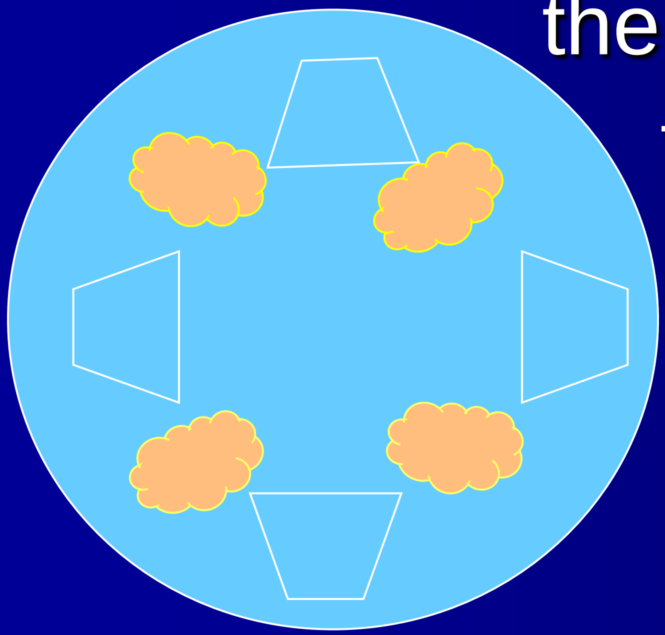
  - dynamically by additional interaction, which does not respect the main symmetry (typically they are weaker → symmetry is approximate)
  eg. isotopic symmetry (p<->n) for nuclear force, is violated by el-mag. interaction

  - spontaneously, when interaction respects symmetry while physical states not (symmetry is hidden).
  eg. gravitational force does not depend on direction but Earth's orbit is not circular .

Spontaneous symmetry breaking- examples

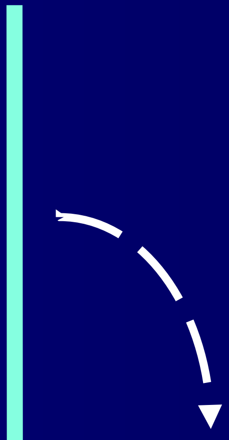
- Sitting around the table : take a cake (left-right?) :   if left

then it forces others to take the left

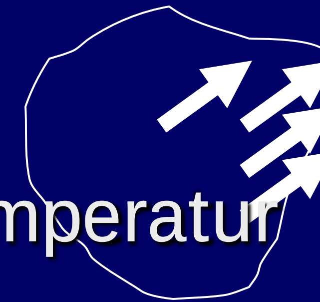


- Vertical stick – where it fall down ?

All direction good, however one is realised



Domens in the metal



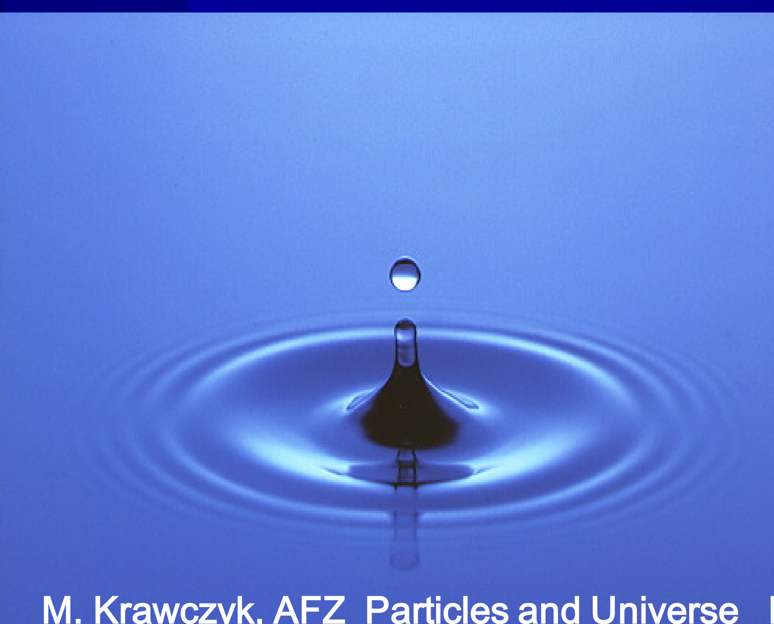
Ferromagnetic has domens below the Curie temperatur in which atoms have the same direction of the magn. dipoles . (Different in the diffrent domens). However there interaction does not depend on direction. In higher temperature domens disappear.

size 10^{-6} m

C. Suplee, Physics in the 20-th century

Spontaneous symmetry breaking

Structure, or smaller symmetry, for lower temperature (smaller energy)



Structure disappers and symmetry grows when temperature rises (higher energy)

Lecture by F. Closa

Gauge principle in theory of particle physics

- QED: invariance of wave function under the local change of phase for the electron **$\psi(x) \to \psi(x)\, e^{\theta(x)}$** → existence of el.- magn field with a massless photon and a particular photon-electron interaction *(a minimal coupling)*

- *Gauge principle* is applied to other fundamental interactions. Invariance of wave function under the local change of phase for the fundamental fermions → there exist gauge fields with gauge bosons: photon, W+/-, Z (*EW interaction*) and gluons (*QCD*).

Description of fundamental interactions – also these beyond the Standard Model - is based on this principle.

Symmetry transformations (groups)

Phase transformations of wave functions constitue a group

there are *rotation group, group of translation..*

E. Noether theorem– with every global, continuous symmetry transformation group there are related conservation laws.

Electric charge conservation – arises from symmetry of el-magn. interaction under change of

a phase $e^{i\theta}$, $\theta \in R$

→ group of unitary transformations U(1)

Fundamental interactions and local symmetries (groups)

- Electromagnetic:

  gauge boson: photon;

  group $U(1)_{em}$ $(U(1)_Q$ *Q – conserved el. charge)*

- Weak (fundamental eg. d $\rightarrow$ u e- antineutrino el.)

  e-m and weak fundamental: unification = electroweak (EW)

  gauge bosons W+,W-, Z and photon γ;

  group $SU(2)_{I\ weak} \times U(1)_{Y\ weak}$ *(I_{weak}, Y_{weak} - conserved quantum numbers)*

  SU(n)- unitary $n \times n$ matricies with determinant 1

- Strong (color);

  gauge bosons – gluons;

  group $SU(3)_{color}$

Electroweak interaction - $SU(2)_{I\ weak} \times U(1)_{Y\ weak}$

I_{weak} – weak isospin (similar to spin ½)
Y_{weak} – weak hypercharge (similar to electric charge)
All fundamental fermions have $I_{weak} = ½$

Relation with el. charge Q: *(similar as for strong interaction)*

$$Q = (I_{weak})_3 + Y_{weak}/2$$

Q, I_{weak}, Y_{weak} - are conserved quantum numbers

$(I_{weak})_3$ = projection of isospin : ½ lub -½
Upper fermions (quarks u,c,t; neutrins) : $(I_{weak})_3 = + ½$
Lower fermions (quarks d,s,b; e-, μ-, τ-) :$(I_{weak})_3 = - ½$

Standard Model

Role of symmetry so large, that we describe a model by writing its groups of symmetry

SM

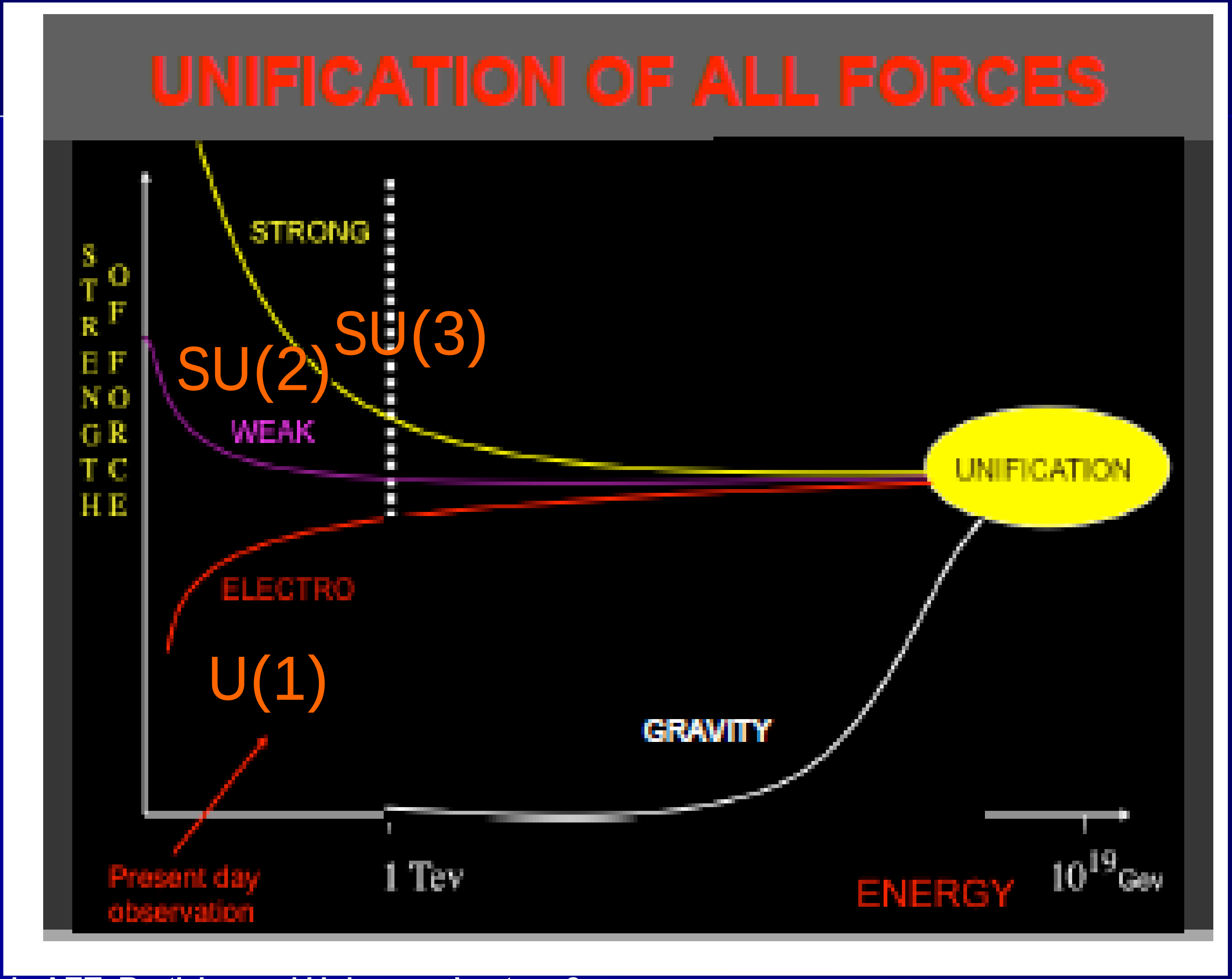
$$SU(2)_{I\ weak} \times U(1)_{Y\ weak} \times SU(3)_{color}$$

Where is $U(1)_{em}$?

in a product $SU(2)_{I\ weak} \times U(1)_{Y\ weak}$

more below

D. Gross, Photon 2005



Local symmetry and mass of gauge bosons

Only massless bosons have an infinite range, however W/Z are massive (80-90 GeV)

We want to have a local symmetry and massive gauge bosons !

HOW?

Massive W/Z

- Massive bosons with spin 1: 3 spin states (-1, 0, +1), massless spin 1 – only 2 (-1 and +1 – as for photon) !
- We need to add fundamental objects
- In SM we add a doublet of spin 0 fields (Higgs doublet)

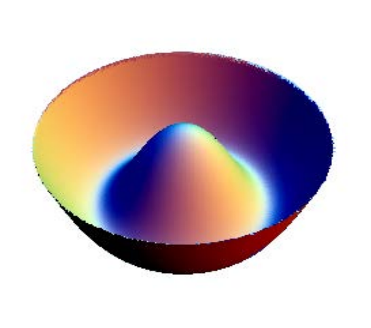
$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

Interacting with W/Z in agreement with gauge symmetry

Spontaneous symmetry breaking $SU(2)_{I\ weak} \times U(1)_{Y\ weak} \rightarrow U(1)_{em}$

Potential energy of the system: the lowest state – a vacuum

Potential for Φ is in the form:



radius – vacuum parametr v

many vacuum states – a symmetry!

Choosing one particular vacuum state – spontaneously breaking of the symmetry $SU(2)_{I\ weak} \times U(1)_{Y\ weak}$ - still the symmetry $U(1)_{em}$ holds !

Mass generation in SM

- Brout-Englert-Higgs (BEH) mechanism ~1964

generation of mass for gauge bosons from SSB

Nobel 2013

- In the Standard Model

→ generation of W/Z mass spontaneously

mass W/Z ~ g v

g- weak coupling and v- vacuum parameter

→ masses of quarks and leptons similarly

(however here there are additional parametres)

Higgs particle

- Field φ^0 can be decomposed

$$\varphi^0 = v + H \quad +..$$

where H – represents particle with spin 0

→ the Higgs boson.

- Remaining fields from Φ used to create spin states for W^+, W^-, Z

(fields φ^0 and φ^+ are complex → 4 degrees of freedom)

Prediction B-E-H → Higgs boson in SM

- Neutral, spin 0, Higgs particle H
- Selfinteraction: λ HHH, λ^2 HHHH
- Mass M= $\sqrt{2\lambda}v$?(unknown); *125 GeV (LHC 2012)*
- Know couplings to bosons to W+/-, Z and quarks and leptons (Yukawa interaction)

→ proportional to their mass

- And such that probability of EW processes not larger than 100% - (danger for energy ~ 300 GeV !)

LHC 4.07.2012

- Higgs particle with mass ~125 GeV observed at ATLAS+CMS

(+Tevatron)

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

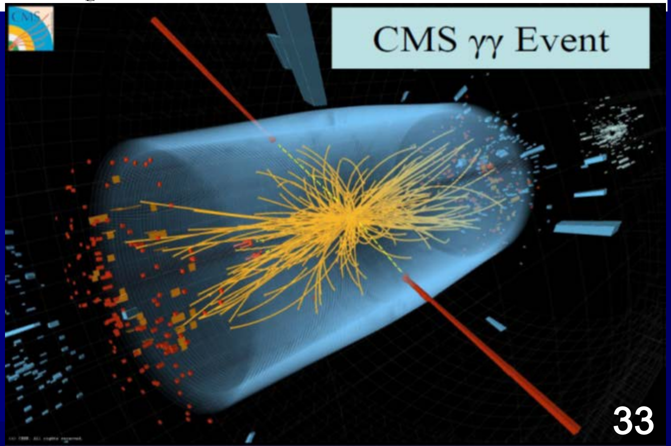
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
ceived 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

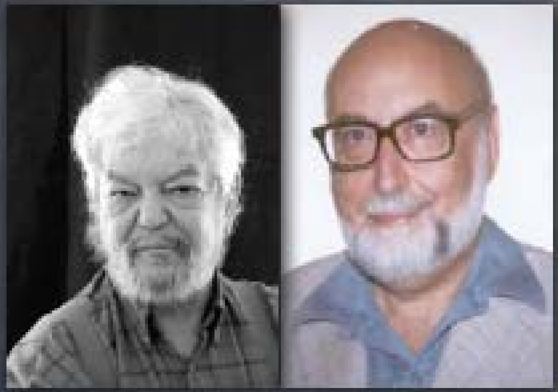
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



Important loop couplings ggH,$\gamma\gamma$H

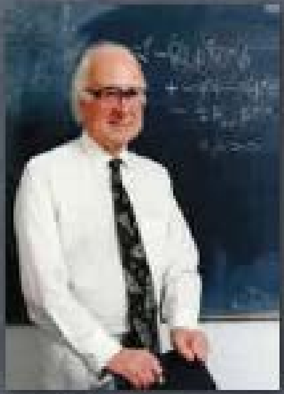
2010 Sakurai Prize

… for "elucidation of the properties of spontaneous symmetry breaking in four-dimensional relativistic gauge theory and of the mechanism for the consistent generation of vector boson masses."



Brout Englert

PRL 13, 321-323 (1964)



Higgs

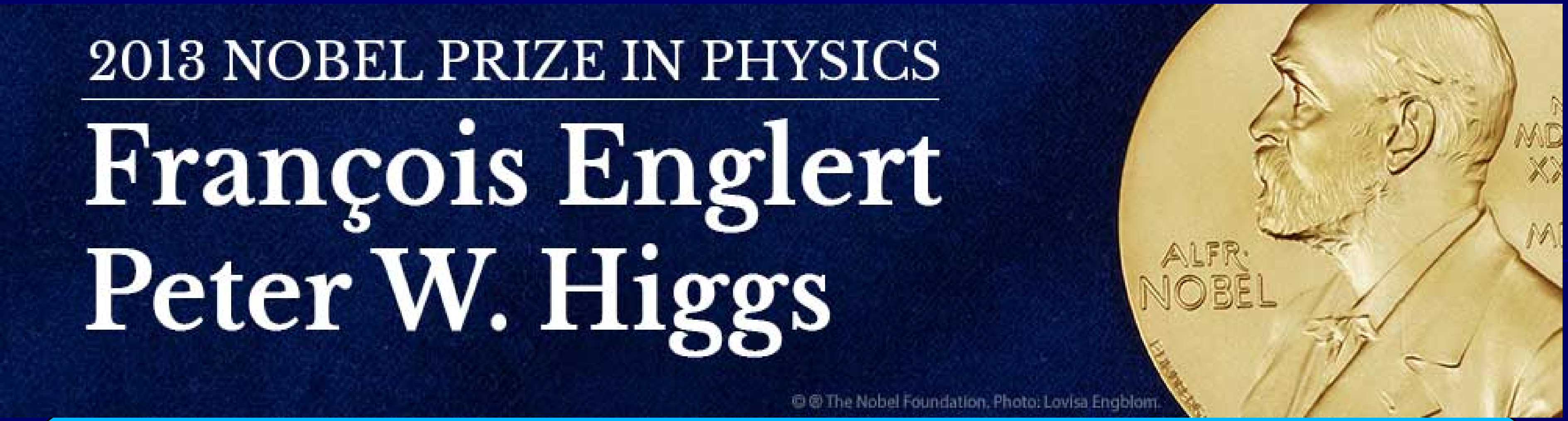
PRL 13, 508-509 (1964)

Hagen Guralnik Kibble

PRL 13, 585-587 (1964)

Nambu, Nobel 2008
For introduction of SSB to particle physics

Ben Kilminster, ICHEP 2010 4



The Nobel Prize in Physics 2013

François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Yoichiro Nambu
NOBEL 2008

For introduction of SSB to particle physics

Spontaneous symmetry breaking was known in solid state physics

He was a visioner... *From http://mag.uchicago.edu/nambu*

I had the idea that if I can find out what Nambu is thinking about now, I'll be 10 years ahead in the game. So I talked to him for a long time. But by the time I figured out what he said, 10 years had passed.

Bruno Zumino (University of California, Berkeley)

Discrete symmetry P, C, CP...

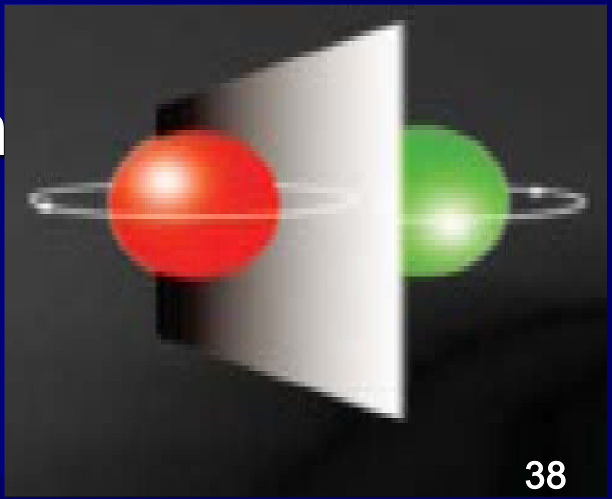
Weak interaction sensitive to spin states of particles

Particle with spin ½ has two spin states + ½ i - ½ →
R (right) and L (left) particles

Weak interaction only between left states !

Yang-Lee 1956
Wu 1957

It means that weak interaction is not symmetric under space reflection (P symmetry, P - parity) which corresponds to L ↔ R



P, C and CP in the EW interaction

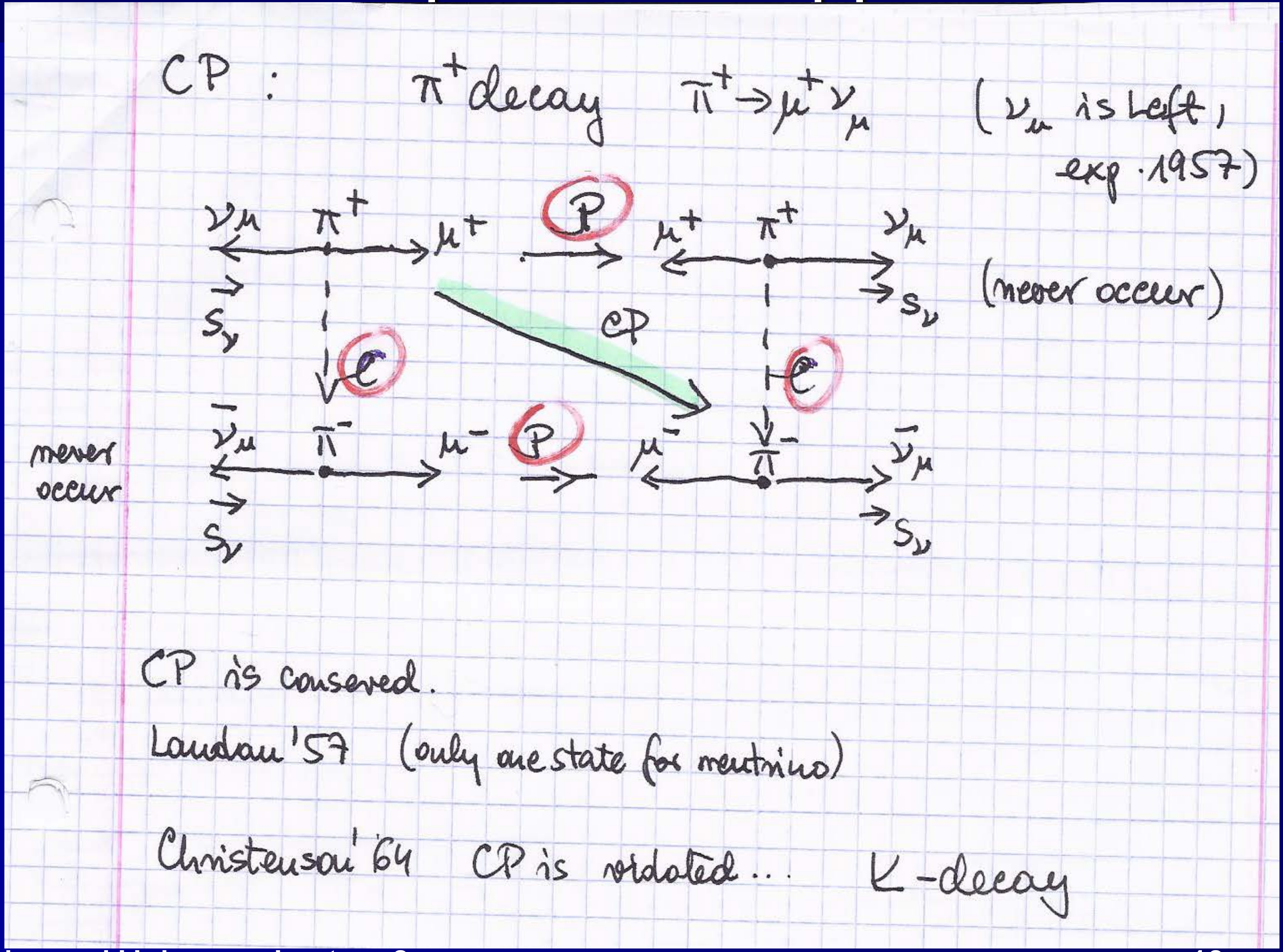
Weak interaction – less symmetry

- P symmetry (reflection): L $\leftrightarrow$ R violated!
- C symetriy (charge conjugation): transforms of a particle to an antiparticle (el. charge to opposite) violated! C transforms neutrino L into antineutrino L, but in nature* antineutrino only right R
- Combined symmetry CP (combination of reflection and charge conjugation) transforms L neutrino to R antineutrino – OK! *Landau 1957*
- CP is almost conserved (violation 10^{-4})

- *Almost* makes difference → a lack of matter-antimatter symmetry in the Universe!

SM: decay $\pi^+ \rightarrow \mu^+ \nu_\mu$

ν left : momentum and spin vector opposite



Kobayashi and Maskawa

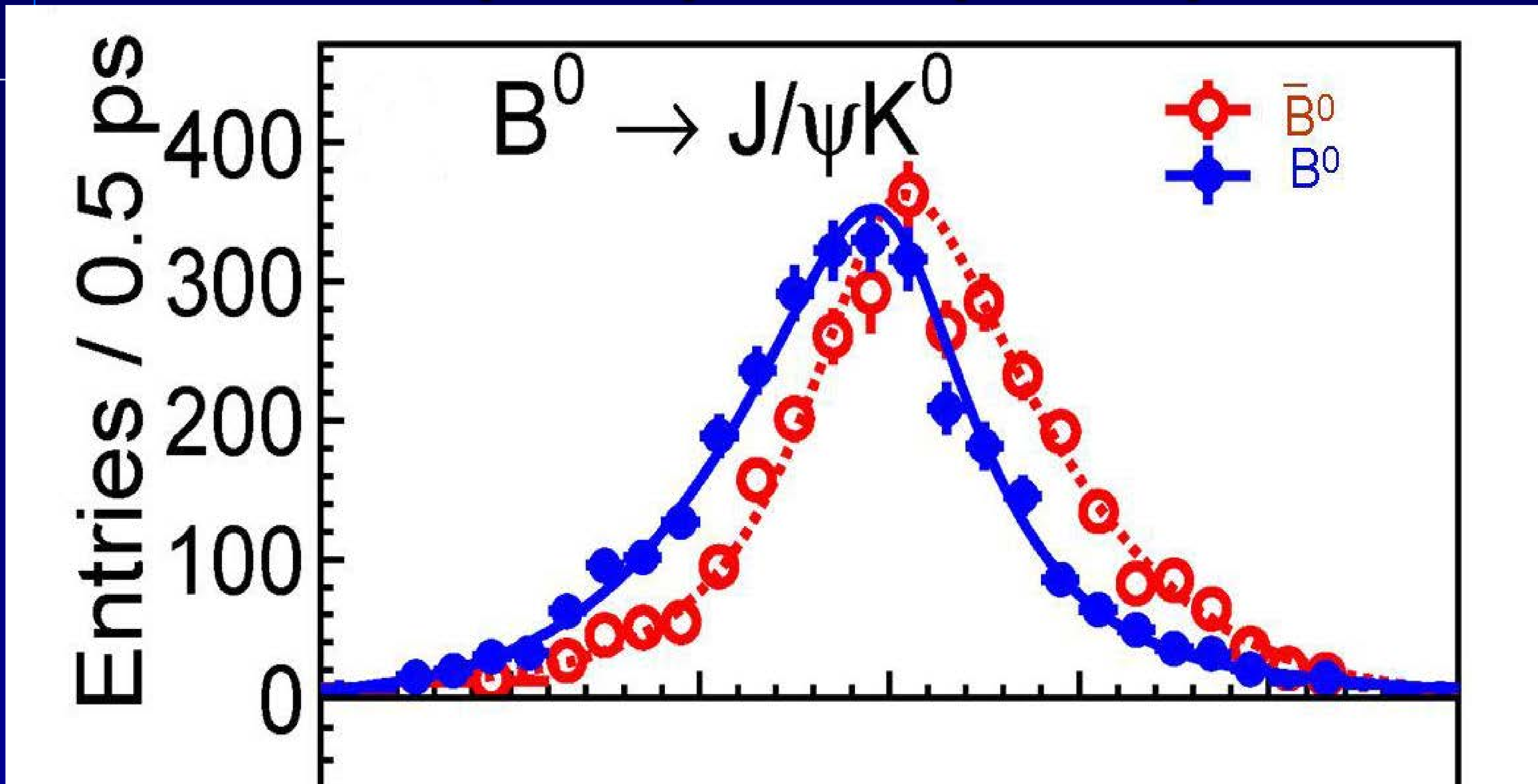
Nobel' 2008

<u>**For explaining SSB for matter-antimatter - CP violation**</u>
in K meson (s quarks) decays in experiment by Fitch-Cronin (1964)

Kobayashi i Maskawa showed in 1973 that broken of CP can appear if in the nature there exist <u>3 pairs of quarks.</u>
Then known were only u, d and s quarks. Discovery in 1977 r. of the b quark from the 3 generation confirms the Kobayashi – Maskawa conjecture.

Full confirmation came when broken CP (eg. difference in decay of particle and antiparticle) observed in b systems.

Asymmetry in decays of mesons: B ($d\ \bar{b}$) i $\bar{B}$($\bar{d}$ b)



Discover:

2001r asymmetry for B mesons (SLAC USA,KEK Japon)

2011r –”– for D mesons (c quarks) (CERN, Europe)

MATTER - ANTIMATTER

- Asymmetry in matter and antimatter in the Universe
- Sacharow's postulate ~1960:
  At beginning of the Universe – symmetry of matter and antimatter , but if C and CP symmetry is broken there may appear a small dominance of matter over antimatter
- In expansion – this small effect yields a present day situation - where antimatter is produced only in the laboratory and in cosmic rays.

more later…

Standard Model
in agreement with experiment

Problems to lecture 8

- Give two examples of continuous transformations
- Does a global symmetry is a consequence of a local one, or vice versa?
- Is a local symmetry the same as a gauge symmetry?
- Does the symmetry dictate the dynamics ?
- Noether theorem describes ...?
- Does the gauge principle apply only to the Standard Model?
- Give two examples of spontaneously symmetry breaking (from every day life)
- How many spin (polarisation) states has massive Z boson ?
- Does in the weak interaction participate a right electron ?
- Spin of Higgs particle is equal to ?
- Is Higgs particle interaction stronger with more massive particle?
- Do Higgs particles interact with themselves ?
- Why is was difficult to find a Higgs particle?
- For what Y. Nambu got the Noble prize?
- What the Sacharow postulate is telling?