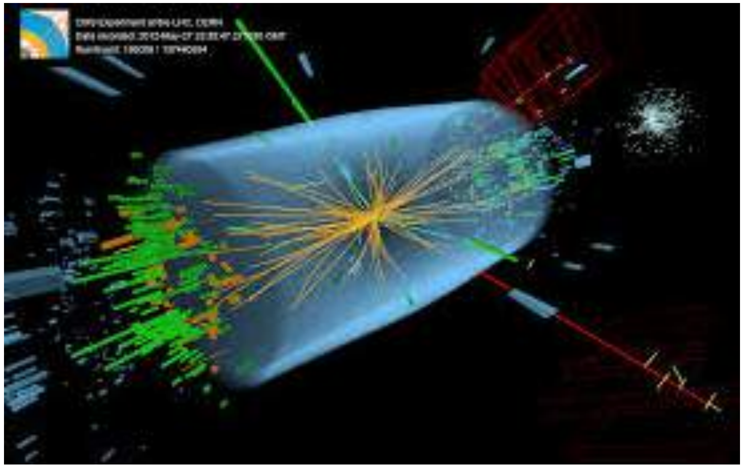
CERN Experiments



Kerem Cankoçak

Near East Un. 26.07.2019

Outline

- Brief Introduction to CERN
- Reminder of Standard Model
- Brout-Englert-Higgs Mechanism and Spontaneous Symmetry Breaking
- Discovery of Higgs Boson at CERN, LHC experiments
- What is next?

Review of Standard Model

Standard Model is

- an effective theory
- A chiral theory
- A gauge theory
- Brout-Englert-Higgs mechanism is not a direct implication of SM ➔ Spontaneous Symmetry Breaking

CERN (www.cern.ch)

“Conseil Européen pour la Recherche Nucléaire

The CERN convention was signed in 1953 by the 12 founding statesBelgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and Yugoslavia, and entered into force on 29 September 1954.
The Organization was subsequently joined by Austria (1959), Spain (1961-1969, re-joined 1983), Portugal (1985), Finland (1991), Poland (1991), Czechoslovak Republic (1992), Hungary (1992), Bulgaria (1999), Israel (2014), Romania (2016) and Serbia (2019). The Czech Republic and Slovak Republic re-joined CERN after their mutual independence in 1993. Yugoslavia left CERN in 1961.

Curiosity Discovery Technology Engineering Knowledge

CERN'e üyelik ve gözlemcilik

CERN has 23 Member States: Austria, Belgium, Bulgaria, CzechRepublic, Denmark, Finland, France, Germany, Greece, Hungary, Israel, Italy, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and United Kingdom.

Cyprus and Slovenia are Associate Member States in the pre-stage to Membership. India, Lithuania, Pakistan, Turkey and Ukraine are Associate Member States.

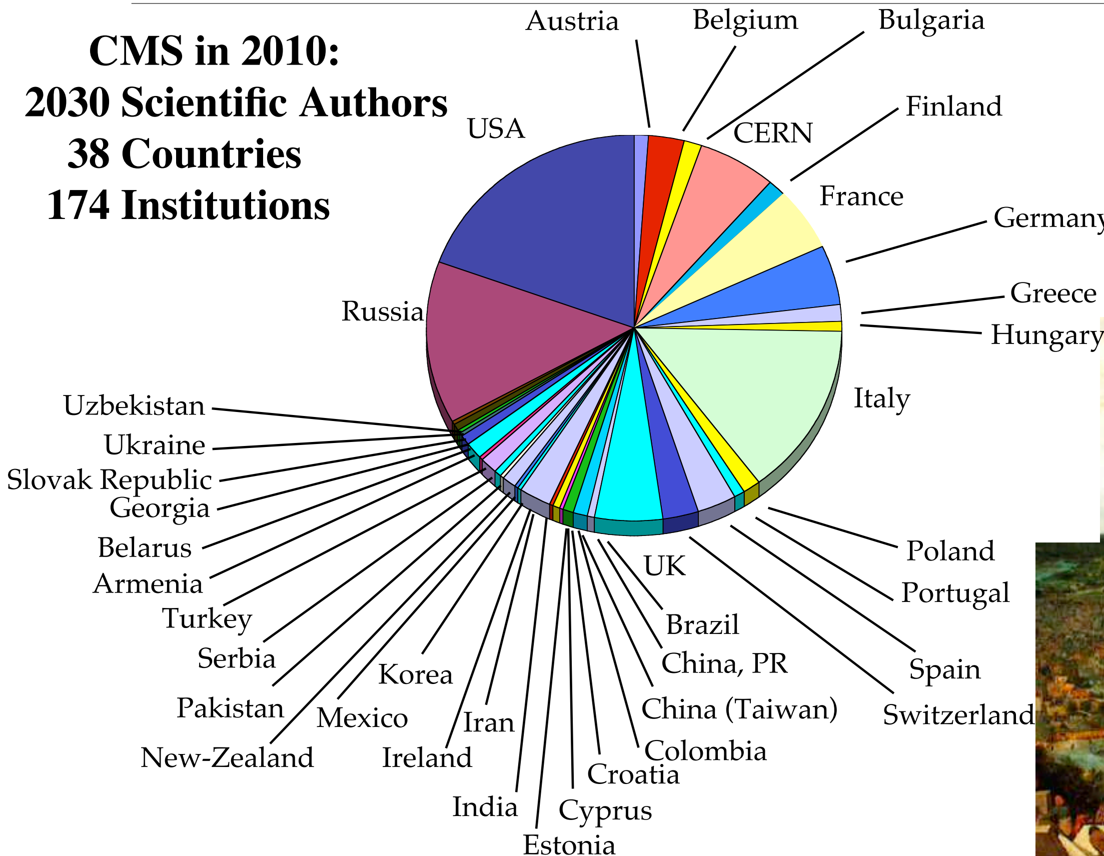
The European Union, Japan, JINR, the Russian Federation, UNESCO and the United States of America currently have Observer status.

Cooperation between nations, universities and scientists is the driving force behind CERN's research.

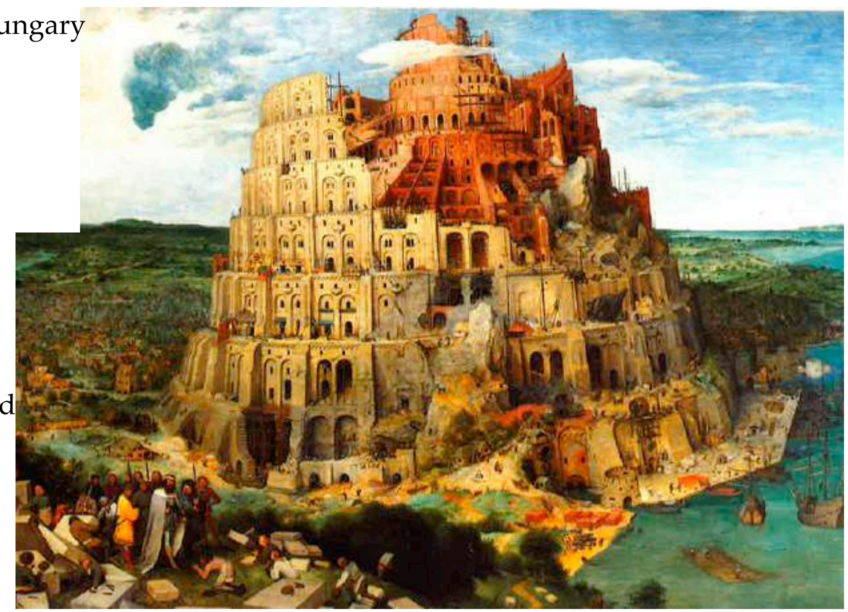
As of 2017, more than **17 500** people from around the world work together to push the limits of knowledge. CERN's staff members, numbering around **2500**, take part in the design, construction and operation of the research infrastructure. They also contribute to the preparation and operation of the experiments, as well as to the analysis of the data gathered for a vast community of users, comprising **over 12 200** scientists of **110 nationalities**, from institutes **in more than 70 countries.**

If these totally globalized experiments did not stall as Babel's Tower did, was due to…….

CMS in 2010:
2030 Scientific Authors
38 Countries
174 Institutions



Breughel,Kunsthistoriches museum,Wien



……..everybody using the metric system (no inches, feet, yards, pounds, imperial gallons etc)……..and the use of english!

Homo sapiens-sapiens has a propensity to build circular structures - and made some progress over past 11.000 years!

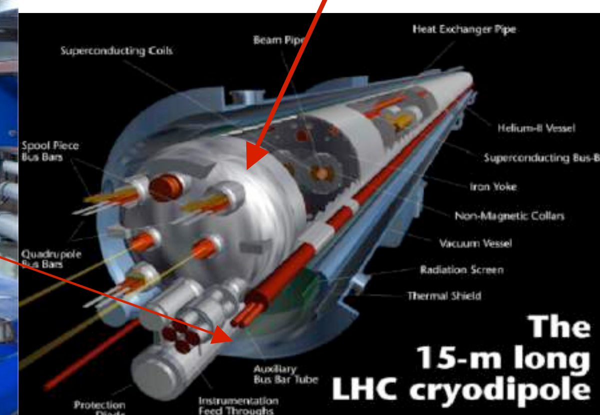



Goebekli-Tepe, ~ 9000 BC, Sanli-Urfa/Turkish-Syrian border, 2012

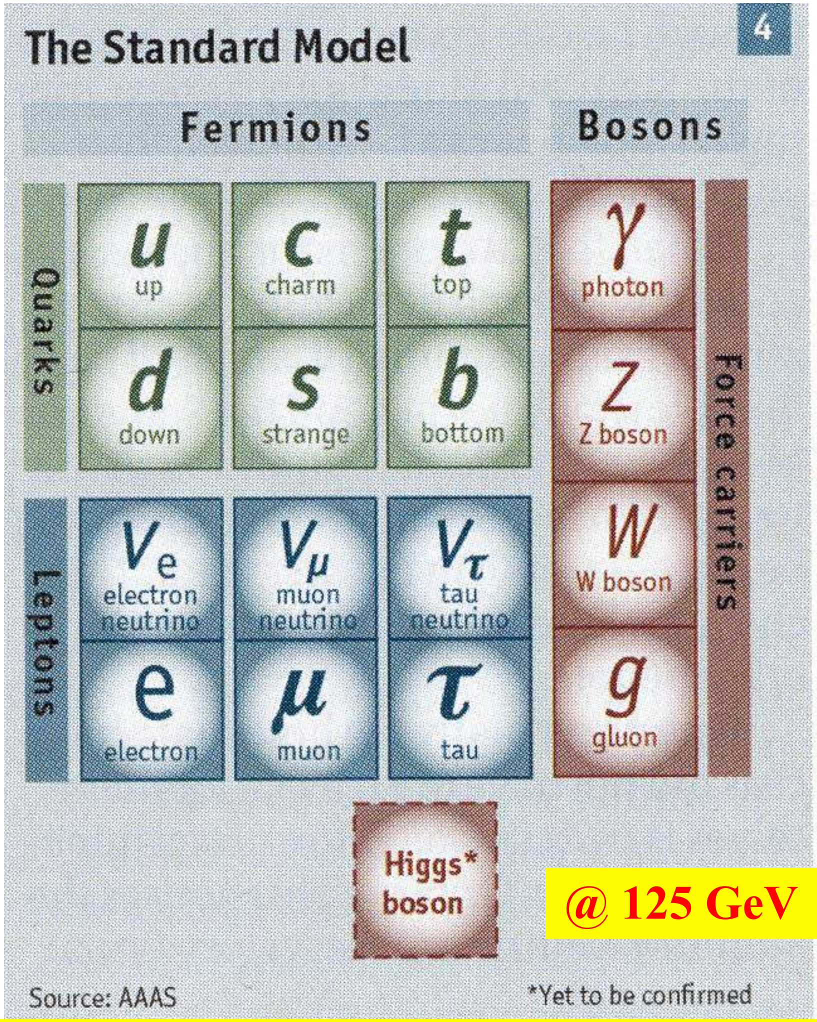
Result of activities of homo sapiens sapiens scientificus, Geneva, French-Swiss border,~ AD 2000

key elements



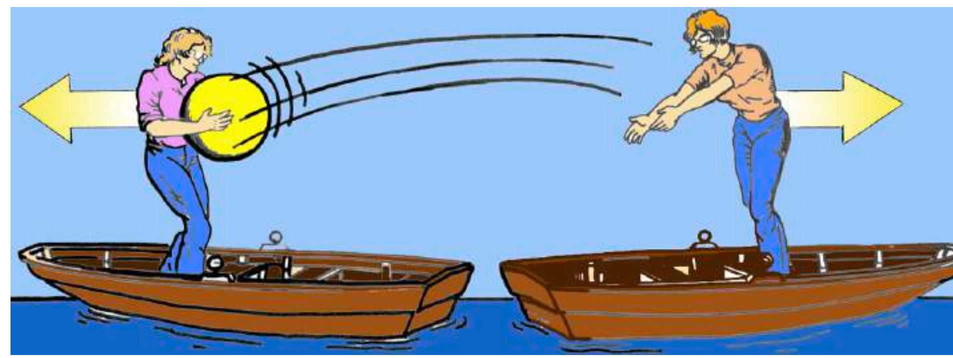


The Universe as we know today



@ 125 GeV

Four fundamental forces:
- Gravitation
- Weak
- Electromagnetic
- Strong



But this was not the case always.
This picture is a result of a **broken symmetry**

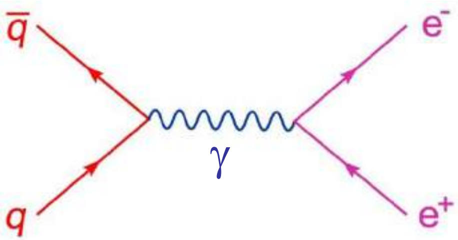
Particles have mass. Particles would have no mass…but they have, thanks to BEH mechanism

Some important concepts of particle physics

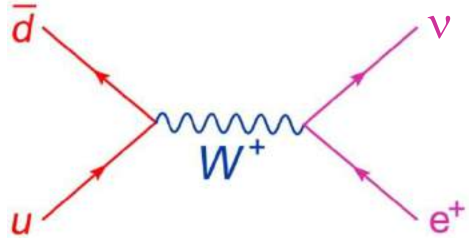
- No real vacuum due to uncertainty principle

$$\Delta x \Delta p \geq \frac{h}{4\pi} = \frac{\hbar}{2}$$

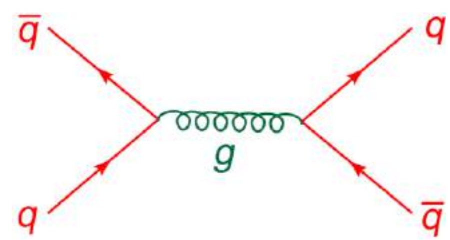
- Decay & fields



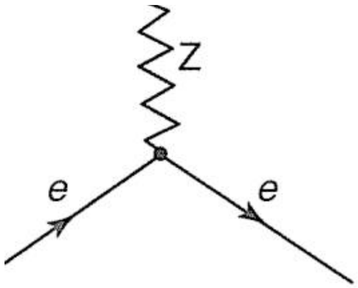
electromagnetism (QED)



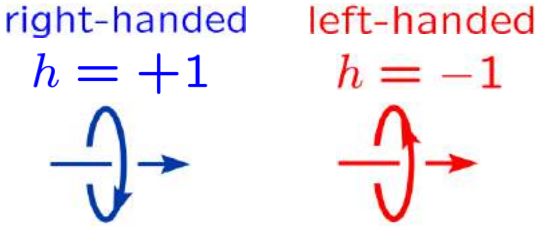
weak



strong (QCD)



Handiness (Chiral theory)
Weak hyper charge of $e_L = 1$;
Weak hyper charge of $e_R=0$



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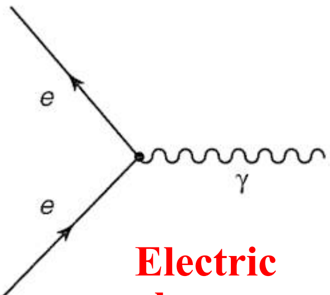
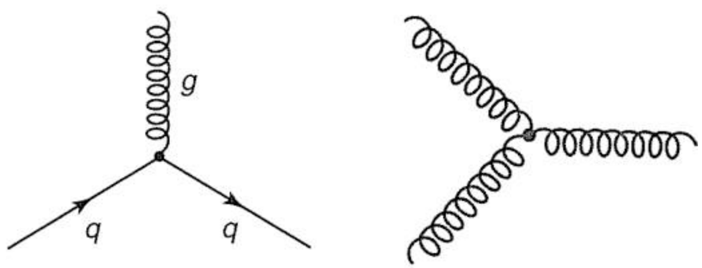
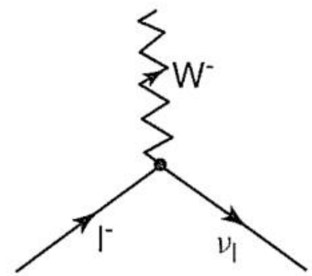


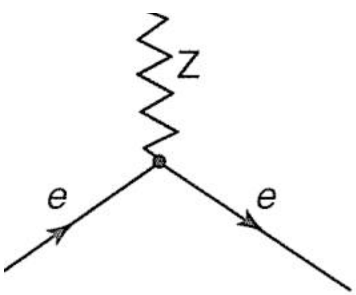
Electric charge



color charge



Weak hyper charge



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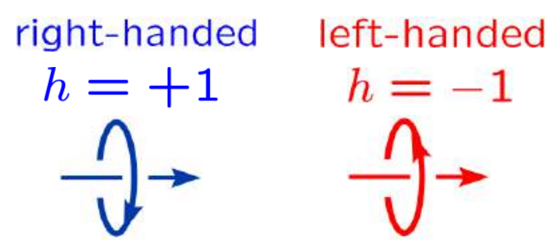
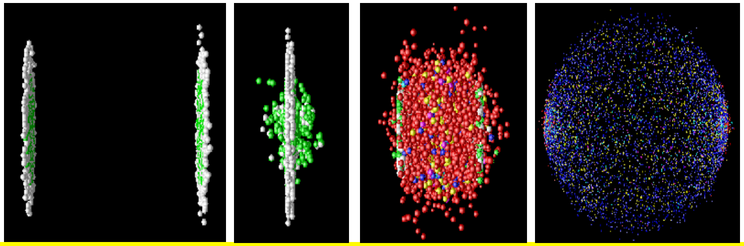


Energy=matter

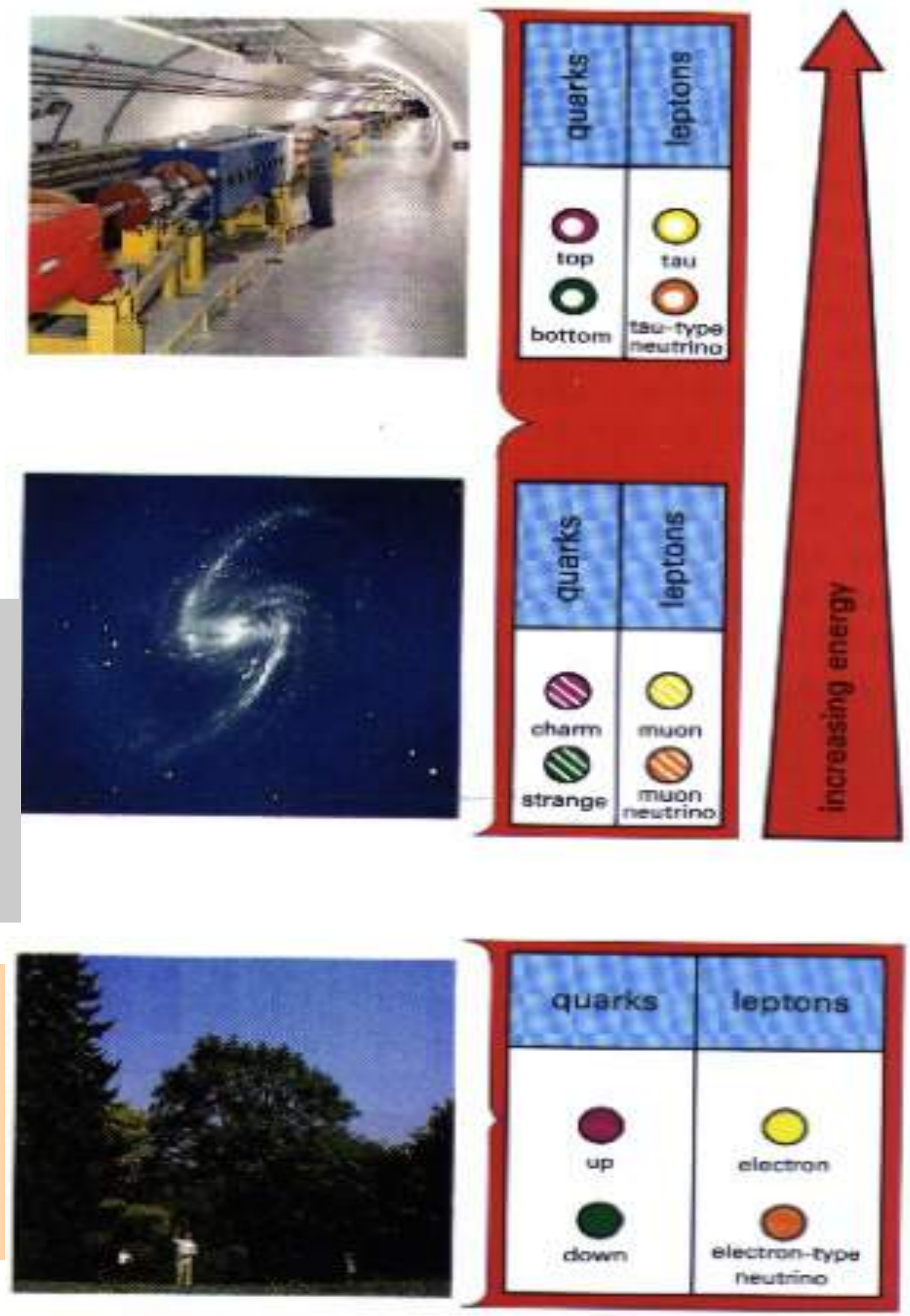


Everything around us consist of 3 fundamental particles:

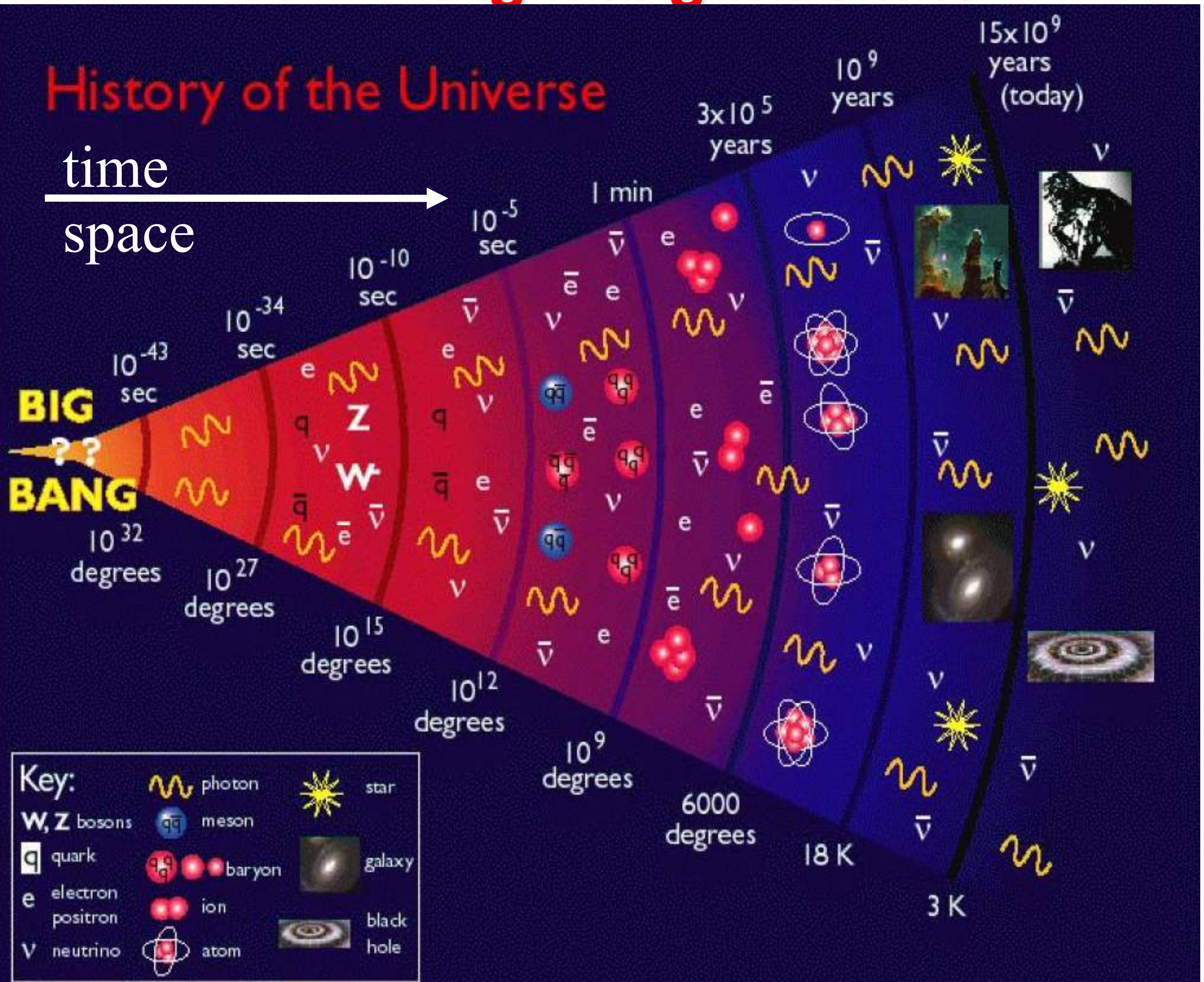
electron
u quark
d quark

But there are infinite number of other particles: 2 more leptons and combined particles (combinations of 2 or 3 quarks)
But they decay to stable particle very fast

Every particle has an anti-particle (opposite quantum number; opposite charge,..).
In total 6 quarks (and 6 anti-quark) ,
6 leptons (and 6 anti-leptons)



Big Bang Machine



Space-time started

~13.7 billion years ago

In the first nanoseconds, all forces (gravitation, electroweak and strong) were **unified.** They are seperated as the universe became colder

In the beginning of time, when the Universe was getting colder, the energy transformed to matter

--> Matter-anti matter symmetry breaking

--> subatomic particles

--> baryons, mesons

--> Nucleo synthesis

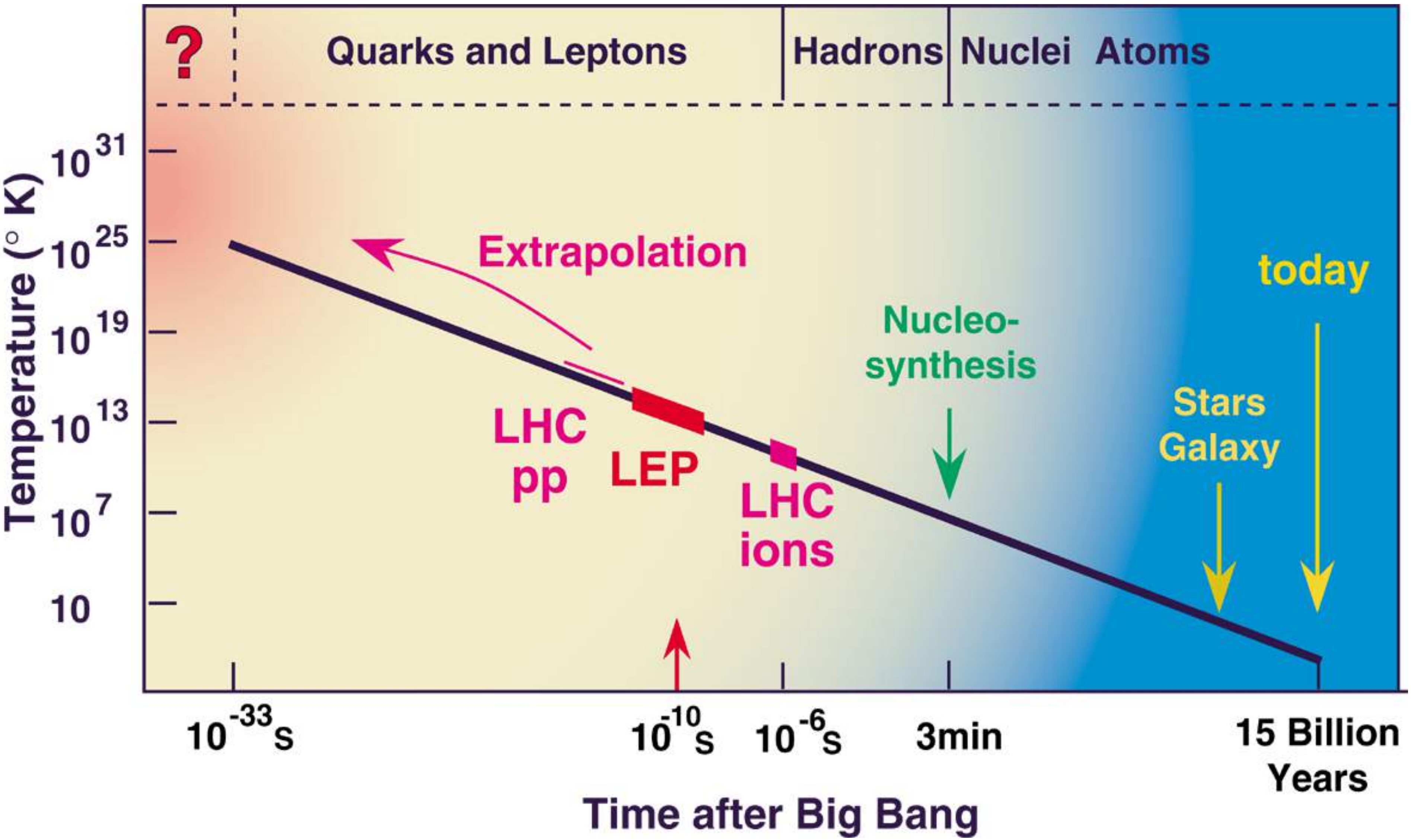
--> transperant universe (CMB)

It looks like everything is going from kaos to order, but on the contrary!

Electron, proton --> hydrojen atom ---> stars --> heavy atoms

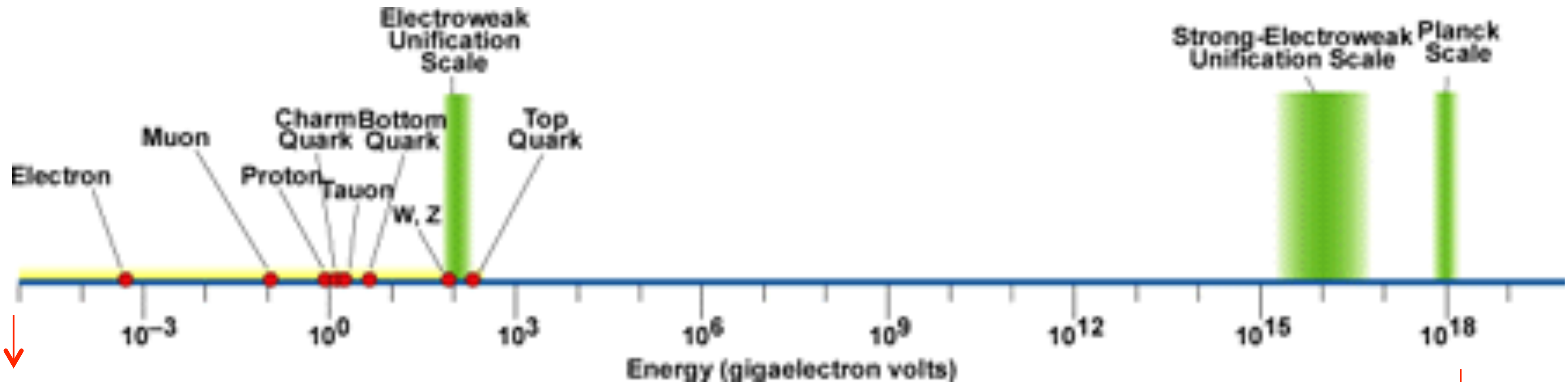
Supernova --> our sun --> earth --> life

(entropy is lowered due to the local energy sources)



(Kerem Cankoçak, Aralık 2008)

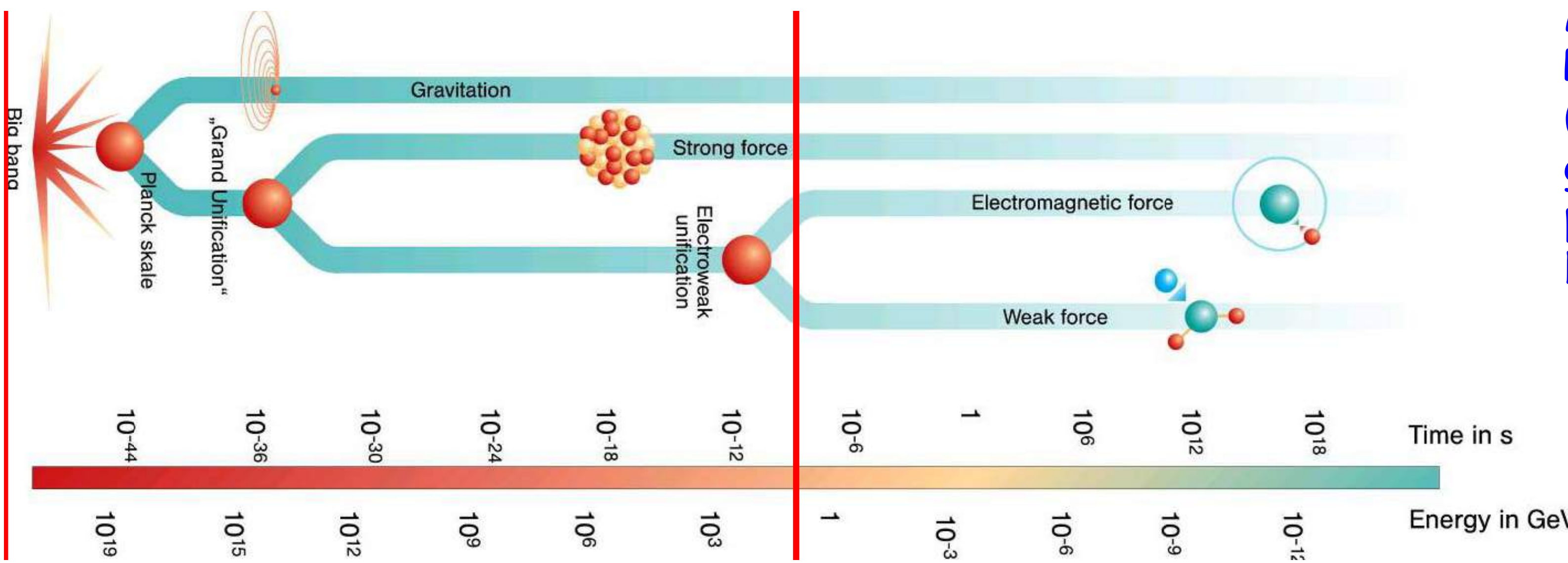
SM as an Effective Theory



10^{28}cm
Hubble
Scale

10^{-17}cm
Weak Scale

10^{-33}cm
Planck Scale



Max mass is **Planck mass** (~1/1000 of a gram) that a particle can have

Symmetries in Physics

A symmetry is a change of something that leaves the physical description of the system unchanged.

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Maxwell's equations do not have this property ➔ Einsteins' Special Relativity does (in fact originally it is called *Invarianten theorie*)

➔ Poincaré groups

Symmetries & groups

Evariste **Galois** , 1832 → group theory

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A set of symmetry operations is a group if it has following properties:

1. Closure.

If R_i and R_j are in the set, then the *product*, R_iR_j is also in the set; that is, there exists some R_k such that $R_iR_j = R_k$.

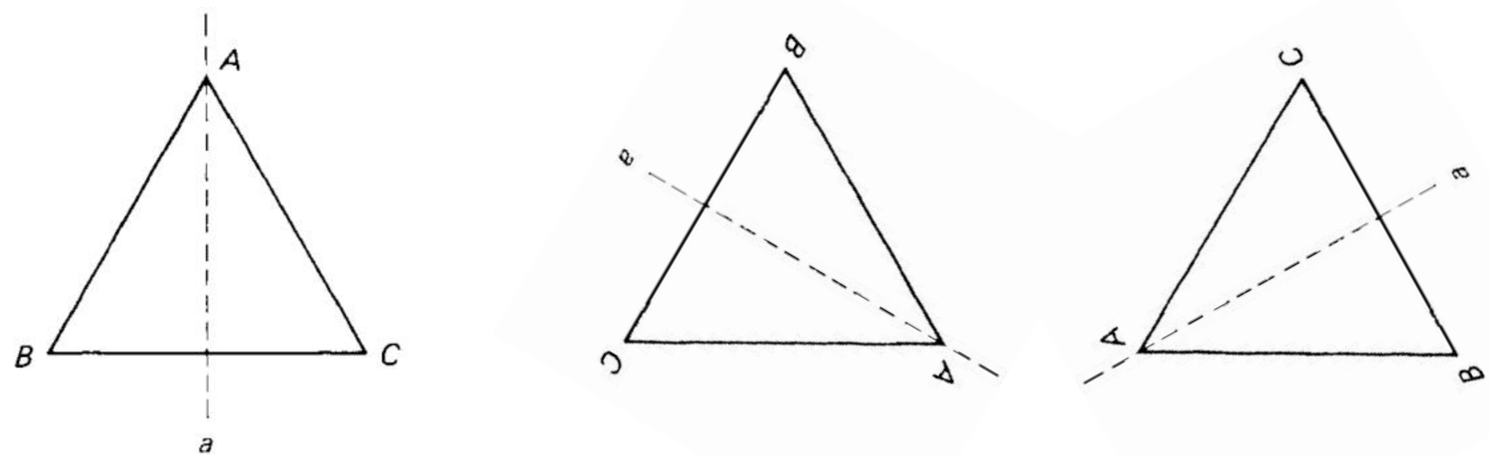
2. ***Identity.***

There is an element I such that $IR_i = R_iI = R_i$ for all elements

3. ***Inverse.***

For every element R_i there is an *inverse*, R_i^{-1} , such that $R_iR_i^{-1} = R_i^{-1}R_i = I$

4. ***Associativity.*** $R_i(R_jR_k) = (R_iR_j)R_k$

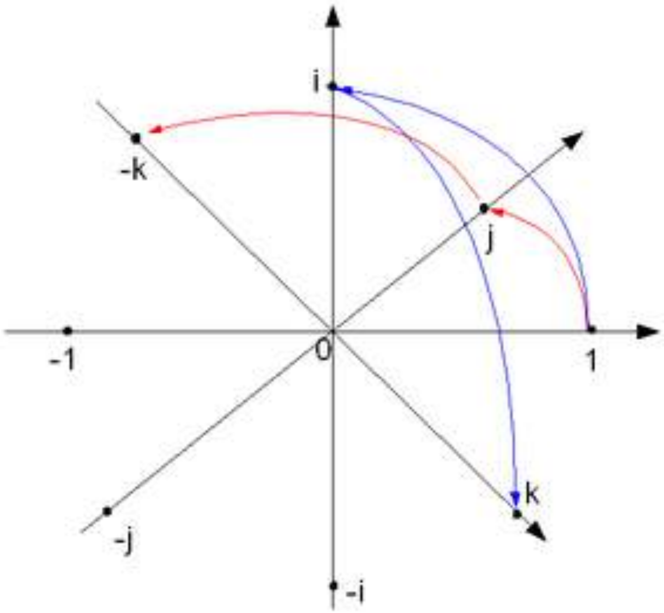


equilateral triangle, clockwise rotation through 120^0

Symmetries & groups

William Rowan Hamilton in (1843) Quaternion:
a + *bi* + *cj* + *dk* **"rotations" of space**

rotations of space: **SO(3)**
relevant group for electrons is **SU(2)**



Graphical representation of quaternion units product as 90°-rotation in 4D-space

ij = k
ji = -k
ij = -ji

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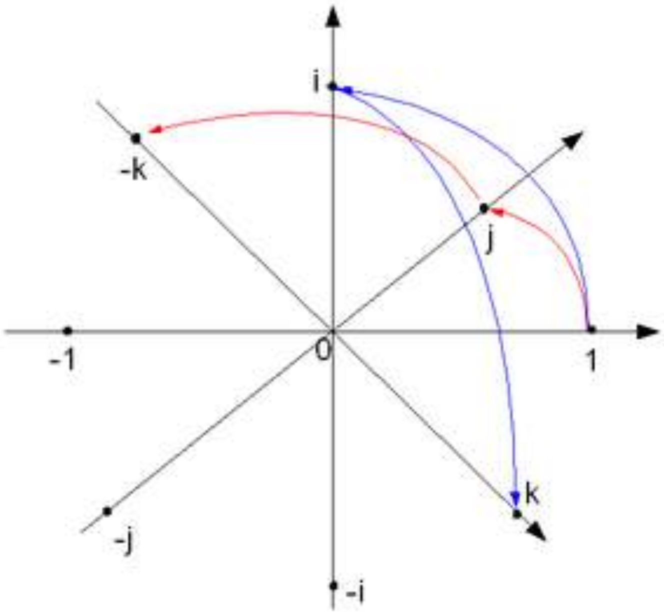

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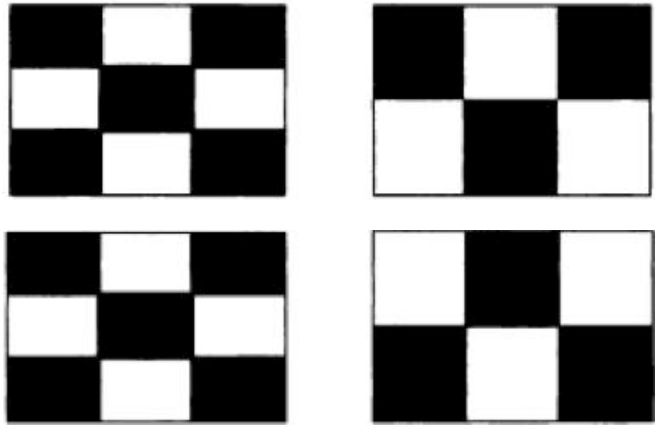
Eugene Wigner, 1927 *Group Theory and Its Application to the Quantum Mechanics of Atomic Spectra*



Left-hand pattern symmetrical
right-hand pattern has swapped dark regions for light.
➔*spontaneous symmetry-breaking*

spectrum of drum frequencies (rotated 180°)

Symmetries in Physics

In classical mechanics we have learned that to each continuous symmetry transformation, which leaves the scalar Lagrange density invariant, can be attributed a conservation law and a constant of movement (E. Noether, 1915)

Continuous symmetry transformations lead to conservation laws

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Symmetry	Invariance under movement in time	Homogeneity of space	Isotropy of space
Transformation	Translation in time	Translation in space	Rotation in space
Conserved quantity	Energy	Linear momentum	Angular momentum

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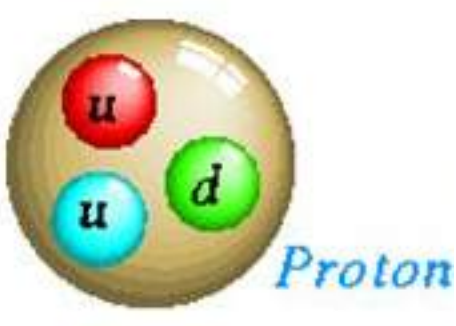
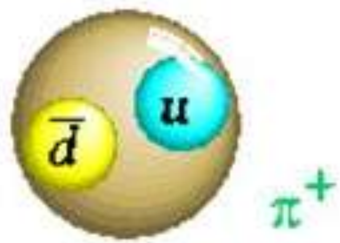
No single evidence for violation of these symmetries has been observed so far

SM & Group theory

baryons, mesons, leptons,….





$e, \mu, \tau, \ldots$

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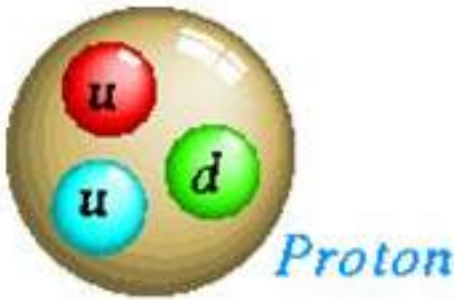
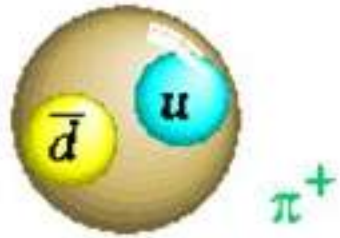
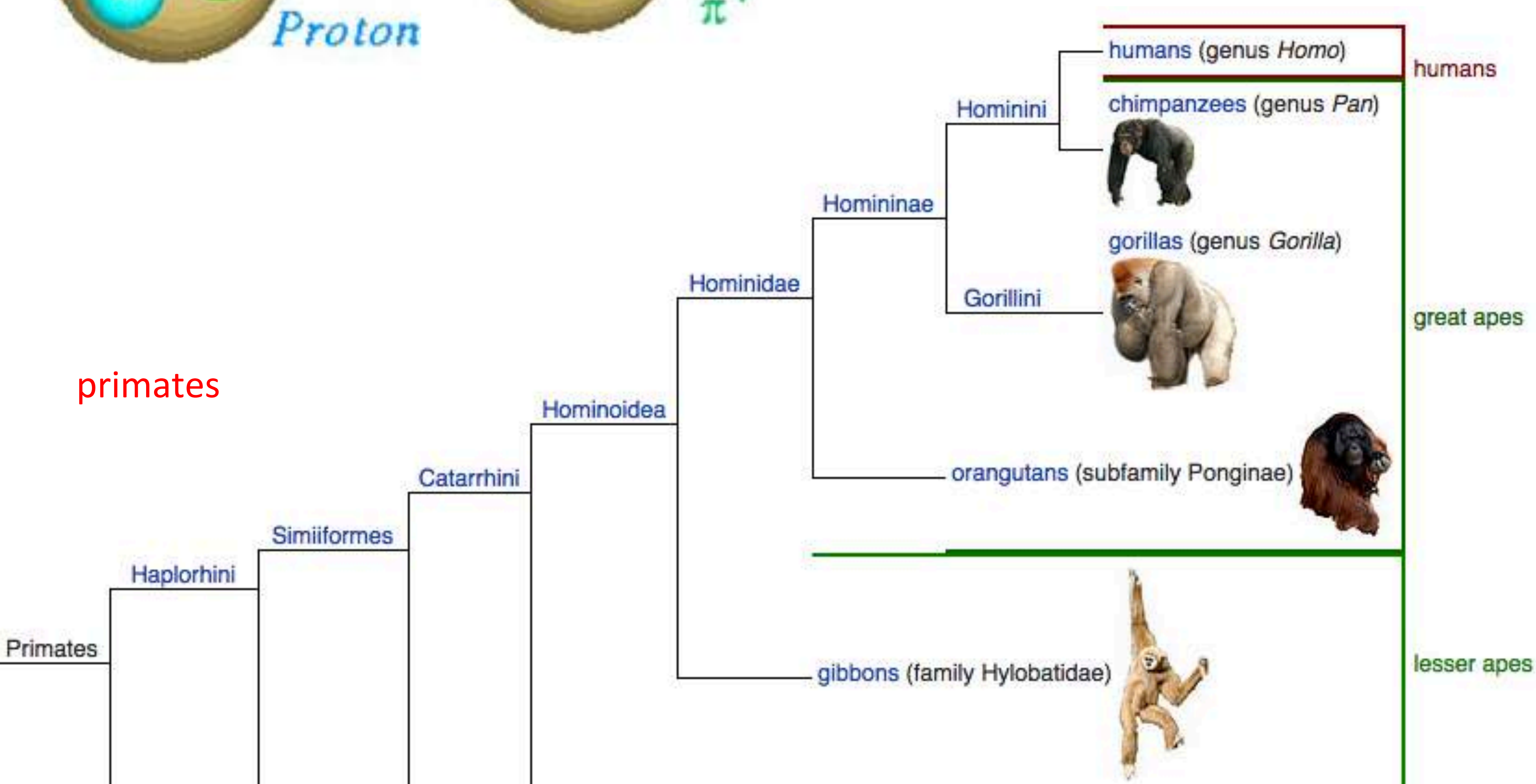




$e, \mu, \tau, \dots$

primates



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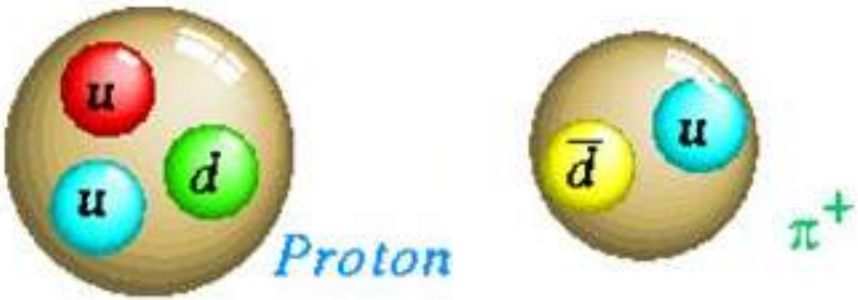
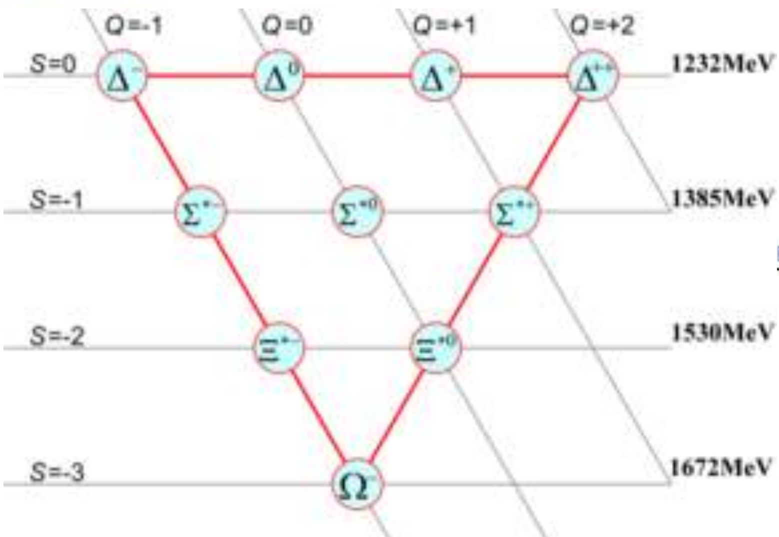
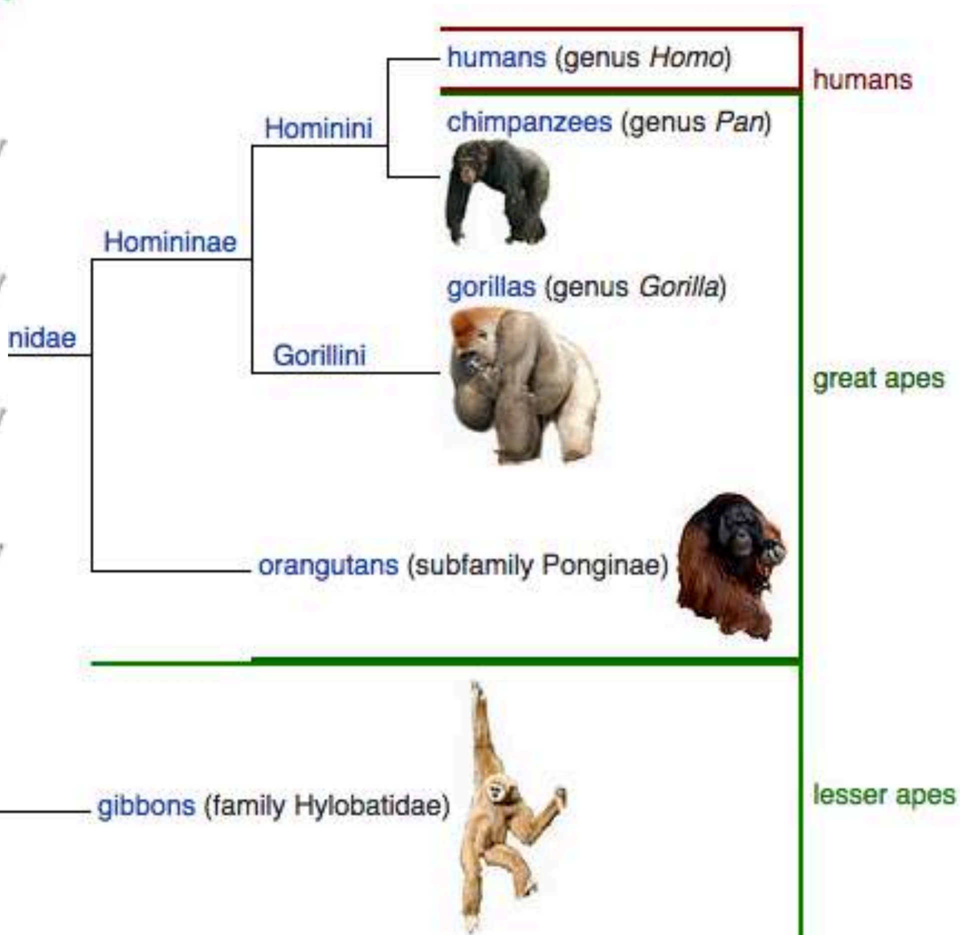
baryons, mesons, leptons,….

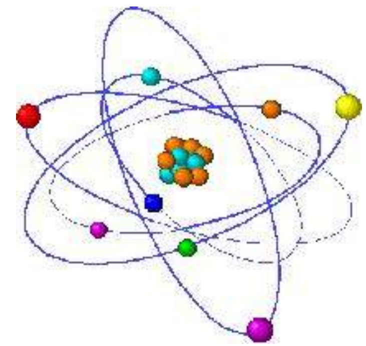


$e, \mu, \tau, \ldots$





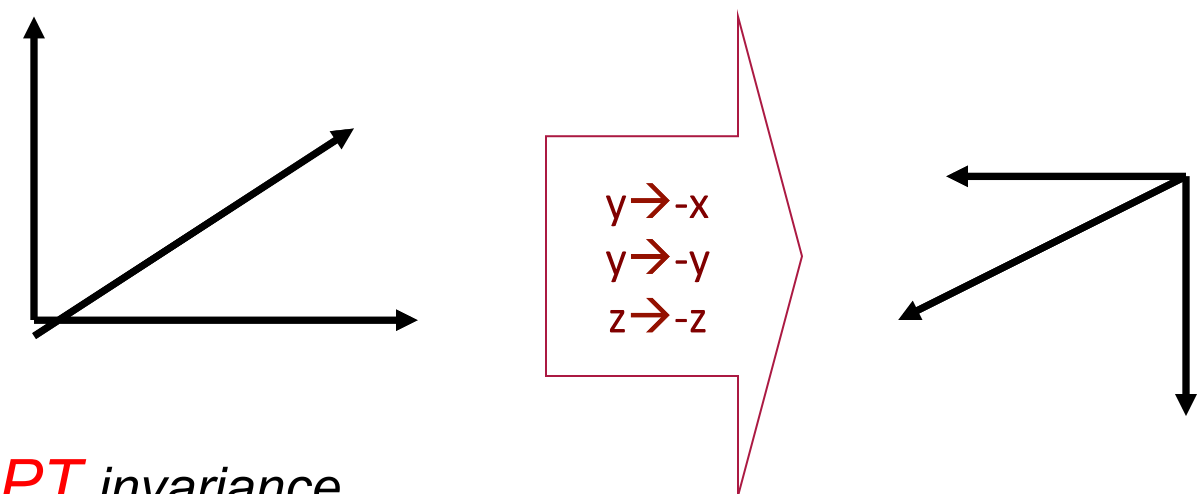
Discrete symmetries



- C – charge
- P – parity
- T – time

C : + → -* ; - → +

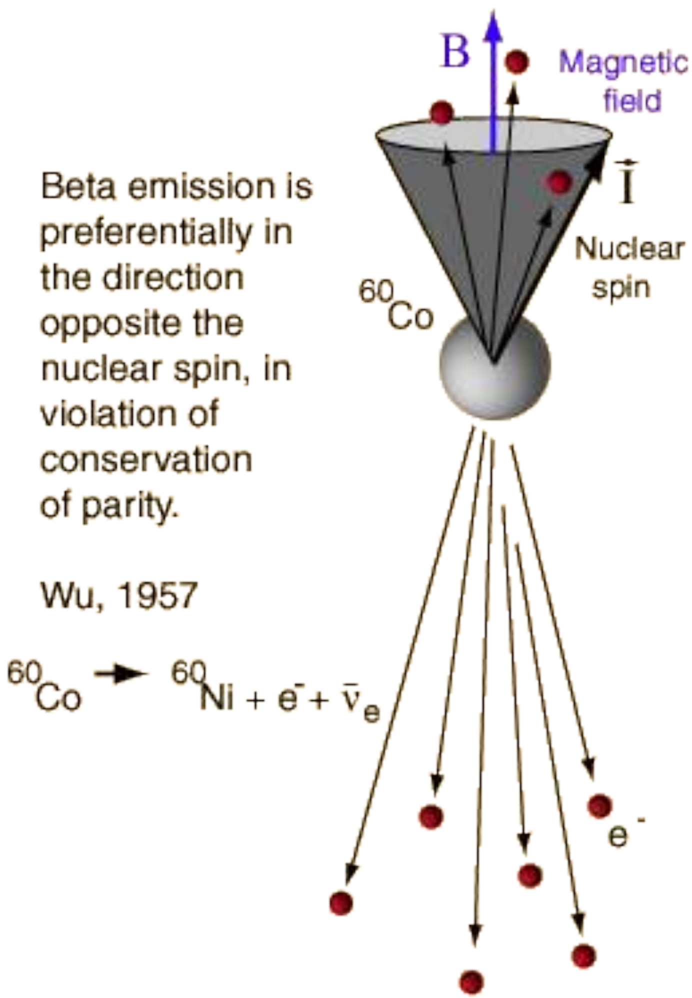
C, P, T, CP, CT, PT are invariant under strong& EM interactions
But heavily violated at weak interactions



CPT invariance

Parity violation in weak interactions !

1956, T.D. Lee and C.N. Yang → Parity might be violated in weak int. (tau puzzle $K \to 2\pi$ *and* 3π)
1957, C.S. Wu proved experimentally that parity is violated



- Angular distribution of electrons

$$I(\theta) = 1 + \alpha \frac{\vec{\sigma} \cdot \vec{P}_e}{E_e} = 1 + \alpha \frac{v}{c} \cos\theta$$

$\vec{\sigma}$ - spin vector of electron

$\vec{P}_e$ - electron momentum

E_e - electron energy

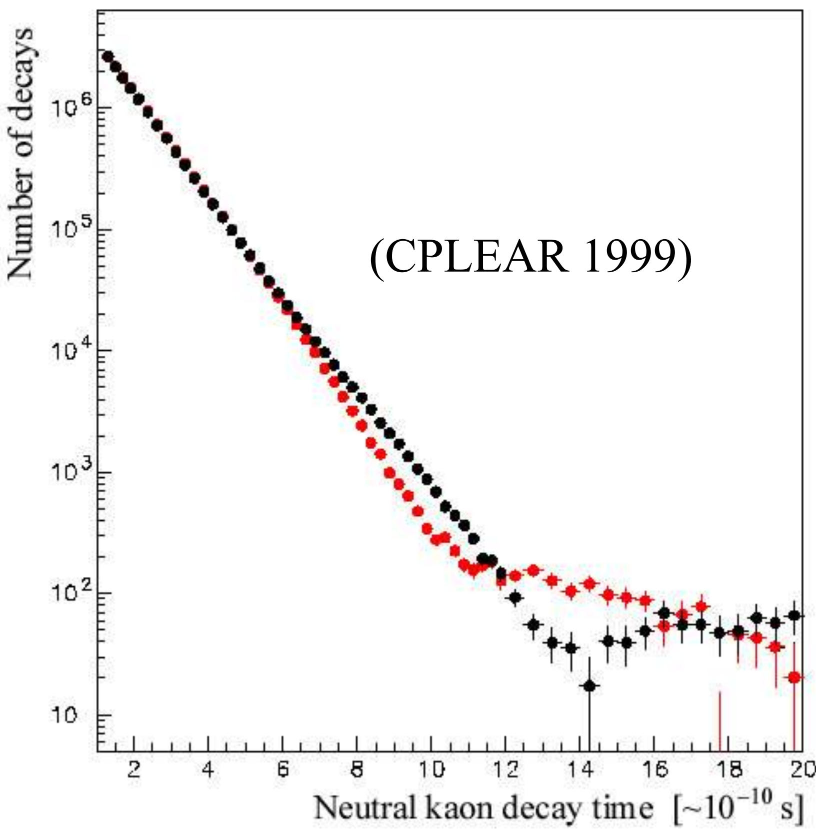
$$\alpha = \begin{cases} -1 & \text{for electron} \\ +1 & \text{for positron} \end{cases}$$

CP violation

$$\pi^+ \to \mu^+_R + \nu_L \xrightarrow{\quad P \quad} \pi^+ \to \mu^+_L + \cancel{\nu}_R$$

$$\pi^+ \to \mu^+_R + \nu_L \xrightarrow{\quad C \quad} \pi^- \to \mu^-_R + \cancel{\overline{\nu}}_L$$

$$\pi^+ \to \mu^+_R + \nu_L \xrightarrow{\quad CP \quad} \pi^- \to \mu^-_L + \overline{\nu}_R$$



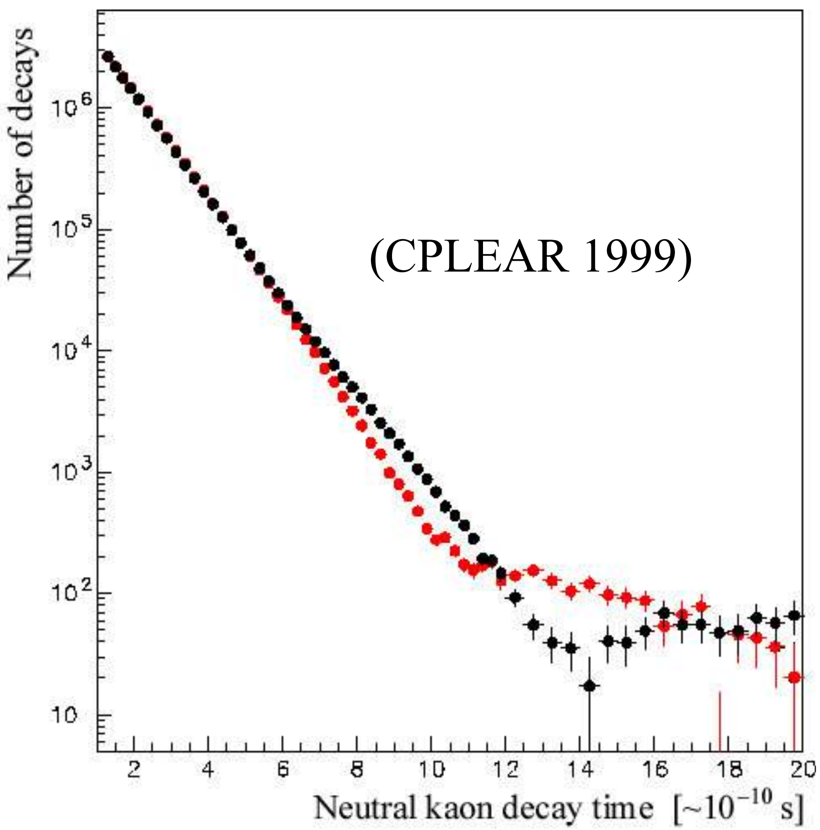
J.Cronin, V.Fitch, 1964:
CP violation in
neutral K-mesons

$$\Gamma(B^0 \to \psi K_S) \neq \Gamma(\overline{B^0} \to \psi K_S)$$

$$K_S, K_L \neq K_+, K_-$$

CP violation

$$\begin{tikzcd}[column sep=huge, row sep=huge]
\pi^+ \to \mu^+_R + \nu_L \arrow[r, "P"] \arrow[d, "C"] \arrow[dr, "CP"] & \pi^+ \to \mu^+_L + \cancel{\nu}_R \\
\pi^- \to \mu^-_R + \cancel{\overline{\nu}}_L & \pi^- \to \mu^-_L + \overline{\nu}_R
\end{tikzcd}$$



Is not enough for baryogenesis!

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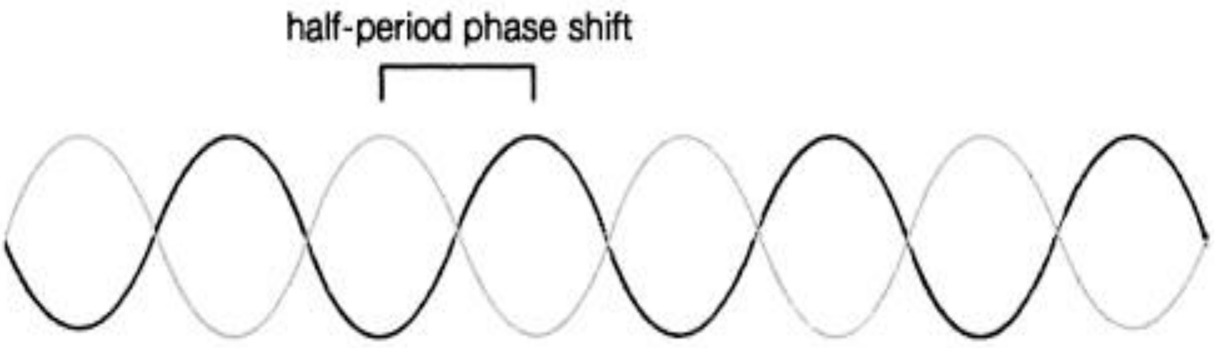
gauge symmetries

Accordingly, the Standard Model Lagrangian satisfies local gauge symmetries (the physics must not depend on local (and global) phases that cannot be observed):

$$\psi \rightarrow e^{-i\omega(x)}\psi$$



gauge symmetry: a symmetry in the **change of phase in light**.

phase of light can be changed at will **at all locations in space and time**, and the laws of physics should remain invariant.

➔ **gauge symmetry of Maxwell's equations**,

and its quantum version: quantum electrodynamics (QED).

… and also QCD

Standard Model as a gauge theory

Theoretical foundation: 1930's – 1970's experimental confirmation 1980's

Symmetry	Electromagnetic interaction	Weak interaction	Strong interaction (QCD)
Transformation	U(1) gauge transformation	SU(2) gauge transformation	SU(3) gauge transformation
Conserved quantity	Electric charge	weak charge (parity is not conserved)	color charge

approximate symmetries)

Quark (baryon) and lepton numbers

evidence for lepton flavor violation in "neutrino oscillation"

Lagrangian

$$S = \int d^4x \mathcal{L}(\phi_i, \partial_\mu \phi_i)$$

$\mathcal{L}$ invariant under Poincaré (Lorentz+translations) tranformations and internal symmetries

The symmetries of the lagrangian specify the interactions

Fields are classified according to their transformation properties under Lorentz group

$$x^\mu \to x'^\mu = \Lambda^\mu_\nu x^\nu$$

$$\phi(x) \to \phi'(x')$$

$$V^\mu \to \Lambda^\mu_\nu V^\nu$$ vector

$$\phi'(x) = \phi(x)$$ scalar

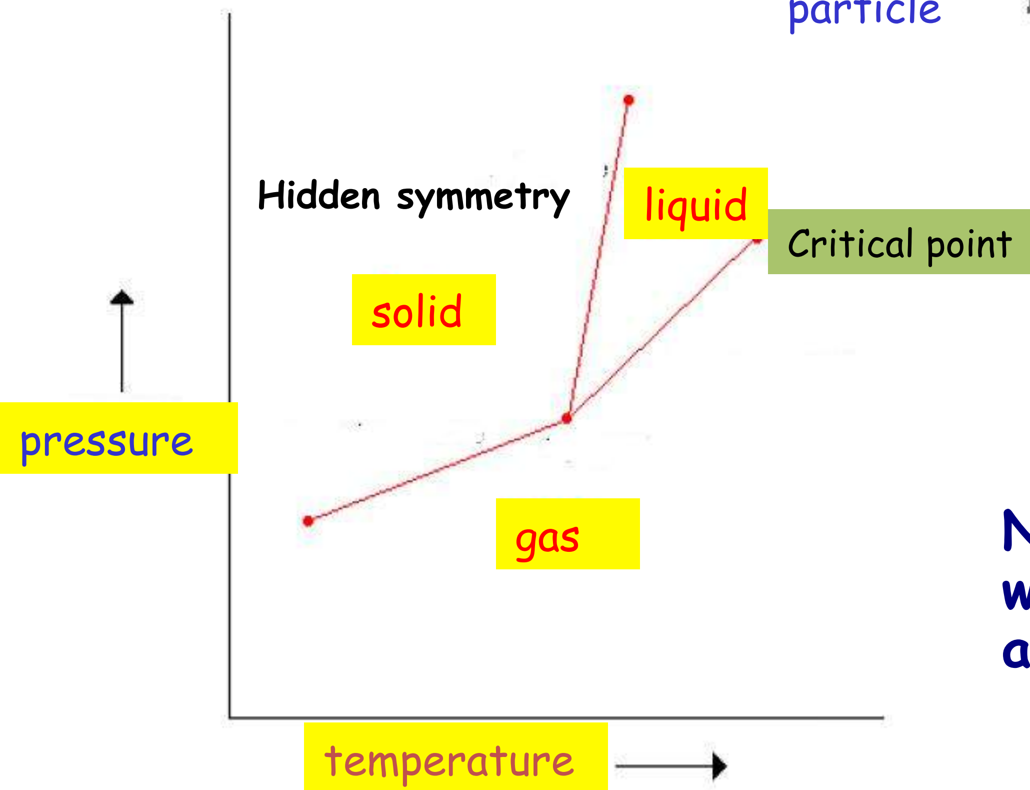
$\delta S = 0$ --> Euler-Lagrange equations

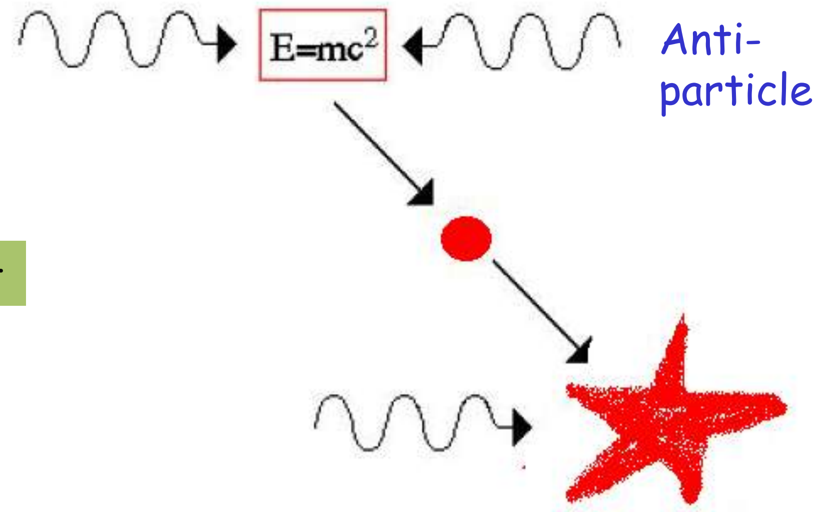
$$\frac{\partial \mathcal{L}}{\partial \varphi_i} - \partial_\mu \frac{\partial \mathcal{L}}{\partial(\partial_\mu \varphi_i)} = 0$$

Invariance of action under continuous global transformation ---> There is a conserved current/charge

$$\partial_\mu j^\mu = 0 \qquad Q = \int d^3x j^0(x,t)$$

Phase transitions and Symmetry Breaking

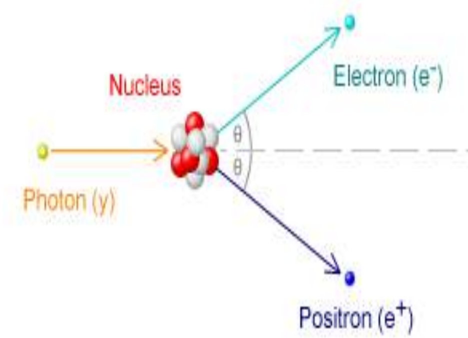




No particle can be creating without the breaking of particle/ anti-particle symmetry

Symmetry breaking ~ phase transition

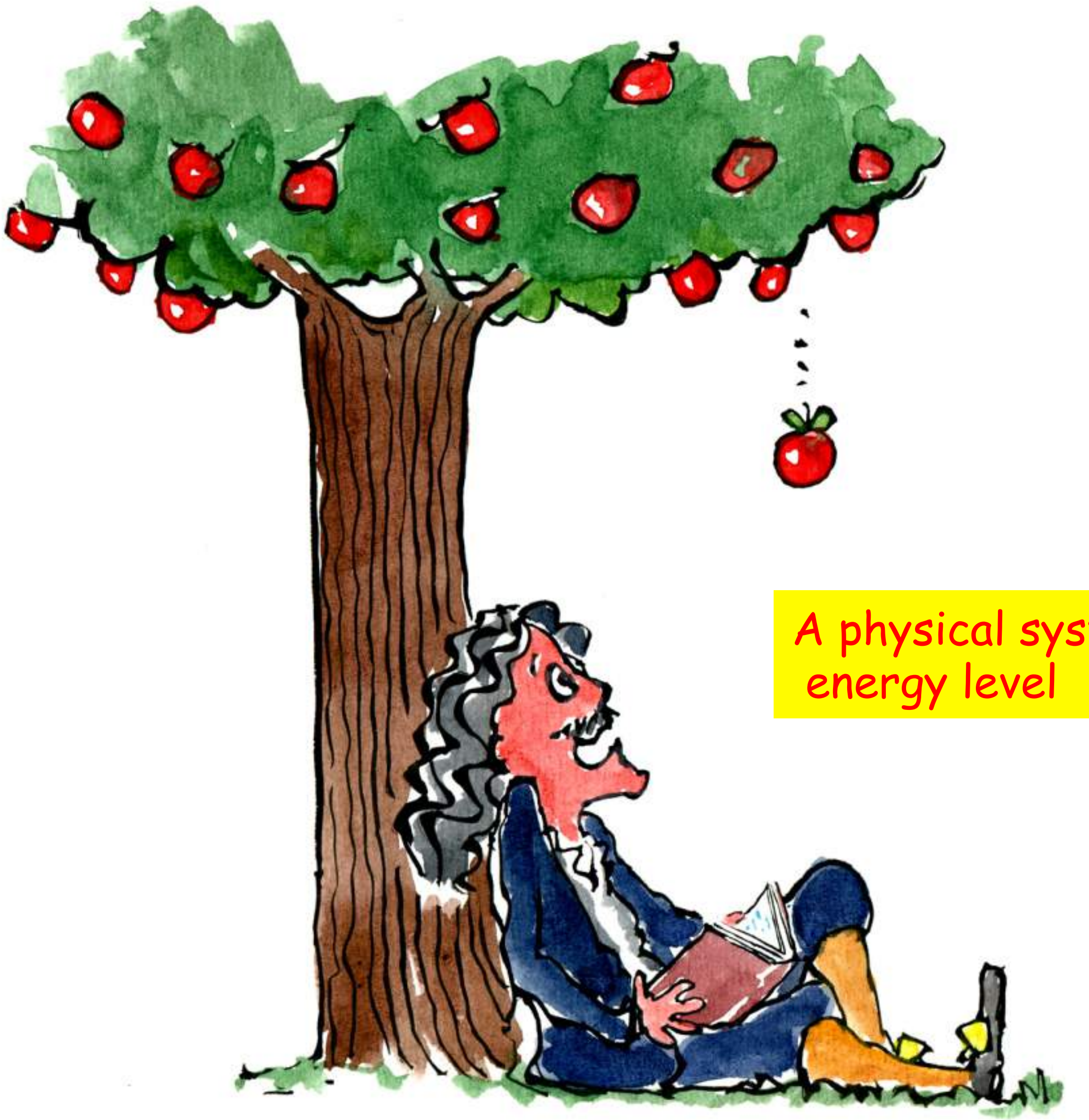
Although the underlying laws of nature are the same at all times, they lead to different behavior at different energies— just as the same laws cause water to be solid at low temperatures, liquid at medium ones, and a gas at high ones.



What Makes Apples Fall From The Tree

by Frits Ahlefeldt

What Makes Apples Fall From The Tree



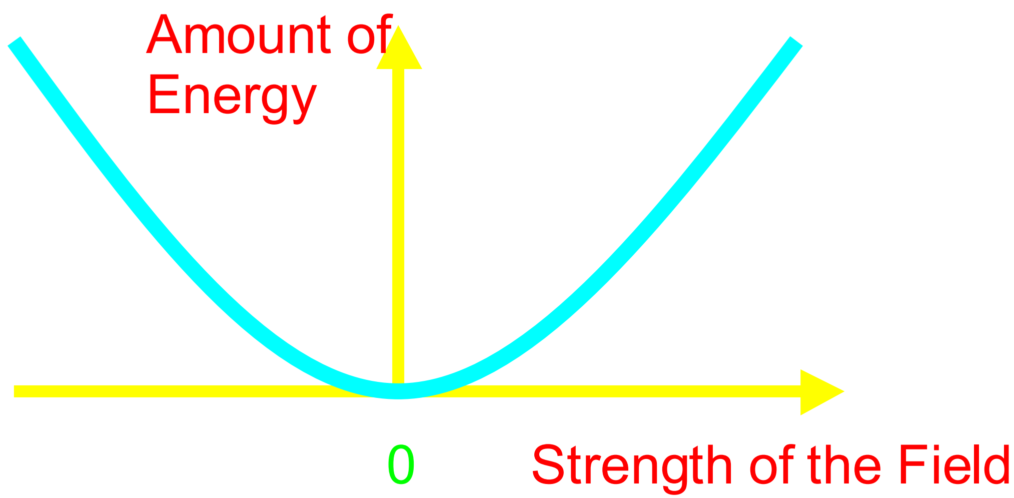
A physical system goes always to its lowest energy level

by Frits Ahlefeldt

A Symmetrical Universe

Field is a condition of the space, which characterizes the behavior of space, functions of space. Empty state (vacuum) is the state of the lowest energy.

All fields contain energy. Consider an empty volume filled, for example, with an electric field. Even though this volume has no particles in it, it contains energy. The energy depends on the strength of the electric field.



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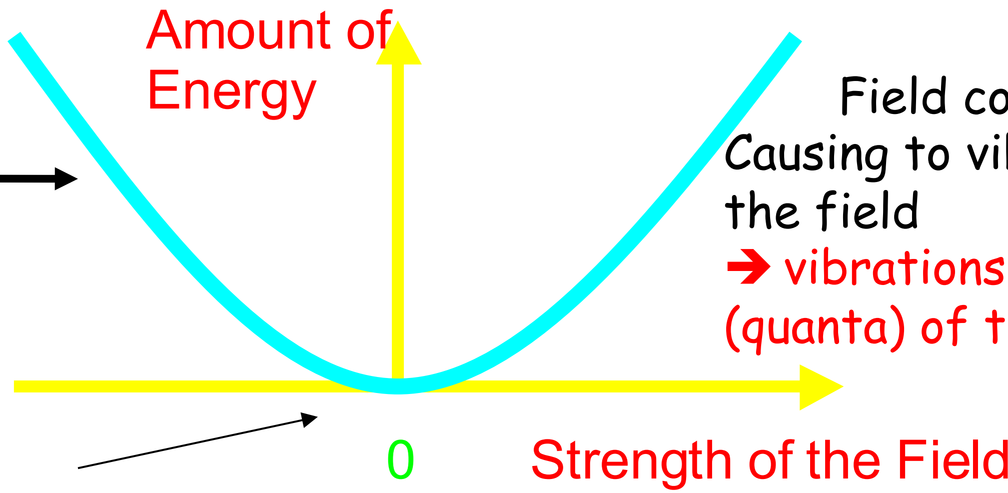
Energy diagram of a Field: Energy is at minimum when the Field is zero



Field cost energy
Causing to vibrate (exciting) the field
➔ vibrations are the particles (quanta) of the field

The Universe settles down to a state with as little energy as possible

This is a Symmetric Universe and nothing happens there

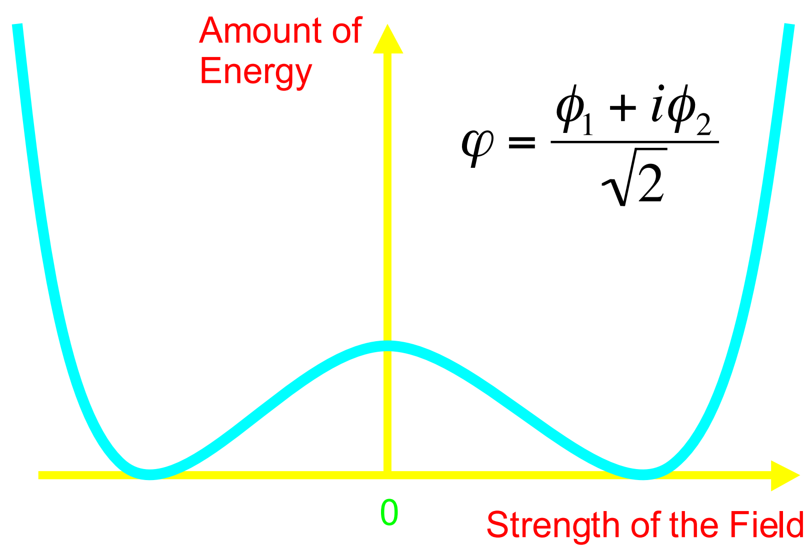
Mexican hat or wine bottle…..

$$L = \partial_\nu \varphi^* \partial^\nu \varphi - V(\varphi)$$

$$V(\varphi) = \mu^2 \varphi^* \varphi + \lambda(\varphi^* \varphi)^2$$

invariant under: $\varphi \rightarrow e^{i\alpha}\varphi$

$\mu^2 < 0$ $\lambda > 0$



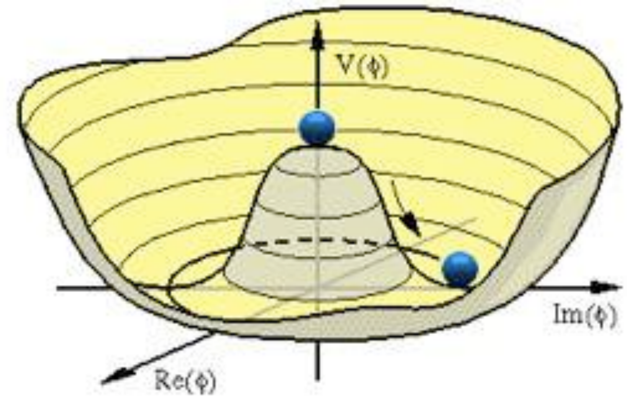
$$\varphi = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$

Intro to Brout –Englert-Higgs Mechanism

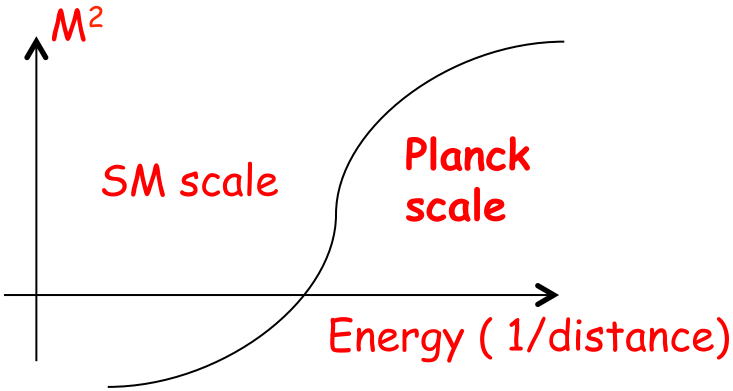
(Anderson, Brout, Englert, Guralnik, Hagen, Higgs, Kibble, 't Hooft)

For the history: Frank Close, *Infinity Puzzle*

If we take M^2 (related to Higgs mass) as negative
Vacum where the field is not zero!



$$E = M^2\ h^2 + Xh^4$$



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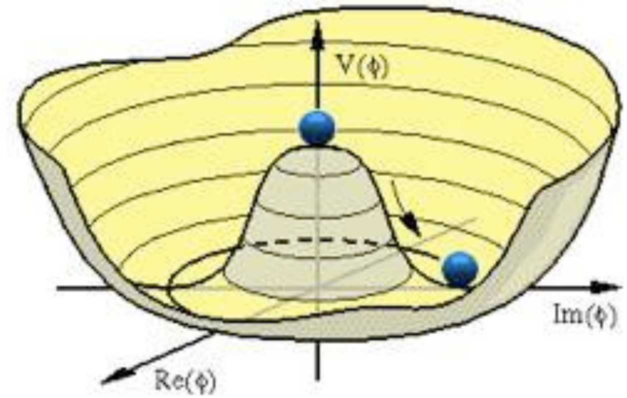

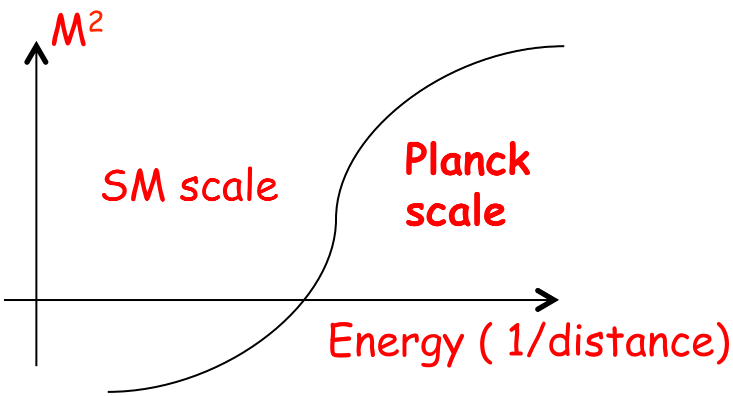

$$E = M^2\, h^2 + X h^4$$

2-D (energy depend both field);
Displacement of the field cost energy.
Imagine a symmetric field.
Circular motion of the field →angular momenta (not in real space but field space)

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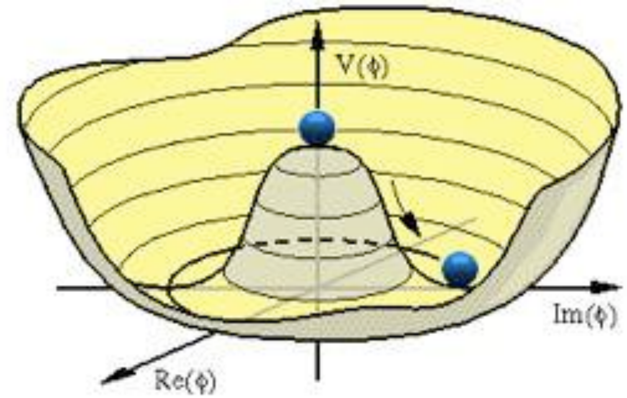

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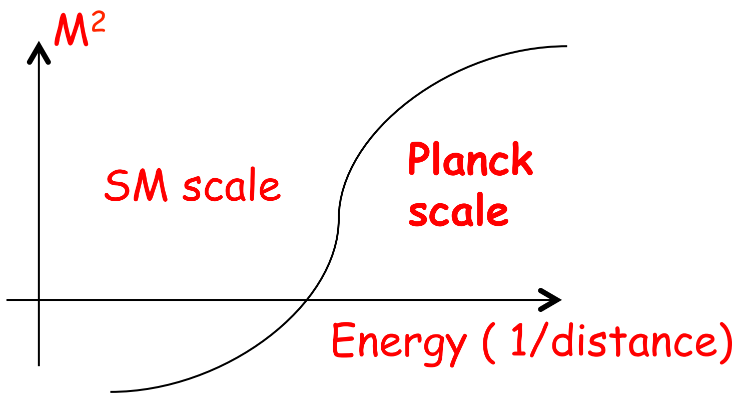

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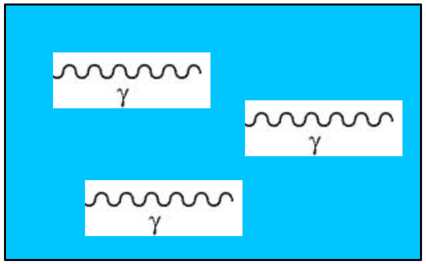
Displacement of the field cost energy.
Imagine a symmetric field.
Circular motion of the field →angular momenta (not in real space but field space)

Electric charge is the excitation of the field rotating in an internal space.

➔ Rotation (charge) will cost no energy . It is called condensate in space: a charge

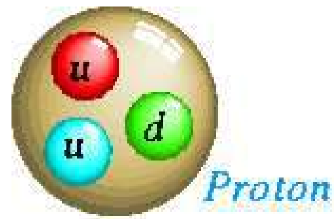
We don’t know what makes the Higgs condensate. We arrange the Higgs potential so that the Higgs condensates but this is just a parametrisation that we are unable to explain dynamically

Why do we need Higgs for Mass?



A "massless" box filled with photons does it have mass? (remember $E=mc^2$)

Ex: proton



Mass of the quarks is only 1% of the protons mass.
Proton mass doesn't need Higgs!

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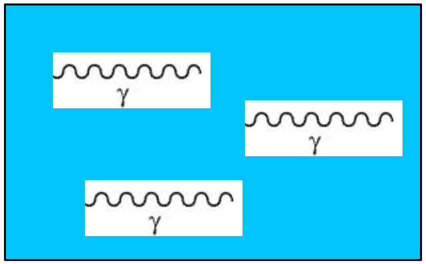

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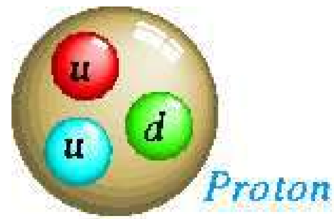

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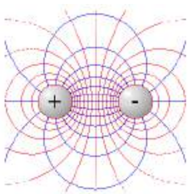
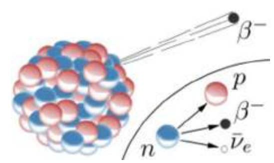
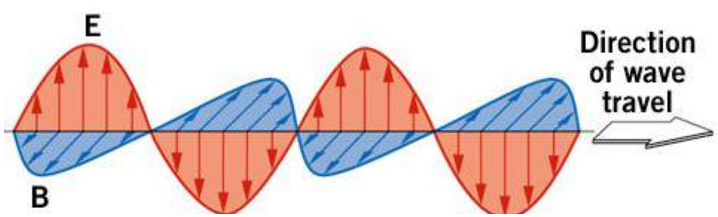
Electromagnetism ➔ infinite range ➔ photon mass =0



Weak force ➔ 10^{-18} m (10^{-3} p radius) ➔ W, Z massive

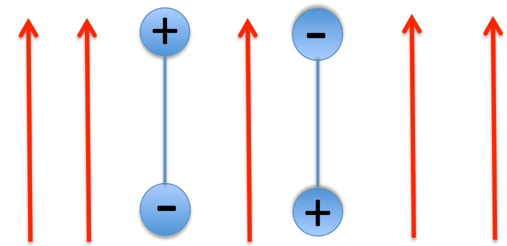




For a massive particle, how can one distinguish longitudinal from transverse polarizations?
How to reconciliate W, Z masses (short-range weak force) with gauge symmetry?

How the field effect mass....

Water molecule analogy to show how a field effect the energy the two configuration of the molecule



$E=mc^2$ ➔ different mass

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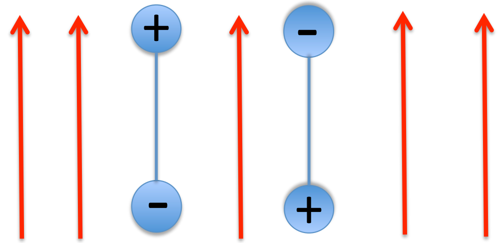

$E=mc^2 \Rightarrow$ different mass

A water molecule like dumbel (+ and – charges). Mass doesn't depend on orientation (space symmetry). Consider them as two kinds of particles, **upside** and **downside**
In an *E* field, energy of the **up** has less energy and **down** has large energy
Water molecule is neutral. There is no net force on it. "**field doesn't slow down it**"
This is how a field creates mass. It increases one mass, decreases other mass

.. -3 -2 -1 0 1 2 3…
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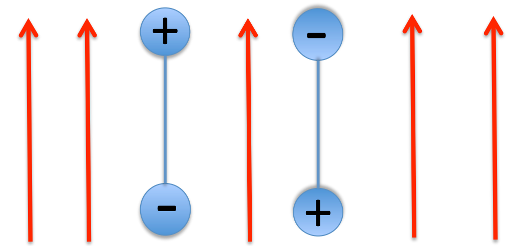

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We can think that *E* field in terms of photons: condensate!
(Indefinite number of photons..)
Water molecule moves in photon condensate constantly emits and absorbs photons.
Real word is not like that with respect to electric charge.
But superconductors are like that.
Condensate of charge where in a region that charge completely uncertain

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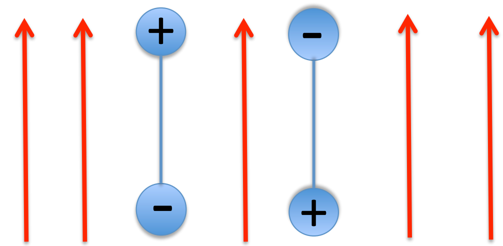

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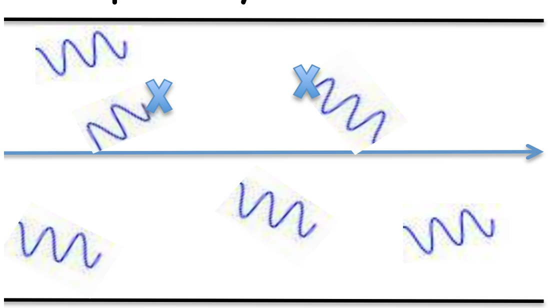
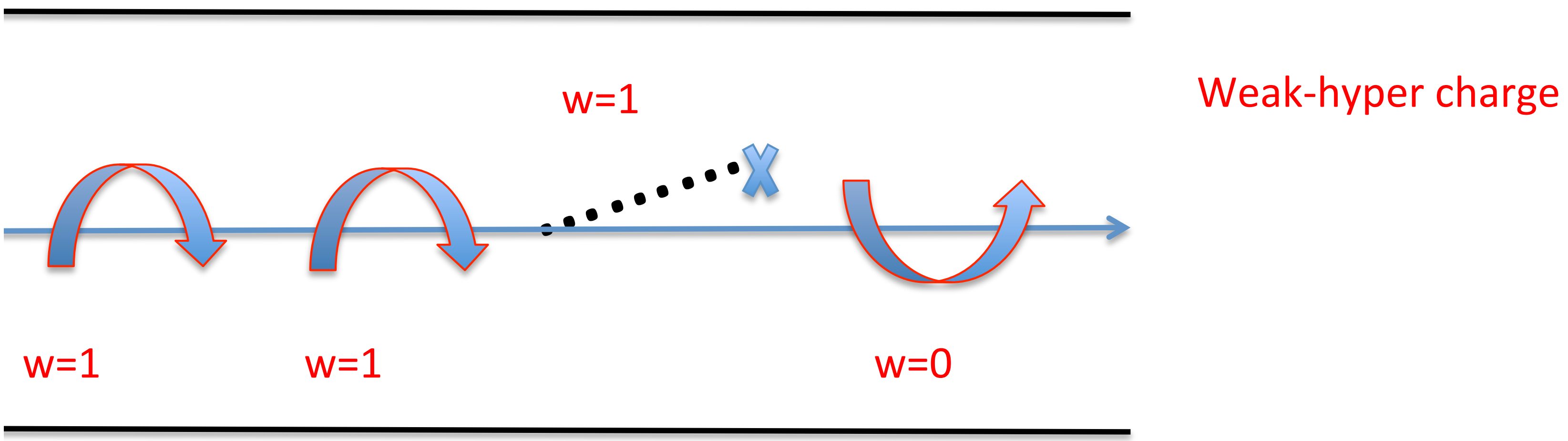
Depending how photons are polarized upside or down, emitting and absorbing photons effects shifting of the energy of the water molecule.



Water molecule

Spontenous Symmetry Breaking of Chiral System

Dirac theory: ***R electron*** can become ***L electron.***
But massless particle cannot flip.
Mass of the particle is related the rate of flipping right-left



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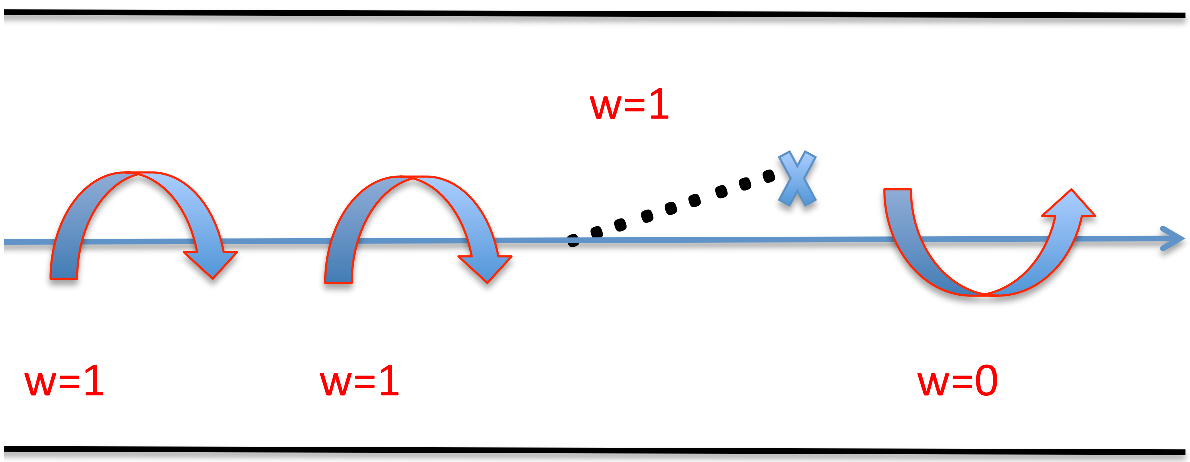


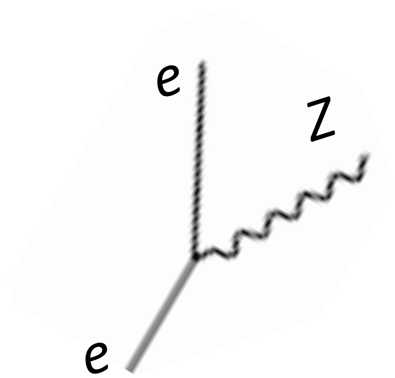
Weak-hyper charge

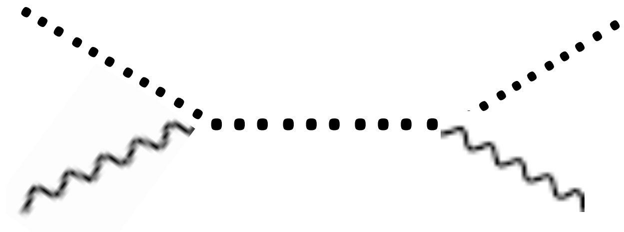
When **a Z-boson** is emitted from electron, it is not electric charge: Weak-hyper charge
Electrons with R-handed and L-handed have the same electric charge,
but different Weak-hyper charge: R = 0, L=1 (w=0, w=1)
But due to **conservation of weak-hyper charge** electron must be massless.
We need a new boson (W mixture): it is like Higgs but condensate with Weak-hyper charge

When flipping w=1 to w=0, it goes to condensate.

Brout –Englert-Higgs Mechanism & the Higss boson

Same for Z-boson: it absorbs and emits Weak-hyper charge from condensate contineously
Z doesn't have Weak hyper charge. It absorbs Ziggs, becomes Ziggs and re-emits Ziggs





W's and Z-boson were discovered 1983

Higgs boson is just left over....

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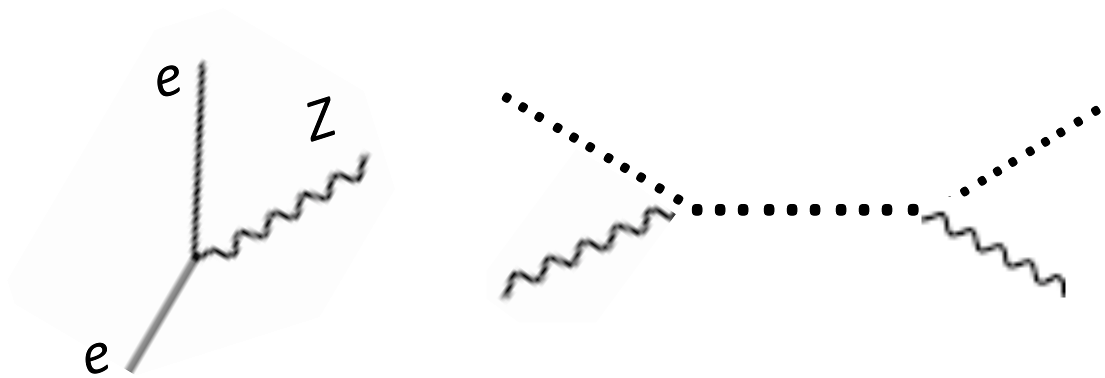

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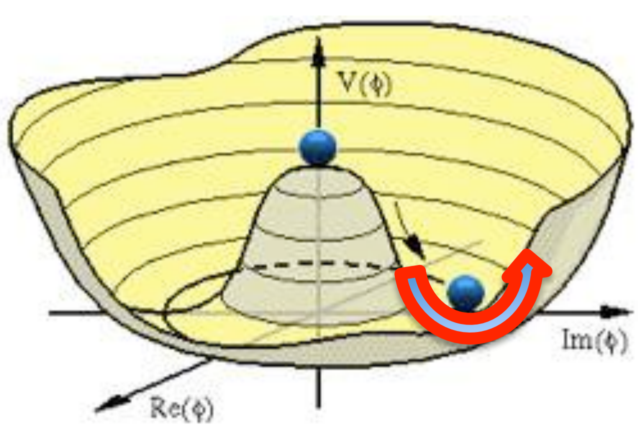
Higgs boson is just left over....

Imagine that the density of the condensate changes (compressional wave)

Higgs boson is like sound wave propagating through the condensate



Further away stronger the condensate
This oscillation is called Higgs boson
And that s what we have discovered at CERN

Short history

Dirac theory (**1928-1940**'s): QED → U1 gauge theory

Yang-Mills theories for non-abelian gauge interactions (**1948**). → SU2 group

Schwinger, Bludman and Glashow: there are three massless gauge bosons. → SU2xU1 theory

$V - A$ as the classification of the weak interaction by **1957**

In **1961** Goldstone argued that the appearance of a massless boson is an unavoidable in SSB

1956: In a superconductor, the ground state contains Cooper Pairs. "BCS Theory."

Nambu: gauge invariance (globally) does hold true in the BCS Theory but has become hidden.

Anderson: The presence of plasma impedes the photon and, in effect, gives it inertia: mass.

Guralnik, Hagen, Kibble, Brout, Englert, Higgs : "Hidden Symmetry," (**1964**)
explaining how gauge bosons could become massive while maintaining gauge invariance.

"The Higgs Mechanism" concerns the way that some gauge bosons—vector particles such as the W and Z, which ought to be massless like the photon—manage to acquire a mass by "eating" Goldstone's massless scalar boson.

Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE

Published: July 4, 2012 | 122 Comments

mass = 134 x $M_{Hydrogen} = M_{Cesium}$

Higgs Discovery at LHC experiments

LHC History

\

1982 : First studies for the LHC project
1994 : Approval of the LHC by the CERN Council
1996 : Final decision to start the LHC construction
2004 : Start of the LHC installation
2006 : Start of hardware commissioning
2008 : End of hardware commissioning and start of commissioning with beam
2009-2030: Physics operation

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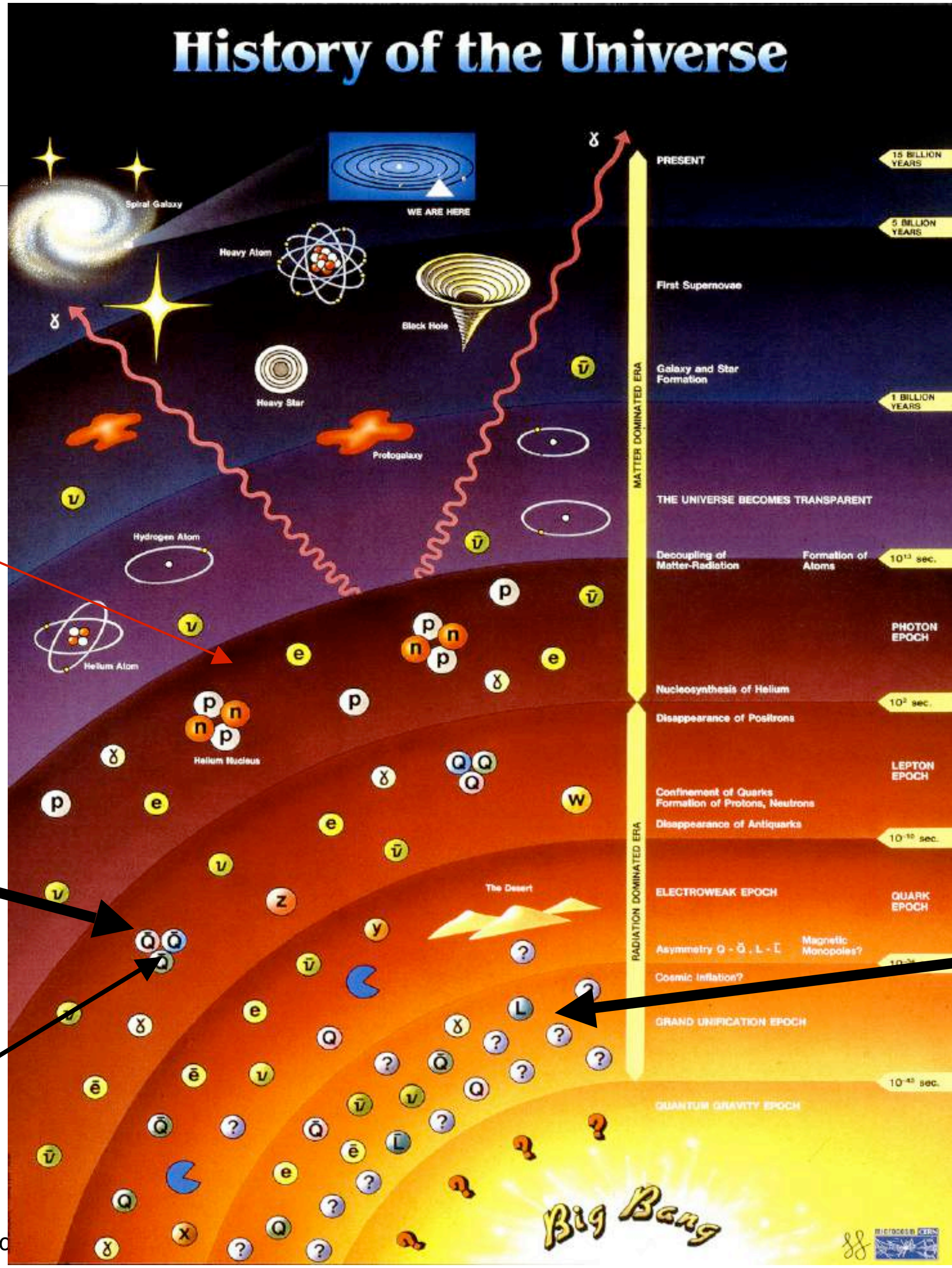
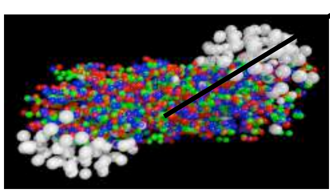
Connecting the LHC and the Big Bang Model



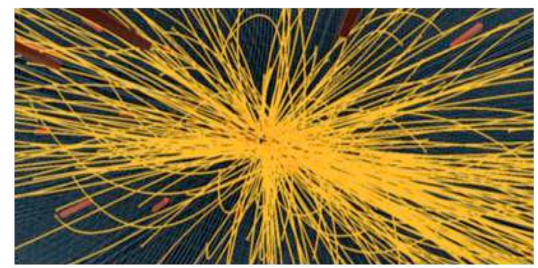
minutes after Big Bang nucleo-synthesis era

10^{-6}sec after Big Bang (hadronization era)

Heavy ions regime at LHC ALICE, CMS,ATLAS

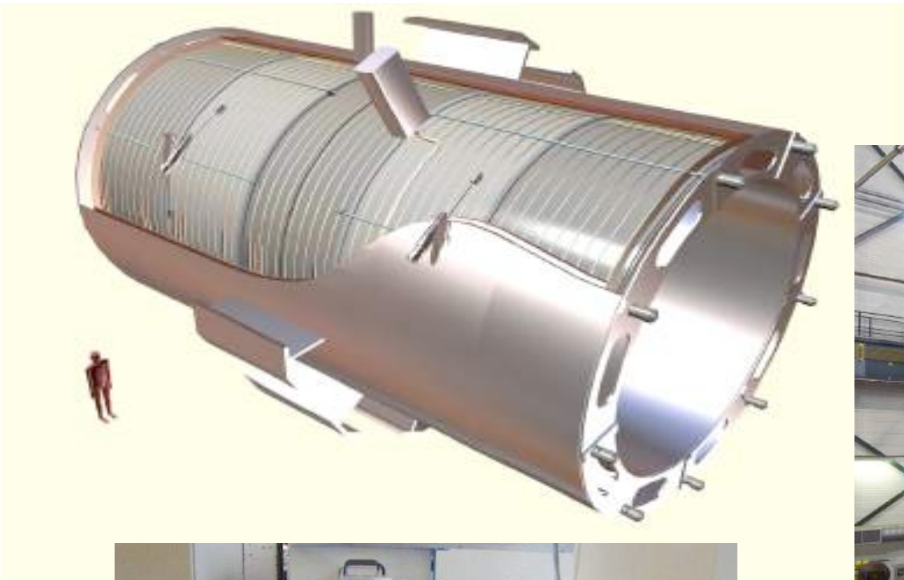


At the beginning there were only elementary particles!

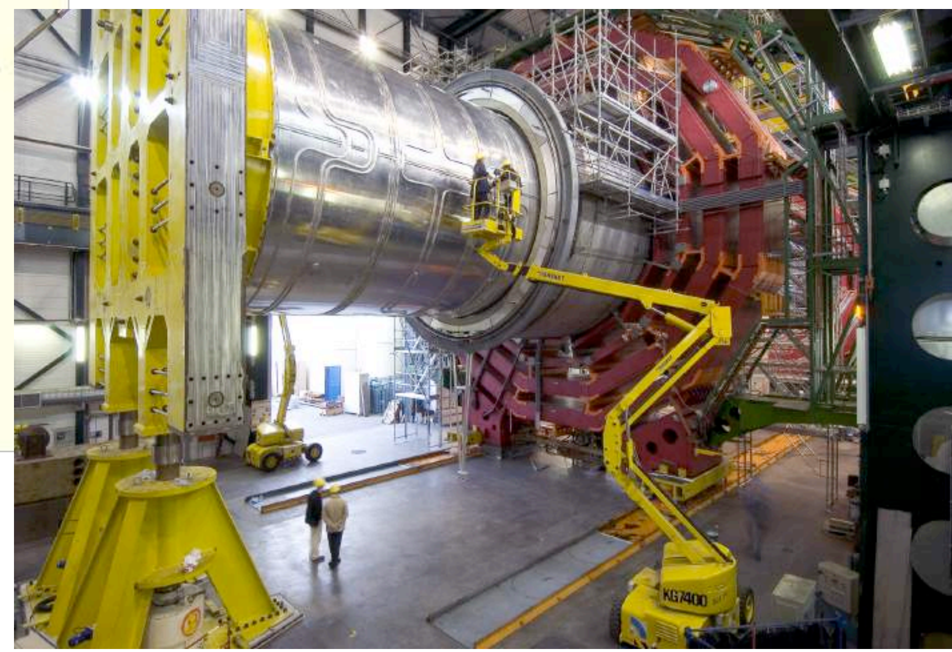


LHC -pp- probes the era at ~ 10^{-12-15} sec after the Big Bang (Electroweak era) CMS, ATLAS

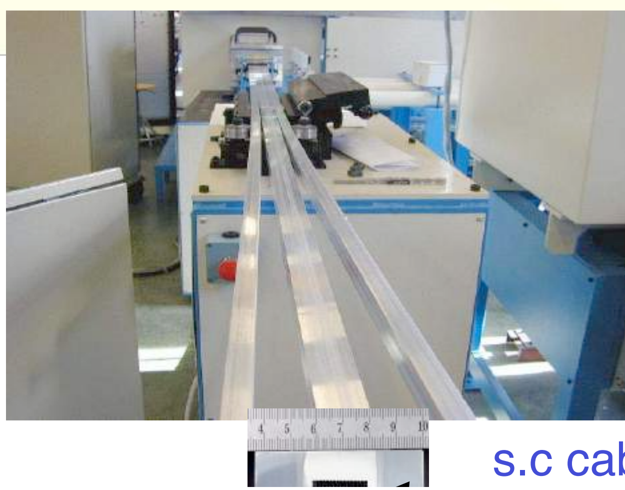
CMS solenoid - largest in the world - cable and coil modules production/assembly



all 5 coil modules finished in 2004
assembly in CMS hall, Jan. 2005

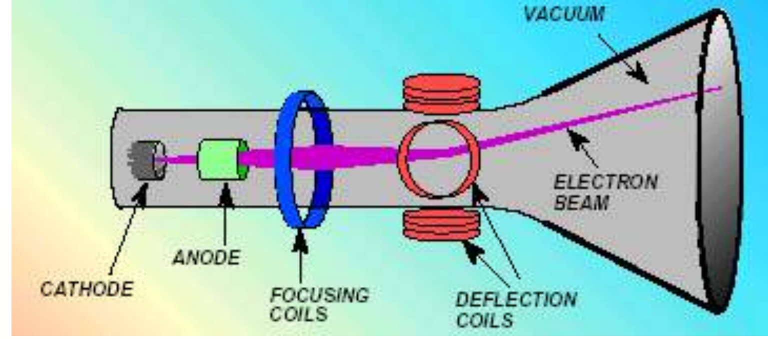


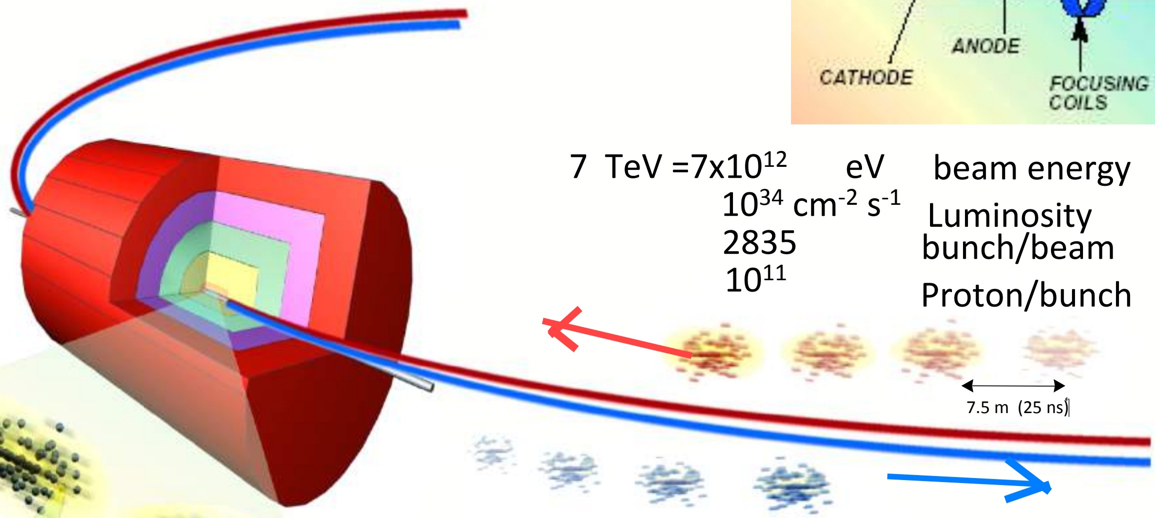
Insertion of coil in vacuum tank in September 2005



s.c cable: all 21 lengths (53 km) finished in 2003

LHC is a huge TV tube



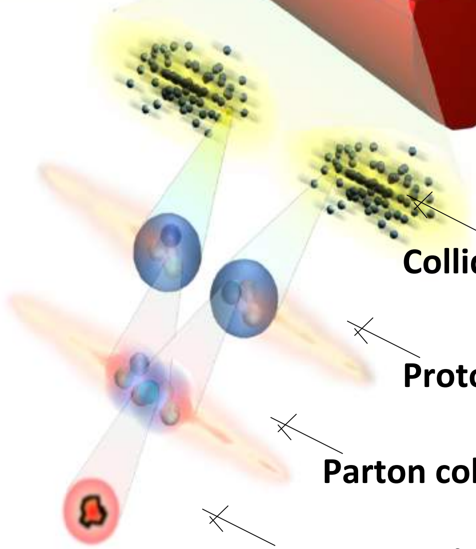


7 TeV = 7×10^{12}	eV	beam energy
10^{34} cm^{-2} s^{-1}		Luminosity
2835		bunch/beam
10^{11}		Proton/bunch

Proton

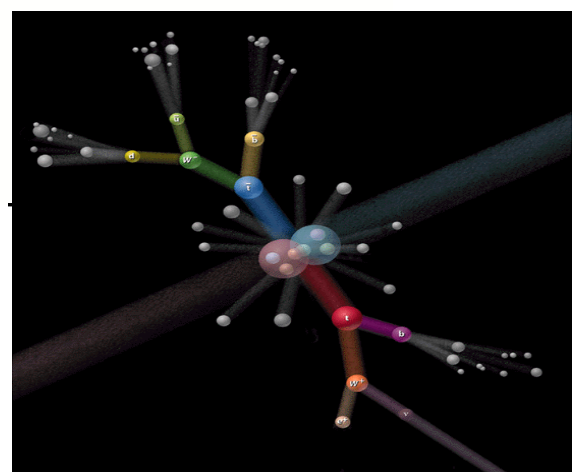
Proton

7 TeV



Colliding bunches	**4×10^7 Hz**
Proton collisions	**10^9 Hz**
Parton collisions	
New particles (Higgs, SUSY, ...)	**10^5 Hz**

Proton mass ~ 1 GeV/c² = 1.783×10^{-27} kg
1 TeV = a mosquito's kinetic energy



Event selection:
1 per 10,000,000,000,000

Theory ←→Observables

cross section: reaction rate per target particle per unit incident flux

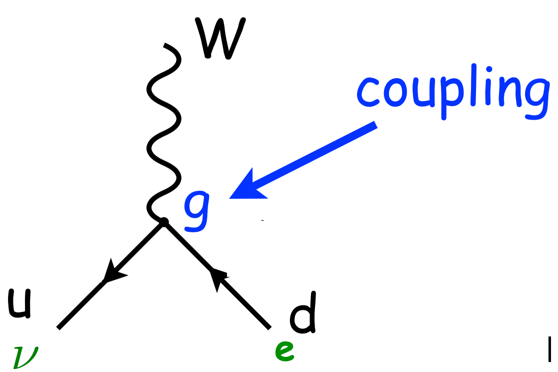
$$\frac{[1/\text{time}]}{[1/(\text{time length}^2)]}$$

--> measured in multiples of 1 barn= $10^{-24}\ \text{cm}^2$

typical relevant LHC cross sections ~ in pb

Decay width (inverse of lifetime of a particle) =transition rate

has dimension [1/time]

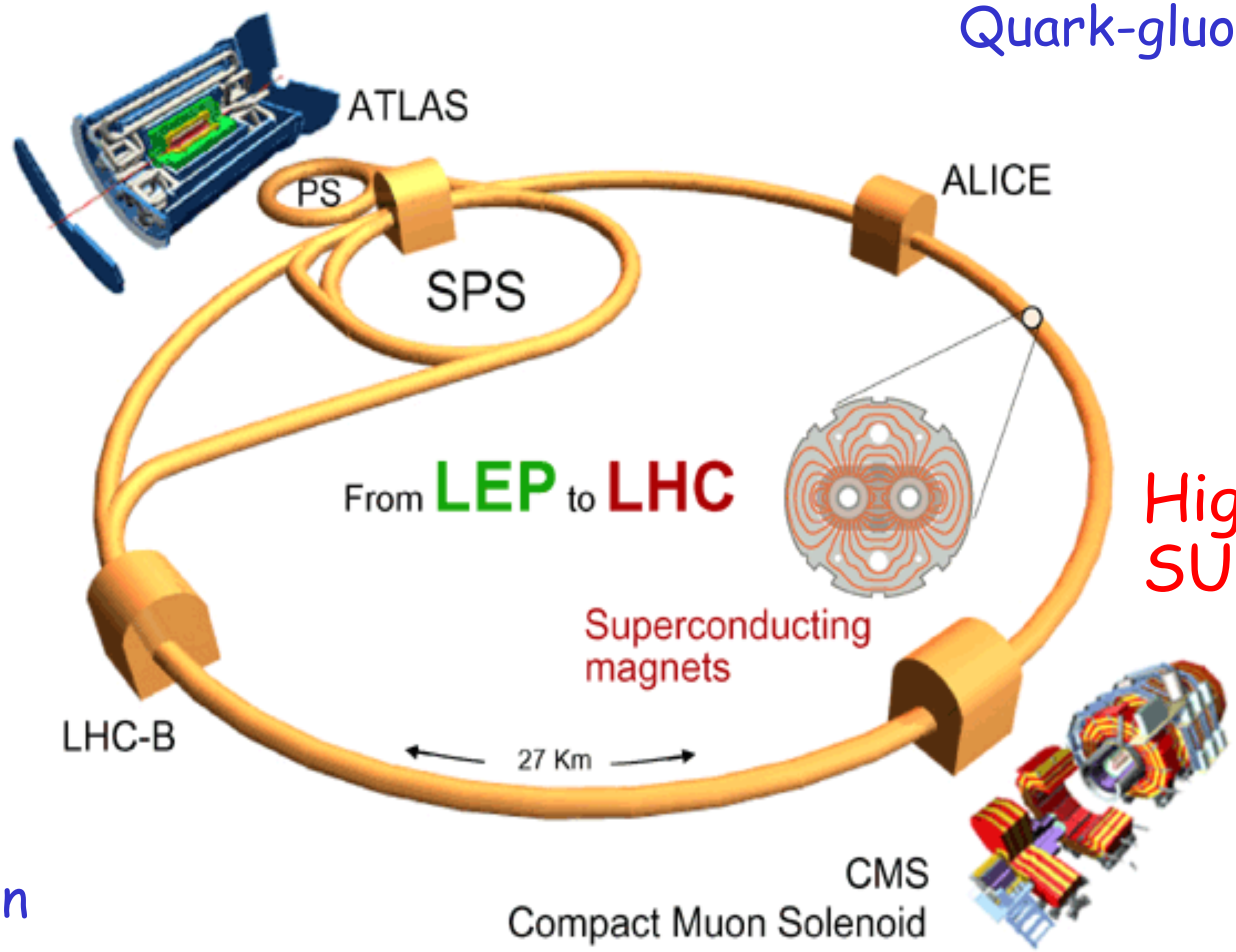


$$\Gamma \propto |\mathcal{M}|^2$$

LHC Experiments

Higgs
SUSY

Quark-gluon plazma

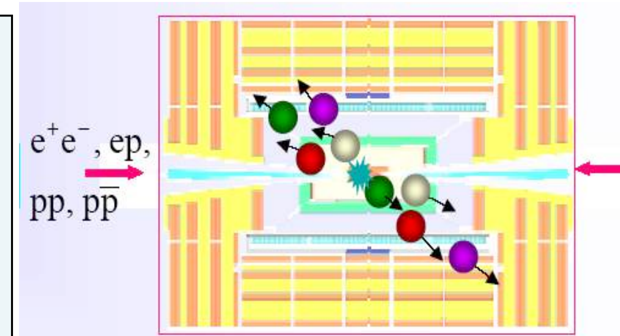


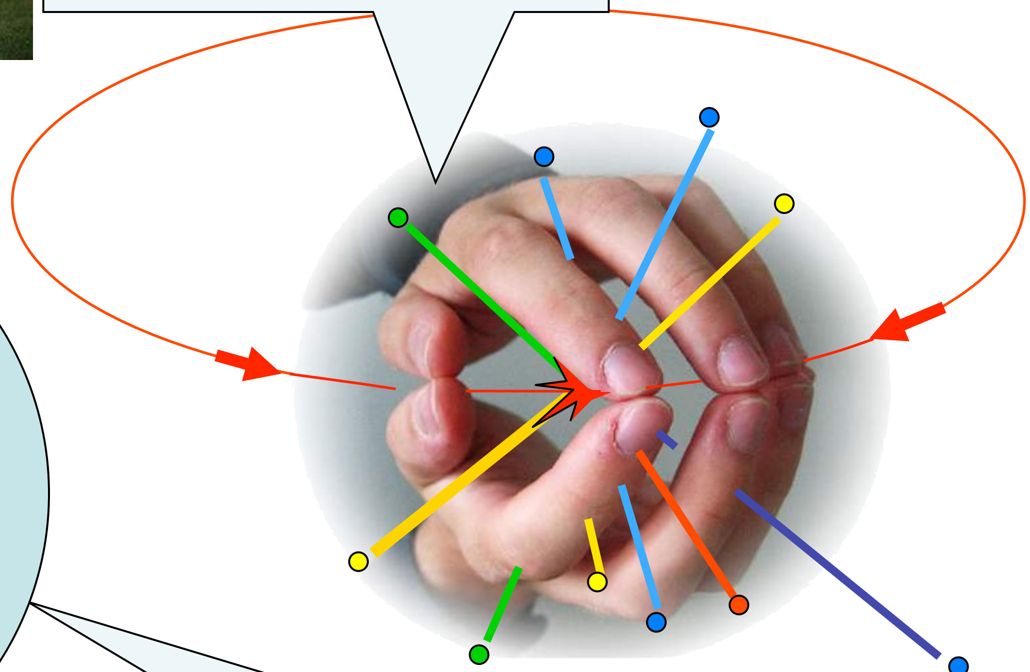
Higgs
SUSY

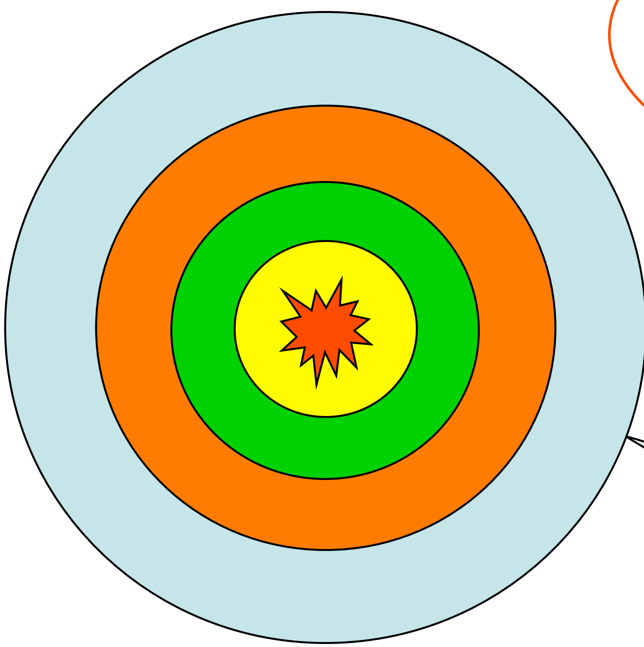
B-physics
CP violation

Detectors

Designed to cathes all particles created at the collisions



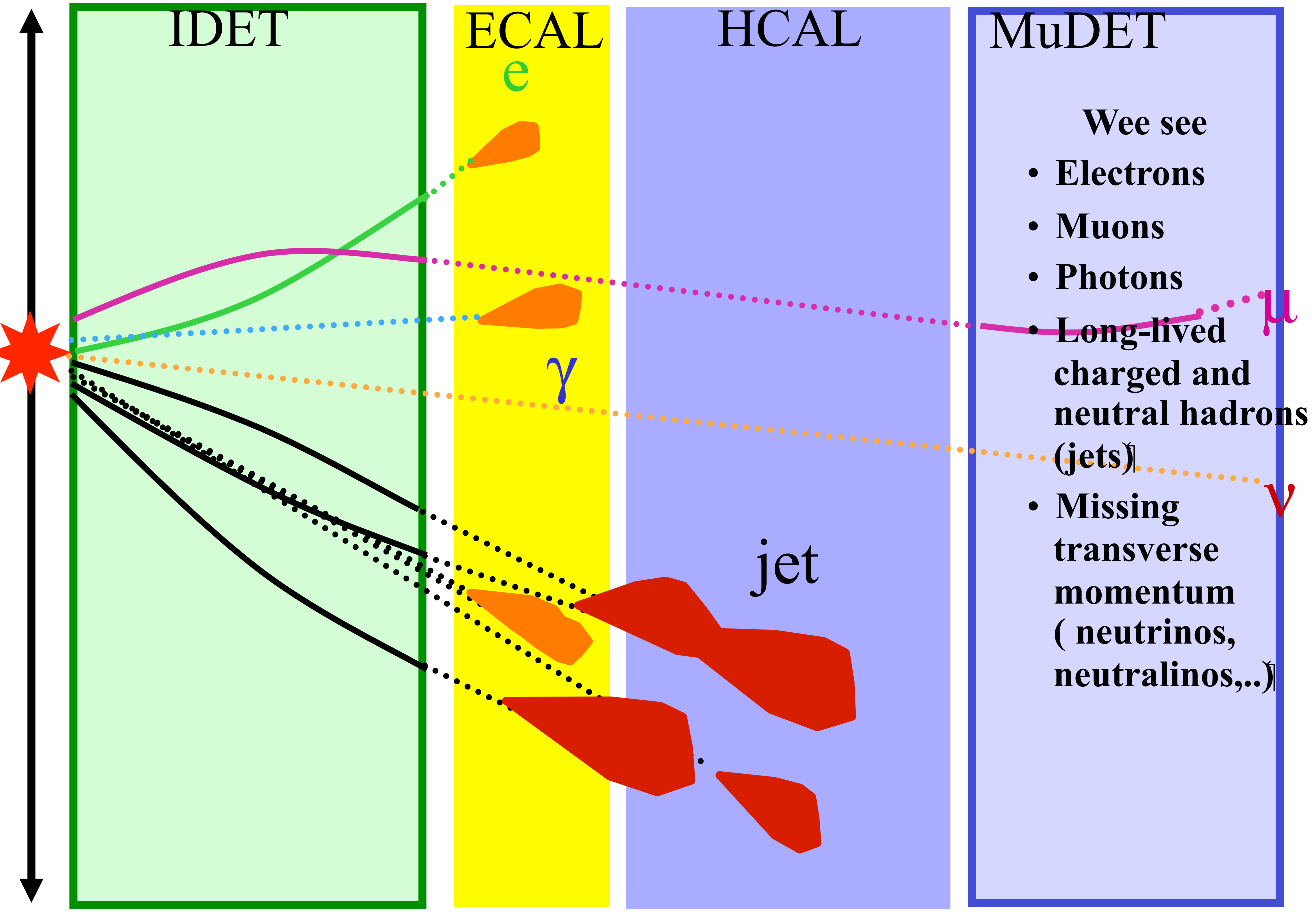




Sub detectors around each others

What do we actually measure?

The detectors give information on comparatively long-lived particles that are generally the decay products of the fundamental objects that we wish to study



We do not directly "see":

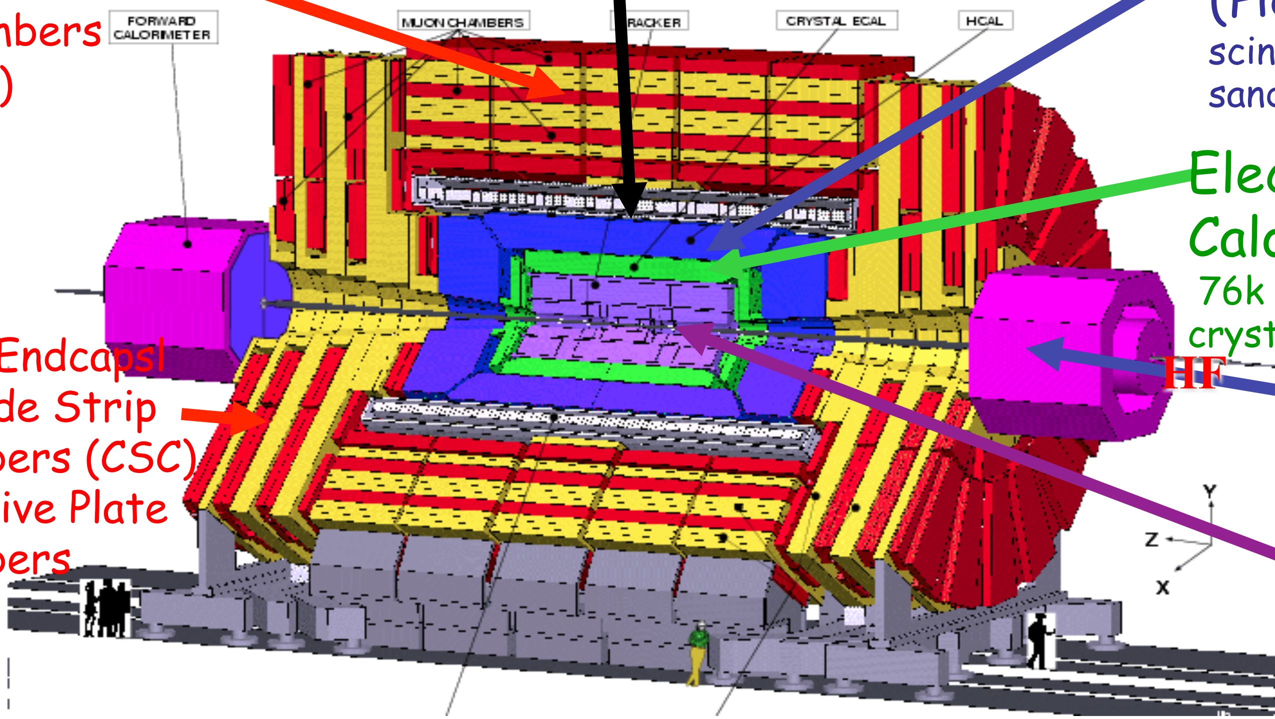
- Up, down, charm, strange and beauty quarks, and gluons (that manifest themselves as jets of hadrons)
- Top quarks that decay rapidly
  (e.g. t --> bW)
- W and Z bosons that decay rapidly to quarks or leptons
- Higgs bosons
- Etc

CMS Detector Systems

Muon Barrel
Drift Tube
Chambers (DT)
Resistive Plate
Chambers
(RPC)

Superconducting Coil, 4 Tesla

Central Hadronic
Calorimeter
(Hcal) Plastic
scintillator/brass
sandwich



Electromagnetic
Calorimeter (Ecal)
76k scintillating PbWO4
crystals

Muon Endcaps
Cathode Strip
Chambers (CSC)
Resistive Plate
Chambers
(RPC)

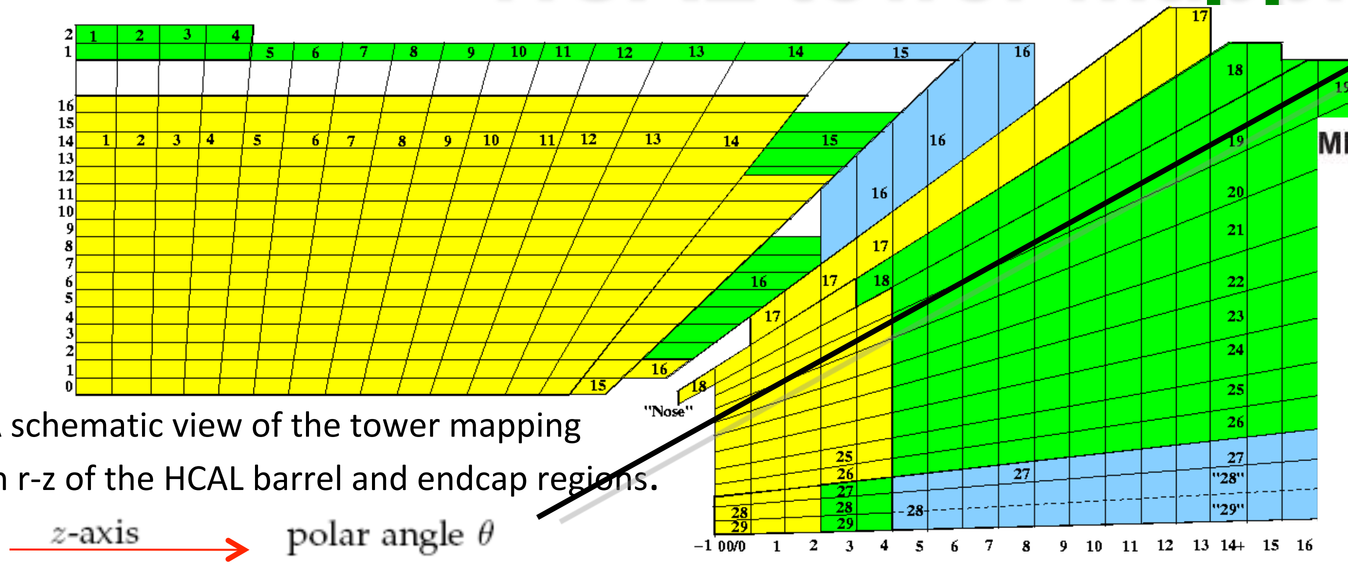
Tracker
Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

67

HCAL tower mapping

Pseudorapidity $\eta = -\ln\tan(\theta/2)$



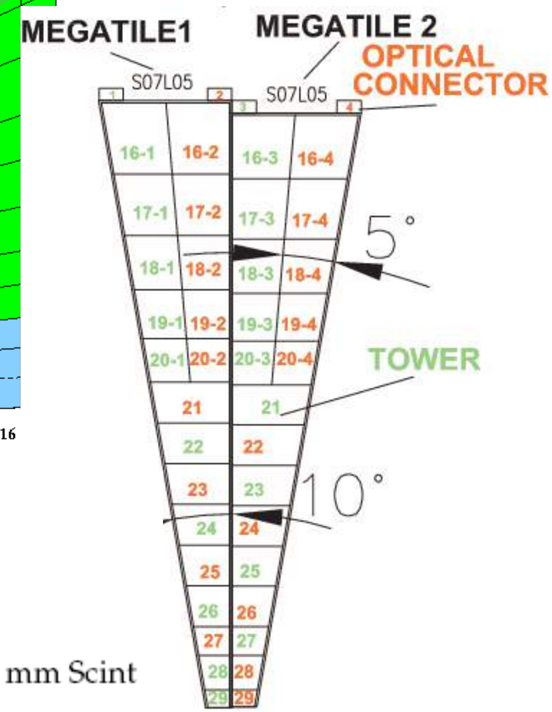
A schematic view of the tower mapping in r-z of the HCAL barrel and endcap regions.

(Layer 0) 9 mm Scint/61 mm Stainless Steel

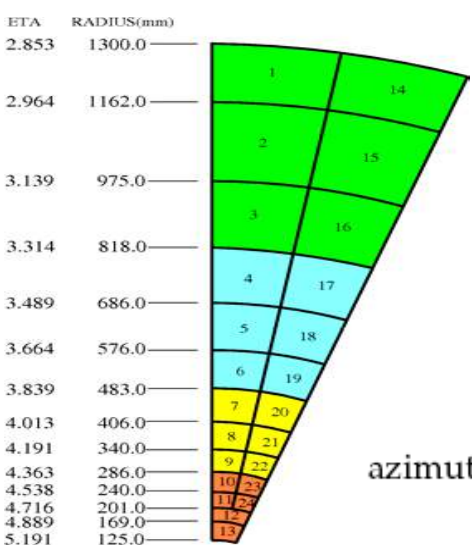
(Layers 1-8) 3.7 mm Scint/50.5 mm Brass

(Layers 9-14) 3.7 mm Scint/56.5 mm Brass

(Layers 15+16) 3.7 mm Scint/75 mm Stainless Steel/9 mm Scint



Numbering scheme for the tiles in adjacent scintillator trays.

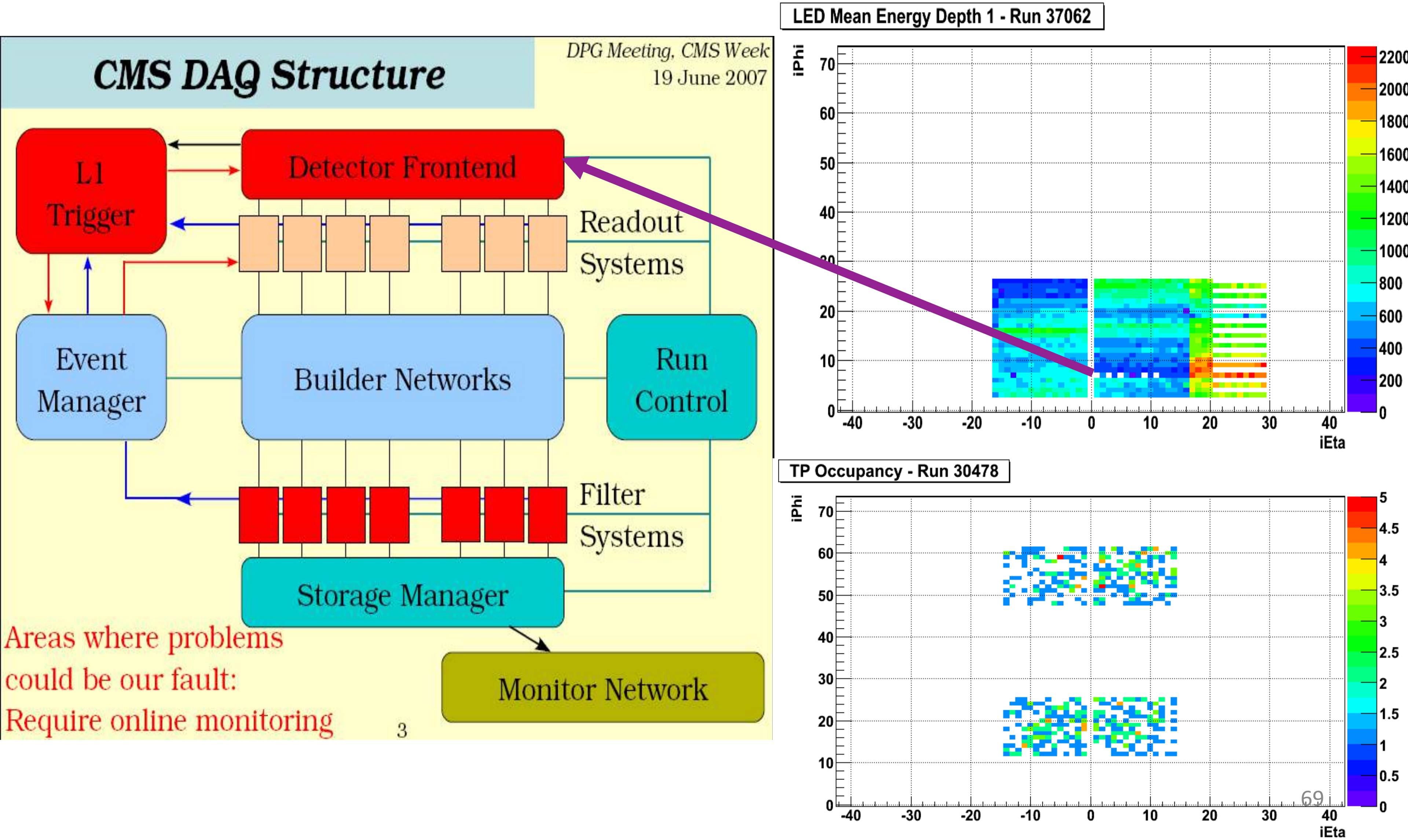


azimuthal angle ϕ x-y plane

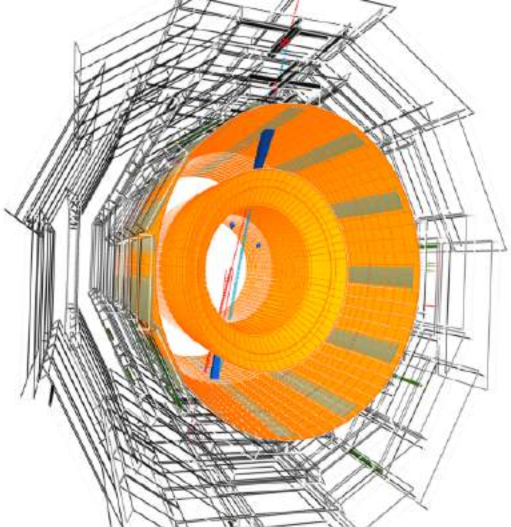
-x axis is horizontal, pointing south to the LHC center.
-y axis is vertical pointing upwards.
- z axis is horizontal pointing west.
-sign of eta=- sign of z.
theta=0 is +z axis, theta=pi is -z axis

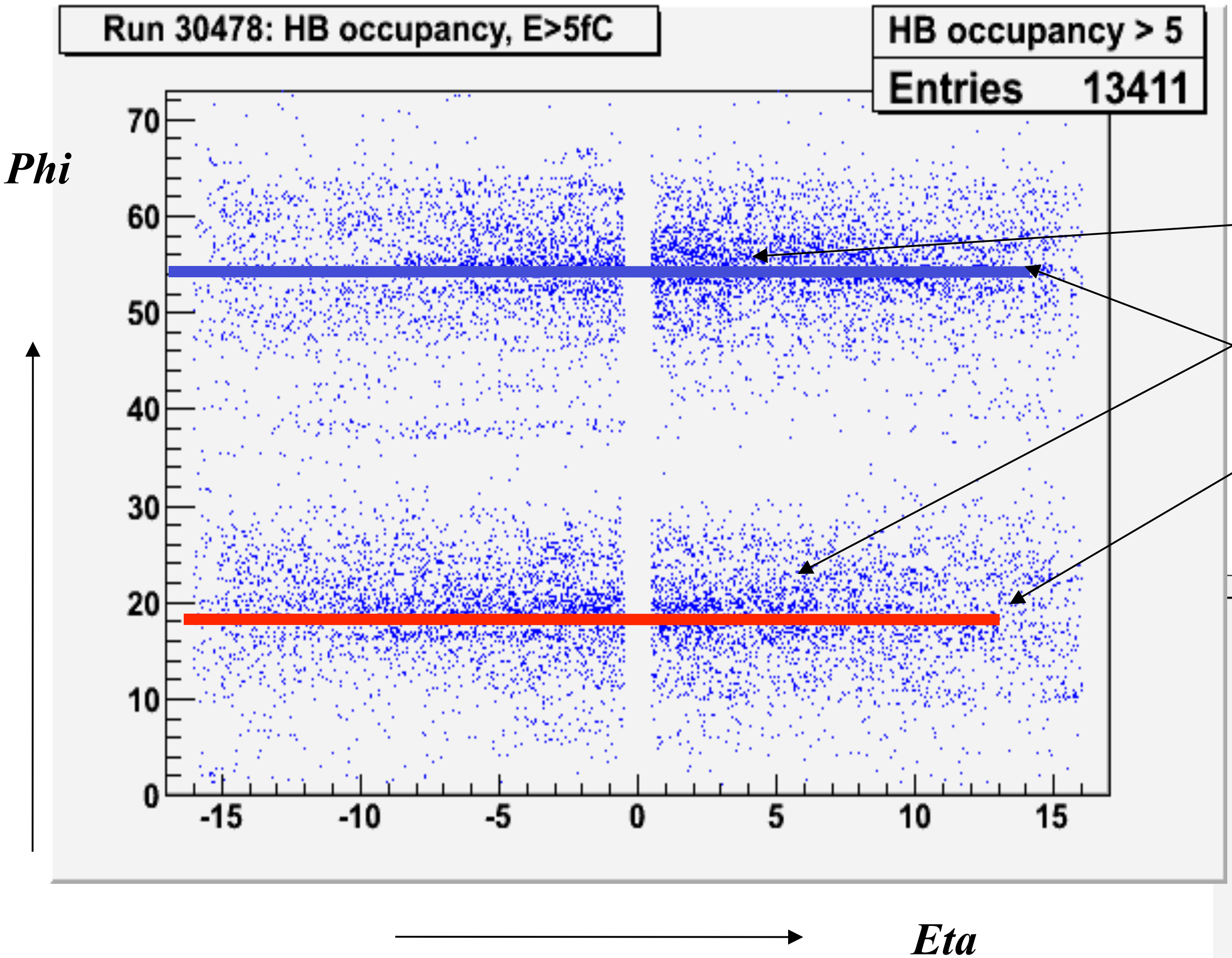
phi=0 is +x axis, phi=pi/2 is +y axis, phi=atan2(y,x)

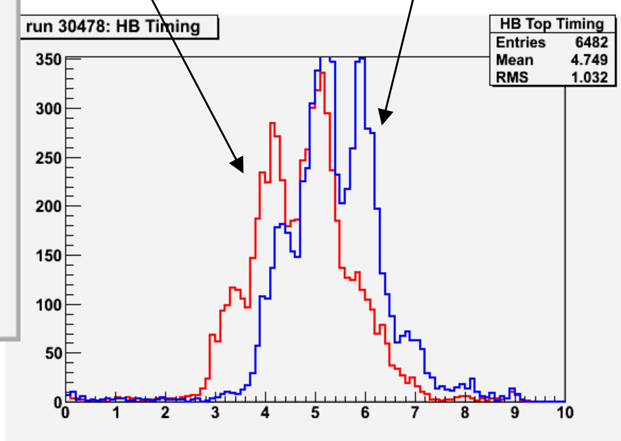
Data Quality Monitorins (DQM)



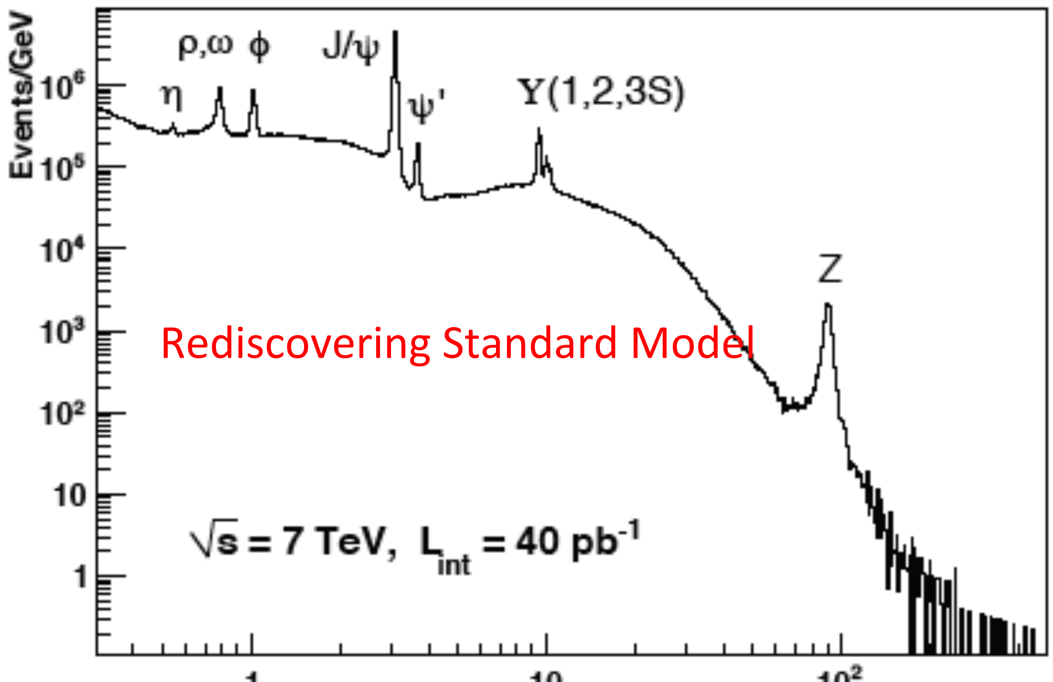
2007-2008: testing with Cosmic Muons







2009-2010 CMS

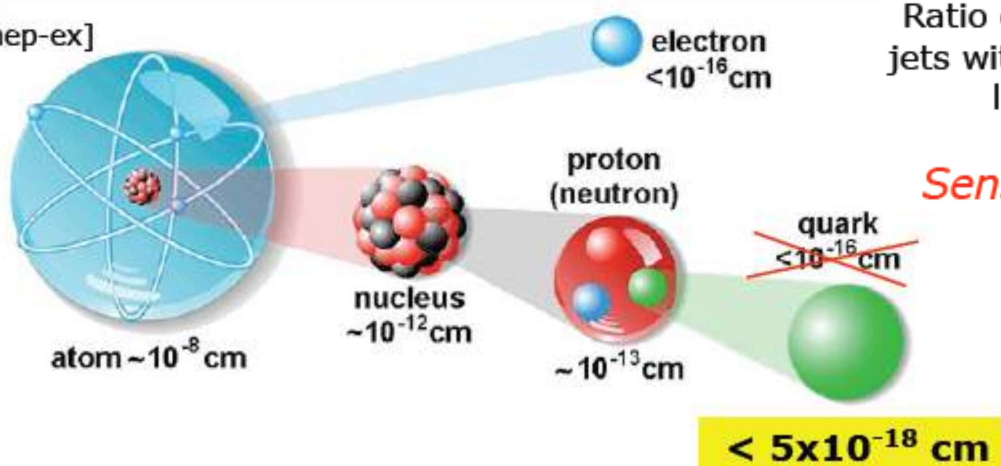


LHC will run through to the end of 2012 with a short technical stop at the end of 2011. The beam energy for 2011 will be 3.5 TeV.
Then, LHC goes into a long shutdown to prepare for higher energy running starting 2014.

Accepted by PRL
arXiv:1010.4439 [hep-ex]

Ratio of number of events with two leading jets within $|\eta| < 0.7$ to the number with both leading jets within $0.7 < |\eta| < 1.3$

Sensitive to Quark Sub-Structure



from **Philipp Schieferdecker (KIT)** **LHC End-Of-Year Jamboree December 17th 2010**

How to detect Higgs particle?!

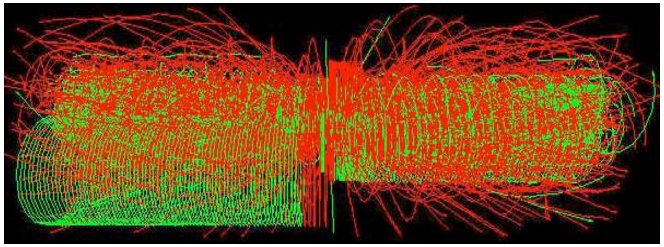
An example

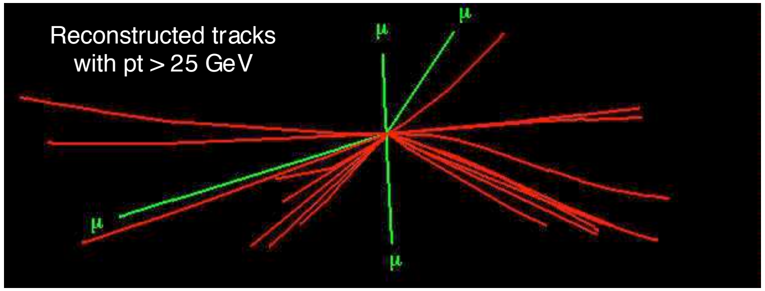
H → ZZ

Z → μμ

H → μμμμ

The cleanest signal

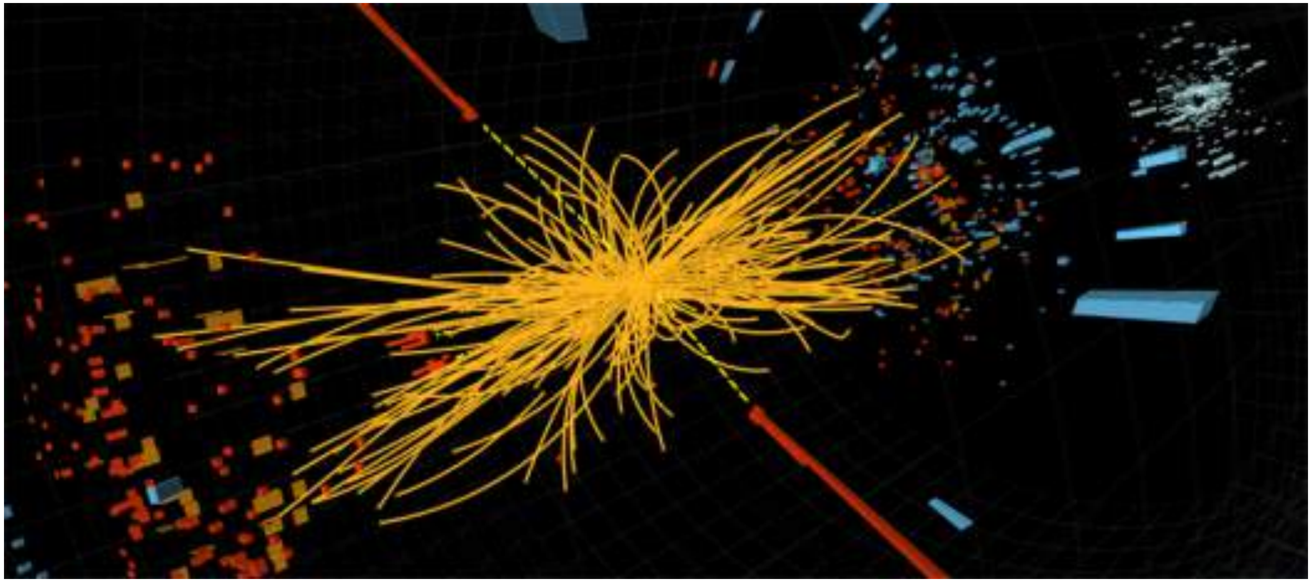




Repeated every 25 ns

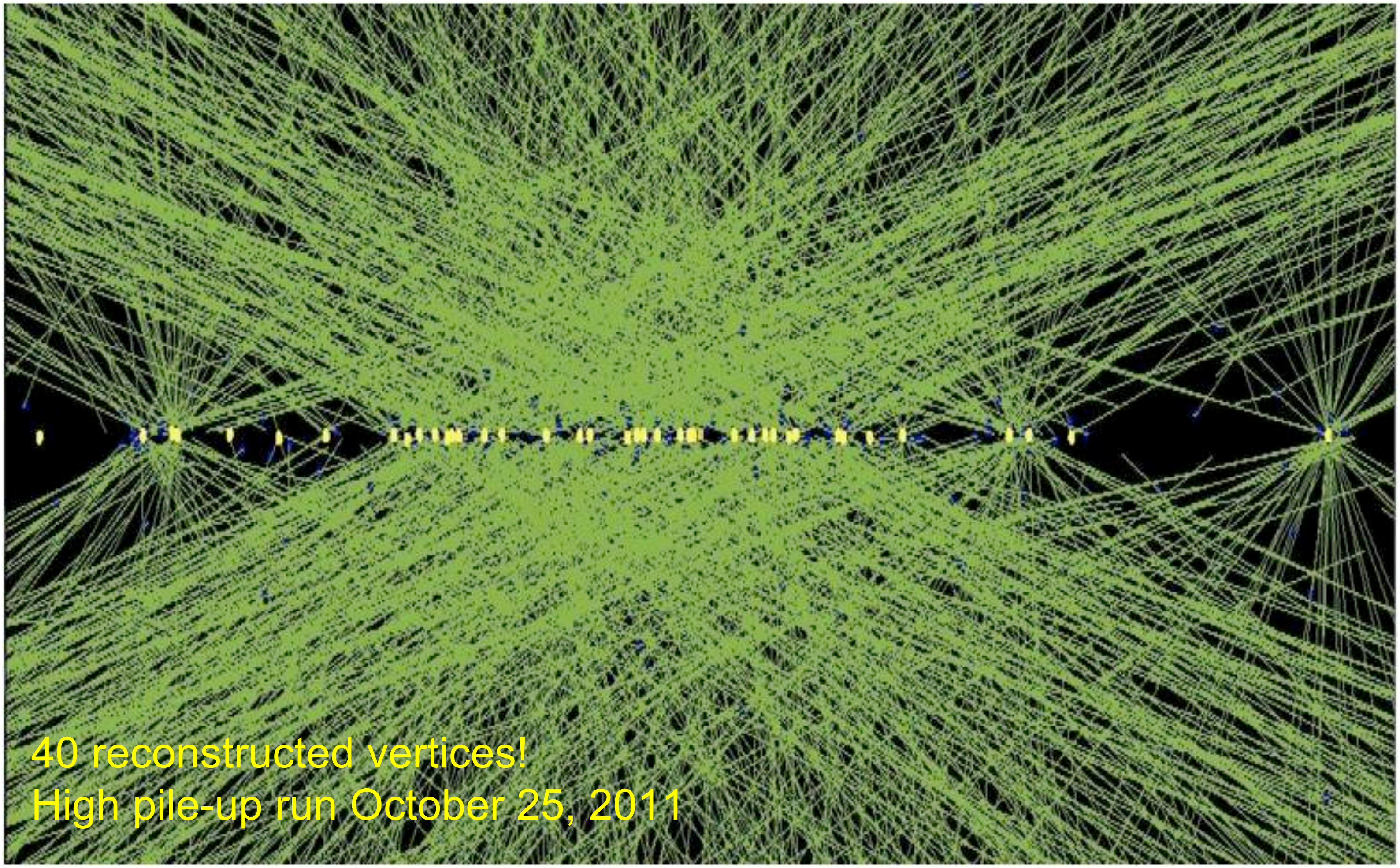
H → γγ

A real event from
4'th July 2012



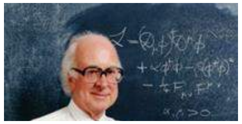
72

LHC operation in 2012 : pile-up, up to ~ 30 (50 nsec bunch spacing)

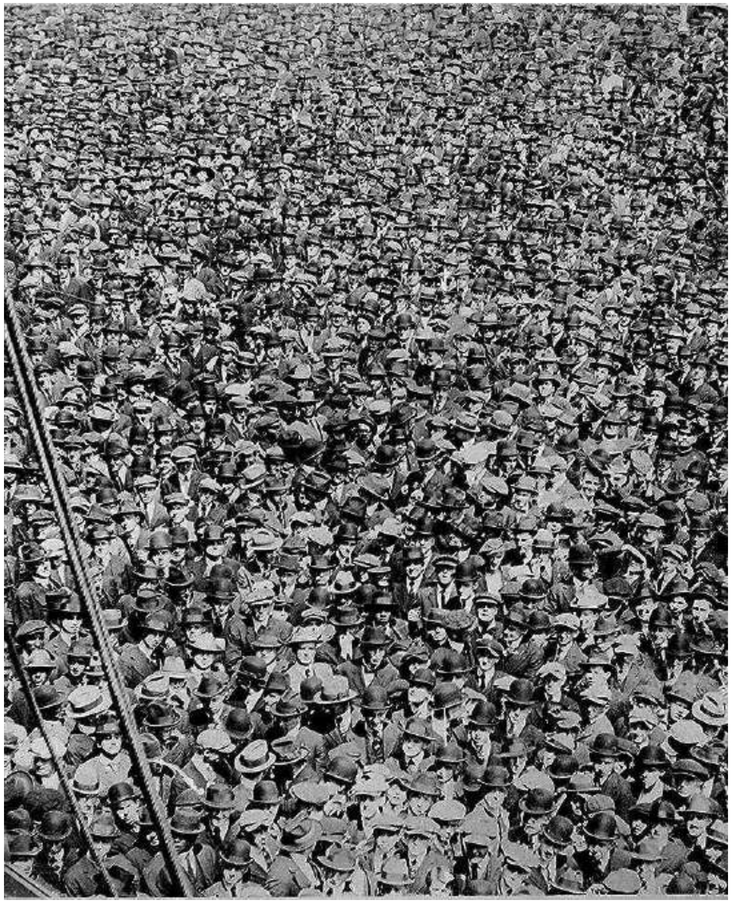


In HL-LHC phase we expect to go to ~100 -150 pile-ups per crossing!

Signals vs. Backgrounds



vs.

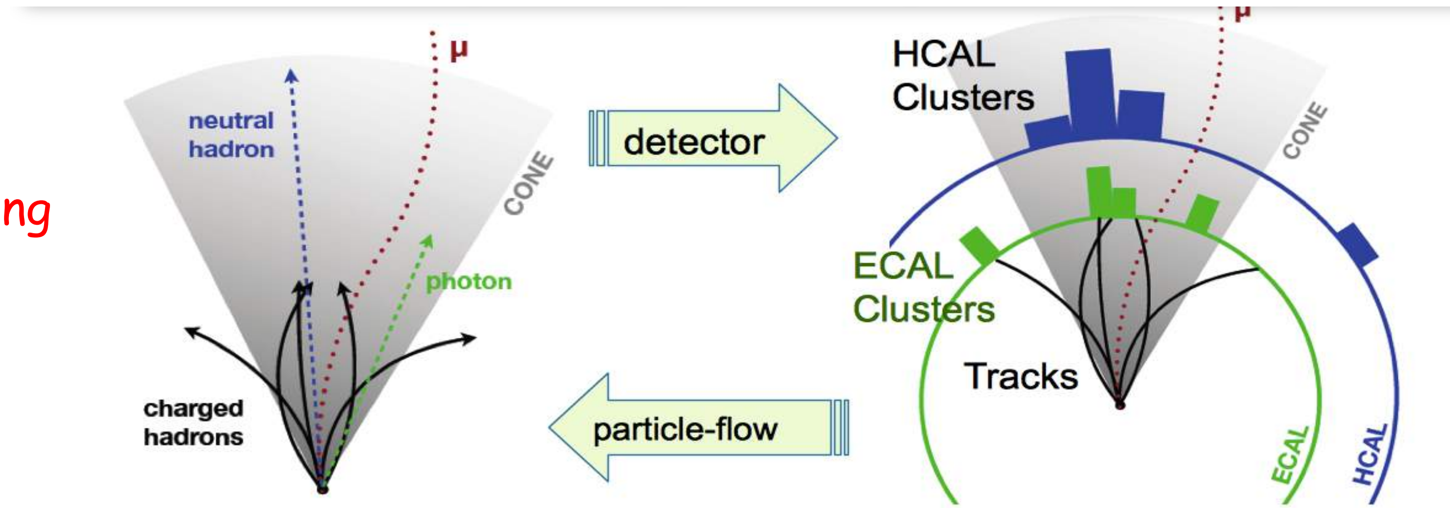


electron-positron colliders
– small backgrounds

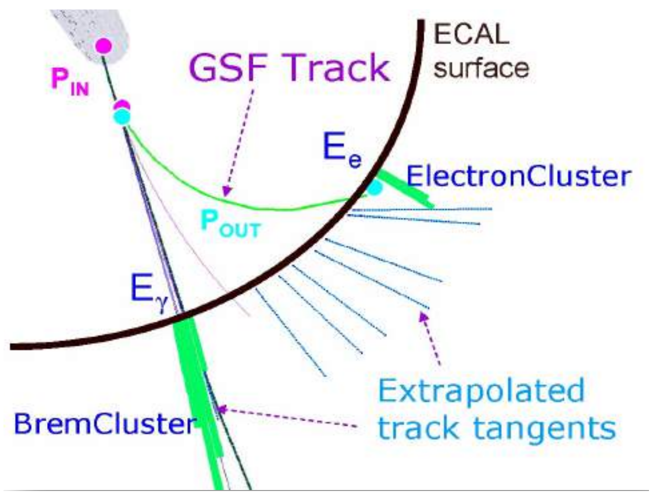
hadron colliders
– large backgrounds

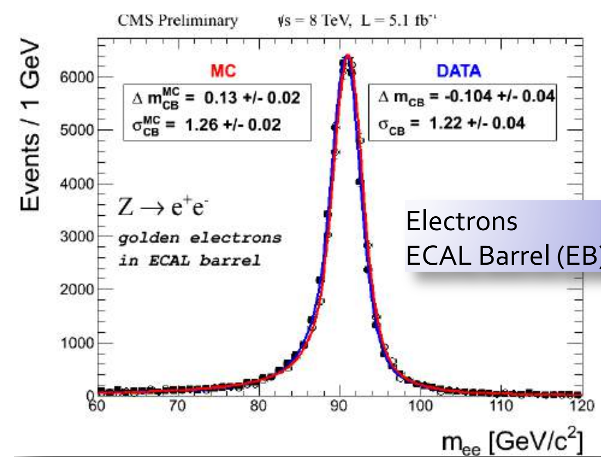
Towards discovery

Reconstructing particles

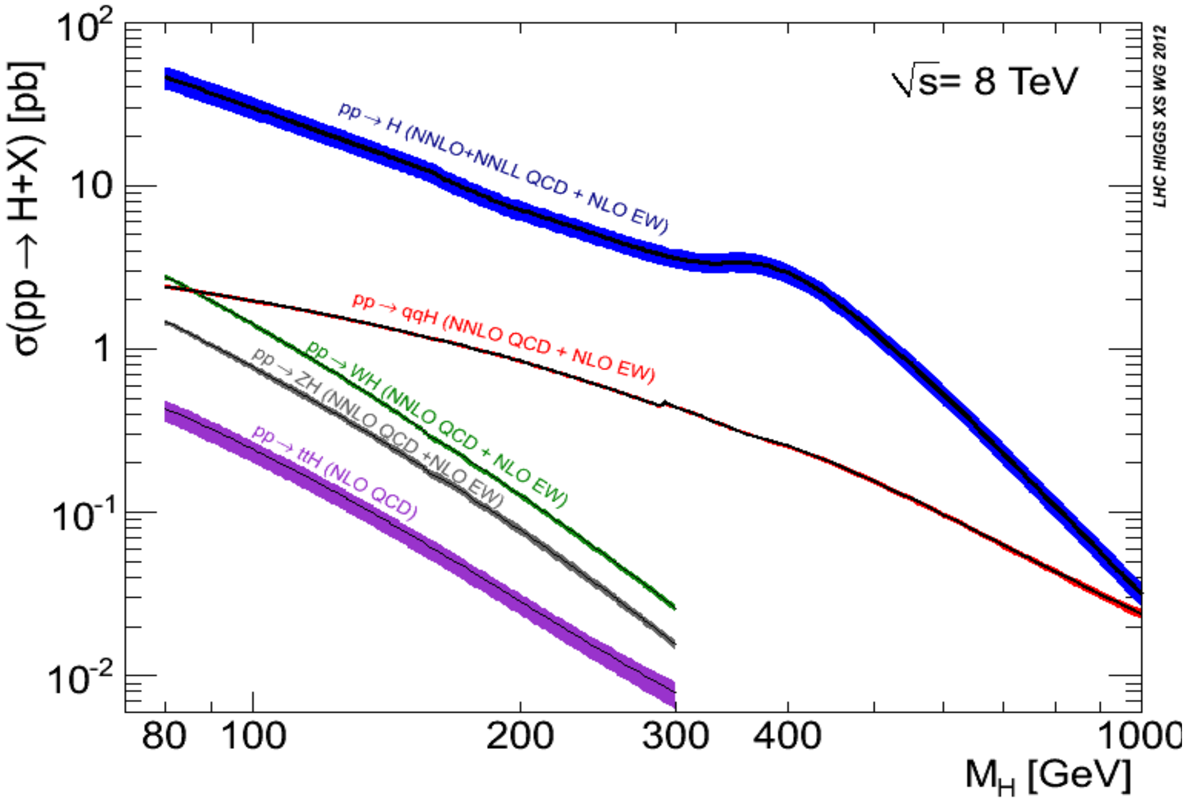


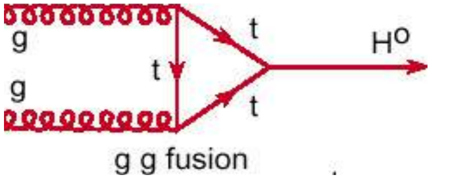
Electron/ photon separation

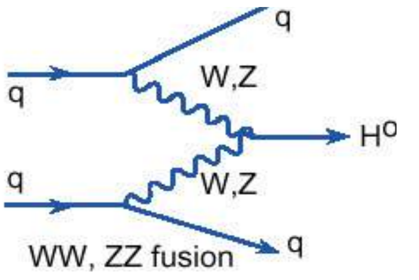


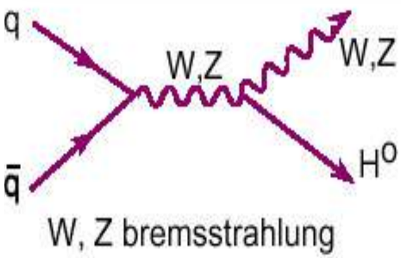


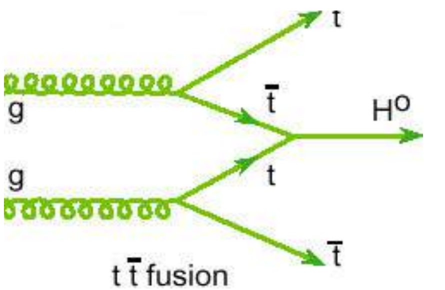
Higgs Production











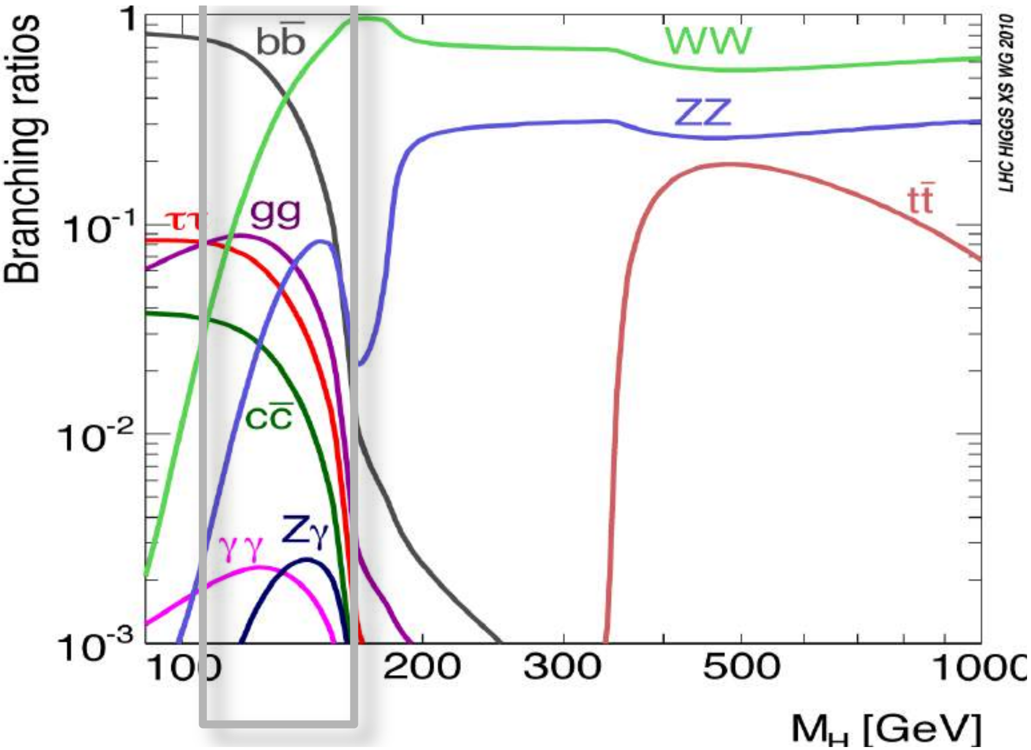
Higgs Decays

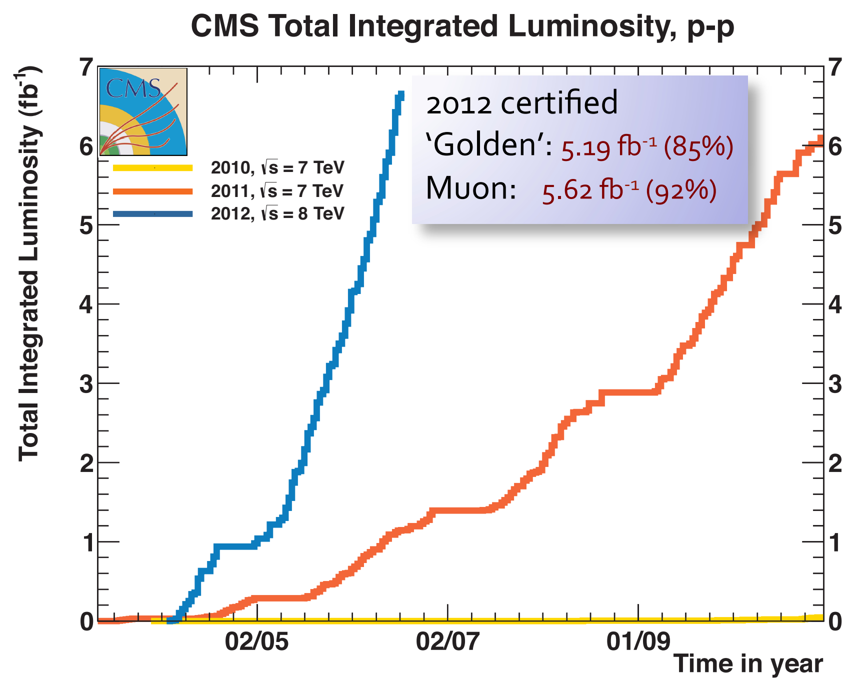
$$N = \sigma \int L dt$$

Number of events

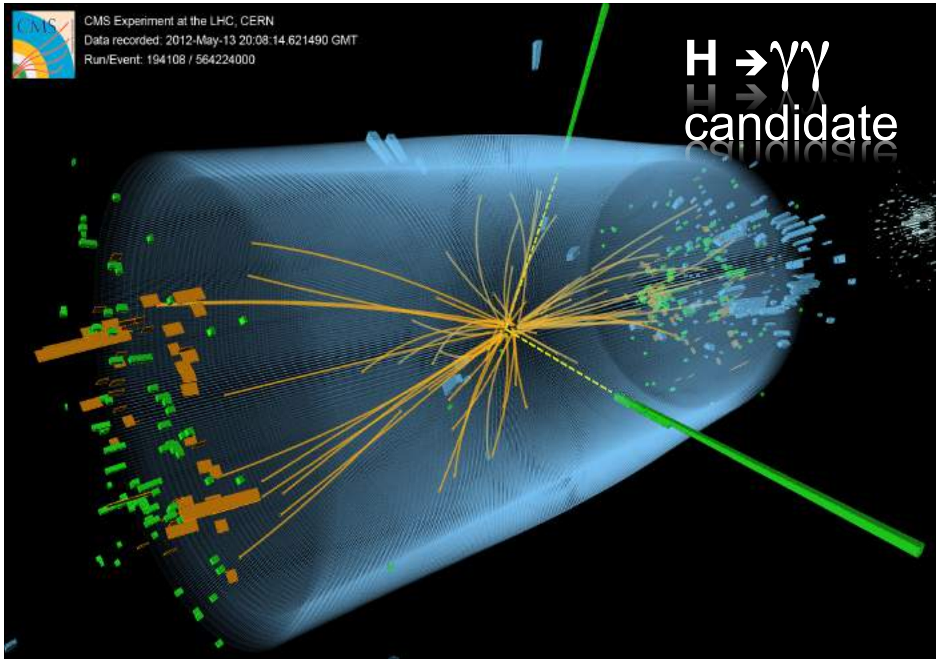
Cross section

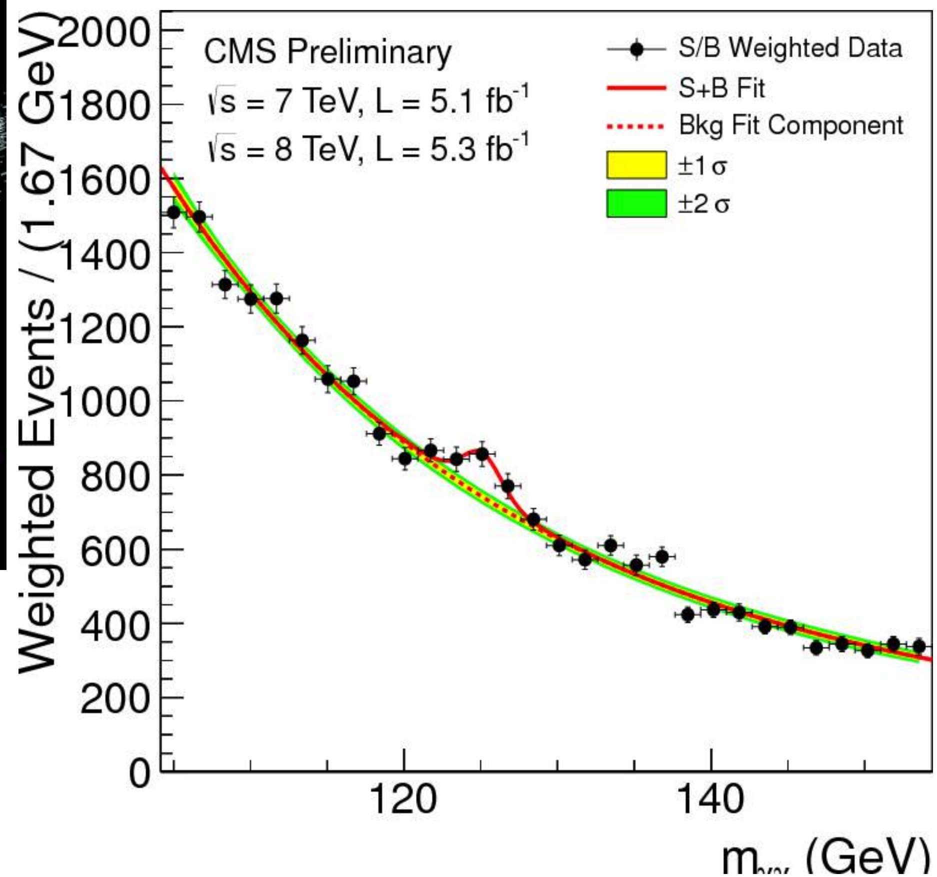
Integrated Luminosity

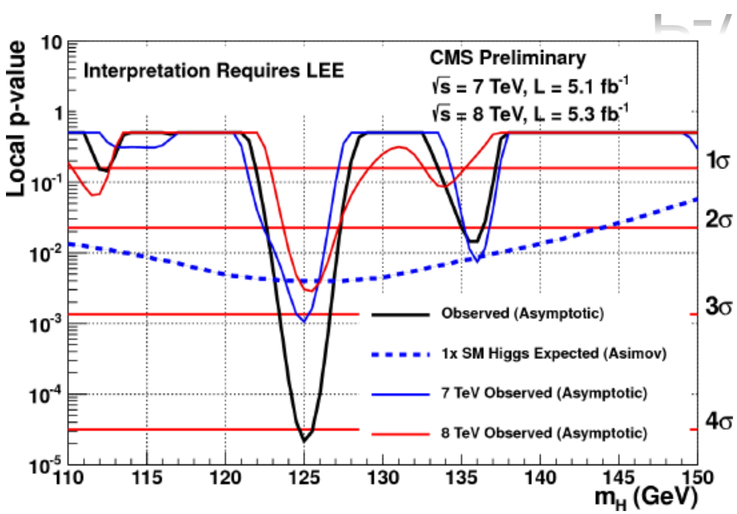




H → γγ

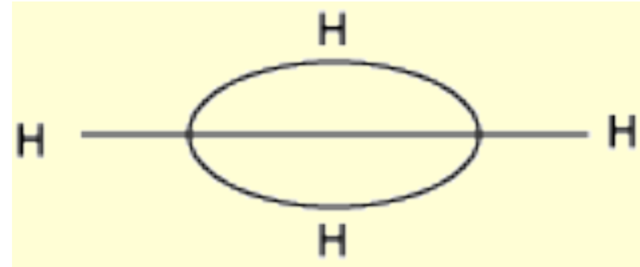

CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H →γγ
candidate


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
mγγ (GeV)


Interpretation Requires LEE
CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
Local p-value
Observed (Asymptotic)
1x SM Higgs Expected (Asimov)
7 TeV Observed (Asymptotic)
8 TeV Observed (Asymptotic)
1σ
2σ
3σ
4σ
mH (GeV)

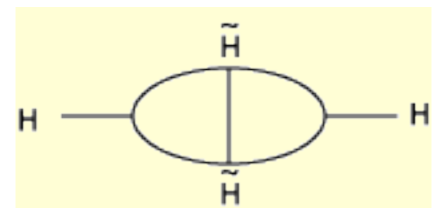
quantum divergencies of Higgs

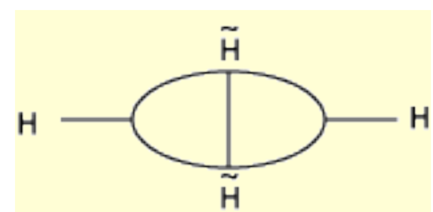
- Just like electron repeling itself because of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force

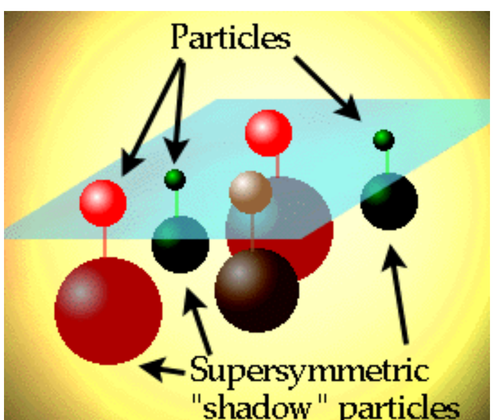


Solution: superpartners

"Vacuum bubbles" of superpartners (spin ½ difference) cancels the energy required to contain Higgs boson in itself





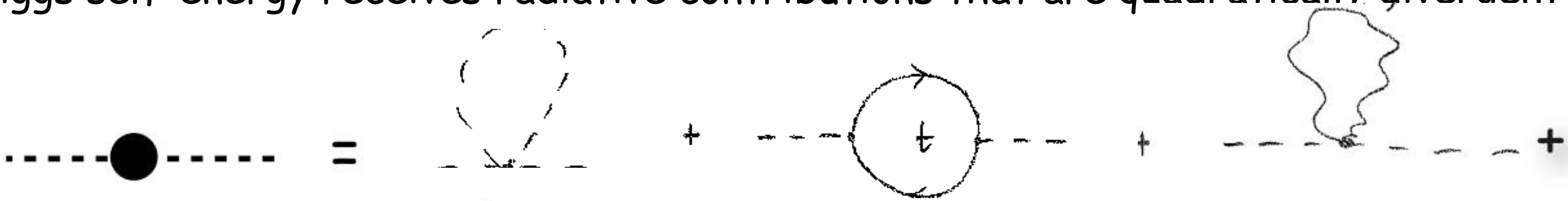


Quark **Lepton**	⟺	**Squark** **Slepton**
Wino **Higgsino**		**W** **H**

Fine tuning: Naturalness problem (hierarchy problem)

a fundamental scalar field in the theory (the Higgs),➔ Hierarchy problem

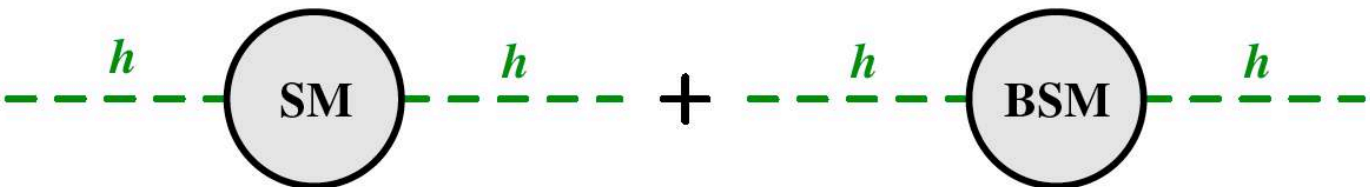
Higgs self-energy receives radiative contributions that are quadratically divergent

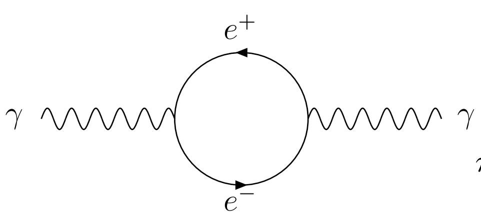


$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2 \quad \int \frac{d^4k}{(2\pi)^4} \frac{k^2}{(k^2 - m^2)^2} \propto \Lambda^2 \quad \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m^2} \propto \Lambda^2$$

$$\delta m_H^2 = \frac{3\Lambda^2}{8\pi^2 v^2} \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \sim -(0.23\ \Lambda)^2$$

To stabilise the Higgs mass at the EW scale against the Planck scale, we need to adjust the parameter of the Higgs potential at a level of 10^{-32}

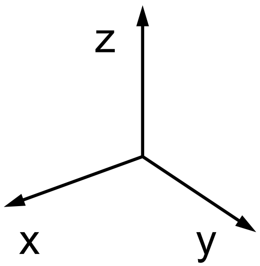


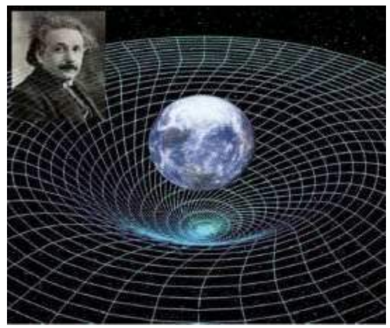


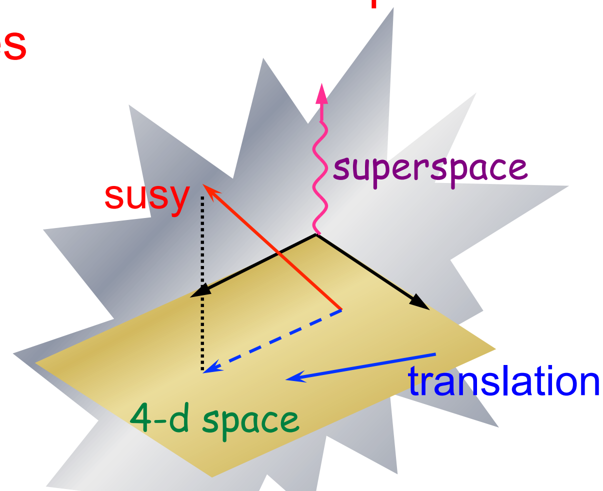
$$\pi_{\gamma\gamma}^{\mu\nu}(0) = -\int \frac{d^4k}{(2\pi)^4} \mathrm{tr}\left[(-ie\gamma^\mu)\frac{i}{\not k - m_e}(-ie\gamma^\nu)\frac{i}{\not k - m_e}\right] = -4e^2 \int \frac{d^4k}{(2\pi)^4} \frac{2k^\mu k^\nu - g^{\mu\nu}(k^2 - m_e^2)}{(k^2 - m_e^2)^2} = 0$$

Intrusion of SUSY to particle physics

Supersymmetry emerges from the search for new space-time symmetries







3-d space	4-d space-time	superspace
translations/rotations	Poincaré	supersymmetry
P = (x,y,z)	P = (t,x,y,z)	P = (t,x,y,z,θ,$\bar{\theta}$)

Grassmann numbers

$$\varphi(x,\theta) = \sum_n \varphi_n(x)\,\theta^n = \varphi_0(x) + \varphi_1(x)\,\theta$$

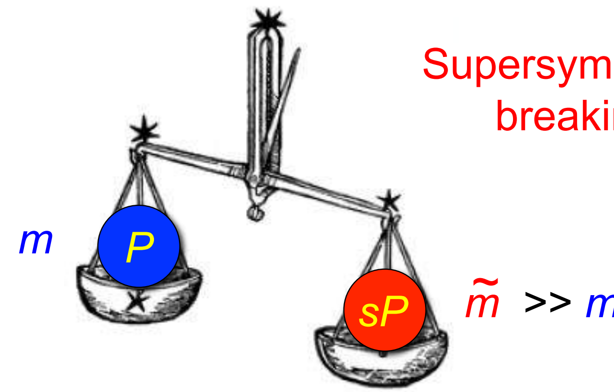
$$\theta \times \eta = -\eta \times \theta \quad \Rightarrow \quad \theta^2 = 0$$

$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle$ $\qquad$ $Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$

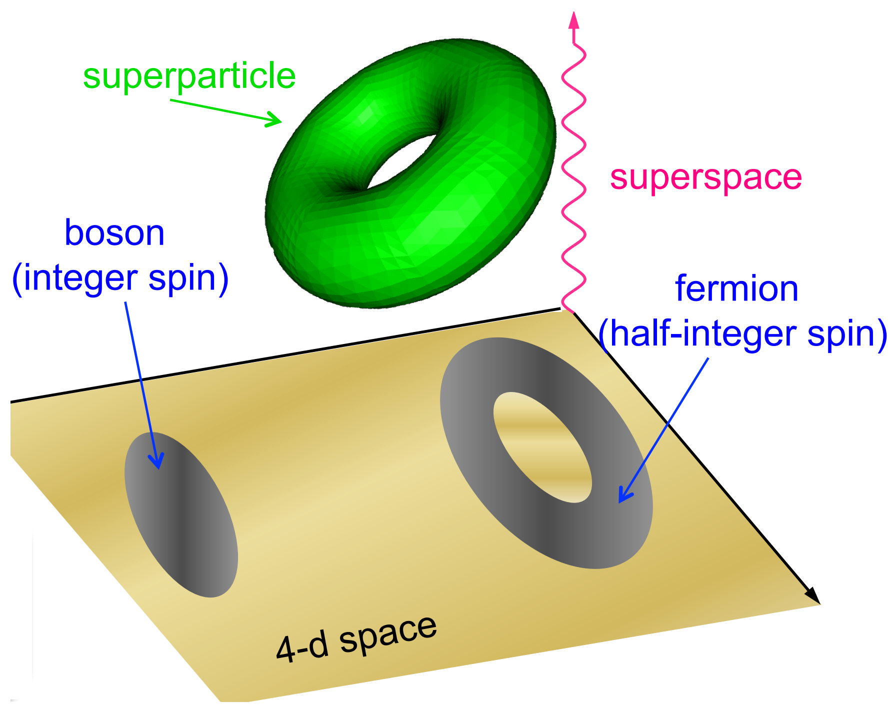
A broken Symmetry

Fields: $\psi(x)$ ➔ particles

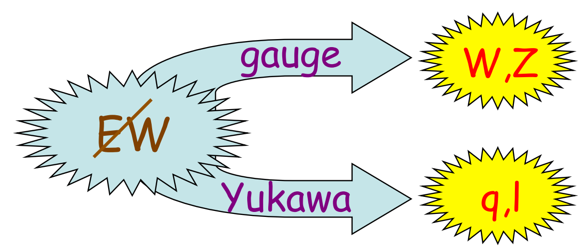
Supersymmetry breaking

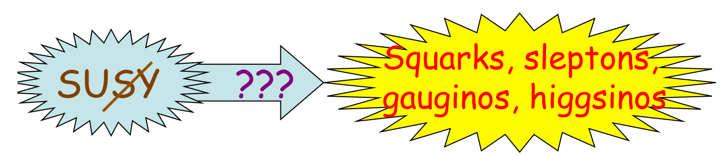


particles propagating in superspace ➔ Superparticle!



gauge symmetry ➔ $m = 0$
supersymmetry ➔ $\tilde{m} = 0$

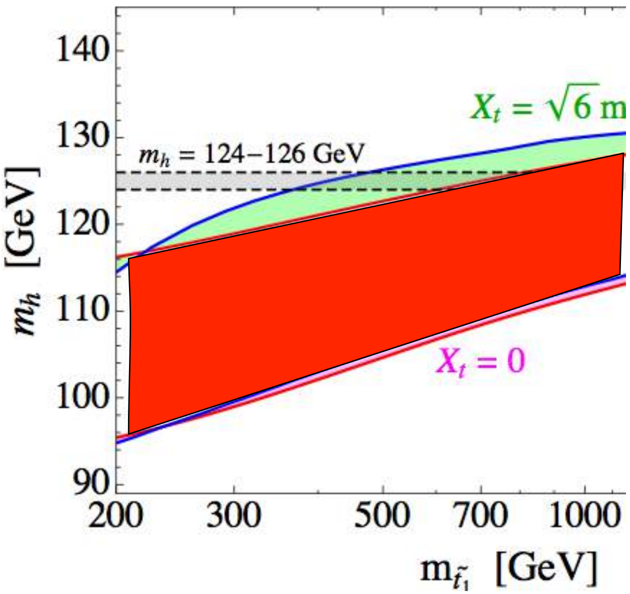




Supersymmetric Higgs (soft breaking)

Higgs potential $$V = \frac{\lambda}{4}\left(|h|^2 - v^2\right)^2$$

$$V = m_1^2|H_1^0|^2 + m_2^2|H_2^0|^2 - m_3^2\left(H_1^0H_2^0 + \text{h.c.}\right) + \frac{g_2^2 + g_Y^2}{8}\left(|H_1^0|^2 - |H_2^0|^2\right)^2$$



$$m_1^2 = m_H^2 + \mu^2;$$
$$m_2^2 = m_{\bar{H}}^2 + \mu^2;$$
$$m_3^2 = B \cdot \mu.$$

$$\frac{g_1^2 + g_2^2}{2}\left(v^2 + \bar{v}^2\right) = M_Z^2 = (91.18\ \text{GeV})^2$$

$$\tan\beta \equiv \bar{v}/v$$

$$m_1^2 = -m_3^2\tan\beta - \frac{1}{2}M_Z^2\cos(2\beta);$$
$$m_2^2 = -m_3^2\cot\beta + \frac{1}{2}M_Z^2\cos(2\beta).$$

$$B \cdot \mu = \frac{1}{2}\left[\left(m_H^2 - m_{\bar{H}}^2\right)\tan(2\beta) + M_Z^2\sin(2\beta)\right]$$

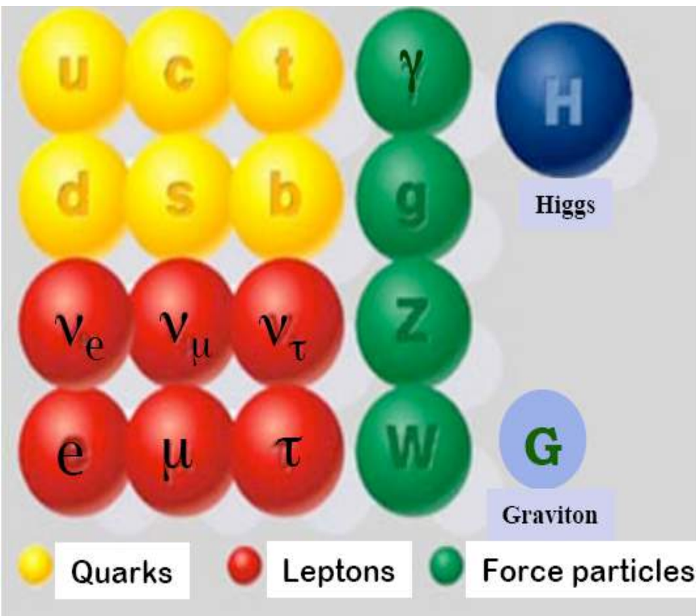
$$\mu^2 = \frac{m_{\bar{H}}^2\sin^2\beta - m_H^2\cos^2\beta}{\cos(2\beta)} - \frac{1}{2}M_Z^2.$$

SUSY Higgs coupling deviates from SM

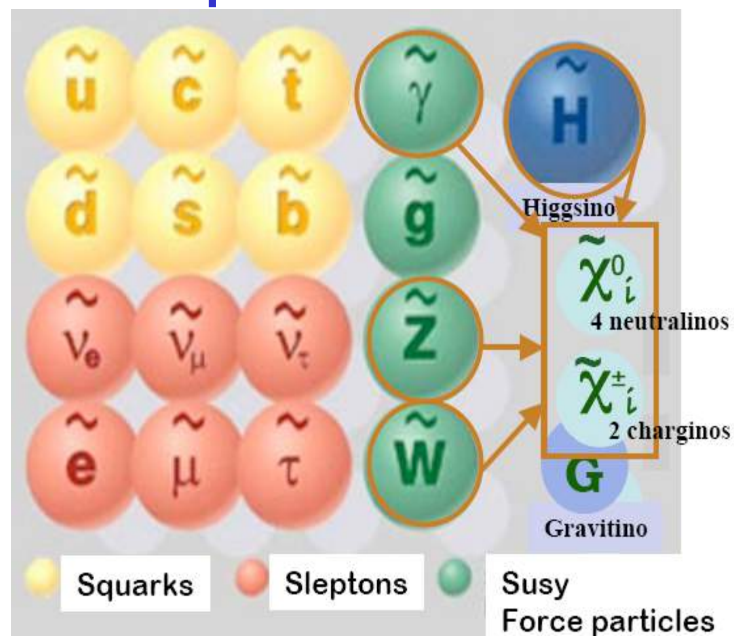
Supersymmetry

Extends the Standard Model by predicting a new symmetry
Spin ½ matter particles (fermions) <–> Spin 1 force carriers (bosons)

Standard Model particles



SUSY particles

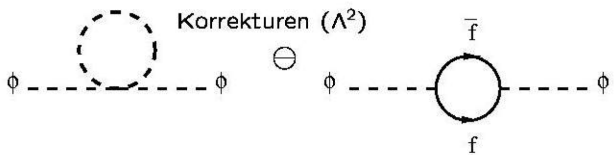


New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

Why SUSY ?

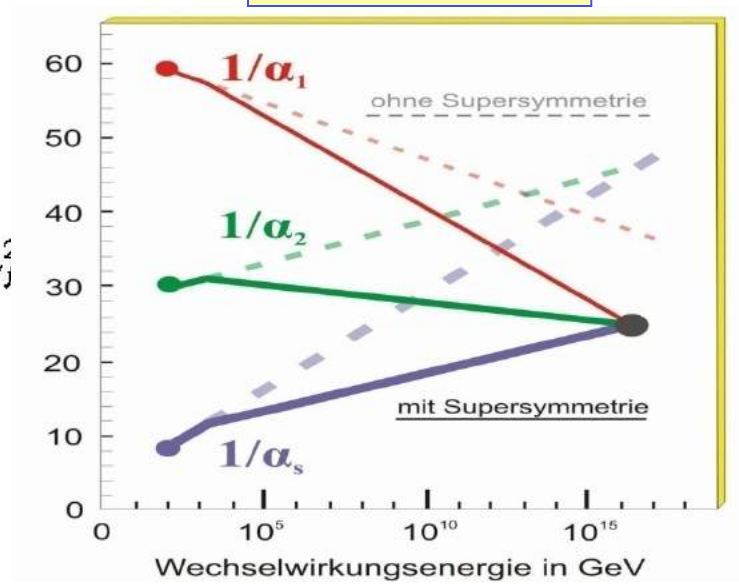
$m_{SUSY} \sim 1$ TeV

Quadratically divergent quantum corrections to the Higgs boson mass are avoided



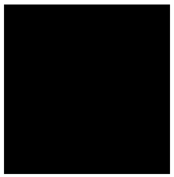
$$\Delta m_H = f(m_B^2 - m_f^2$$

(Hierarchy or naturalness problem)



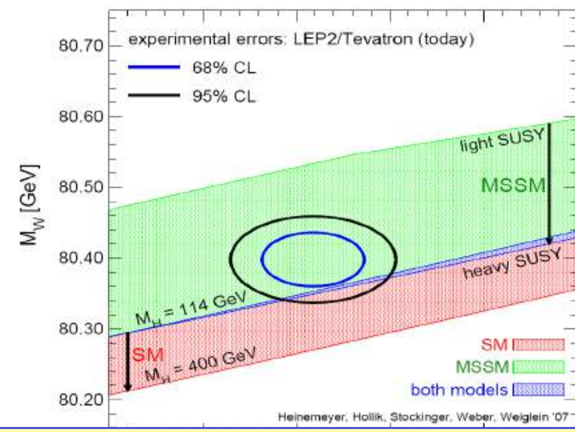
Unification of coupling constants of the three interactions seems possible

SUSY provides a candidate for dark matter,



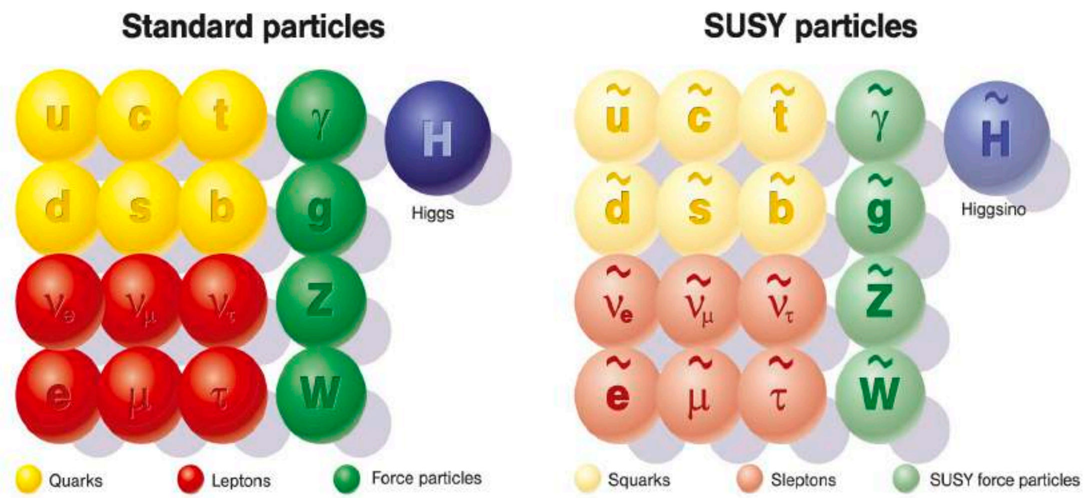
The lightest SUSY particle (LSP)

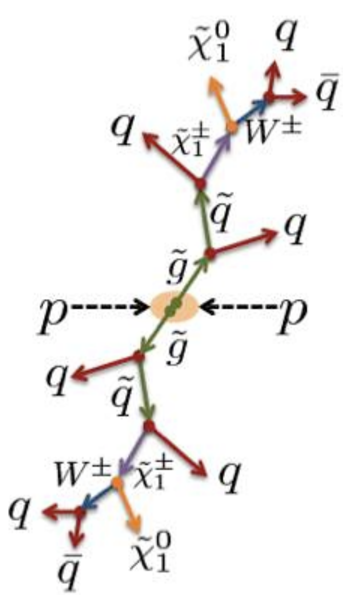
A SUSY extension is a small perturbation, consistent with the electroweak precision data

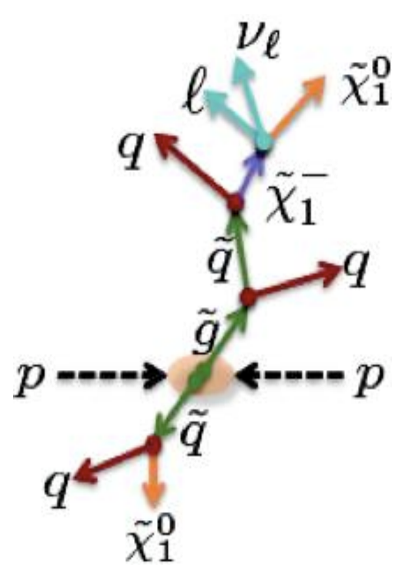


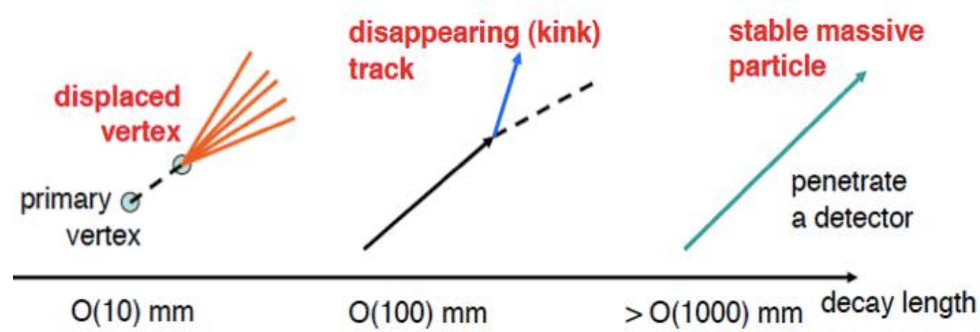
Present mass limits :	m (sleptons, charginos)	>	90-103 GeV	LEP II
	m (squarks, gluinos)	>	~ 250 GeV	Tevatron Run 1
	m (LSP, lightest neutralino)	>	~ 45 GeV	LEP II

SUSY searches





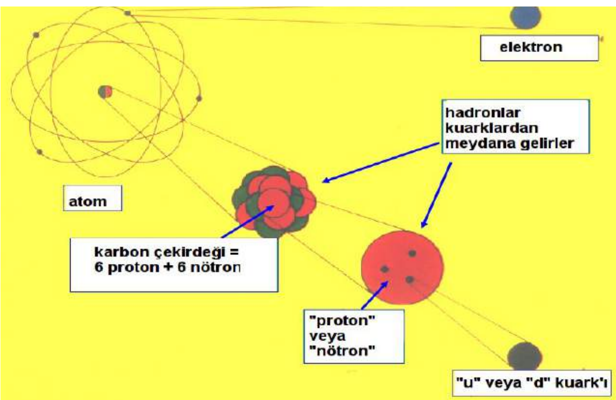


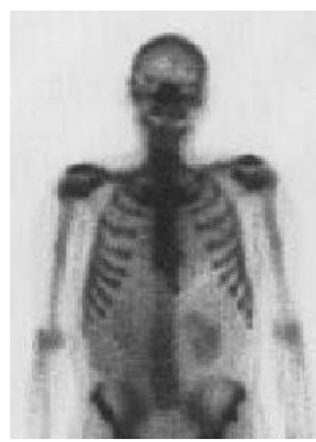


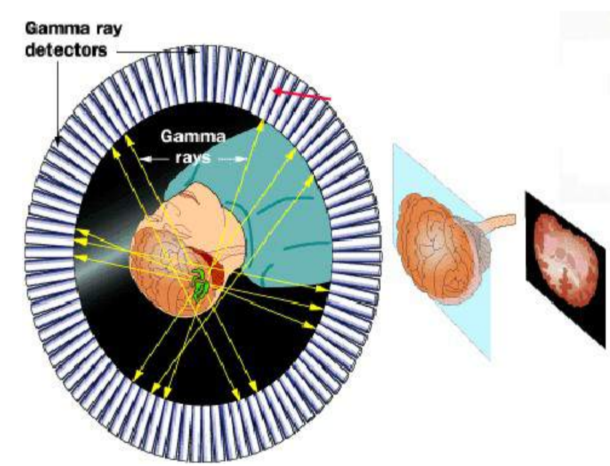
Yeni bir radyoterapi yöntemi: Hadron terapi

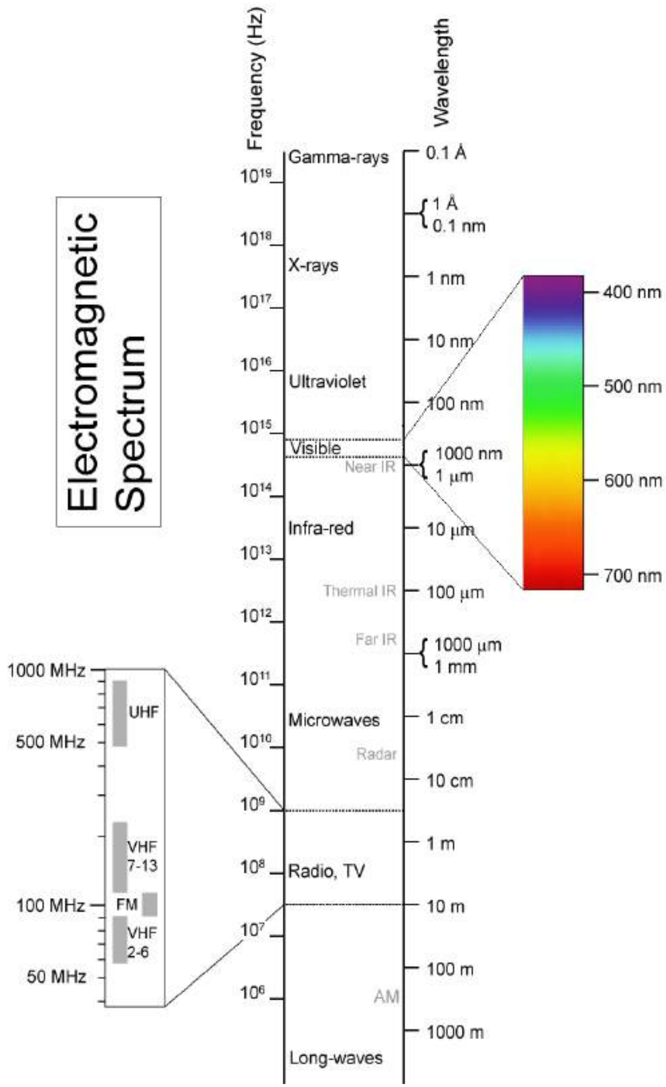
Hadron terapi, nükleer kuvvetlerle (**yeğin kuvvet**) etkileşen parçacıkları kullanarak yapılan bir radyasyon tedavi (ışın tedavisi) yöntemidir. Bu parçacıklar protonlar, nötronlar, pionlar ve çeşitli ionlardır (alpha, Ne, C,..vb gibi).

Hadron terapinin, yaygın olarak kullanılan ışın tedavisinden farkı, tümörlü hücreleri bombardıman ederken kullandığı mermilerin **ağır parçacıklar** oluşudur. **Işın tedavisinde** foton (bildiğimiz ışık) kullanılır. **Fotonlar**, elektromanyetik etkileşimin kuvvet taşıyıcılarıdır ve **kütlesiz** parçacıklardır. Oysa hadron terapide kullanılan "hadronlar" adı üstünde "ağır" parçacıklardır. Örneğin protonun kütlesi 1 milyar eV'dur (elektronun kütlesinin 2000 katı). Ağır parçacık kullanmanın zorluğu yanında, bir çok avantajı bulunmaktadır: protonlar radyasyon dozunu çok iyi bir şekilde dağıtabilirler, istenilen yere odaklayabilirler; nötronlar ise çok iyi bir tümör katilidirler.

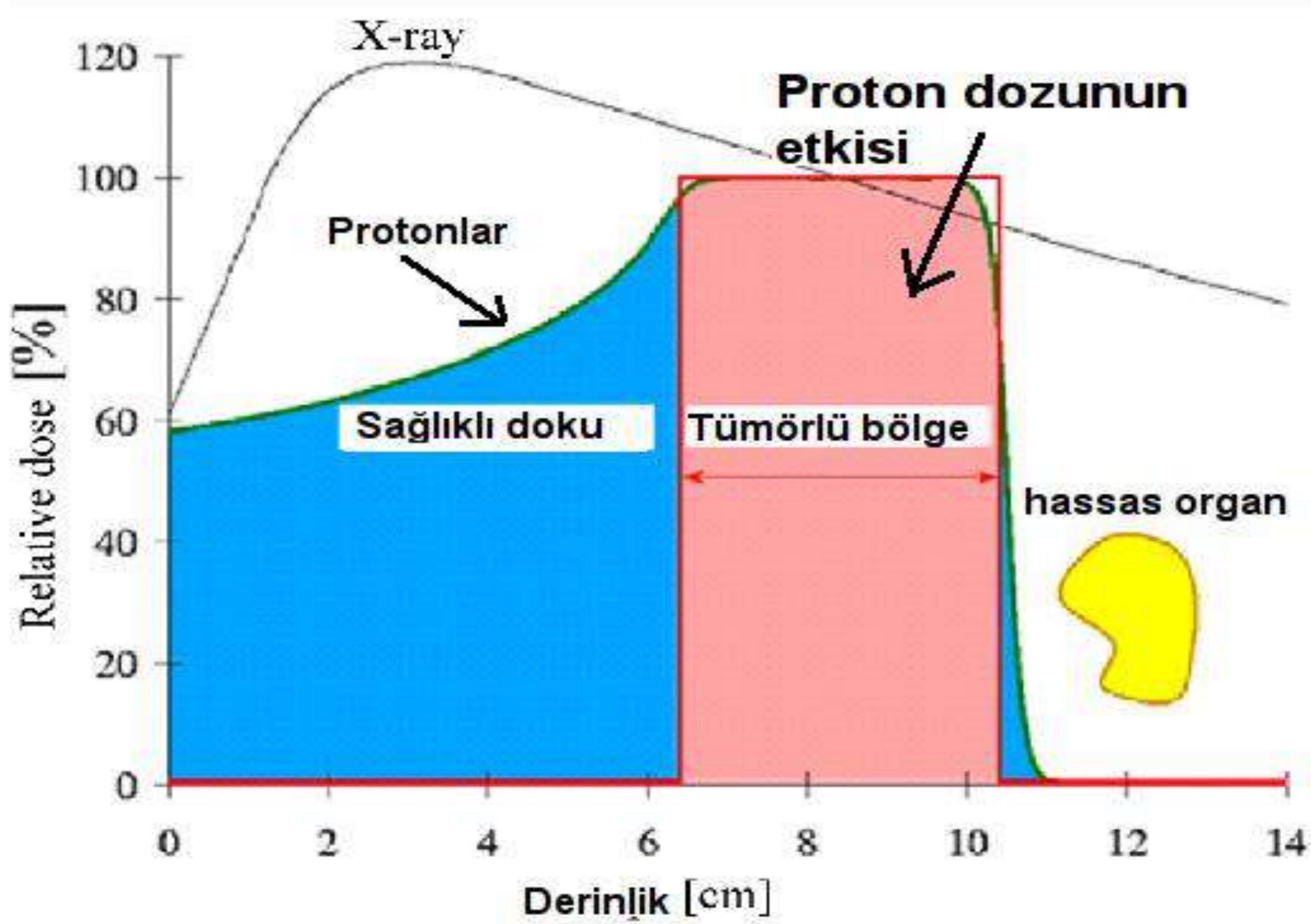


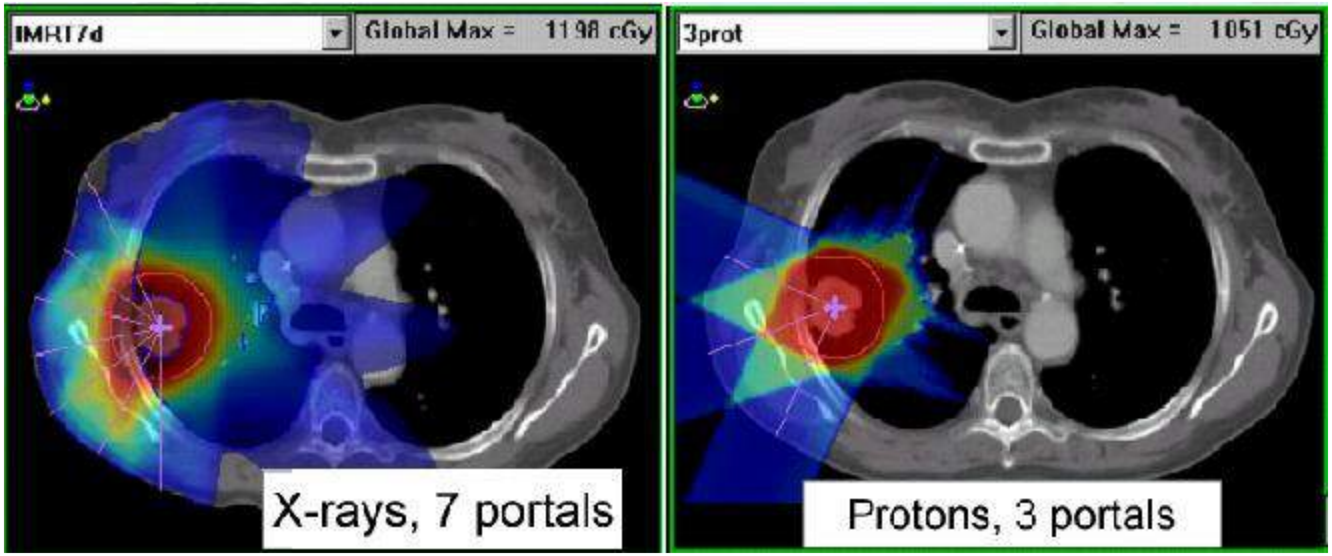


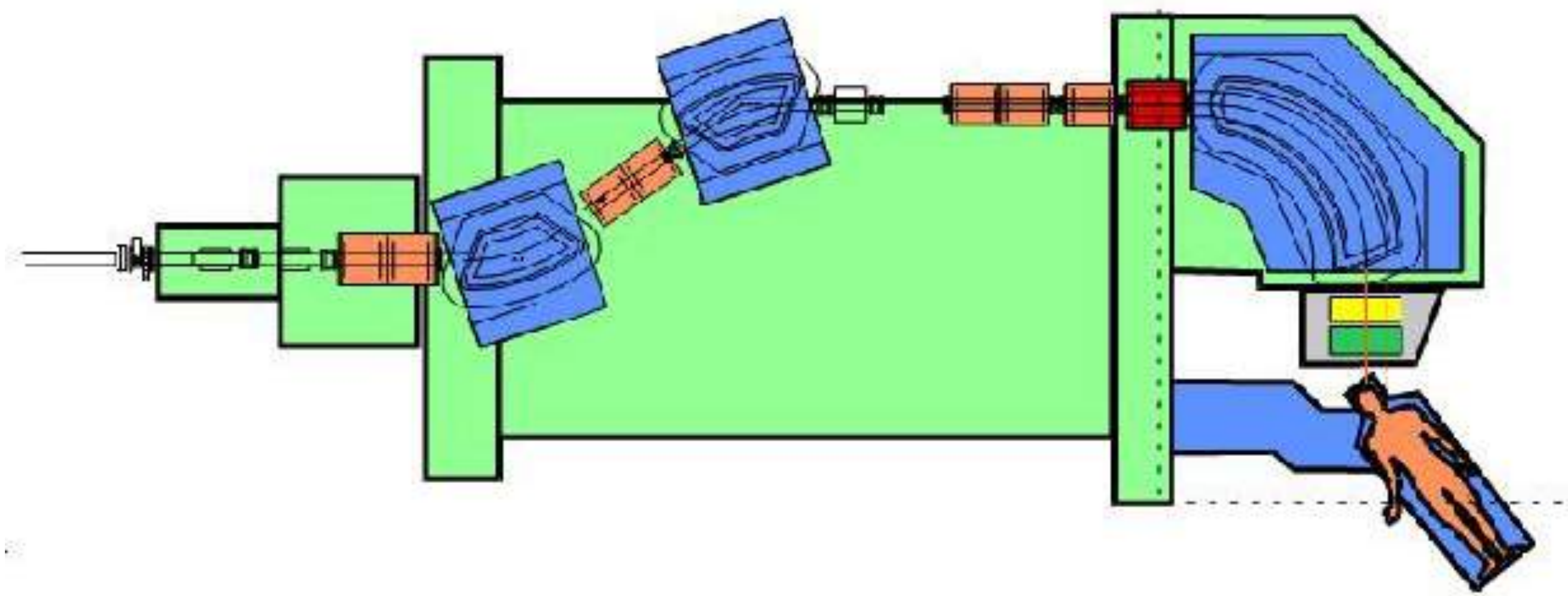


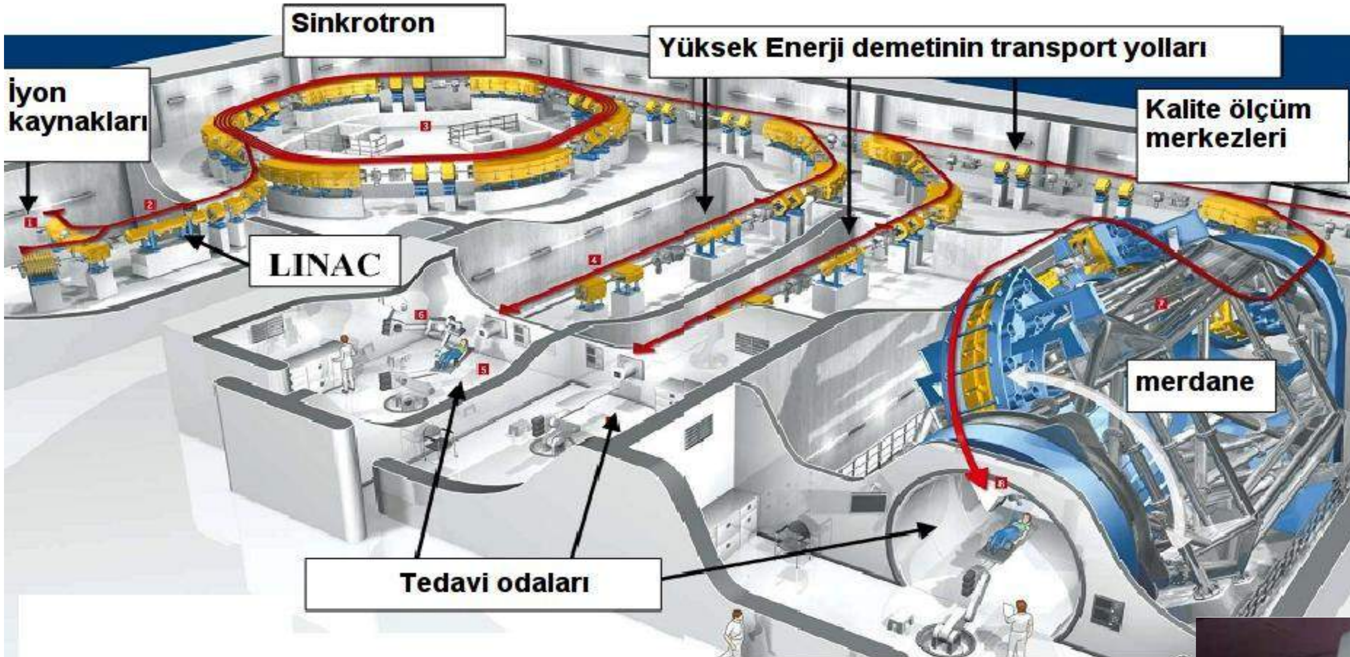


Electromagnetic Spectrum
Frequency (Hz)
Wavelength
Gamma-rays
X-rays
Ultraviolet
Visible
Near IR
Infra-red
Thermal IR
Far IR
Microwaves
Radar
Radio, TV
AM
Long-waves
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
0.1 Å
1 Å
0.1 nm
1 nm
10 nm
100 nm
1000 nm
1 μm
10 μm
100 μm
1000 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1000 m
400 nm
500 nm
600 nm
700 nm
1000 MHz
500 MHz
100 MHz
50 MHz
UHF
VHF 7-13
FM
VHF 2-6

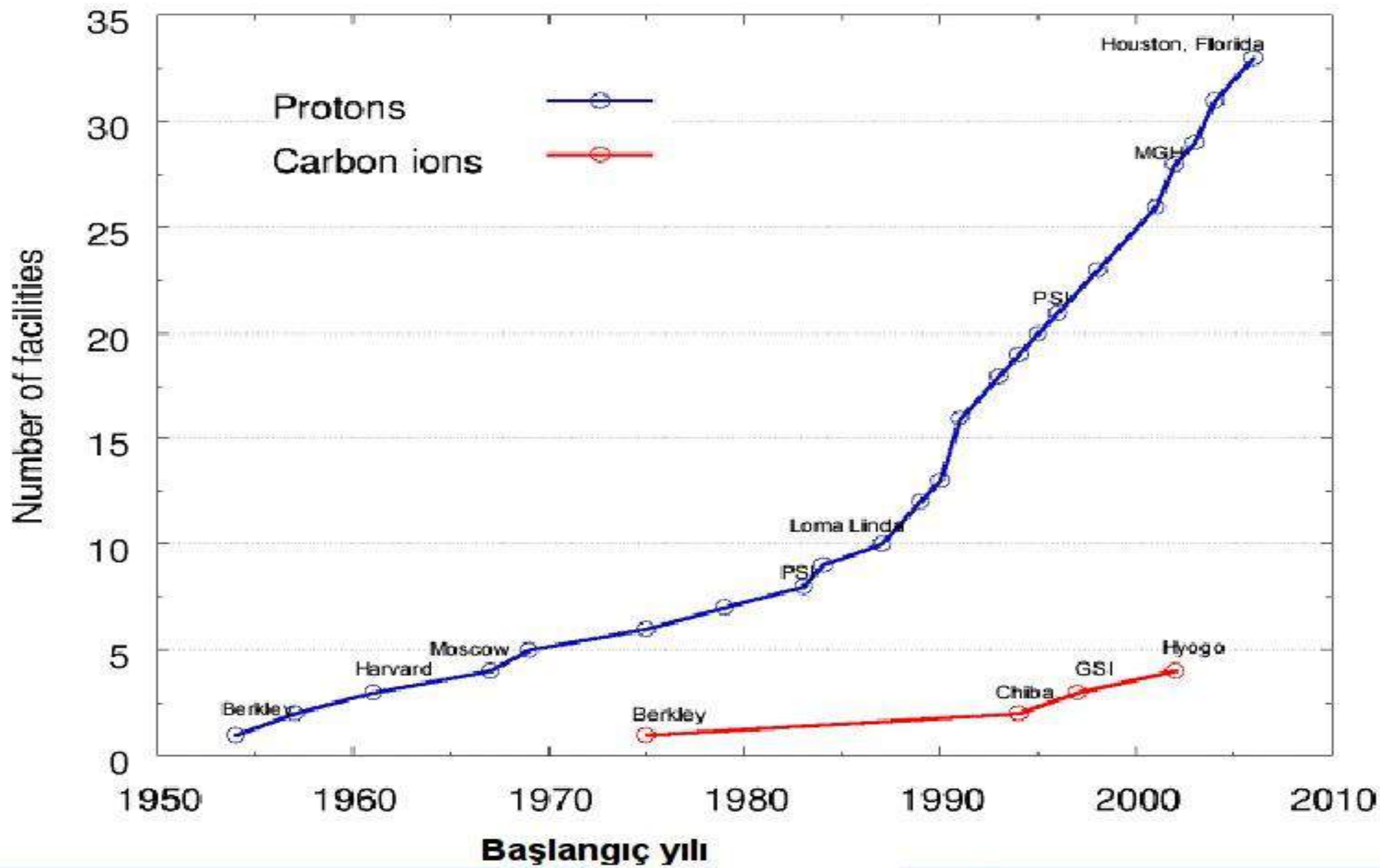

X-ray
Proton dozunun etkisi
Protonlar
Sağlıklı doku
Tümörlü bölge
hassas organ
Relative dose [%]
Derinlik [cm]
0
20
40
60
80
100
120
0
2
4
6
8
10
12
14

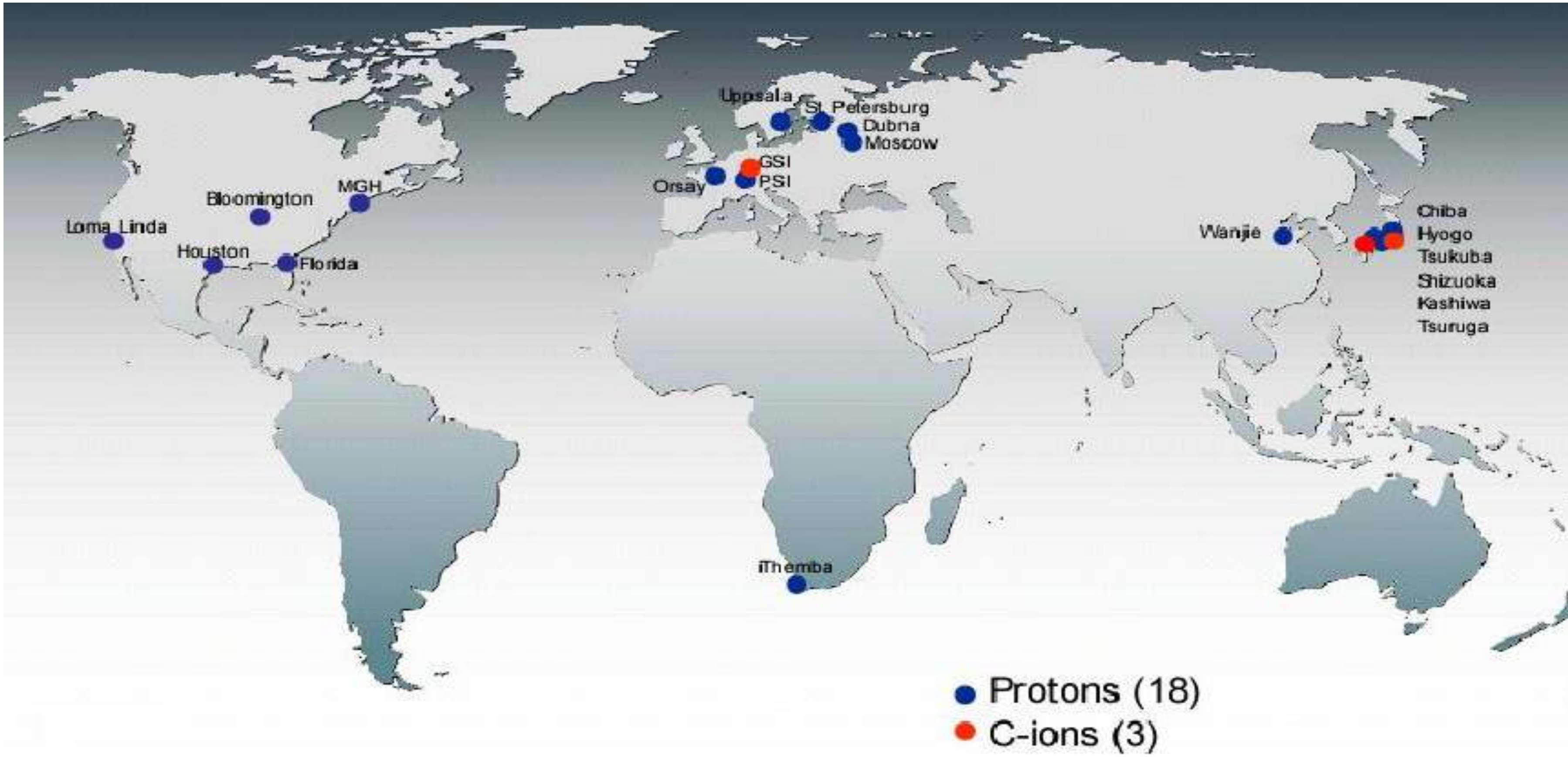

IMRT7d
Global Max = 1198 cGy
3prot
Global Max = 1051 cGy
X-rays, 7 portals
Protons, 3 portals




Sinkrotron
Yüksek Enerji demetinin transport yolları
İyon kaynakları
Kalite ölçüm merkezleri
LINAC
merdane
Tedavi odaları


MEVATRON


Protons
Carbon ions
Number of facilities
Başlangıç yılı
Houston, Florida
MGH
PSI
Loma Linda
PSI
Moscow
Harvard
Berkley
Berkley
Chiba
GSI
Hyogo
35
30
25
20
15
10
5
0
1950
1960
1970
1980
1990
2000
2010

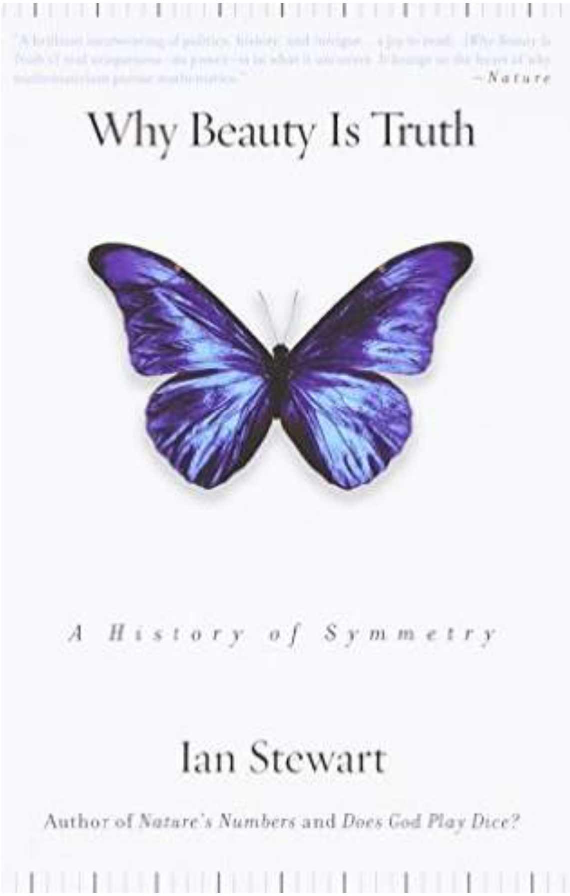


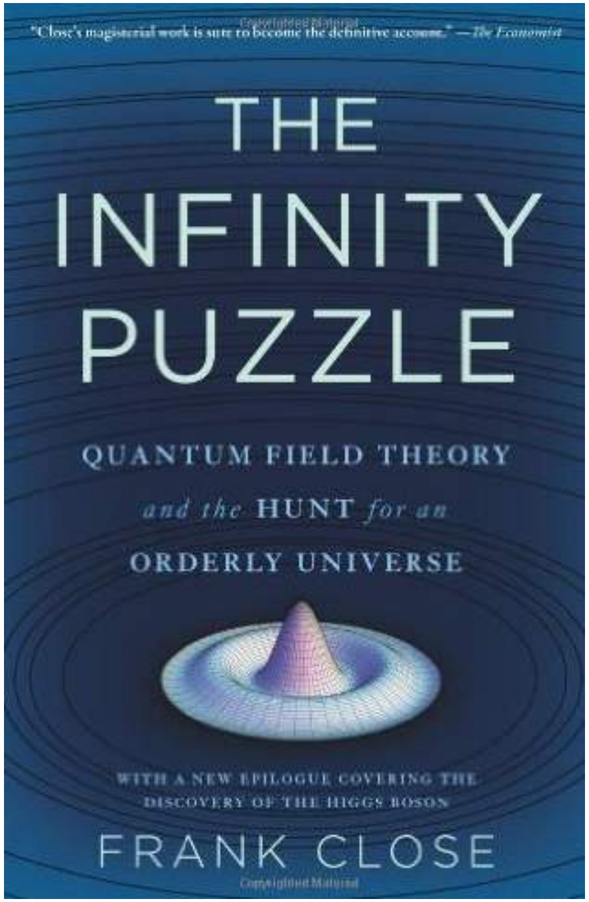
Dünyadaki belli başlı Hadron Terapi merkezleri

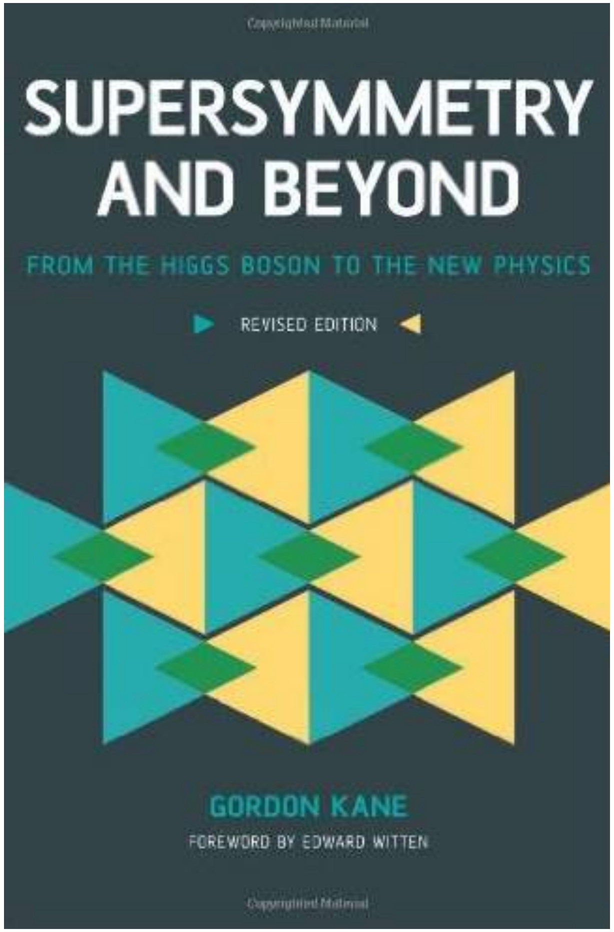
ve belki de CERN’deki en önemli buluş

Tim Berners-Lee' nin ilk World Wide Web browser' ı
(CERN, 1990)

Further reading





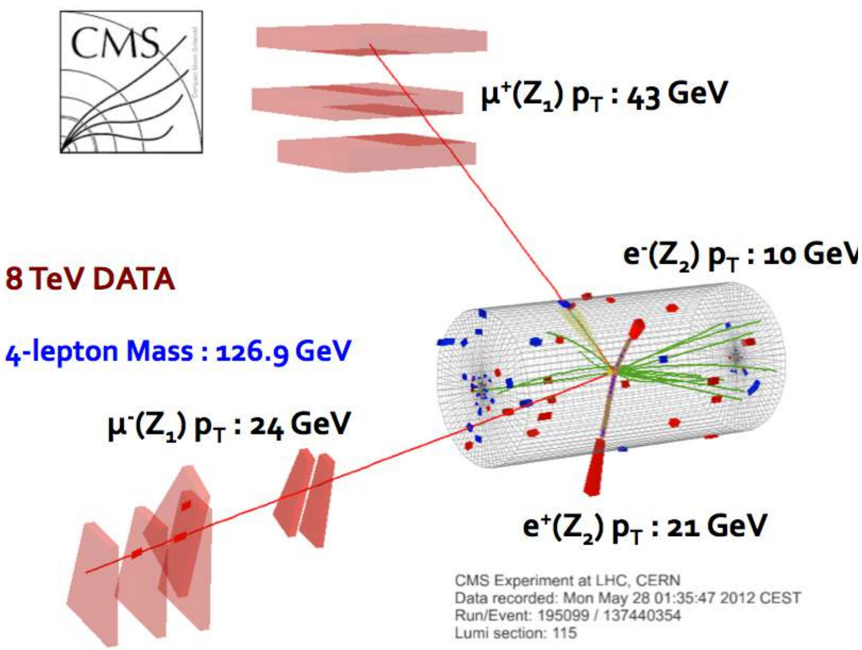


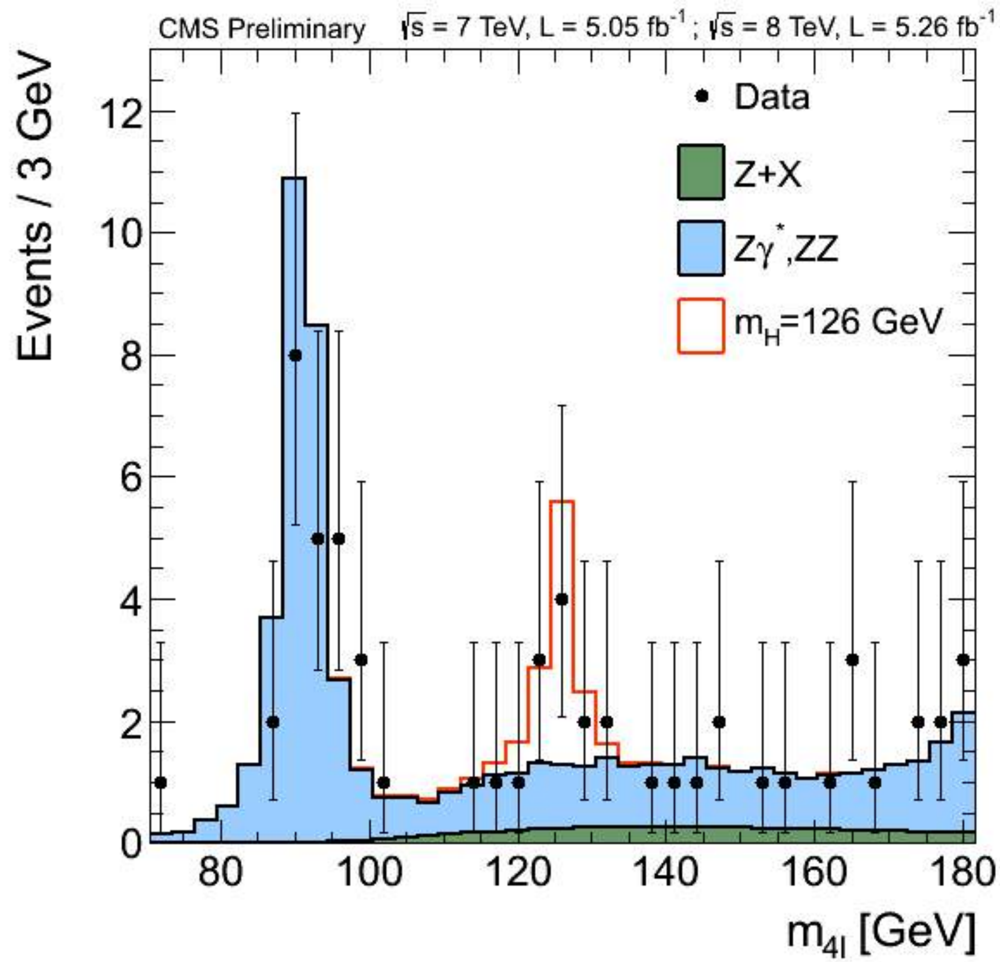
Among many nice CERN lectures:

The Brout-Englert-Higgs Theory of Electroweak Symmetry Breaking
James Wells
University of Michigan, Ann Arbor
Lecture 1, CERN, May 26, 2015


Thank you!

H → ZZ


CMS
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
8 TeV DATA
4-lepton Mass : 126.9 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115


CMS Preliminary
$\sqrt{s}$ = 7 TeV, L = 5.05 fb^{-1} ; $\sqrt{s}$ = 8 TeV, L = 5.26 fb^{-1}
Events / 3 GeV
Data
Z+X
$Z\gamma^*$,ZZ
m_H=126 GeV
0
2
4
6
8
10
12
80
100
120
140
160
180
m_{4l} [GeV]

mode	signature	S/B	Mass Resol.	N events in $10fb^{-1}$	Good For
$H \rightarrow bb$	two b-jets, Z or W, bb inv. mass	low $O(0.1)$	10%	$\sim 10^5$ ~30 (sel)	couplings to fermions
$H \rightarrow \tau\tau$	had tau, leptons, MET	low $O(0.1)$	15%	$\sim 10^4$ ~20 (sel)	couplings to fermions
$H \rightarrow WW$	two leptons with opposite charge MET	medium $O(1)$	-	$\sim 10^3$ ~60 (sel)	cross section, BR, couplings to V
$H \rightarrow \gamma\gamma$	two photons peak in inv. mass	low $O(0.1)$	2%	400 ~200 (sel)	H mass, couplings $C_V C_F$, discovery
$H \rightarrow ZZ$	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	20 ~6 (sel)	H mass, discovery

intrinsic quantum numbers S, P, CP **of Higgs**

$H \rightarrow \gamma\gamma$ angular distributions

Spin-0 → Cosθ
Spin-2 → polynomial $Cos^2θ$