Физика на елементарните частици

Lecture 2

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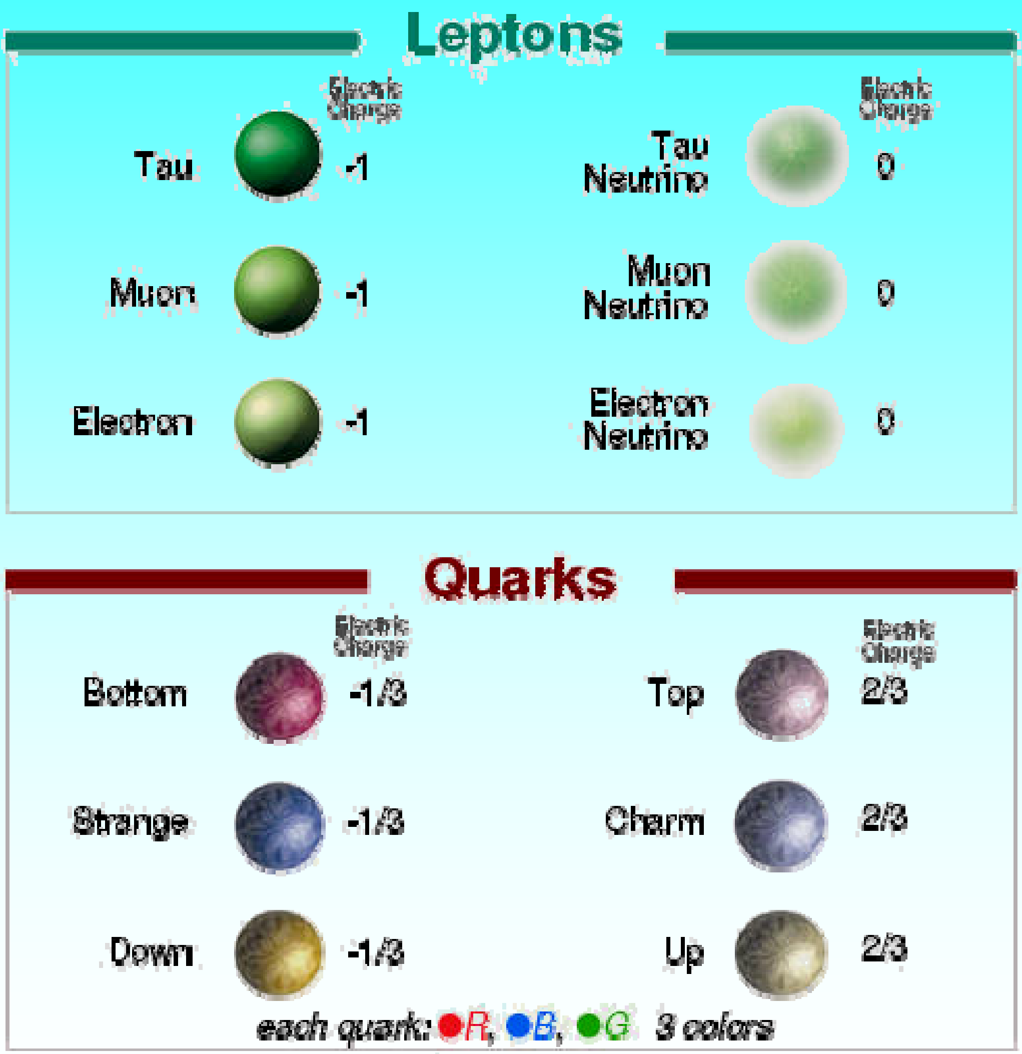
Опитва се да отговори на на два фундаментални въпроса

-Кои са елементарните съставящи на материята?

-Кои са фундаменталните сили контролиращи
тяхното поведение ?

Фундаментални частици



The particle drawings are simple artistic representations

Симетрии

The symmetry plays a crucial role in the particle physics

Symmetry Principe

The global symmetries of a given physical system define the suitable physical variables for its description and conserving quantities

The local symmetry of the system defines its dynamics (interactions)

Neuter theorem

Consider a lagrangian density

$$\mathcal{L}(\phi, \partial\phi)$$

functions of a set of fields $\phi_i, i = 1, \dots, n$. The transformation

$$\delta\phi_i = i\eta^A T^A_{ij}\phi_j; \quad (T^A)^\dagger = T^A; \quad [T^A, T^B] = if^{ABC}T^C$$

is a symmetry transformation if

$$\delta\mathcal{L} = \eta^A \partial^\mu K^A_\mu \Rightarrow \delta S[\phi] = \delta \int d^4x\, \mathcal{L} = 0$$

As a consequence, a set of *conserved currents* exists:

$$\partial^\mu J^A_\mu = 0; \quad J^A_\mu = T^A_{ij}\phi_j \frac{\partial\mathcal{L}}{\partial\partial^\mu\phi_i} - K^A_\mu$$

$$Q^A(t) = \int d^3x\, J^A_0(t, \mathbf{x}); \quad \frac{d}{dt}Q^A(t) = 0; \quad [Q^A, Q^B] = if^{ABC}Q^C$$

Symmetries

An example – we live in 4-dimensional homogeneous and isotropic space-time

The physical variables for any system in this space time – Mass and Spin

Conserving quantities –

From homogeneity P_{μ} 4-momentum

Energy and momentum conservation laws

From isotropic – Angular momentum –$M_{\mu\nu}$

Angular momentum conservation law

This a space-time symmetry

Internal Symmetries – correspond to conservation of electric charge, charm, strangeness, barion number, lepton number, iso-spin etc.

Continues Symmetries

1) Transformation, symmetries, invariance

Important concept in physics…

Space translation

continuous

Space rotation

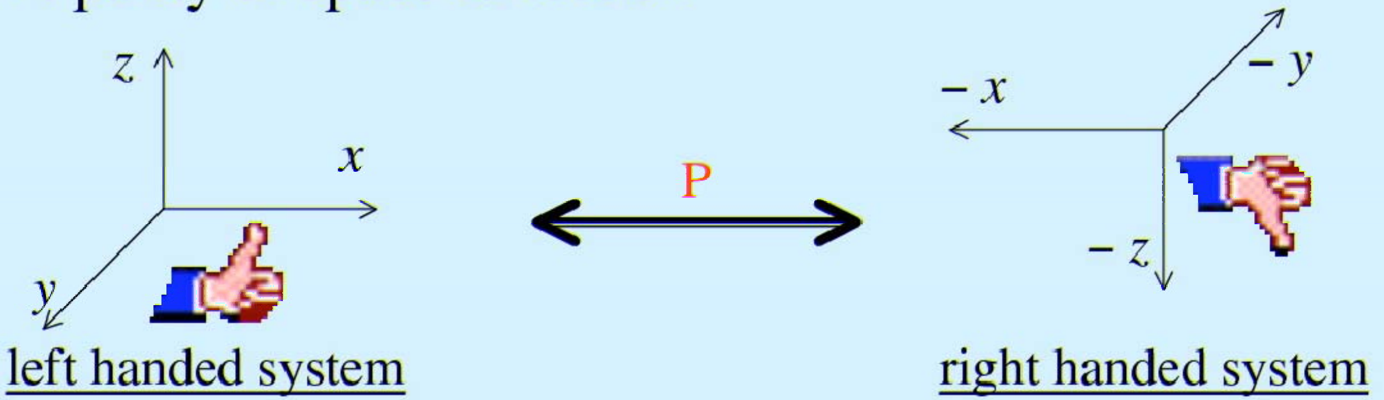
continuous

If system remains invariant ⇒ conservation of

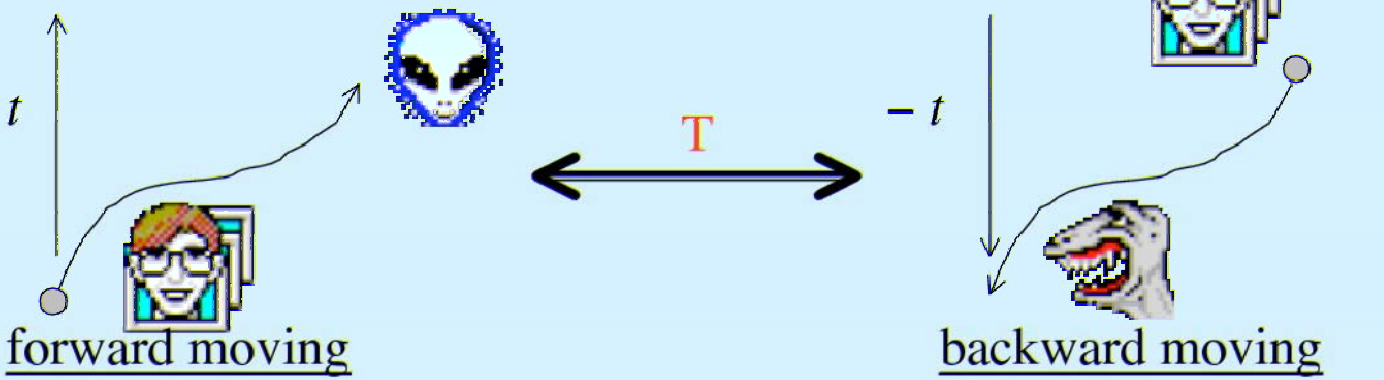
momentum　　　　　　　　　　angular momentum

2) P, T and C transformation

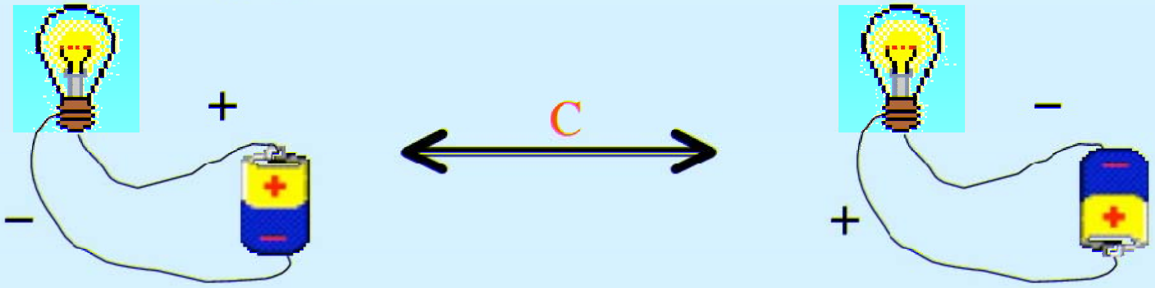
P: parity or space reflection



T: time reversal



C: charge conjugation



In particle physics reversing internal quantum numbers

charged states

e^- (electron)	⇔	e^+ (positron)
p (proton)	⇔	$\bar{p}$ (anti proton)
π^+ (positive pion)	⇔	π^- (negative pion)
u (u quark)	⇔	$\bar{u}$ (anti u quark)

neutral states

n (neutron)	⇔	$\bar{n}$ (anti neutron)
K^0 (k-zero meson)	⇔	$\bar{K}^0$ (anti k-zero meson)
π^0 (neutral pion)	⇔	π^0 (neutral pion)

Discrete Symmetries

C, P and T are discrete transformations

Reflection
(parity)

R

Я

discrete

3) Conservation of symmetries

If no difference seen between

"this world" and "space reflected world"

$\Longrightarrow$ We say:

- parity is conserved,
- P symmetry is conserved,
- world is invariant under P transformation
- etc.

example

More "professional" description,

$\hat{H}$ Hamiltonian operator describing a system

$\hat{P}$ Parity transformation operator

$\hat{P}^{\dagger}\hat{H}\hat{P} = \hat{H}^{P}$ parity transformation of Hamiltonian

If $\hat{H}^{P} \neq \hat{H}$

Parity violation, Parity non-conservation etc. etc.

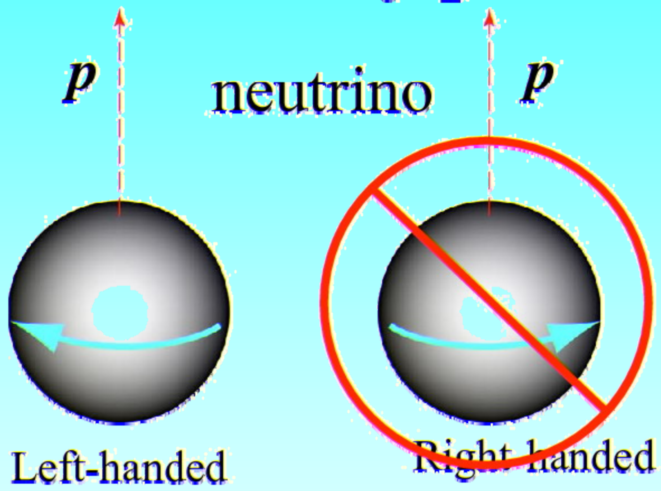
C and CP

A similar terminology applies to C and T.

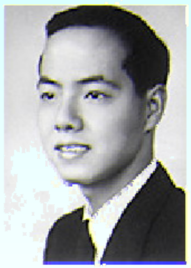
Strong and electromagnetic interactions conserve:
flavour quantum numbers,
C, P, T, CP, CT, PT and CPT

Discrete Symmetries

And in elementary particle world



theory of parity violation



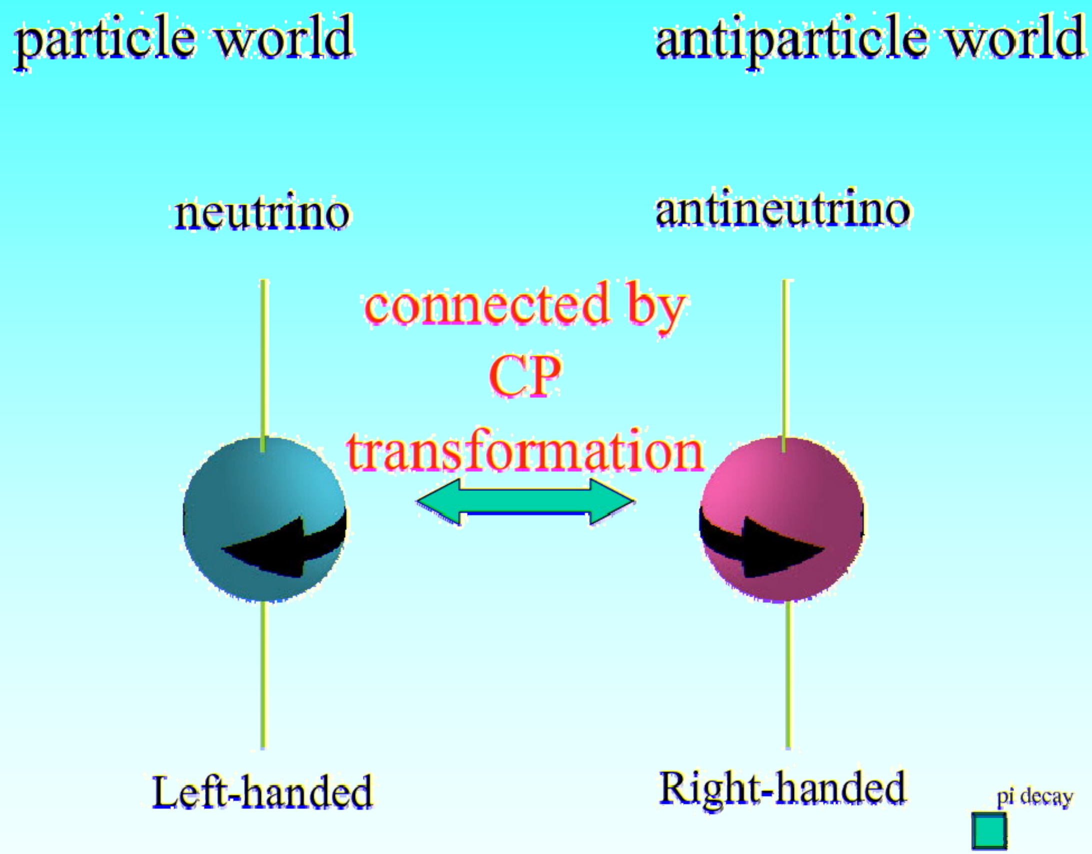
1956, T.D. Lee and C.N.Yang

experiment of parity violation

1957, C.S.Wu

back to list

Discrete Symmetries



Discrete Symmetries

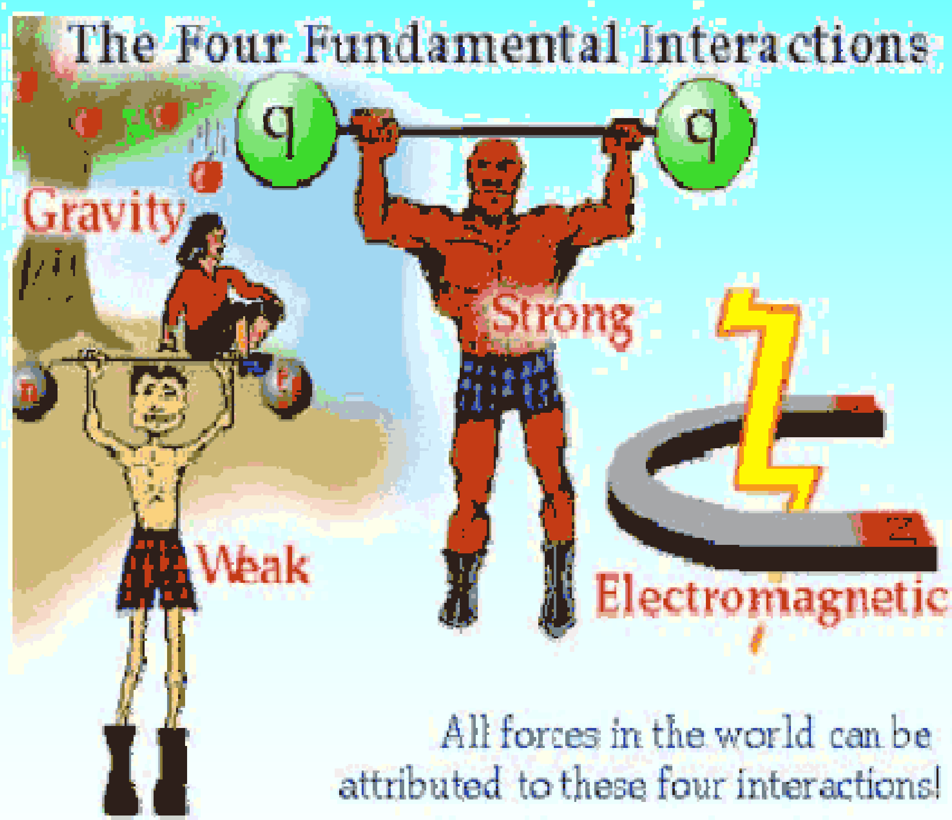
In the weak interactions
C, P and CP symmetries are violated!
General theorem – CPT is conserving in all interactions

Взаимодействия

Видове взаимодействия

How are the composite objects held together ?

by forces

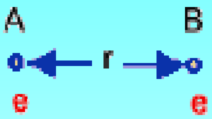


Как стават?

Interaction between two matter particles e.g. electrons

Action at a distance

$$F \propto \frac{e^2}{r^2}\,\hat{r}$$

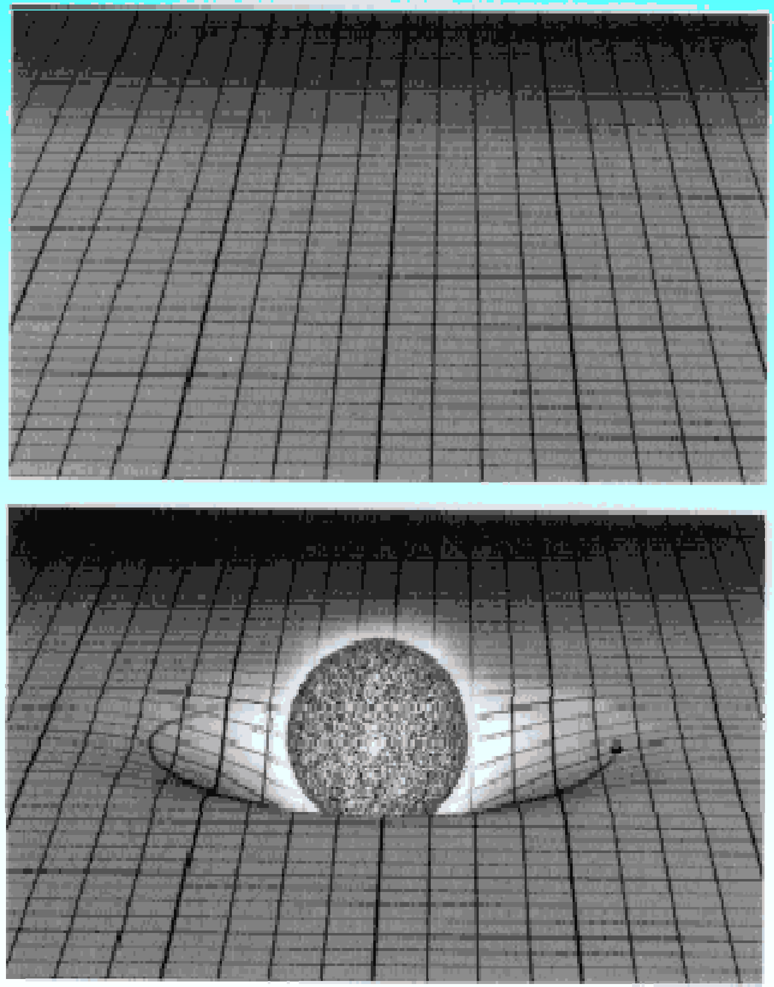


Newton
Force on A depends on where B is.
But how does A know where B is ?

Interaction through Fields

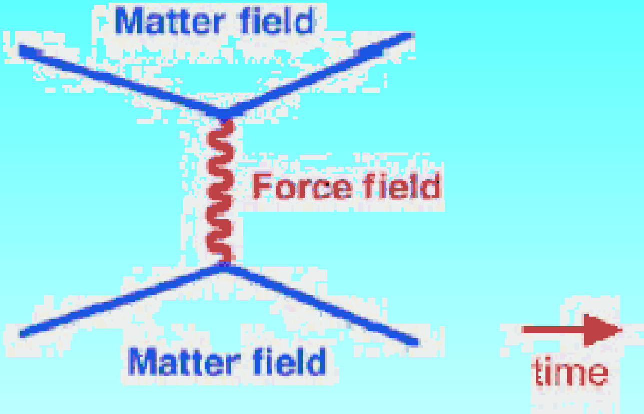
Maxwell
B produces a field, characterized by a number (e/r^2) at every point in space.
Force on A is towards the direction in which the number changes fastest
A determines its response by 'sniffing' in its immediate neighbourhood

Gravity



Как стават?

BUT - still no tangible connection between A and B



Forces are produced by exchange of force or 'messenger' particles

Feynman:

B continually emits carriers of the electromagnetic force - 'photons'
Electron A absorbs the photons and recoils - repulsive force between the electrons.
In Quantum Field Theory both signs of impulse are possible.

Преносители на взаимодействия

What characterizes a force ? Strength, range and source charge of the field.

Interaction	Exchanged quantum *(source ch)*	Range (m)	Relative Strength	Examples in nature
Strong	gluon *colour*	10^{-15}	1	proton (quarks)
Electromagnetic	photon *electric*		$<10^{-2}$	atoms
Weak	W, Z *hypercharge*	$<10^{-17}$	10^{-5}	radioactivity
Gravity	graviton ? *mass*		10^{-38}	solar system

Ratio of electrical to gravitational force between two protons is ~ 10^{38} !!

Can such different forces have the same origin ??

Стандартен Модел

Fundamental particles

LEPTONS

- ❖Do not participate in strong interactions
- ❖Spin ½
- ❖Observed as free particles
- ❖Pointlike (r < few x 10^{-17}cm)

QUARKS

- ❖Strong interactions bind them into hadrons
- ❖Not observed as free particle – confinement
- ❖Spin ½ ; pointlike; (r < few x 10^{-17}cm)
- ❖$Q_u = 2/3$; $Q_d = -1/3$

Family (Generation) Structure

$$\begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix}$$

$N_G = 3$

Standard Model - interactions

In QFT – the local invariance of **L** defines the interactions

Electromagnetic Interactions: γ

Quantum Electrodynamics (QED) U(1)

In the Standard Model

QED + Weak Interactions: γ, Z^0, $W^\pm$

Electroweak Theory $SU(2)_L \otimes U(1)_Y$

Strong Interaction **8 Gluons**

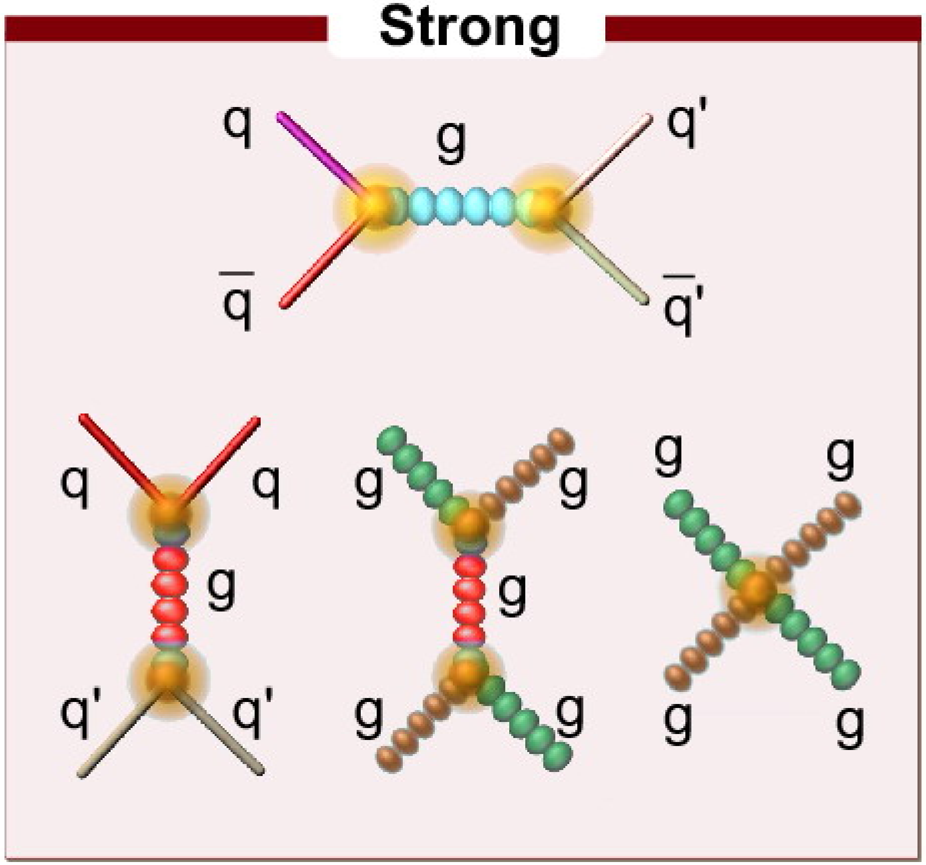
Quantum Chromodynamics (QCD) $SU_c(3)$

Силни взаимодействия

Strong Interactions – Quantum Chromo Dynamics

- In the strong interactions –
  - Colour is the strong charge – like electric charge in the EM interactions
  - Quarks – have 3 colours
  - Gluons – eight colours (main difference with the photon)
  - Gluon self interactions
- QCD –
  - flavor conserving
  - only one parameter - α_s
  - due to gluon self interactions $\alpha_s(Q^2)$ – Q is a 4- momentum transferred by the gluon
  - Asymptotic freedom

QCD interactions



Range ~ 10^{-15} m, relative strength = 1

QCD - confinement

Free quarks, gluons have never been observed experimentally; only indirect evidence from the study of hadrons – WHY?

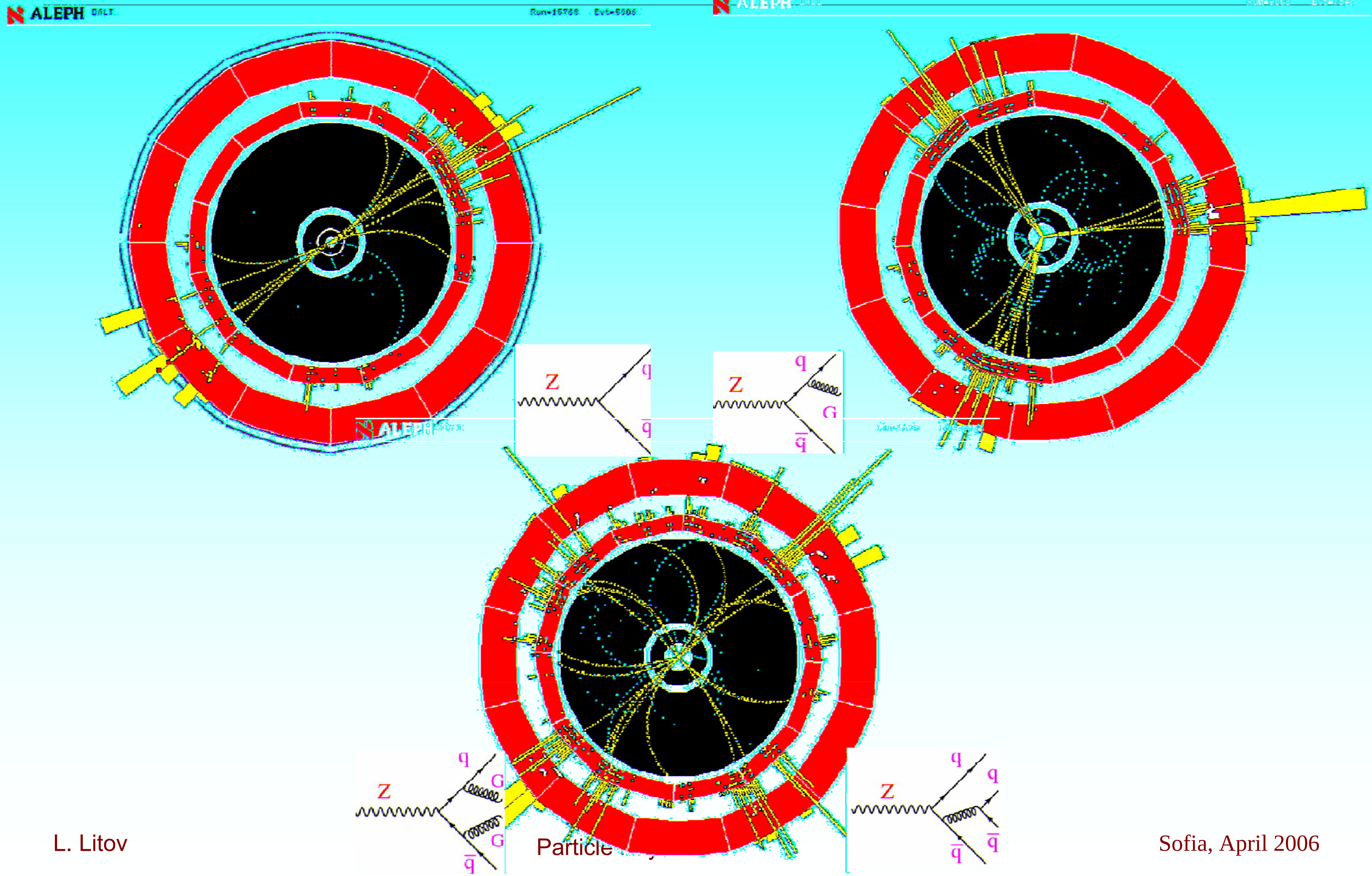
CONFINEMENT: coloured particles are confined within colourless hadrons because of the behaviour of the colour forces at large distances

The attractive force between coloured particles increases with distance ⇒ increase of potential energy ⇒ production of quark – antiquark pairs which neutralize colour ⇒ formation of colourless hadrons (hadronization)

At high energies (e.g., in $e^+e^- \rightarrow q + \bar{q}$) expect the hadrons to be produced along the initial direction of the $q - \bar{q}$ pair ⇒ production of hadronic "jets"

CONFINEMENT, HADRONIZATION: properties deduced from observation. So far, the properties of colour forces at large distance have no precise mathematical formulation in QCD.

QCD – experimental test



Електрослаби взаимодействия

Fundamental particles

Three Families

$$\begin{pmatrix} \nu_e & u \\ e^- & d' \end{pmatrix} \quad \begin{pmatrix} \nu_\mu & c \\ \mu^- & s' \end{pmatrix} \quad \begin{pmatrix} \nu_\tau & t \\ \tau^- & b' \end{pmatrix}$$

Family Structure

$$\begin{pmatrix} \nu_l & q_u \\ l_j & q_d \end{pmatrix} \equiv \left\{ \begin{pmatrix} \nu_l \\ l^- \end{pmatrix}_L, (\nu_l)_R, l_R^- \right\}; \left\{ \begin{pmatrix} q_u \\ q_d \end{pmatrix}_L, (q_u)_R, (q_d)_R \right\}$$

Charged Currents $W^{\pm}$

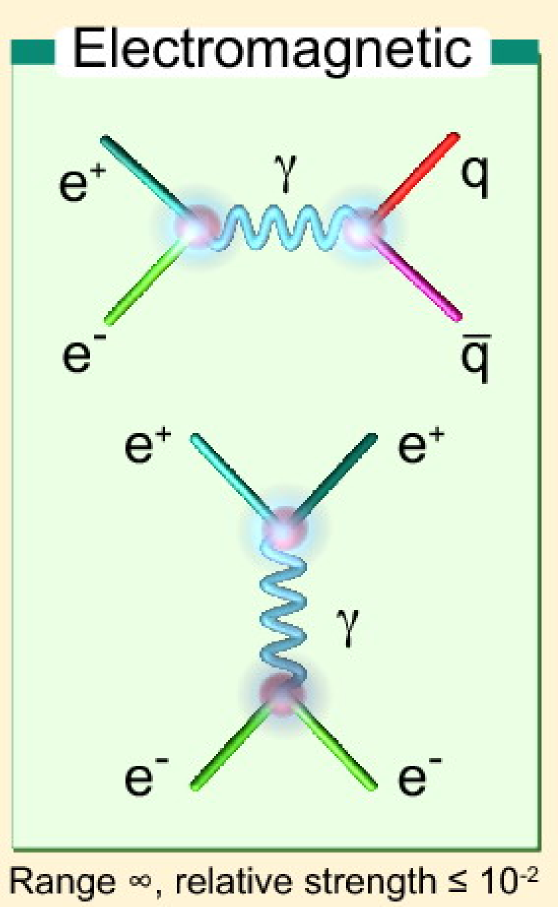
Left-handed fermions only

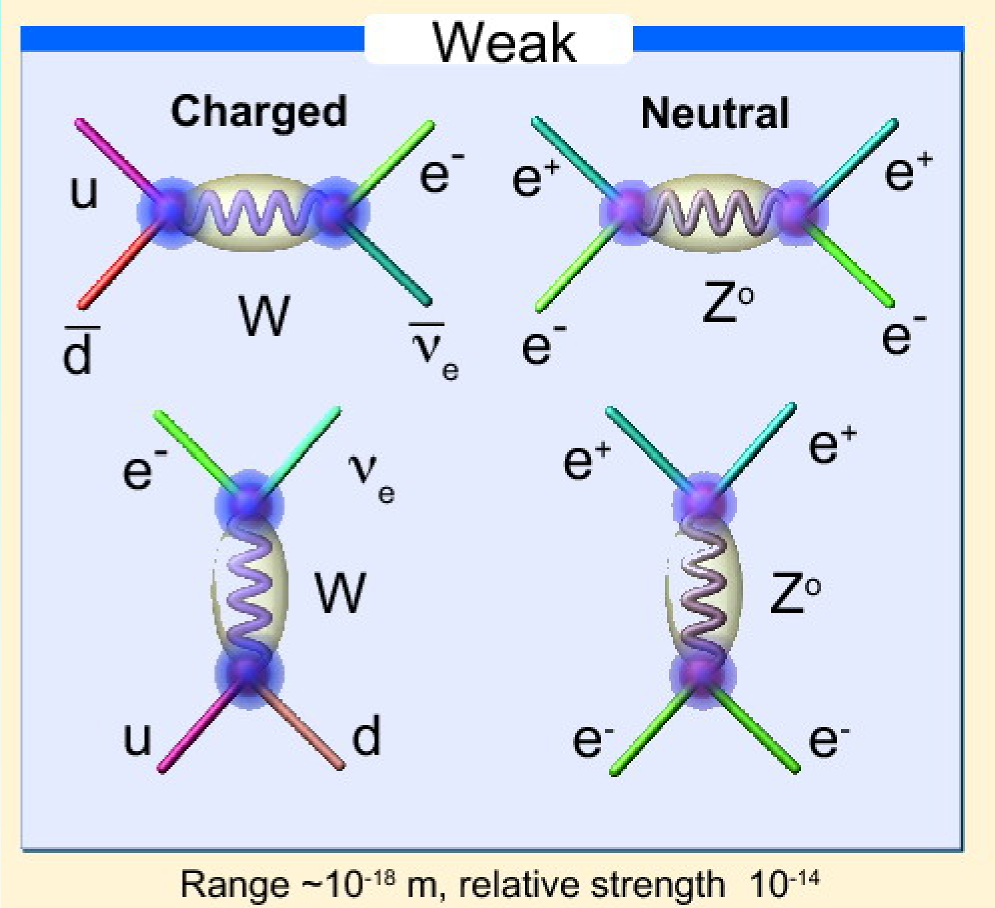
Flavor changing: $\nu_l \Leftrightarrow l$, $q_u \Leftrightarrow q_d$

Neutral Currents γ, Z

Flavor Conserving $f_i \Leftrightarrow f_i$

Electroweak interactions





PROBLEM WITH MASS SCALES

Gauge Symmetry → $m_\gamma = 0$ Good

$M_W = M_Z = 0$ Bad!

$M_W = 80.43$ GeV

$M_Z = 91.19$ GeV

Moreover $\mathcal{L}_{m_f} = -m_f\,\bar{f}\,f = -m_f\,(\bar{f}_L\,f_R + \bar{f}_R\,f_L)$

Also Forbidden by Gauge Symmetry → $m_f = 0 \quad \forall f$

All Particles Massless

Spontaneous Symmetry Breaking

In the SM masses are generated trough

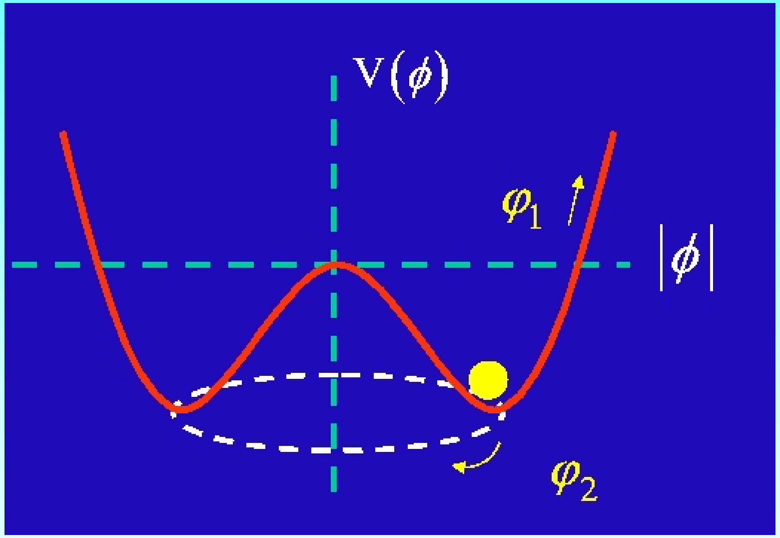
Spontaneous Symmetry Breaking (**SSB**) – Higgs Mechanism

Introduce Scalar Higgs doublet →

The Lagrangian is invariant

However its vacuum state is degenerate –

$$|\langle 0 | \Phi_0 | 0 \rangle| = \frac{v}{\sqrt{2}}$$



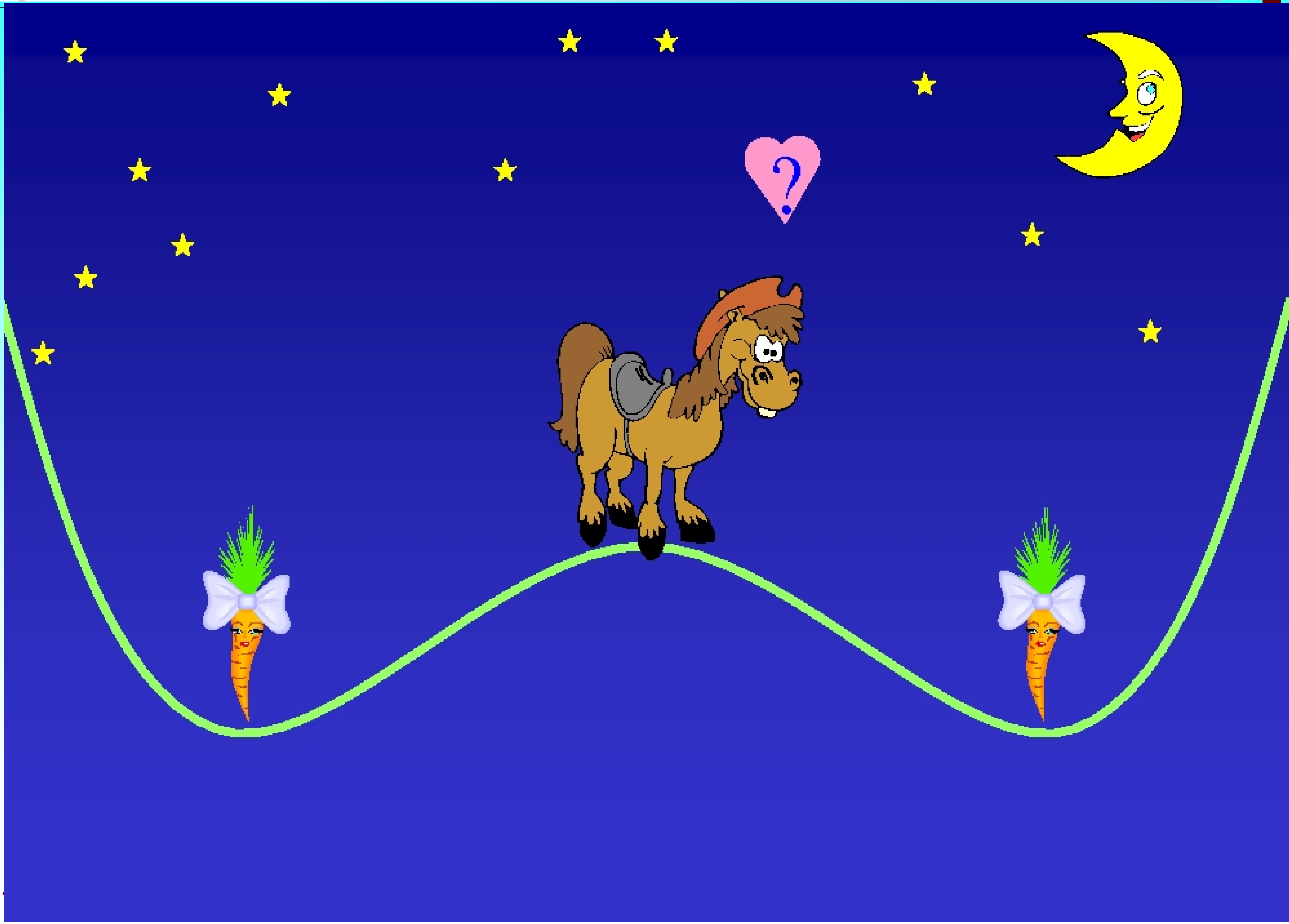
Choice of the vacuum state – leads to SSB

$SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$

Couplings with gauge bosons and fermions – induce mass terms

Price – new particle **H-boson** – to be discovered

Spontaneous Symmetry Breaking



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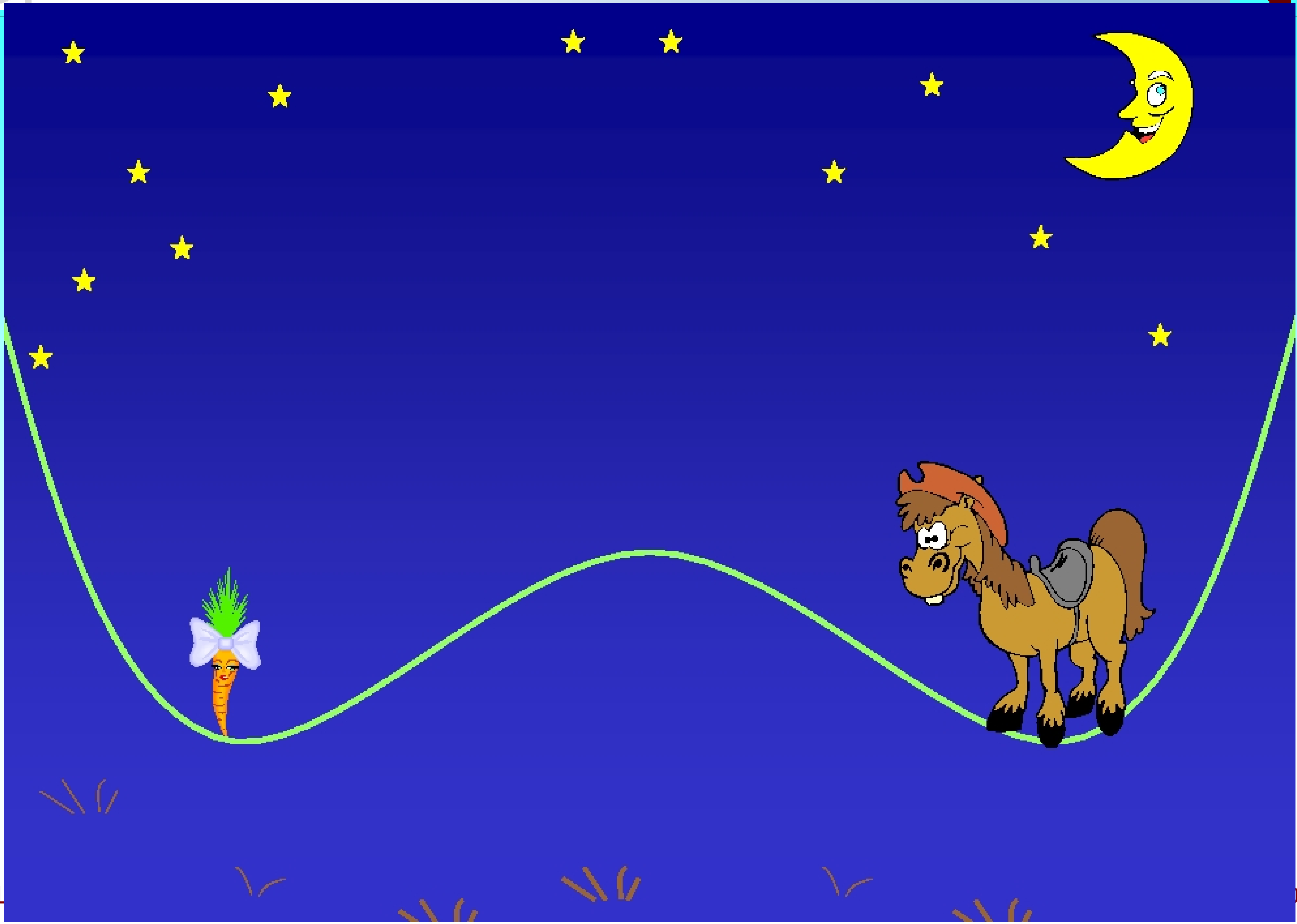

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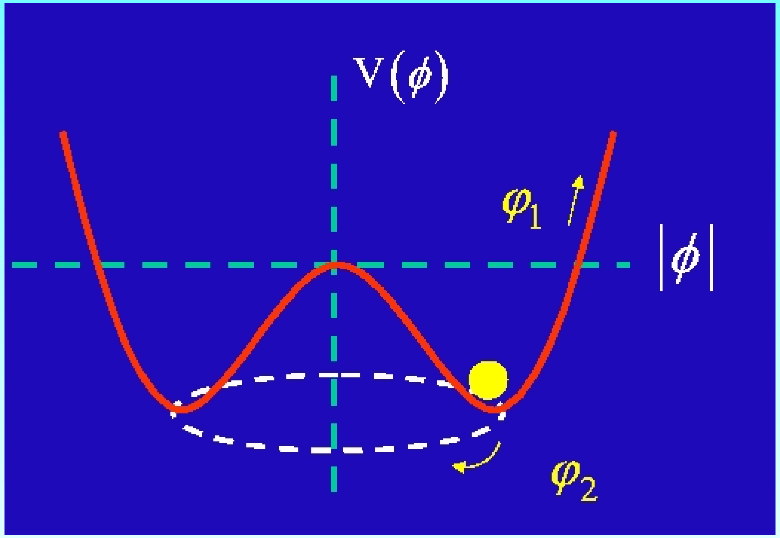

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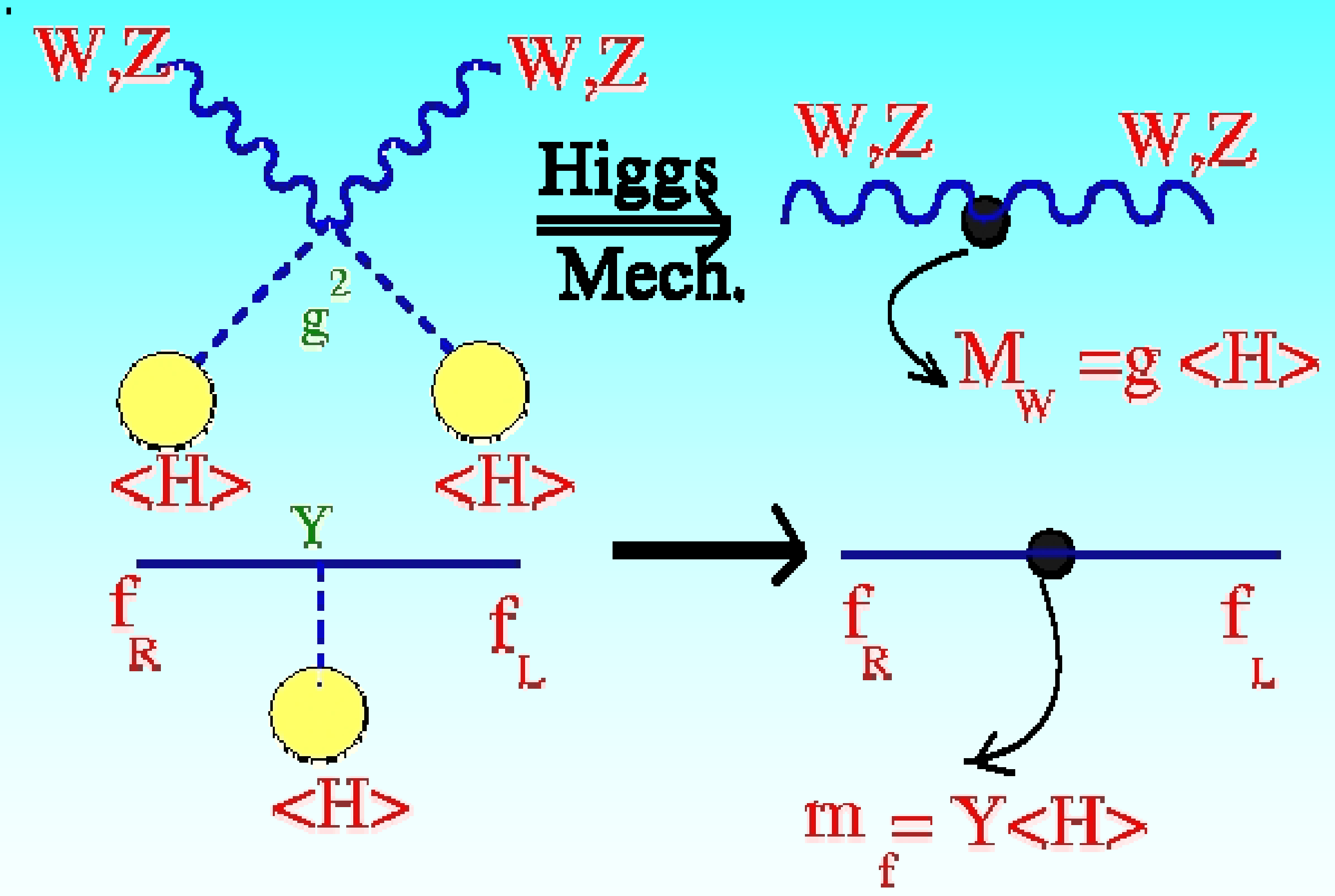
Higgs interactions



Fermion Masses

$$\begin{pmatrix} \nu'_j & u'_j \\ l'_j & d'_j \end{pmatrix}$$

N_G=3 identical copies : f' are massles weak eigenstates

Scalar doublet couples with fermions – allowed by the Gauge Symmetry

SSB

$$L_Y = -\left(1+\frac{H}{v}\right)[\overline{d'_L} M'_d d'_R + \overline{u'_L} M'_u u'_R + \overline{l'_L} M'_l l'_R + h.c.]$$

Arbitrary Non-Diagonal Complex Mass Matrices

$$[M'_d, M'_u, M'_l]_{jk} = -[c^{(d)}_{jk}, c^{(u)}_{jk}, c^{(l)}_{jk}]\frac{v}{\sqrt{2}}$$

Diagonalization of Mass Matrices

$$M'_f = S_f^+ M_f S_f U_f \qquad S_f^+ S_f = 1 \qquad U_f^+ U_f = 1$$

$$L_Y = -\left(1 + \frac{H}{v}\right)[\bar{d} M_d d + \bar{u} M_u u + \bar{l} M_l l]$$

$$M_u = diag(m_u, m_c, m_t) \qquad M_d = diag(m_d, m_s, m_b) \qquad M_l = diag(m_e, m_\mu, m_\tau)$$

$$f_L = S_f f'_L \qquad f_R = S_f U_f f'_R$$

Mass Eigenstates # Weak Eigenstates

$$\overline{f'_L} f'_L = \overline{f_L} f_L \qquad \overline{f'_R} f'_R = \overline{f_R} f_R \qquad \Rightarrow \qquad L'_{NC} = L_{NC}$$

$$\overline{u'_L} d'_L = \overline{u_L} V d_L \qquad V = S_u S_d^+ \qquad \Rightarrow \qquad L'_{CC} \neq L_{CC}$$

Quark Mixing → V ← **CKM Matrix**

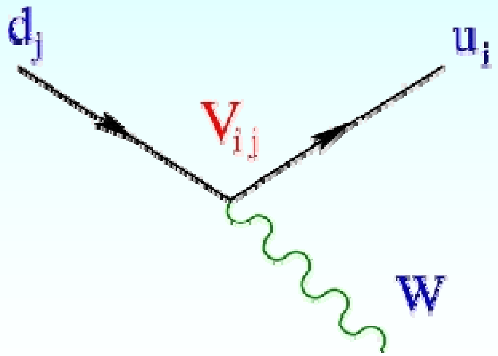
Quark Mixing

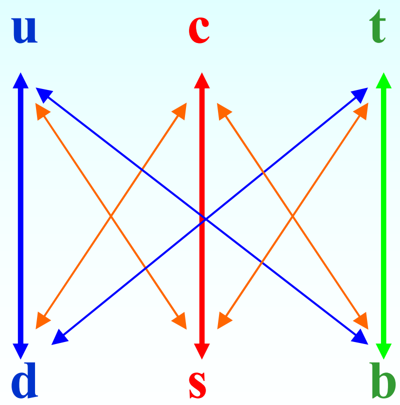
$$L_{NC}^{Z} = \frac{e}{2\sin\theta_W \cos\theta_W} Z_\mu \sum_f \overline{f}\gamma_\mu[v_f - a_f\gamma_5]f$$

Flavour Conserving Neutral Current

$$L_{CC}^{W} = \frac{g}{2\sqrt{2}} W_\mu^+ [\sum_{ij} \overline{u_i}\gamma^\mu(1-\gamma_5)V_{ij}d_j + \sum_l \overline{\upsilon_l}\gamma^\mu(1-\gamma_5)l_j] + h.c.$$

Flavour Changing Charged Current





Fundamental particles

Predictions

Massive force carriers - $W^{\pm}$, Z^0

Charge current interactions ($W^{\pm}$) –

describe known processes like muon and β-decays

Neutral currents (Z^0) – new phenomena

Higgs mechanism - H – boson

Quark mixing – 3 - generations

Need experimental confirmation

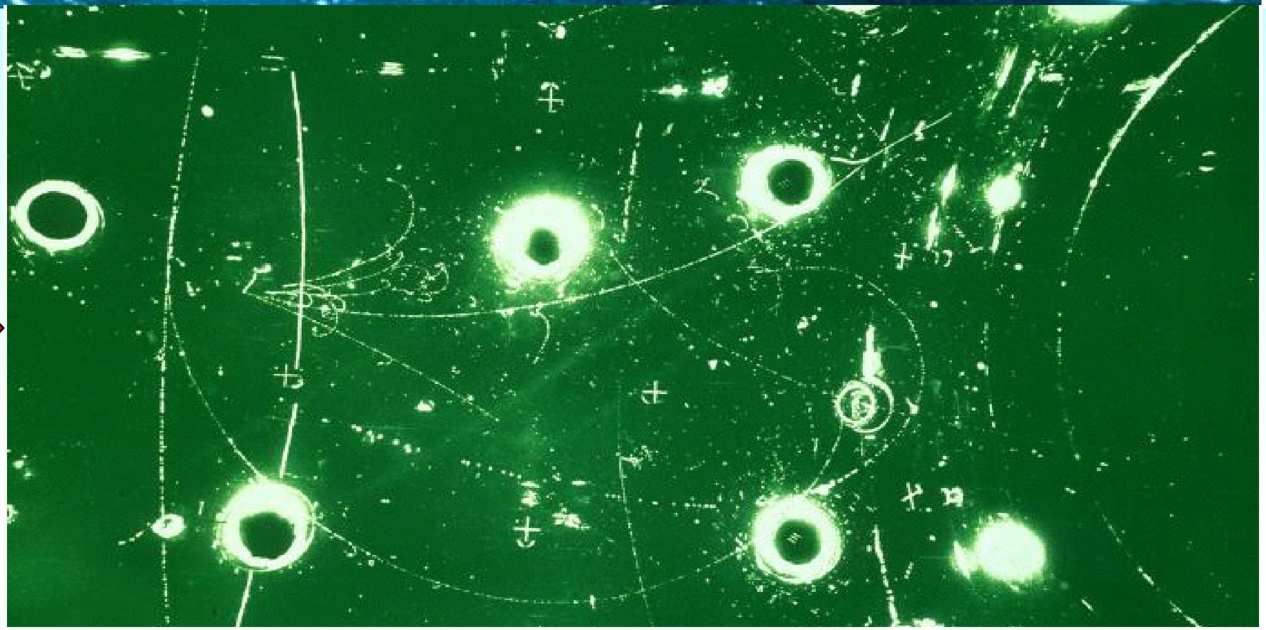
Neutral Current processes

Heavy liquid bubble chamber Gargamelle at the CERN PS (1973)

Example of
$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$
(elastic scattering)
Recoil electron
energy = 400 MeV

($\bar{\nu}_\mu$ beam from π^- decay
in flight)

Example of
$\nu_\mu + p\ (n) \rightarrow \nu_\mu$ + hadrons
(inelastic interaction)
(ν_μ beam from π^+ decay
in flight)



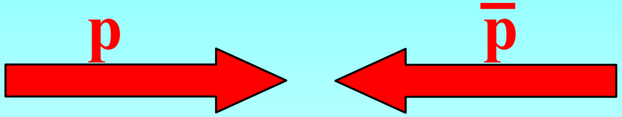
L. Litov

Observation of W and Z

$M_W \approx 70 - 90$ GeV/c^2 ; $M_Z \approx 80 - 100$ GeV/c^2

too high to be produced at any accelerator in operation in the 1970's

1975: Proposal to transform the new 450 GeV CERN proton synchrotron (SPS) into a proton – antiproton collider (C. Rubbia)



Beam energy = 315 GeV $\Rightarrow$ total energy in the centre-of-mass = 630 GeV

Beam energy necessary to achieve the same collision energy on a proton at rest :

$$(E + m_p c^2)^2 - p^2 c^2 = (630\ \text{GeV})^2 \quad \Longrightarrow \quad \boldsymbol{E} = 210\ \text{TeV}$$

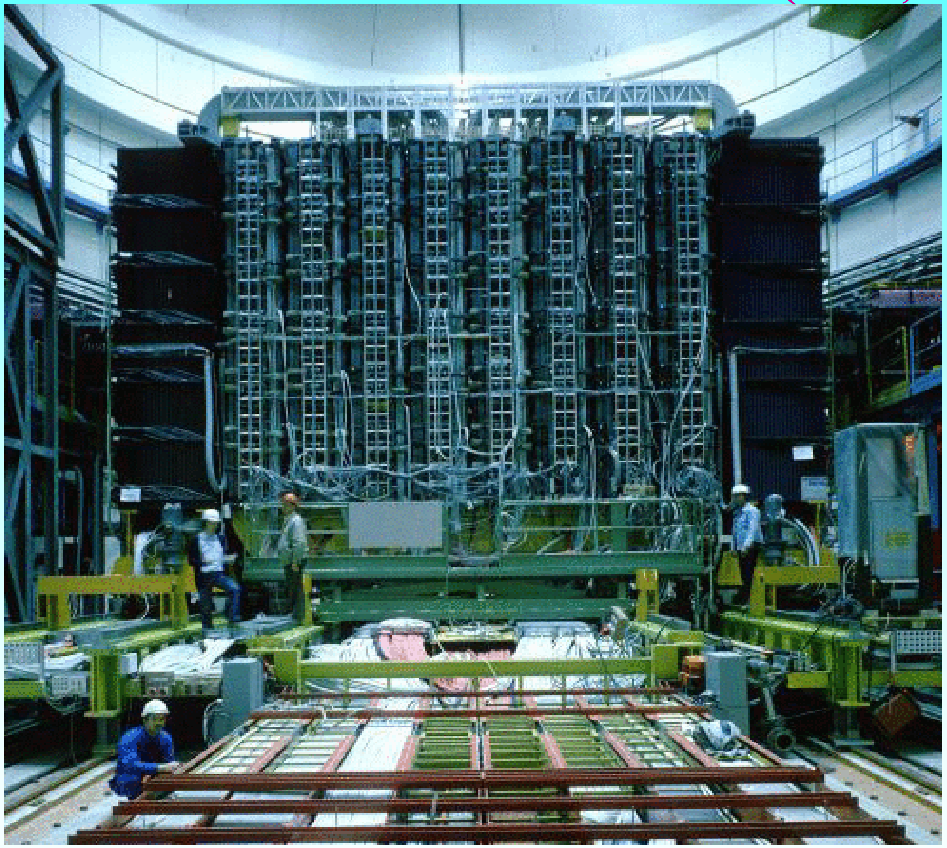
Production of W and Z by quark – antiquark annihilation:

$$u + \bar{d} \to W^+ \qquad \bar{u} + d \to W^-$$

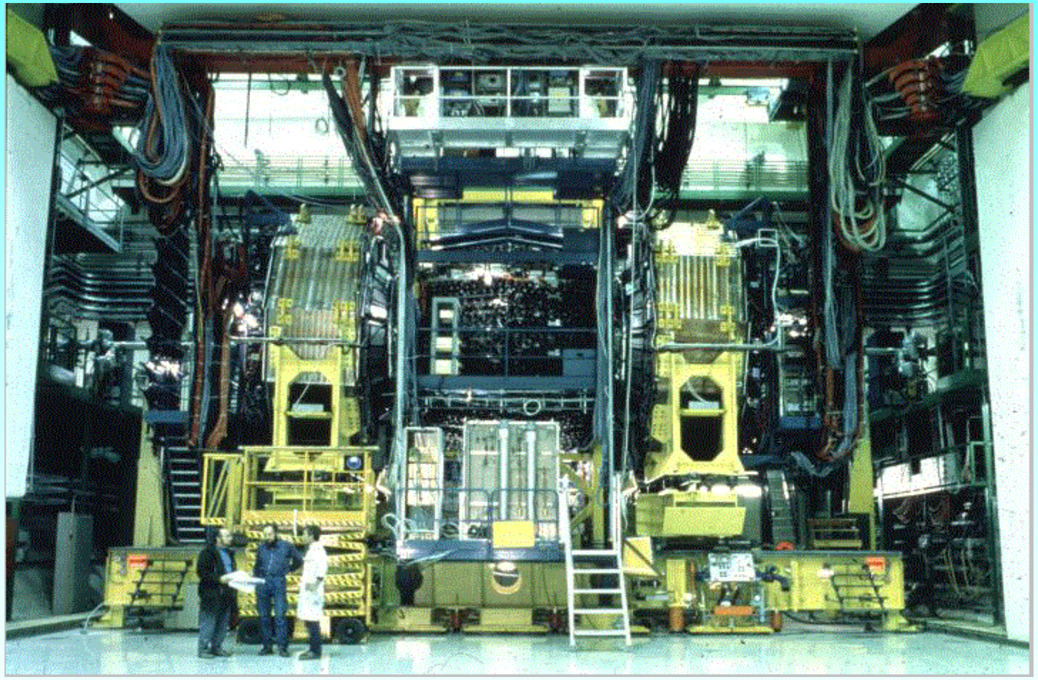
$$u + \bar{u} \to Z \qquad d + \bar{d} \to Z$$

Observation of W and Z

Search for $W^{\pm} \rightarrow e^{\pm} + \nu$ (UA1, UA2) ; $W^{\pm} \rightarrow \mu^{\pm} + \nu$ (UA1)
$Z \rightarrow e^{+}e^{-}$ (UA1, UA2) ; $Z \rightarrow \mu^{+}\mu^{-}$ (UA1)

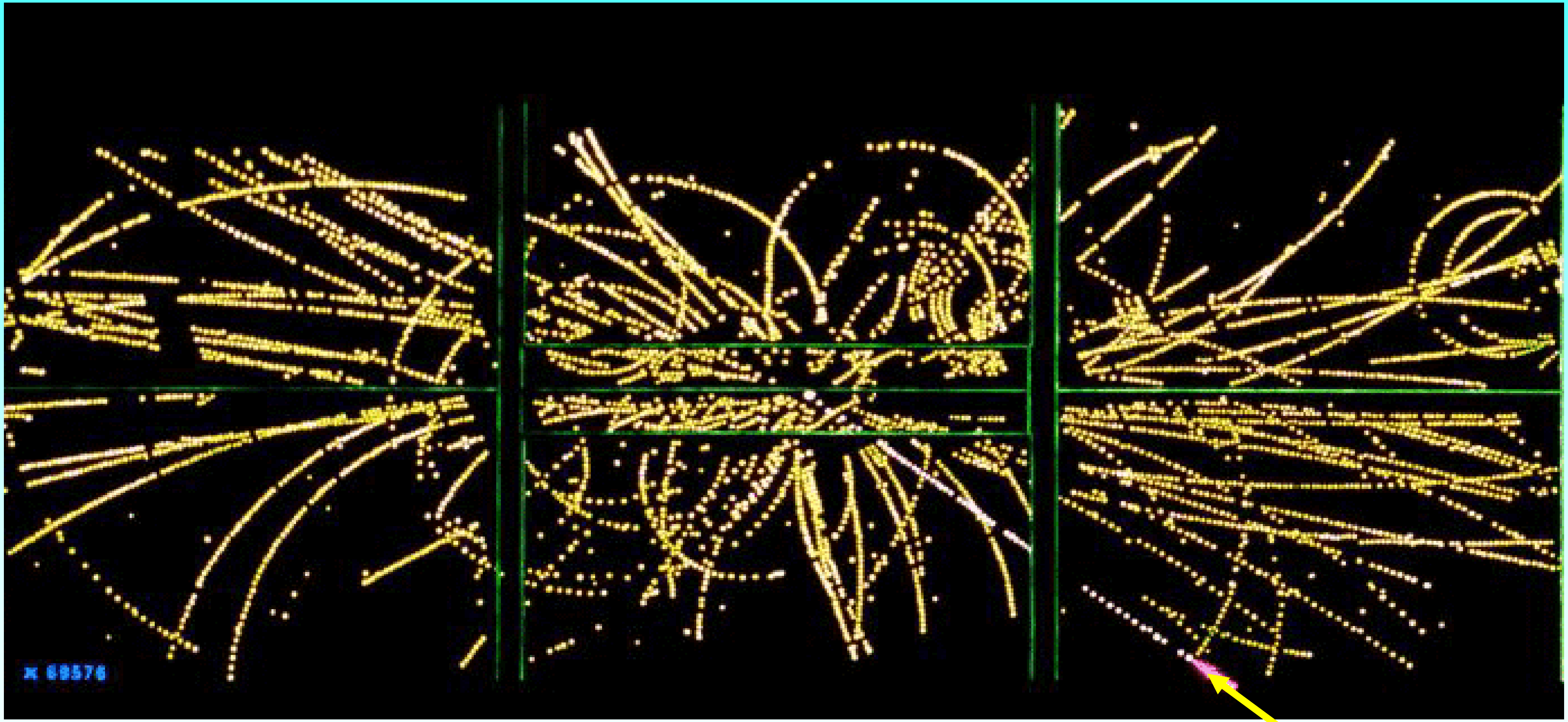


UA1: magnetic volume with trackers, surrounded by "hermetic" calorimeter and muon detectors



UA2: non-magnetic, calorimetric detector with inner tracker

Observation of W and Z

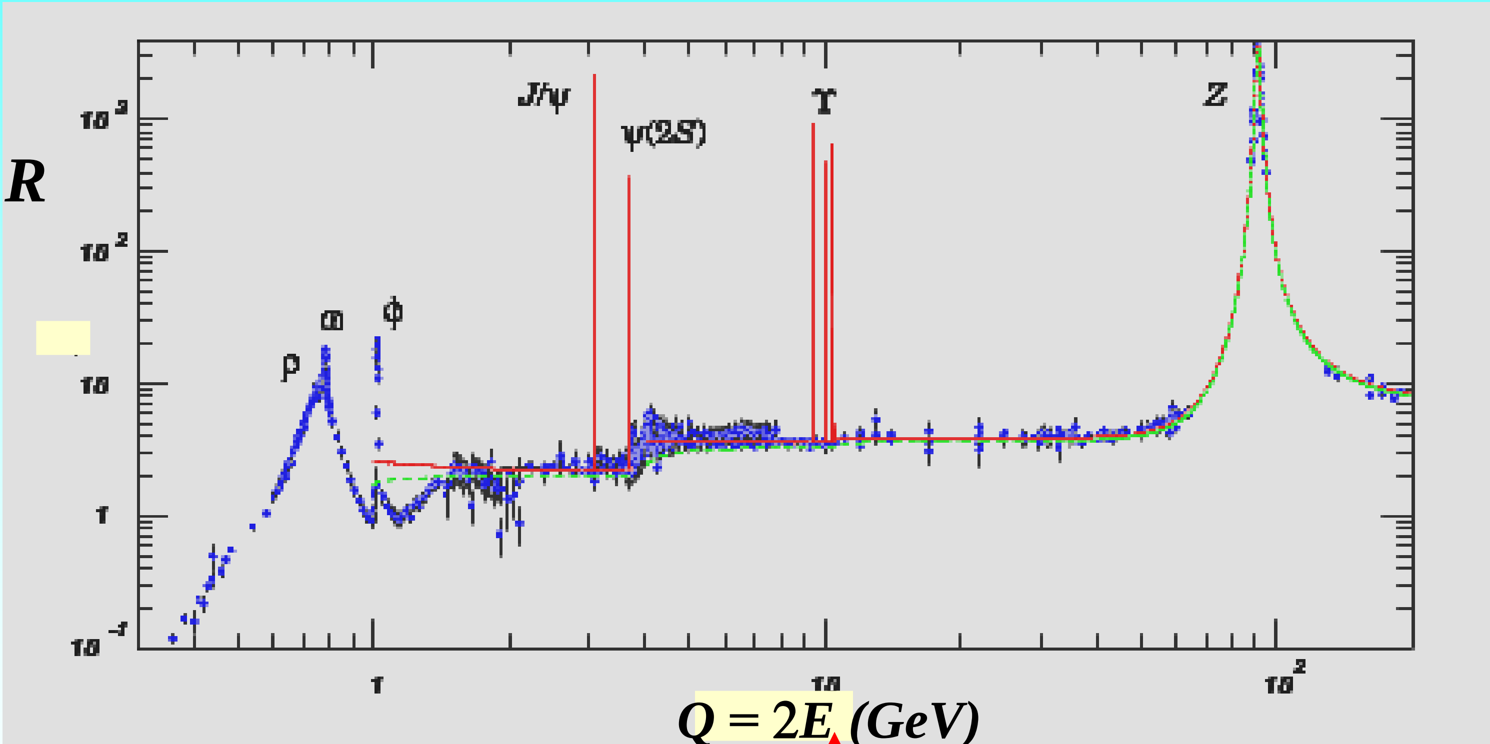


48 GeV electron identified by surrounding calorimeters

One of the first $W \rightarrow e + \nu$ events in UA1

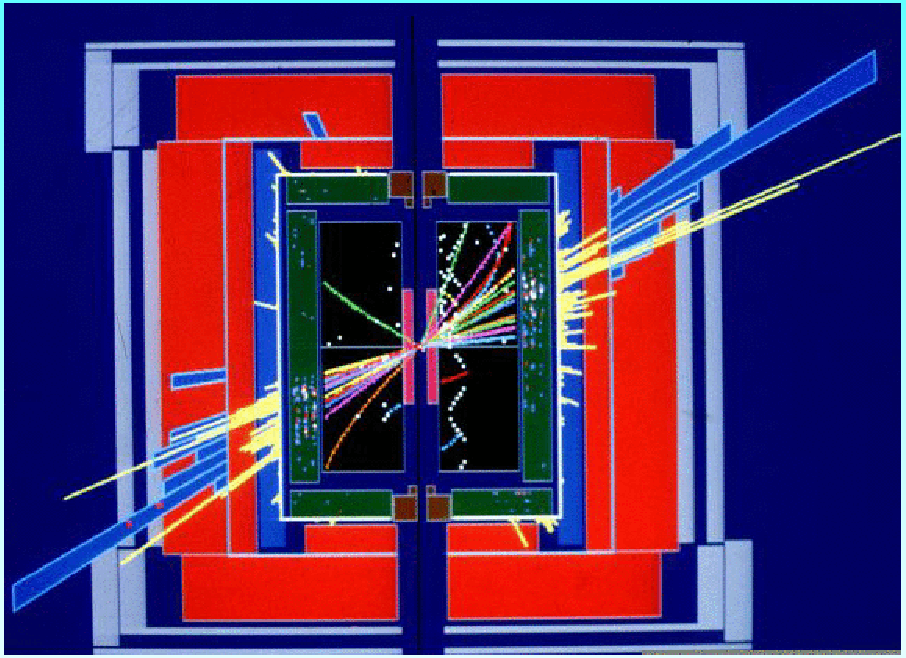
Standard Model

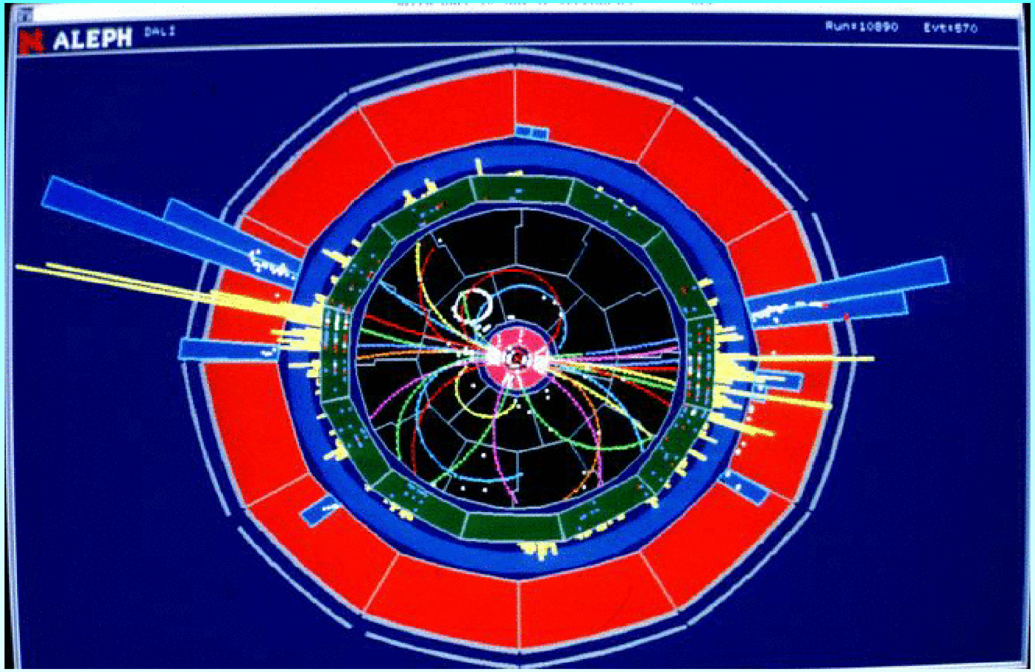
$$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$ between 0.3 and 200 GeV



$e^+e^- \to b\ \bar{b}$
(the 5th quark: $e = -1/3$)

$e^+e^- \to Z \to q\ \bar{q}$





The two orthogonal views of an event $Z \to q\,\overline{q} \to$ hadrons at LEP (ALEPH detector)

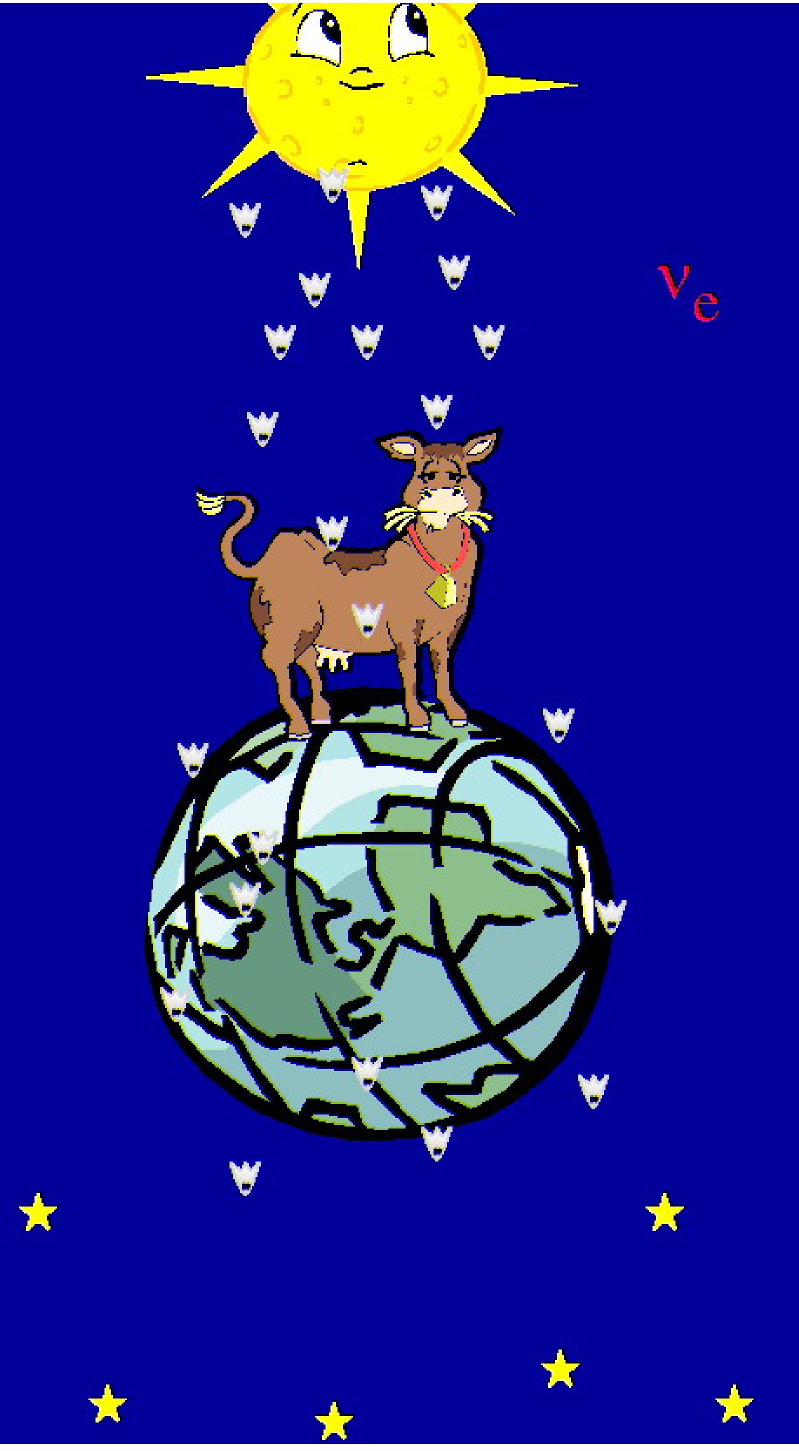

WANTED
Higgs
GREAT REWARD
STOCKHOLM

NEUTRINOS

- Weakly Interacting Particles
- Among most abundant particles in the Universe
- Each second pass through your body

$\sim 10^{14}\ \nu_e$ from the SUN

$$p\,p \rightarrow d\ e^{+}\nu_e\ ,\ \ldots$$



NEUTRINOS

Each second pass through your body

$\sim 10^{14}\ \nu_e$ from the SUN

$$p\,p \rightarrow d\ e^{+}\nu_e\ , \ldots$$

They also come

from below!

NEUTRINOS
are produced in
the atmosphere by
COSMIC RAYS

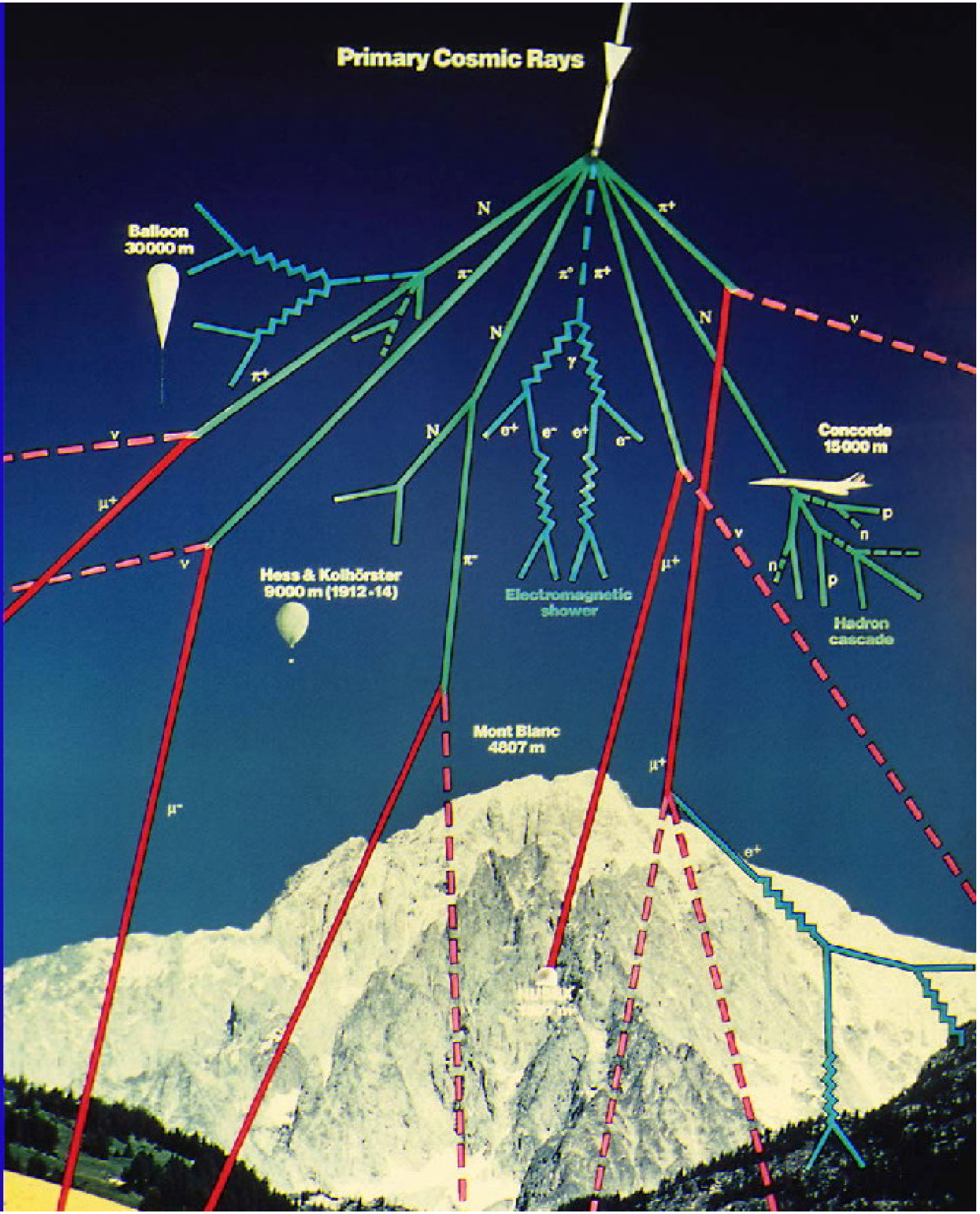
$$p\,X \rightarrow \pi\,X'$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \quad ; \quad \mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$$

- Produced by Nuclear Reactors

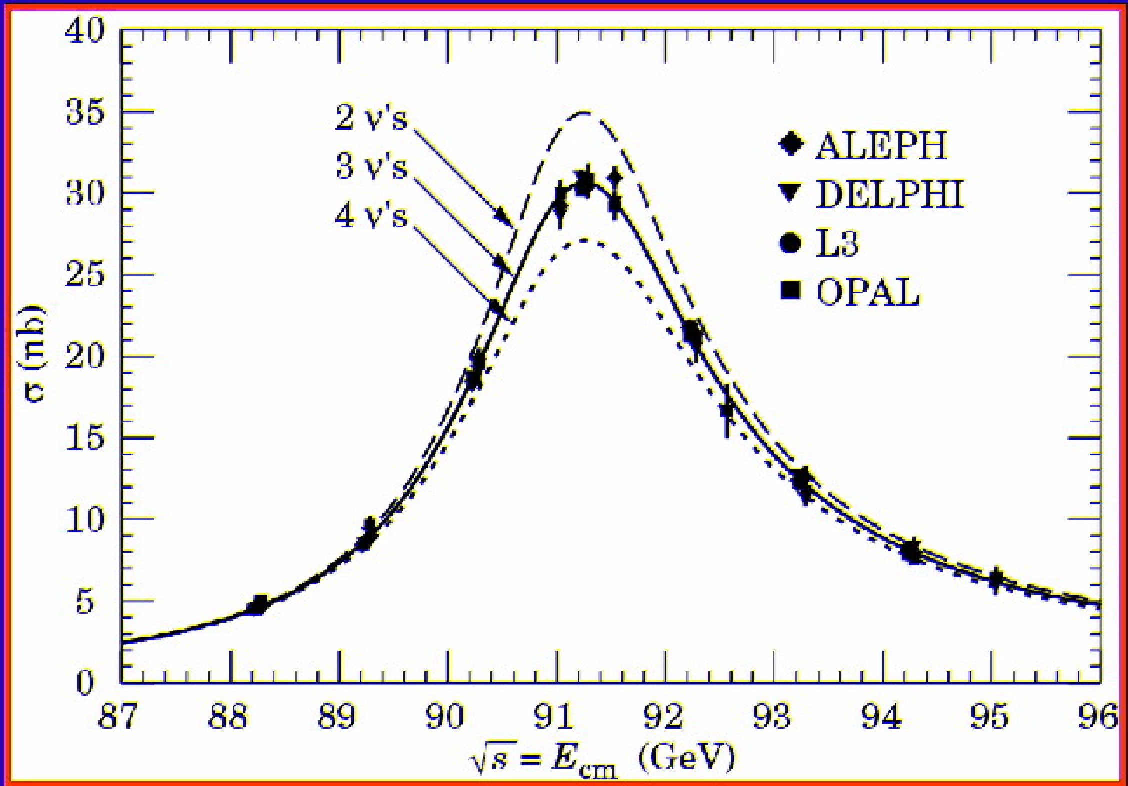
$$n \rightarrow p\,e^- \bar{\nu}_e$$

- Produced at CERN



HOW MANY NEUTRINOS ?

$\sigma(Z \rightarrow \text{hadrons})$

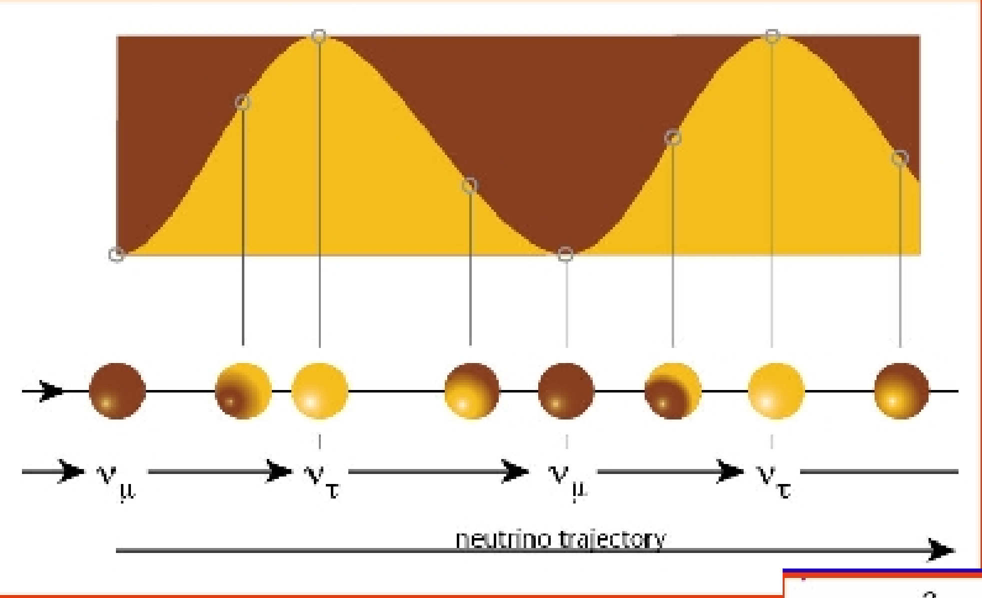


$$N_\nu = \frac{\Gamma(Z \rightarrow \text{invisible})}{\Gamma(Z \rightarrow \nu_i \bar{\nu}_i)_{\text{Th}}}$$

$$= 2.9840 \pm 0.0082$$

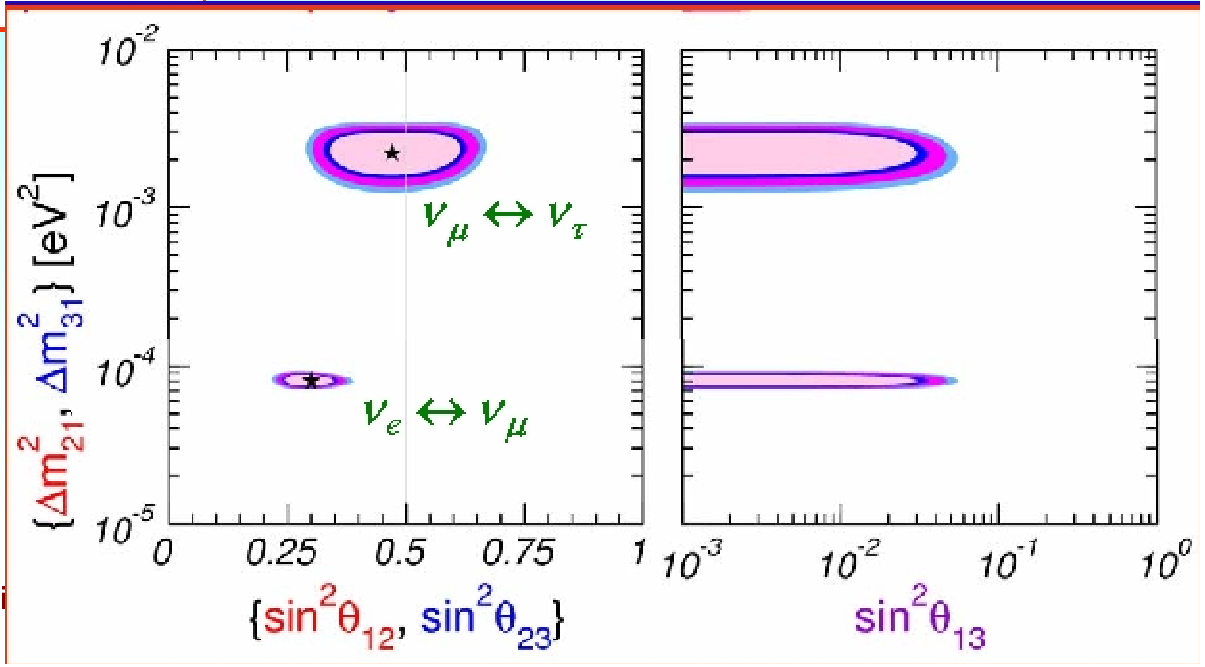
$$\Gamma(Z \rightarrow \text{invisible}) \equiv \Gamma(Z \rightarrow \text{all}) - \Gamma(Z \rightarrow \text{visible})$$

Маса и осцилации на неутриното



Ако ν имат маси, е възможно да се смесват и да осцилират

Осцилации се наблюдават експериментално

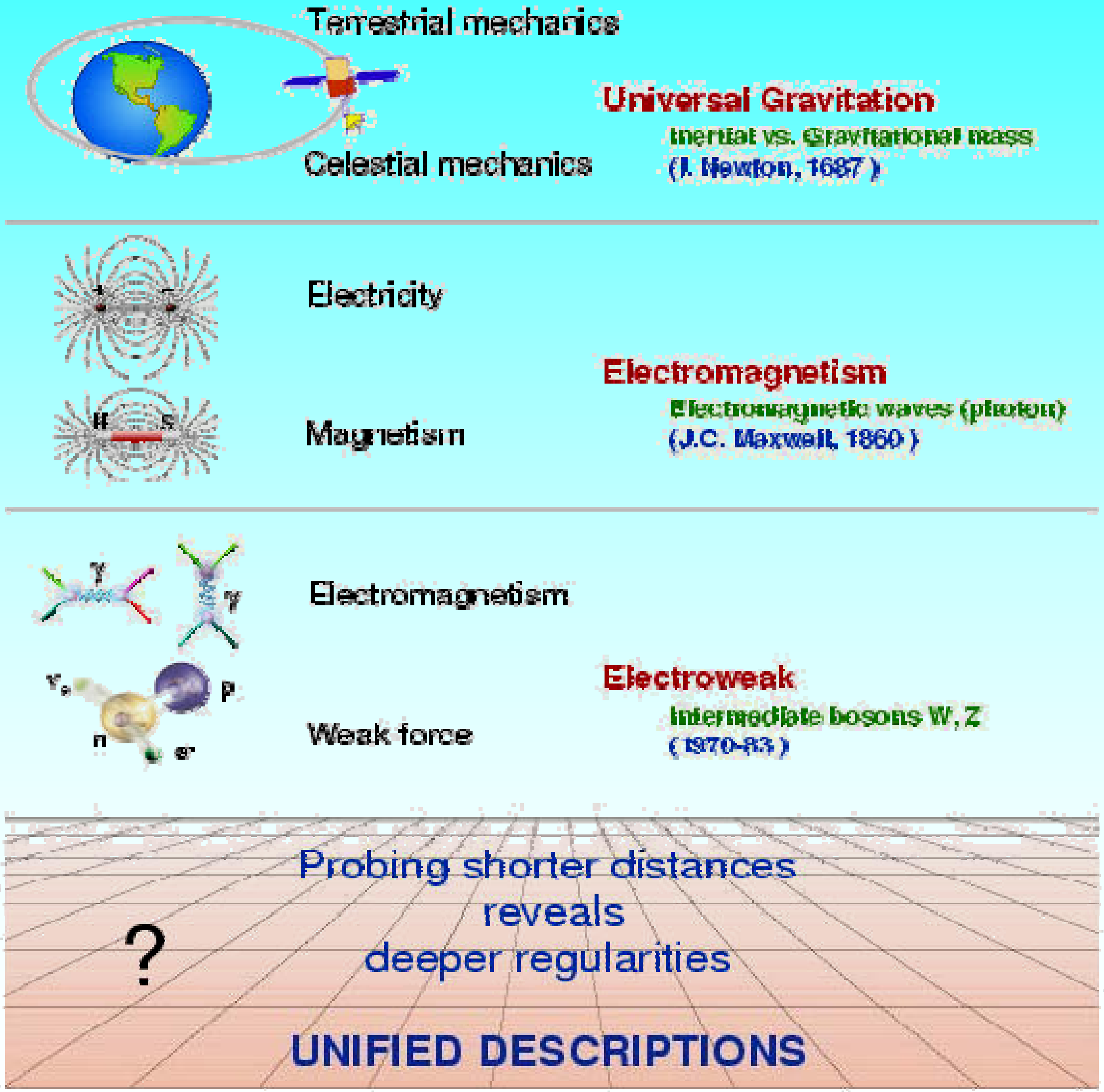


Проблеми на СМ

- Маси на преносителите на взаимодействия и материалните полета
- 15 допълнителни параметъра
- Защо 3 поколения
- Асиметрия между ляво и дясно
- Нарушение на CP инвариантността т.е. материя – антиматерия
- Higgs – бозон – експериментално наблюдение
- Масси на неутриното – смесване на неутриното
- Йерархия на масите

Обединение на взаимодействията

Обединение на взаимодействията

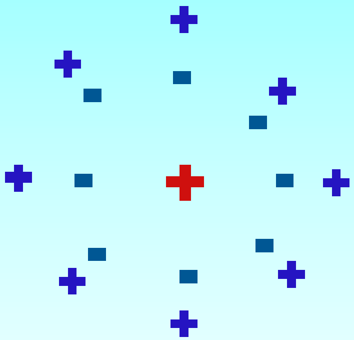


Grand Unification

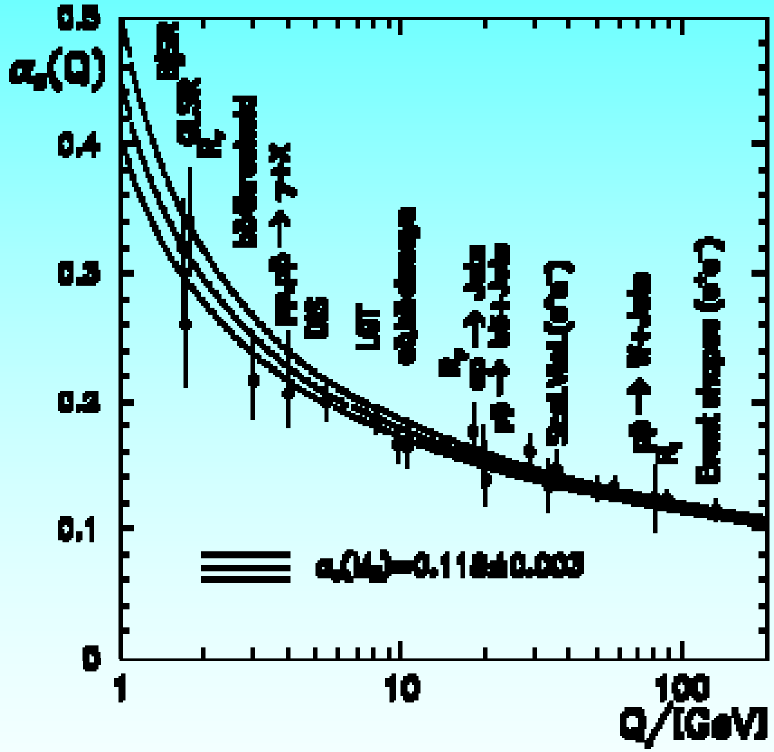
Running Coupling Constants

"Bare" charge v/s
experimentally measured charge

e.g. electric charge



$$\alpha(q^2) = \alpha(q_0^2)\left[1+\delta\ln\left(\frac{q^2}{q_0^2}\right)\right]$$



Grand Unification

GUT : Perhaps strong and electroweak forces are related at ~ 10^{16} GeV

Quarks and leptons are put on the same footing
they can make transitions amongst themselves

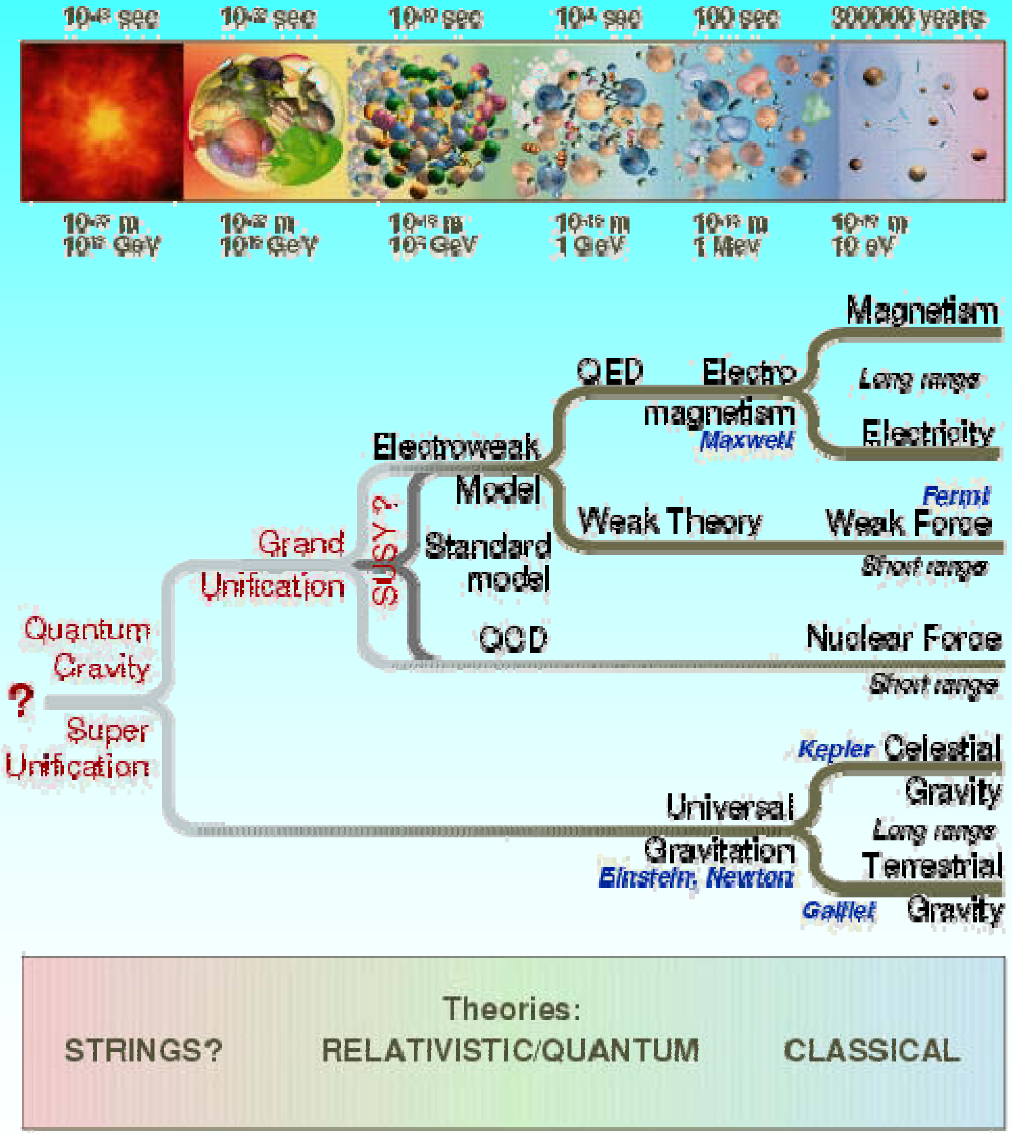
Protons will be unstable e.g. $p \rightarrow e^+ \pi^0$

Charge is quantized: $Q[d_1\ u_1\ u_2\ e\text{-}\ \nu_1] = 0$

Neutrinos have a small mass

$$M_\nu \approx \frac{M_g^2}{M_{GUT}} \approx 10^{-6} - 10^{-3}\ eV$$

Обединение на взаимодействията



Гравитация – свойства на пространство - времето

Суперсиметрия

How to unify ?

Gravity - space-time symmetry

Electroweak - internal symmetry

Strong - internal symmetry

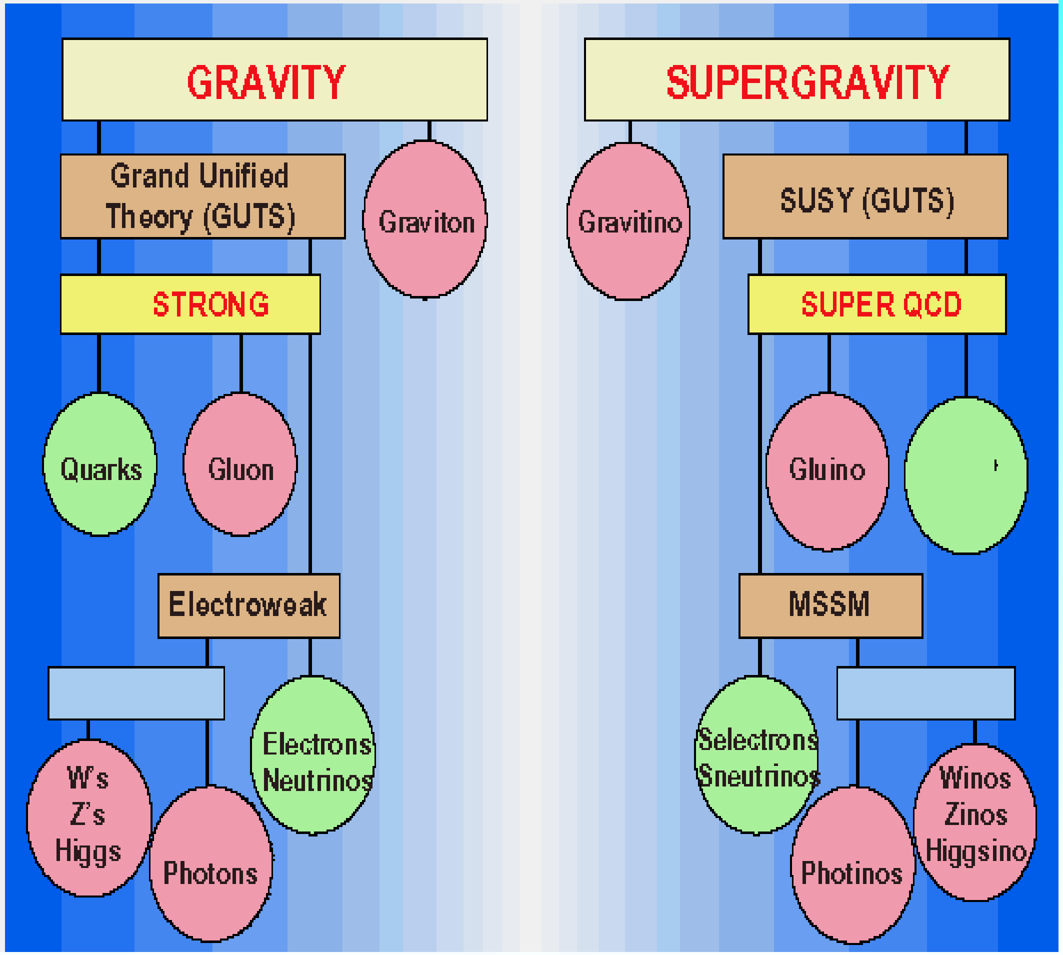
Supersymmetry – symmetry between bosons and fermions

Works well, but

Price to pay: many new particles!

To every fundamental particle – new boson

To every mediator – new fermion



Колко мерно е пространство-времето?

Two fundamental scales:

- Electroweak — $M_{EW} \sim 10^2\text{-}10^3$ GeV
- Planck — $M_{Pl} \sim 10^{19}$ GeV

Observation:

- M_{EW} is established experimentaly
  - EW interactions are tested down to distances $1/M_{EW} \sim 10^{-17}$ cm
- M_{Pl} is just a number
  - gravity tested only down to ~ 1 mm, far away from $1/M_{Pl} \sim 10^{-35}$ m

Solution: cut the Gordian Knot!

- There is only one fundamental scale: M_{EW}
- M_{Pl} is just an effective constant
- Its high value is caused by additional spatial dimentions, compactified at radius R ~ 1 mm

Extra dimension perspectives

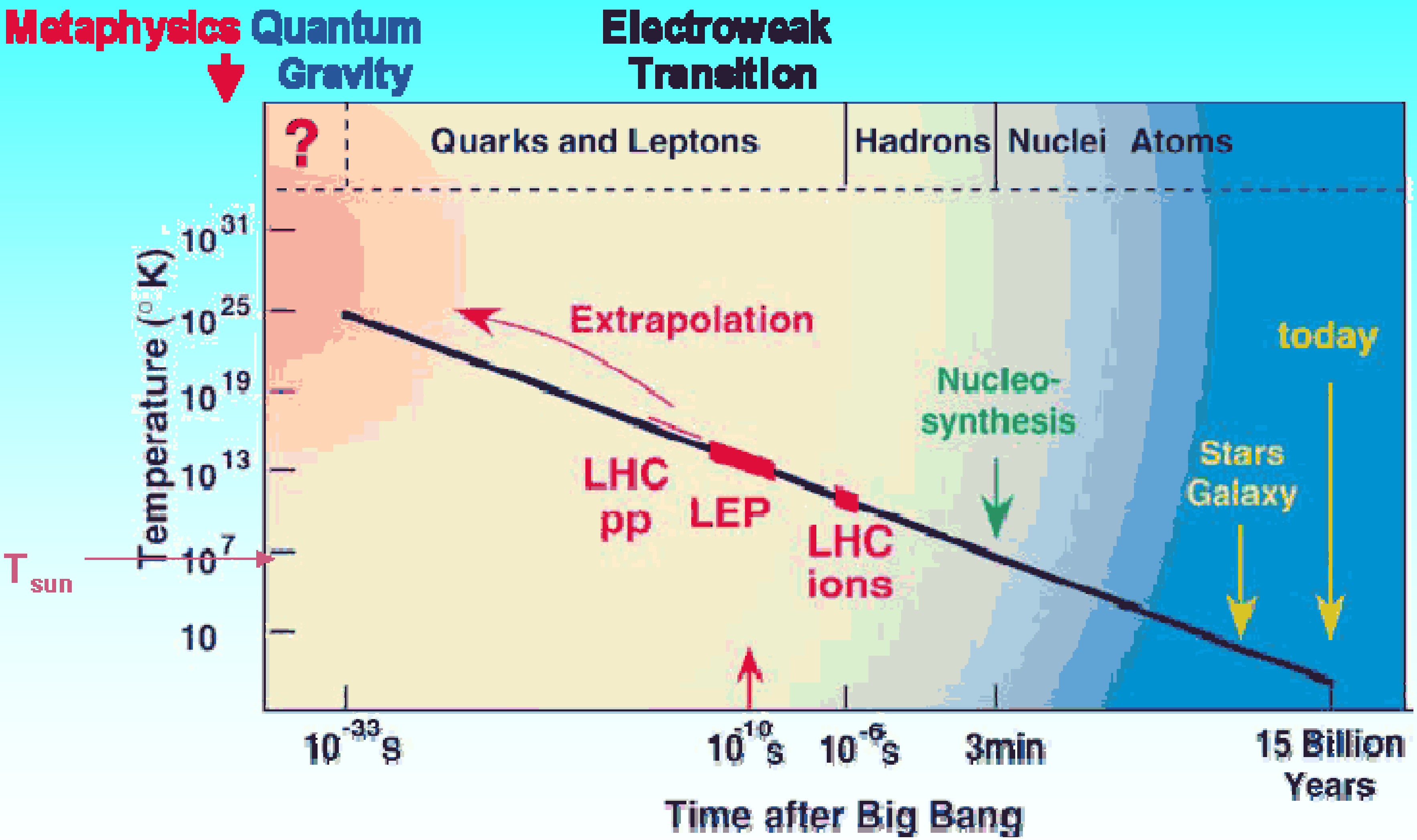
Models with extra dimensions can

- unify all interactions
- solve the hierarchy problem
- link String Theory to Standard Model
- make Quantum Gravity and String Theory accessible at LHC
  like Prometeus made the divine fire accessible for people

Perhaps it is only a dream...

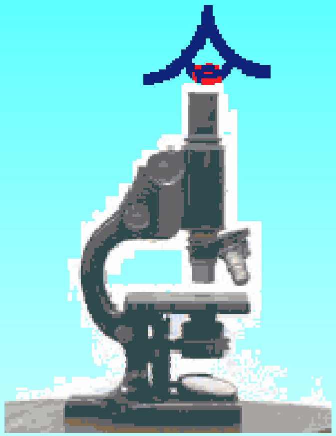
But I wish you and me this dream to come true!

Назад към началото



Как го правим?

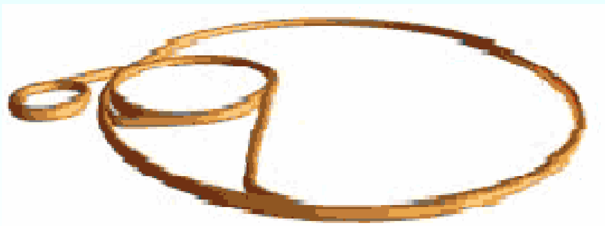
Как го правим?

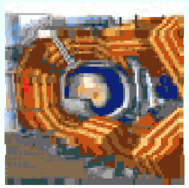


Wavelength of probe radiation should be smaller than the object to be resolved

$$\lambda \ll \frac{h}{p} = \frac{hc}{E}$$

Object	Size	Energy of Radiation
Atom	10^{-10} m	0.00001 GeV (electrons)
Nucleus	10^{-14} m	0.01 GeV (alphas)
Nucleon	10^{-15}m	0.1 GeV (electrons)
Quarks	?	> 1 GeV (electrons?)

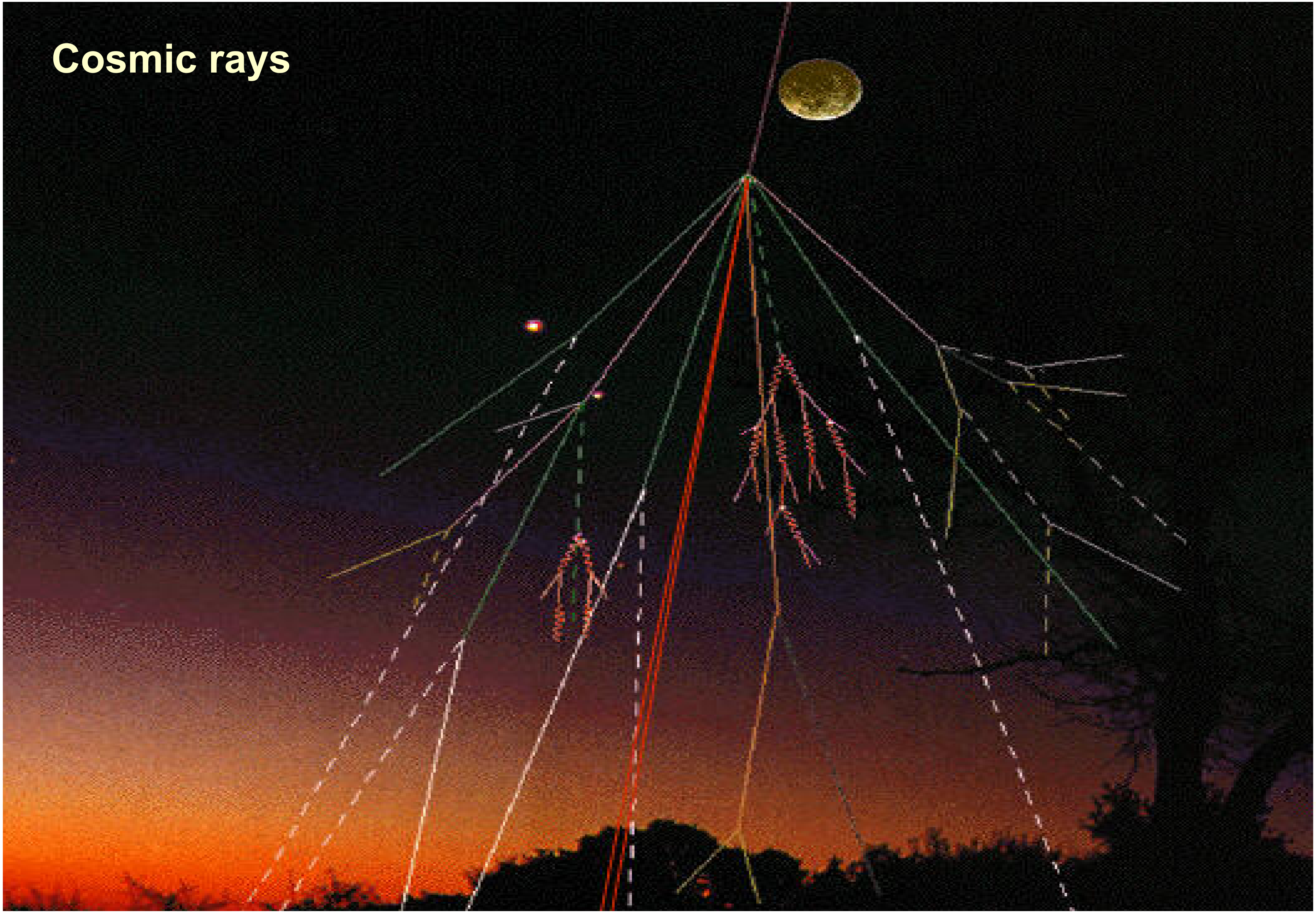




"electronic eyes"

Radioactive sources give energies in the range of MeV

Need accelerators for higher energies.

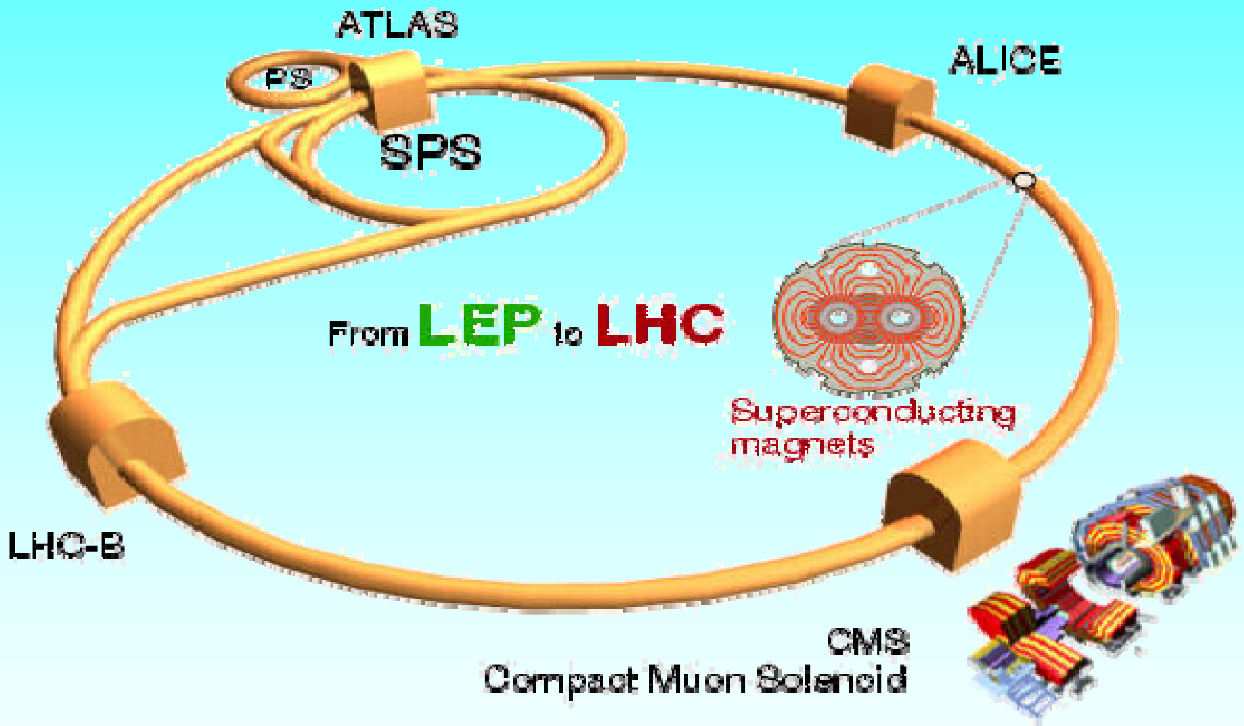

Cosmic rays

Ускоретели

Ускорители

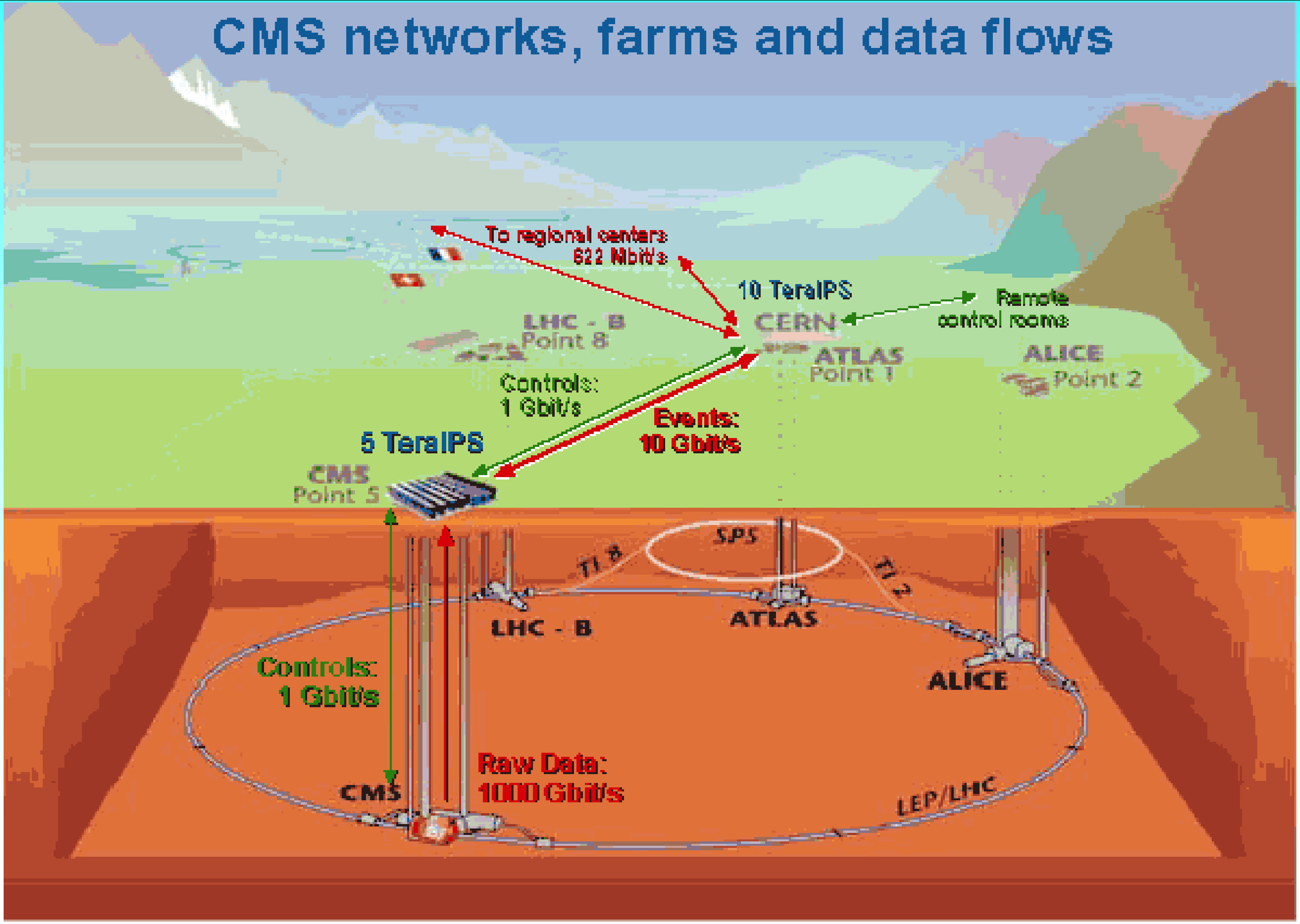
LHC

The Large Hadron Collider (LHC)



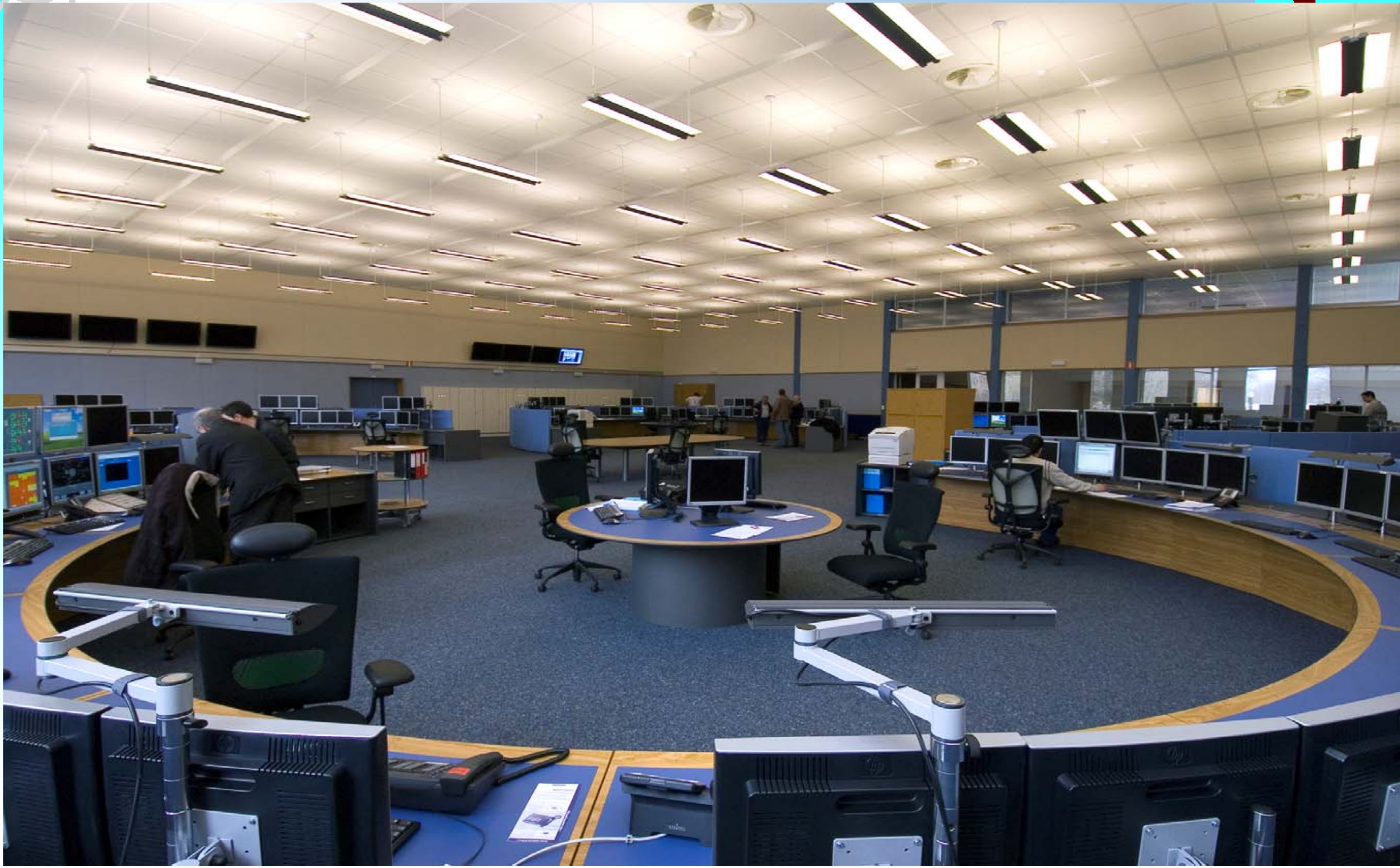
	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} $cm^{-2}s^{-1}$
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

LHC



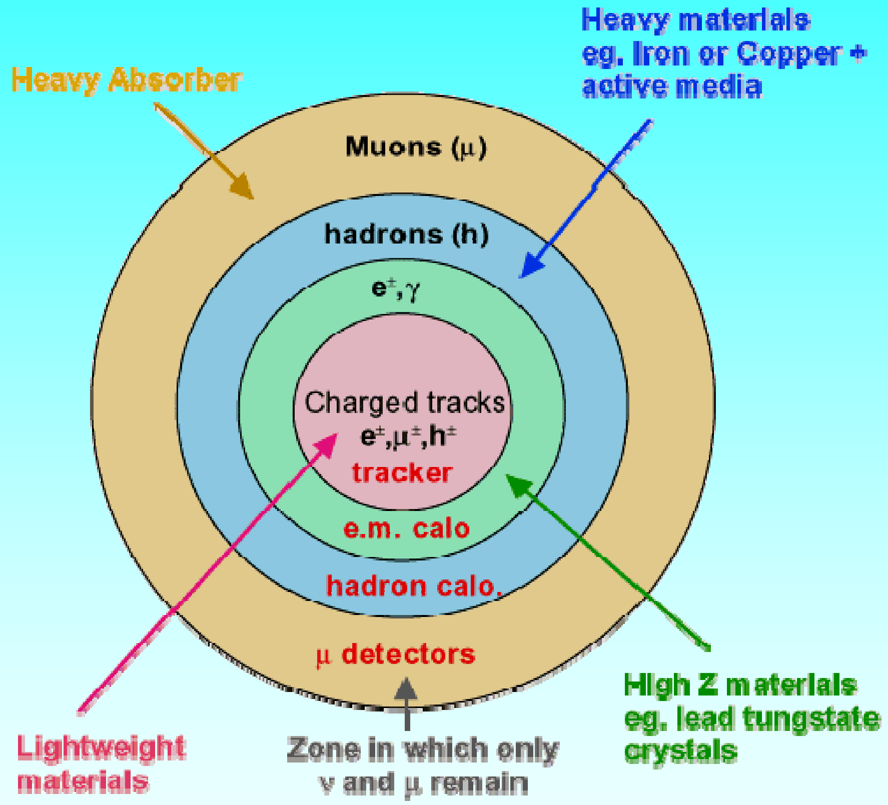
CMS networks, farms and data flows
To regional centers
622 Mbit/s
10 TeraIPS
CERN
Remote
control rooms
LHC - B
Point 8
ATLAS
Point 1
ALICE
Point 2
Controls:
1 Gbit/s
Events:
10 Gbit/s
5 TeraIPS
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
Controls:
1 Gbit/s
Raw Data:
1000 Gbit/s
CMS
LEP/LHC

LHC: Контролна зала



LHC: в тунела

Структура на детекторите



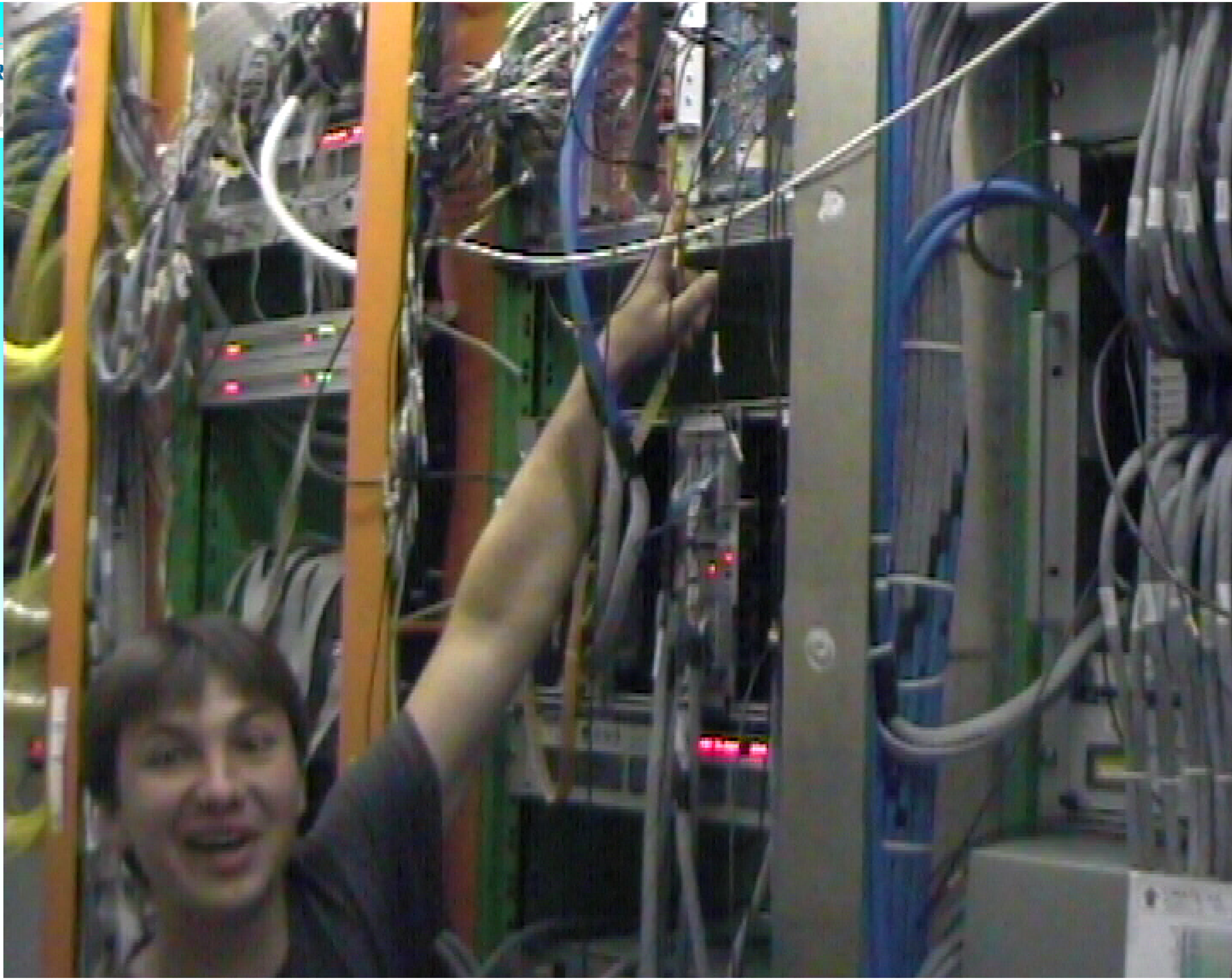
Each layer identifies and measures (or remeasures) the energy of particles unmeasured by the previous layer

No single detector can determine identity and measure energies/momenta of all particles

Как и какво измерваме

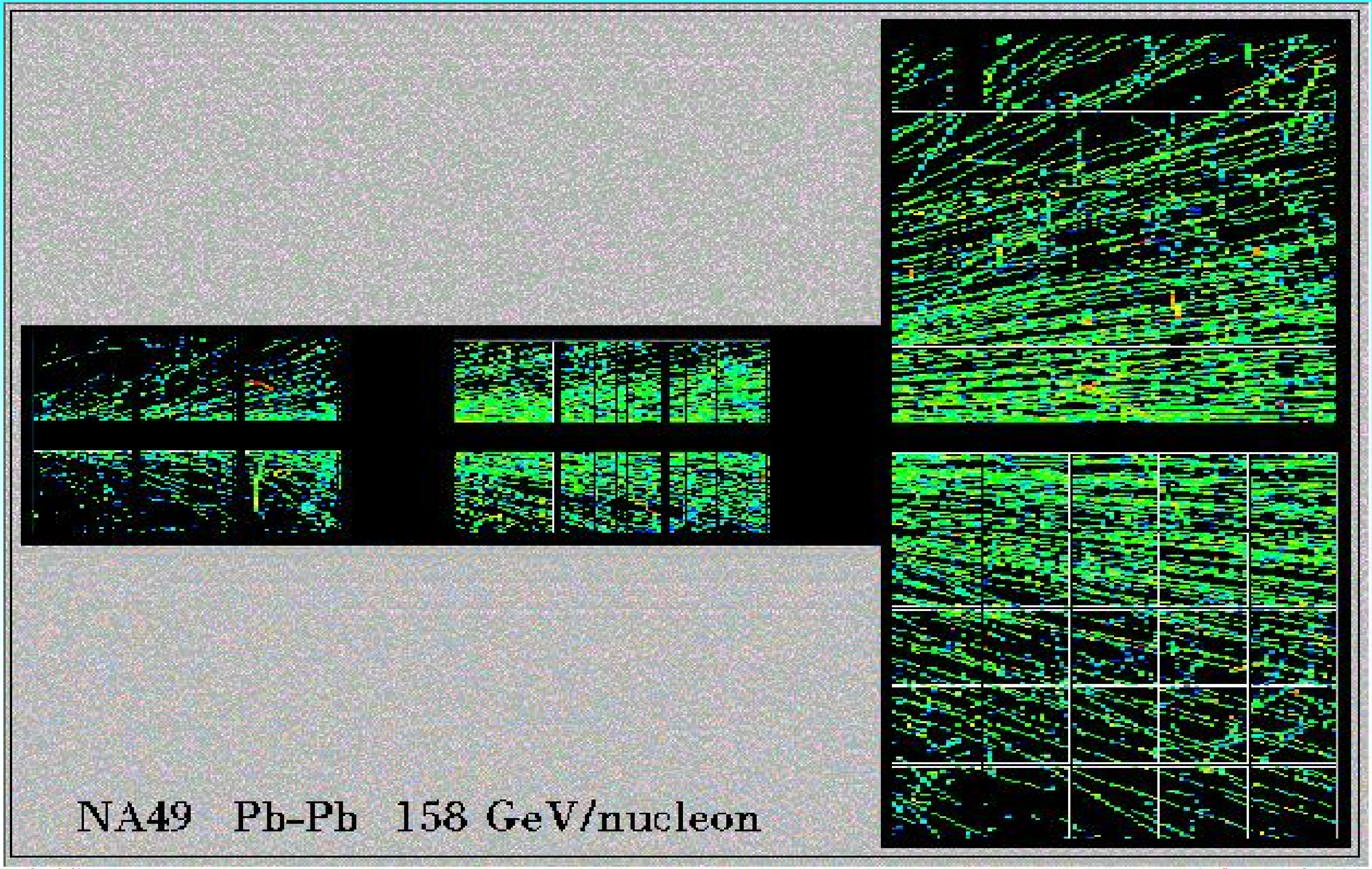
NA48 experiment

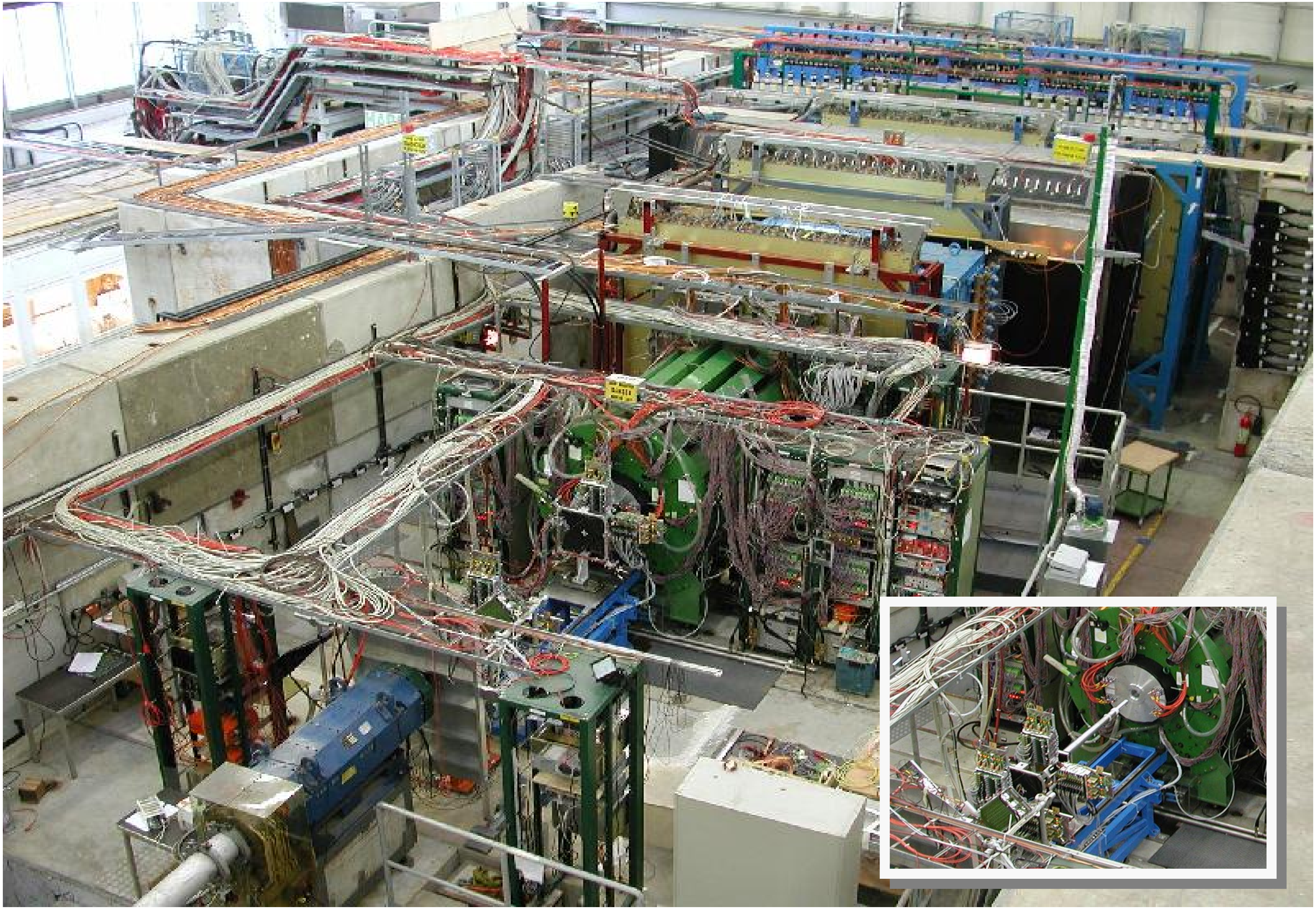
2006




62 GeV Gold + Gold
RHIC at BNL

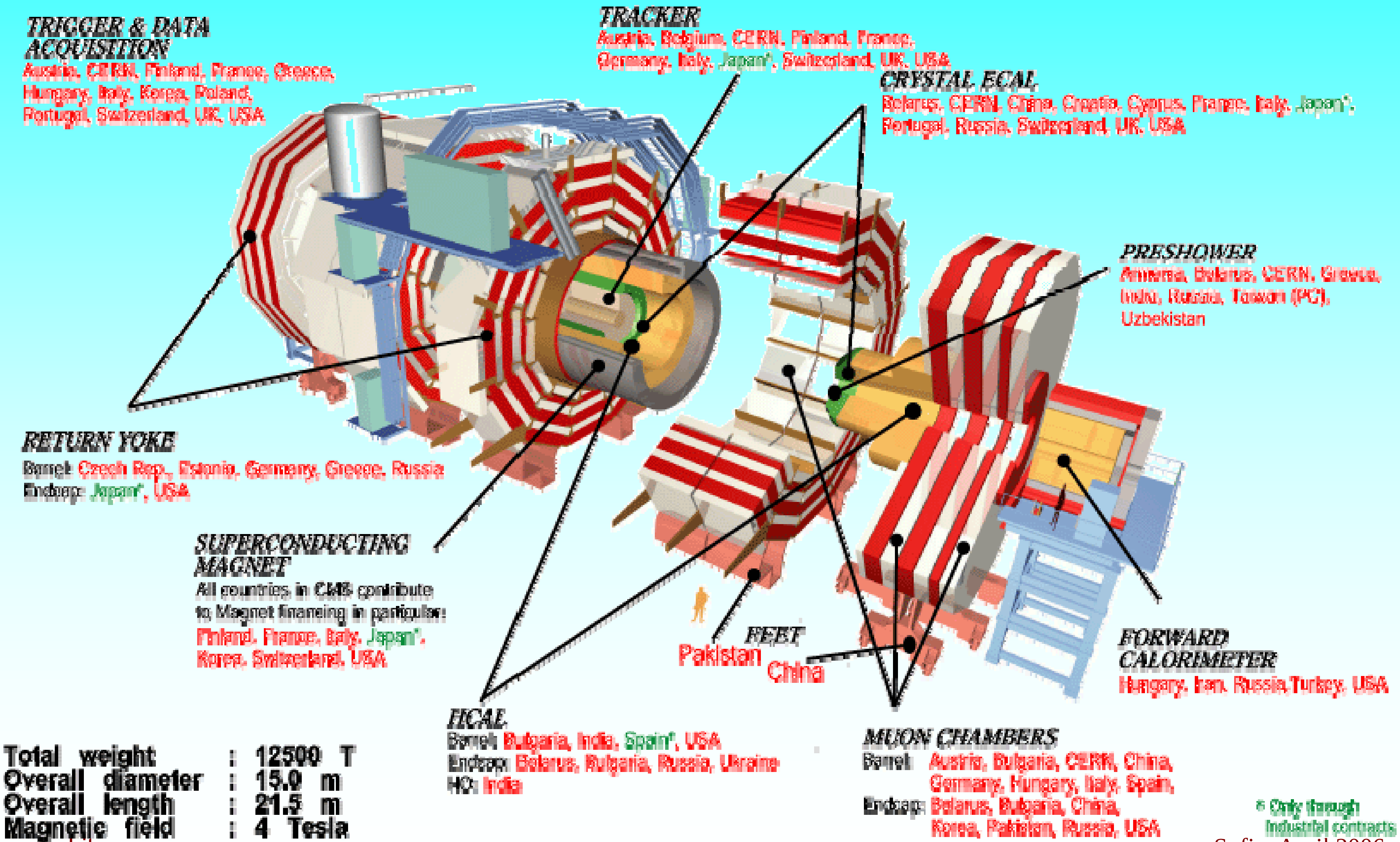
NA49 PbPb event



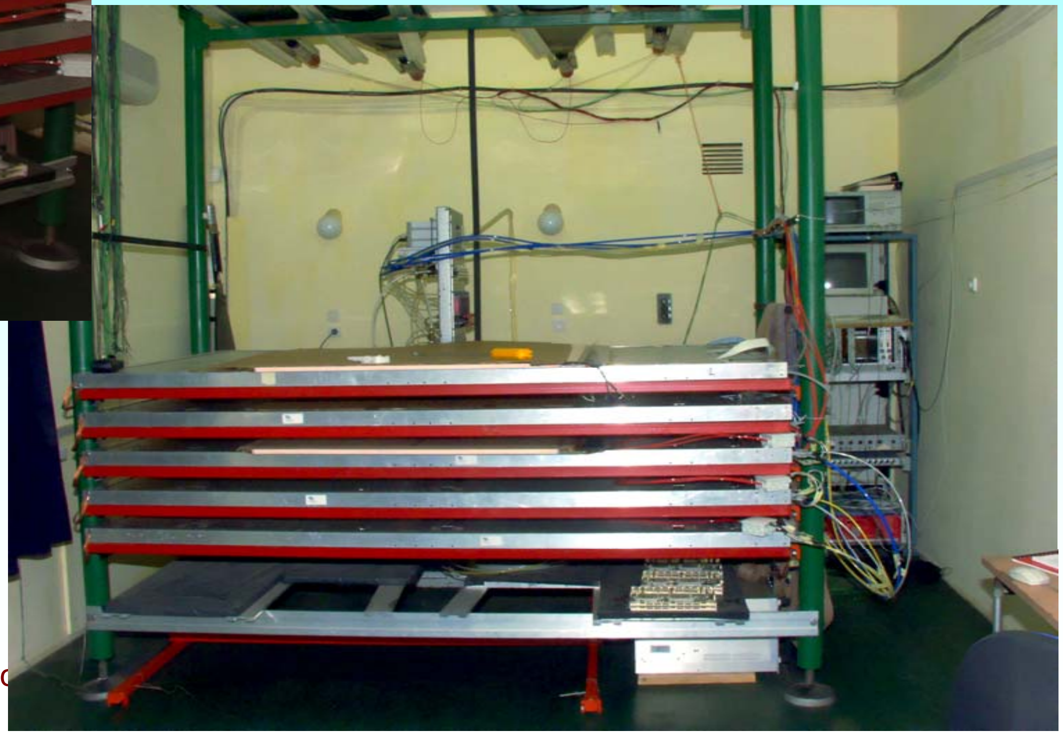


CMS Detector

31 Nations, 150 Institutions, 1870 Scientists



София: мюонен телескоп

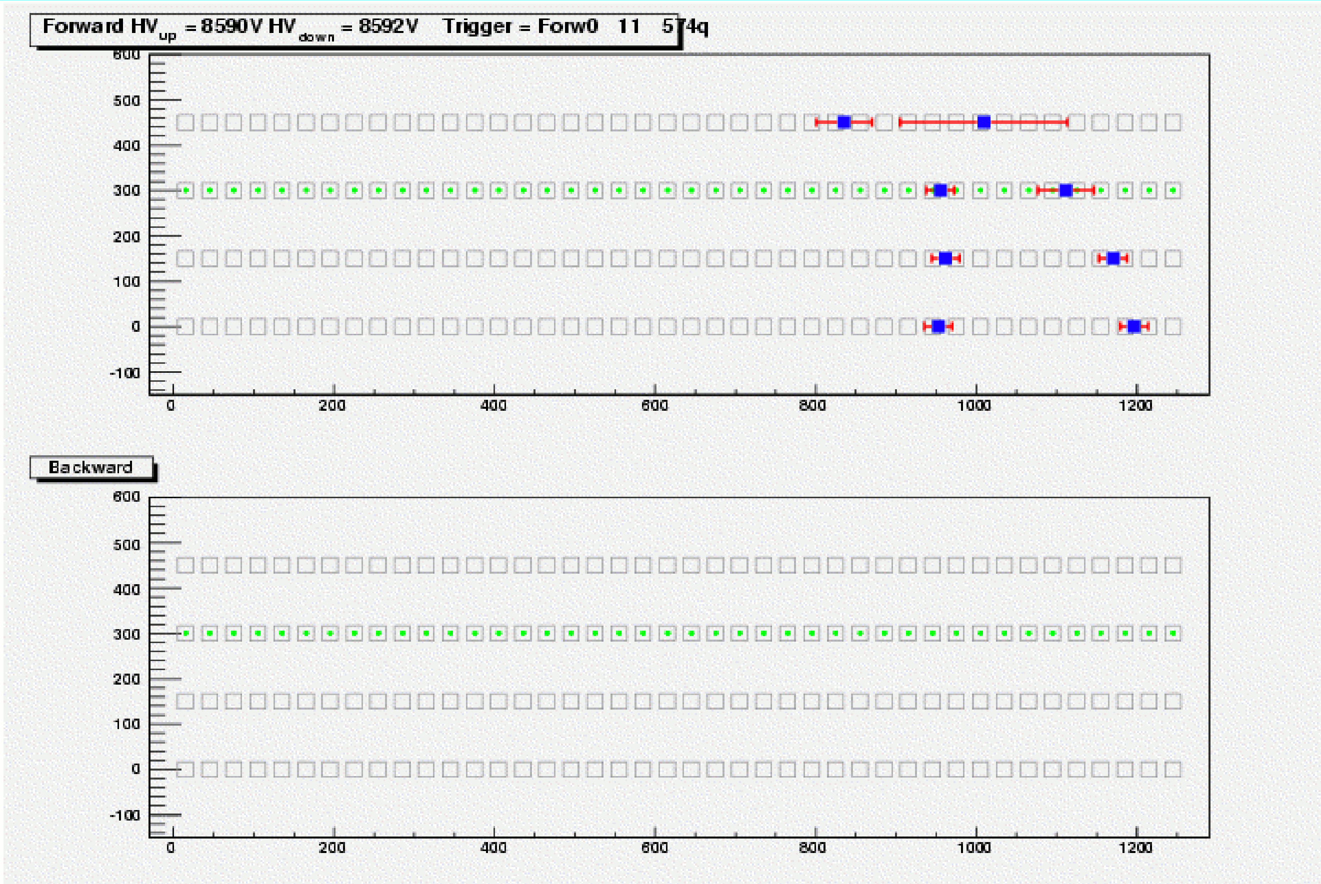


Реконструиране на мюонни следи

Брой камери = **4**

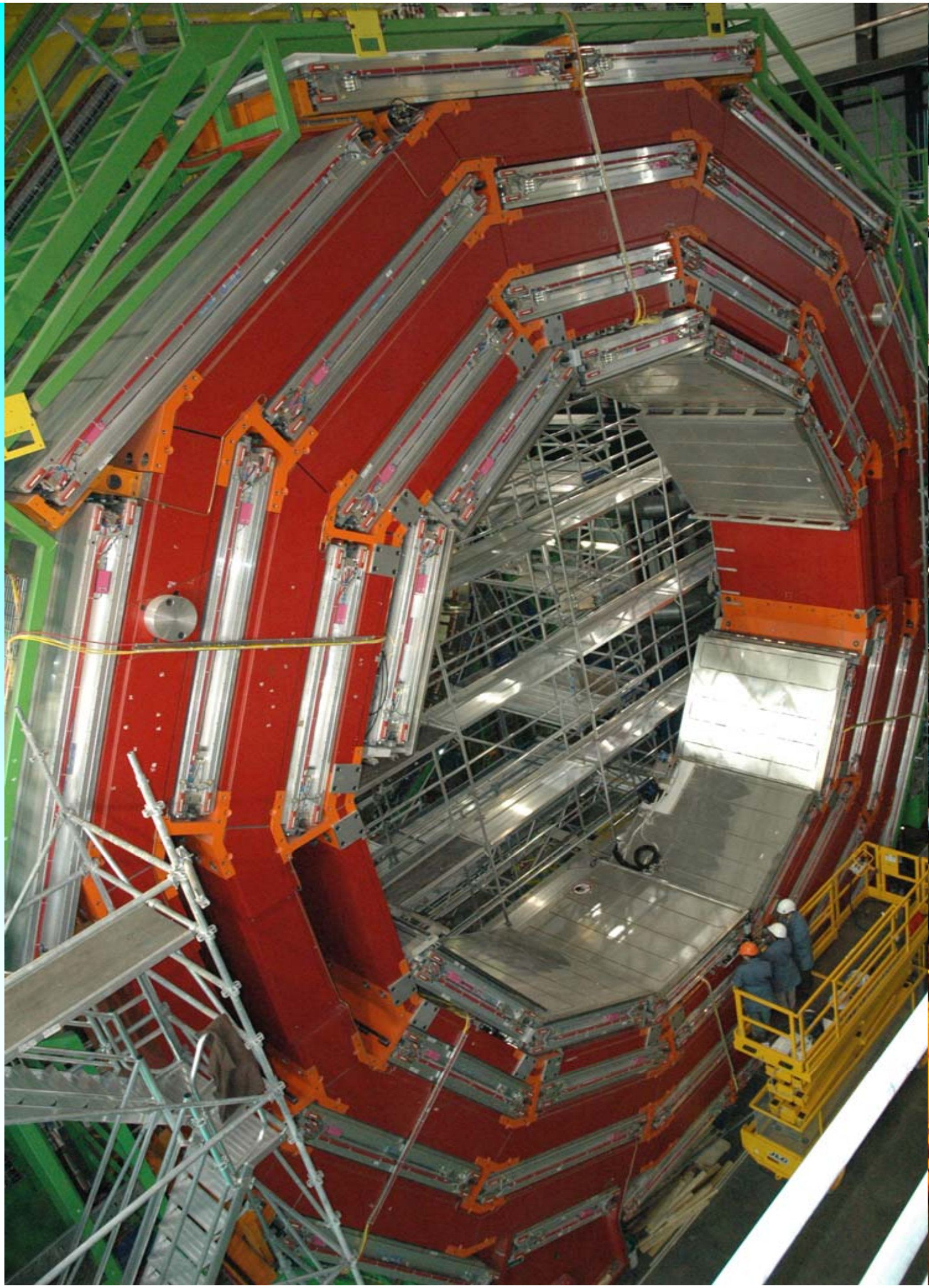
Избор на тестова станция

3 съвместими клъстера в рефените станции, точно по един във всяка, с големина ≤ 7

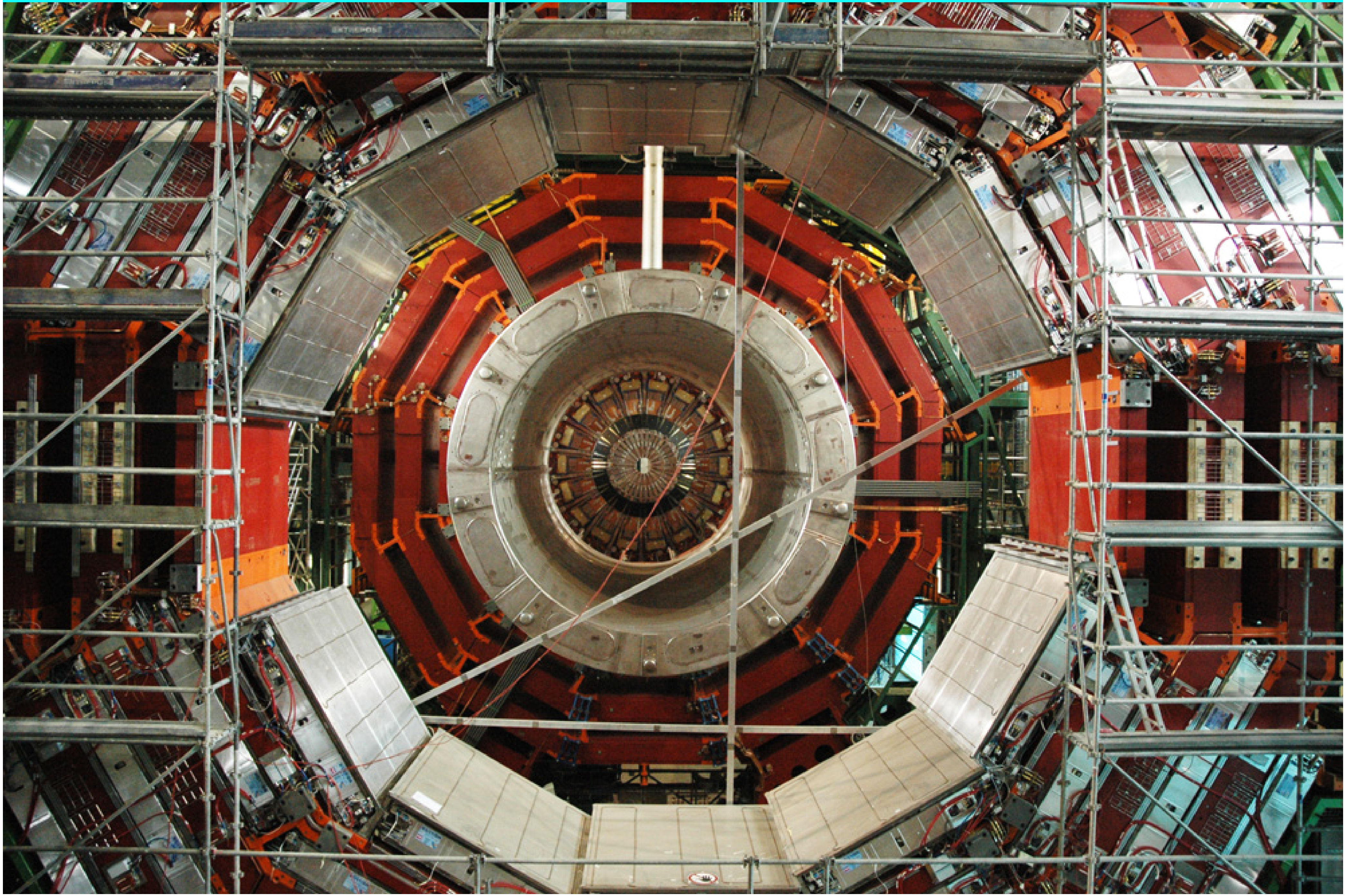


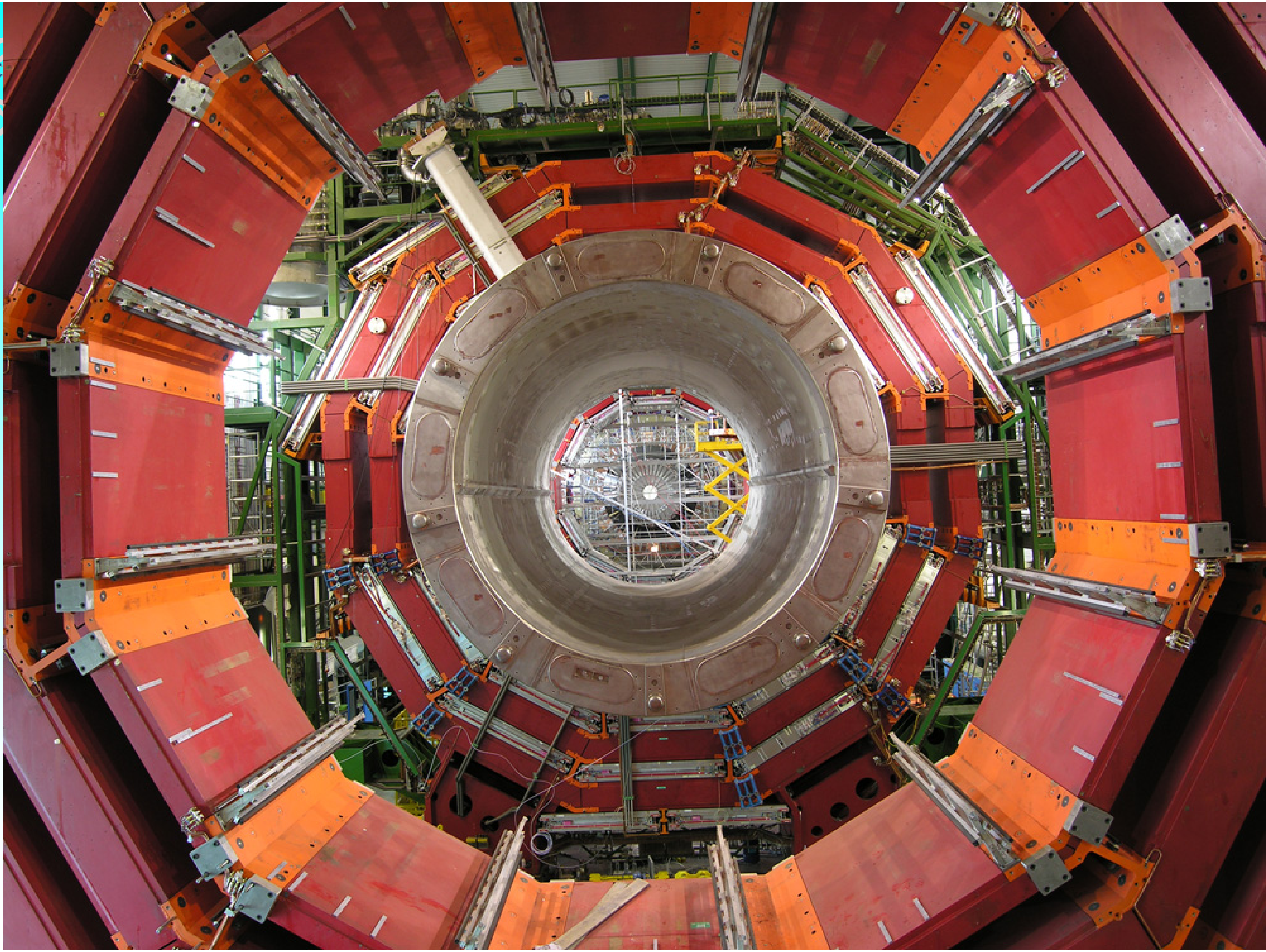
Реконструиране на мюонната следа

Камерата се счита за ефективна, ако в нея има клъстер съвместим със следата

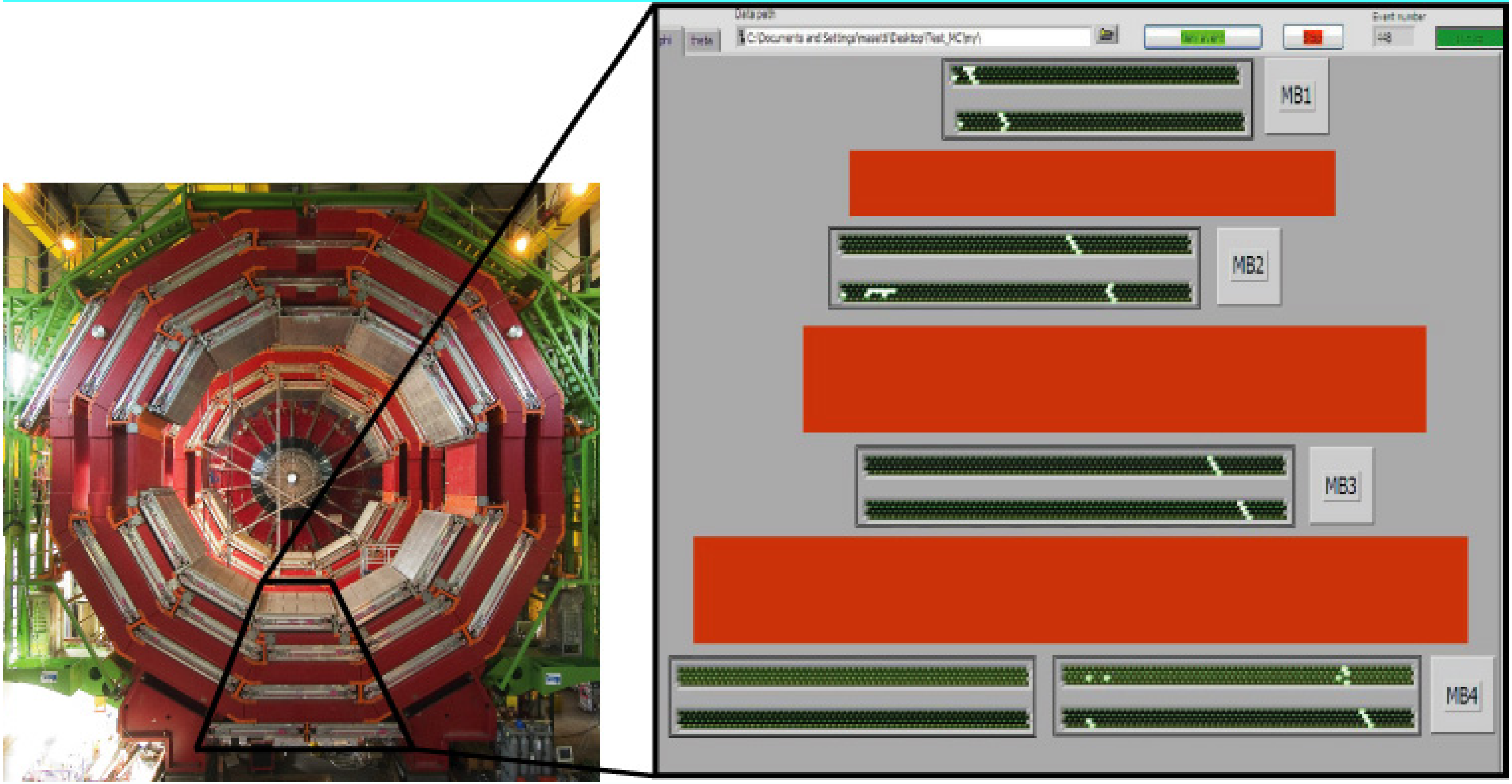



SL 153-12 E 2WD
LIFTLUX

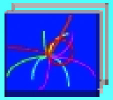




CMS Muon system



DAQ



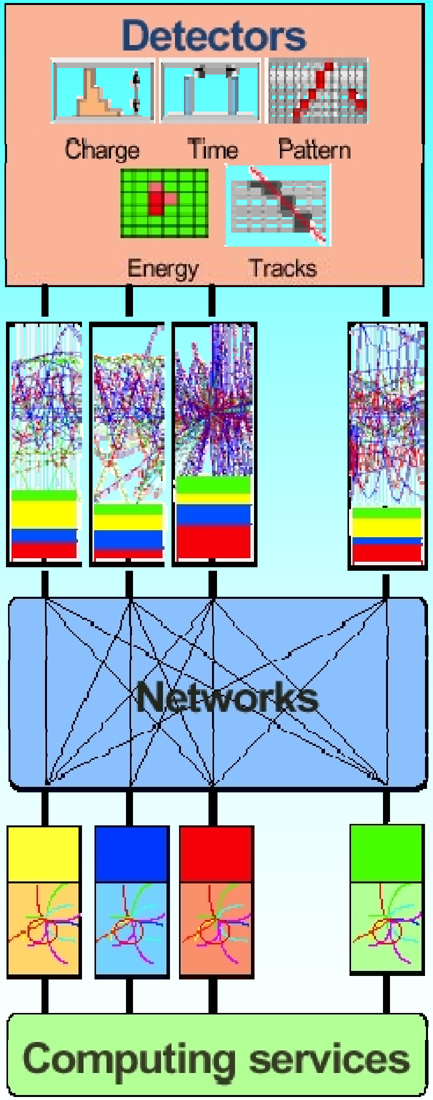
40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

Gigabit/s SERVICE LAN



16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

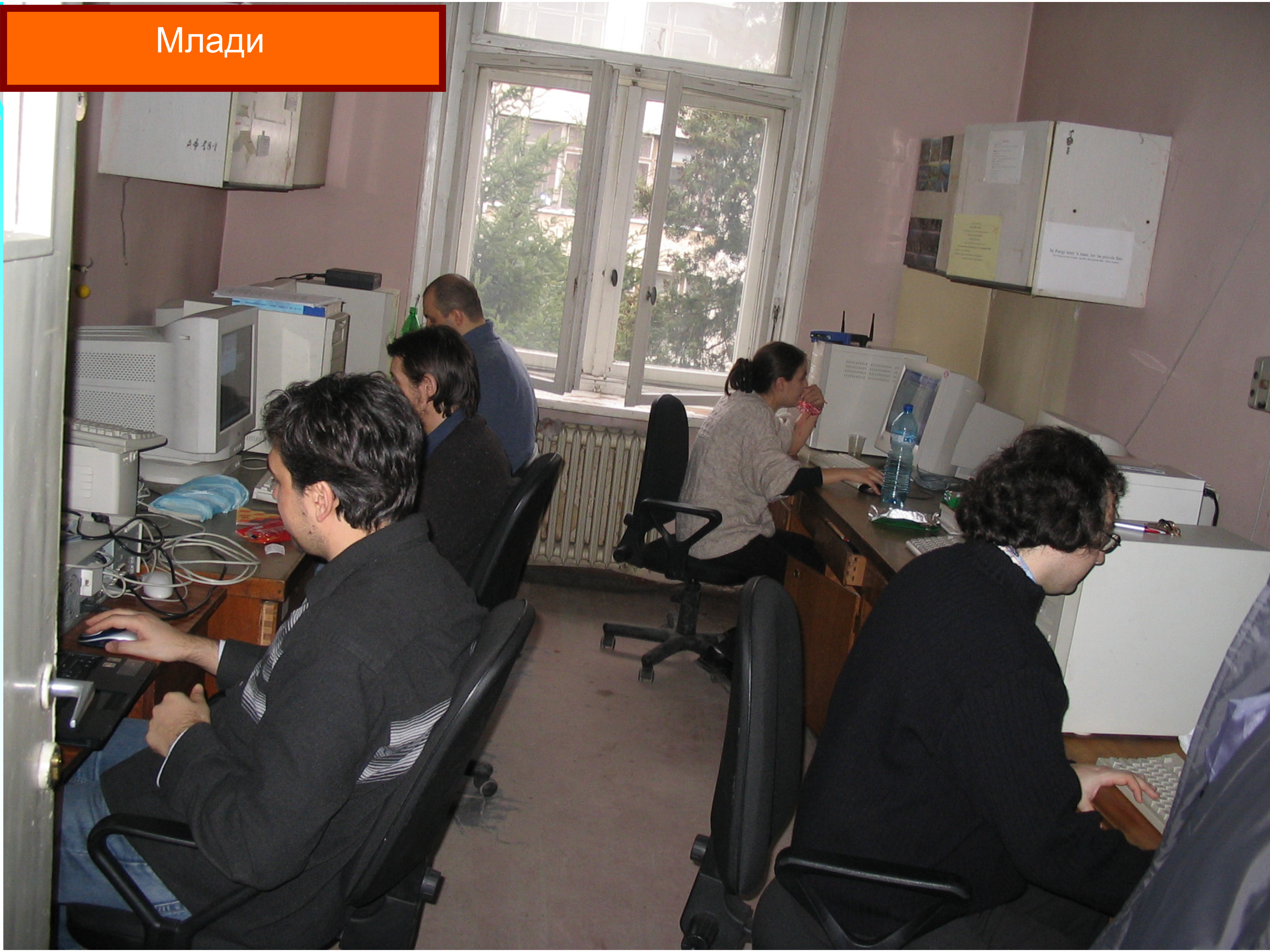
5 TeraIPS

EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

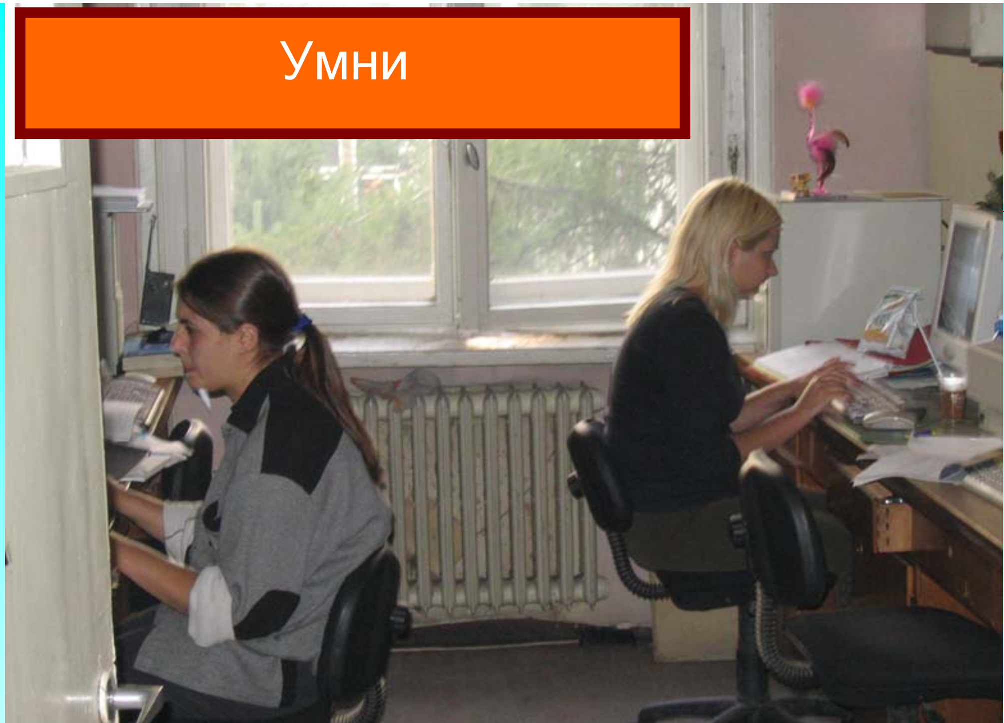
Petabyte ARCHIVE

Кой го прави?

Млади



Умни



Красиви

А вие искате ли?

Изборни курсове

- Квантова теория на полето
- Теория на групите
- Увод във физиката на елементарните частици
- Увод в теория на елементарните частици
- Калибровъчни теории на полето
- Експериментална ядрена физика
- Теоретична ядрена физика
- Ядрена електроника
- Дозиметрия и лъчезащита

Заключение

Физиката на ел. Частици е най-:

- Фундаменталния раздел на физиката
- Сложна от теоретична гл. точка
- Развита експериментално
- скъпа
- възбуждаща

Изисква

Тя дава:

- Ново знание и разбиране на света
- Нови технологии
- Голямо удоволствие