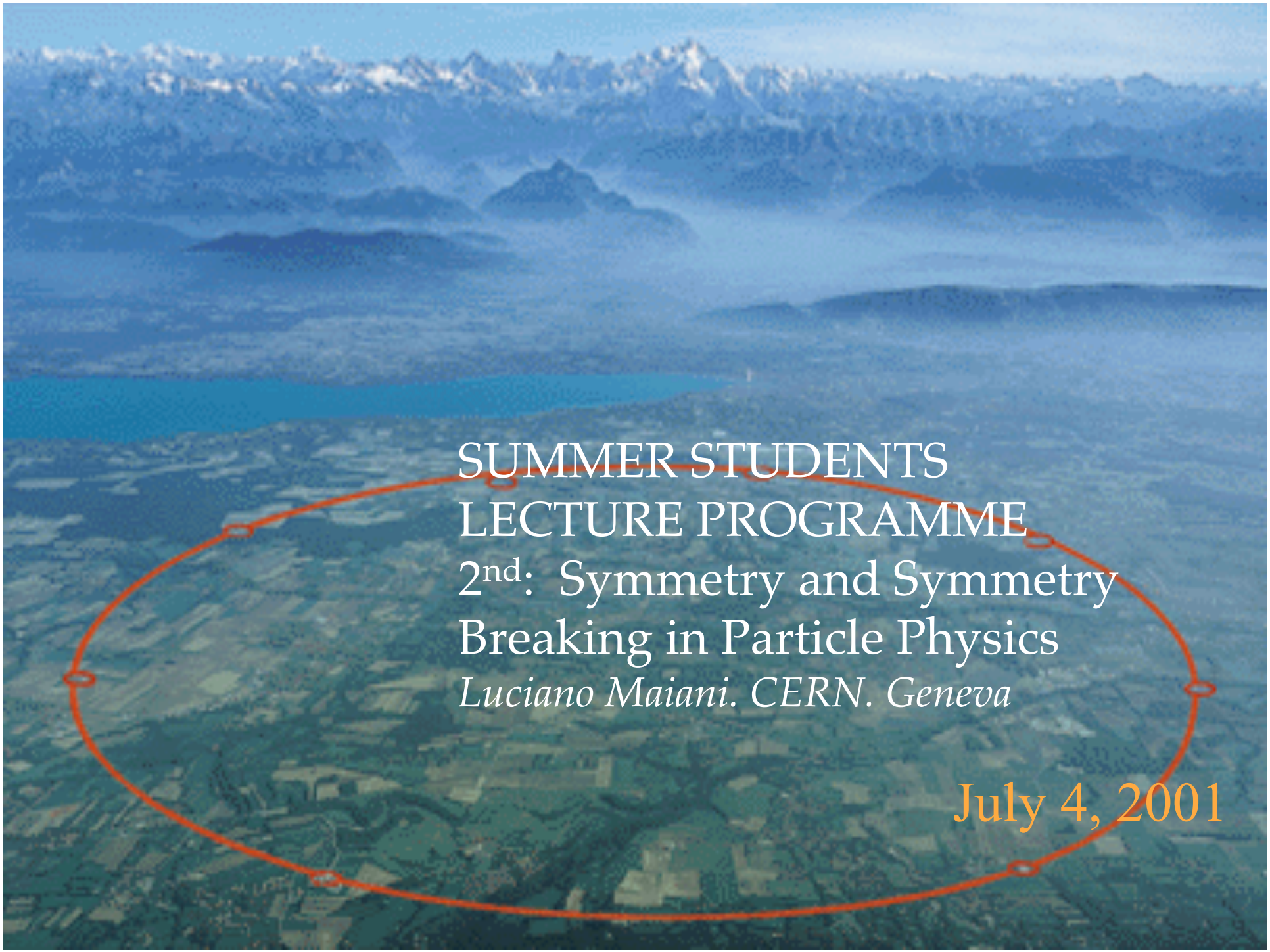
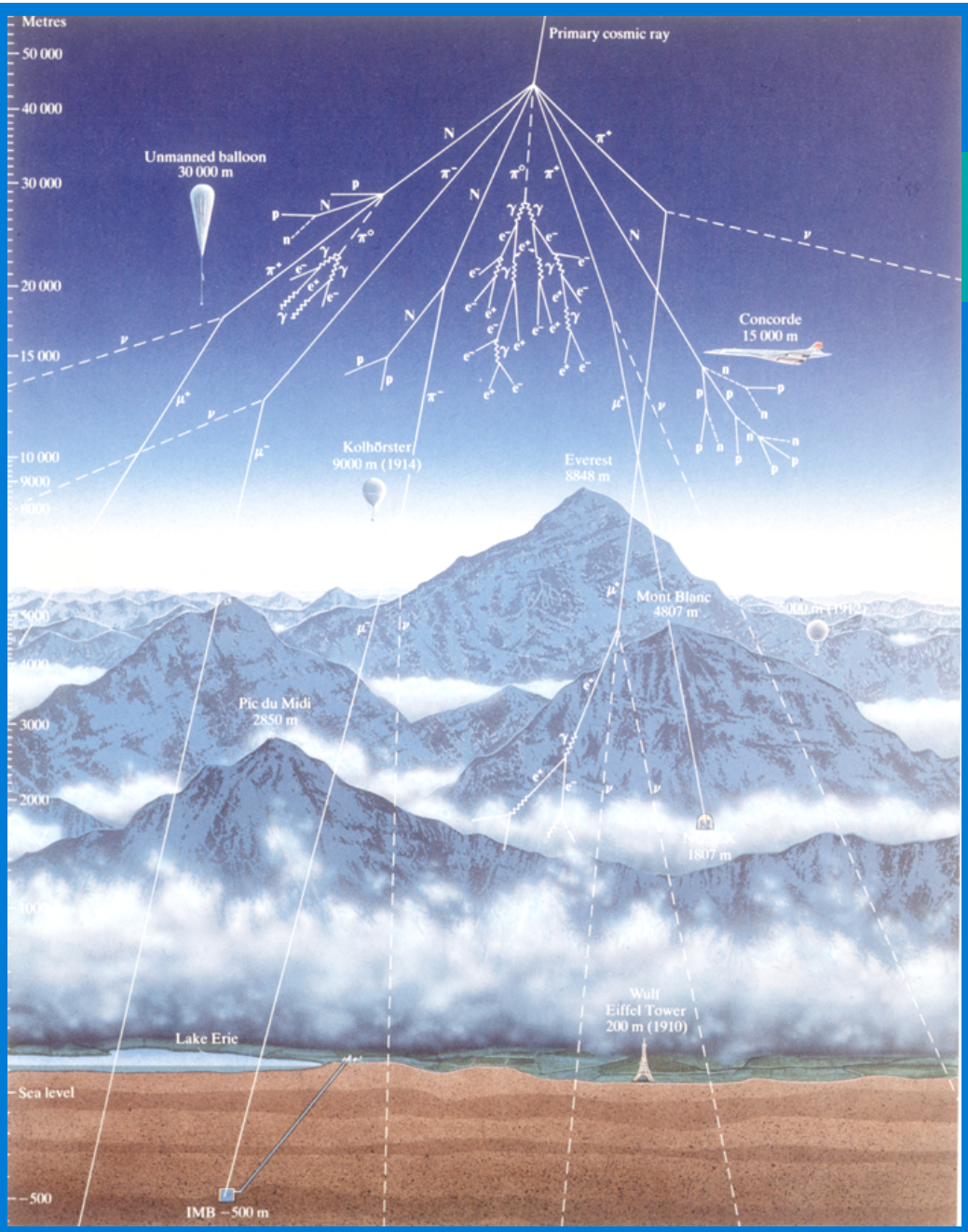


SUMMER STUDENTS LECTURE PROGRAMME

2nd: Symmetry and Symmetry Breaking in Particle Physics

Luciano Maiani. CERN. Geneva

July 4, 2001

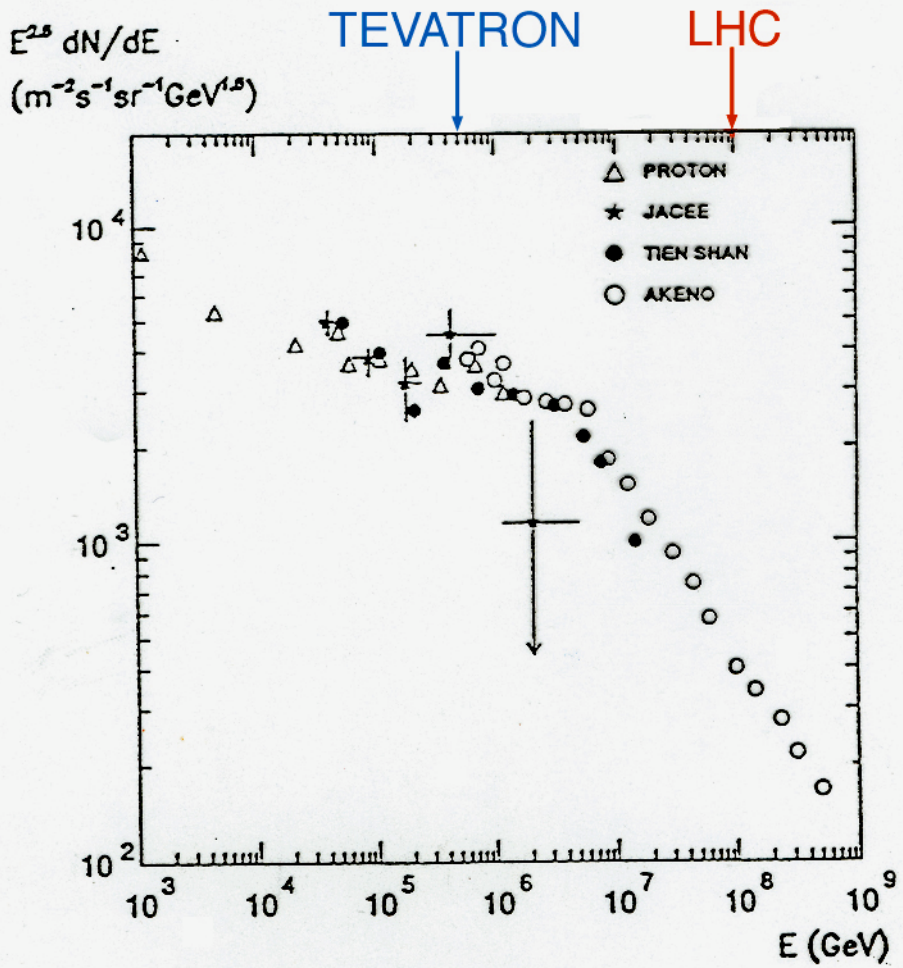


Cosmic ray shower in the atmosphere

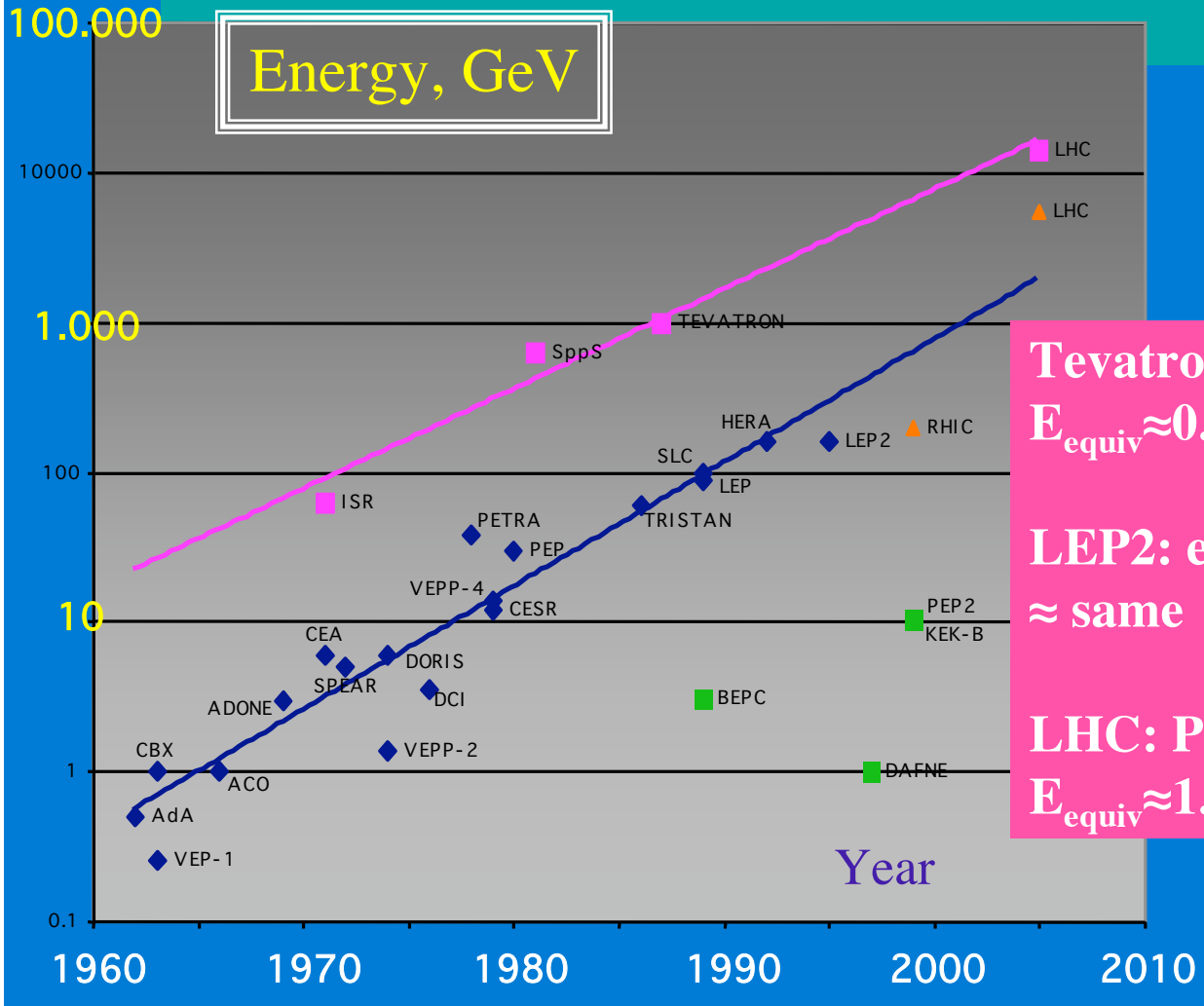
new particles are produced in the collisions (muon, strange particles….)
do not arise from further subdivision of normal matter (atoms, nuclei, nucleons, atomic and nuclear forces)

… a new world to be explored

The Energy spectrum of Cosmic Rays



Energy available at Collider facilities vs. time



Equivalent energy in fixed target (P):

Tevatron: P-Pbar, 1987
$E_{equiv} \approx 0.5\ 10^{15}$ eV

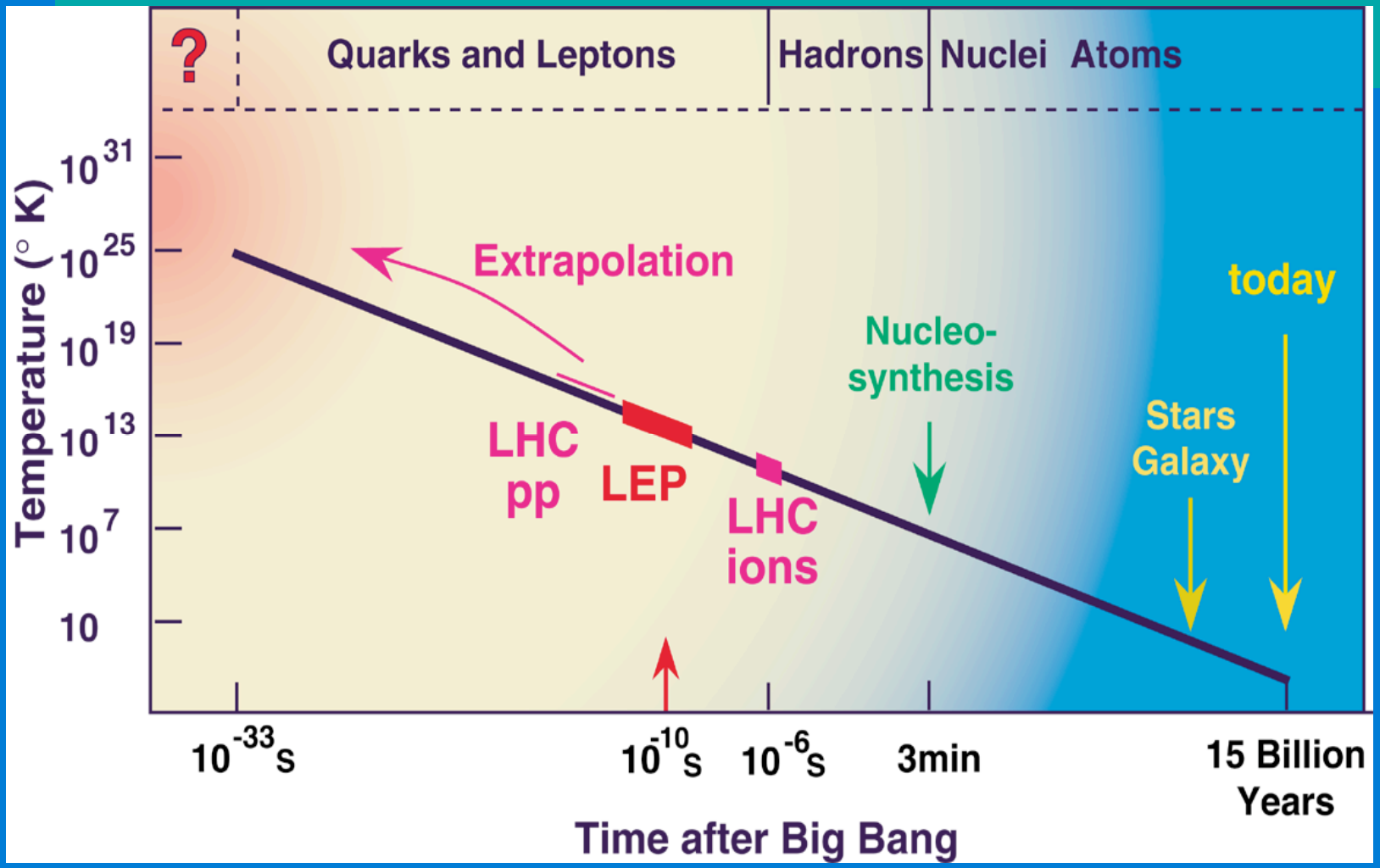
Cosmic rays "knee"

LEP2: $e^+ e^-$, 1995
≈ same en. range as Tevatron

LHC: P-P , 2006
$E_{equiv} \approx 1.1 \cdot 10^{17}$ eV

+ X-factories
+Heavy Ions...

Towards the origin

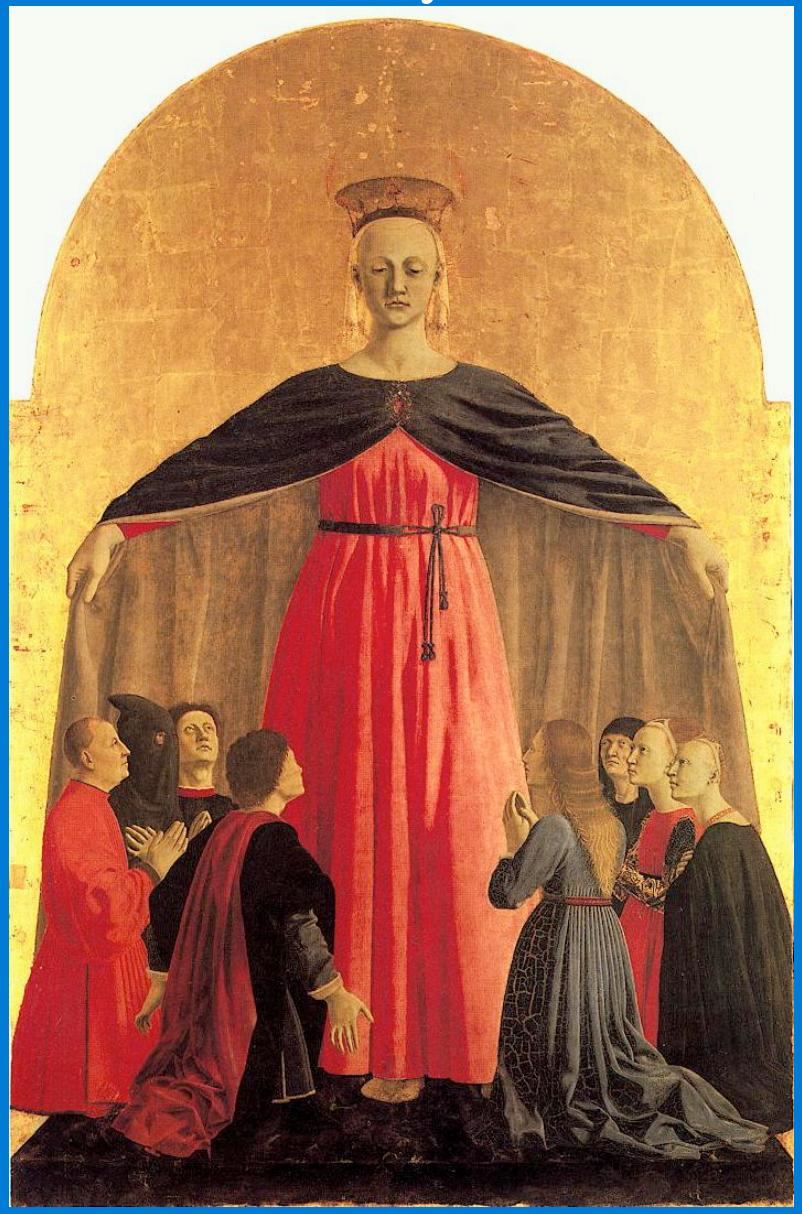


Symmetry and Symmetry Breaking in Particle Physics
Summary

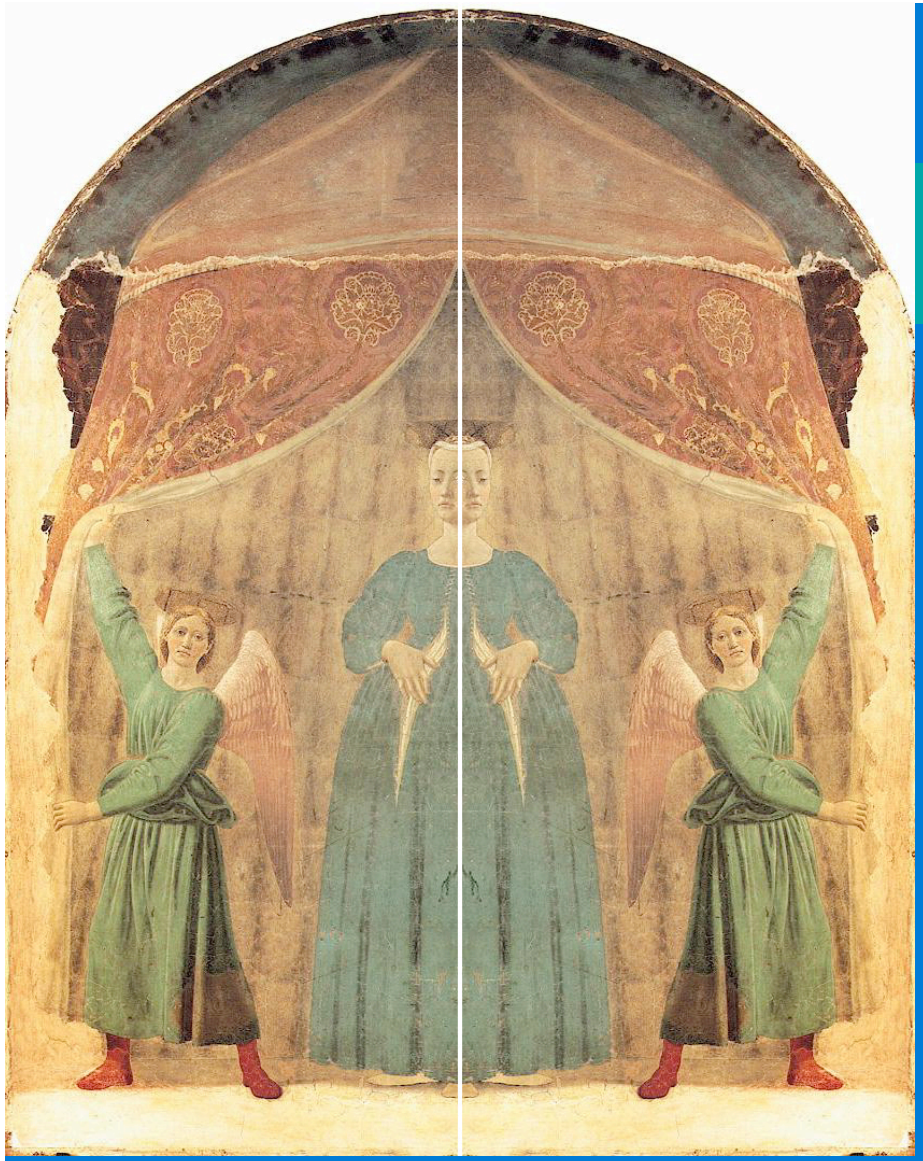
- Symmetry: the key to new particles
- “Three quarks for Muster Mark”
- A gauge symmetry cannot be broken !
- Spontaneous Breaking and Higgs bosons
- Higgs hunting at CERN and elsewhere
- More symmetry at high energy?
- Extra space dimensions
- Neutrinos and hidden mass
- Perspectives

Symmetry= Ability to predict

In the real picture, Symmetry is wonderfully broken

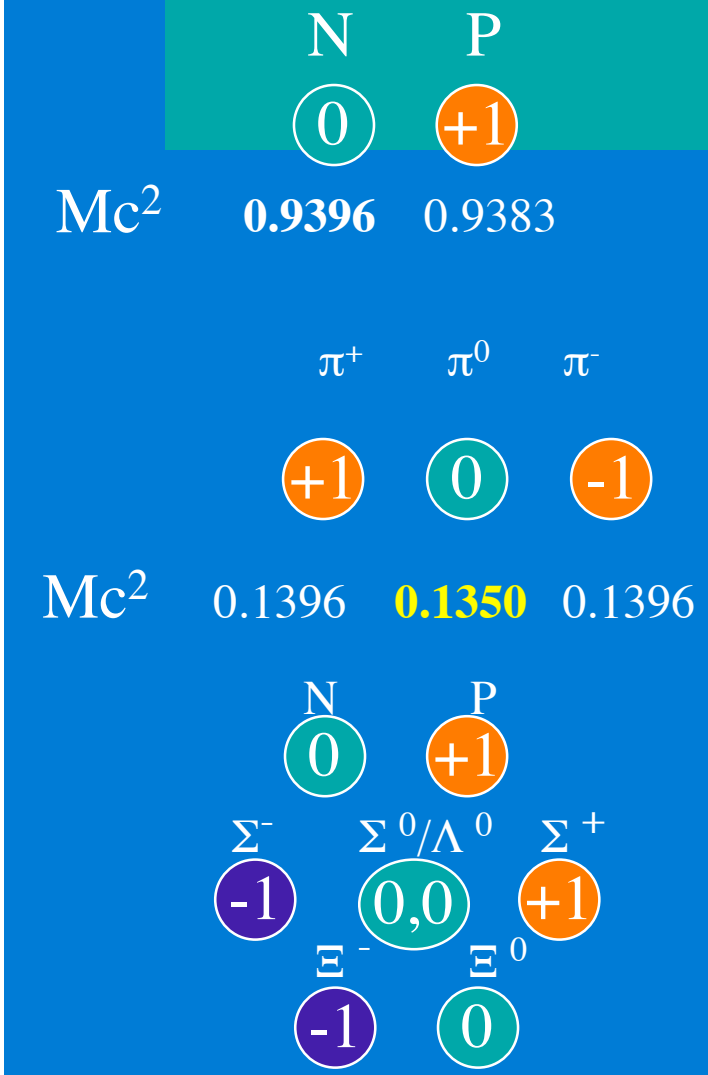


Piero della Francesca: Polittico della



Piero della Francesca: Madonna del Parto

Symmetry in particle physics: predictions vs. reality



Isopic Spin (SU2)

Equal Masses

$M(\pi^0)=M(\pi^+)$??

Eightfold Way (SU3)

All equal masses?

Deviations from symm.:

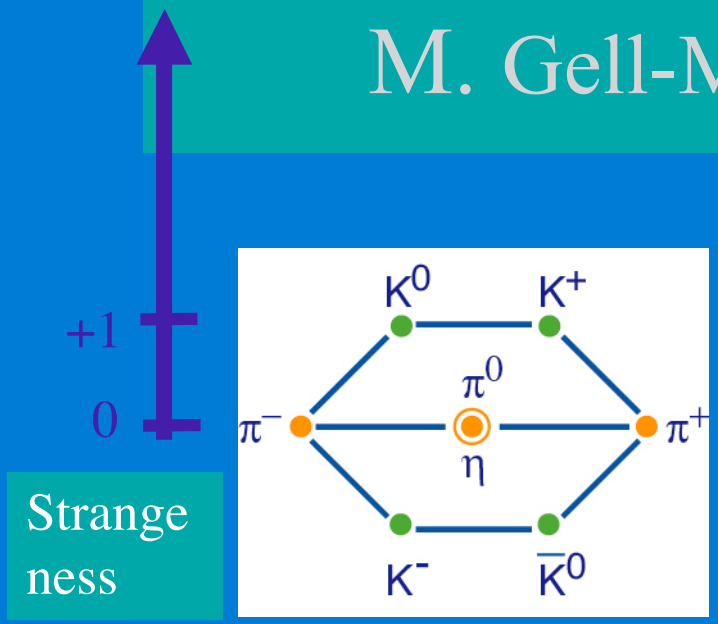
0.14%

3.3%

≈ 30%

The Eightfold Way

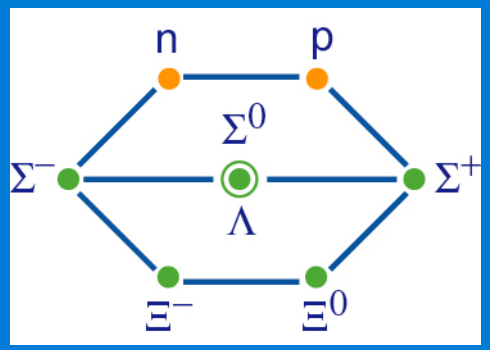
M. Gell-Mann, Y. Ne'eman, 1962

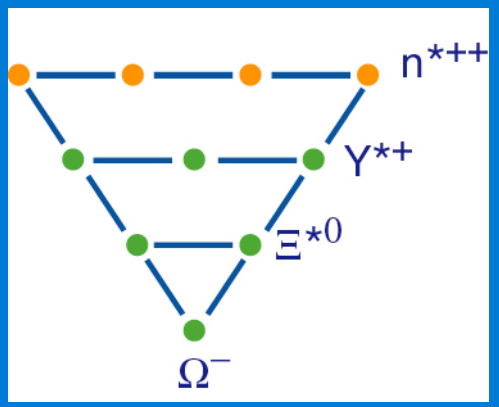


Mesons

Baryons

These figures are typical of the symmetry SU3. Why this symmetry?





« Three quarks for Muster Mark… »

Proton = [uud]
Neutron = [ddu]
Mesons = [$q\bar{q}'$]

The fact that nuclear particles proton, neutron, pions, as well as the « strange particles » are made of quarks of different masses explains the observed global symmetries (e.g. SU2 and SU3) as well as the pattern of symmetry violations,
in much the same way as the electronic structure of atoms explains the Mendeleev 's « Table of the Elements »

Ordinary Matter (Galaxy, Earth, us...) :

QUARKS
(Gell-Mann, Zweig, 1962)

$\begin{bmatrix} u \\ d \end{bmatrix}$ — Color

LEPTONS

$\begin{bmatrix} \nu_e \\ e \end{bmatrix}$ — Flavor

Proton = [uud]
Neutron = [ddu]

$N \rightarrow P + e^- + \bar{\nu}_e$ (Pauli, Fermi, ≈ 1930)

2. Analogous Structures at Higher Energy:

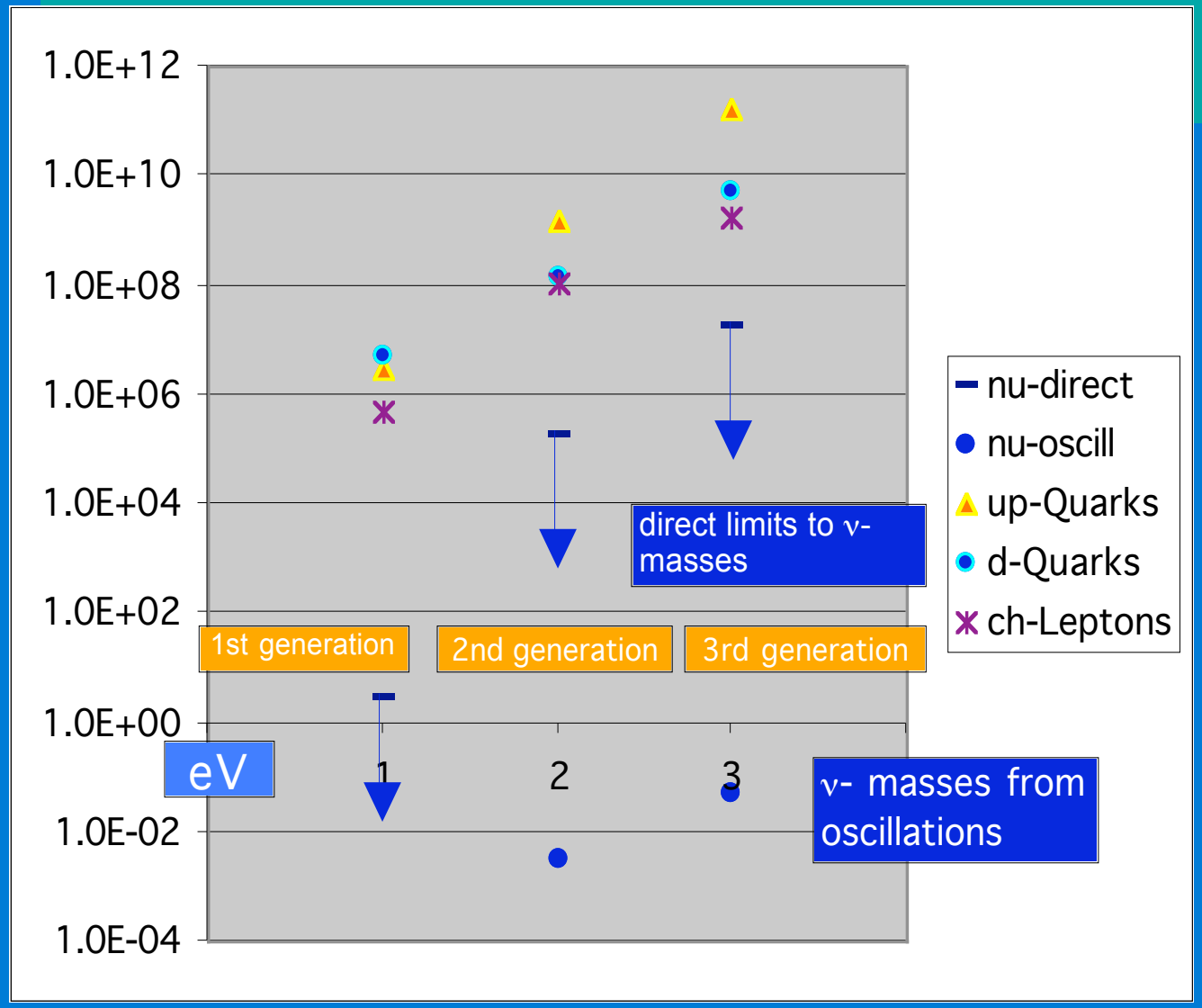
$\begin{bmatrix} c(1974) \\ s \end{bmatrix}$ $\begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix}$

$\begin{bmatrix} t(1994) \\ b(1976) \end{bmatrix}$ $\begin{bmatrix} \nu_\tau \\ \tau(1975) \end{bmatrix}$

3. Forces:

Gravity	→	GRAVITON (Not yet seen)
Electromagnetic	→	PHOTON (Einstein, 1905)
Strong (Nuclear)	→	GLUONS (Not seen in isolation)
Weak	→	INTERMEDIATE BOSONS (CERN, 1983)
Mass generation	→	HIGGS BOSON (?)

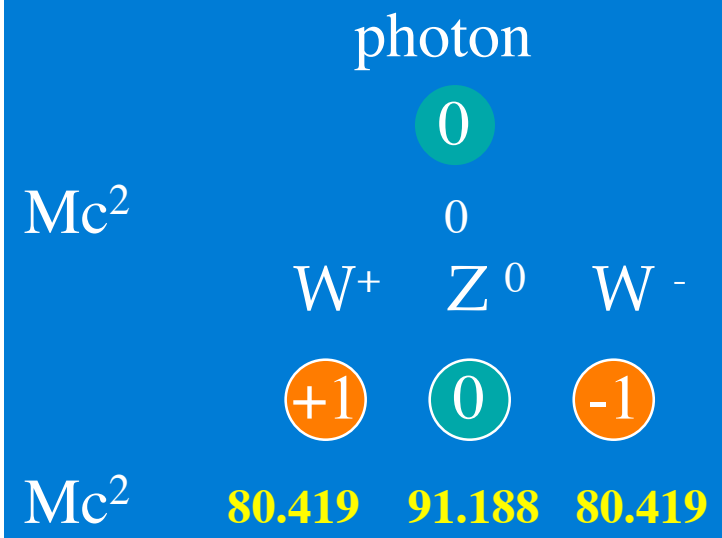
The spectrum of elementary constituents



Global vs. Gauge Symmetries

- Global: the same symmetry transformation is applied **everywhere** (e.g. turn all protons in the Universe into neutrons and viceversa)
- Local (Gauge Symmetry) different transformations are applied in different points of space-time (e.g. turn protons into neutrons and viceversa "**here and now** " only)
- examples of "local symmetries":General Relativity, QED, Yang-Mills theories
- in the local case, symmetry determines the dynamics (geometrization of forces!)

Symmetry in particle physics: predictions vs. reality: "local symmetries"



Mass (photon)=0

Mass (W, Z) = 0 !!!!

The "gauge symmetry" of fundamental forces is broken

It is **mathematically inconsistent** to break the force-law determined by a gauge symmetry !!!!

The Origin of mass

•A **field pervades all space** and affects the way particles move

• the field "recognises" particles related by symmetry

…. W, Z acquire a mass, the photon remains massless, etc.,

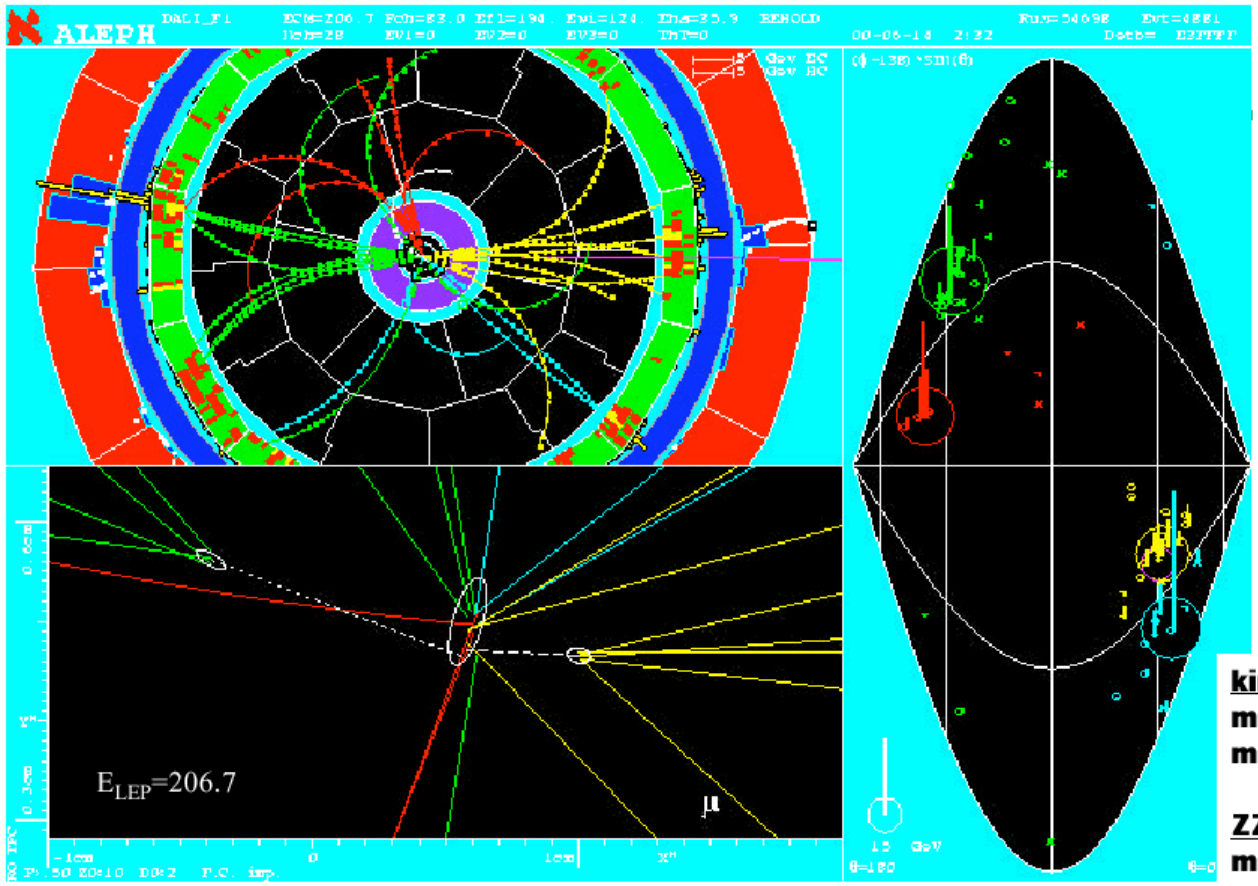
• **VACUUM** is like the surface of a **calm lake**

• In collisions, waves can be produced...

... some of which correspond to a new particle: the **HIGGS BOSON**

• The Higgs boson is needed for theory to agree with Nature...
but gives a vision of Vacuum which may explain new phenomena :
(inflation, chaotic universe, …)

ALEPH: candidate for e+e-→Z+H (Summer 2000)



2 b cand.

HZ hyp.
m_H=114 GeV
±3 GeV

NN = 0.996

jet b-tag:

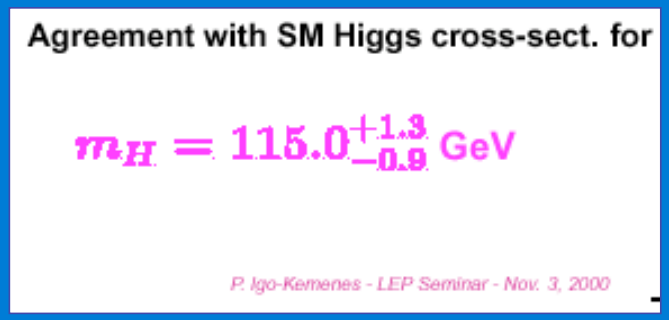
	Z
1	0.14
2	0.01
	H
3	0.99
4	0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV

Higgs hunting

- **Evidence for a Higgs particle at about 115 GeV/c^2 was found at CERN, in the last months of LEP operation in 2000, but could not reach the "discovery limit"**

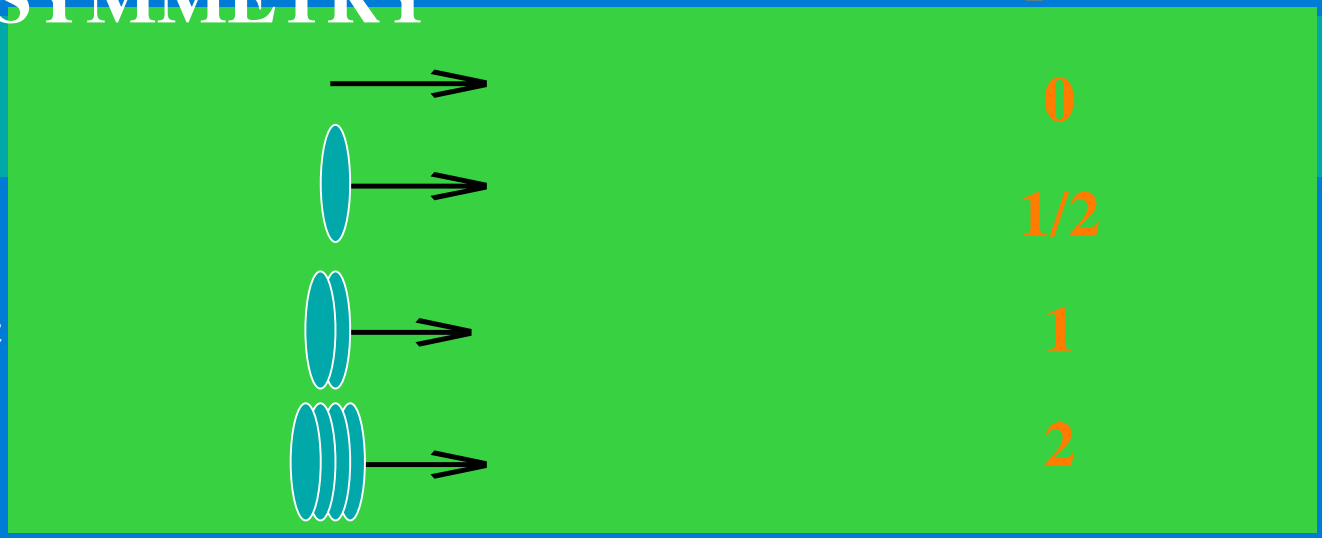


Statistical Significance

2.2 σ	September 5
2.3 σ	LEP fest
2.9 σ	November 2

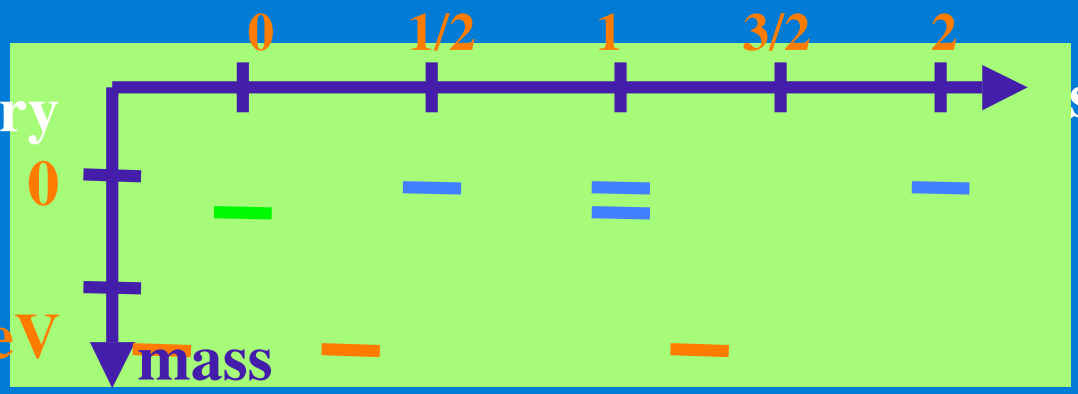
- **It is for Tevatron and for the LHC to confirm this evidence and establish definitely the existence of the Higgs boson**

More Symmetry: SUPERSYMMETRY



Unification of Forces **requires** a Symmetry to relate different spins

Particles in Supersymmetry

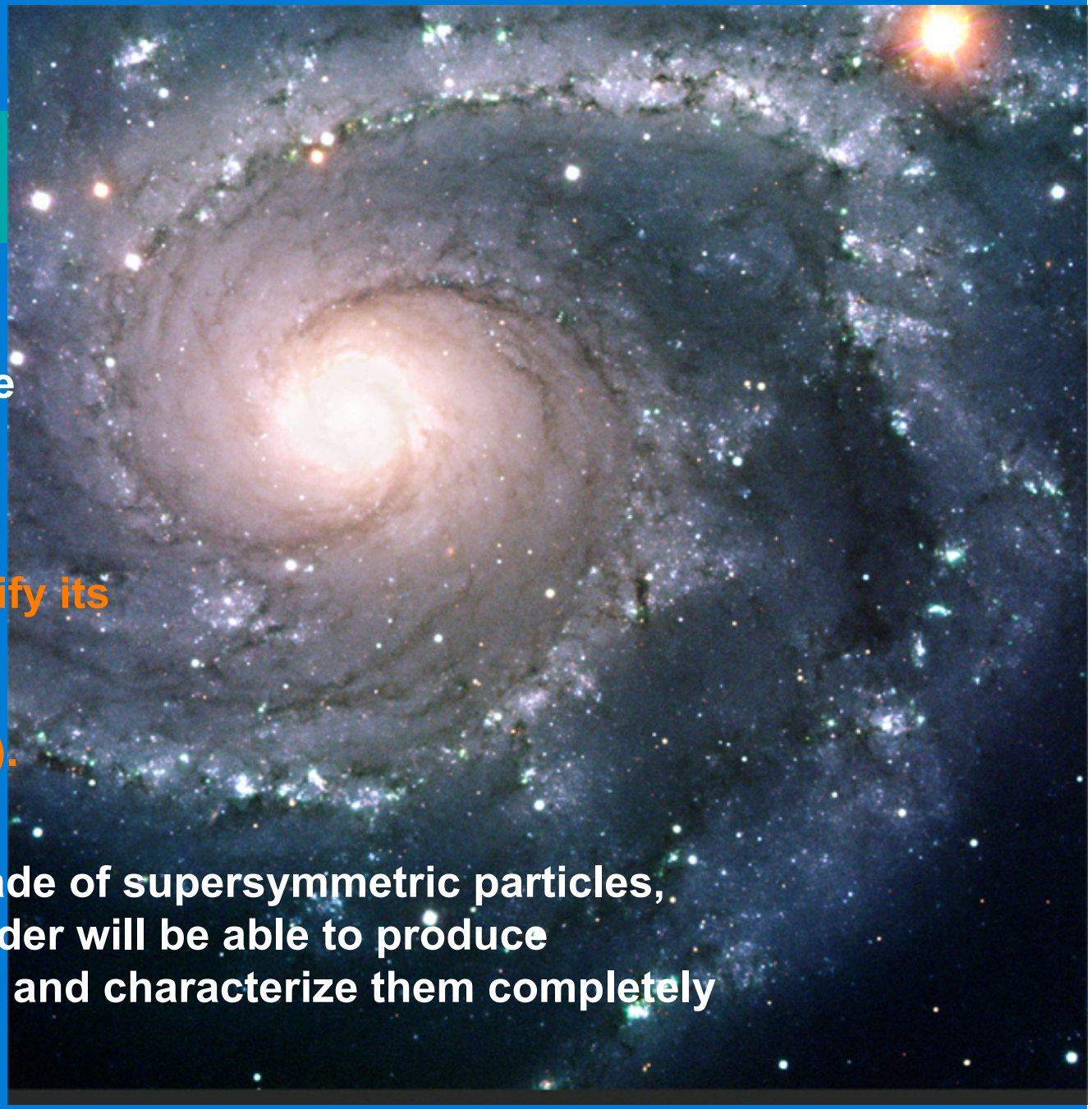


Lightest SP may still be around from BIG-BANG

Identified matter (H, He,…), accounts for less than 1/6 of the mass of the Universe

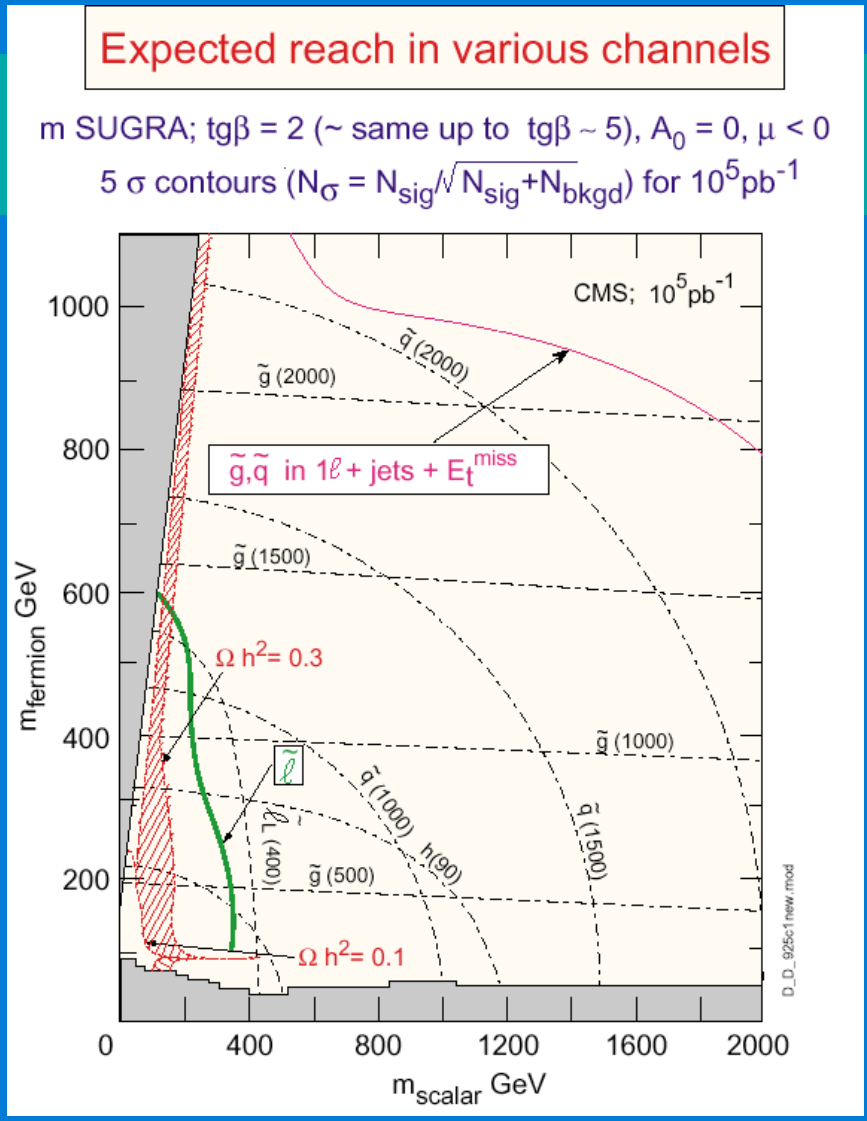
Astronomical observations may trace the distribution of the dark matter,

but are unable to identify its physical properties (Neutrinos? Cosmic strings? Neutralinos?).



If the dark matter is made of supersymmetric particles, the Large Hadron Collider will be able to produce them in the Laboratory and characterize them completely

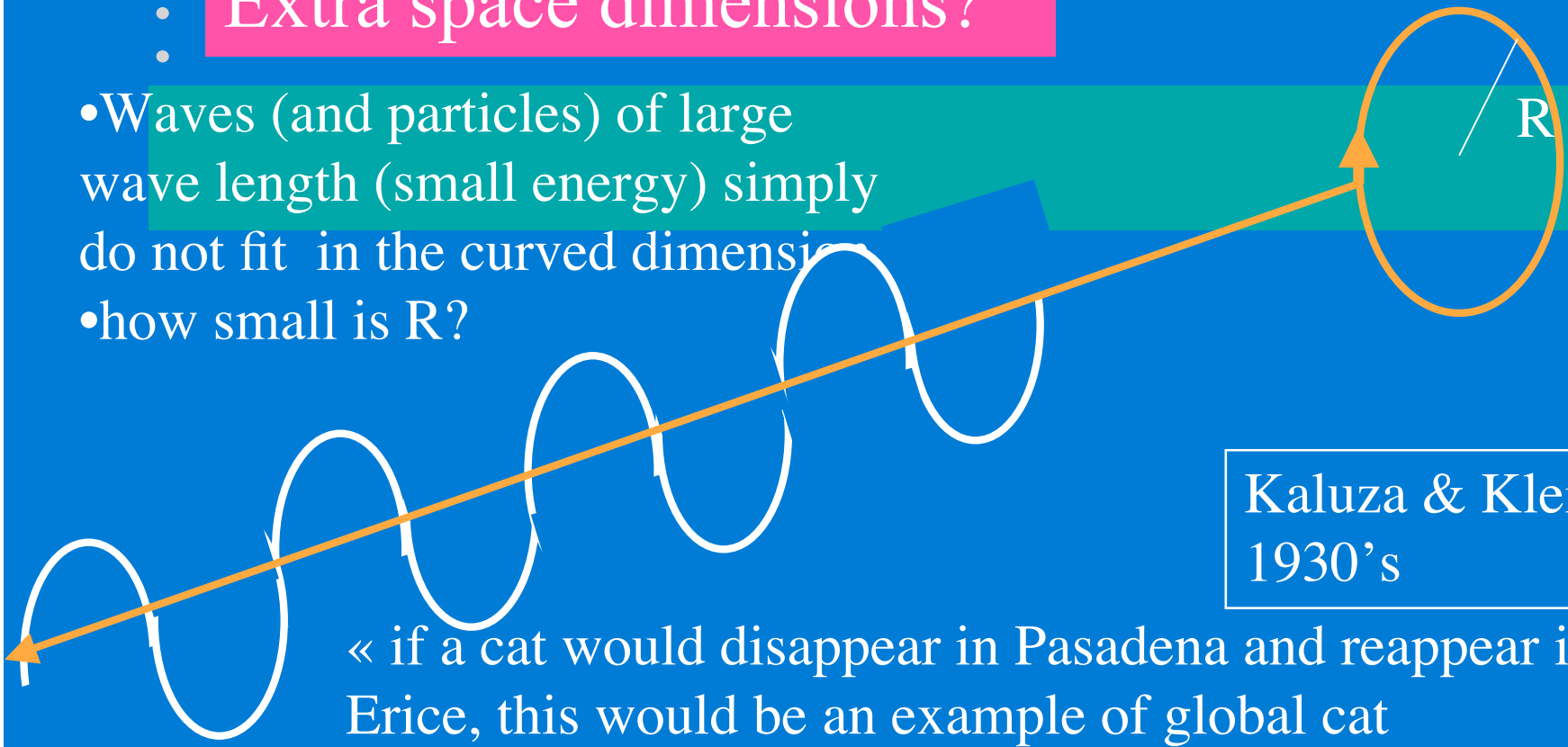
Expected reach of CMS in various channels & the cosmological parameters



Extra space dimensions?

•Waves (and particles) of large wave length (small energy) simply do not fit in the curved dimensions

•how small is R?



Kaluza & Klein
1930's

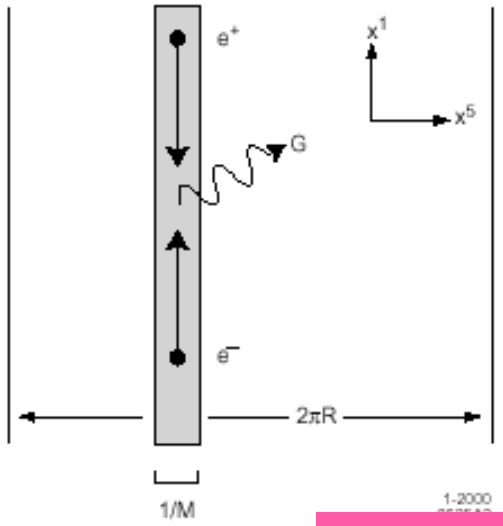
« if a cat would disappear in Pasadena and reappear in Erice, this would be an example of global cat conservation. This is not the way cats are conserved »
(R.P. Feynman)

... in 4 dimensions

Superstring theory not consistent in 4 dimensions
Extra curved dimensions required
Scale? $\approx 1/M_{Planck}$?

Extra Dimensions at mm scale?

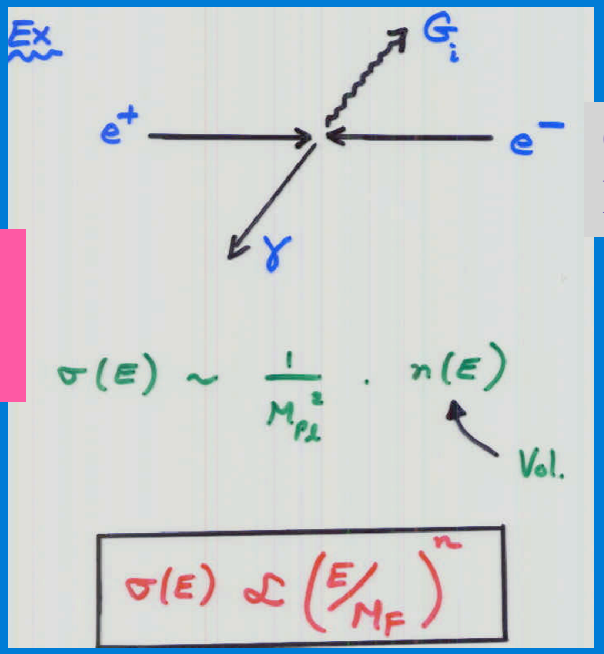
Arkani-Hamed, Dimopoulos, Dvali (1998)



The universe viewed in the small: quarks, leptons, and gauge fields are bound to a D-brane localised in an extra compact dimension.

$e^+e^- \rightarrow \gamma$ + KK tower of Gravitons

In: L. Hall
ICHEP2000, Osaka



Giudice, Rattazzi, Wells

Mirabelli Perelstein Peskin 11/98

Cosmological numbers &facts

$$\rho_{crit} = \frac{3(H_0)^2}{8\pi G} \approx 6GeV/m^3 \left(\frac{H_0}{75km/\sec/\ Mpc}\right)^2$$

$$\Omega_B = \frac{\rho_B}{\rho_{crit}} = 0.02 \div 0.04$$

Note:

$$\Omega_{stars} \approx 0.5 \cdot 10^{-2}$$

$$n_{\nu+\bar{\nu}} \approx 2\frac{0.901}{\pi^2}\left(\frac{kT}{\hbar c}\right)^3 \approx 100\,cm^{-3}$$

$$\Omega_{\nu+\bar{\nu}} \approx 1.8 \cdot 10^{-2}\left(\frac{m_\nu}{1eV}\right)\left(\frac{75km/s/Mpc}{H}\right)^2$$

$$\Omega_{tot} = \Omega_\lambda + \Omega_{mass} \approx 1$$

$$\Omega_{mass} \approx 0.3 \div 0.4; \Omega_\lambda \approx 0.7 \div 0.6$$

Power spectrum of CMWB fluctuations, Boomerang, 2000

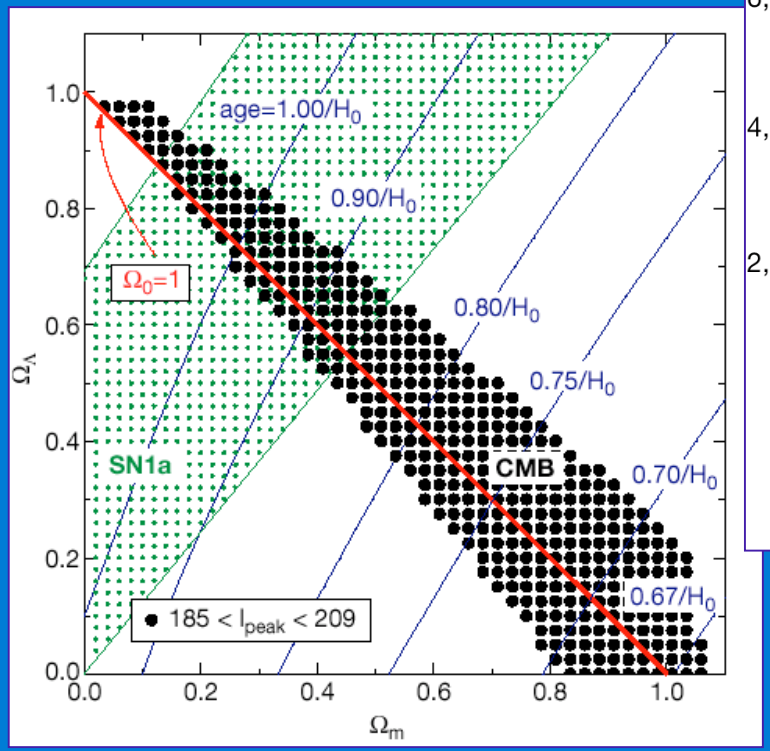
Type Ia Supernovae, 1999

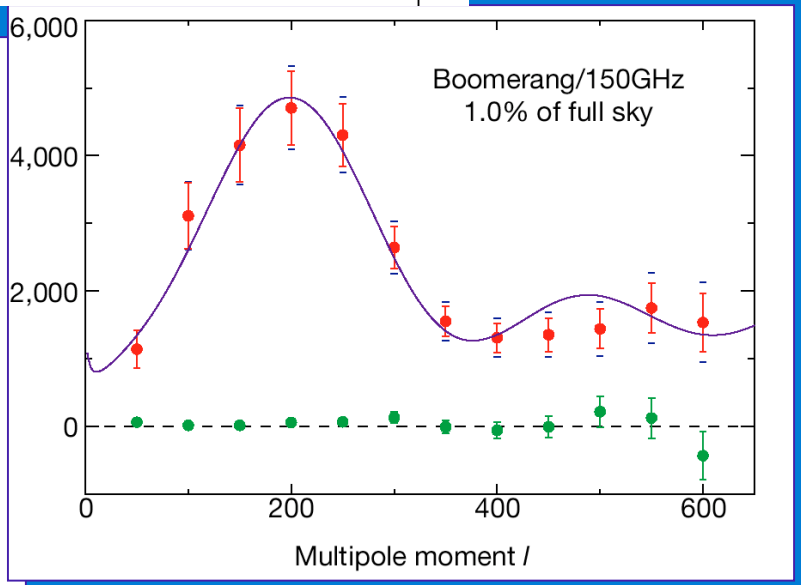
articles

A flat Universe from high-resolution maps of the cosmic microwave background radiation

P. de Bernardis[1], P. A. R. Ade[2], J. J. Bock[3], J. R. Bond[4], J. Borrill[5,12], A. Boscaleri[6], K. Coble[7], B. P. Crill[8], G. De Gasperis[9], P. C. Farese[7], P. G. Ferreira[10], K. Ganga[8,11], M. Giacometti[1], E. Hivon[8], V. V. Hristov[8], A. Iacoangeli[1], A. H. Jaffe[12], A. E. Lange[8], L. Martinis[13], S. Masi[1], P. V. Mason[8], P. D. Mauskopf[14,15], A. Melchiorri[1], L. Miglio[16], T. Montroy[7], C. B. Netterfield[16], E. Pascale[6], F. Piacentini[1], D. Pogosyan[4], S. Prunet[4], S. Rao[17], G. Romeo[17], J. E. Ruhl[7], F. Scaramuzzi[13], D. Sforna[1] & N. Vittorio[9]

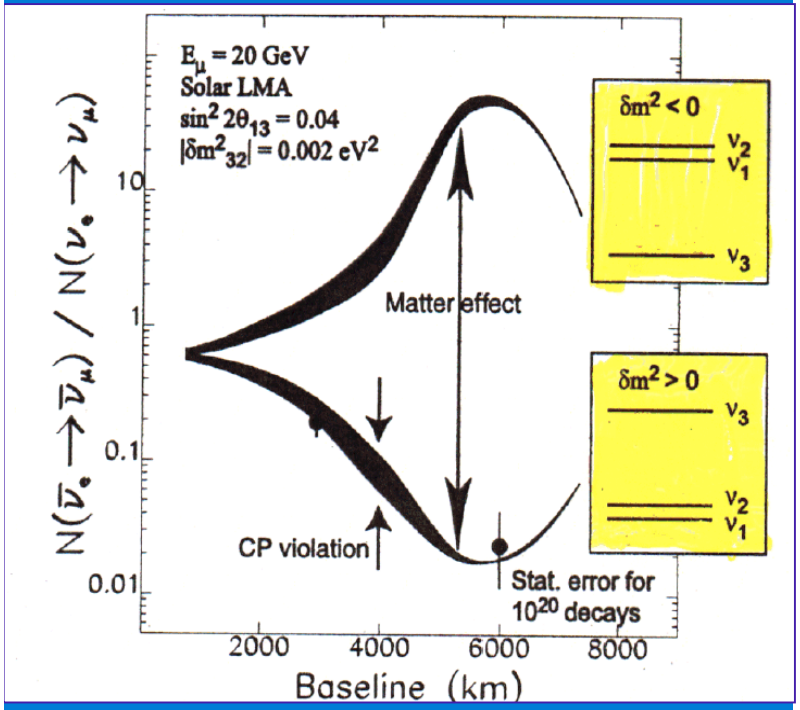
Nature, Vol. 404, 27 April 2000





Search for long-baseline detector laboratories

Best long baseline is around 3000km for CP violation + matter effects.



search for possible underground sites (H. Wenninger et al)
Gran Canaria (Spain); Spitzbergen (Svalbard,Norway);
Center for underground physics Pihäsalmi(Finland)

P. Gruber

…on the High Energy Frontier, beyond the LHC….

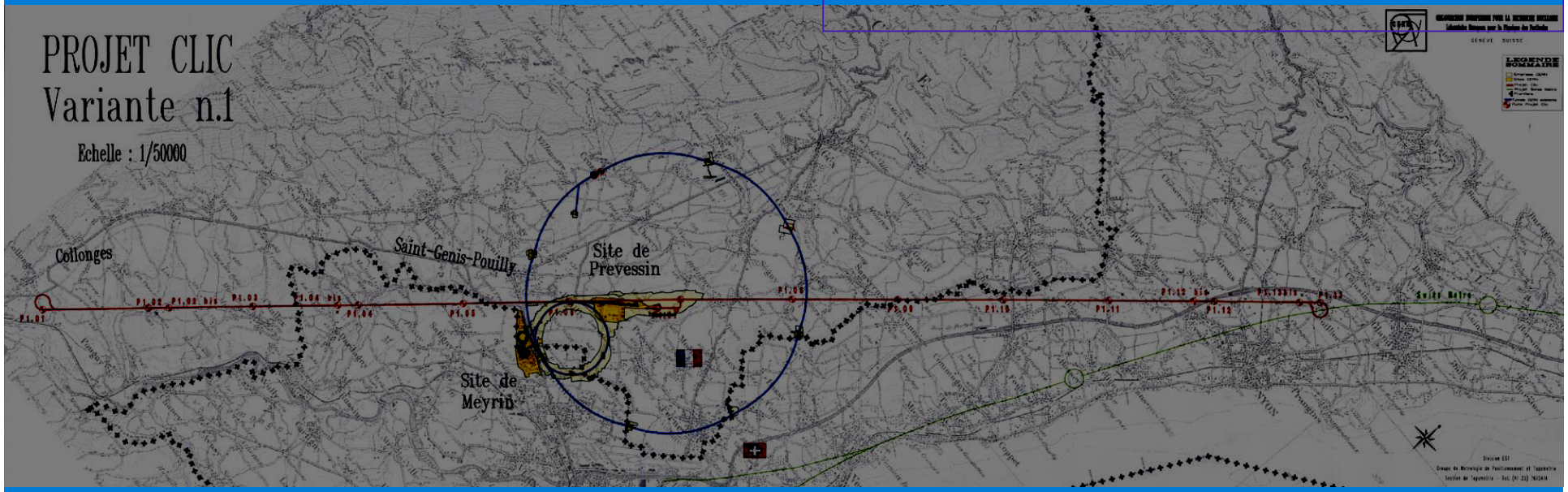
- elucidation of Higgs boson(s) spectrum & spontaneous Symm. Break.
- elucidation of SUSY spectrum (if any)
- direct signals of extra dimensions (extra vector bosons, KK tower…)
- contact interactions as signal of new energy scales beyond the TeV

Compact Linear Collider CLIC

A new technology:

- limear electron-positron collider
- Two beam acceleration
- Effective energy in collisions: 3-5 * LHC

Fitting CLIC at CERN



Projet 240 km - Variantes Est et Ouest

SITUATION

VLHC at CERN?
(Circ. = 240 Km)

GADZ
GEOTECHNIQUE
APPLIQUEE
DERIAZ S.A.,
CH-1213 PETIT-LANCY 2

Pr. J.C. Fourneaux

04/07/2001

L. Maiani_Symm.&Symm.Breakin

Exploratory study shows prohibitive tunnel cost

A forward look : The long term future

- There are many fascinating problems in the High Energy Frontier, in Neutrino Physics, in Cosmology….
- Particle Physics Programme:
  i. LHC(phase 1+2), NLC/JLC/TESLA: TeV exploration
  ii. CLIC, VLHC: multi-TeV (muon-collider later?)
  iii. ν -superbeams, ν -factory
- This would allow for a full exploration of the world beyond the Standard Theory as we can conceive it today

Side programmes as gate-ways to other sciences & industrial applications:

- Free Electron Laser
- Neutron Spallation sources
- Data Grids

•After the LHC, CERN and Europe will have the capability to be major players in (ii) and (iii);

•R&D done today leaves open all possibilities…

STAY WITH US!!