Present and future scientific programme at CERN

- Introduction on CERN
- The LHC programme
- The non LHC programme
- Brief summary

CERN

« An establishment of an international laboratory for the purpose of carrying out an agreed programme of research of a pure scientific and fundamental character relating to high-energy physics »

CERN Convention, 1954

High-energy Physics/ Particle Physics

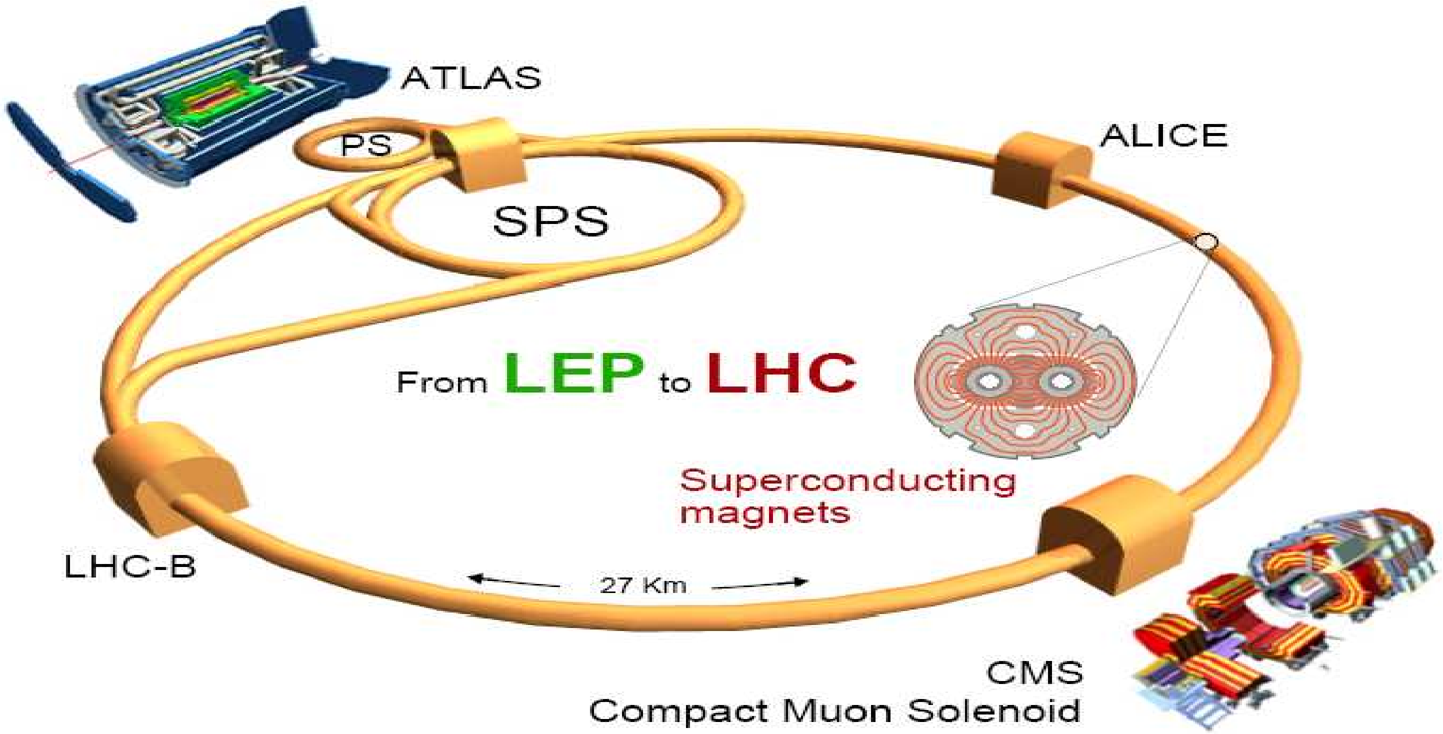
Aim to discover what the universe is made of and how it works.

-What are the elementary constituents of matter?

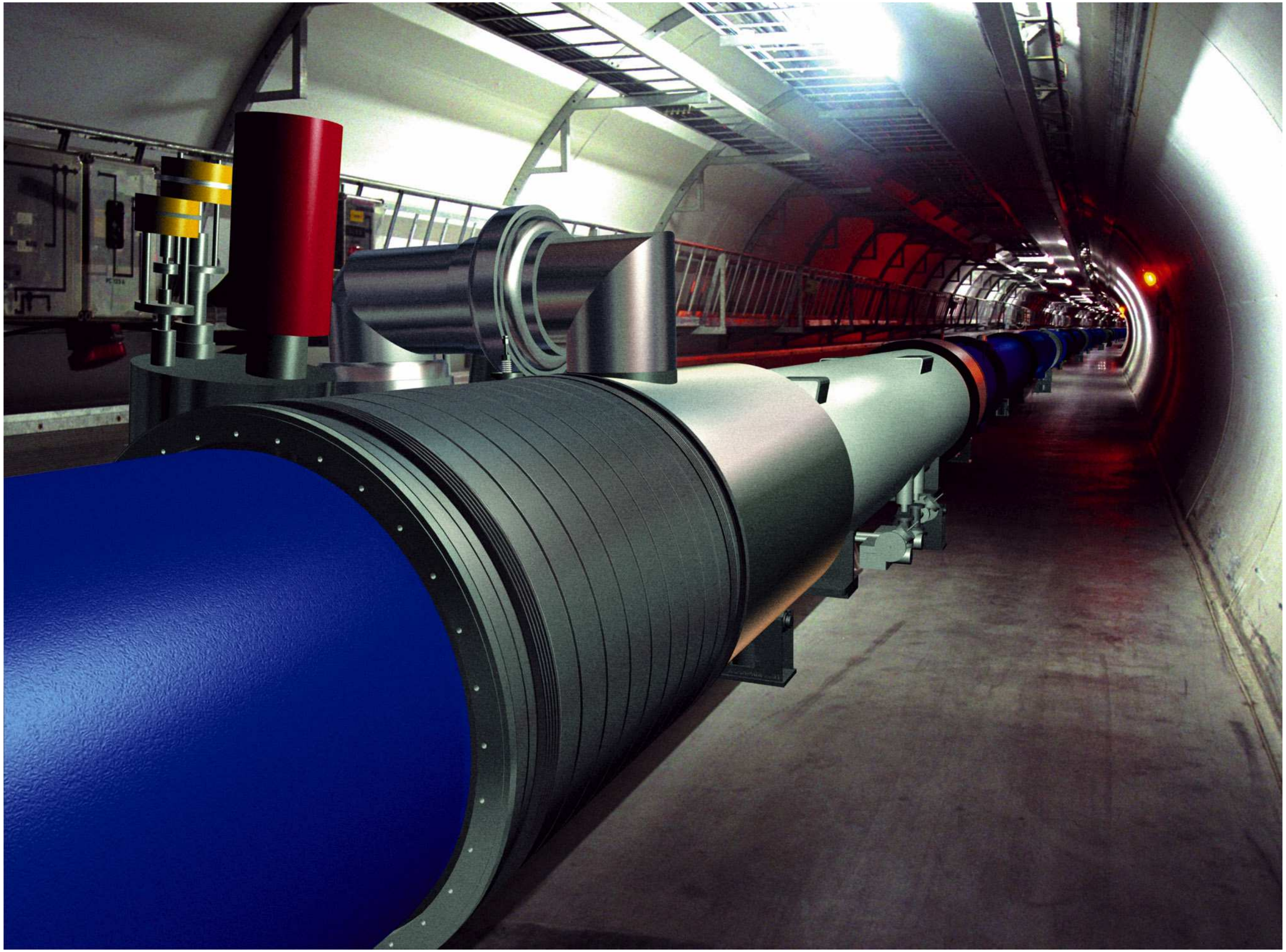
-What are the fundamental forces that control their behaviour at the most basic level ?

CERN Member States

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}



this is how it will look

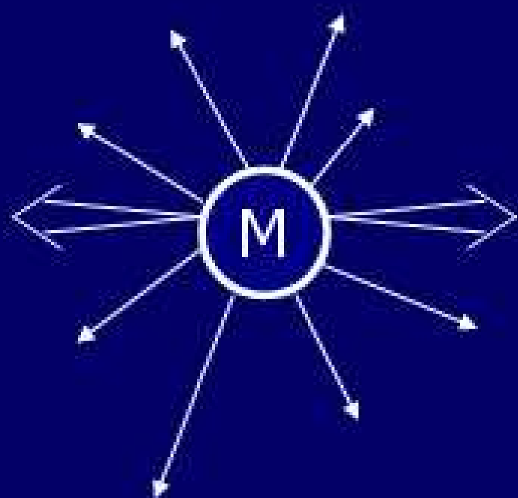
ATLAS Cavern

$E=MC^2$

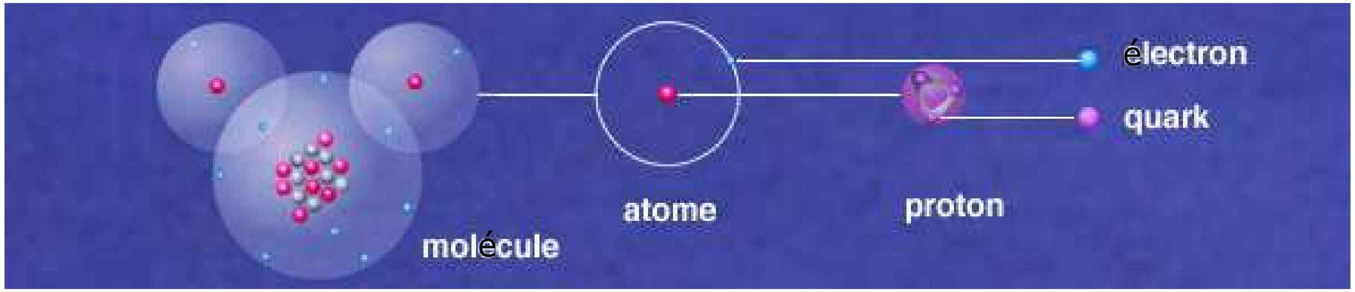
At Large Hadron Collider:

Before collision — proton E=7 TeV → ← proton E=7 TeV

After collision



In the heart of matter



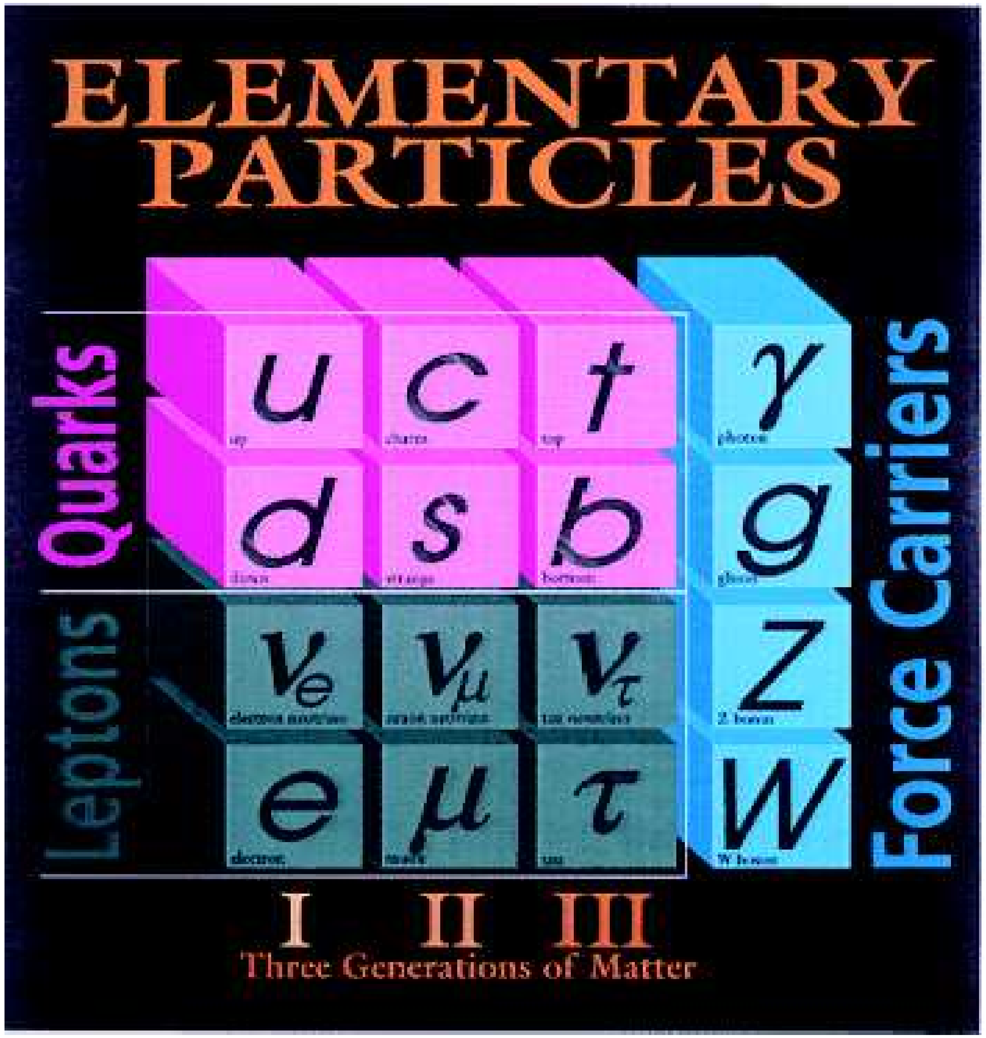
$O(10^{-10}$ m) $O(10^{-15}$ m) $< O(10^{-19}$ m)

- Matter is built up from “elementary” particles, the mass is concentrated inside the atomic nucleus.
- Stable matter in the universe is made of 4 elementary particles.

QUARKS

LEPTONS

The Standard Model



M_e ~ 0.5 MeV
M_ν ~ 0
M_t ~ 175,000 MeV!

M_γ = 0
M_Z ~ 100,000 MeV

The standard model has been tested at the permil level at LEP and in many other facilities in the world.

Origin of mass and the Higgs mechanism

Simplest theory – all particles are massless !!

A field pervades the universe

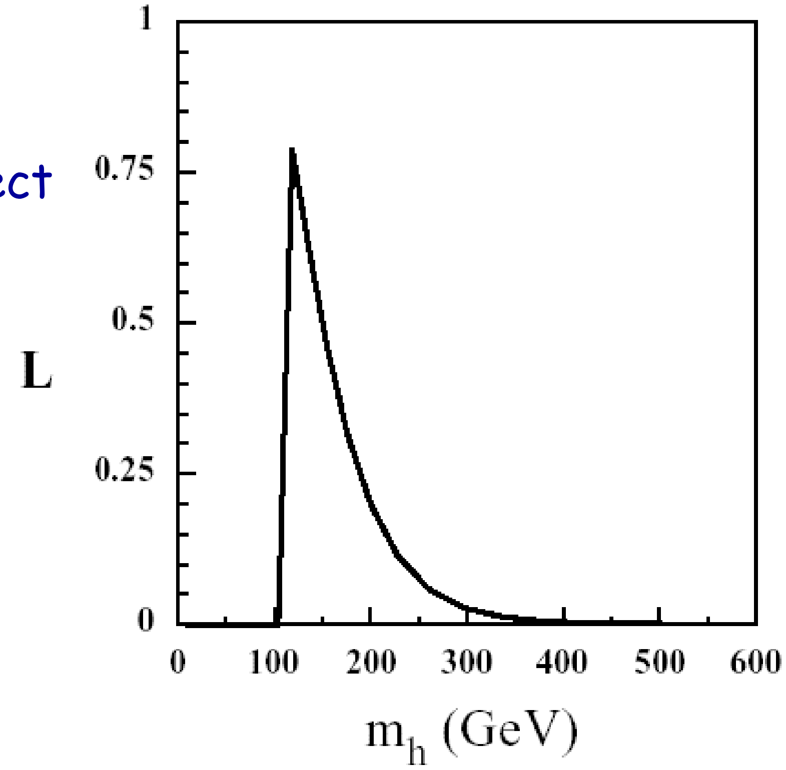
Particles interacting with this field acquire mass – stronger the interaction larger the mass

The field is a quantum field – the quantum is the Higgs boson

Finding the Higgs establishes the presence of the field

What do we know about the Higgs?

Probability for m_H combining direct and indirect information



$114.4 < M_{higgs} < 237$ GeV

The Standard model is a low energy approximation of a more fundamental theory

- SM contains too many apparently arbitrary features.

- SM does not incorporate gravity.

- Only five percent of the universe is made of normal, visible matter described by the standard model! What is the nature of the dark matter which prevades our galaxy and the universe ?

All this calls for

A more fundamental theory of which SM is low-E approximation ➡ New Physics

Difficult task : solve SM problems without contradicting experimental data

Best candidates : Supersymmetry
Extra-dimensions
String theory

⟵ all predict New Physics at ≈ **TeV scale**

➡ **need a machine to explore the ~ TeV energy range**

SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

For every particle there exists an antiparticle. For example : proton and antiproton, electron and positron, etc..

Similarly, Supersymmetry predicts that for every known particle there exists a superpartner particle

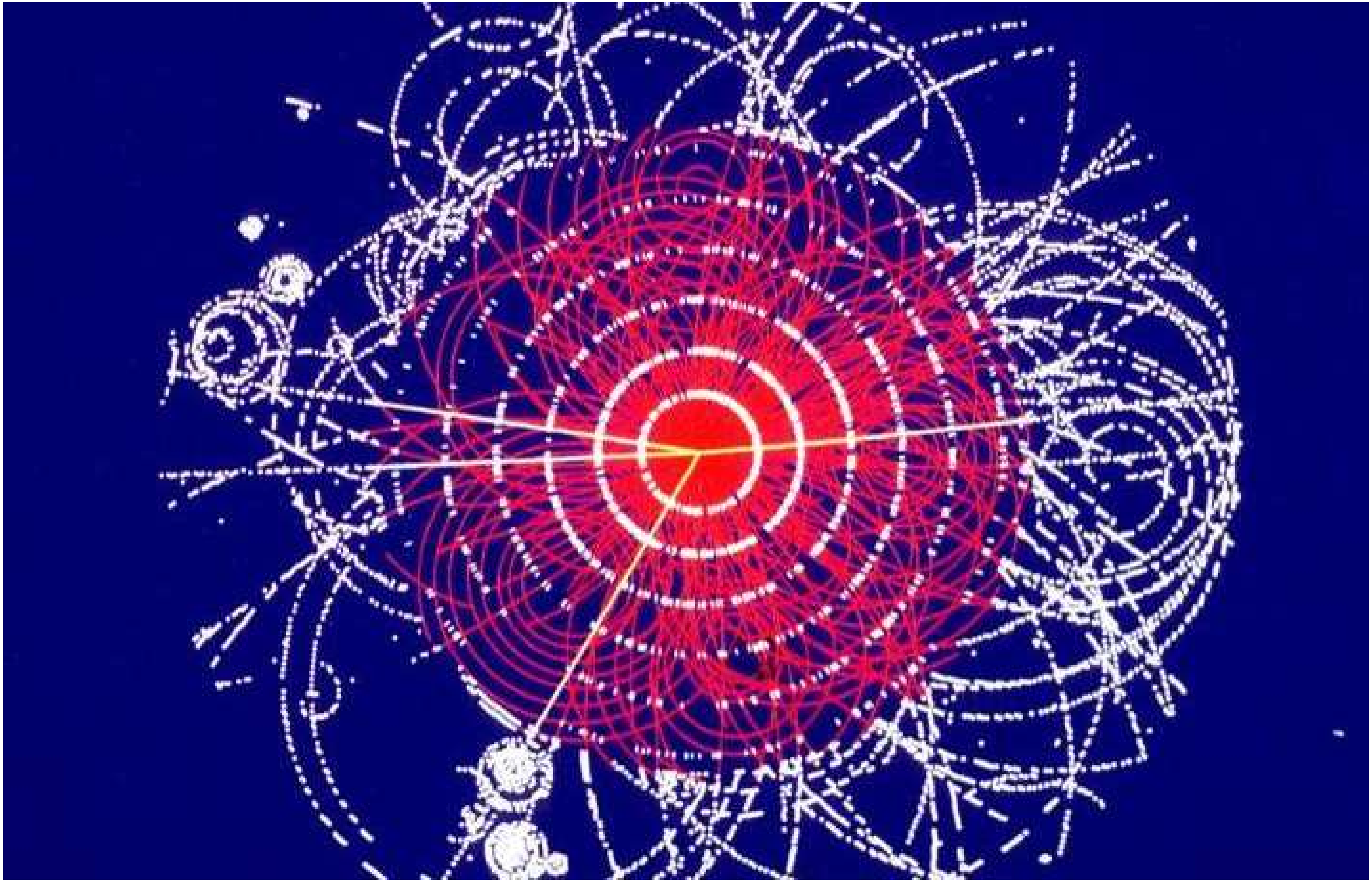
SM particle	SUSY partner		spin
ℓ	sleptons	$\tilde{\ell}$	0
q	squarks	$\tilde{q}$	0
g	gluino	$\tilde{g}$	1/2
$W^{\pm}$ (+Higgs)	charginos	$\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos	$\chi^{0}_{1,2,3,4}$	1/2

+ 5 Higgs : h, H, A, $H^{\pm}$

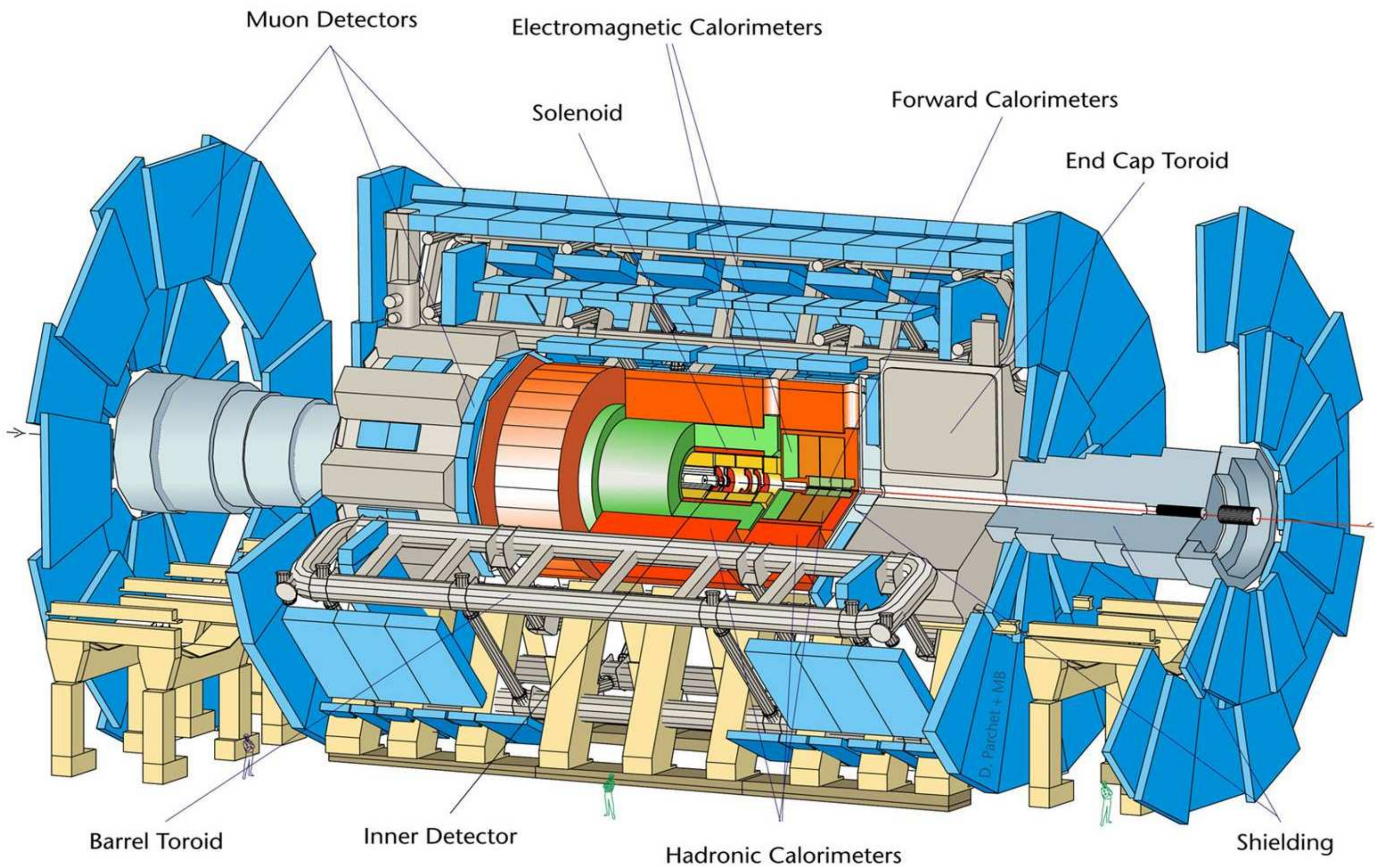
$m_h < 135$ GeV

In the simplest models :
The Lightest Supersymmetric Particle (LSP) is stable.
All Supersymmetric particles decay to LSP. ⟷
The LSP is a neutralino.
The neutralino is a natural candidate for dark matter.

The Result of a Collision



ATLAS



Diameter	***25 m***
Barrel toroid length	***26 m***
End-cap end-wall chamber span	***46 m***
Overall weight	***7000 Tons***

300 mg/cm^3

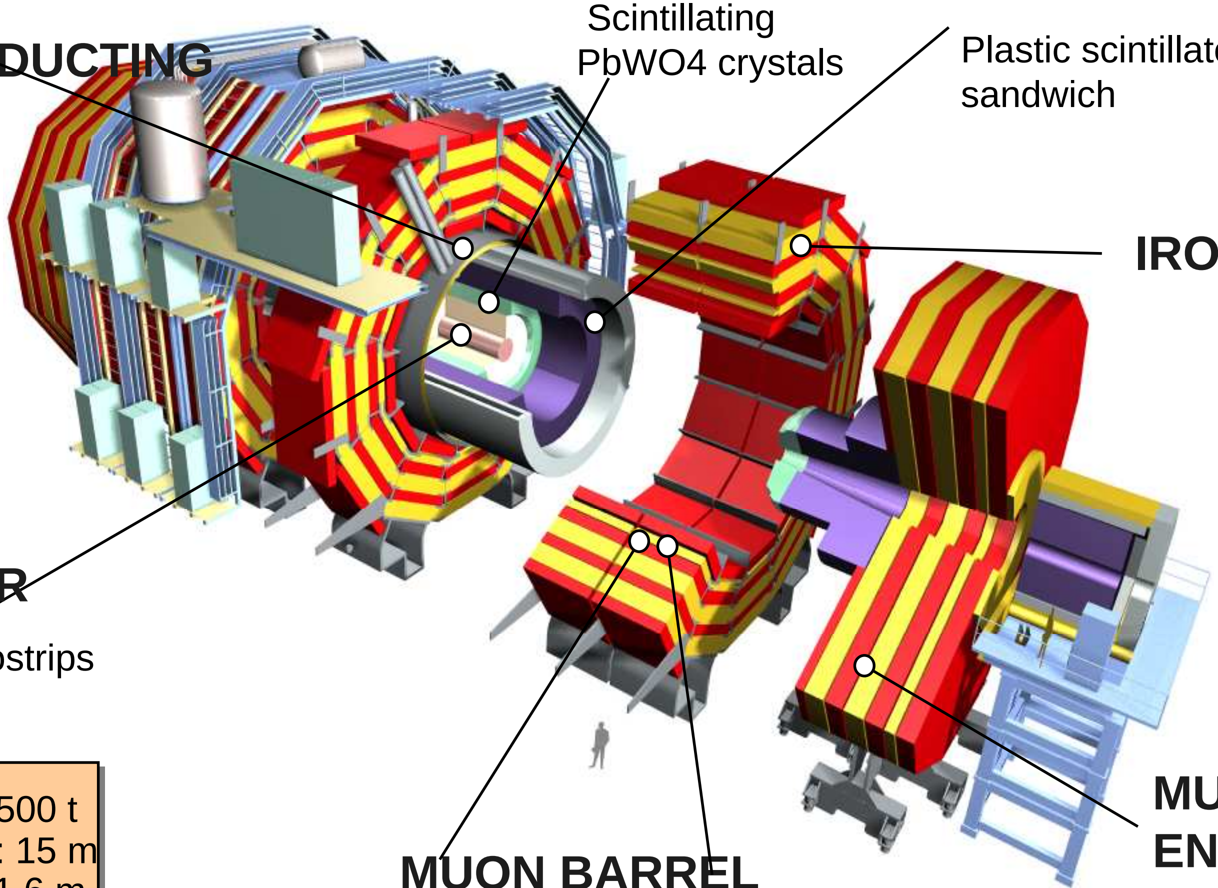
ATLAS Collaboration

34 Countries
151 Institutions
1700 Scientific Authors

U.S. participation in numbers:
34 Institutions (22.5% of the total)
283 Scientific authors total (16.6%)
233 Scientific authors holding a PhD or equivalent (17.9%)

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, Bern, Birmingham, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brookhaven NL, Bucharest, Cambridge, Carleton/CRPP, Casablanca/Rabat, CERN, Chinese Cluster, Chicago, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, INP Cracow, FPNT Cracow, Dortmund, JINR Dubna, Duke, Frascati, Freiburg, Geneva, Genoa, Glasgow, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Irvine UC, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Lancaster, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, Mannheim, CPPM Marseille, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Naples, Naruto UE, New Mexico, Nijmegen, Northern Illinois, BINP Novosibirsk, Ohio SU, Okayama, Oklahoma, LAL Orsay, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Ritsumeikan, UFRJ Rio de Janeiro, Rochester, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, Southern Methodist Dallas, NPI Petersburg, Stockholm, KTH Stockholm, Stony Brook, Sydney, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo UAT, Toronto, TRIUMF, Tsukuba, Tufts, Udine, Uppsala, Urbana UI, Valencia, UBC Vancouver, Victoria, Washington, Weizmann Rehovot, Wisconsin, Wuppertal, Yale, Yerevan

The CMS Detector

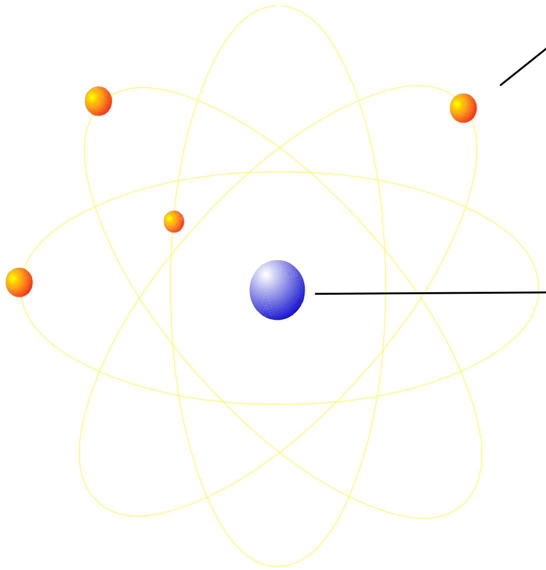


Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

3 g/cm^3

LHCb is an experiment to look for a sign of New Physics through CP violation in B meson decays

From atoms to quarks



Leptons are fundamental e.g.

electron
muon
neutrinos

Hadrons are made of quarks, e.g.

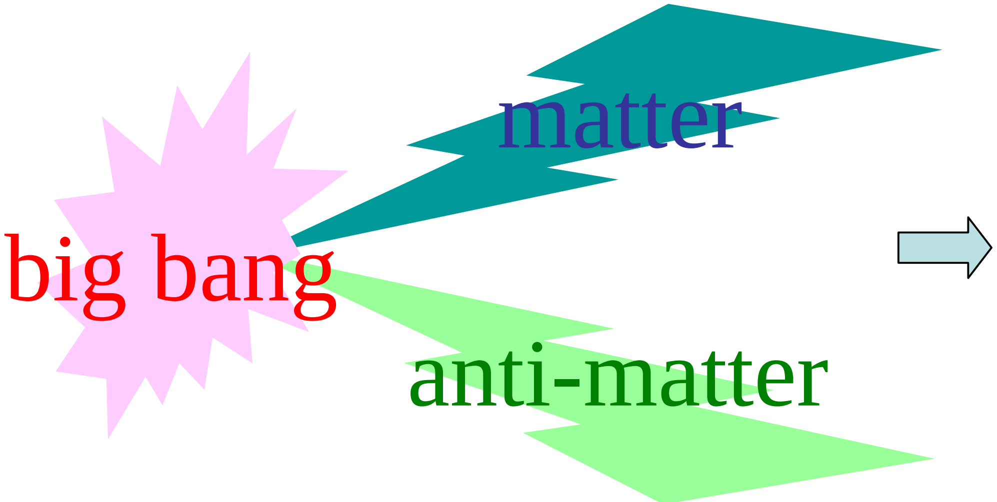
$p = uud$
$\Lambda^0 = uds$
$\Lambda^0_b = udb$

Baryons

$\pi^+ = u\bar{d}$
$K^+ = u\bar{s}$
$B^+ = u\bar{b}$

Mesons

CP Violation in Evolution of Universe



$$\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \left(= \frac{\text{Number of baryons } (N_B)}{\text{Number of photons } (N_\gamma)} \right)$$

$= 0$

$= 10^{-9} \sim 10^{-10} \neq 0$

Problem

Observed CP violation in particle physics (kaon and B-meson) so far can be explained by the Standard Model.

The Standard Model cannot explain the observed ratio of N_B/N_γ

Further more…

Physics beyond the Standard Model, such as Supersymmetry with much more particles, generates a new source of CP violation

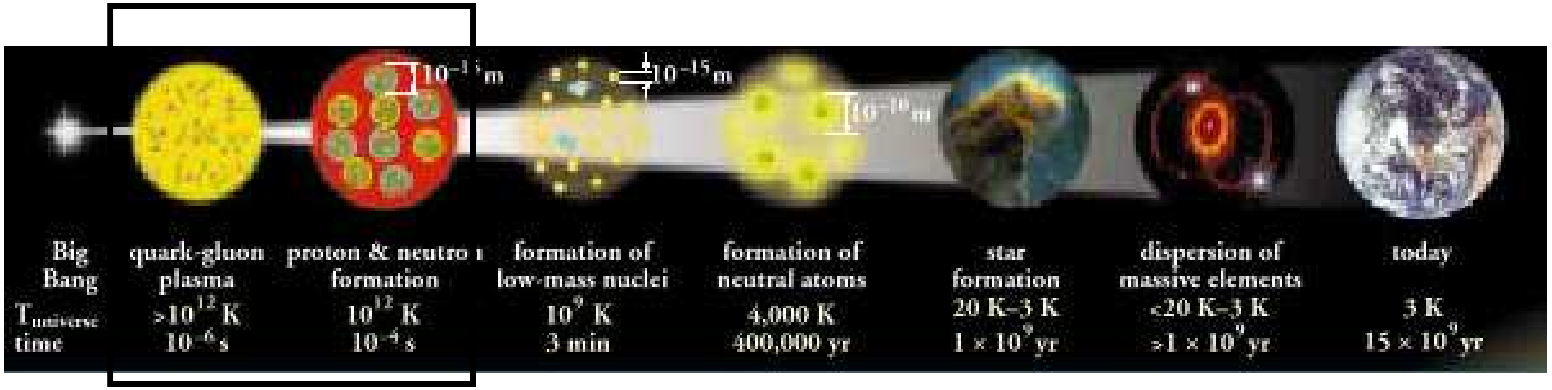
LHCb is an experiment to look for a sign of New Physics through CP violation in B meson decays

Why B meson decays? For some decay modes, Standard Model CP violation effects are well predicted. Large effects are predicted in B meson decays.

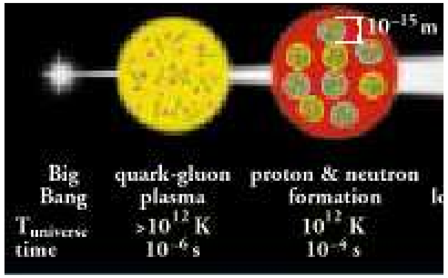
I.e. any deviation is a clear sign of New Physics

Why at LHC? LHC will be the most powerful source of b hadrons, producing not only B^0 and $B^\pm$ but also B_s, B_c and b-baryons.

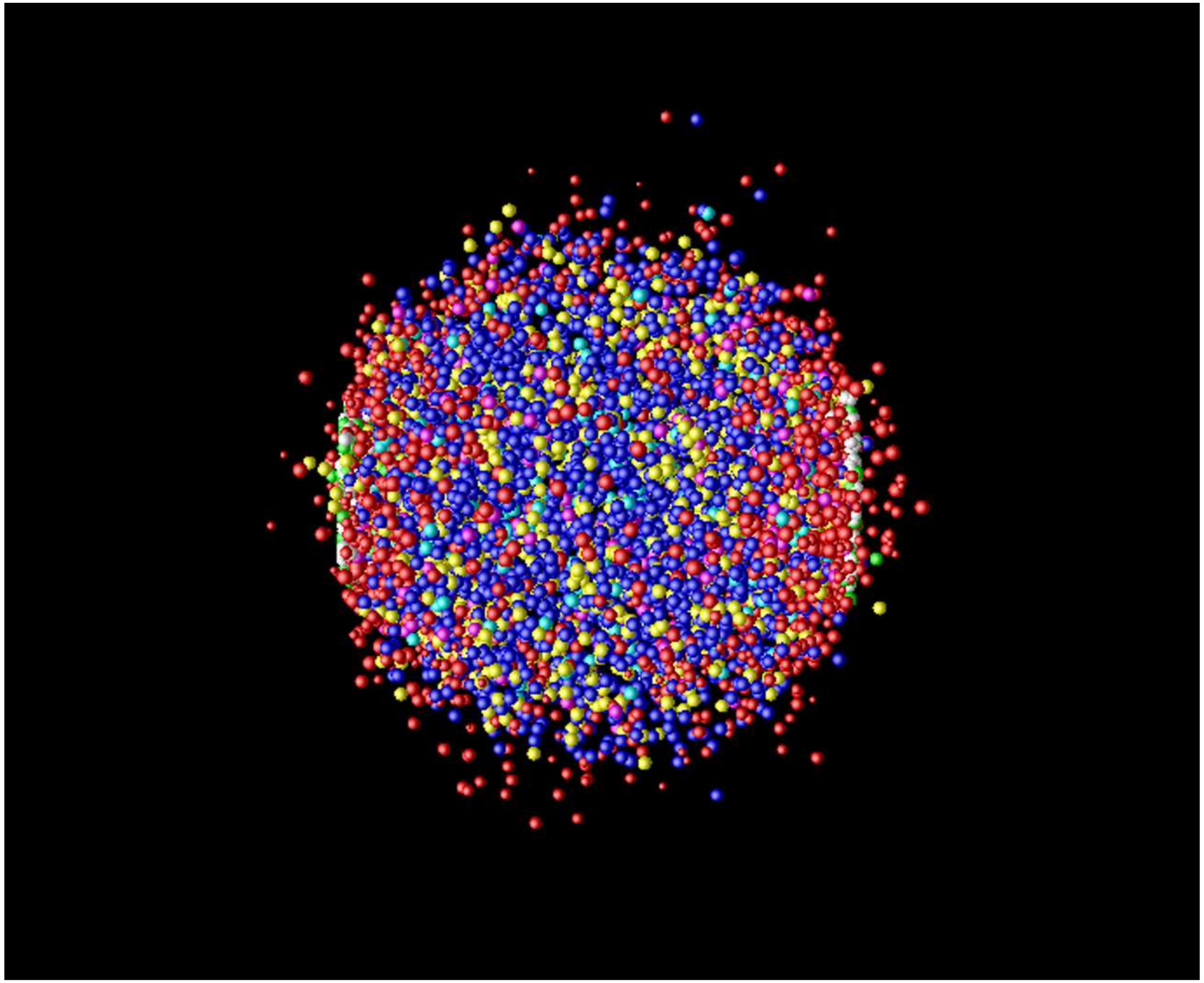
Let’s go backwards



How did the strong interaction give rise to the composite particles which constitute the universe ?



Laboratory experiment



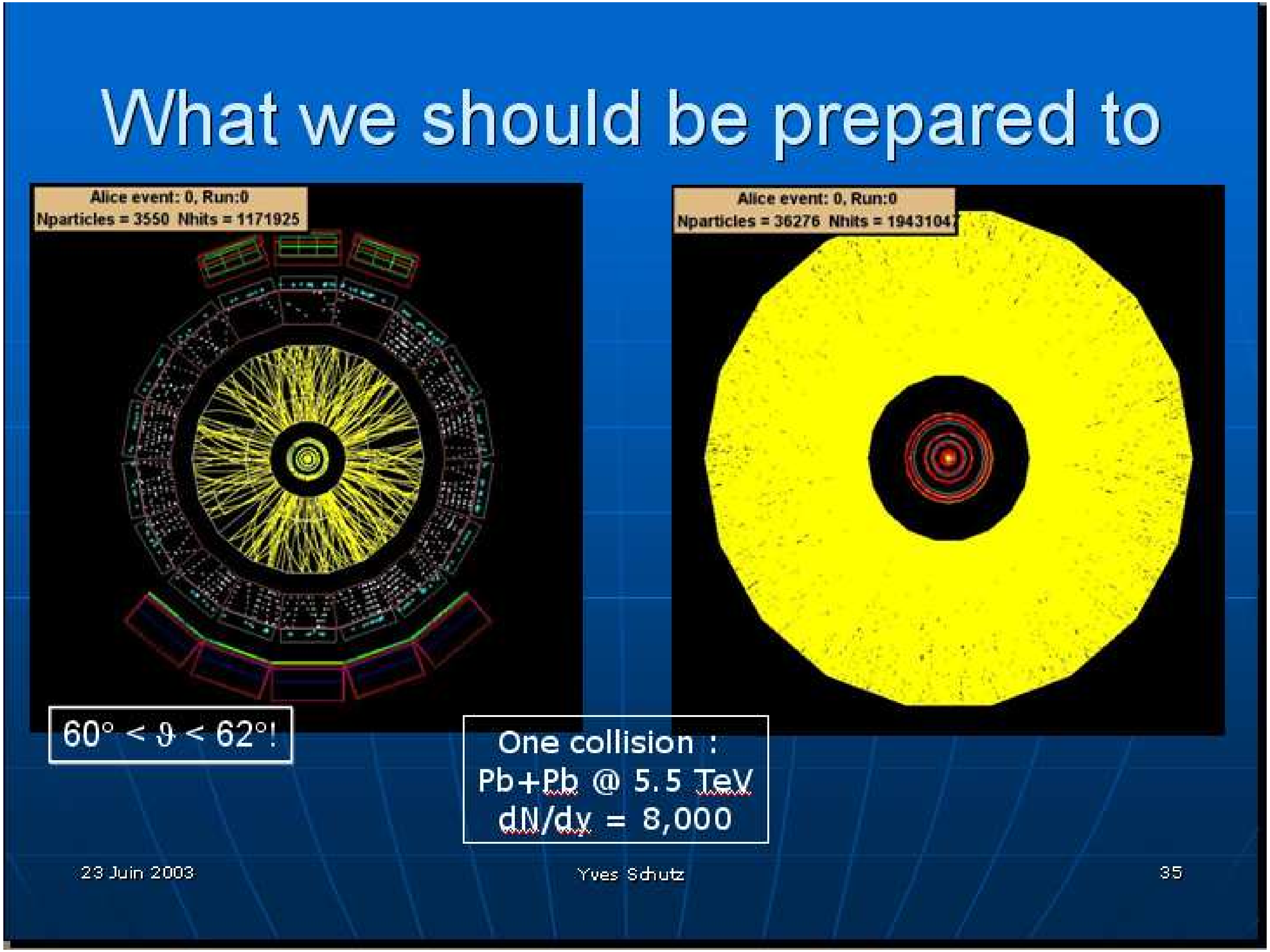
1. Accelerated ions in the LHC collide head on

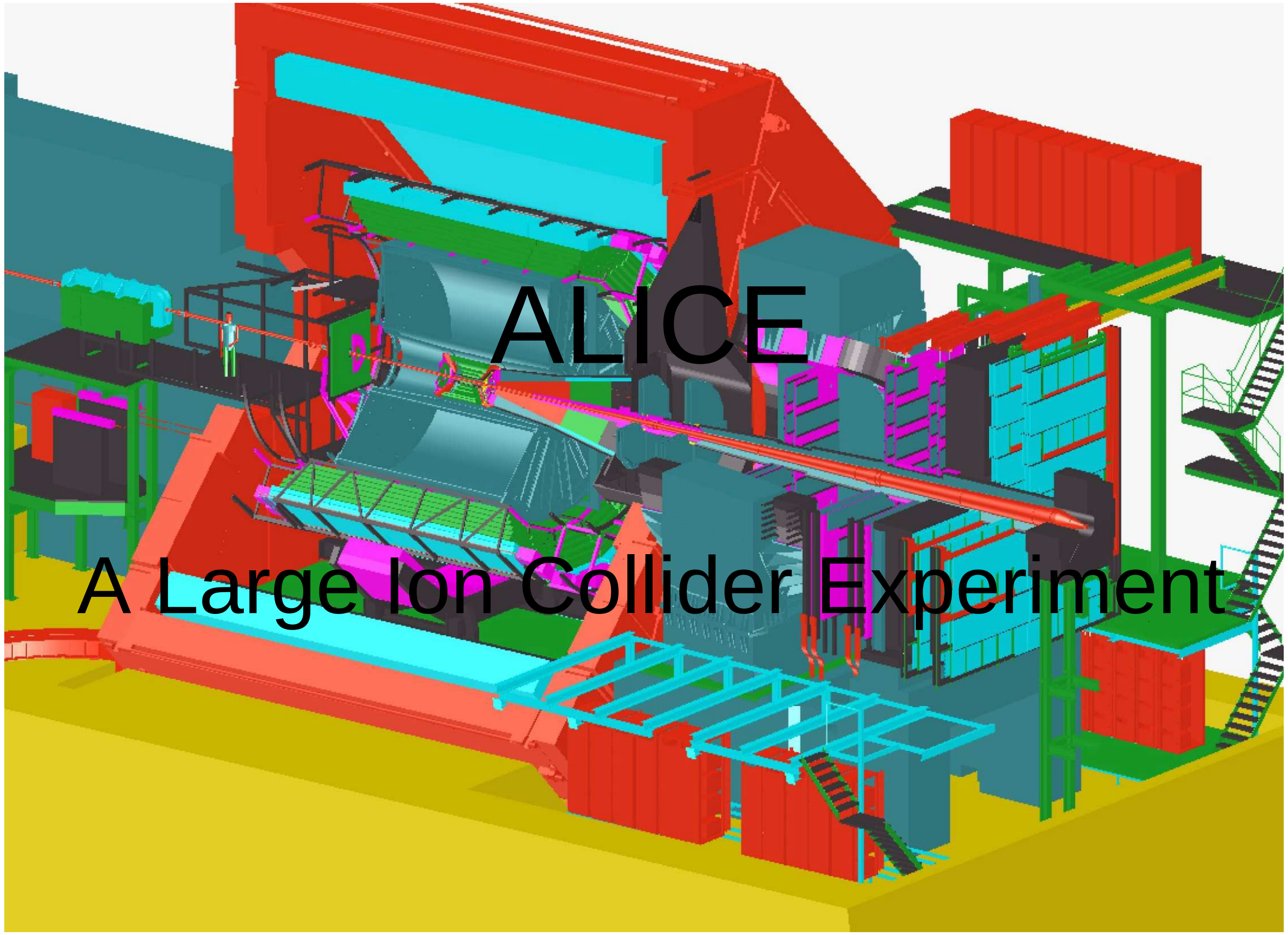
2. The energy of collision is materialized into quarks and gluons

3. Quarks and gluons interact via the strong interaction: matter equilibrates

4. The system expands and cools down

5. Quarks and gluons condensate into hadrons


What we should be prepared to
Alice event: 0, Run:0
Nparticles = 3550 Nhits = 1171925
Alice event: 0, Run:0
Nparticles = 36276 Nhits = 19431047
60° < ϑ < 62°!
One collision :
Pb+Pb @ 5.5 TeV
dN/dy = 8,000
23 Juin 2003
Yves Schutz
35


ALICE
A Large Ion Collider Experiment

The LHC physics goals

Search for the Standard Model Higgs boson over ~ $115 < m_H < 1000$ GeV.

Search for physics beyond the SM (Supersymmetry, Extra-dimensions, ….) up to the TeV-range

Precise measurements :

- -- W mass
- -- top mass, couplings and decay properties
- -- Higgs mass, spin, couplings (if Higgs found)
- -- etc…

B-physics : CP violation, rare decays, B0 oscillations

Study of phase transition at high density from hadronic matter to plasma of deconfined quarks and gluons.

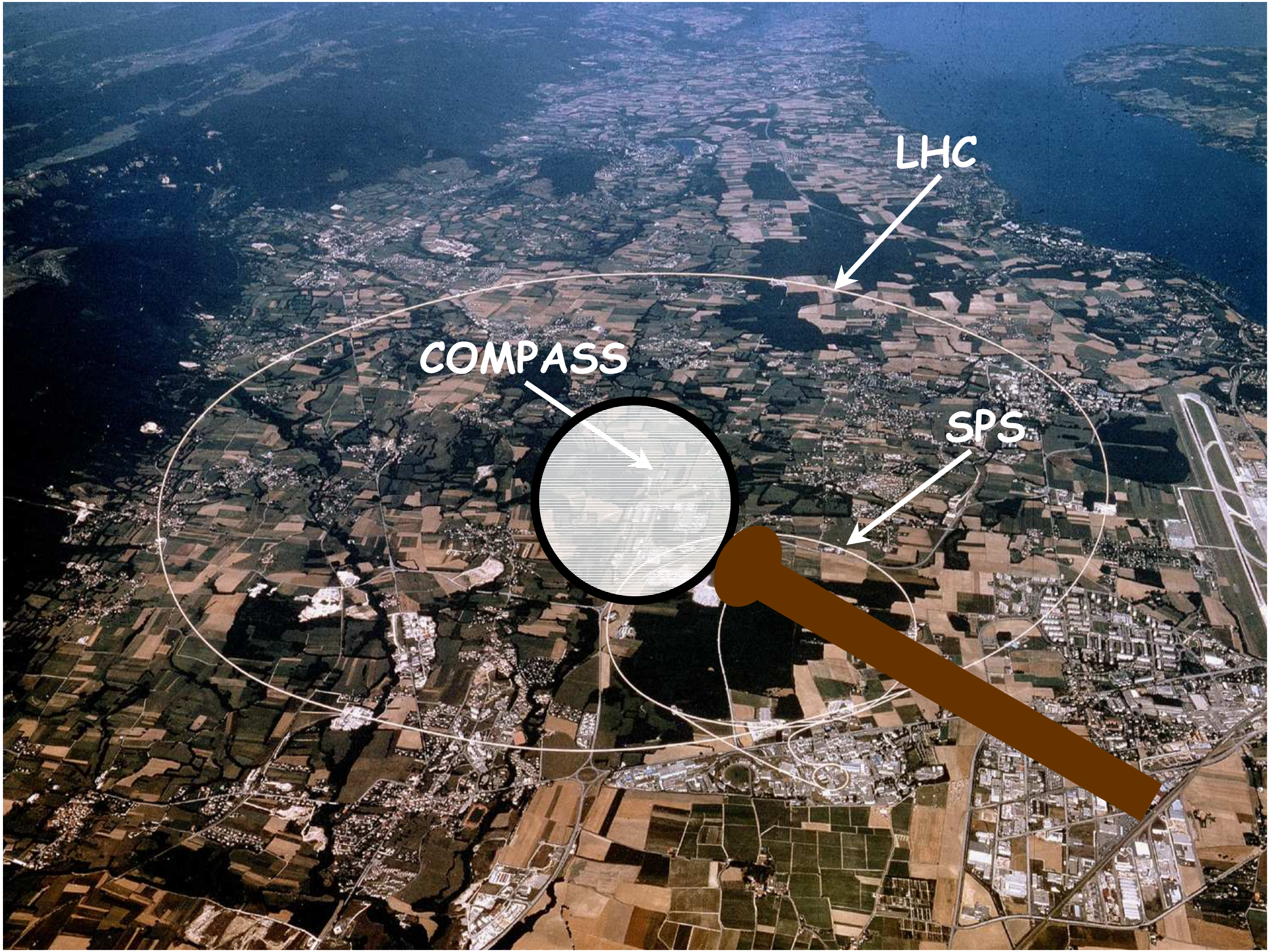
Etc. etc. …..

There is a bit more than the LHC

- Proton physics
- Kaon physics (CP violation, rare decays)
- Heavy ion physics on fixed target

- Future neutrino physics

- ISOLDE
- Cold anti-hydrogen


LHC
COMPASS
SPS

The structure of the Proton

Proton is not, in fact, simply made from three quarks (uud)

There are actually 3 “valence” quarks (uud) + a “sea” of gluons and short-lived quark-antiquark pairs

Quark & gluon spin

Nucleon spin: $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$

Quark "spin": $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ Gluon "spin": ΔG

Orbital angular momentum of q & g: L_z

Very naïve: $\Delta\Sigma \sim 1$ Ellis-Jaffe ~ 0.6

EMC: $\Delta\Sigma = 0.12\ (0.17)$ $\Delta s = -0.19\ (0.06)$

"spin crisis !!"

Neutrinos

Neutrinos are the most mysterious of the known particles of the universe

Neutrinos are elusive and full of surprises.

They interact so weakly with other particles that trillons of them pass through our bodies each second without leaving a trace.

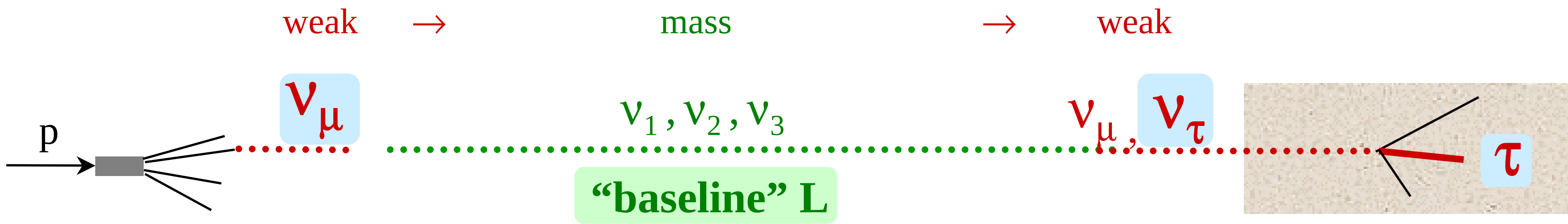
They have a tiny mass different of zero!!

They oscillate.

How $m_\nu > 0$ results in ν oscillation

P.Strolin

✸ Quantum Mechanics

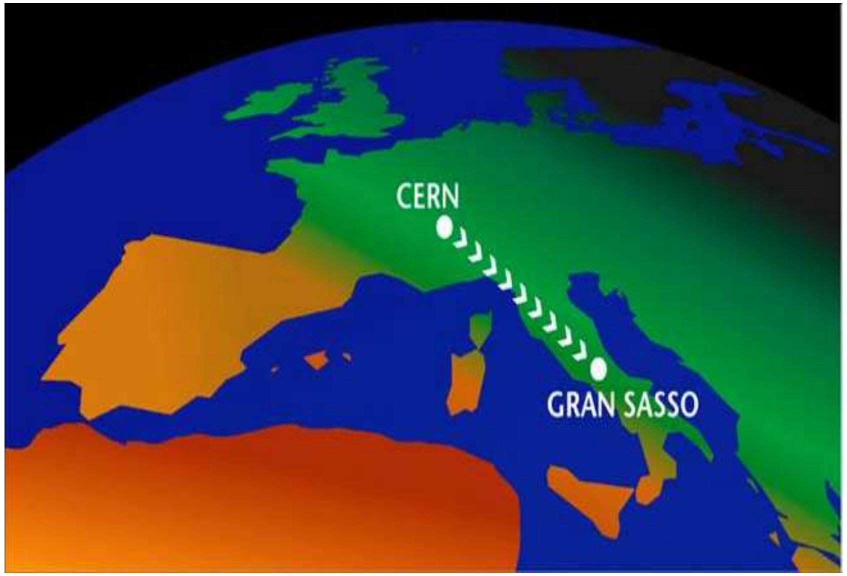


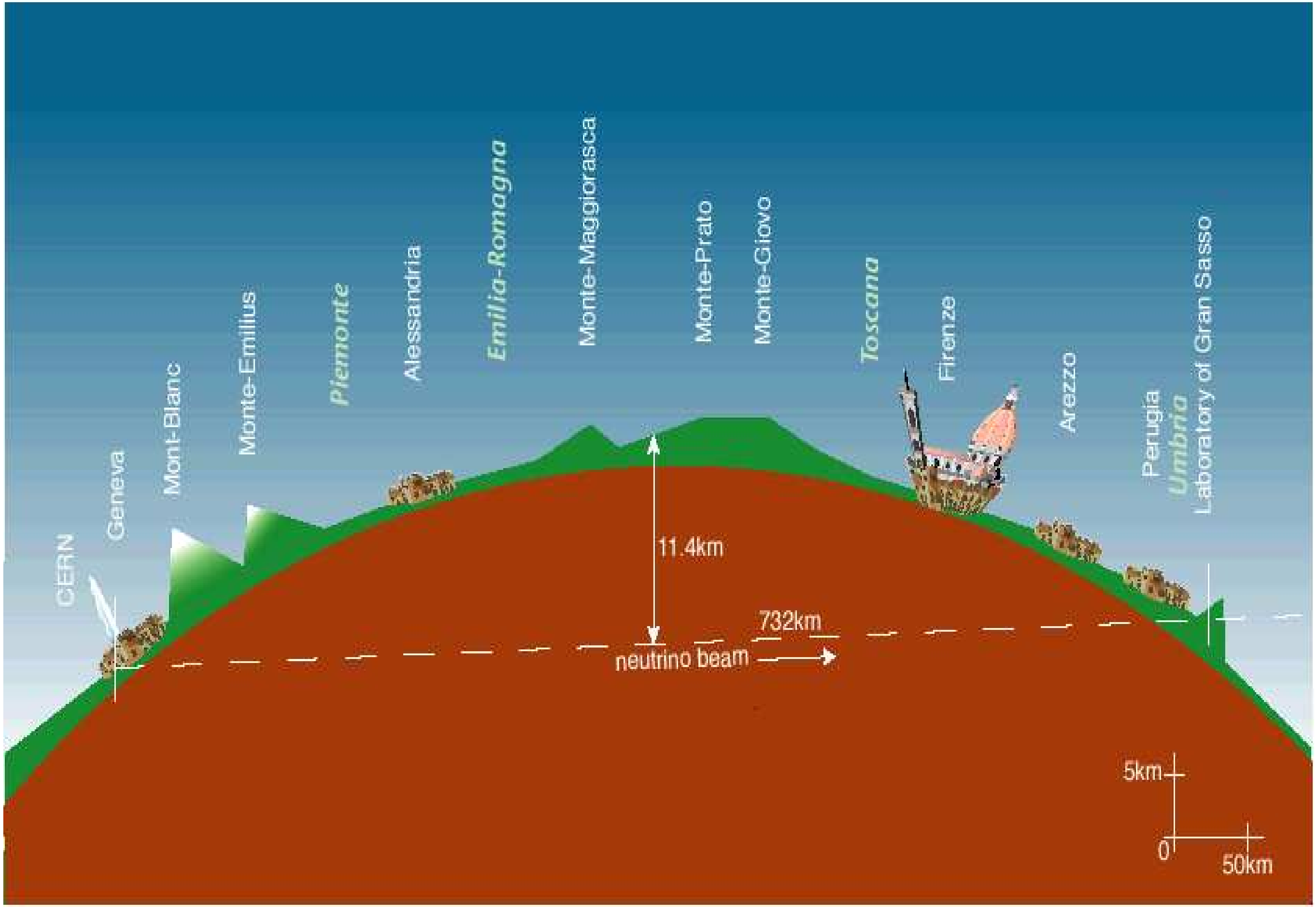
ν_μ production

ν_τ detected, although ν_μ was produced !

***M.C. Escher, Metamorphose** III (1967-68), part of a "**long baseline**" xylograph (**19 cm x 680 cm**)*

CERN Neutrinos to Gran Sasso




CERN
Geneva
Mont-Blanc
Monte-Emilius
Piemonte
Alessandria
Emilia-Romagna
Monte-Maggiorasca
Monte-Prato
Monte-Giovo
Toscana
Firenze
Arezzo
Perugia
Umbria
Laboratory of Gran Sasso
11.4km
732km
neutrino beam
5km
0
50km

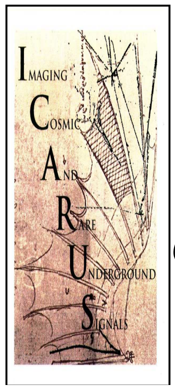
CNGS : Physics Motivation

CNGS PROGRAM:

- Provide an unambiguous evidence for $\nu_\mu \rightarrow \nu_\tau$ oscillations in the region of atmospheric neutrinos by looking for ν_τ appearance in a pure ν_μ beam
- Search for the subleading $\nu_\mu \rightarrow \nu_e$ oscillations (measurement of Θ_{13})

- ν_τ appearance experiments

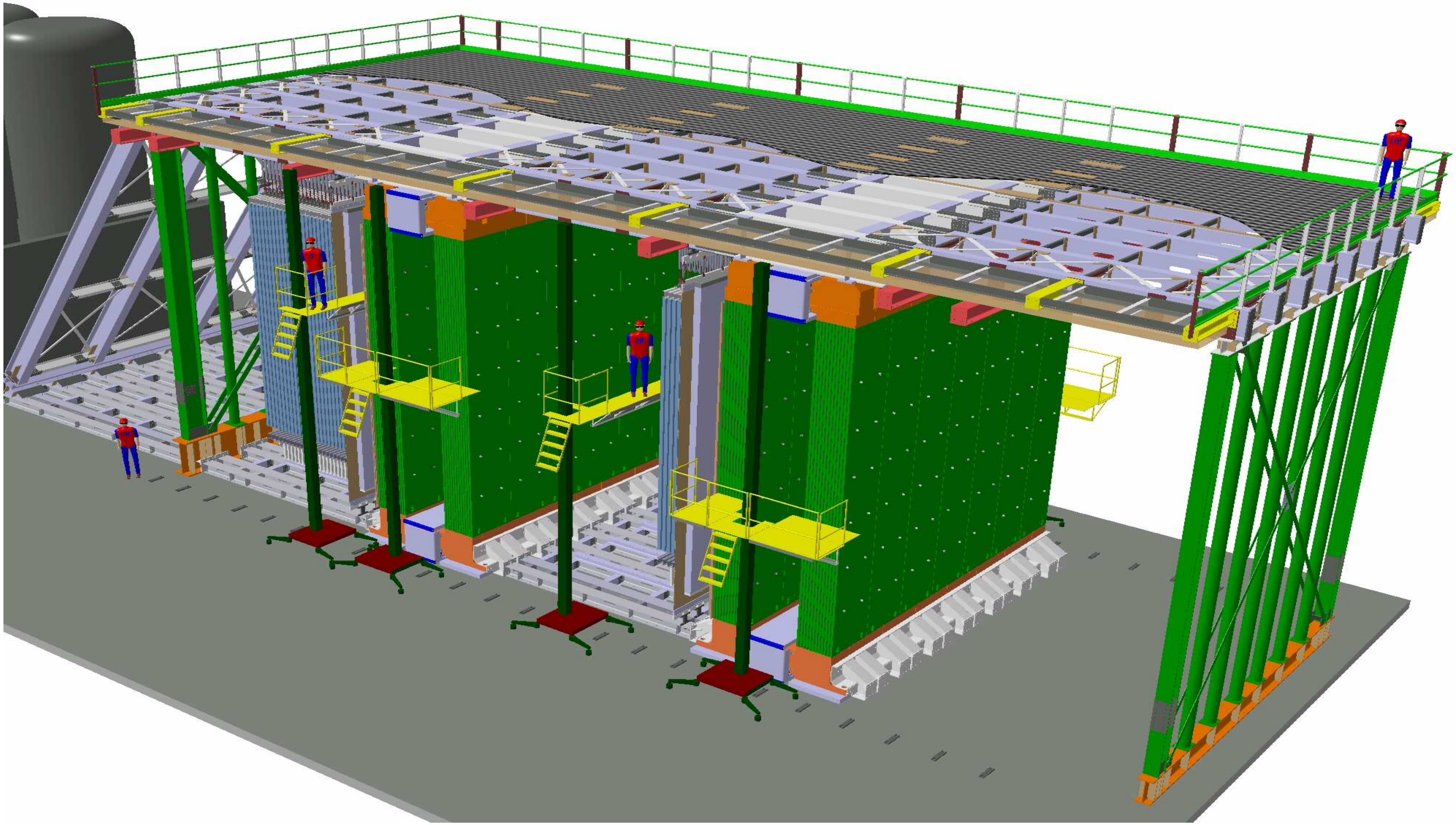
CNGS1 (2000)



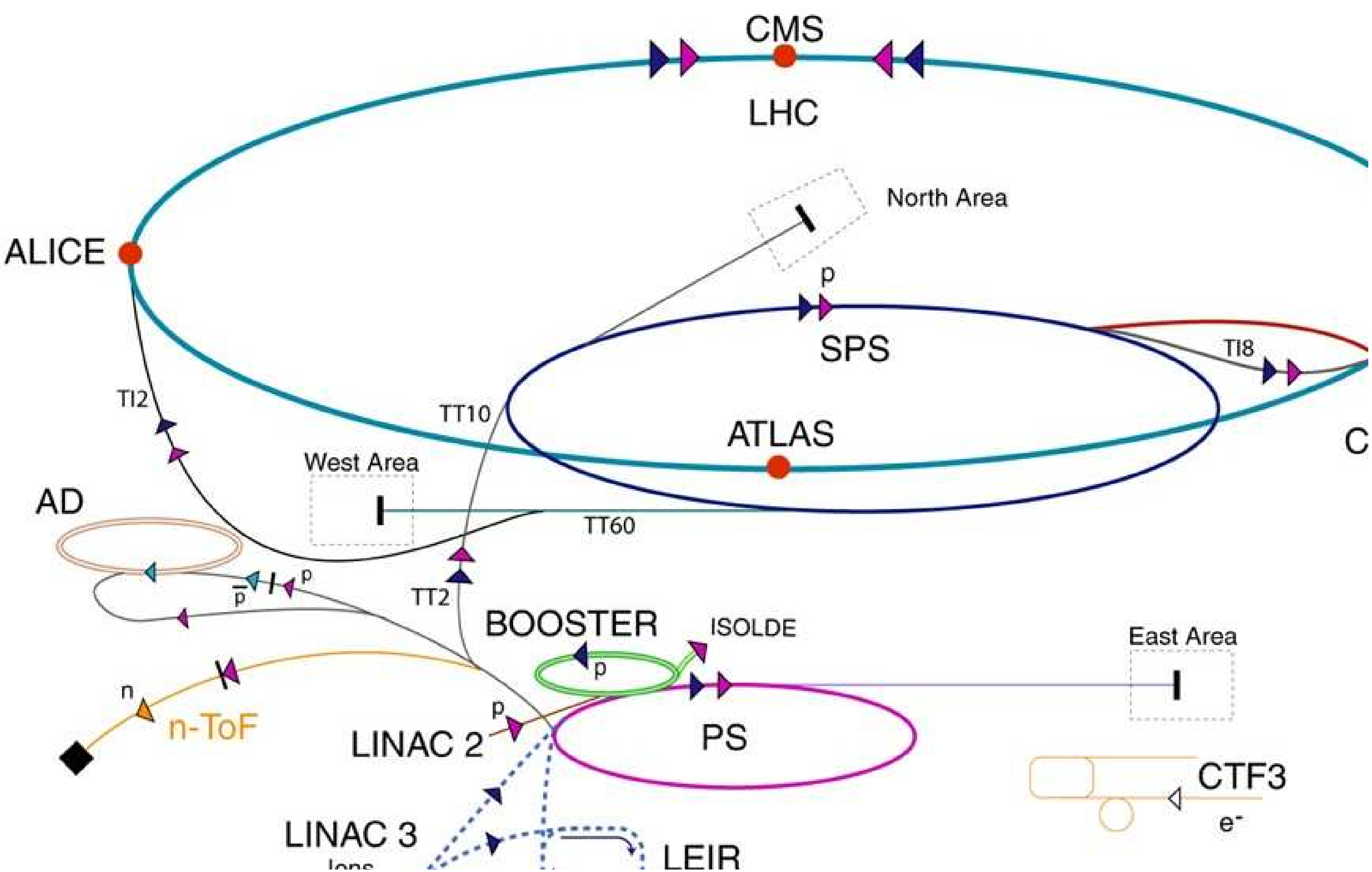
CNGS2 (2002)

OPERA Final Design with 2 SuperModules

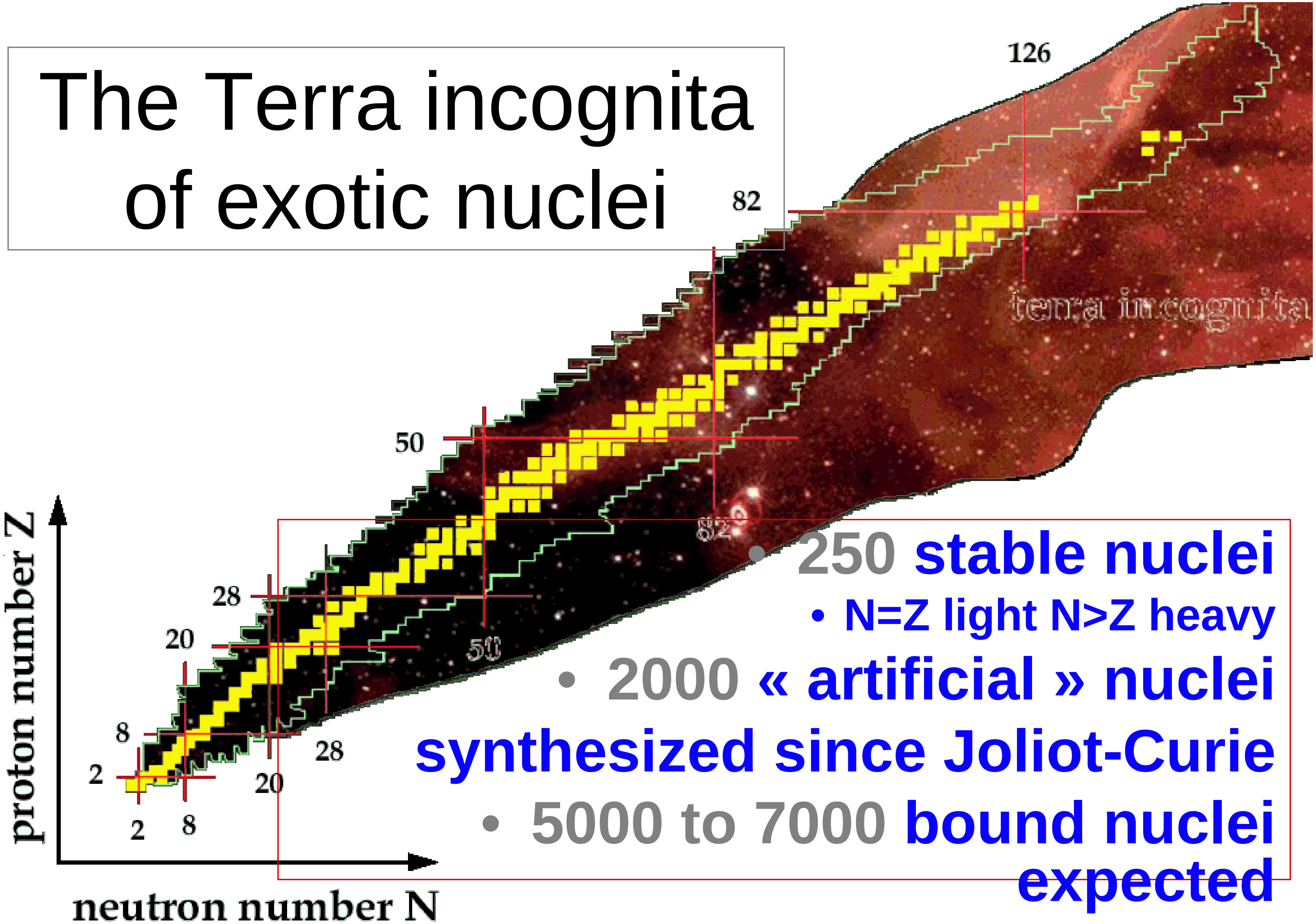
31 target planes / Super-Module (206336 bricks, 1766 tons)



CERN: the World's Most Complete Accelerator Complex (not to scale)

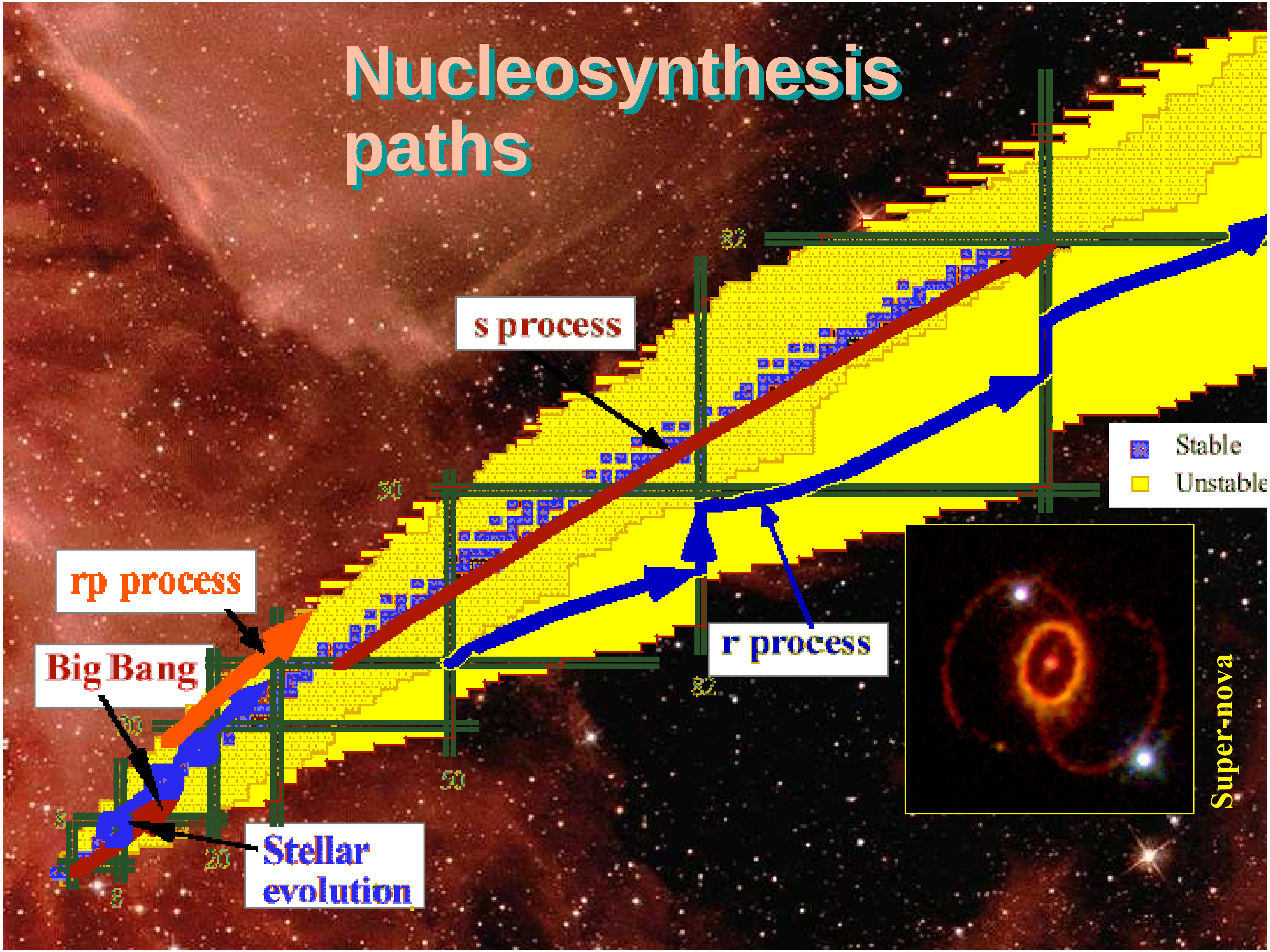


The Terra incognita of exotic nuclei



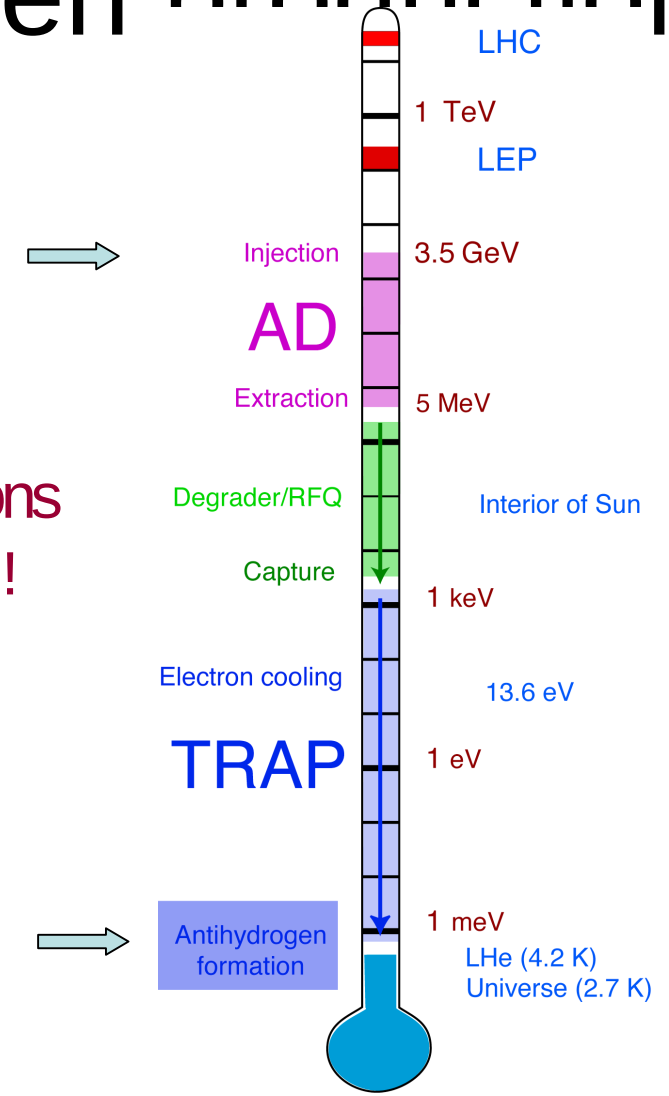
- **250 stable nuclei**
  - **N=Z light N>Z heavy**
- **2000 « artificial » nuclei synthesized since Joliot-Curie**
- **5000 to 7000 bound nuclei expected**

Nucleosynthesis paths



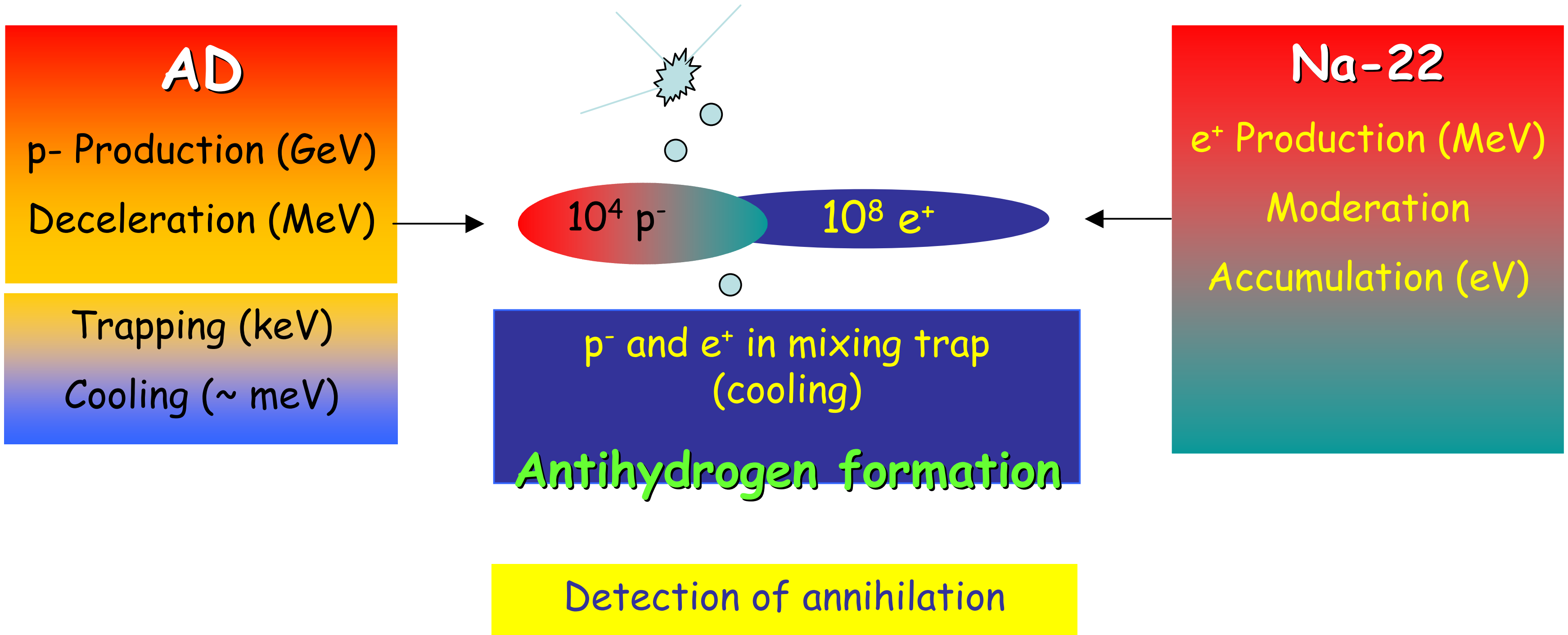
"Cold" antihydrogen production

Reduce energy of antiprotons
by 13 orders of magnitude !



Step 1 towards spectroscopy

PRODUCTION AND DETECTION OF COLD ANTIHYDROGENk



Main lines of present and future CERN scientific programme

	2004		2005		2006		2007		2008		2009		2010
LHC/ATLAS													
LHC/CMS													
LHC/LHCb	INSTALLATION/COMMISSIONING							RUNNING					
LHC/ALICE													
SPS/COMPASS						Under consideration							
SPS/KAON						?							
SPS/HEAVY IONS											?		
CNGS/OPERA													
CNGS/ARGUS													
PS/AD(Antiproton)						?							
REX/ISOLDE													
Accelerator R&D													

Summary

- Looking for the most elementary constituents of matter is fascinating.It is a journey of exploration into the mystery and beauty of the universe at the smallest and the largest scale.

- Since 50 years CERN has been at the forefront of international research in particle physics. With the LEP Programme CERN has become the world leader laboratory. This will continue with the LHC which should open a new window in particle physics and cosmology.

Additional slides

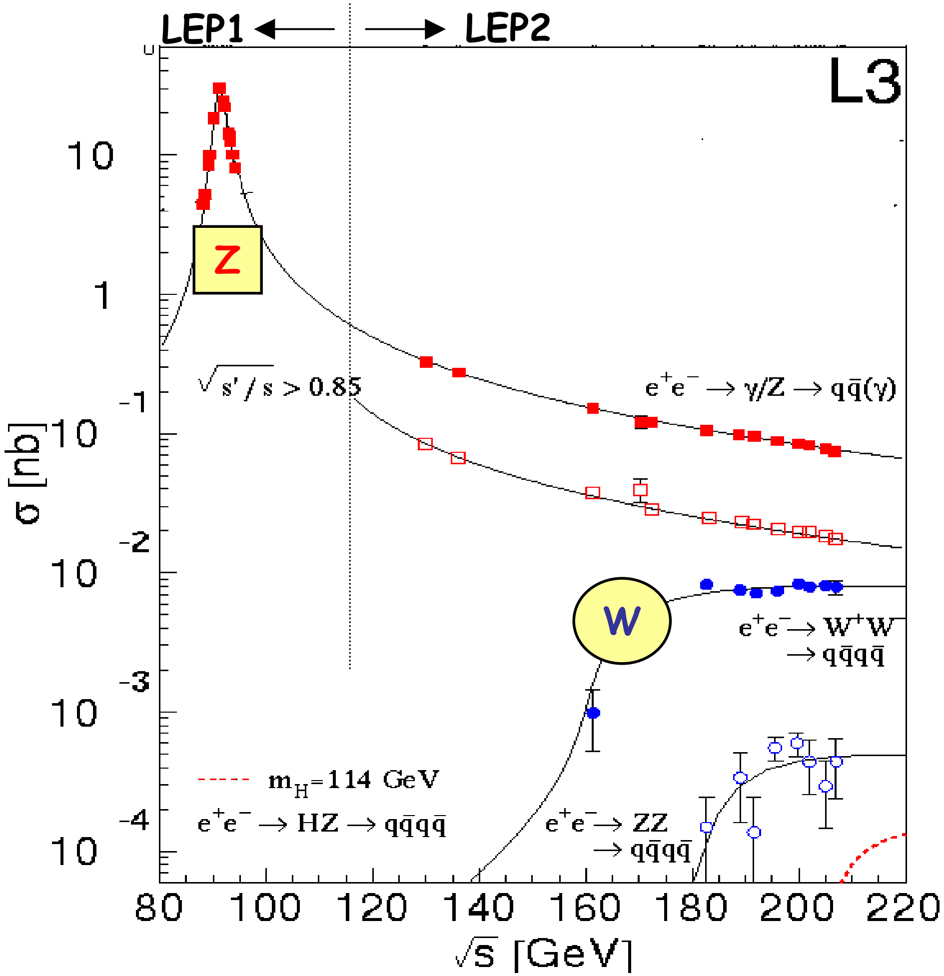
The LHC experiments

- The multipurposes detectors: ATLAS and CMS
- The CP violation LHCb experiment :LHCb
- The heavy nuclei experiment: ALICE

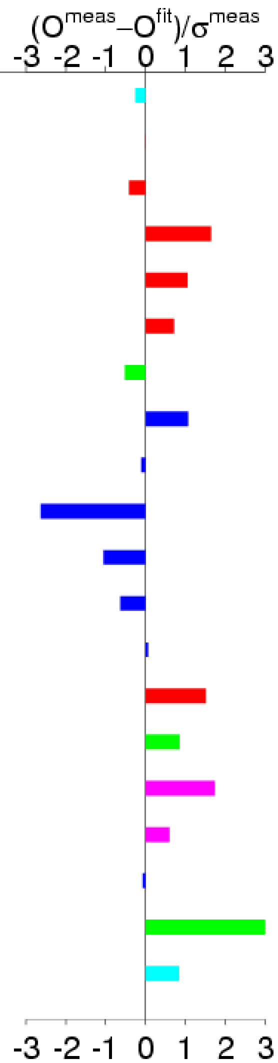
The LEP e+e- Collider at CERN

1989-2000 : $\sqrt{s} \approx m_Z \rightarrow 209$ GeV

Precise measurements of Z particle and of m_W, and search for new particles (Higgs !)

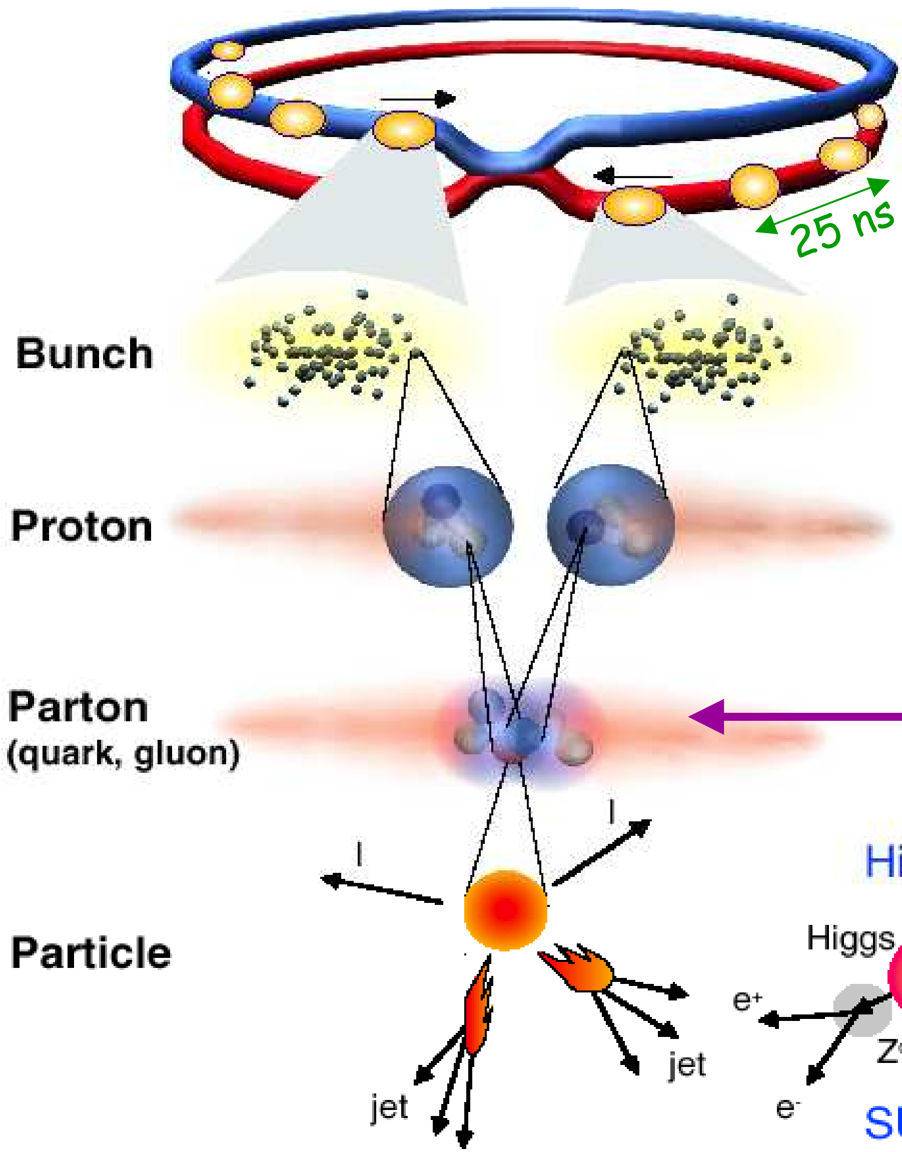


	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
m_Z [GeV]	91.1875 ± 0.0021	.01
Γ_Z [GeV]	2.4952 ± 0.0023	-.42
σ^0_{had} [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.05
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
R_b	0.21646 ± 0.00065	1.06
R_c	0.1719 ± 0.0031	-.11
$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.50
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
m_W [GeV]	80.451 ± 0.033	1.73
Γ_W [GeV]	2.134 ± 0.069	.59
m_t [GeV]	174.3 ± 5.1	-.08
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
Q_W(Cs)	-72.39 ± 0.59	.84



Many spectacular measurements: agreement theory-data at the permil level !

Collisions at LHC



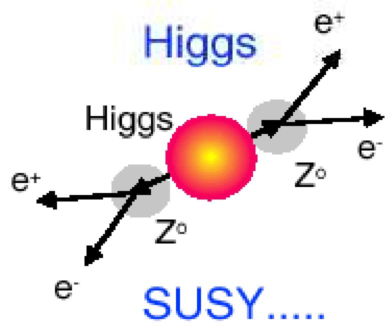
Proton-Proton	
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}

Event rate in ATLAS :

$N = L \times \sigma\,(pp) \approx$ 10^9 interactions/s

Mostly soft (low p_T) events

Interesting hard (high-p_T) events are rare



Selection of 1 in 10,000,000,000,000

→ very powerful detectors needed

Kaons @ CERN

- Kaon physics has a long tradition at CERN
- Direct CP-Violation amounts to a different probability for a particle and its anti-particle to disintegrate into the same final state
- Since the discovery of CP violation a question was pending :"Does Direct CP-Violation exist?"
- The CERN/NA48 experiment employing intense beam of neutral kaons has settled the question

The Future of kaon physics at CERN

- The focus now shifts to those decays where very precise theoretical predictions can be made
- In particular, the Collaboration plans to address the “Holy Grail” of kaon rare decays:

$$K \rightarrow \pi \bar{\nu} \nu$$

- Any deviation from the precise Standard Model prediction will be a sign of New Physics

Direct CP-Violation

NA48 97-2001:Re $\varepsilon'/\varepsilon = 14.7 \pm 2.2 \times 10^{-4}$