Experimental exploration of the Terascale

Towards completion and extension of the Standard Model
of elementary particles and fields

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Energy (mass) scales

Are important in the description of Nature. For example, if I study the collision of two protons at an energy of 10^2 eV I will observe elastic scattering only, perfectly described by electrodynamics.

If I study proton proton scattering at 10^{12} (=1 Tera) eV I observe a much more diverse phenomenology: particle production through the strong interaction; production of W, Z particles (weak interaction); production of 'jets' of particles resulting from the collisions of quarks inside the protons; etc. ('new physics'?)

In raising the energy we have entered domains with 'new physics' – either gradually or by crossing a threshold. Why do particles have the masses they have; why do interactions have the strength they have; is there one fundamental energy scale from which all the rest follows?

$E=Mc^2$: high E allows production heavy (elementary) particles → 'new physics'

$\lambda=1/M$: large M allows probing small distances → new physics?

Hierarchy of Scales

In fact the very different scales occurring in Nature can be quite intriguing. One famous ‘hierarchy problem’ concerns the very large difference in strength of the weak interaction and the next weakest interaction: gravity. 32 orders of magnitude!

Possible answers come from ‘supersymmetry’ (see later), from large extra dimensions (if we have time) or by simply invoking the anthropic principle

Energy (mass) scales

For (arbitrary) reference: proton mass = 1 GeV

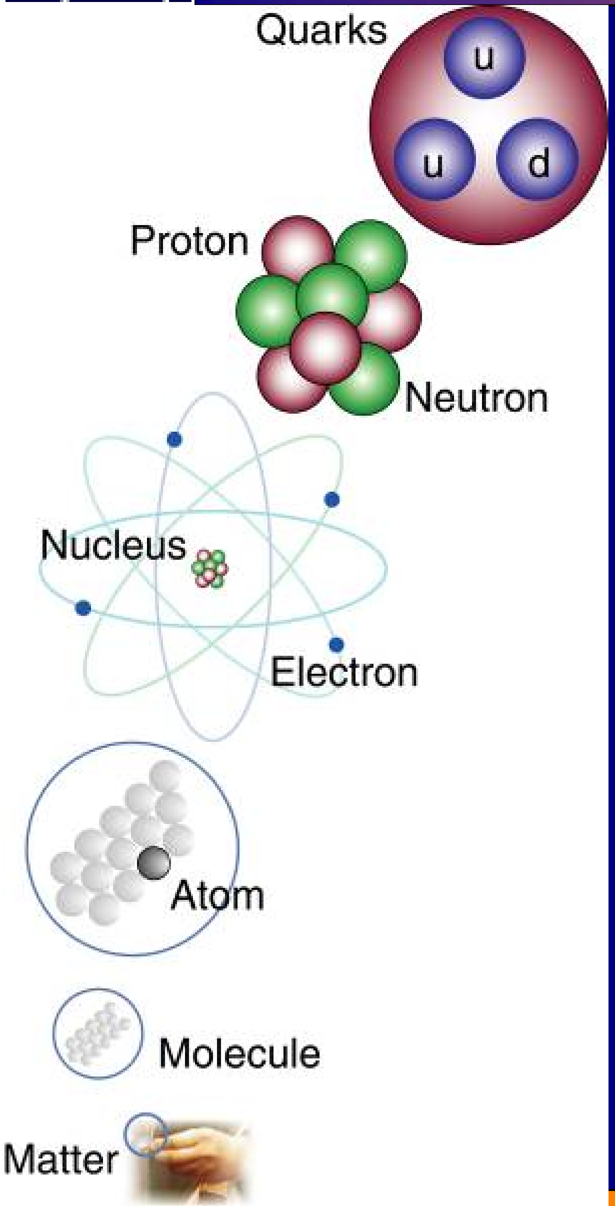
Atomic transitions: eV – keV
Nuclear transitions: MeV

Hadron (e.g. proton) masses: GeV – up to 175 GeV (top quark)
Lepton (e.g. electron) masses: from almost zero (neutrino) to 1.8 GeV (Tau)

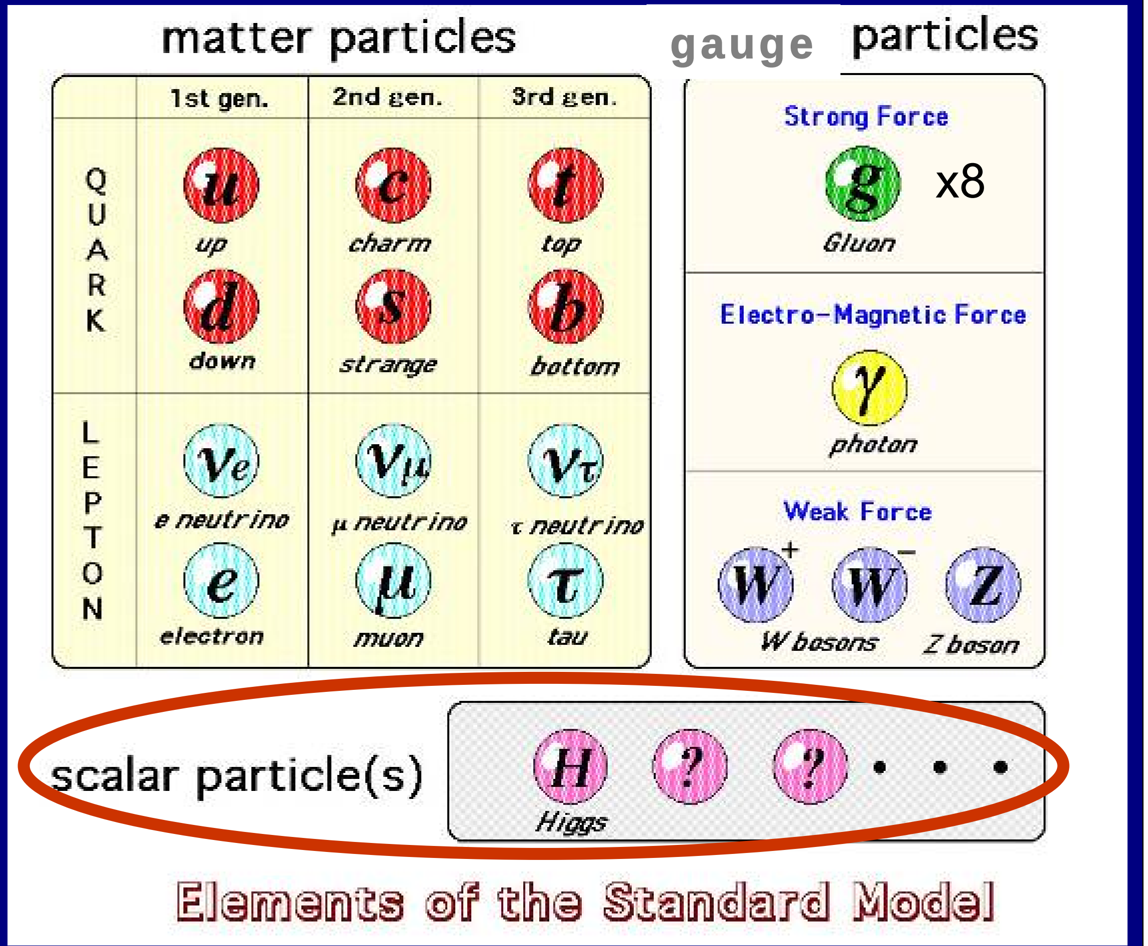
Photon: strictly zero
W, Z bosons: 80, 90 GeV
} cf 'electroweak symmetry breaking'

Up to 100 – 200 GeV elementary particles and fields and their interactions have been explored experimentally; a fantastically accurate theory is available: the Standard Model

A cartoon



Quarks
u
u
d
Proton
Neutron
Nucleus
Electron
Atom
Molecule
Matter

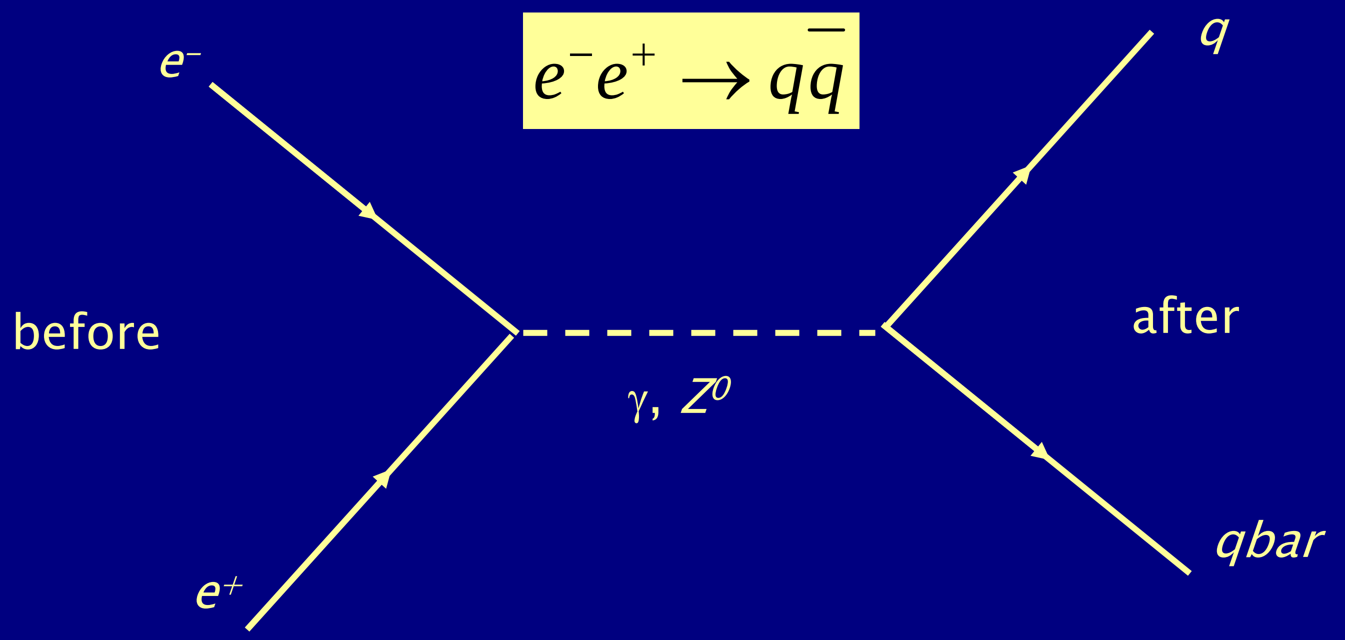


matter particles
gauge particles
1st gen.
2nd gen.
3rd gen.
QUARK
u up
c charm
t top
d down
s strange
b bottom
LEPTON
νe e neutrino
νμ μ neutrino
ντ τ neutrino
e electron
μ muon
τ tau
Strong Force
g Gluon
x8
Electro-Magnetic Force
γ photon
Weak Force
W+ W− W bosons
Z Z boson
scalar particle(s)
H Higgs
? ? . . .
Elements of the Standard Model

Elementary Reactions: A Feynman diagram

Example: electron – positron annihilation into quark – antiquark

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



Amplitude = current x charge x field strength x charge X current

current: ‘matter particles’

field strength: ‘field particles’, i.e. γ or Z^0 in this example (→ propagator)

charge: electrical charge ~ coupling constant α for e.m. interactions

weak coupling constant for weak interactions

A few formulae

The Lagrangian of QED

$$L = \overline{\psi}(i\gamma^{\mu}\partial_{\mu} - m)\psi + e\overline{\psi}\gamma^{\mu}\psi A_{\mu} - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$$

is invariant under local U(1) transformations

$$\psi \to e^{i\alpha(x)}\psi$$

$$A_{\mu} \to A_{\mu} + \frac{1}{e}\partial_{\mu}\alpha$$

a massive gauge (photon) field would introduce terms like

$$m^2 A_{\mu}A^{\mu}$$

and would destroy gauge invariance (and destroy renormalizability) weak interactions are mediated by 3 gauge bosons, generating the group of SU(2) gauge transformations. These bosons are massive; gauge invariance is preserved by introducing a scalar field ('Higgs')

Another formula

The full GSW Lagrangian, including the Higgs sector

$$L_{GSW} = L_0 + L_H + \sum_l \left\{ \frac{g}{2} \bar{L}_l \gamma_\mu \vec{\tau} L_l \vec{A}^\mu + g' \left[\bar{R}_l \gamma_\mu R_l + \frac{1}{2} \bar{L}_l \gamma_\mu L_l \right] B^\mu \right\} +$$

$$+ \frac{g}{2} \sum_q \bar{L}_q \gamma_\mu \vec{\tau} L_q \vec{A}^\mu +$$

$$+ g' \left\{ \frac{1}{6} \sum_q \left[\bar{L}_q \gamma_\mu L_q + 4 \bar{R}_q \gamma_\mu R_q \right] + \frac{1}{3} \sum_{q'} \bar{R}_{q'} \gamma_\mu R_{q'} \right\} B^\mu$$

SU(2)xU(1)

$$L_H = \frac{1}{2} (\partial_\mu H)^2 - m_H^2 H^2 - h\lambda H^3 - \frac{h}{4} H^4 +$$

$$+ \frac{g^2}{4} (W_\mu^+ W^\mu + \frac{1}{2\cos^2\theta_W} Z_\mu Z^\mu)(\lambda^2 + 2\lambda H + H^2) +$$

$$+ \sum_{l,q,q'} (\frac{m_l}{\lambda} \bar{l} l + \frac{m_q}{\lambda} \bar{q} q + \frac{m_{q'}}{\lambda} \bar{q}' q') H$$

Makes theory gauge invariant (renormalizable)
Also preserves unitarity

Mass terms !

Higgs mass

There is a hard, direct experimental lower limit from the four LEP experiments ALEPH, DELPHI, L3 and OPAL:

$M_{Higgs} > 114.4$ GeV

There is an indirect measurement from 'Standard Model fits', i.e. through quantum corrections, leading to a preferred value below 100 GeV, albeit with a large error

'Unitarity arguments' want a Higgs mass below ~850 GeV

The only way forward is through experimental exploration – we may find 'the' Higgs, we hope to find much more. (What if we find nothing..?)

So: we need to access the Terascale, 1 TeV (1000 GeV)

The Cosmic Connection

Through the 'Hot Big Bang' model the laws of Elementary Particle Physics determine the early stages of cosmic evolution

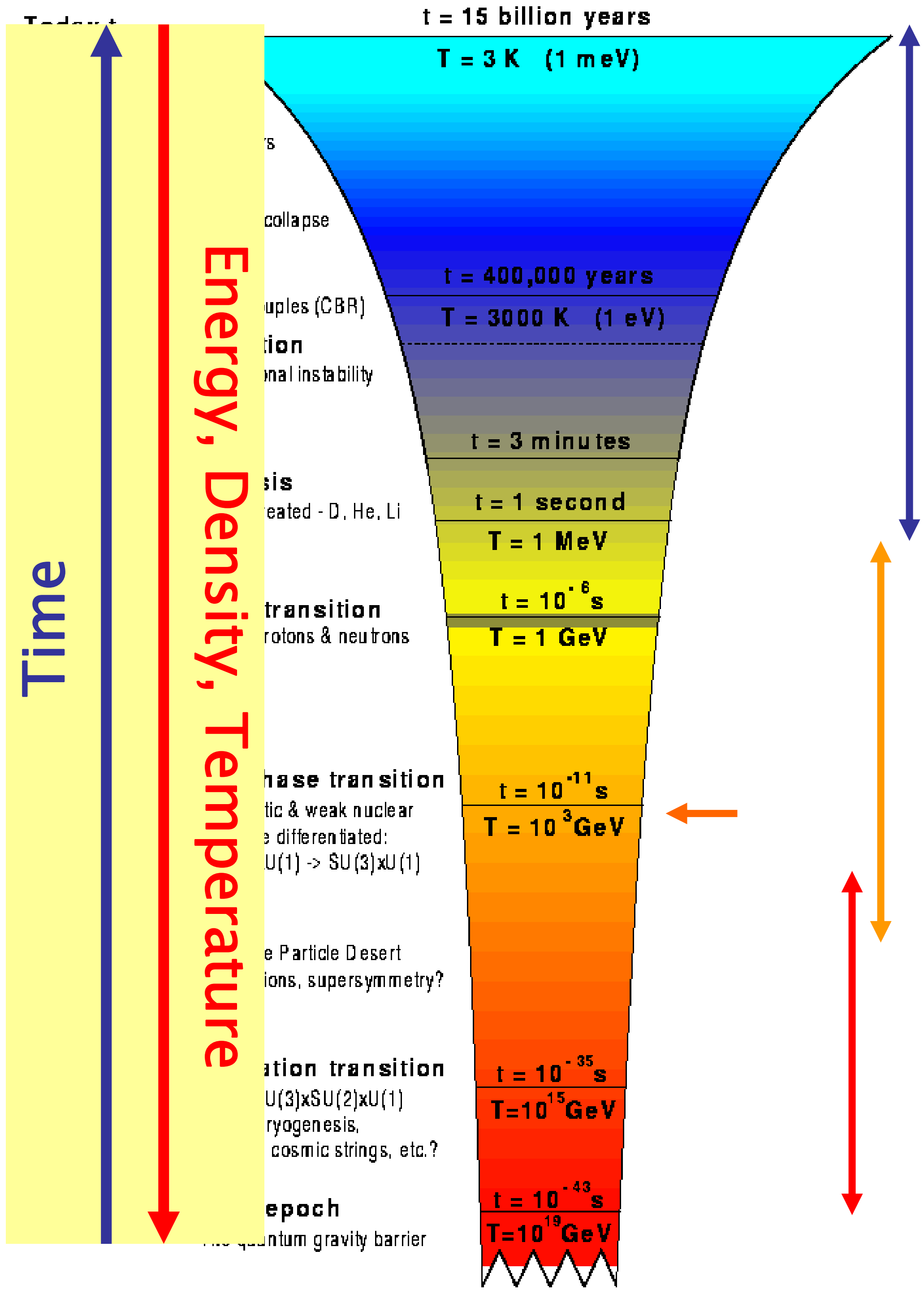
A next, crucial step in discovering these laws will be the exploration of phenomena around and above 1 TeV – electroweak symmetry breaking and more (supersymmetry?)

At high energies we effectively emulate, at an elementary level, the conditions that prevailed in the early universe

Cosmologists have a very good model for times > 0.01 sec
For earlier times (higher temperature, density) particle physics is relevant, but not all of it is known – we try to push back boundaries!

For the earliest times: energies become so high that gravity has to start playing a role in elementary particle interactions – string theory? I have no clou...

Let us have a look at another cartoon:



Standard Cosmology

Supported by considerable observational evidence

Elementary Particle Physics

From the Standard Model into the unknown: towards energies of 1 TeV and beyond: the **Terascale**

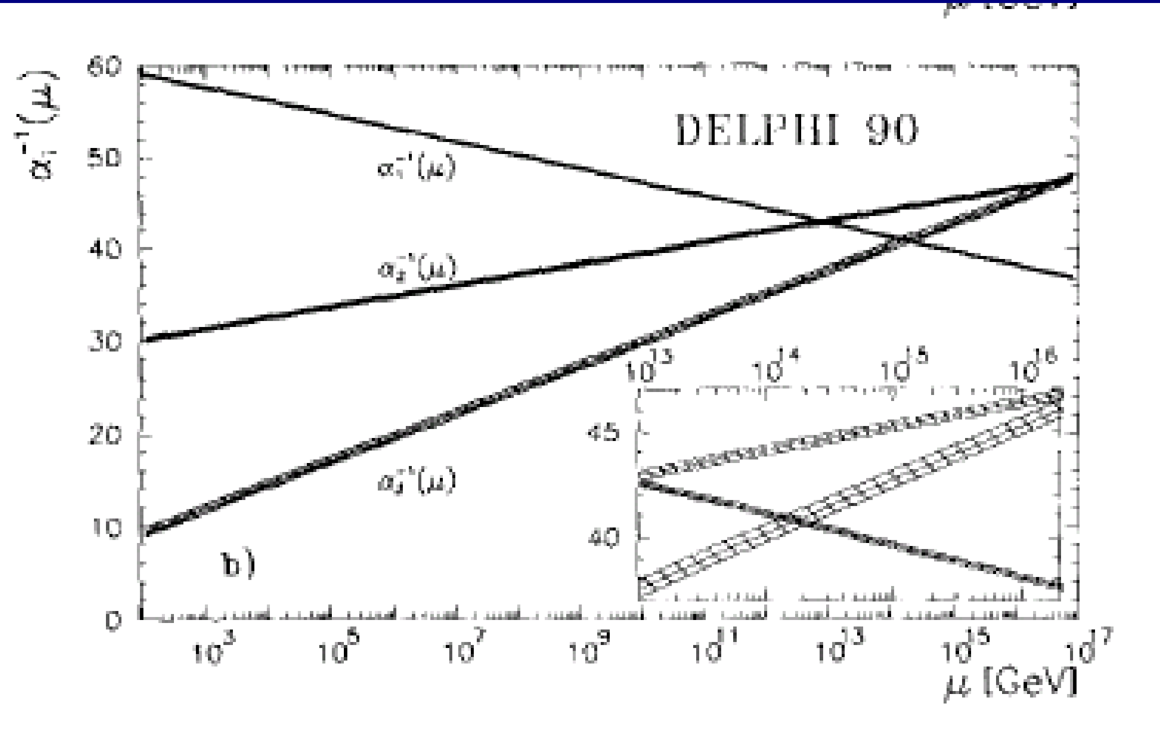
Towards Quantum Gravity

From the unknown into the unknown...

http://www.damtp.cam.ac.uk/user/gr/public/bb_history.html

Running Coupling Constants

The dimensionless coupling constants of the electromagnetic, weak and strong interactions vary with energy in a way which is quantitatively governed by the theory underlying the Standard Model

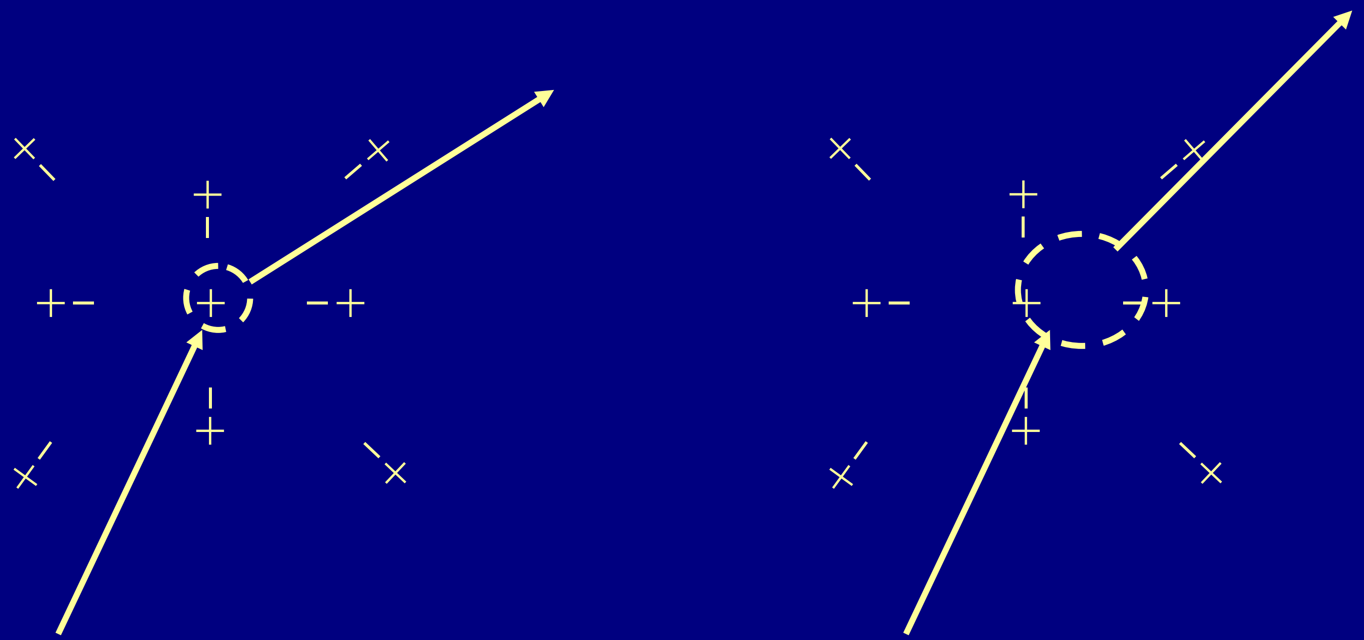


Do these coupling constants converge to one value (do the interactions 'unify'?) at some high energy?

No, but we can make them unify if we invoke Supersymmetry, setting in around the Terascale

Running Coupling Constants

Why is the electromagnetic coupling larger at higher energy (smaller distance)?
Vacuum polarization (quantum fluctuations):



Different 'sign' for weak and strong interactions, not intuitive, governed by gauge group – however, it should be clear that:

Running Coupling Constants

the ‘running’ of the coupling constants is determined by the vacuuum that is probed by a certain interaction at a certain distance/energy scale

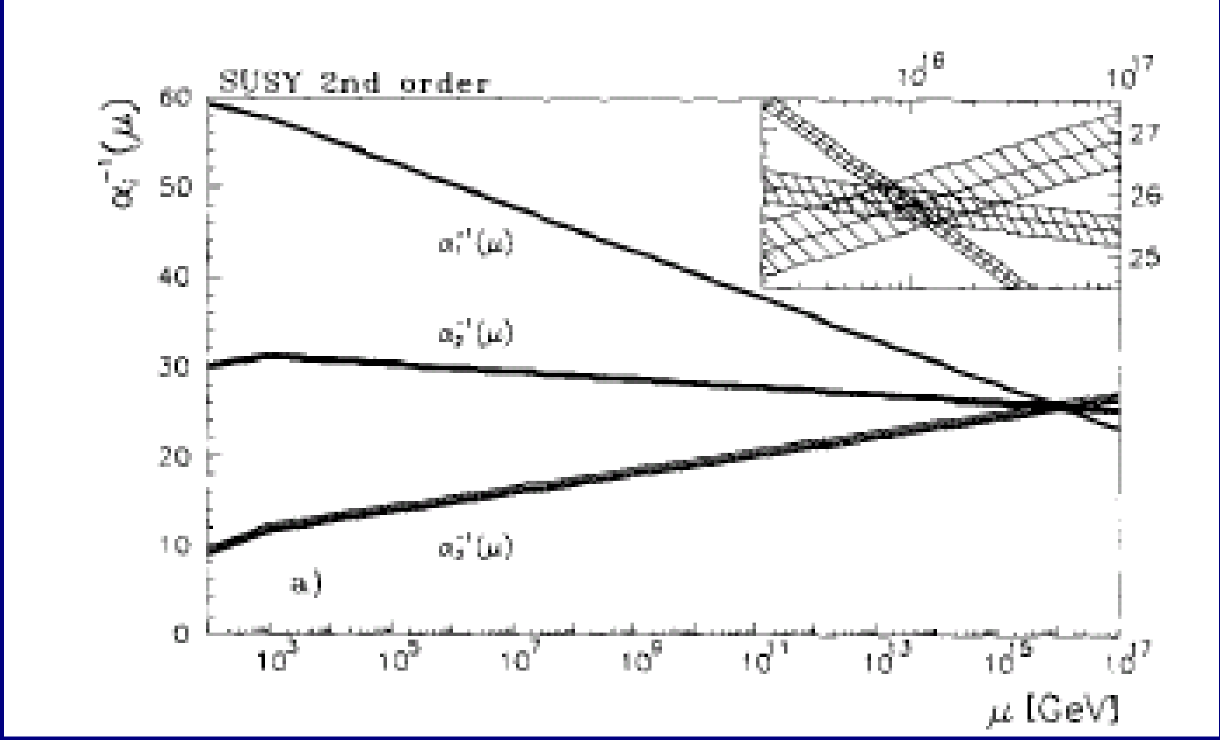
if at a certain small distance (high energy) new (heavy) particles ‘pop up’ in the vacuum, the interactions coupling to these particles will exhibit a change in the ‘running’ of the corresponding coupling constants from that energy onwards

‘Supersymmetry’ offers such new particles, affecting the running of the electromagnetic, the weak and the strong coupling constants and allowing them to converge to a single value.

Grand Unification

For SUSY setting in around 1 TeV, a unification point is found at 10^{16} GeV

Gravity not included, it is expected to 'join' at the Planck scale of 10^{19} GeV



Amaldi, De Boer, Fuerstenau, 1991

If the lightest SUSY particle is stable (if there is a conserved SUSY quantum number) and neutral, it is a dark matter candidate

SUSY doubles the number of elementary particles, that is not necessarily an attractive feature

The Terascale

In summary:
we expect something new to happen around 1 TeV – we should see evidence for the Higgs mechanism or otherwise get insight into electroweak symmetry breaking

we might see evidence for Supersymmetry (giving rise to a larger Higgs sector). Supersymmetry, by the way, also provides a possible explanation of 'dark matter'

we might see real surprises; I did not discuss 'large extra dimensions', in these theories the Planck scale might be much lower (around the Terascale..!)

There is only one way forward:
let us go and look, let us explore the Terascale experimentally

Particle Accelerators

Accelerate stable, charged particles: electrons, protons (or their anti–particles) (also: nuclei)

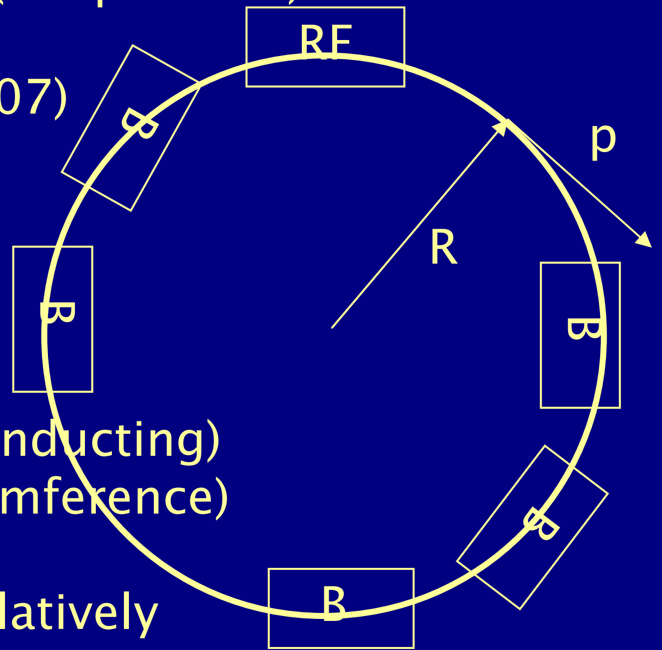
Synchrotrons, colliding beams

LEP (closed in 2000): 100 + 100 GeV electron–positron

Tevatron: 1000 + 1000 GeV proton – antiproton (in operation)

LHC: 7000 + 7000 GeV proton – proton (from 2007)

$$p = 0.3\ BR$$



So: need high B (state of the art magnets, superconducting) and large R (a circular tunnel with a large circumference)

Also need: high collision rates (cf. sensitivity to relatively low cross section, i.e. rare, processes)

Large Hadron Collider

Not a small project, not decided casually, discussions started in the high energy physics community more than 15 years ago...

A few characteristics:

The LHC features 1232, 15 m long, 9 T, superconducting dipoles
The tunnel is 27 km in circumference

protons can thus be accelerated to 7 TeV, allowing

14 TeV proton-proton collisions

in the CM

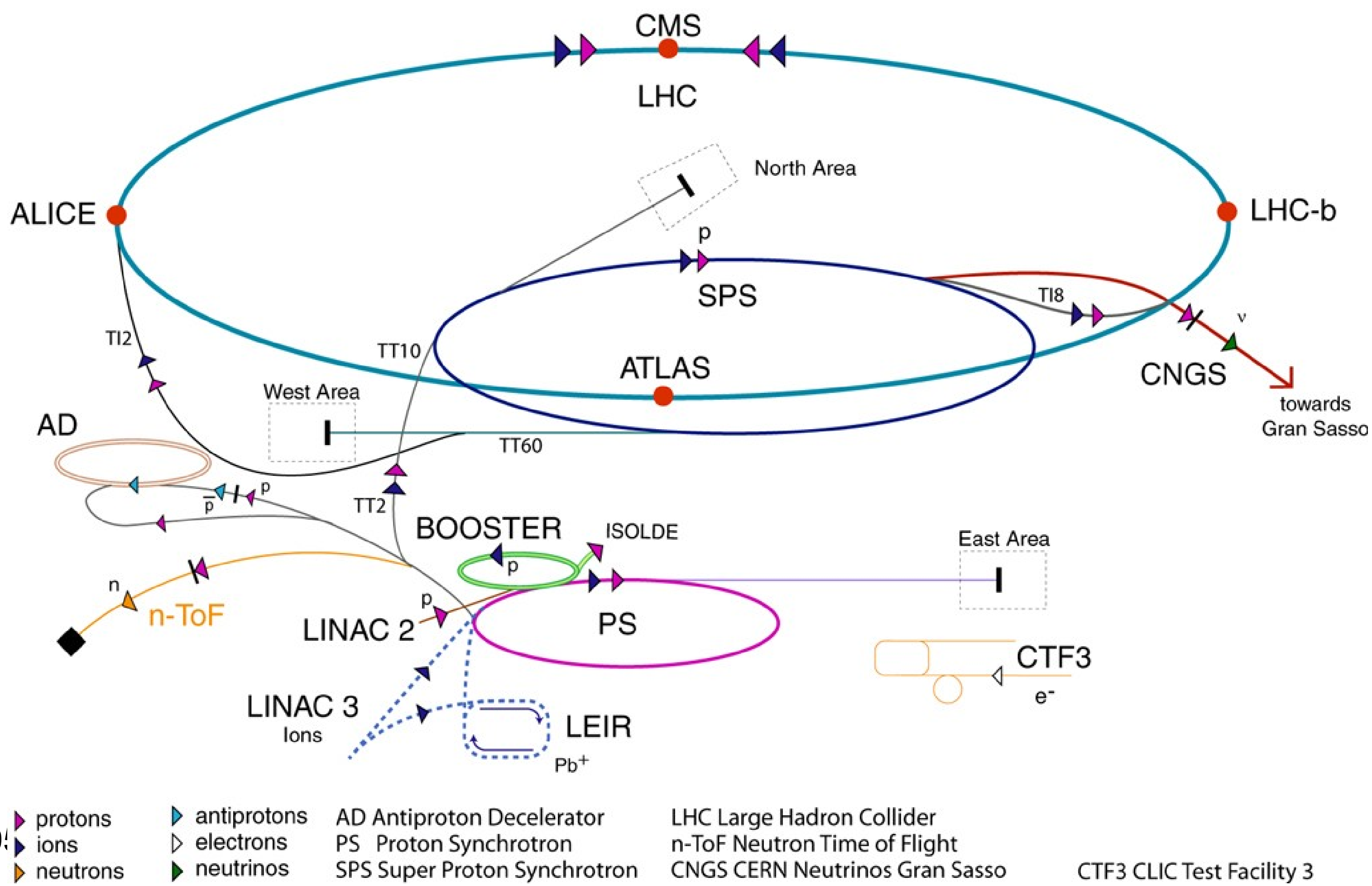
The proton beams consist of compact bunches of 10^{11} protons each, 25 ns apart, leading to a collision rate normalized to the cross section of

Luminosity = 10^{34} $cm^{-2}s^{-1}$

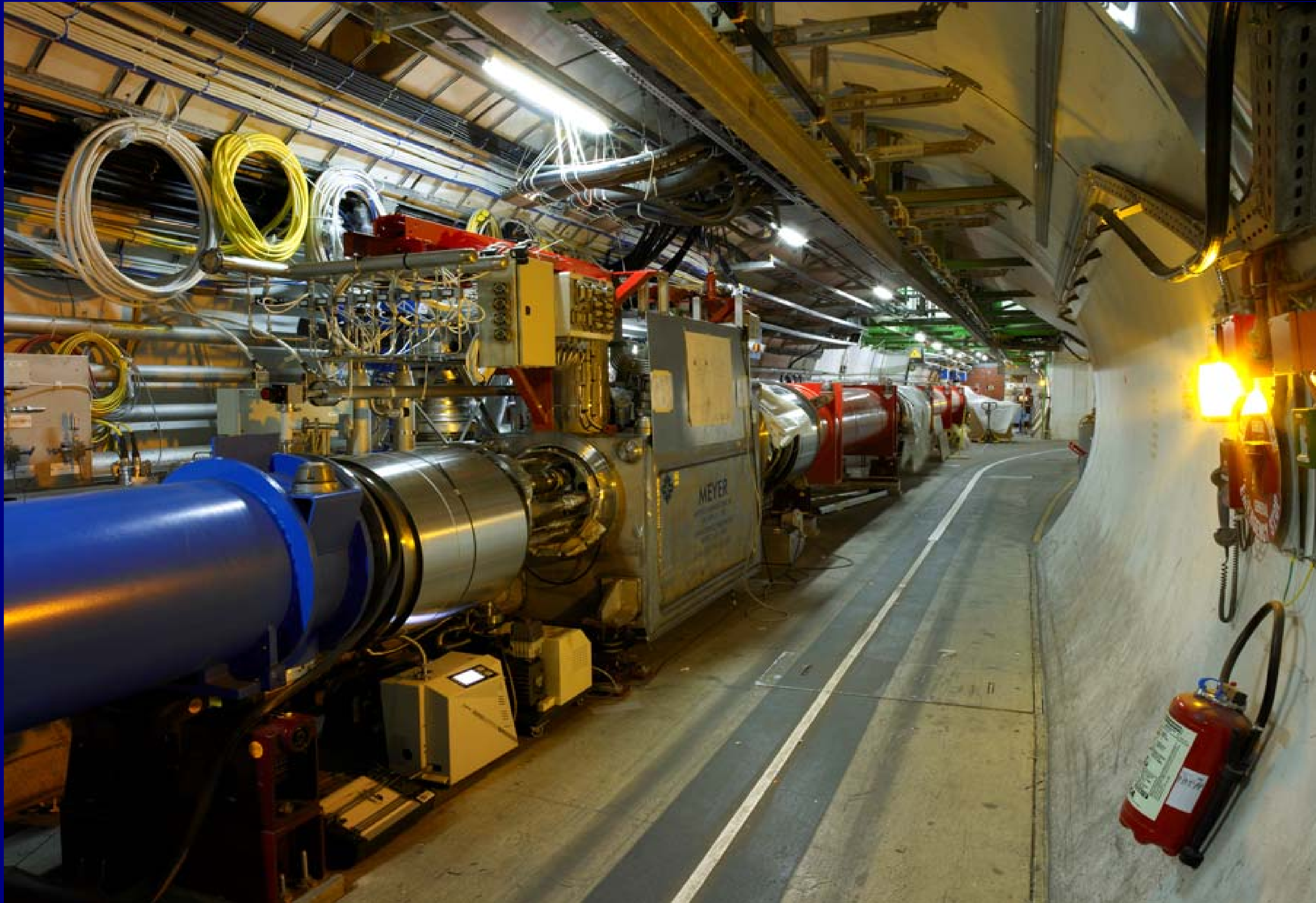

1954-2004
CERN

CERN: the World’s Most Complete Accelerator Complex

(not to scale)

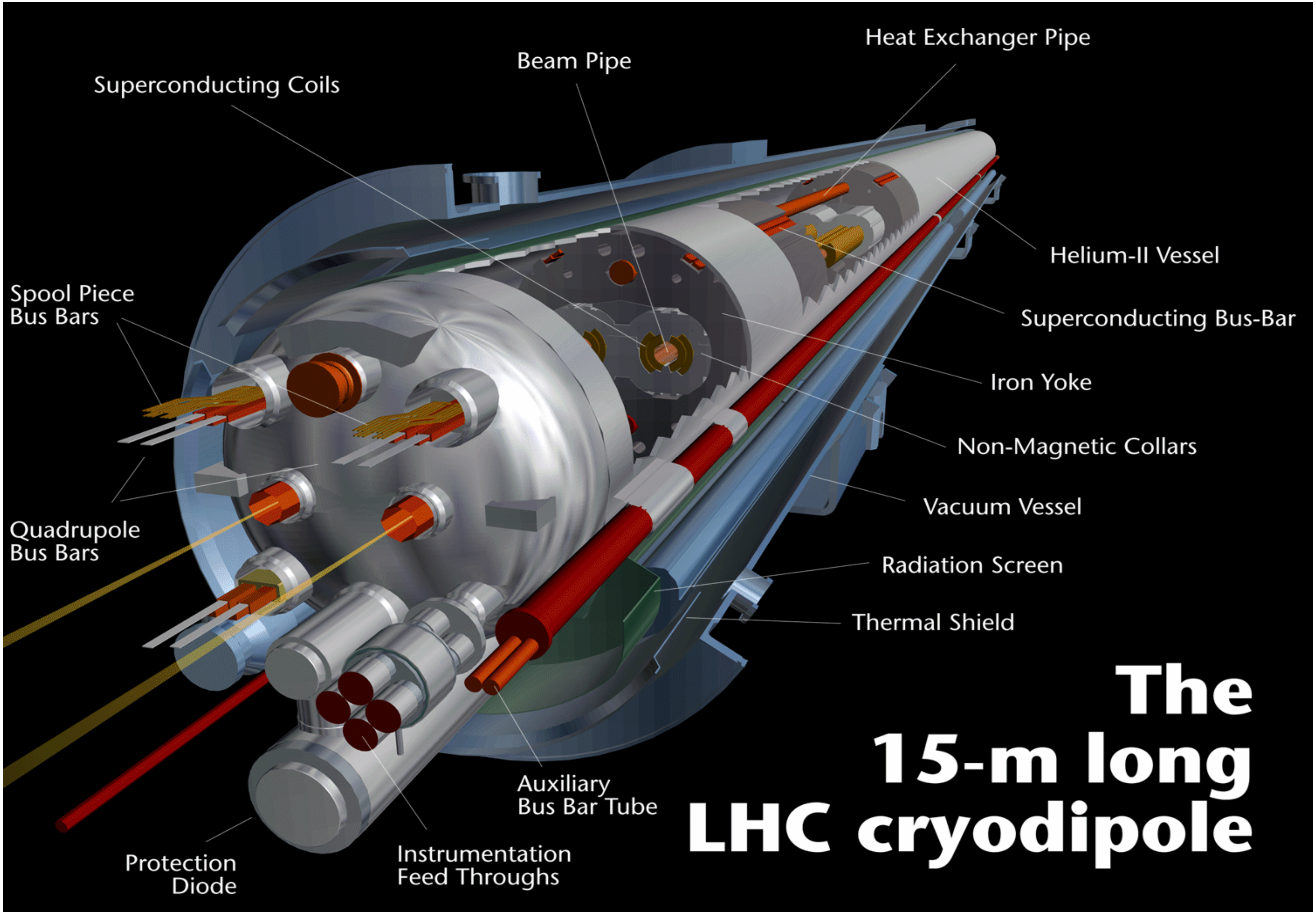


Looking Towards Collision Point

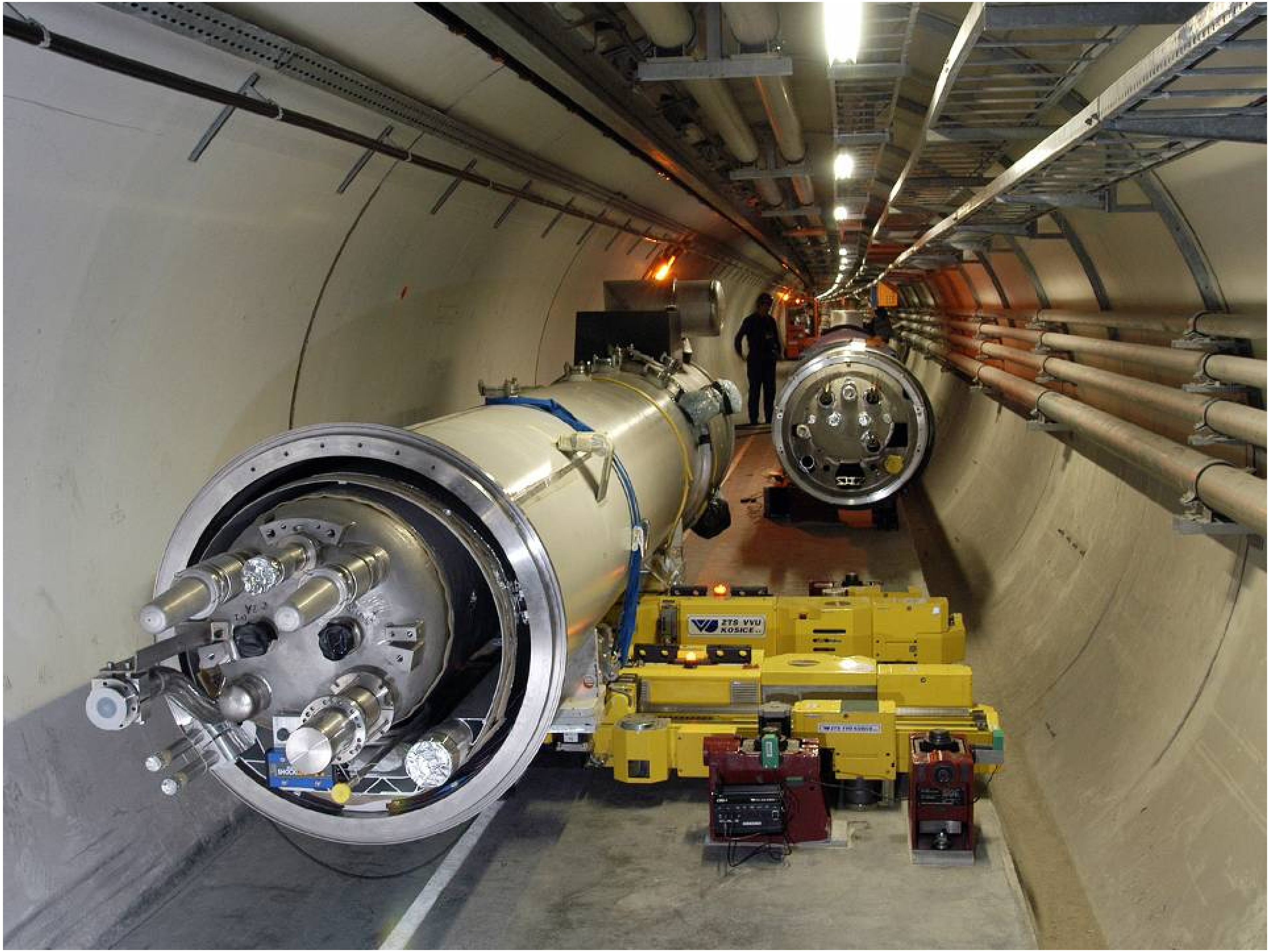


Looking over the shoulder

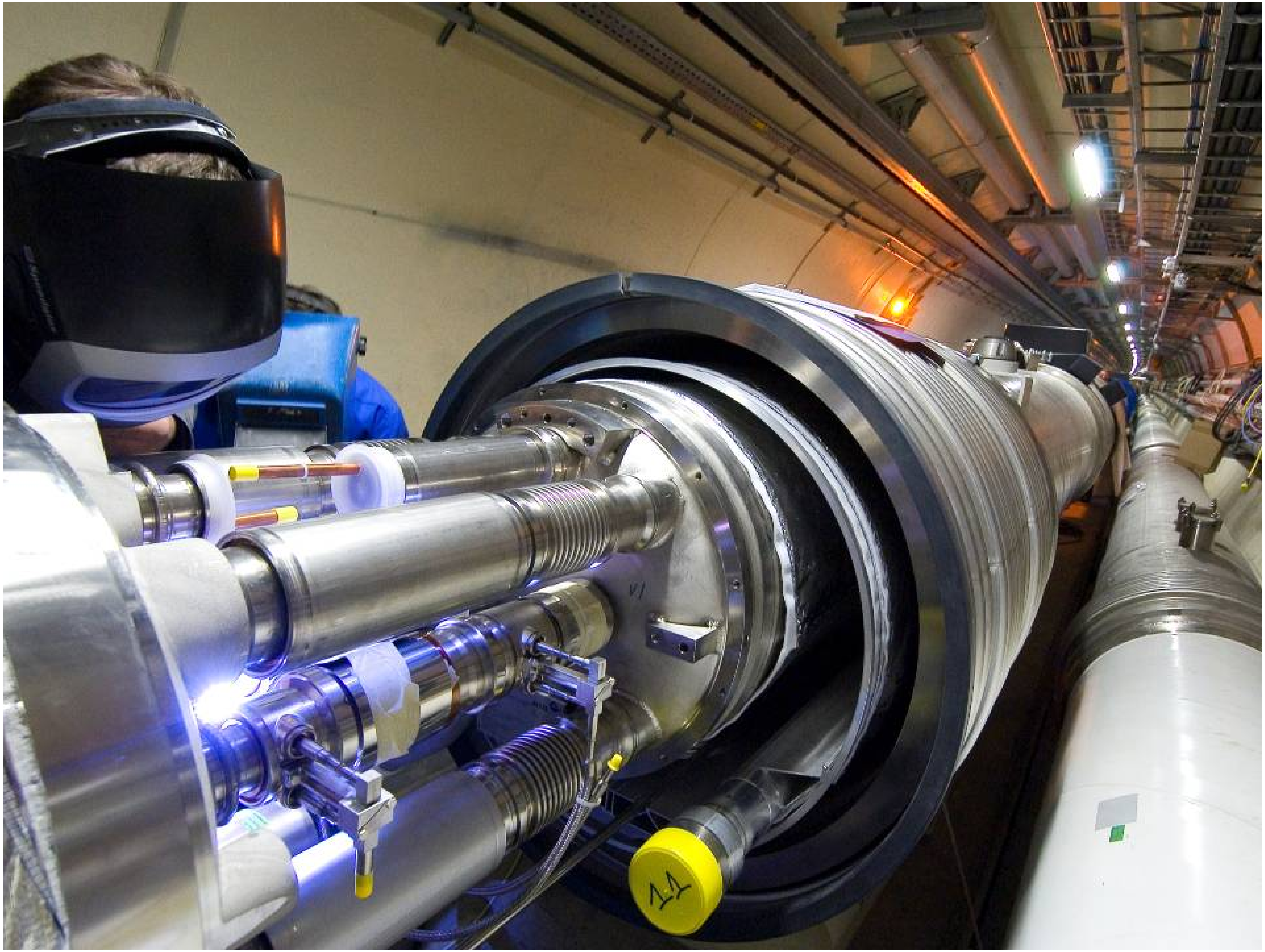
Magnet installation


Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Quadrupole
Bus Bars
Vacuum Vessel
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Instrumentation
Feed Throughs
Protection
Diode


MAF


ZTS VVU
KOSICE


D



Milestones

Last magnet delivered	October 2006
Last magnet tested	December 2006
Last magnet installed	March 2007
Machine closed	August 2007
First collisions	November 2007

Not only dipoles...

Quadrupoles, Sextupoles, ...

Current Feed Boxes (high temperature s.c.)

Cryogenic infrastructure: refigerators (4.5K, 1.8K), cryogenic distribution line (27 km)

RF station (400 MHz)

Fast ‘septum’, kicker magnets (injection, beam abort)

Collimation system (350 MJ per beam!)

Commissioning

Operation

One more picture (injection line)

Commissioning Plan

Sectors 7-8 and 8-1 will be fully commissioned up to 7 TeV in 2006-2007. If we continue to commission the other sectors up to 7 TeV, we will not get circulating beam in 2007.

The other sectors will be commissioned up to the field needed for de-Gaussing.

Initial operation will be at 900 GeV (CM) with a static machine (no ramp, no squeeze) to debug machine and detectors.

Full commissioning up to7 TeV will be done in the winter 2008 shutdown

The Large Hadron Collider – experiments

Two 'general purpose' 4π detectors are in preparation

$$\int_0^{2\pi} d\phi \int_{-1}^{1} d\cos\theta = 4\pi$$

pp collisions at high L; some capabilities for PbPb

ATLAS and CMS

One dedicated PbPb detector with some capabilities for pp

ALICE

One dedicated detector for studying B mesons (CP violation; rare decays), prolifically produced in the forward (backward) hemisphere

LHCb

$$\sigma_{b\bar{b}} \approx 500\,\mu b$$

$$gg \to b\bar{b}$$

The Large Hadron Collider – experiments

Furthermore:

precision (1%) measurement of total cross section (and more)
TOTEM (σ_{tot}~100 mb)

$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \times \frac{(dN/dt)\big|_{t=0}}{N_{el} + N_{inel}}$$

study of forward production of π^0 s
LHCf (LHC energy equivalent to 10^{17} eV beam on fixed target – cf cosmic rays)

search for magnetic monopoles
Moedal

Experimental Challenge

High Interaction Rate: *$N = L\sigma = 10^{34} \times 100 \times 10^{-27}$*

pp interaction rate   10⁹ interactions/s
data for only ~100 out of the 40 million crossings can be recorded per sec (100 – 150 MB/sec)
need fast, pipelined, intelligent electronics and sophisticated data-acquisition

High Energy and Large Particle Multiplicity

~ <20> superposed events in each crossing
~ 1000 tracks stream into the detector every 25 ns
need highly granular detectors with good time resolution for low occupancy
large detectors, a large number of channels

High Radiation Levels

radiation hard (tolerant) detectors and electronics

Physics Requirements

Follow from requirements to observe Higgs boson whether it is heavy or light, to observe Supersymmetry if it is there (missing energy), to find other new physics if it is there; all this in the presence of a huge background of standard processes (QCD)

Very good muon identification and momentum measurement
trigger efficiently and measure charge of a few TeV muons

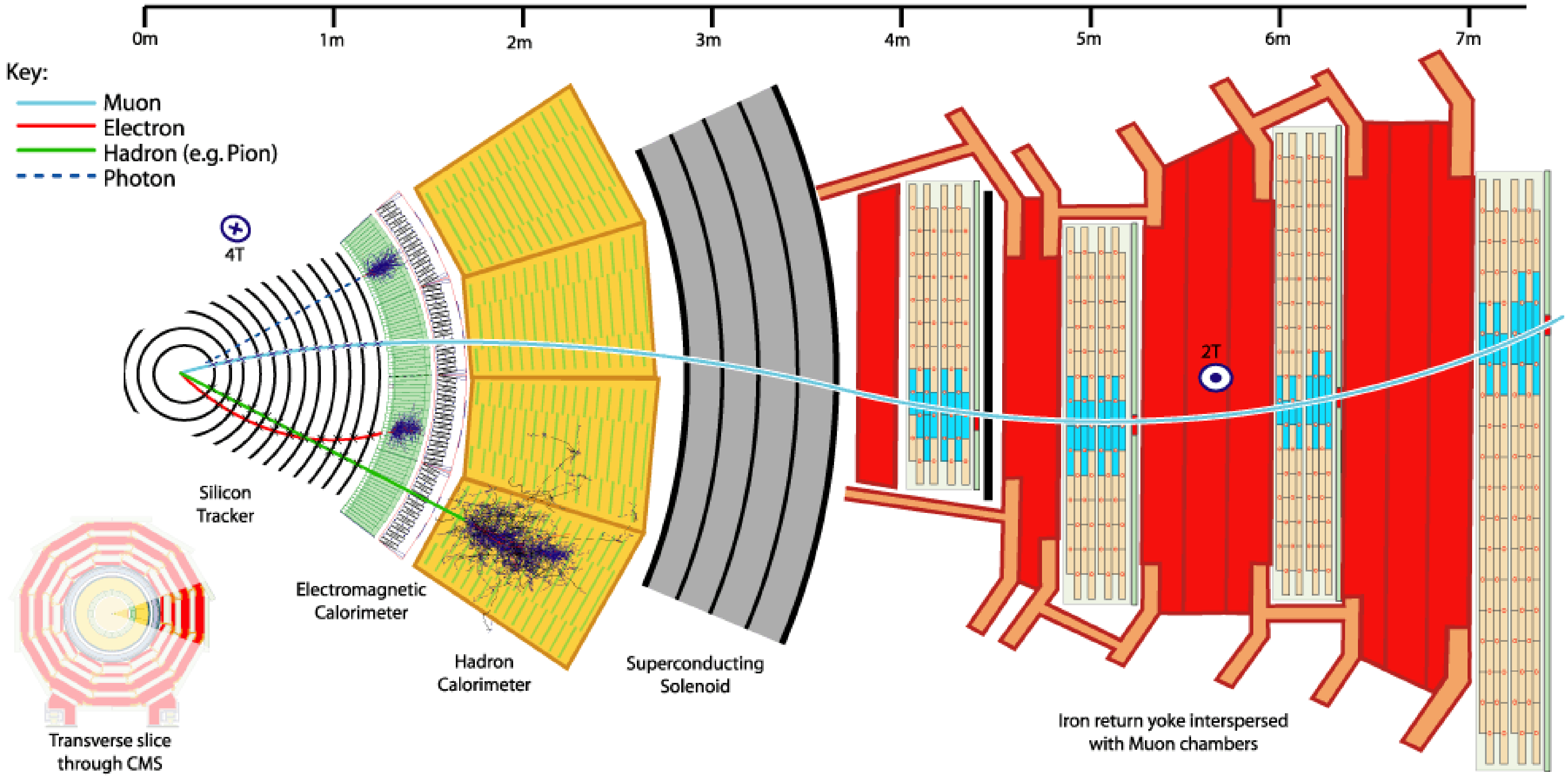
High energy resolution electromagnetic calorimertry
~ 0.5% @ E_T~50 GeV

Powerful inner tracking systems
factor 10 better momentum resolution than at LEP

Hermetic calorimetry
good missing E_T resolution

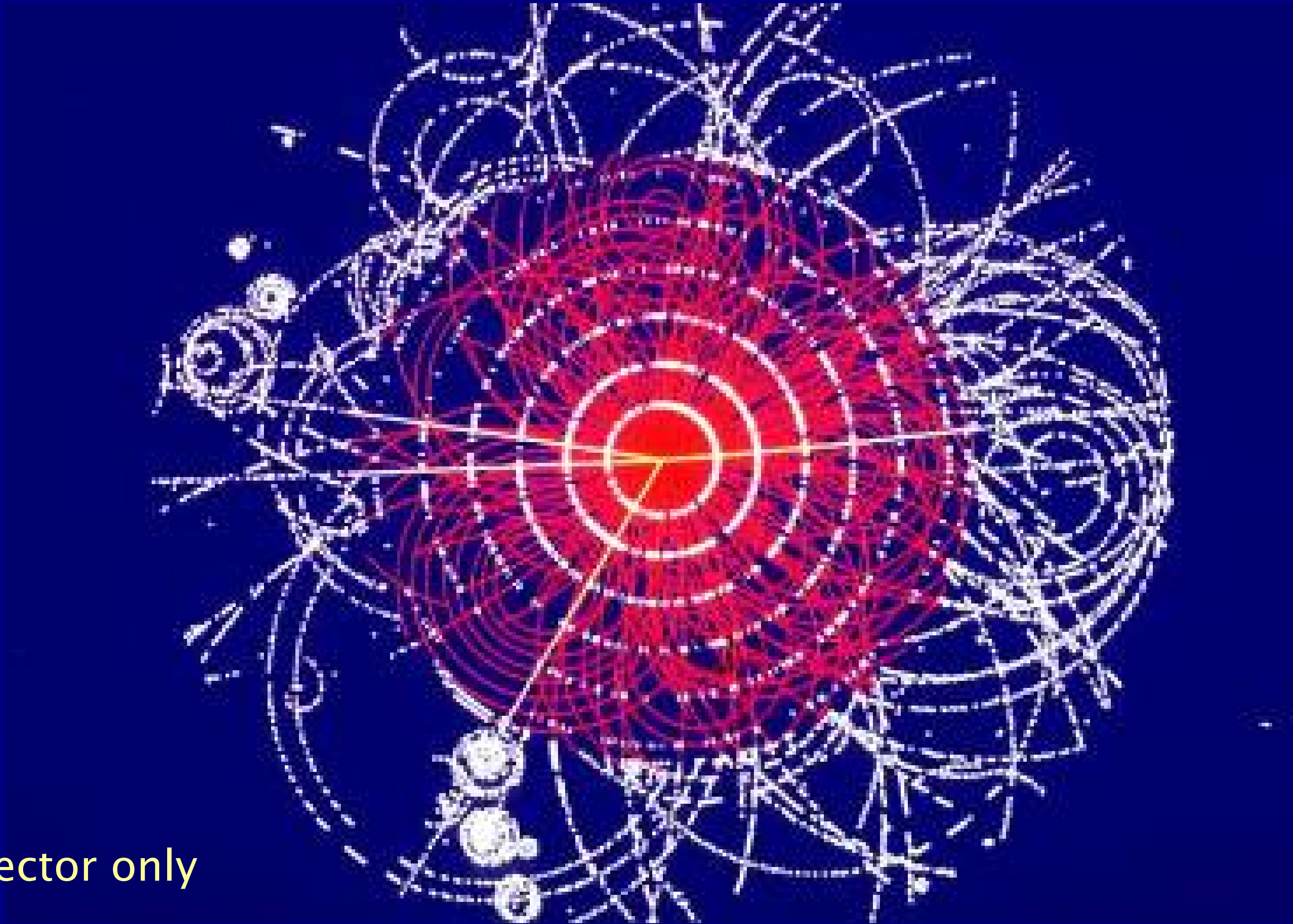
(Affordable detector)

‘Generic’ experimental set-up



Deflection ~ BL^2/p → need high B (s.c.) and large magnets; need high resolution position measurements (10 100μ) at large p; also energy and position measurement thru total absorption (photon, electron, hadron)

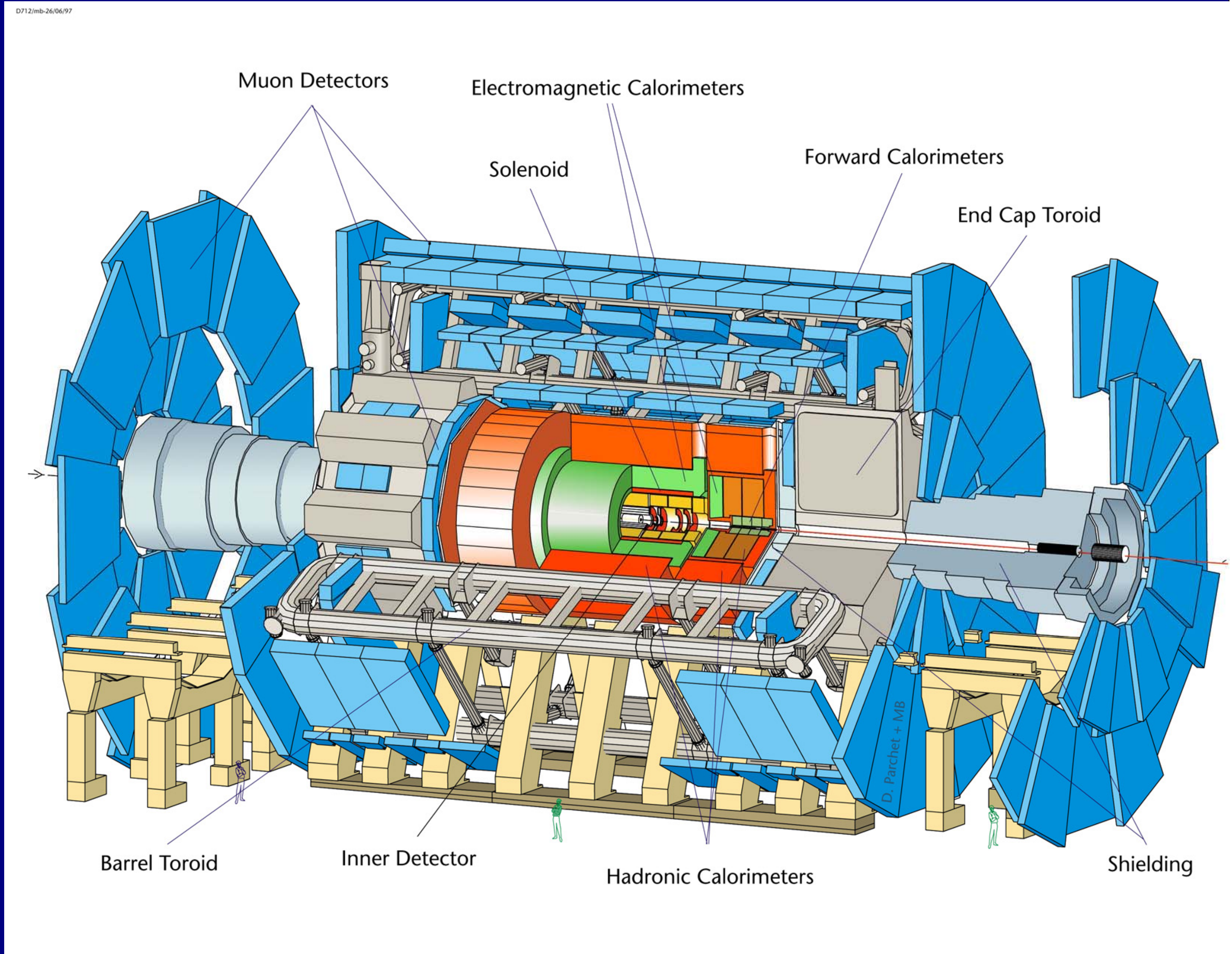
Particles produced in one bunch crossing, beams into screen.
Computer simulation (ATLAS); red = generated, white = digitized
'Higgs' tracks highlighted (also white, sorry)



Inner detector only

The ATLAS Detector

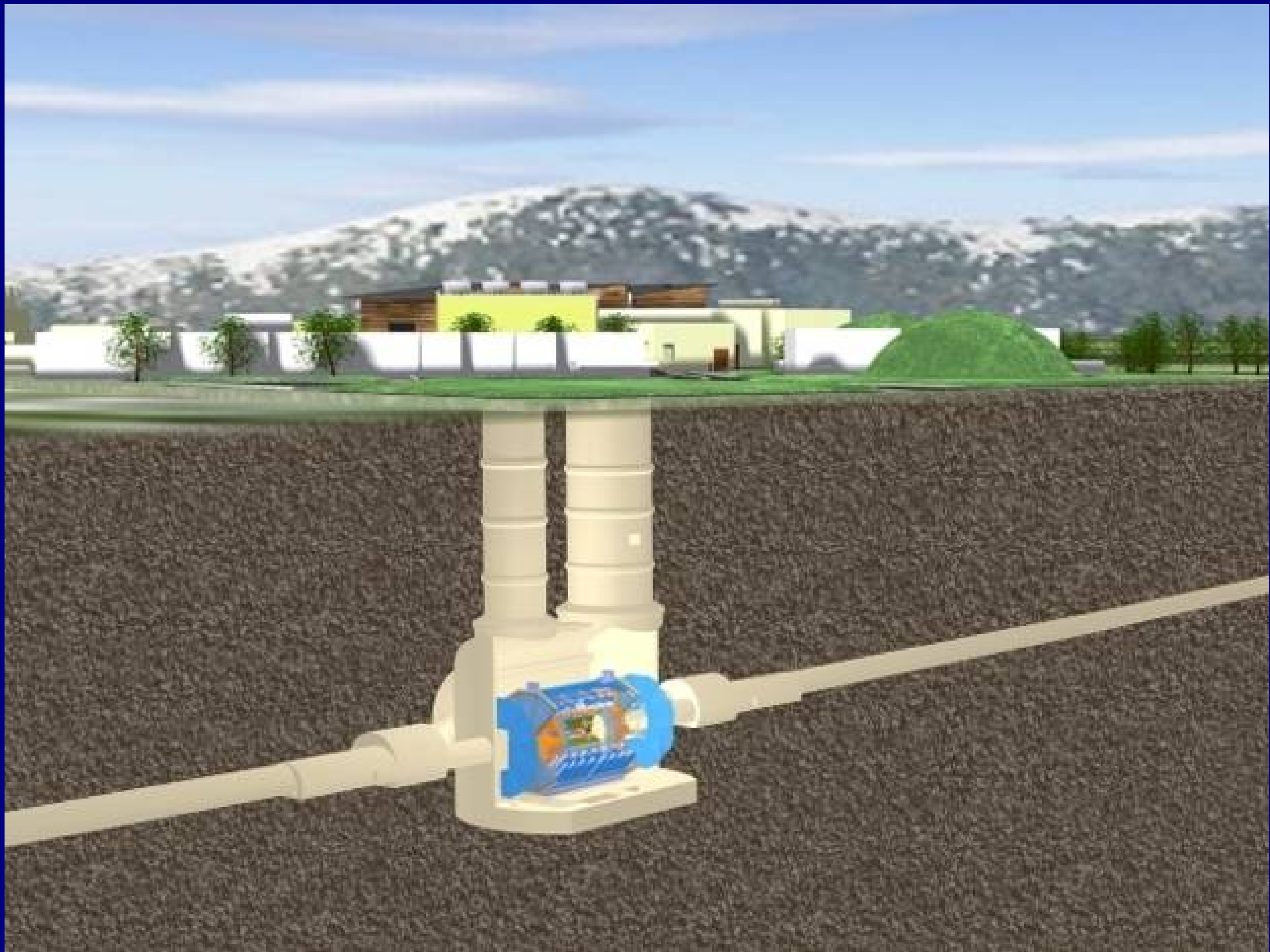
A Toroidal LHC ApparatuS



Diameter 25m
Barrel toroid 26m
End-end 46m
Weight 7000 tons

10^8 electronic channels

The Underground Cavern at Pit-1 for the ATLAS Detector

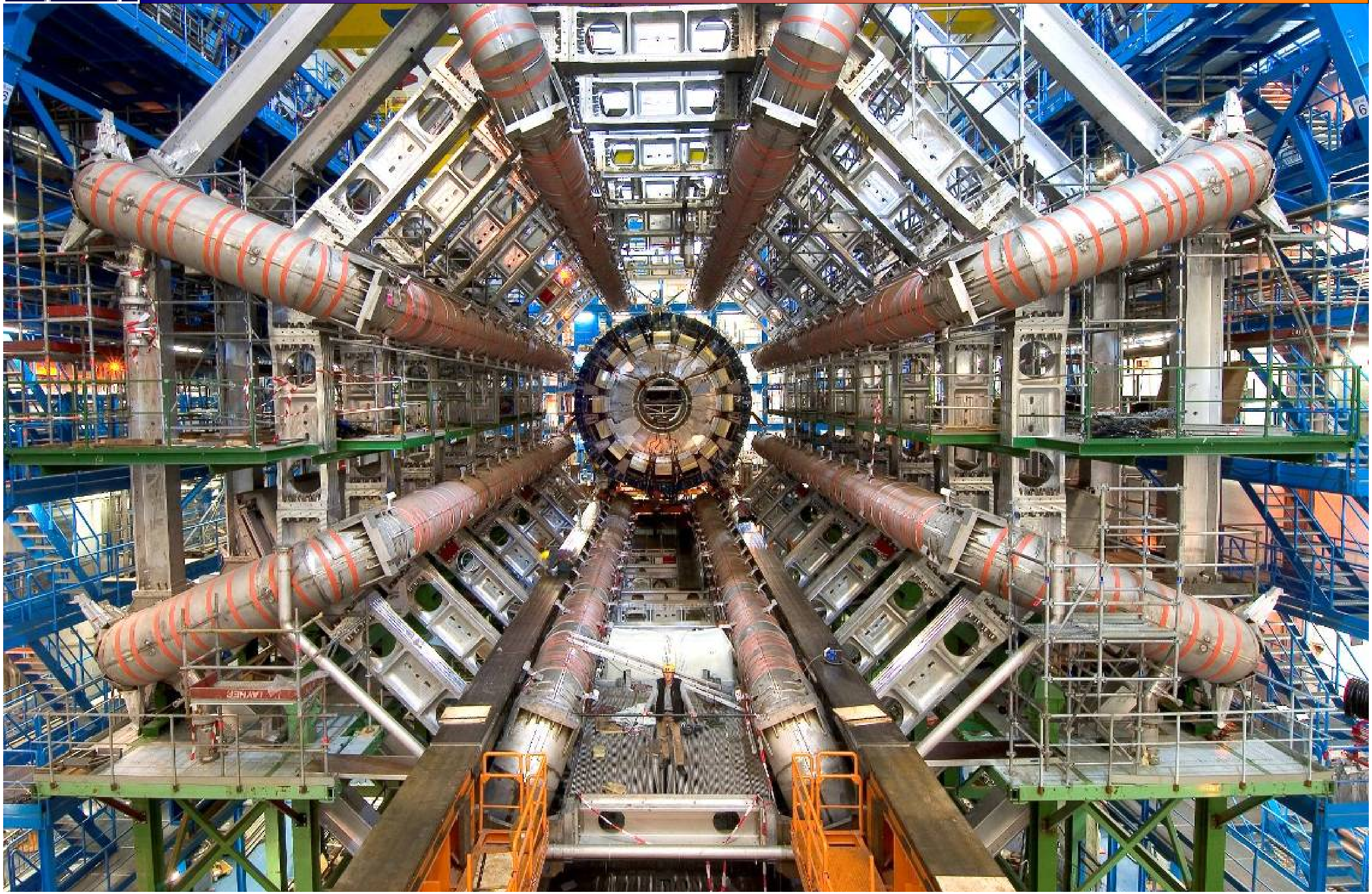


Length = 55 m
Width = 32 m
Height = 35 m

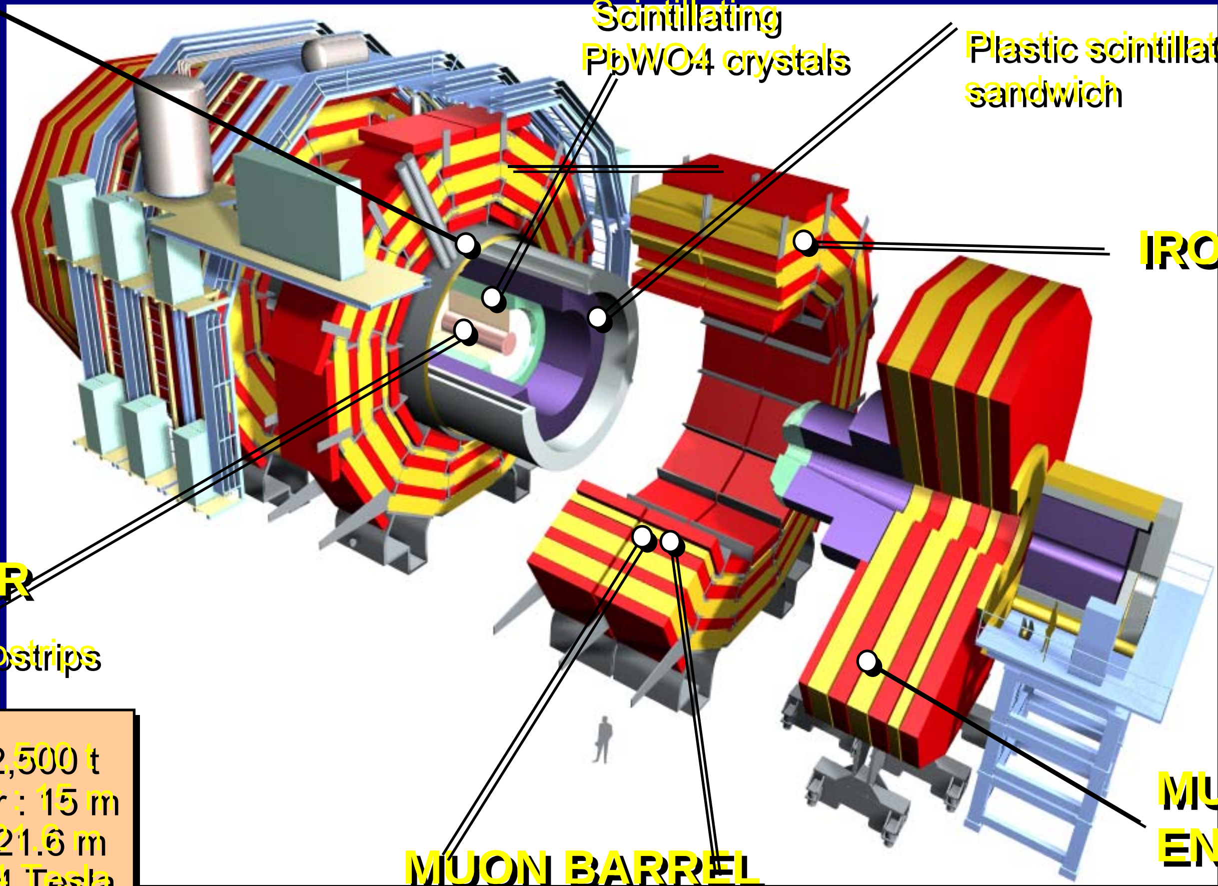
An Aerial View of Point-1

Across the street from the CERN main entrance

ATLAS, still open (a year ago)



The CMS Detector



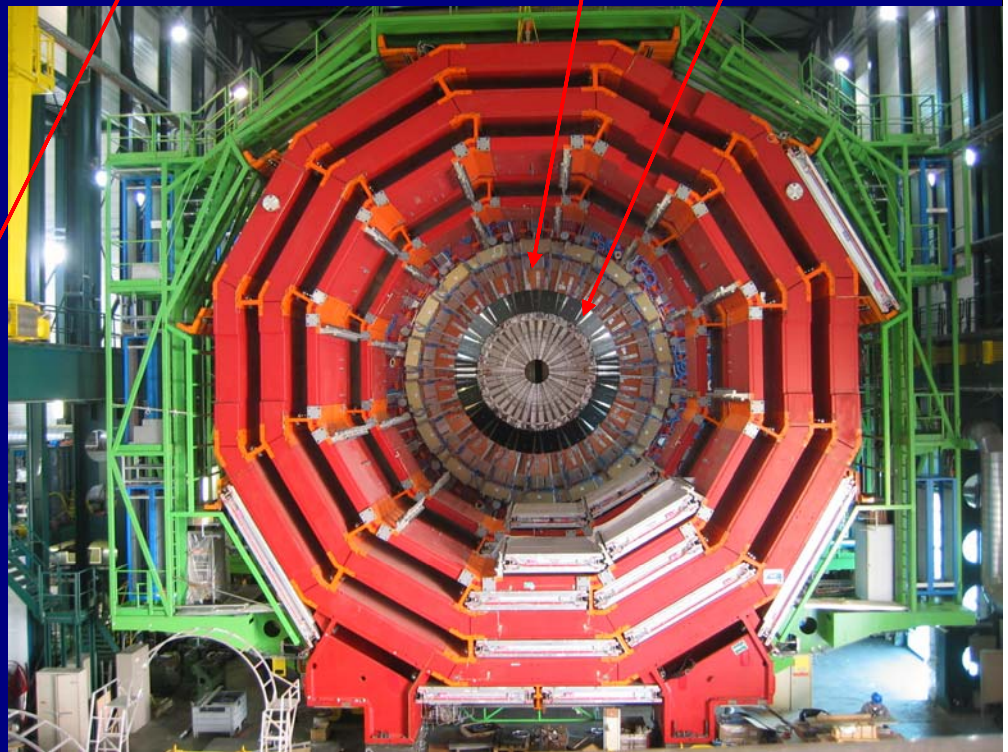
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

CMS assembly

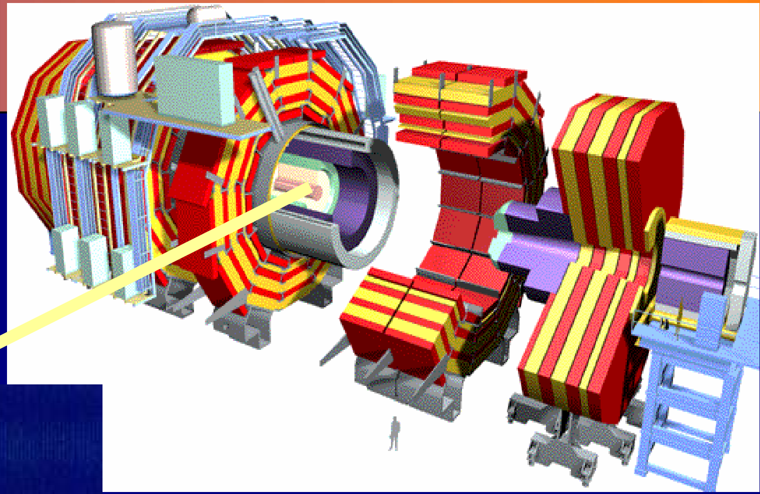
Magnet Test and Detector Test - Jul-Aug06

Solenoid is cold
HB inserted in coil
2 ECAL SM
Tracker Components
DT + RPCs

HCAL Endcap
CSCs



LHC Data; computing



This is reduced by online computers that filter out a few hundred "good" events per sec.

To be organised, distributed and analysed worldwide

Which are recorded on disk and magnetic tape at > 100 MegaBytes/sec

→ ~15 PetaBytes per year for all experiments

The GRID

CERN can only provide ~20% of the required computing capacity

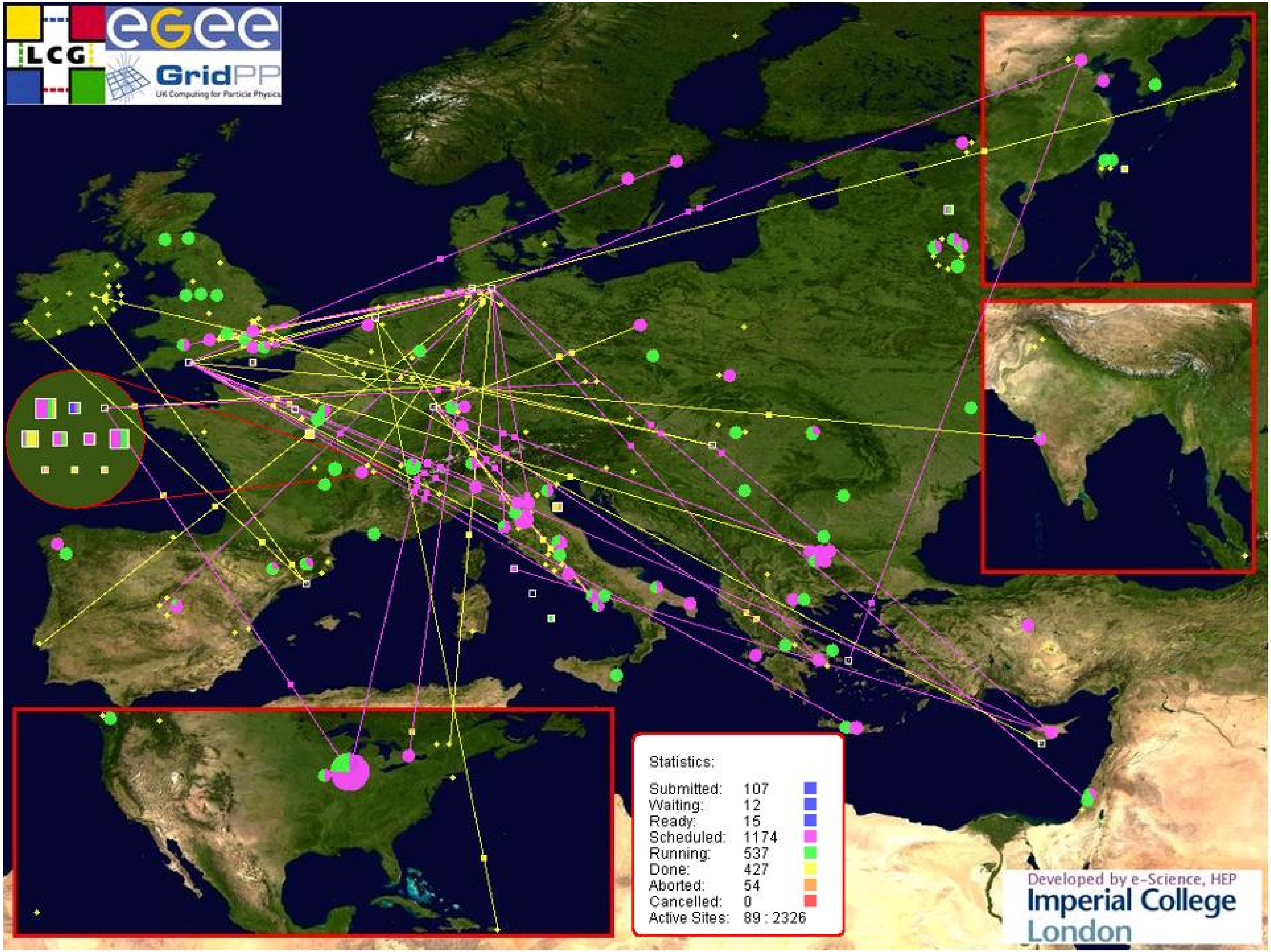
Therefore, the LHC relies on many computing centres around the world interconnected using Grid technology

CERN leads two major global Grid projects:

- **WLCG**: World-wide LHC Computing Grid Collaboration
- **EGEE**: Enabling Grid for E-sciencE project for all sciences

The LHC Computing Grid project launched a service with 12 sites in 2003. Today 200 sites in 40 countries with 20,000 PCs

WLCG depends also on OSG and other Grid projects


eGee
LCG
GridPP
UK Computing for Particle Physics
Statistics:
Submitted: 107
Waiting: 12
Ready: 15
Scheduled: 1174
Running: 537
Done: 427
Aborted: 54
Cancelled: 0
Active Sites: 89 : 2326
Developed by e-Science, HEP
Imperial College
London

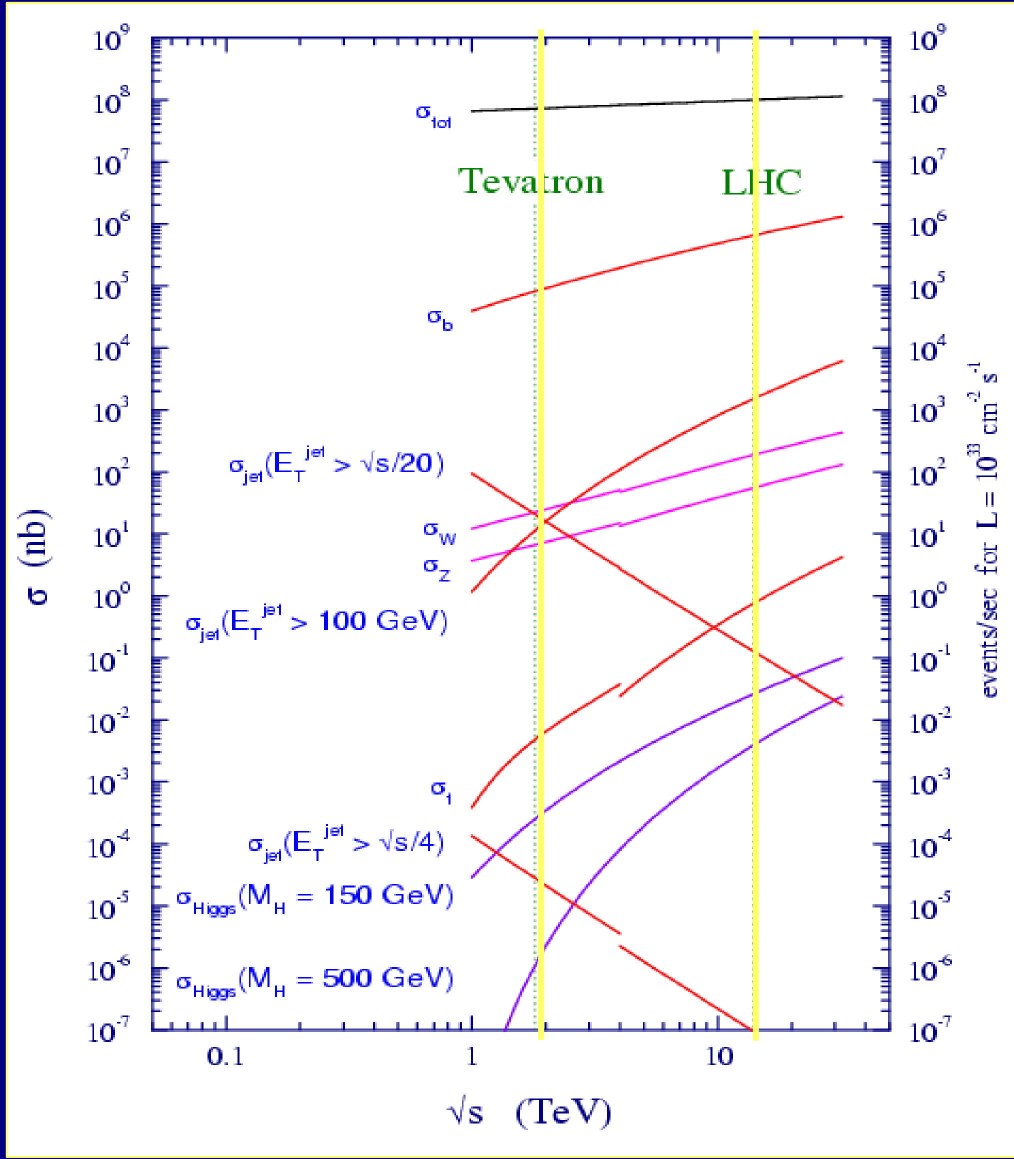
Physics in first year(s)

Expected event rates at production in ATLAS or CMS at $L = 10^{33}\ cm^{-2}\ s^{-1}$

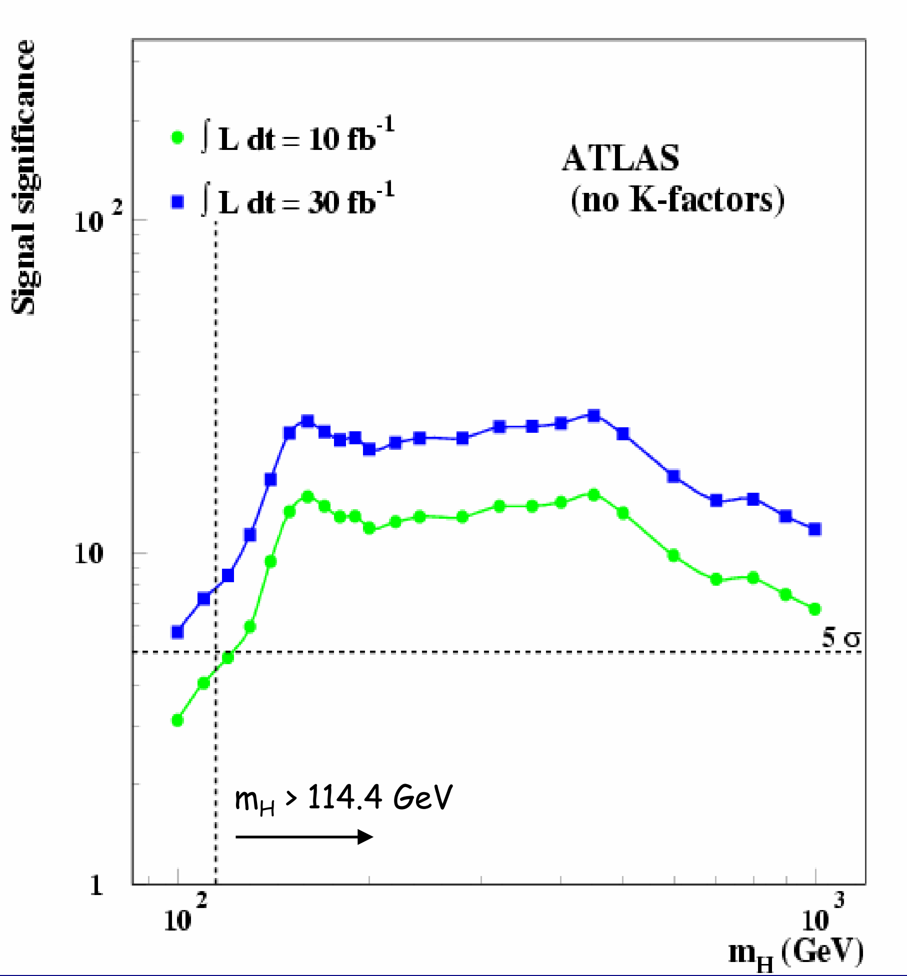
Process	Events/s	Events for 10 fb^{-1}	Total statistics collected at previous machines by 2007
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
t tbar	1	10^7	10^4 Tevatron
b bbar	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar
H m=130 GeV	0.02	10^5	?
gluino gluino m= 1 TeV	0.001	10^4	---
Black holes m > 3 TeV (M_D=3 TeV, n=4)	0.0001	10^3	---

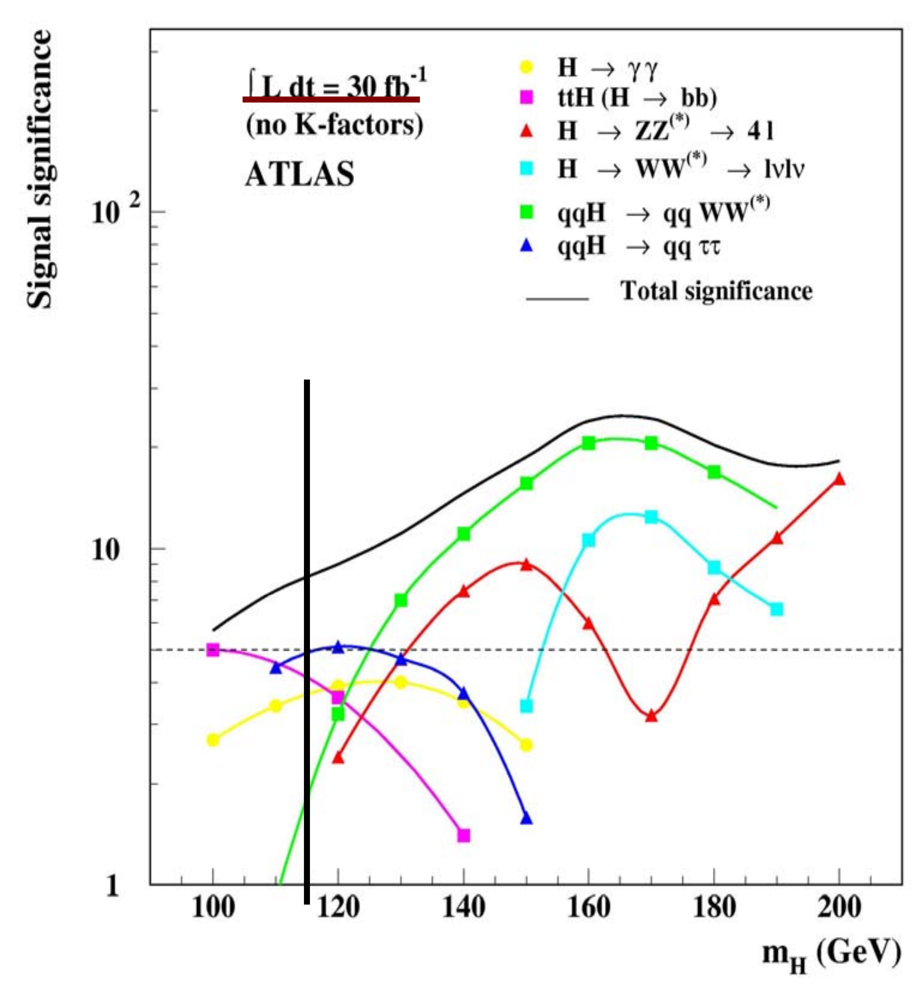
Already in first year, large statistics expected from:
-- known SM processes $\to$ understand detector and physics at $\sqrt{s}$ = 14 TeV
-- several New Physics scenarios

Large background from QCD processes



Standard Model Higgs





and more,

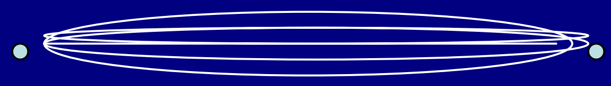
extensive Monte Carlo studies have been performed,

very soon ‘real data’ at the Terascale

will be available and we will take the ‘next step’,

a crucial step, in high energy physics!

Constant field in a hypothetical one dimensional world



That same hypothetical world with one extra dimension in which the field can spread: at distances from the source comparable to the size of the extra dimension or smaller, the field increases rapidly