The Large Hadron Collider

Project at CERN

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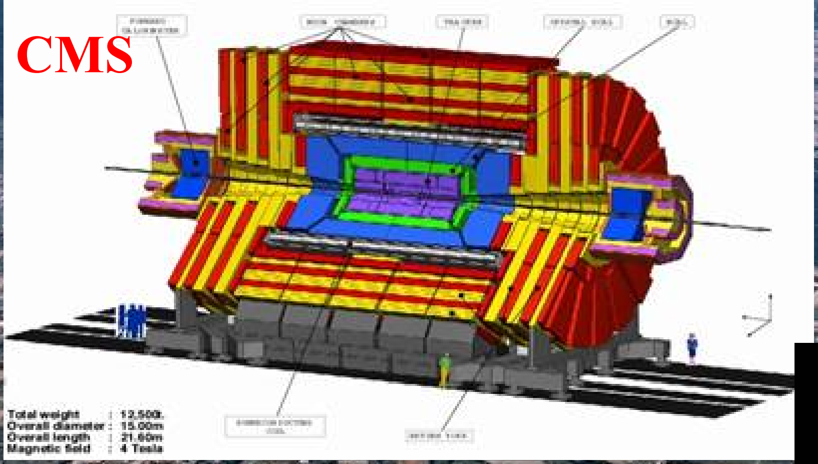
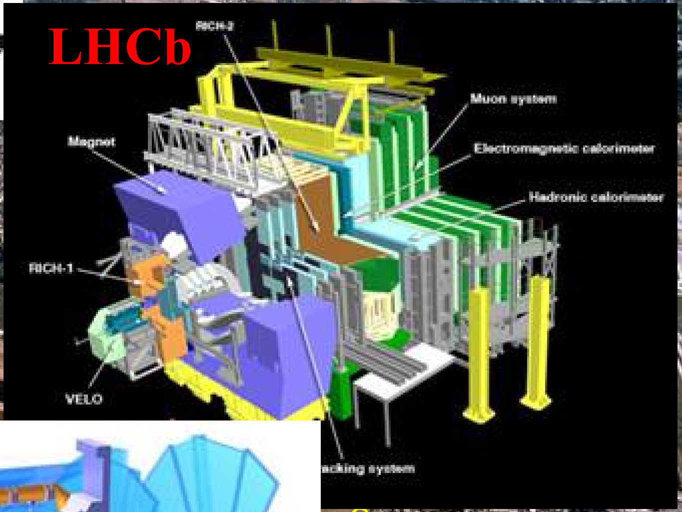
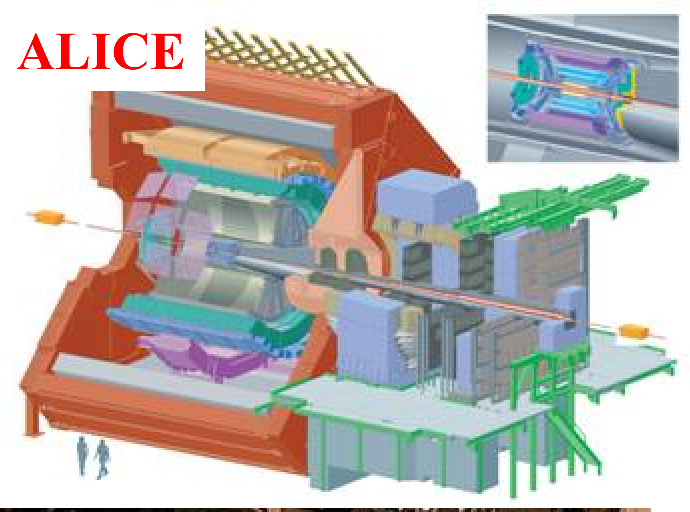
Outline

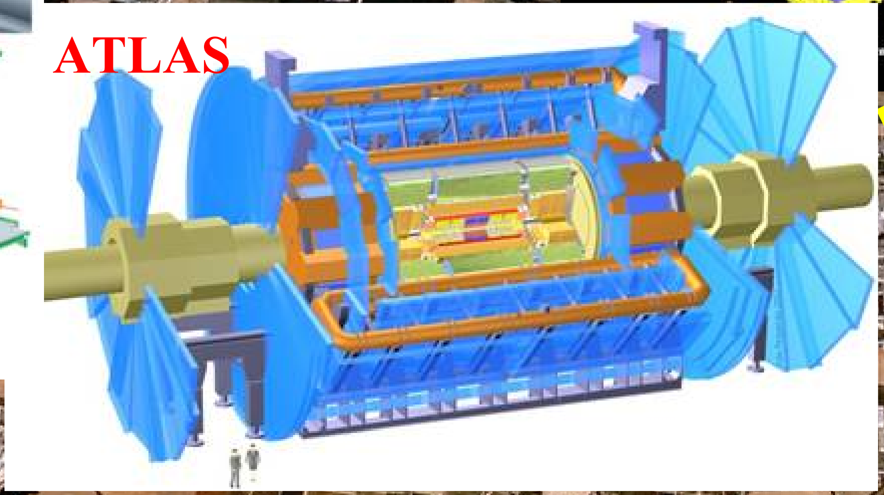
- **What?** Introduction
- **Why?** Physics Motivation
- **How?** Technological Challenges
- **Where are we today?** Status and Expectations

The Large Hadron Collider (LHC)









CERN

- European Organization for Nuclear Research
- Founded in 1954
- 20 European Member States
- Located close to Geneva across the franco-swiss border
- Largest particle physics laboratory world-wide

The Large Hadron Collider (LHC)

LHC time table:

- Early 1980‘s: first ideas about a multi-TeV proton collider at CERN
- Oct 1990: ECFA workshop on LHC in Aachen
- 16 Dec 1994: CERN council approves the LHC
- Feb 1996: approval of ATLAS and CMS
- Apr 1998: start civil engineering
- 7 Mar 2005: first dipole magnet installed
- 26 Apr 2007: last dipole installed
- 10 Sep 2008: first circulating beams
- Oct 2009: first pp-collisions expected

The Large Hadron Collider (LHC)

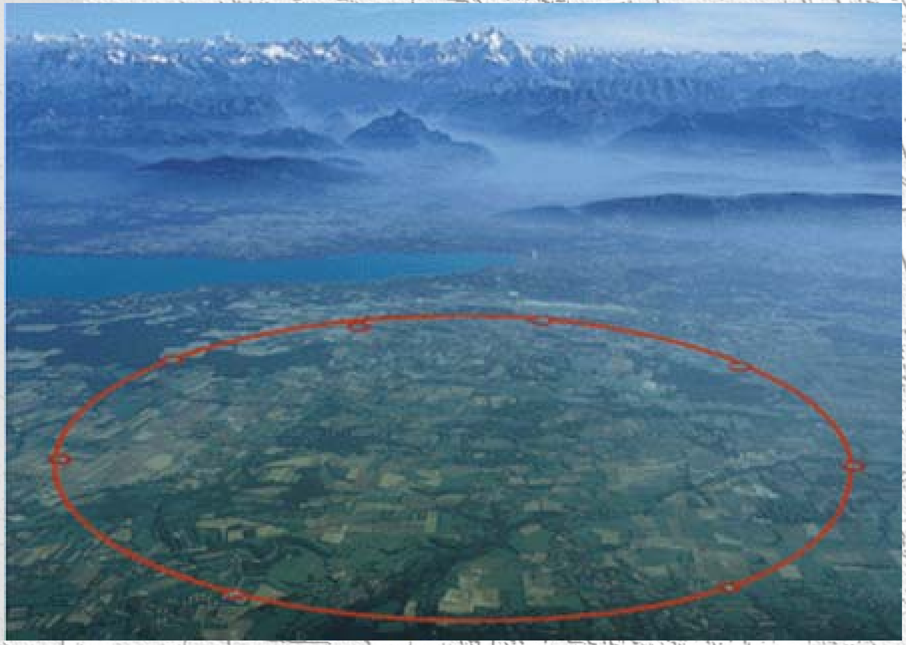
- Proton-proton collider in the former LEP tunnel
- Highest ever energy per collission

  14 TeV in the pp-system

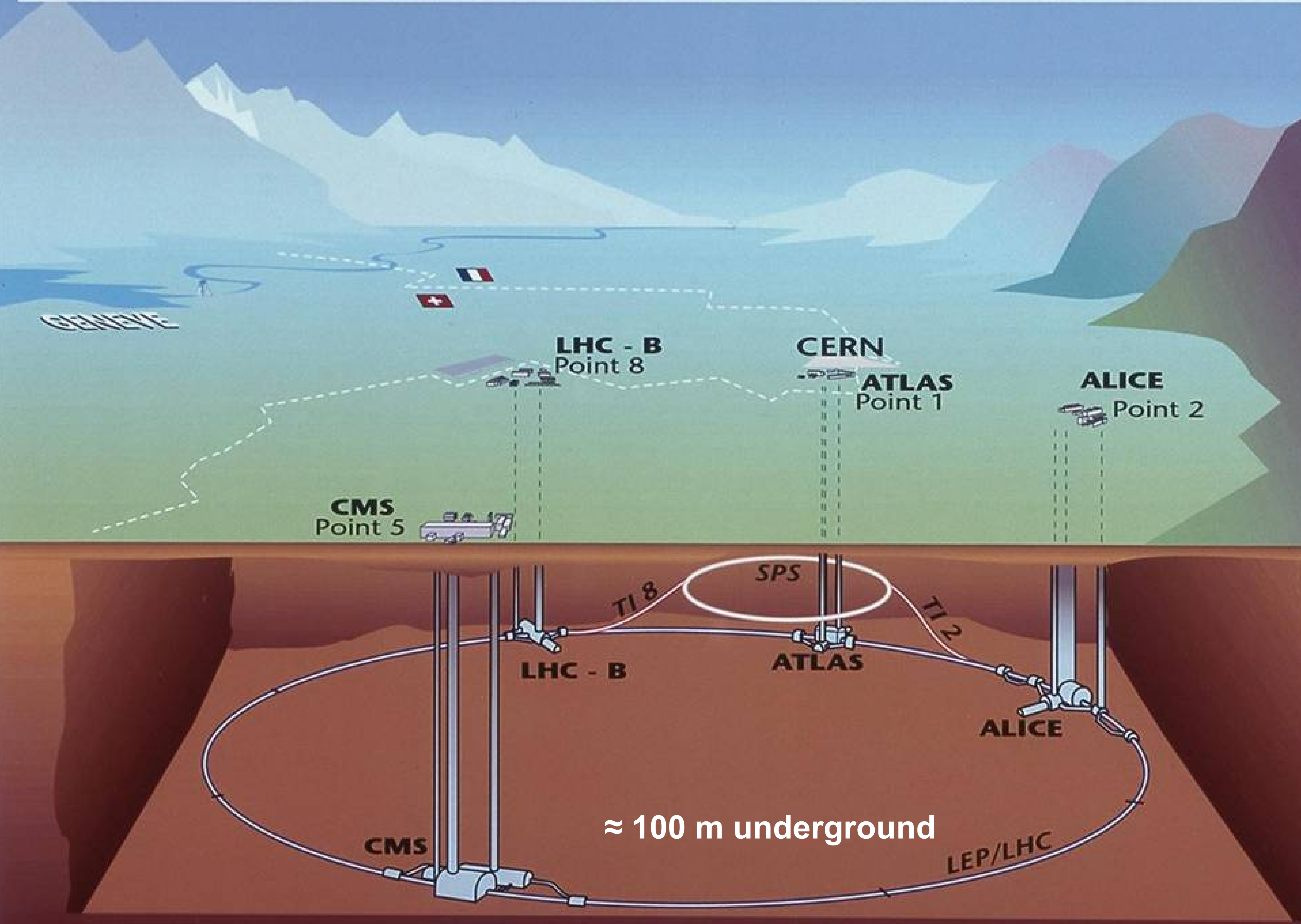
  cf. Tevatron at 2 TeV
- High luminosity (rate of pp-interaction)

  up to $10^{34}/cm^2/s$
- Conditions as 10^{-13} – 10^{-14} s after the Big Bang
- 4 experiments:
  - ATLAS
  - CMS
  - LHCb specialised on b-physics
  - ALICE specialised for heavy ion collisions
- LHC and experiments were constructed in global collaborations

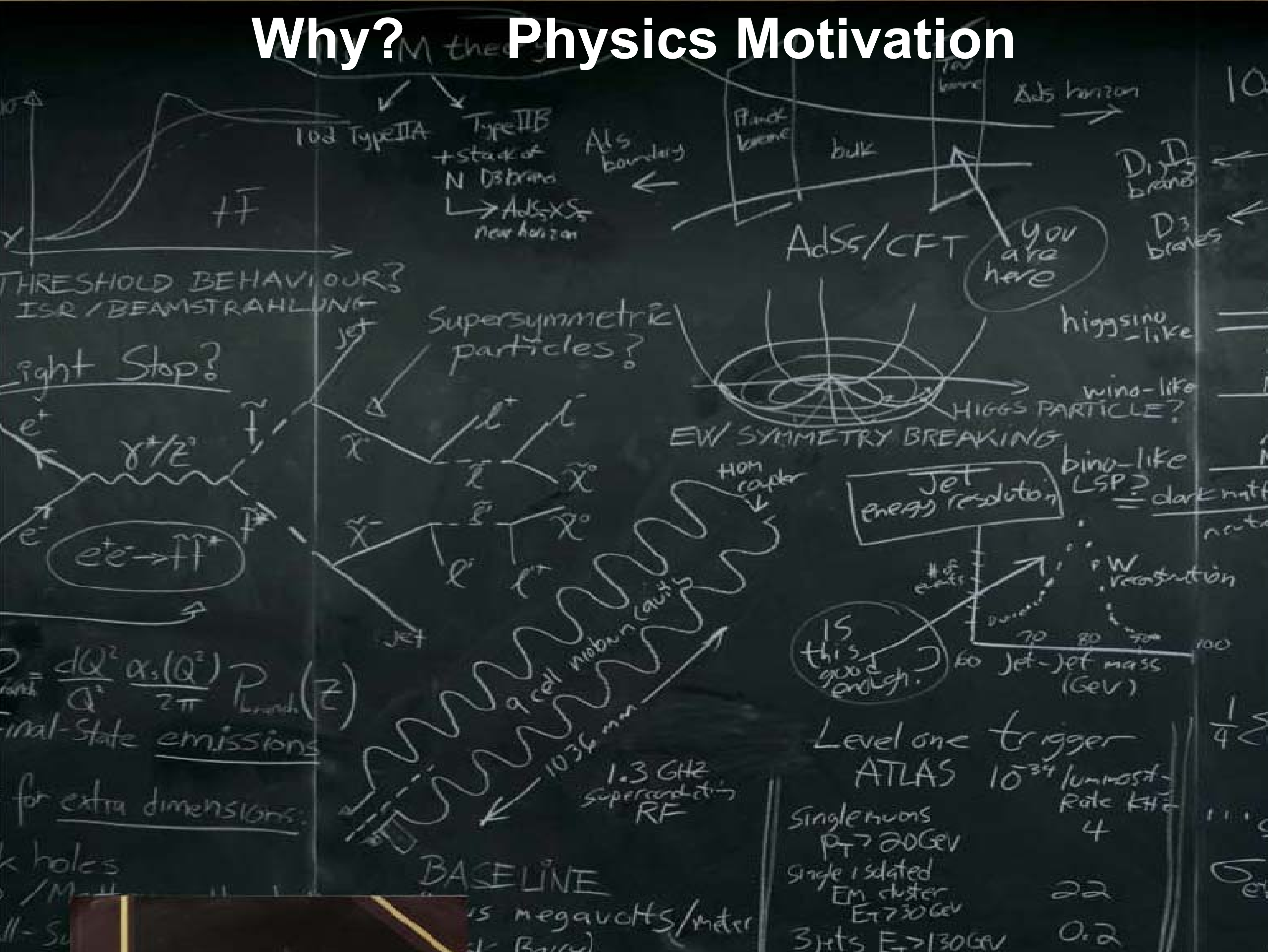
1 000 eV	= 1 keV
1 000 000 eV	= 1 MeV
1 000 000 000 eV	= 1 GeV
1 000 000 000 000 eV	= 1 TeV



Overall view of the LHC experiments.



Why? Physics Motivation



Theoretical Particle Physics

- **Relativity**
  - Mass is energy and energy is mass
  - Producing heavy particles requires high energy

$$E = mc^2$$

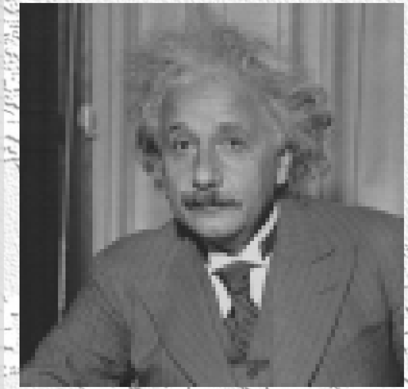
- **Quantum mechanics**
  - Particles are waves and waves are particles
  - High momentum p (or energy) means smaller wave length

$$\lambda = h/p$$

- **Uncertainty principle**
  - Position and momentum are not defined with arbitrary accuracy

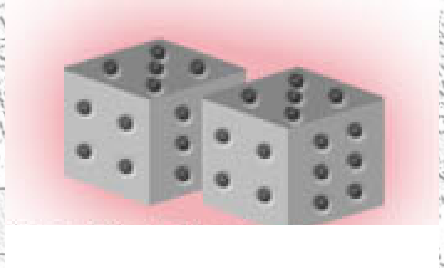
$$\Delta x \, \Delta p \approx \hbar$$

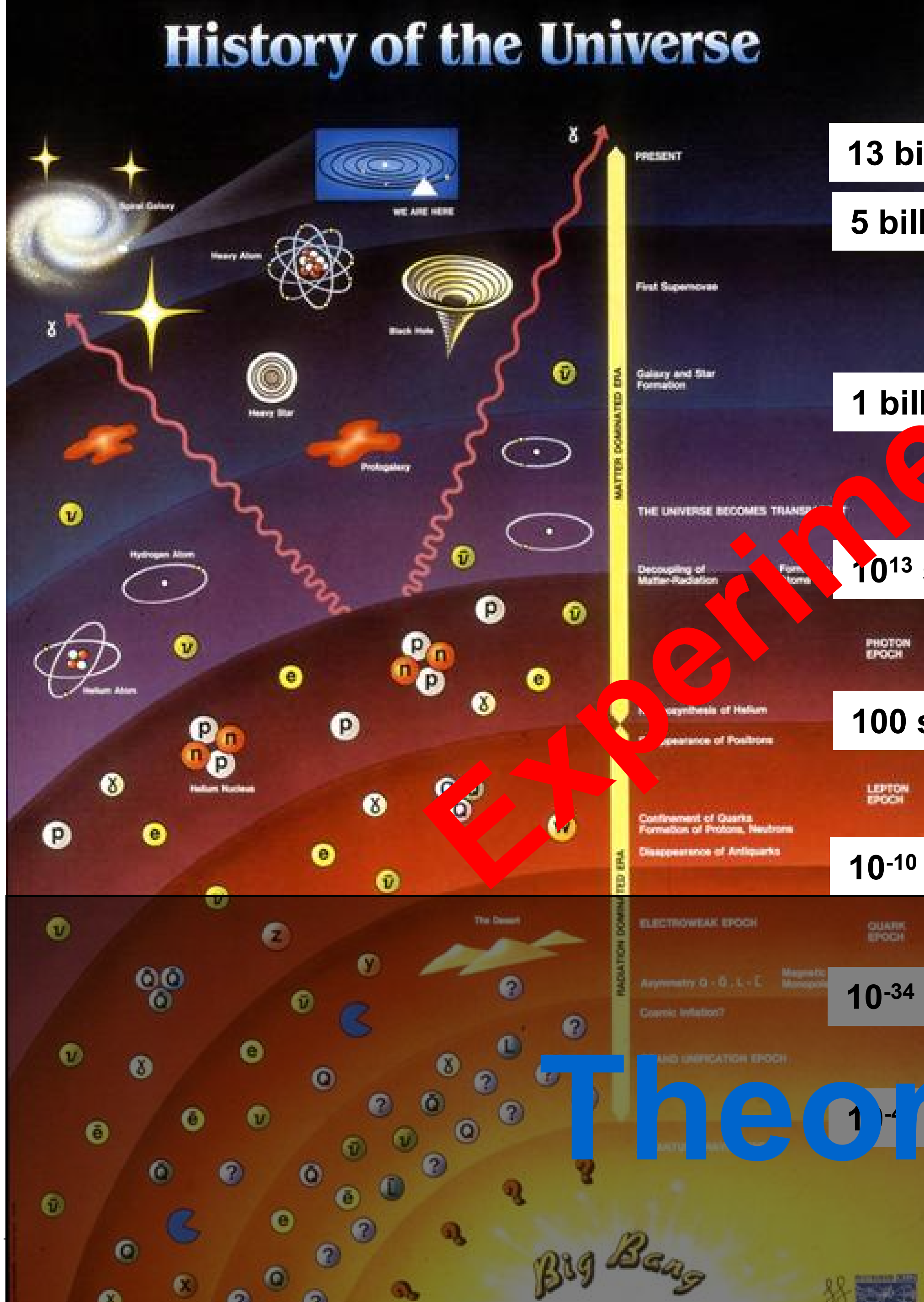
- **…and God still plays dice**
  - Elementary quantum processes are not deterministic, only probabilites are calculable
  - Experiments must be repeated frequently


Albert Einstein

M. Planck

W. Heisenberg





Time

Energy

13 billion years

5 billion years

First supernovae

Galaxy and star formation

1 billion years

Transparent universe

10^{13} seconds — Formation of atoms

100 seconds — Nucleosynthesis of Helium

Disappearance of positrons

10^{-10} seconds — Formation of protons and neutrons

Disappearance of antiquarks

10^{-34} seconds

Cosmic inflation?

10^{-43} seconds

Quantum gravity epoch

Experiment

Theory

Standard Model of Particle Physics

- All known matter consists of four fundamental particle (fermions)

I.

		Charge	Spin
Leptons	ν_e neu...	0	½
	e^- ele...		
Quarks	u up...		
	d do...		

II.

Leptons	ν_μ muon-neutrino	0	½
	μ^- mu...		
Quarks	c ch...		
	s str...		

III.

		Charge	Spin
Leptons	ν_τ tau-neutrino	0	½
	τ^- tau	–1	½
Quarks	t top-quark	+2/3	½
	b bottom-quark	–1/3	½

- There exist 2 copies of each fermion (called generations or families)
  - Identical, except for the mass
- Antimatter:
  - Each fermion has a partner with opposite charge
    e.g. the positron (e^+) is the antiparticle of the electron (e^-)

Standard Model of Particle Physics

Fundamental Interactions (forces):

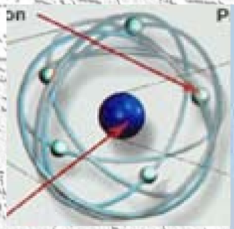
1) Gravitation

$$F = G\frac{mM}{r^2}$$

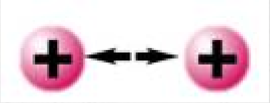
- Elementary particles: too weak, not part of the Standard Model

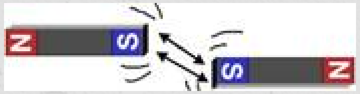
2) Electromagnetic Interactions

$$F = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{r^2}$$

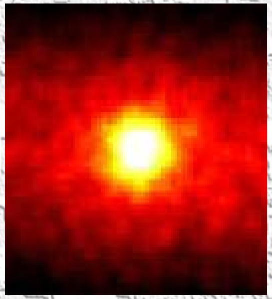


- Electrostatic Magnetism



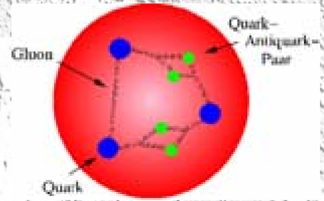


- Bind electrons and nuclei to atoms and atoms to molecules



3) Weak Interactions

- Important in certain nuclear and particle reactions, e.g. neutron decay $n \rightarrow p\, e^- \nu_e$

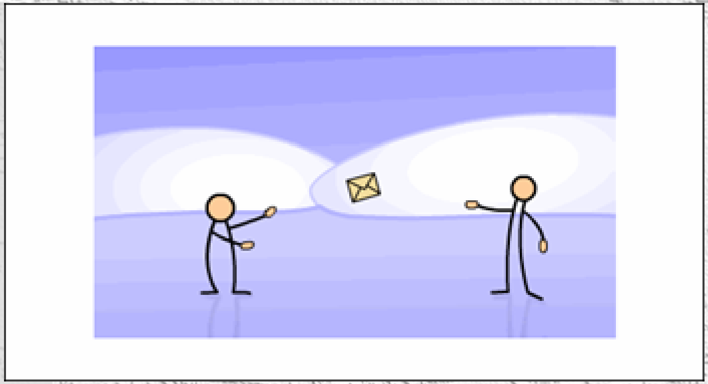


4) Strong Interactions

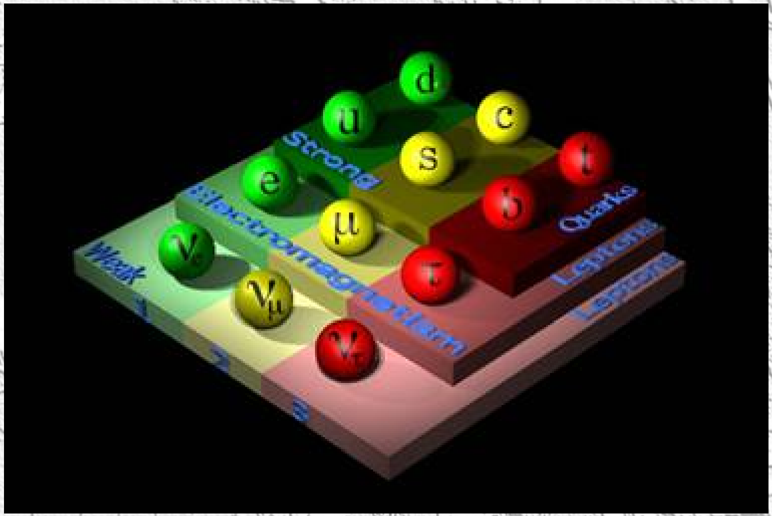
- Bind quarks in protons and neutrons

Standard Model of Particle Physics

- **Fundamental Interactions are mediated by the exchange of particles**
  - **Spin 1, therefore called bosons**
- **Fundamental particles are mathematically described by symmetries**
  - **Local gauge symmetries**

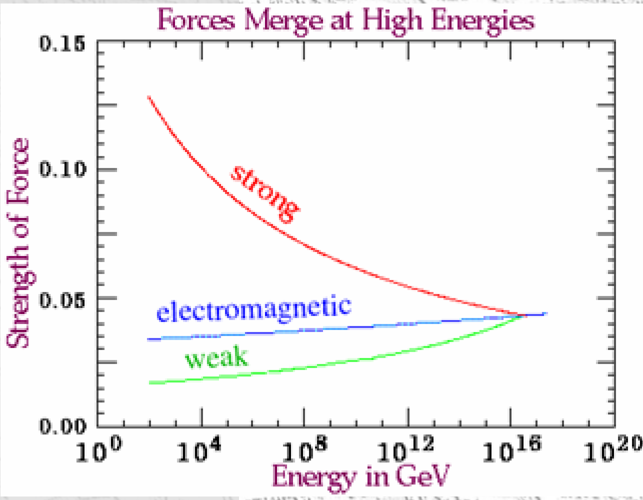


Interaction	Mediating Particle	Mass [GeV]	Symmetry Group
Gravitation	?	?	?
Electromagnetic	Photon γ	0	U(1)
Weak	$W^{\pm}$,Z Bosons	80, 91	SU(2)
Strong	Gluons g	0	SU(3)



Open Questions

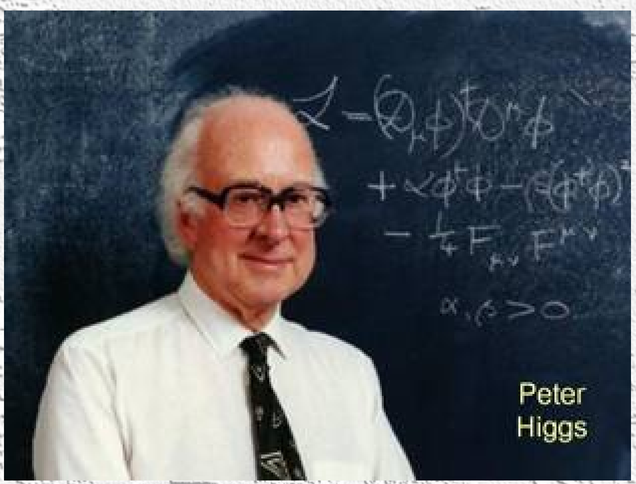
- The Standard Model is very succesful in describing phenomena up to a few 100 GeV
- But it leaves many open questions, e.g.
  - Why there are 3 copies of the fundamental fermions? Related to particle-antiparticle asymmetry in the universe?
  - What is the reason for U(1)×SU(2)×SU(3) Is there only one fundamental interaction at high energy?
  - Gravitation? At high energy 10^{19} GeV gravitation matters
  - Origin of Mass?
  - Dark Matter
  - …
- Experiments at the LHC are expected to provide some answers to these fundamental questions

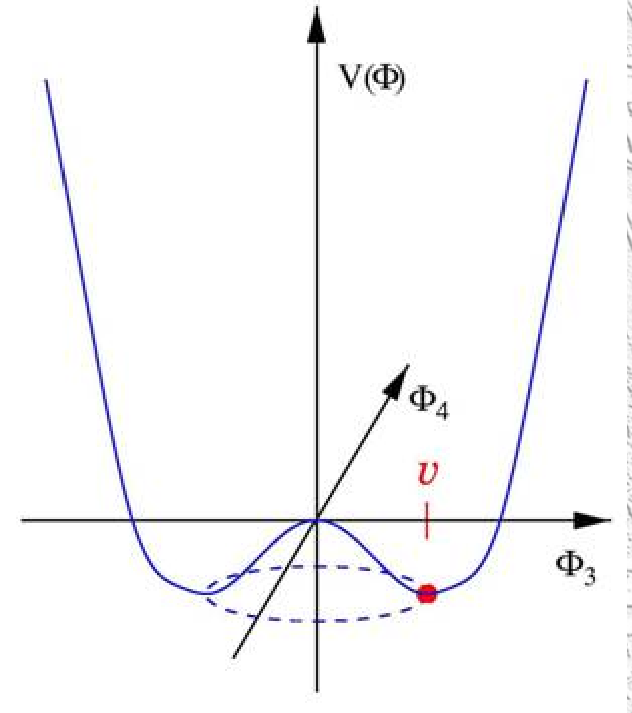


Origin of Mass: The Higgs Boson

- Concept of local gauge symmetries requires massless exchange particles
  - Uncertainty principle:
    massive exchange particle
    = limited reach of interaction
  - Ok for photon and gluons
  - Manifestly violated in case of W & Z Bosons!

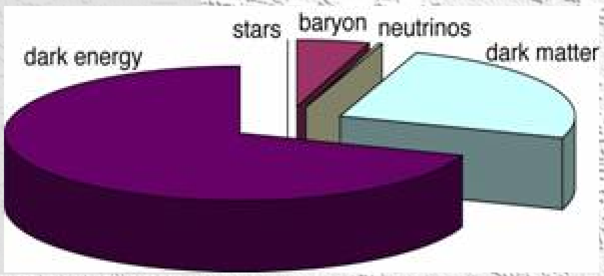
- Solution is Higgs mechanism
  - Vacuum is filled with a field
  - Gives mass to W,Z bosons and fermions
  - Requires existence of the Higgs boson
  - Important: its mass must be less than 1 TeV
    LHC will definitely decide on this issue!

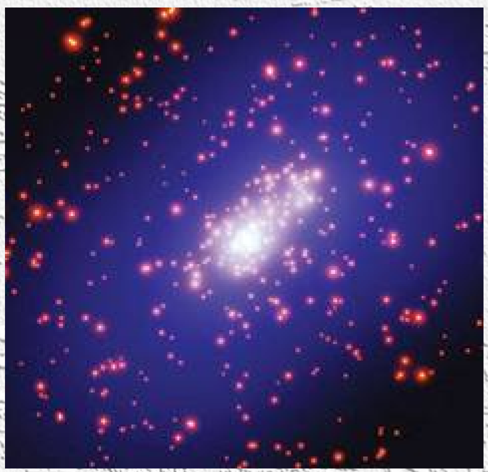




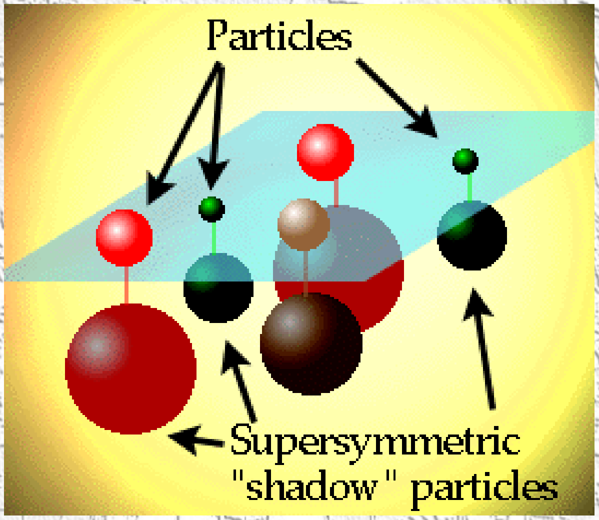
Dark Matter and Supersymmetry

- **Astronomy:**
  - Only about 5% of our universe are made of known matter!
  - ≈ 20% dark matter
  - ≈ 75% dark energy





- **Theory of Supersymmetry:**
  - Symmetry between force and matter particles
  - Predicts a mirror world of new particles (a shadow world like anti-matter)
  - Solves many of the open questions
  - Contains a particle for Dark Matter



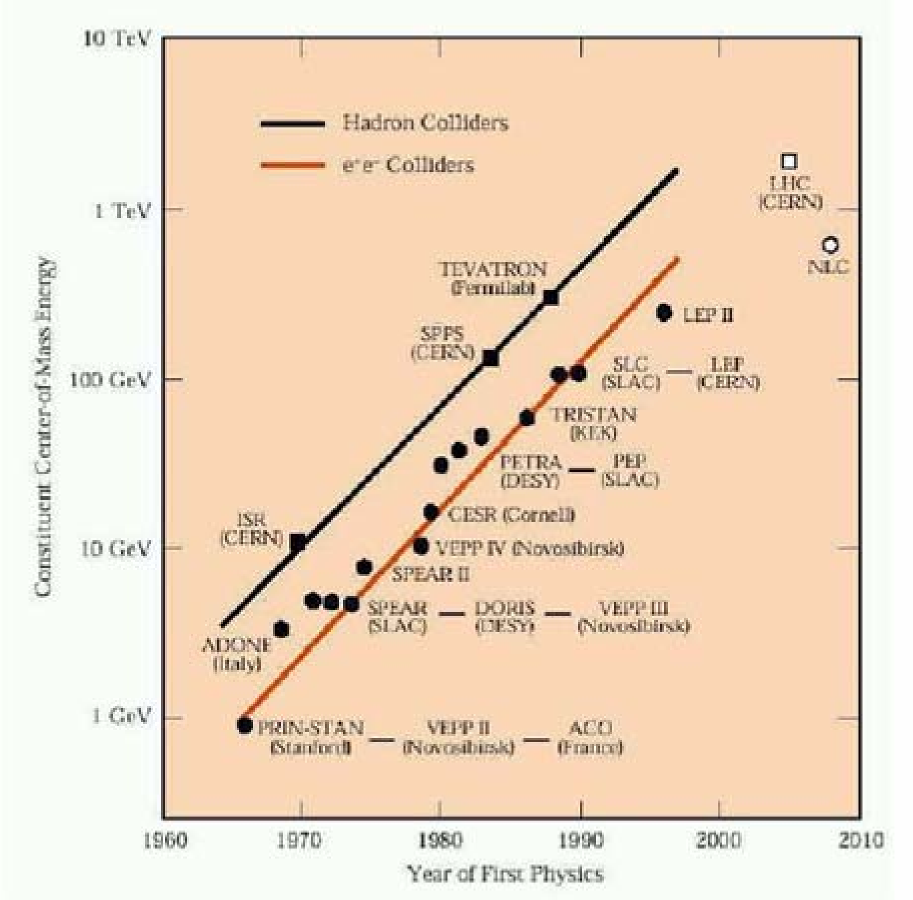
How? Technological Challenges

2000: „Concept“ of the CMS tracking detector

Sergio Cittolin

A Collider for the Terascale

- **Electron-Positron Collider**
  - **Like DORIS & PETRA at DESY or LEP at CERN**
  - **Point-like particles**
  - **But limited in energy by synchrotron radiation**
- **Proton-(anti)proton collider**
  - **Higher energy reach limited by magnet bending power**
  - **But much harder for experiments**



Challenges for the LHC: Magnets

- Superconducting dipole magnets to keep 7 TeV protons on a circular path (r ≈ 3 km)

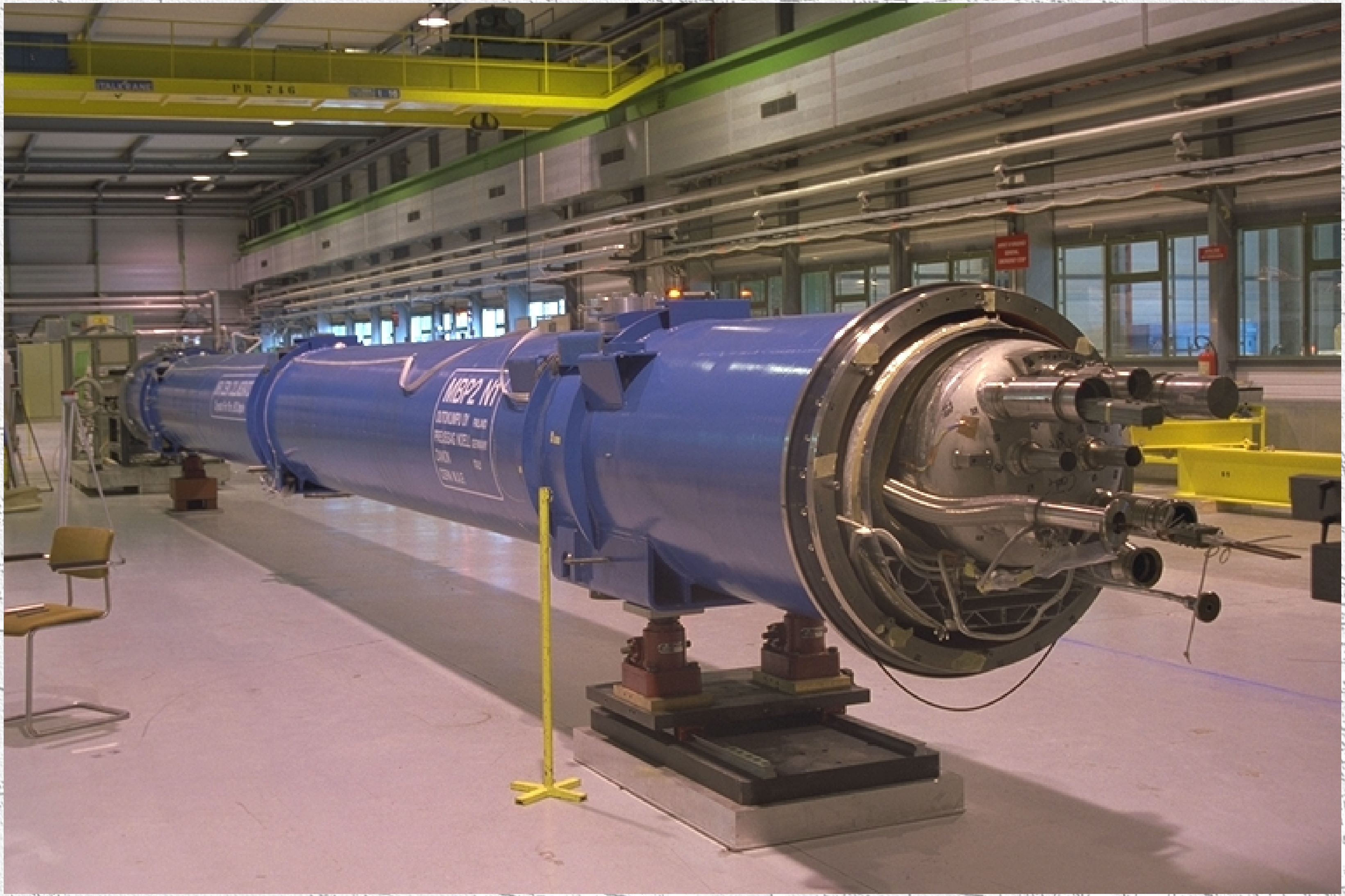
  |B| = 8.33 Tesla

- 1232 dipole magnets needed each is 15 m long (+ quadrupoles, sextupoles, etc.)
  - 1.9 K operating temperature
  - Supraliquid Helium
  - Largest cryogenic facility in the world
- Quench protection
  - Stored energy in one dipole: 8 MJ corresponds to a 40 t truck at 50 km/h

- LHC dipole design incorporates reversed field for oppositely rotating proton beams

LHC Dipoles

- **Around 1999: construction of dipoles start**

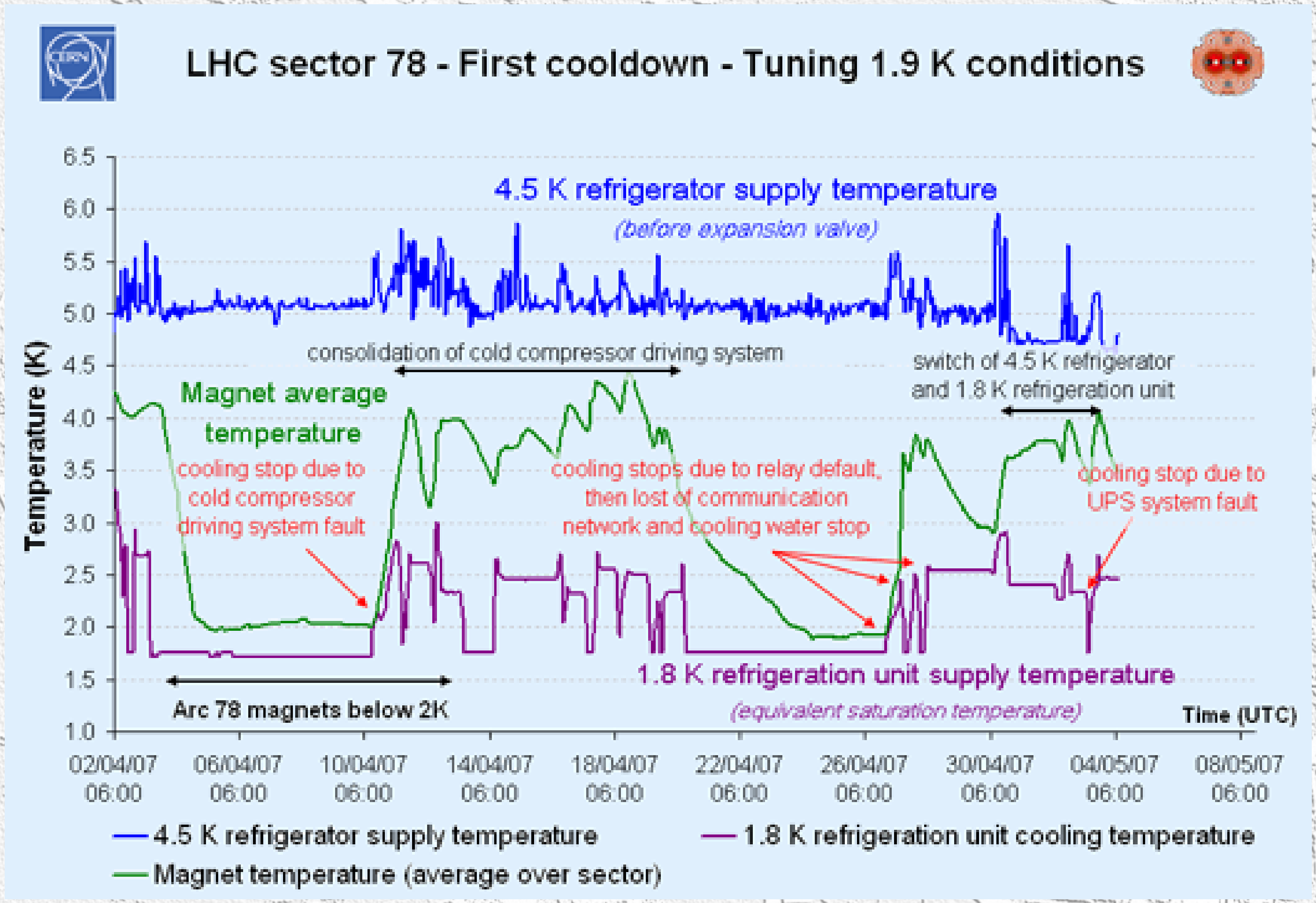


LHC Dipoles

Dipoles in the LHC Tunnel

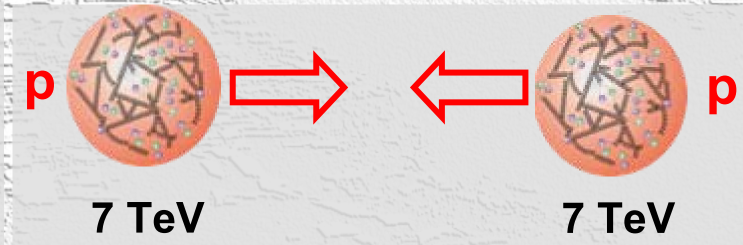
Cryogenics

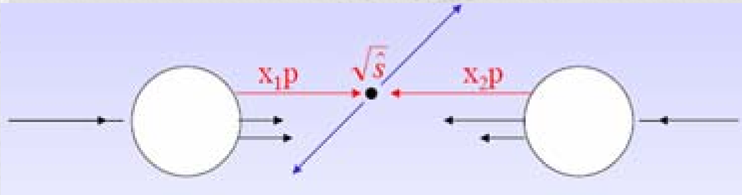
- First cool down of an LHC sector (> 3 km) in April 2007
- 1.9 K: colder than the universe

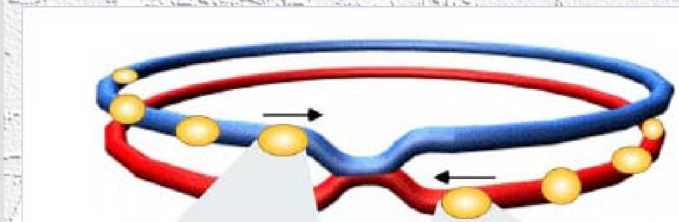


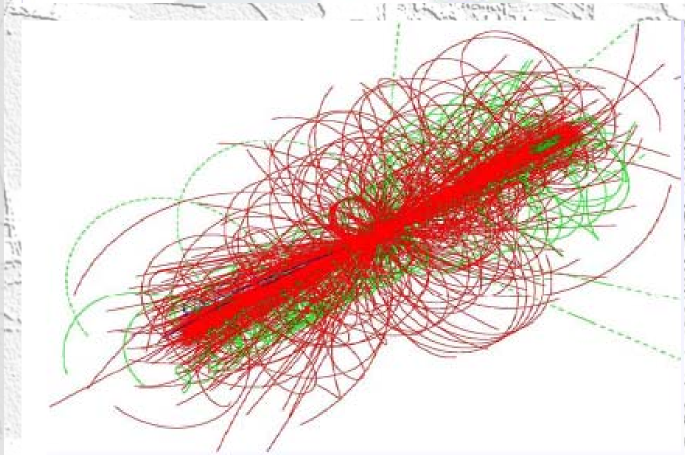
Challenges for LHC Detectors

- **Protons are composite particles**
  - **Bags filled with quarks and gluons**
  - **Quark-quark and gluon-gluon collisions are the fundamental processes**
  - **Screened by interactions of other quarks & gluons**
- **LHC is filled with 2835 + 2835 proton bunches**
  - **Collisions every 25 ns**
    40 MHz crossing rate
- **10^{11} protons per bunch**
  - **25 pp interactions per crossing (pile-up)**
  - **Each bunch collision produces ≈ 1600 charged particles**

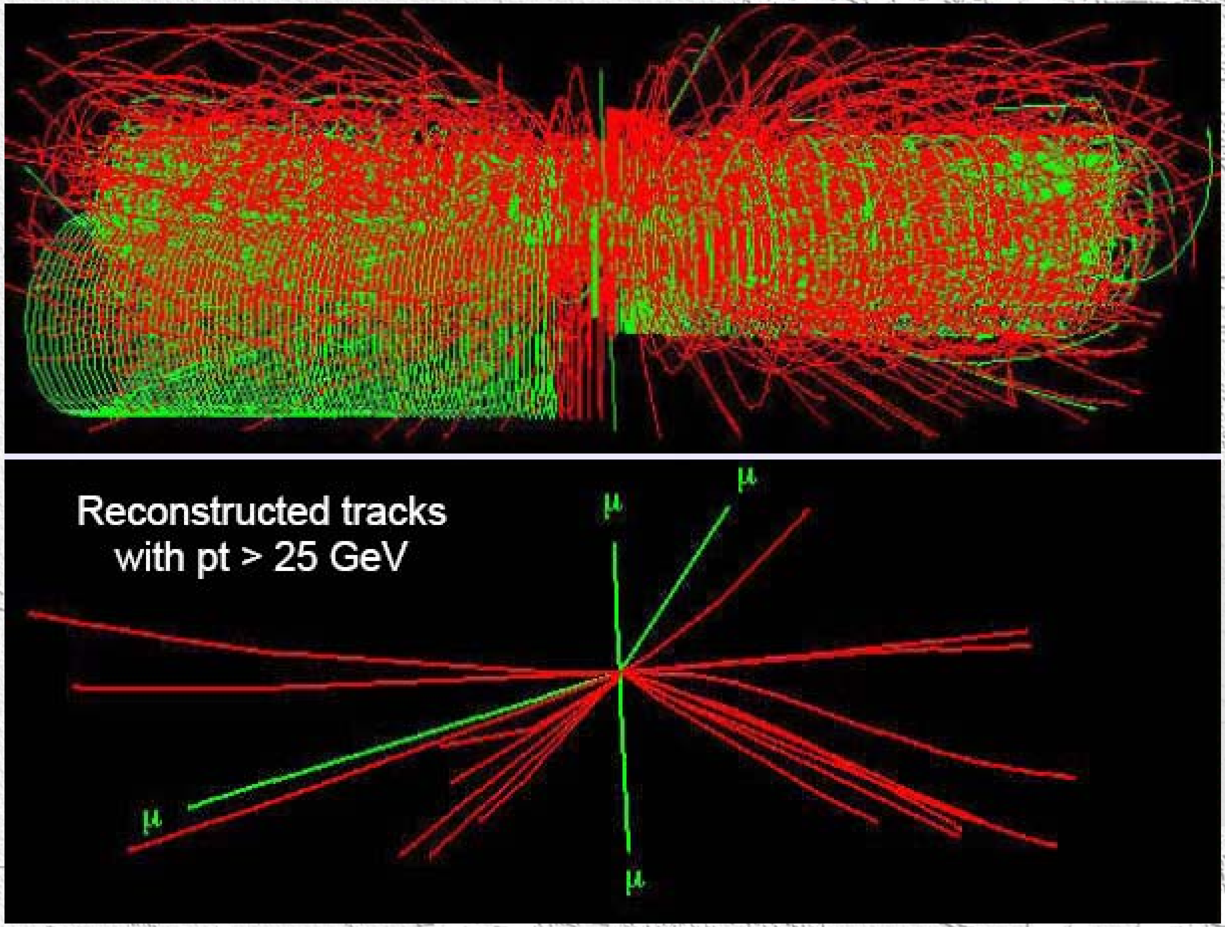








A Collision Producing a Higgs Boson

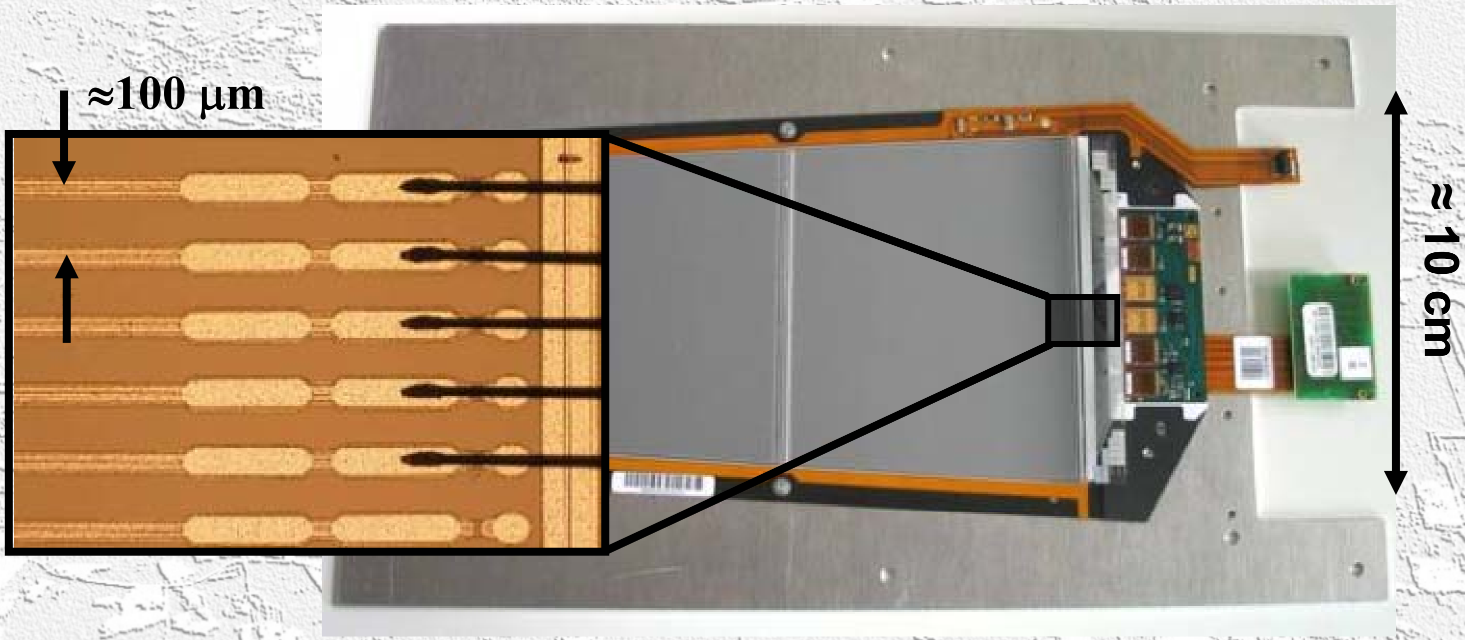


- with 25 pile-up interactions
- Remove low energy tracks (p_T < 25 GeV)
- H → ZZ → 4 muons

- Identify each track **requires a highly granular detector**
- Reconstruct every track **takes a lot computing power**

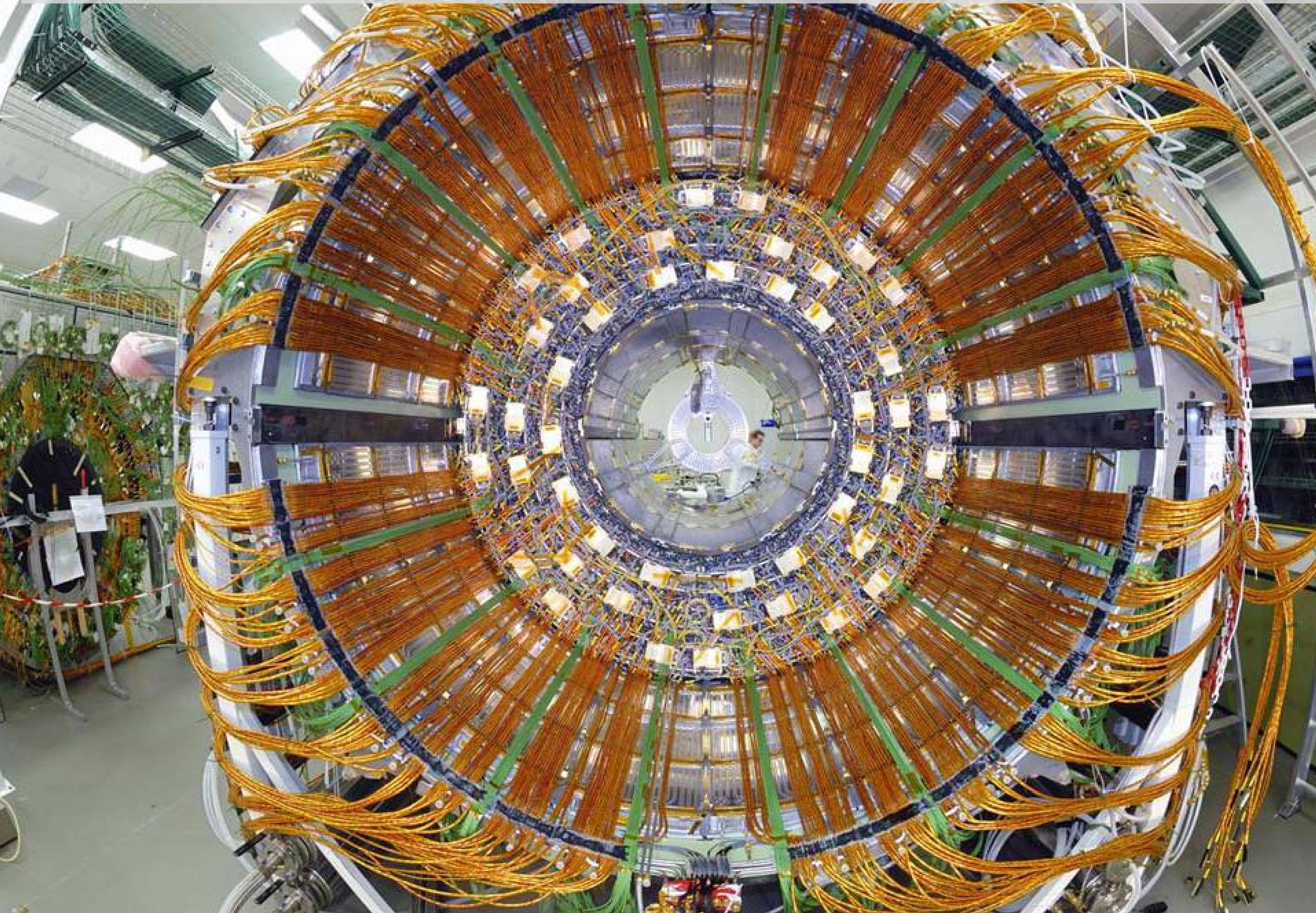
Example: CMS Tracking Detector

- Silicon strip detector



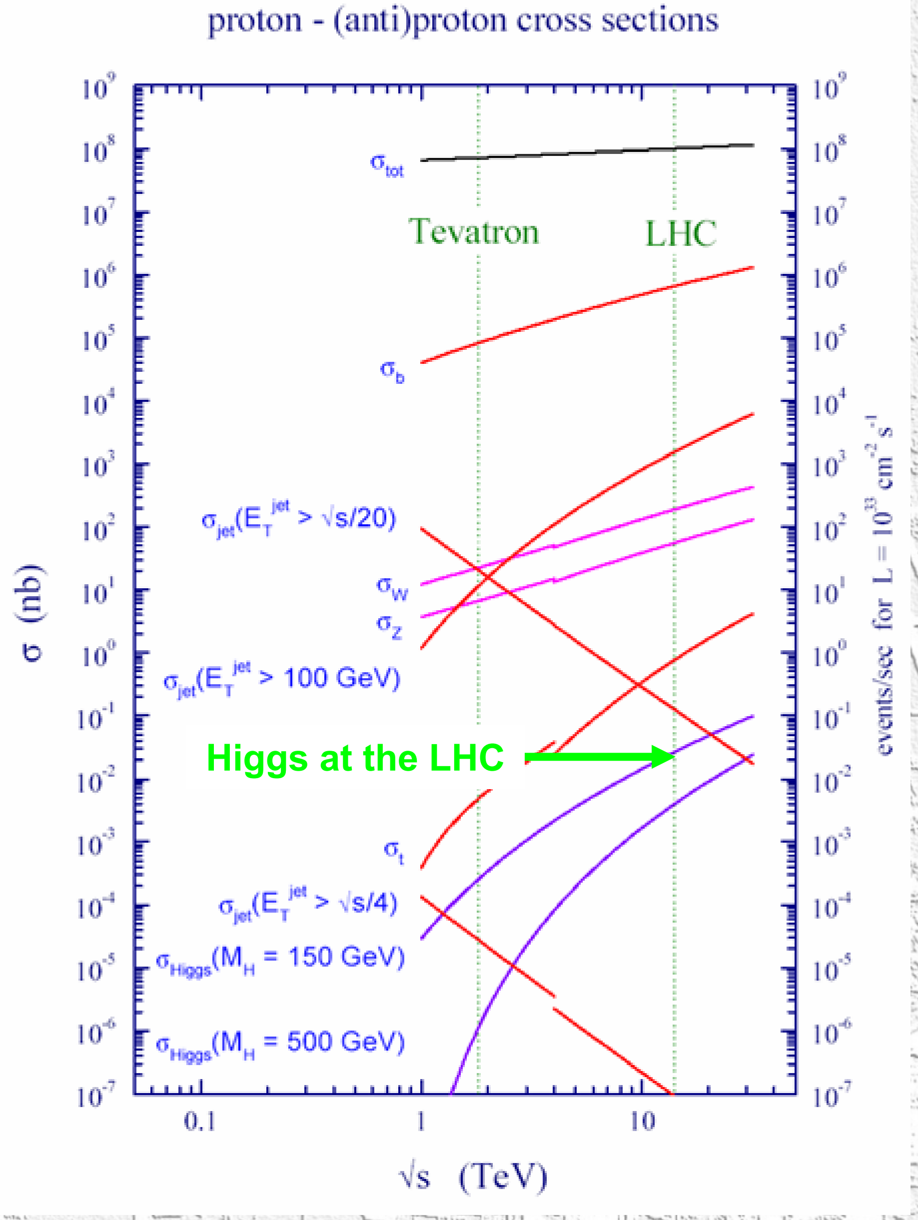
- 16000 such modules built
- 220 m^2 of silicon surface (almost a tennis court…)
- Largest silicon detector ever built

A Dream Becomes Reality...



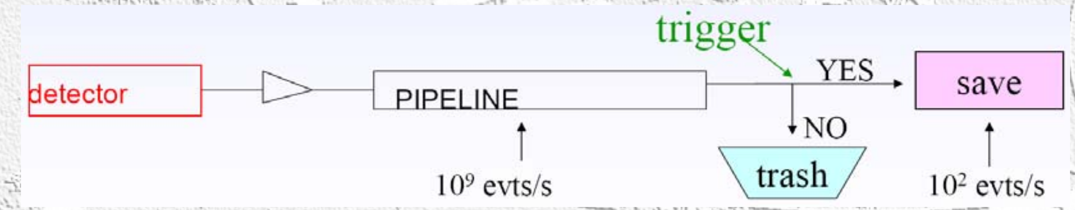
Looking for a Needle in a Haystack

- Protons are large particles 10^{-15} m diameter
- Not pointlike as e.g. electrons (diameter < 10^{-18} m)
- Huge proton-proton interaction rate at the LHC
  - 10^9 per second
  - 10^8 per second in initial phase
- However, most interesting processes are rather rare
- E.g. about 1 Higgs boson per minute will be produced



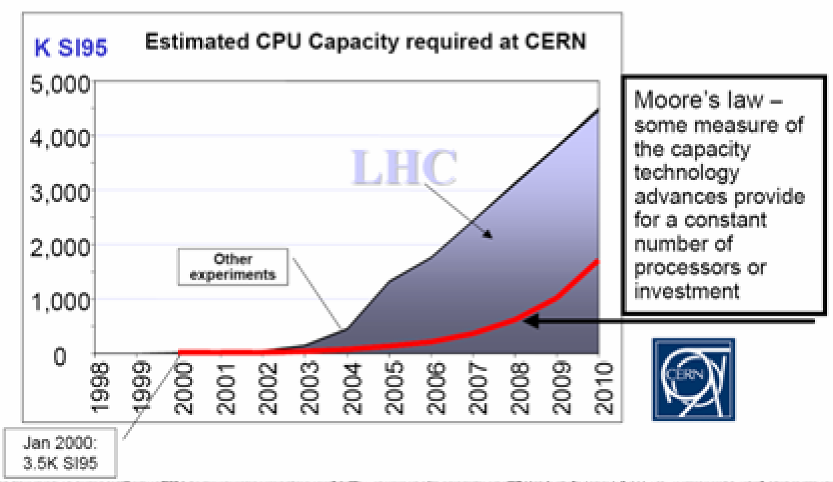
Finding the Higgs Boson

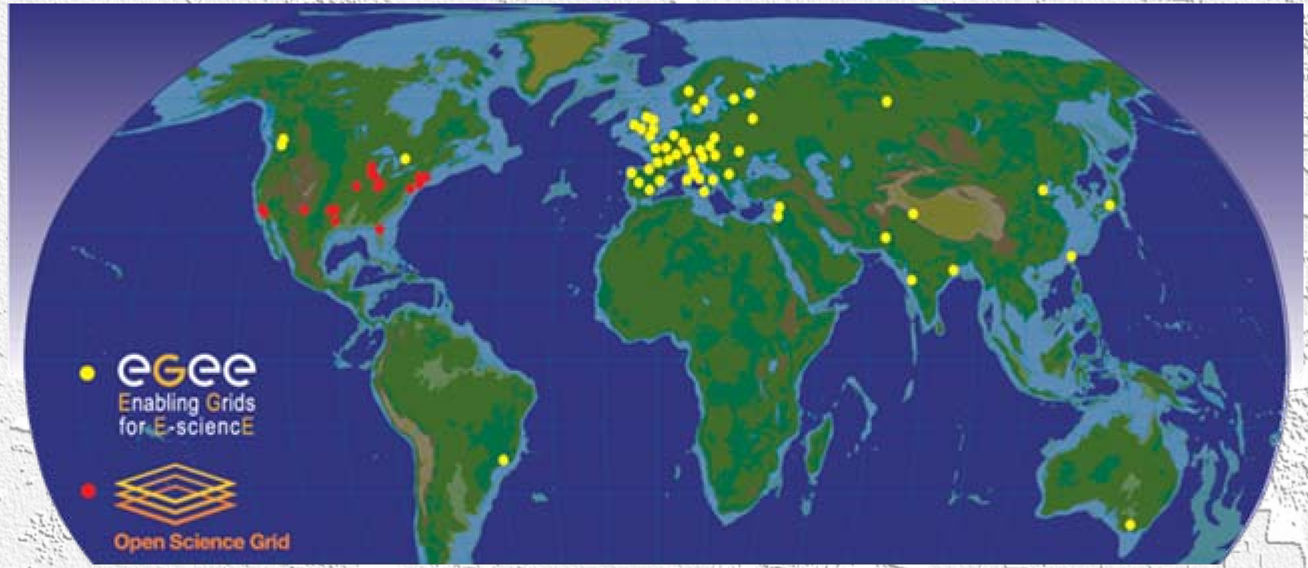
- **Online trigger**
  - **Only a tiny fraction of the collision can be stored for detailed inspection**
    - **Interaction rate ≈ 10^9 events/s**
    - **Max. record rate ≈ 100 events/s event size ≈ 1 MByte ⇒ 1000 TByte/year**
  - **Trigger rejection ≈ 10^7**
- **Collision interval is 25 ns corresponds to 5 m cable delay**
- **Trigger decision takes a few μs (1st level)**
  ⇒ store massive amount of data in front-end pipelines
  ⇒ massive parallel computing



The Worldwide Computing Grid

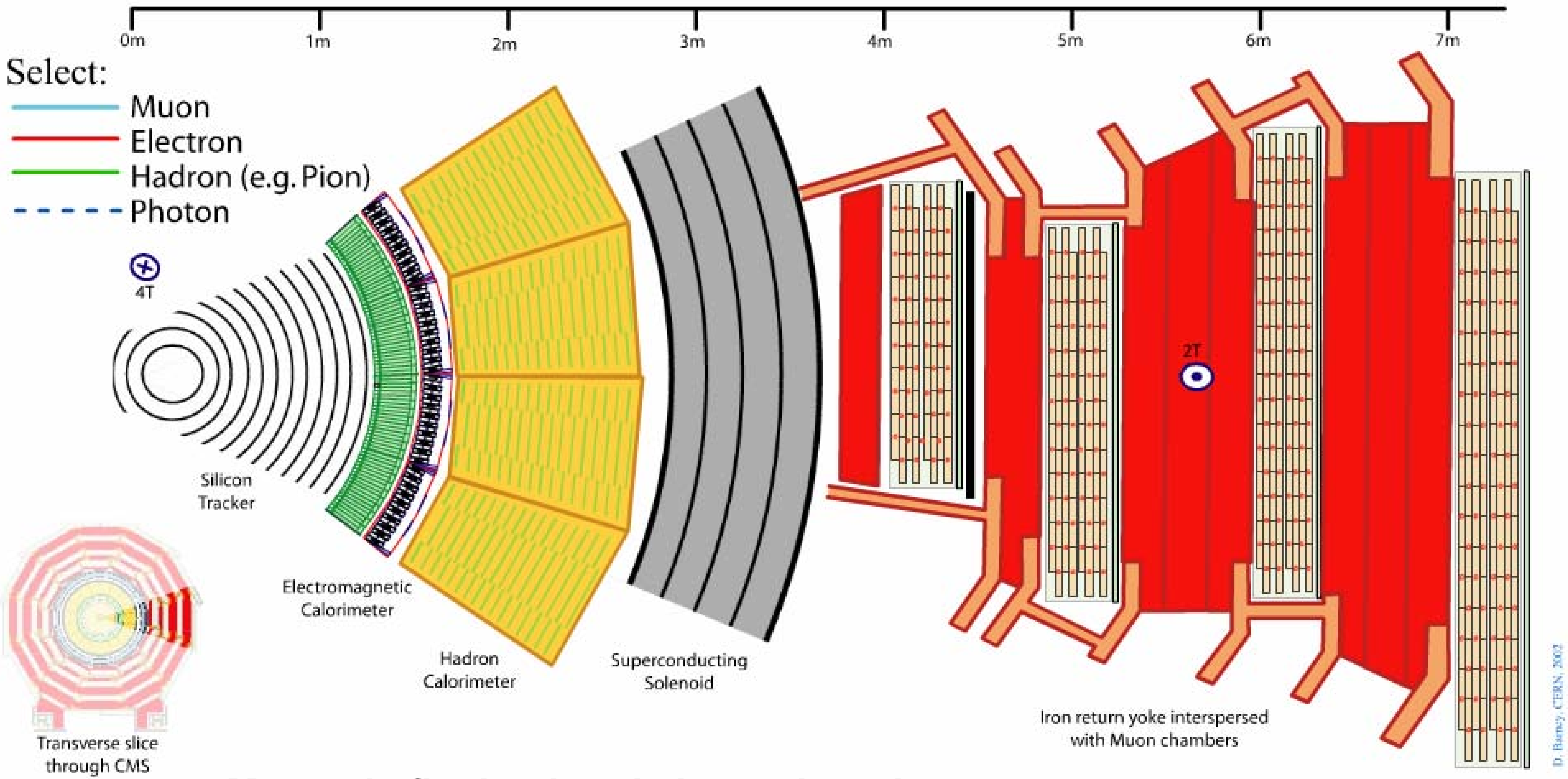
- **1000 TByte/year and experiment are still huge + simulation + calibration + reconstruction + …**
- **Grid Computing a world-wide computing centre**





Principle of Particle Physics Detectors

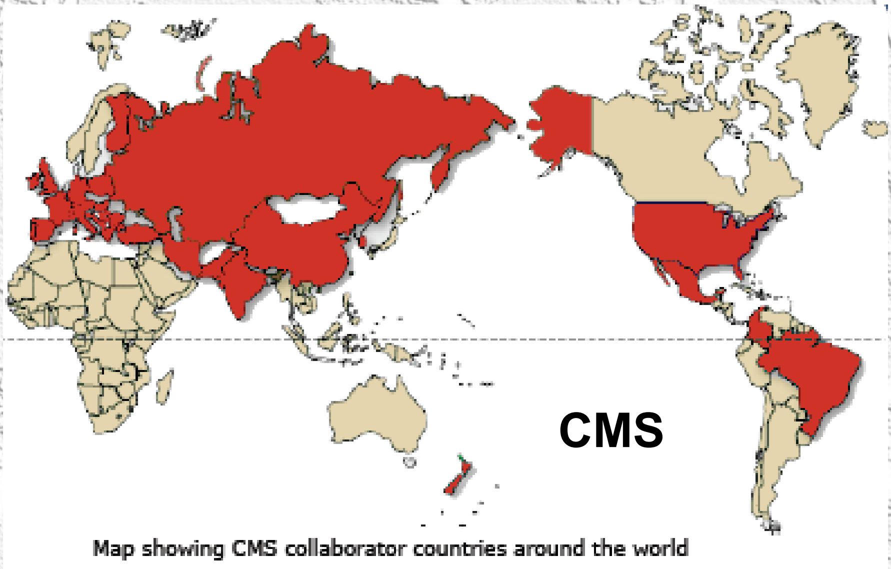
- **Slice through the CMS detector**



Magnetic field to bend charged particles

ATLAS and CMS

- **ATLAS and CMS are the two large multi-purpose detectors at the LHC**
- **Each collaboration counts about 2500 scientists & engineers from about 40 different countries**



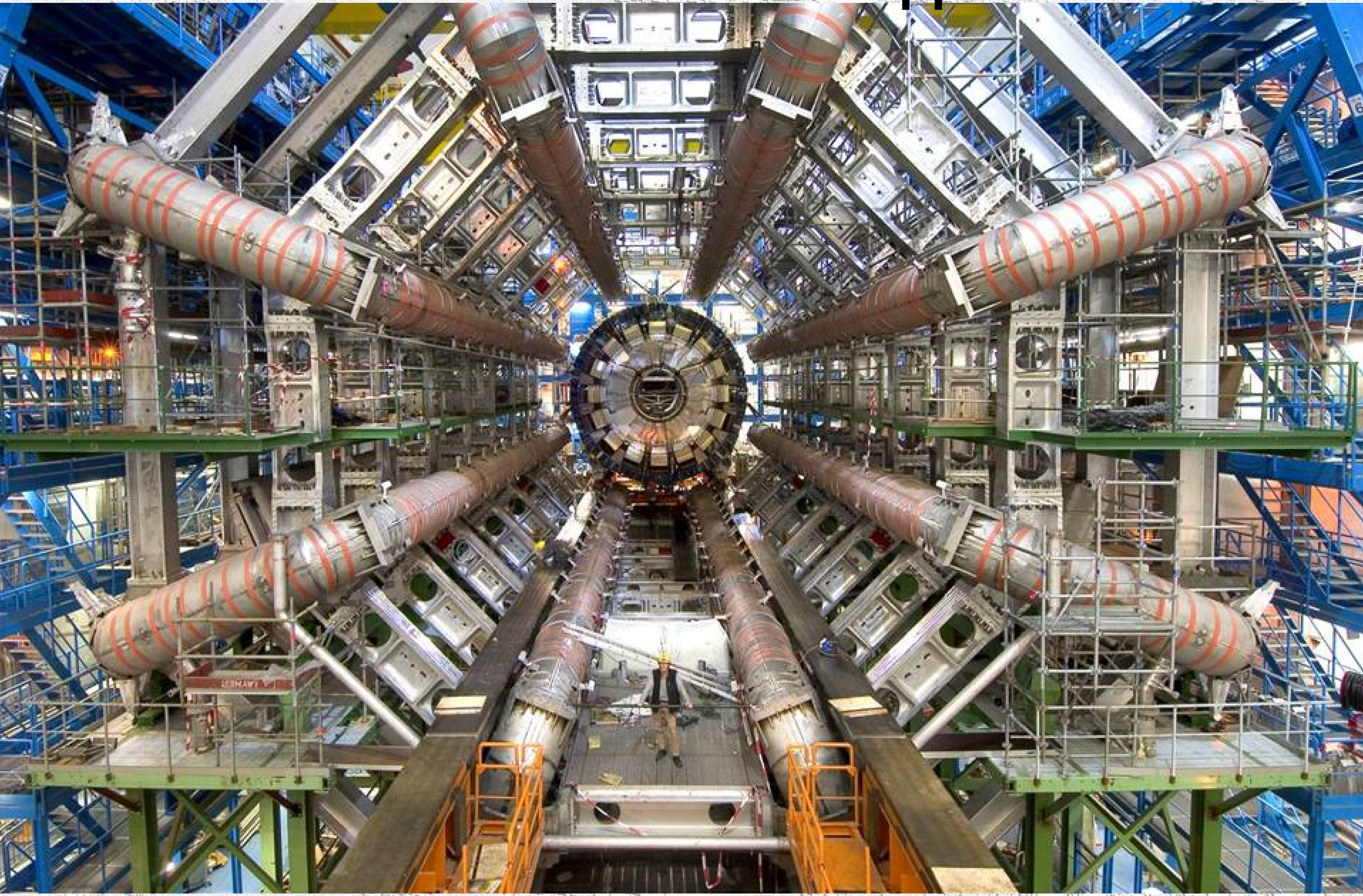
International Collaboration

International Collaboration

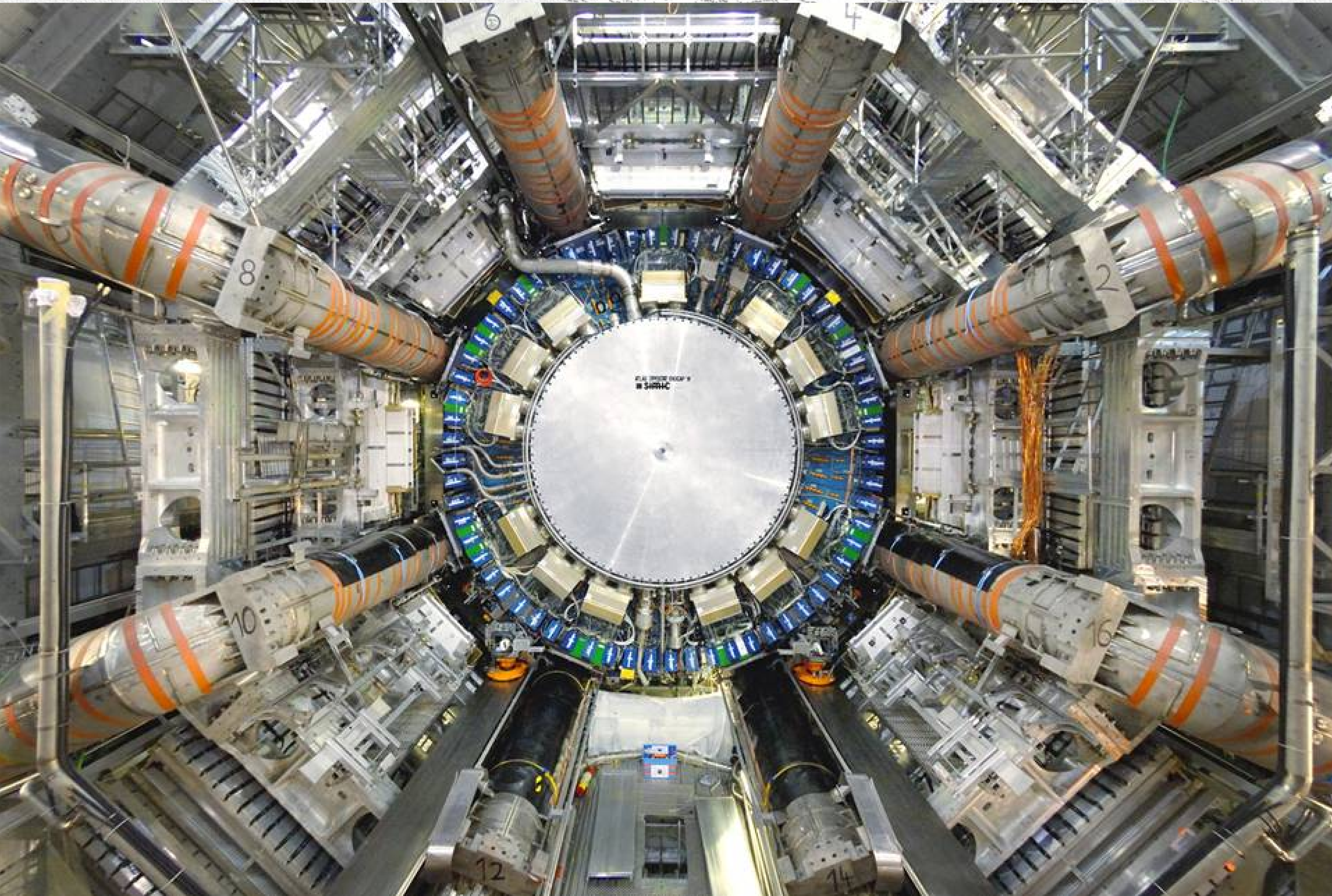
- **Brass casings of decommissioned shells of the Russian Nothern Fleet**

- **Converted to brass absorbers for the CMS calorimeter**

ATLAS: A Toroidial LHC ApparatuS

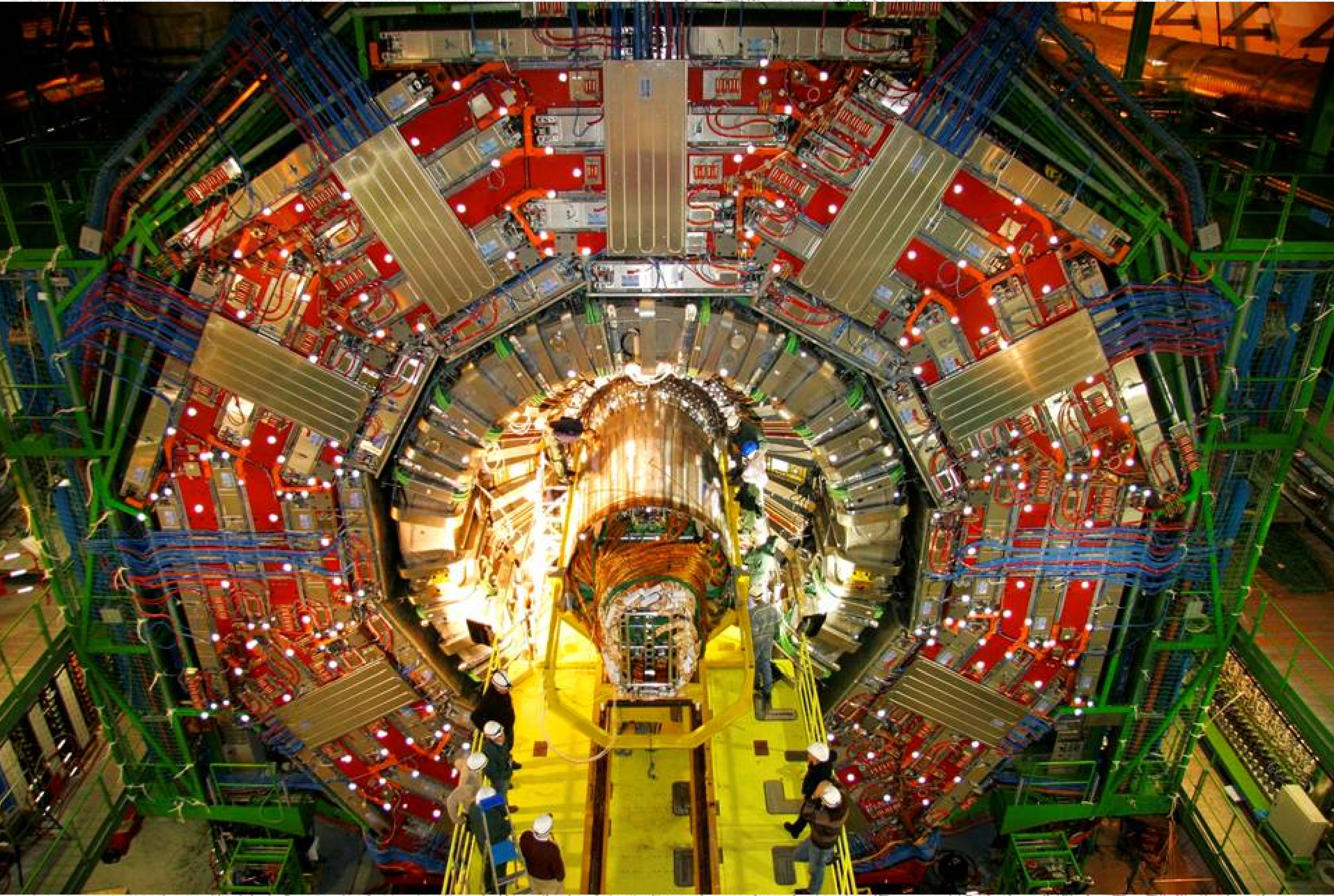


ATLAS with inner Detectors

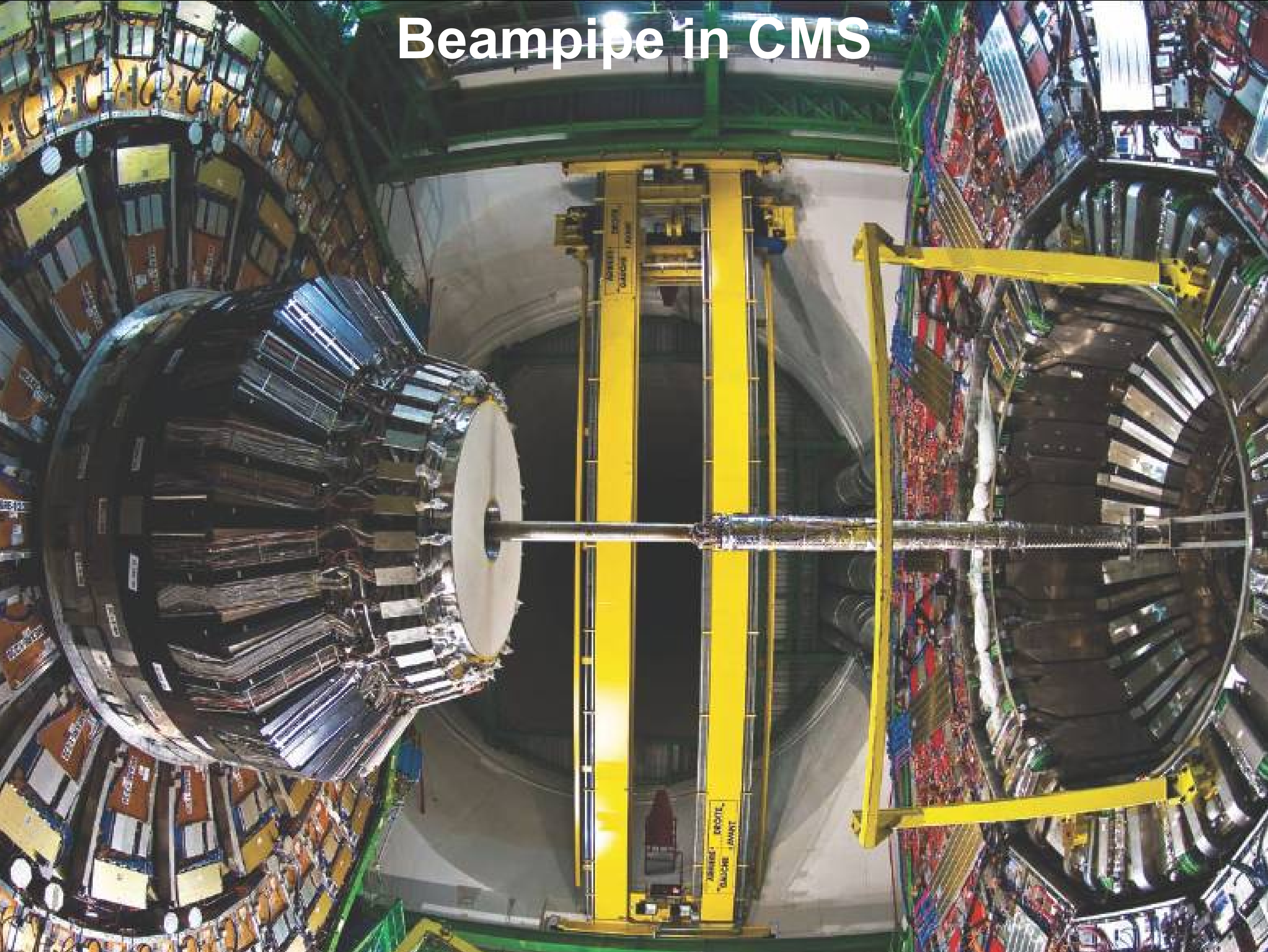


CMS: Compact Muon Solenoid

CMS

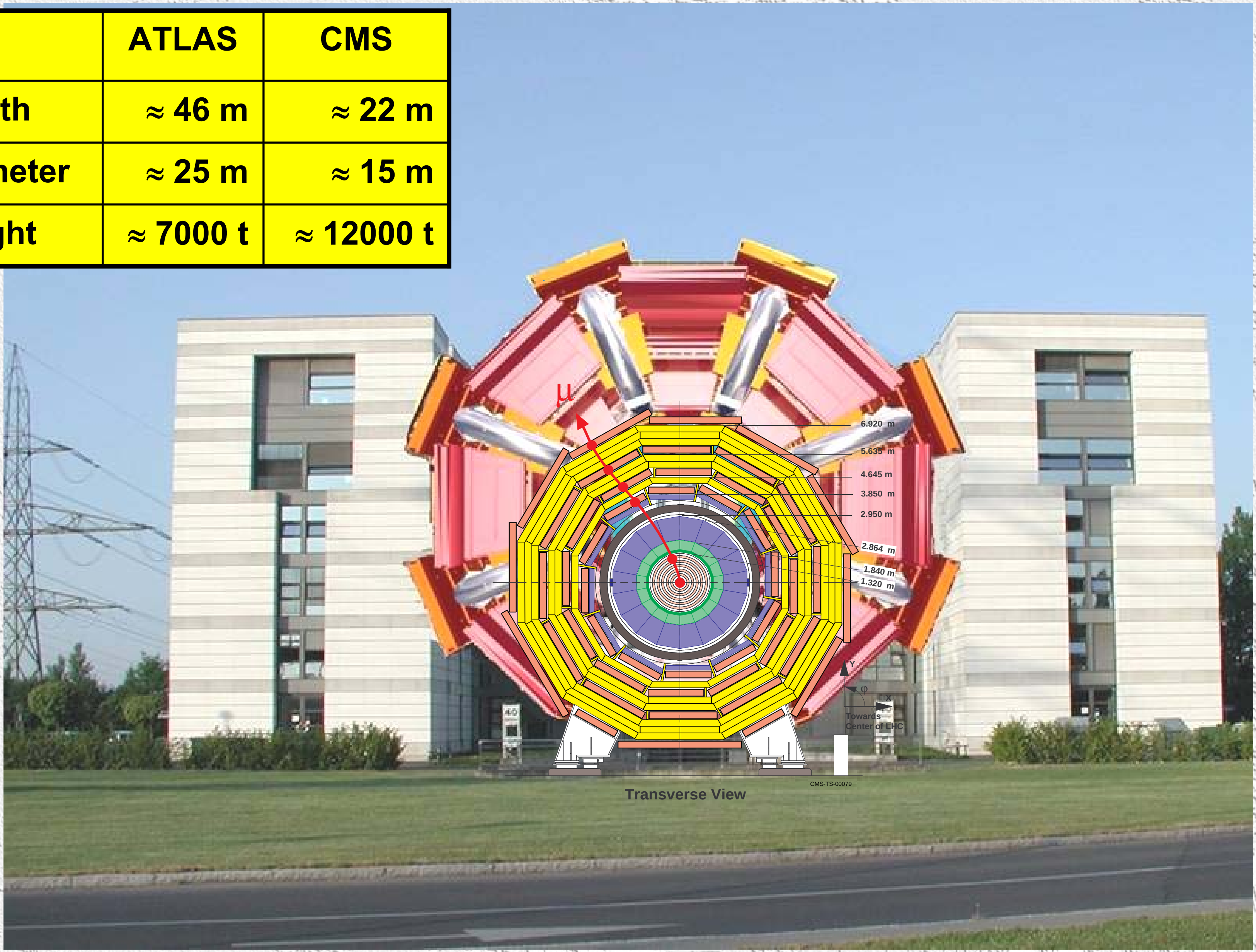


Beampipe in CMS



Comparison ATLAS and CMS

	ATLAS	CMS
length	≈ 46 m	≈ 22 m
diameter	≈ 25 m	≈ 15 m
weight	≈ 7000 t	≈ 12000 t

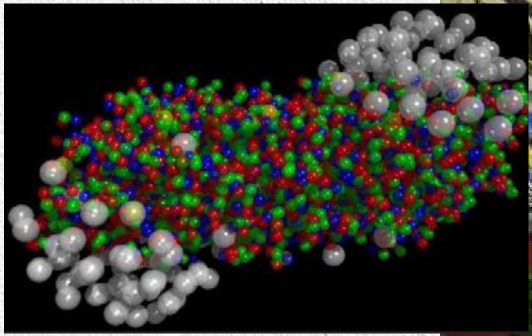


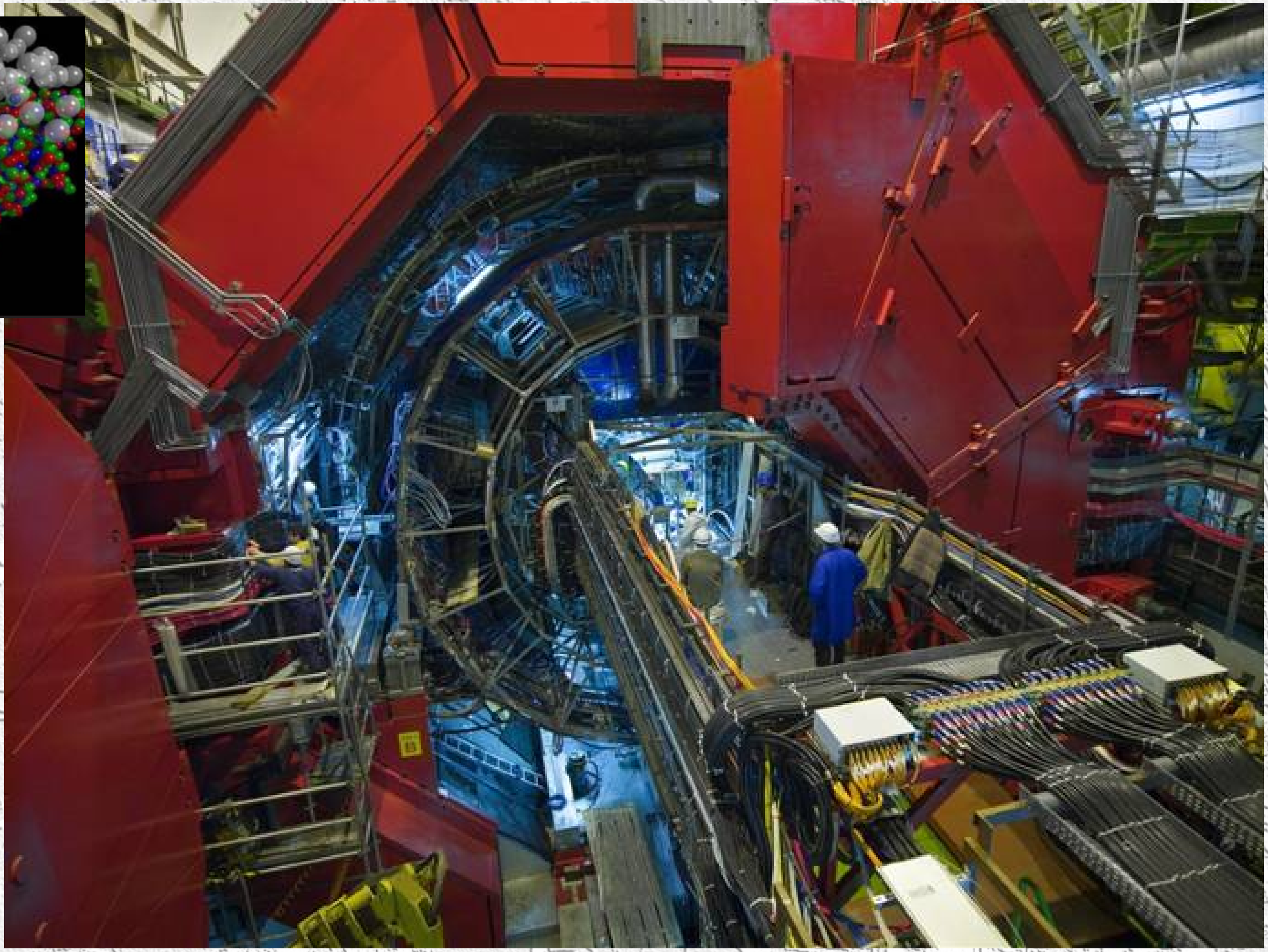
LHCb

- **Experiment to address the question of matter-antimatter asymmetry**

ALICE

- **Experiment addresses new state of matter: the quark-gluon plasma**





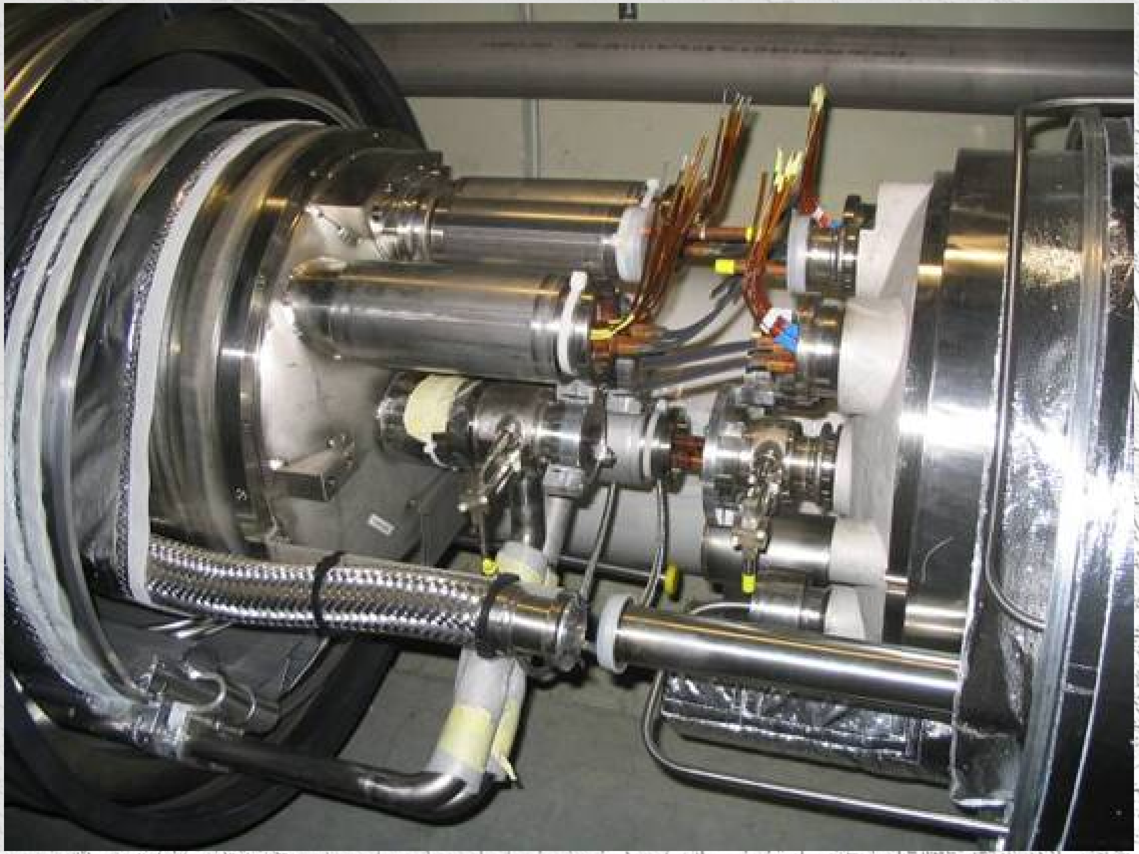
- **Heavy ion collisions, eg. Pb-Pb**

Where are we today? Status and Expectations

- **First circulating beams on September 10, 2008**

LHC Accident

- **Major accident on September 19, 2008**
  - **Bad connection between 2 magnets (resistance >> 1 nΩ)**
  - **Heat load ≈ 10 W cannot be cooled away**
  - **Thermal runaway**
- **Quench protection of magnets worked well**
- **But light arc between magnets**
  - **Destroyed a Helium vessel**
  - **2 tons of He effused**
  - **Shock wave in tunnel**



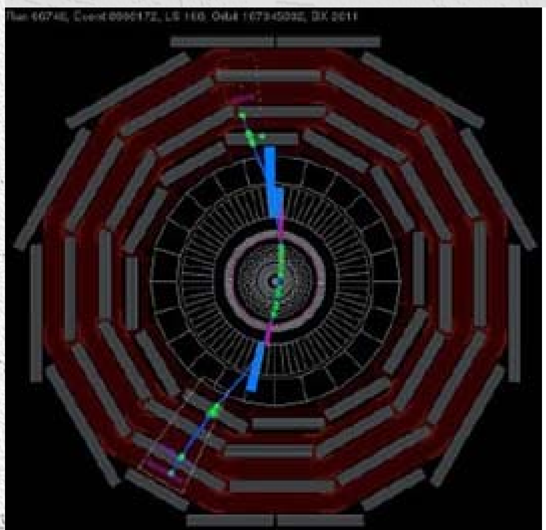
Damage

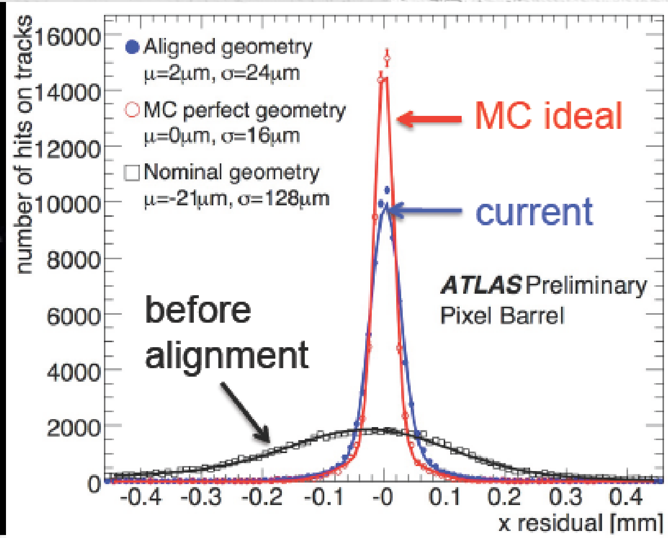
53 magnets inspected, repaired & reinstalled

Plans

- **Improve protection systems**
- **Restart LHC in September 2009**
- **First collisions in October 2009**
- **Operation until end 2010**
  - **reduced energy (5 TeV)**

- **Detectors are ready and preparing for data taking with cosmic rays**

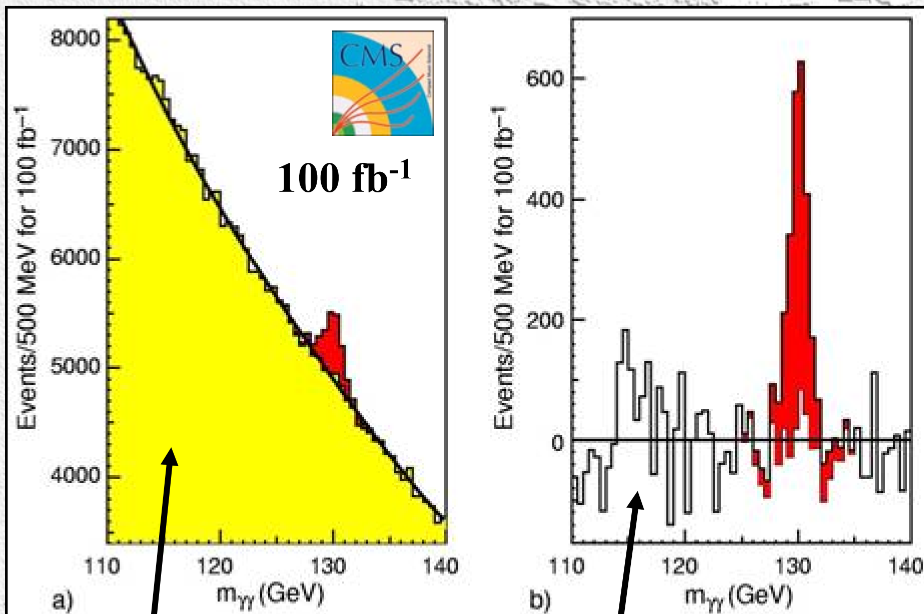


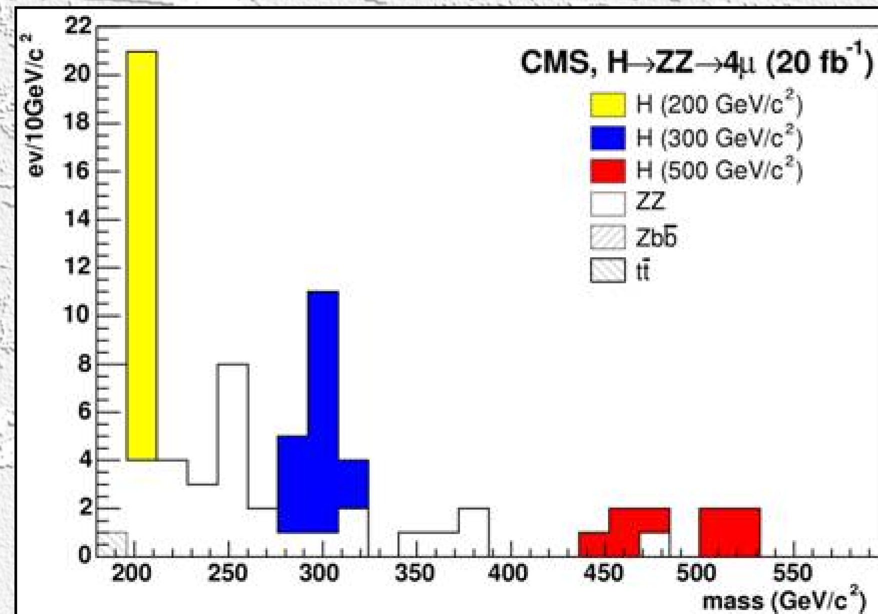


Possible Higgs Discovery in 201x

$H \rightarrow \gamma\gamma$:
$m_H = 130$ GeV
$\sigma_{mH} \approx 1$ GeV

$H \rightarrow ZZ \rightarrow 4\mu$:
$m_H = 200\ (300, 500)$ GeV





large combinatorial background

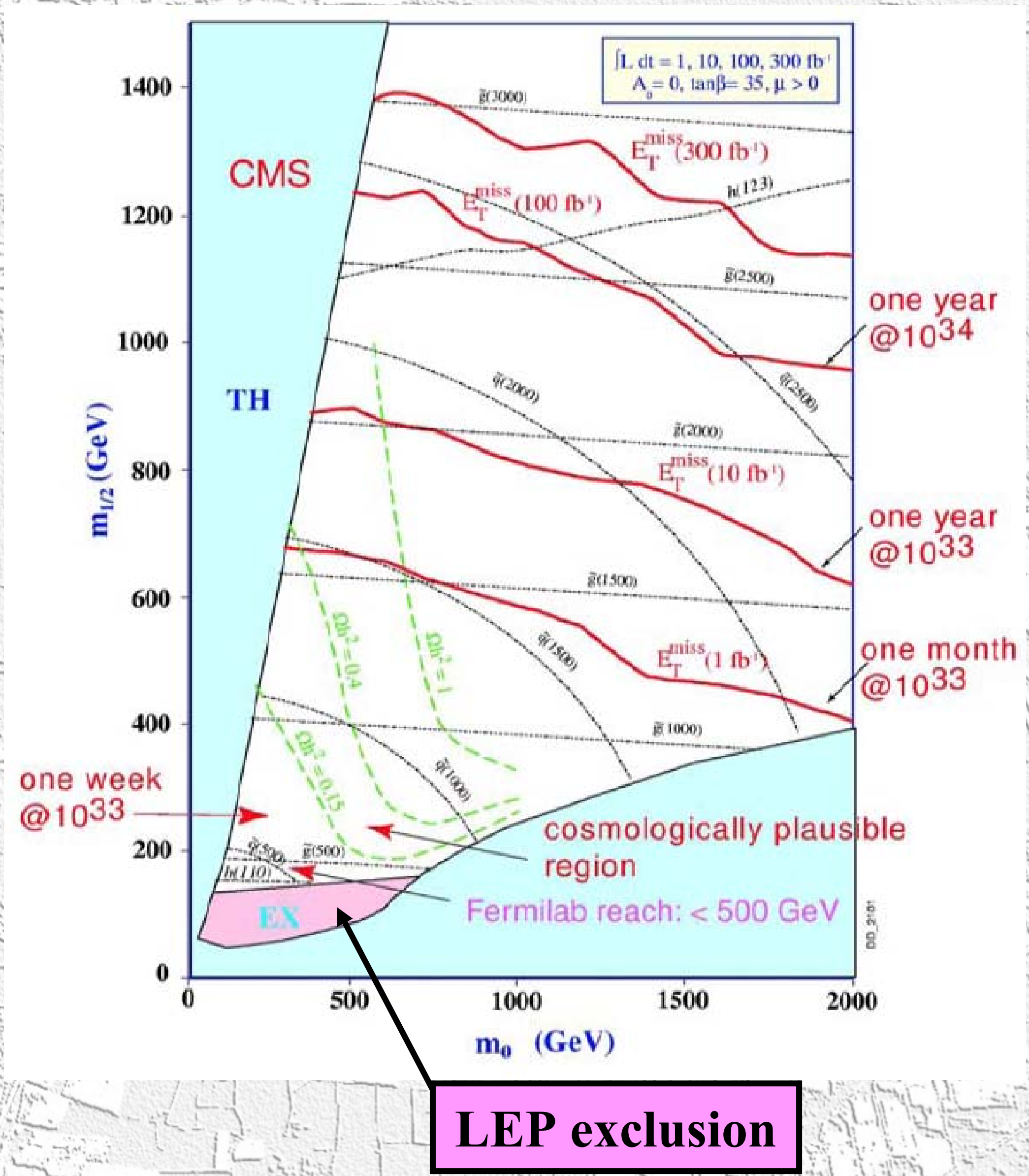
background subtracted

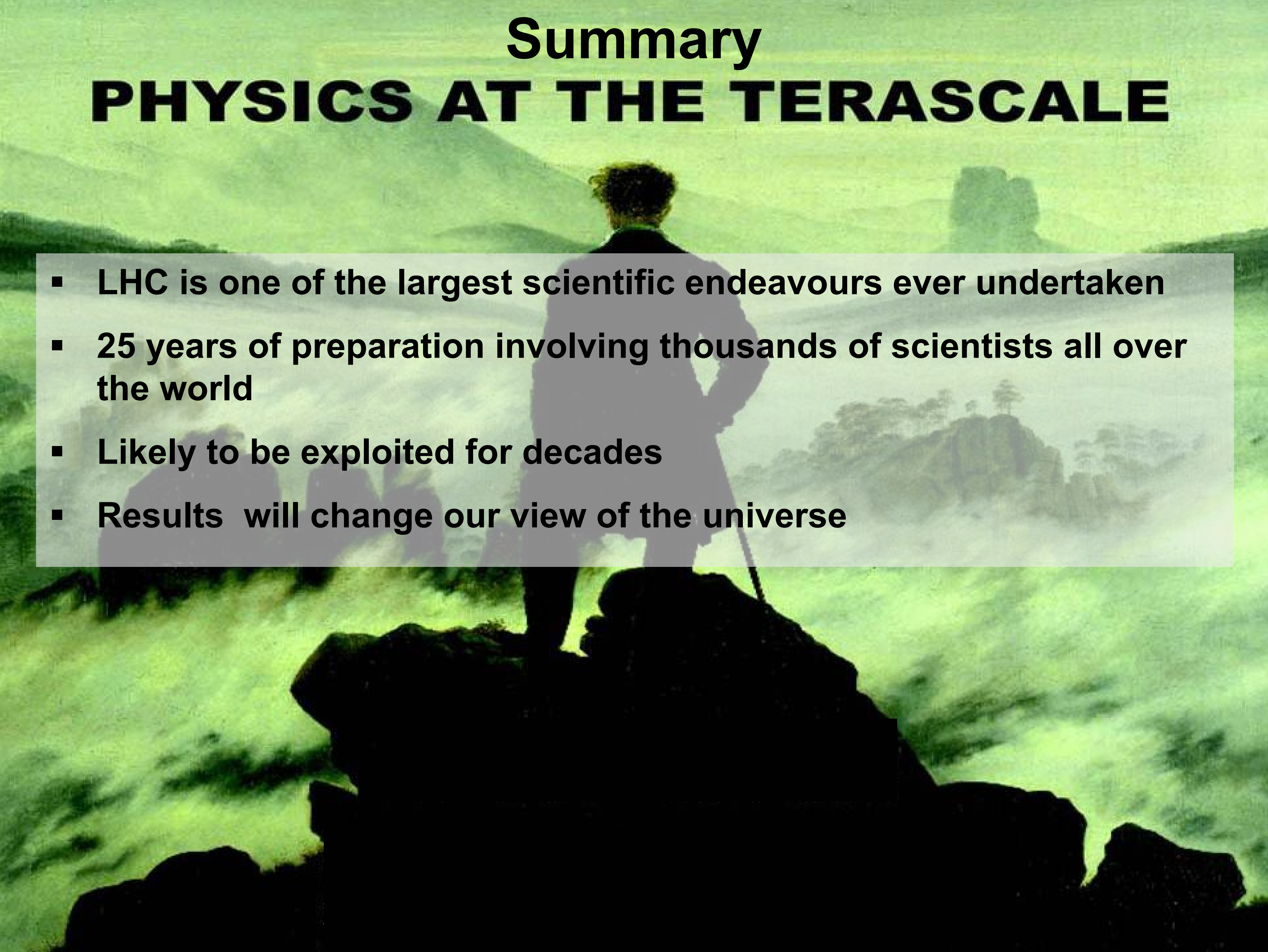
Note the increasing signal width

Supersymmetry

- **LHC will eclipse previous experiments and chart new territory in the parameter space**

- **Example:
discovery reach as function of luminosity and model parameters which fix the mass scale of SUSY parameters**





Summary

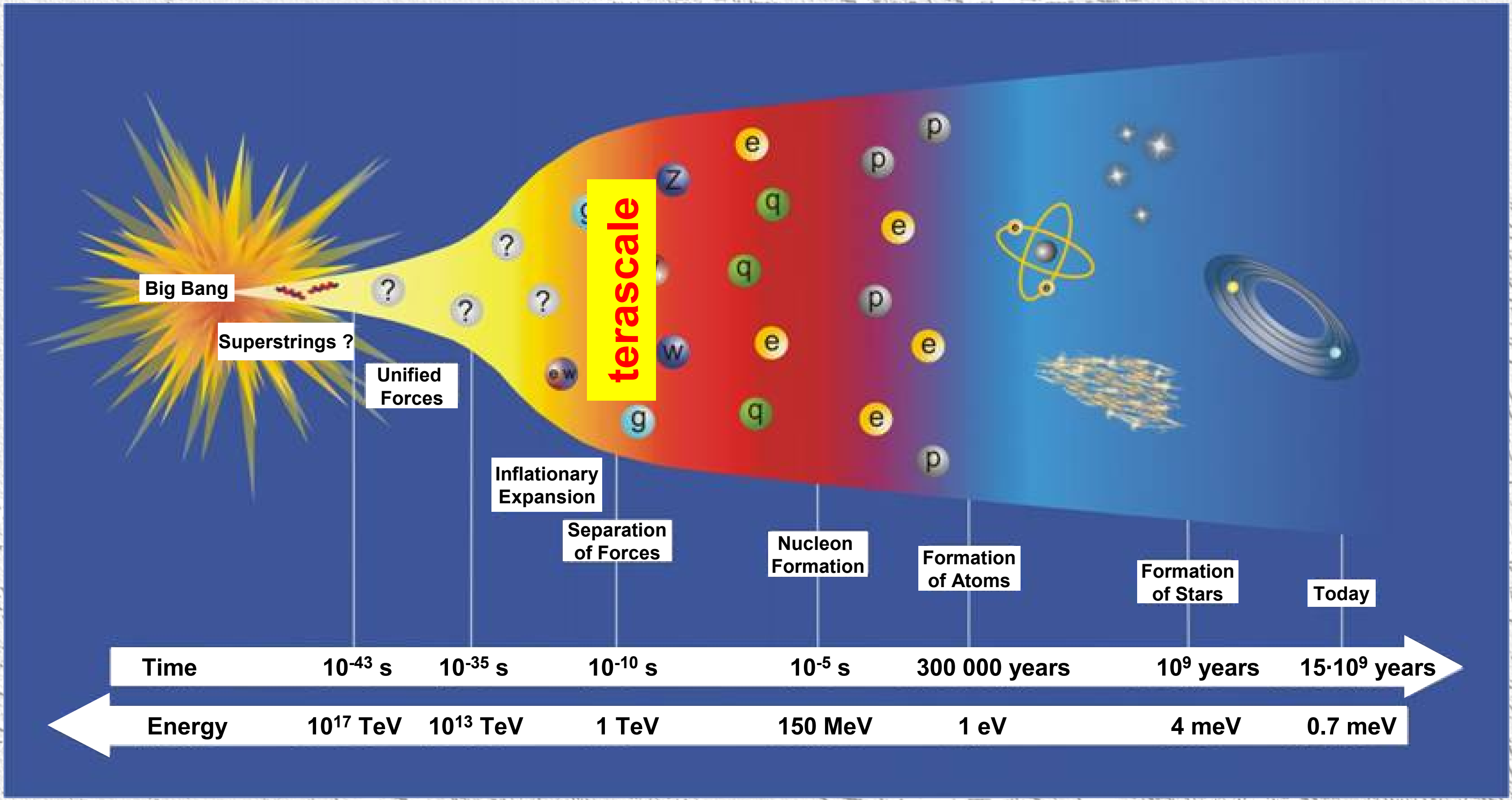
PHYSICS AT THE TERASCALE

- LHC is one of the largest scientific endeavours ever undertaken
- 25 years of preparation involving thousands of scientists all over the world
- Likely to be exploited for decades
- Results will change our view of the universe

- **Backup slides**

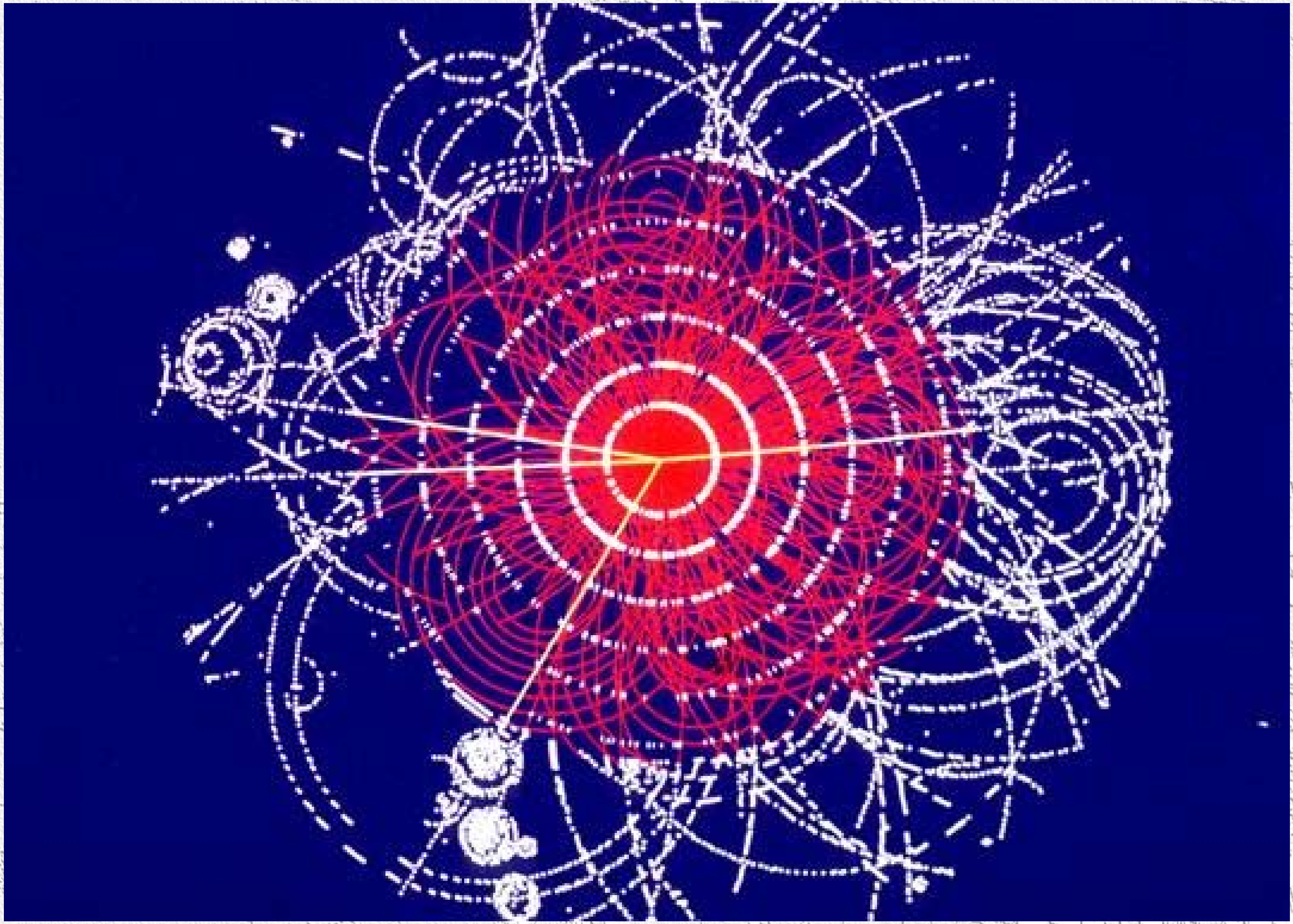
Vision

- Revolutionary advances in understanding the microcosm
- Connect microcosm with early Universe



Particle Physics at the Energy Frontier with highest collision energies ever will change our view of the universe

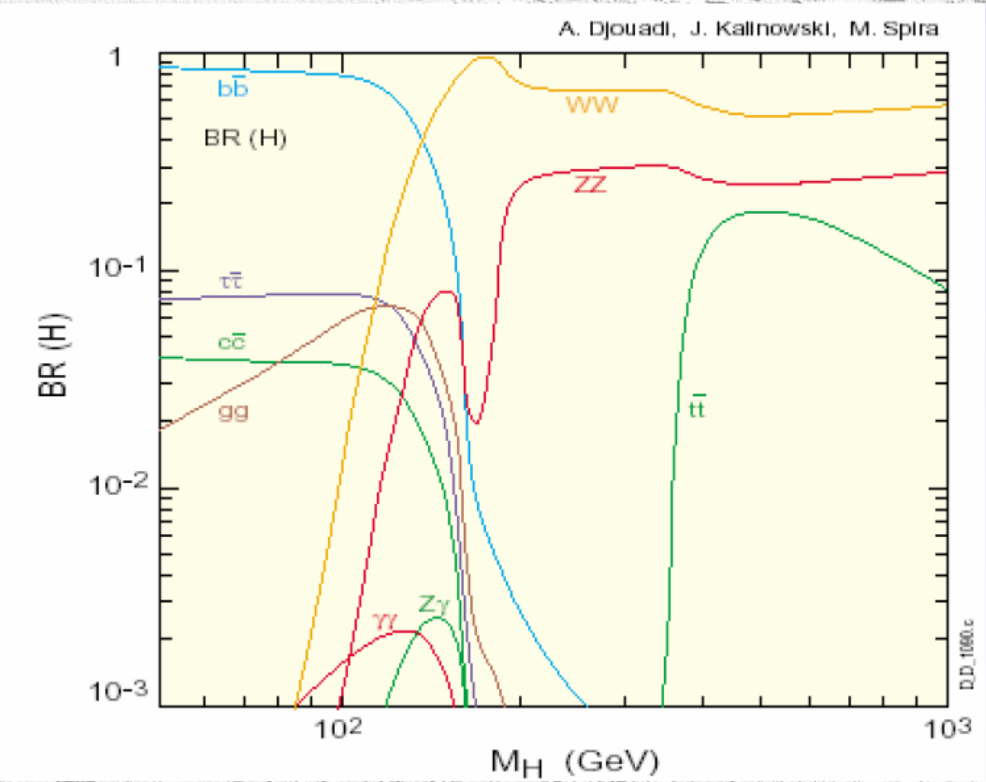
A Collision Producing a Higgs Boson



Higgs Boson Decay

Higgs couples proportional to masses
⇒ preferentially decaying into heaviest particle kinematically allowed

Branching ratio versus m_H:



- **Low mass (115 < m_H < 140 GeV**
  H → bb make up most of the decays problem at the LHC because of the huge QCD background !
- **Intermediate (140 < m_H < 180 GeV)**
  H → WW opens up use leptonic W decay modes
- **High mass (m_H > 180 GeV)**
  H → ZZ → 4 leptons golden channel!